Dark Matter in the Universe

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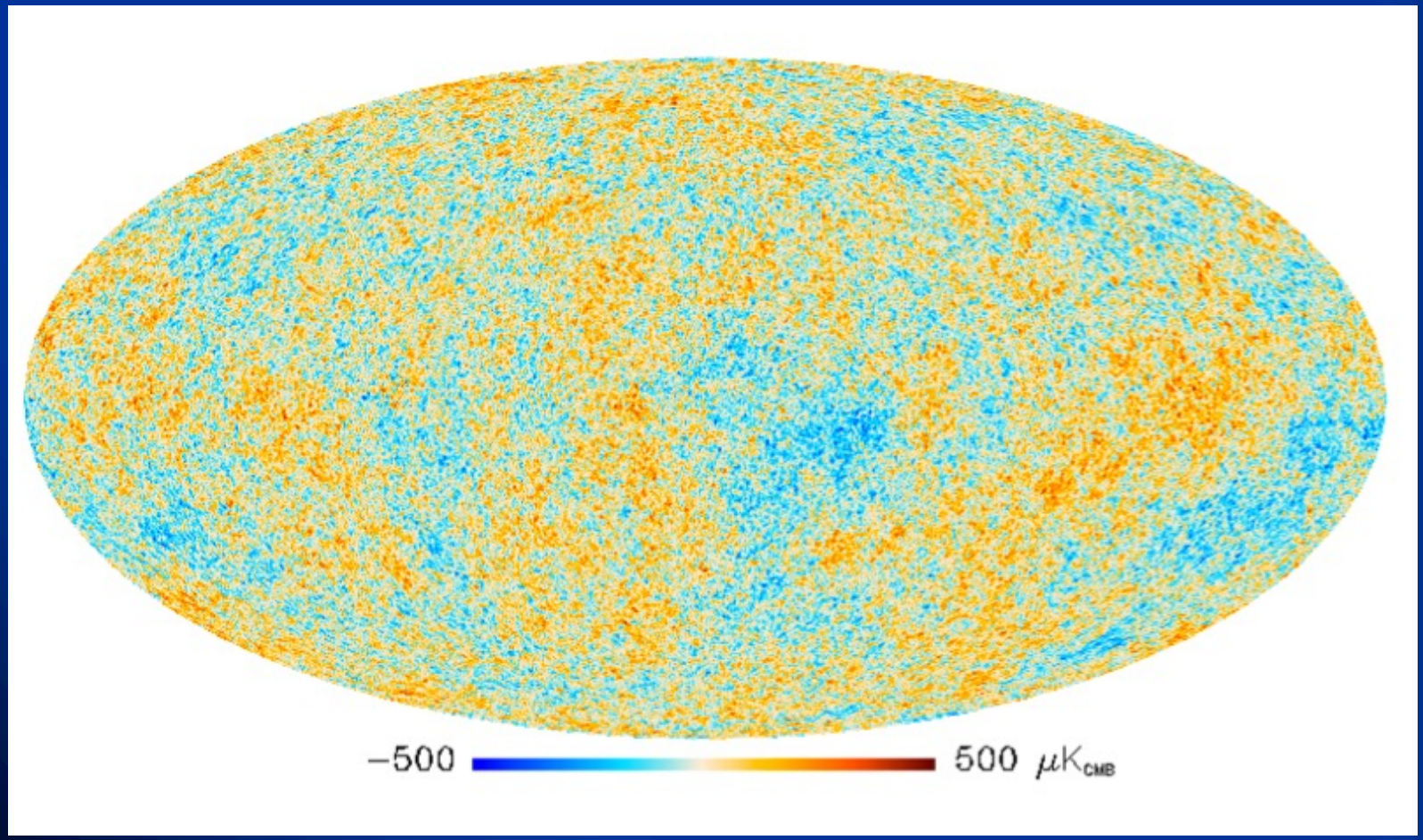
ENORMOUS PROGRESS OVER THE LAST CENTURY

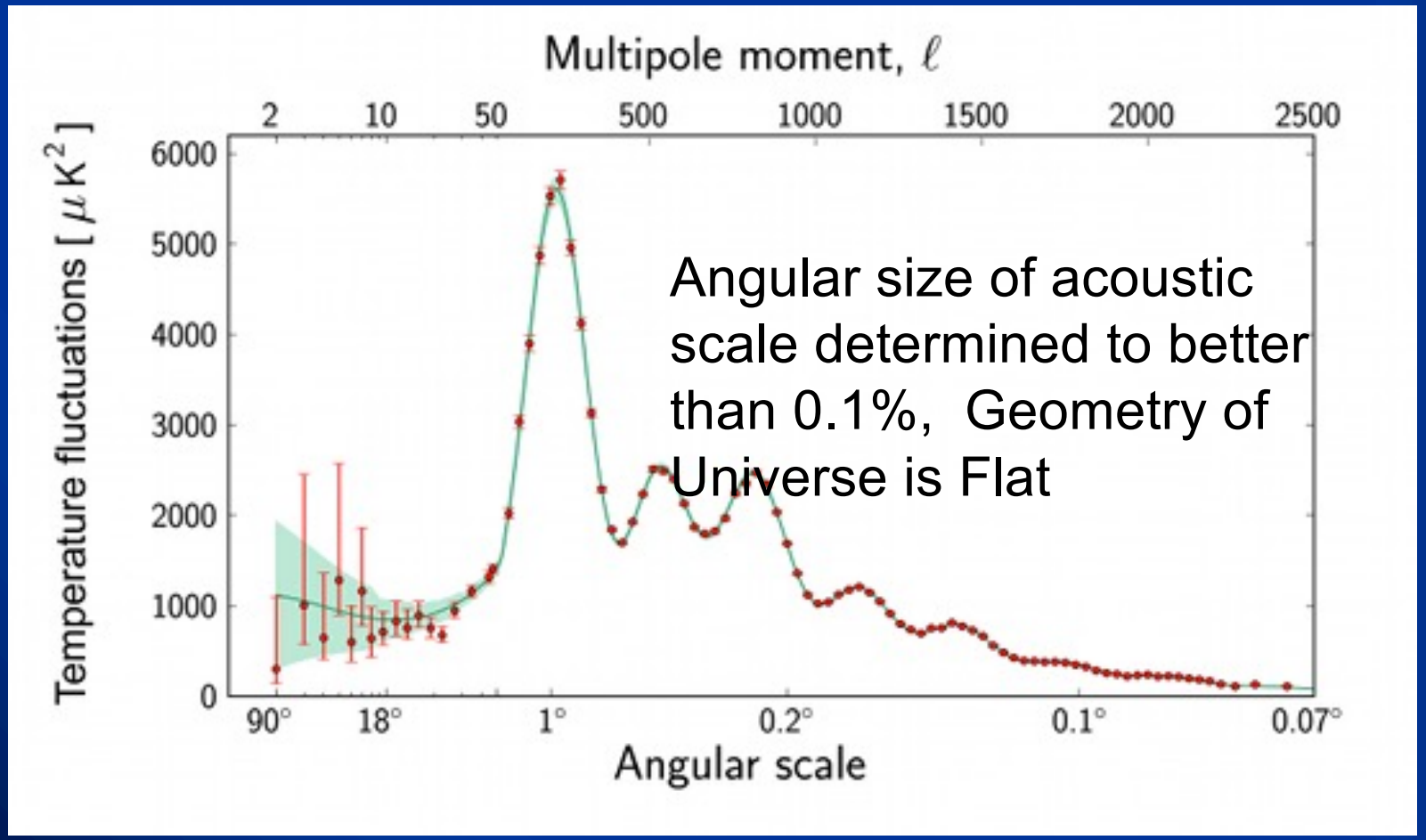
At the turn of the Millenium, recent experiments answered BIG QUESTIONS:

- We know the geometry of the universe
- We know the energy density of the universe
- We know the age of the Universe
- We understand the physics all the way to the edge of the observable universe (the horizon)
- BUT many questions remain: what is the universe made of (dark matter and dark energy)? How did it begin? How will it end?

The Universe according to ESA's Planck Space Telescope



Planck Satellite (7 acoustic peaks)



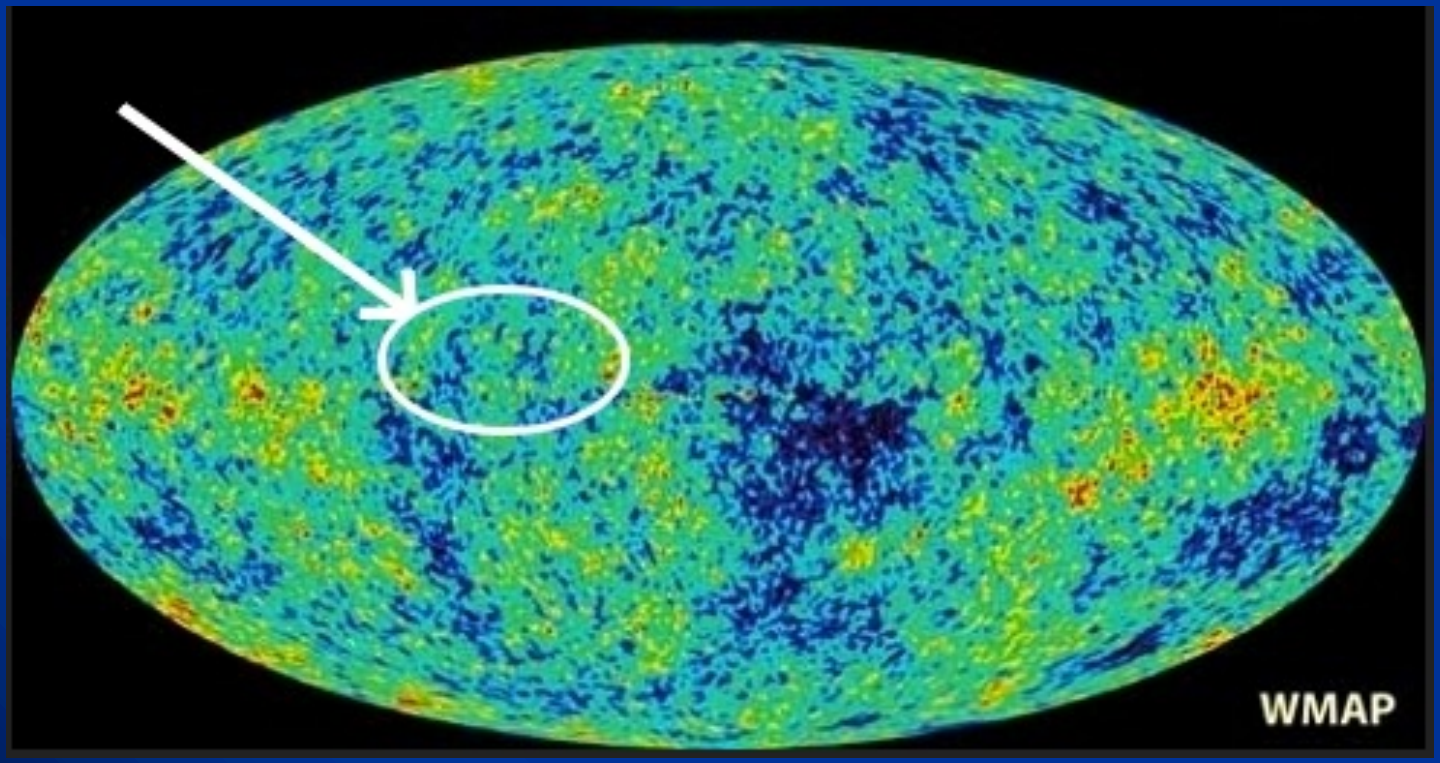
Implies energy density of the Universe is

$$\rho = \rho_c = 10^{-29}\ \mathrm{gm/cm^3}$$

Cosmological Parameters from Planck

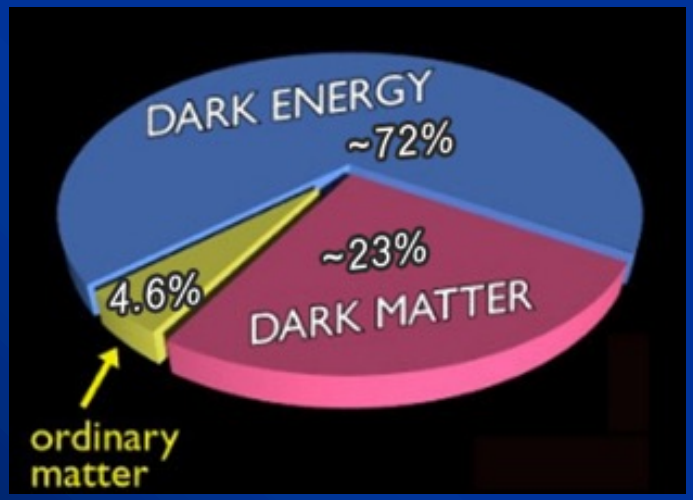
	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

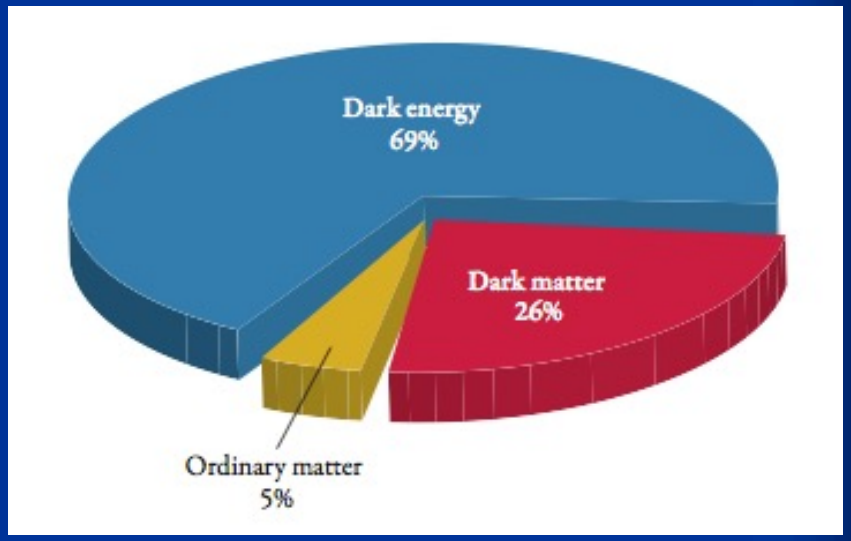
SH initials in WMAP satellite data



More Dark Matter (Planck vs. WMAP)

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy





Less than 5% ordinary matter.

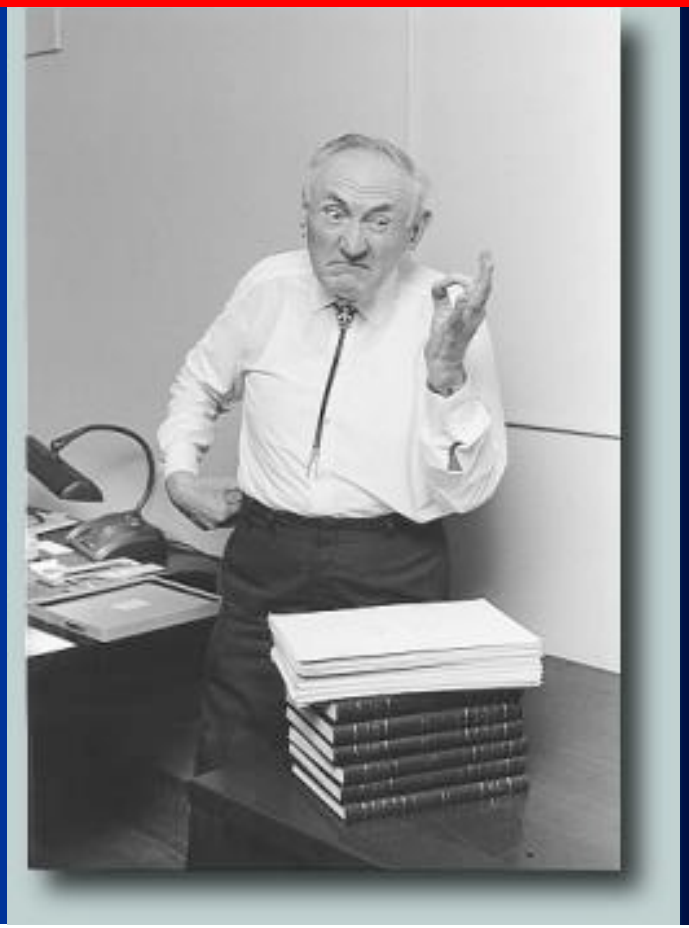
What is the dark matter? What is the dark energy?

The Dark Matter Problem is 90 years old: Dates back to Knut Lundmark in 1930 and Fritz Zwicky in 1933

Galaxies in the Coma cluster were moving too rapidly.

Proposed "Dunkle Materie" as the explanation.

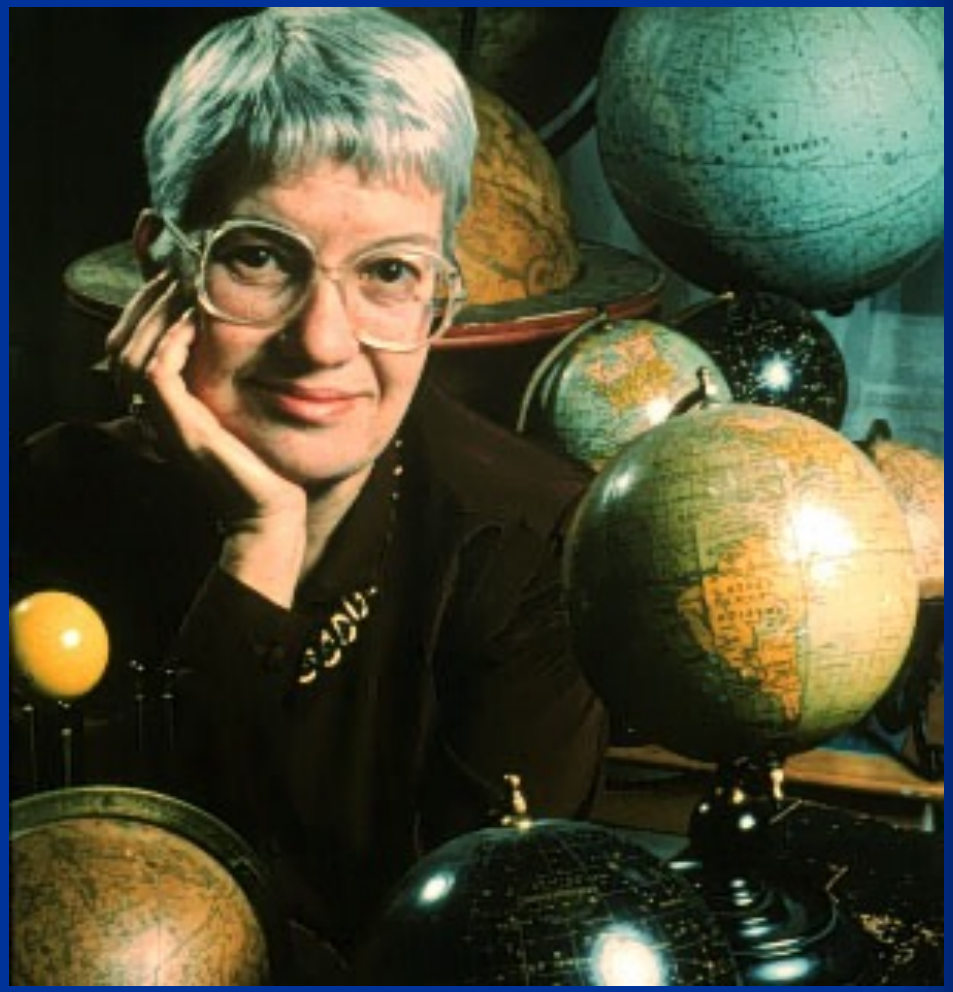
It's not stars, it doesn't shine.
It's DARK.



Vera Rubin and Kent Ford in 1970s

Studied rotation curves of galaxies, and found that they are all FLAT.

This work led to scientific consensus that the DM problem is ubiquitous.



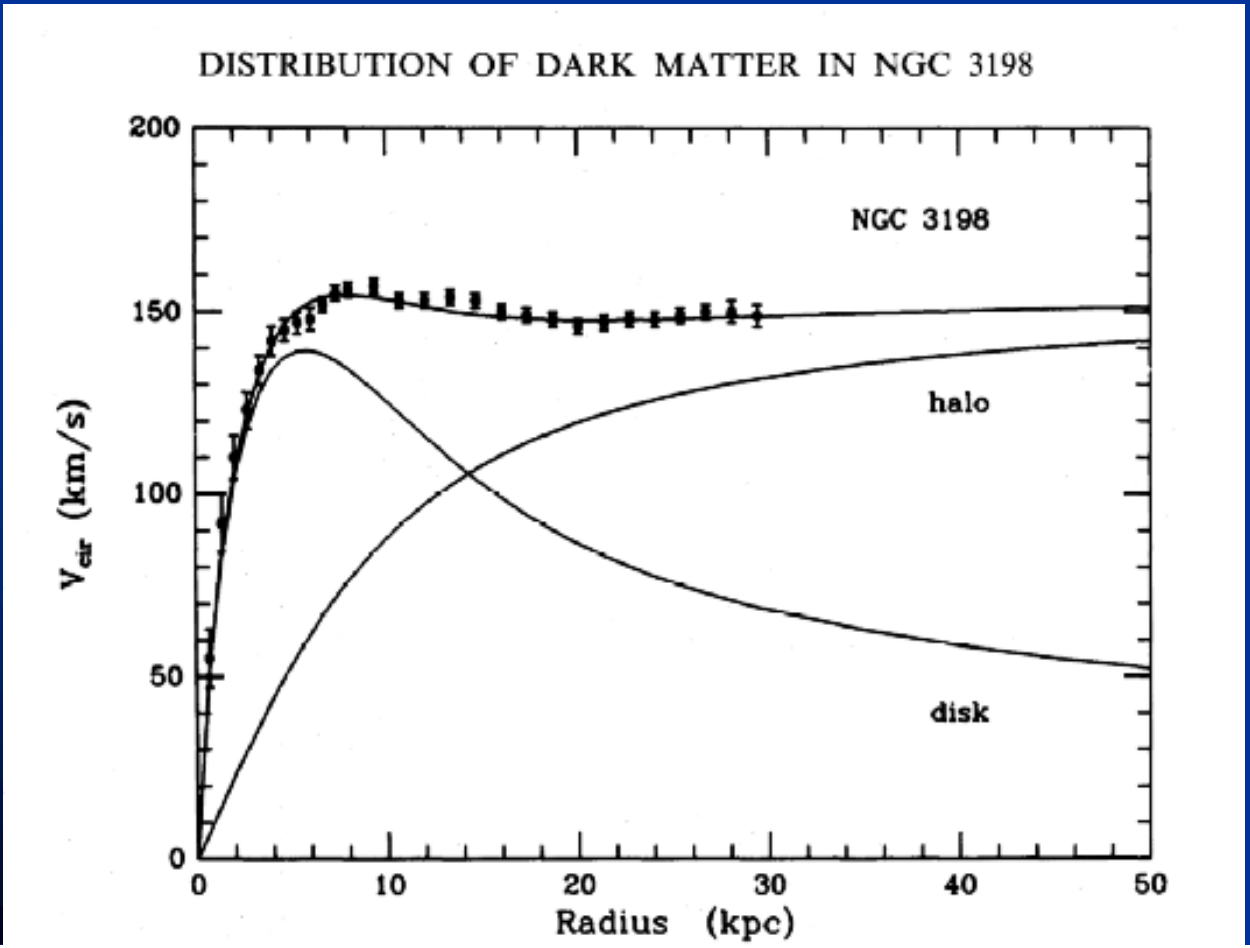
Rotation Curves of Galaxies

Orbit of a star in a Galaxy: speed is Determined by Mass. Larger mass causes faster orbits.

$$\frac{GM(r)m}{r^2} = \frac{mv^2}{r}$$

95% of the matter in galaxies is unknown dark matter

- Rotation Curves of Galaxies:



OBSERVED:
FLAT ROTATION CURVE

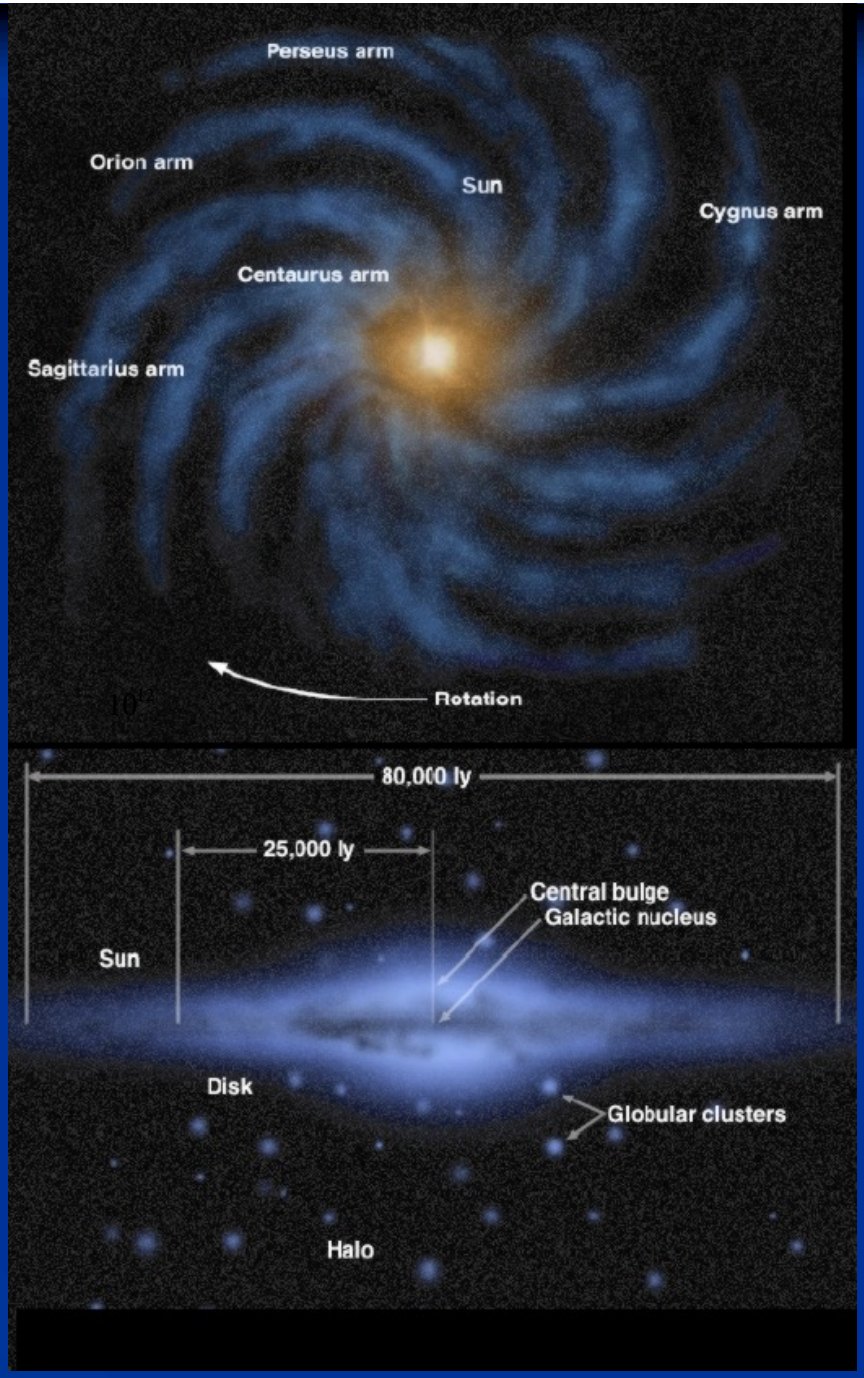
EXPECTED FROM STARS

Albert Bosma
1978

Our Galaxy: The Milky Way

The mass of the galaxy:

10^{12} solar masses

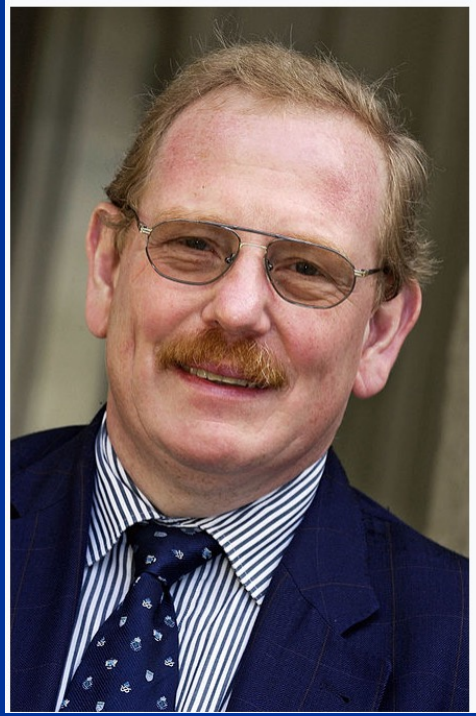


2020 Nobel Prize in Physics

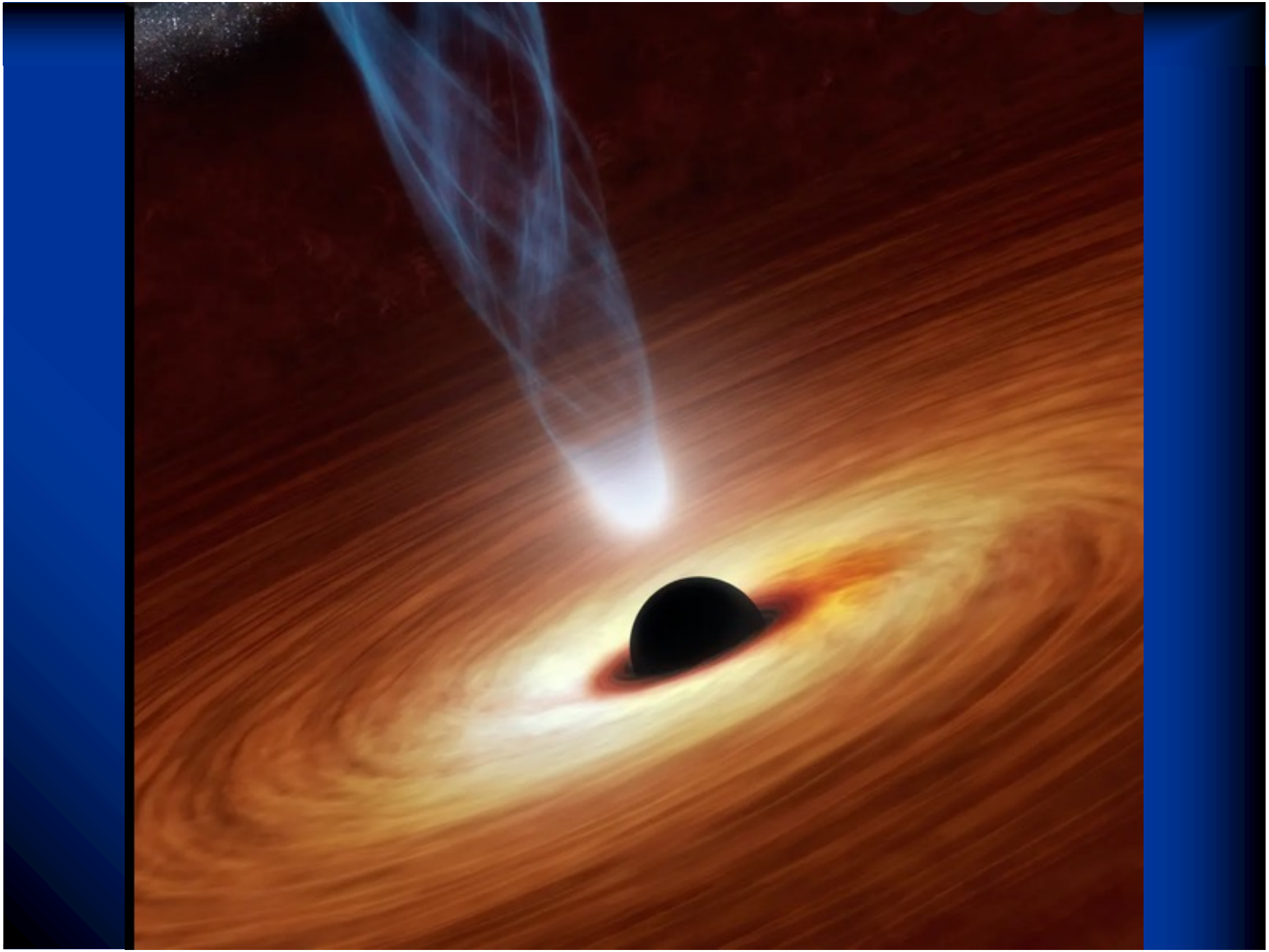
(half) for the discovery of the supermassive black hole at the center of our Galaxy

Andrea M. Ghez

Reinhard Genzel



The BH weighs 4 million Suns

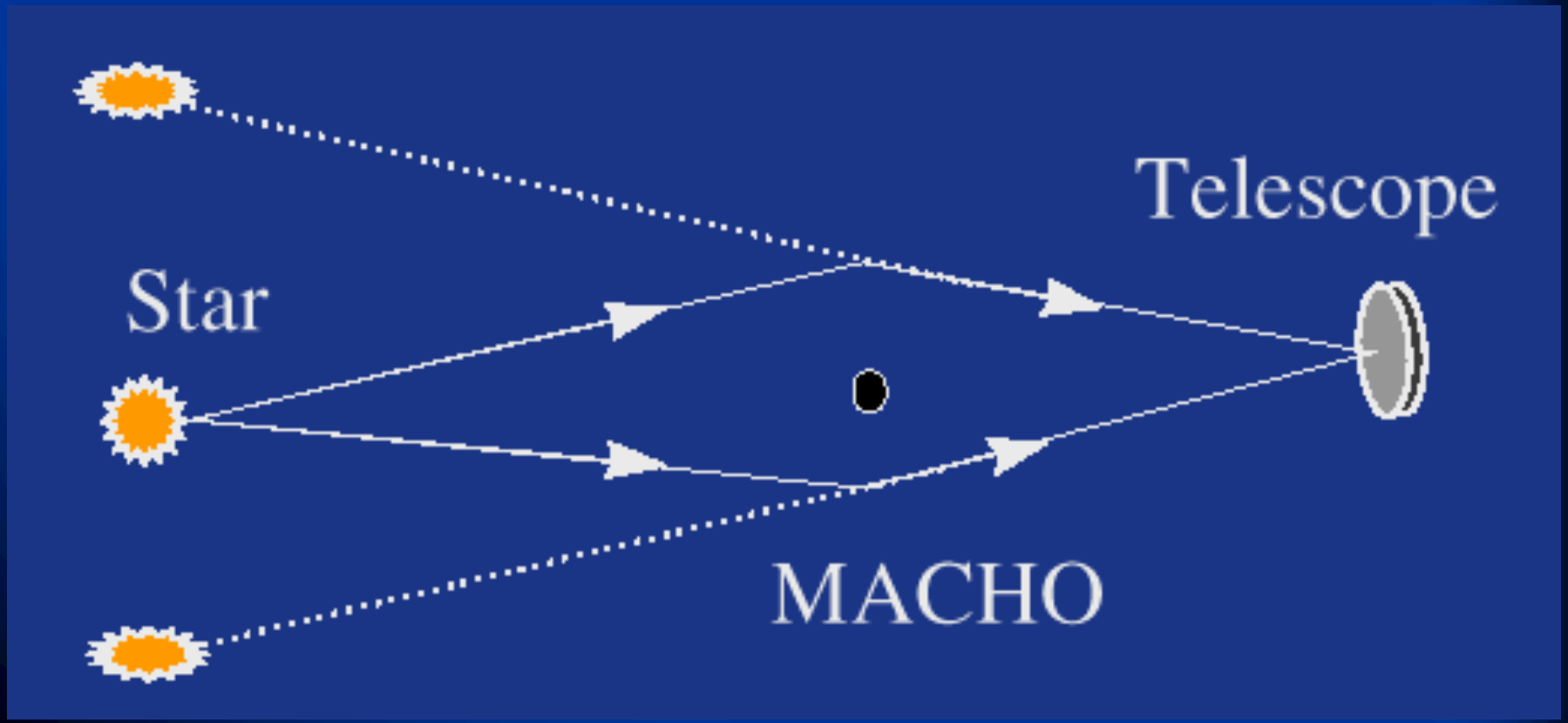


SUPERMASSIVE BLACK HOLES are NOT the DARK MATTER

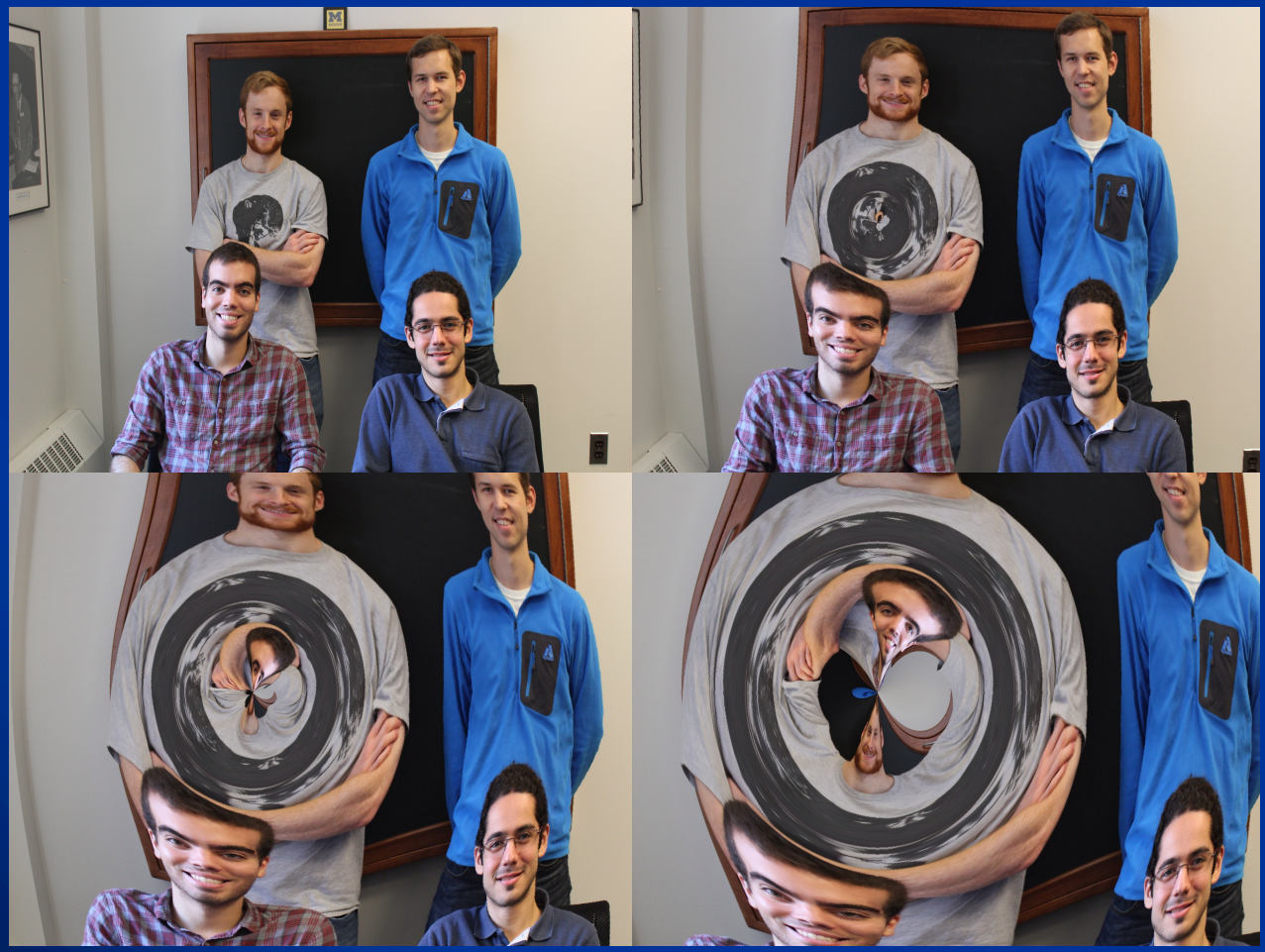
Every galaxy has one at the center, but they make up only a tiny fraction of the Universe as a whole

Galaxies have Dark Matter Haloes

Einstein's Lensing: Another way to detect dark matter: it makes light bend

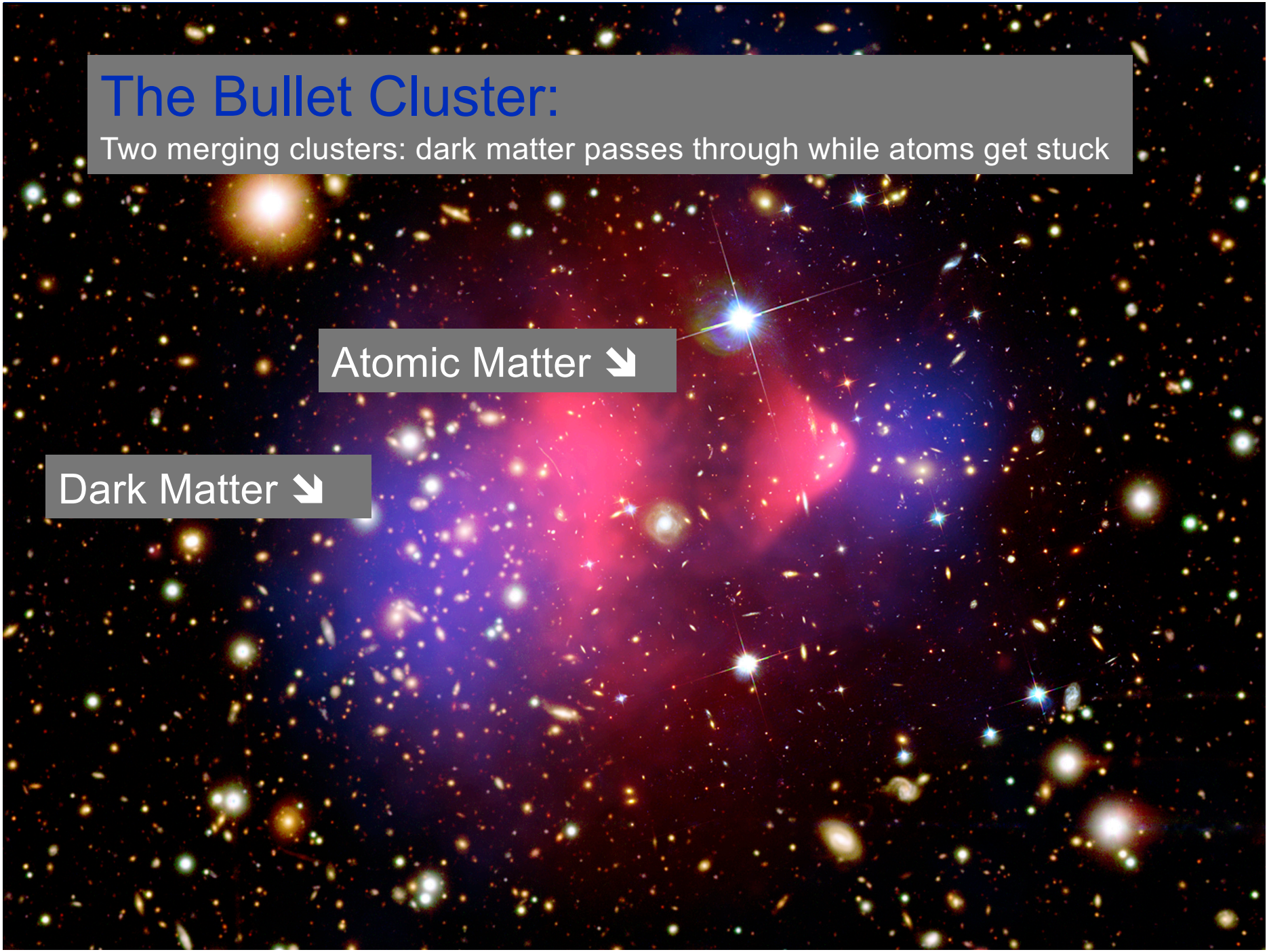


Lensing of students



Strong lensing by dark matter

Mass / area (g/sq.cm)
4
3
2
1
0
800
Thousand light-years
0
-800
-800
Thousand light-years
0
800


The Bullet Cluster:
Two merging clusters: dark matter passes through while atoms get stuck
Atomic Matter ↘
Dark Matter ↘

The Dark Matter Problem :

95% of the mass in galaxies and clusters of galaxies consists of an unknown dark matter component.

Known from:

rotation curves (out to tens kpc),

gravitational lensing (out to 200kpc),

Bullet Cluster.

Big Bang Nucleosynthesis

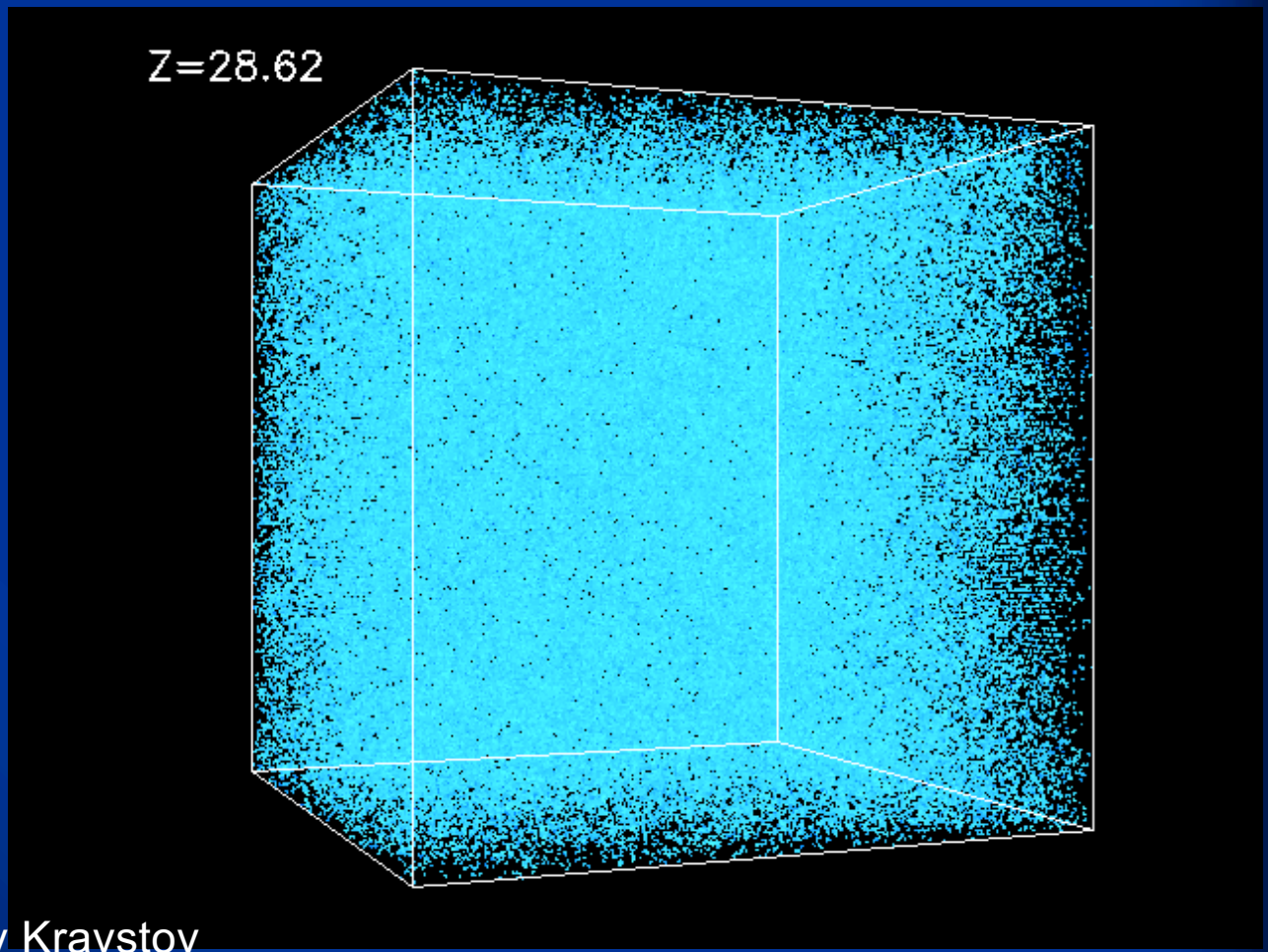
Peaks in the Cosmic Microwave Background.

Evidence for Dark Matter: Formation of Structure, Computer Simulations

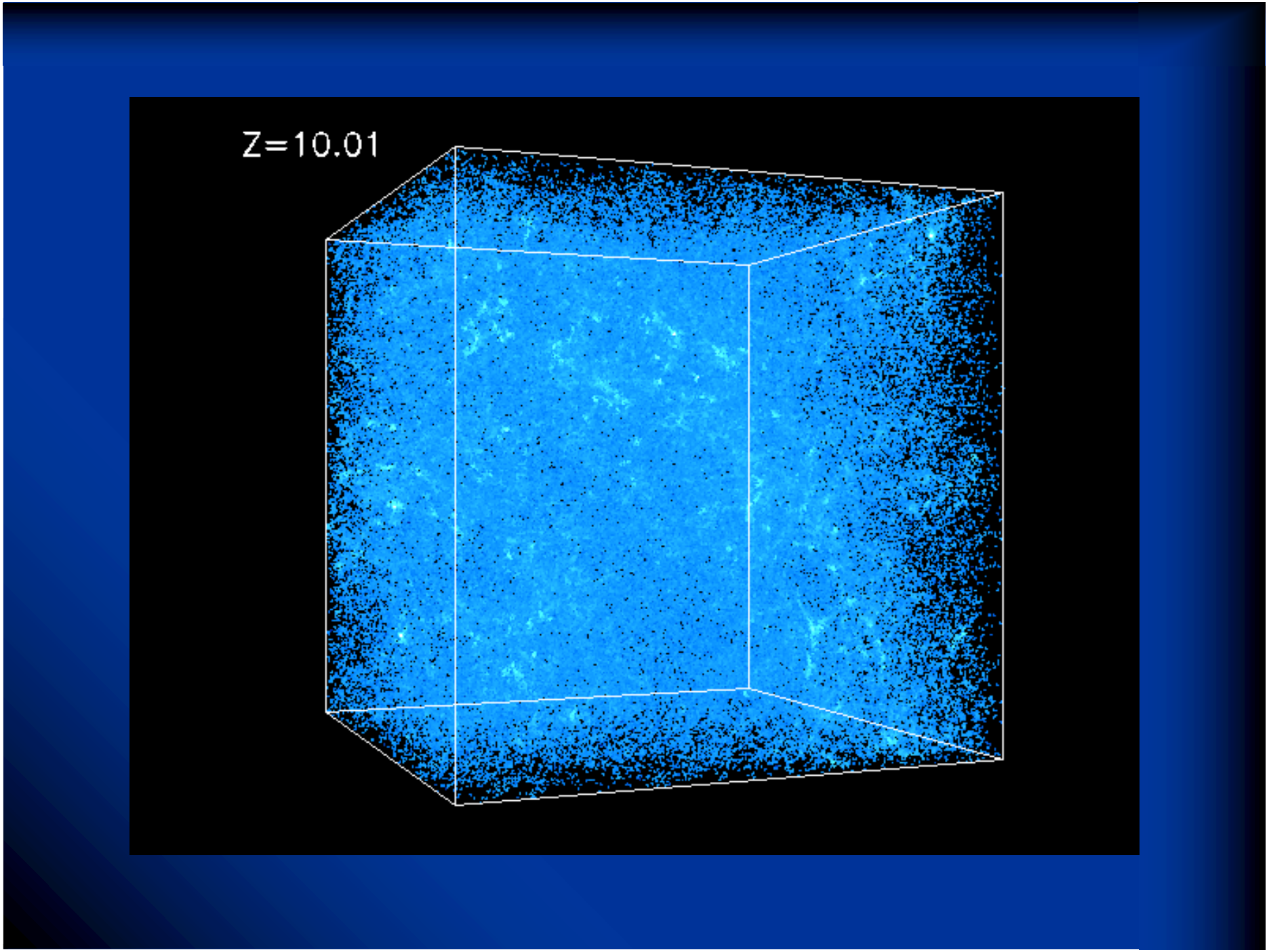
Initial conditions from inflation

Dark Matter particles come together to make galaxies, clusters, and larger scale structures

Computer simulations with dark matter match the data



simulations by Kravstov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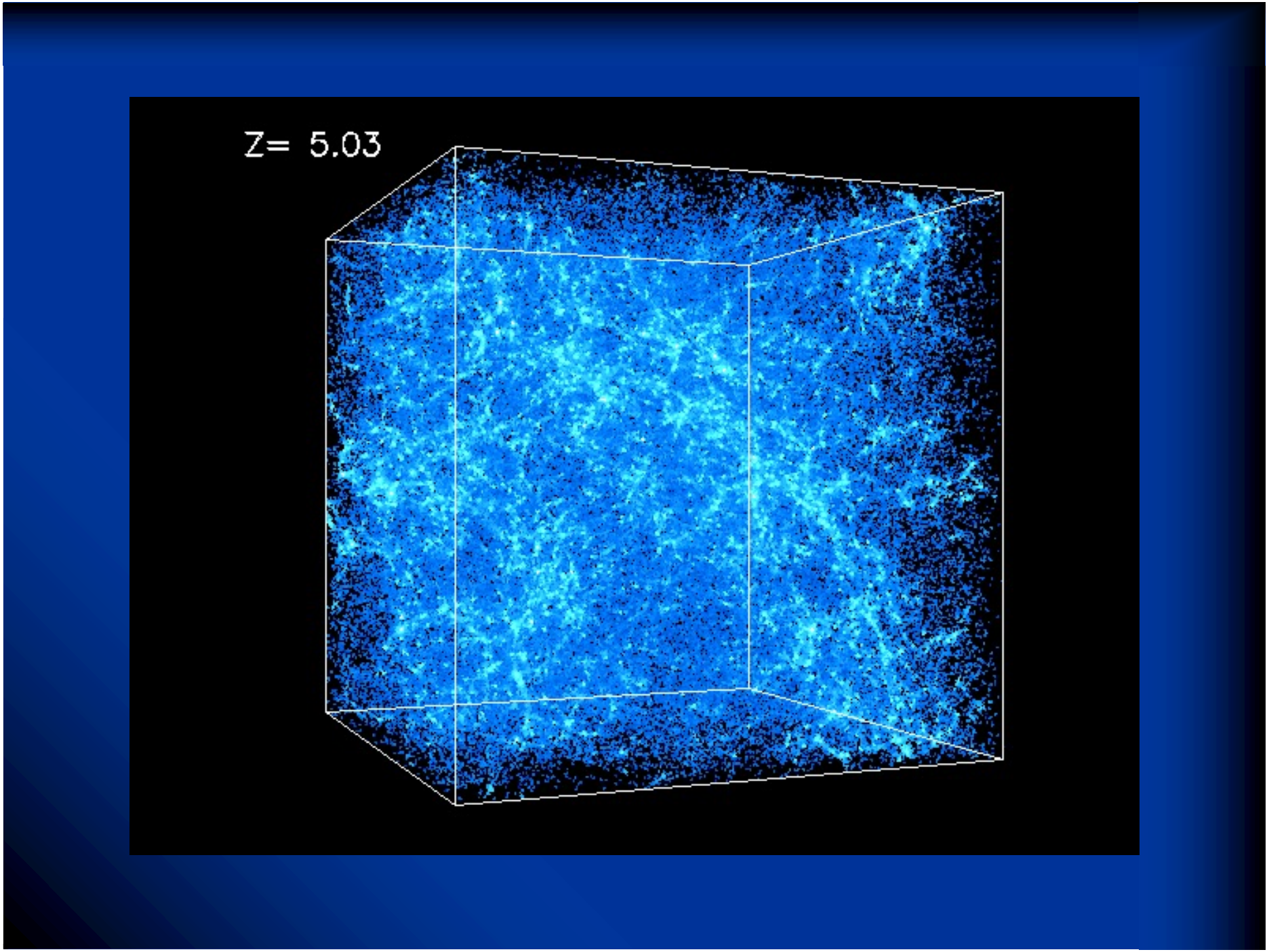
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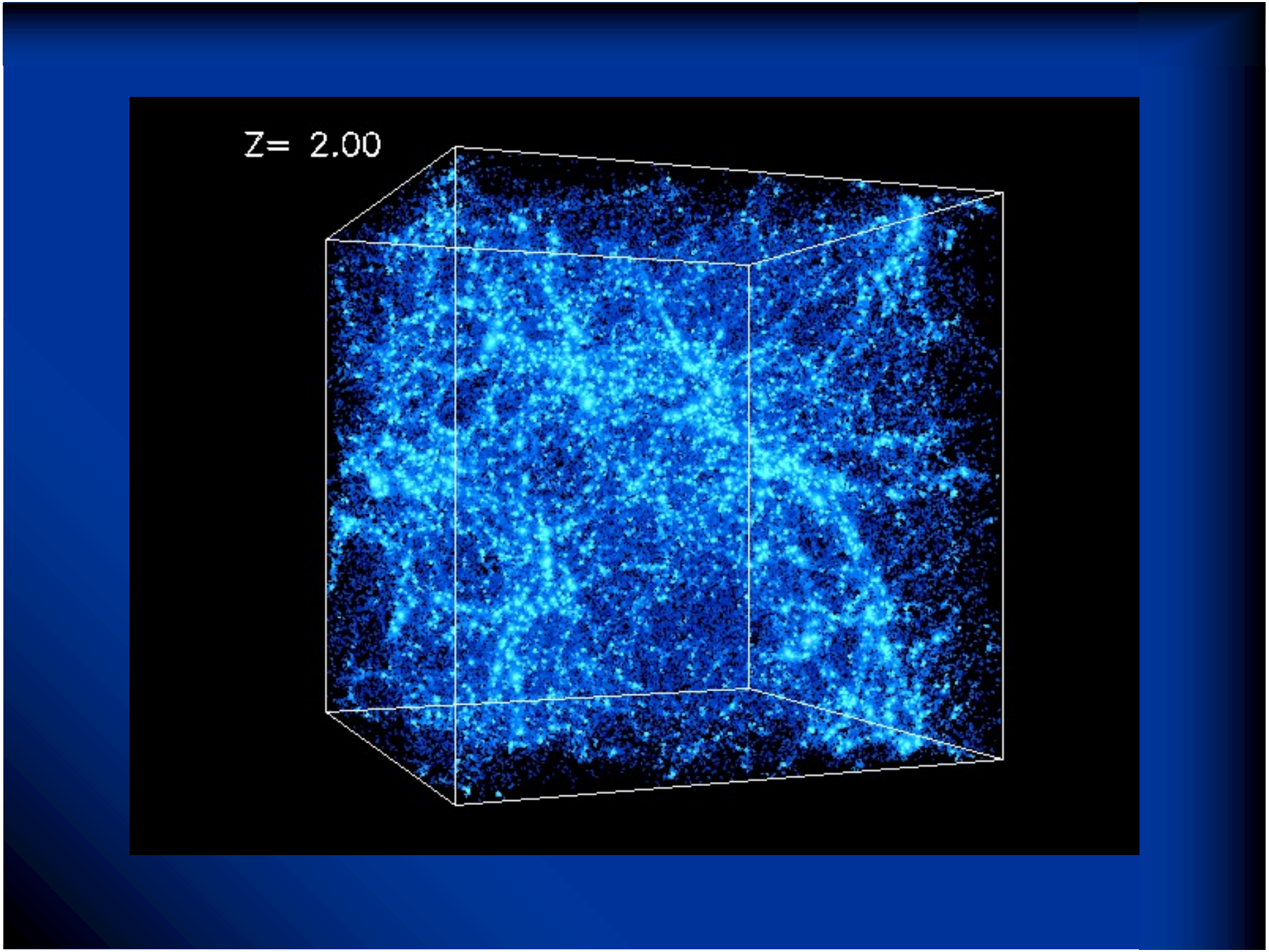
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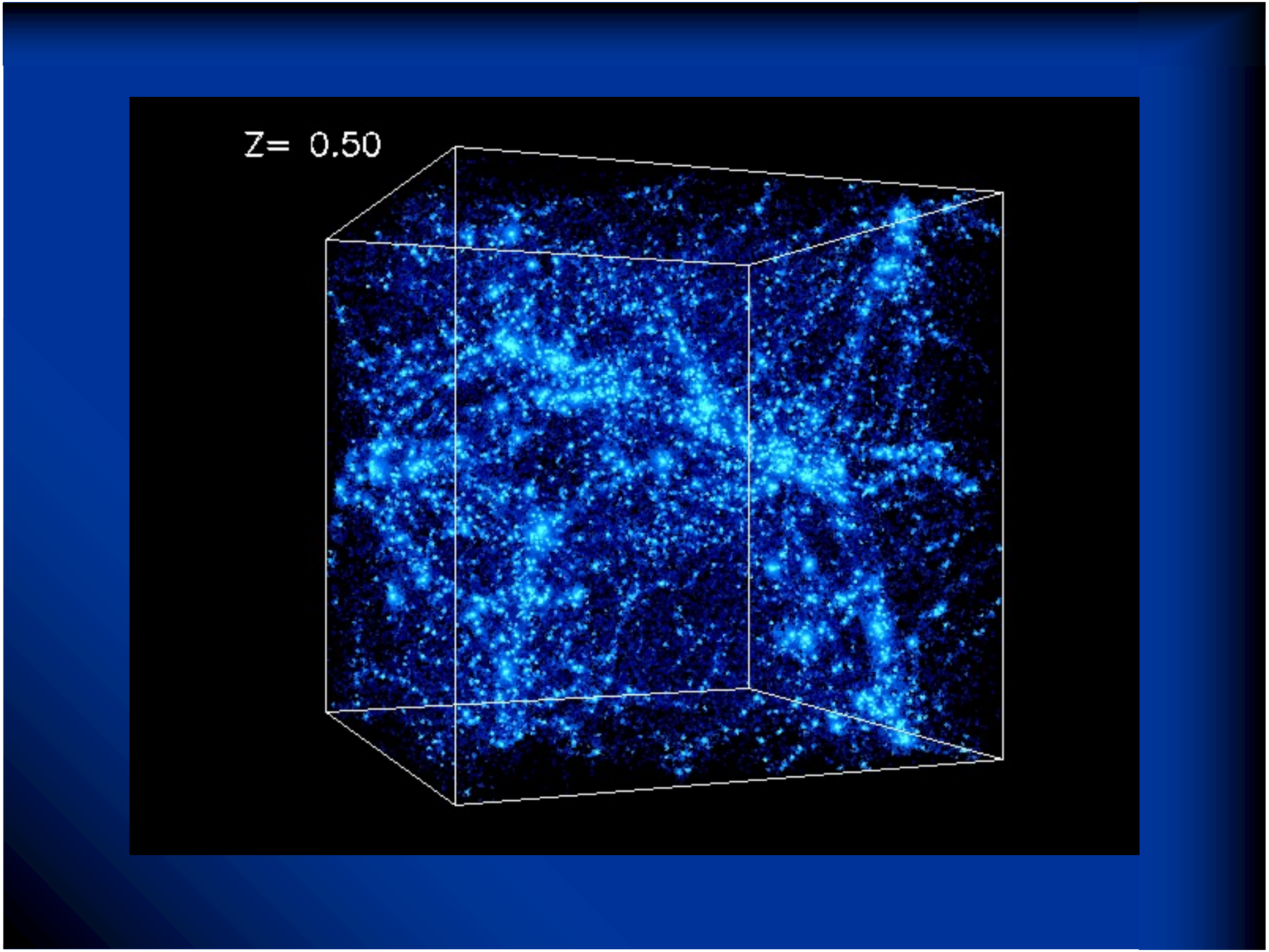
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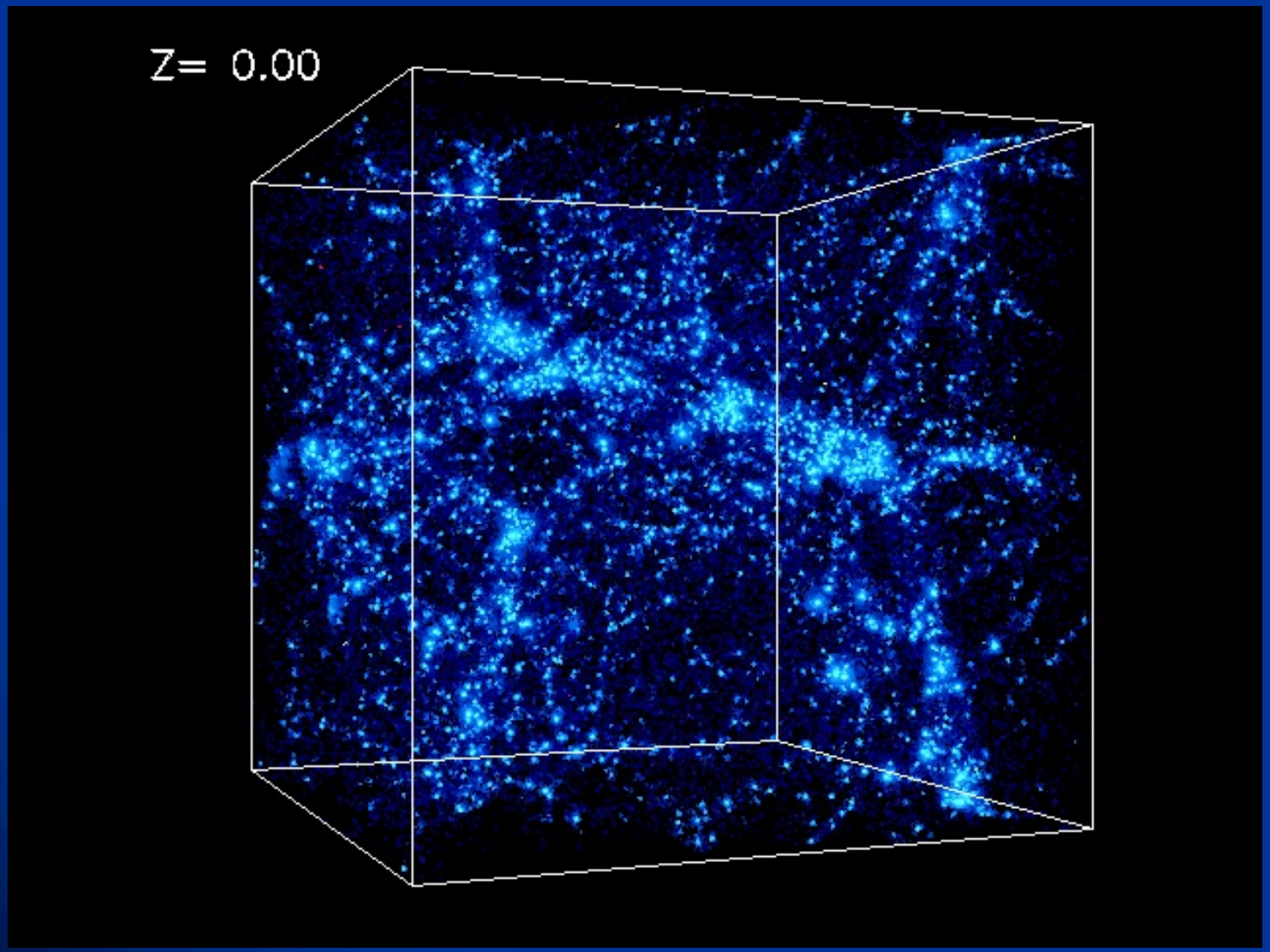
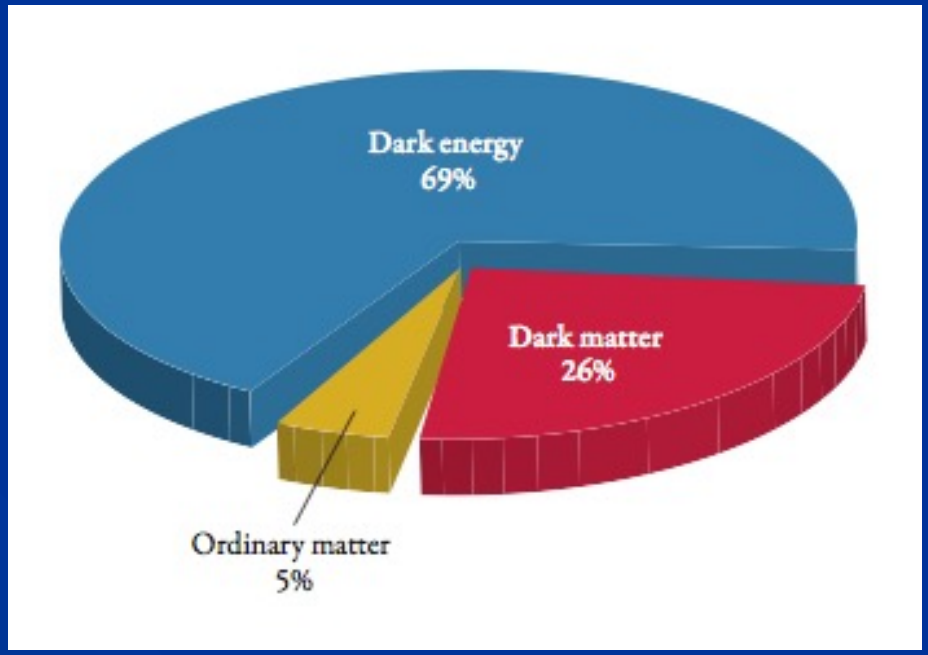

Z= 0.00

PIE CHART OF THE UNIVERSE



WHAT ARE THE PIECES OF THE PIE???

WHAT IS THE DARK MATTER?

The Dark Matter is NOT

- Diffuse Hot Gas (would produce x-rays)
- Cool Neutral Hydrogen (see in quasar absorption lines)
- Small lumps or snowballs of hydrogen (would evaporate)
- Rocks or Dust (high metallicity)

(Hegyi and Olive 1986)

Before 2000, there were two camps

The believers in MACHOs (Massive Compact Halo Objects)

vs.

The believers in WIMPs, axions and other exotic particle candidates

MACHOS (Massive Compact Halo Objects)

- Faint stars
- Substellar Objects Objects (Brown Dwarfs)
- Stellar Remnants:
  - White Dwarfs
  - Neutron Stars
  - Black Holes

From a combination of observational and theoretical arguments, we found that THESE CANNOT EXPLAIN ALL THE DARK MATTER IN GALAXIES. STILL A POSSIBILITY: 15% OF THE MASS IN THE GALAXY CAN BE MADE OF WHITE DWARFS.

Baryonic Dark Matter is NOT enough

Death of stellar baryonic dark matter **candidates**
(Fields, Freese, and Graff 2000)

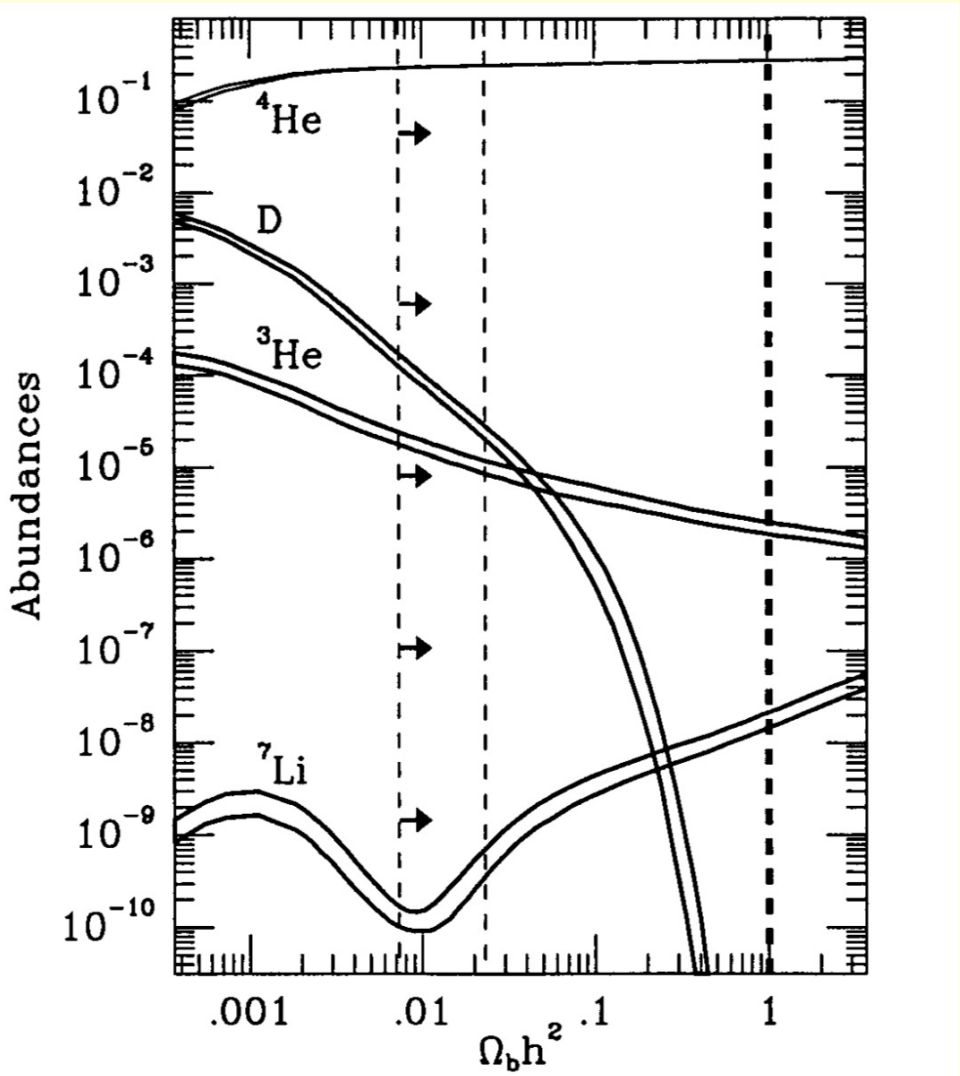


FIG. 1. BBN abundance yields vs. baryon density (Ω_b) and $\eta \equiv \frac{\eta_r}{\eta\gamma}$ for a homogeneous universe. ($h \equiv H_0/100$ km/sec per Mpc; thus, the concordant region of $\Omega_b h^2 \sim 0.015$ corresponds to $\Omega_b \sim 0.06$ for $H_0 = 50$ km/sec per Mpc.) Figure is from Copi, Schramm, and Turner (8).

Copi, Schramnn, Turner 1994 *Science*

Original work from the Early 1980s

What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ----------
- Neutrinos are known to exist! But too light, ruin galaxy formation
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- Asymmetric Dark Matter
- Light Dark Matter, Fuzzy Dark Matter
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas, Planck-scale DM

Neutrinos as Dark Matter? No

- Nearly relativistic, move large distances, destroy clumps of mass smaller than clusters
- Too light,

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.5\mathrm{eV}}$$

- 50 eV neutrinos would "close" the Universe.
- BUT
- The sum of the neutrino masses adds to roughly 0.1 eV
- Neutrinos contribute ½% of the mass of the Universe.

PRIMORDIAL NUCLEOSYNTHESIS: A CRITICAL COMPARISON OF THEORY AND OBSERVATION

J. YANG,[1,2] M. S. TURNER,[2,3] G. STEIGMAN,[4] D. N. SCHRAMM,[2,3] AND K. A. OLIVE[3]

Received 1983 August 25; accepted 1983 December 20

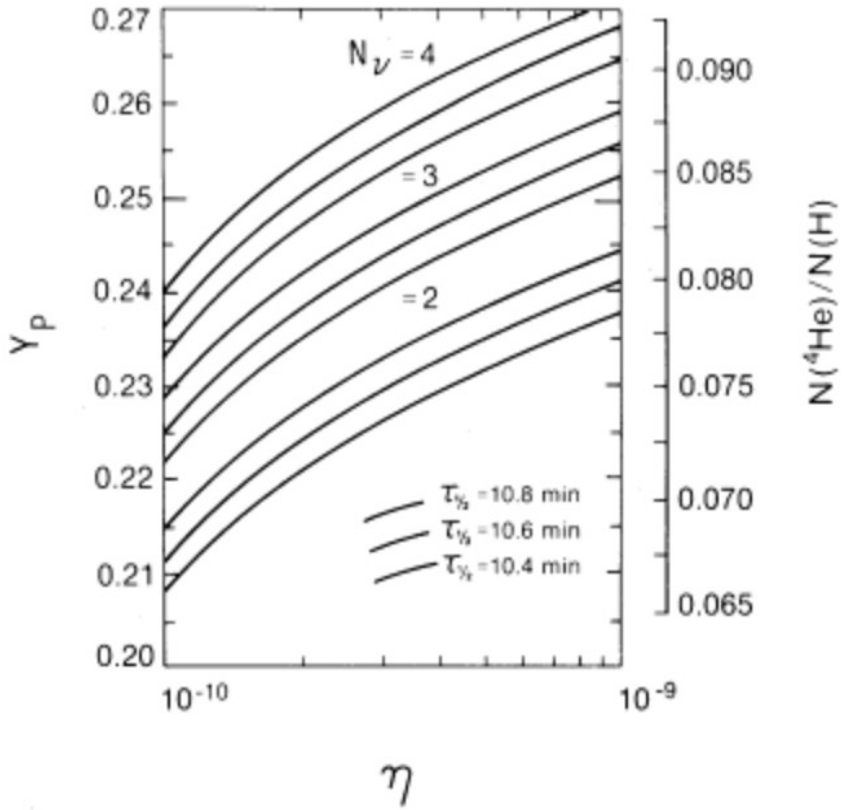


FIG. 1.—The abundance of ^{4}He (by mass and by number) as a function of the nucleon-to-photon ratio (η) for $N_\nu = 2, 3, 4$ species of light, two-component neutrinos and for three choices for the neutron half-life ($\tau_{1/2} = 10.4, 10.6, 10.8$ minutes).

Current
Bounds on Number of Neutrino Species:

Planck TT+BAO gives
Neff=3.15\pm0.23 at 68% CL.
If there are only 3 active neutrinos, the expected value is Neff=3.046

Therefore, models with
Delta Neff=1 are ruled out at almost 3sigma level.

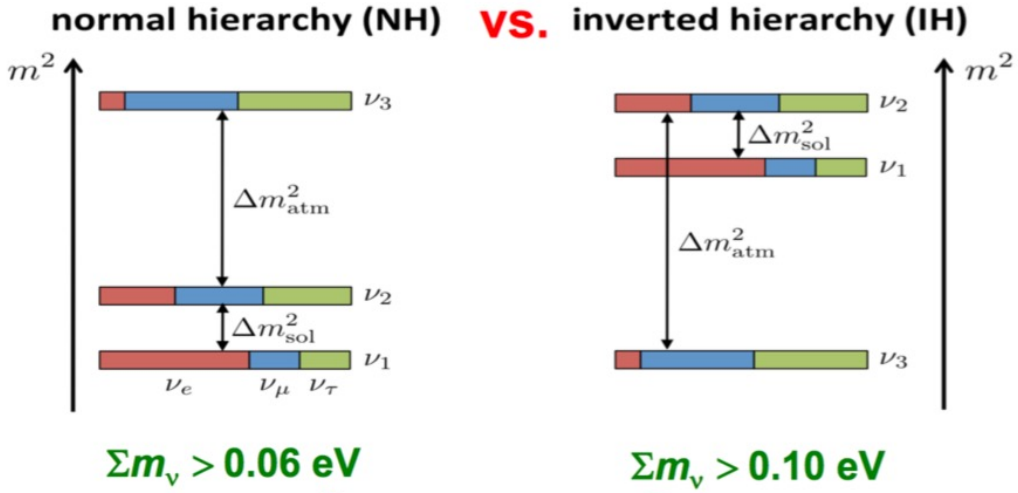
NEUTRINO MASS

We know from the observation of neutrino oscillations that neutrinos have mass (Nobel prize 2015 to Kajita & McDonald!)
However, oscillations measure mass ***differences*** (with few % accuracy):

$\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV^2

$|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ eV^2 (NH)
2.4×10^{-3} eV^2 (IH)

We do not know yet the mass pattern (hierarchy) nor the absolute mass scale



$\Sigma m_\nu > 0.06$ eV

$\Sigma m_\nu > 0.10$ eV

Oscillations put a ***lower limit*** on the mass scale

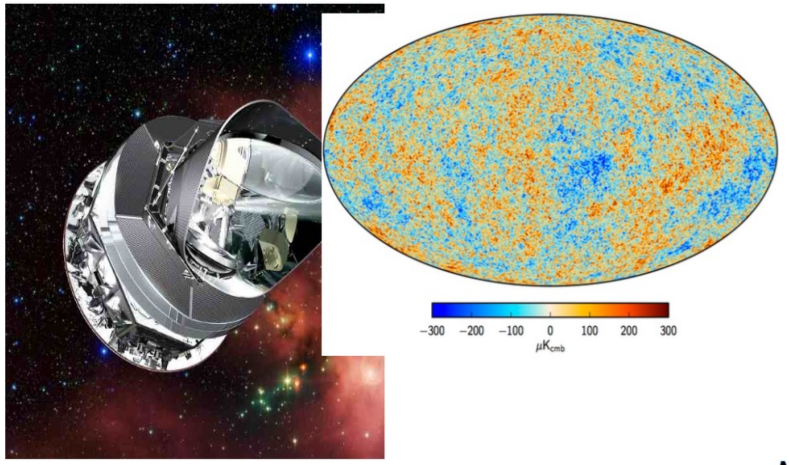
(depending on the hierarchy)

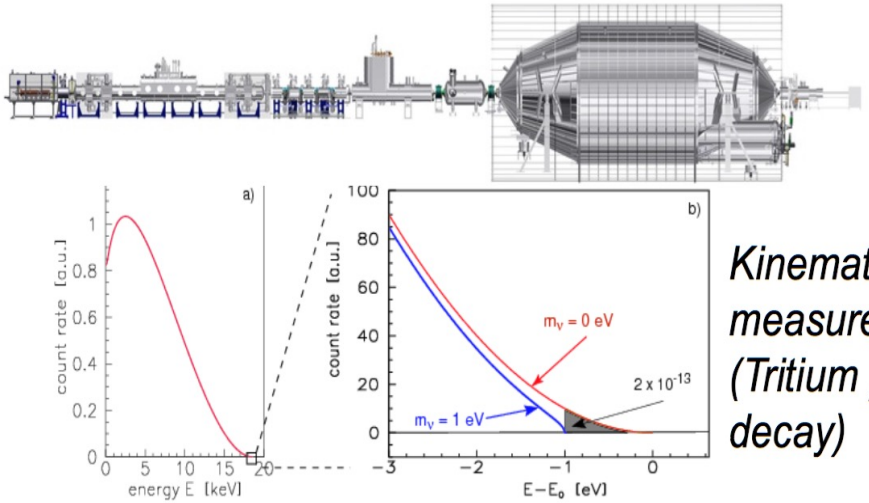
Figure credit: Juno Collaboration

The tiny neutrino masses are a puzzle for the Standard Model of particle physics

The absolute scale of neutrino masses can be measured in different ways

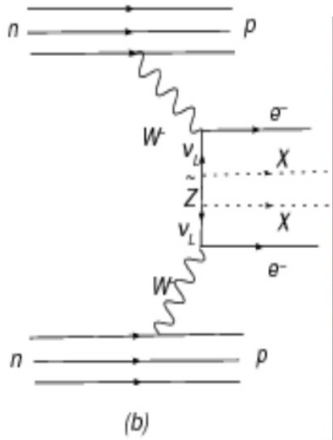
Cosmological observations (CMB, LSS)





Kinematic measuremets (Tritium β decay)

Neutrinoless double β decay



The absolute mass scale can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 1.1 \text{ eV @ 90\%CL}$$ (KATRIN)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| \quad < 0.06 - 0.16 \text{ eV @ 90\%CL}$$

(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i \quad < 0.12 - 0.24 \text{ eV @ 95\%CL}$$

(Planck+…)

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Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE

D. Q. Adams *et al.* (CUORE Collaboration)
Phys. Rev. Lett. **124**, 122501 – Published 26 March 2020

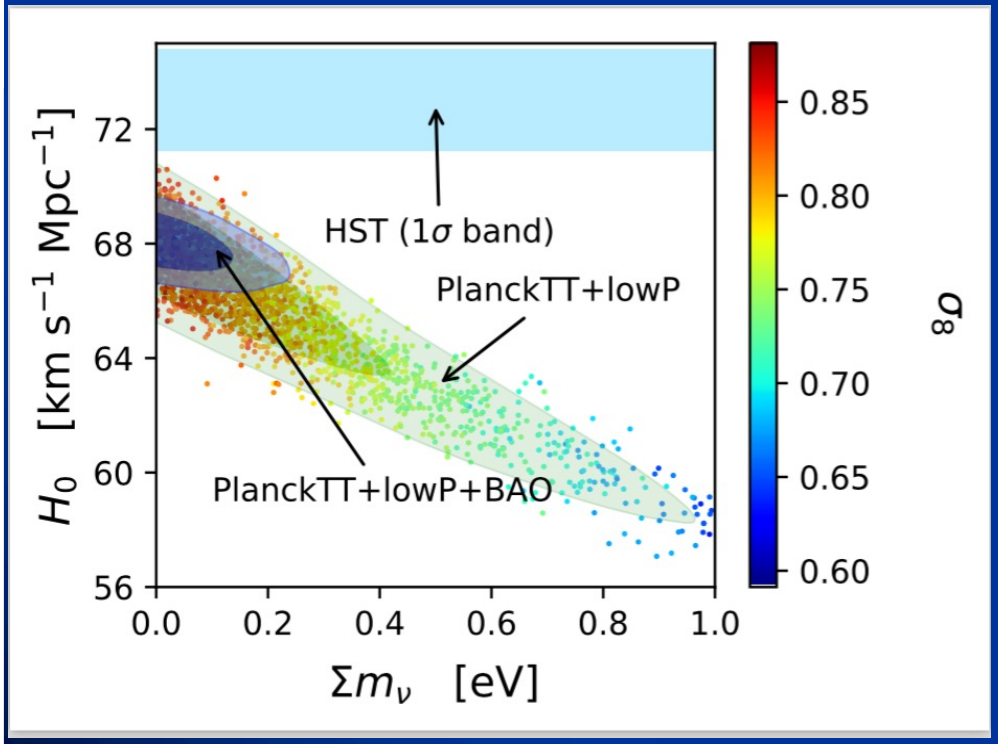
Doug Quincy Adams

Article References No Citing Articles PDF HTML Ex

ABSTRACT

We report new results from the search for neutrinoless double-beta decay in ^{130}Te with the CUORE detector. This search benefits from a fourfold increase in exposure, lower trigger thresholds, and analysis improvements relative to our previous results. We observe a background of $(1.38 \pm 0.07) \times 10^{-2}$ counts/(keV kg yr)) in the $0\nu\beta\beta$ decay region of interest and, with a total exposure of 372.5 kgyr, we attain a median exclusion sensitivity of 1.7×10^{25} yr. We find no evidence for $0\nu\beta\beta$ decay and set a 90% credibility interval Bayesian lower limit of 3.2×10^{25} yr on the ^{130}Te half-life for this process. In the hypothesis that $0\nu\beta\beta$ decay is mediated by light Majorana neutrinos, this results in an upper limit on the effective Majorana mass of 75–350 meV, depending on the nuclear matrix elements used.

Cosmological data (CMB plus large scale structure) bound neutrino mass



$\sum m_\nu$ < 0.15 eV at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXIv:1701.0872

Planck Satellite: < 0.12 eV

DESI mv < 0.072 (0.113) eV

Assumes standard Lambda CDM
If w>-1, stronger bounds

From oscillations: >0.06 eV

Giusarma, KF etal arXiv:1405:04320
Neutrino Properties in Particle Data Group's Review of Particle Properties

DESI Collaboration 2024

combining the DESI and CMB data yields an upper limit $\sum m_\nu < 0.072$ (0.113)

eV at 95% confidence for a $\sum m_\nu > 0$ ($\sum m_\nu > 0.059$) eV prior.

arXiv:2404.03002

LARGE SCALE STRUCTURES

Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias

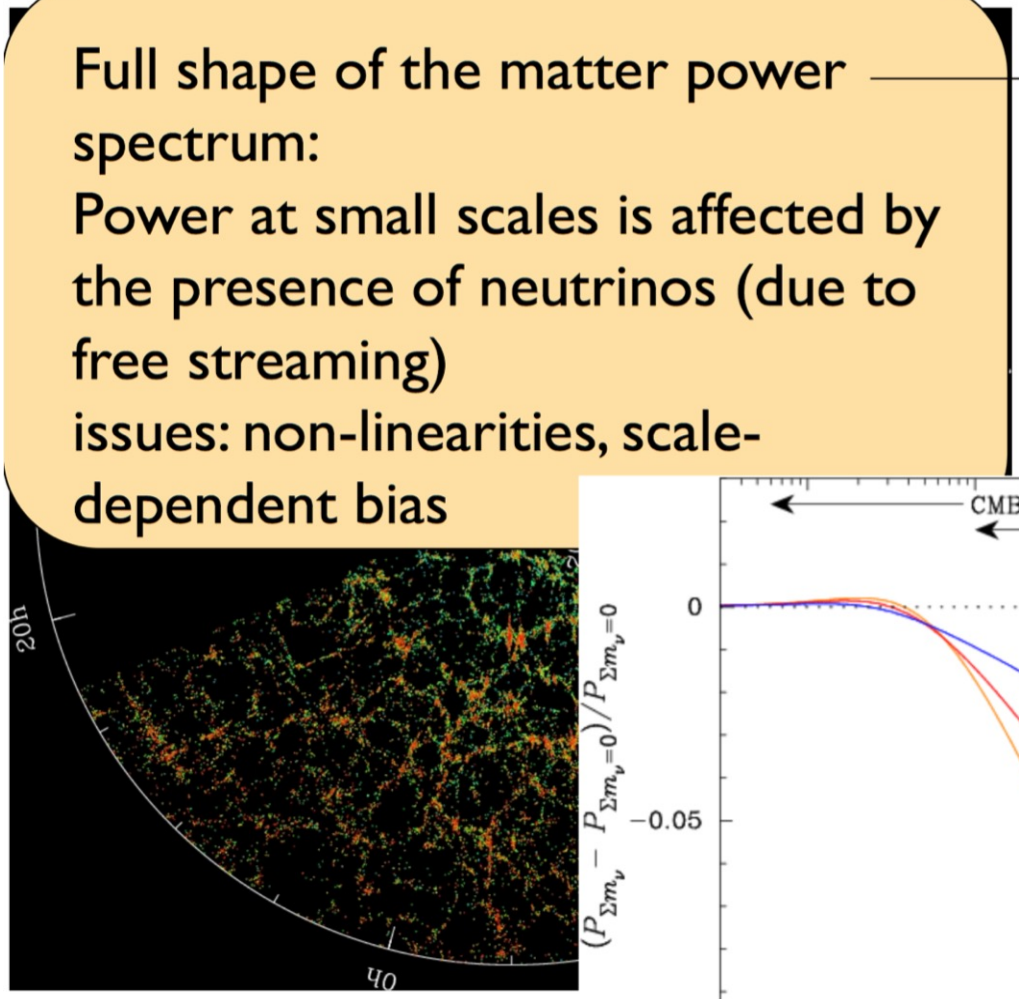
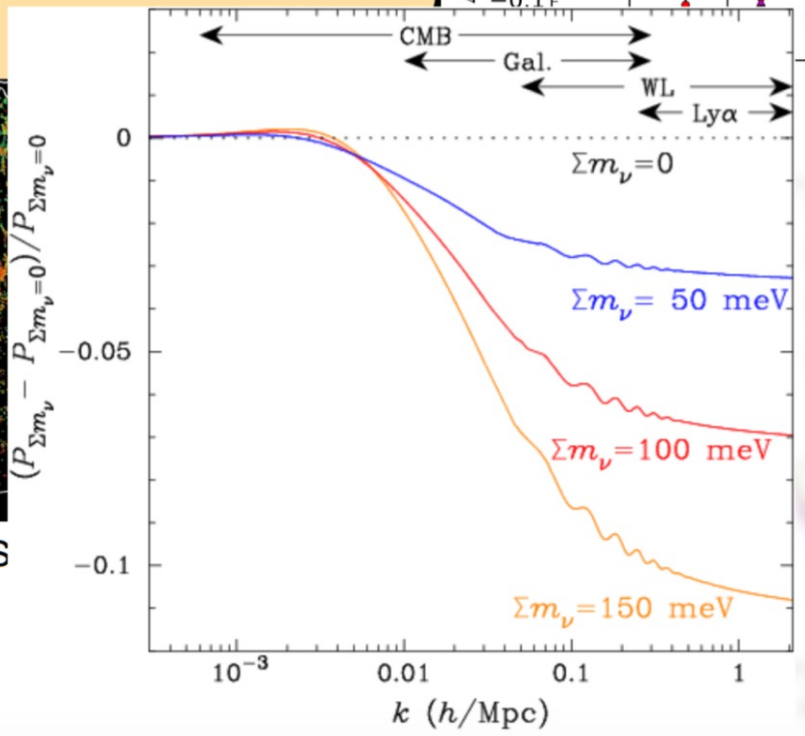


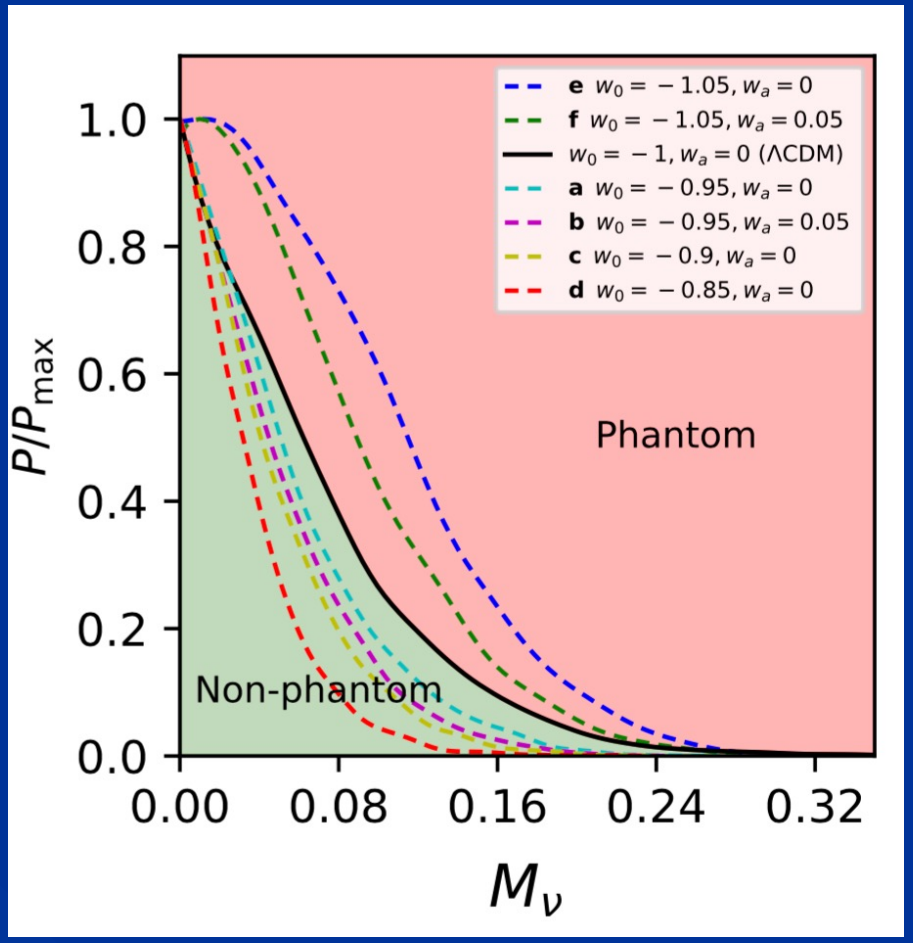
Image Credit: M. Blanton and the S



Neutrino Mass bounds are tighter for arbitrary dark energy with w>-1 (nonphantom) than for Lambda CDM

MARTINA GERBINO

SUNNY VAGNOZZI



Vagnozzi, Gerbino, KF, etal http://lanl.arxiv.org/pdf/1801.08553

Ongoing Cosmic Microwave Background Experiments

My group has joined these two experiments

Jon Gudmundsson

Adri Duivenvoorden

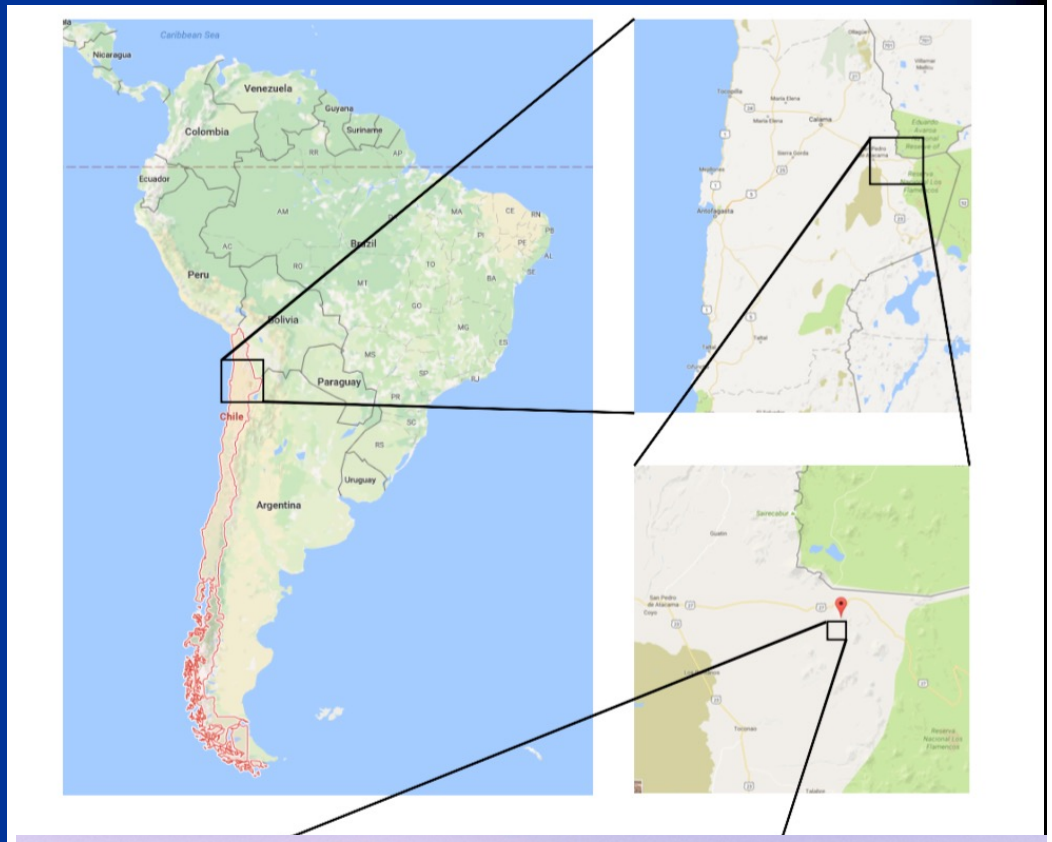
SPIDER at South Pole

Simons Observatory

Nick Galitzki, new Prof at UT

Simons Observatory

- The Simons Observatory will be located in the high Atacama Desert in Northern Chile at 5,200 meters (17,000 ft) above sea level.



Simons Observatory Science Goals

Table 9
Summary of SO key science goals[a]

	Parameter	SO-Baseline[b] (no syst)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k = 0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa$ × LSST-LSS + 3-pt
		1	**2**	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.035	**0.04**	0.03		tSZ-N × LSST-WL
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z = 1 - 2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS
		1.2%	**2%**	1%		tSZ-N × LSST-WL
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)

[a] All of our SO forecasts assume that SO is combined with *Planck* data.

Neutrino Mass close to being measured (for the 3 active neutrinos)

- From oscillation experiments:

- $\sum m_\nu$ > 0.06 eV (Normal Hierarchy)
- > 0.1 eV (Inverted Hierarchy)

- From cosmology (CMB + Large Scale Structure +BAO)

$\sum m_\nu$ < 0.15 eV at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXiv:1701.0872

Planck Satellite: < 0.12 eV

Sterile Neutrinos?

- Additional neutrinos beyond electron, muon, and tau neutrinos
- No standard model interactions.
- Do mix with three active species
- Several Anomalies:
- Hints of detection?
- Miniboone low energy excess, LSND

An intriguing signal: 3.5 keV line. From sterile neutrino?

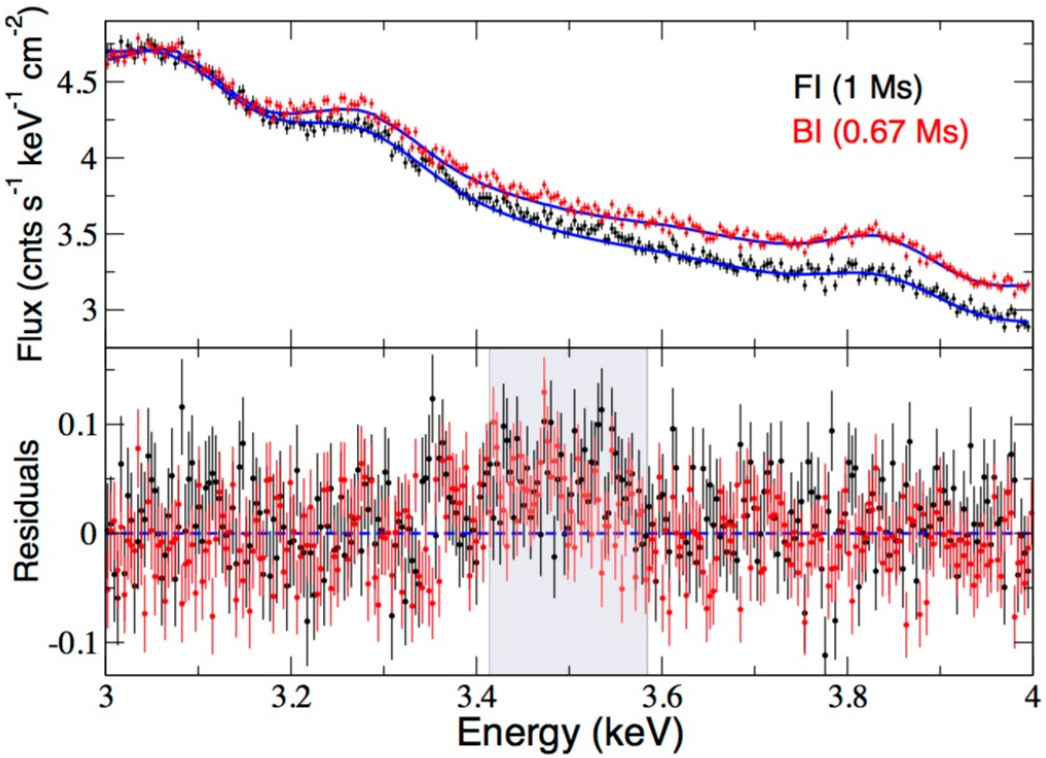


Figure 2. Observed *Suzaku* FI and BI Spectrum of the Perseus cluster core (Region 1). The residuals around 3.5 keV (redshifted) are visible clearly (shaded area in the bottom panel). The model shown in the figure includes contributions from the nearby K XVIII, Cl XVII, and Ar XVII lines.

Perseus Cluster in Suzaku x-ray satellite

(Franse, Bulbul, etal 2016)

2) What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ----------
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- Asymmetric Dark Matter
- Light Dark Matter
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas

Primordial Black Holes

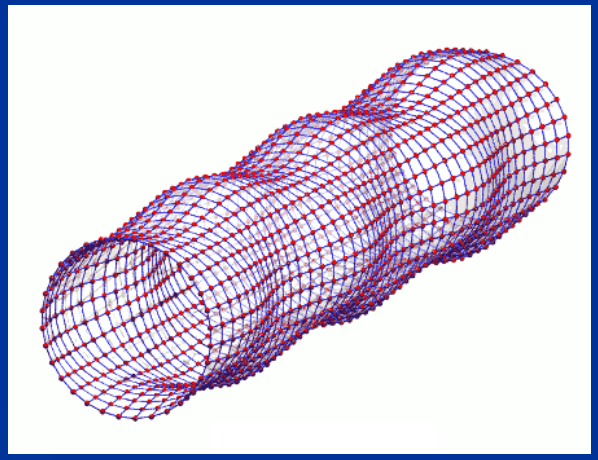
Florian Kuhnel

Primordial Black Holes as Dark Matter?

- Primordial: they would have been born in the Universe's first fractions of a second, when fluctuations in the density led to small regions having enough mass to collapse in on themselves.
- One possibility: they formed at the transition in the early Universe when free quarks became bound together into protons, neutrons, etc. Pressure drop led to black holes.
- Resurgence of interest as possible explanation of gravitational waves seen in LIGO detector in 2016 due to merging black holes as massive as 30 suns.
- There could be millions of these between us and the center of the Milky Way.

Gravitational Waves

- Gravitational waves alternately stretch and squeeze space-time both vertically and horizontally as they propagate.



Detection of Gravitational Waves by LIGO

Two arms, 4km each, length of one increases while the other decreases – by a fraction of the size of a proton -- when gravitational waves come by that stretch the spacetime differently in perpendicular directions

2017 Nobel Prize to Barish, Thorne, and Weiss

Primordial Black Holes in LIGO

30 May 2016

Did LIGO detect dark matter?

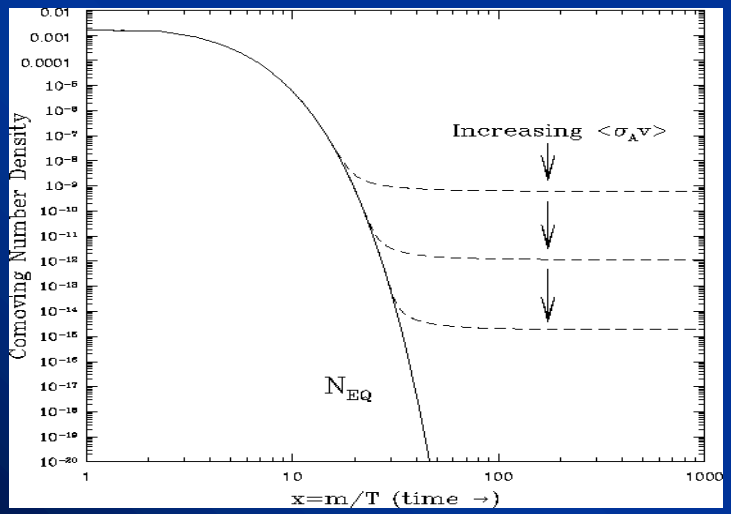
Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2 - 53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

Best motivated Dark matter candidates: cosmologists don't need to "invent" new particles

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



- Axions

$m_a \sim 10^{-(3\text{-}6)}$ eV

arise in Peccei-Quinn solution to strong-CP problem

(Weinberg; Wilczek; Dine, Fischler, Srednicki; Zhitnitskii)

Axions

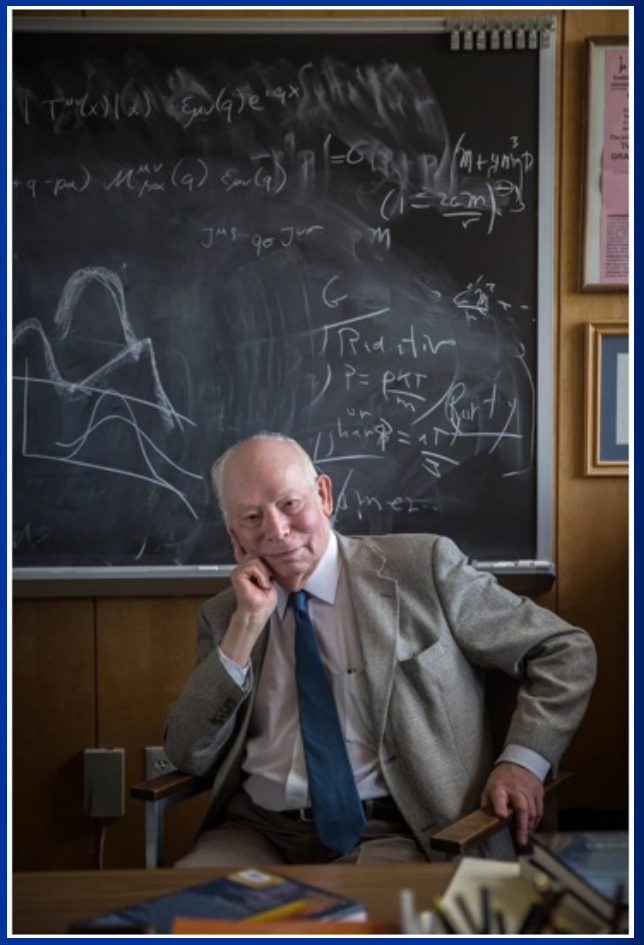
- Axions automatically exist in a proposed solution to the strong CP problem in the theory of strong interaction. They are very light, weighing a trillionth as much as protons; yet they are slow-moving. Axions are among the top candidates for dark matter.

Steven Weinberg

Frank Wilczek

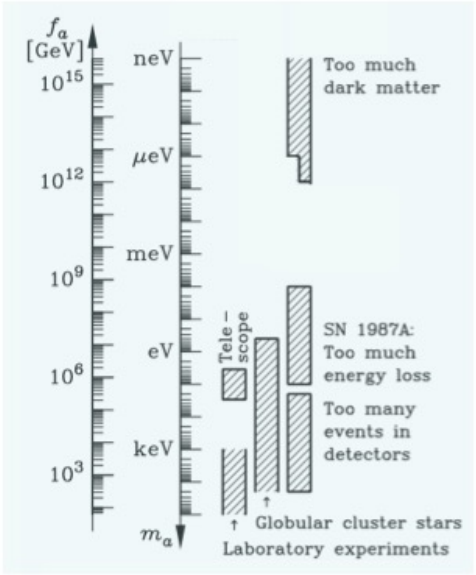
Steven Weinberg, 1933- July 23, 2021

- Driver of some of the most groundbreaking ideas of the last half century. One of the most important thinkers on the planet and a wonderful human being.
- Foundational work creating the Standard Model of Particle Physics.
- We will miss him terribly in Austin--
- A major loss for us and for the world!



Axion masses

Bounded window of allowed axion masses AXION



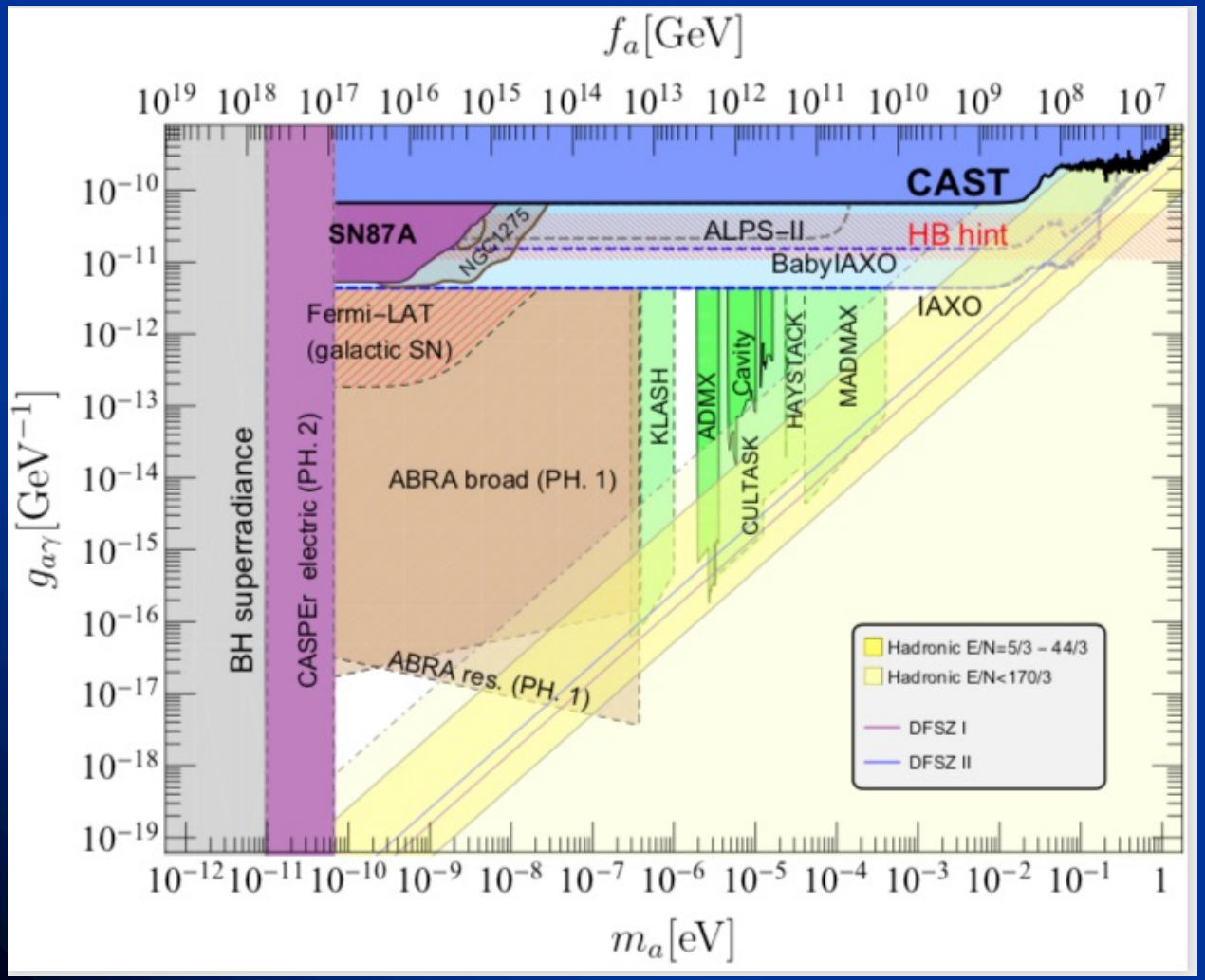
Very light axions forbidden: else too much dark matter

⇐Dark matter range:"axion window"

Heavy axions forbidden: else new pion-like particle

SLACSI-02aug04-ljr

Bounds on Axions and ALPs



From review by
Luca Visinelli
2003.01100

Among theTop candidates for Dark Matter : WIMPs

- Weakly Interacting Massive Particles
- Billions pass through your body every second (one a day—month hits)
- No strong nuclear forces
- No electromagnetic forces
- Yes, they feel gravity
- Of the four fundamental forces, the other possibility is weak interactions
- Weigh 1-10,000 GeV

Two reasons we favor WIMPs: First, the relic abundance

Weakly Interacting Massive Particles Many are their own antipartners. Annihilation rate in the early universe determines the density today.

$$\Omega_\chi h^2 = \frac{3\times10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

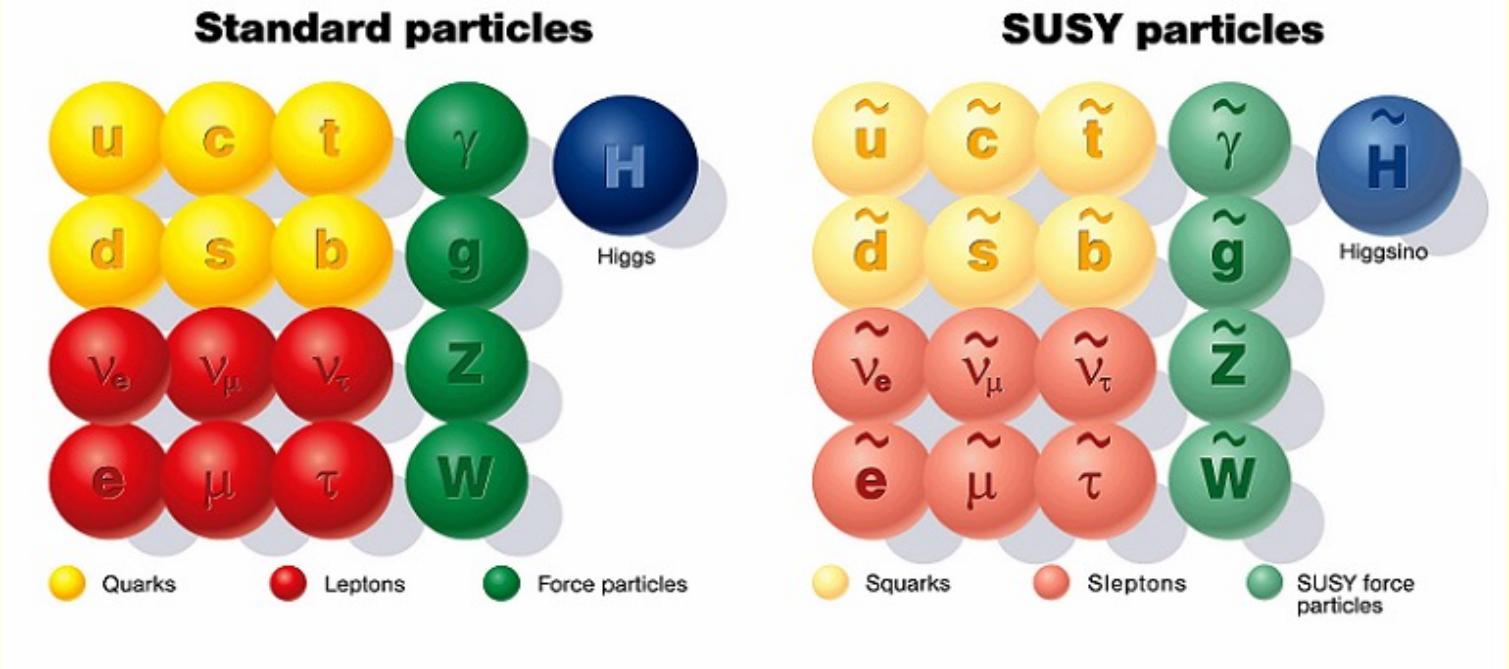
n.b. thermal WIMPs

This is the mass fraction of WIMPs today, and gives the right answer if the dark matter is weakly interacting

WIMP mass: GeV – 10 TeV

Second reason we favor WIMPS: in particle theories, eg supersymmetry

- Every particle we know has a partner

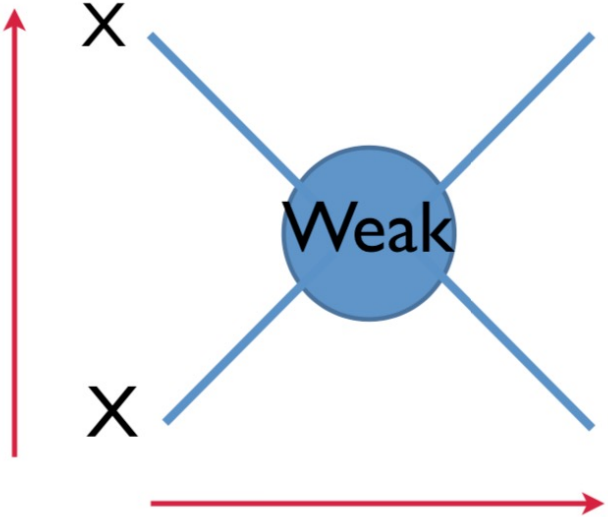


- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION

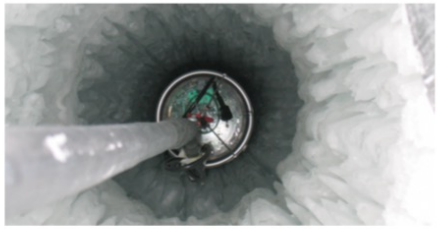
Collider Search (make it)

Direct detection (shake it)



Indirect detection (break it)

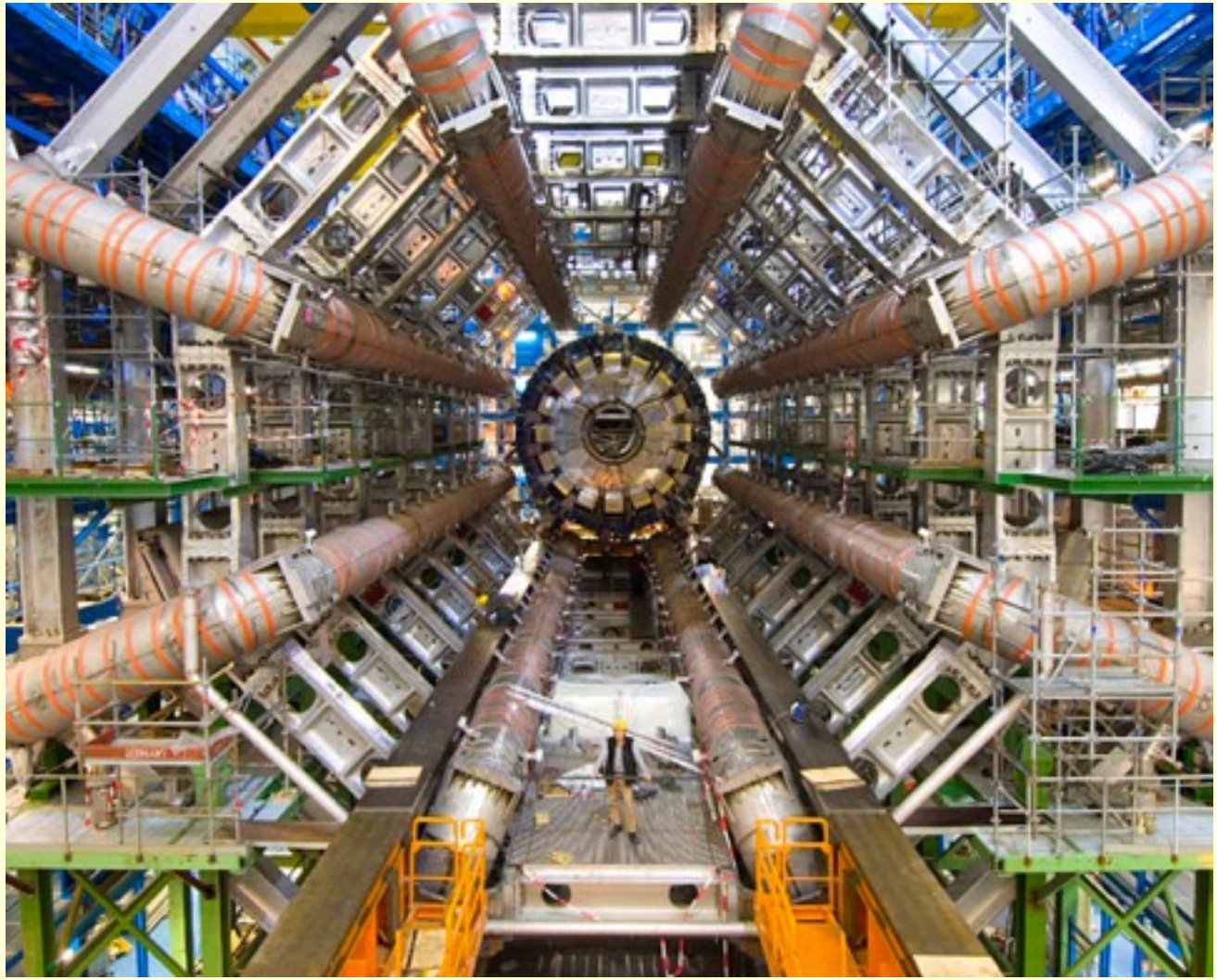
FOURTH PRONG: DARK STARS



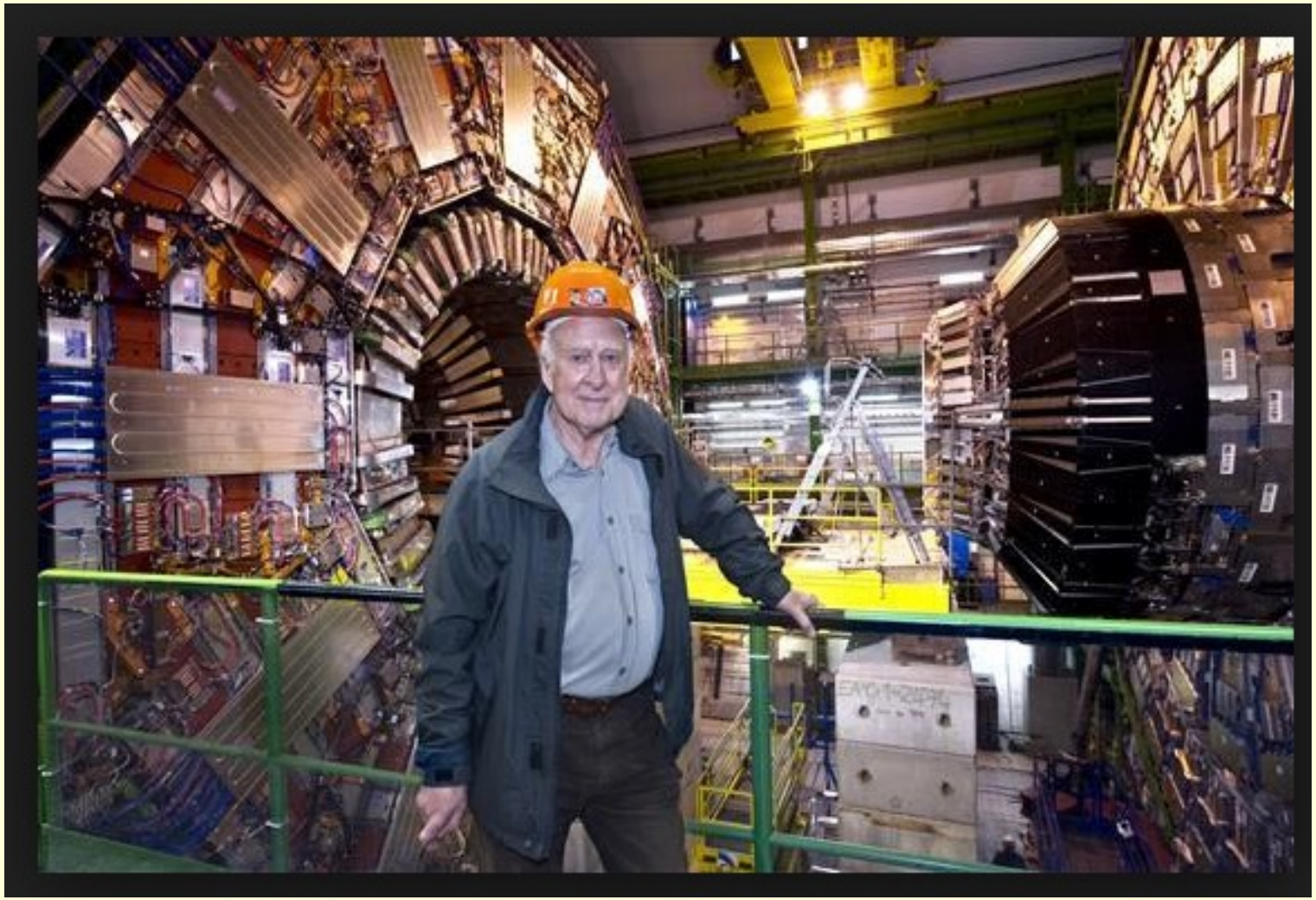
FIRST WAY TO SEARCH FOR WIMPS

Ring that is 27 km around.
Two proton beams traveling underground in opposite directions collide at the locations of the detectors

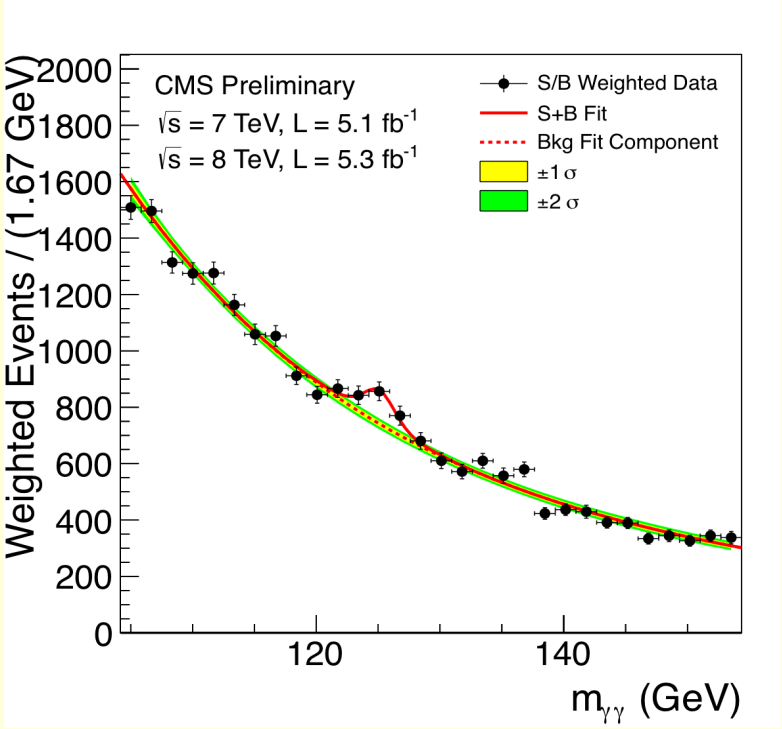
ATLAS Detector at CERN



Peter Higgs and CMS detector



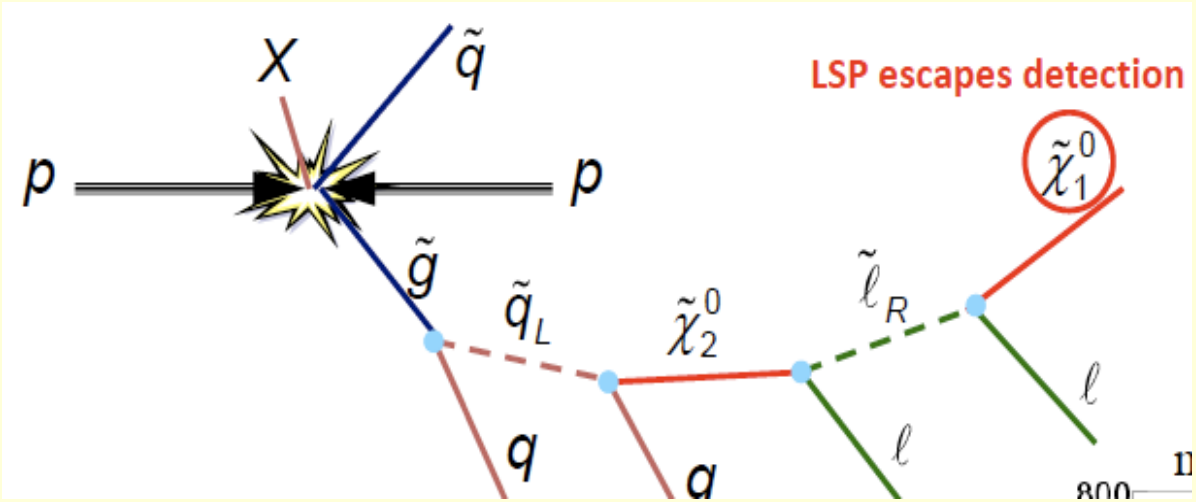
LHC's first success
Discovery of Higgs boson
weighing 125 GeV



Key role of Higgs:
imparts mass
to other particles

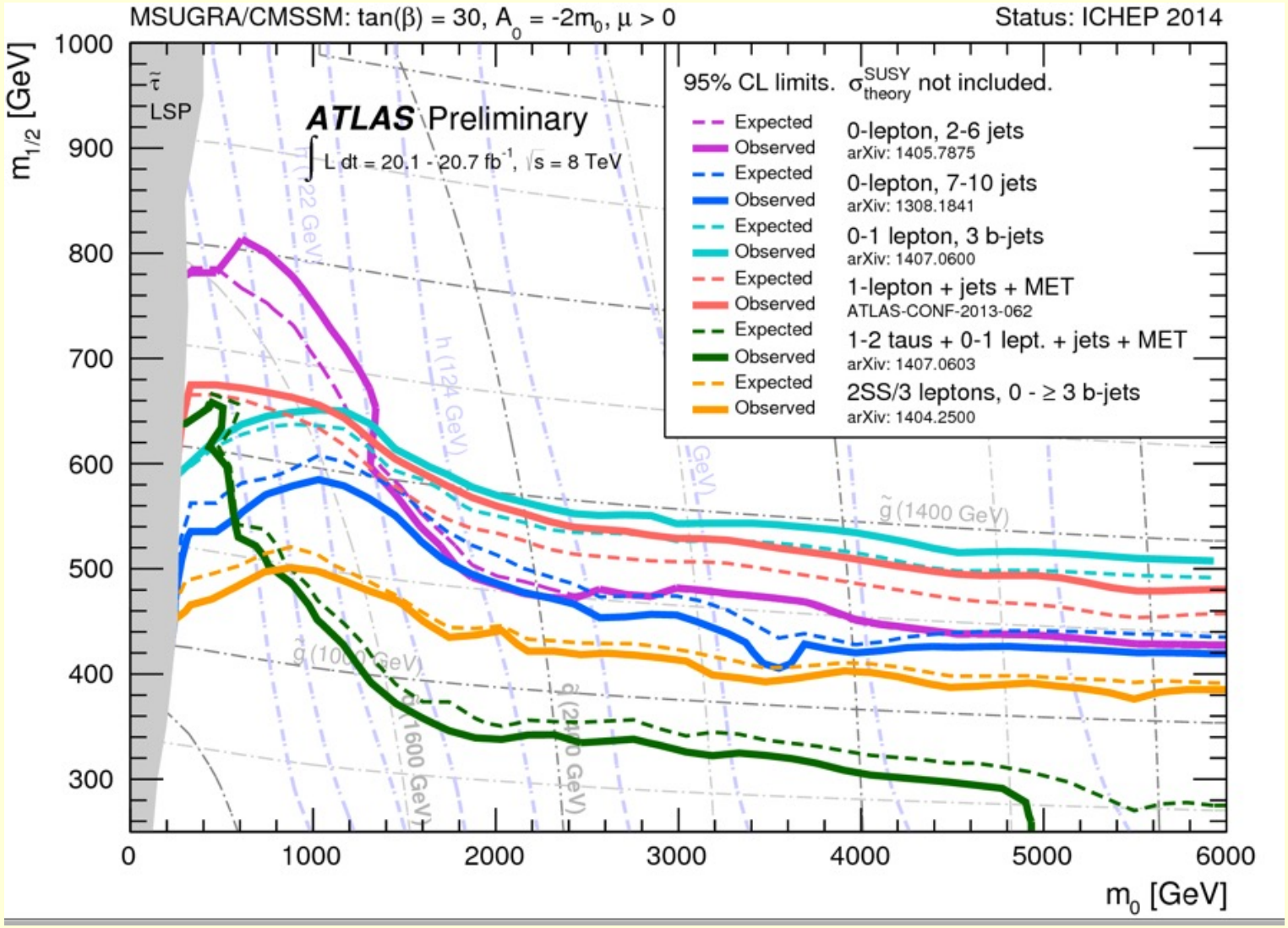
Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet: particle masses pushed to higher masses

ATLAS bounds on CMSSM



Comments on DM at LHC

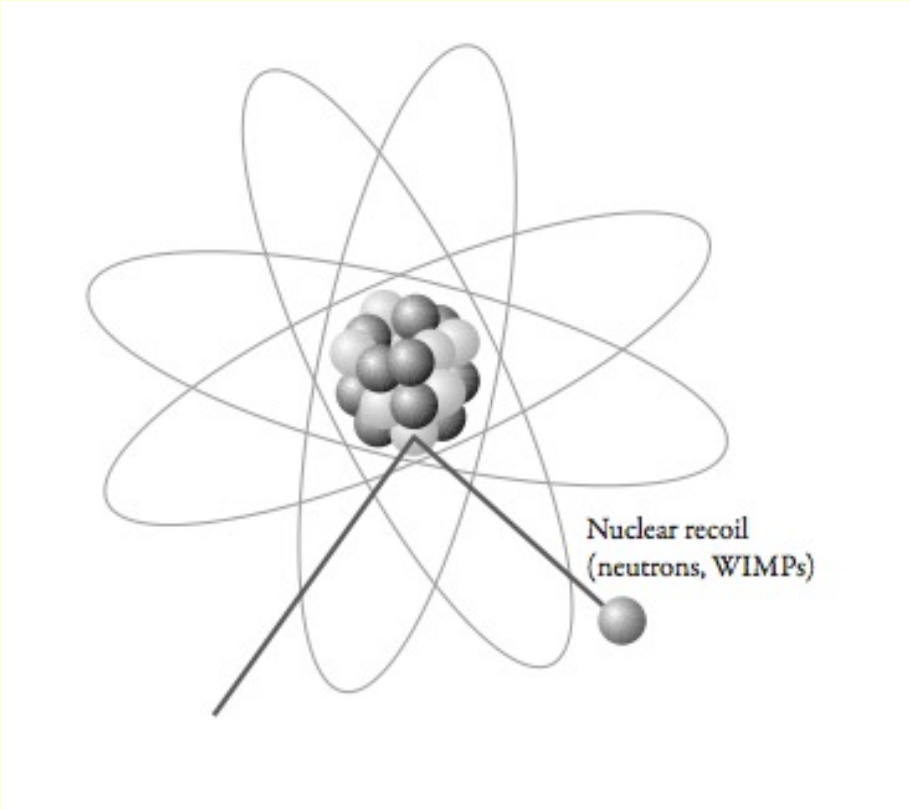
- If the LHC sees nothing, can SUSY survive? Yes.
- It may be at high scale,
- It may be less simple than all scalars and all fermions at one scale, e.g. NUHM (Pearl Sandick)
- Even is SUSY is found at LHC, we still won't know if particles are long-lived; to see if it's dark matter, need other approaches

SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

DIRECT DETECTION OF WIMP DARK MATTER

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



Expected Rate: less than one count/kg/day!

How did I get into Dark Matter?

PhD Advisor at Univ of Chicago, David Schramm
ADVICE to students: Find a great mentor

Drukier, Freese, & Spergel (1986)

We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal

Event rate

(number of events)/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

$$= \frac{\rho \sigma_0 F^2(q)}{2m\mu^2} \int_{v>\sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v$$

Spin-independent $\sigma_0 = \frac{A^2\mu^2}{\mu_p^2}\sigma_p$

Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi}\left|\langle S_p \rangle G_p + \langle S_n \rangle G_n\right|^2$

Canonical DM distribution in halo

use a Maxwellian distribution, characterized by an rms velocity dispersion σ_v, to describe the WIMP speeds, and we will allow for the distribution to be truncated at some escape velocity $v_{\rm esc}$,

$$\widetilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{\rm esc} \\ 0, & \text{otherwise.} \end{cases}$$

Here

$$N_{\rm esc} = \mathrm{erf}(z) - 2z\exp(-z^2)/\pi^{1/2},$$

with $z \equiv v_{\rm esc}/\overline{v}_0$, is a normalization factor. The most probable speed,

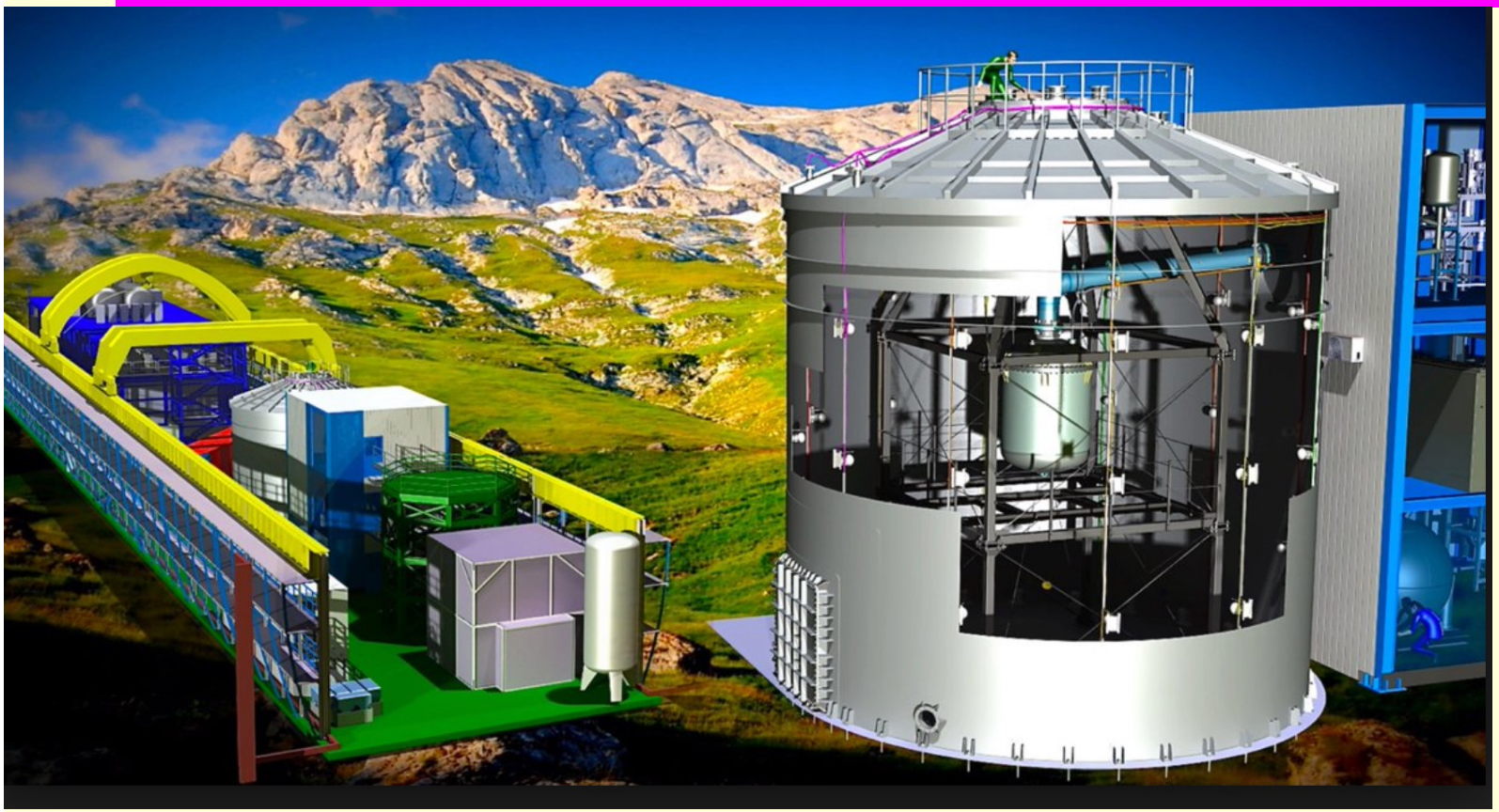
$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

$$dR/dE \propto e^{-E/E_0}$$

$$E_0 = 2\mu^2 v_c^2/M \text{ so}$$

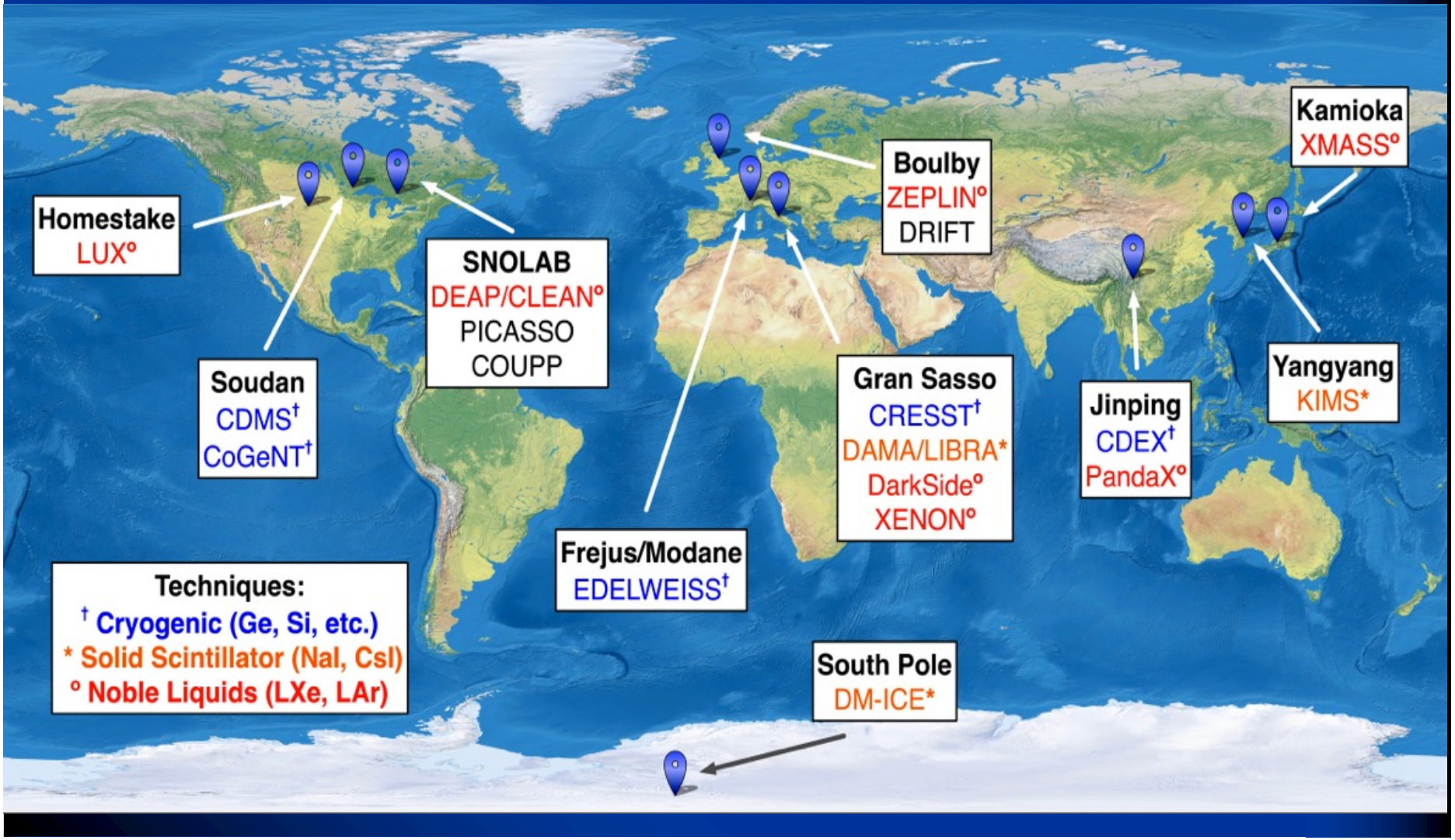
WIMP detectors must be in underground laboratories



Need to shield from Cosmic Rays

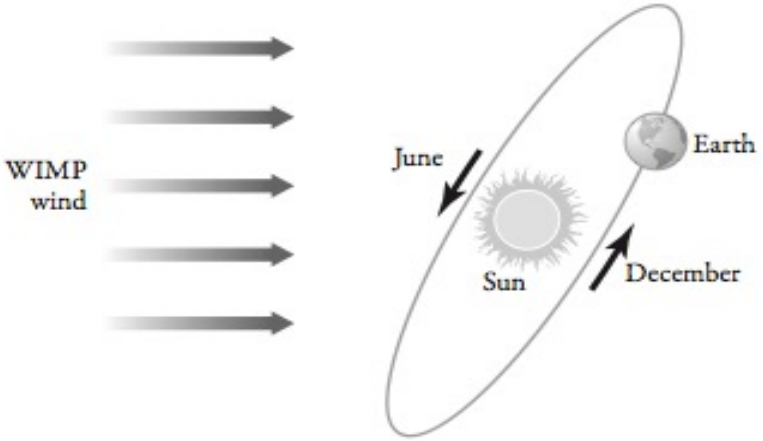
XENON experiment in Gran Sasso Tunnel

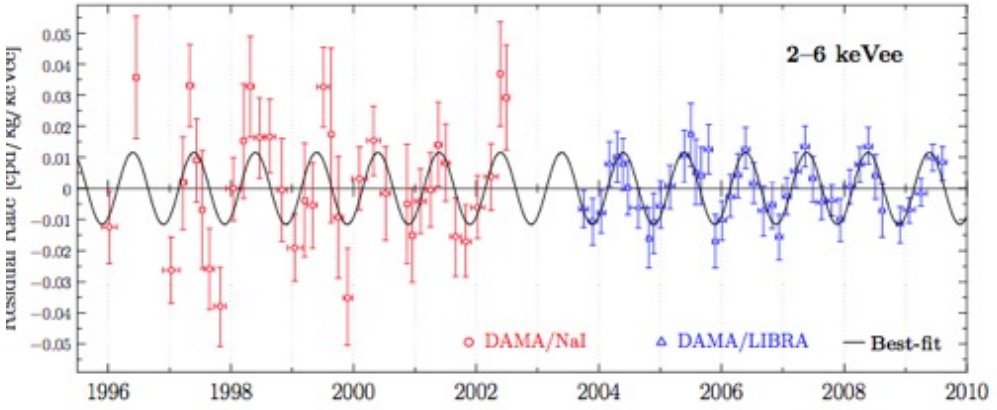
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

Drukier, Freese, and Spergel (1986);
Freese, Frieman, and Gould (1988)





NaI crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation at 12 sigma! Peak in June, minimum in December (as predicted). Are these WIMPs??

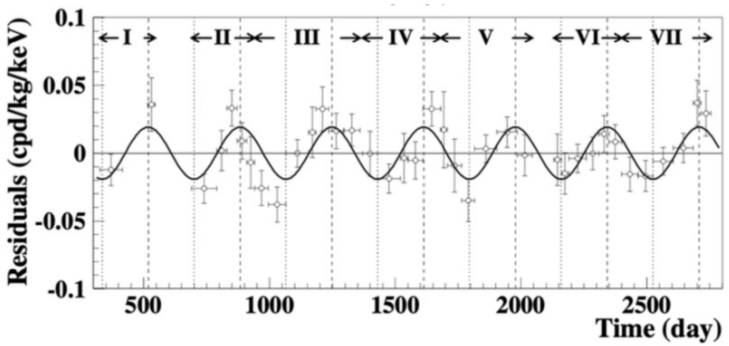


Figure 24: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/NaI in the (2–6) keV energy interval as a function of the time (exposure of 0.29 ton $\times$ yr) . The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}).

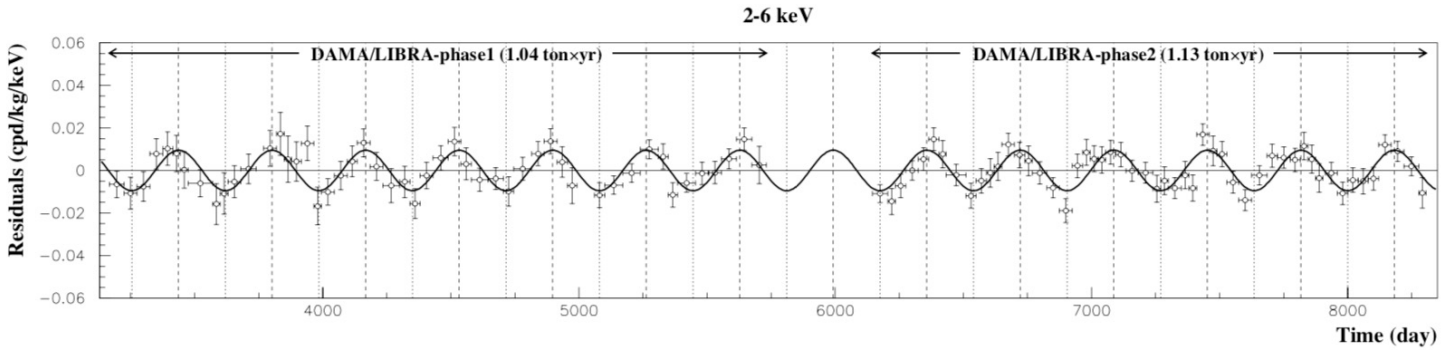


Figure 25: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit on the data points of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2. For details see caption of Fig. 23.

Two Issues with DAMA

- 1. The experimenters won't release their data to the public

- 2. Comparison to other experiments:

null results from XENON, CDMS, LUX.

But comparison is difficult because

experiments are made of different

detector materials!

“I’m a Spaniard caught between two Italian women”

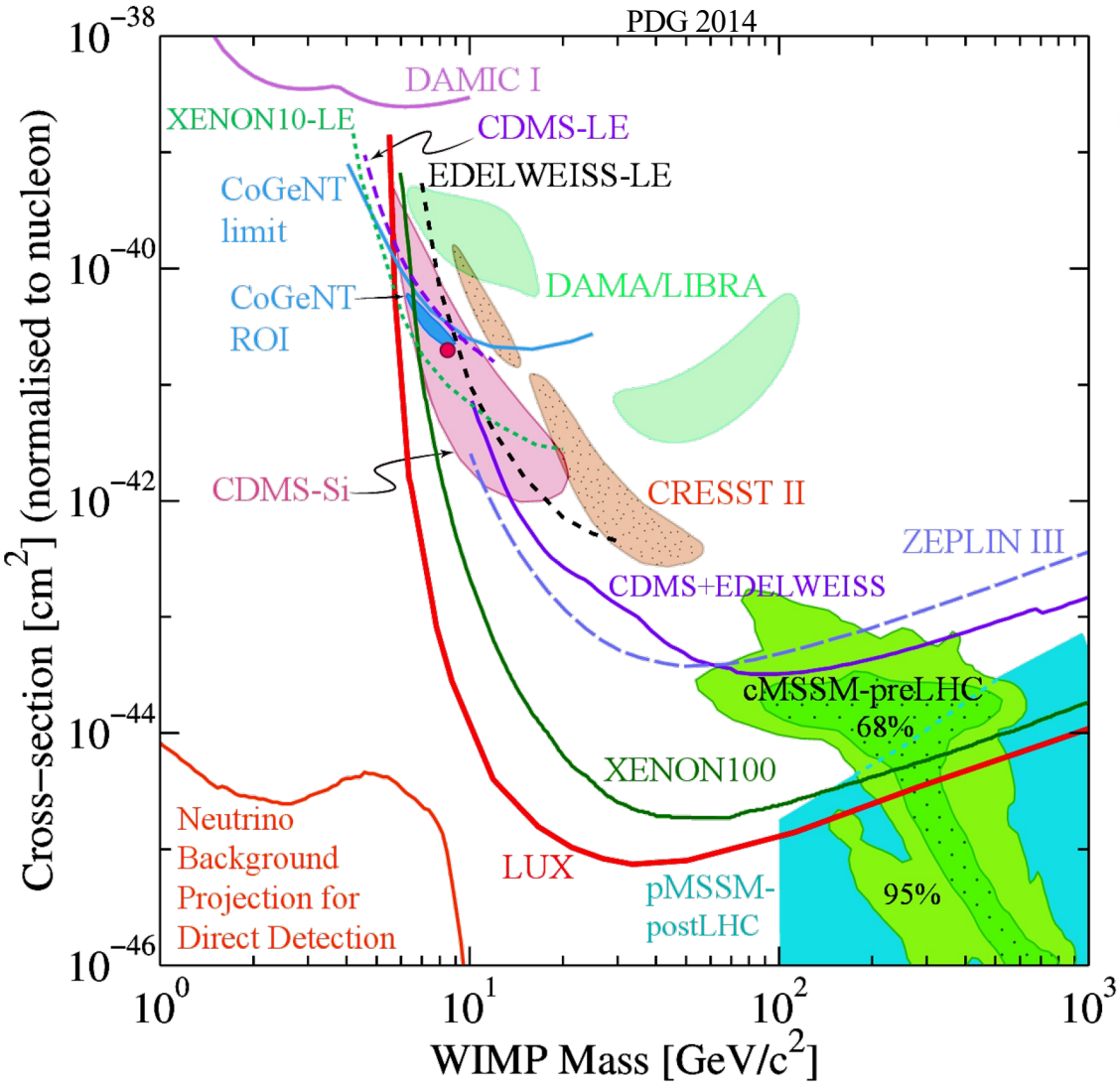
Rita Bernabei, DAMA

Juan Collar, PICO

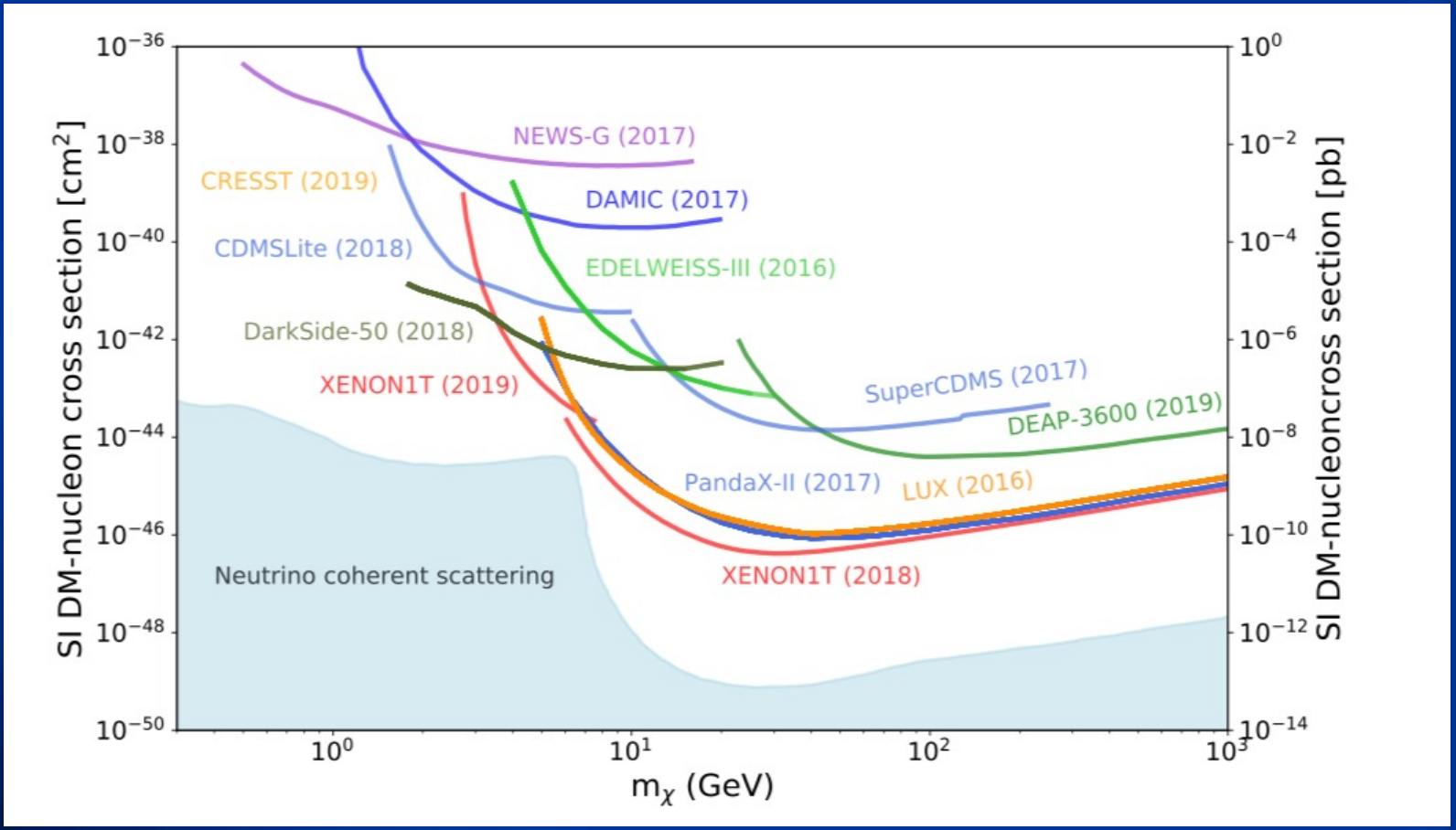
Elena Aprile, XENON

Bounds on Spin Independent WIMPs

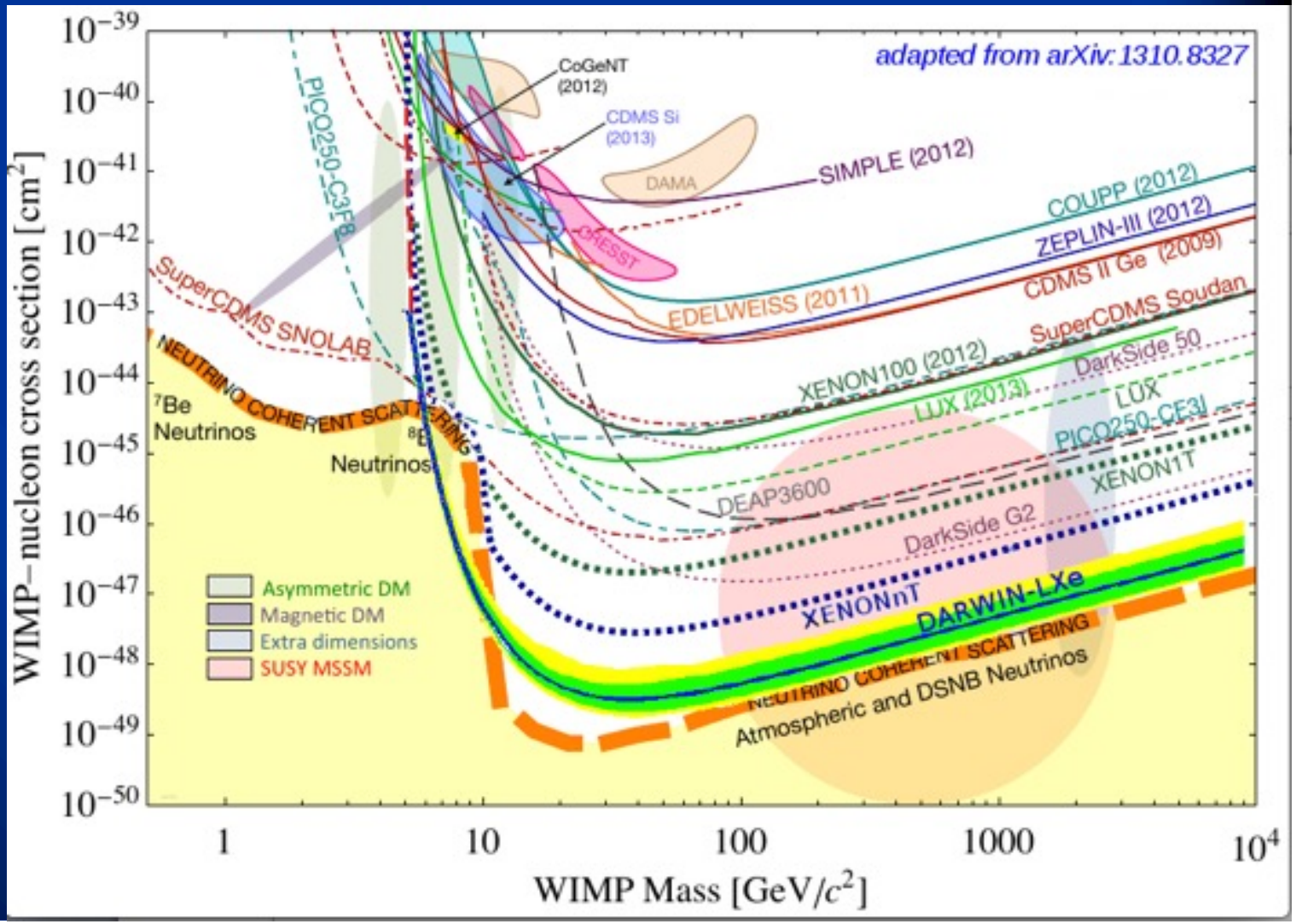
BUT:
--- it's hard to compare results from different detector materials
--- can we trust results near threshold?



From PDG 2019



Future experiments

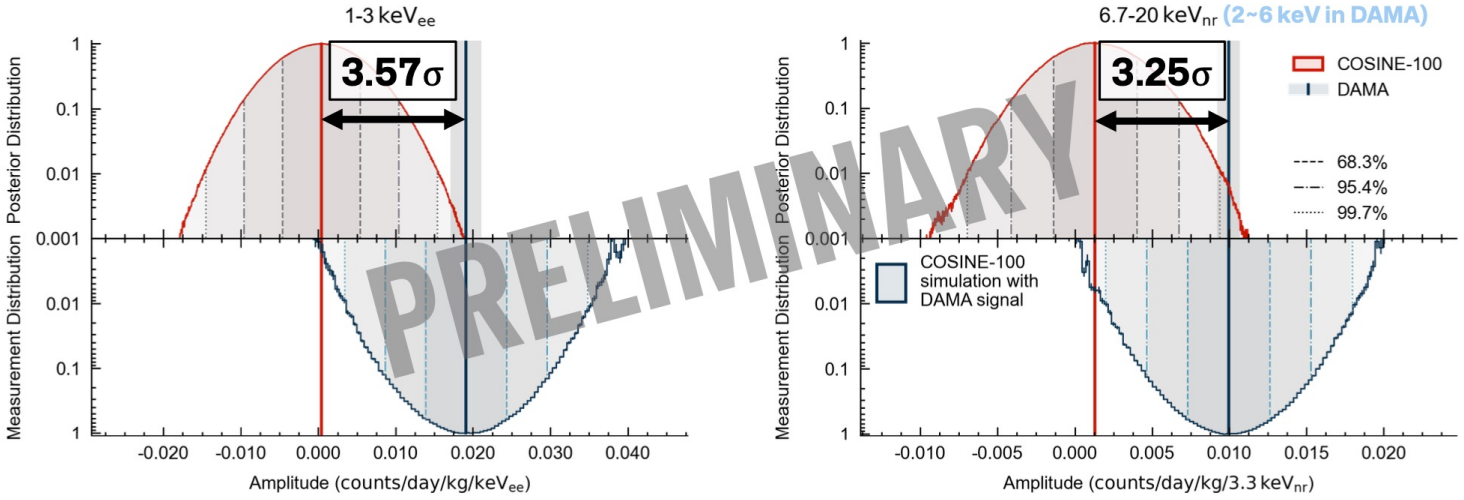


To test DAMA within next 5 years

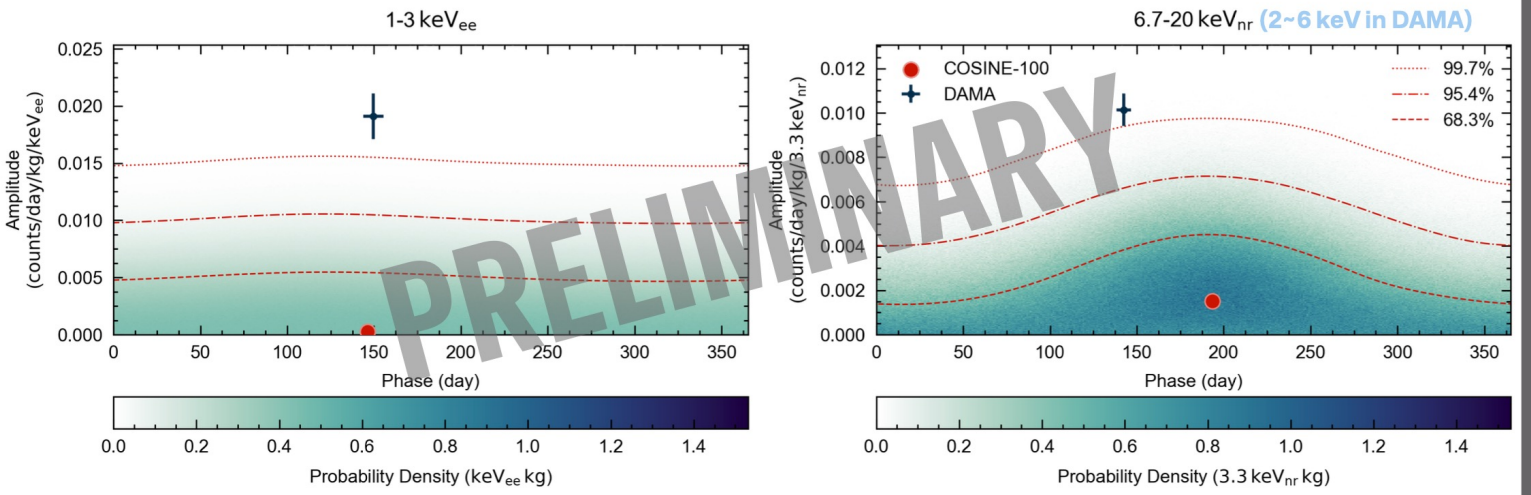
- The annual modulation in the data is still there after 13 years and still unexplained.
- New DAMA data down to keV still see modulation (DAMA all by itself is not compatible with SI scattering) Baum, Freese,Kelso 2018
- Other groups are using NaI crystals:
- COSINE-100 and ANAIS see no modulation
- SABRE (Princeton) with Australia
- COSINUS

COSINE-100 does not confirm DAMA annual modulation

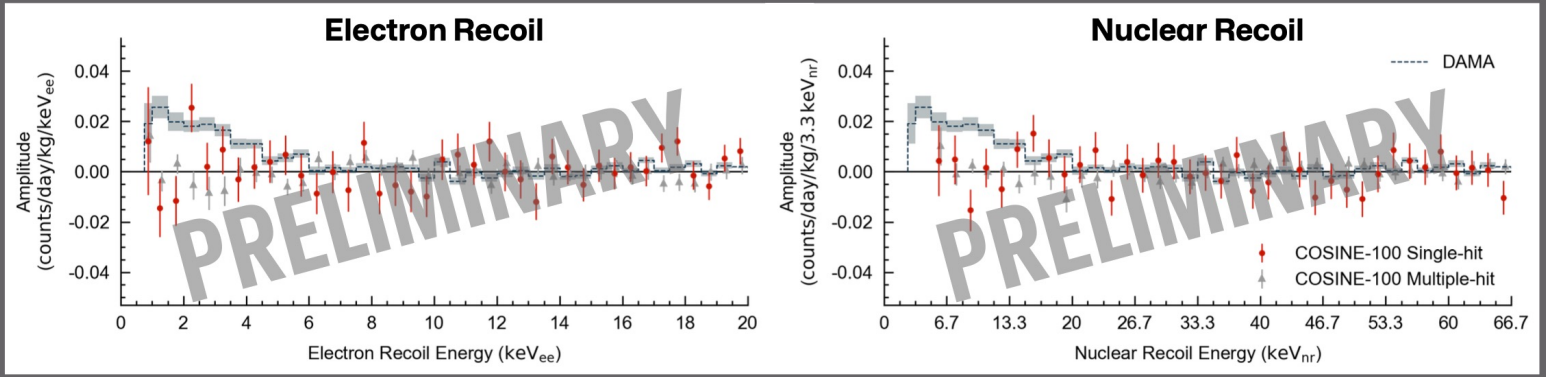
No Modulation Detected



No Modulation Detected



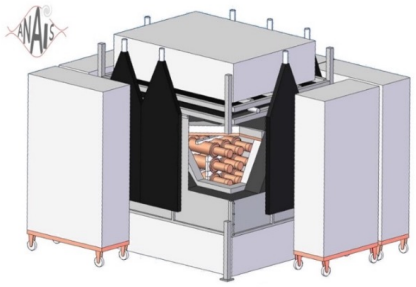
No Modulation Detected



E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	0.0004 ± 0.0050	0.0191 ± 0.0020
1~6	0.0017 ± 0.0029	0.01048 ± 0.00090
2~6	0.0053 ± 0.0031	0.00996 ± 0.00074

E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	0.0013 ± 0.0027	0.00996 ± 0.00074

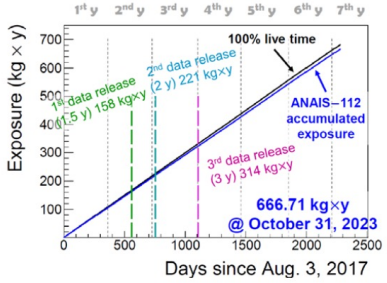
ANAIS sees no modulation



ANAIS-112 experiment
112.5 kg NaI(Tl)
Taking data at Canfranc Underground Laboratory since 2017

Previous Data Releases

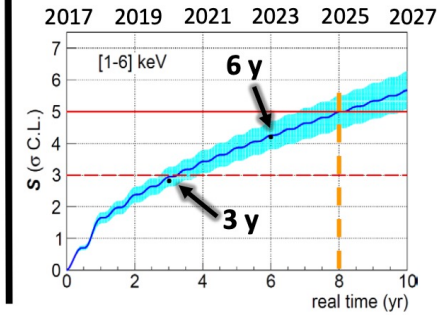
- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: Phys. Rev. D 103, 102005 (2021
- **3y + ML: 2404.17348**

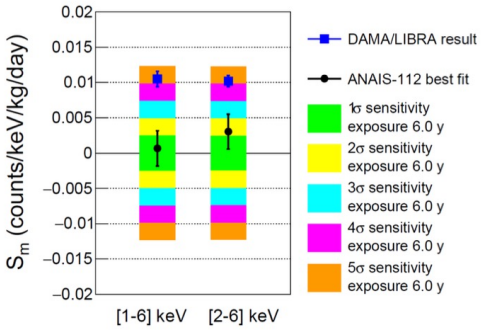


PRELIMINARY RESULTS for 6 years exposure (642,05 kg y)

Best fit **incompatible with DAMA/LIBRA** at 3.9 (2.9) σ for [1-6] ([2-6]) keV

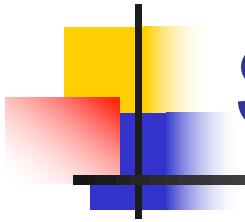
Sensitivity with 6 years data: 4.2 (4.1) σ for [1-6] ([2-6]) keV





Sensitivity prospects

5 σ sensitivity expected by the end of 2025



Status of DM searches

- Difficulty: comparing apples and oranges, since detectors are made of different materials.
- Theory comes in: Spin independent scattering, Spin dependent, try all possible operators, mediators, dark sector, etc.
- Interesting avenue: nuclear physics. (Fitzpatrick, Haxton, etal)

To go beyond the neutrino floor

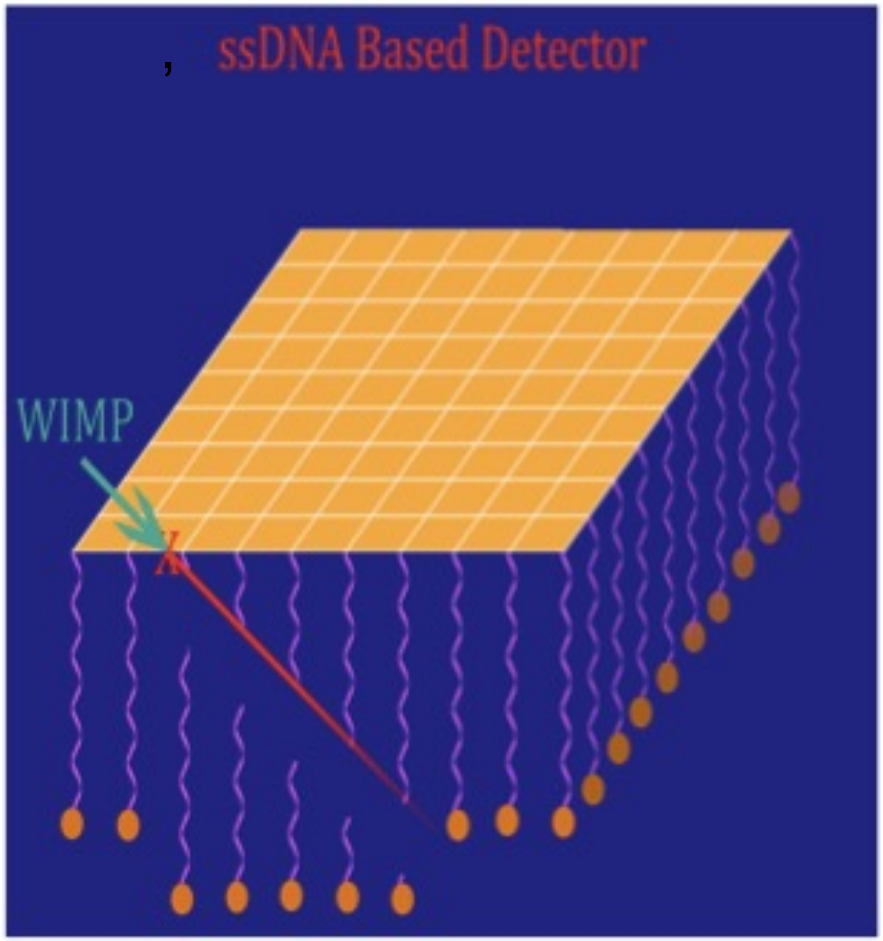
A major Step Forward: Directional Capability

to figure out what direction the WIMP came from

- Nuclei typically get kicked forward by WIMP collision
- Goal: identify the track of the recoiling nucleus i.e. the direction the WIMP came from
- Expect ten times as many into the WIMP wind vs. opposite direction.
- This allows dark matter discovery with much lower statistics (10-100 events).
- This allows for background rejection using annual and diurnal modulation.

DNA/RNA Tracker: directional detector with nanometer resolution

- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

Drukier, KF, Lopez, Spergel, Cantor, Church, Sano

Paleodetectors

WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

Collecting tracks for 500 Myr.

Backgrounds: Ur-238 decay and fission
Take advantage of nanotools: can identify nanometer tracks in 3D

Baum, Drukier, Freese, Gorski, Stengel arXiv:1806.05991

Pat Stengel

Sebastian Baum

article in New Scientist

Digging for dark matter

Despite making up most of the universe, we still haven't detected dark matter. A clue could lie buried in ancient rocks, says physicist **Sebastian Baum**

MOST of our universe is missing. Observations of the smallest galaxies to structures spanning the entire universe show that ordinary matter – the stuff that makes up you, me and everything we see in the cosmos around us – accounts for only one-fifth of all matter. The remaining 80 per cent is a mystery. After decades trying to hunt down this

Projected sensitivity of paleodetectors

2106.06559 (w Tom Edwards)

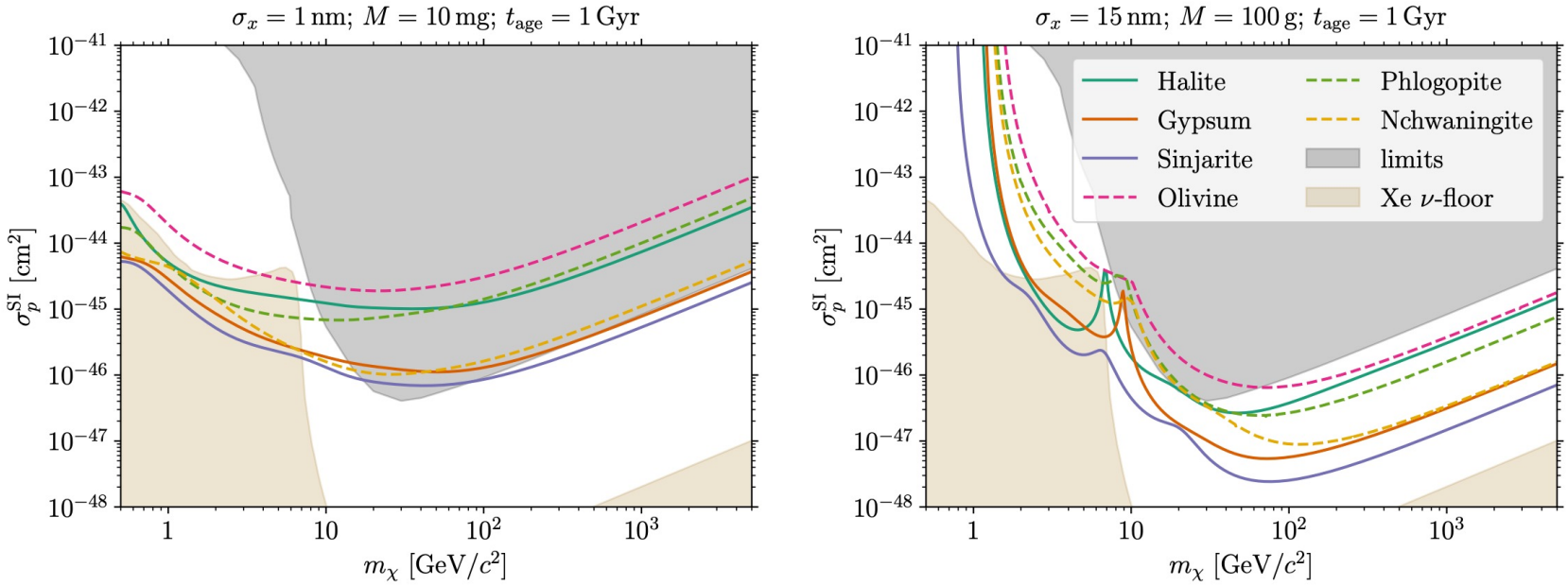
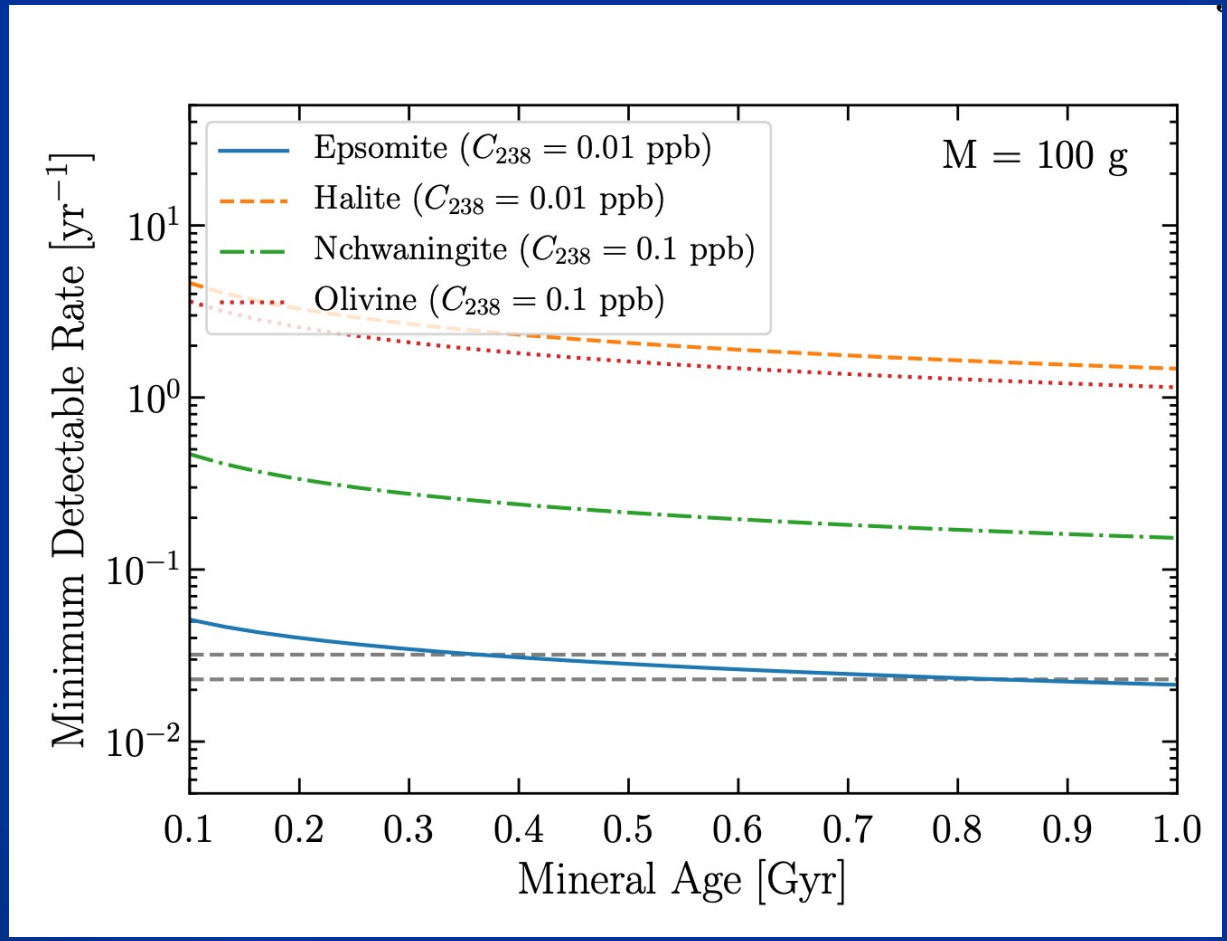


Figure 3. Projected 90 % confidence level upper limits in the WIMP mass (m_χ) – spin-independent WIMP-nucleus scattering cross section (σ_p^{SI}) plane in the high-resolution (sample mass $M = 10\,\mathrm{mg}$, track length resolution $\sigma_x = 1\,\mathrm{nm}$; left panel) and high-exposure ($M = 100\,\mathrm{g}$, $\sigma_x = 15\,\mathrm{nm}$; right panel) readout scenarios. The different lines are for different target materials as indicated in the legend, see Table 1. The gray-shaded region of parameter space is disfavored by current upper limits from direct detection experiments [12, 14, 17, 105, 150], while the sand-colored region indicates the *neutrino floor* for a Xe-based experiment [151]. Colors and linestyles are the same in both panels.

Paleodetectors for Galactic Supernova Neutrinos

Tom Edwards

Smallest galactic CC SN rate detectable at 3 sigma vs. mineral age



Baum, Edwards, Kavanagh, Stengel, Drukier, Freese, G´orski, Weniger, arxiv: 1906.05800

Time Dependence of local SN rate

- Paleodetectors would also contain information about the time-dependence of the local supernova rate over the past ~ 1 Gyr. Since the supernova rate is thought to be directly proportional to the star formation rate, such a measurement would provide a determination of the local star formation history.
- Eg we studied ten samples weighing M = 100g each, which have been recording events for different times {0.1, 0.2, 0.3, . . . , 1.0} Gyr.

Conference in Trieste: Mineral Detection of Dark Matter and Neutrinos (Oct 17-21)

- The aim of MDDMv is to bring together astroparticle theorists who have been making the scientific case for mineral detection and experimentalists who have initiated preliminary studies of their feasibility. As these searches incorporate various aspects of geology, materials science and astroparticle physics, the participants in MDDMv are a diverse group with expertise encompassing these fields.

Mineral Detection of Dark Matter and Neutrinos

Oct 17 – 21, 2022
IFPU
Europe/Rome timezone

Overview

Scientific Program and Timetable

Participants

Patrick Stengel

pstengel56@gmail.com

Participants

Participants

Gabriela Araujo (U Zurich)

Sebastian Baum (Stanford)

Yilda Boukhtouchen (Queen's)

Joe Bramante (Queen's)

Thomas Edwards (Johns Hopkins)

Ulrich Glasmacher (Heidelberg U)

Arianna Gleason-Holbrook (Stanford); online

Katherine Freese (UT Austin/Stockholm U)

Shigenobu Hirose (JAMSTEC); online

Patrick Huber (Virginia Tech)

Takenori Kato (Nagoya U); online

Bradley Kavanagh (Cantabria U)

Chris Kenney (SLAC); online

Tatsuhiro Naka (Toho U); online

Paola Sala (INFN Milano)

Patrick Stengel (INFN Ferrara)

Kai Sun (U Michigan)

Reza Ebadi (U Maryland); online

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

Recoiling nuclei lead to defects:
Fission tracks, vacancies in crystal lattice, etc

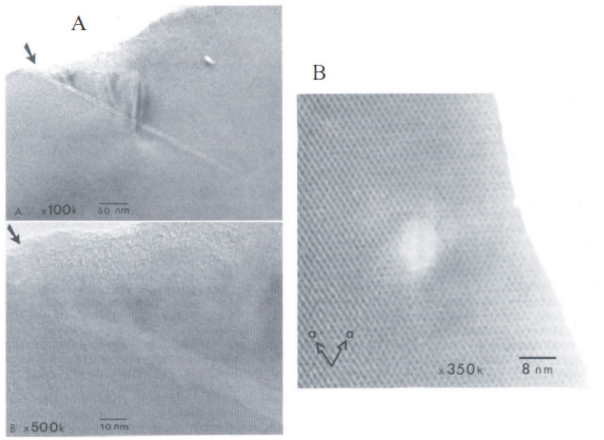


Figure 1: TEM-images of latent fission-tracks in apatite. *Left (A)*: Images taken parallel to the flight trajectory (light grey). *Right (B)*: Image taken perpendicular to the flight trajectory. Core of a fission-track is visible in the central part of the image. Figure taken from Ref. [90].

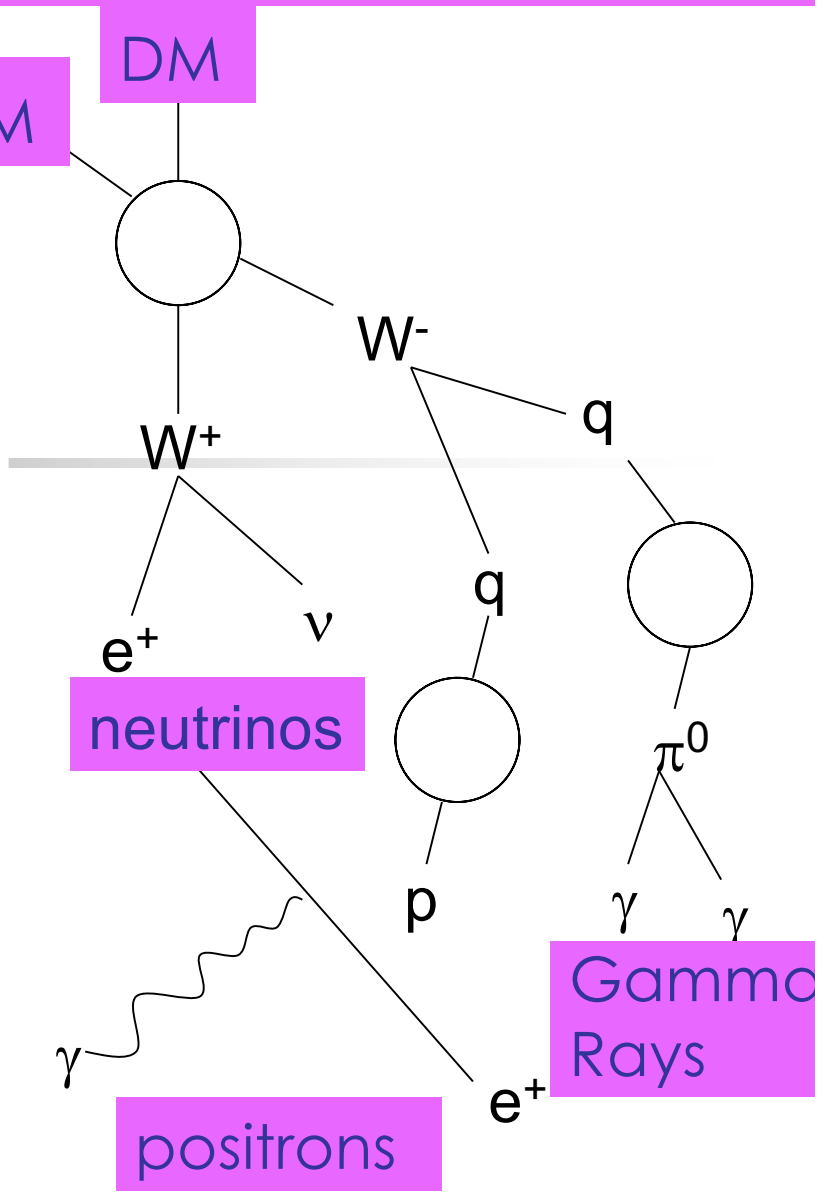
Color Centers:
Vacancies in crystal lattice,
e pairs fill in, get excited and fluoresce,
the crystal changes color

https://arxiv.org/pdf/2301.07118.pdf

Third Way to Search for WIMPs: Indirect Detection of WIMP Annihilation

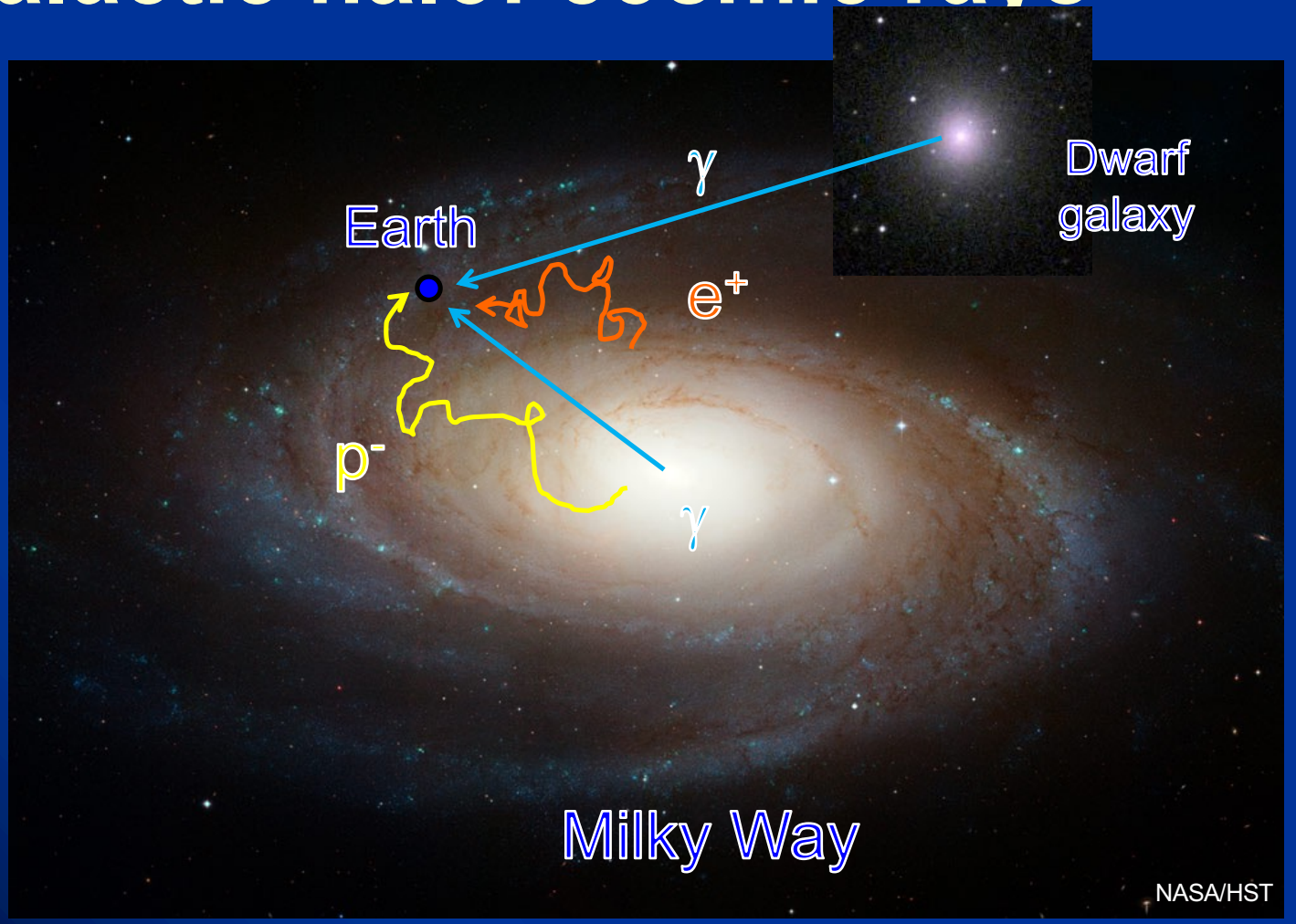
Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power Stars (dark stars)



Silk & Srednicki (1984); Ellis, KF et al. (1988)
Gondolo & Silk (1999)

Galactic halo: cosmic rays



AMS, Fermi/LAT, HESS, …

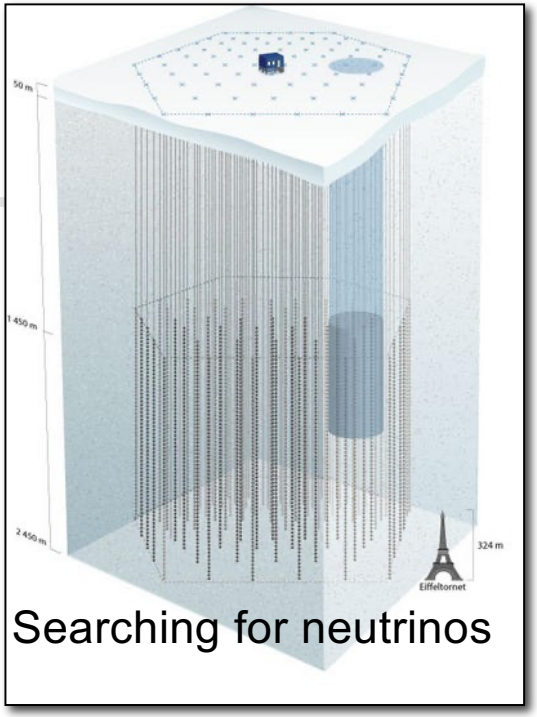
Indirect Detection: looking for DM annihilation signals

AMS aboard the International Space Station

Found excess e+

FERMI

IceCube
At the South Pole



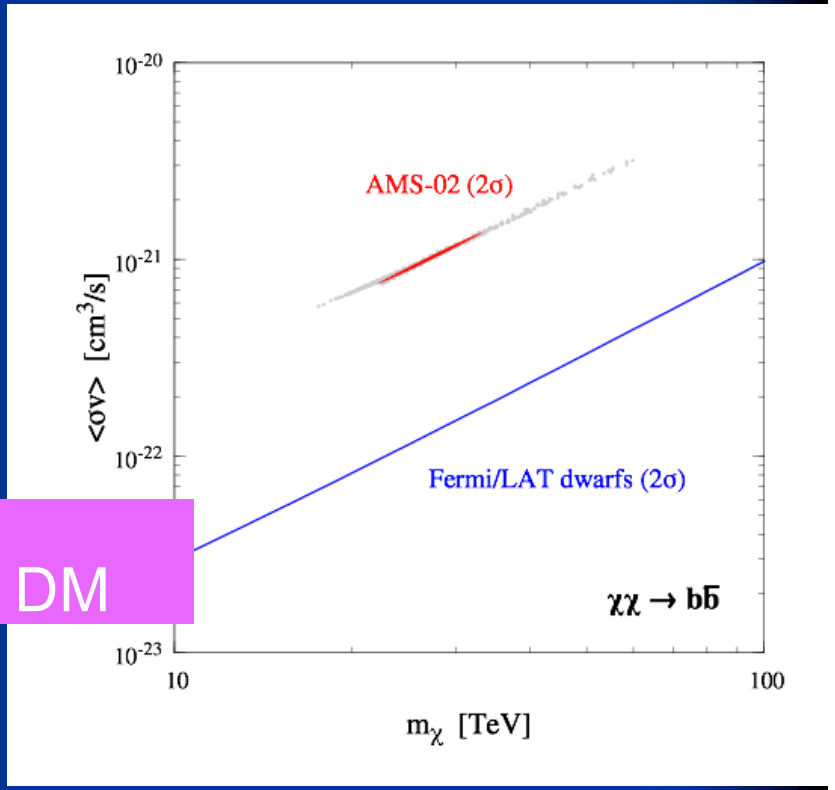
Searching for neutrinos

FERMI bounds rule out most channels of dark matter interpretation of AMS positron excess

- Lopez, Savage, Spolyar, Adams (arxiv:1501.01618)
- Almost all channels ruled out,

Including all leptophilic channels

(e.g. b bar channel in plot)



AMS positron excess is not from DM

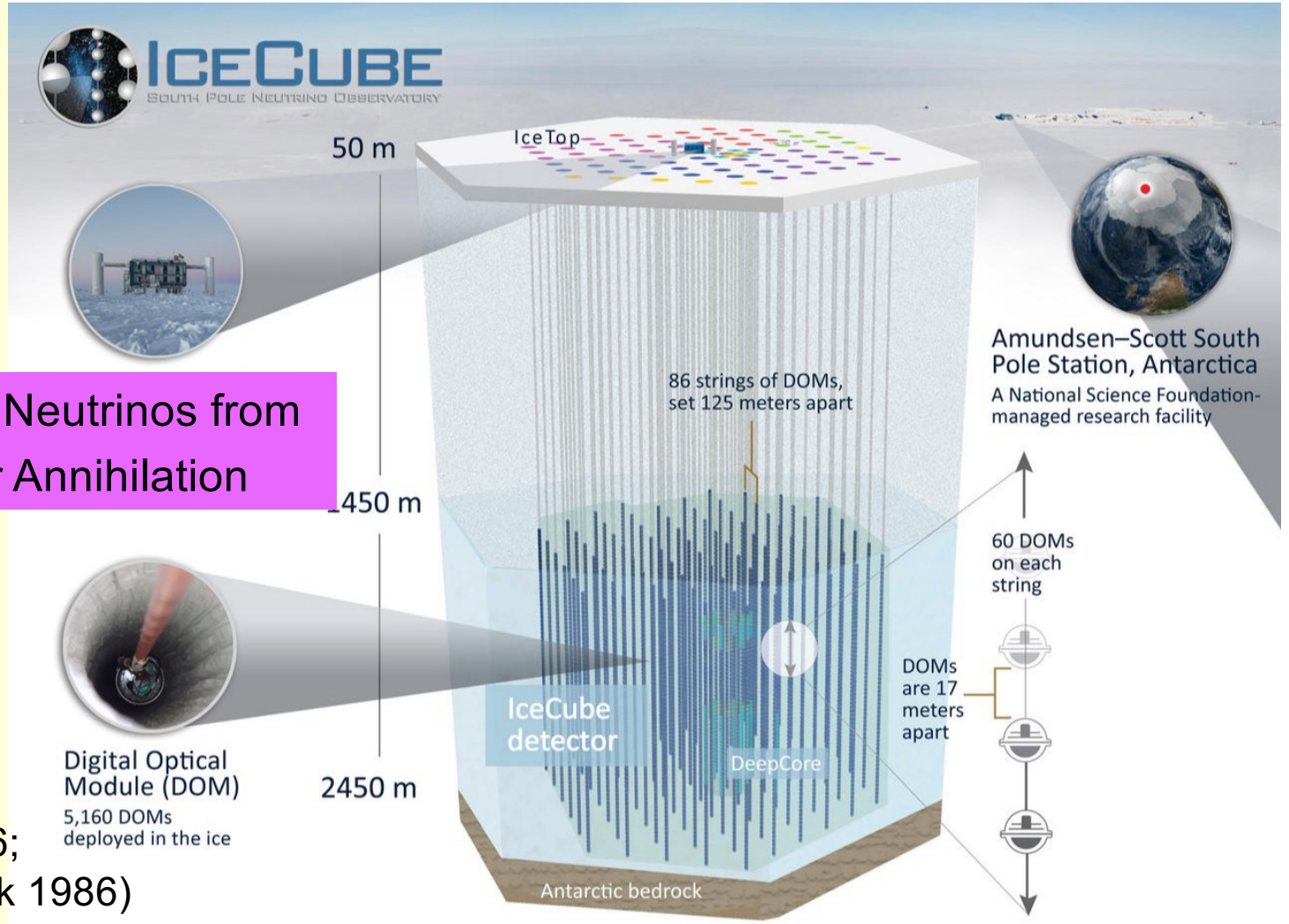
Indirect Detection of Neutrinos
IceCube at the South Pole

Ben Jones
UT Arlington

Looking for Neutrinos from Dark Matter Annihilation

Sun (Silk, Olive, Srednicki 80s)

Earth (Freese 1986; Krauss and Wilczek 1986)

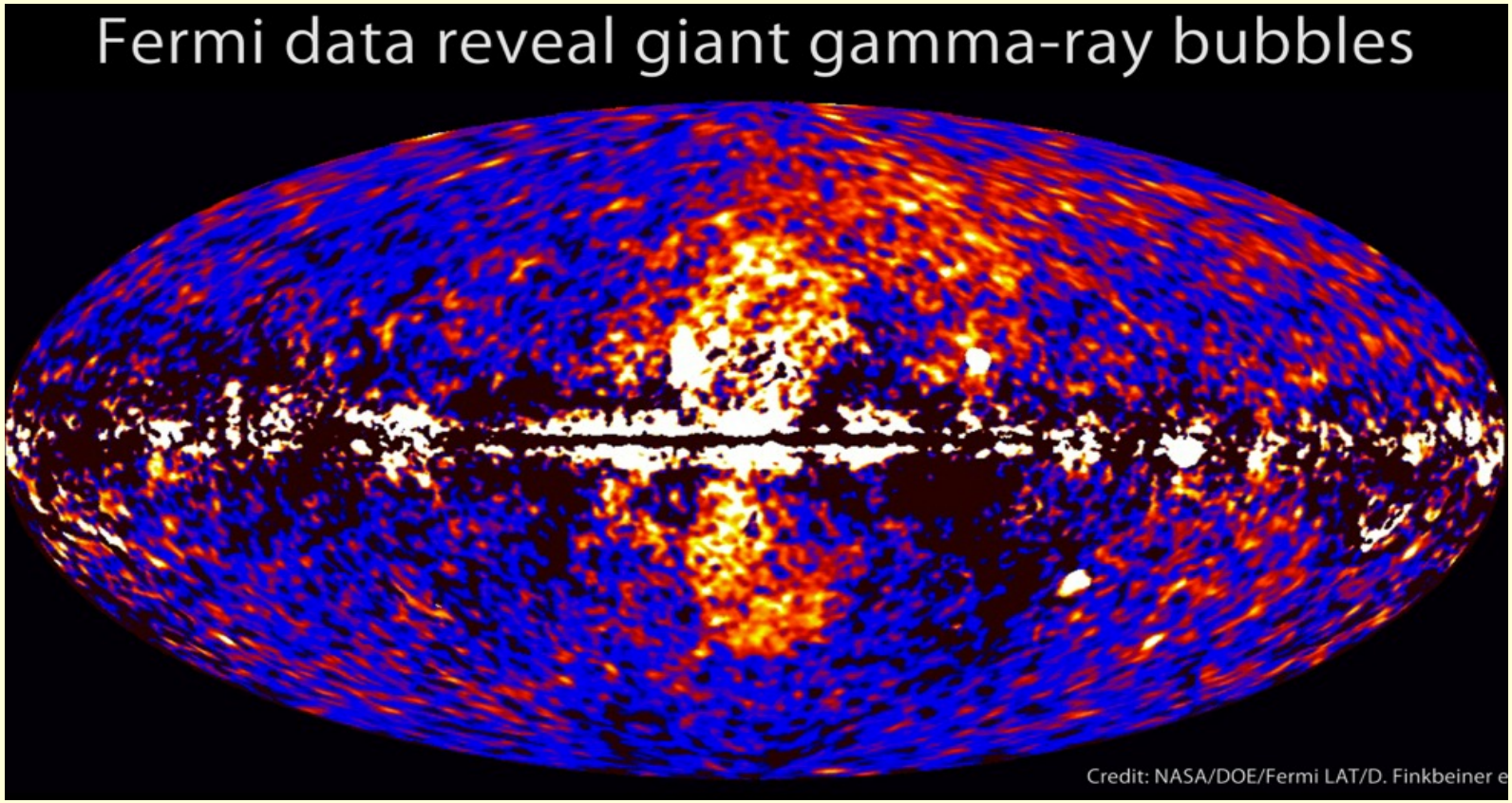


INDIRECT DETECTION of HIGH ENERGY PHOTONS (GAMMA-RAYS)

Are they from DM annihilation?

THE FERMI SATELLITE

The gamma ray sky



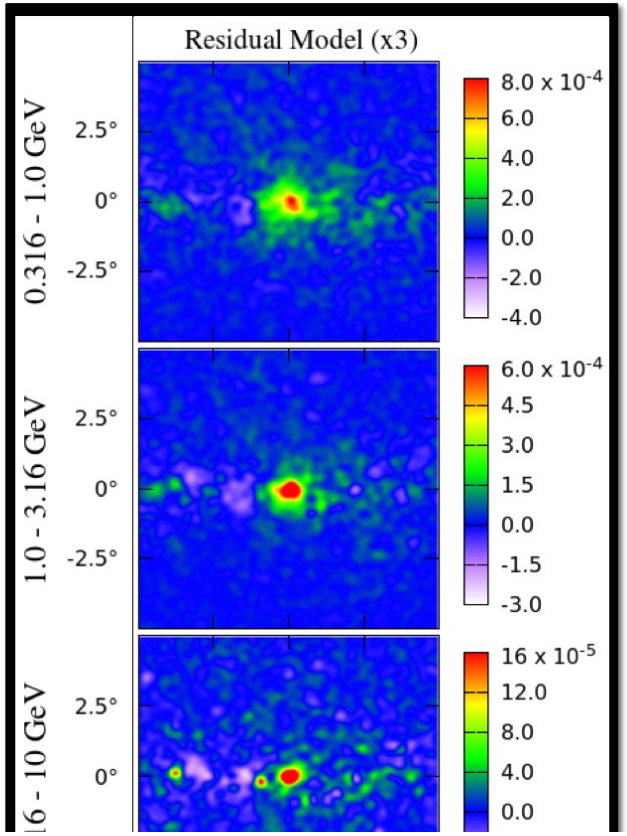
Doug Finkbeiner (Fermi Bubbles)

The Galactic Center Gamma-Ray Excess

- The Fermi data contains an excess of GeV-scale emission from the direction of the Inner Galaxy, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter

Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014
Murgia, et al. (2015)
Ackermann et al. (2017)

Fermi



- The spectrum of the excess is well fit by a ~20-65 GeV particle annihilating to quarks or gluons

Possible evidence for Dark Matter detection already now:

- Direct Detection:
  - DAMA annual modulation
  - (but no signal in other experiments)
- Indirect Detection:
  - FERMI gamma ray excess near galactic center
- Theorists are looking for models in which some of these results are consistent with one another (given an interpretation in terms of WIMPs)

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

Fourth Way: Find Dark Stars (hydrogen stars powered by dark matter) in James Webb Space Telescope, sequel to Hubble Space Telescope

W Doug Spolyar, P. Gondolo

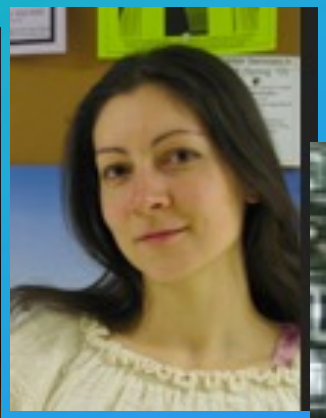
Collaborators

Doug Spolyar

Paolo Gondolo

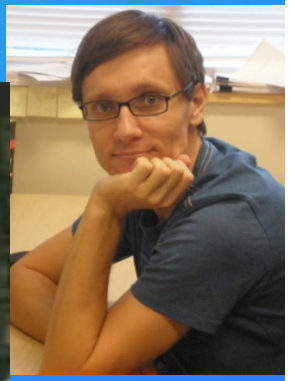
Luca Visinelli

Pearl Sandick



Tanja Rindler -Daller

Peter Bodenheimer



Cosmin Ilie

Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion. Dark stars are made almost entirely of hydrogen and helium, with dark matter constituting 0.1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to ten billion times as bright as the Sun. **We have found candidates in James Webb Space Telescope**
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: **IS THIS THE ORIGIN OF SUPERMASSIVE BLACK HOLES?**

Basic Picture

- The first stars form 200 million years after the Big Bang in the centers of protogalaxies --- right in the DM rich center.
- As a gas cloud cools and collapses en route to star formation, the cloud pulls in more DM gravitationally.
- DM annihilation products typically include e+/e- and photons. These collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

The Bottom Line

- JWST has found ~ 700 high redshift objects with z > 10. They call them “galaxy candidates”
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published..

(W/out spectra, can’t be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- OUR RESULTS: Three of the four hi-z JWST objects we studied are consistent with Dark Stars
- New data: one of them has metal lines (not a DS?) .

The role of Weakly Interacting Massive Particles (WIMPs) or Self Interacting Dark Matter

- Re WIMPs:

  Mass 1Gev-10TeV (canonical 100GeV)

  Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3\times10^{-26} cm^3/\text{sec}$$

Same annihilation that leads to correct WIMP abundance in today's universe

Same annihilation that gives potentially observable signal in FERMI, PAMELA, AMS

Dark Matter Heating

Heating rate:

$$Q_{ann} = n_\chi^2 < \sigma v > \times m_\chi$$

$$= \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

$$\Gamma_{DMHeating} = f_Q \, Q_{ann}$$

f_Q:

1/3 electrons

1/3 photons

1/3 neutrinos

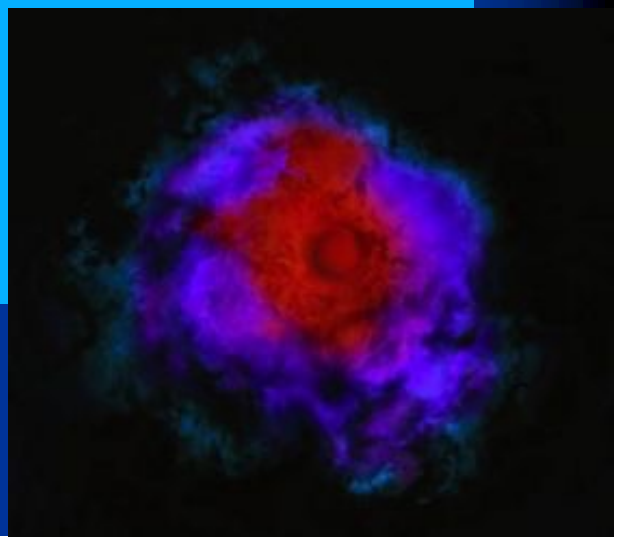
Dark Matter Power vs. Fusion

- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

Three Conditions for Dark Stars
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H2 Cooling ?

New Phase



DS Basic Properties

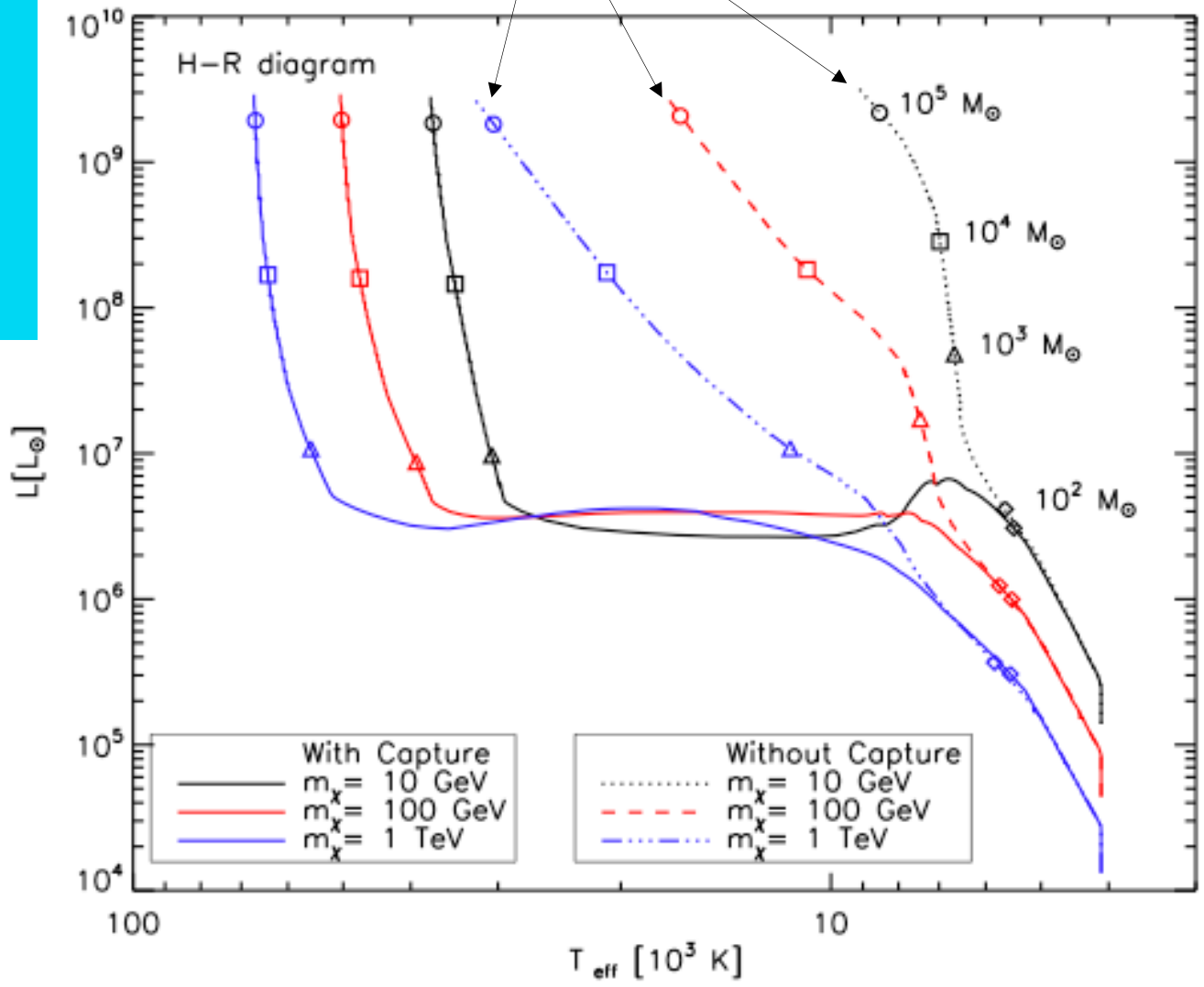
- We find that DS are big puffy objects:
  - Massive: can grow to $10^7 M_\odot$
  - Large- 10 a.u. (radius of Earth's orbit around Sun)
  - Luminous: up to $10^{10} L_\odot$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till today?.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

Building up the mass

- Start with a few $M_\odot$ Dark Star, find equilibrium solution
- Accrete mass, one $M_\odot$ at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until you run out of DM fuel
- VERY LARGE FIRST STARS. Then, star contracts further, temperature increases, fusion will turn on, eventually make black hole
- The largest ones collapse directly to black holes

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

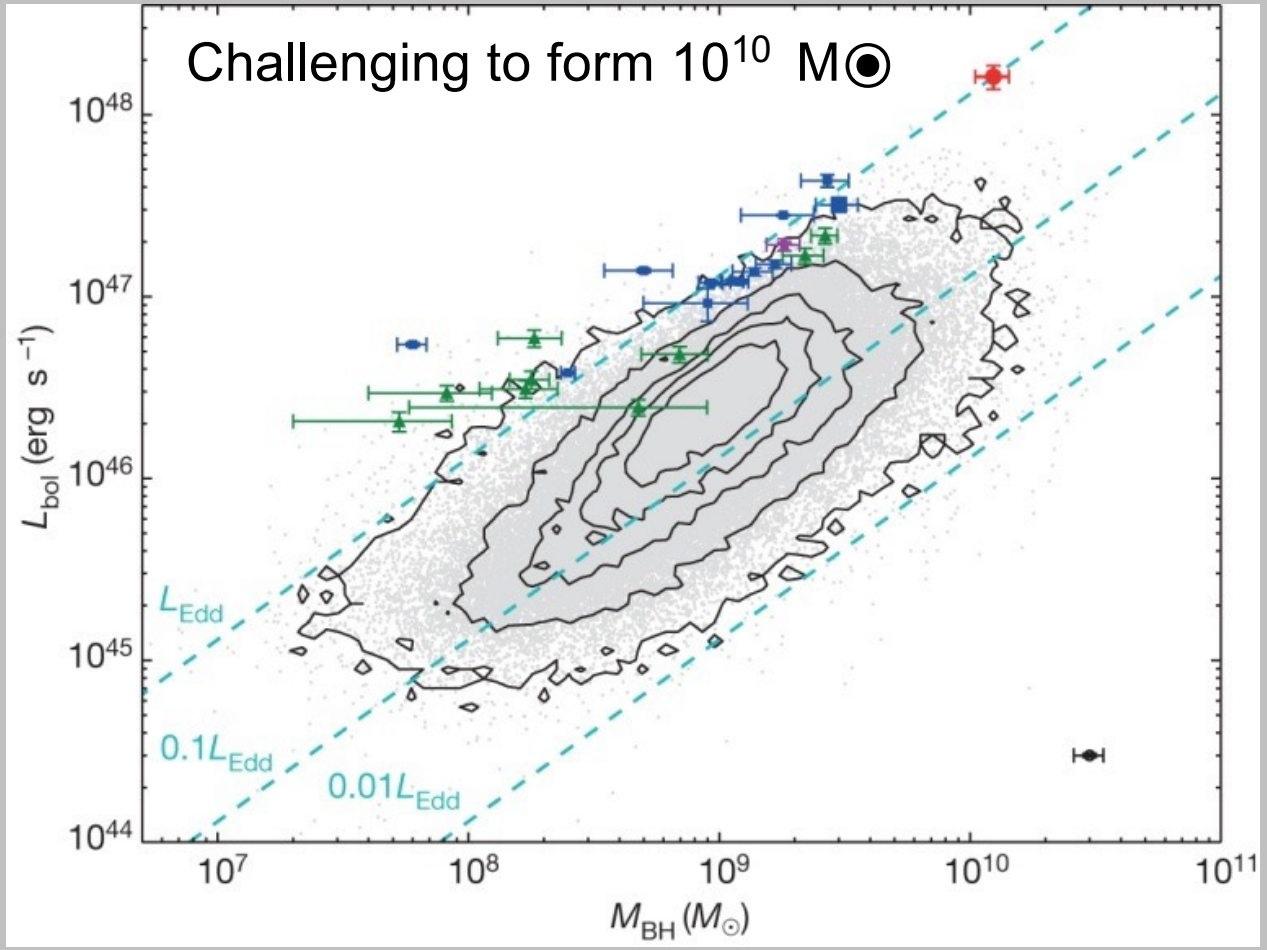
Assuming all of the baryons can accrete in a 10^6 $M_\odot$ halo



What happens next?
BIG BLACK HOLES

- Star reaches $T=10^7 K$, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse directly to BH
- Less massive ones live a million years, then collapse to Black Holes
- Helps explain observed black holes:
- (i) in centers of galaxies
- (ii) billion solar mass BH in the early Universe: the BIG BLACK HOLE PROBLEM
- (iii) intermediate mass BH

SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses at z=6
Challenging to form supermassive BH this early



X-B Wu *et al. Nature* **518**, 512-515 (2015) doi:10.1038/nature14241

nature

arXiv:1712.01860v1 [astro-ph.GA] 5 Dec 2017

An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5

Eduardo Bañados[1,*], Bram P. Venemans[2], Chiara Mazzucchelli[2], Emanuele P. Farina[2], Fabian Walter[2], Feige Wang[3,4], Roberto Decarli[2,5], Daniel Stern[6], Xiaohui Fan[7], Fred Davies[8], Joseph F. Hennawi[8], Rob Simcoe[9], Monica L. Turner[9,10], Hans-Walter Rix[2], Jinyi Yang[3,4], Daniel D. Kelson[1], Gwen Rudie[1], and Jan Martin Winters[11]

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[2]Max Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
[3]Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
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[5]INAF – Osservatorio Astronomico di Bologna, via Gobetti 93/3, 40129, Bologna, Italy
[6]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
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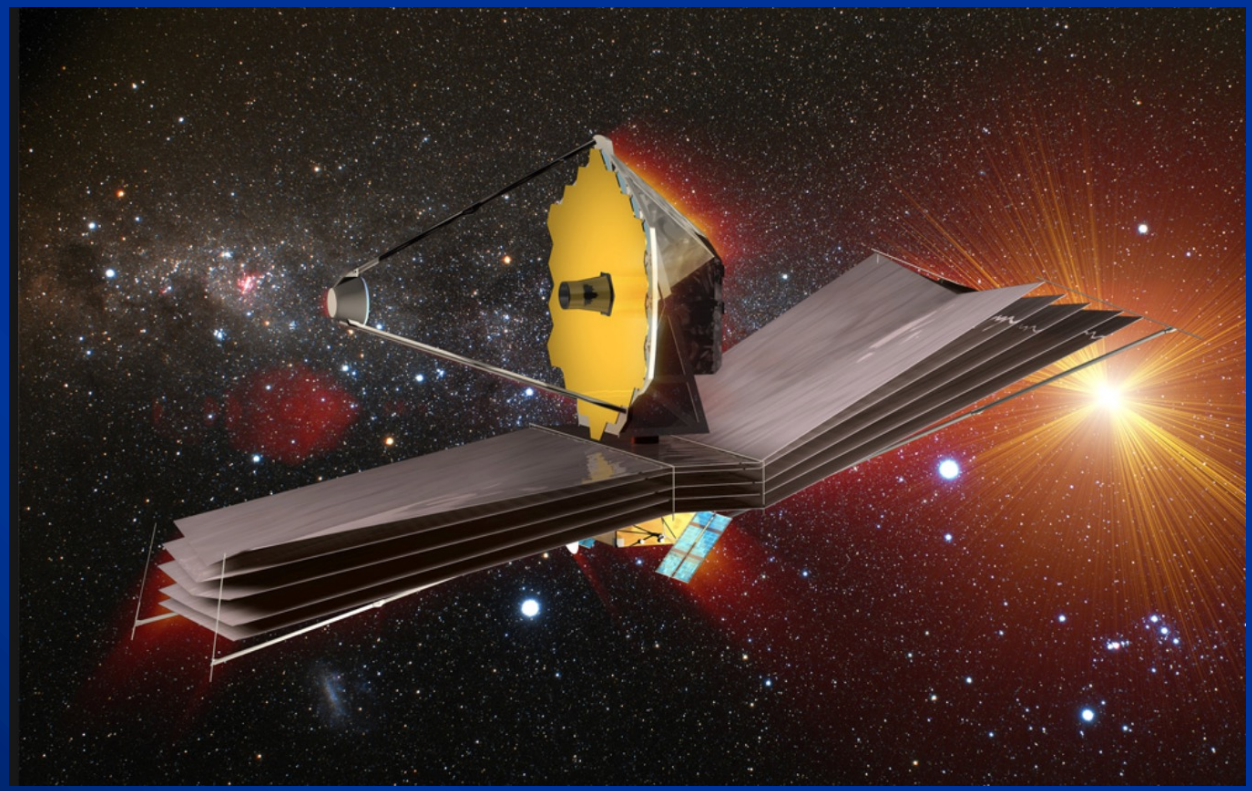
[8]Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106–9530, USA
[9]MIT-Kavli Center for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
[10]Las Cumbres Observatory, 6740 Cortona Dr, Goleta, CA 93117, USA
[11]Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint Martin d'Hères, France
[*]ebanados@carnegiescience.edu

ABSTRACT

Quasars are the most luminous non-transient objects known, and as such, they enable unparalleled studies of the universe at the earliest cosmic epochs. However, despite extensive efforts from the astronomical community, the quasar ULAS J1120+0641 at $z = 7.09$ (hereafter J1120+0641) has remained as the only one known at $z > 7$ for more than half a decade[1]. Here we report observations of the quasar ULAS J134208.10+092838.61 (hereafter J1342+0928) at a redshift of $z = 7.54$. This quasar has a bolometric luminosity of $4 \times 10^{13} L_{\odot}$ and a black hole mass of $8 \times 10^{8} M_{\odot}$. The existence of this supermassive black hole when the universe was only 690 Myr old, i.e., just 5% its current age, reinforces early black hole growth models that allow black holes with initial masses $\gtrsim 10^{4} M_{\odot}$[2,3] or episodic hyper-Eddington accretion[4,5]. We see strong evidence of the quasar's Lyα emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding J1342+0928 is significantly neutral. We derive a significant neutral fraction, although the exact value depends on the modeling. However, even in our most conservative analysis we find $\bar{x}_{\rm HI} > 0.33$ ($\bar{x}_{\rm HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

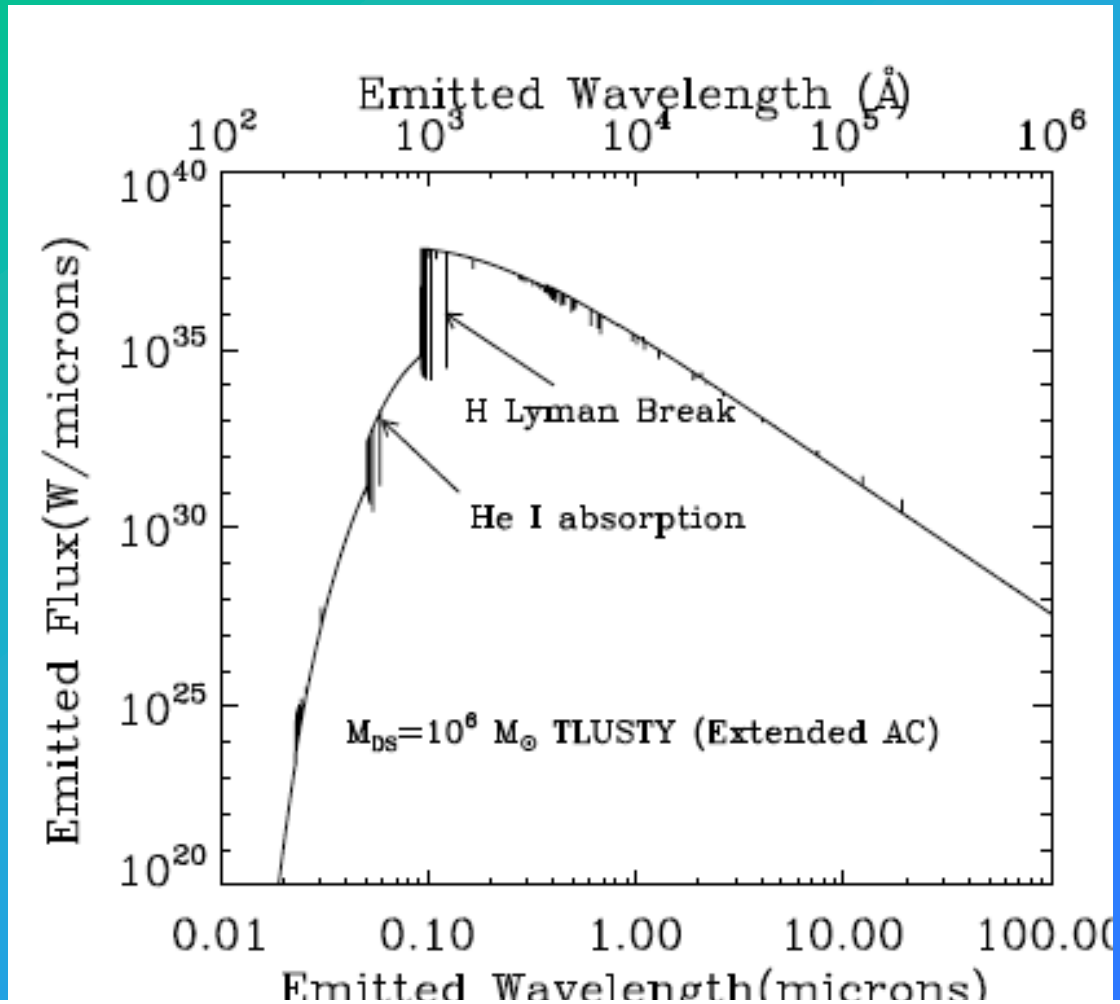
James Webb Space Telescope



Has JWST discovered Supermassive Dark Stars:
They would be a billion times brighter than the Sun
But the same temperature as the Sun. Unique signature.

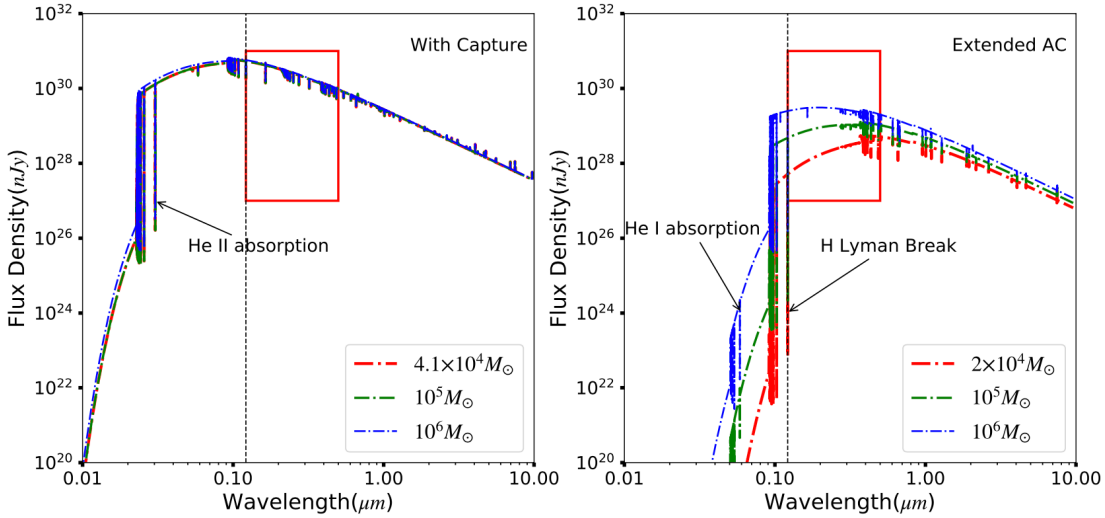
OBSERVING DARK STARS

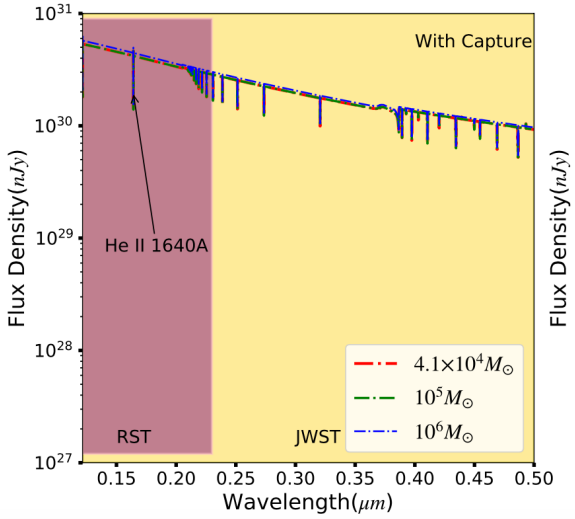
DS Spectrum from TLUSTY (stellar atmospheres code)

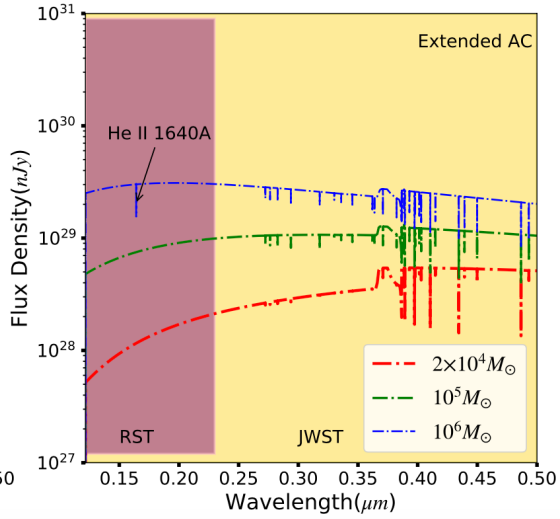


n.b. DS are made of hydrogen and helium only

Dark Star spectra

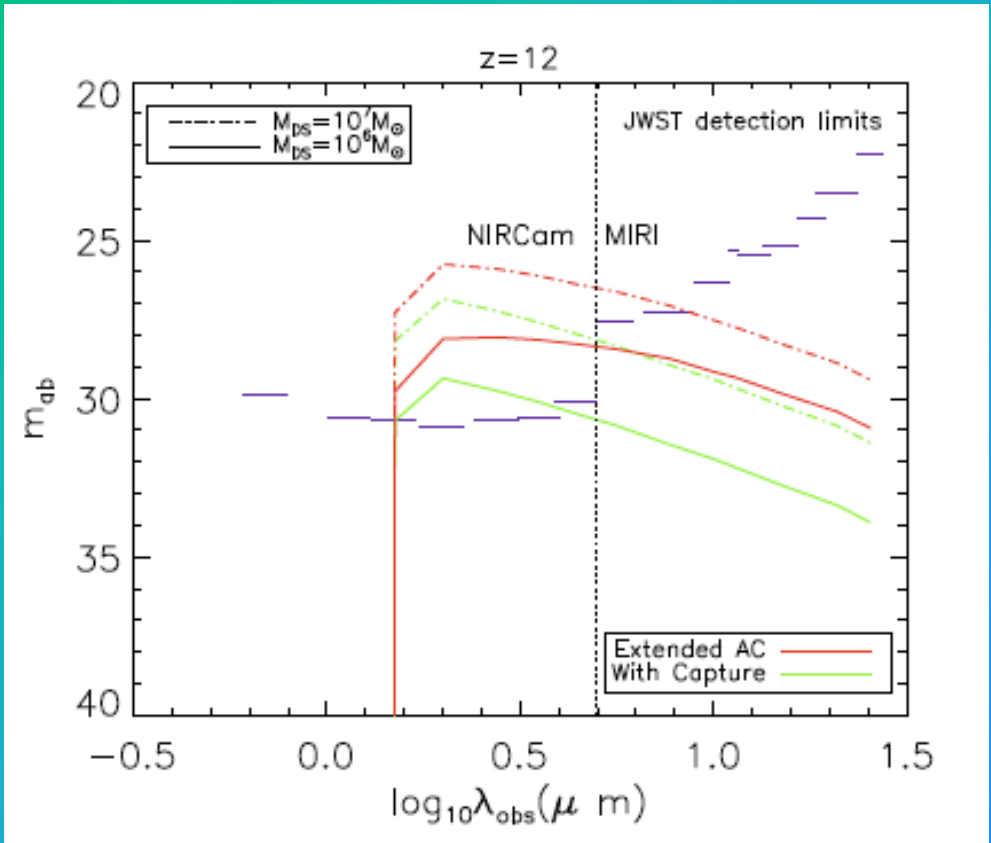




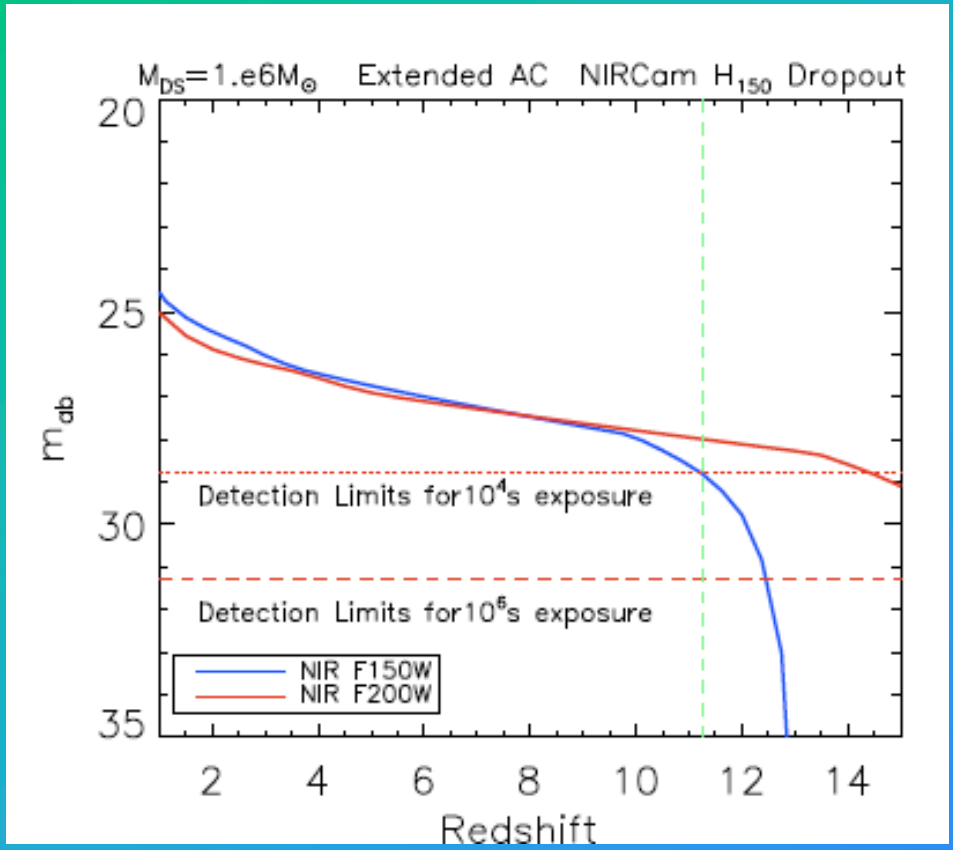


Assumes z =10 object

Dark Stars in JWST

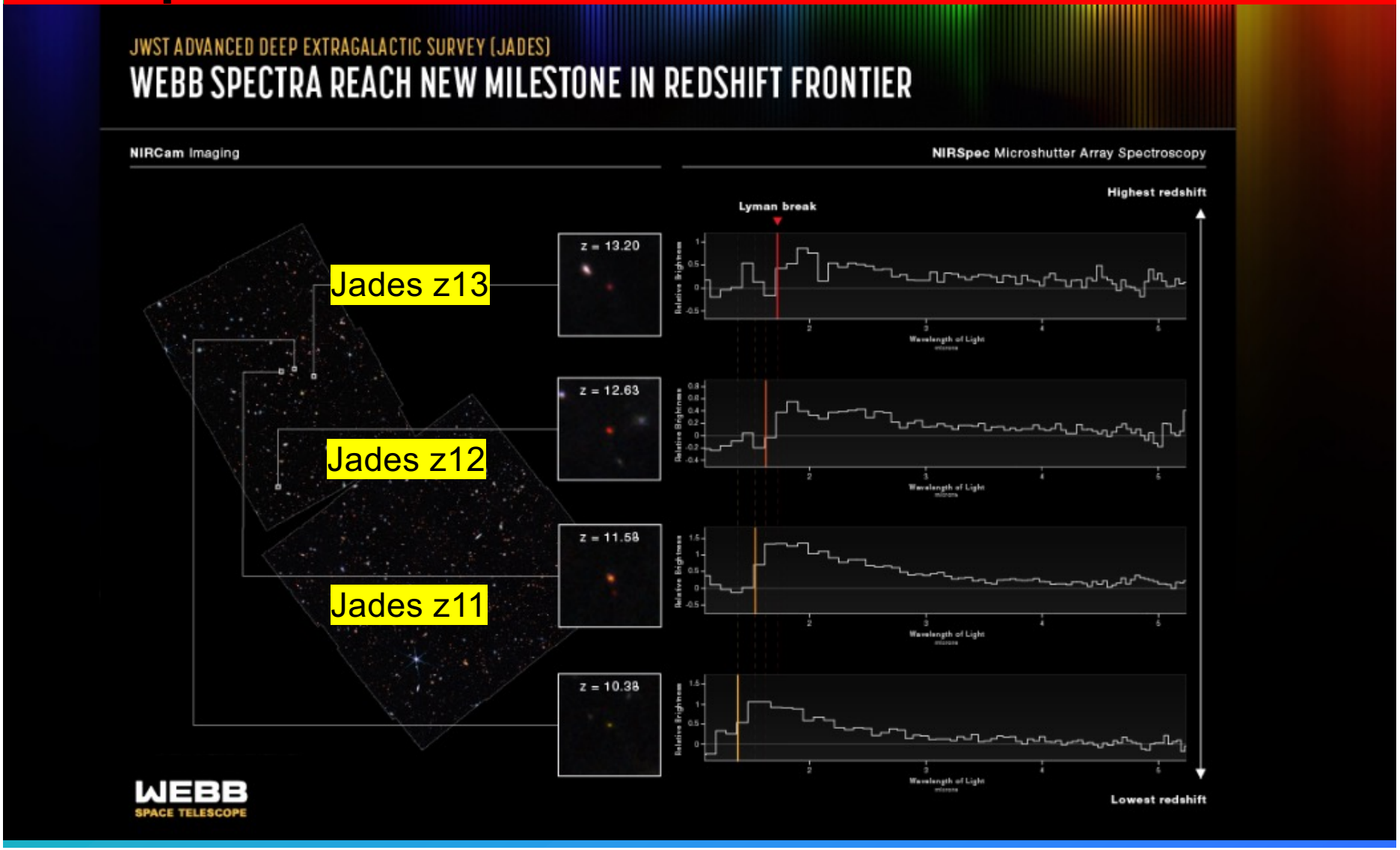


Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

Of 5 objects in JWST data with spectra: 3 could be Dark Stars!



Cosmin Ilie

Colgate University

Jillian Paulin

Criteria for hi-z objects to be Supermassive Dark Star candidates

- 1) Point object (SMDS) vs. resolved (galaxy)
- 2) DS spectra match data. We used photometric data (not noisy spectra for which data are not public).
- 3) Dark stars predict HeII1640 absorption line vs. galaxies predict emission line and a lot of other lines too. Spectra are too noisy so far but will get better with longer exposure.

All four JADES objects could be point objects

- Authors fit to spectral SEDs plus to galaxy profile (Sersic) and claimed best fit sizes of 0.04” and 0.02”, ~ the size of one NIRCam pixel, and one order of magnitude below the resolution limit ~0.1”

SMDS fits to JWST photometric data (brightness in 9 wavelength bands)

- Jillian Paulin did MCMC to optimize chi^2 for Dark Matter mass m= 100GeV with three parameters:
- Mass of SMDS (10^4,10^5, 10^6)$M_\odot$
- Redshift of object
- Magnification due to lensing

n.b. could be mu=10,
or, most lines of light have mu < 1

(Wang, Holz, Wald)

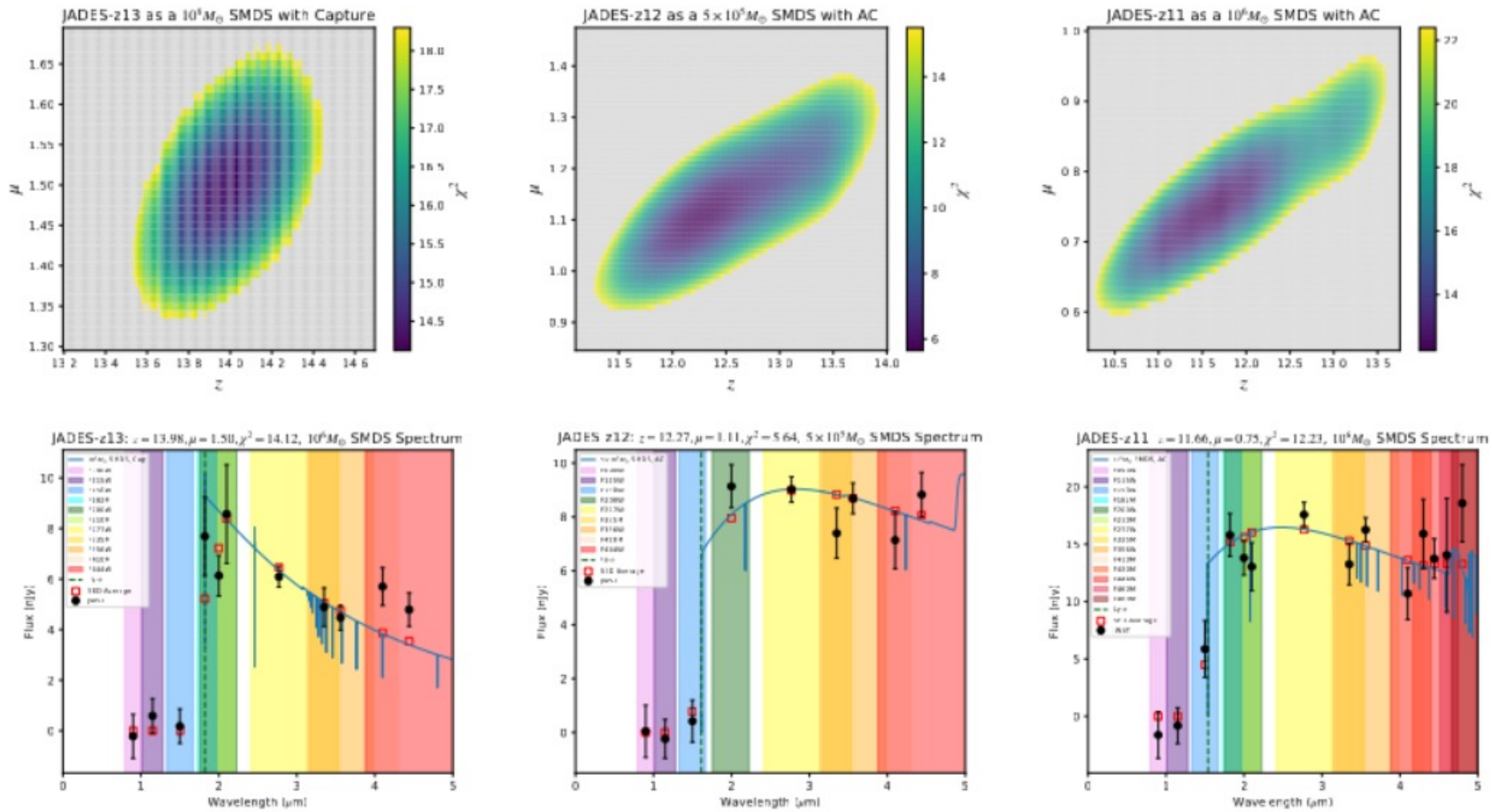
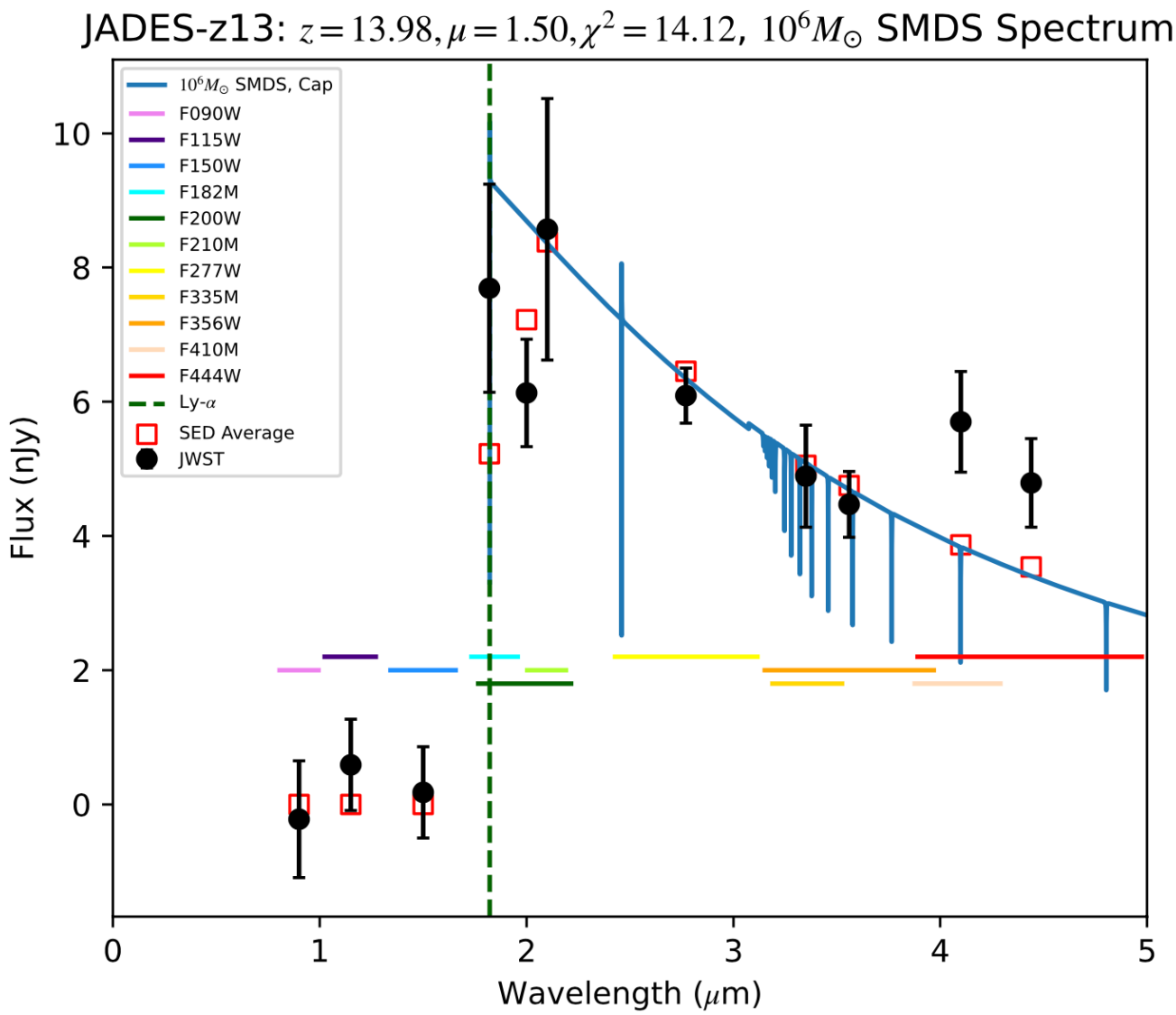


FIG. 1. (Top Row) Optimal fit regions in the z vs μ (magnification) parameter space for Supermassive Dark Star fits to JADES-GS-z11-0 , JADES-GS-z12-0 , and JADES-GS-z13-0 photometric data. The heatmap is color coded according to the value of the χ^2, and is cut off (grayed out) at the critical value corresponding to 95% CL. In addition to labeling the object, the title in each panel includes the the mass and formation mechanism for the SMDSs model considered. (Bottom Row) For each case we plot our best fit SEDs against the photometric data of [25] in each band (color coded and labeled in legend).


JADES-z13: $z = 13.98, \mu = 1.50, \chi^2 = 14.12$, $10^6 M_\odot$ SMDS Spectrum
$10^6 M_\odot$ SMDS, Cap
F090W
F115W
F150W
F182M
F200W
F210M
F277W
F335M
F356W
F410M
F444W
Ly-α
SED Average
JWST
Flux (nJy)
Wavelength (μm)
0
2
4
6
8
10
0
1
2
3
4
5

Criteria for hi-z objects to be Supermassive Dark Star candidates

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GNz11: An object with beautiful spectrum: a galaxy

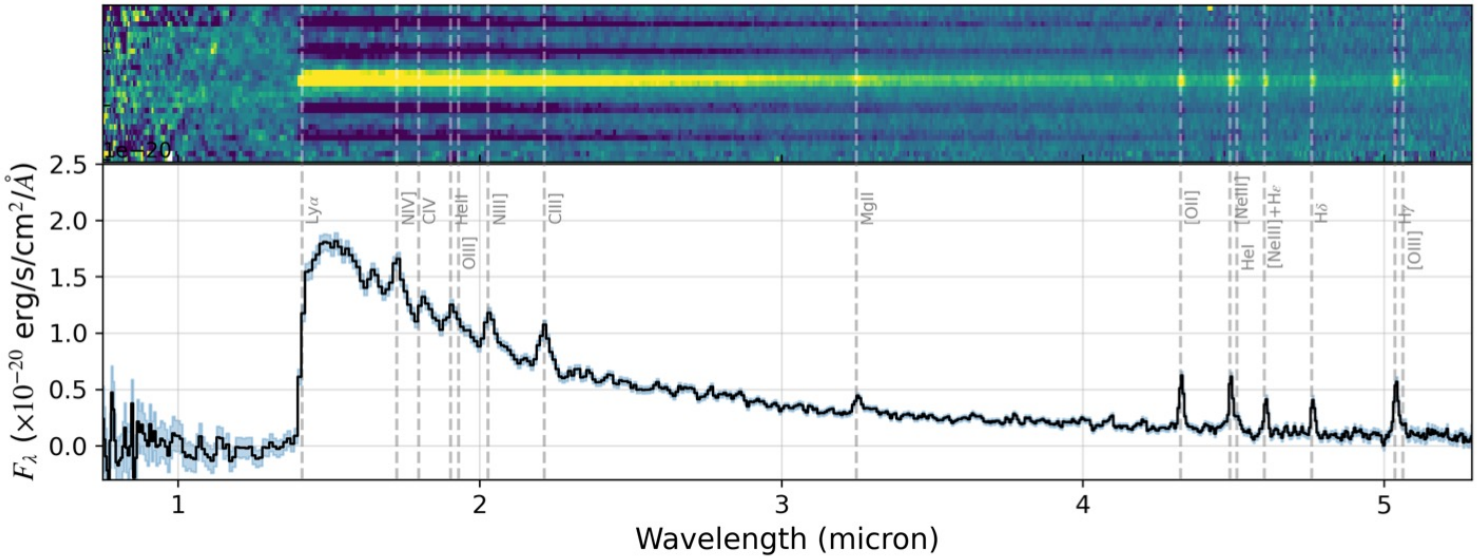


Fig. 1. 2D (top) and 1D (bottom) spectra of GN-z11 using PRISM/CLEAR configuration of NIRSpec. Prominent emission lines present in the spectra are marked. The signal to noise ratio (SNR) of the continuum is high and the emission lines are clearly seen in both the 1D and 2D spectra.

Best bet to distinguish SMDS vs. early galaxies

- HeII 1640 absorption line is smoking gun for SMDS.
- Need to get better spectra: take data for a longer time, find a highly magnified object
- Also: Since SMDS are point object, maybe find Airy (diffraction) pattern if it's a strong signal (magnified bright object)
- Also: at lambda>5 micron, spectra differ!

The Bottom Line

- JWST has found ~ 700 high redshift objects with z > 10. They call them “galaxy candidates”
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published..

(W/out spectra, can’t be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- OUR RESULTS: Three of the four hi-z JWST objects we studied are consistent with Dark Stars
- New data: one of them has metal lines (not a DS?) .

Roman Space Telescope

- SMDS are also visible in RST which has MUCH larger field of view, making them easier to find.
- Find them with RST, then go study them with JWST which has much better angular resolution (n.b. JWST also goes to higher wavelength and hence higher z).
- Paper with Saiyang Zhang (student) and Cosmin Ilie

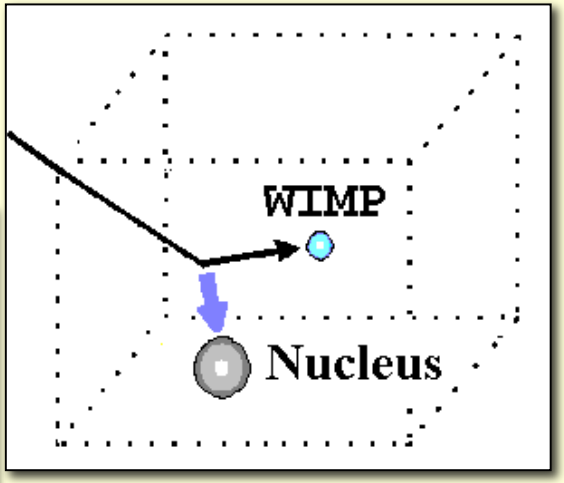
Dark Stars (conclusion)

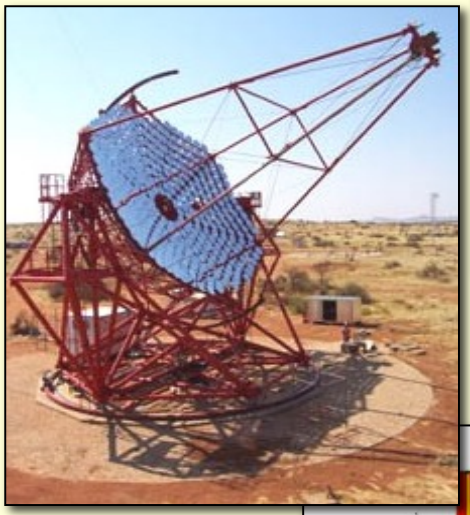
- The dark matter can play a crucial role in the first stars. Though made of hydrogen and helium, they may be powered by DM heating rather than fusion
- Dark stars may be very massive (up to ten million $M_{\odot}$) and bright (up to ten billion solar luminosities), and can be precursors to Supermassive Black Holes
- SMDS may already have been discovered by JWST; need to find He absorption line as smoking gun
- SMDS are also detectable in Roman Space Telescope
- WIMPs and their properties could first be detected by discovering Dark Stars

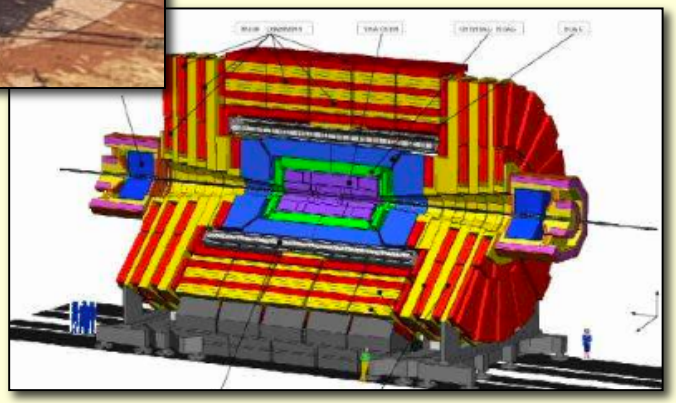
WIMP Hunting: Good chance of detection this decade

- **Direct Detection**
- **Indirect Detection**
- **Collider Searches**

Looking for Dark Stars







Final Intriguing Signal: 511 keV line in INTEGRAL data

Seen in Galactic bulge, out to 6 degrees (3 kpc).

No clear astrophysical explanation. Low mass xray binaries were most compelling option but not looking good

Is it DM annihilation to e+e- pairs?

Would be MeV dark matter.

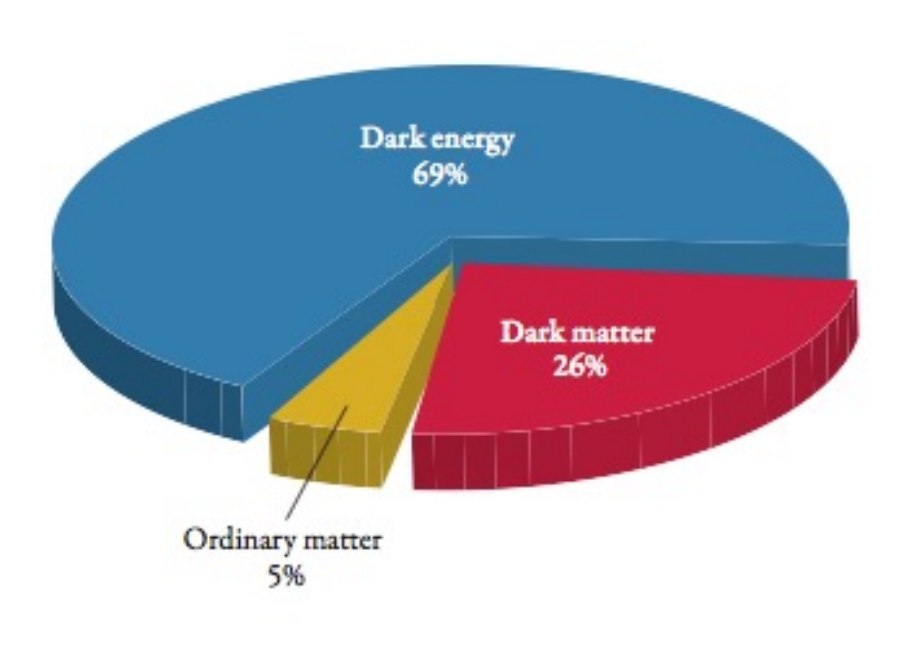
(Boehm, Hooper, Silk, Casse, Paul 2003)

Summary

- 1) Neutrino mass ~ 0.1 eV. We are close to knowing the answer. Cosmology is very powerful.
- 2) WIMP searches: what is going on with DAMA? It is not Spin-Independent.

  COSINE-100 and ANAIS are testing it (also consist of NaI crystals, same material as DAMA.
- 3) Dark Stars: the first stars could have been powered by Dark Matter rather than by fusion. Powered by WIMPs or SIDM or …

Even stranger: Dark Energy



DARK ENERGY: Galaxies are accelerating apart from one another!

The panel on “The Dark Side of the Universe” at the World Science Festival in NY in June 2011

The three women representing Dark Matter are, from the right, Katherine Freese, Elena Aprile, and Glennys Farrar. Continuing to the left are three men representing Dark Energy: Michael Turner, Saul Perlmutter and Brian Greene (co-host of the Festival).

“Dark matter is attractive, while dark energy is repulsive!”

THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE