

# Dark Matter in the Universe

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# OUTLINE

- Evidence for dark matter
- What is dark matter?
- Claims of detection over the past few years. Are they real?
- 2009: discovery potential!
- Dark Stars: a new phase of stellar evolution powered by stars

# The Dark Matter Story

- Zwicky (1933), Rubin, Ford (1970's): galactic rotation curves
- Primordial nucleosynthesis: it cannot all be baryonic
- Constraints on baryonic DM: microlensing, HST, infrared background etc imply that faint stars  $< 3\%$  and white dwarfs  $< 20\%$  of galactic DM
- Microwave background measures total mass density plus pieces (baryonic, DM)
- Consistent picture: N-body simulations and observations (lensing)
- New element: Dark Stars. The first stars to form in the universe may be DM powered (not fusion). Can we find these?

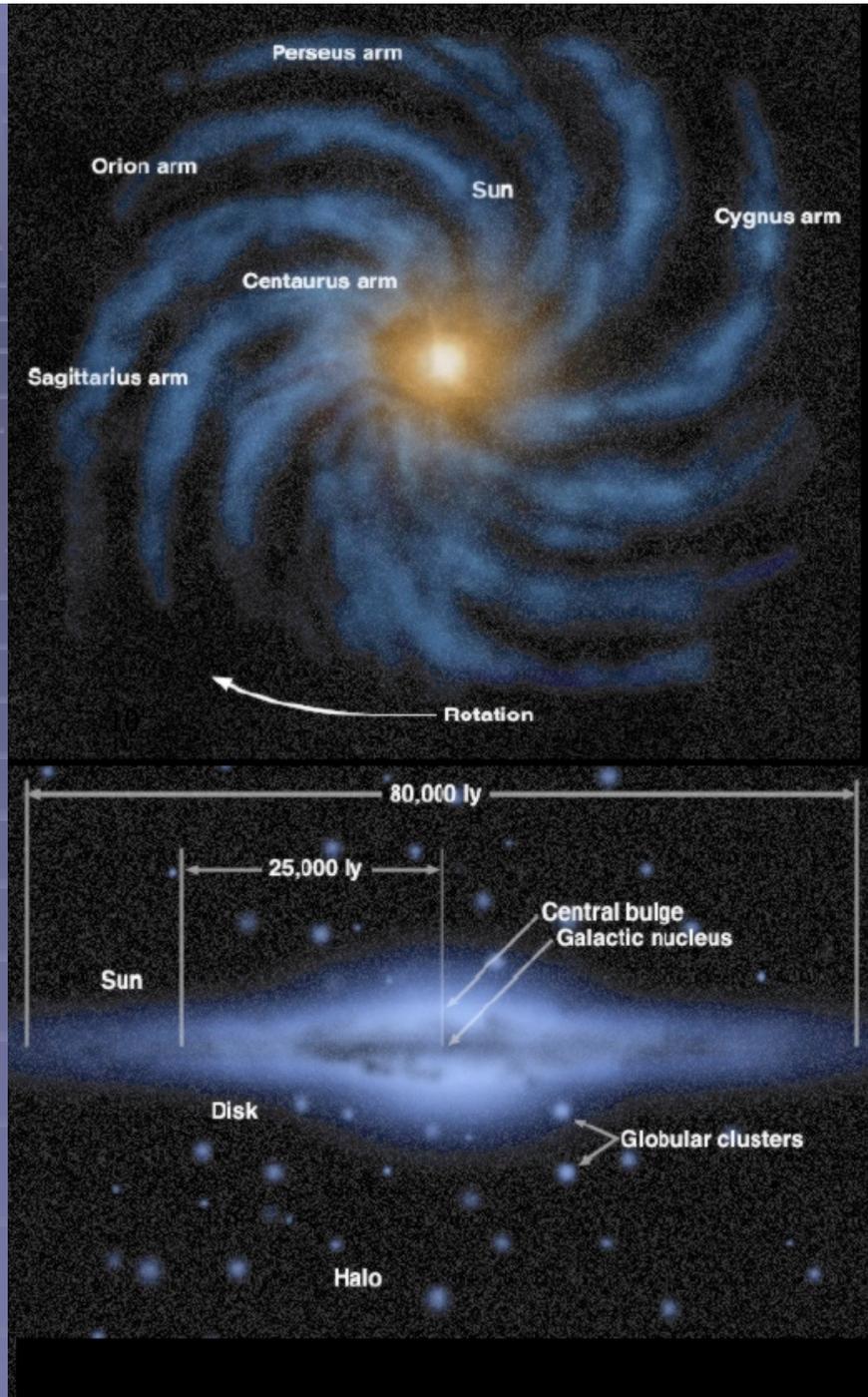
# I. Evidence for Dark Matter: Galaxies

- What do galaxies look like?
- Observational Evidence:
  - rotation curves
  - lensing
  - hot gas in clusters

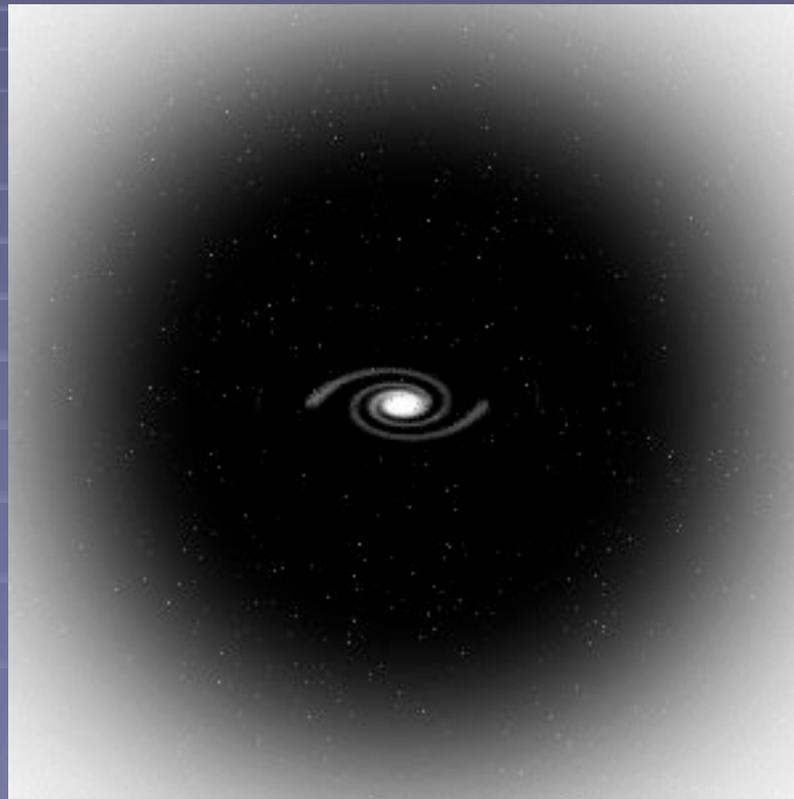
# Our Galaxy: The Milky Way

The mass of the galaxy:

$10^{12}$  solar masses



# Galaxies have Dark Matter Haloes



# Dark Matter Observations

- Galactic rotation Curves:  
out to tens kpc
- Gravitational Lensing:  
galactic haloes out to 200 kpc
- Hot gas in clusters

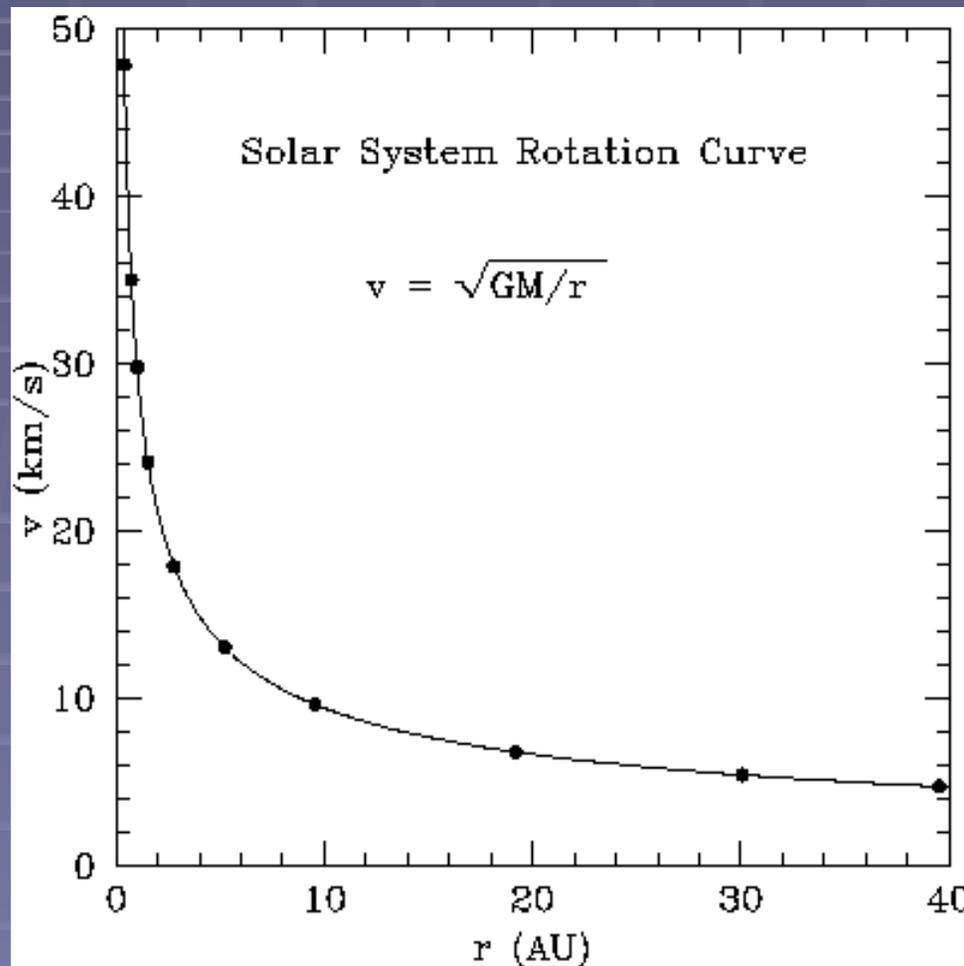
# Rotation Curves

- How do we know that galaxies have dark matter haloes? Rotation Curves.
- Example: Solar System Rotation Curve
- 95% of the mass of galaxies is made of an unknown component!!!

# Solar System Rotation Curve

## Average Speeds of the Planets

As you move out from the Sun, speeds of the planets drop.



# Tyco Brahe (1546-1601)

Lost his nose in a duel,  
and wore a gold and  
silver replacement.

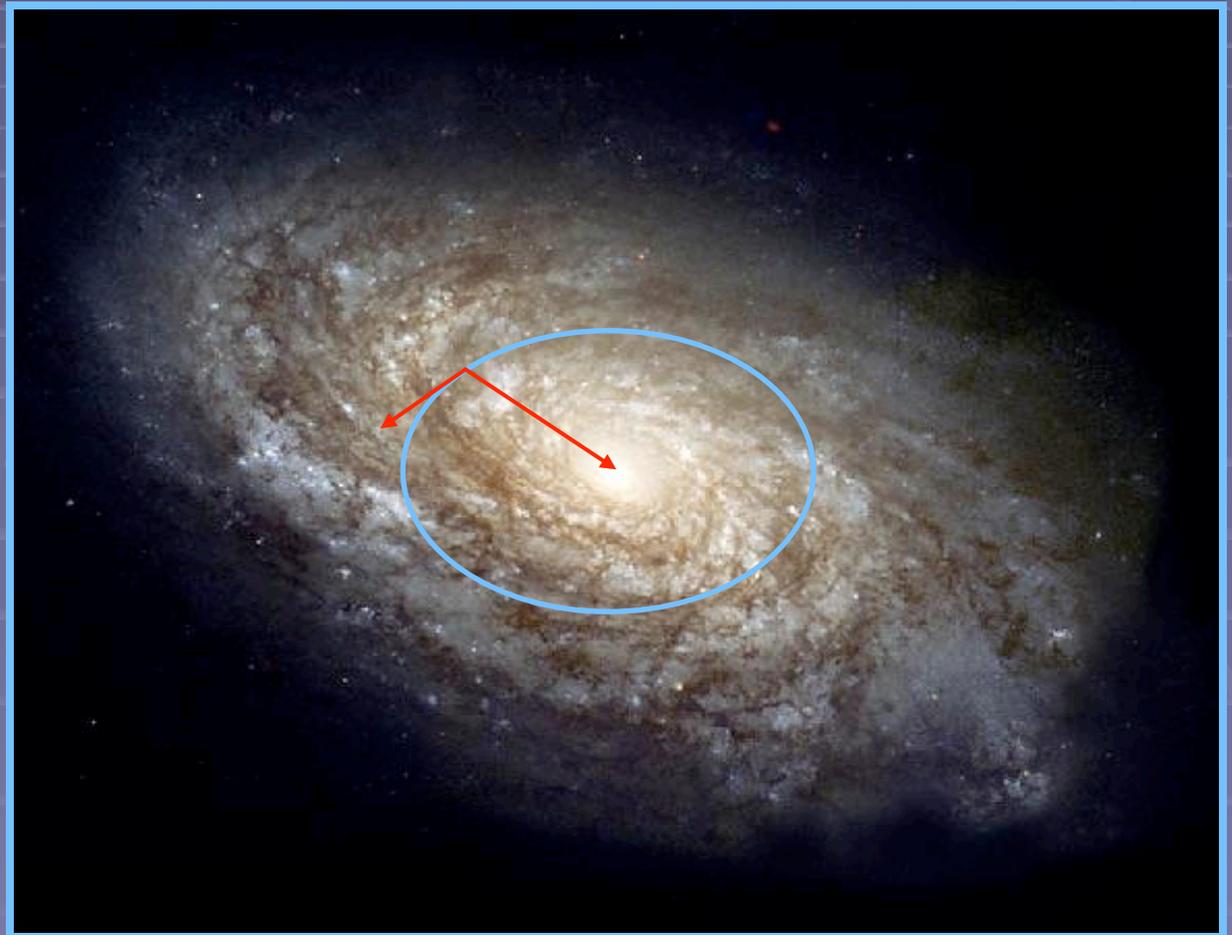
Studied planetary orbits.

Died of a burst bladder  
at a dinner with the king.



# Rotation Curves of Galaxies

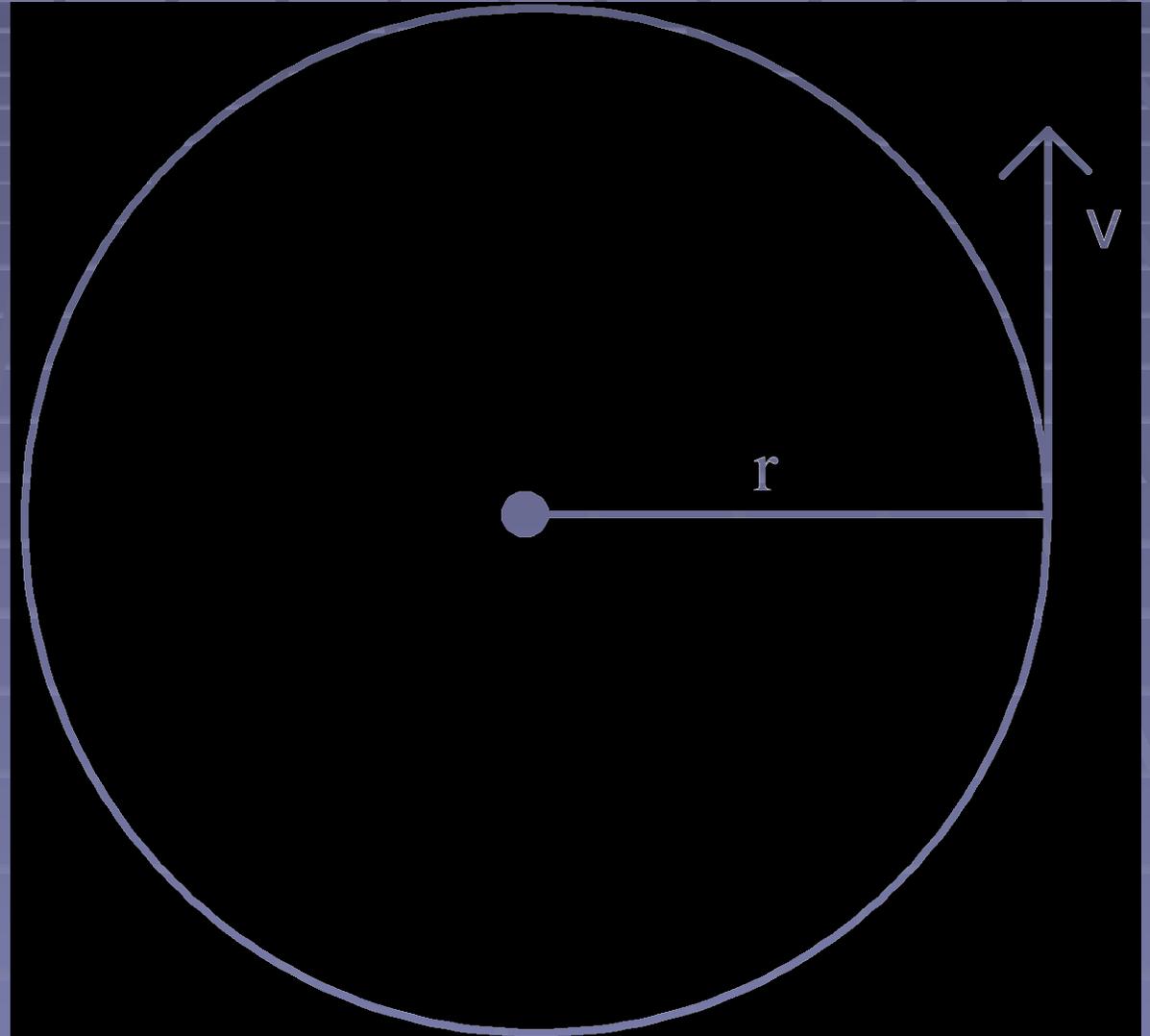
Orbit of a star in a Galaxy: speed is Determined by Mass



# Speed is determined by Mass

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

The speed at distance  $r$  from the center of the galaxy is determined by the mass interior to that radius. Larger mass causes faster orbits.



# First indication of dynamical mass measurement for dark matter

- Zwicky 1933: velocity dispersion of Coma implies  $M/L = 250$

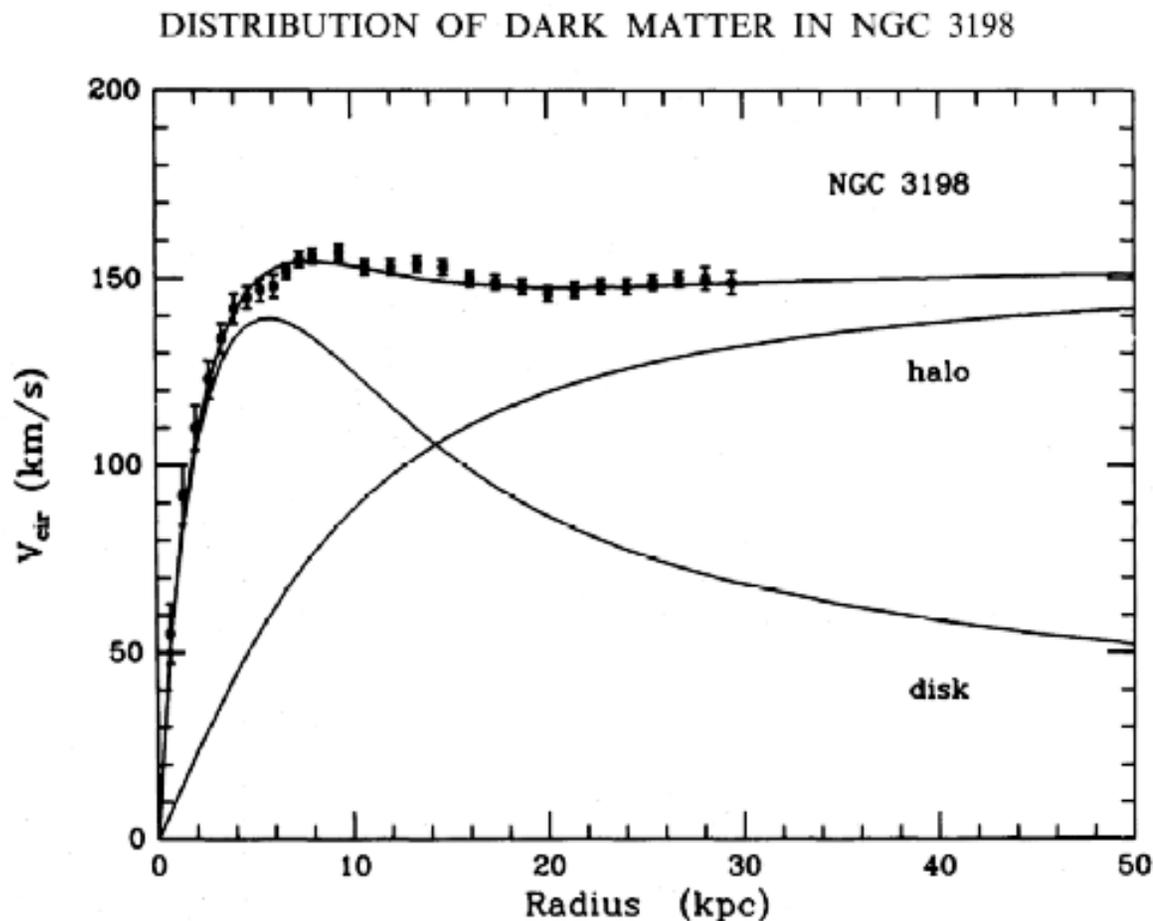
# Vera Rubin

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



# 95% of the matter in galaxies is unknown dark matter

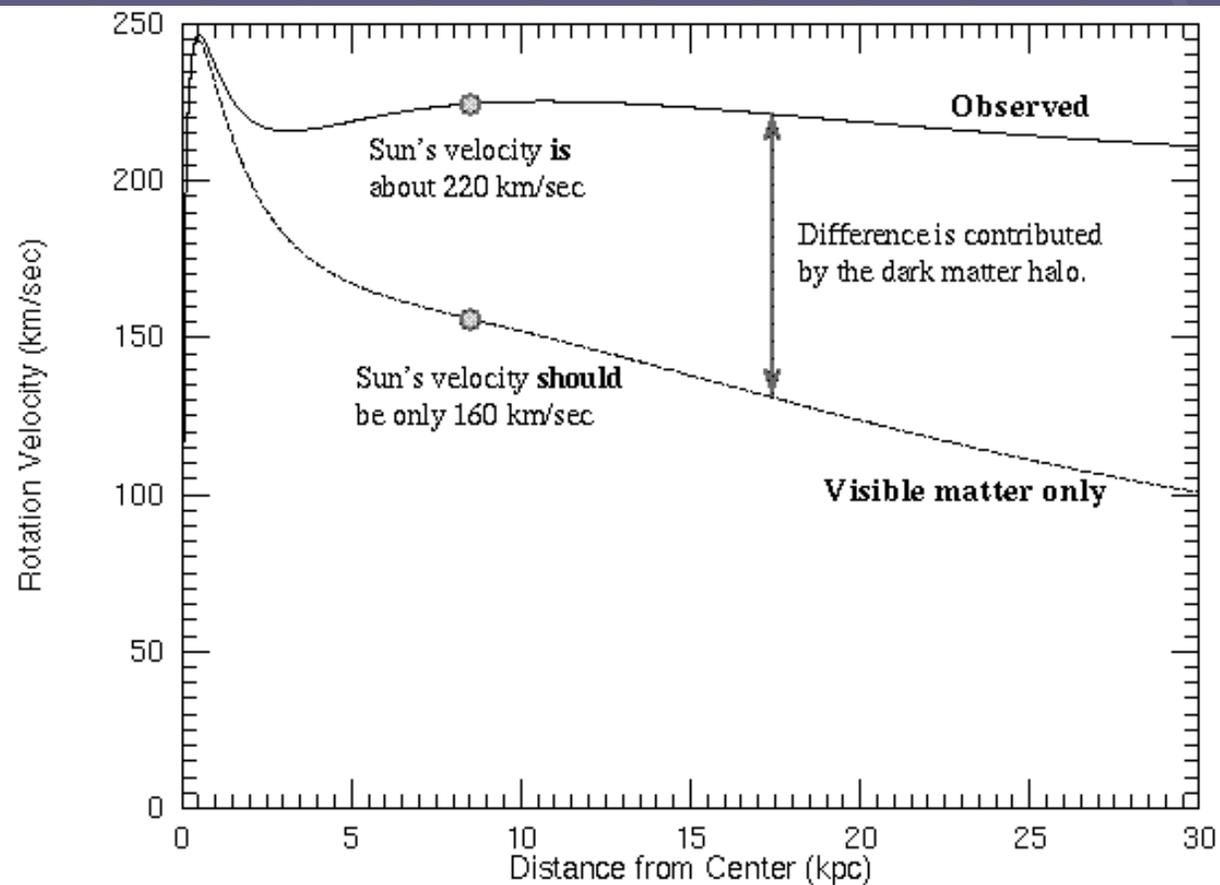
- Rotation Curves of Galaxies:



OBSERVED:  
FLAT ROTATION  
CURVE

EXPECTED  
FROM STARS

# Sun's orbit is sped up by dark matter in the Milky Way

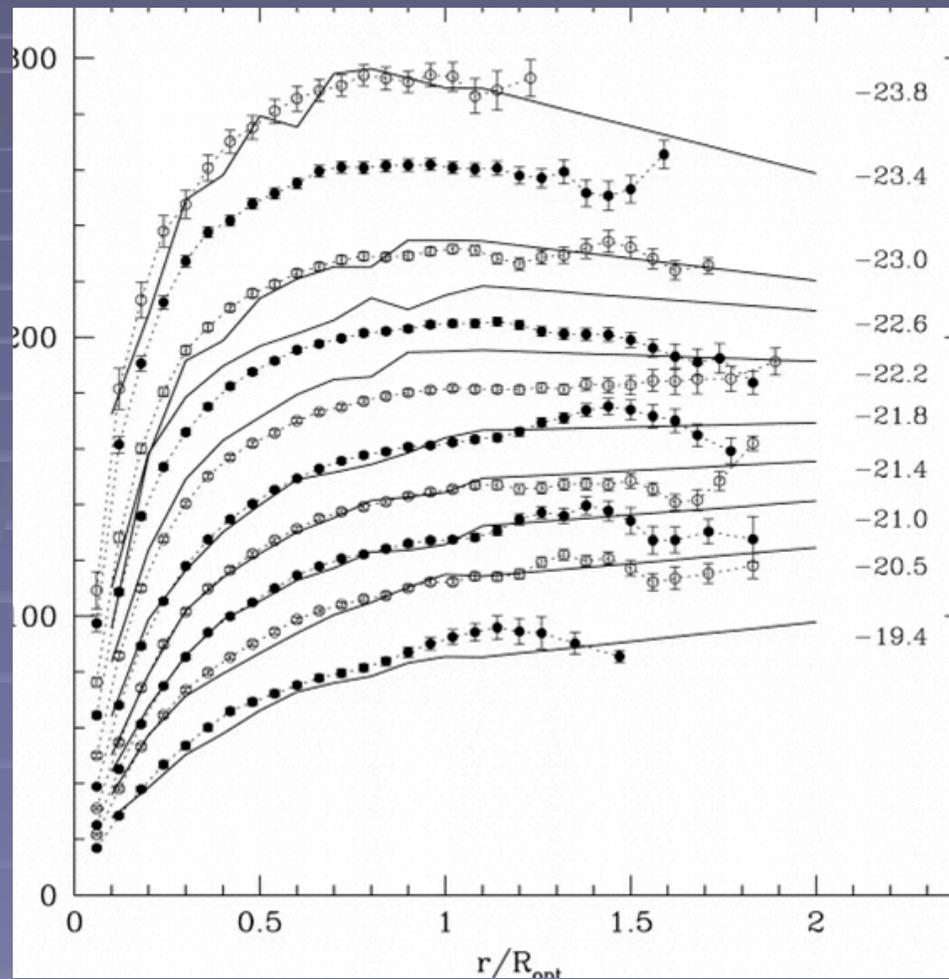


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo**.

# Limitations of Rotation Curves

- Can only look out as far as there is light or neutral hydrogen (21 cm): to tens of kpc
- See beginnings of haloes, but don't trace where most of it is

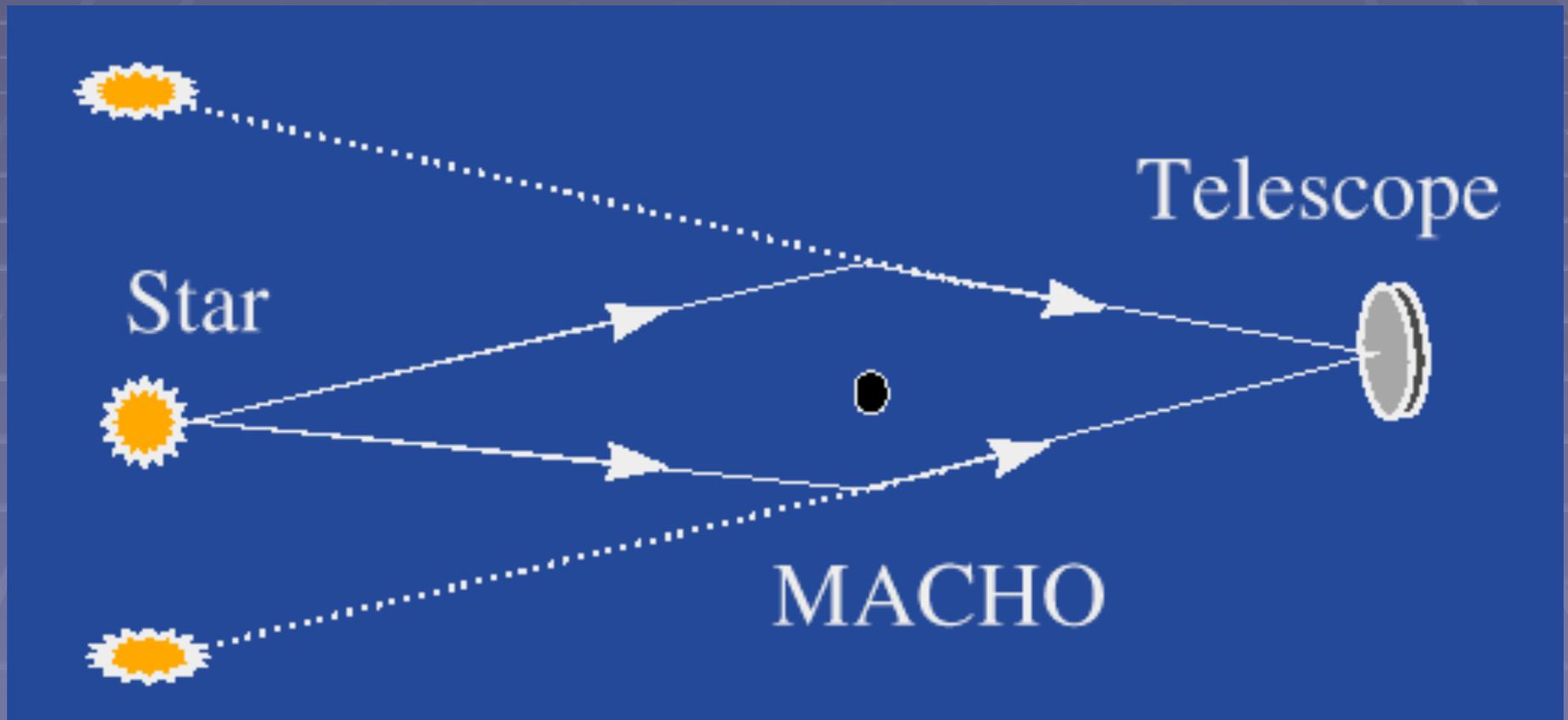
# Today's galaxies: Paolo Salucci



Bigger:  
 $R_{opt}=25$ kpc

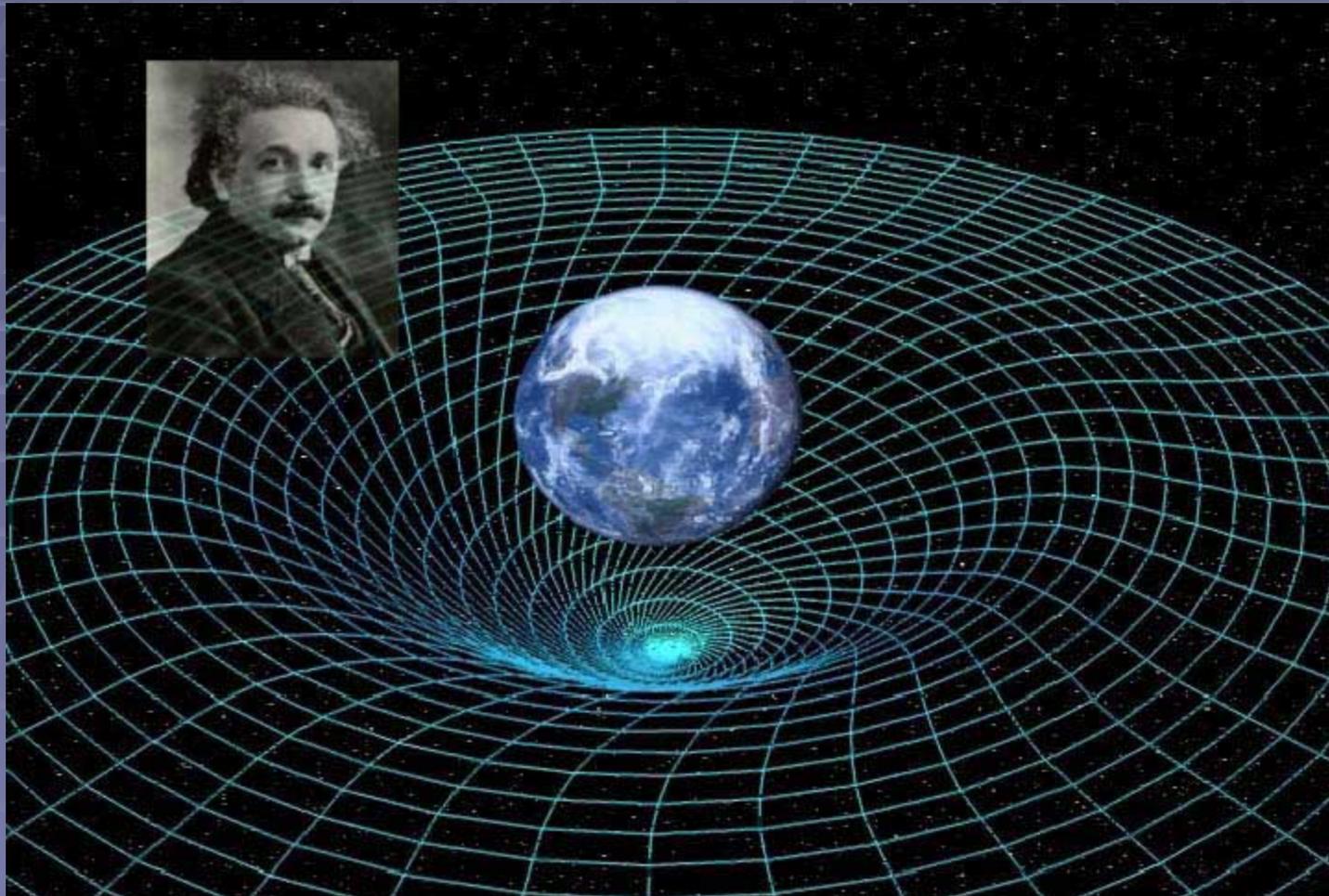
Smaller  
 $R_{opt}=2$ kpc

# Lensing: Another way to detect dark matter: it makes light bend



# Geometry is Determined by Matter Content

Warping of Spacetime:



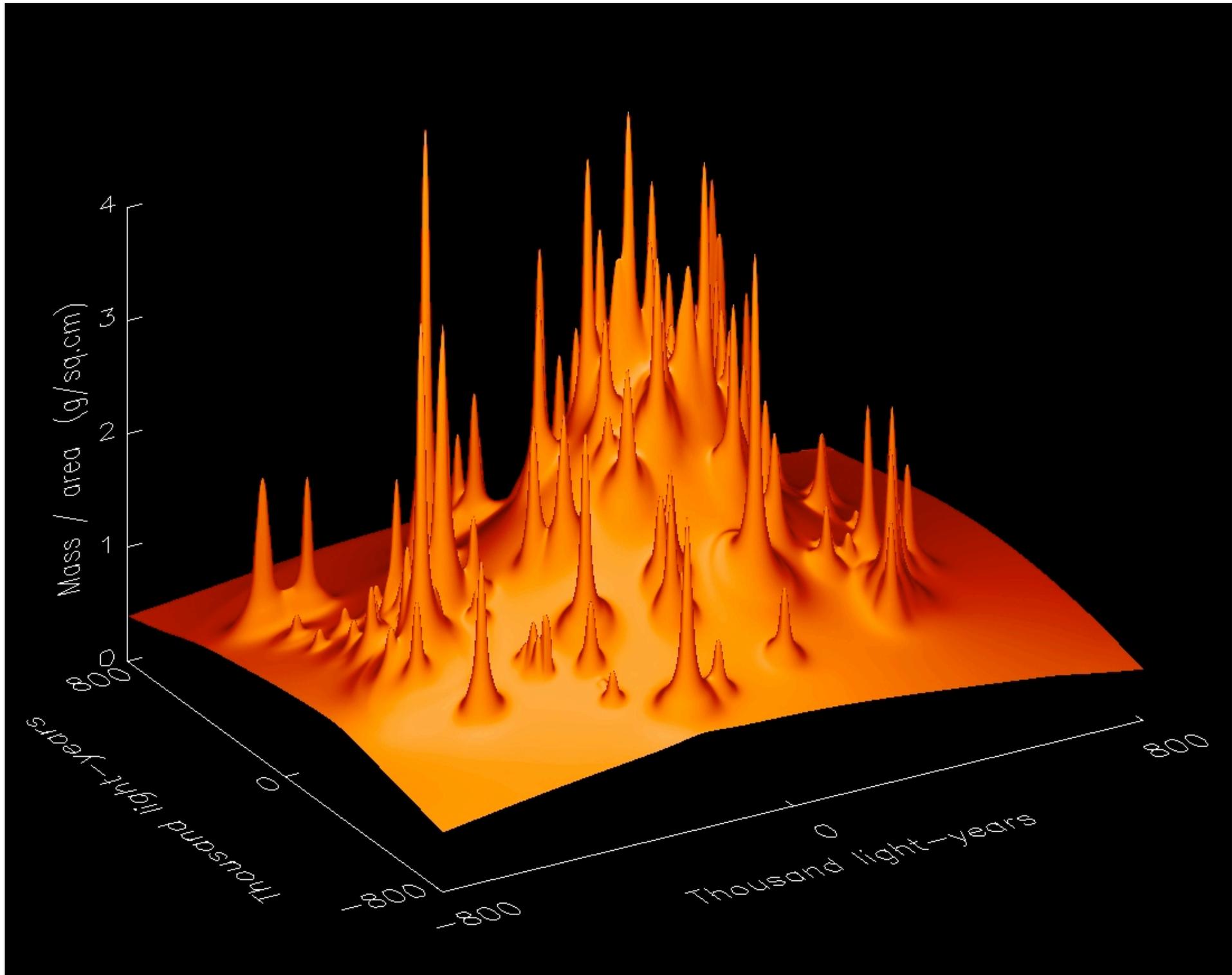
# Strong lensing by dark matter



**Gravitational Lens in Abell 2218**

HST · WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

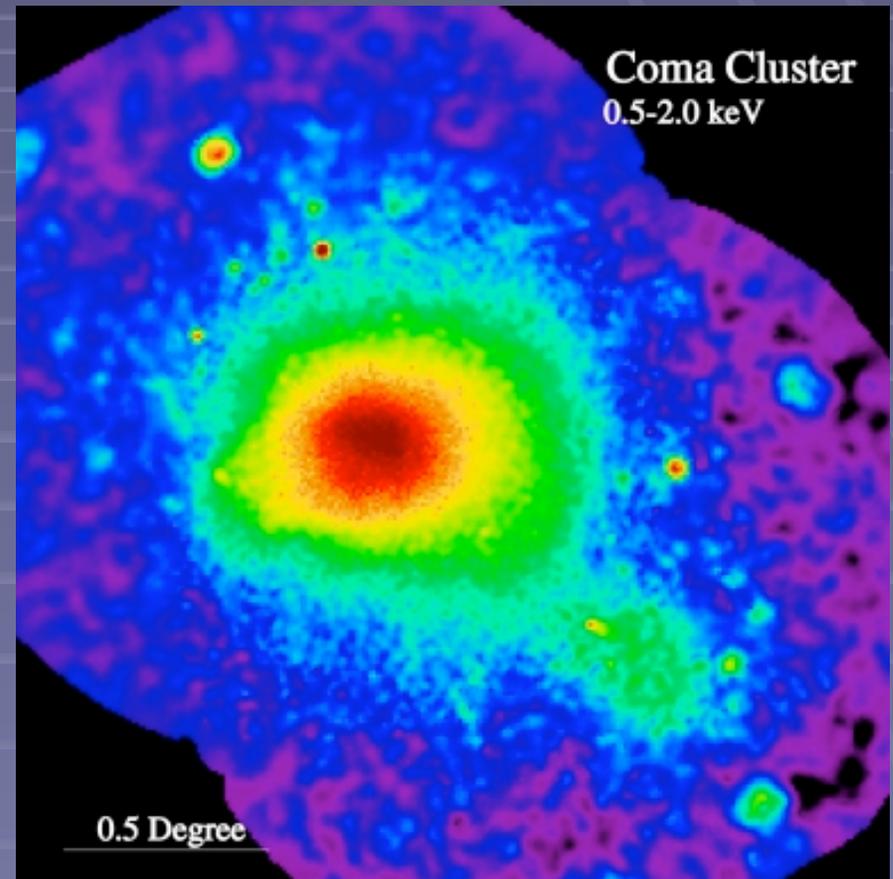


# Hot Gas in Clusters: The Coma Cluster

Without dark matter, the hot gas would evaporate.



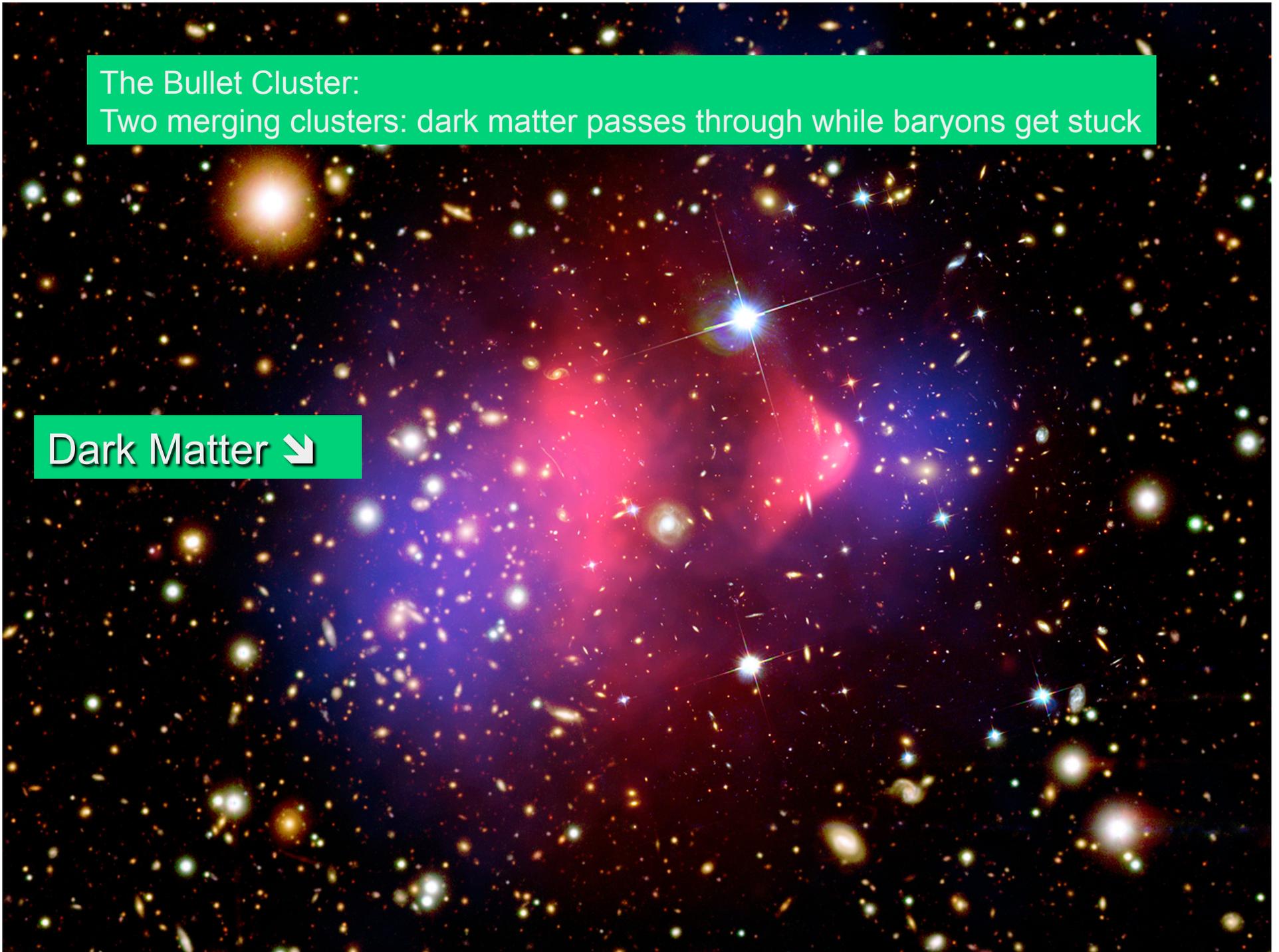
Optical Image



X-ray Image from the ROSAT satellite

The Bullet Cluster:  
Two merging clusters: dark matter passes through while baryons get stuck

Dark Matter ↘



# The Dark Matter Problem :

- 95% of the mass in galaxies and clusters of galaxies are made of an unknown dark matter component

Known from: rotation curves (out to tens kpc),  
gravitational lensing (out to 200kpc),  
hot gas in clusters.

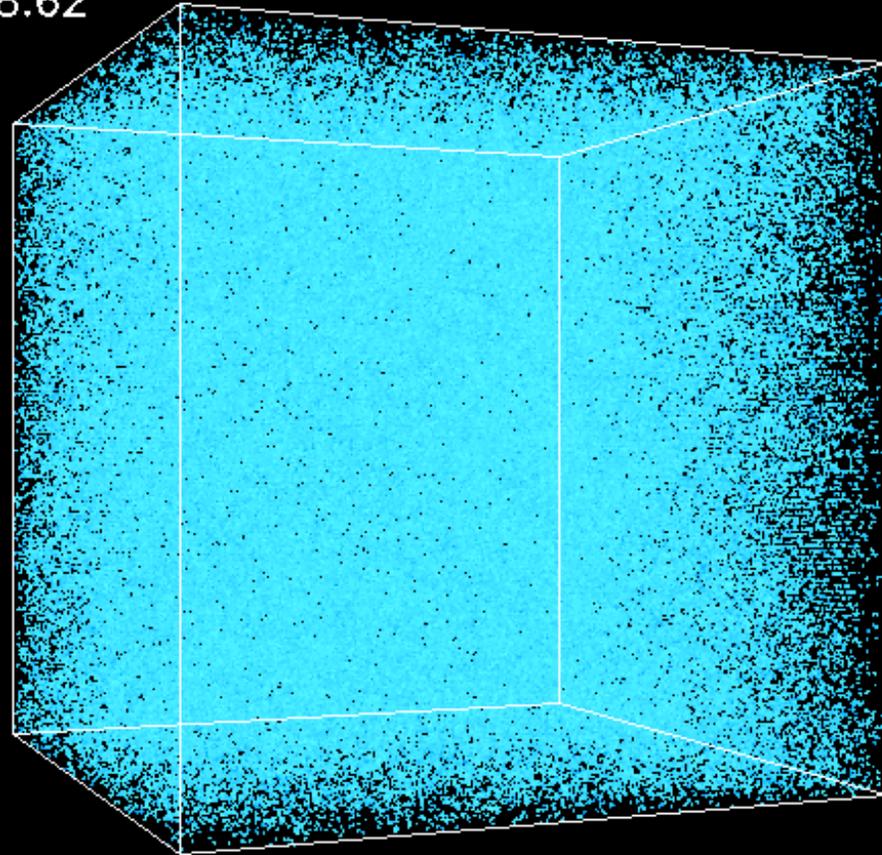
# Evidence for Dark Matter: Formation of Structure, Computer Simulations

Initial conditions  
from inflation

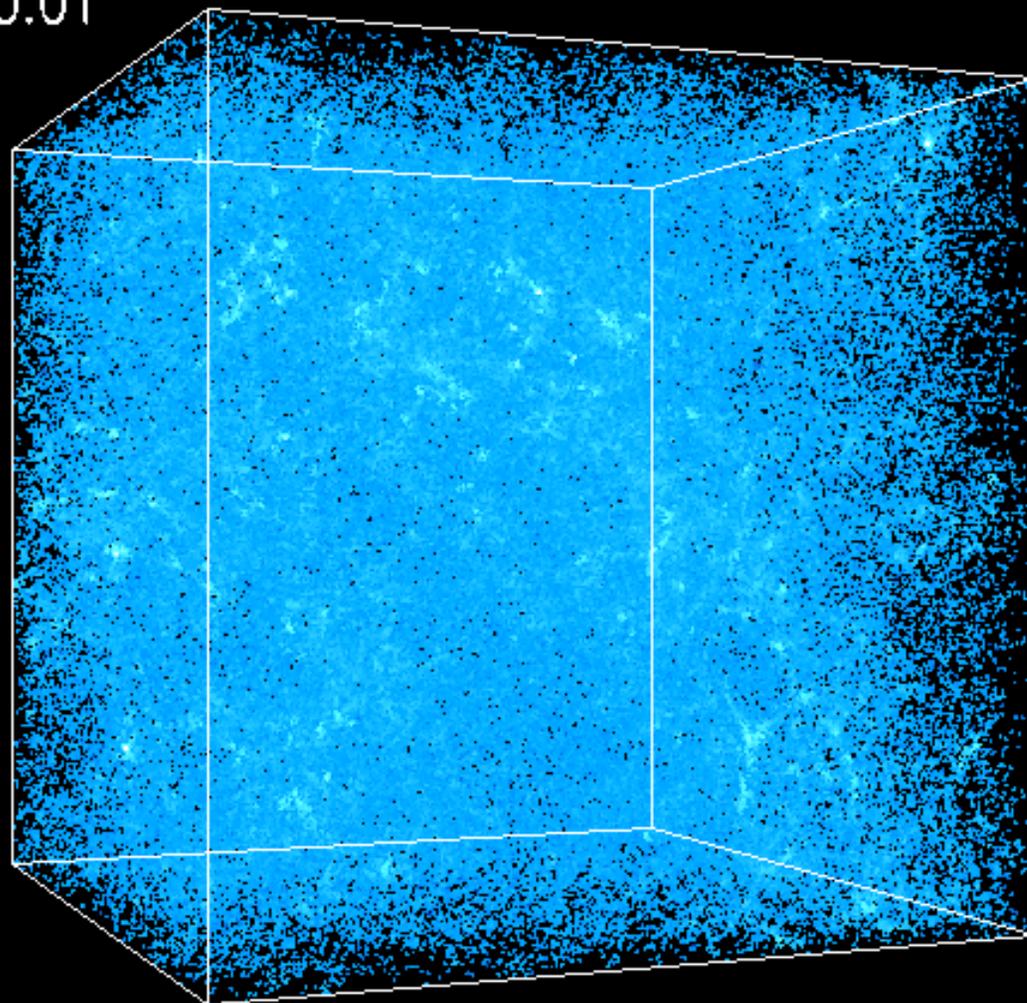
Dark Matter particles  
come together to  
make galaxies,  
clusters, and larger  
scale structures

Computer simulations  
with dark matter  
match the data

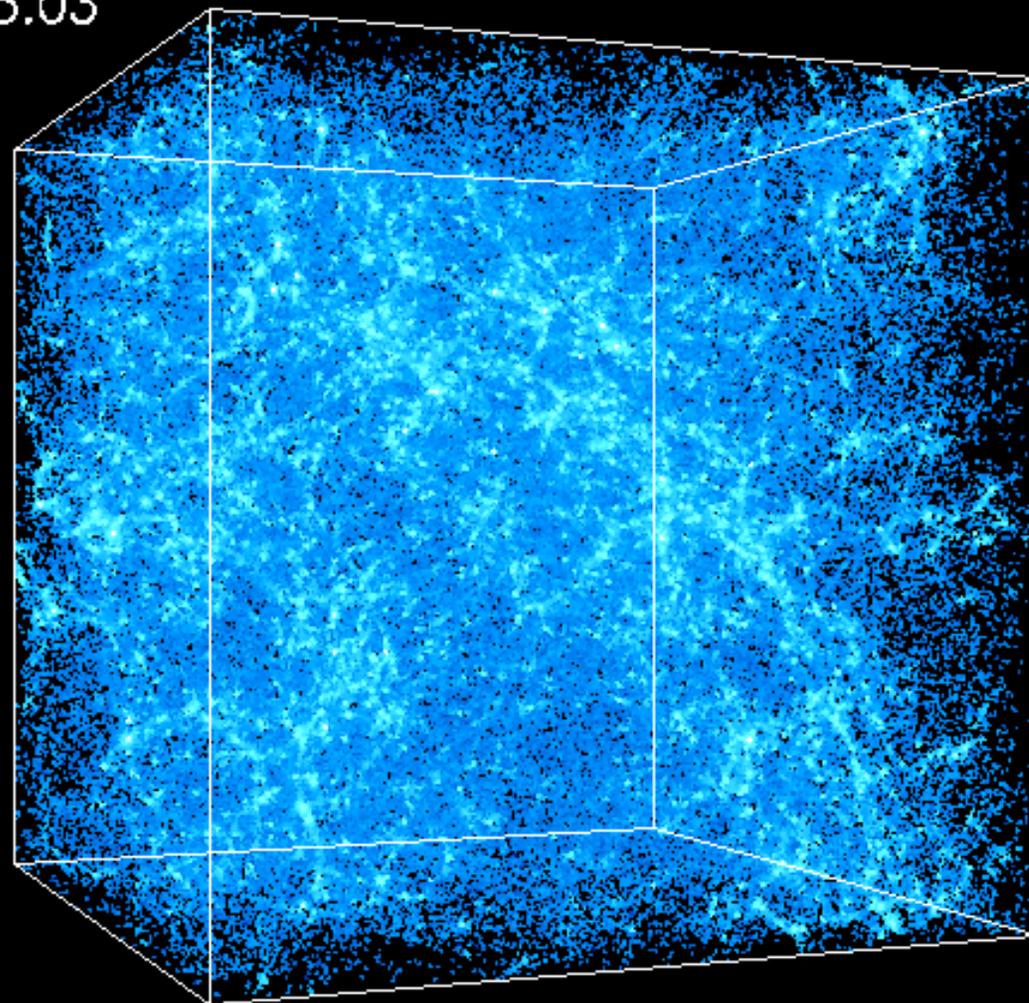
$Z=28.62$



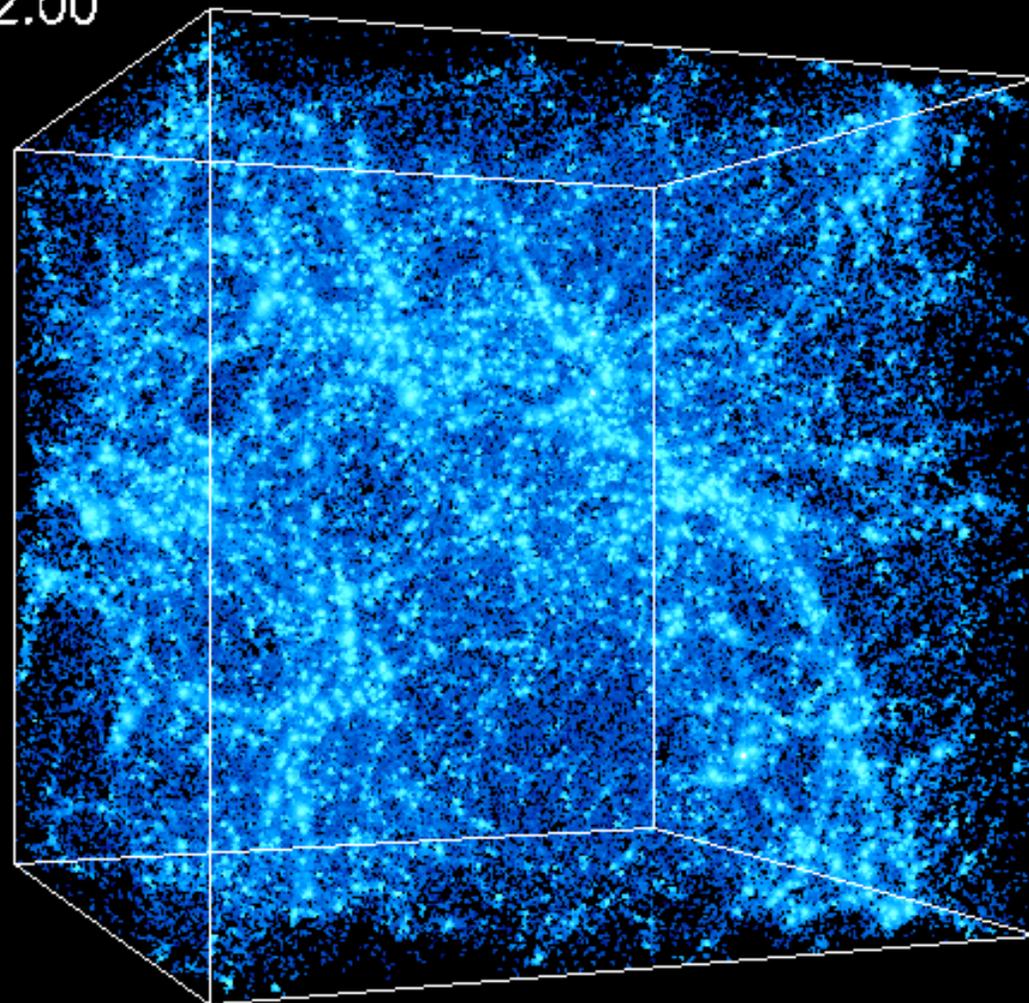
Z=10.01



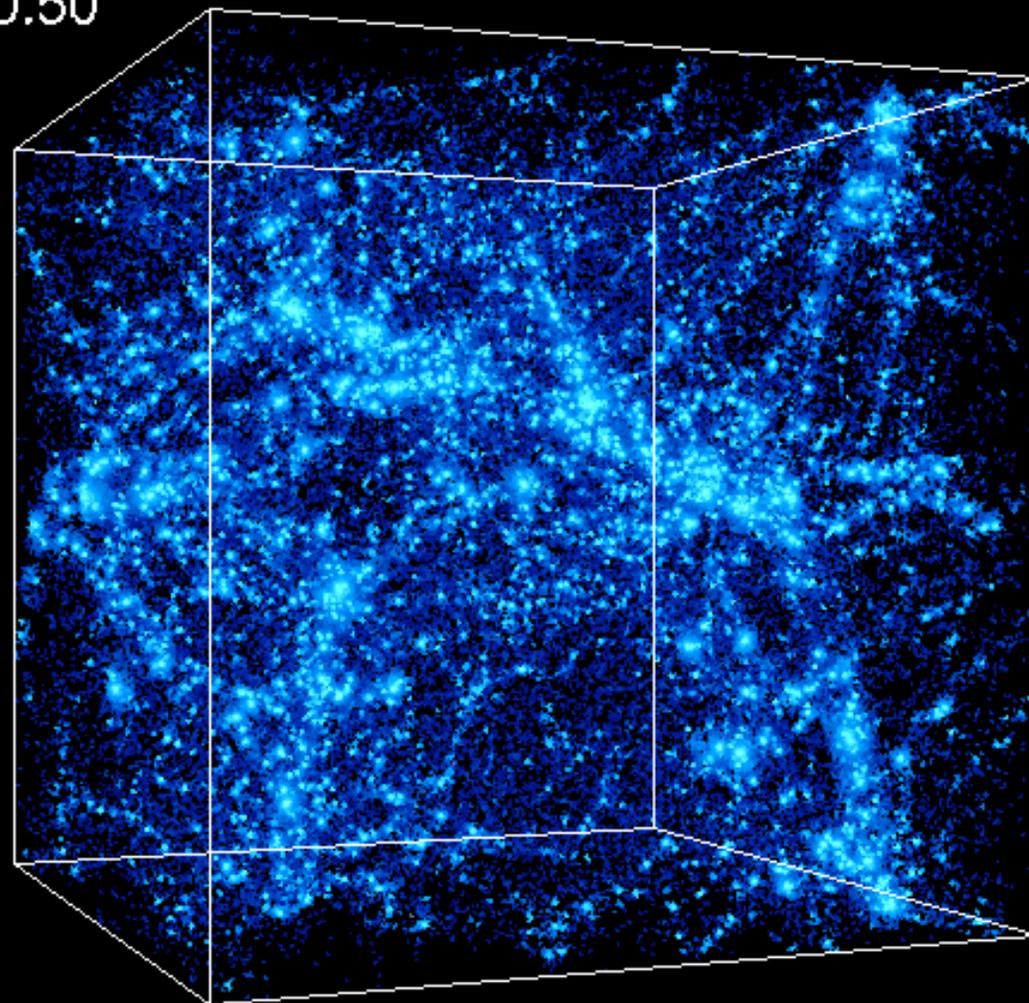
$Z = 5.03$



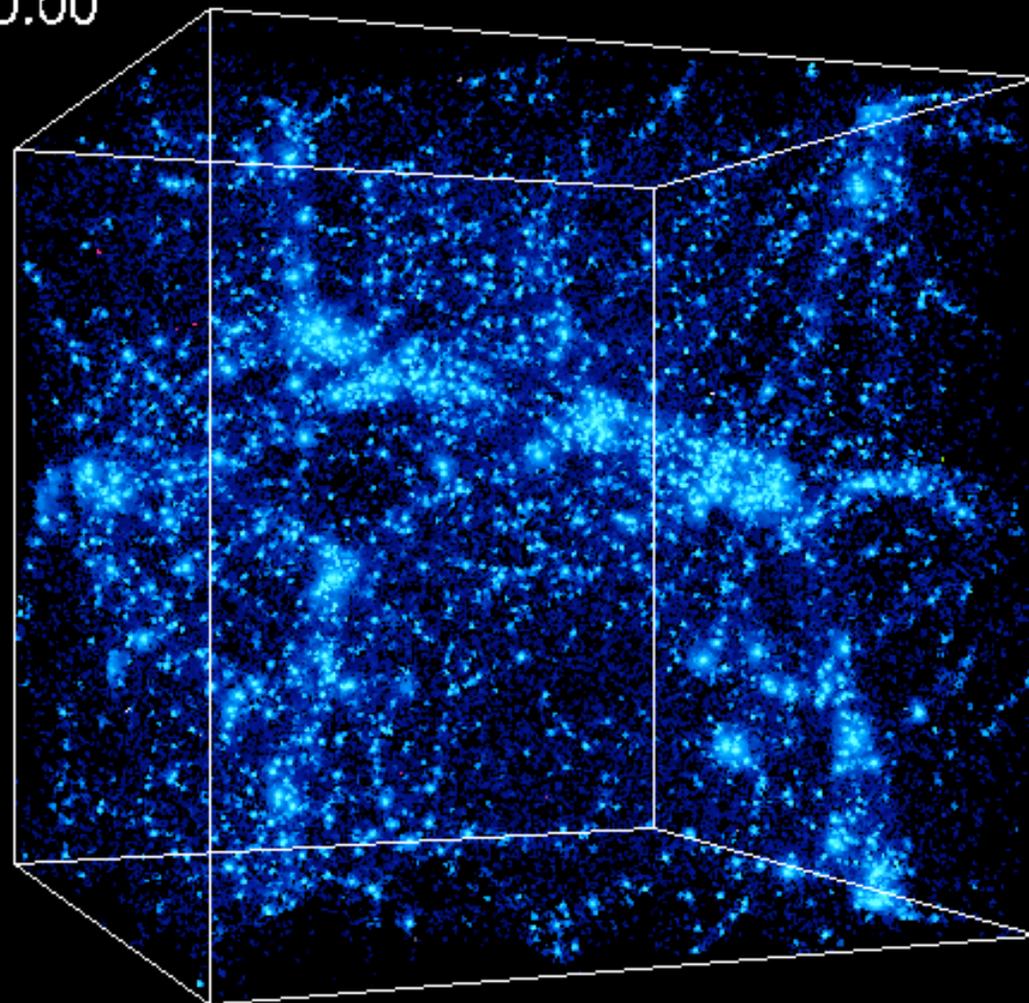
$Z = 2.00$



$Z = 0.50$

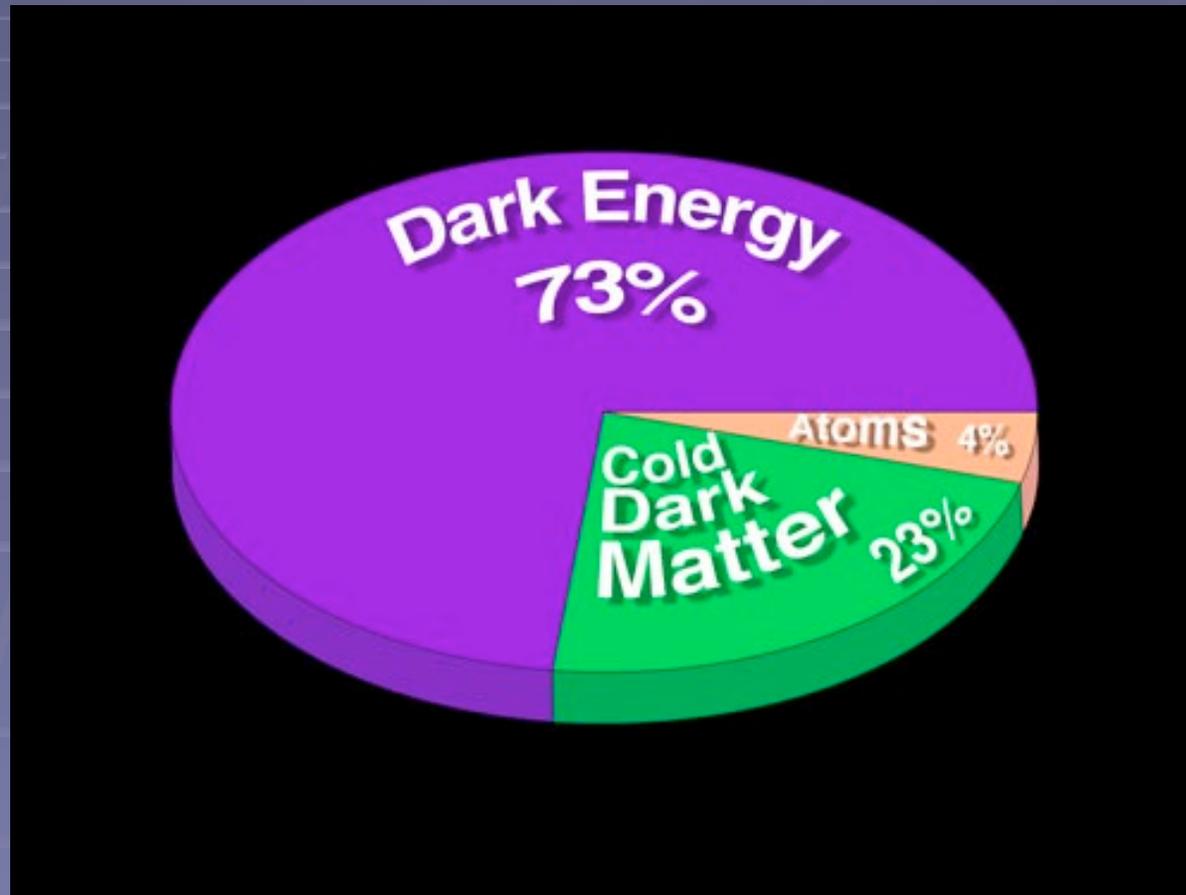


$Z = 0.00$



## II. How does dark matter fit into the big picture?

### Pie Chart of The Universe



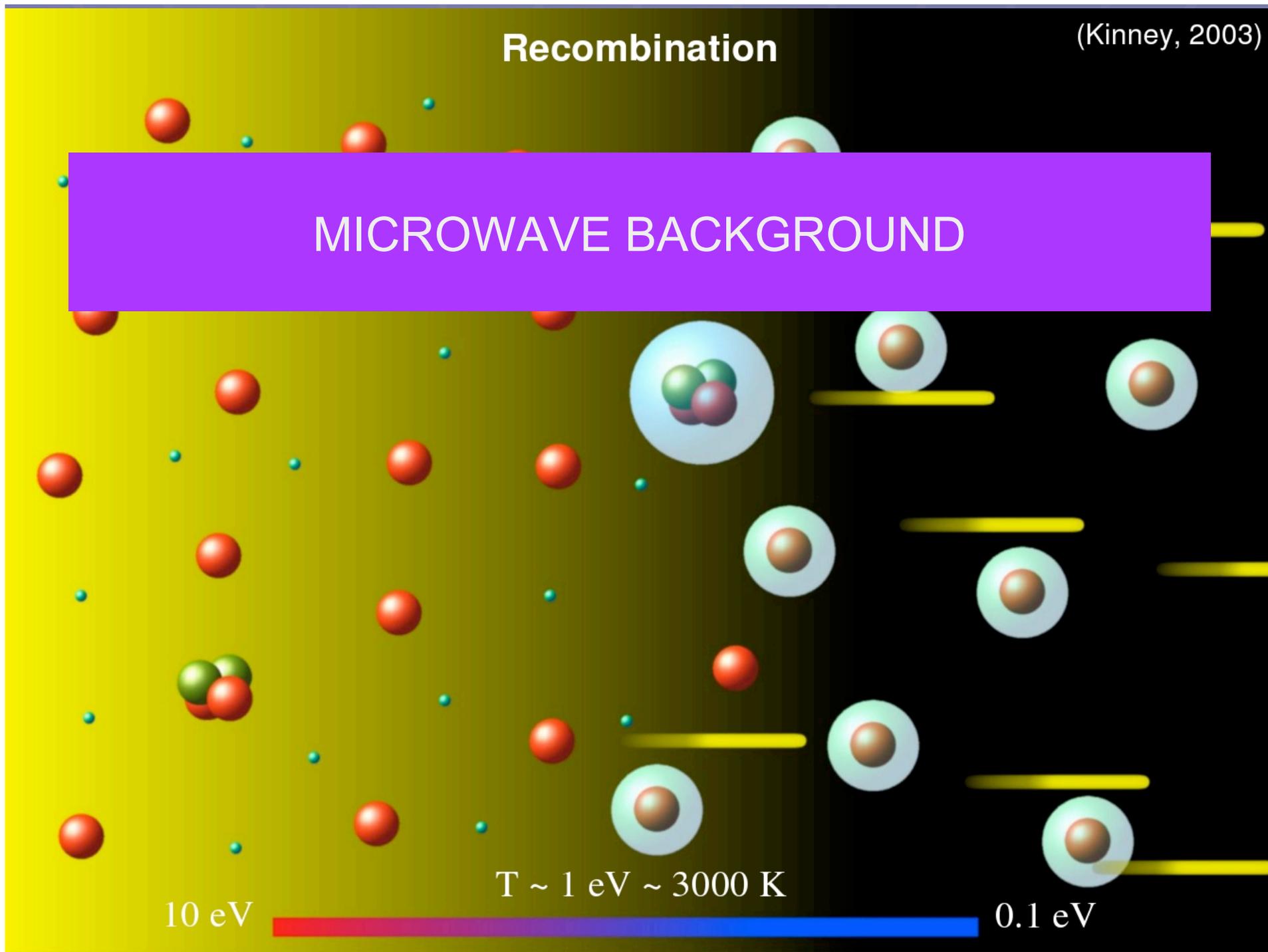
# Cosmic Abundances tell a consistent story

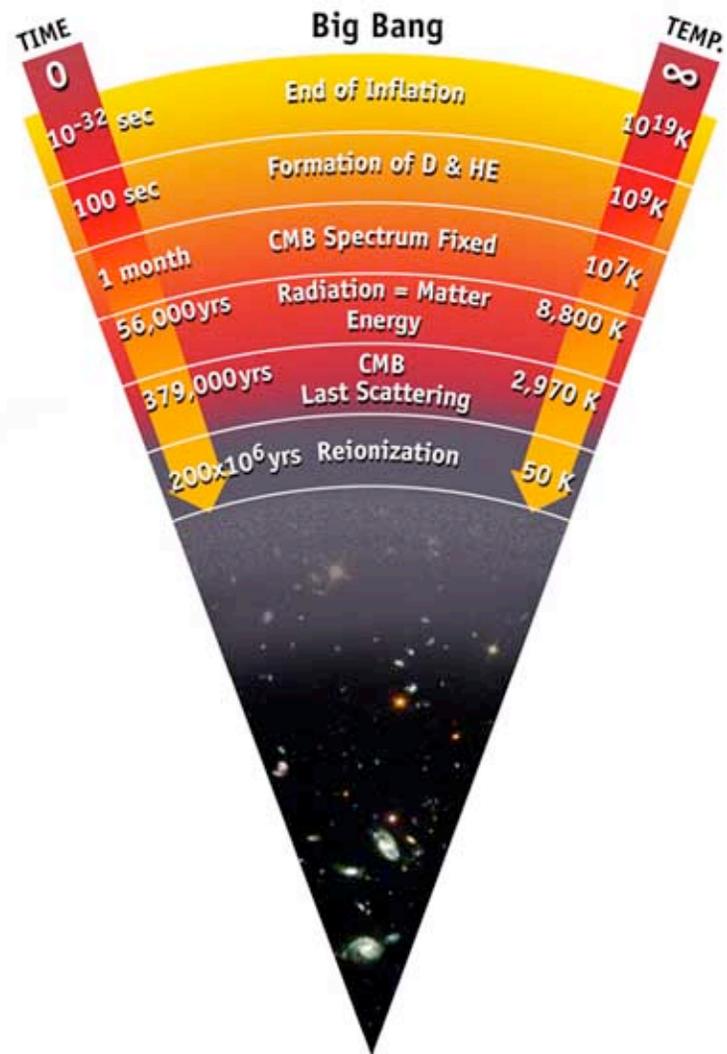
- How do we know the total mass density and geometry? From measurements of the Cosmic Background Radiation.
- How do we know that ordinary baryonic matter is only 4% of the total? Element abundances from nucleosynthesis and the CBR.
- How do we know about the 65% dark energy in the universe? Supernovae.

# Recombination

(Kinney, 2003)

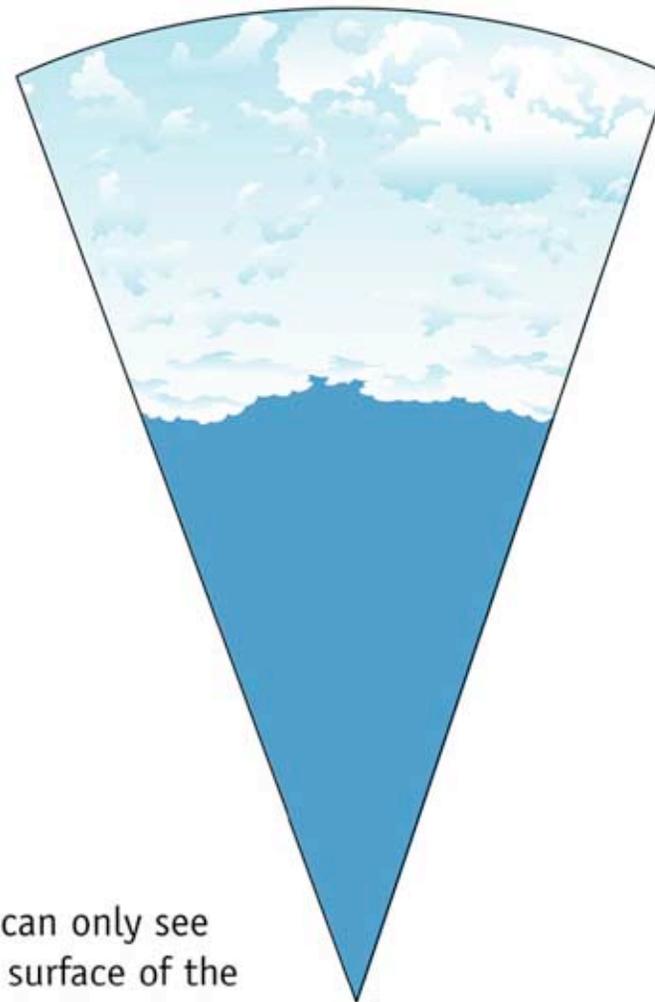
## MICROWAVE BACKGROUND





**PRESENT**  
13.7 Billion Years  
after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered



# Surface of Last Scattering

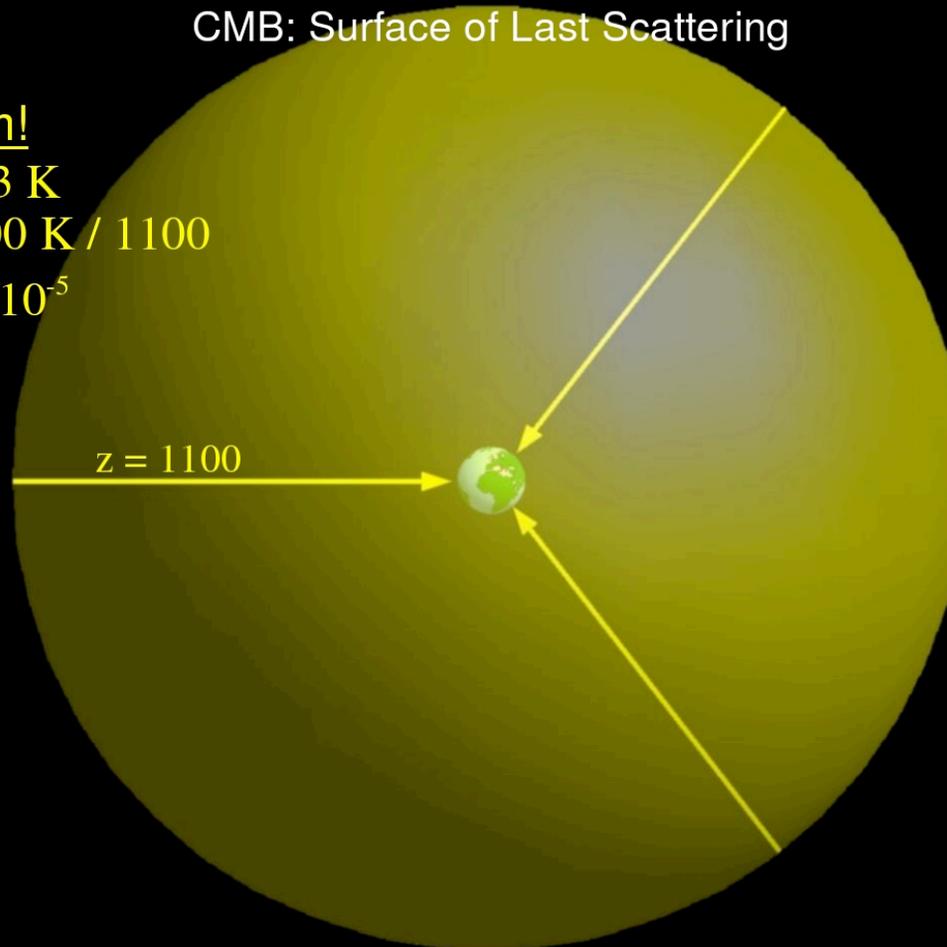
CMB: Surface of Last Scattering

(Kinney, 2003)

Uniform!

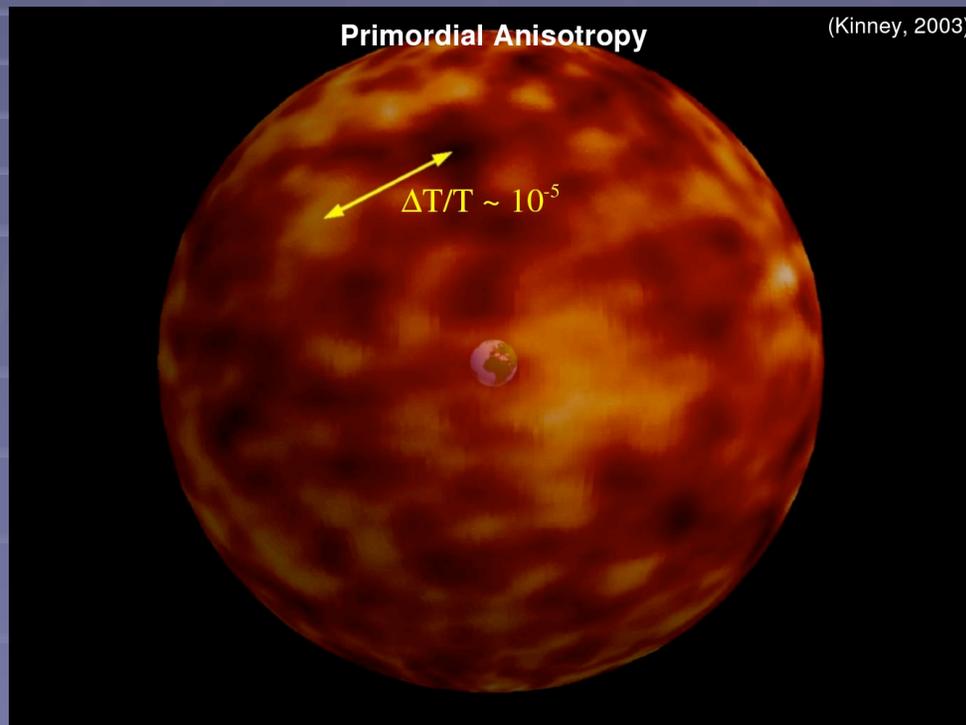
$$T = 2.73 \text{ K} \\ = 3000 \text{ K} / 1100$$

$$\Delta T/T \sim 10^{-5}$$

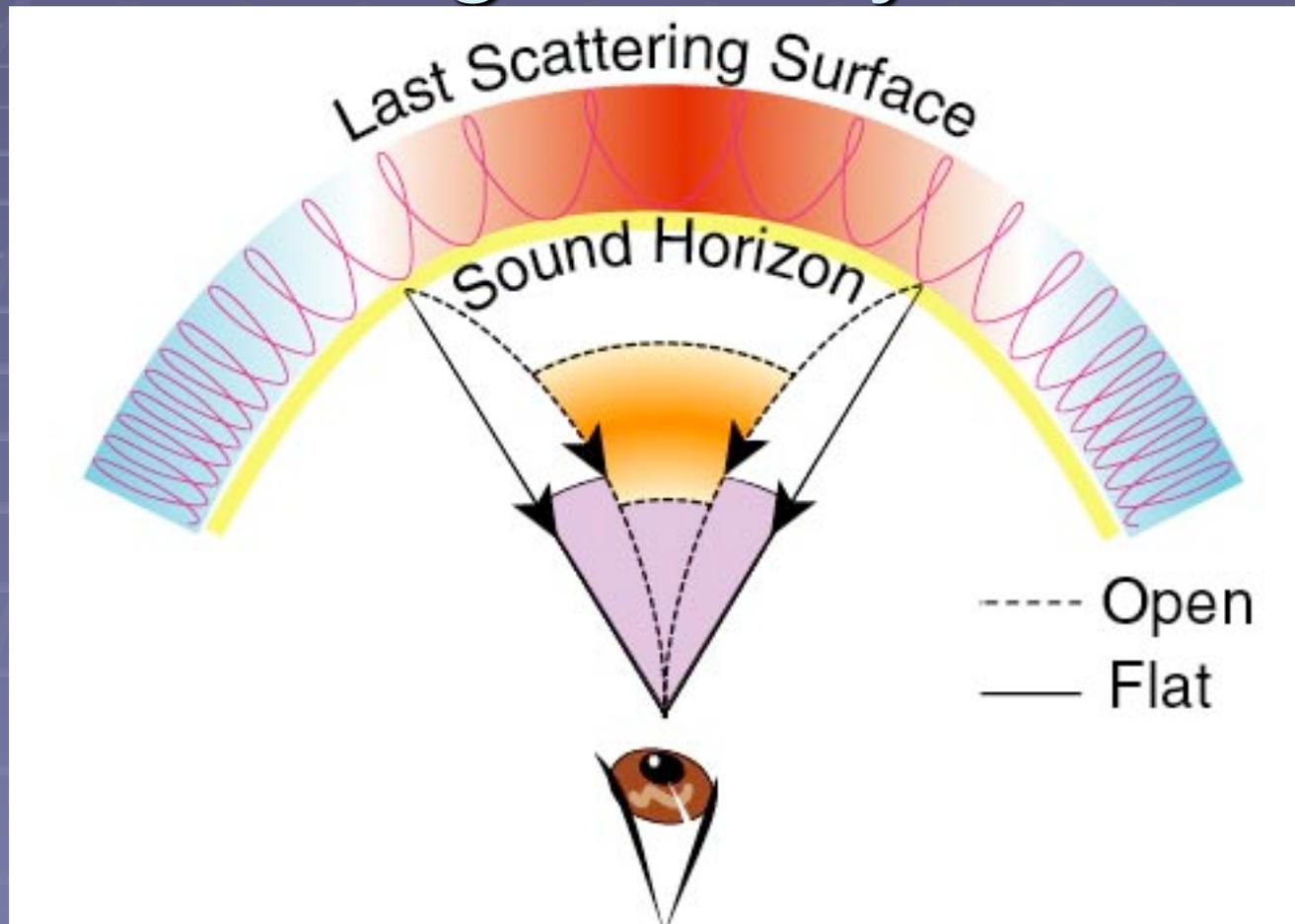


# Temperature Anisotropies

- Look at deviations in the microwave background in different directions.



# How can Microwave Background tell us about geometry?



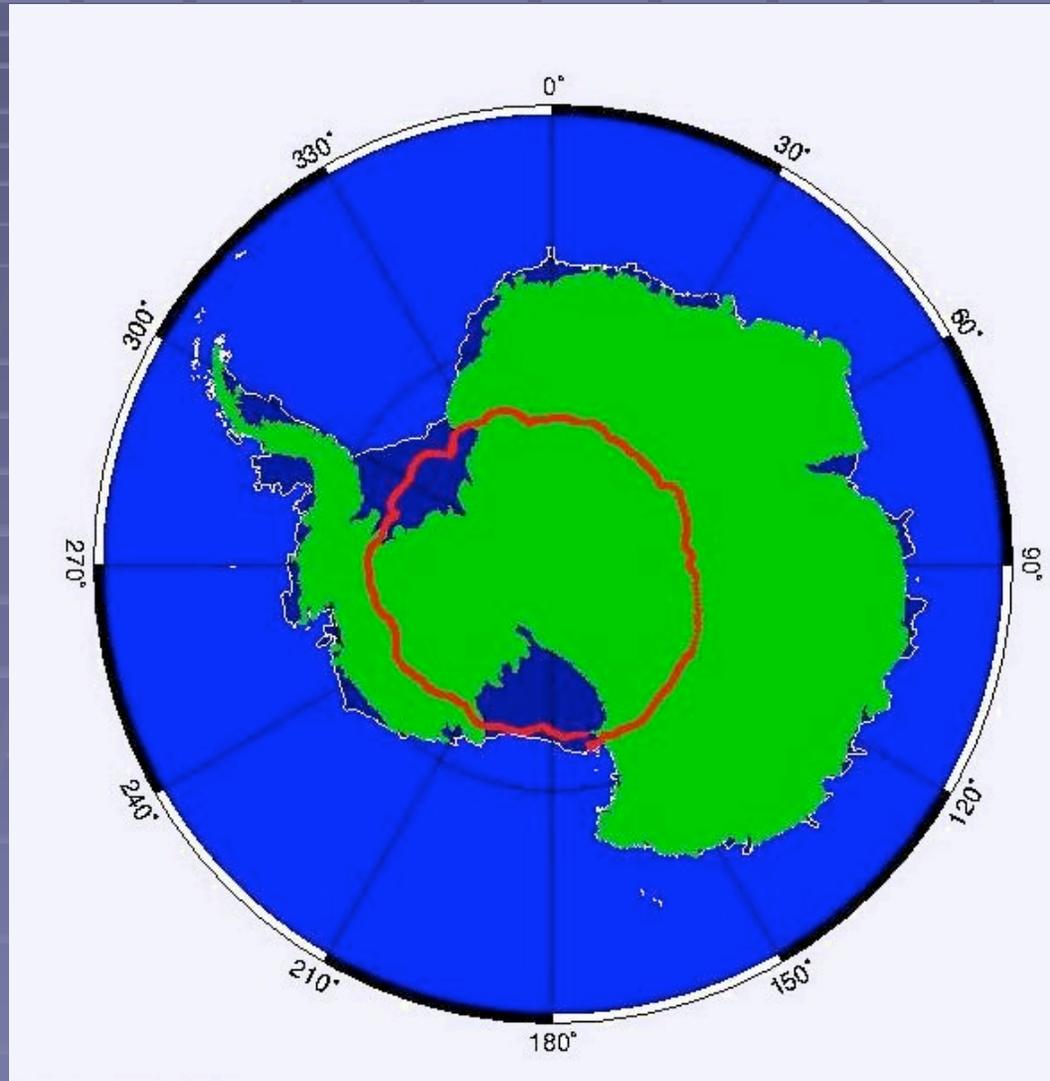
# The Doppler Peak

- Acoustic oscillations in the photon/atom fluid are imprinted at last scattering. We expect a peak in the microwave background at the sound horizon (distance sound could travel in the age of the universe).
- If the universe is flat, the peak is at one degree.
- If the universe is a saddle, the peak is at less than one degree.

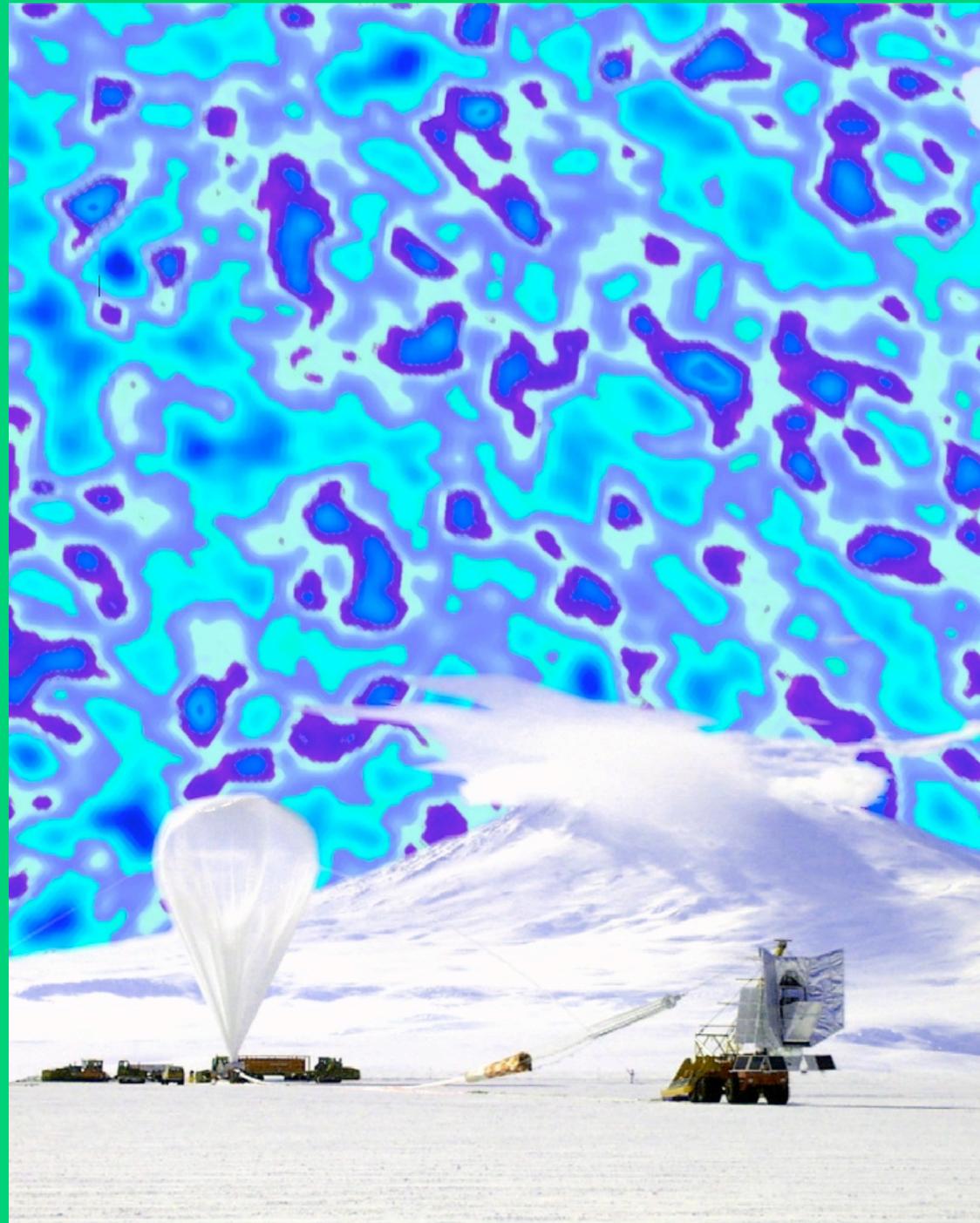
# BOOMERANG

- BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) used a telescope suspended from a balloon that circumnavigated the South Pole for 10.5 days at an altitude of 120,000 feet. Revealed patterns of structure in the microwave background.
- SPACETIME IS FLAT
- ENERGY DENSITY IS DETERMINED

# Path of BOOMERANG

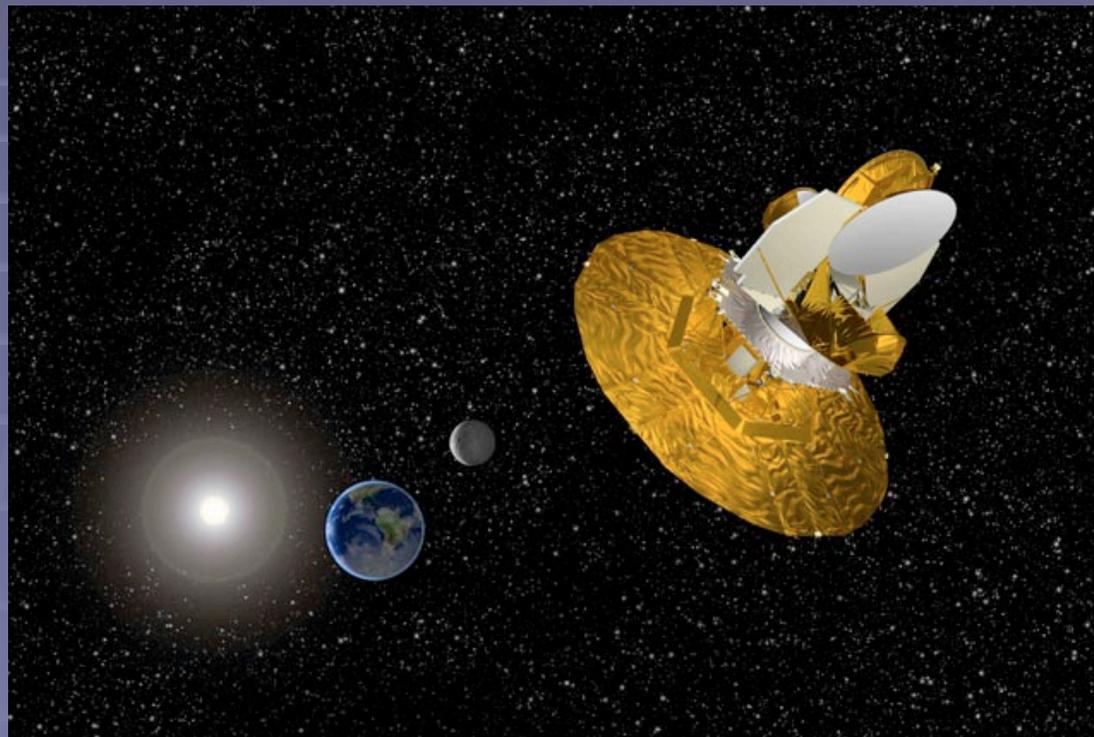


# BOOMERANG SKY

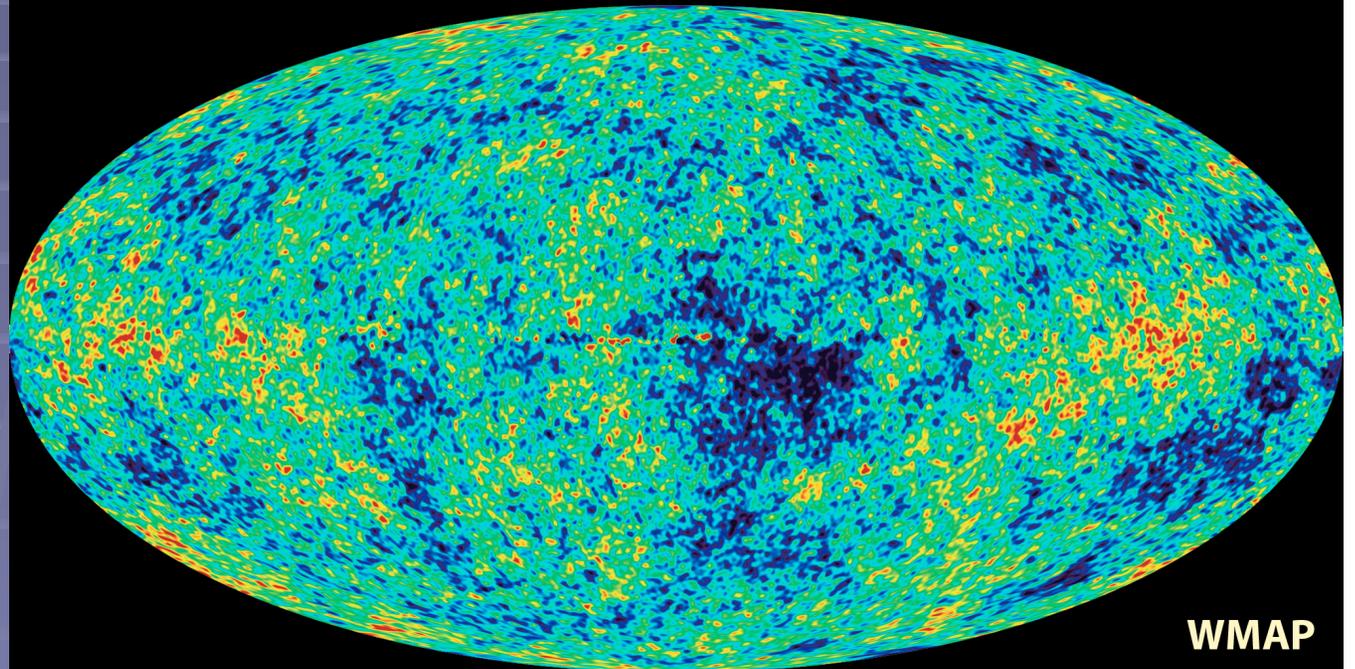
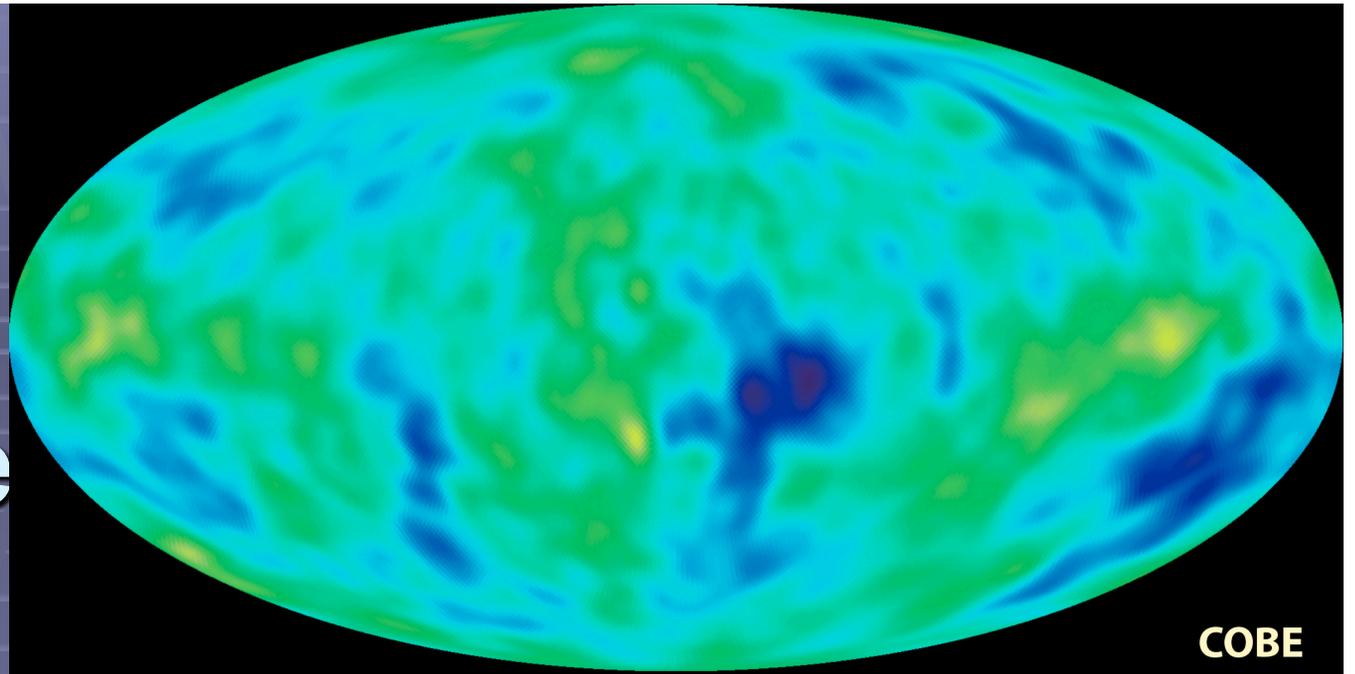


# WMAP Satellite

- Launched June 2002
- WMAP 1 Data 2003, WMAP 5 data 2008

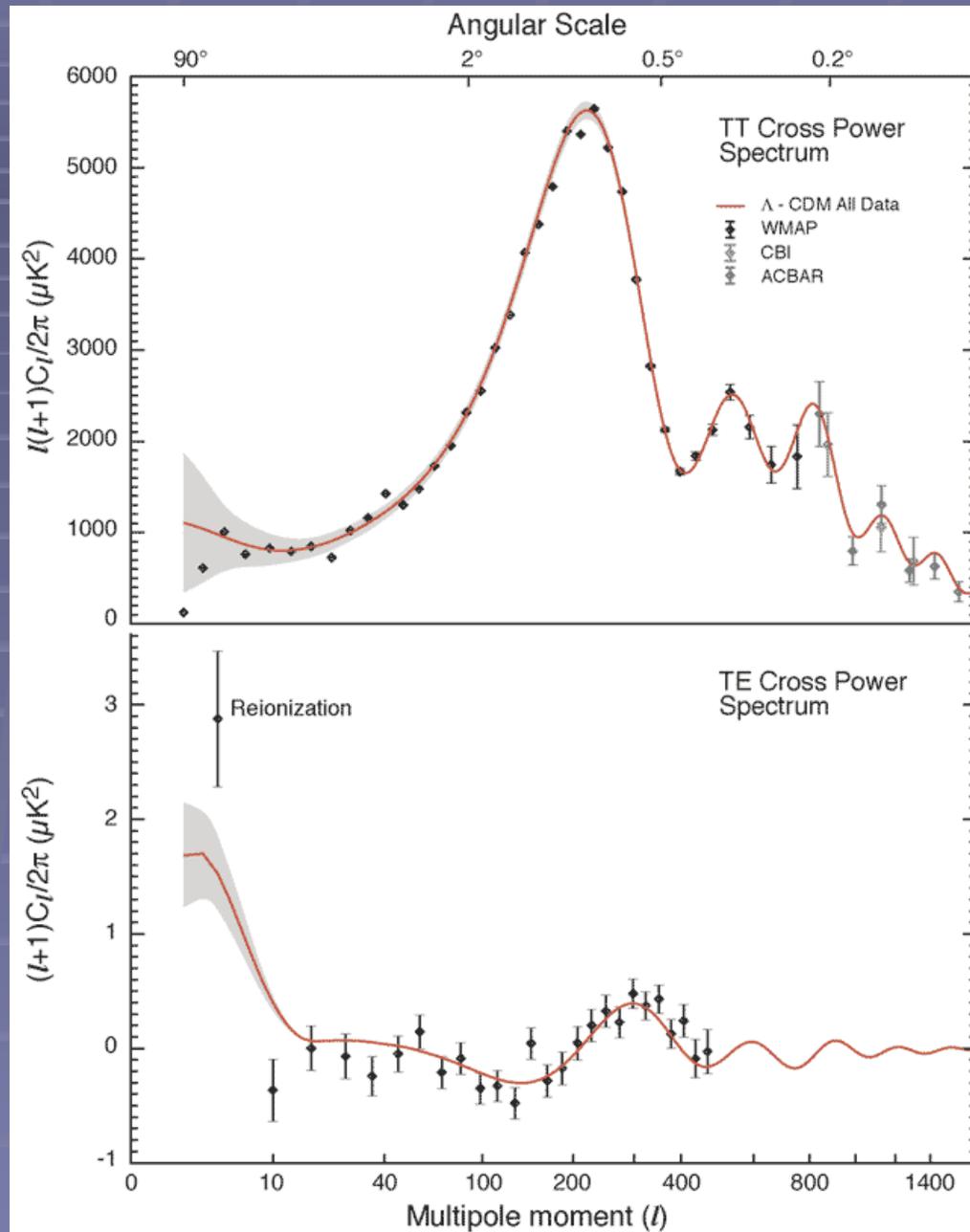


# The Microwave Sky



# Doppler Peak at 1 degree

Exactly as predicted for flat geometry, determines overall mass density of universe



# WMAP 5 year results

SUMMARY OF THE COSMOLOGICAL PARAMETERS OF  $\Lambda$ CDM MODEL AND THE CORRESPONDING 68% INTERVALS

Class	Parameter	WMAP 5-year ML <sup>a</sup>	WMAP+BAO+SN ML	WMAP 5-year Mean <sup>b</sup>	WMAP+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	$2.273 \pm 0.062$	$2.265 \pm 0.059$
	$\Omega_c h^2$	0.1081	0.1136	$0.1099 \pm 0.0062$	$0.1143 \pm 0.0034$
	$\Omega_\Lambda$	0.751	0.724	$0.742 \pm 0.030$	$0.721 \pm 0.015$
	$n_s$	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	$\tau$	0.089	0.080	$0.087 \pm 0.017$	$0.084 \pm 0.016$
	$\Delta_{\mathcal{R}}^2 (k_0^e)$	$2.41 \times 10^{-9}$	$2.42 \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	$\sigma_8$	0.787	0.811	$0.796 \pm 0.036$	$0.817 \pm 0.026$
	$H_0$	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	$70.1 \pm 1.3$ km/s/Mpc
	$\Omega_b$	0.0432	0.0458	$0.0441 \pm 0.0030$	$0.0462 \pm 0.0015$
	$\Omega_c$	0.206	0.230	$0.214 \pm 0.027$	$0.233 \pm 0.013$
	$\Omega_m h^2$	0.1308	0.1363	$0.1326 \pm 0.0063$	$0.1369 \pm 0.0037$
	$z_{\text{reion}}^f$	11.2	10.5	$11.0 \pm 1.4$	$10.8 \pm 1.4$
	$t_0^g$	13.69 Gyr	13.72 Gyr	$13.69 \pm 0.13$ Gyr	$13.73 \pm 0.12$ Gyr

# What have we learned from CMB?

- The peak at 1 degree tells us that the geometry of the universe is flat.
- This geometry corresponds to an energy density of  $10^{-29} \text{ gm/cm}^3$
- Height of second peak tells us that 4% of the total is ordinary atoms.
- Matching all the peaks tells us that 23% of the total is dark matter.

# Big Bang Nucleosynthesis

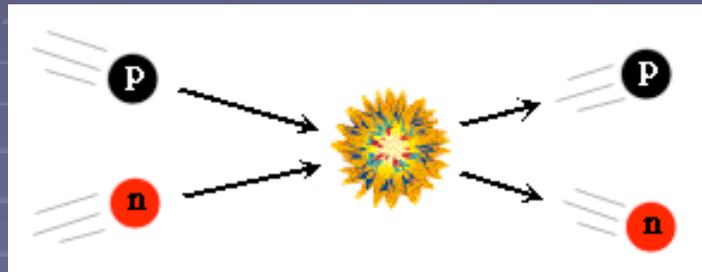
- When the universe is 3 minutes old, at a temperature of ten billion degrees K, Deuterium becomes stable:



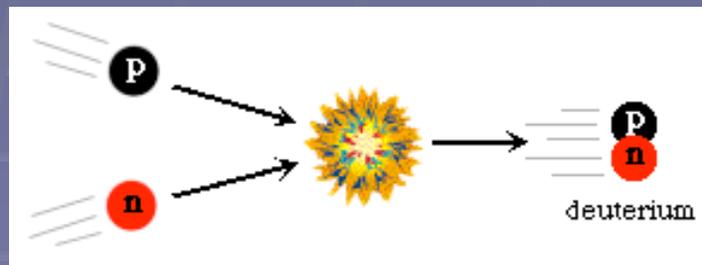
- Make Deuterium, Helium, Lithium
- To make heavier things like C,N,O need high densities in stars (3 He turns into C); this happens much later.

# Before and After the first three minutes:

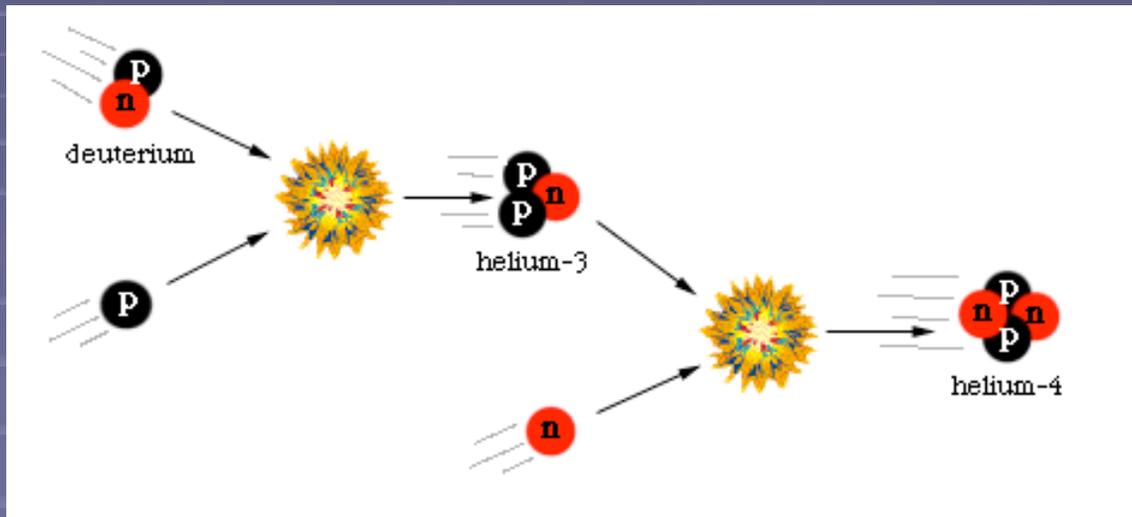
Before the universe is 3 minutes old, Deuterium isn't stable:



After the universe is 3 minutes old, Deuterium is stable:



# Helium formation



Once Deuterium forms, Helium and Lithium also form

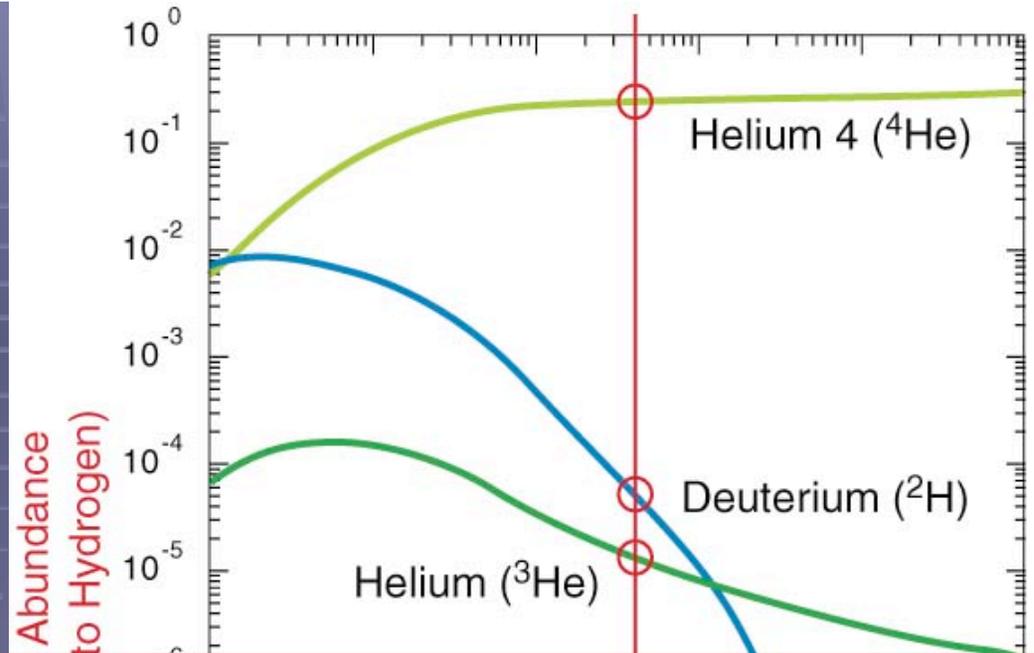
# Element Abundances

Predictions from Big Bang (e.g. 25% Helium 4) exactly match the data

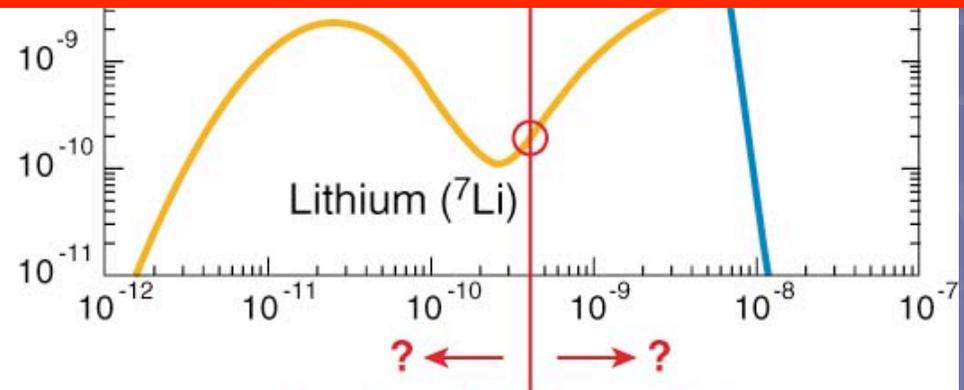
IF

ATOMS ARE 4% OF THE TOTAL

Only <4 particle families allowed: any additional neutrino species contributes an additional 1% to He4 abundance (Schramm, Steigman).

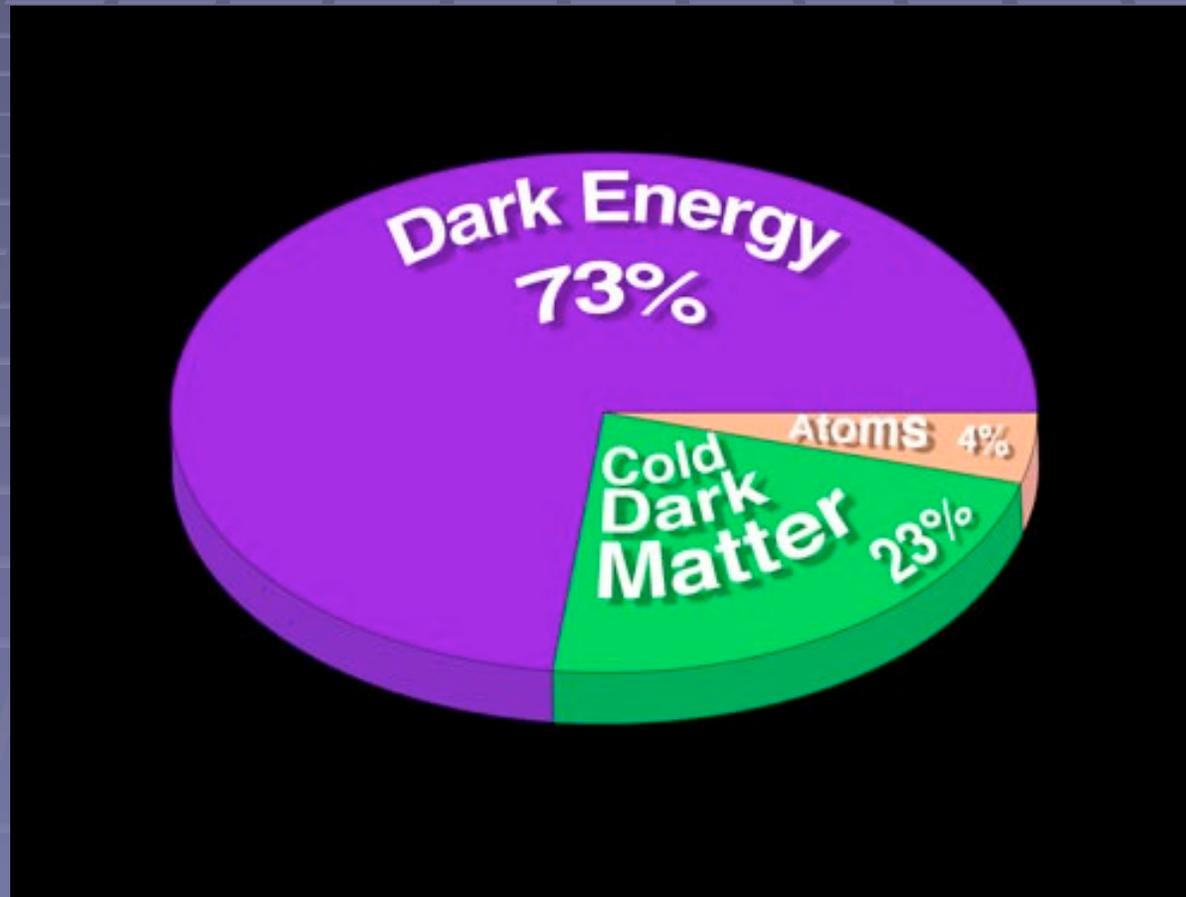


- Big Bang Nucleosynthesis yields  $\Omega_B h^2 \sim 0.01-0.02$
- Total matter density is much larger,  $\Omega_M h^2 \sim 0.13$



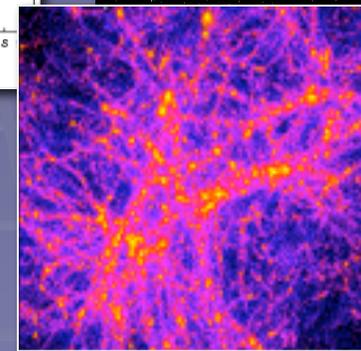
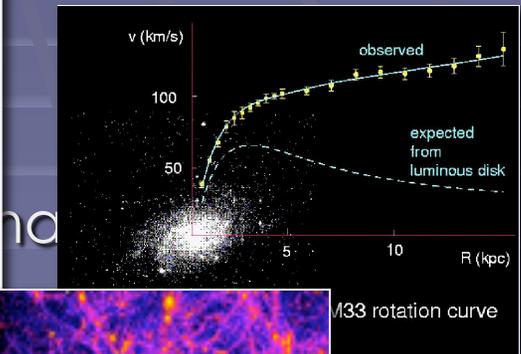
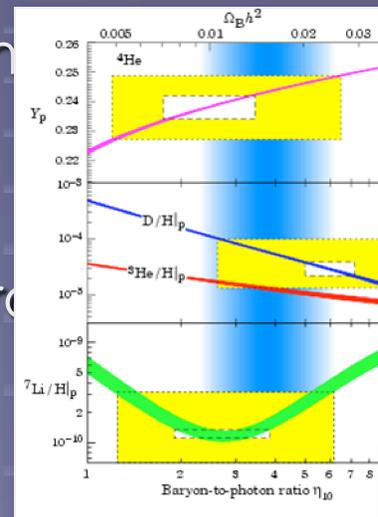
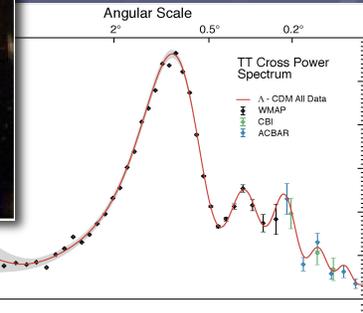
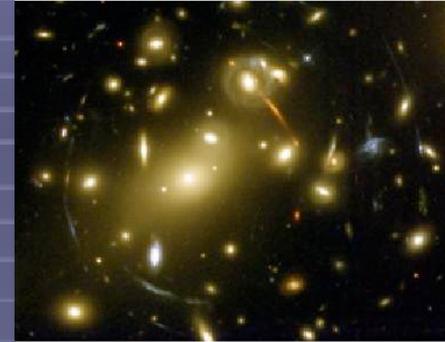
Density of Ordinary Matter (Relative to Photons)

# Pie Chart of The Universe



# Evidence for Dark Matter Redux

- We have seen that there exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter's presence through
- Still no observations of dark matter's electroweak interactions (or other non-gravitational interactions)



(Slide from Dan Hooper)

# III. What is the Dark Matter?

## Candidates:

- MACHOs (massive compact halo objects)
- WIMPs
- Axions
- Neutrinos (too light)
- Primordial black holes
- WIMPzillas
- Kaluza Klein particles

# Baryonic Dark Matter is NOT enough



**Death of stellar baryonic dark matter candidates  
(Fields, Freese, and Graff, astro-ph/0007444)**

# 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)

# Fifteen Years ago, there were two camps

- I. The believers in MACHOs (Massive Compact Halo Objects)
  
- II. The believers in WIMPs, axions and other exotic particle candidates

# MACHOS

## (Massive Compact Halo Objects)

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

From a combination of observational and theoretical arguments, we have found that THESE CANNOT EXPLAIN ALL THE DARK MATTER IN GALAXIES

# Is Dark Matter Made of Stars?

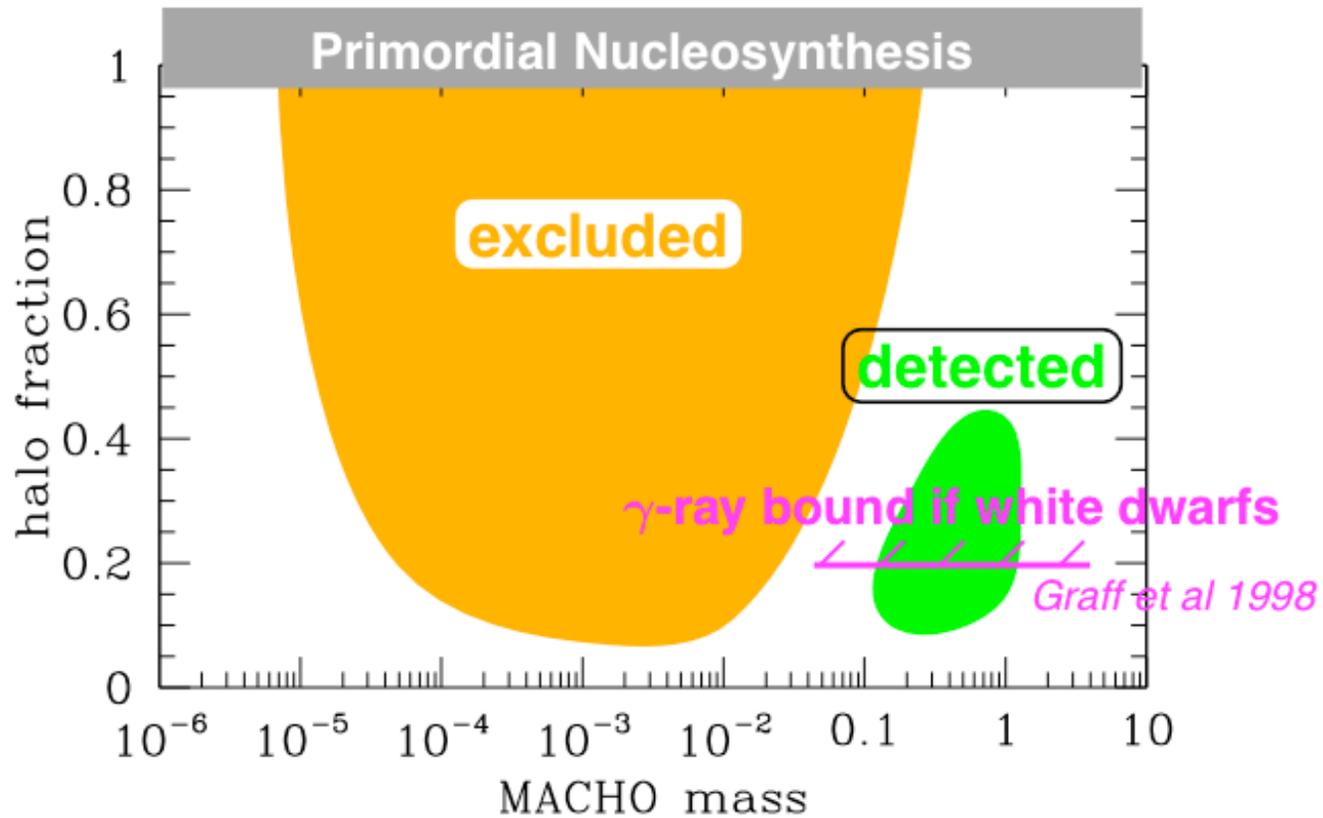
## NO

- Faint Stars: Hubble Space Telescope
- Planetary Objects:
  - parallax data
  - microlensing experiments

Together, these objects make up less than 3% of the mass of the Milky Way.

(Graff and Freese 96)

# MACHOs!



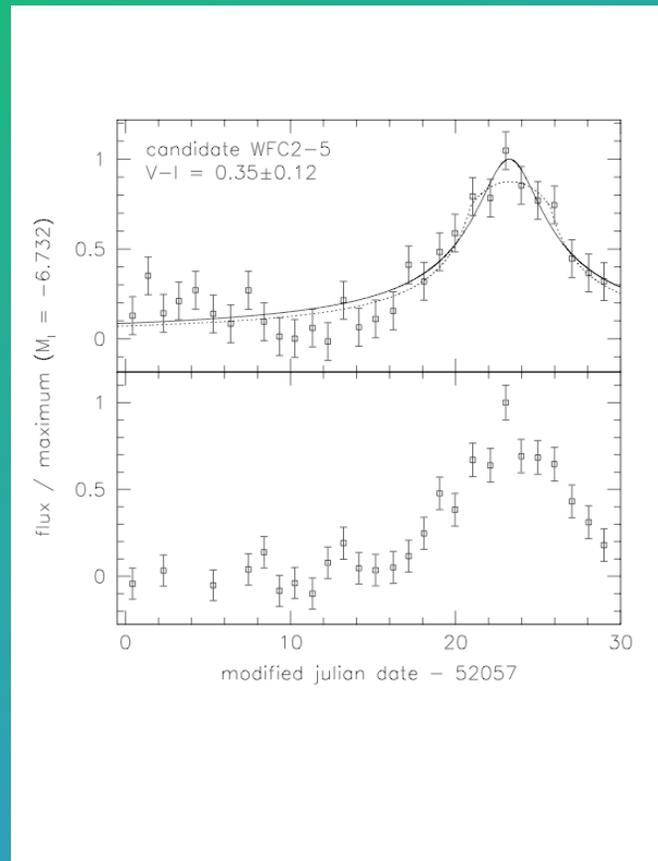
*MACHO & EROS 1996-2000*

# Is Dark Matter made of Stellar Remnants (white dwarfs, neutron stars, black holes)? partly

- Their progenitors overproduce infrared radiation.
- Their progenitors overproduce element abundances (C, N, He)
- Enormous mass budget.
- Requires extreme properties to make them.
- NONE of the expected signatures of a stellar remnant population is found.
- **AT MOST 20% OF THE HALO CAN BE MADE OF STELLAR REMNANTS**

[Fields, Freese, and Graff (ApJ 2000, New Astron. 1998); Graff, KF, Walker and Pinsonneault (ApJ Lett. 1999)]

# Candidate MACHO microlensing event in M87 (giant elliptical galaxy in VIRGO cluster, 14 Mpc away)



Baltz, Gondolo,  
and Shara  
(ApJ 2004)

Consistent with  
MACHO data in  
Milky Way (to LMC)

I HATE MACHOS!

DESPERATELY  
LOOKING FOR WIMPS!

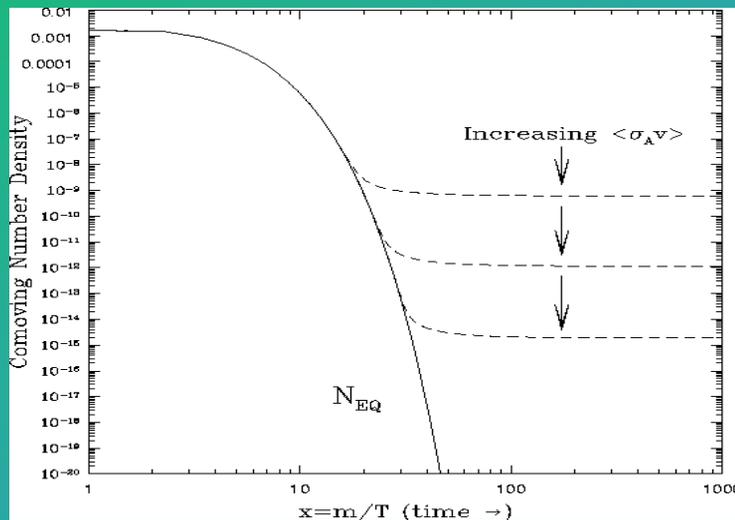
# Good news: cosmologists don't need to "invent" new particle:

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

- Axions

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

arises in Peccei-Quinn solution to strong-CP problem

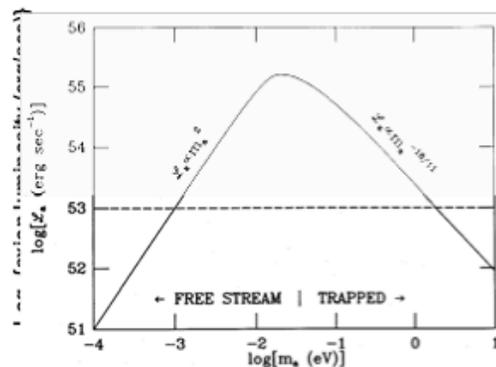


# AXIONS

## Summary of astrophysical bounds: The axion mass is small

AXION

Example: neutrinos from SN1987A



Supernova in the LMC.  
Neutrinos are trapped and diffuse out  
over timescales of around 10 seconds.

**Kamiokande and IMB together recorded  
19 neutrinos from SN1987A.**

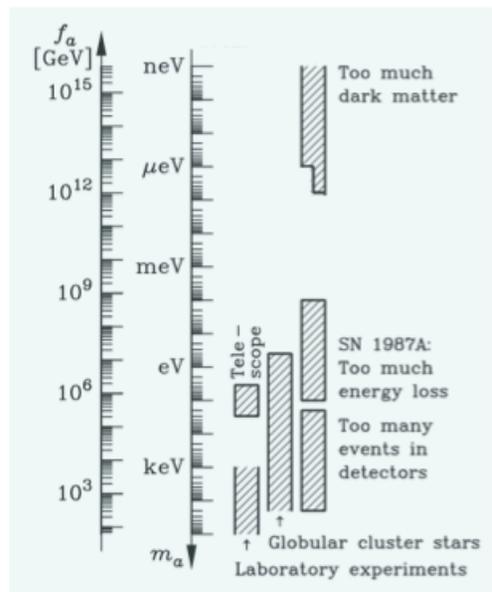
An axion of mass between  $10^{-3}$  and 2 eV would take so much energy out that... the length of the explosion would be observably forshortened.

**Overall summary: Astrophysics (stellar evolution and SN1987A), cosmology, and laboratory experiments leave the invisible CDM axion window  $10^{-6} < m_a < 10^{-3}$  eV (with large uncertainties)**

# 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

# AXION BOUNDS from ADMX RF cavity experiment (1998)

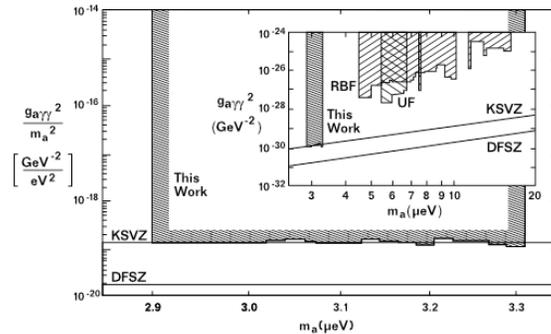
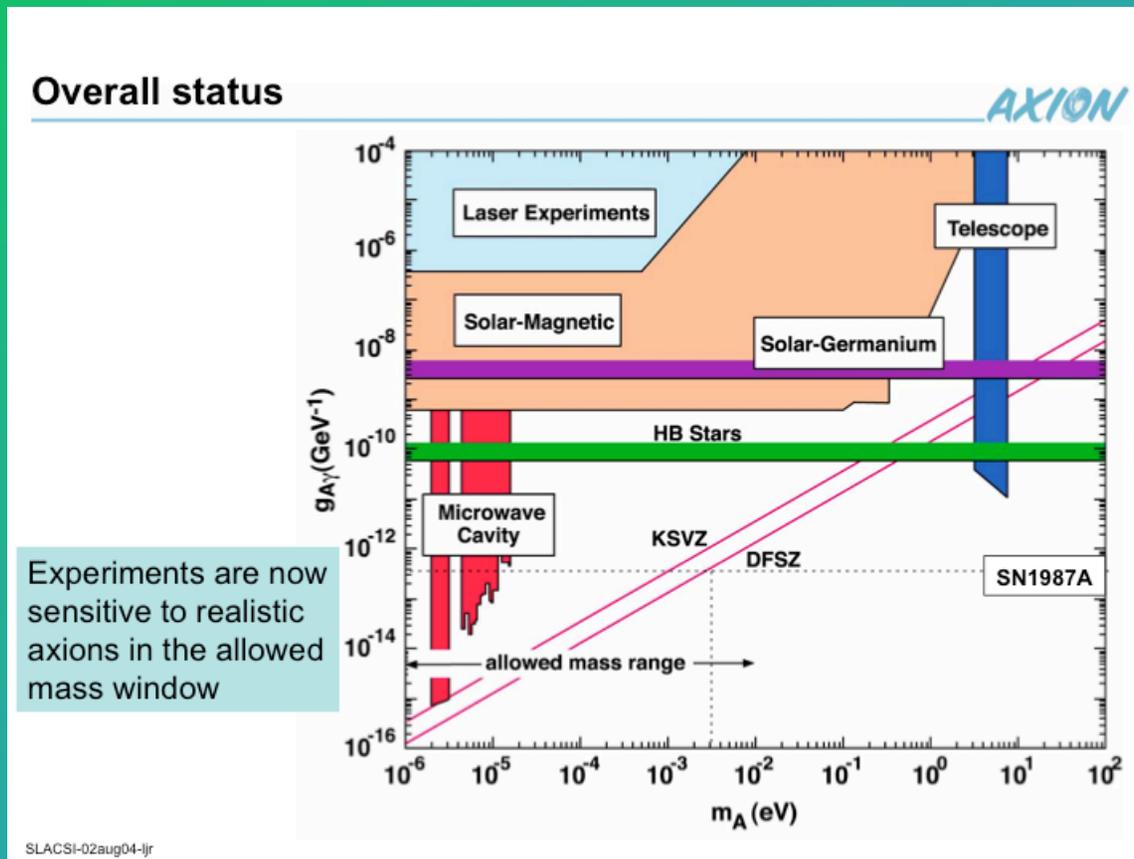


Fig. 4

# Overall status of axion bounds

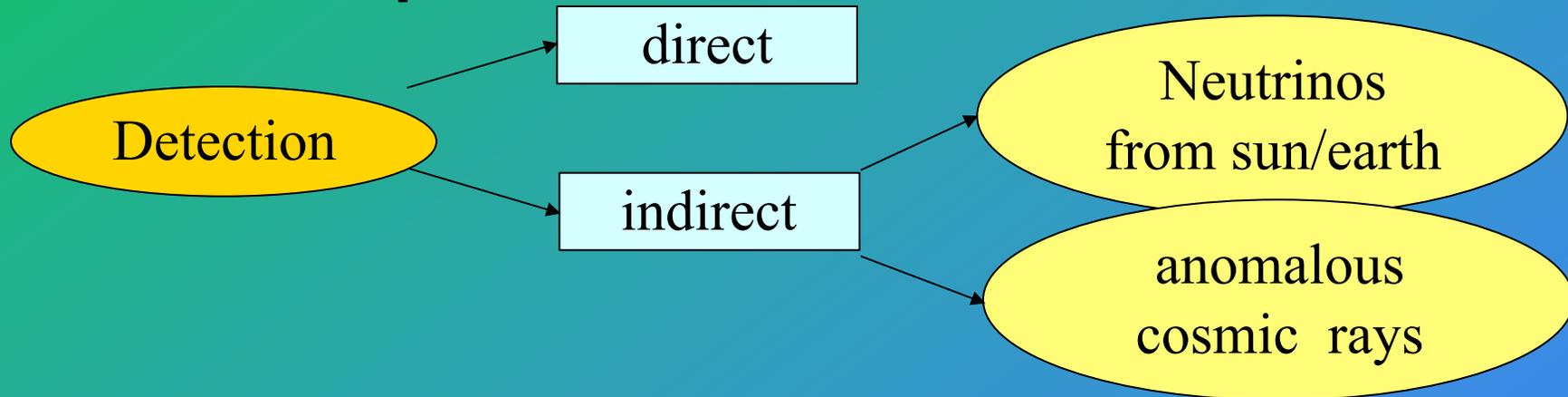


Pierre Sikivie first proposed the idea of resonant cavities

# WIMPs

Relic Density:  $\Omega_\chi h^2 \approx (3 \times 10^{-26} \text{ cm}^3/\text{sec} / \sigma_{\chi\chi \rightarrow \text{sm}})$

## Prospects for detection:



WIMP candidate motivated by SUSY:

**Lightest Neutralino, LSP in MSSM**

# Supersymmetry

- Particle theory designed to keep particle masses at the right values
- Every particle we know has a partner:

photon	photino
quark	squark
electron	selectron
- The lightest supersymmetric partner is a dark matter candidate.

# Lightest Super Symmetric Particle: neutralino

- Most popular dark matter candidate.
- Mass **1Gev-10TeV**  
(canonical value **100GeV**)
- Majorana particles: they are their own antiparticles and thus annihilate with themselves
- Annihilation rate in the early universe determines the density today.
- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

# The WIMP miracle

- Annihilation mediated by weak interaction.
- Thus for the standard neutralino (WIMPS):

$$\Omega_{\chi} h^2 = \frac{3 \times 10^{-27} \text{ cm}^3 / \text{sec}}{\langle \sigma v \rangle_{ann}}$$

- This is the mass fraction of WIMPs today, and gives the right answer (23%) if the dark matter is weakly interacting.

# The WIMP Miracle

**Weakly Interacting Massive Particles are the best motivated dark matter candidates**, e.g.: Lightest Supersymmetric Particles (such as neutralino) are their own antipartners. Annihilation rate in the early universe determines the density today.

- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

$$\Omega_{\chi} h^2 = \frac{3 \times 10^{-27} \text{ cm}^3 / \text{sec}}{\langle \sigma v \rangle_{ann}}$$

This is the mass fraction of WIMPs today, and gives the right answer (23%) if the dark matter is weakly interacting

# Lightest Supersymmetric Particle: Weakly interacting DM

- Sets Mass 1Gev-10TeV (take 100GeV)
- Sets annihilation cross section (WIMPS):

$$\langle \sigma v \rangle_{ann} = 3 \times 10^{-26} \text{ cm}^3 / \text{sec}$$

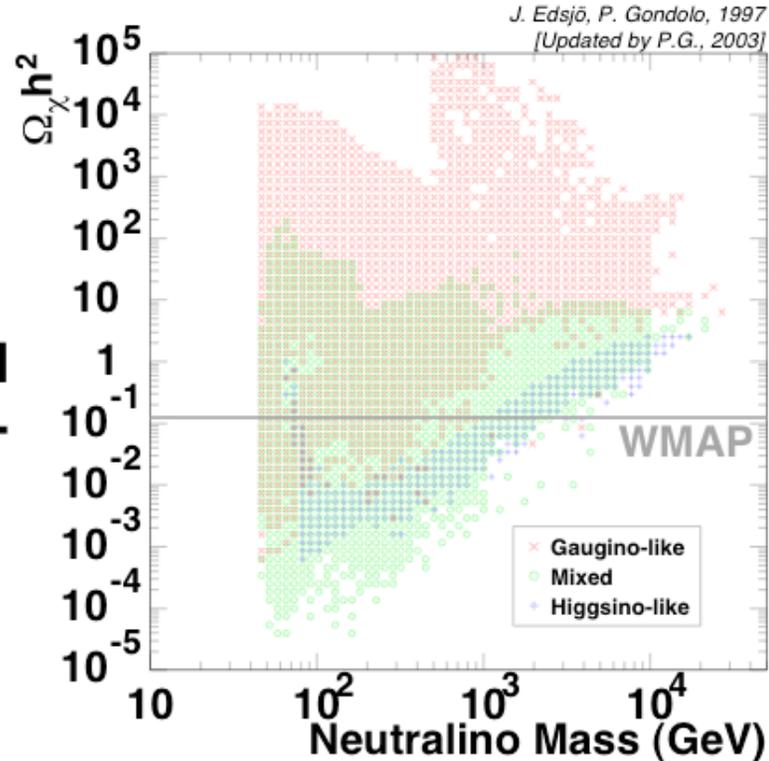
- **On going searches:**
- Motivation for LHC at CERN: 1) Higgs 2) Supersymmetry.
- Other experiments: DAMA, LUX, CDMS, XENON, WARP, DEEPCLEAN, CRESST, EDELWEISS, COUPP, TEXONO, GLAST, GAPS, HESS, MAGIC, HEAT, PAMELA, AMANDA, ICECUBE

# SUSY dark matter

## Supersymmetric dark matter

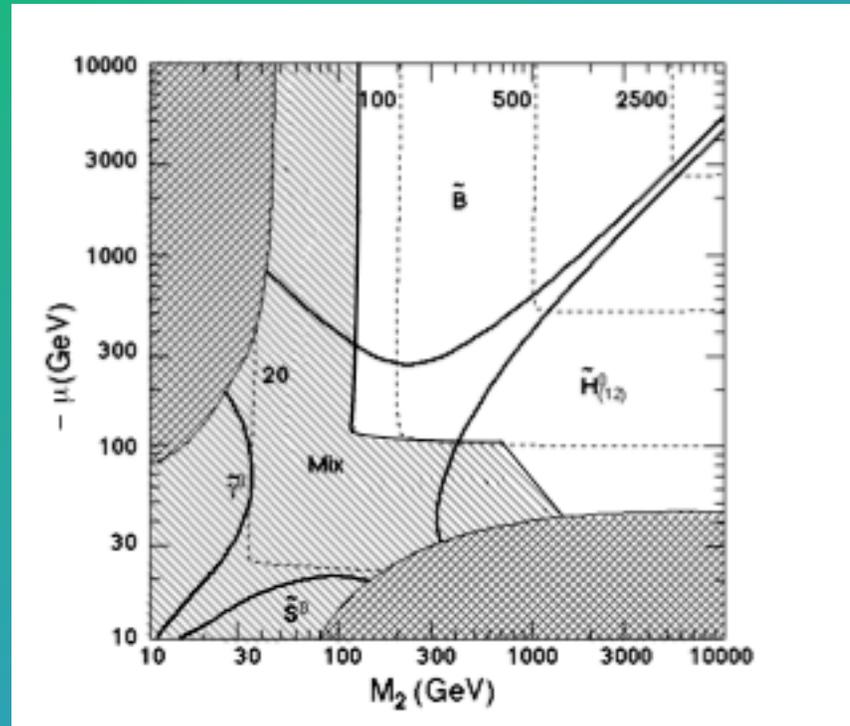
The lightest supersymmetric particle is a good dark matter candidate

Coannihilation included  
(Binetruy, Girardi, and Salati 1984);  
Griest and Seckel 1991)



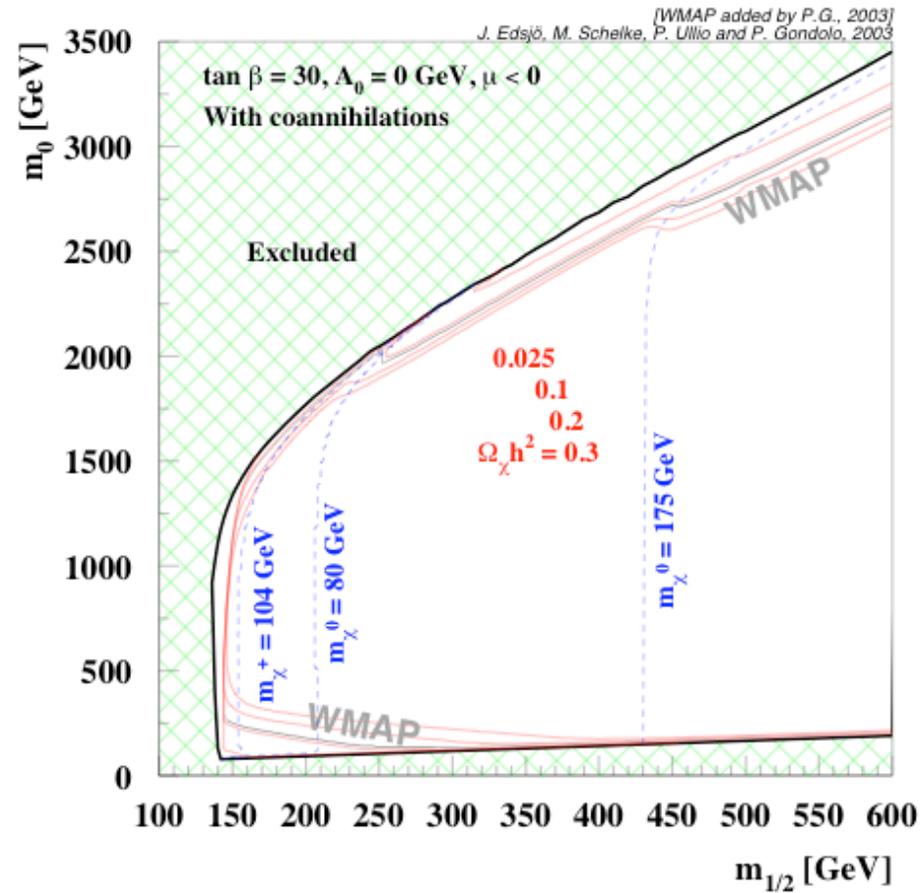
Updated from Edsjö, Gondolo 1997

# Mass contours and composition of nearly pure LSP states in the MSSM



Olive  
2003

# Some results in mSUGRA



# Searching for dark WIMPs

- Direct Detection (Goodman and Witten 1986; Drukier, Freese, and Spergel 1986)
- Neutrinos from Sun (Silk, Olive, and Srednicki 1985) or Earth (Freese 1986; Krauss and Wilczek 1986)
- Anomalous Cosmic rays from Galactic Halo (Ellis, KF et al 1987)
- Neutrinos, Gamma-rays, radio waves from galactic center (Gondolo and Silk 1999)
- N.B. SUSY WIMPs are their own antiparticles; they annihilate among themselves to  $1/3$  neutrinos,  $1/3$  photons,  $1/3$  electrons and positrons

# IV. Detecting WIMP Dark Matter Particles

- Collider Searches
- Direct Detection
- Indirect Detection (**Neutrinos**)
  - Sun (Silk, Olive, Srednicki '85)
  - Earth (Freese '86; Krauss, Srednicki, Wilczek '86)
- Indirect Detection (**Gamma Rays, positrons**)
  - Milky Way Halo (Ellis, KF et al '87)
  - Galactic Center (Gondolo and Silk 2000)
  - Anomalous signals seen in HEAT, PAMELA ( $e^+$ ), HESS, CANGAROO, WMAP, EGRET, etc.

An aerial photograph of a valley with a yellow circular outline and text overlay. The background shows a vast landscape with a large body of water, a city, and distant mountains under a blue sky. The text is centered in the lower half of the image.

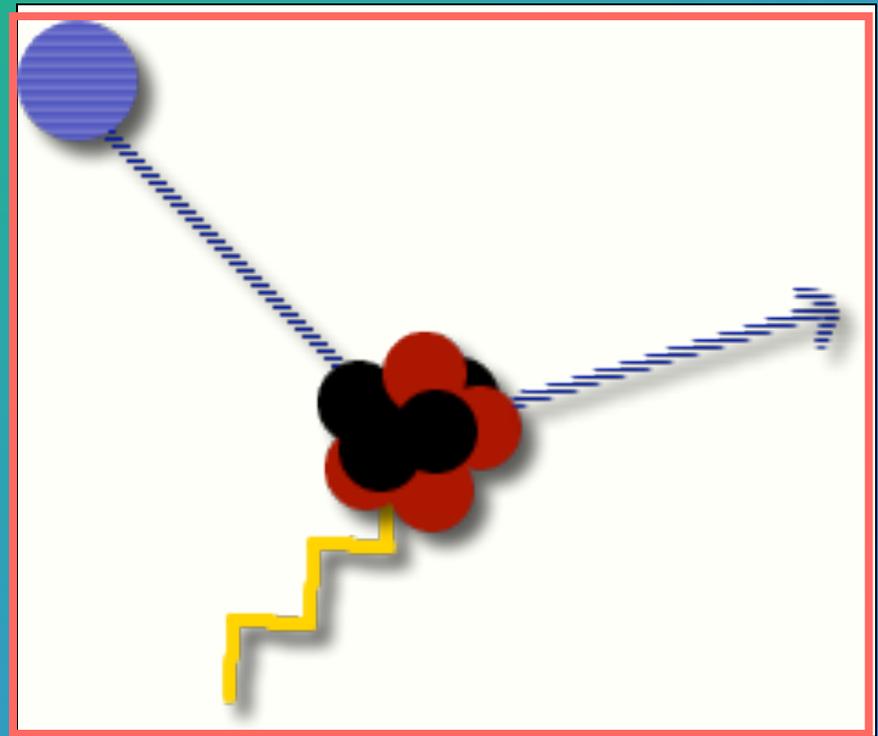
LHC-Making DM  
Coming Soon  
(We hope)

# Supersymmetric Particles in LHC

- Signature: missing energy when SUSY particle is created and some energy leaves the detector
- Problem with identification: degeneracy of interpretation
- SUSY can be found, but, you still don't know how long the particle lives: fractions of a second to leave detector or the age of the universe if it is dark matter
- Proof that the dark matter has been found requires astrophysical particles to be found

# 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!

# WIMP Dark Matter Phenomenology: History

- Looking for neutrinos (Drukier and Stodolsky)
- First paper suggesting direct detection: Goodman and Witten 1986
- Second paper on direct detection: we were the first to (i) take into account WIMP distribution in galaxy and (ii) suggest annual modulation (Drukier, Freese, and Spergel 1986).
- A followup paper (Freese, Frieman, Gould 1988) suggested using annual modulation to pull out signal from background. This is how the only current claim for direct detection was done (DAMA experiment).

# Event rate

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

$$\begin{aligned}\frac{dR}{dE} &= \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv f(v,t) d^3v \\ &= \frac{\rho\sigma_0 F^2(q)}{2m\mu^2} \int_{v > \sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v\end{aligned}$$

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

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

rate detector mass for a WIMP mass  $m$ , typically given in units of cpa/kg/keV (where cpa is counts per day), can be written as:

$$\frac{dR}{dE} = \frac{\sigma(q)}{2m\mu^2} \rho \eta(E, t) \quad (1)$$

where  $q = \sqrt{2ME}$  is the nucleus recoil momentum,  $\sigma(q)$  is the WIMP-nucleus cross-section,  $\rho$  is the local WIMP density, and information about the WIMP velocity distribution is encoded into the mean inverse speed  $\eta(E, t)$ ,

$$\eta(E, t) = \int_{u > v_{\min}} \frac{f(\mathbf{u}, t)}{u} d^3u. \quad (2)$$

Here

$$v_{\min} = \sqrt{\frac{ME}{2\mu^2}} \quad (3)$$

represents the minimum WIMP velocity that can result in a recoil energy  $E$  and  $f(\mathbf{u}, t)$  is the (time-dependent) distribution of WIMP velocities  $\mathbf{u}$  relative to the detector

# Canonical DM distribution in halo

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

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

Here

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

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

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

Typical particle speed is about 270 km/sec.

# Three claims of WIMP dark matter detection: how can we be sure?

- 1) The DAMA annual modulation
- 2) The HEAT and PAMELA positron excess
- 3) Gamma-rays from Galactic Center

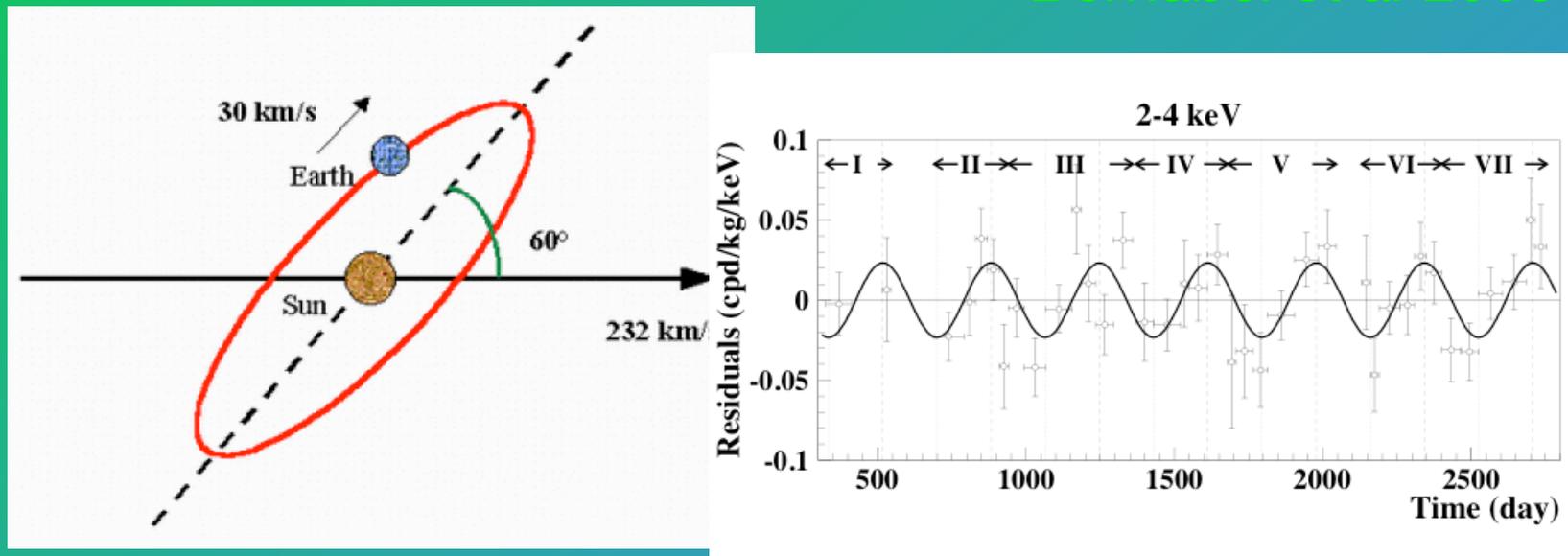
HAS DARK MATTER BEEN  
DISCOVERED?

*The DAMA Annual  
Modulation*

# DAMA annual modulation

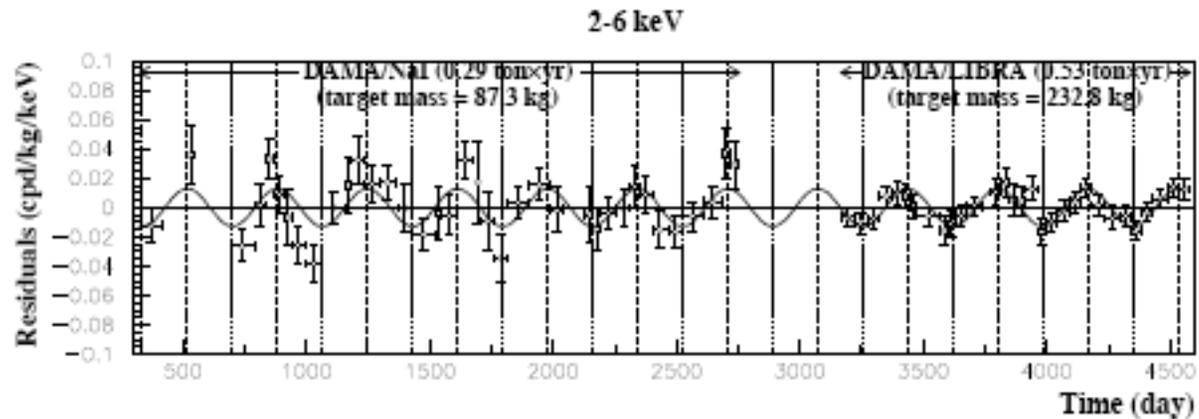
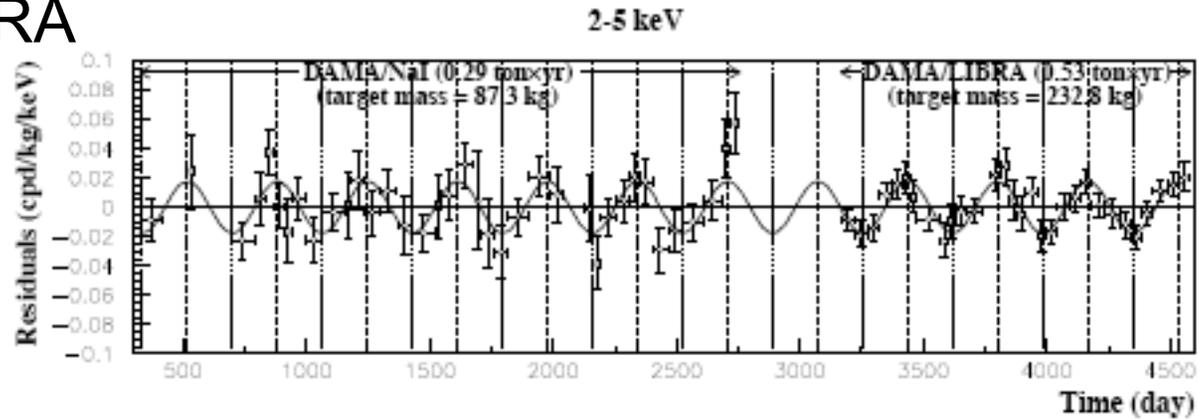
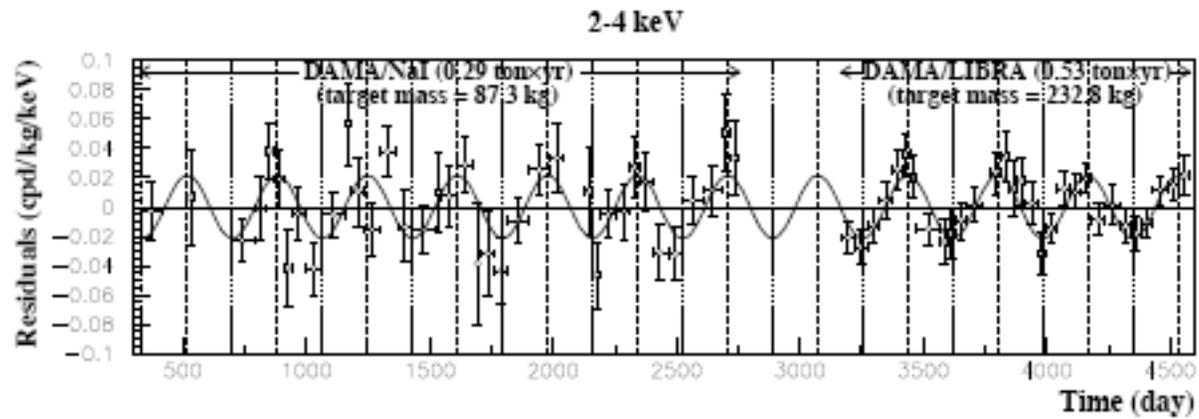
Drukier, Freese, and Spergel (PRD 1986);  
Freese, Frieman, and Gould (PRD 1988)

*Bernabei et al 2003*



Data do show a  $8\sigma$  modulation  
WIMP interpretation is controversial

DAMA/LIBRA  
(April 17,  
2008)  
8 sigma



# Can the positive signal in DAMA be compatible with null results from other experiments?

Experiment	Element	Exposure [kg-day]	Energies [keVee]	Quenching Factor ( $Q$ )
DAMA	NaI	$2.99 \times 10^5$	2–20	0.3, 0.09 ( $\ddagger$ )
CDMS	Si	6.58	5–55	1 (§)
	Ge	397.8	10–100	1 (§)
CoGeNT	Ge	8.38	0.23–4.1	0.2
CRESST I	Al <sub>2</sub> O <sub>3</sub>	1.51	0.6–20	1 (§)
TEXONO	Ge	0.338	0.2–8	0.2
XENON10	Xe	316.4	6.1–36.5	1 (§)

Savage, Gelmini, Gondolo, and Freese, arxiv:0808:3607

(see also papers by Hooper and Zurek; Fairbairn and Schwetz;  
Chang, Pierce and Weiner 2008)

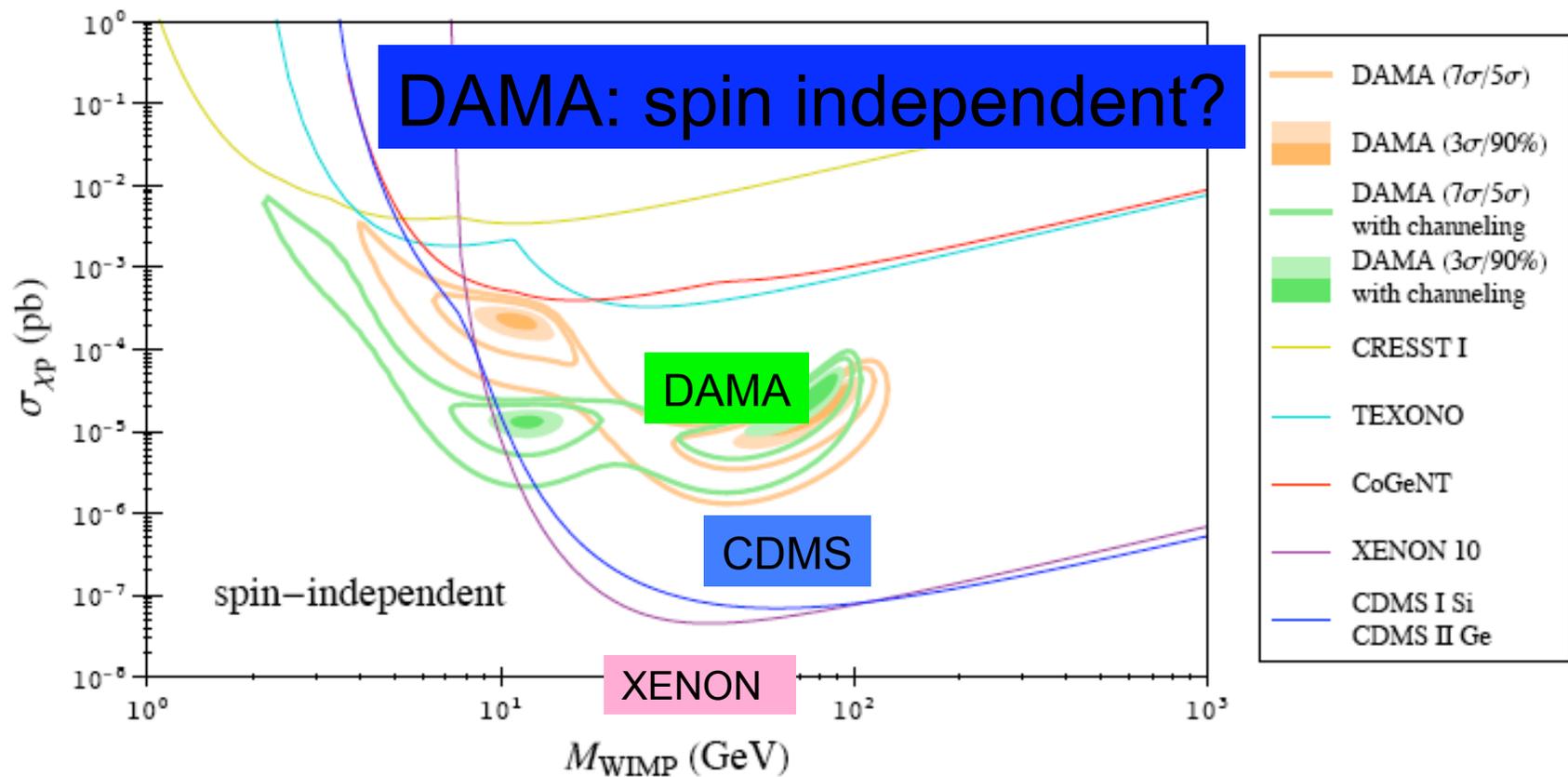
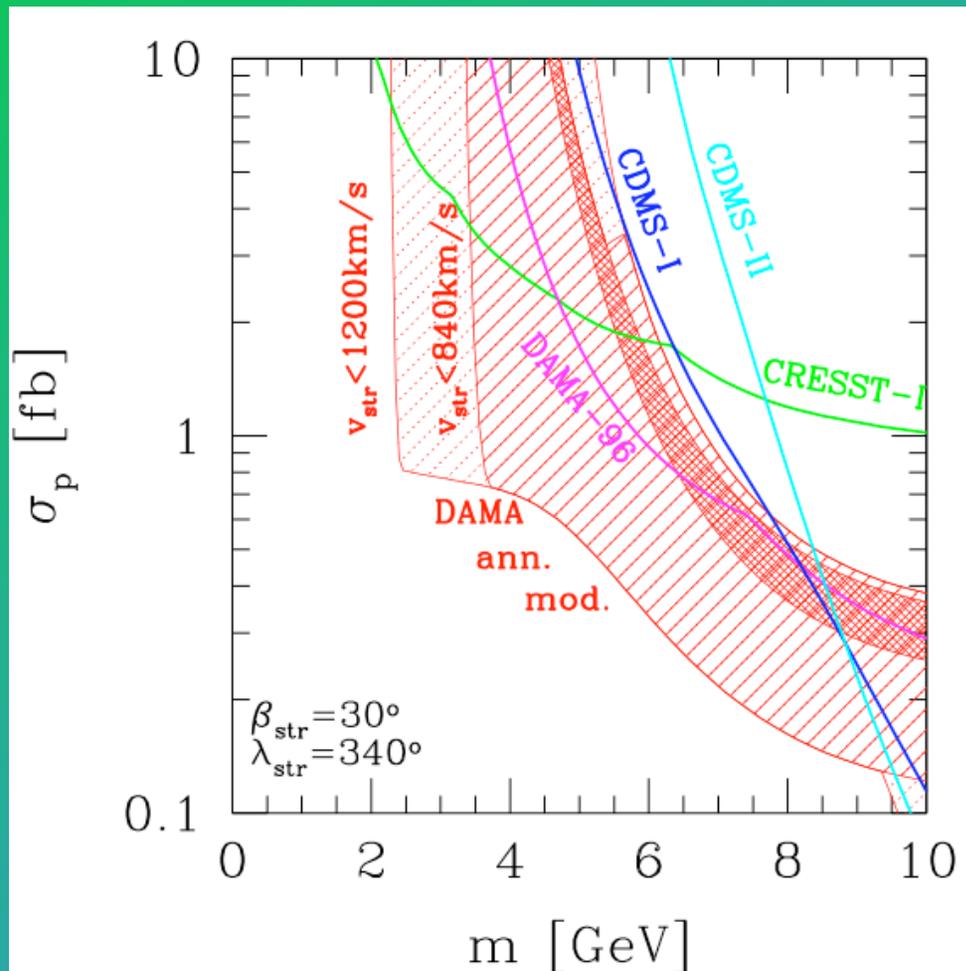


FIG. 5: Experimental constraints and DAMA preferred parameters for SI only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect.

Small remaining region at 10 GeV WIMP mass

# DAMA: spin-independent?



*Gondolo, Gelmini 2004*

- Possible at small masses with
  - canonical halo and Maxwellian distribution
  - Galactic or extragalactic dark matter streams

# DAMA and Spin-dependent cross sections

Remaining window around 10 GeV.

Removing SuperK: WIMP mass up to 70 GeV allowed

Savage, Gelmini, Gondolo, Freese  
0808:3607

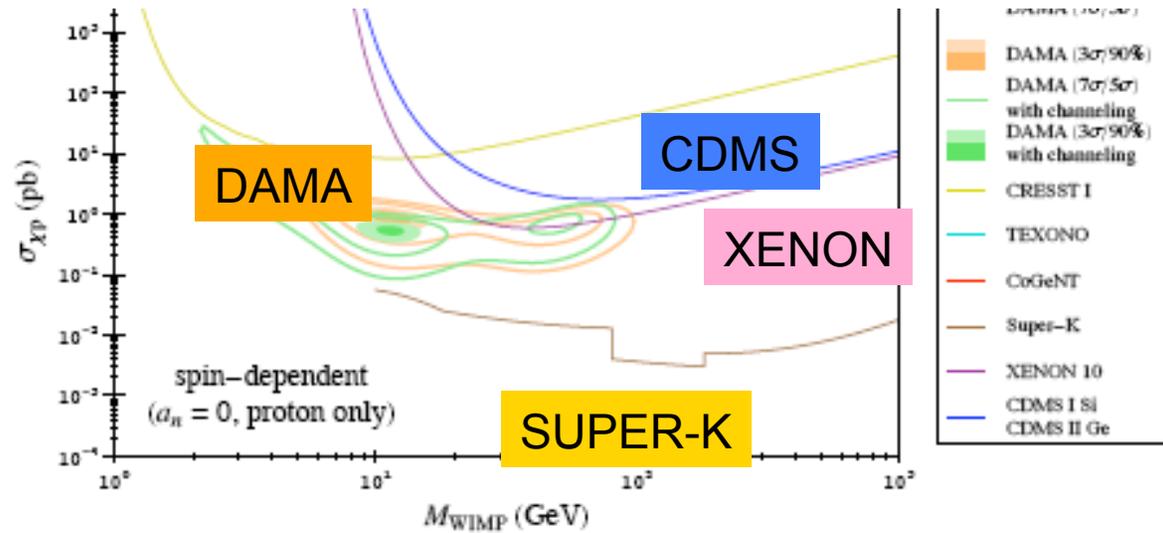
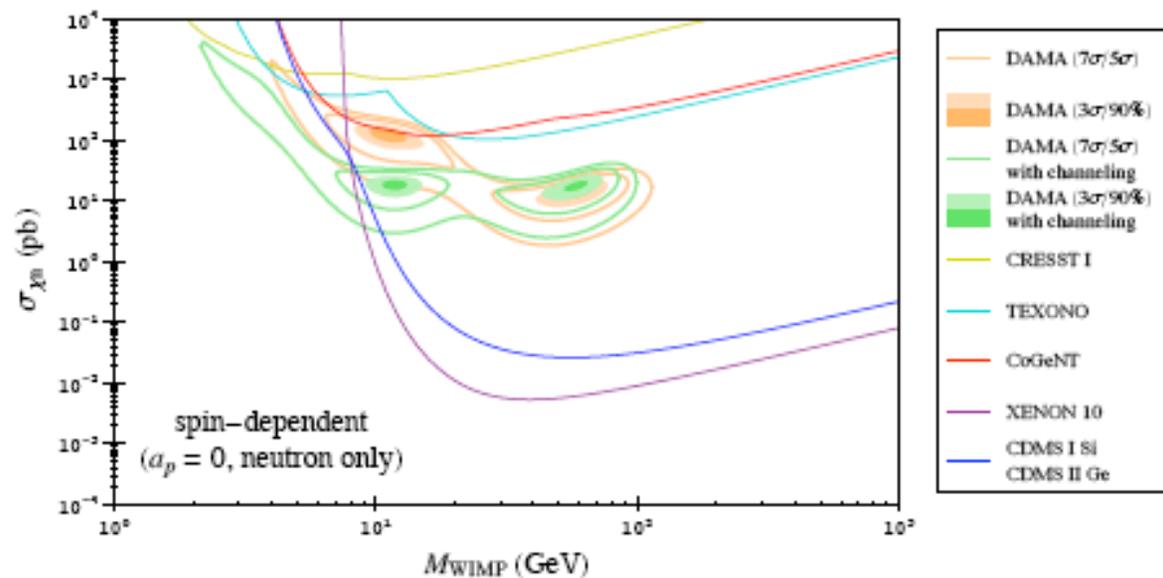


FIG. 6: Experimental constraints and DAMA preferred parameters for SD proton-only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect. The CoGeNT and TEXONO constraints are too weak to fall within the shown region.



# Alternatives to explain DAMA plus all other data

WIMPs with inelastic scattering?

Weiner, Finkbeiner, Pierce

Dark Sector with Hierarchy of Masses like  
our own?

Finkbeiner, Arkani-Hamed, Slatyer, Weiner

# Direct Detection

- In past two years, two orders of magnitude increase in sensitivity:

(i) CDMS

(ii) XENON-10

New technology: liquid noble gases

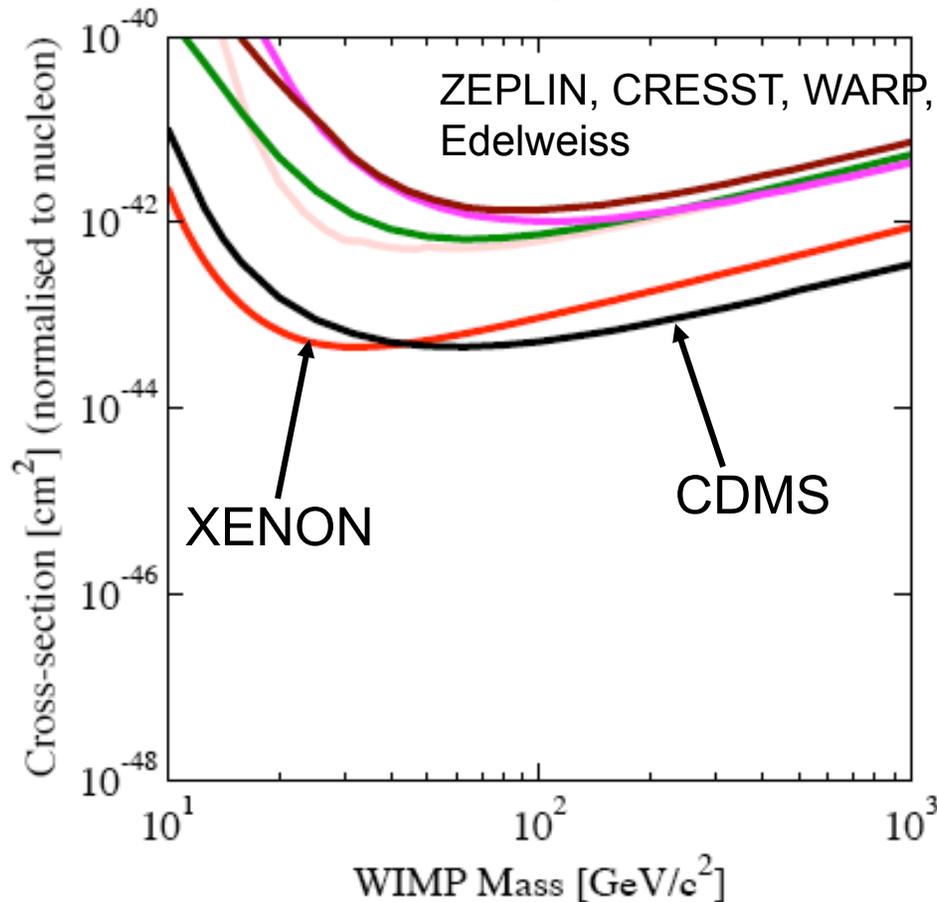
XENON, LUX

WARP (argon)

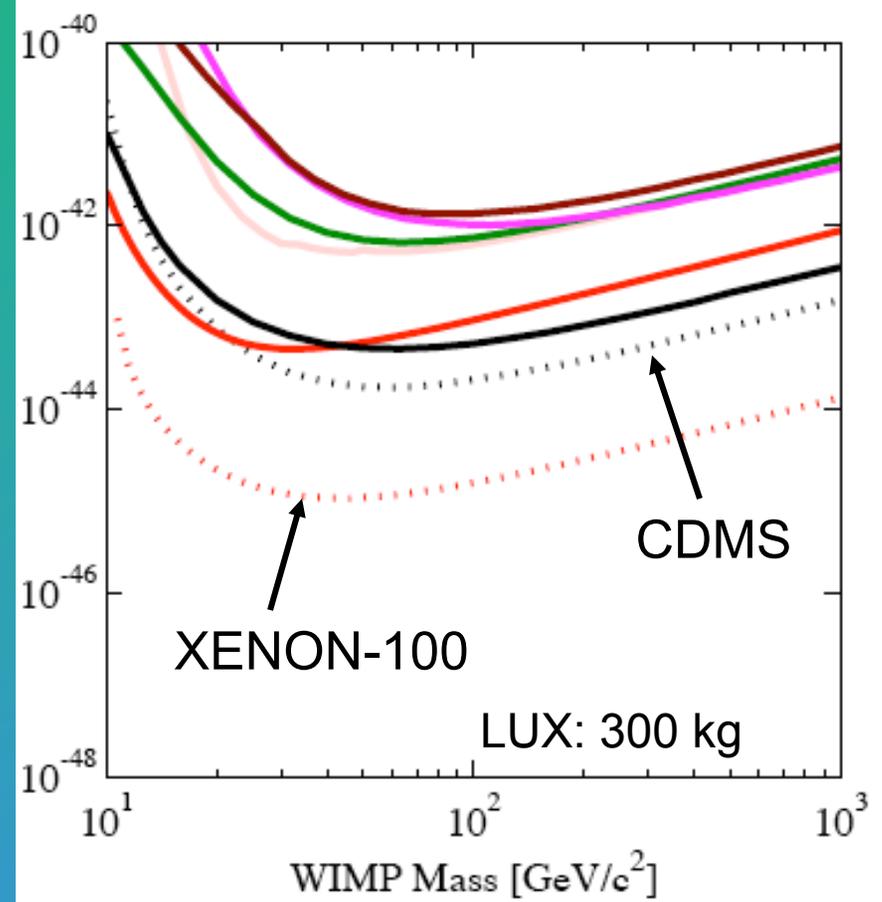
DEEPCLEAN (argon and neon)

# Direct Detection Experiments

## Current Status



## Near Future



The future: one ton detectors! XENON, LUX, CRESST/  
EDELWEISS, DEEP-CLEAN, SUPERCDMS

*The HEAT and  
PAMELA Positron  
Excess*

# The Indirect Detection of Dark Matter

## 1. WIMP Annihilation

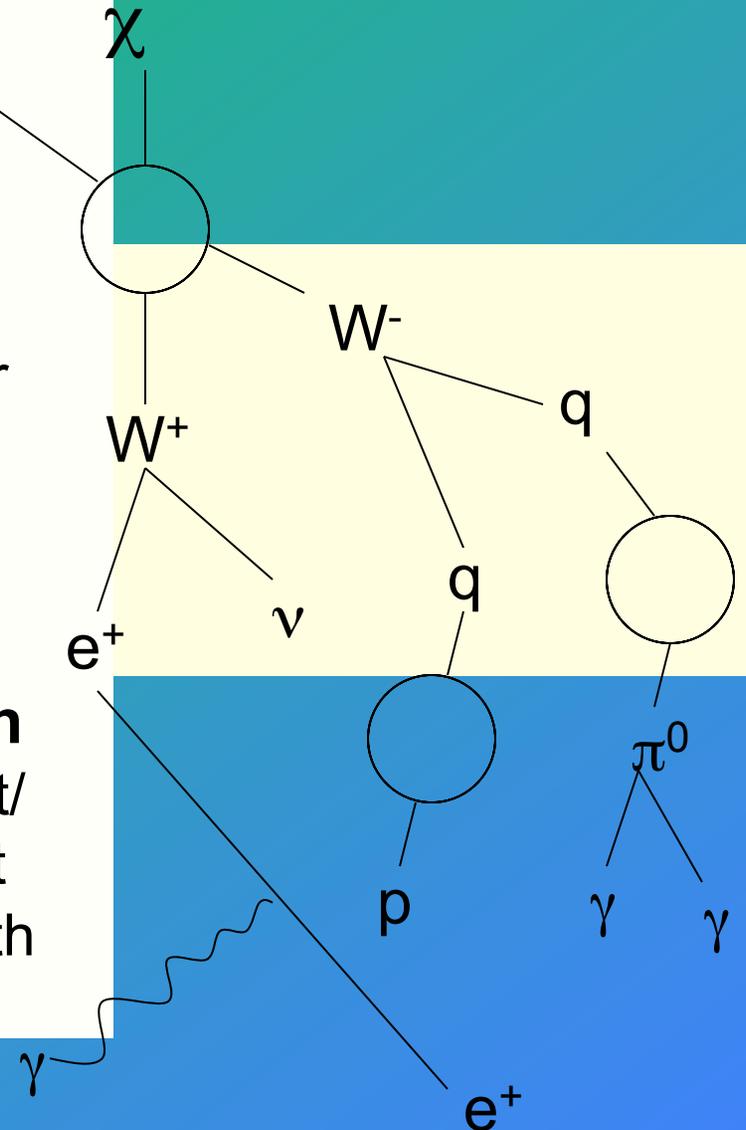
Typical final states include heavy fermions, gauge or Higgs bosons

## 2. Fragmentation/Decay

Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

## 3. Synchrotron and Inverse Compton

Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



# Annihilation Products

- $1/3$  electron/positrons
- $1/3$  gamma rays
- $1/3$  neutrinos
- Typical particles have energies roughly  $1/10$  of the initial WIMP mass
- All of these are detectable!

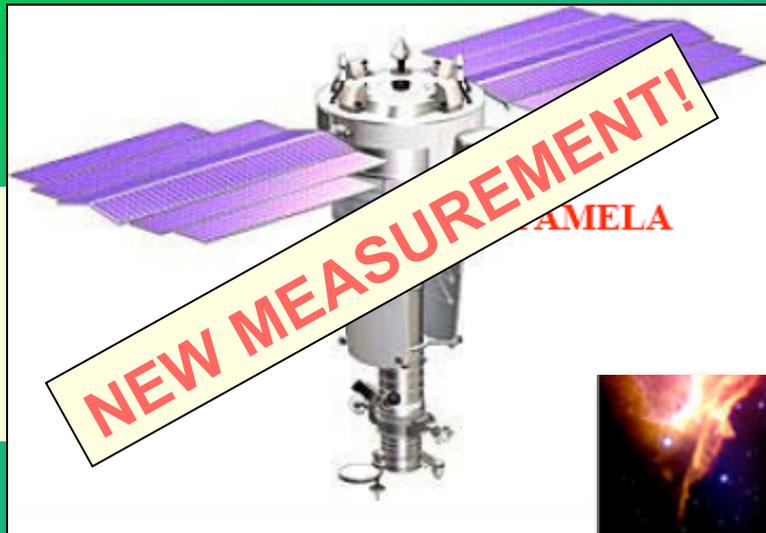
# Indirect Detection History

- Indirect Detection (**Neutrinos**)
  - Sun (Silk, Olive, Srednicki '85)
  - Earth (Freese '86; Krauss, Srednicki, Wilczek '86)
- Indirect Detection (**Gamma Rays, positrons**)
  - Milky Way Halo (Ellis, KF et al '87)
  - Galactic Center (Gondolo and Silk 2000)
  - Anomalous signals seen in HEAT (e+), HESS, CANGAROO, WMAP, EGRET, PAMELA.

# New Indirect Detection Results!

(When it rains it pours)

Pamela



IceCube

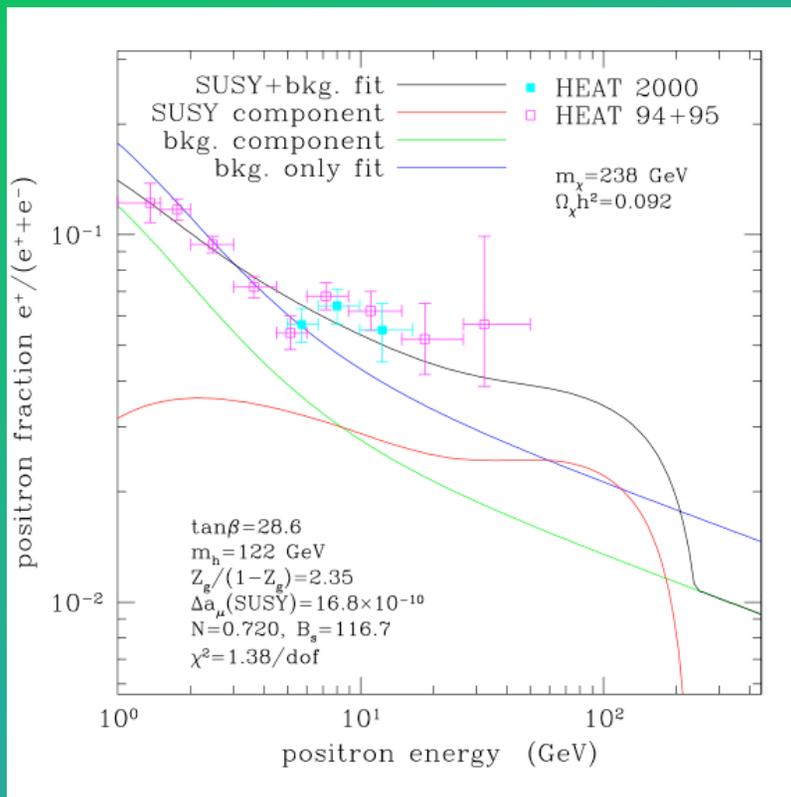


Glast



**Dan Hooper** - Direct and Indirect Searches For Particle Dark Matter

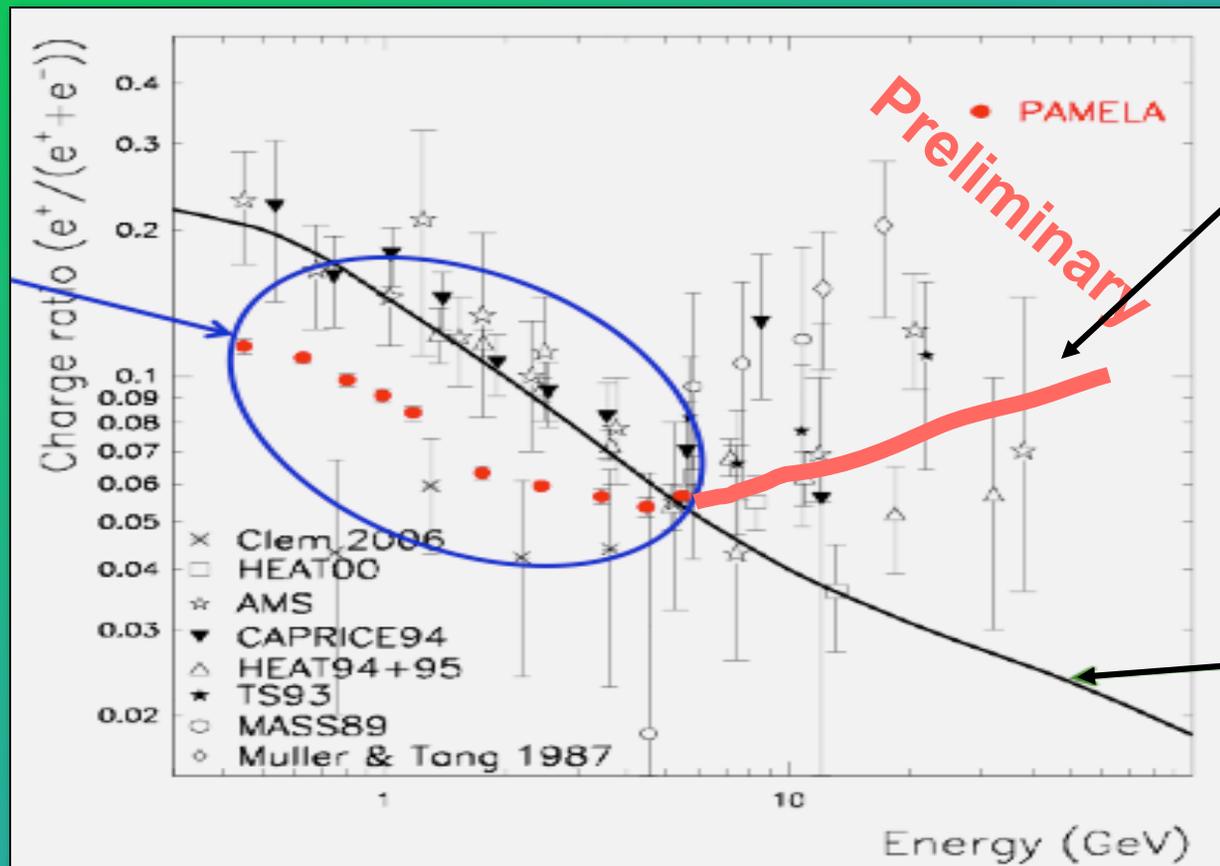
# Positron excess



- HEAT balloon found anomaly in cosmic ray positron flux
- Explanation 1: dark matter annihilation
- Explanation 2: we do not understand cosmic ray propagation

*Baltz, Edsjo, Freese, Gondolo 2001*

# Pamela's New Positron Measurement



■ The positron content of the cosmic ray spectrum begins to rise at 8-10 GeV, and climbs to ~10% at 60 GeV

Astrophysical expectation (secondary production)

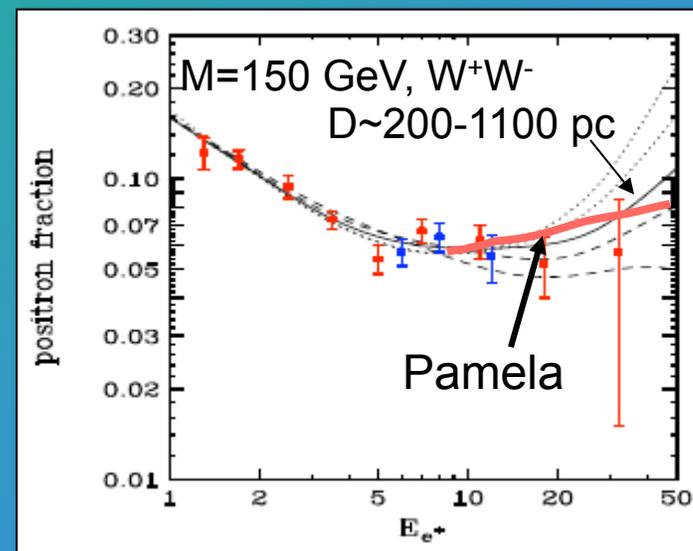
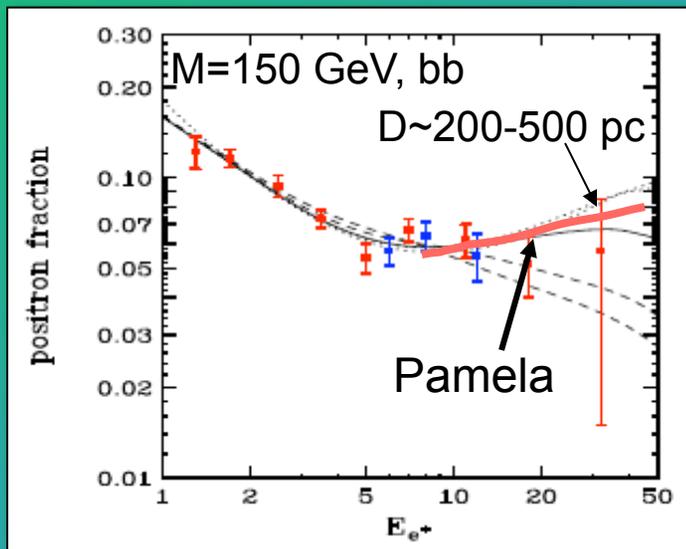
# How to understand this?

- 0) Pulsars: the best bet?
- 1) Astrophysics. Propagation of charged particles in the galaxy poorly understood. See Delahaye and Salati 08.
- 2) proton background (misidentified as positrons), is known to rise with energy. PAMELA doesn't identify each event (HEAT did)
- 3) We happen to live in a hot spot of high dark matter density (boosted by at least factor 10)
- 4) nonstandard WIMPs: e.g., nonthermal WIMPs; Kaluza Klein particles
- WHO KNOWS?

# A Dark Matter Interpretation of Pamela's Positrons

Could be accommodated by:

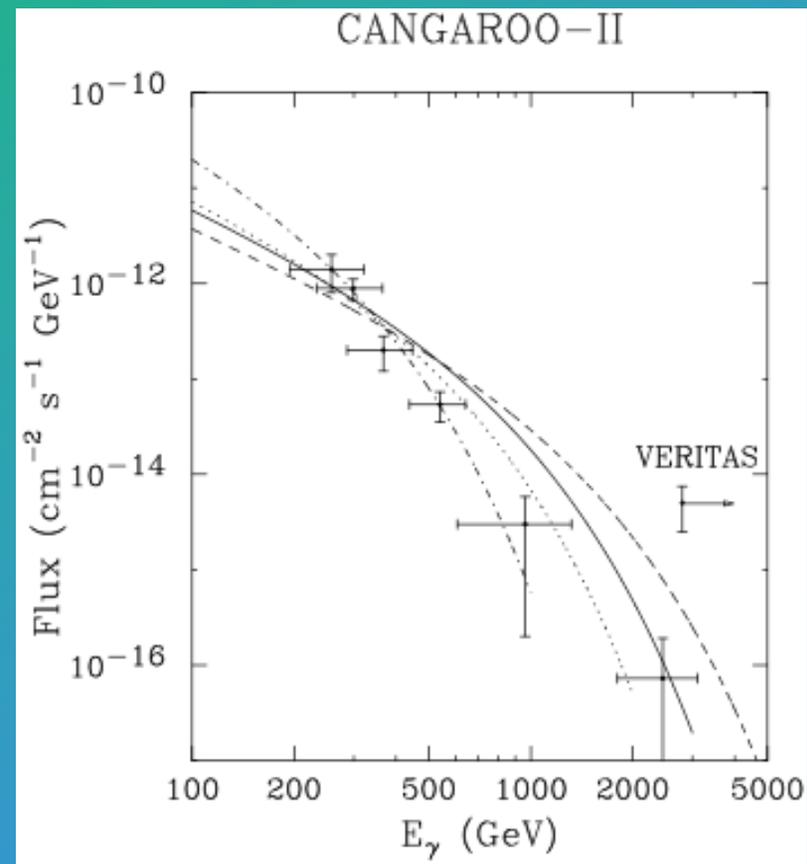
- 1) Very hard injection spectrum (annihilation modes)
- 2) A narrow diffusion region or large diffusion coefficient
- 3) A nearby source/clump of annihilating dark matter



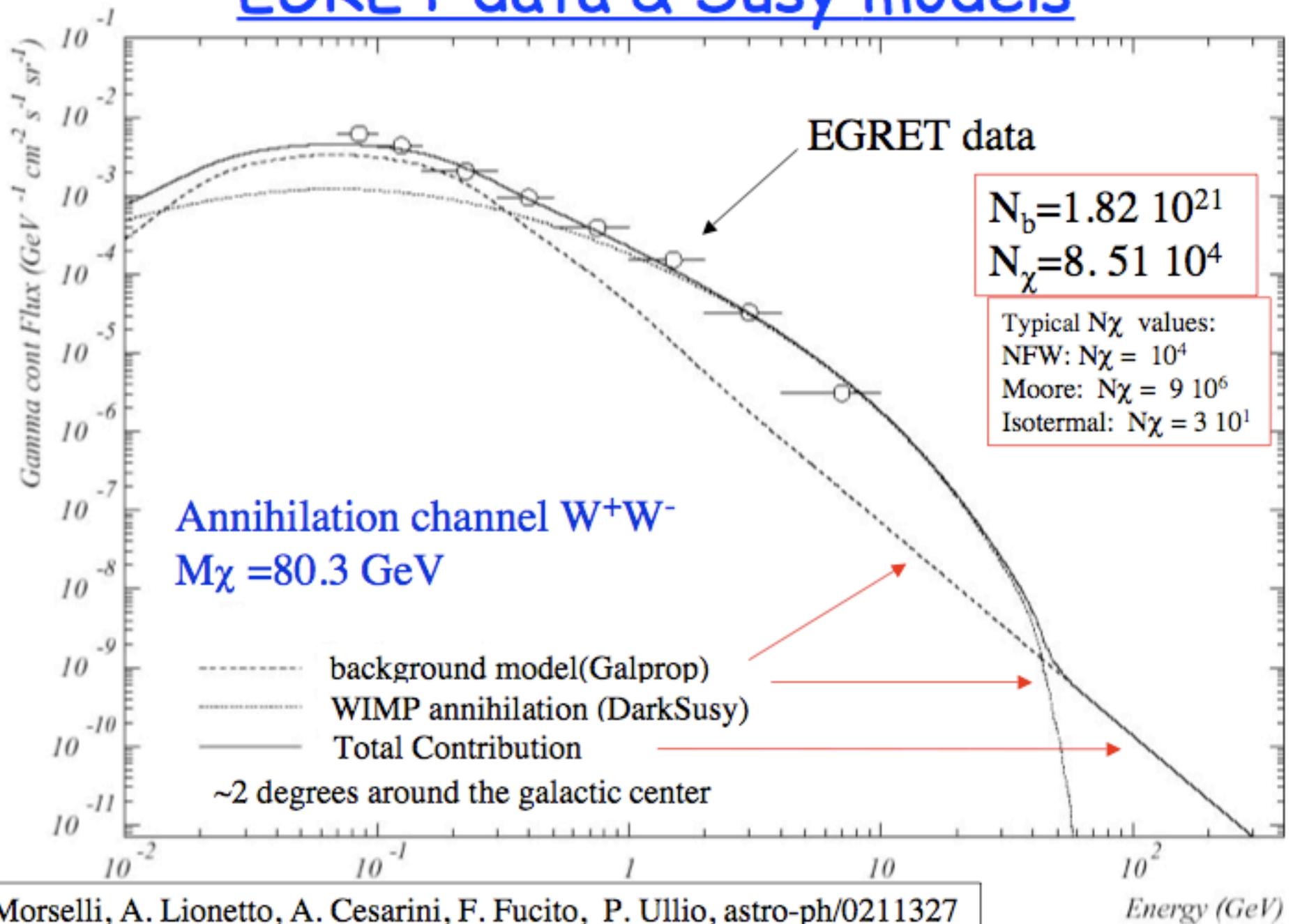
*Gamma-rays from  
the Galactic  
Center*

# Dark Matter at Galactic Center?

- CANGAROO observations of gamma-rays from Galactic Center  
*Tsuchiya et al 2004*
- Possible interpretation in terms of WIMP annihilation  
*Hooper et al 2004*

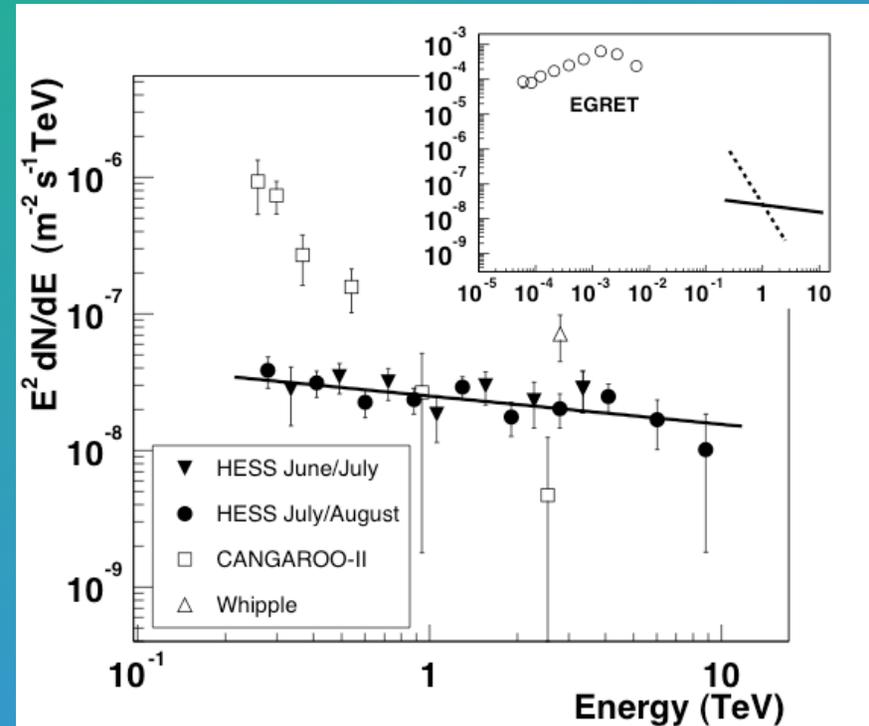
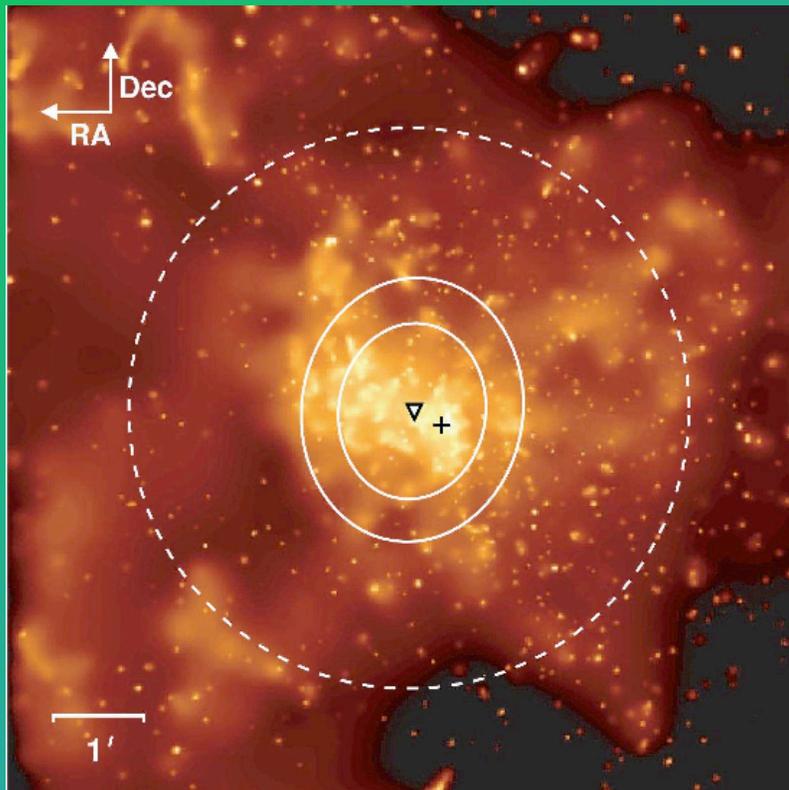


# EGRET data & Susy models



# HESS Gamma-ray Data

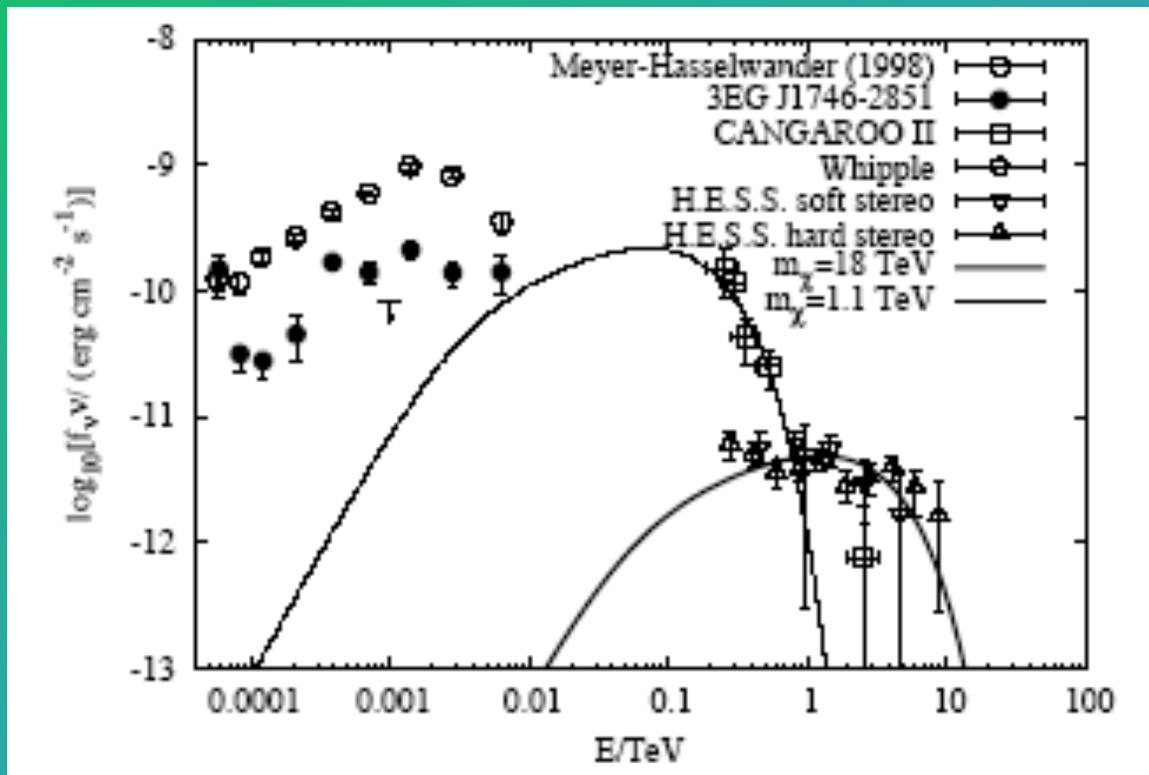
*Aharonian et al 2004*



# WIMPs at Galactic Center?

One can fit either CANGAROO and HESS spectra (but not both)

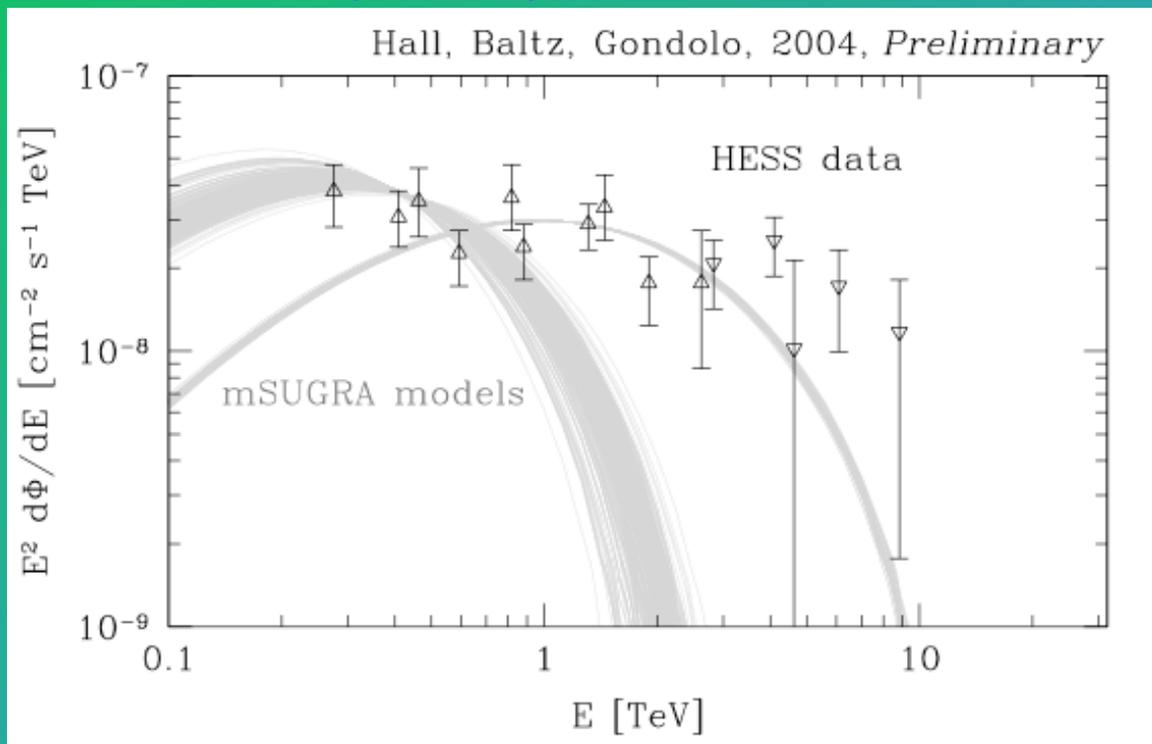
*Horns 2004*



# Neutralinos at Galactic Center?

mSUGRA study

Hall, Baltz, Gondolo 2004



- Compact source: 0.01 - 1 pc
- $J \sim 10$  or  $10^3$
- Compatible with mass from stellar motions

*Ghez et al 2003*

*Genzel et al 2003*

# Gamma Ray Status: from WIMP annihilation in Galactic Center?

- CANGAROO: possible detection up to 10TeV
- HESS: different power law
- Can explain with astrophysics?
- Not easy to get intensity in SUSY
- New decay channel for Kaluza-Klein particles
- CACTUS observed Draco (nearby dwarf galaxy).

# WMAP microwave emission interpreted as dark matter annihilation in inner galaxy?

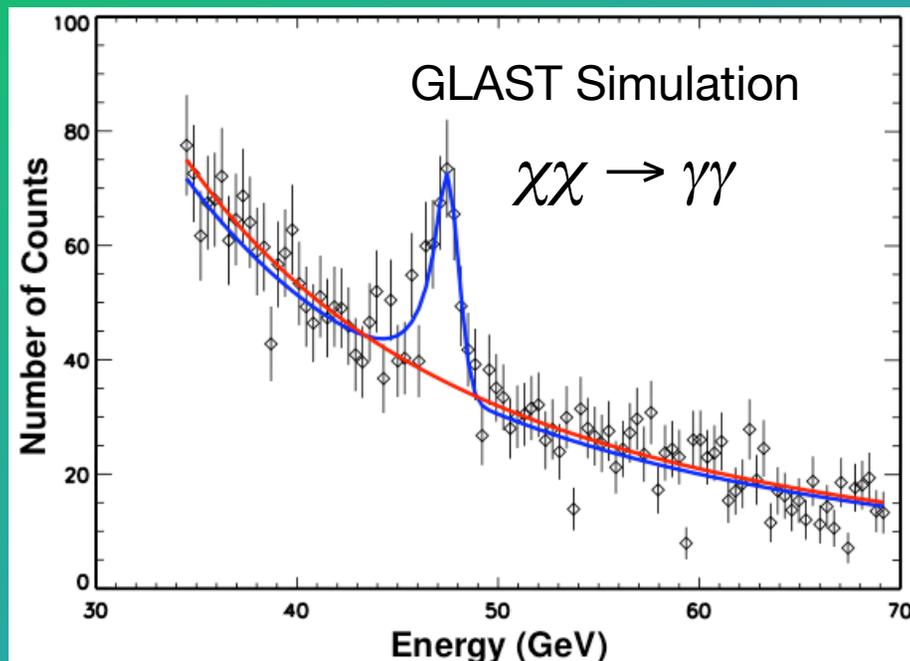
Excess microwave emission observed in the inner Galaxy (inner  $\sim 1 - 2$  kpc) is consistent with synchrotron emission from highly relativistic  $e^+e^-$  pairs produced by dark matter particle annihilation. More conventional sources for this emission, such as free-free (thermal bremsstrahlung), thermal dust, spinning dust, and the softer Galactic synchrotron traced by low-frequency surveys, have been ruled out.

Consistent with 100 GeV WIMPs.

Finkbeiner 2005; Hooper,  
Dobler 2007

# Gamma-ray line

- Characteristic of WIMP annihilation
- Need good energy resolution



- GLAST may do it below  $\sim 80$  GeV

Bergstrom, Ullio and Buckley 1998

# Possible evidence for WIMP detection already now:

- The DAMA annual modulation
- The HEAT/PAMELA positron excess
- Gamma-rays from Galactic Center
- Theorists are looking for models in which these results are consistent with one another (given an interpretation in terms of WIMPs)

# V. Upcoming Data: will the Dark Matter be found in 2008/9?

- LHC (find SUSY)
- Indirect Detection due to annihilation:
  - GLAST first light May 27, 2008 (gamma rays)
  - PAMELA (positrons)
  - ICECUBE (neutrinos)
  - GAPS (antideuterons)
- Direct Detection: CDMS, LUX, XENON, DEEP-CLEAN, WARP, CRESST-EDELWEISS, ZEPLIN, COUPP, KIMS ...

# GAPS

- Chuck Hailey (Columbia)
- Balloon experiment looking for (rare) antideuterons from WIMP annihilation
- Antimatter captured into exotic atoms
- Look for x-rays from atomic de-excitation

# On FERMI (formerly GLAST)

- First light, May 27, 2008
- DM annihilation to gamma rays

# Where To Look For Dark Matter With GLAST?

## The Galactic Center

- Brightest spot in the sky
- Considerable astrophysical backgrounds

## The Galactic Halo

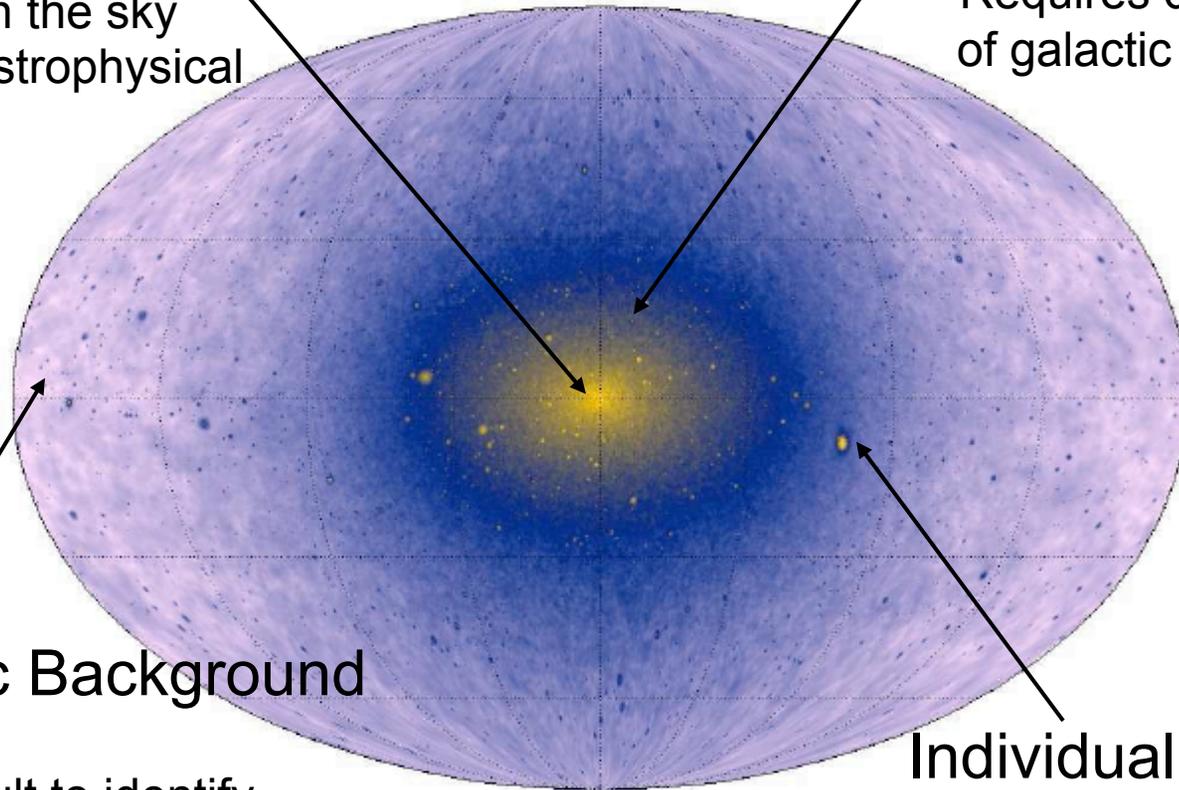
- High statistics
- Requires detailed model of galactic backgrounds

## Extragalactic Background

- High statistics
- potentially difficult to identify

## Individual Subhalos

- Low backgrounds



## Supersymmetry introduces free parameters:

In the **MSSM**, with Grand Unification assumptions, the masses and couplings of the SUSY particles as well as their production cross sections, are entirely described once **5** parameters are fixed:

- $M_{1/2}$  the common mass of supersymmetric partners of gauge fields (gauginos)
- $m_0$  the common mass for scalar fermions at the GUT scale
- $\mu$  the higgs mixing parameters that appears in the neutralino and chargino mass matrices
- $A$  is the proportionality factor between the supersymmetry breaking trilinear couplings and the Yukawa couplings
- $\tan \beta = v_2 / v_1 = \langle H_2 \rangle / \langle H_1 \rangle$  the ratio between the two vacuum expectation values of the Higgs fields

mSUGRA

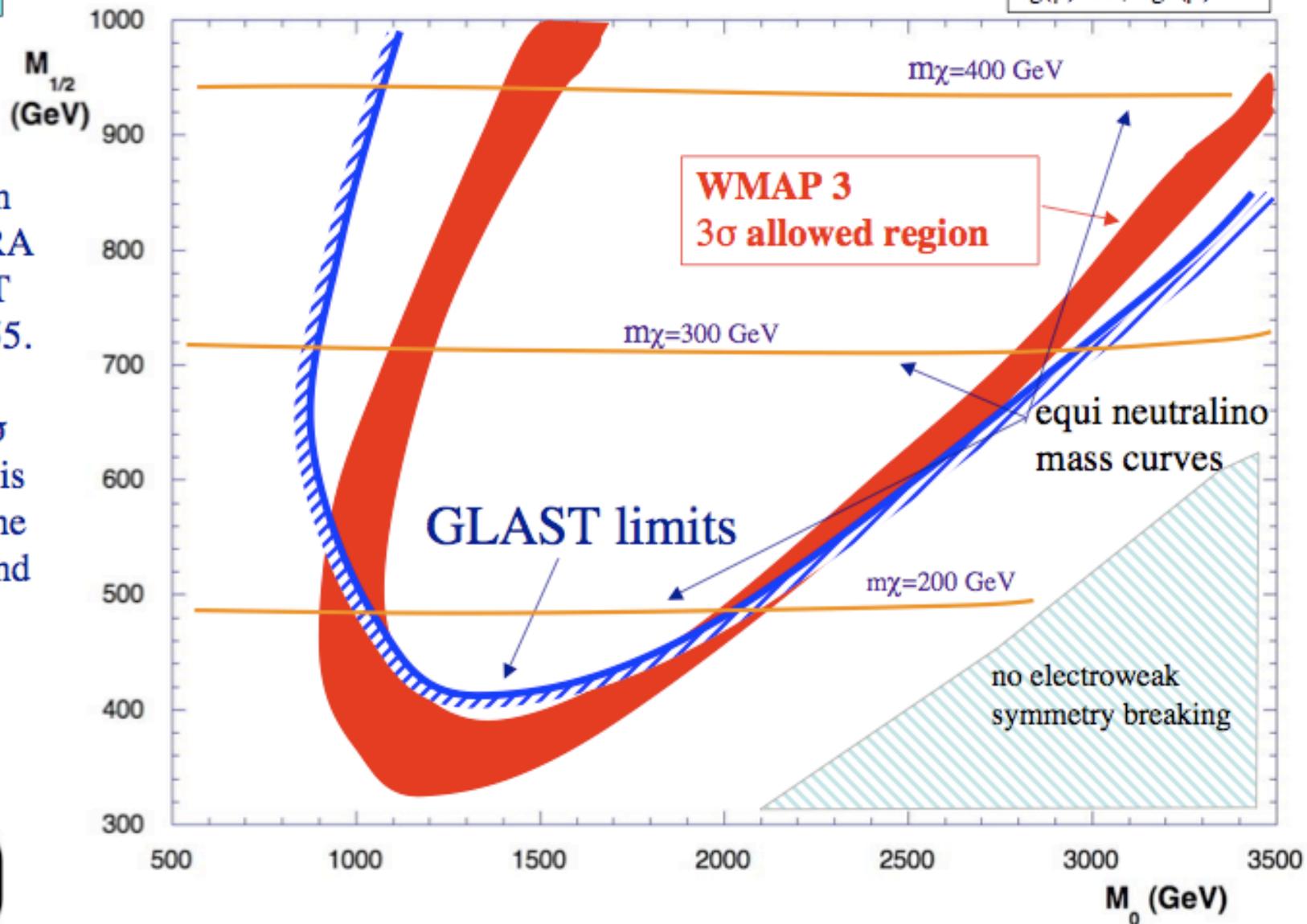
Sensitivity plot for 5 years observation of mSUGRA for GLAST for  $\text{tg}(\beta)=55$ .

GLAST  $3\sigma$  sensitivity is shown at the blue line and below for truncated NFW halo profile



$3\sigma$  Sensitivity plot for for GLAST for a truncated (NFW) halo profile

$\text{tg}(\beta)=55, \text{sign}(\mu)=+1$

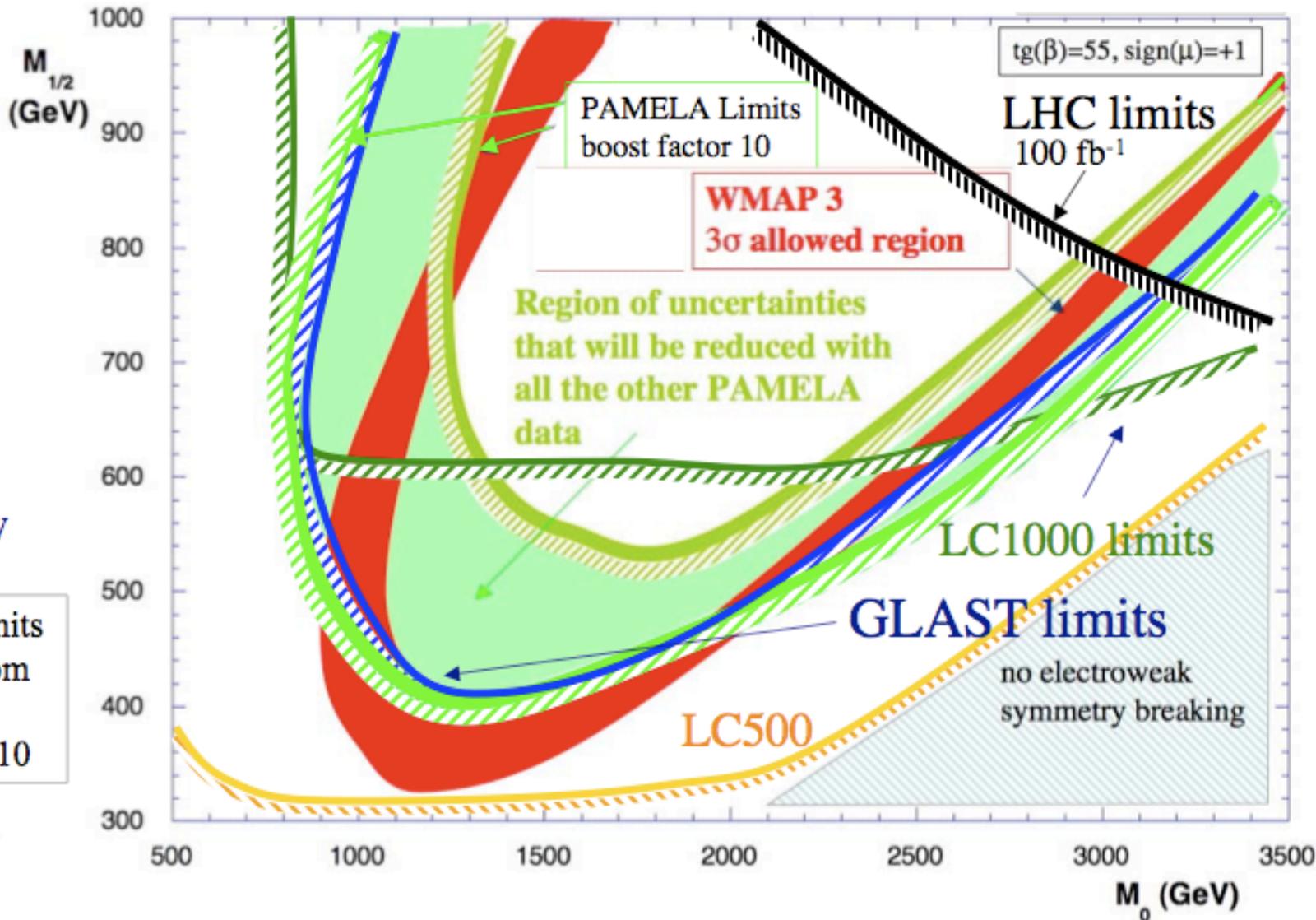


### mSUGRA

Sensitivity plot for 5 years observation of mSUGRA for GLAST for  $\text{tg}(\beta)=55$  and for other experiments. GLAST  $3\sigma$  sensitivity is shown at the blue line and below for truncated NFW halo profile

accelerator limits @  $100 \text{ fb}^{-1}$  from H.Baer et al., hep-ph/0405210

## GLAST, PAMELA, LHC, LC Sensitivities to Dark Matter Search



# Model independent results for the GC

- Assume a truncated NFW profile -
- Assume a dominant annihilation channel (good assumption except for  $\tau^+ \tau^-$ )

Differential yield  
for each  
annihilation  
channel

WIMP mass=200GeV

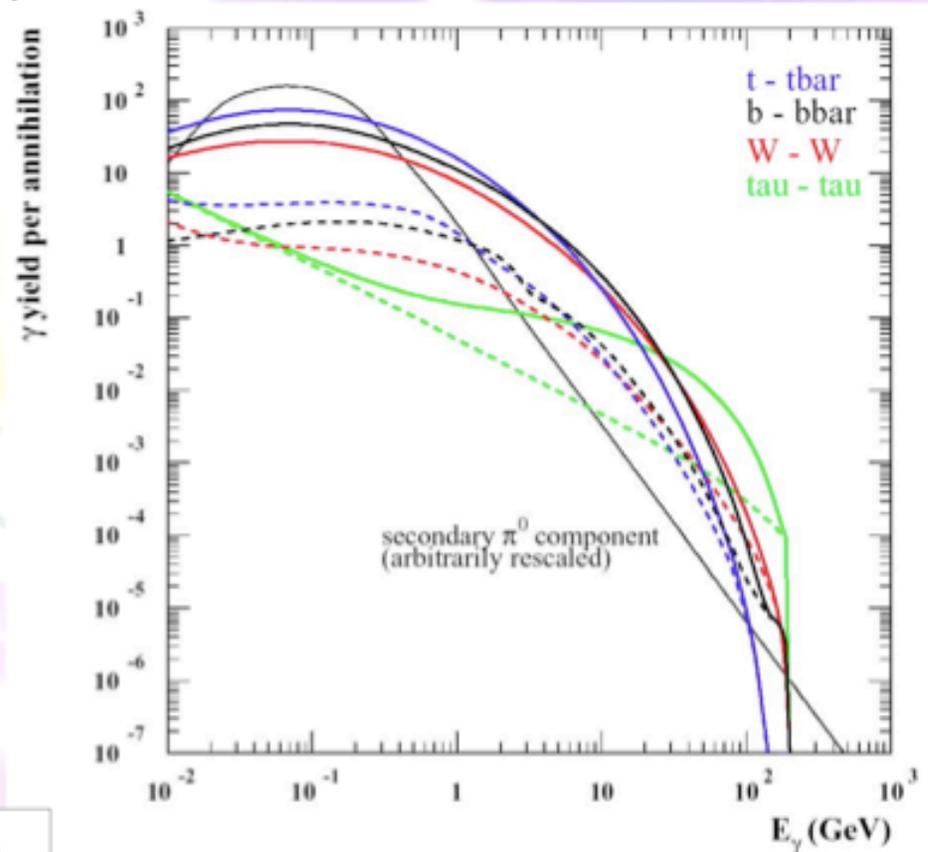


figure from: A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio,  
Astroparticle Physics, 21, 267-285, June 2004 [astro-ph/0305075]

# Model independent results for the GC

WIMP contribution higher than the maximum allowed by EGRET

uncertainties:  
H column density

$$\langle J(\psi) \rangle = 10^4$$

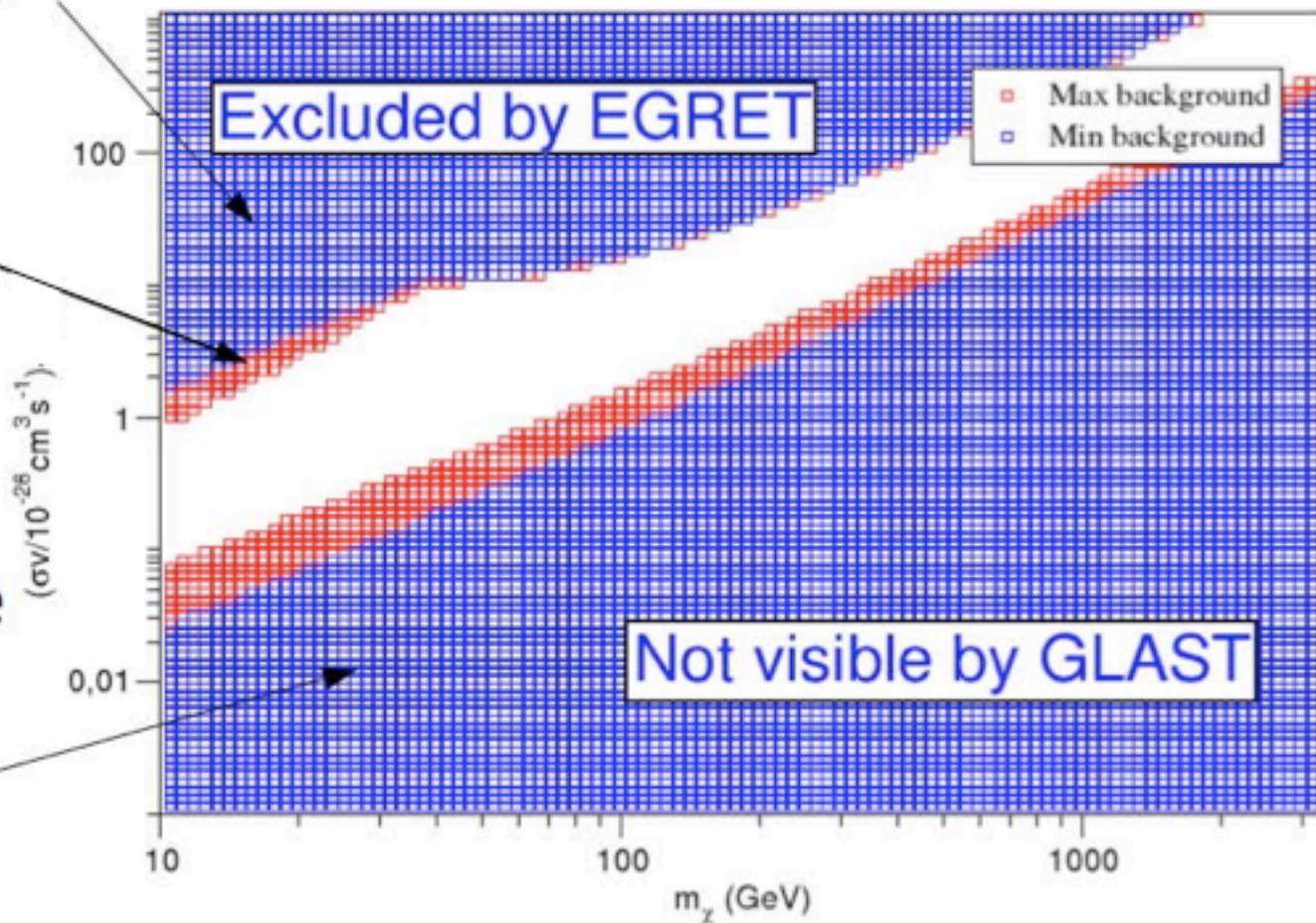
$$\Delta\Omega \sim 10^{-5} \text{ sr}$$

Effective exposure (per year)  
 $3.7 \cdot 10^{10} \text{ cm}^2 \text{ s}^{-1}$

4 years exposure

**3  $\sigma$**

Model independent GLAST reach ( $3\sigma$ )  
*NFW profile,  $\pi^0$  background,  $b\bar{b}$  annihilation channel*

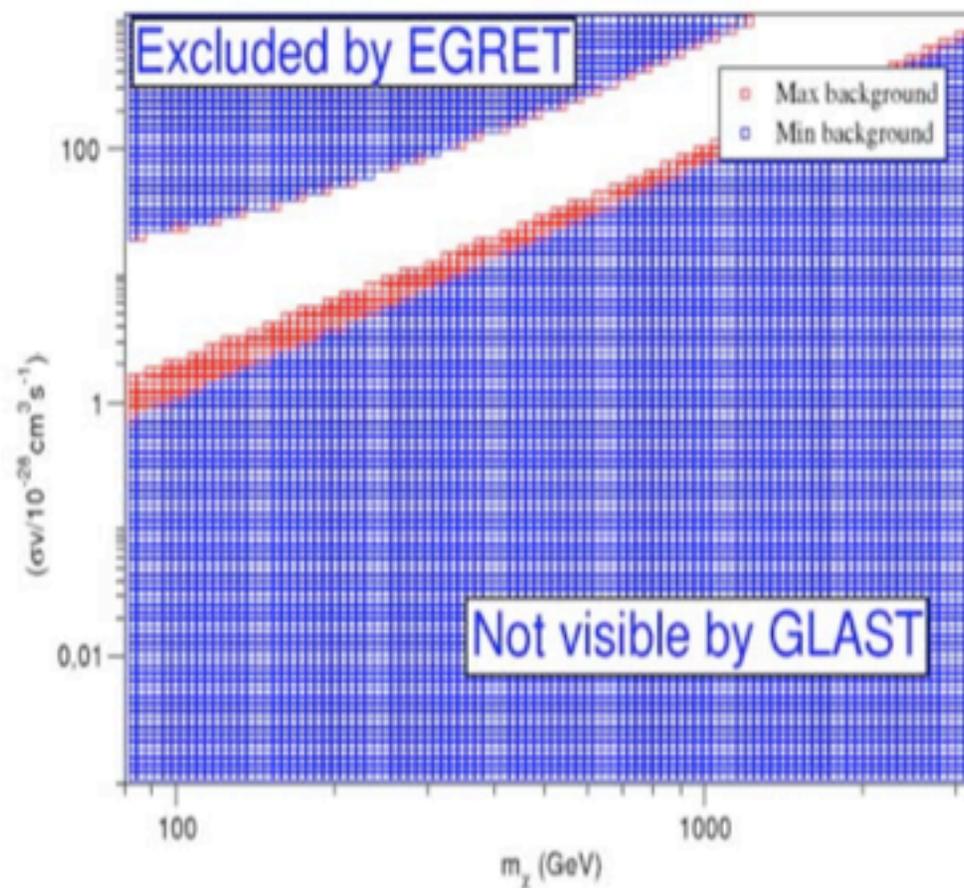


# Model independent results for the GC

## Results for different dominant annihilation channel

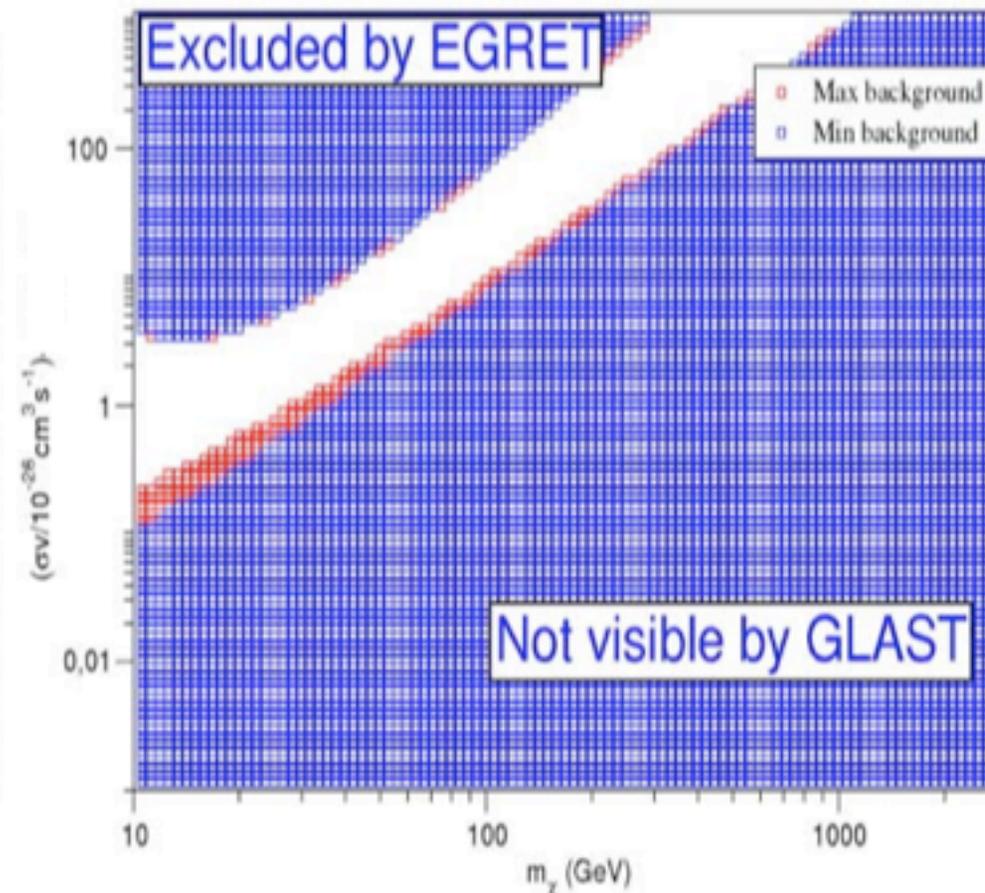
Model independent GLAST reach ( $3\sigma$ )

*NFW profile,  $\pi^0$  background,  $w^+w^-$  annihilation channel*



Model independent GLAST reach ( $3\sigma$ )

*NFW profile,  $\pi^0$  background,  $\tau^+\tau^-$  annihilation channel*



# GLAST RESULTS MAY 1, 2009

Excess of combined electrons and positrons confirmed:

Consistent with PAMELA, inconsistent with ATIC

# Dark Matter Distribution in Halo affects Signal in Detectors

# Signal rate from Supersymmetry

gamma-ray flux from  
neutralino annihilation

$$\phi(E, \Delta\Omega) \propto \left( \frac{\sigma v}{m_\chi^2} \right) \int_{l.o.s} \int_{\Delta\Omega} \rho^2(l) dl d\Omega$$

governed by  
supersymmetric  
parameters

$J(\varphi)$ :

governed by  
halo distribution

# Streams of WIMPs

- For example, leading tidal stream of Sagittarius dwarf galaxy may pass through Solar System

*Majewski et al 2003, Newberg et al 2003*

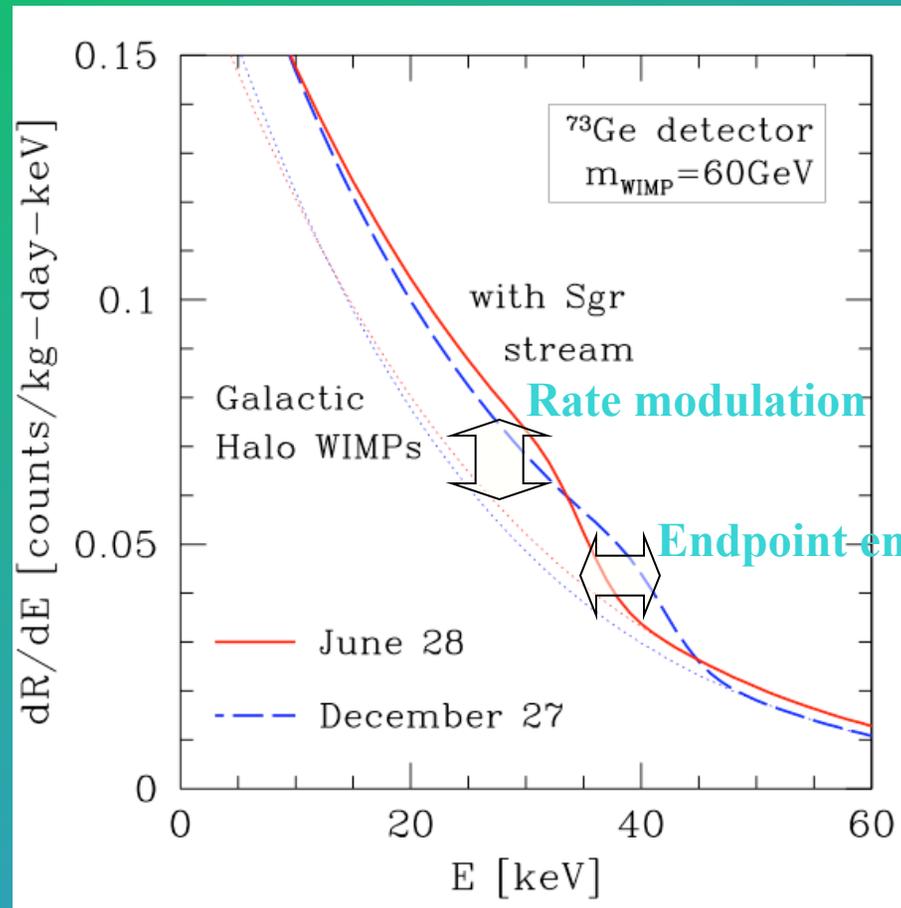
- Dark matter density in stream  $\sim 0.01^{+0.20}_{-0.01} \rho_{local}$

*Freese, Gondolo, Newberg 2003*

- New annual modulation of rate and endpoint energy; difficult to mimic with lab effects

*Freese, Gondolo, Newberg, Lewis 2003*

# Sagittarius stream

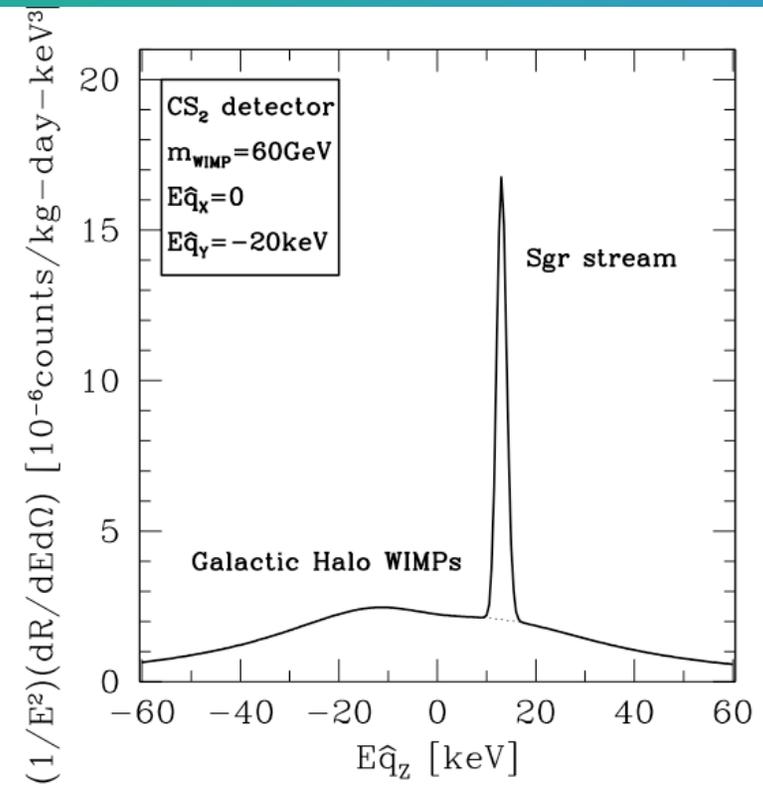
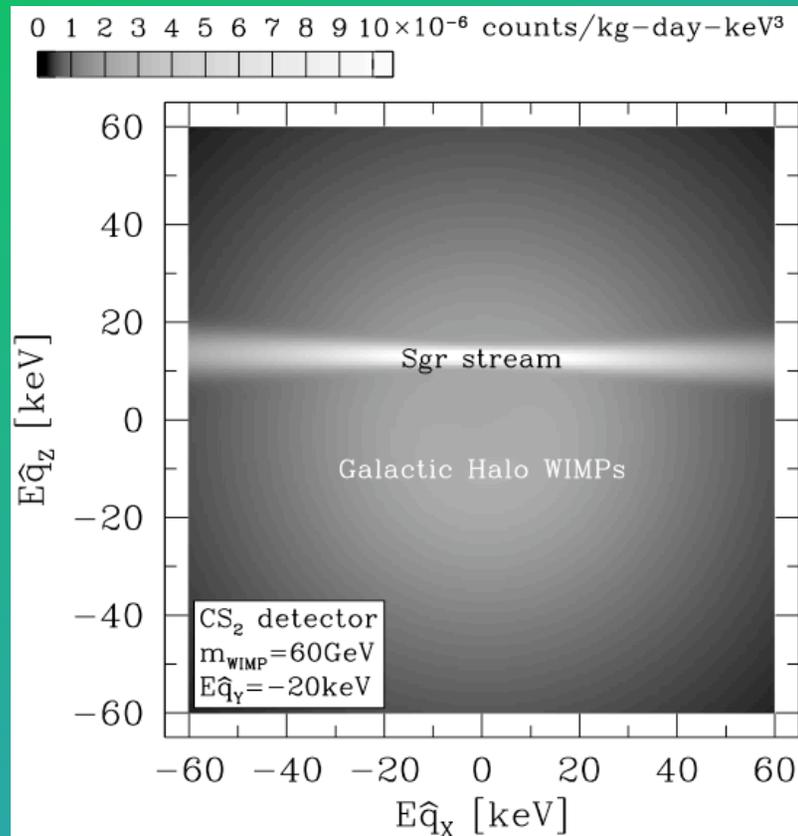


Plot for 20% Sgr stream density (to make effect visible);  $\sigma_{\text{xp}} = 2.7 \times 10^{-42} \text{ cm}^2$

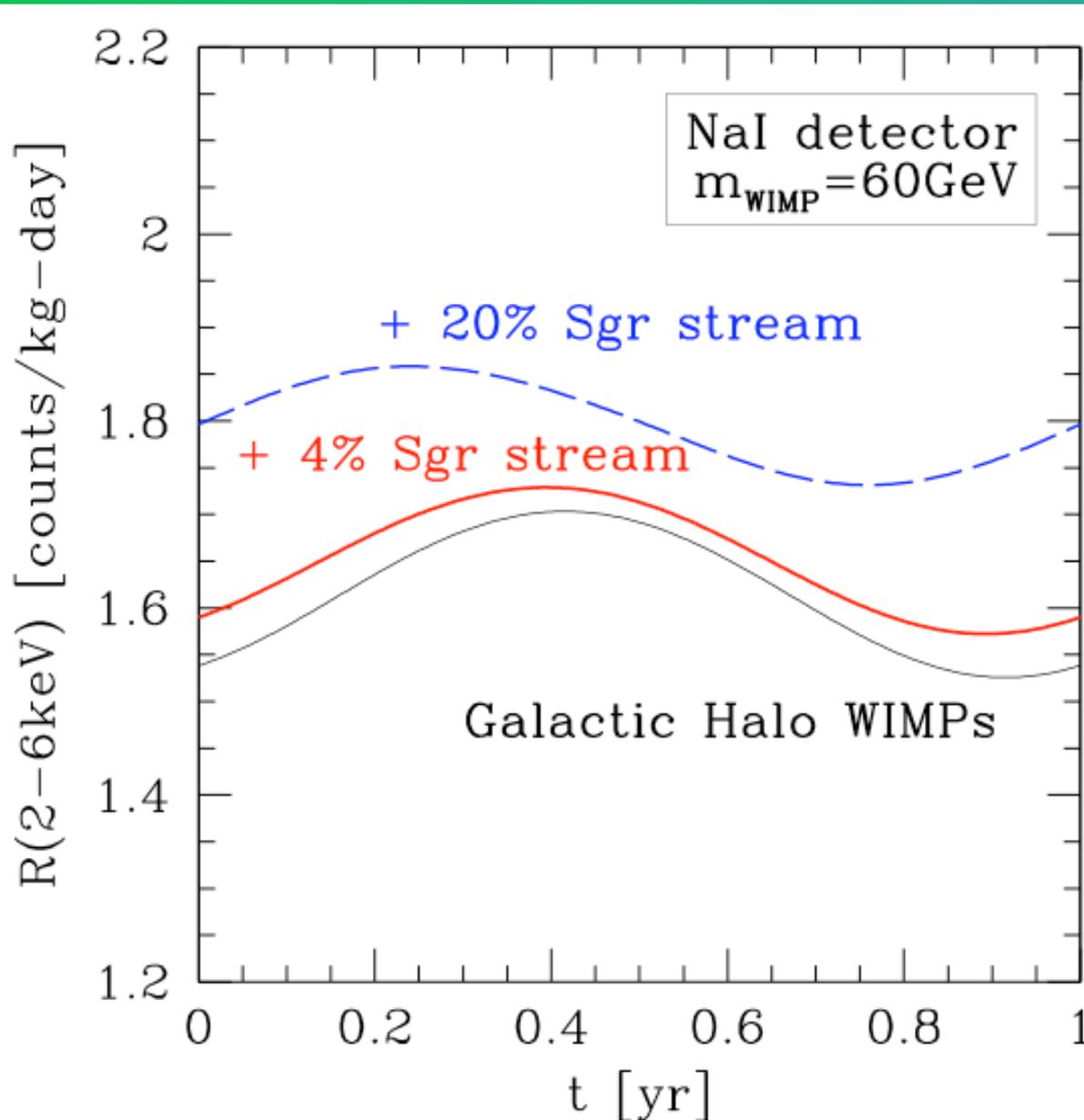
# Sagittarius stream

Freese, Gondolo, Newberg 2003

## Directional detection with DRIFT-II



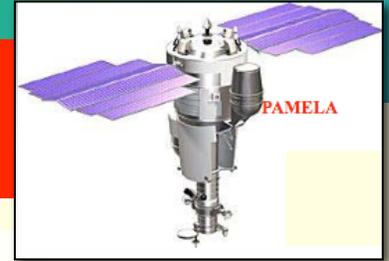
# Stream shifts peak date of annual modulation



# Sagittarius stream

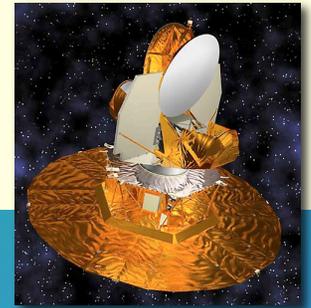
- Increases count rate in detectors up to cutoff in energy spectrum
- Cutoff location moves in time
- Sticks out like a sore thumb in directional detectors
- Changes date of peak in annual modulation
- Smoking gun for WIMP detection

# THE FUTURE



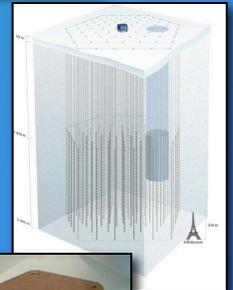
## One Year From Now

- New limits from CDMS, LUX, XENON-100, at or below the  $\sim 10^{-8}$  pb level, ruling out essentially the entire focus point SUSY region (or the first observation of WIMP-nuclei scattering)
- First full year of GLAST data
- PAMELA positron spectrum up to 100-200 GeV?



## Three Years From Now

- Ton-scale direct detection experiments
- Results from Planck, IceCube, Glast, Pamela
- Discovery of SUSY or other new physics at the LHC



# Dark Stars: Dark Matter Annihilation in the First Stars.

Phys. Rev. Lett. **98**, 010001 (2008), arxiv:0705.0521

D. Spolyar, K. Freese, and P. Gondolo

PAPER 1

arXiv:0802.1724

K. Freese, D. Spolyar, and A. Aguirre

arXiv:0805.3540

K. Freese, P. Gondolo, J.A. Sellwood, and D. Spolyar

arXiv:0806.0617

K. Freese, P. Bodenheimer, D. Spolyar, and P. Gondolo

And N. Yoshida

DAVID GRANT presents  
A JOHN CARPENTER film

From  
ALAN DEAN FOSTER  
FIRST

2001: A SPACE ODYSSEY

THEN

THE POSEIDON ADVENTURE

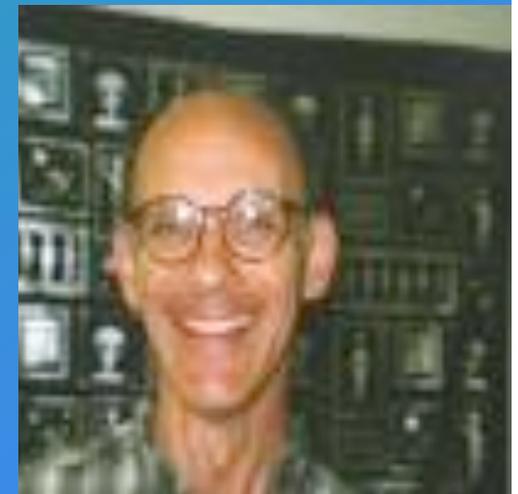
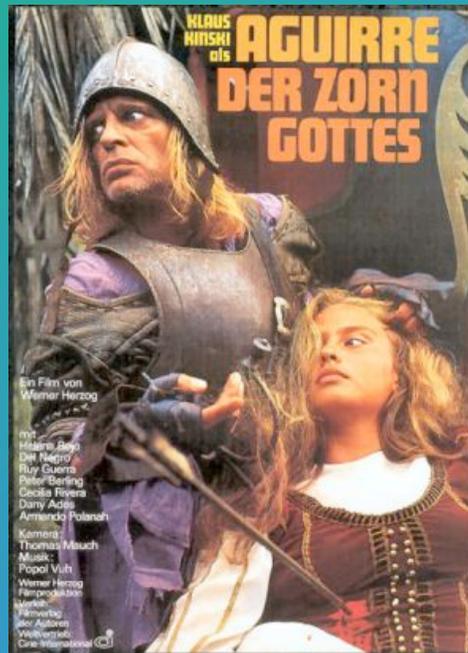
NOW

# DARK STAR

bombed out in space  
with a spaced out bomb!

OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN OBANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

# Collaborators



# Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 1% of the mass of the star).

- This new phase of stellar evolution may last over a million years

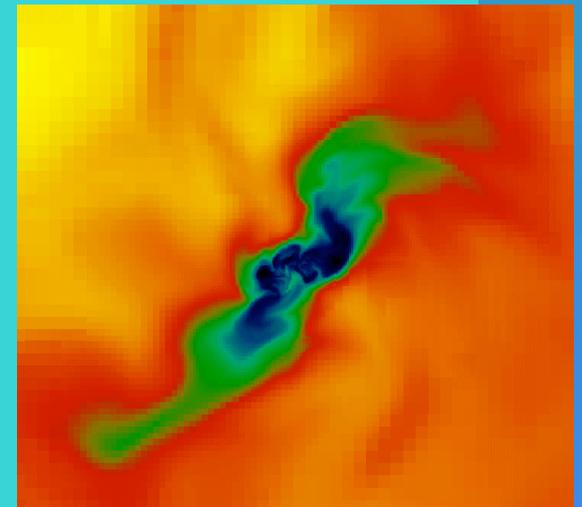
# First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At  $z = 10-50$
  - Form inside DM haloes of  $\sim 10^6 M_{\odot}$
  - Baryons initially only 15%
  - Formation is a gentle process

Made only of hydrogen and helium  
from the Big Bang.

Dominant cooling Mechanism is

$H_2$   
Not a very good coolant



(Hollenbach and McKee '79)

# The First Stars Also The First Structure

- Important for:
  - End of Dark Ages.
  - Reionize the universe.
  - Provide enriched gas for later stellar generations.
  - May be precursors to black holes which power quasars.



# Our Results

- Dark Matter (DM) in haloes can dramatically alter the formation of the first stars leading to a new stellar phase driven by DM annihilation.
- Hence the name- Dark Star (DS)
- Change: Reionization, Early Stellar Enrichment, Early Big Black Holes.
- Discover DM.

# Basic Picture

- The first stars form in a DM rich environment
- As the gas cools and collapses to form the first stars, the cloud pulls DM in as the gas cloud collapses.
- DM annihilates more and more rapidly as its densities increase
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms which stops the cloud from continuing to cool and collapse.

# Basic Picture Continued

- Thus a gas cloud forms which is supported by DM annihilation
- More DM and gas accretes onto the initial core which potentially leads to a very massive gas cloud supported by DM annihilation.
- If it were fusion, we would call it a star.
- Since it is DM annihilation powered, we call it a Dark Star
- DM in the star comes from Adiabatic Contraction and DM capture.

# Three Conditions for Dark Stars

(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- 1) Sufficiently High Dark Matter Density to get large annihilation rate
- 2) Annihilation Products get stuck in star
- 3) DM Heating beats H<sub>2</sub> Cooling
  
- Leads to New Phase

# Dark Matter Heating

Heating rate:

$$Q_{ann} = n_{\chi}^2 \langle \sigma v \rangle \times m_{\chi}$$

$$= \frac{\rho_{\chi}^2 \langle \sigma v \rangle}{m_{\chi}}$$

Fraction of annihilation energy deposited in the gas:

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

Previous work noted that at  $n \leq 10^4 \text{ cm}^{-3}$  annihilation products simply escape (Ripamonti, Mapelli, Ferrara 07)

$f_Q$ :

1/3 electrons

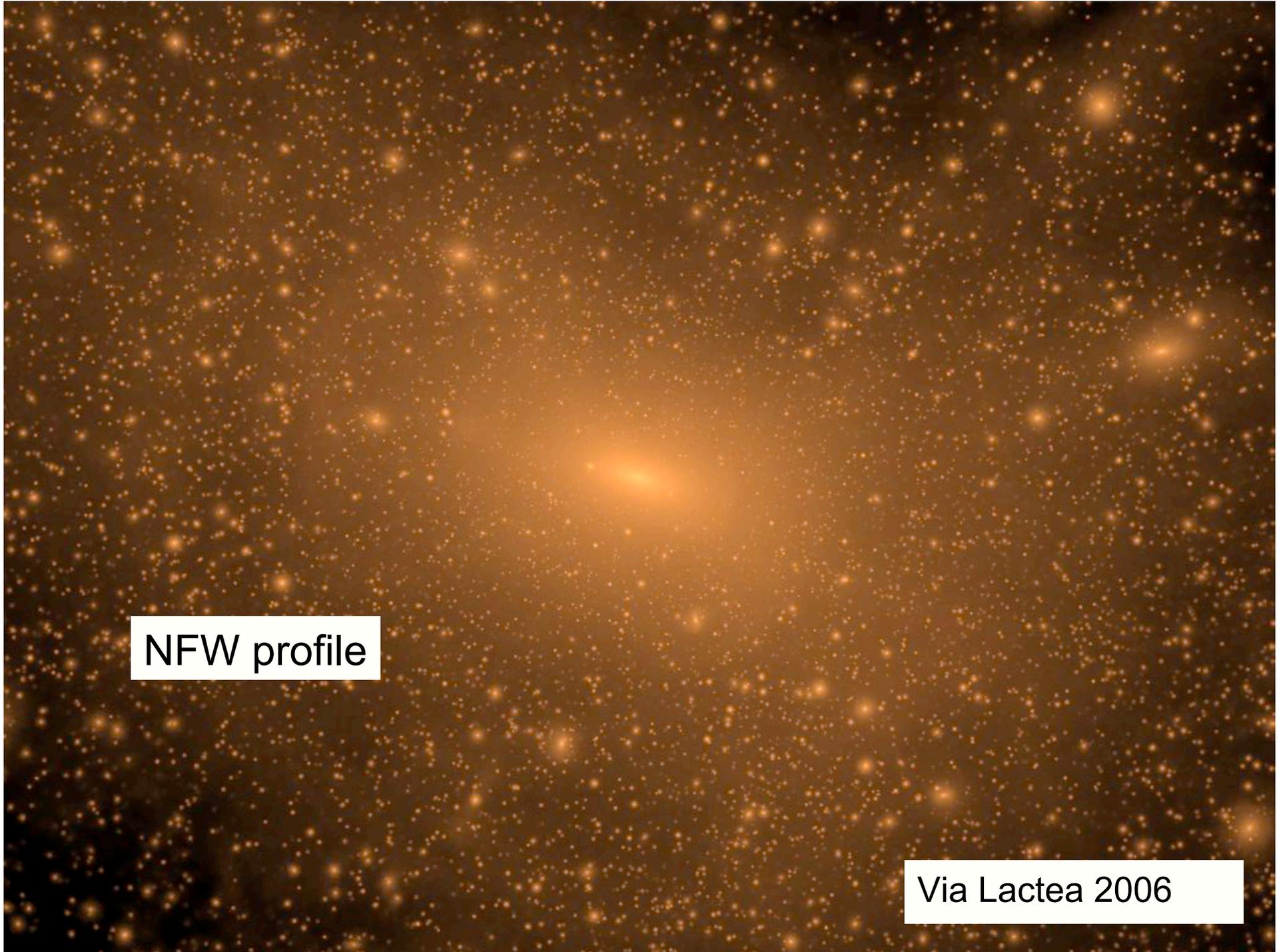
1/3 photons

1/3 neutrinos

Depending upon the densities.

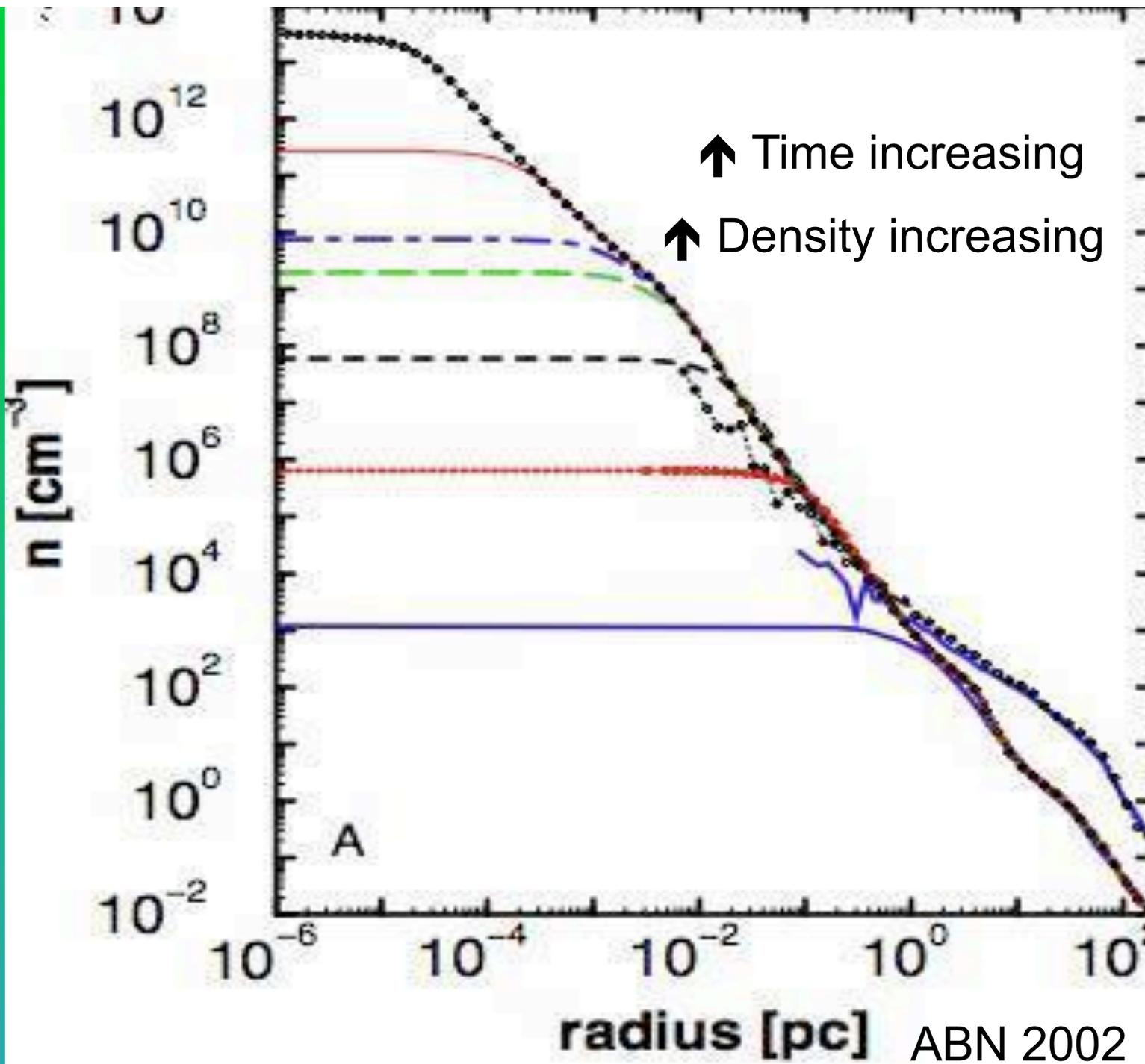
# First Condition: Large DM density

- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as  $(1+z)^3$  and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms in the center of the halo, it gravitationally pulls in more DM. Treat via adiabatic contraction.
- If the scattering cross section is large, even more gets captured (treat this possibility later).

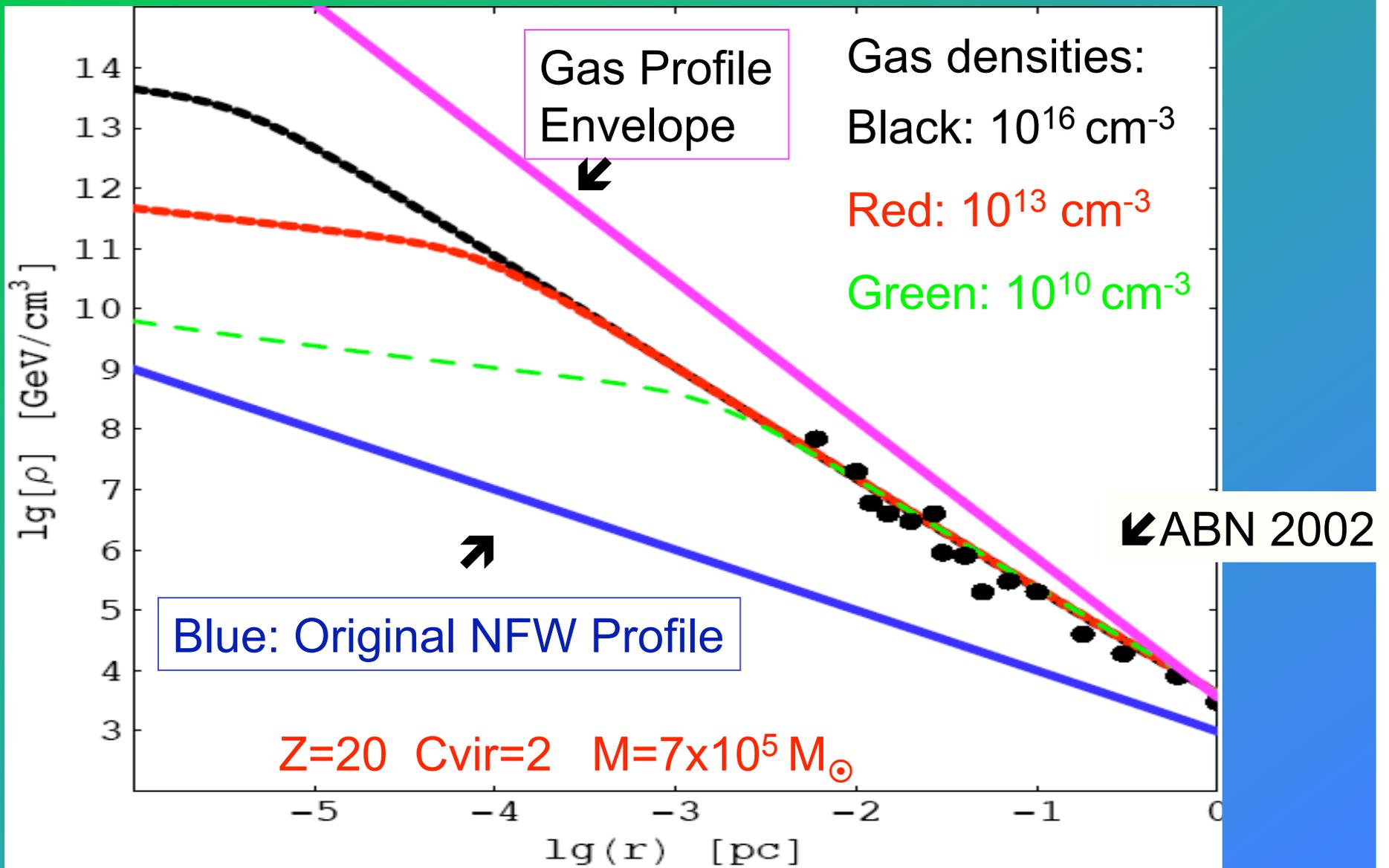


NFW profile

Via Lactea 2006



# DM profile and Gas



# Crucial Transition

- At sufficiently high densities, most of the annihilation energy is trapped inside the core and heats it up

- **When:**

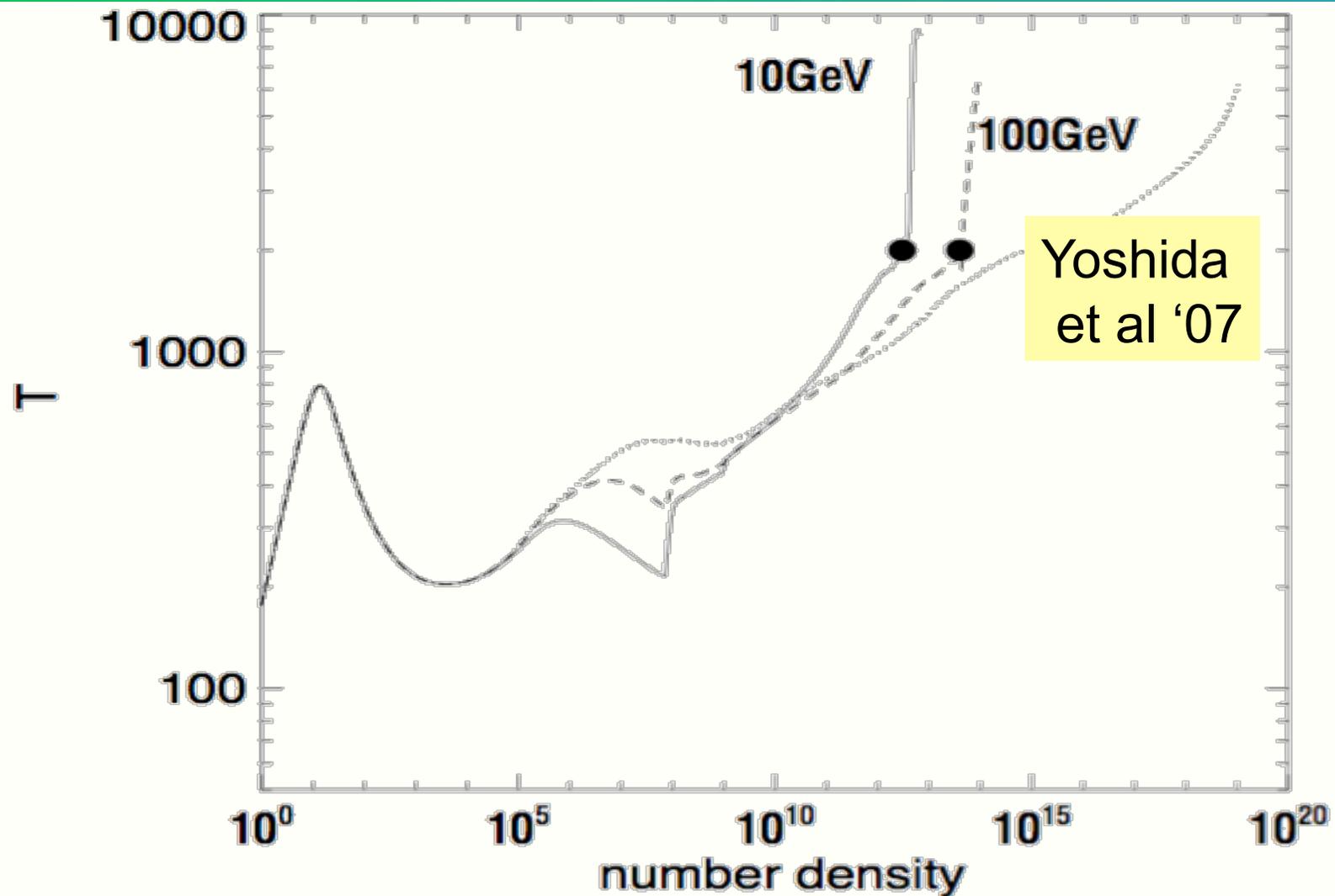
$$m_{\chi} \approx 1 \text{ GeV} \quad \rightarrow \quad n \approx 10^9 / \text{cm}^3$$

$$m_{\chi} \approx 100 \text{ GeV} \quad \rightarrow \quad n \approx 10^{13} / \text{cm}^3$$

$$m_{\chi} \approx 10 \text{ TeV} \quad \rightarrow \quad n \approx 10^{15-16} / \text{cm}^3$$

- The DM heating dominates over all cooling mechanisms, impeding the further collapse of the core

# New proto-Stellar Phase: fueled by dark matter



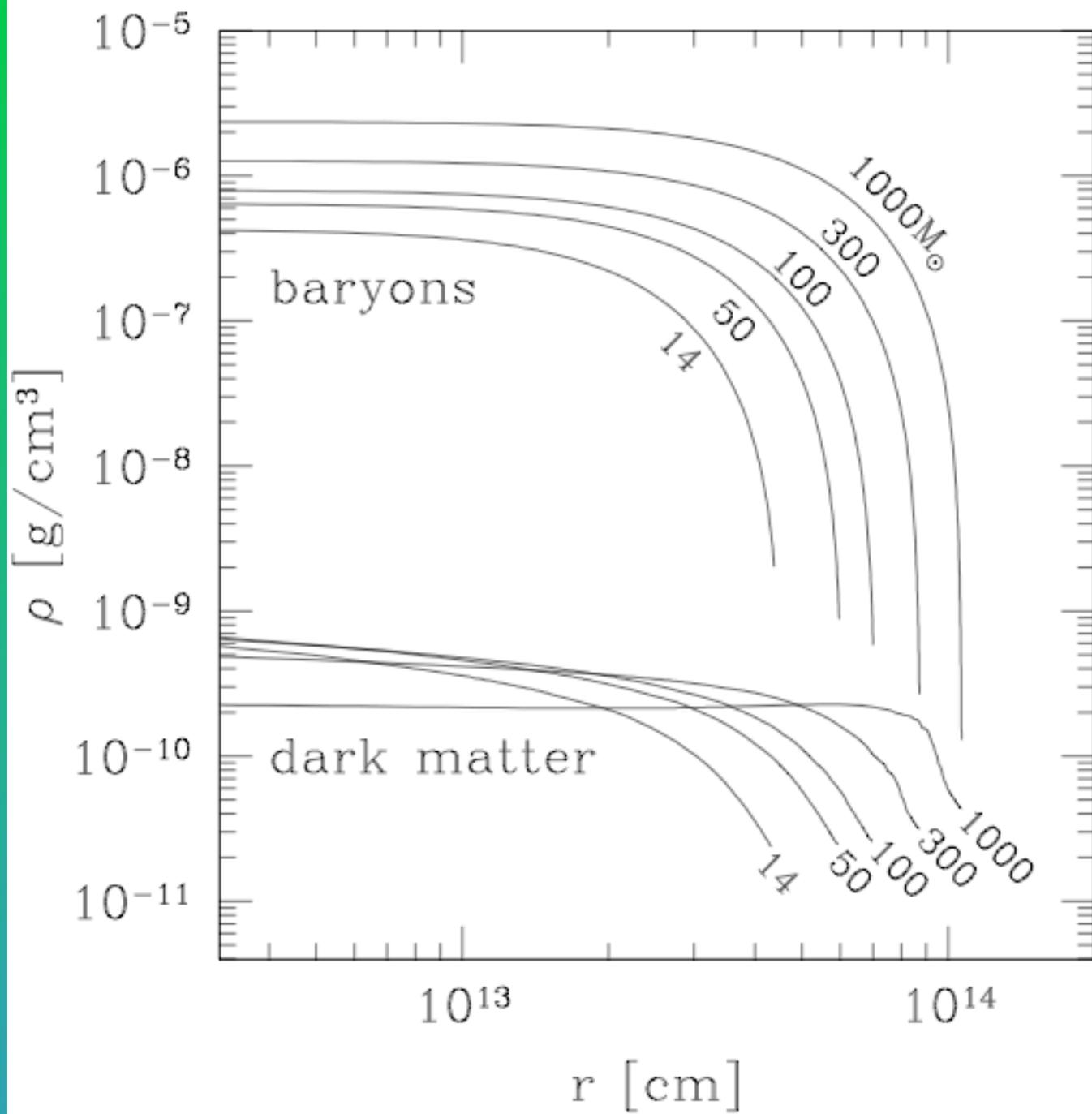
# DS Evolution (w/ Peter Bodenheimer)

- Find hydrostatic equilibrium solutions
- Look for polytropic solution,  $p = K \rho^{1+1/n}$   
for low mass  $n=3/2$  convective,  
for high mass  $n=3$  radiative  
(transition at 100-400  $M_{\odot}$ )
- Start with a few solar masses, guess the radius, see if DM luminosity matches luminosity of star (photosphere at roughly 6000K). If not adjust radius until it does. Smaller radius means larger gas density, pulls in more DM via adiabatic contraction, higher DM density and heating. Equilibrium condition:

$$L_{DM} = L_*$$

# 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
- DM annihilation powered DS continues to  $800 M_{\odot}$ .
- **VERY LARGE FIRST STARS!** Then, star contracts further, temperature increases, fusion will turn on, eventually make BH.



# Predictions for Dark Stars

- Very luminous between  $10^6 L_{\odot}$  and  $10^7 L_{\odot}$
- Cool: 6,000-10,000 K vs. 30,000 K plus in standard Pop III
  - Very few ionizing photons, just too cool.
- Life time: at least a million years.
- Leads to very massive Pop III.1 Main Sequence stars: 800  $M_{\odot}$
- Helps with formation of  $10^9 M_{\odot}$  black holes at  $z=6$ ?
- Atomic and molecular hydrogen lines
- **Reionization:** Can study with upcoming measurements of 21 cm line.
  - Heat Gas, but not ionize until DS phase finishes

# Observables

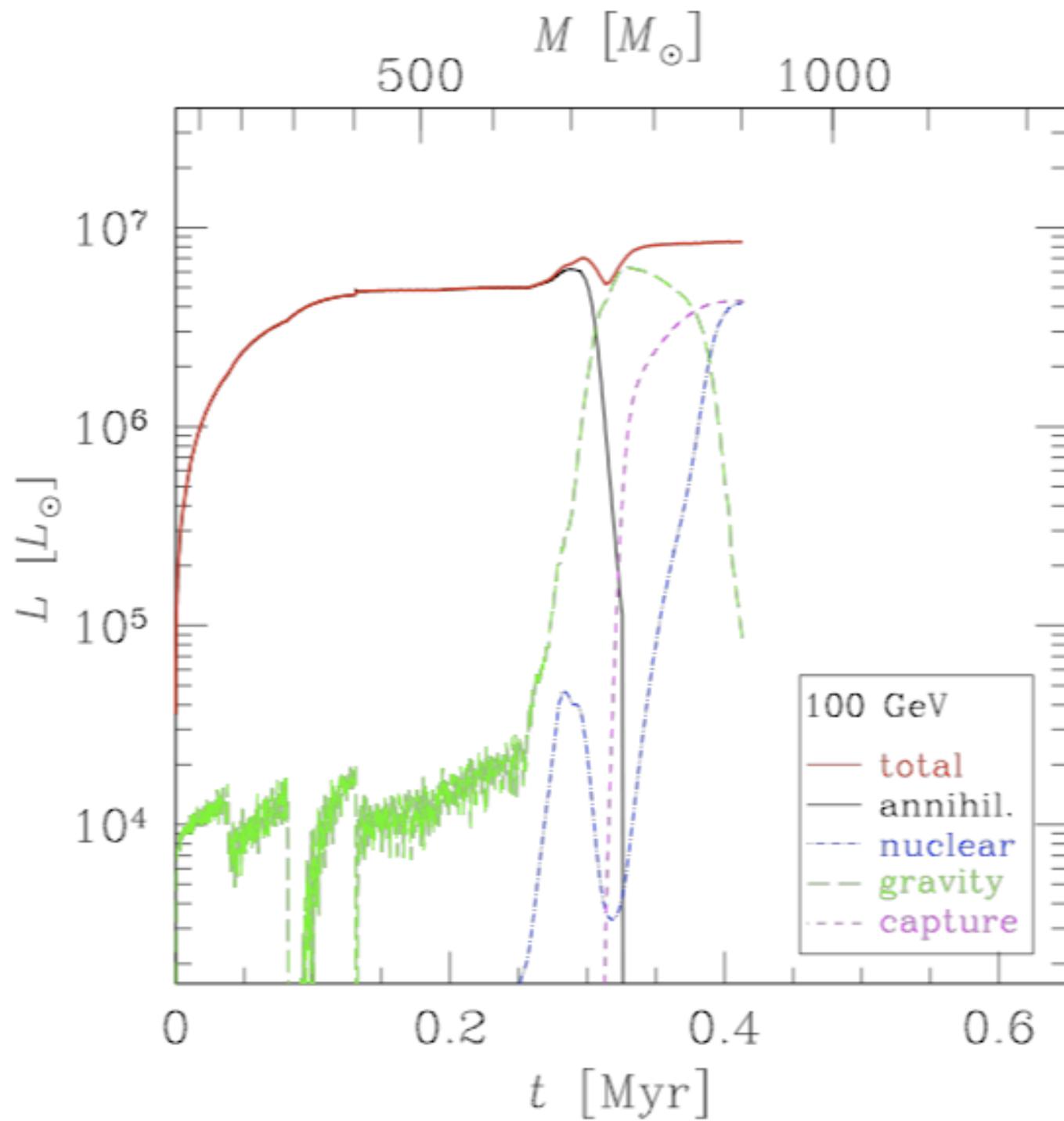
- Dark stars are giant objects with 6000K and  $10^6 L_{\odot}$ 
  - Find them with JWST?  
NASA's 4 billion dollar sequel to HST hopes to see the first stars and should be able to differentiate standard fusion driven ones from dark stars, which will be cooler
- $\nu$  annihilation products in AMANDA or ICECUBE? Can neutralinos be discovered via dark stars or can we learn more about their properties?
- Very high mass: can avoid Pair instability SN which arise from 140-260 solar mass stars (and whose chemical imprint is not seen; low metallicity stars will be studied by Marla Geha)
- If DM is replenished in the Dark stars, they can live up to today and be seen as cool bright stars

# What happens next?

If star reaches  $T=10^7\text{K}$ , fusion sets in.

- Key question: is high DM density inside star maintained by capture from ambient medium so that DM luminosity can continue to dominate?
- Two uncertainties:
- (I) ambient DM density: need the star to remain in a high density environment
- (II) is DM scattering off of gas important?

Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a free parameter, set only by bounds from direct detection experiments.



# Capture replenishes DM in Dark Stars?

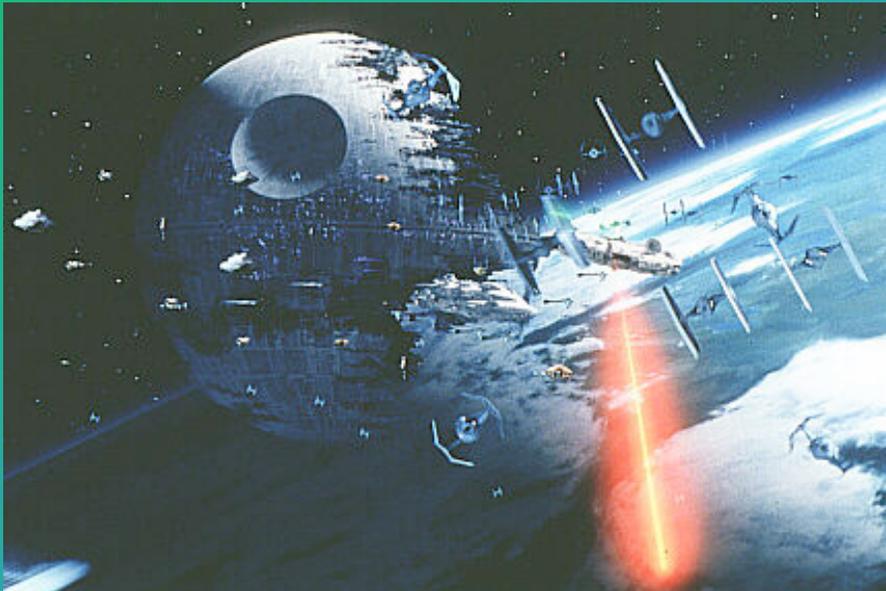
- Within a few days of each other, we and Fabio Iocco posted the same basic idea:
  - Both groups found that the DM luminosity can be larger than fusion for the first stars. (Freese, Spolyar, Aguirre 08; Iocco 08)

Uncertainties: scattering cross section, amount of DM in the ambient medium to capture from

IF the star remains in high DM density, fusion might never win, even today, so that dark stars might still exist today.

# Return of the Dark Star

- Even once the first stars reach the main sequence, DM annihilation can still be very important.
  - DM Can again be the dominant heat source.
  - DM heating may also determine the mass of the first stars.



(Freese, Spolyar, Aguirre 08; Iocco 08)

# Dark Star's Return Heralds?

- The first stars live in a DM rich environment
- DM Capture can alter the first stars.
  - DM luminosity larger than fusion Luminosity
  - May uniquely determine Mass of first stars
- Conversely- the first stars may offer the best bounds or opportunity to measure the the scattering cross section of DM.

# Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars
- The first stars in the Universe may be powered by DM heating rather than fusion
- These stars may be very large (800 solar masses)

