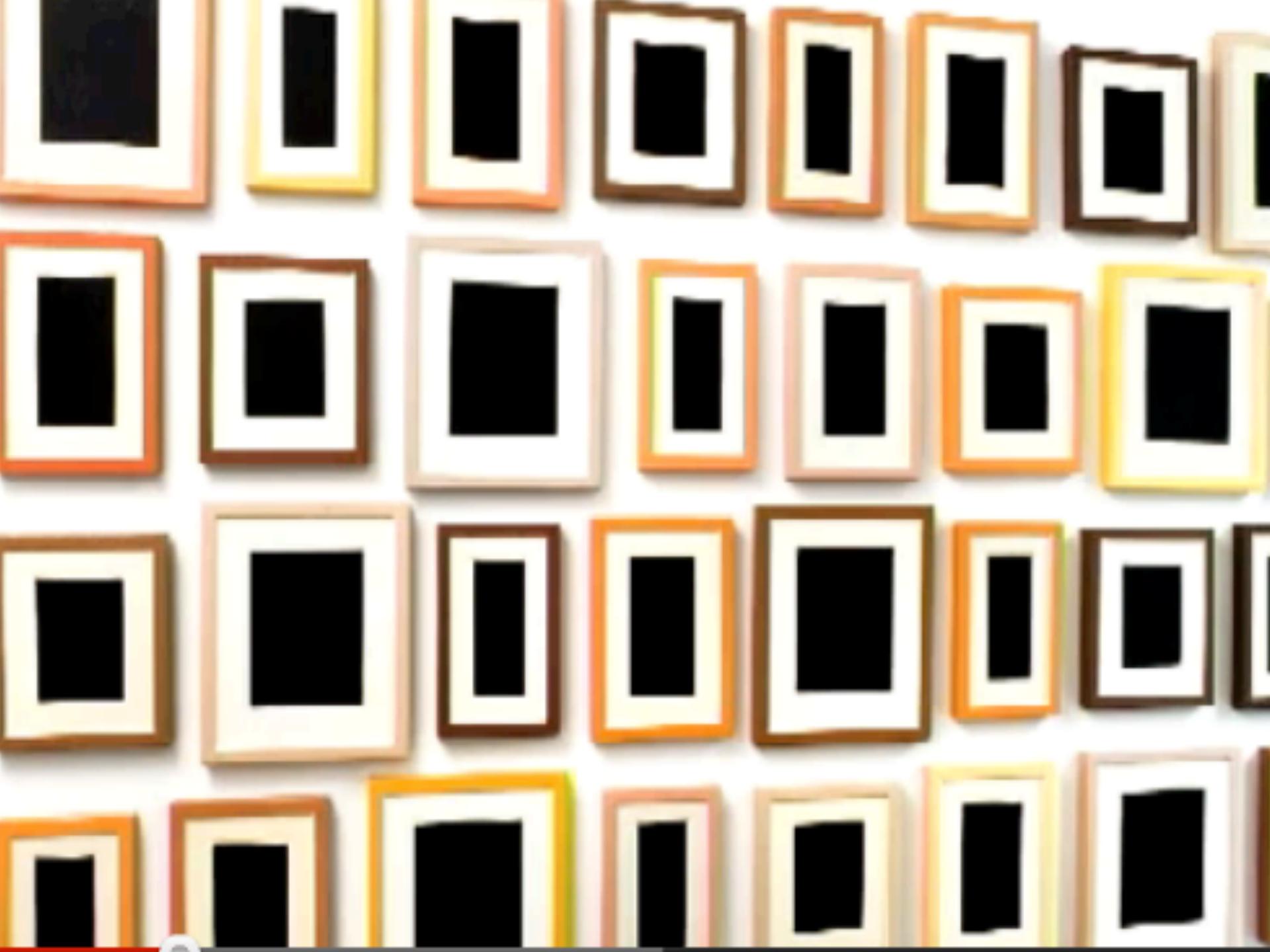
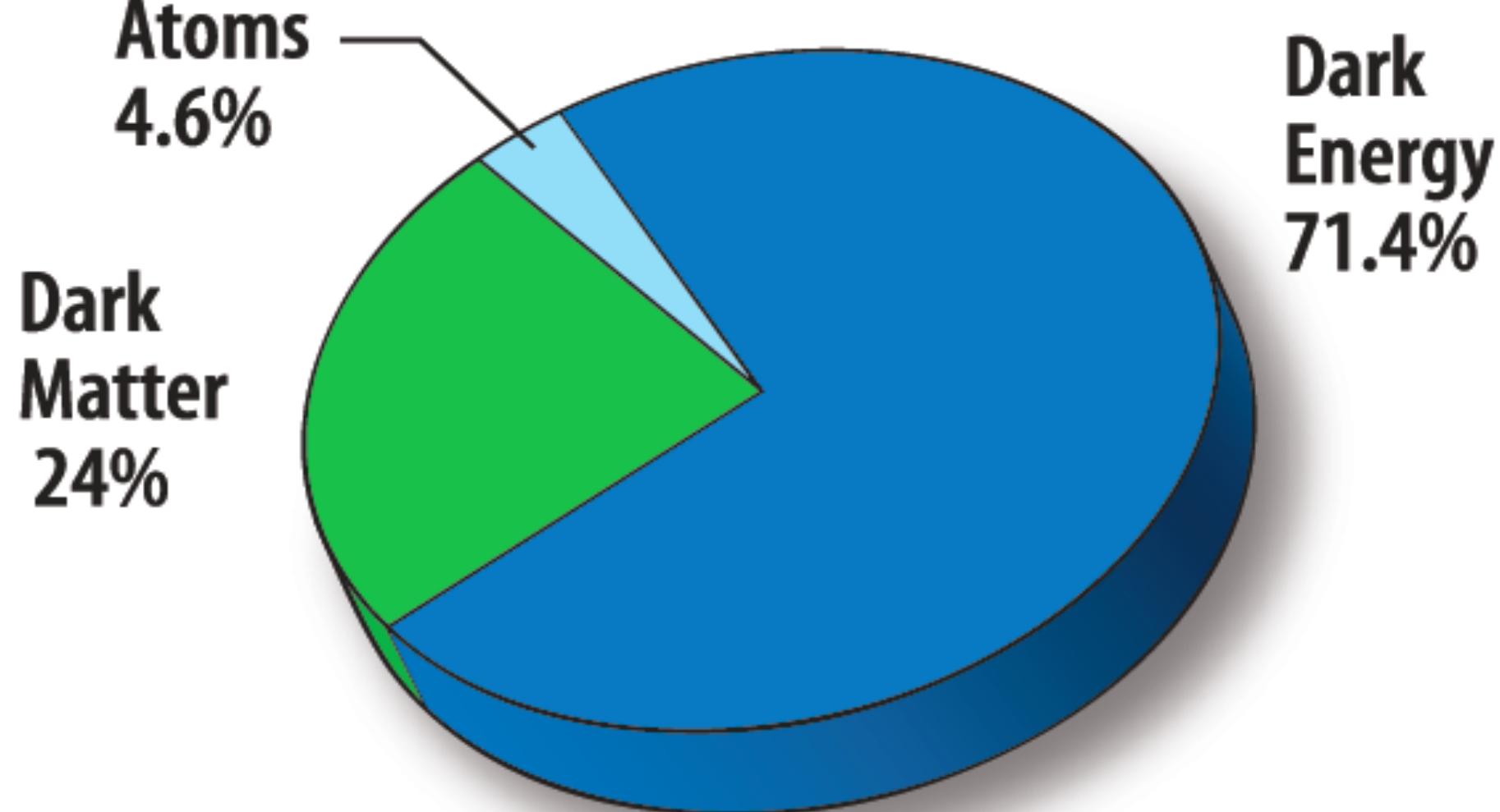


# DARK MATTER and COSMOLOGY

Joe Silk (IAP, JHU)

INVISIBLES SCHOOL 2014 Gif-sur-Yvette

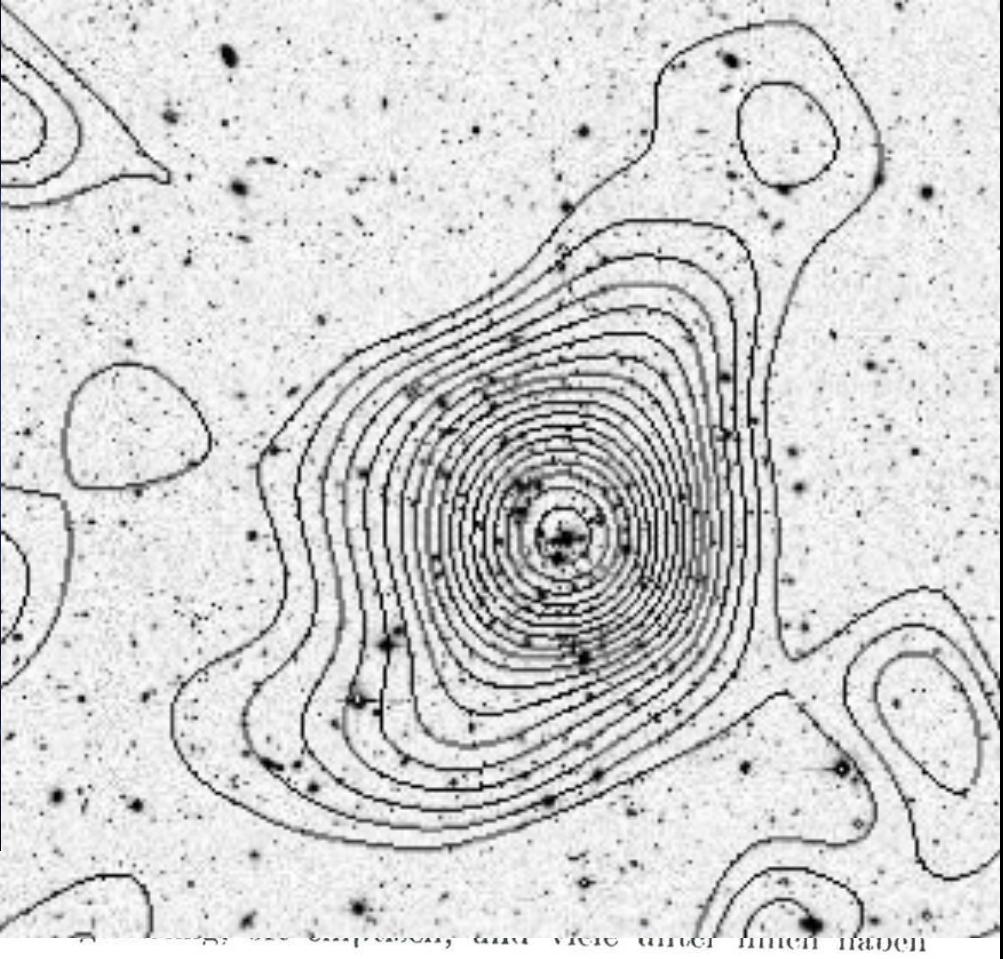
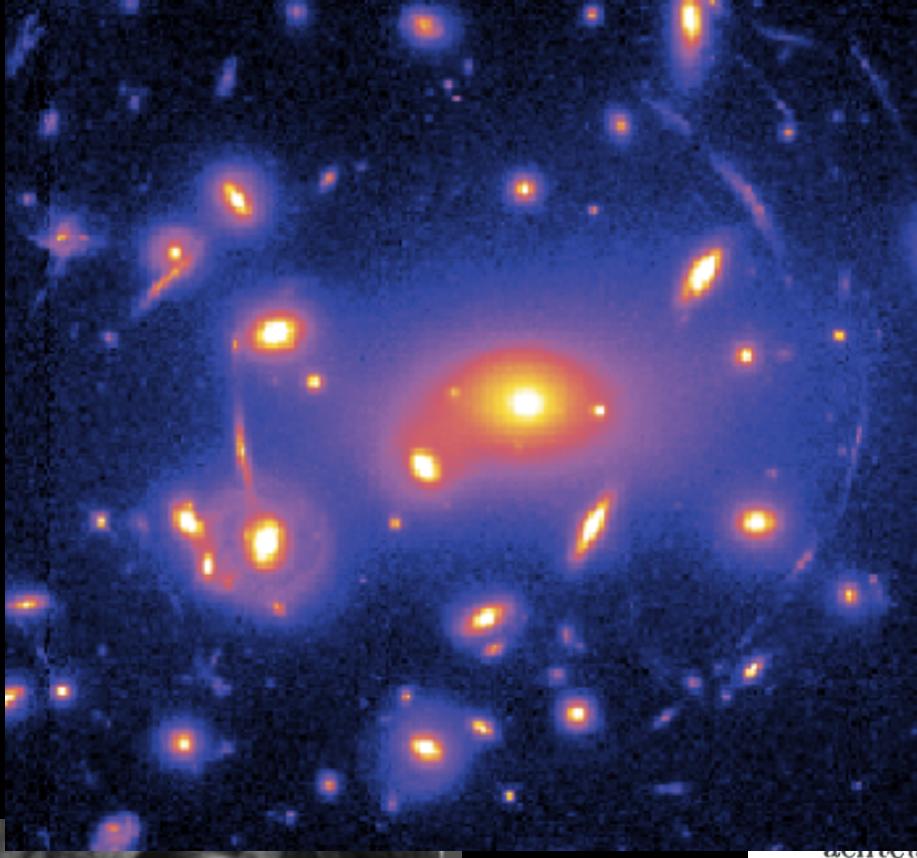




1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

1

# GRAVITATIONAL LENSING

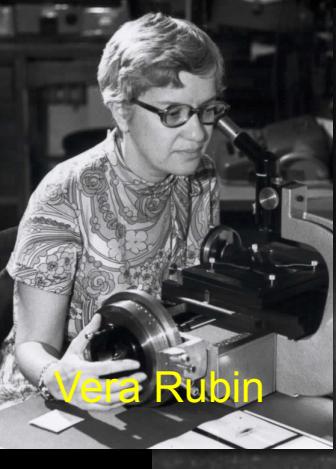


### Rotverschiebung extragalaktischer Nebel.

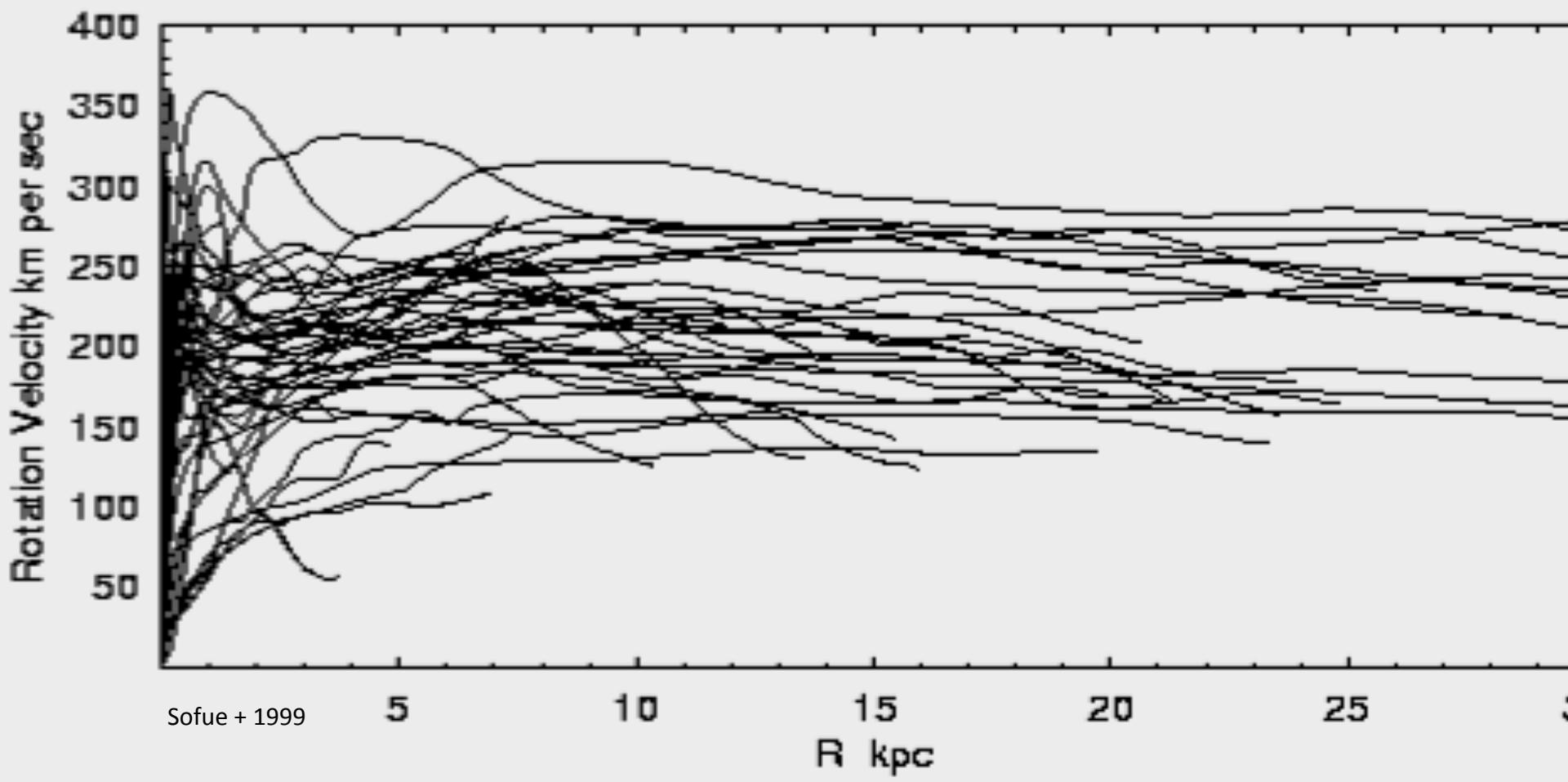
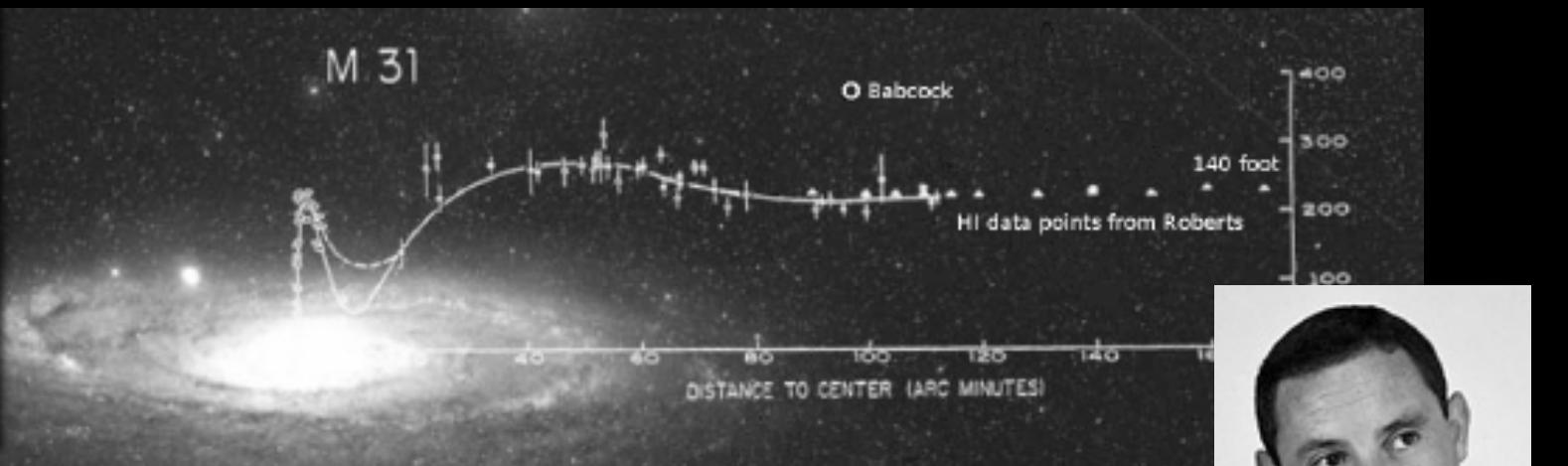
wie beobachtet, einen mittleren Dopplereffekt von  $\pm 5$  oder mehr zu erhalten, müsste also die mittlere Densität des Galaxiensystems mindestens 400 mal grösser sein als die auf Beobachtungen an leuchtender Materie abgeleitete<sup>1)</sup>. Dies bewahrheiten sollte, würde sich also das überraschend ergeben, dass dunkle Materie in sehr viel grösserer Menge vorhanden ist als leuchtende Materie.

Fritz Zwicky

# GALAXY ROTATION CURVES

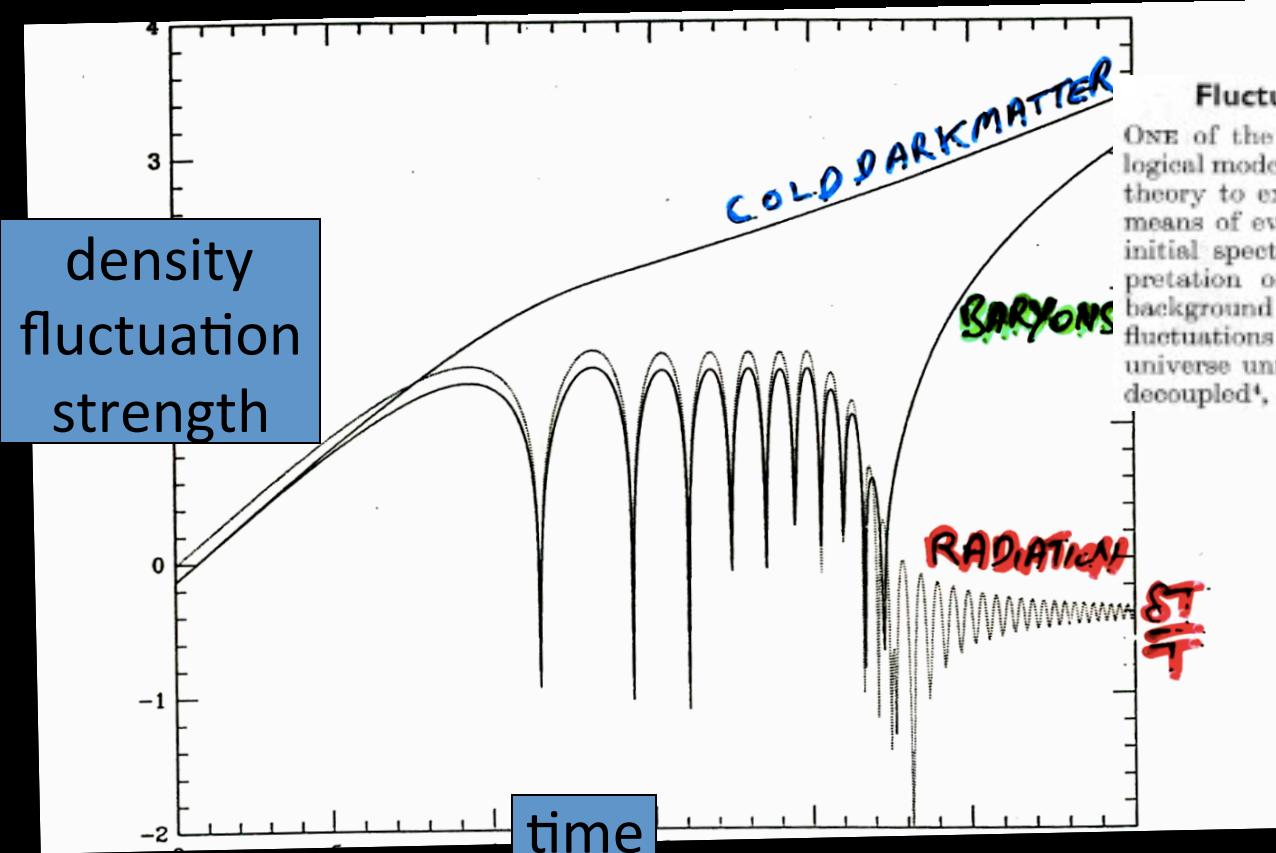


Vera Rubin



# ACOUSTIC OSCILLATIONS IN CMB

# PRIMORDIAL SOUND WAVES IN THE PHOTON-BARYON PLASMA BECOME DENSITY FLUCTUATIONS IN DARK MATTER-DOMINATED ERA



## Fluctuations in the Primordial Fireball

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's theory to explain the process of galactic formation. One means of evading this problem has been to assume that the initial spectrum of primordial fluctuations<sup>7</sup>. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin<sup>8,9</sup> implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled<sup>4</sup>, at a temperature  $T_D$  of the order of 4,000° K.

Silk 1967

**WEAKLY INTERACTING  
DARK MATTER BOOSTS  
FLUCTUATION GROWTH**

FINE-SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND IN A  
UNIVERSE DOMINATED BY COLD DARK MATTER

NICOLA

Vittorio and Silk 1984

Roma

AND

JOSEPH SILK

Department of Astronomy, University of California, Berkeley

Received 1984 May 30; accepted 1984 July 10

CAN A RELIC COSMOLOGICAL CONSTANT RECONCILE INFLATIONARY  
PREDICTIONS WITH THE OBSERVATIONS?

NICOLA VITTORIO<sup>1,2,3</sup>

AND

JOSEPH SILK<sup>1,2</sup>

Received 1985 April 11; accepted 1985 July 9

COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES  
DOMINATED BY NONBARYONIC DARK MATTER

J. R. BOND<sup>1,2</sup> AND G. Efstathiou<sup>2,3</sup>

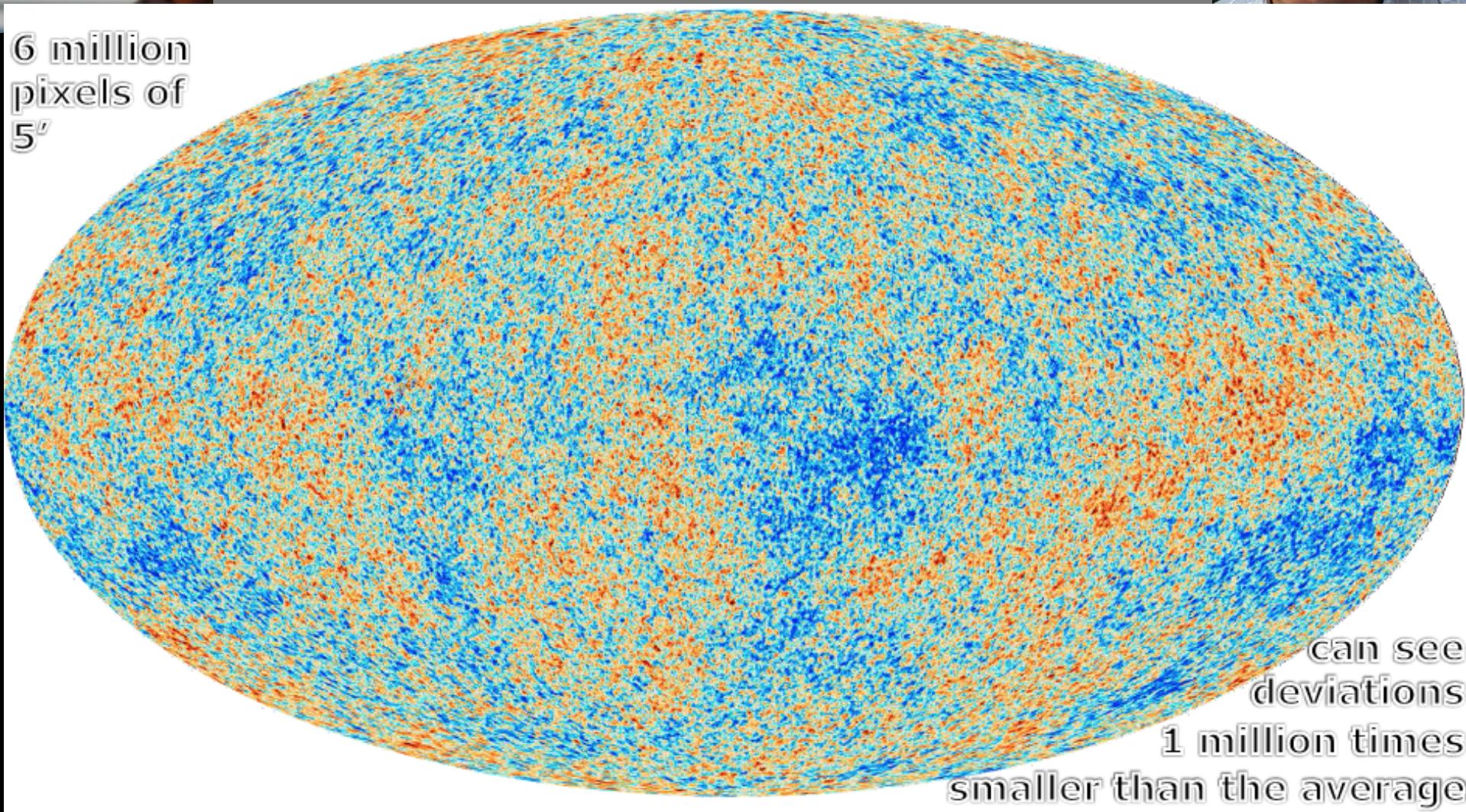
Received 1984 June 4; accepted 1984 July 17

Bond and Efstathiou 1984

# 2013



6 million  
pixels of  
5'



can see  
deviations  
1 million times  
smaller than the average

# FROM DENSITY FLUCTUATIONS TO GALAXIES

Angular scale

90°

18°

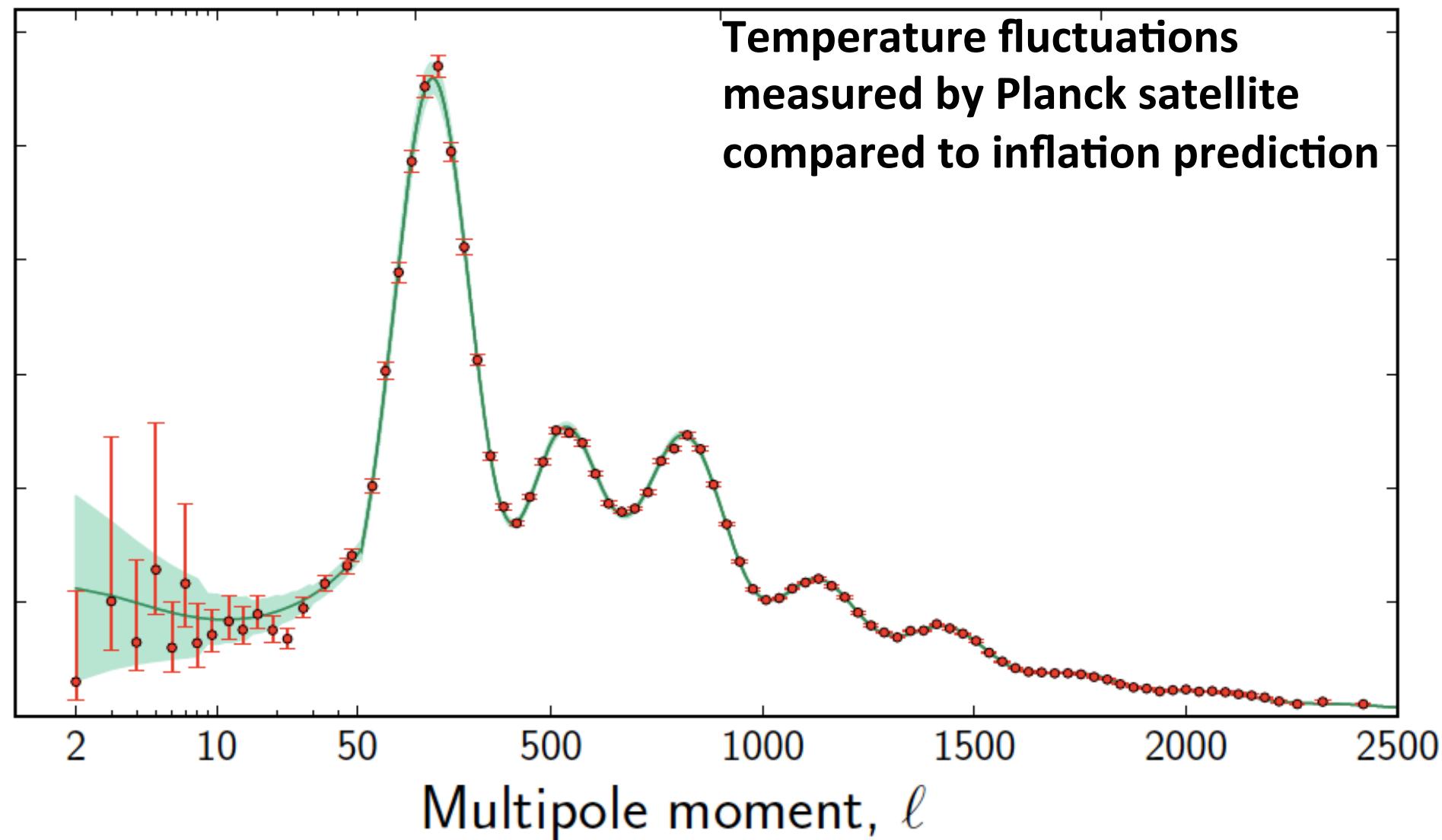
1°

0.2°

0.1°

0.07°

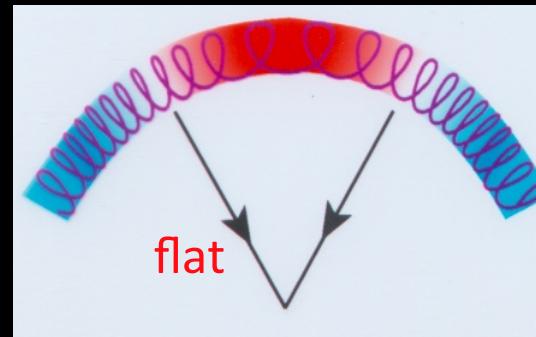
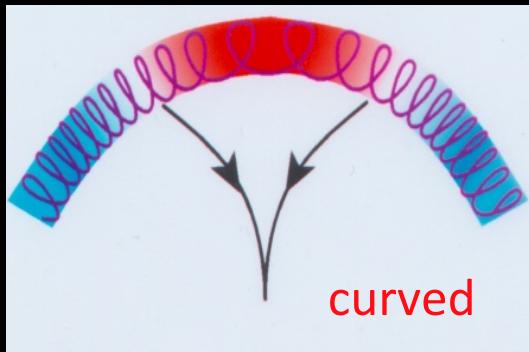
Temperature fluctuations  
measured by Planck satellite  
compared to inflation prediction



# EUCLIDEAN or flat space FITS TO HIGH PRECISION!

$$\Omega = 8\pi G\rho / 3H_0^2$$

$$H_0 = 68 \pm 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$



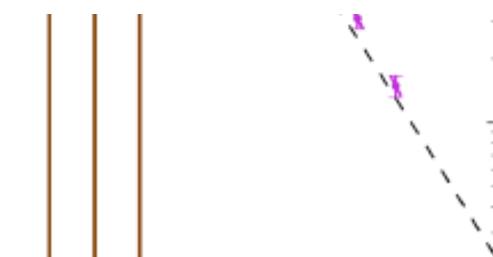
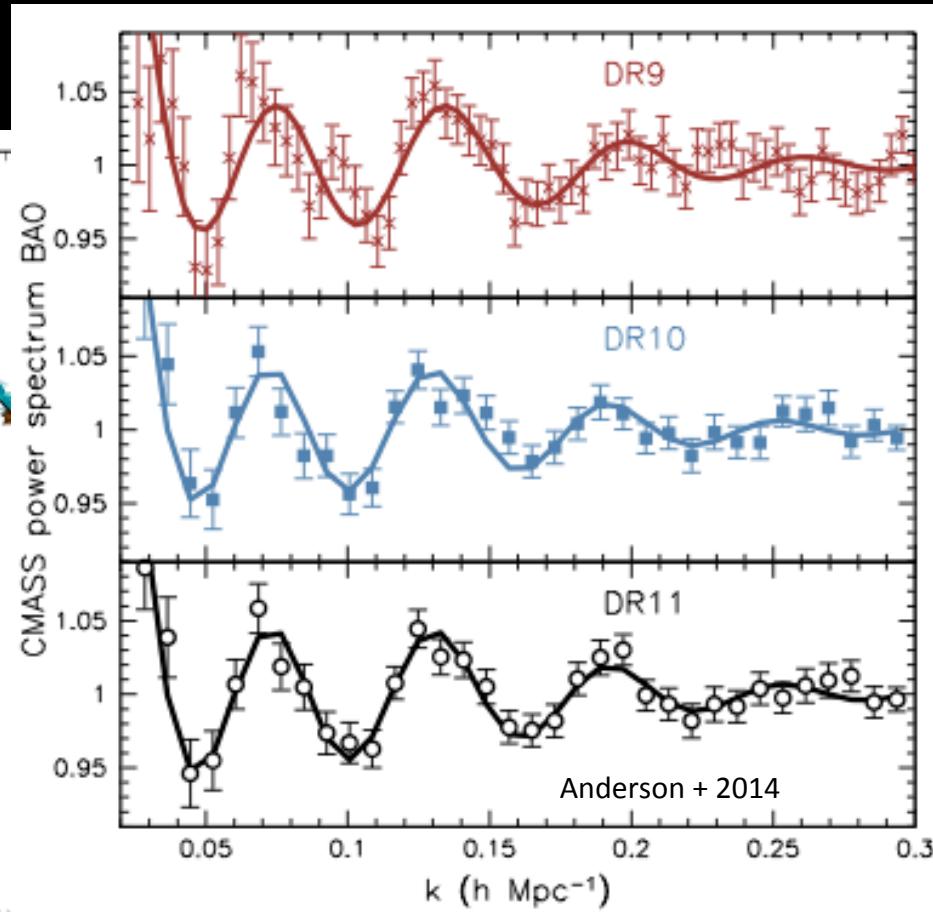
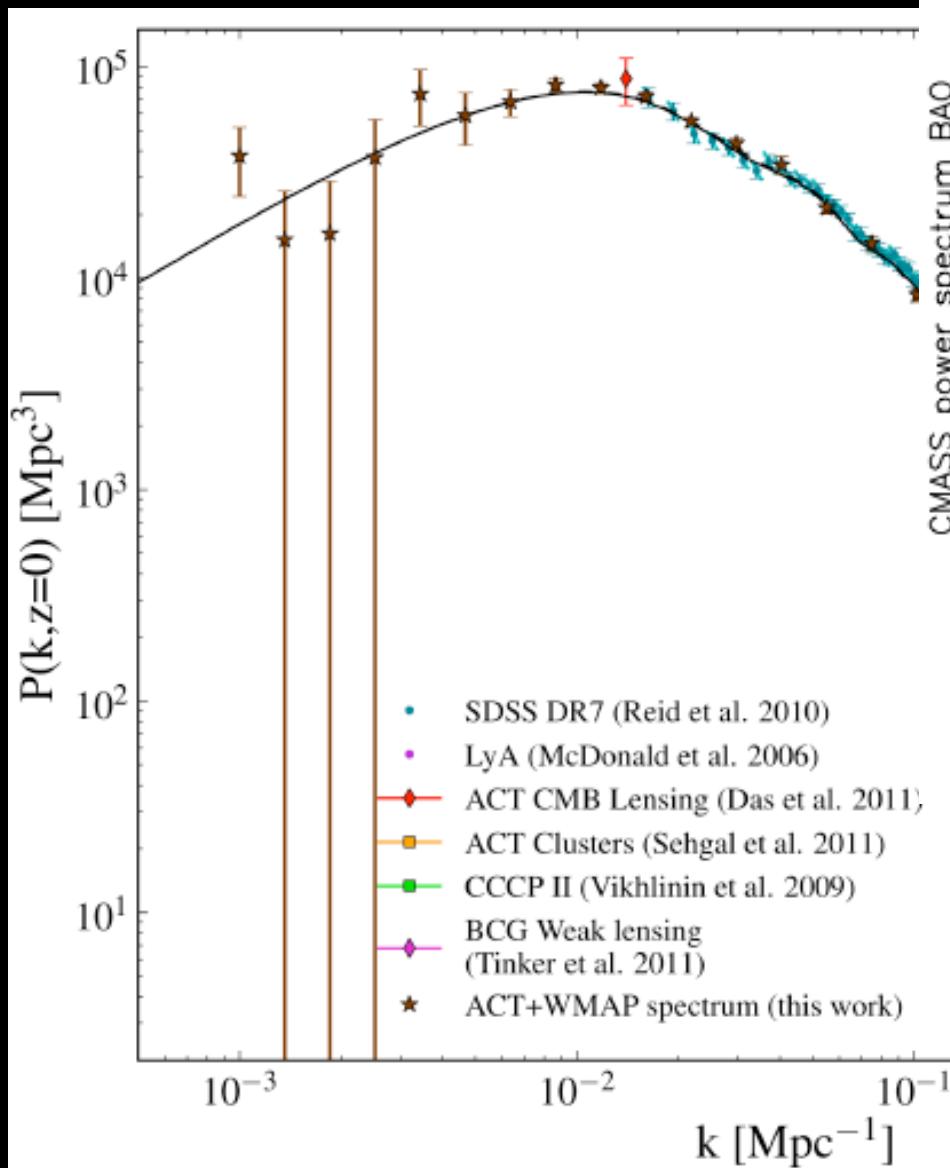
$$\Omega_\Lambda = 0.697 \pm 0.011$$

$$\Omega_m = 0.303 \pm 0.011$$

$$\Omega_B = 0.0484 \pm 0.0007$$

$$t_0 = 13.804 \pm 0.058 \text{ Gyr}$$

# ACOUSTIC OSCILLATIONS IN BARYONS



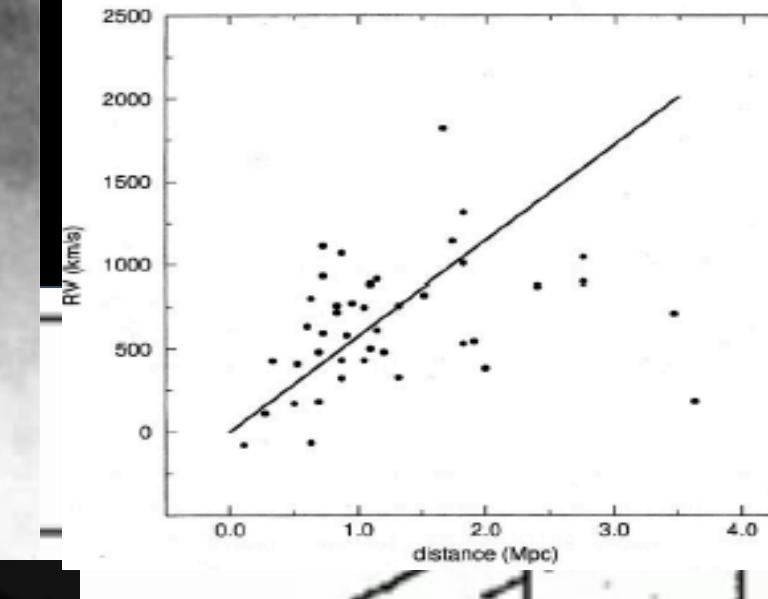
# SUPERNOVAE AS STANDARD CANDLES FOR COSMOLOGY



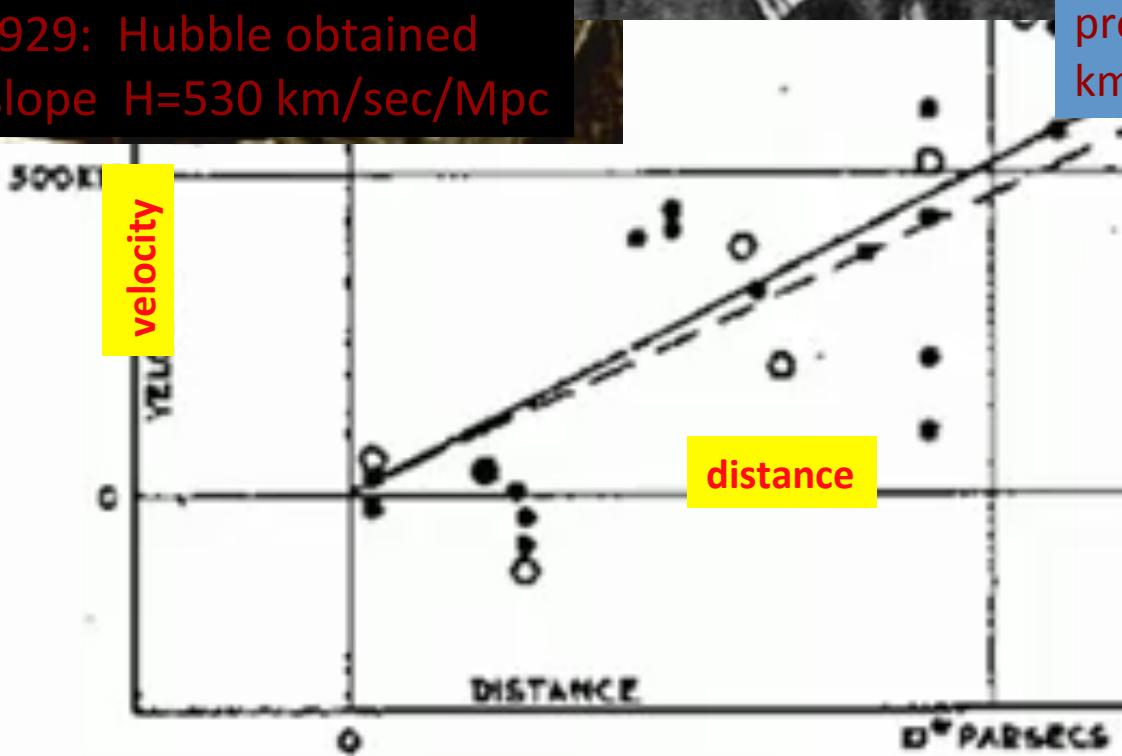
1929: Hubble obtained  
slope  $H=530 \text{ km/sec/Mpc}$



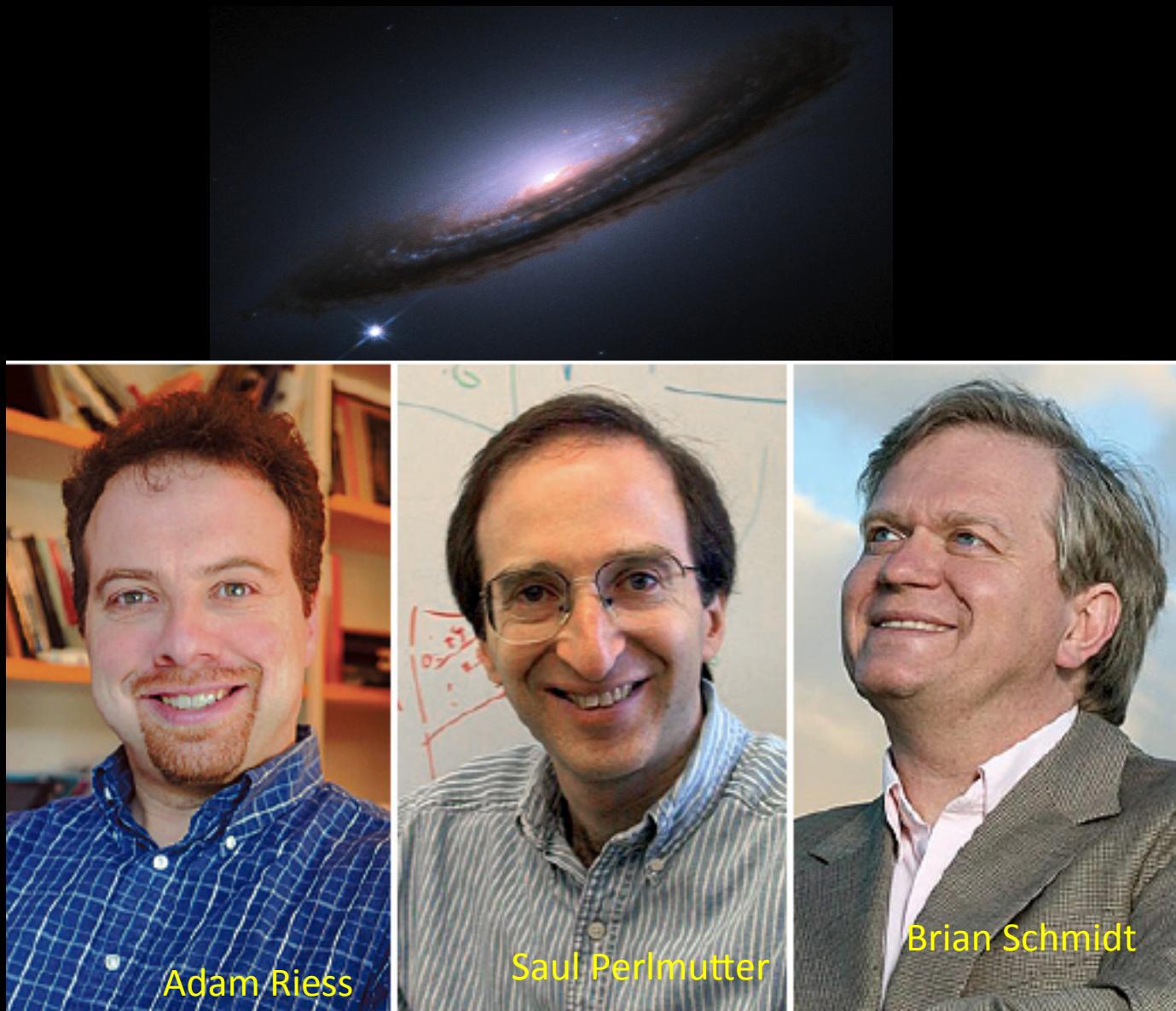
Alexander Friedmann: 1924  
prediction of expansion

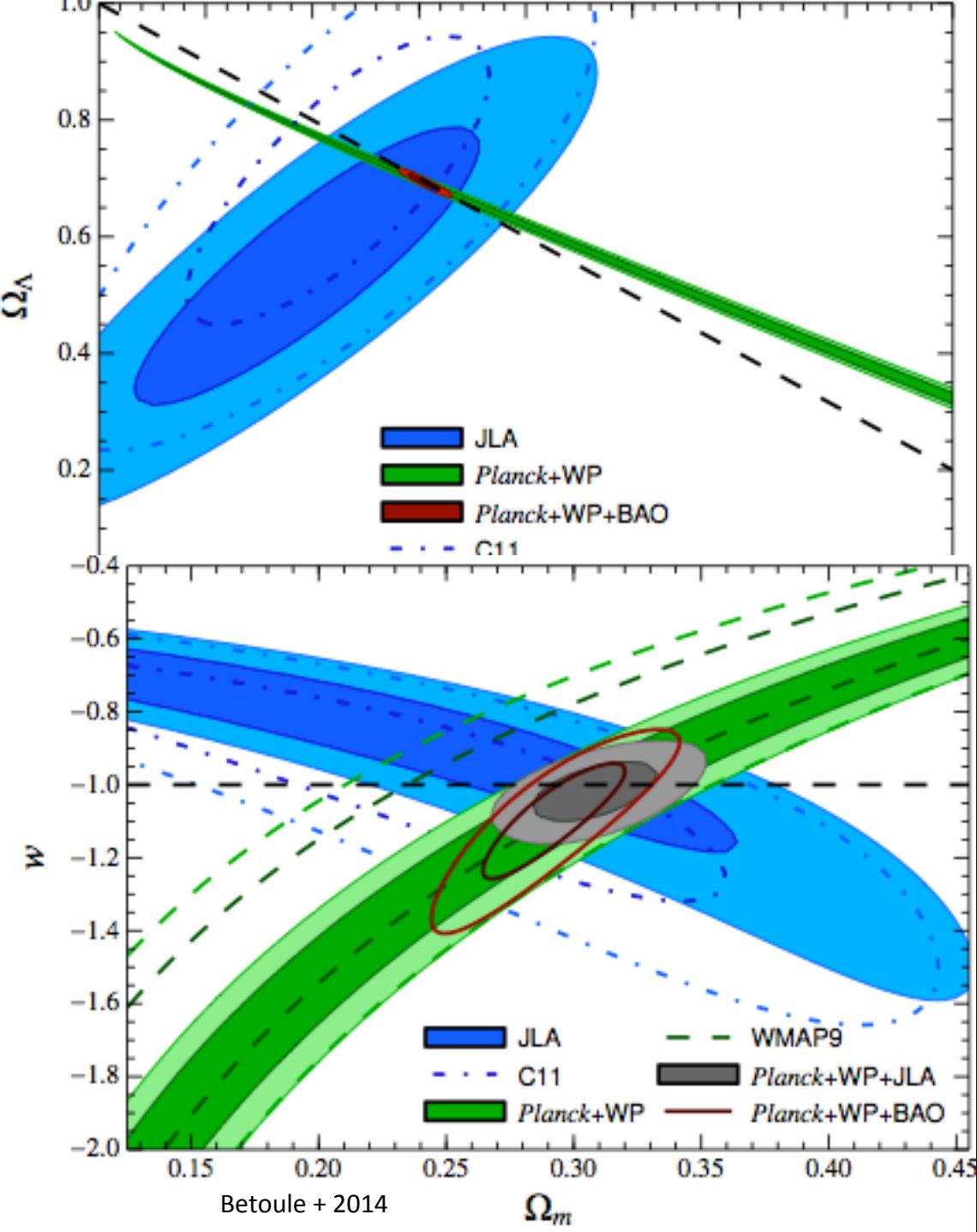
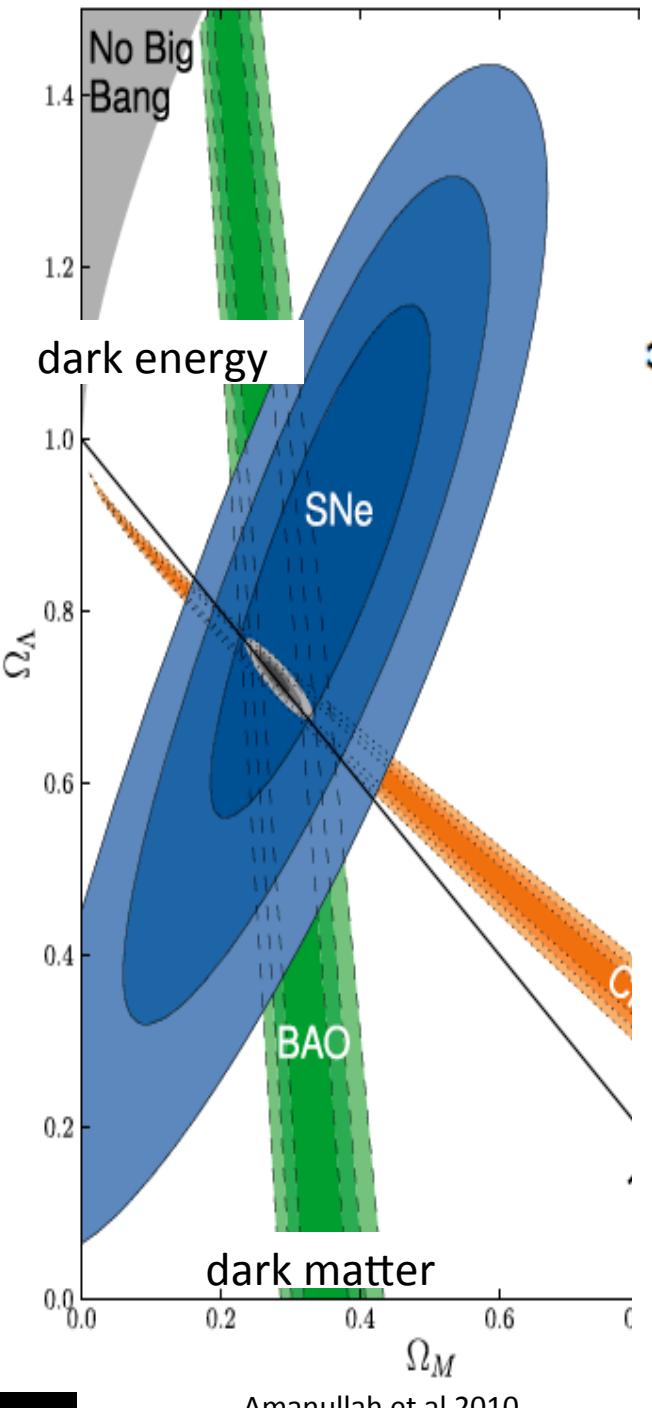


1927: Georges Lemaître independently  
predicted expansion, obtained  $H=625$   
 $\text{km/sec/Mpc}$  but published in French

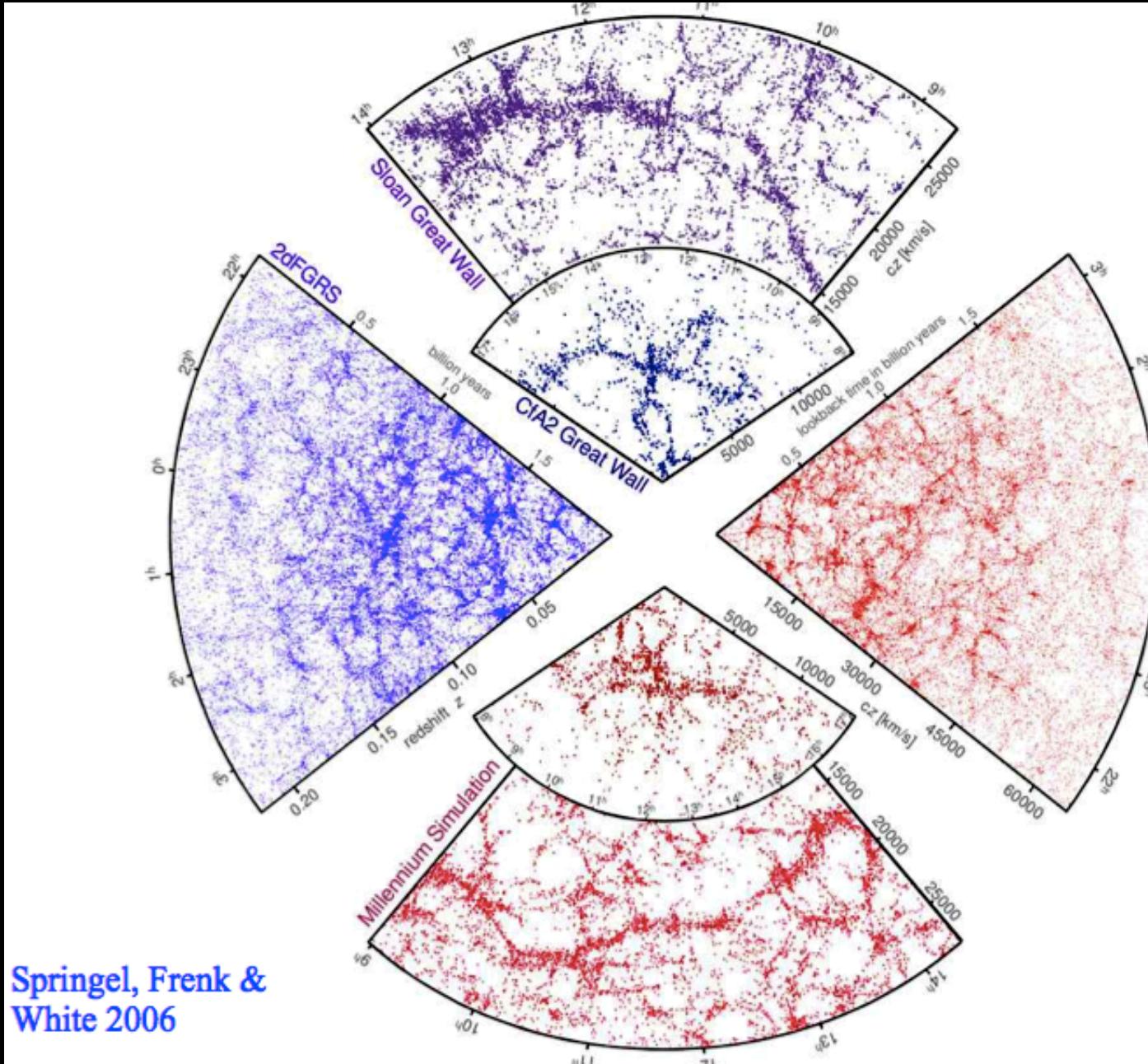


Distant type Ia supernovae are too faint by ~25%  
most of the mass-energy in the universe is dark





# Dark Matter is weakly interacting & cold



Springel, Frenk &  
White 2006



1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

2

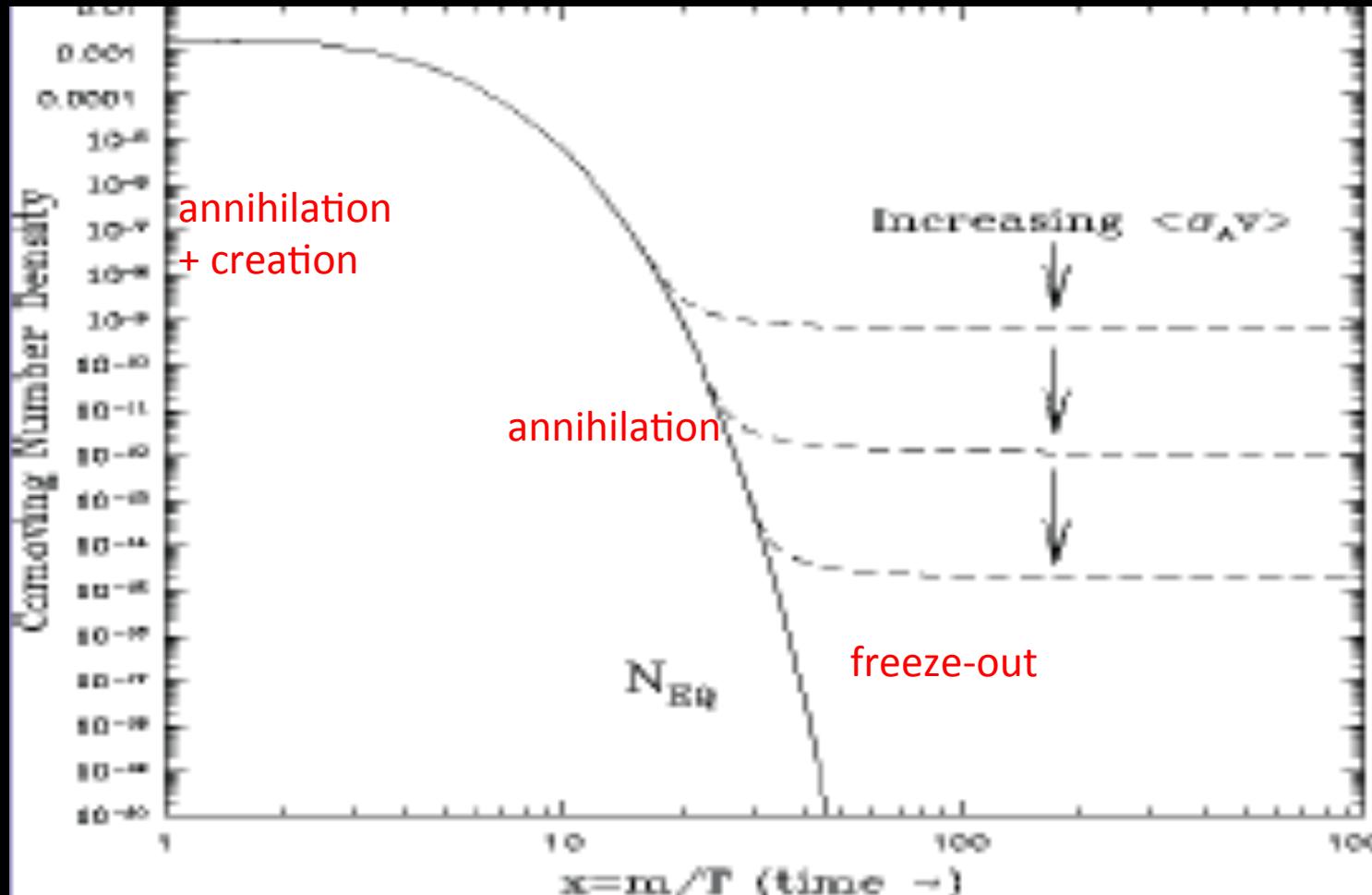
SUSY WIMP in thermal equilibrium

relic abundance if  $\langle\sigma_{\text{ann}}v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim 0.23/\Omega_x$

generic WIMP

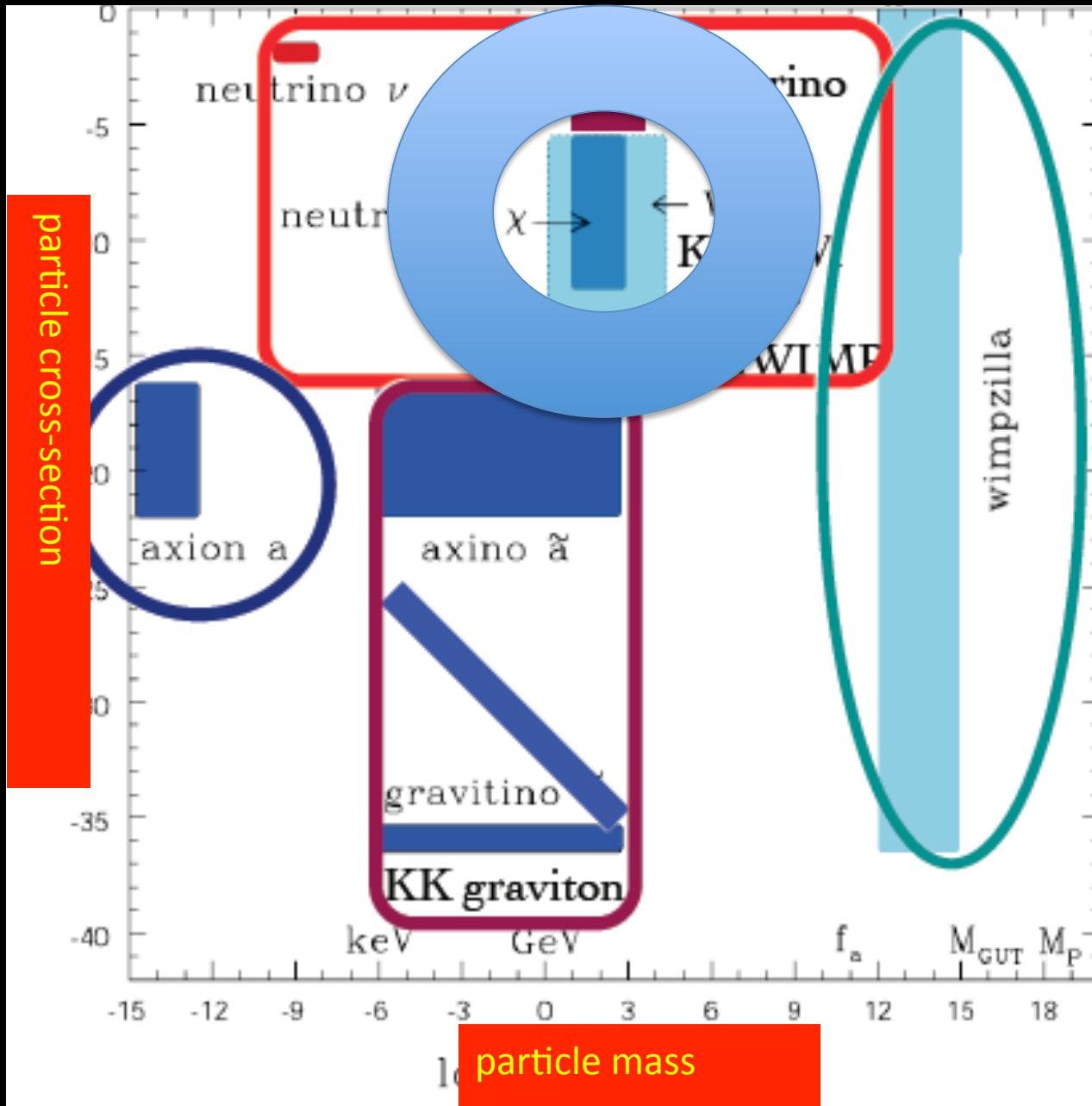
$\langle\sigma_{\text{ann}}v\rangle \sim \alpha_w^2/m_x^2 = \alpha_w^2/1 \text{ TeV}^2$

## PREDICTING $\langle\sigma v\rangle$



SUSY has 100+ free parameters

# WIMPS or nonWIMPs



NOW its one of many DM candidates...

One natural choice is asymmetric DM  
for which  $m_x = 5 \text{ GeV}$

lepton-like asymmetry:  $\rho_B = \eta_B n_\gamma m_B$        $\rho_x = \eta_B n_x m_x$

Nussinov, Kaplan....

of interest for direct detection...

Another is minimal DM for which  $m_x = 10 \text{ TeV}$

SM + quintuplet..... neutral, stable, thermal freeze-out + relic abundance

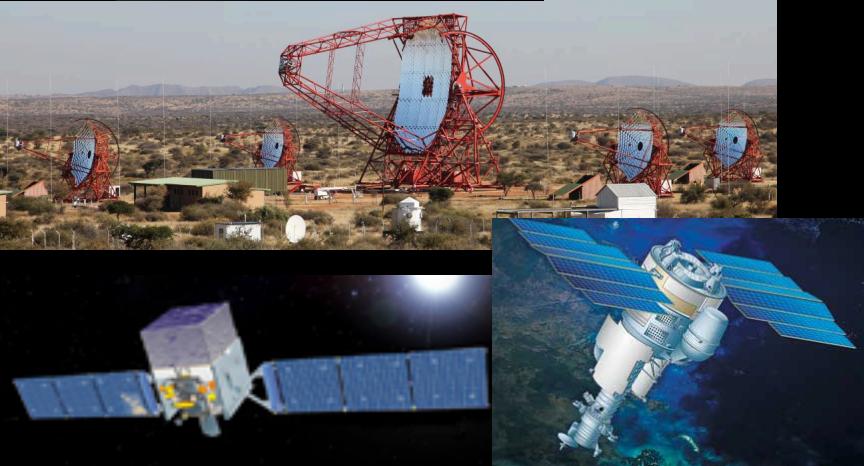
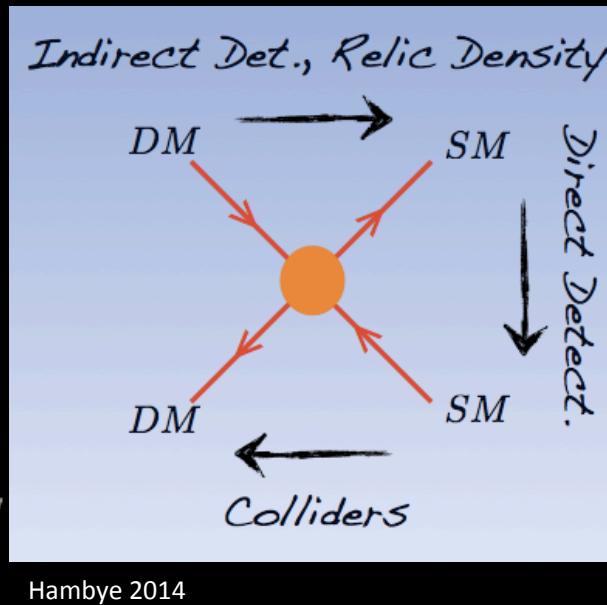
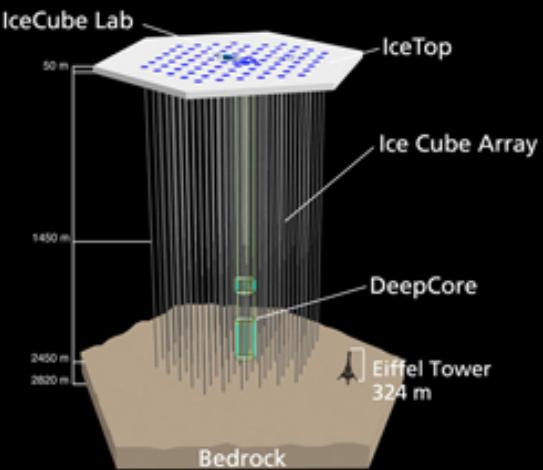
of interest for indirect detection....

Cirelli +

# DARK MATTER DETECTION

Indirect detection  
of high energy  $\gamma$ ,  $\nu$ ,  $e^+$ ...

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$
$$\sigma_{\text{ann}} \sim 10^{-36} \text{ cm}^2$$



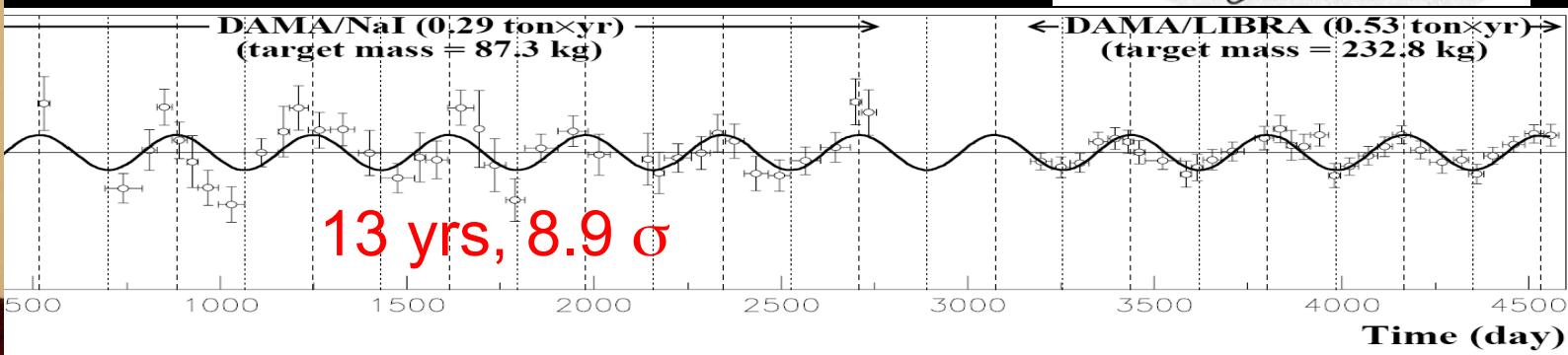
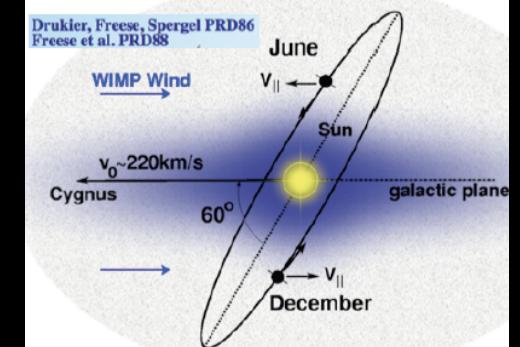
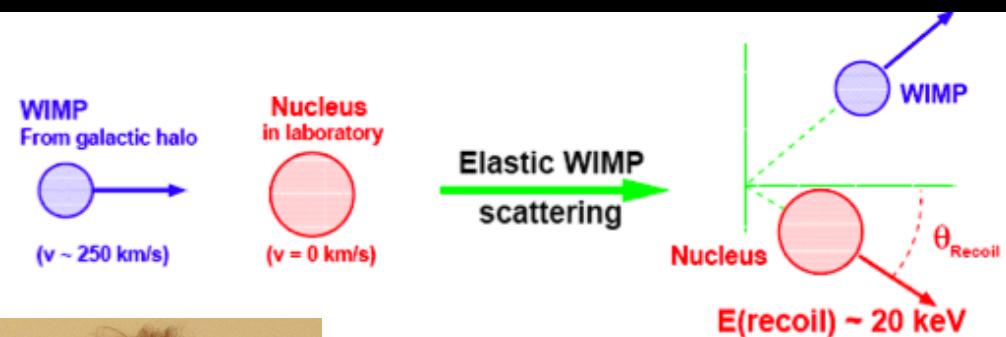
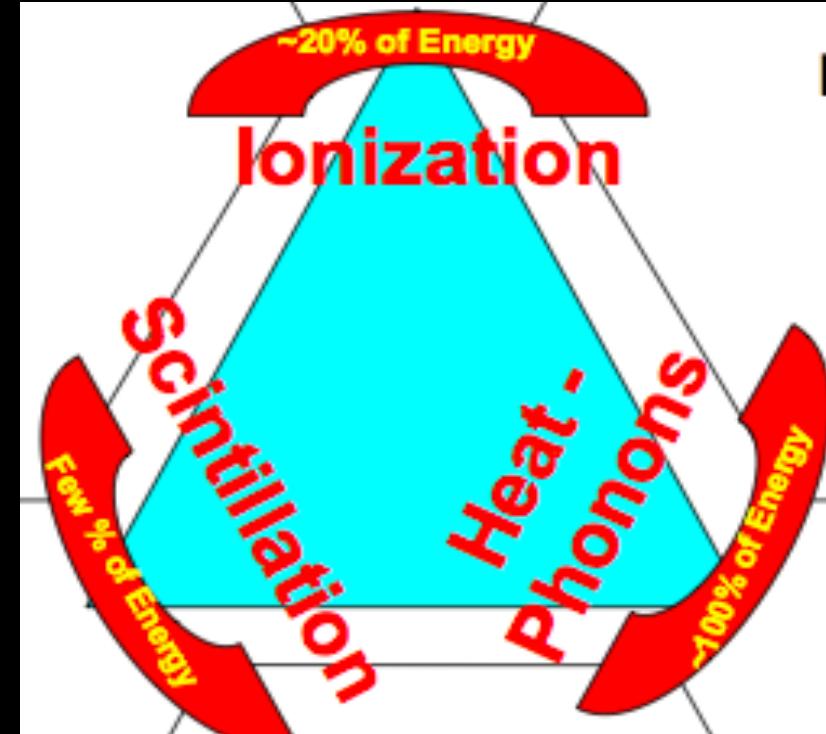
direct detection  
and colliders

$$\sigma_{\text{sca}} \sim 10^{-38} \text{ cm}^2$$

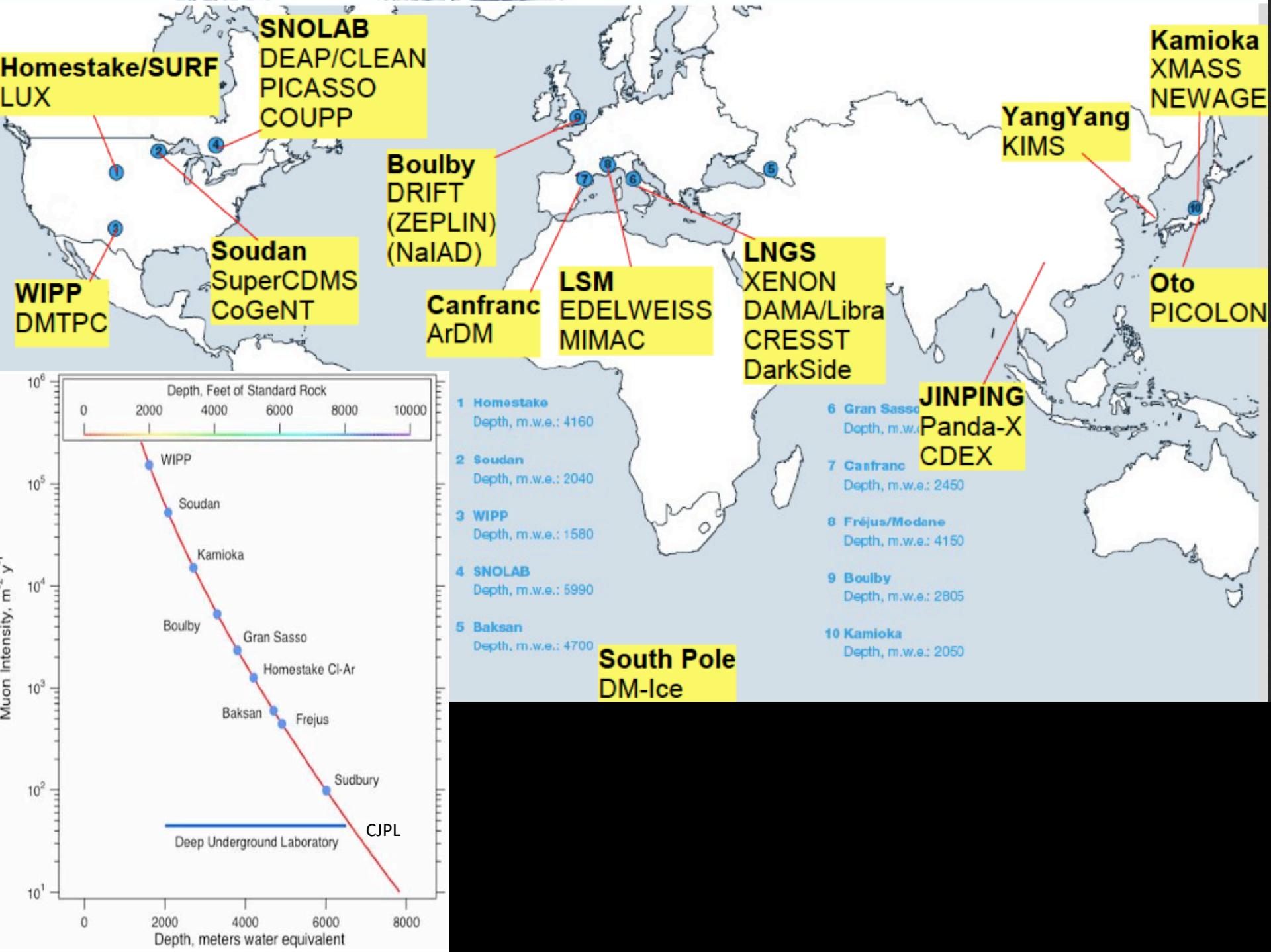


# DIRECT DETECTION

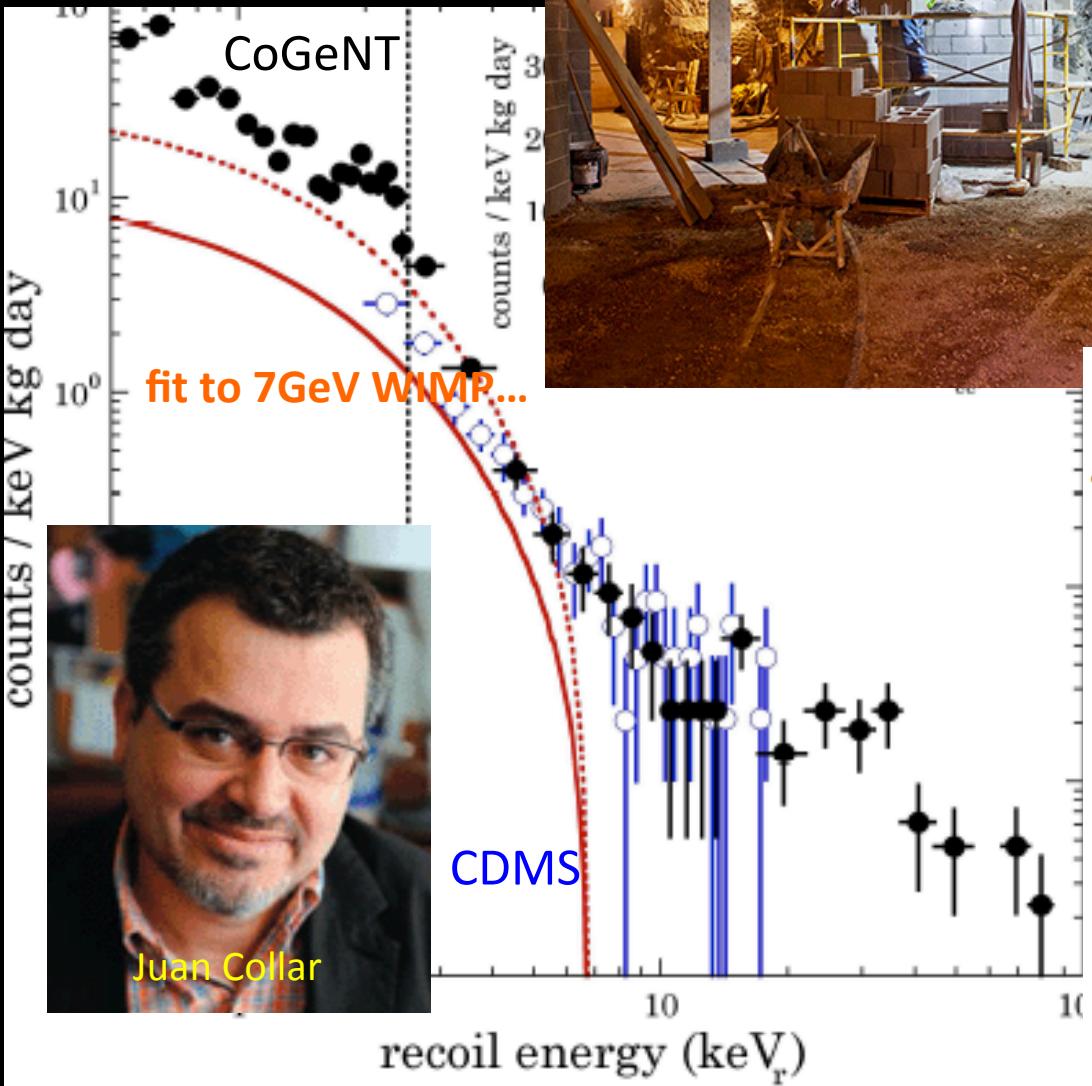
many WIMPs pass through lab per second



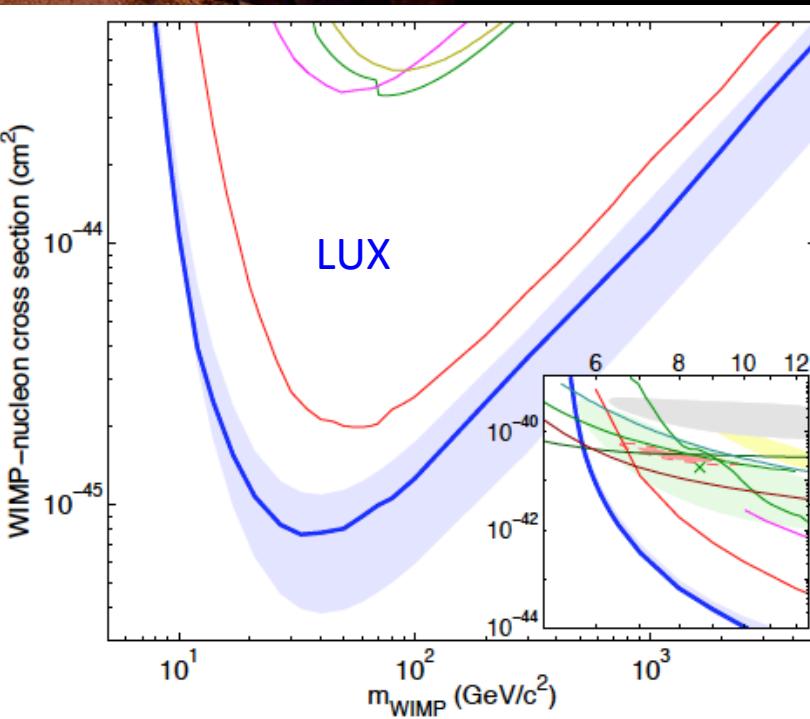
Rita Bernabei



Spin-independent elastic scattering is coherent, and all nucleons contribute

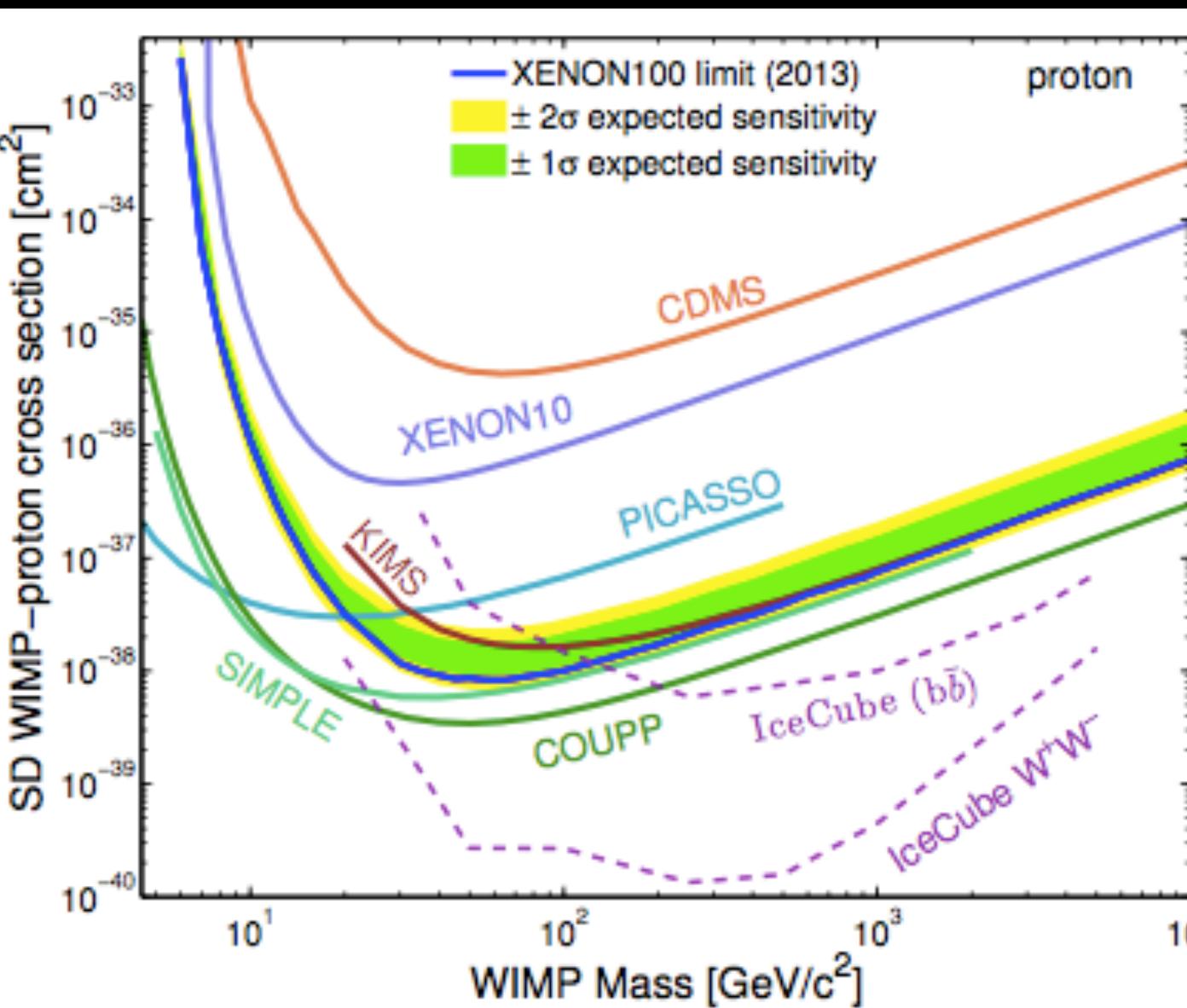


Rick Gaitskell



# Spin-dependent elastic scattering sums incoherently

(couples to nucleon spin, cancels in pairs)



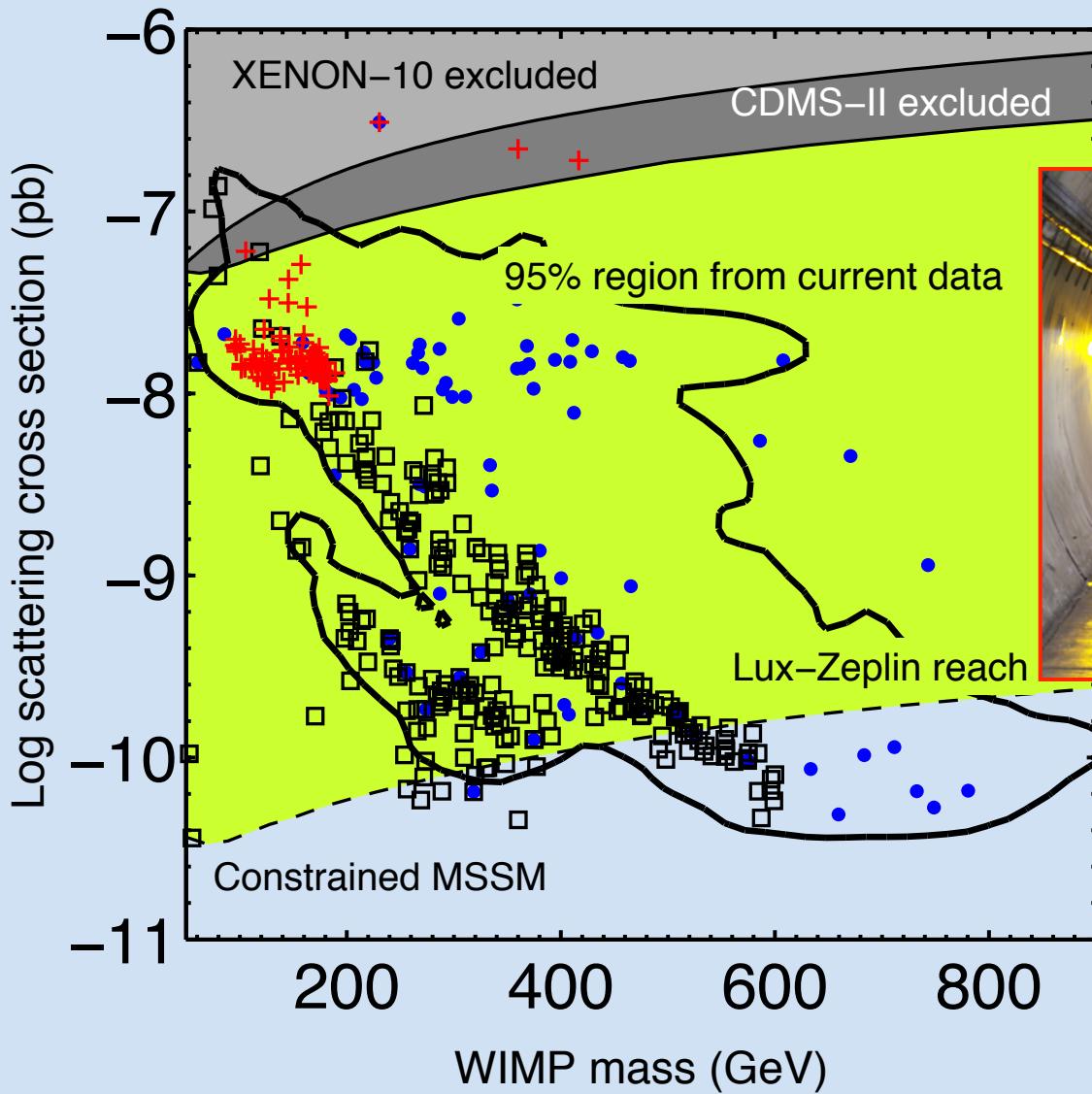
# LHC reach

- ◻ Models within LHC reach (18.3 %)
- Models favoured by Planck (5.7 %)
- + Models within IceCube reach (6.5 %)

300/fb at 14 TeV energy in 2015

WMAP mean with 5- $\sigma$  Planck uncertainty

5- $\sigma$  for 1 yr of 80 strings data



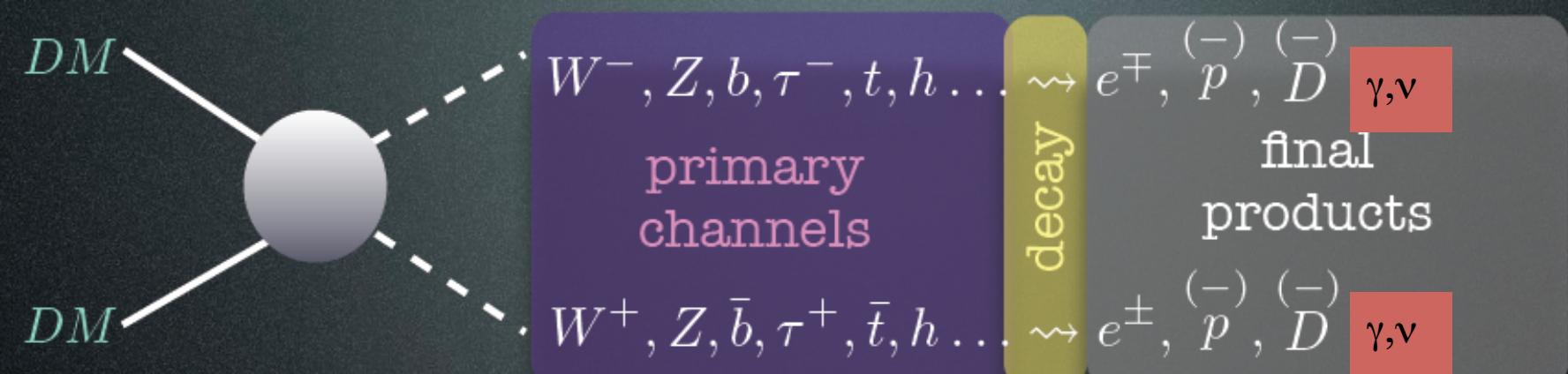
Trotta et al. 2011

1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

3

# INDIRECT DETECTION

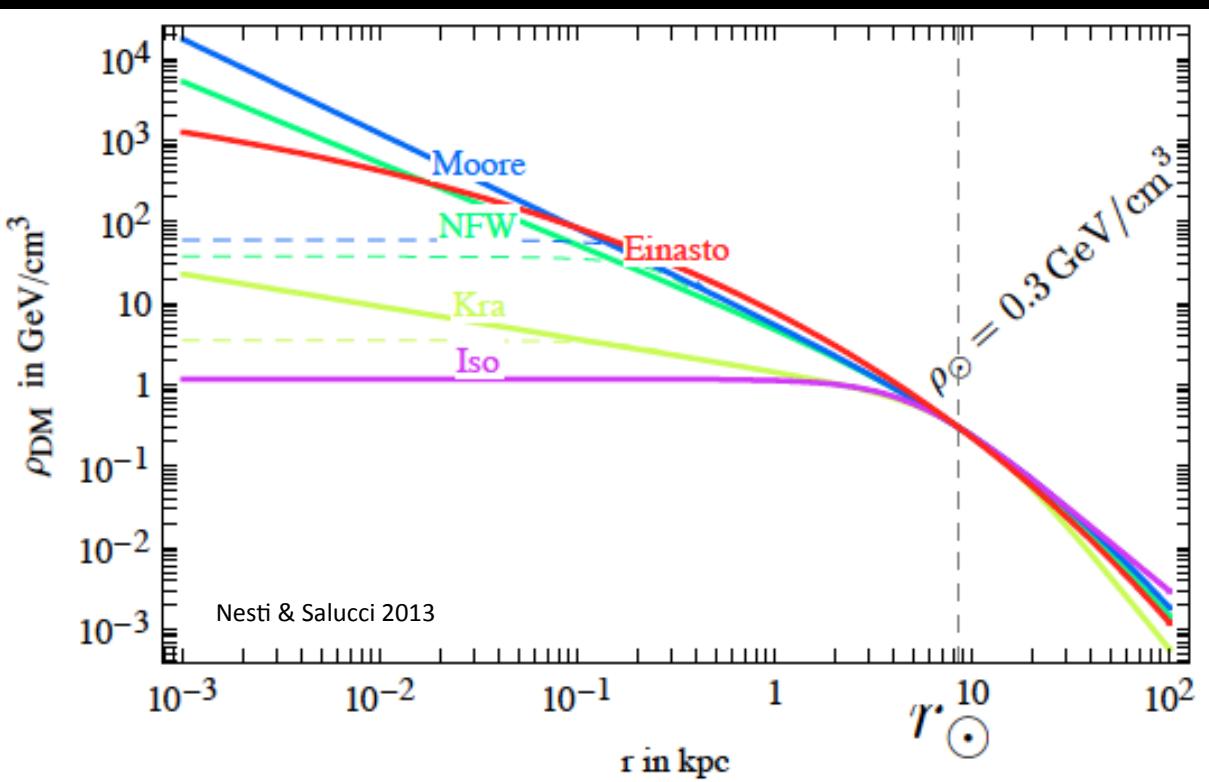
halo WIMPS occasionally annihilate into energetic particles



# UNCERTAINTIES

Dark matter distribution  
profiles, streams, clumps, velocity distribution  
Cosmic ray propagation  
diffusion, solar modulation, energy losses  
Particle physics issues  
fragmentation codes,  
higher order corrections at TeVscales  
Astrophysical backgrounds

Possible dark matter profiles in our galaxy

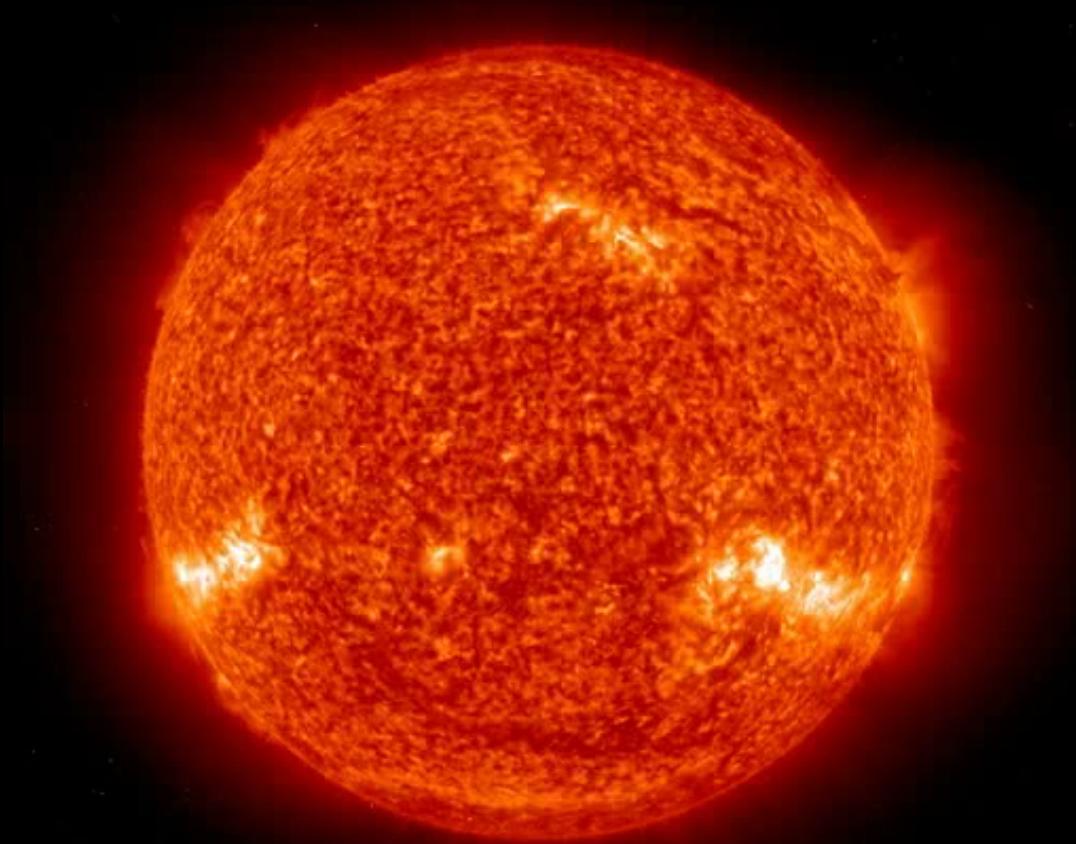


1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

stars

3a

# THE SUN



1998/03/30 18:50

## The Photino, the Sun, and High-Energy Neutrinos

Joseph Silk

*Department of Astronomy, University of California, Berkeley, California 94720*

and

Keith Olive

*Theoretical Astrophysics Group, Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

and

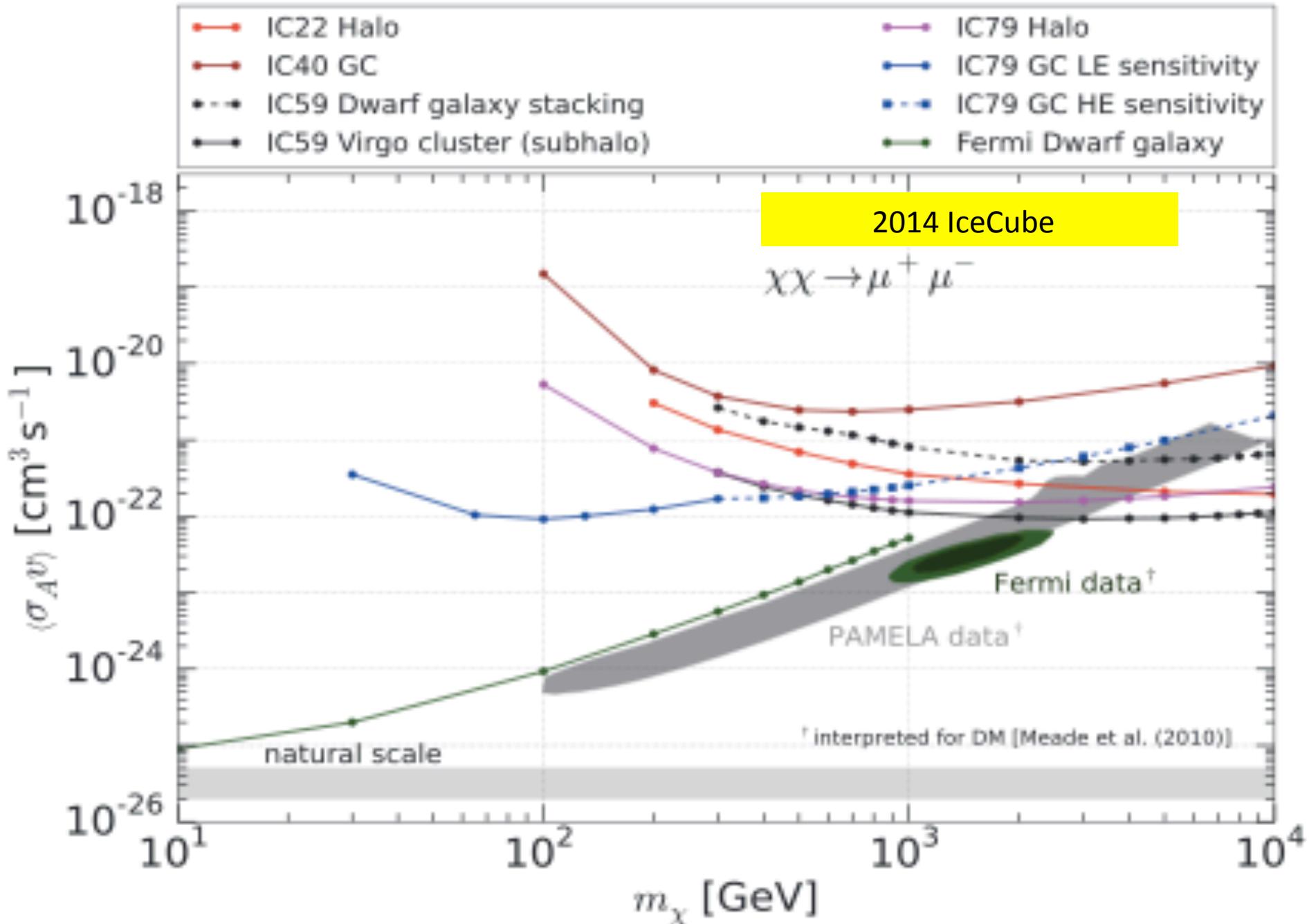
Mark Srednicki

*Physics Department, University of California, Santa Barbara, California 93106*

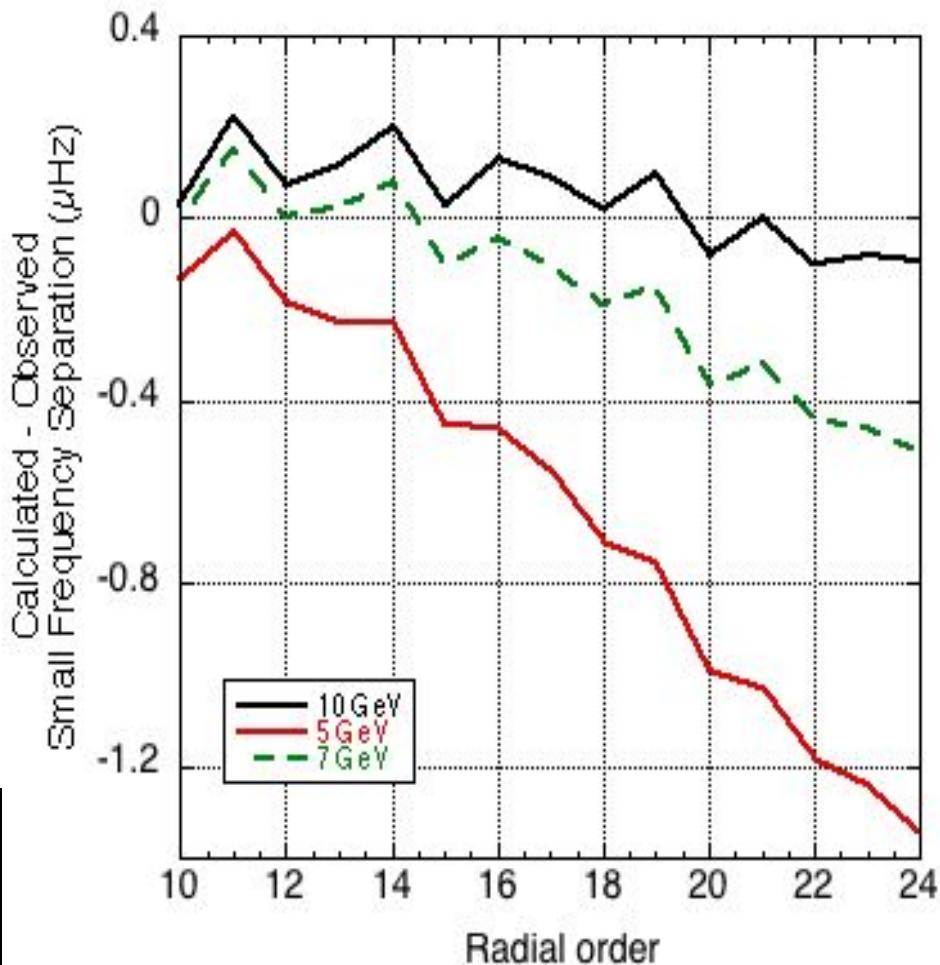
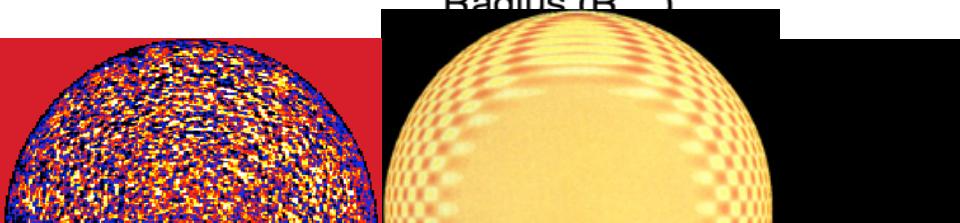
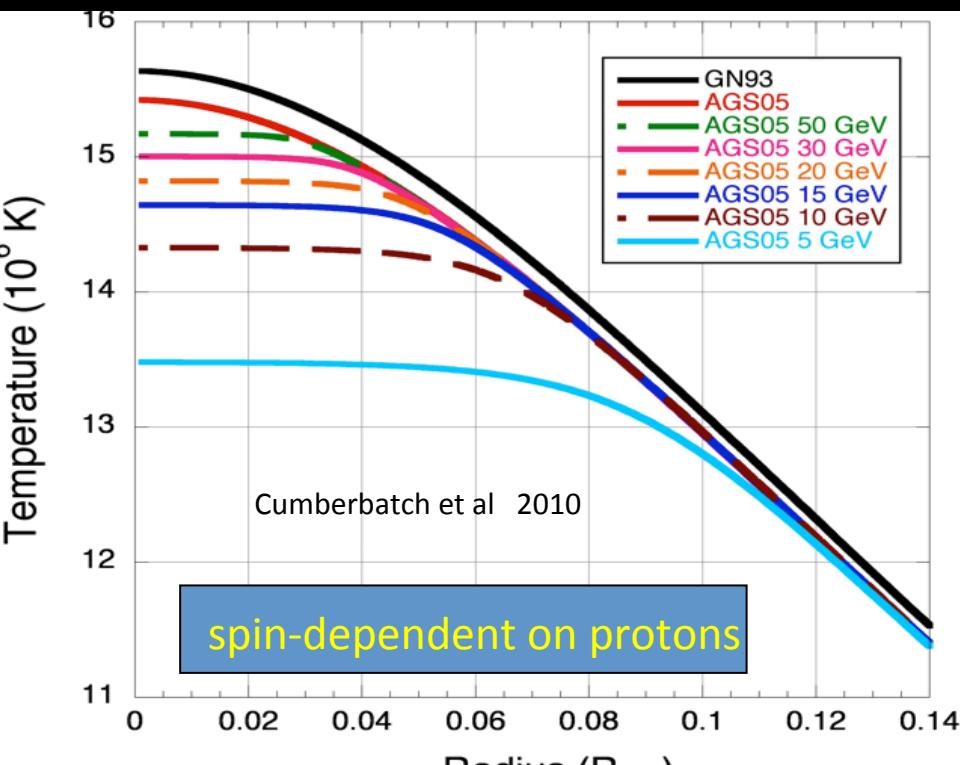
(Received 29 April 1985)

If the Universe contains a nearly critical density of photinos which are also assumed to constitute the dark matter in our galactic halo, then gravitational trapping by the Sun and ensuing annihilation in the solar core yields a significant flux of  $\sim 250$ -MeV neutrinos. This results in about two neutrino-induced events per kiloton-year in an underground proton-decay detector.

# ENERGETIC NEUTRINOS FROM WIMPs ANNIHILATING IN THE SUN



low mass ( $m_x \sim 5\text{-}10$  GeV) WIMPS are trapped, fill the solar core.... and modify  $T(r)$  if non-annihilating

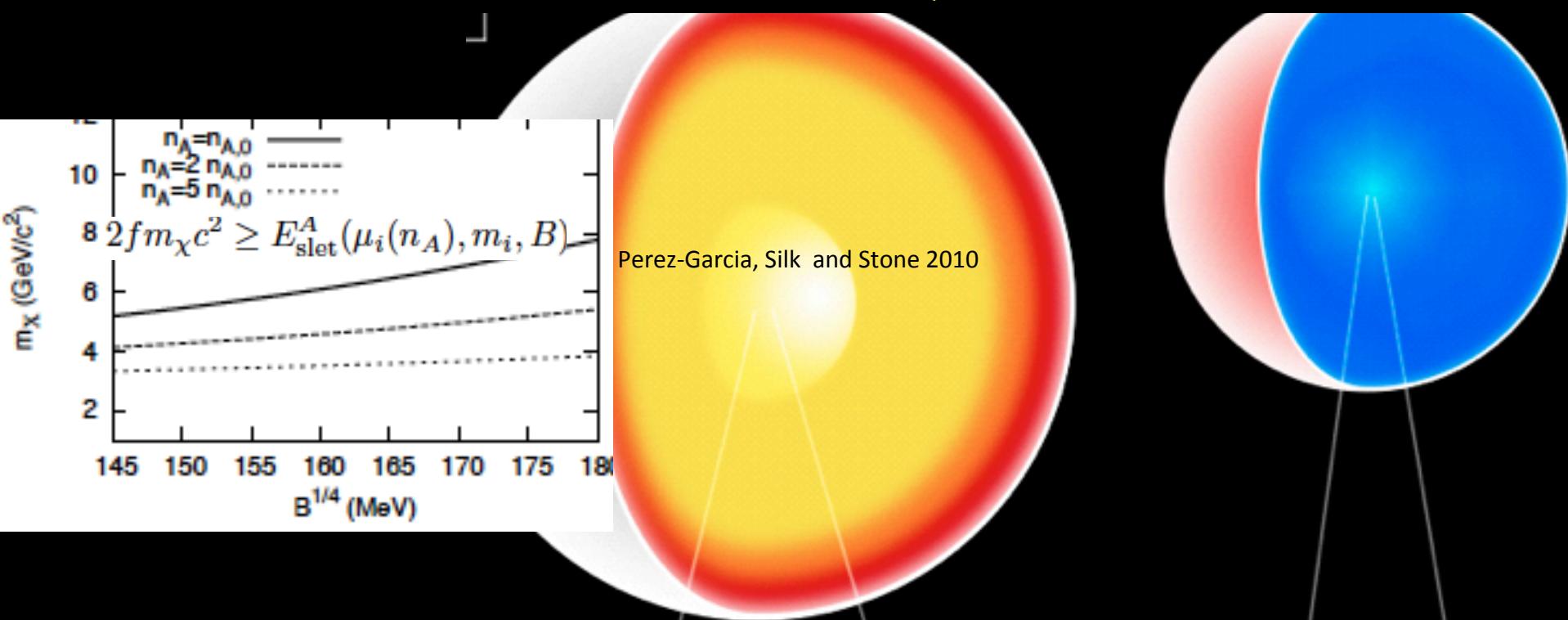


helioseismology rules out 5 GeV  
in some cases...

# NEUTRON STARS

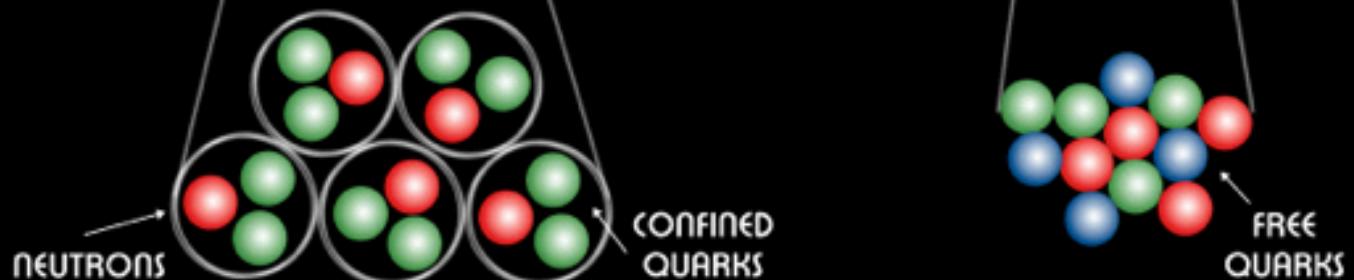
# NEUTRON STARS

WIMP ANNIHILATIONS MAY CONVERT A NEUTRON STAR TO A QUARK STAR if neutron matter is metastable



This would be a dramatic explosion... and produce compact pulsars

- Up Quark
- Down Quark
- Strange Quark



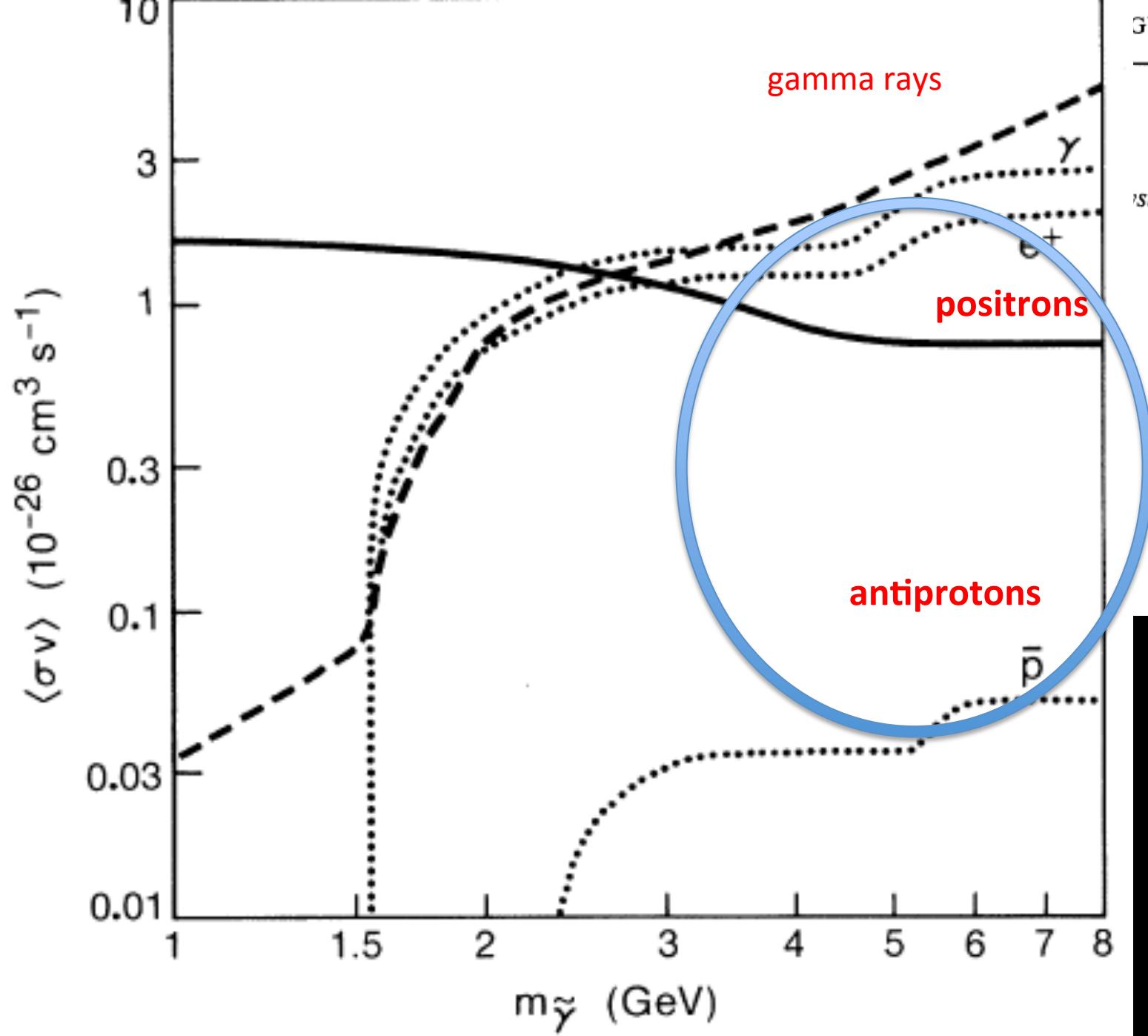
1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

stars

positrons

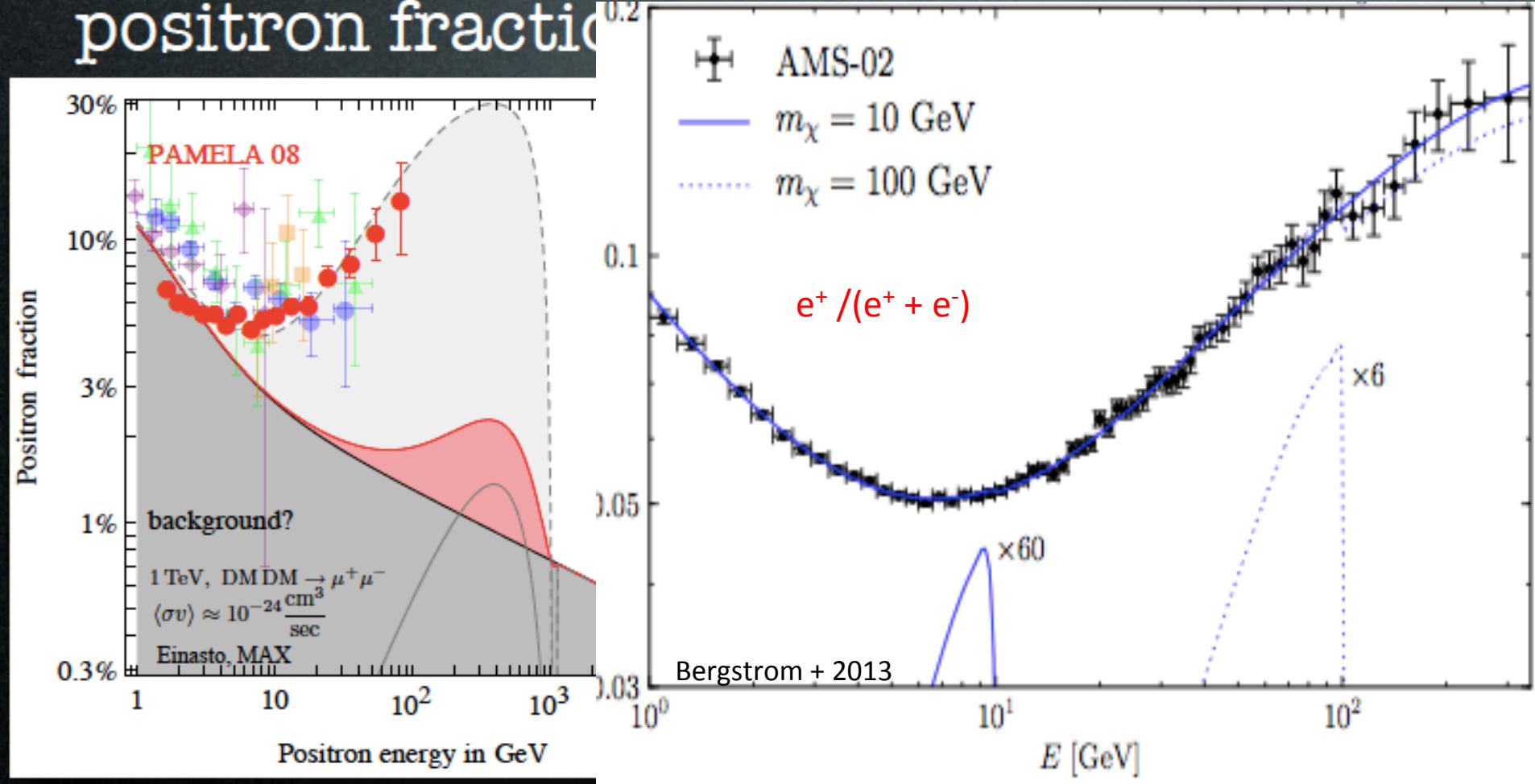
3b

Astron.

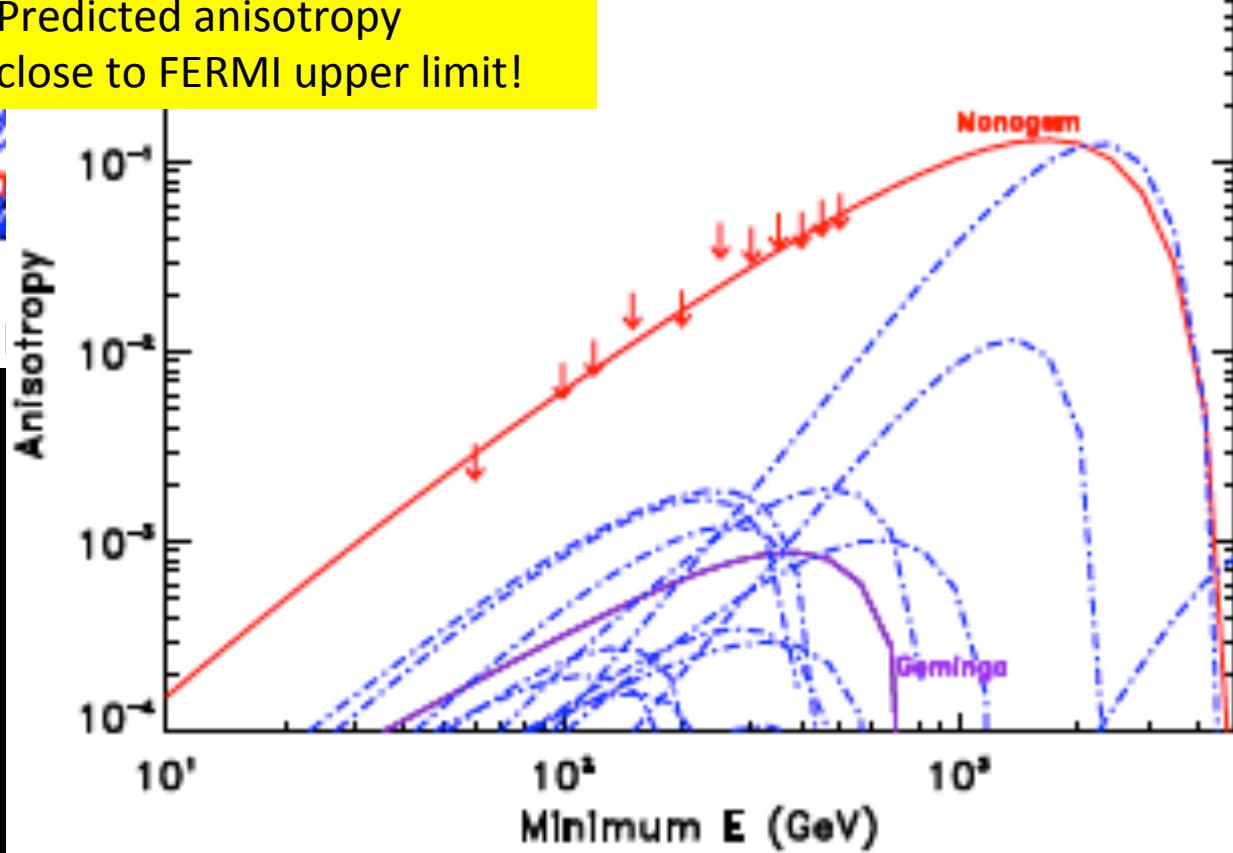
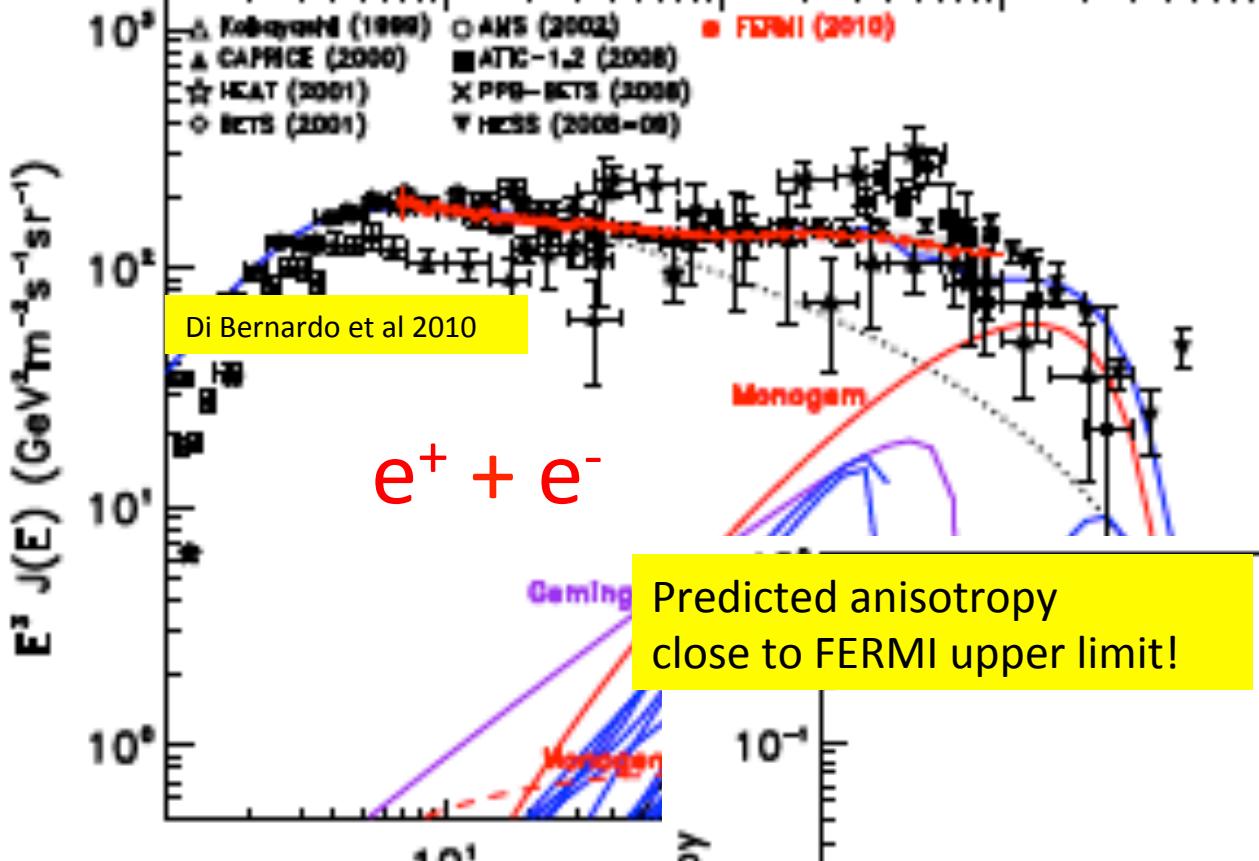


# The dark matter view

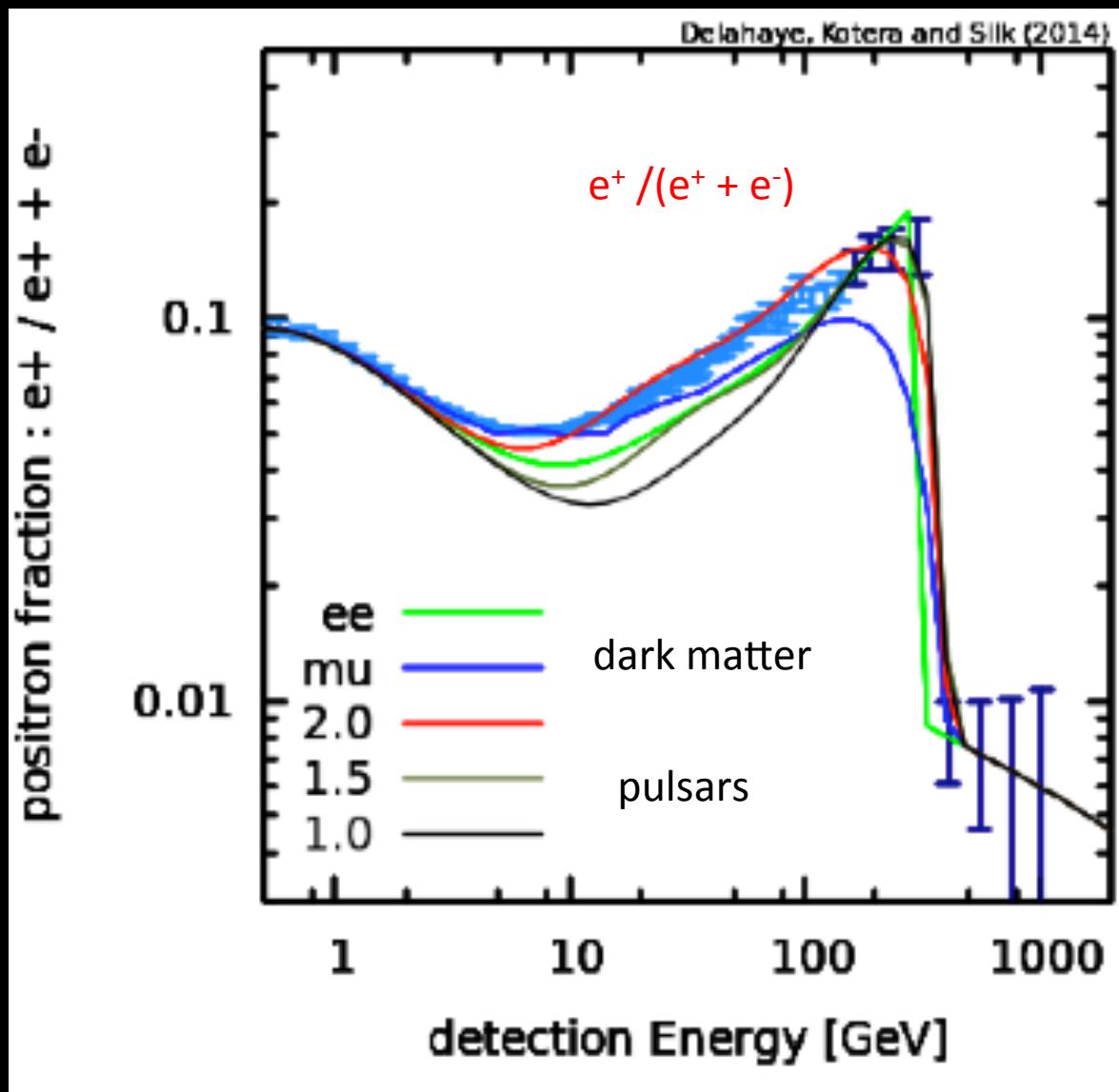
## positron fraction



astrophysical origin  
via PULSAR WIND



cannot distinguish the two..whatever AMS finds!



1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

stars

positrons

$\gamma$  rays

3C

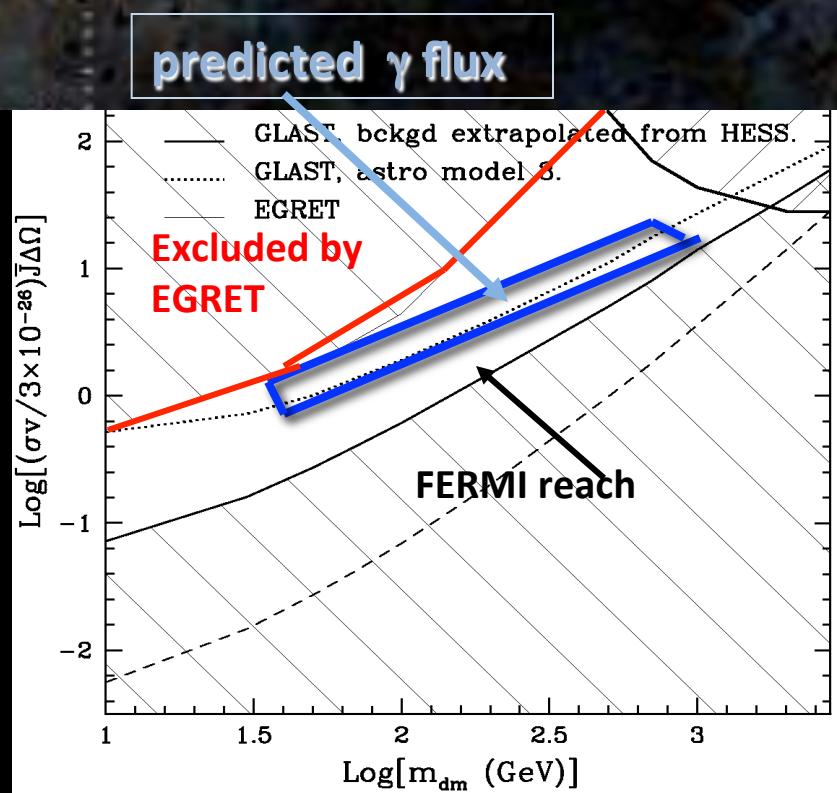
# Radio synchrotron emission

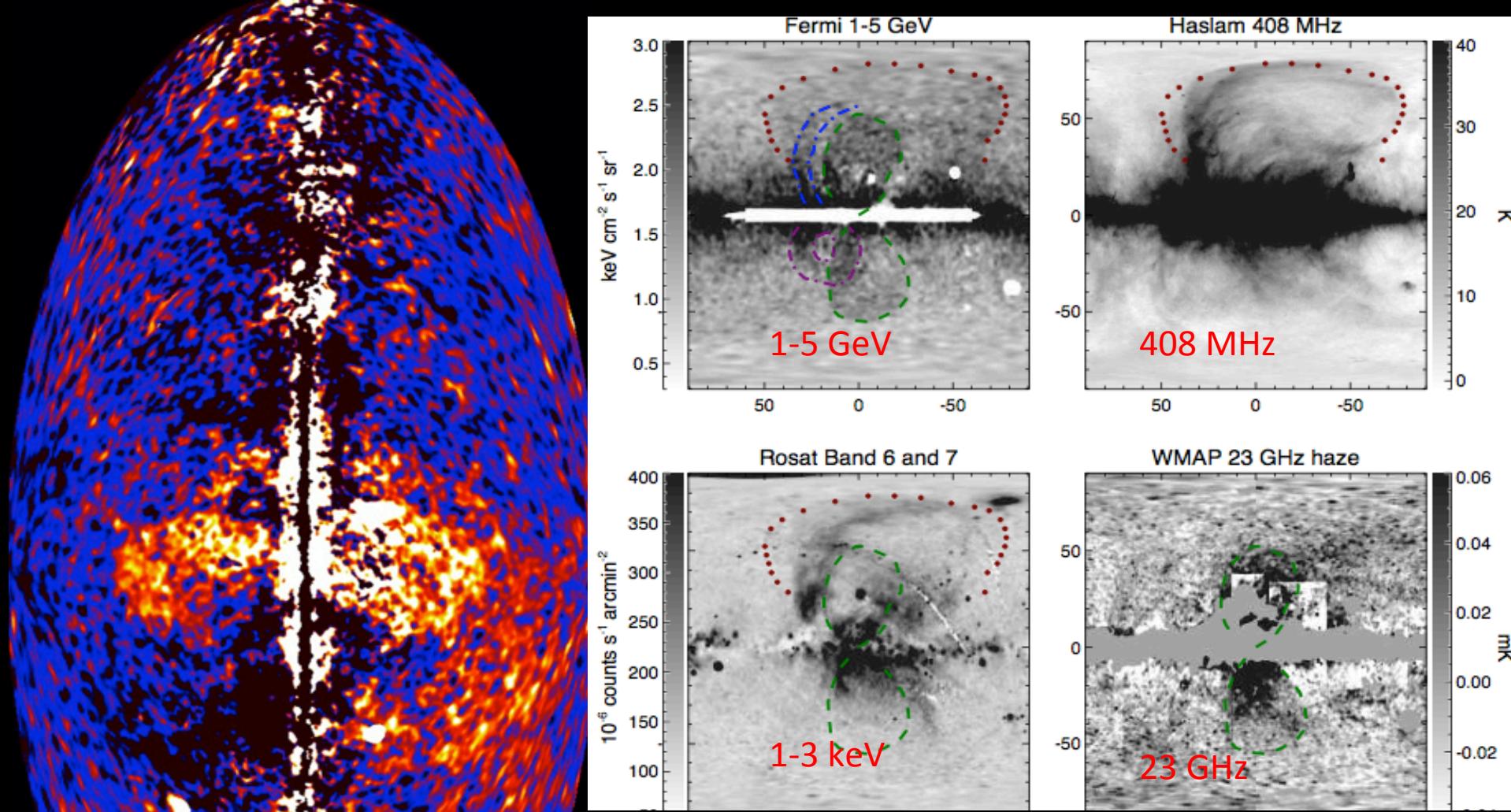
## The WMAP microwave haze

Finkbeiner 2007



Hooper and Zaharias 2007





# Giant gamma ray bubbles ...not dark matter

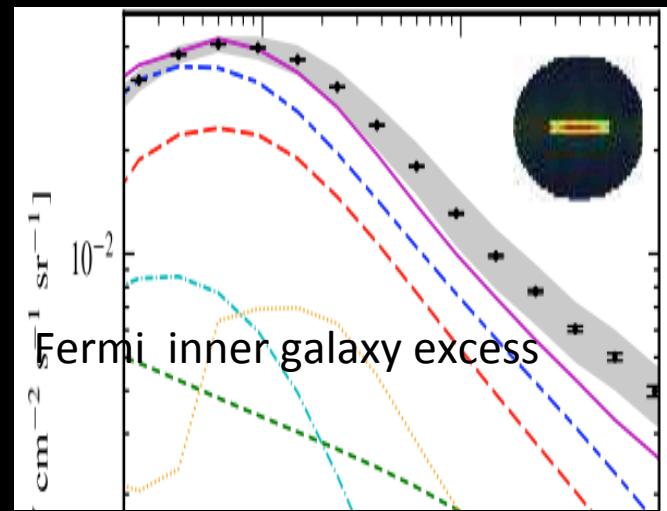
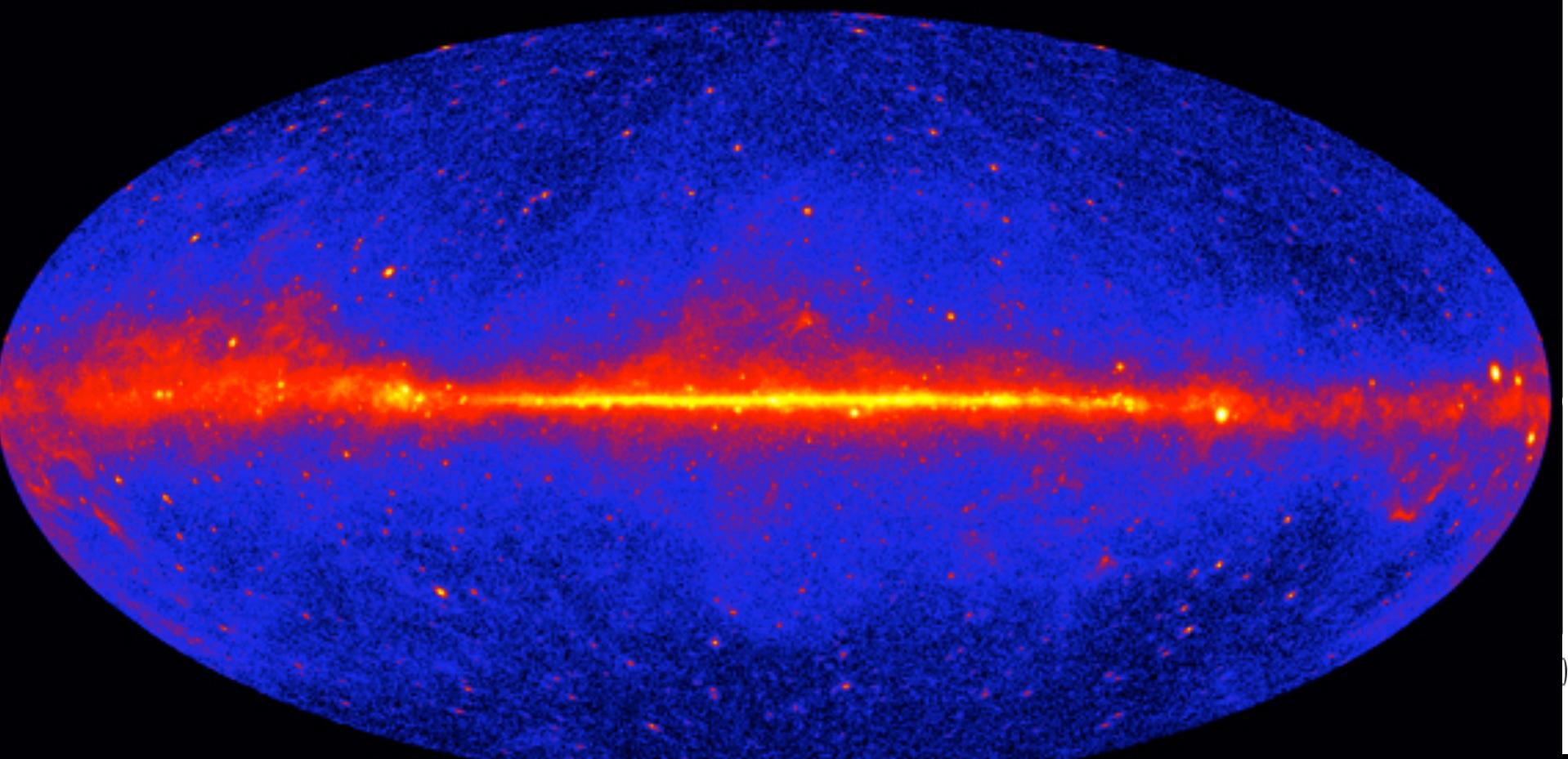
Fermi haze is inverse Compton of e<sup>+</sup>e<sup>-</sup> on interstellar radiation

Via Lactea 2 simulation  
( $10^9$  particles of  $4000 M_\odot$ )

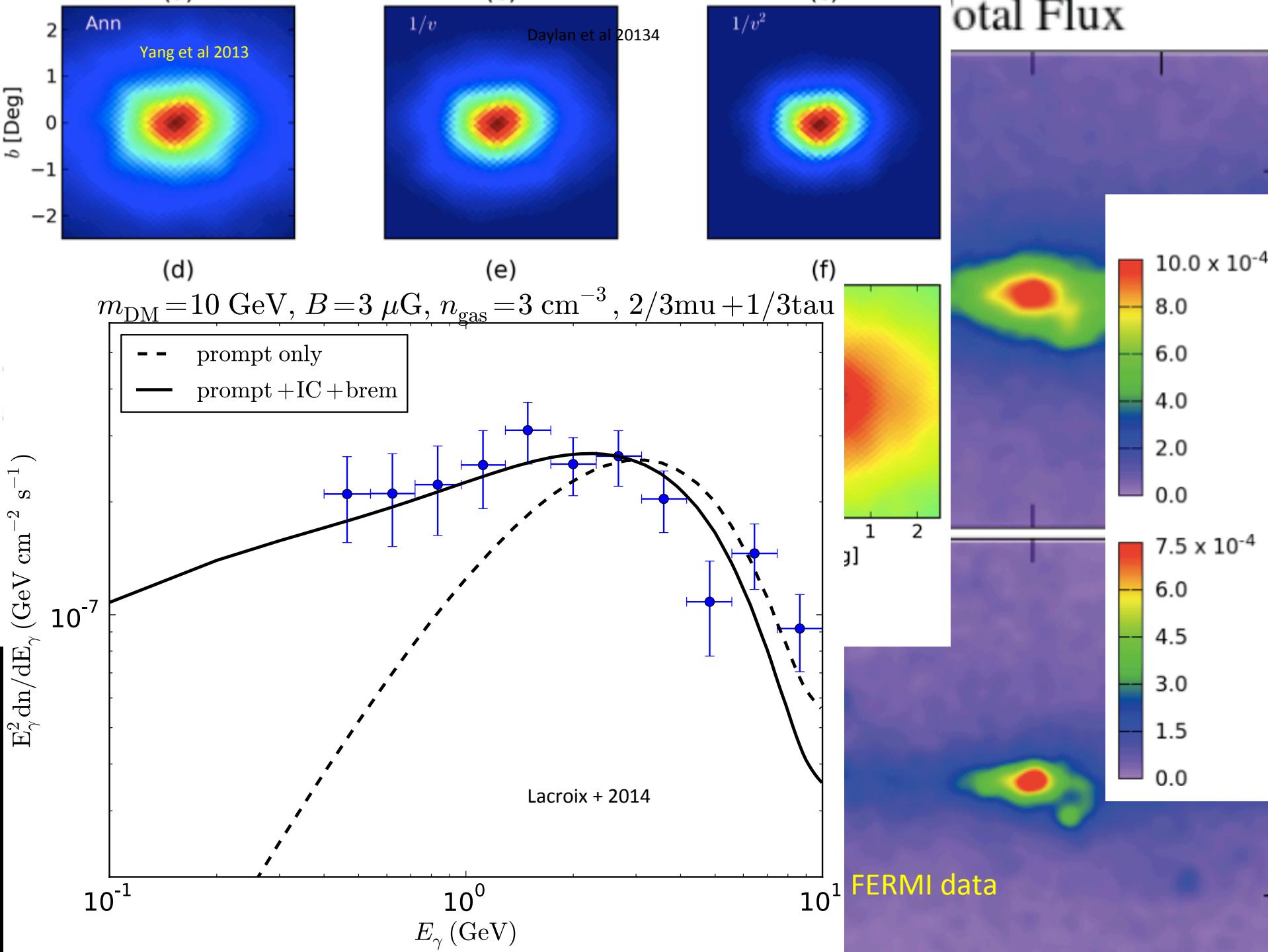


Fermi inner galaxy excess

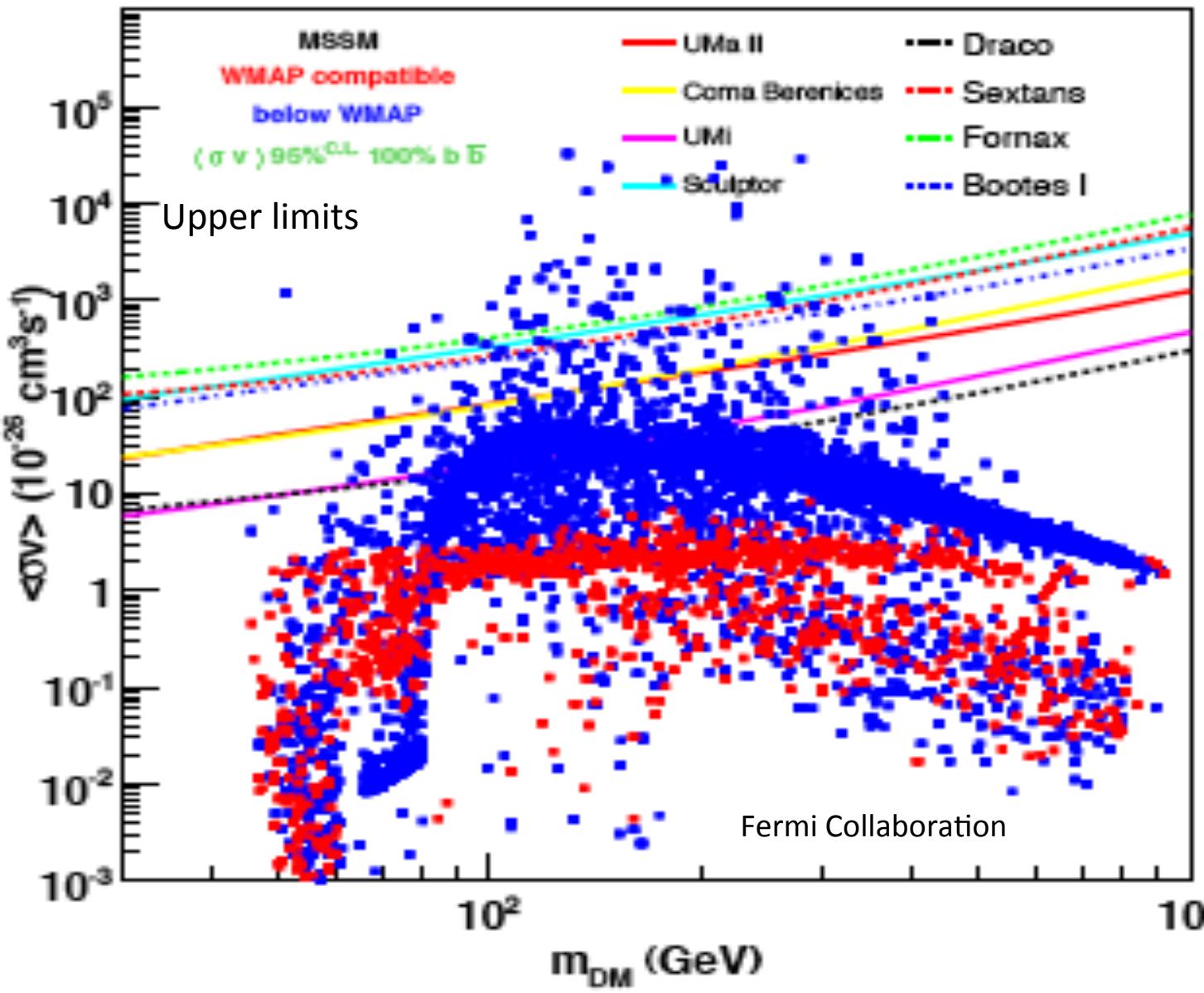
DM renderings by Lin Yang (2013)



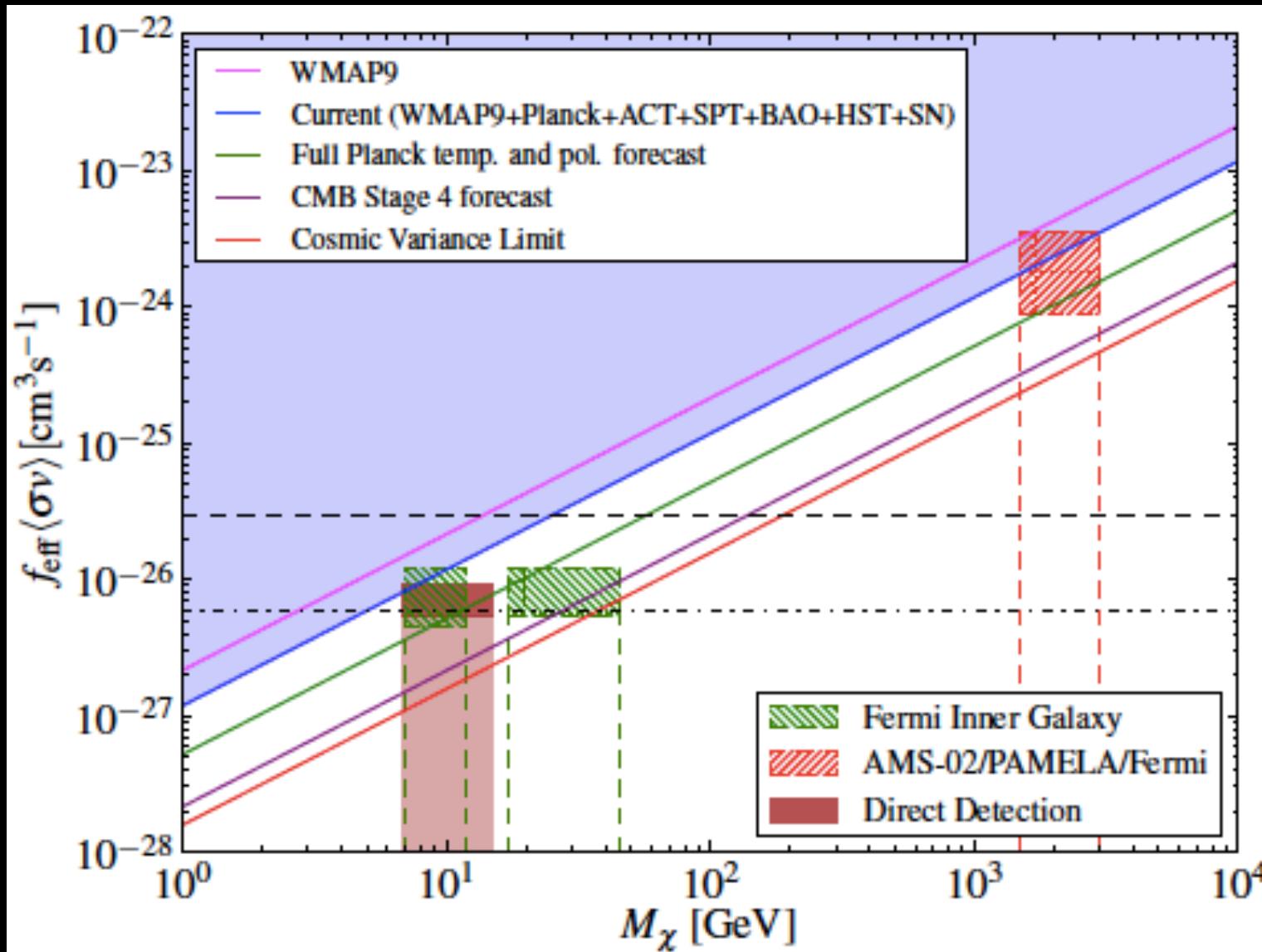
THE GALACTIC CENTER 7°x7°



If GC is DM signal, then we should soon detect dwarf spheroidal galaxies: ideal DM laboratories



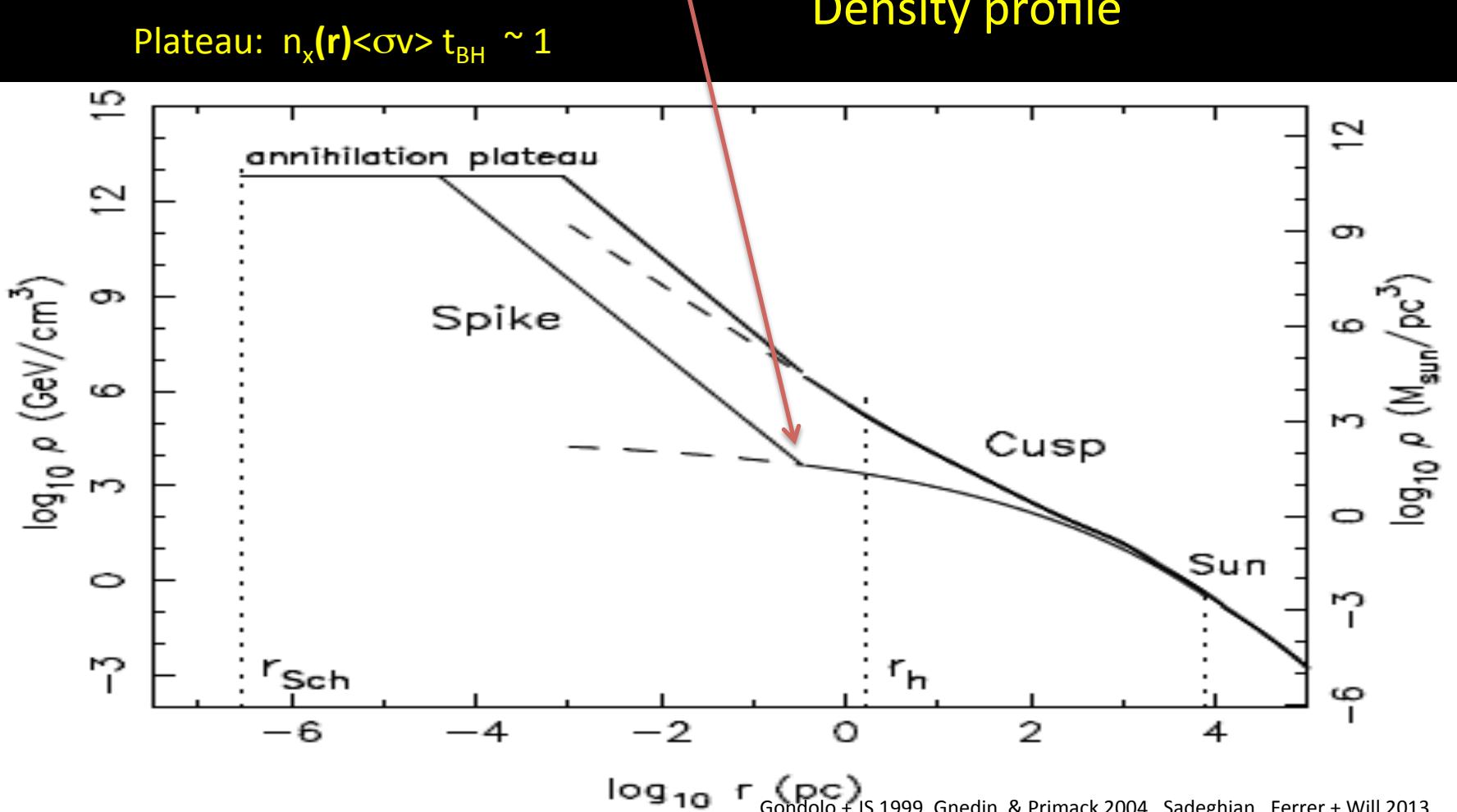
# CMB



# Dark Matter around our SMBH

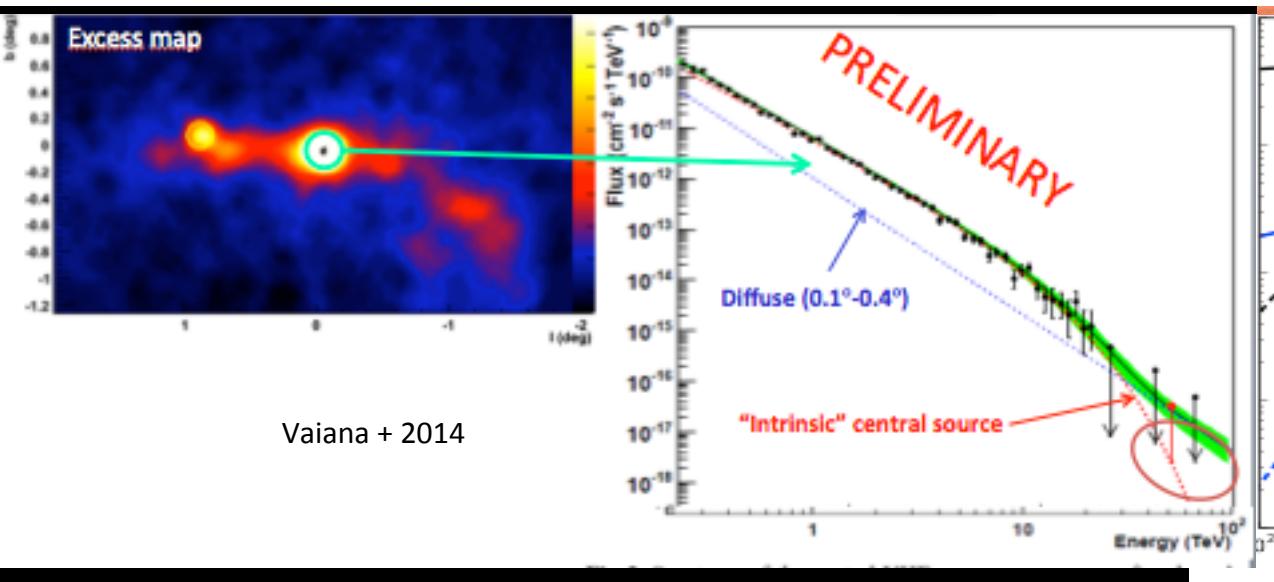
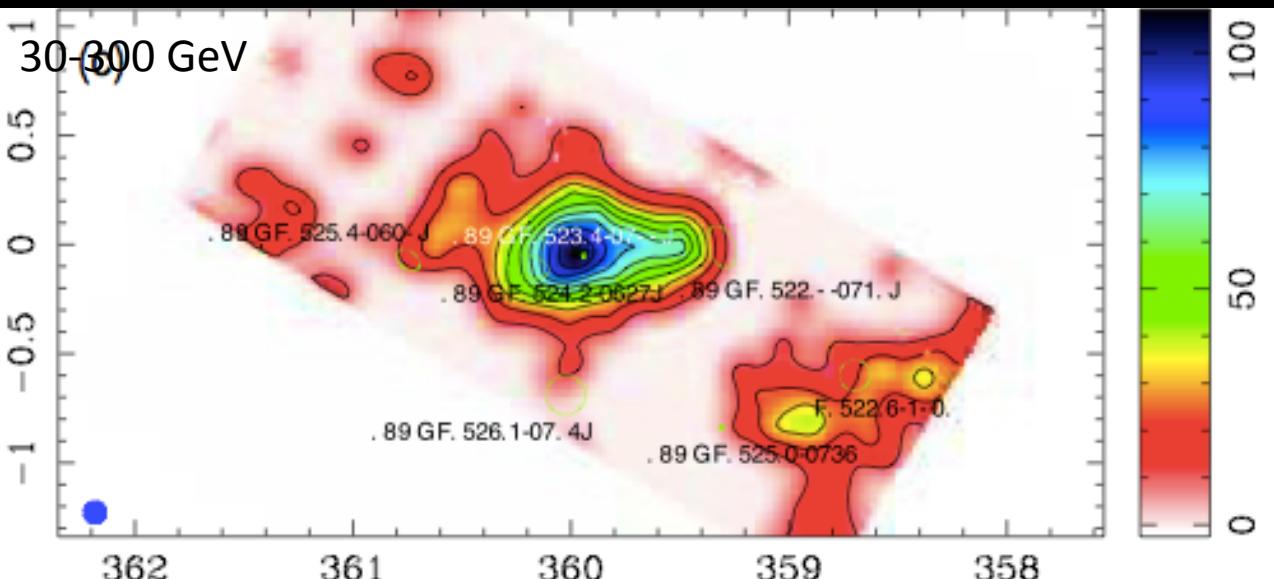
CDM cusp steepens by adiabatic growth  
of IMBH:  $\rho \propto r^{-\gamma} \Rightarrow \rho \propto r^{-\gamma'}$ , with  $\gamma' = \frac{9-2\gamma}{4-\gamma}$

Annihilation rate is amplified within a  
radius  $GM_{bh}/\sigma^2 \sim 0.003(M_{BH}/10^5 M_\odot) \text{pc}$



# supermassive black hole at Galactic Center

prediction for CTA: superexponential signature of TeV DM annihilations



Vaiana + 2014

# NEARBY AGN

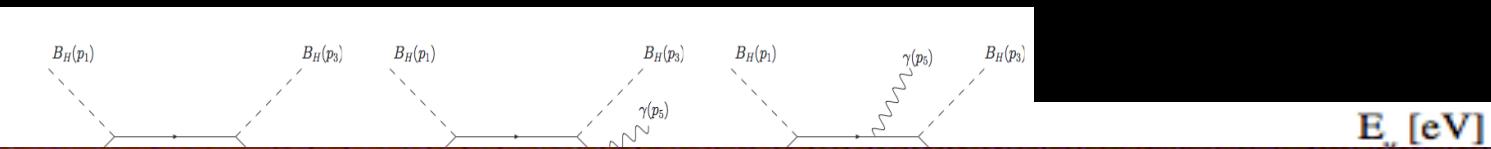
M87 is an attractive target

Distance 2000 x GC but  $M_{BH}$  1000 x SagA\*

Flux  $\sim n_x^2 \langle \sigma v \rangle (2r_p)^3 \sim M_{BH}^3 / \langle \sigma v \rangle$  for low  $\langle \sigma v \rangle$   
 $n_x(r_p) \langle \sigma v \rangle t_{BH} \sim 1$

Dynamical heating of spike  $\sim 10^{14}$  yr vs  $10^9$  yr (GC)

relativistic jets emanate from ergosphere, so  
high energy e,p collide with DM spike particles



1. ASTROPHYSICAL CONSTRAINTS
2. DIRECT DETECTION
3. INDIRECT DETECTION

stars

positrons

$\gamma$  rays

supermassive black holes

3d

# THE EXTRAGALACTIC $\gamma$ RAY BACKGROUND

# THE COSMIC $\gamma$ -RAY BACKGROUND FROM THE ANNIHILATION OF PRIMORDIAL STABLE NEUTRAL HEAVY LEPTONS

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Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center

*Received 1977 December 12; accepted 1978 February 14*

## ABSTRACT

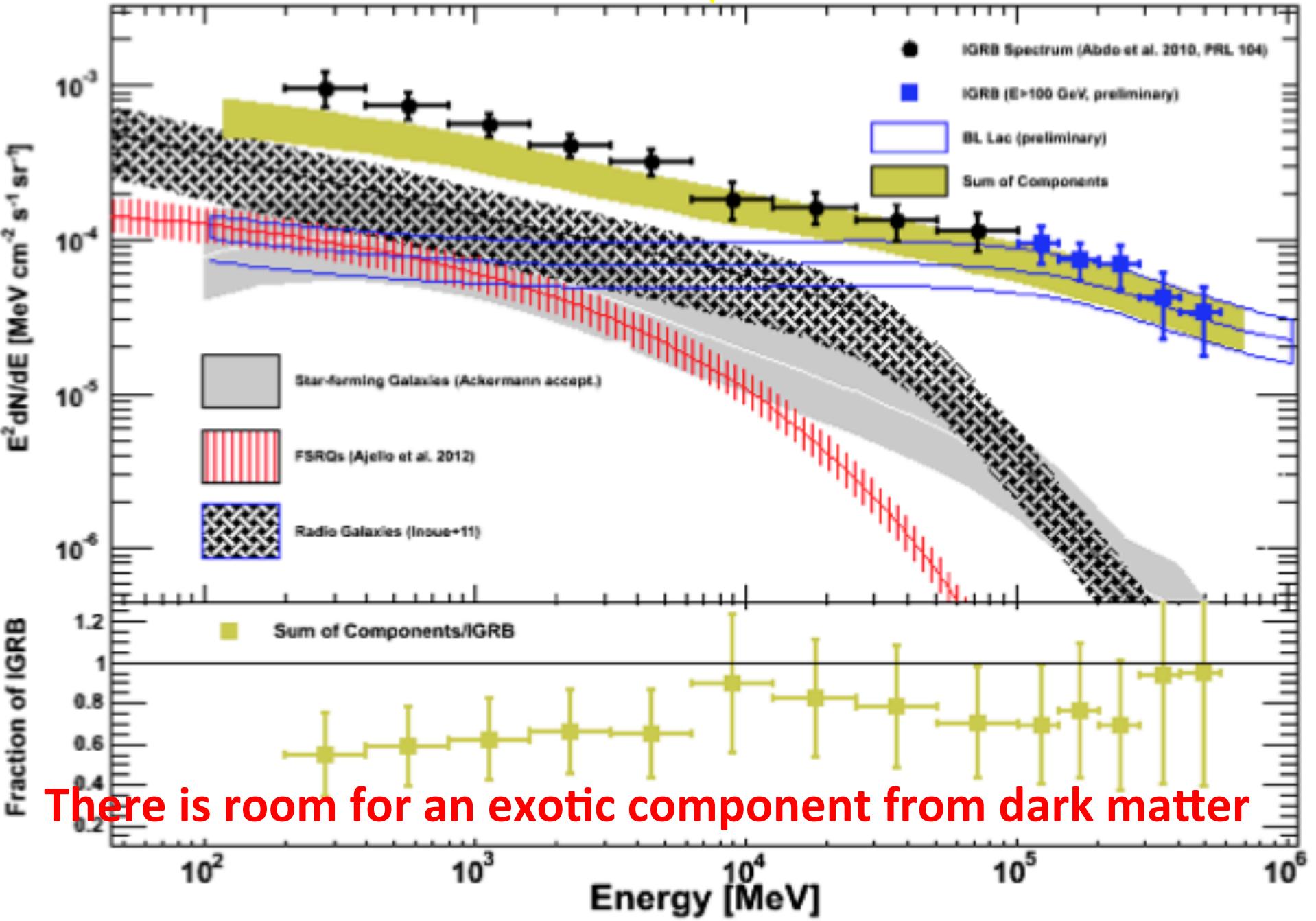
In light of the recent work on the astrophysical implications of the possible existence of stable neutral heavy leptons and the suggestion that continuing annihilation of heavy leptons produced in the big bang might produce a substantial cosmic  $\gamma$ -ray background radiation, we examine in detail the spectra and intensities of such radiation from (1) a homogeneous cosmic lepton background, (2) a possible lepton halo around the Galaxy, and (3) integrated background radiation from possible lepton halos around other galaxies and from rich galaxy clusters. In the case of our own galactic halo,  $\gamma$ -radiation from heavy-lepton annihilation appears to be able to account for the intensity of the observed background only if there are  $\sim 100$   $\gamma$ -rays produced per annihilation. However, in that case both the energy spectrum and isotropy would be inconsistent with the observations. More likely lepton annihilation fluxes from a galactic halo would be confused with cosmic-ray-produced radiation and therefore would be difficult to observe. Heavy-lepton annihilation radiation from the halos of other galaxies accounts for at most  $5 \times 10^{-3}$  of the background intensity, and those from rich clusters account for at most  $5 \times 10^{-5}$  of the background intensity. Those from a homogeneous cosmological lepton background appear to be able to account for  $\lesssim 10^{-4}$  of the observed cosmic  $\gamma$ -ray background, although the spectrum and isotropy in this case would be consistent with the data.

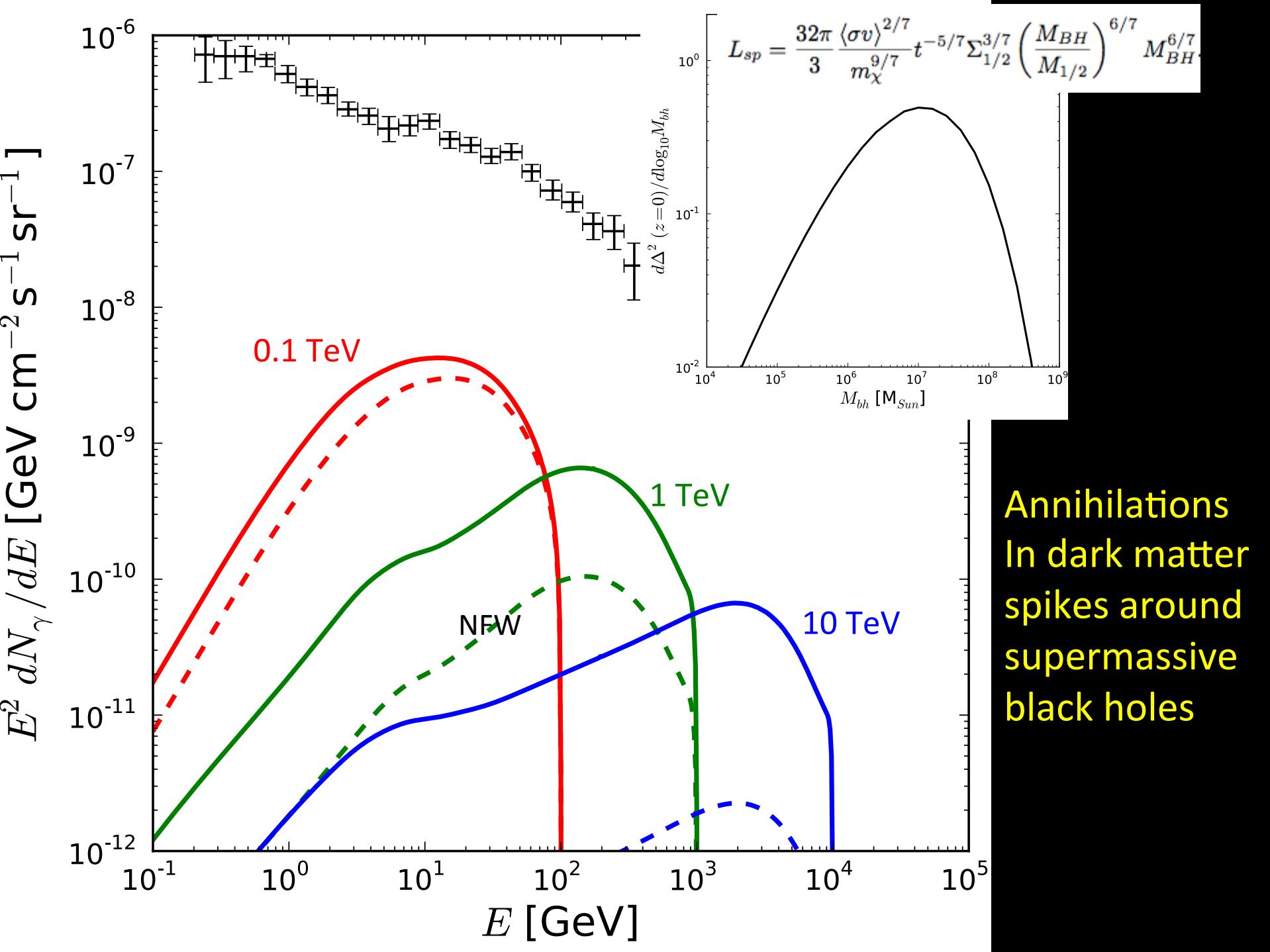
requirements are compared with objects that are intense in the infrared and millimeter bands (e.g., Seyfert nuclei and QSOs), and we show that radio-quiet QSOs might be the most suitable objects.

## ABSTRACT

The isotropic X-ray background may be interpreted by means of the superposed contributions from *normal* galaxies, provided that one takes into account evolutionary effects of the type suggested by the radio source counts.

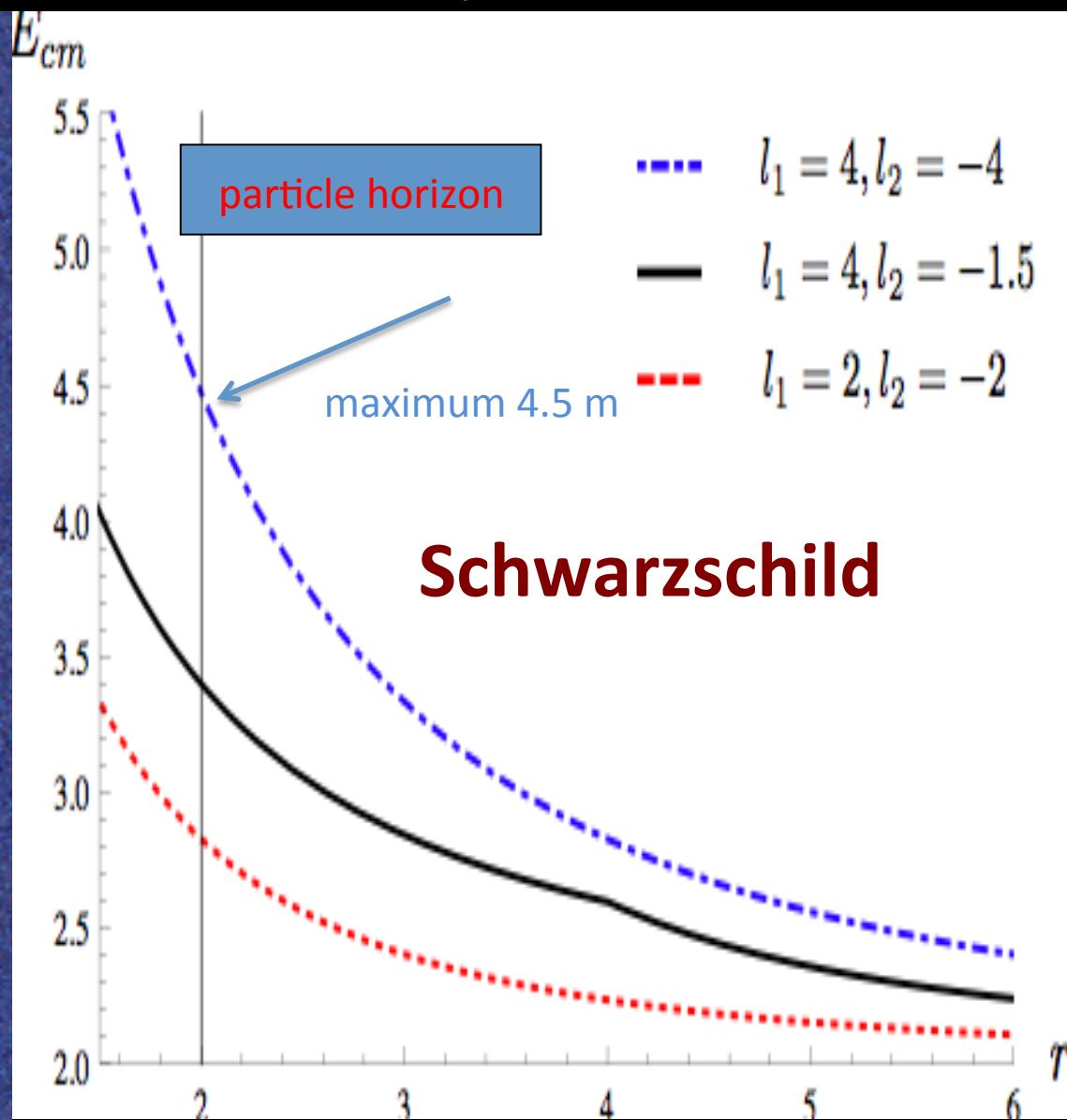
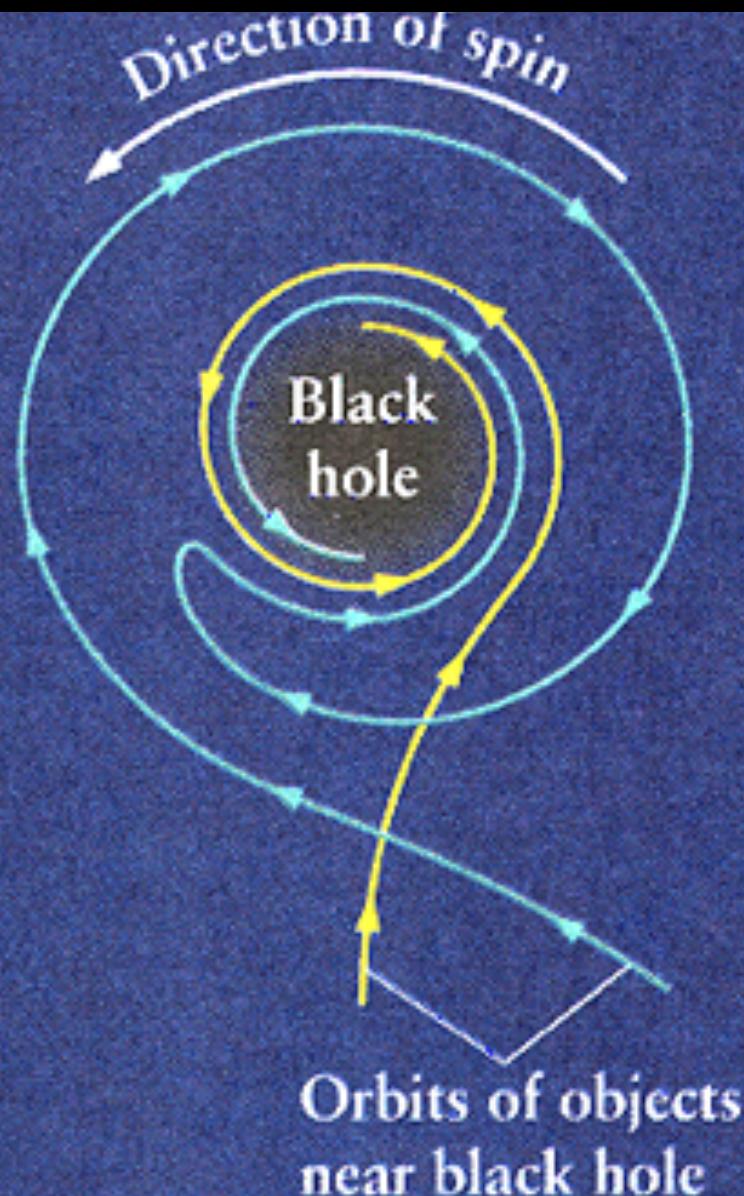
# EXTRACALACTIC DIFFUSE $\gamma$ RAY BACKGROUND





# BLACK HOLES

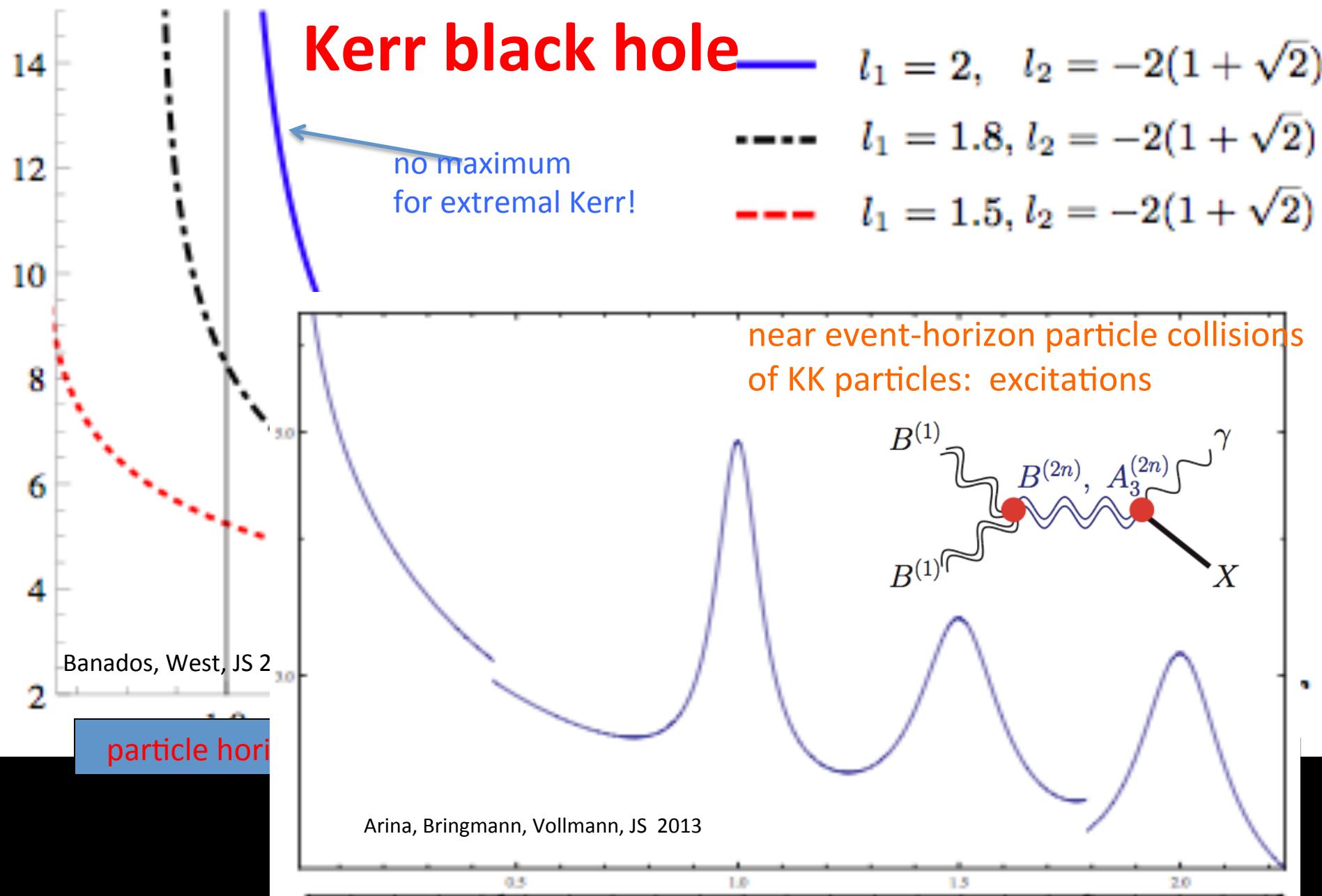
THE ULTIMATE PARTICLE ACCELERATOR: dark matter cusp around black hole



# NEAR KERR BLACK HOLES

Rotating black hole can feed Penrose effect via DM particle collisions

$E_{cm}$

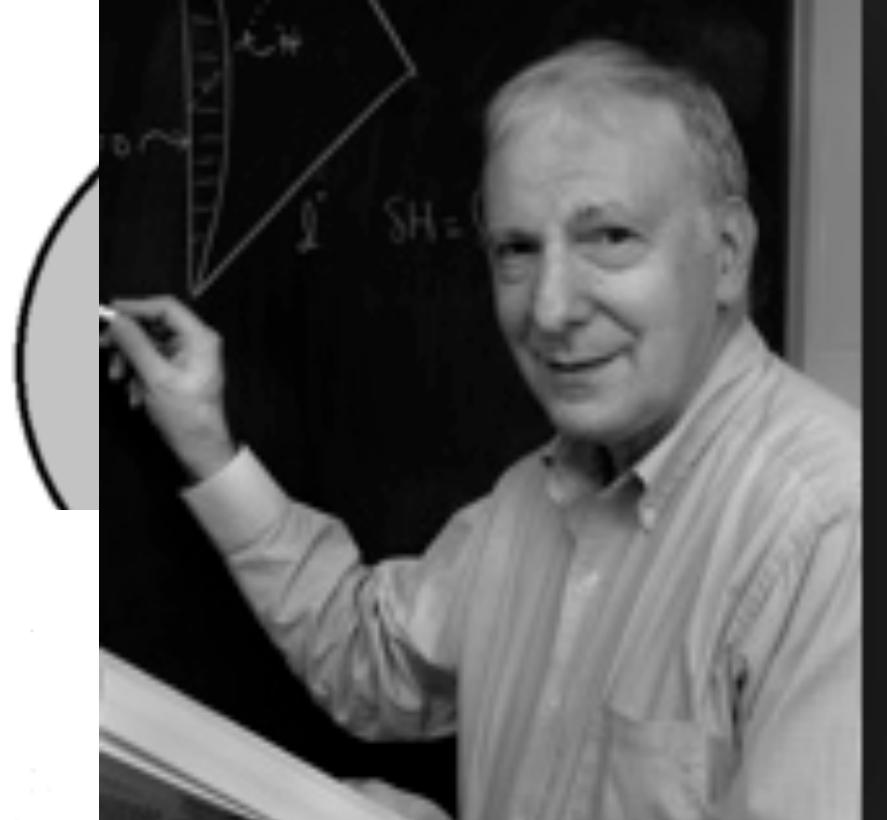


# Extraction of Rotational Energy from a Black Hole

THERE has been considerable interest recently in the gravitational collapse of a massive body and the astrophysical consequences of the existence of black holes which general relativity predicts should some of such a collapse. In particular, the question of whether the mass-energy content of a black hole could, in certain circumstances, be a source of available energy.

ASTROPHYSICAL JOURNAL, 191:231-233, 1974 July 1

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## ENERGY LIMITS ON THE PENROSE PROCESS

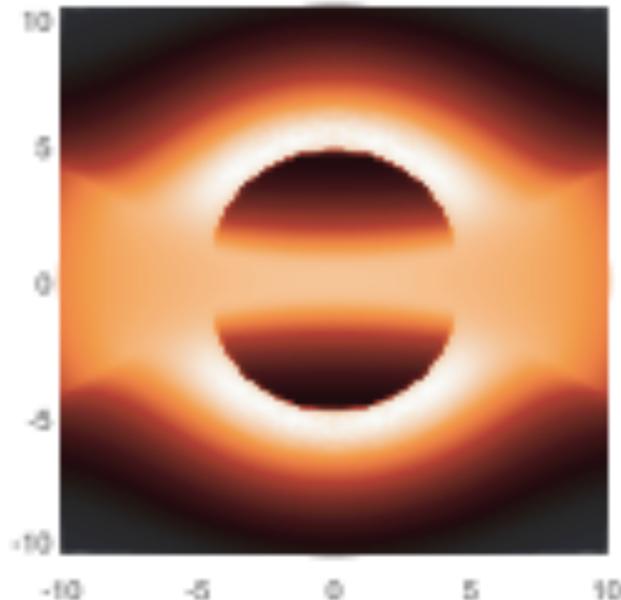
ROBERT M. WALD

Department of Physics and Astronomy, University of Maryland, College Park

*Received 1973 December 26*

### ABSTRACT

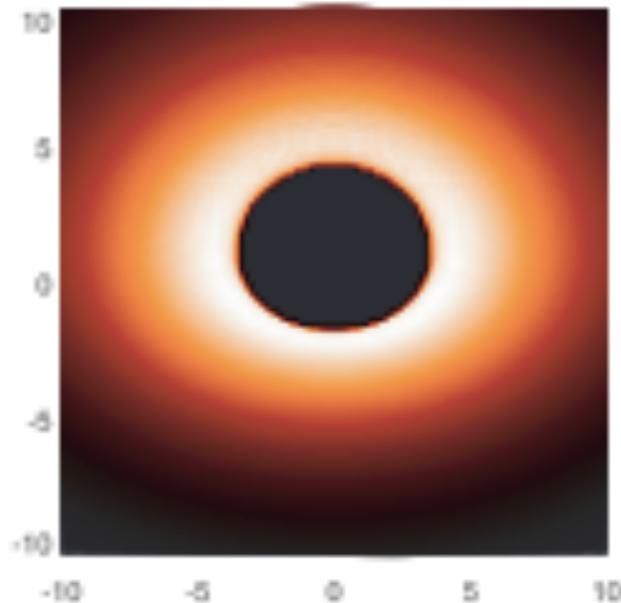
If a body in the vicinity of a rotating black hole breaks apart into two or more fragments, then under appropriate conditions the rotational energy of the black hole can be used to enhance the energy of one of the fragments (Penrose process). Wheeler and others have suggested that the Penrose process could serve as an energy mechanism for jets. In this paper we derive strict limits on the energies which can be achieved by the Penrose process. It is shown that in no case can one obtain energies which are greater by a significant factor than those which already could be obtained by a similar breakup process without the presence of a black hole.



# Black hole shadow

Event Horizon Telescope

Simulated image at 1mm  
 $\sim 10 \text{ GM/c}^2$  at  $50 \mu \text{ arcsec}$



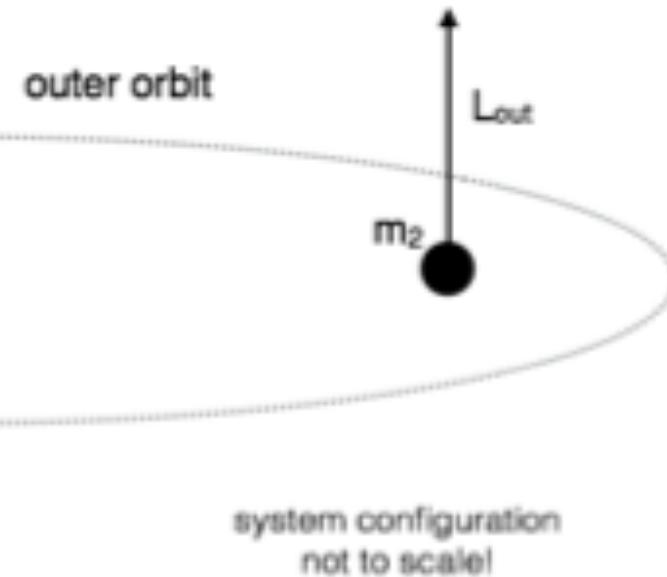
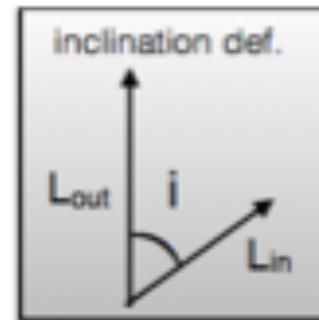
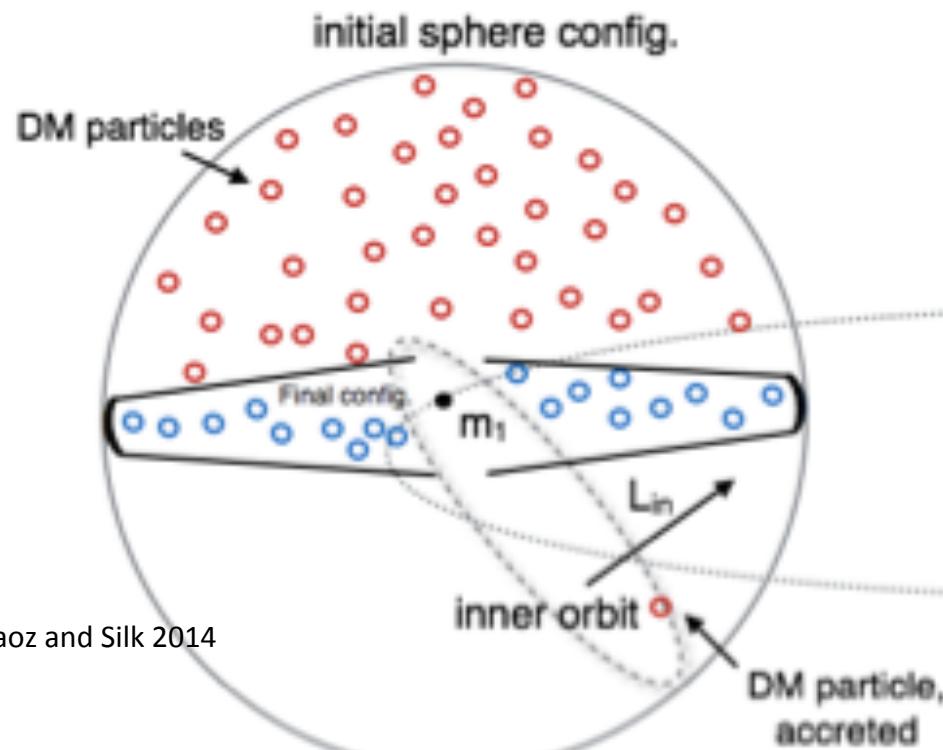
Huang + 2007

# NEAR BINARY BLACK HOLES

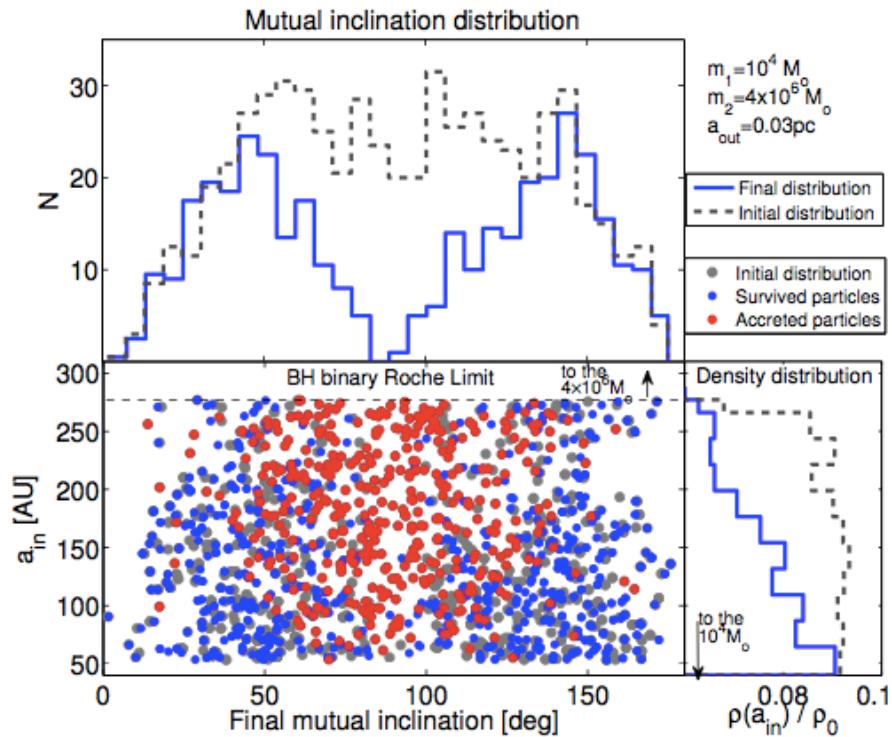
Kozai mechanism drives resonant infall of DM  
in eccentric orbits.....operates for binary black hole

Supermassive black holes don't merge!

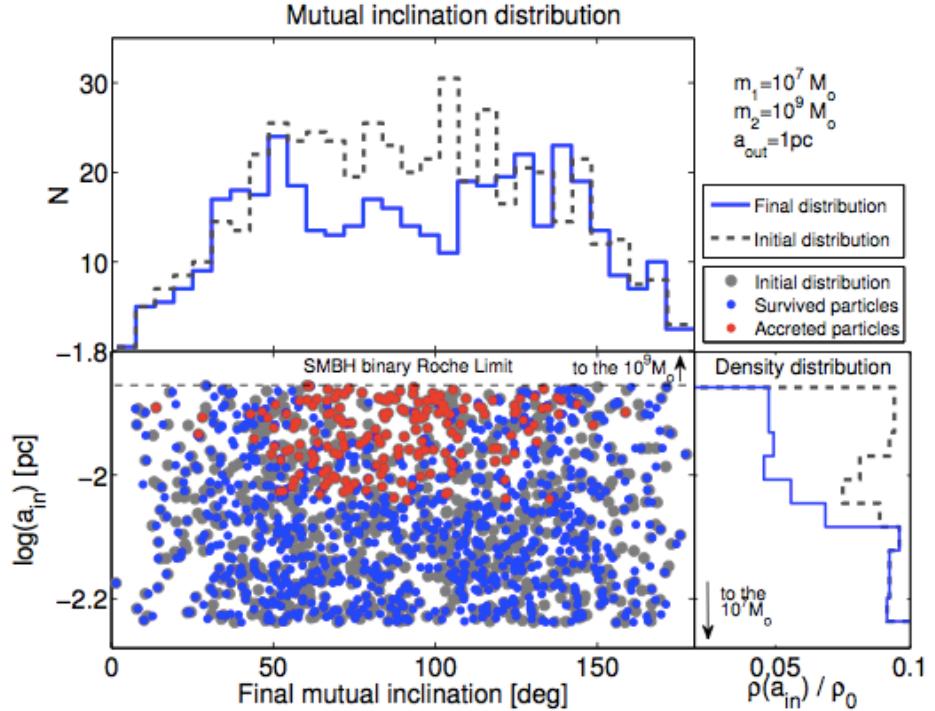
Tremaine



## Dark Matter Torii in BH binaries



**Figure 7.** The final DM particles around IMBH with a growing MBH. Results are shown after the MBH grows by a factor of  $\sim 2$ . Same convention as figure 3,  $a_{out} = 0.03 \text{ pc}$ , with MBH set initially to  $10^6 M_\odot$ . The plot shows the result of 1195 runs.



**Figure 8.** The final DM particles around SMBH after 1Gyr of evolution. We consider  $m_1 = 10^7 M_\odot$  at 1 pc from the  $m_2 = 10^9 M_\odot$ . Same as Figure 3. The plot shows the result of 1000 runs. Note that the horizontal axis of the bottom left panel shows the separation in units of pc and  $\log_{10}$ .

1. ASTROPHYSICAL CONSTRAINTS
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stars

positrons

$\gamma$  rays

supermassive black holes

galaxy clusters

3e

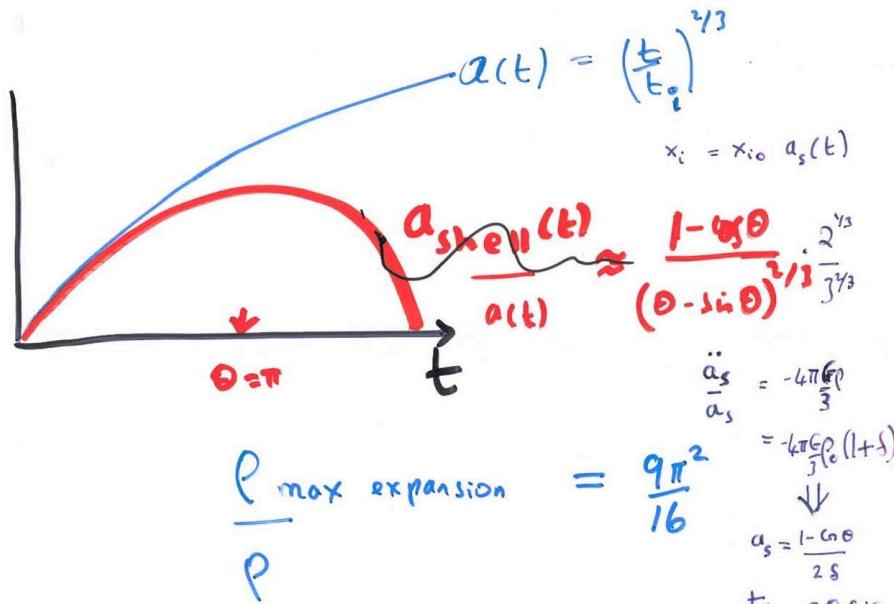
# Universal dark matter density profile

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2},$$

$$c_{\text{vir}} \equiv R_{\text{vir}}/r_s.$$

$\Delta_{\text{vir}} \simeq (18\pi^2 + 82x - 39x^2)/\Omega(z)$ , where  $x \equiv \Omega(z) - 1$ , and  $\Omega(z)$  is the ratio of mean matter density to critical density at redshift  $z$ .

## NONLINEAR SPHERICAL COLLAPSE



## FINAL RADIUS (no dissipation)

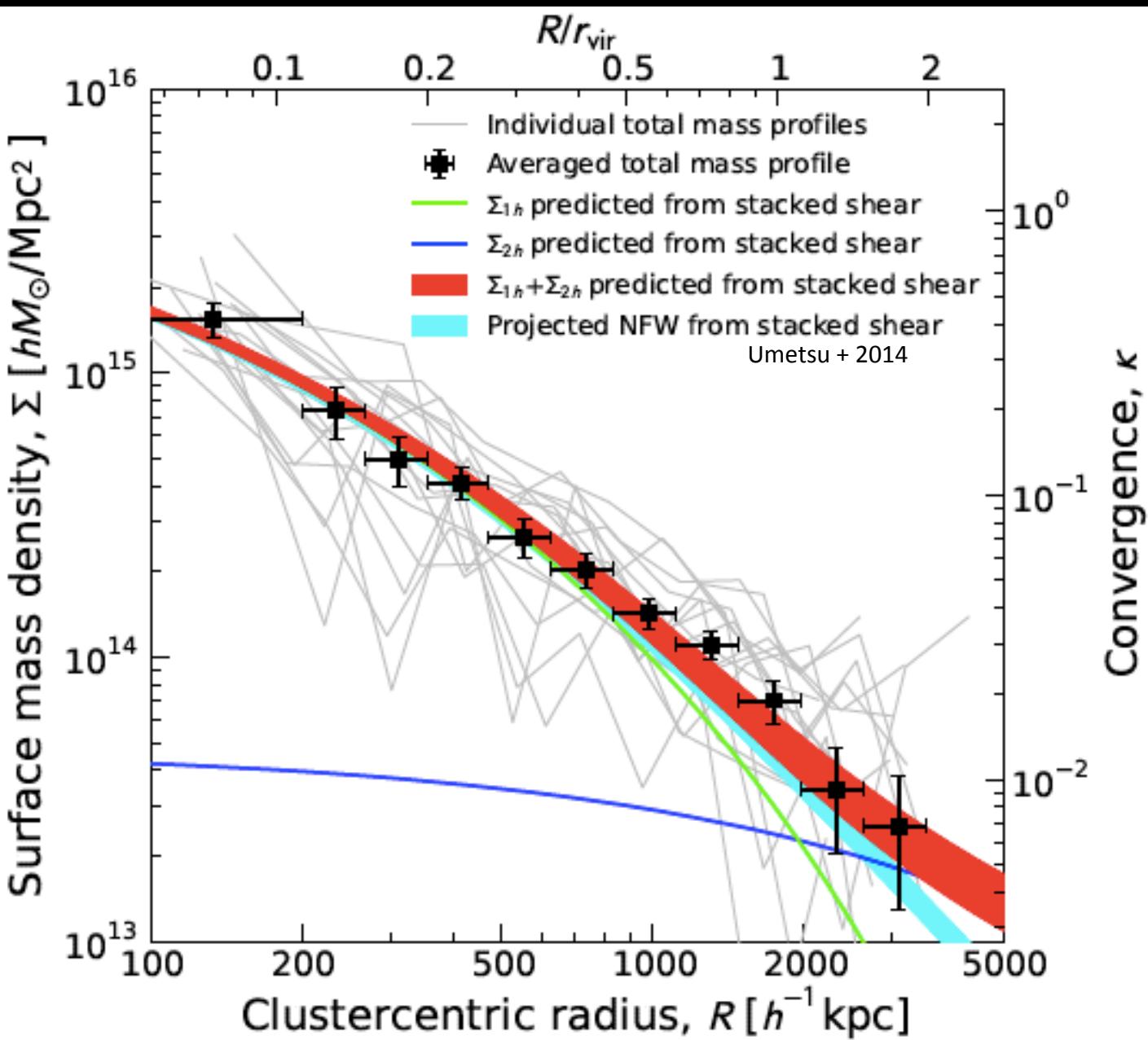
$$= \frac{1}{2} R_{\text{max}}$$

galaxy "formation" epoch  
 $= \frac{3\pi}{4} \delta_i^{-3/2} t_i$

"FINAL" ( $t_{\text{virialization}} = 2 t_{R_{\text{max}}}$ )

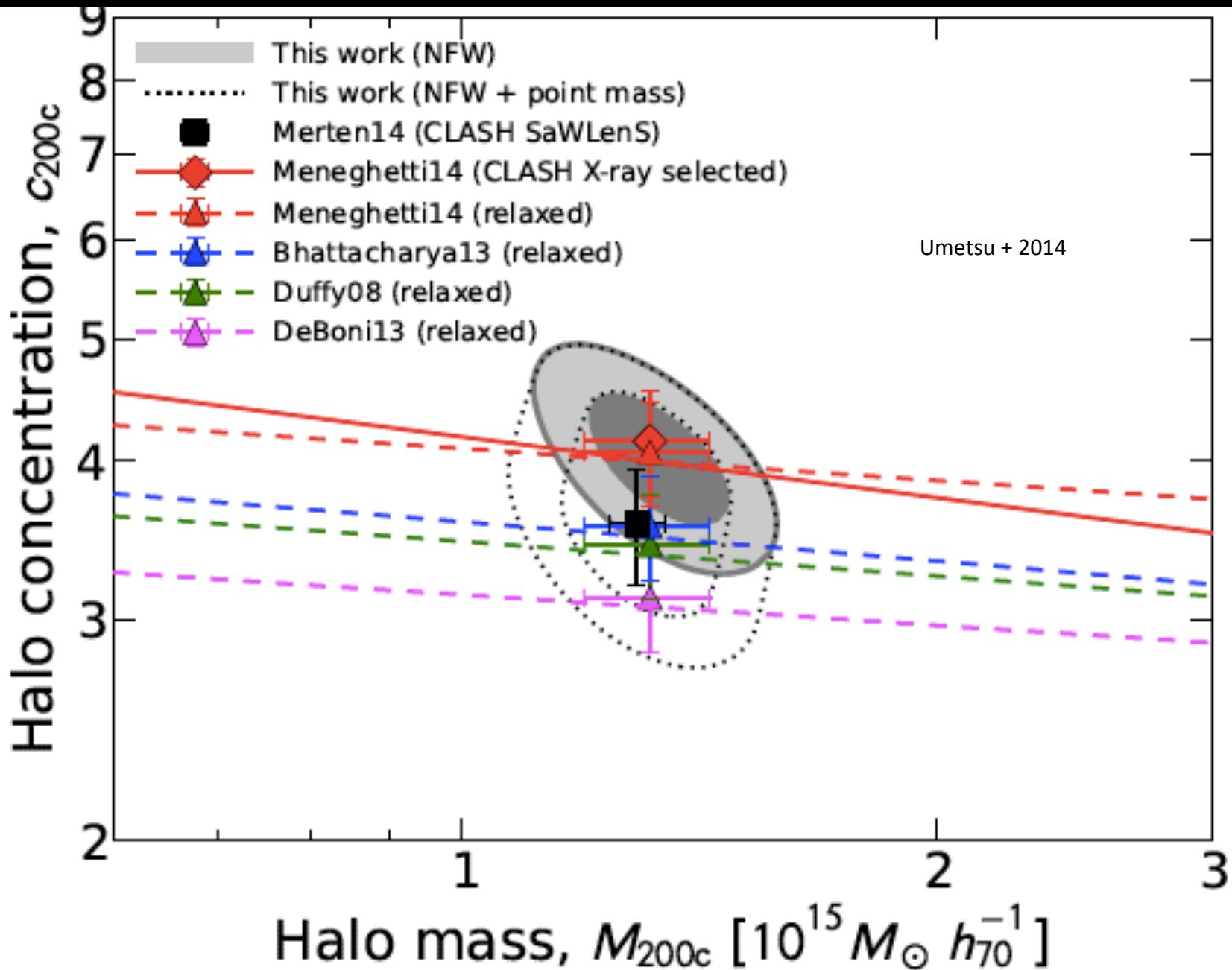
$$\frac{\rho_{\text{virial}}}{\rho(t_{\text{virial}})} = \frac{9\pi^2}{16} \times \frac{8}{\gamma_4} = 18\pi^2$$

# CLUSTER PROFILE

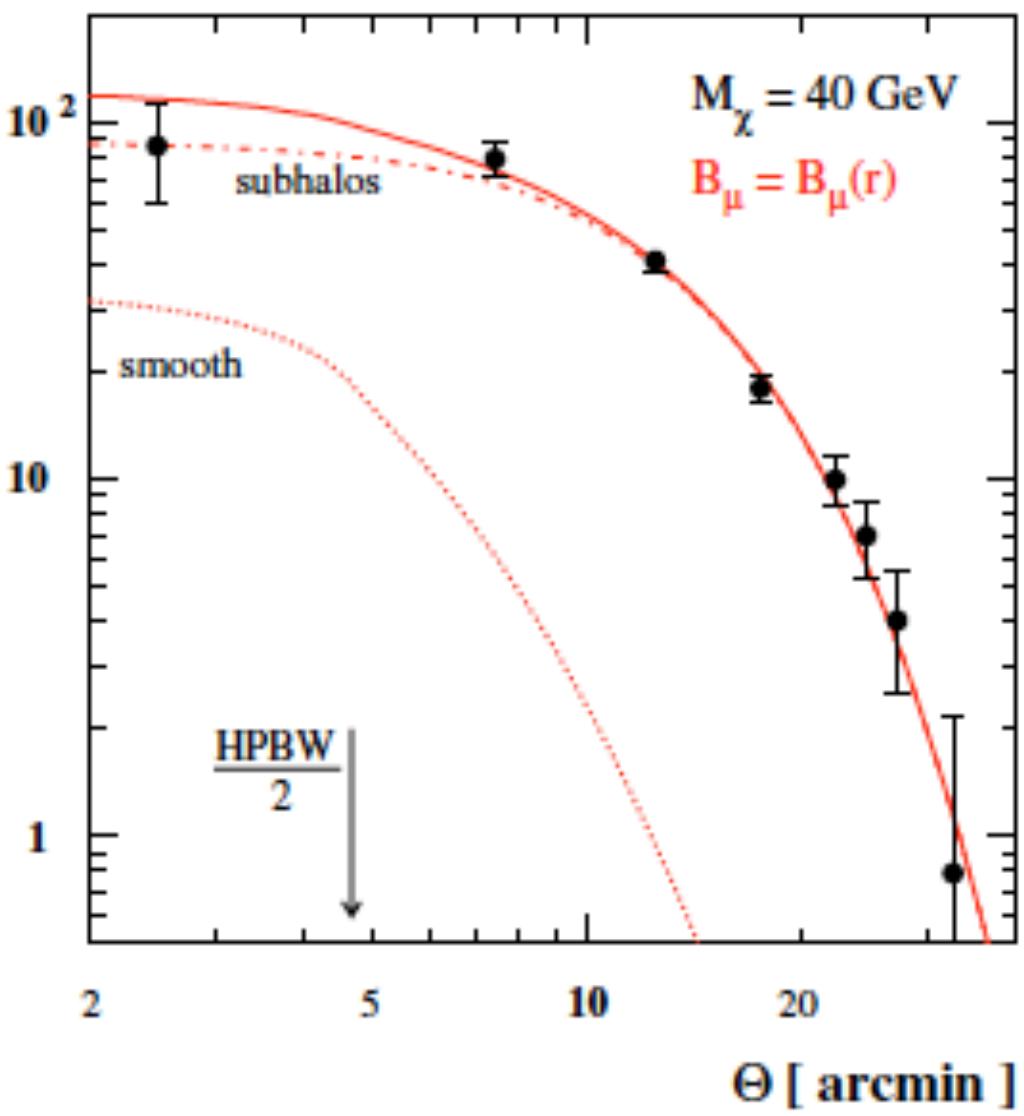
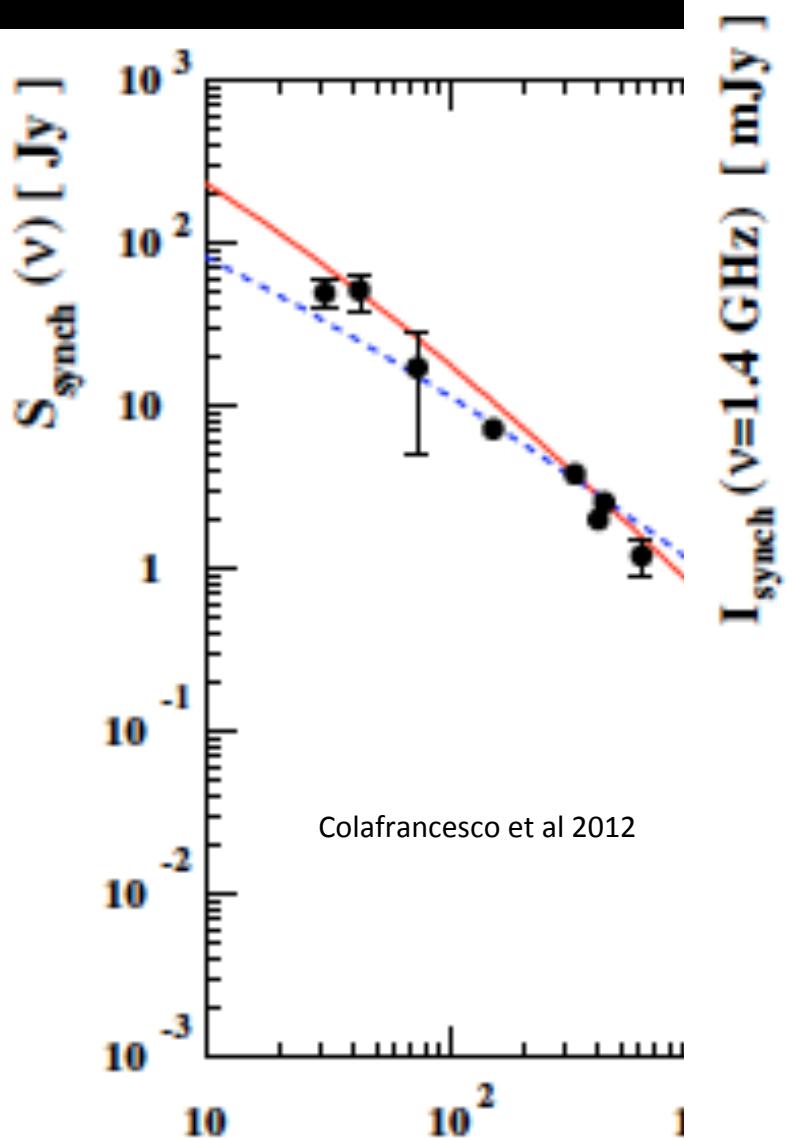


shear  
+magnification

# CLUSTER CONCENTRATION



# Fitting diffuse radio data for the COMA cluster of galaxies



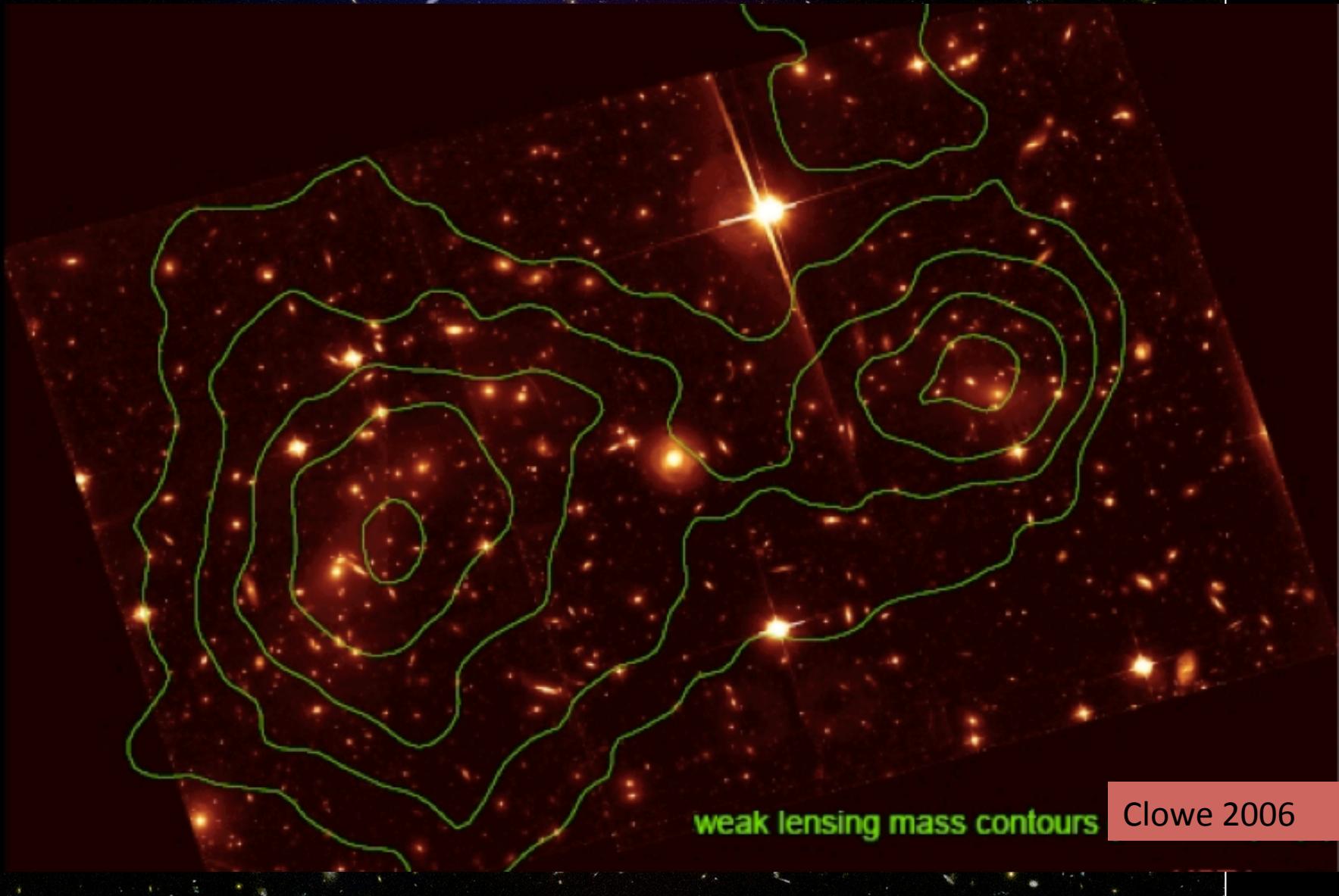
$$B(r) = B_0 \left(1 + \frac{r}{r_{c1}}\right)^2 \cdot \left[1 + \left(\frac{r}{r_{c2}}\right)^2\right]^{-\beta} \quad \text{with } B_0 = 0.55 \mu\text{G}, \beta = 2.7, r_{c1} = 3', r_{c2} = 17.5'$$

# SELF-INTERACTING DARK MATTER

If dark matter self-interacts with cross-section  $0.1\text{-}1 \text{ cm}^2/\text{g}$ , dwarf bulges are cored

clusters constrain this via multiple components and shape

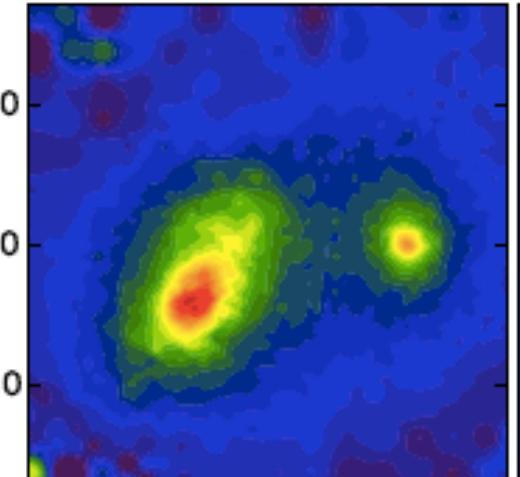
# BULLET CLUSTER



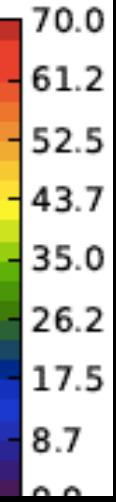
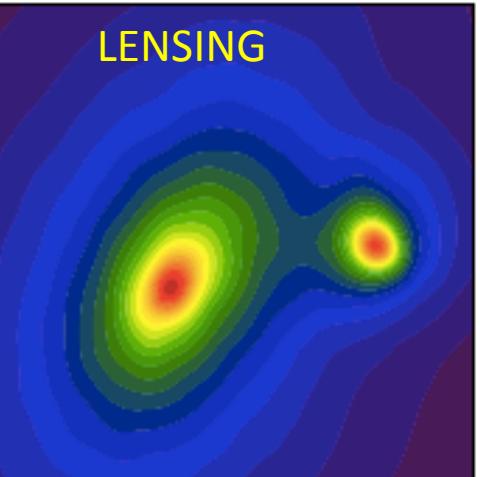
weak lensing mass contours

Clowe 2006

Data

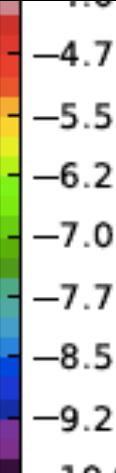
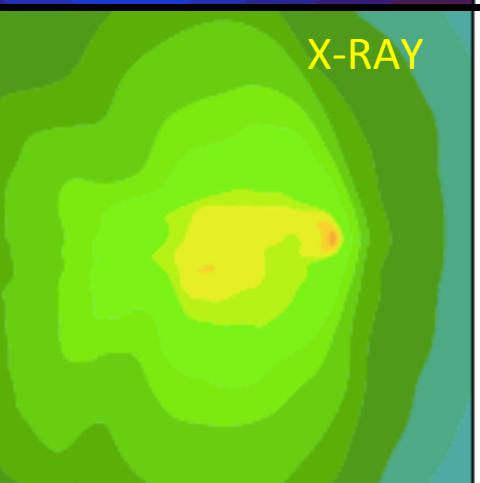
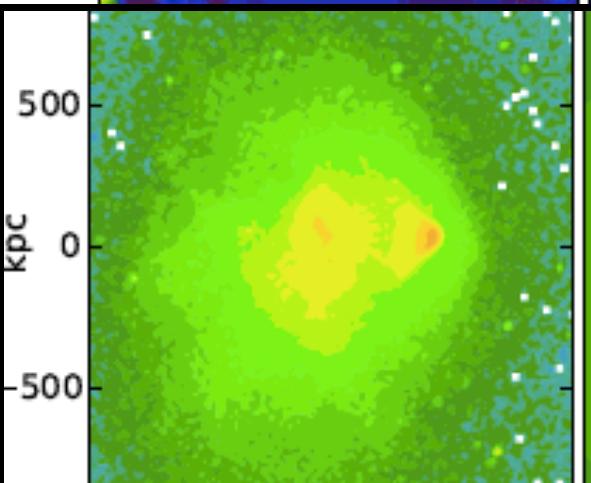


Simulation



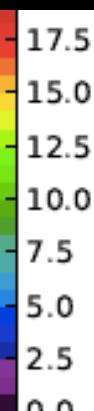
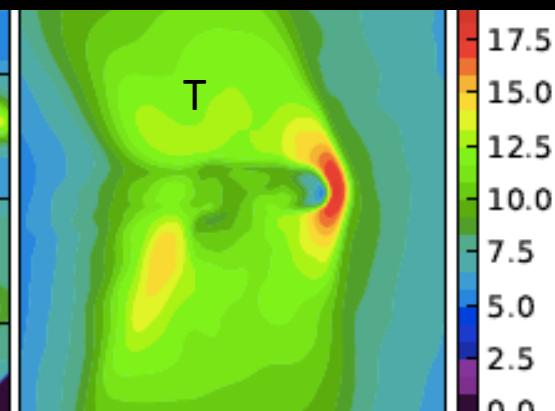
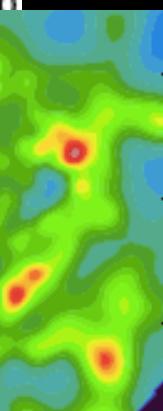
Lage &amp; Farrar 2014

# CDM accounts for Bullet Cluster

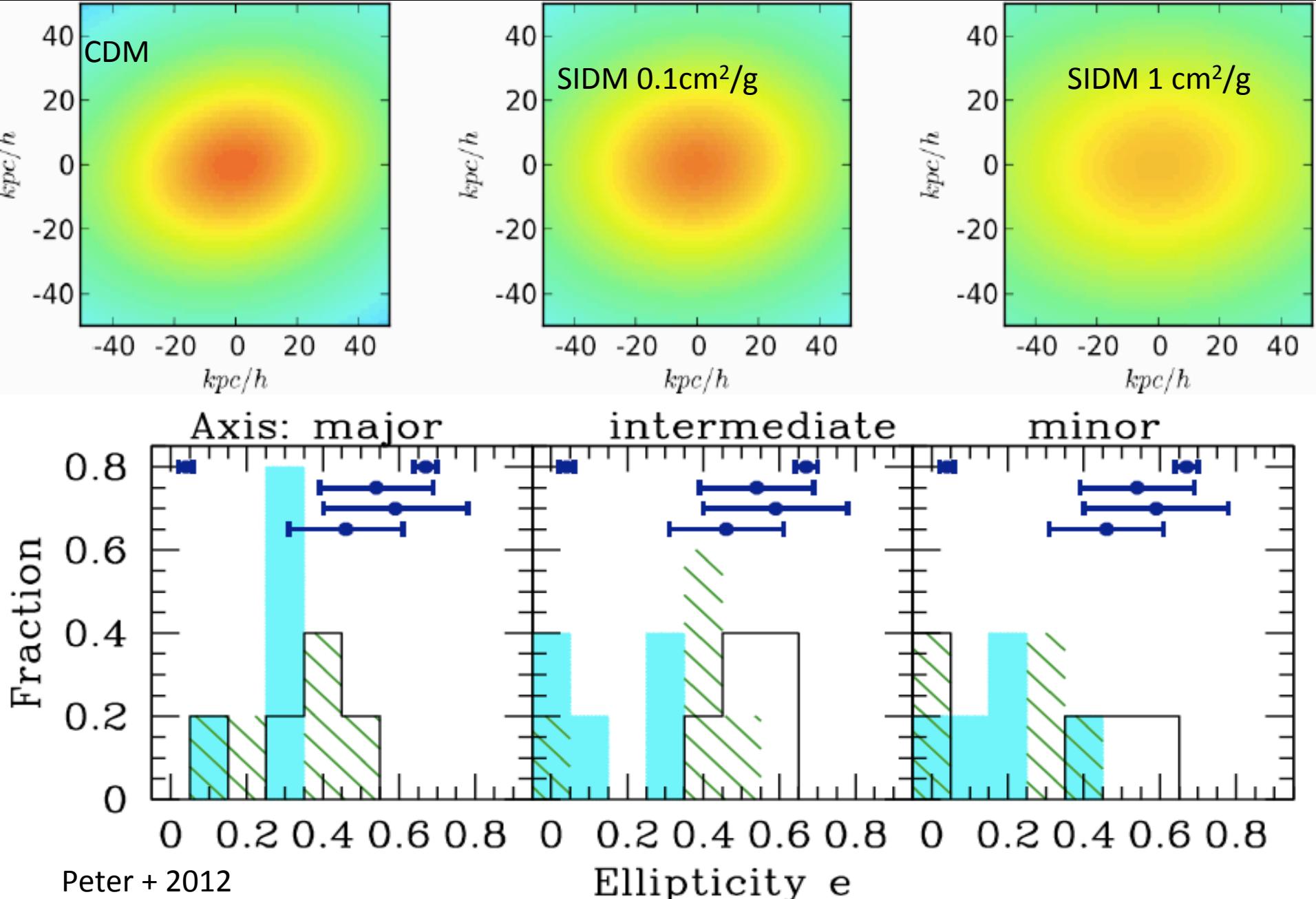


SZ

SZ

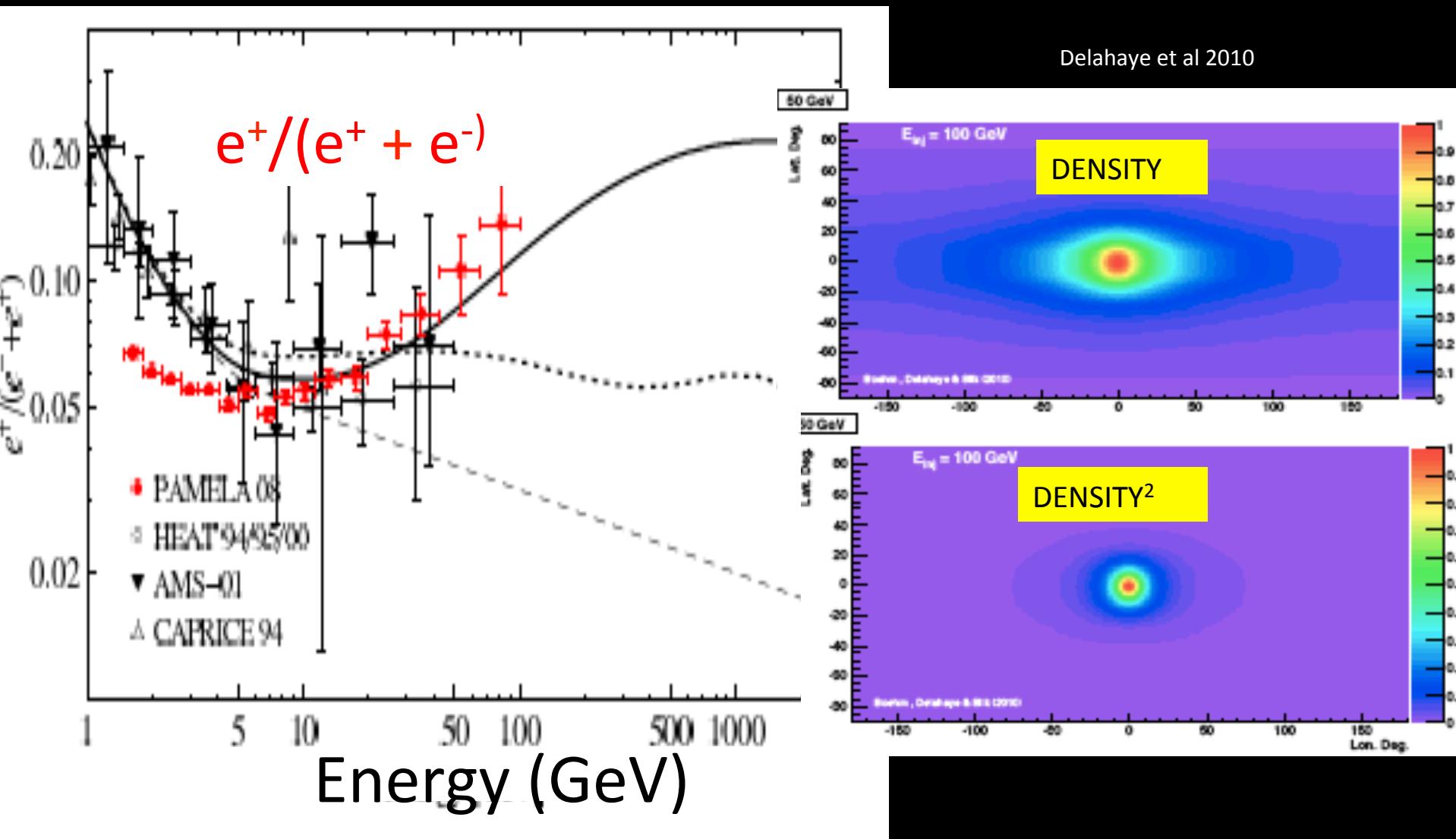


# Self-interacting dark matter



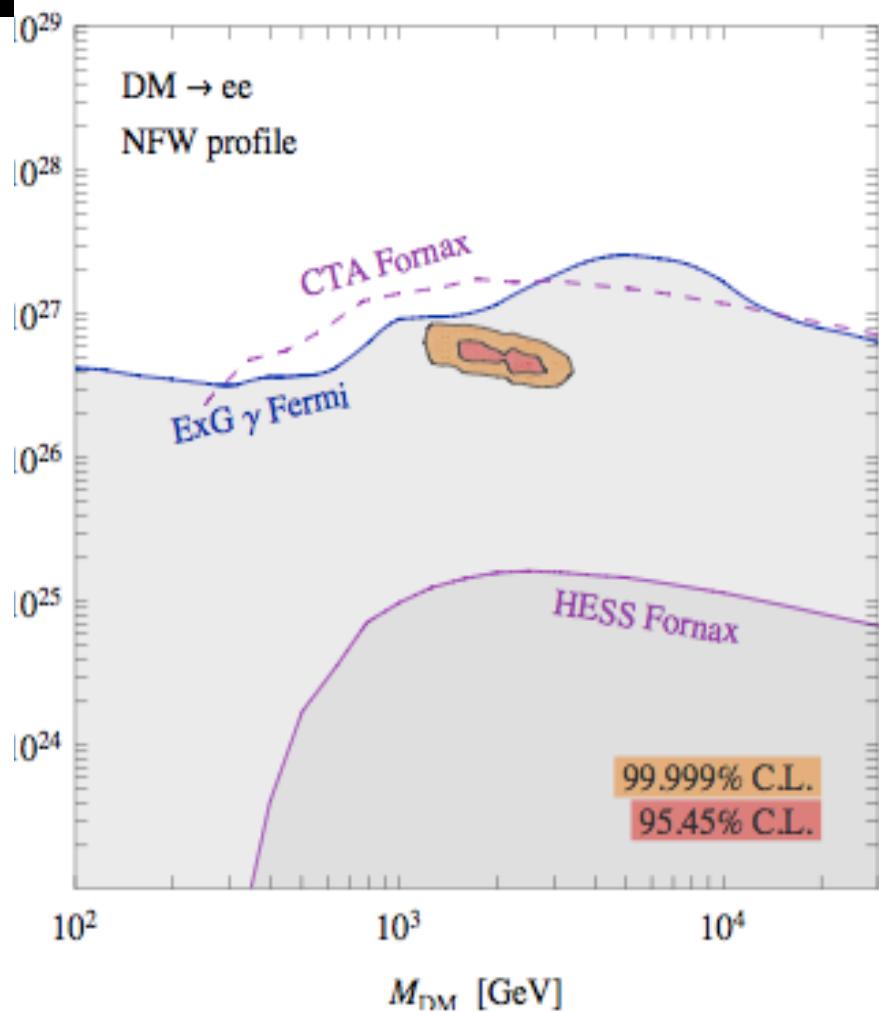
# DECAYING DARK MATTER

massive neutralino requires decay time  $\sim 10^{26}$  sec

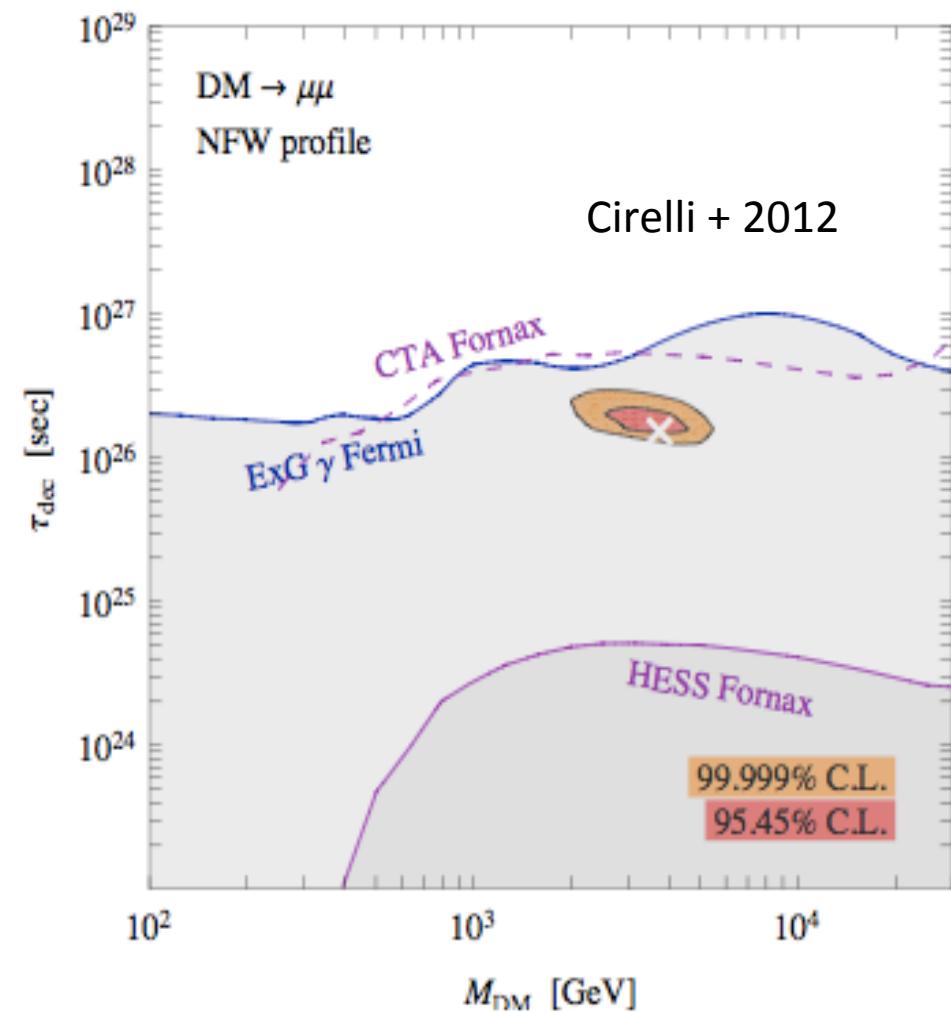


# limits on Decaying Dark Matter

$\text{DM} \rightarrow \mu\mu$



Angle from GC  $\theta$  [deg]



Cannot exclude AMS02  $e^+e^-$

but CTA will

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stars

positrons

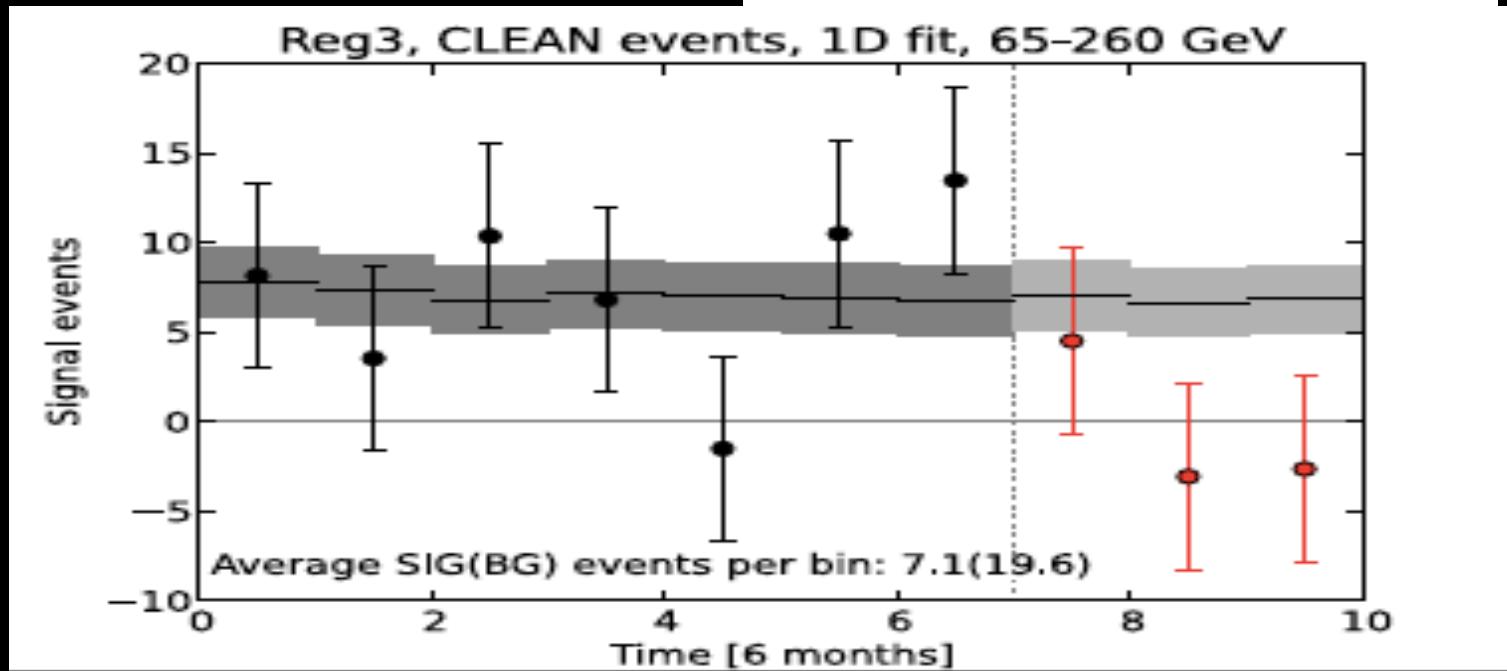
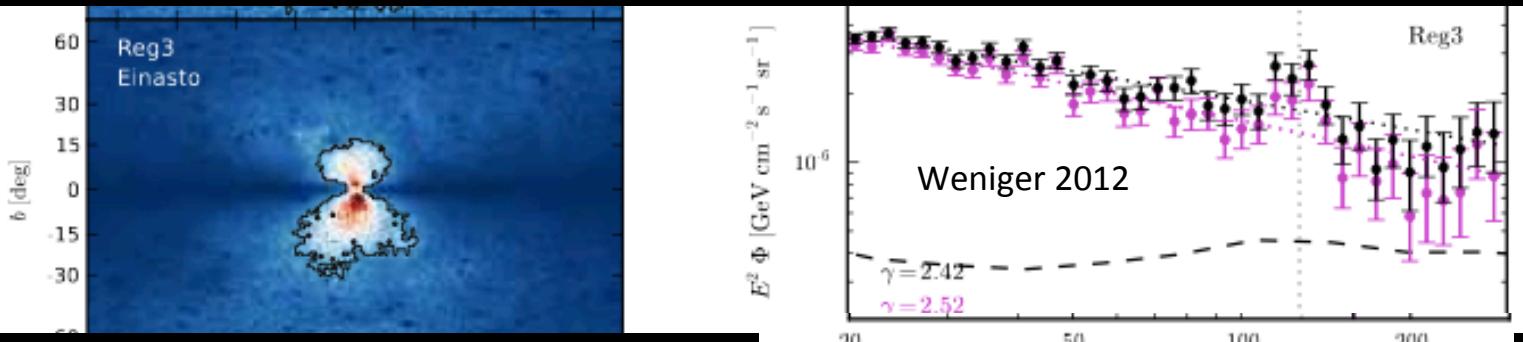
$\gamma$  rays

supermassive black holes

galaxy clusters

spectral lines

3f



Courtesy C. Weniger 2014

# If dark matter is a sterile neutrino

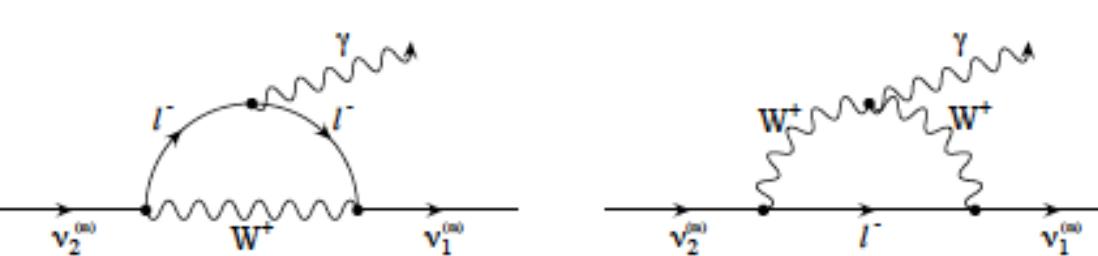
- Lyman alpha forest and hi z galaxies fix minimum mass  $\sim 1$  keV

Markovic & Viel 2013

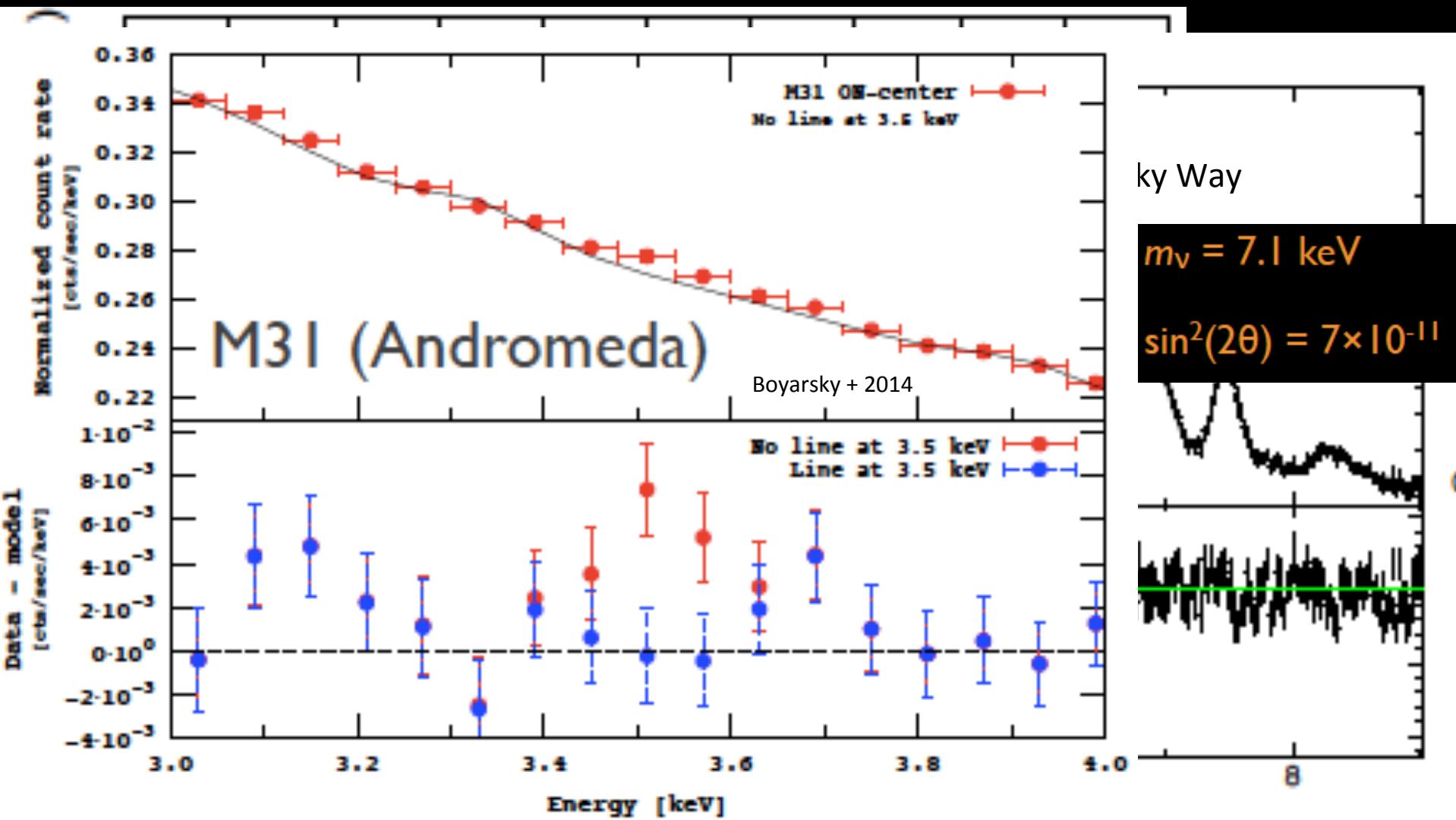
- maximum mass has to be warm  
( $\sim 5$  keV  $\sim$  co-moving mass of dwarf galaxy) Pacucci + 2013
- decay time (+ mixing angle) specifies relic abundance
- 7 keV  $\nu$  decays into 3.5 keV photons
- the favoured mass range is constrained:

$$\begin{aligned}\Gamma_{\nu_s \rightarrow \gamma \nu_a} &= \frac{9}{256\pi^4} \alpha_{\text{EM}} G_F^2 \sin^2 \theta m_s^5 \\ &= \frac{1}{1.8 \times 10^{21} \text{s}} \sin^2 \theta \left( \frac{m_s}{\text{keV}} \right)^5\end{aligned}$$

Kusenko 2009



# a 3.5 keV line ?



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stars

positrons

$\gamma$  rays

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galaxy clusters

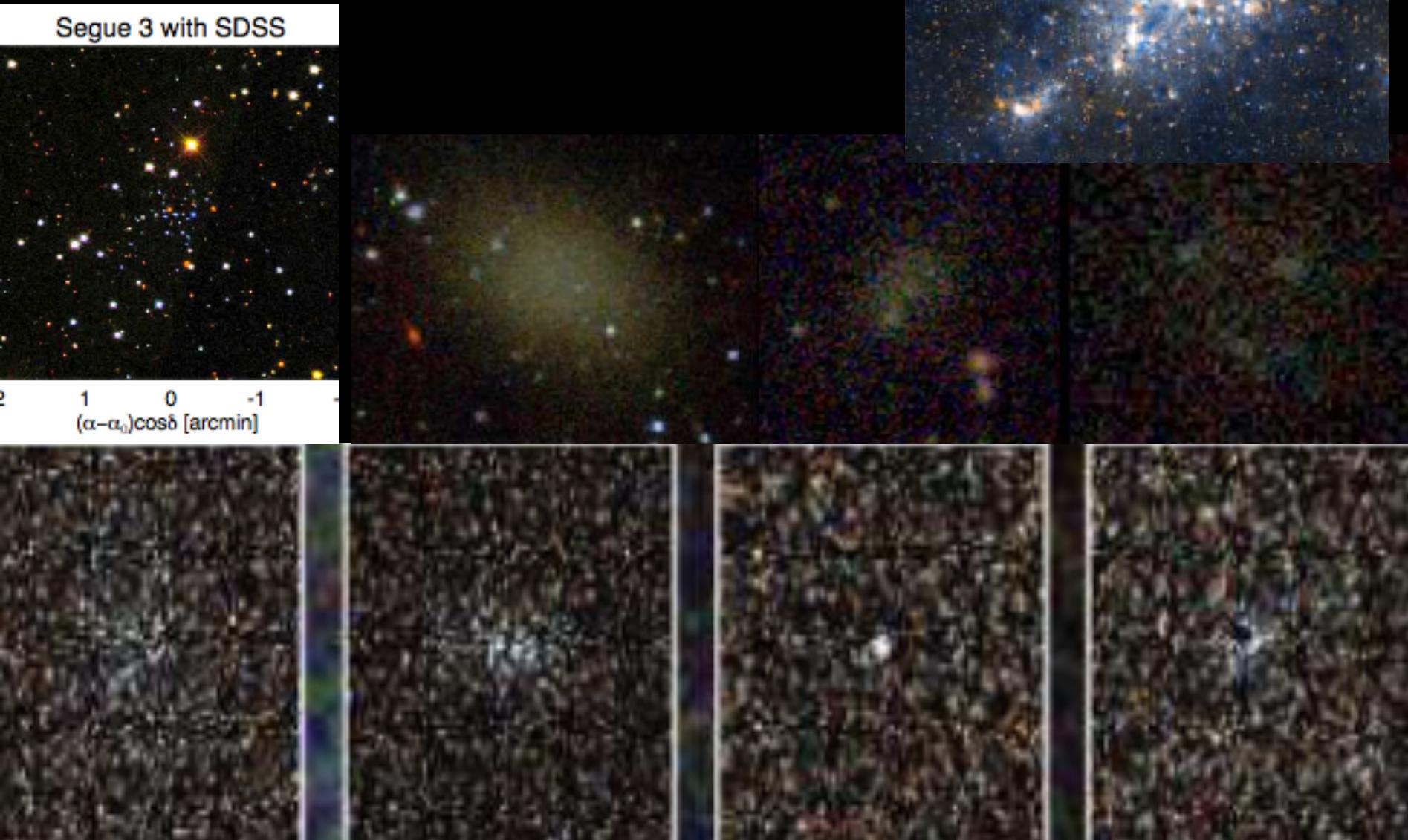
spectral lines

dwarf galaxies

3g

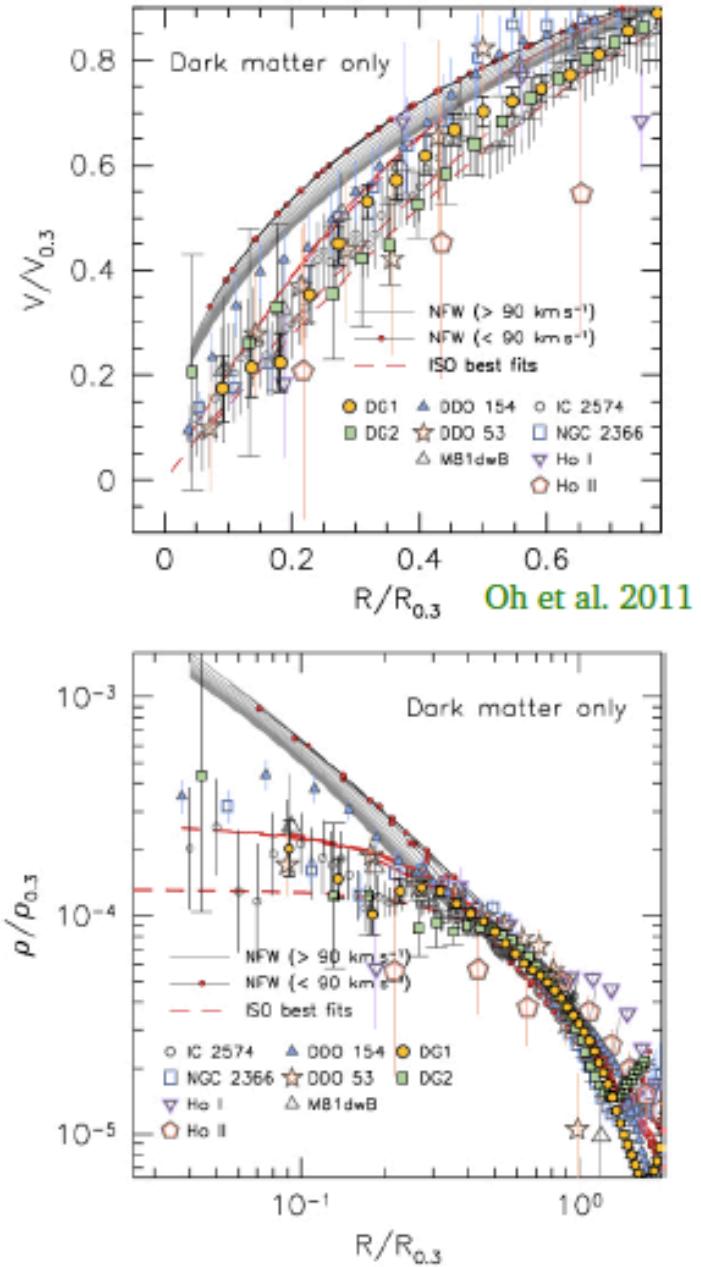
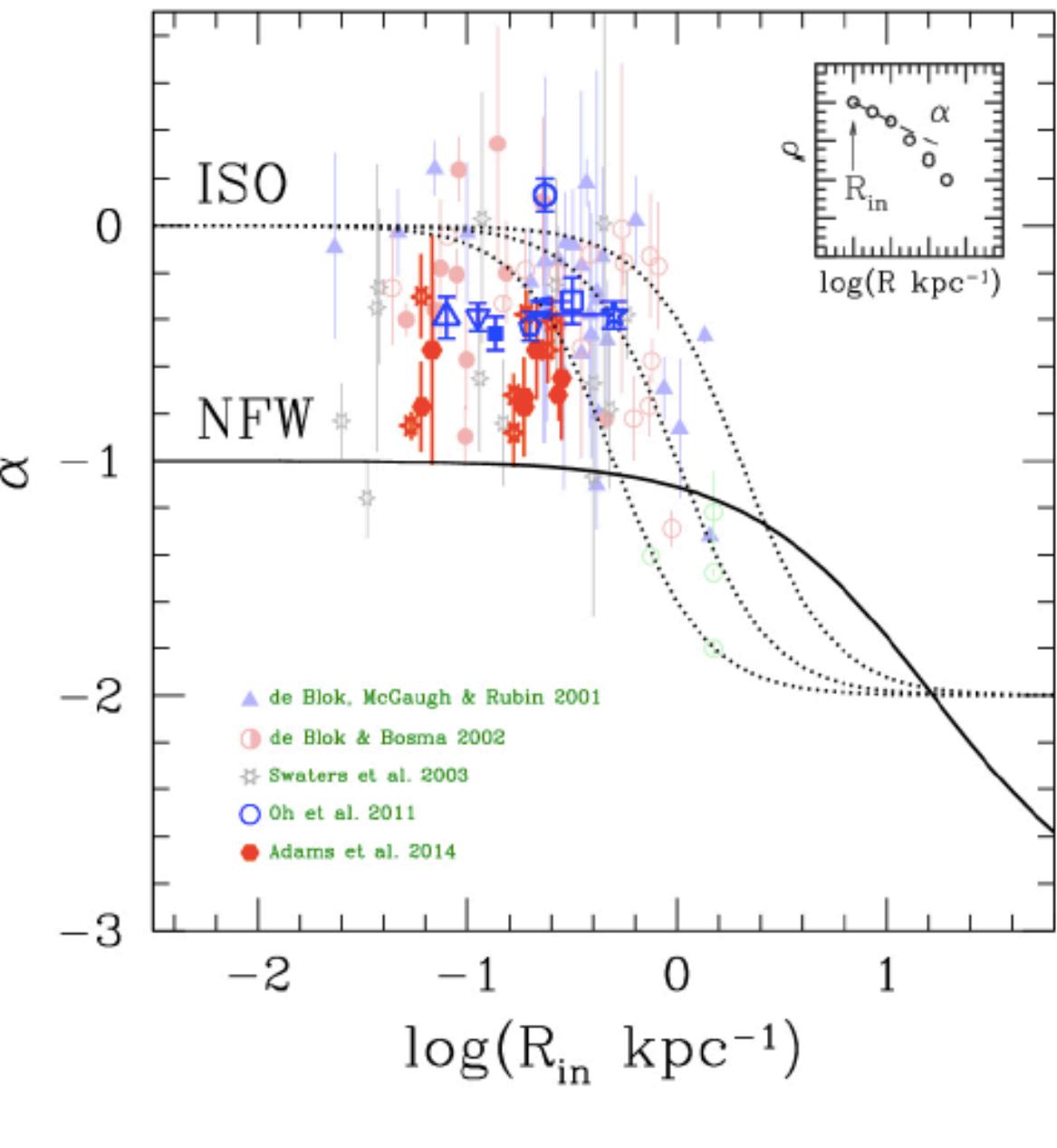
# Ultra-faint dwarf galaxies

Segue 3 with SDSS



Dwarf galaxies have cores

Explained by baryon feedback



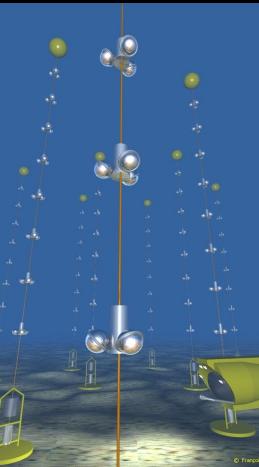
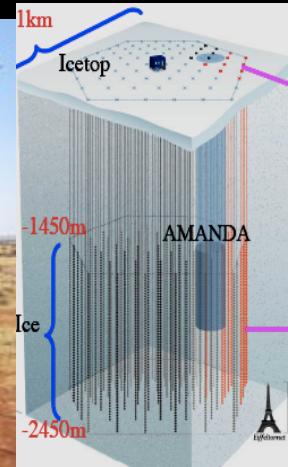
## THE FORMATION OF A BULGELESS GALAXY WITH A SHALLOW DARK MATTER CORE

**Fabio Governato** (University of Washington)  
**Chris Brook** (University of Central Lancashire)  
**Lucio Mayer** (ETH and University of Zurich)  
and the N-Body Shop

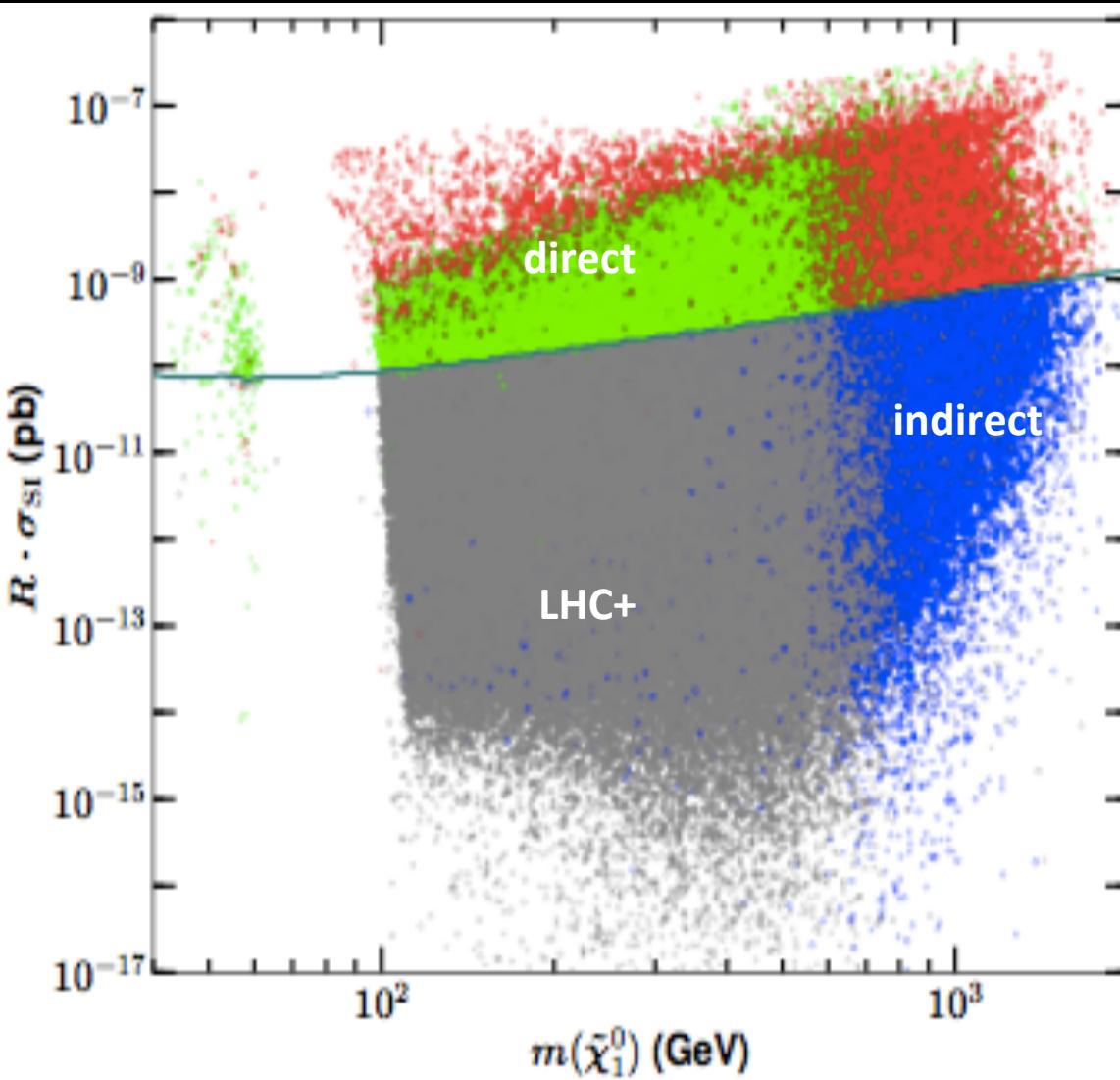
KEY: Blue: gas density map. The brighter regions represent gas that is actively forming stars. The clock shows the time from the Big Bang. The frame is 50,000 light years across.

Simulations were run on Columbia (NASA Advanced Supercomputing Center) and at ARSC

# Current searches for indirect detection of particle dark matter



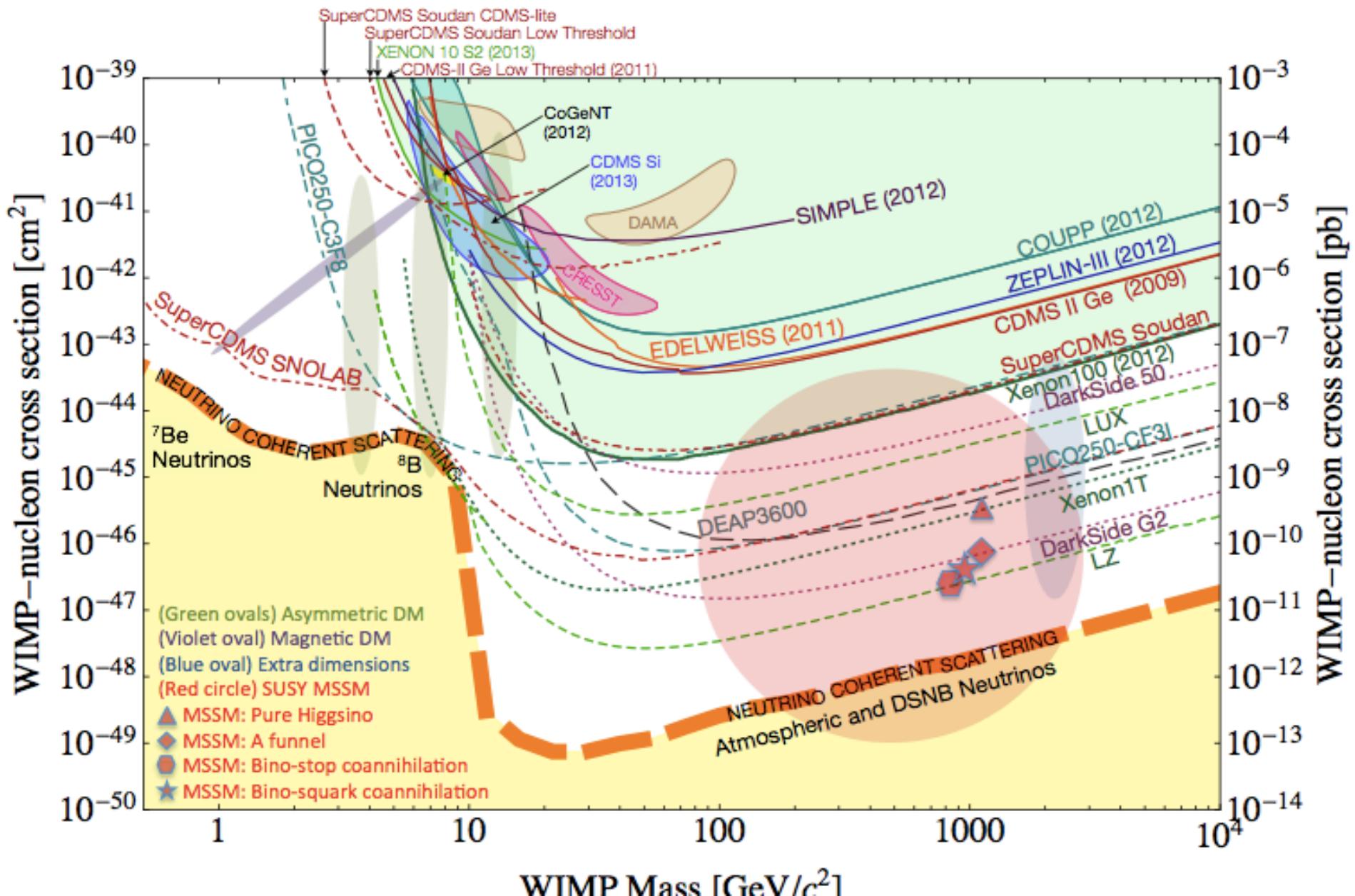
# THE FUTURE



Following the light Higgs discovery and the failure to find evidence for SUSY, the new frontier for particle physics is likely to be a 100 TeV collider

The new frontier for DM detection will shift from light DM (10-100 GeV) where the constraints are increasingly tight to heavy DM (1-30 TeV)

# The ultimate limit



# THE FUTURE FOR ASTROPHYSICAL SEARCHES FOR DARK MATTER & DARK ENERGY

