

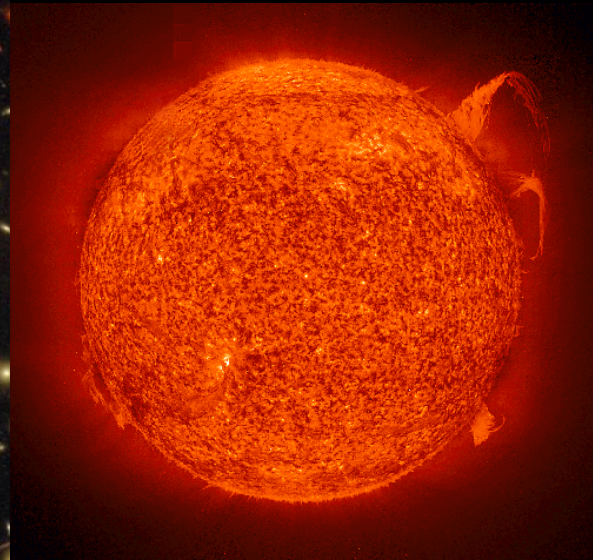
La matière Noire et le Centre Galactique

Joe Silk

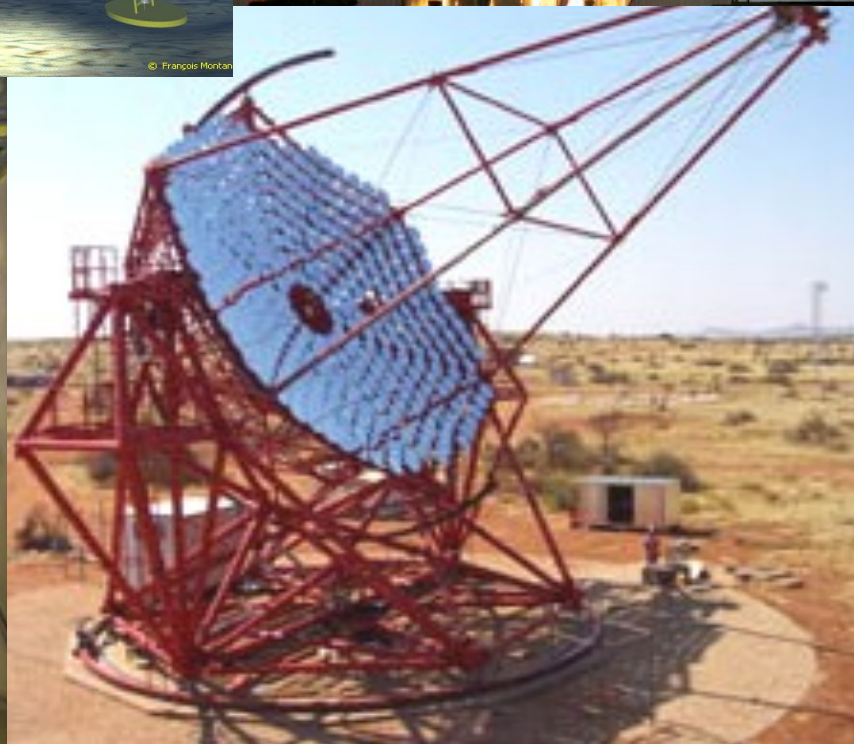
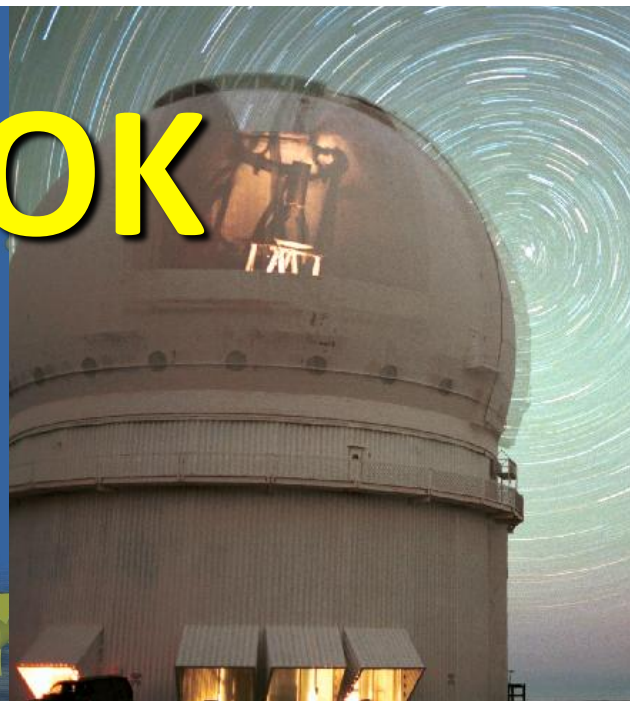
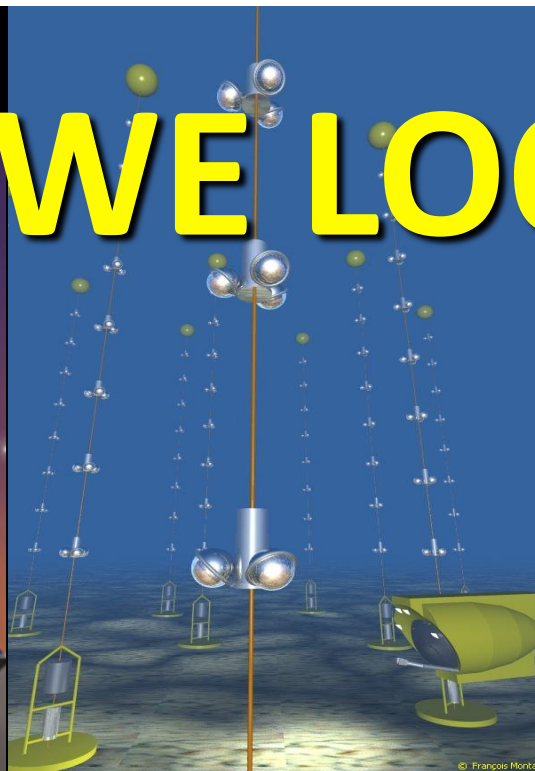
Oxford/IAP

24 Mai, 2011

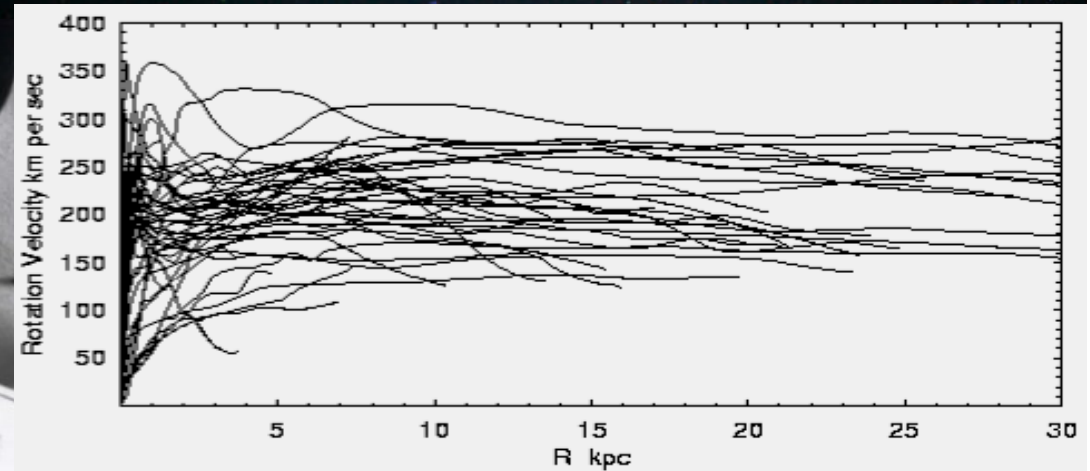
WHERE WE LOOK



HOW WE LOOK



Dark Matter in Galaxies



Die Rotverschiebung von extragalaktischen Nebeln

von F. Zwicky.

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

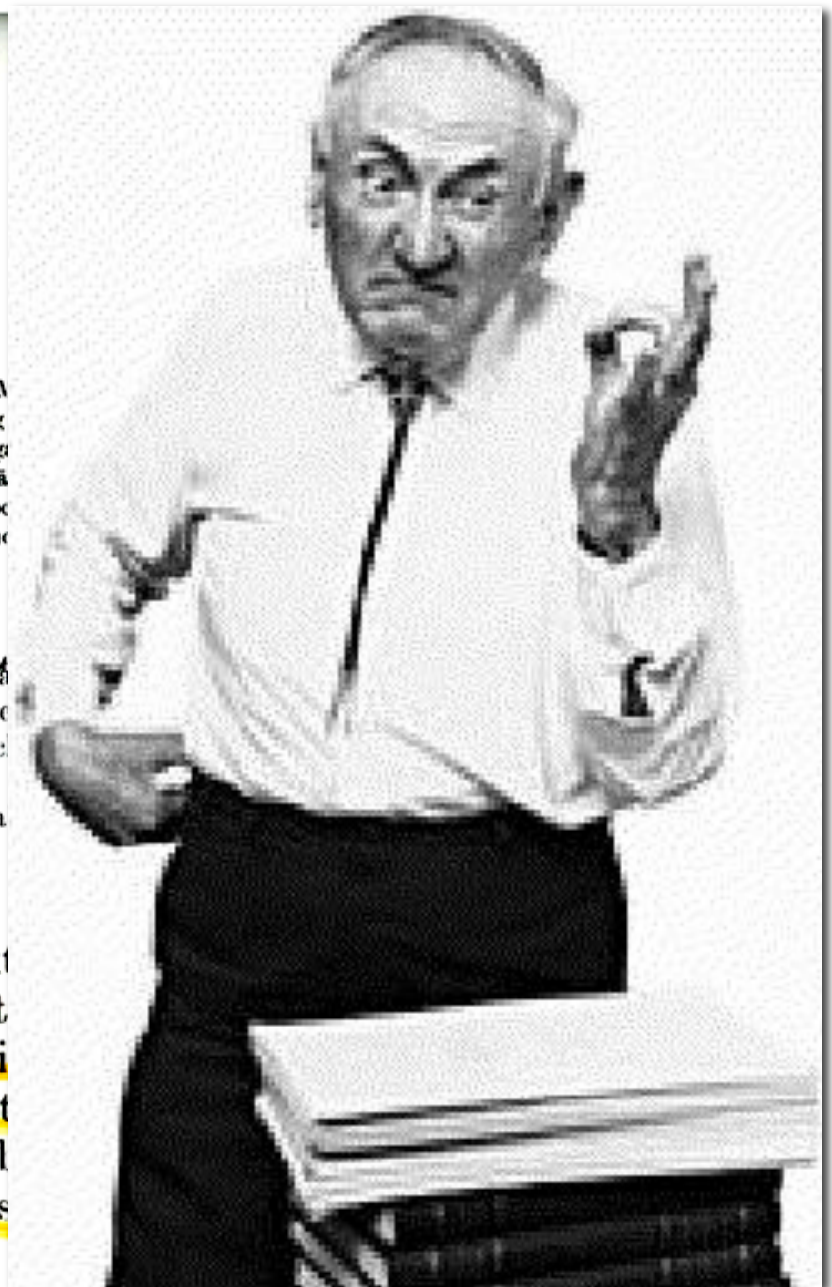
§ 1. Einleitung.

Es ist schon seit langer Zeit bekannt, dass es im Weltall gewisse Objekte gibt, welche, wenn mit kleinen Teleskopen beobachtet, als stark verschwommene, selbstleuchtende Flecke erscheinen. Diese Objekte besitzen verschiedenartige Strukturen. Sind sie kugelförmig, oft elliptisch, und viele unter ihnen ha-

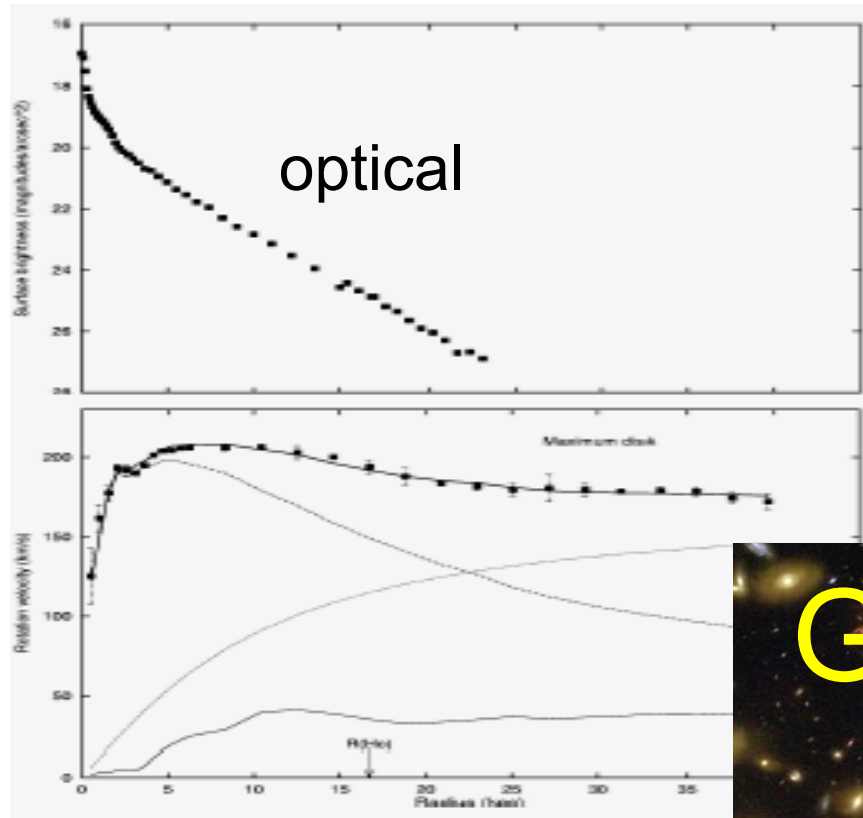
Rotverschiebung extragalaktischer Nebel.

Um, wie beobachtet, einen mittleren Dopplereffekt von 100 km/sek oder mehr zu erhalten, müsste also die mit der Materie im Comasystem mindestens 400 mal grösser sein als die von Beobachtungen an leuchtender Materie abgeleitet. Nach dies bewahrheiten sollte, würde sich also das übliche Resultat ergeben, dass dunkle Materie in sehr viel grösserer Menge vorhanden ist als leuchtende Materie.

2. Man kann auch annehmen, dass das Comasystem sich nicht im stationären Gleichgewicht befindet, sondern dass die ganze verfügbare potentielle Energie als kinetische Energie er-

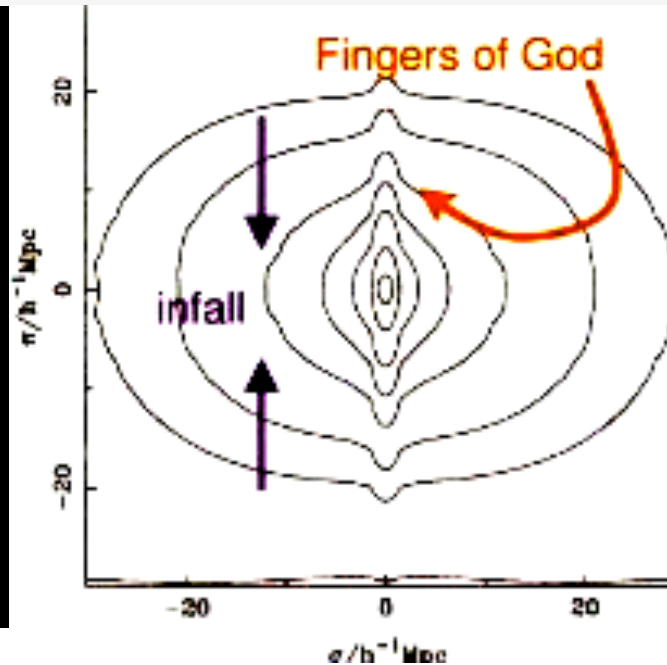


Rotation curves

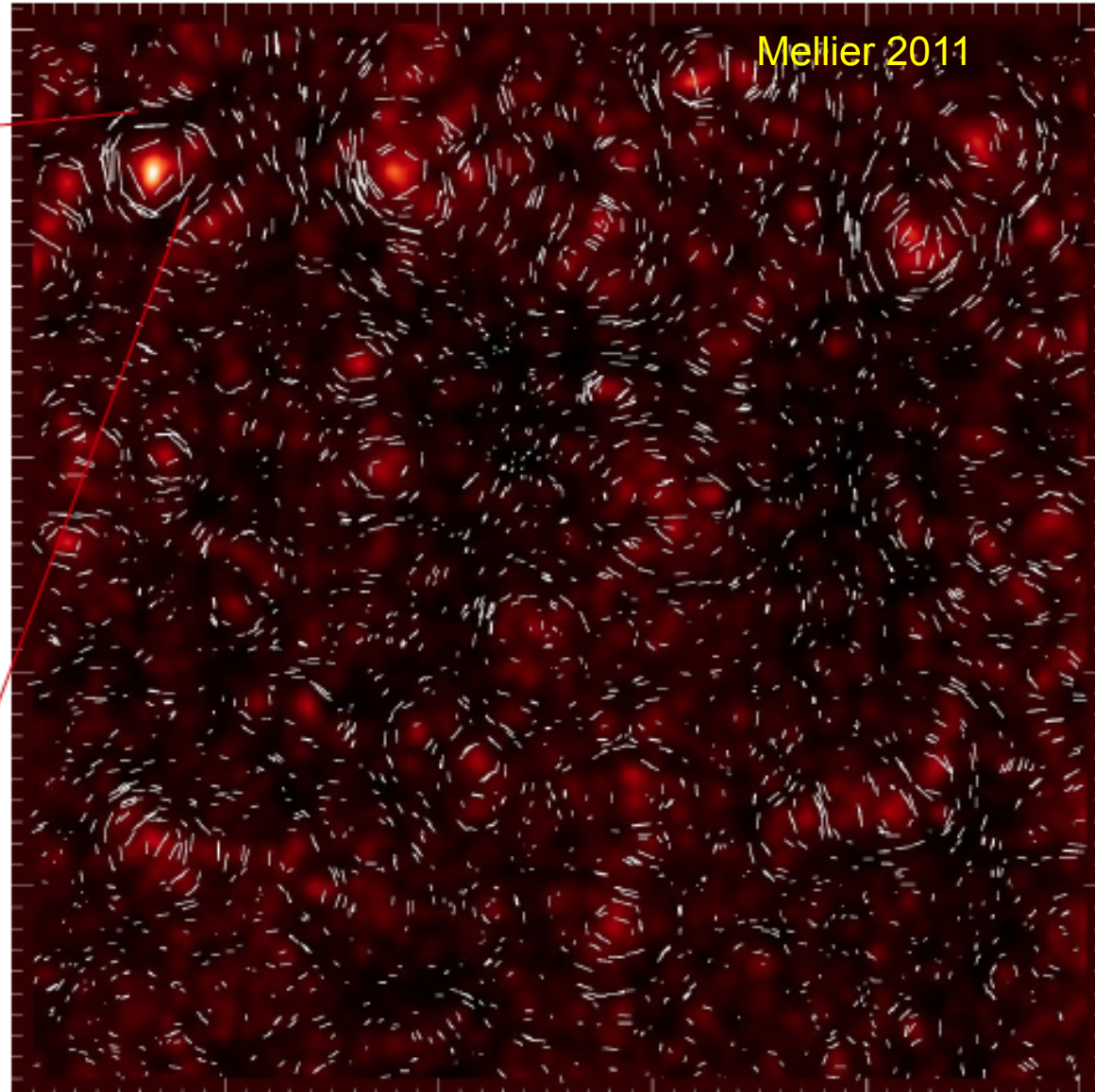


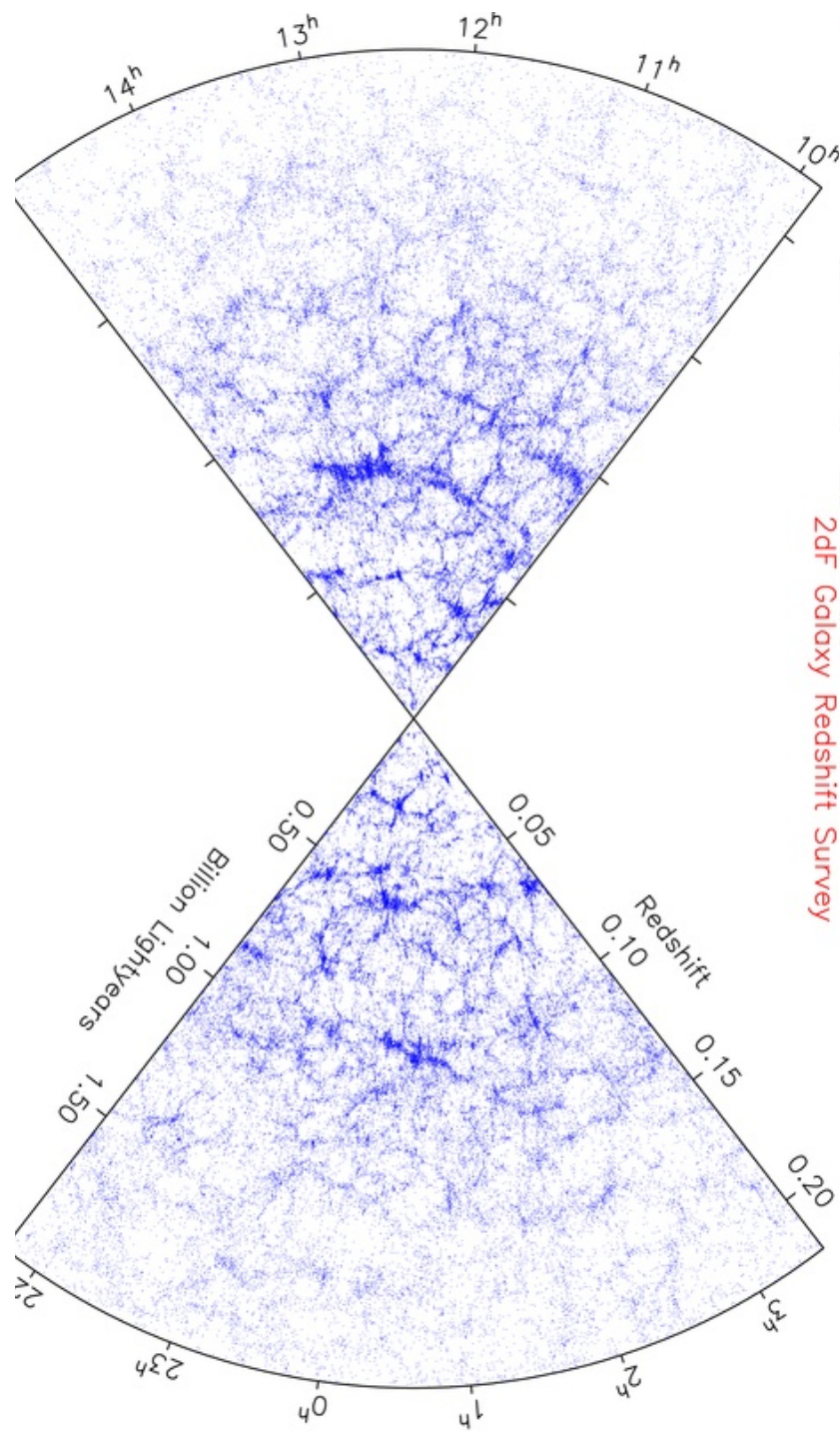
Gravitational lensing

Redshift distortions

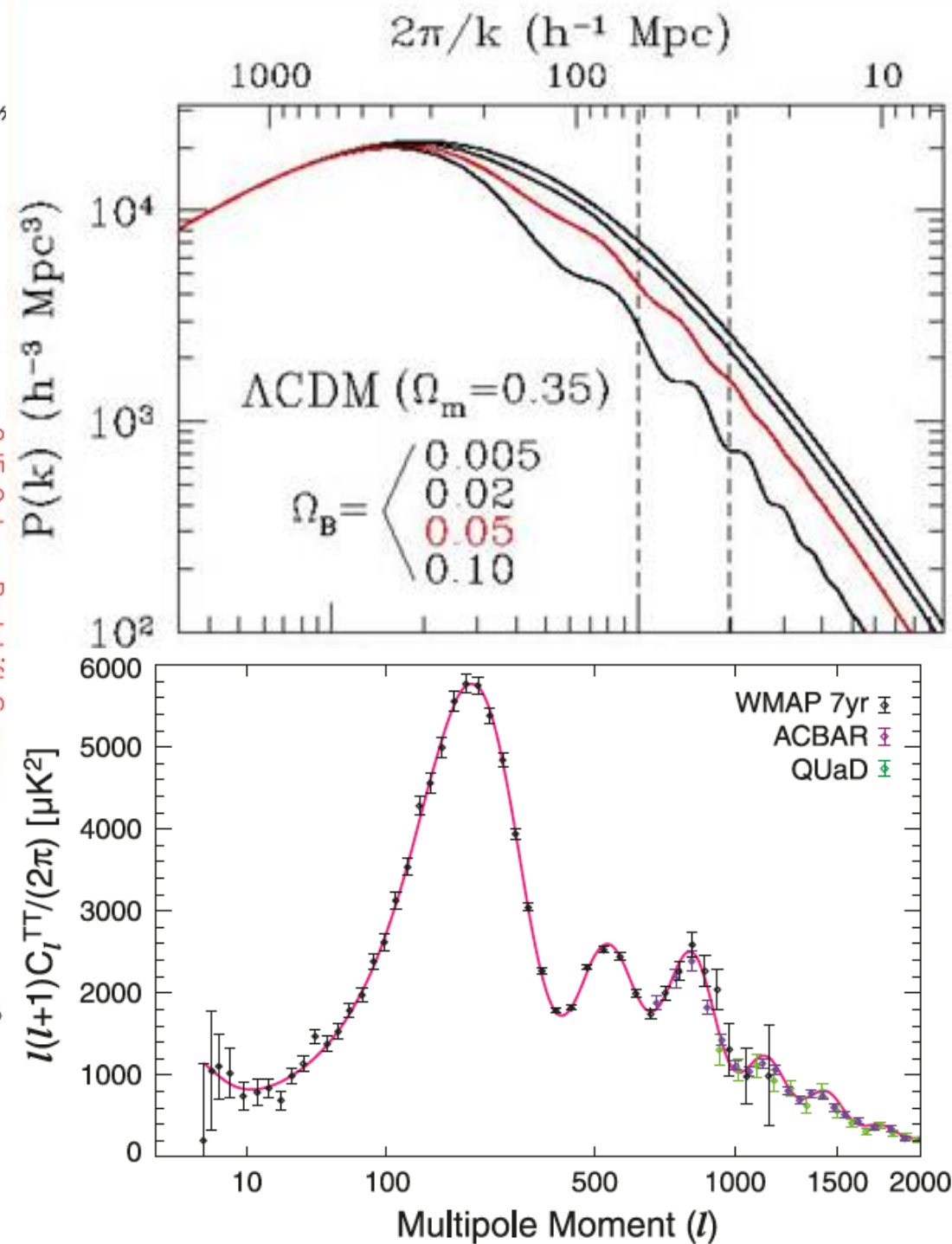


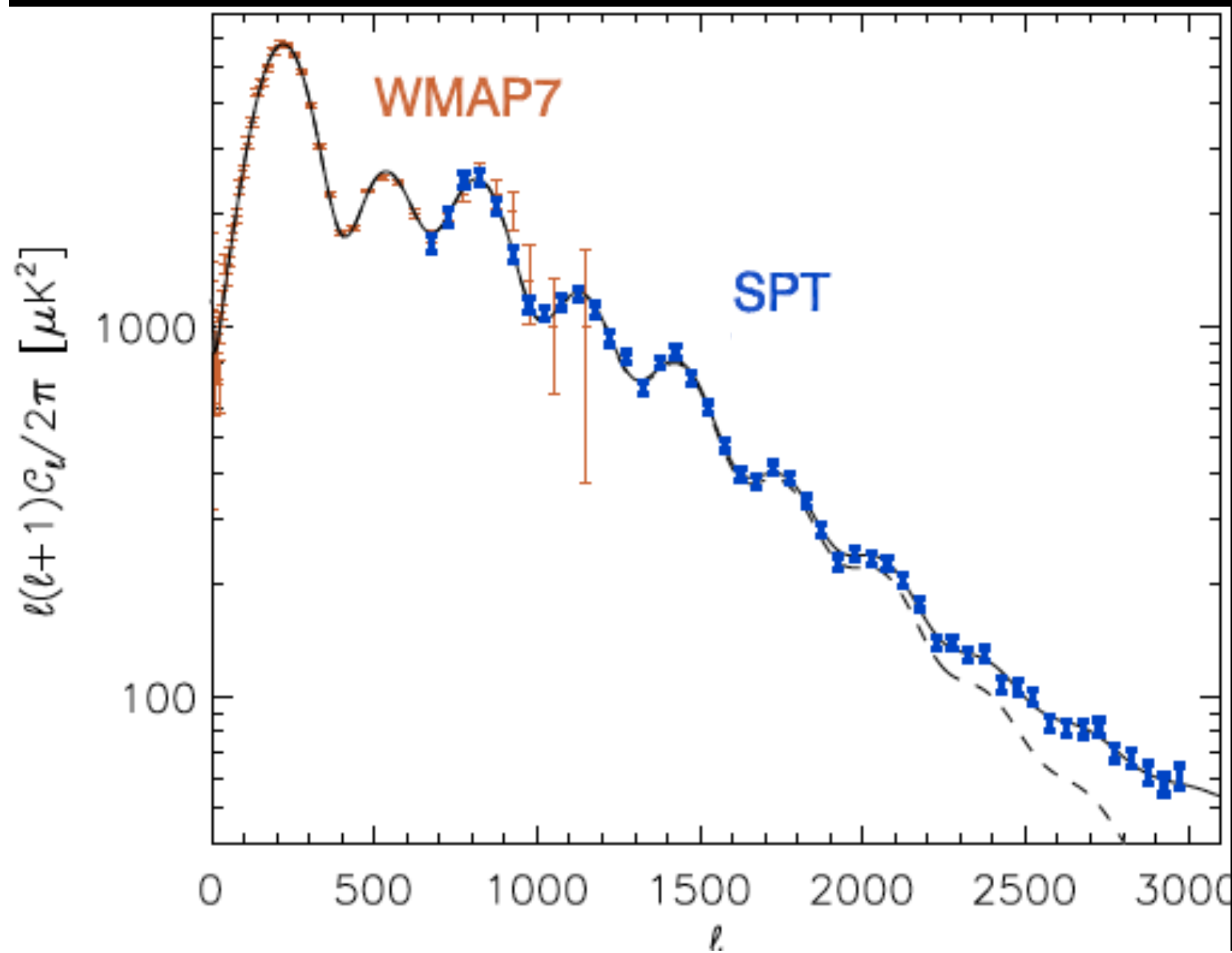
Cosmological distortion field projected on the sky





2dF Galaxy Redshift Survey

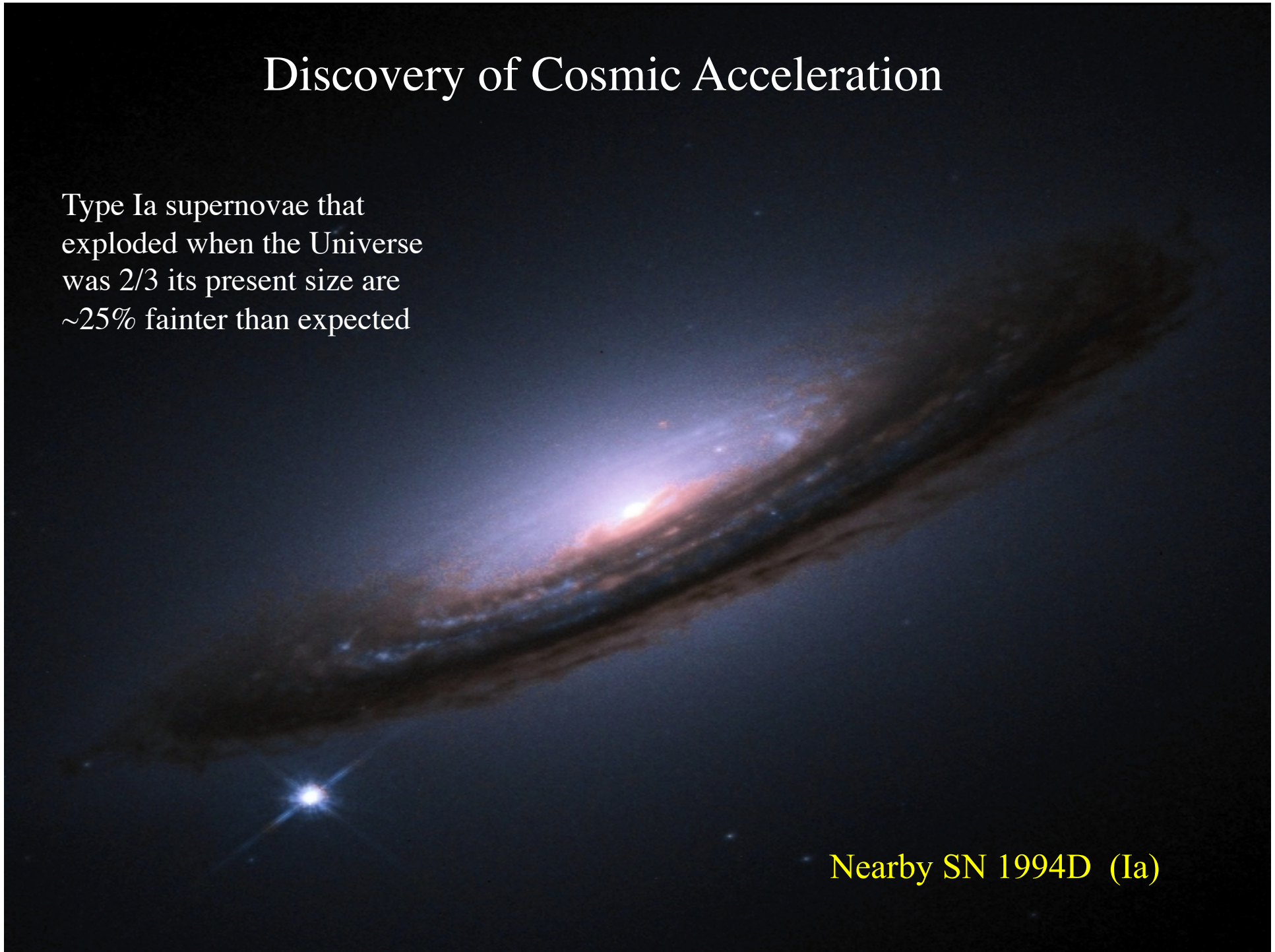




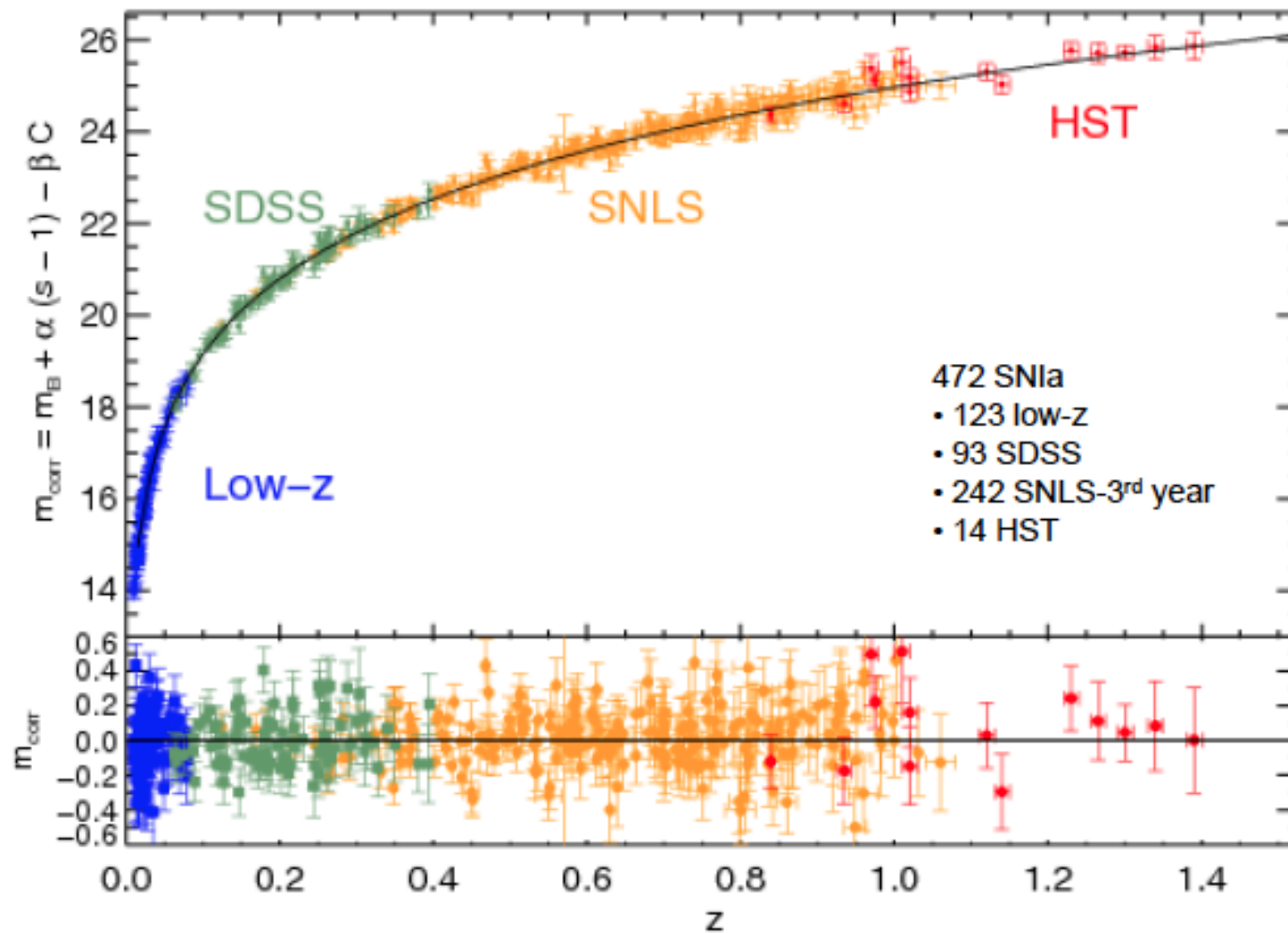
Discovery of Cosmic Acceleration

Type Ia supernovae that
exploded when the Universe
was $2/3$ its present size are
 $\sim 25\%$ fainter than expected

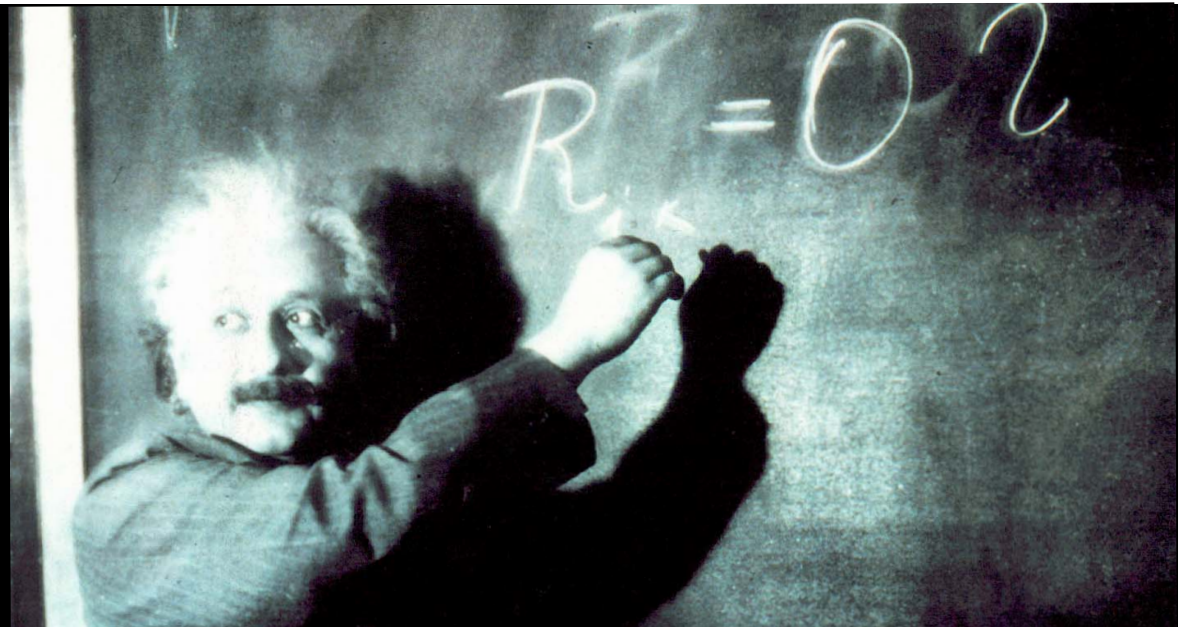
Nearby SN 1994D (Ia)



Hubble diagram SNIa



Conley et al 2011

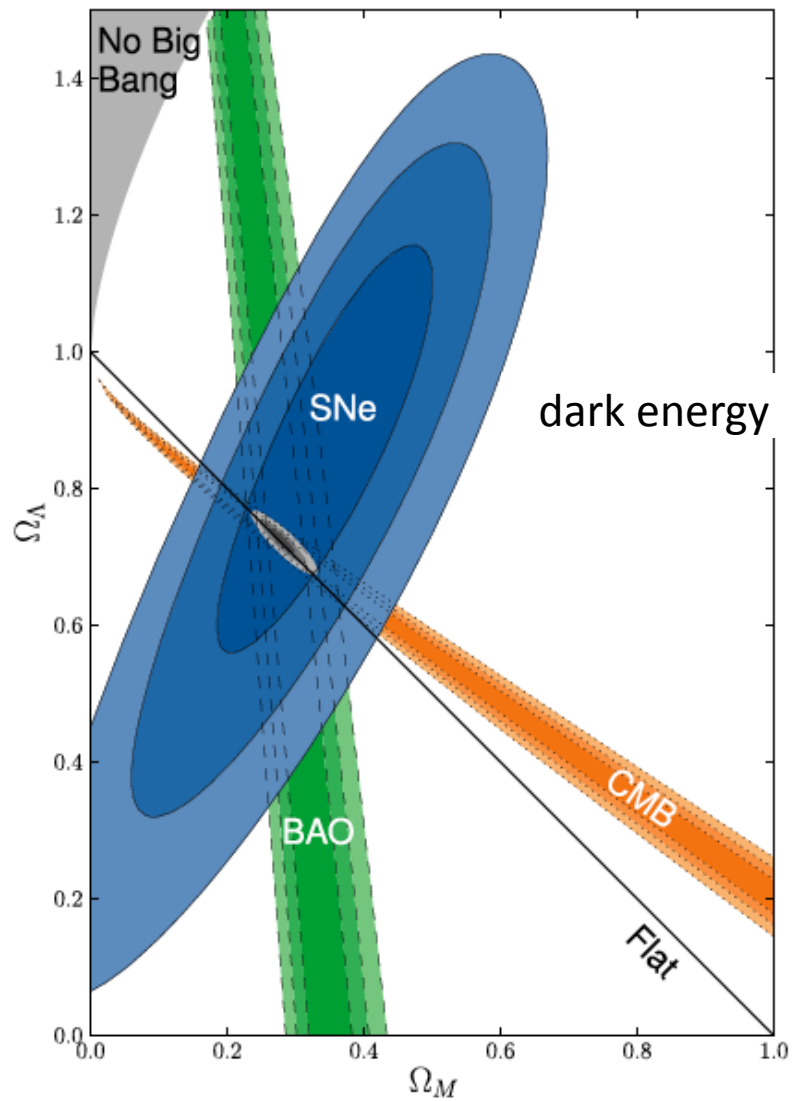


CURVATURE = ENERGY-MOMENTUM

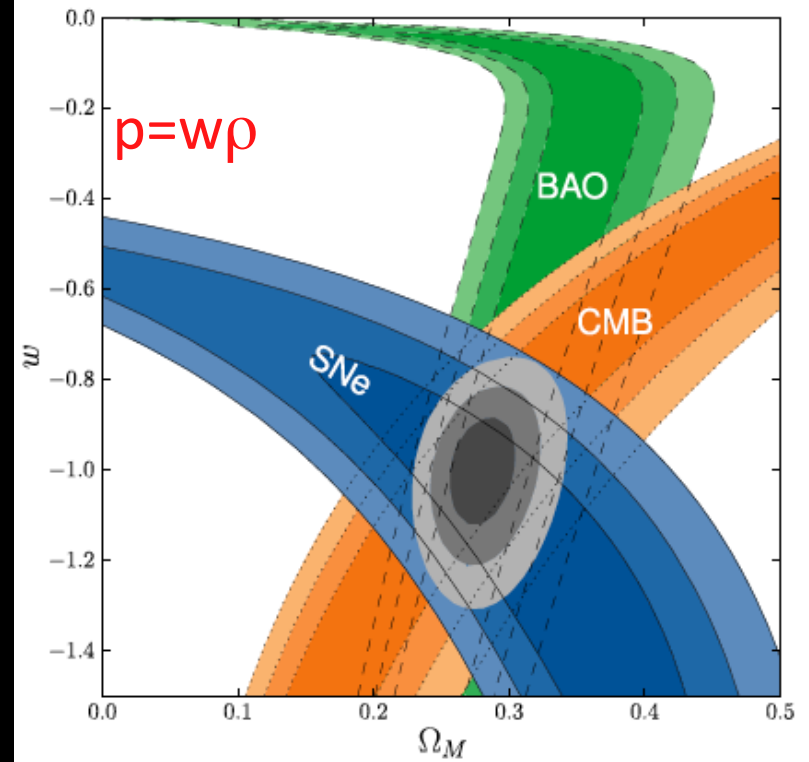
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$



dark matter



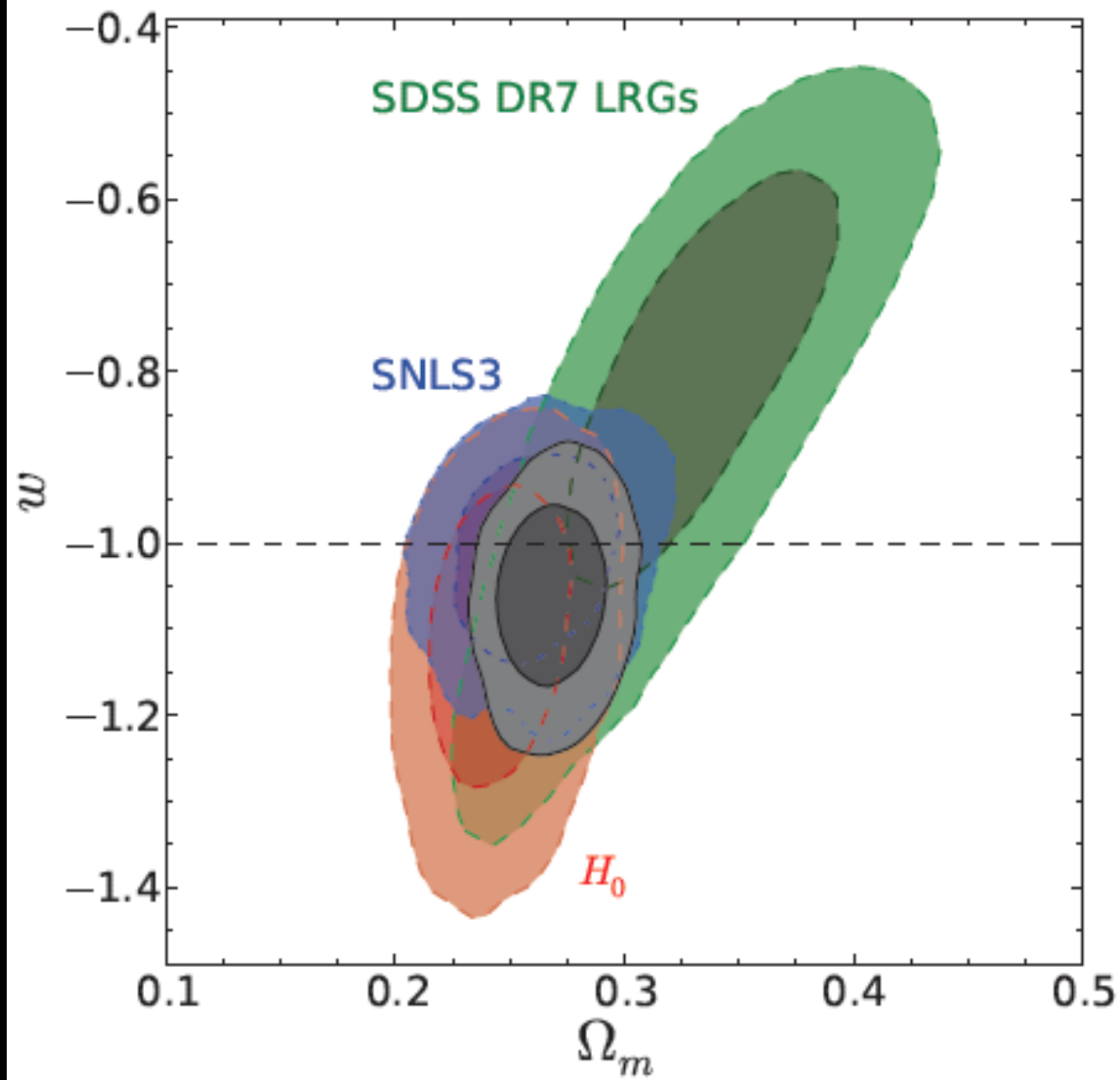
Amanullah et al 2010

Large-scale structure (BAO): DM

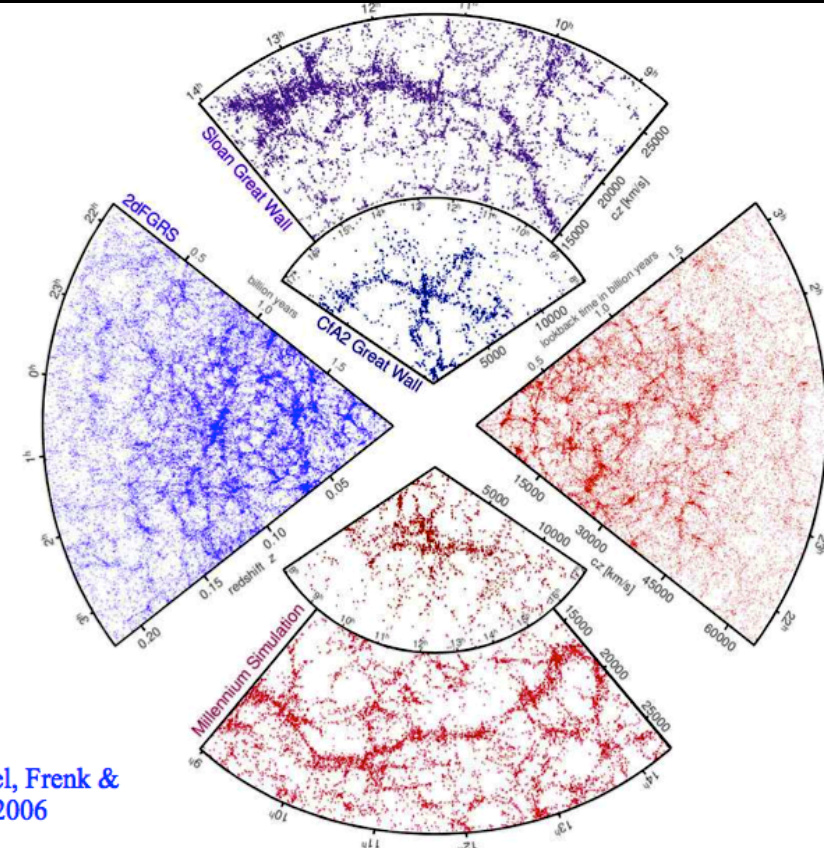
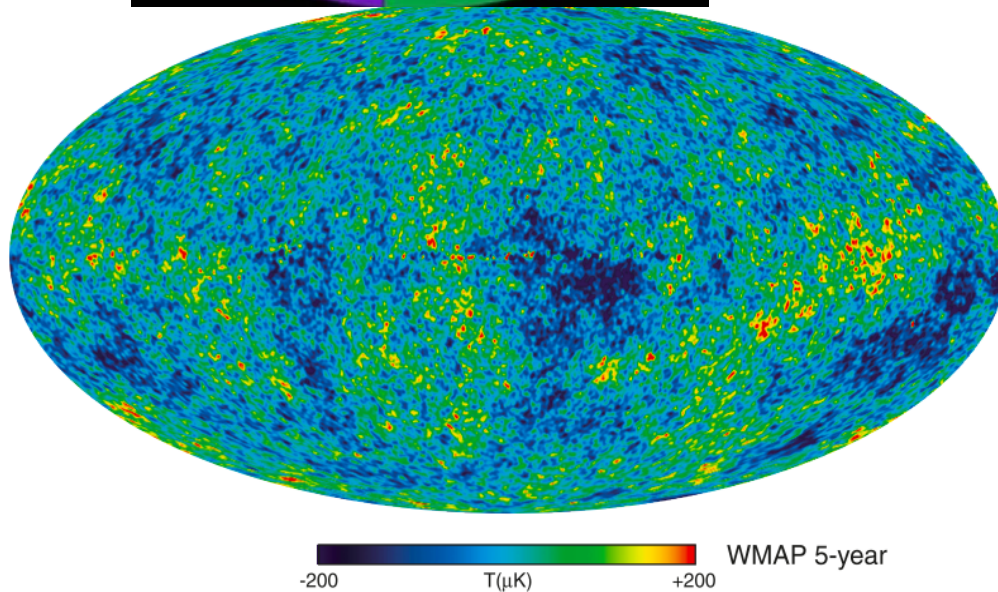
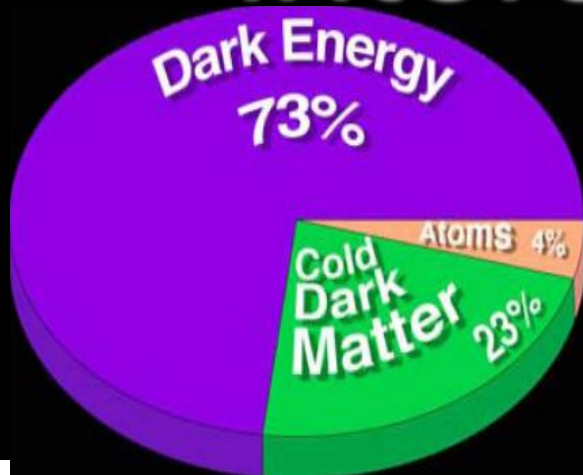
CMB fluctuations: DM +DE

Supernovae: DM - DE

WMAP7 + ...

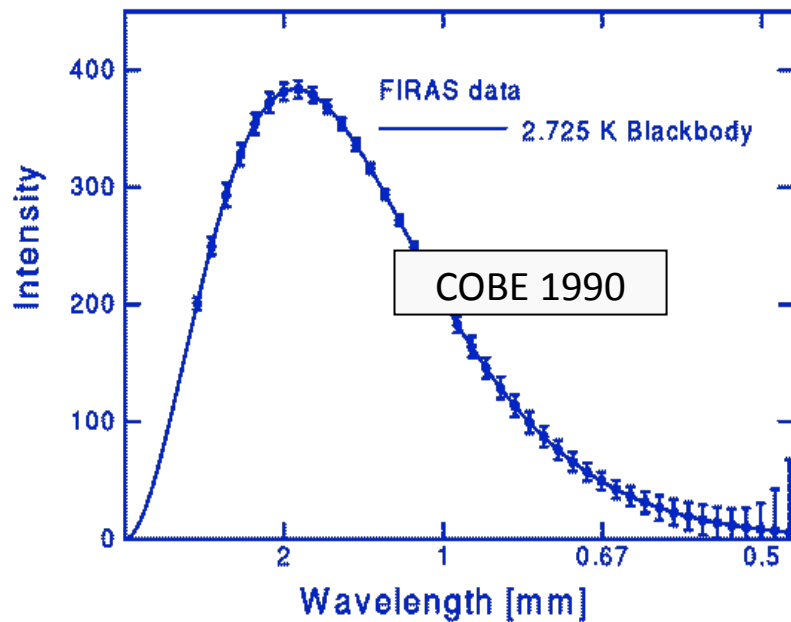


Dark Matter is weakly interacting & cold

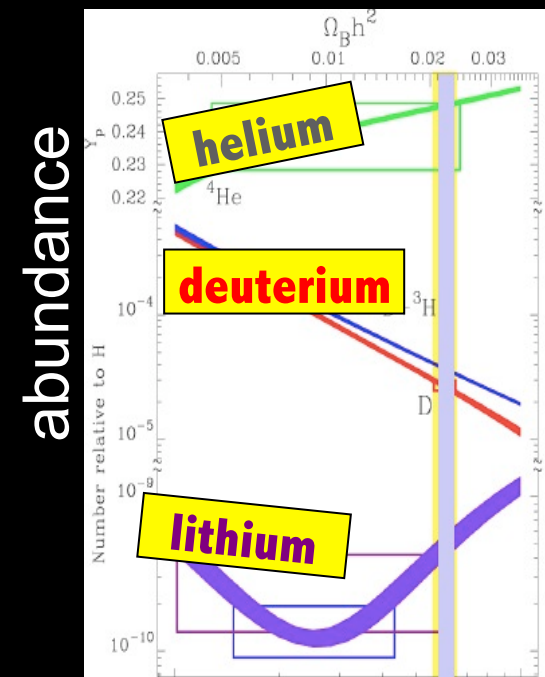


Springel, Frenk &
White 2006

Dark matter is not baryons

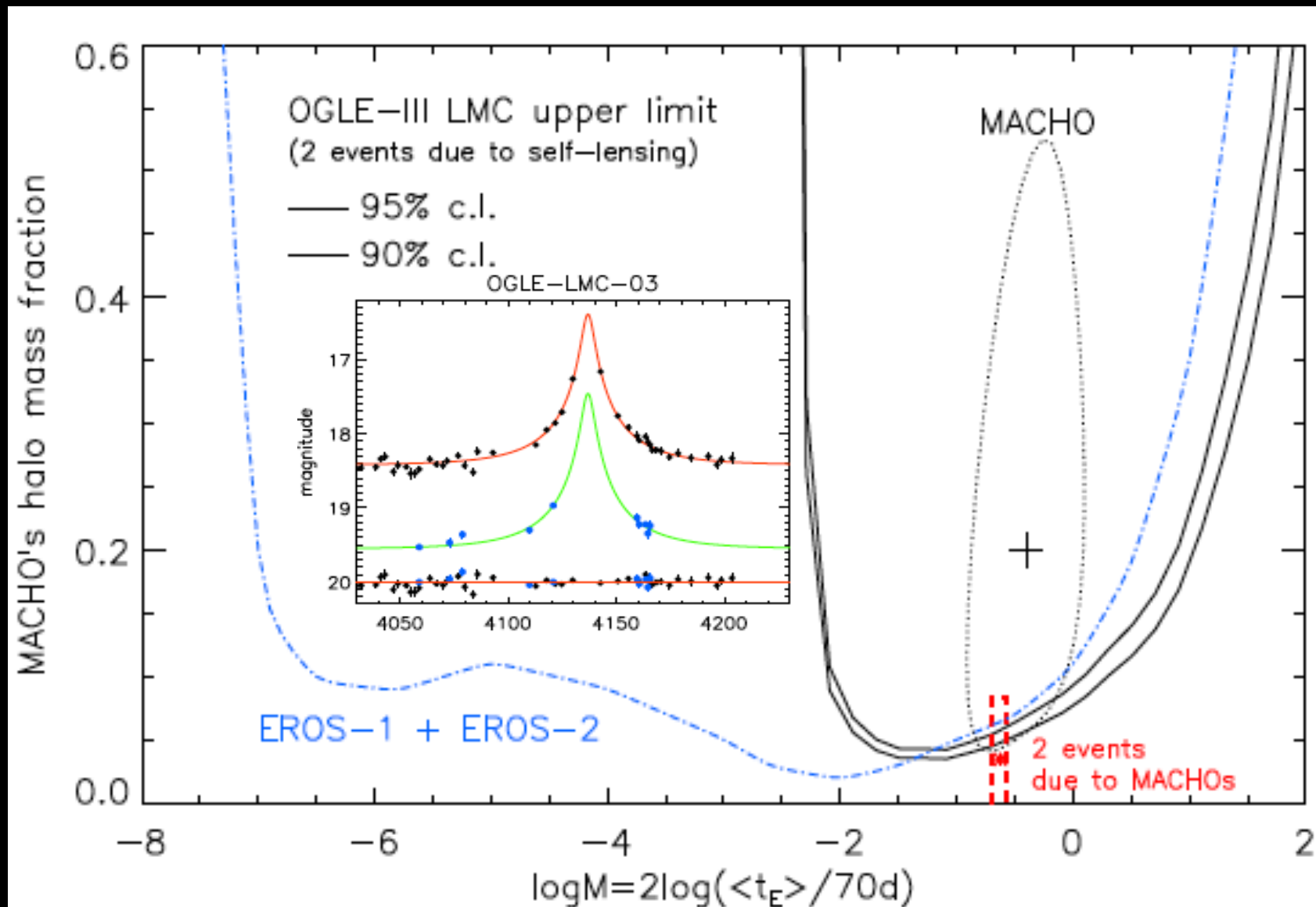


baryon density



Dark matter is not MACHOs

massive compact halo objects

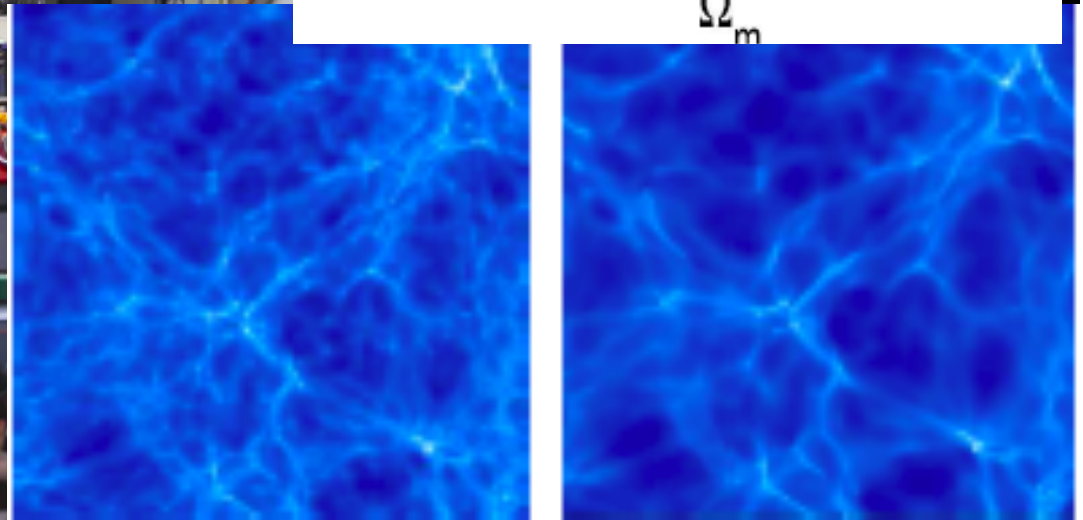
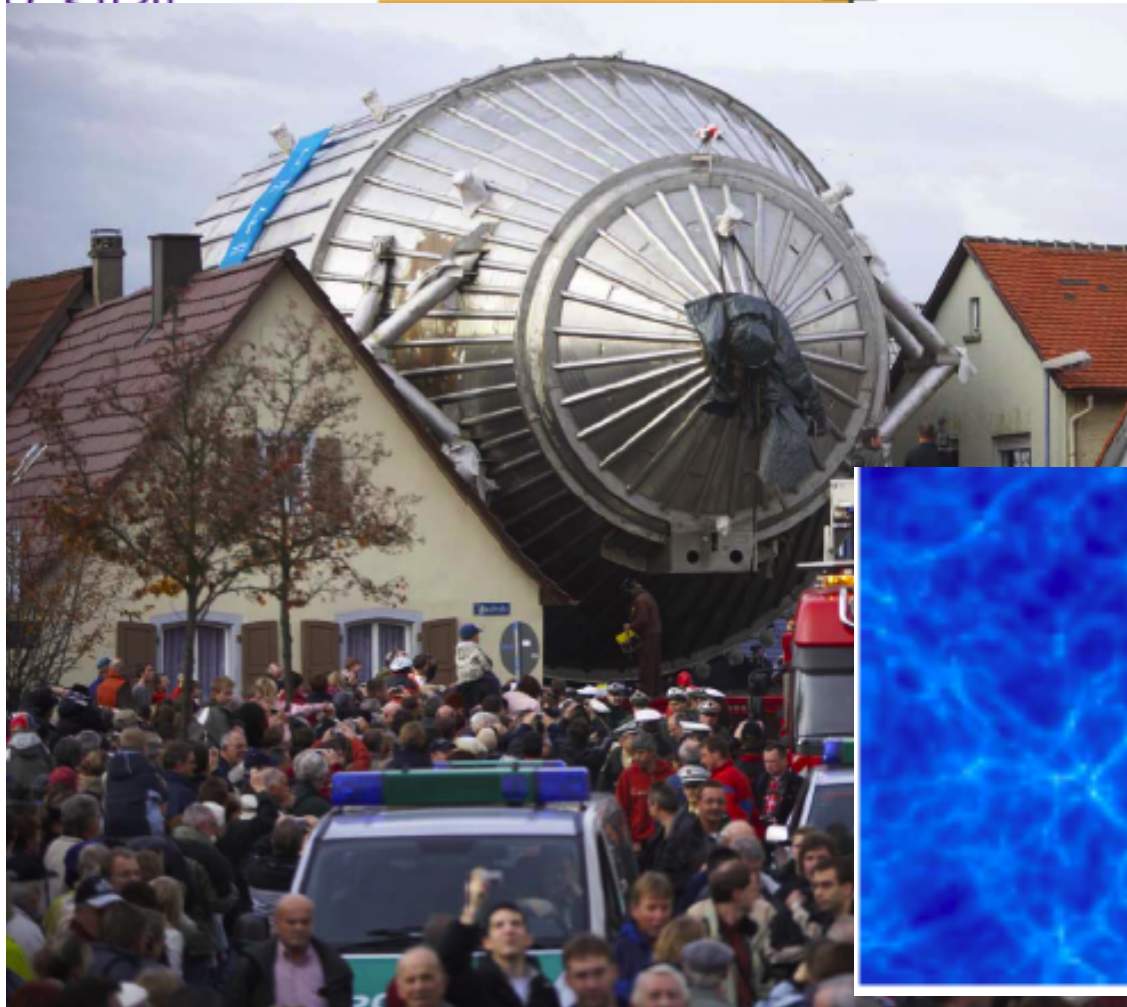
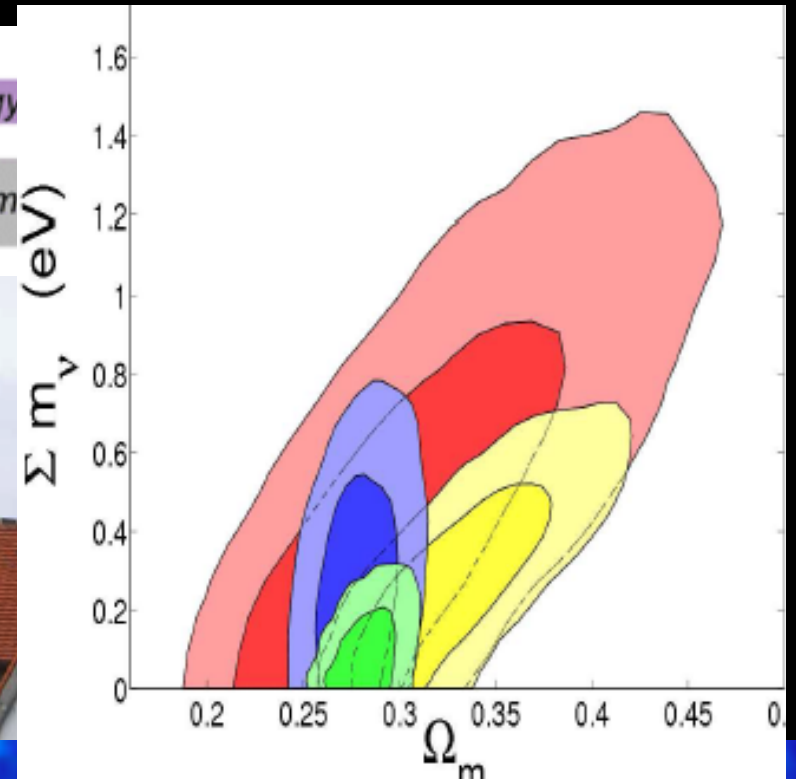
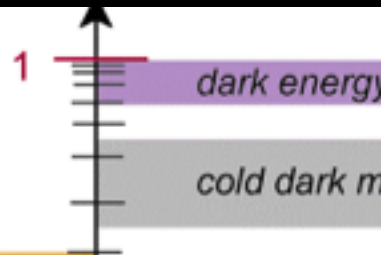


Dark matter is not neutrinos

primordial neutrinos as hot dark matter

$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$

Hubble parameter $h = 0.65$ (65 km/s/Mpc)

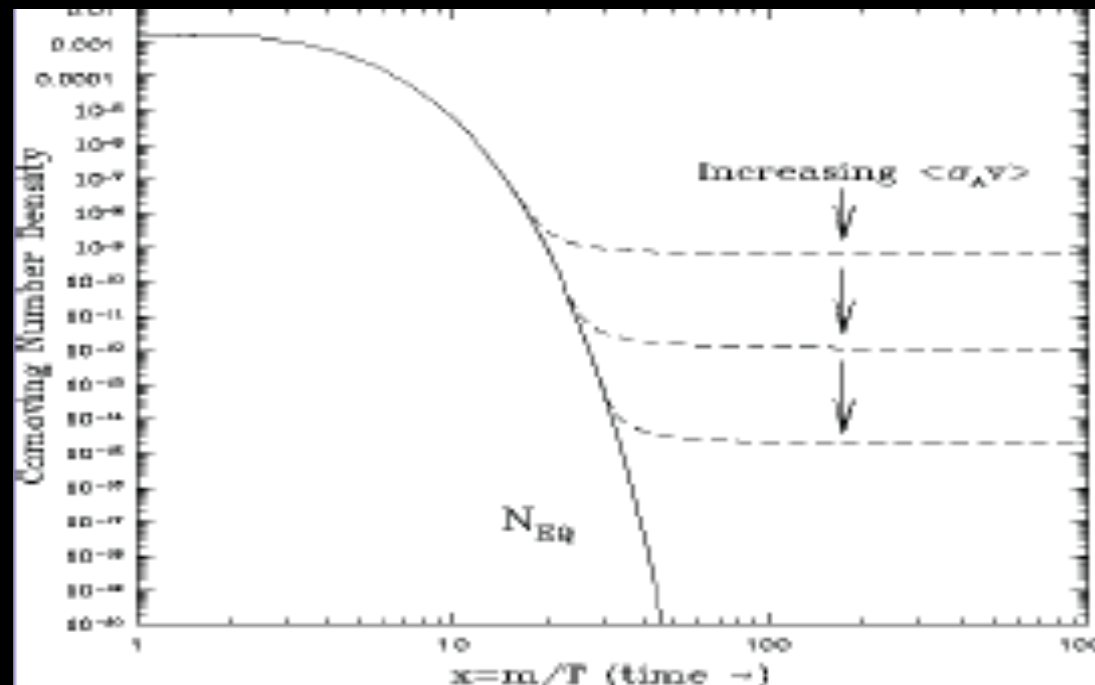


Dark matter most likely is a weakly interacting (massive?) particle

Eg WIMP (or LSP) motivated by theory of supersymmetry

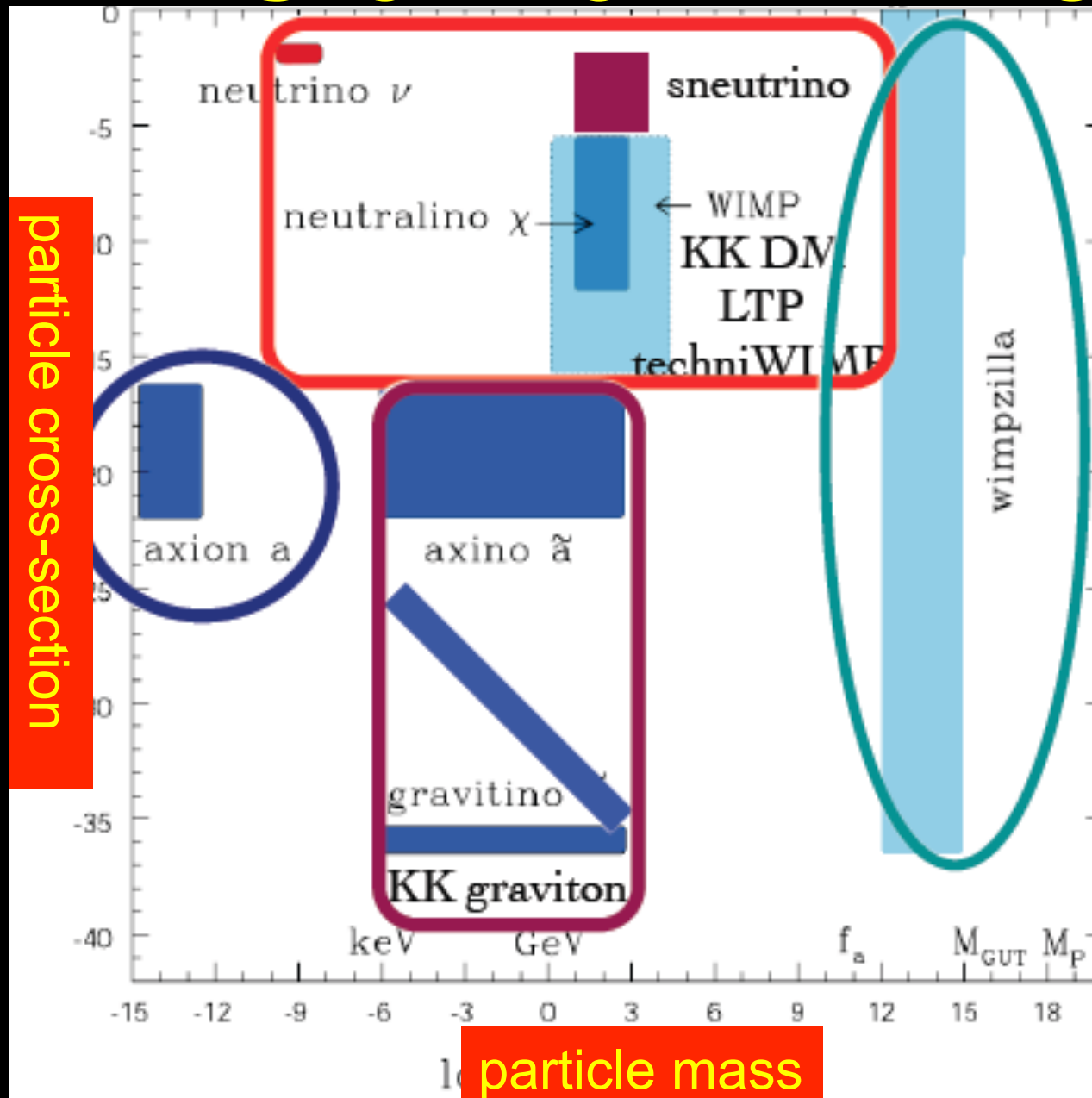
Favoured SUSY candidate is a WIMP in mass range 0.01-10 TeV

The WIMP miracle: relic abundance if $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim 1/\Omega_x$



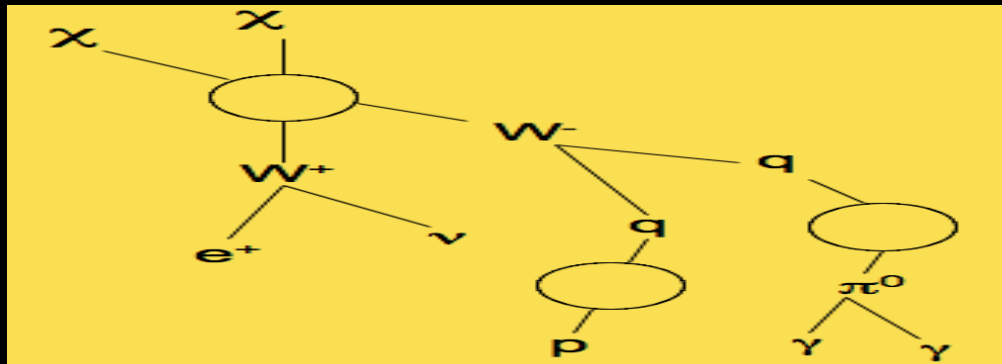
Astrophysical probes complement collider experiments

WIMPS or nonWIMPS



NEUTRALINO DARK MATTER

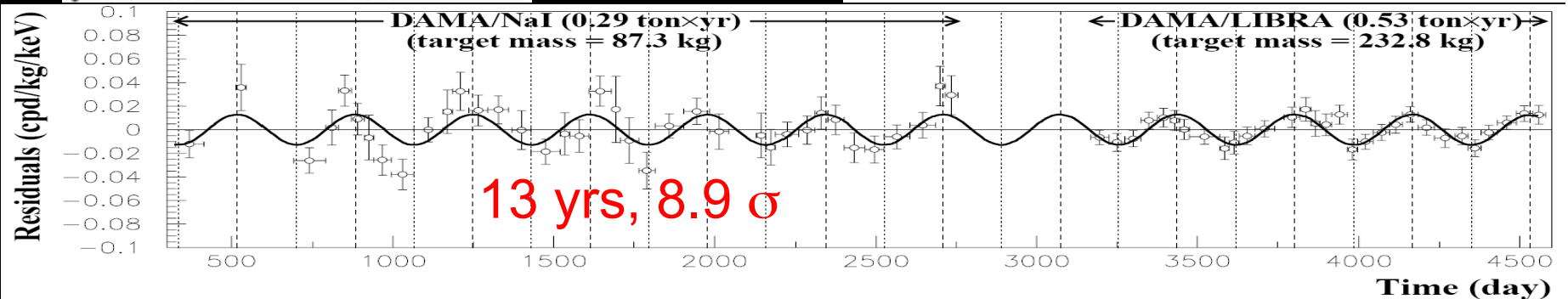
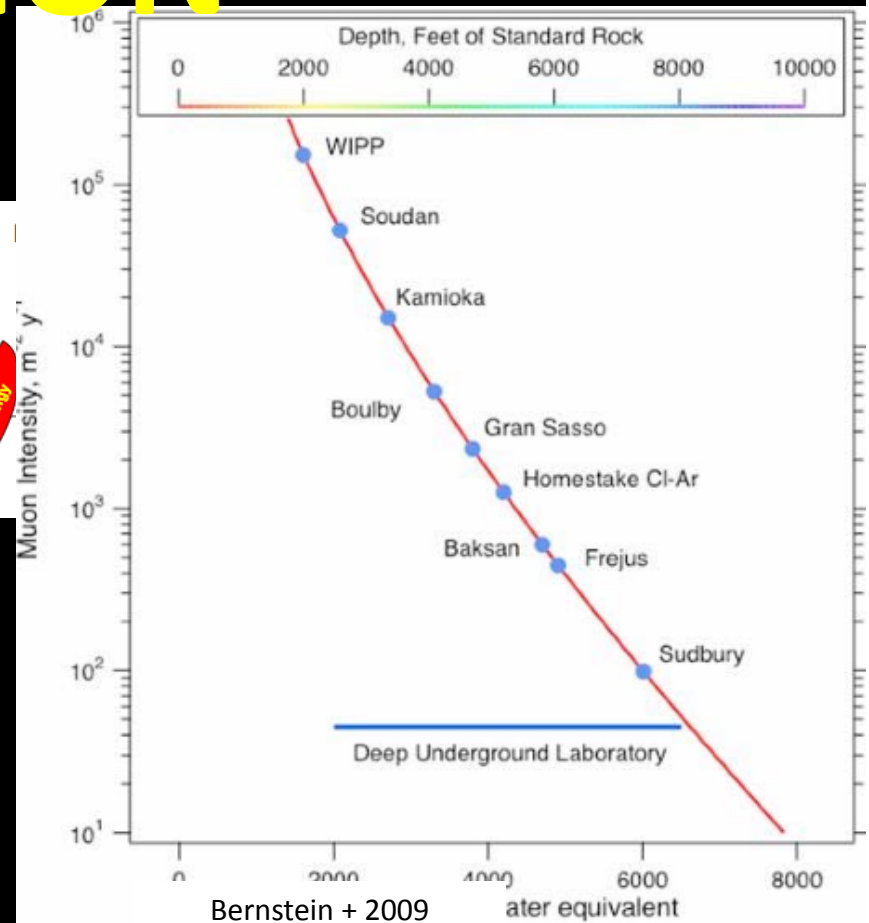
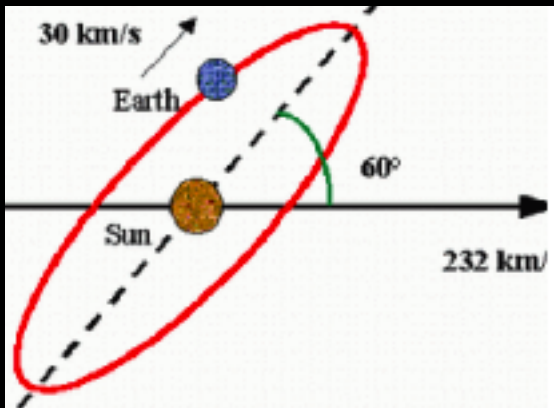
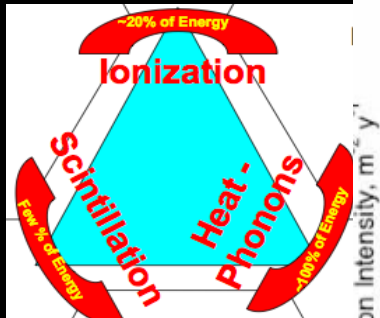
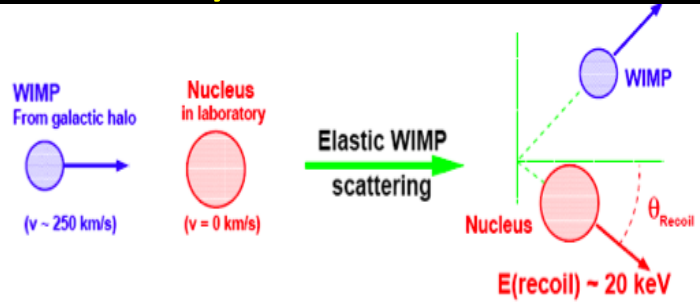
DETECTION IN SPACE OR DEEP UNDERGROUND OFFERS STRATEGY TO PROBE MASS RANGE THAT COMPLEMENTS ANY FUTURE COLLIDERS



$\sim 10^{39}$ GeV/s in total annihilation power in energetic gamma rays, e^+ , \bar{p} , ν

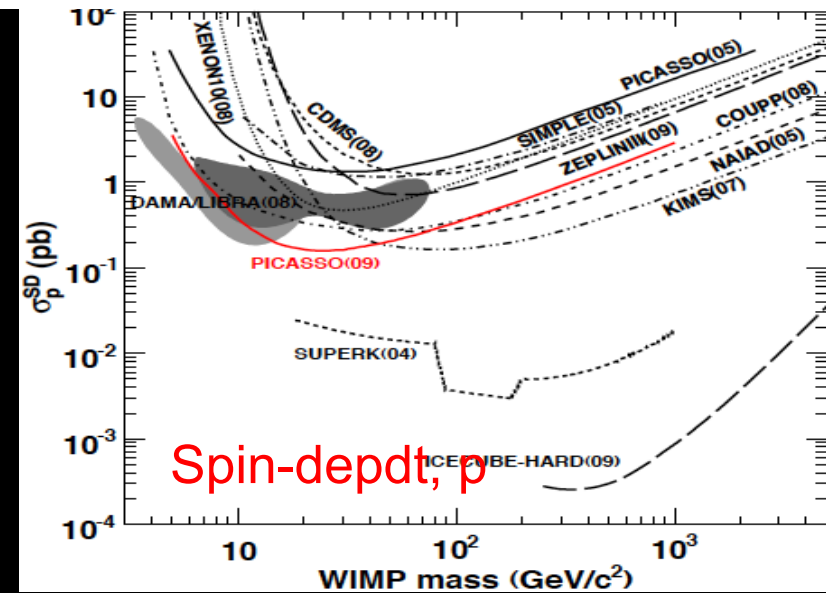
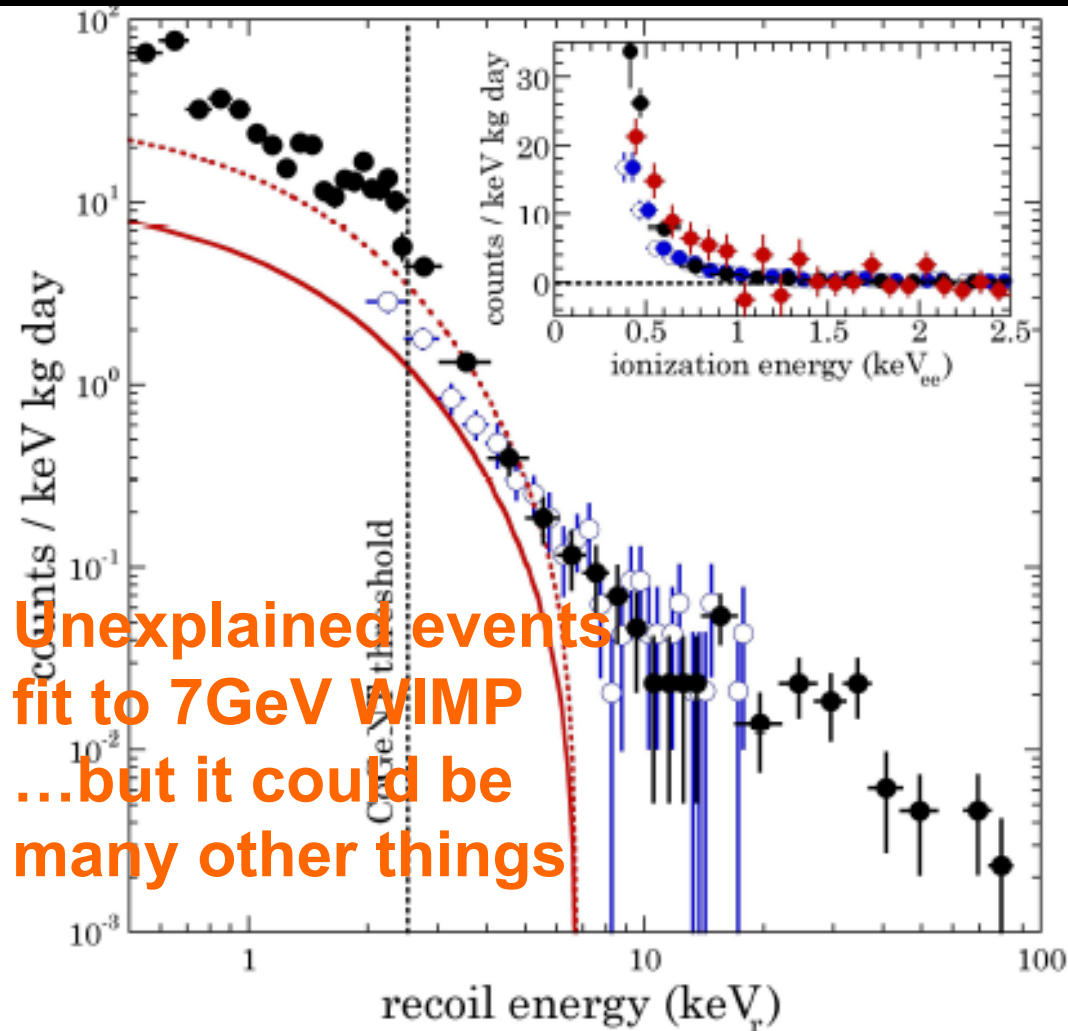
DIRECT DETECTION

many WIMPs pass through
us every second



THE LATEST....

Collar 2011



CoGeNT

15 month modulation, in phase, 2.8σ

CDMS

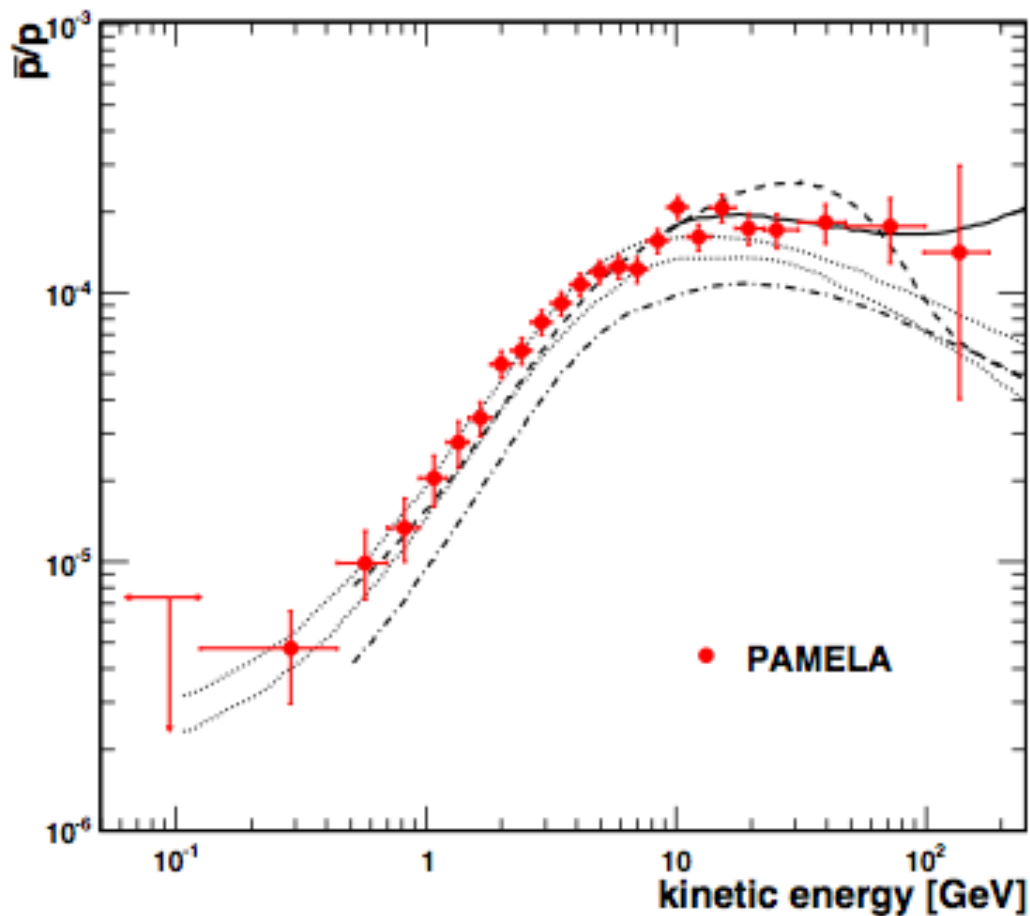
INDIRECT DETECTION

halo WIMPS occasionally
annihilate today

into energetic particles: ν, γ, p, e^+

COSMIC RAYS

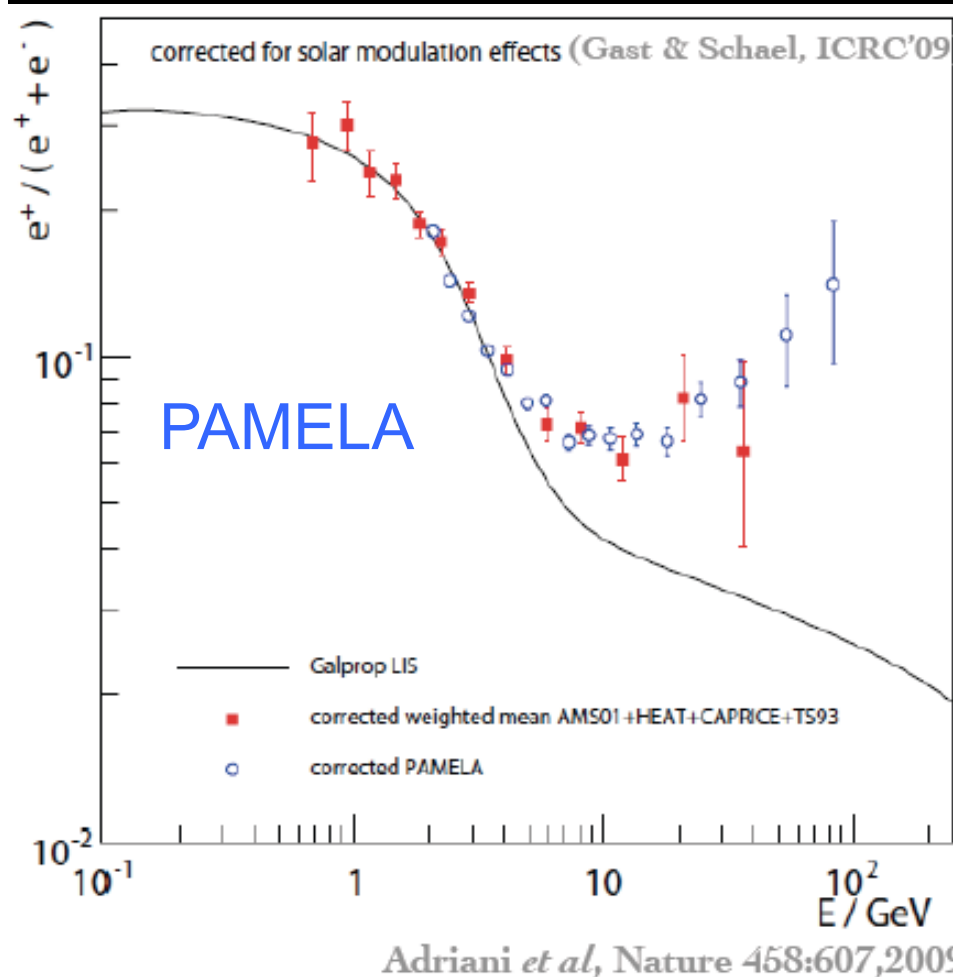
search for antiprotons

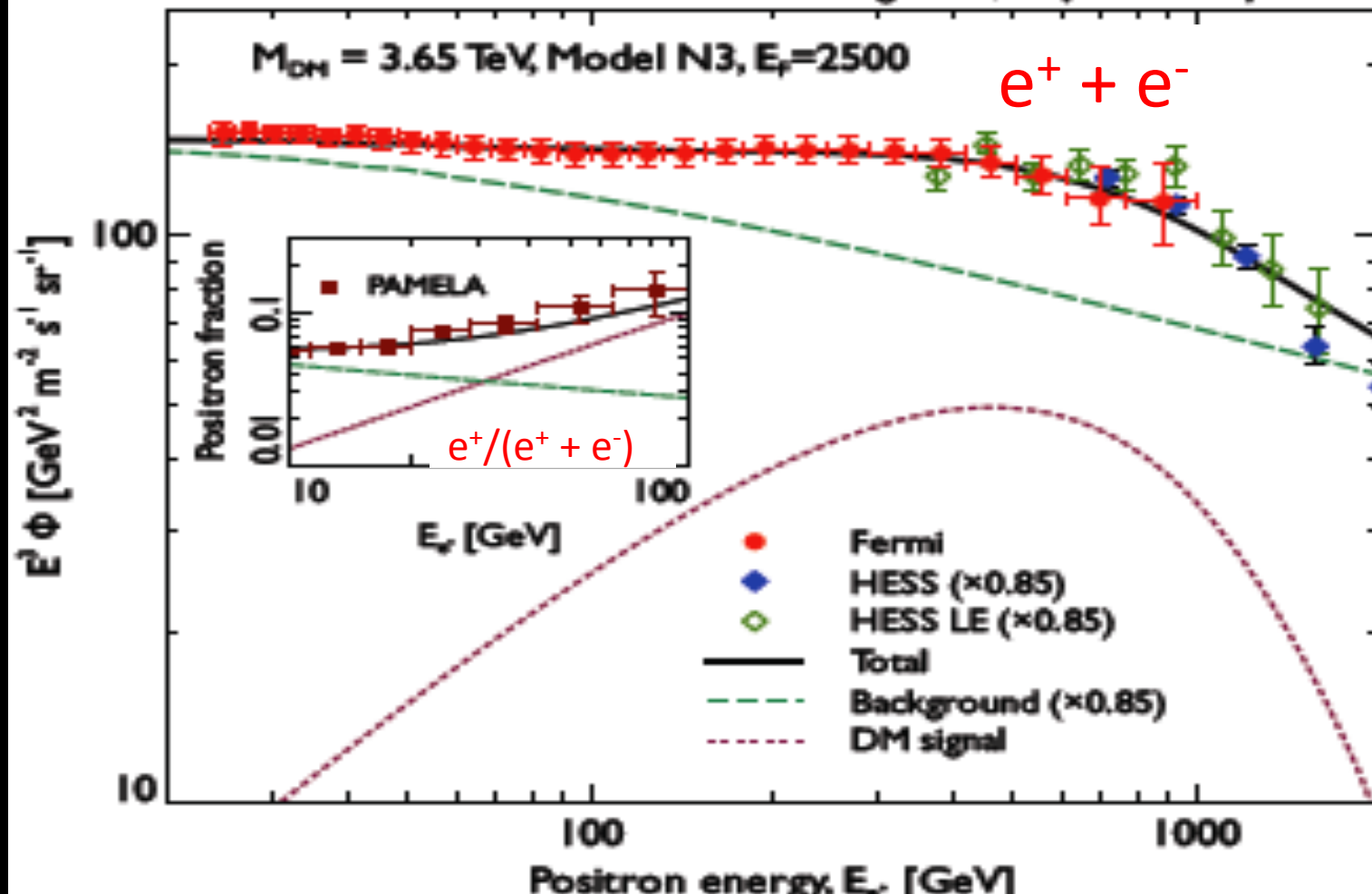


No surprises so far!

high energy positrons

Could be a dark matter signature, but the rise plausibly has an astrophysical origin





massive neutralino requires large boost

PARTICLE PHYSICS SOLUTION with annihilating dark matter

Sommerfeld effect provides boost

since $\text{flux} \sim \rho/m_\chi^2$

QM counterpart to gravity

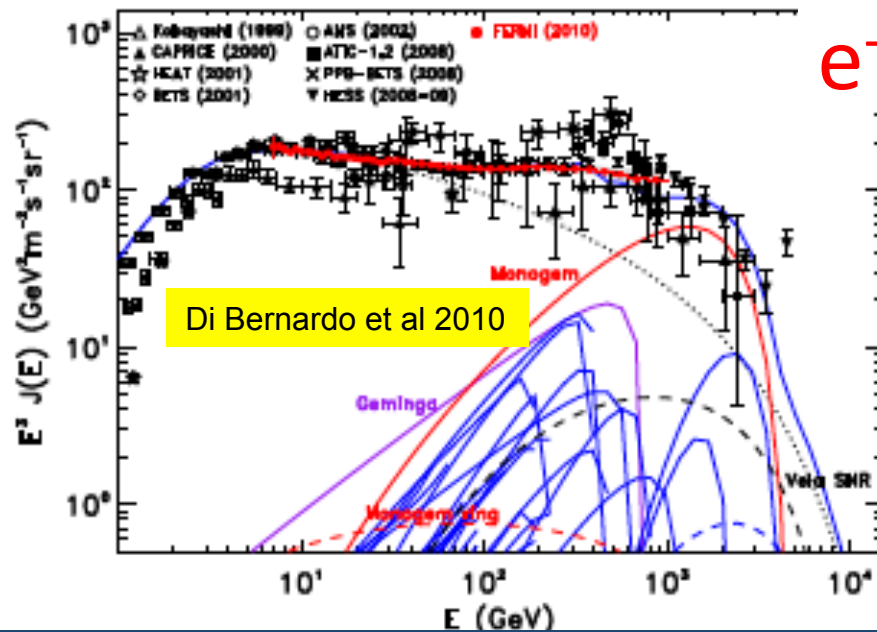
$$S = S_0 [1 + (v_{\text{esc}}/v)^2]$$

due to DM bound states

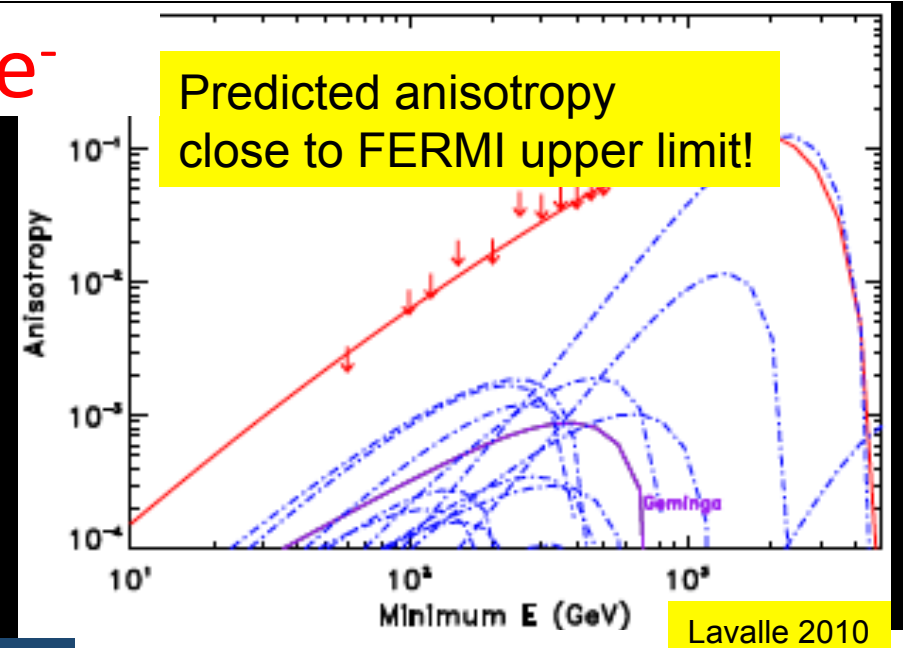
Arkani-Hamed et al 2008

Lattanzi and JS 2008

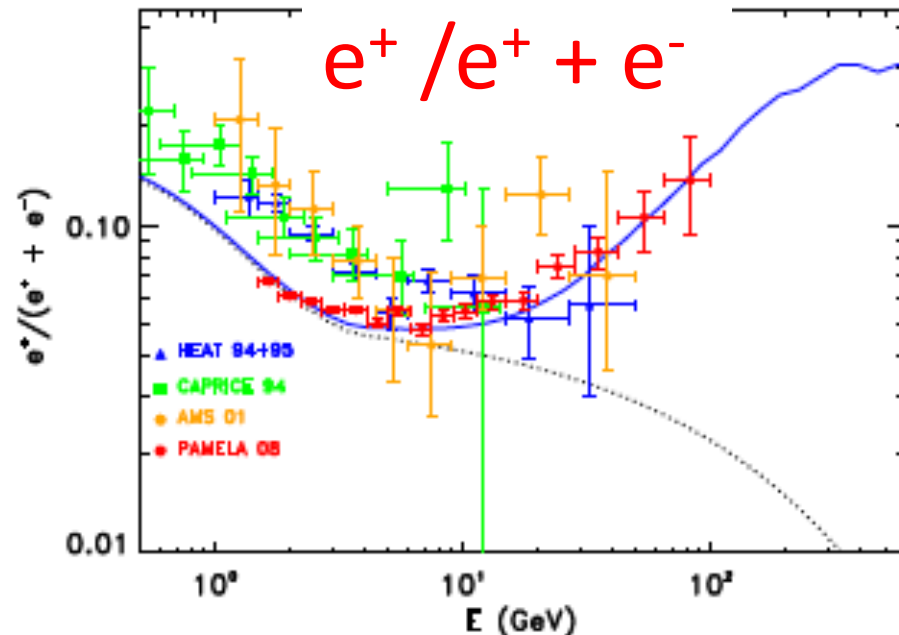
March-Russell and West 2809



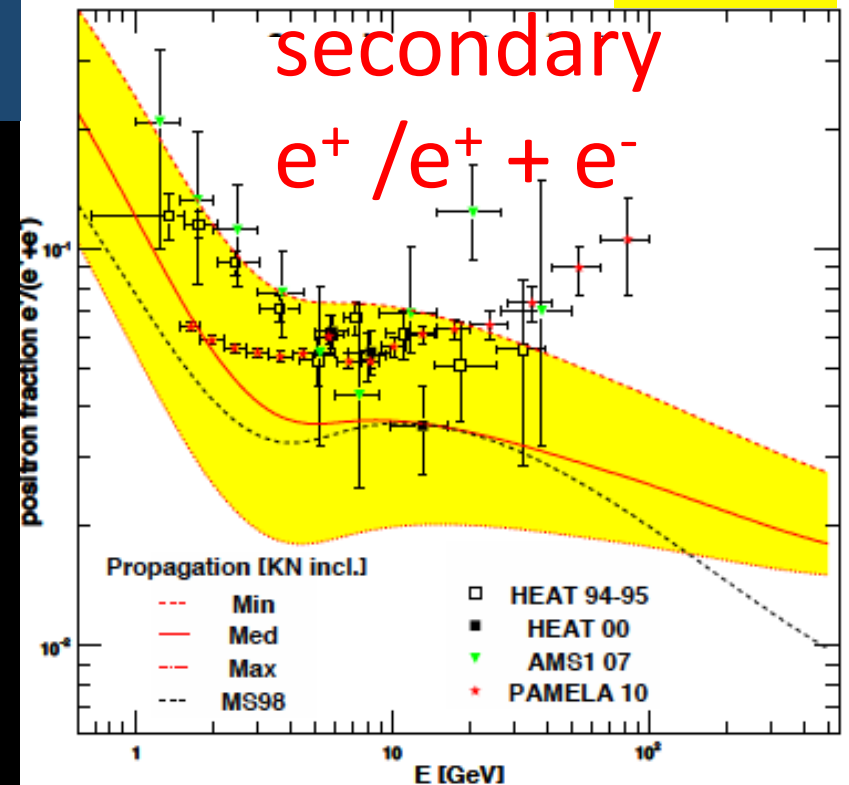
$e^+ + e^-$



ASTROPHYSICS SOLUTIONS



$e^+ / e^+ + e^-$

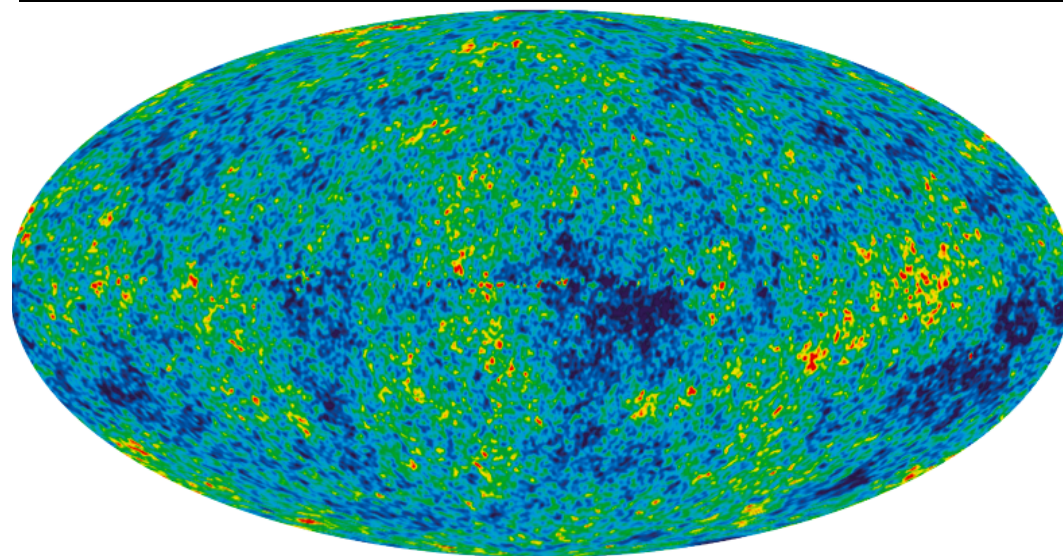


The WMAP microwave haze

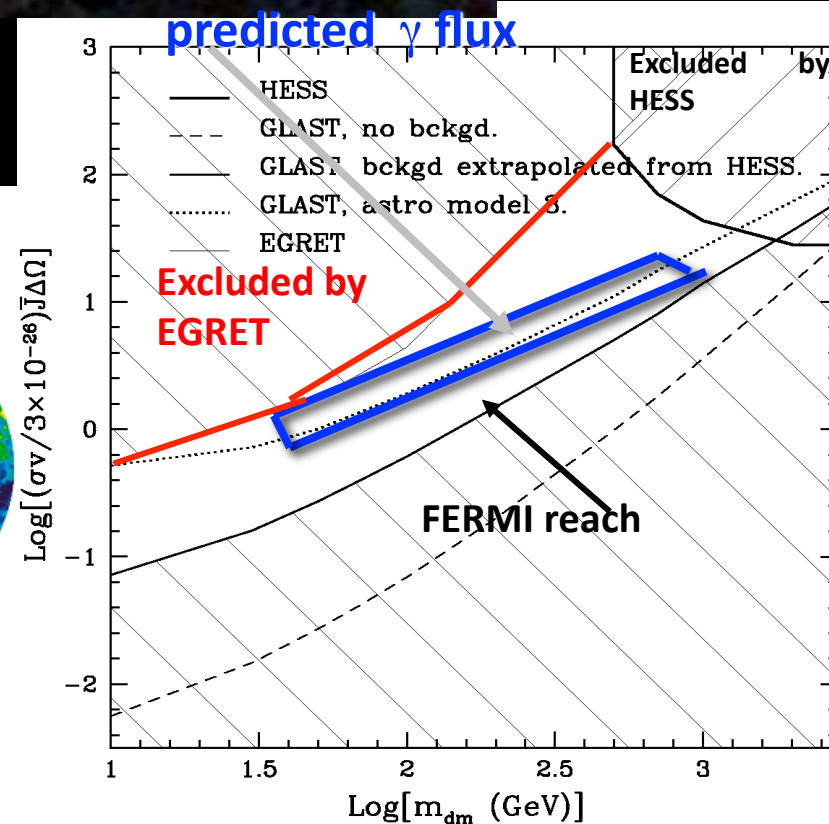
Finkbeiner 2007



Hooper and Zaharias 2007

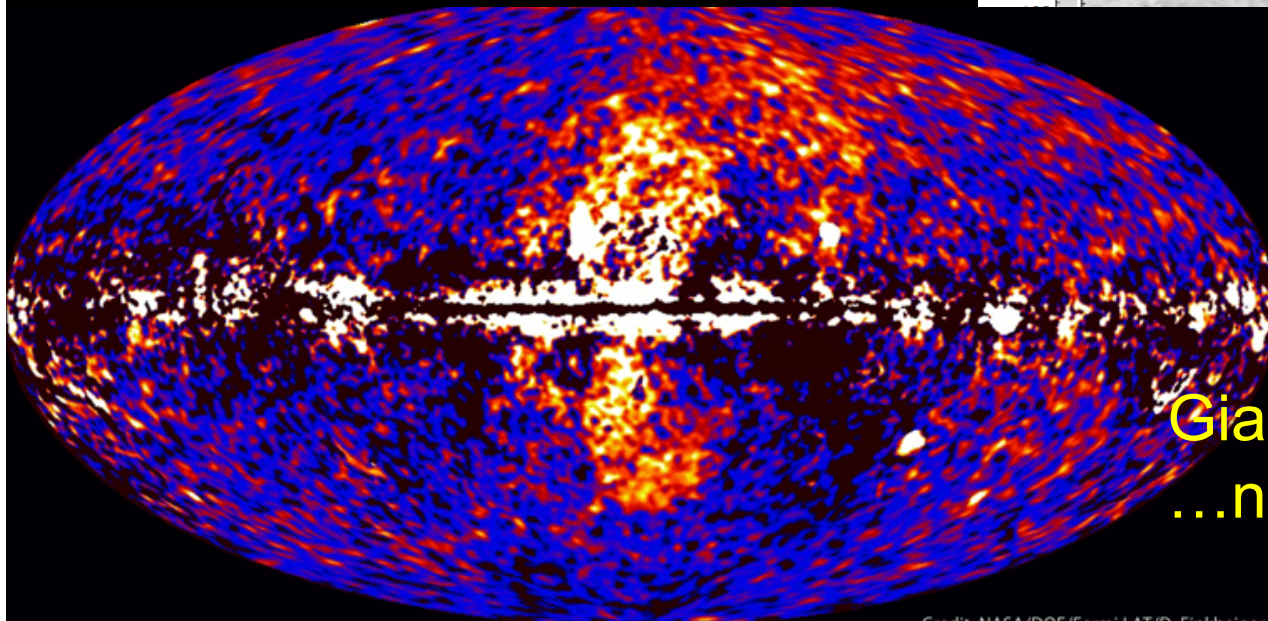
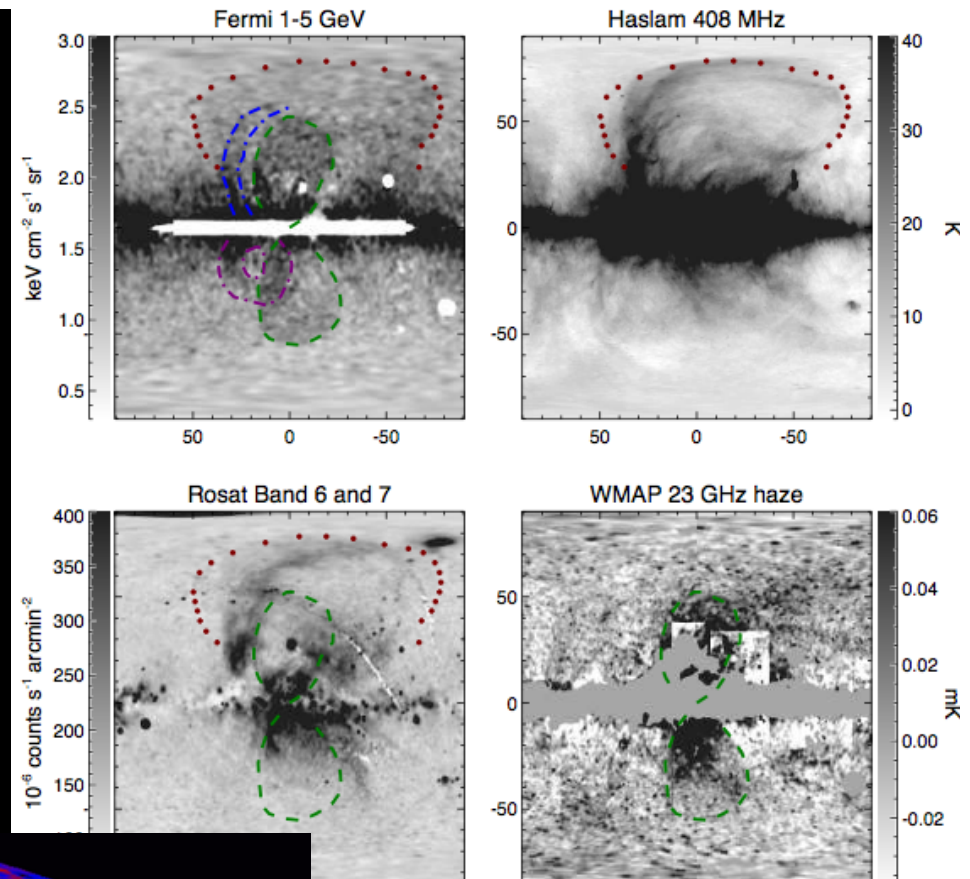


-200 $T(\mu\text{K})$ +200 WMAP 5-year

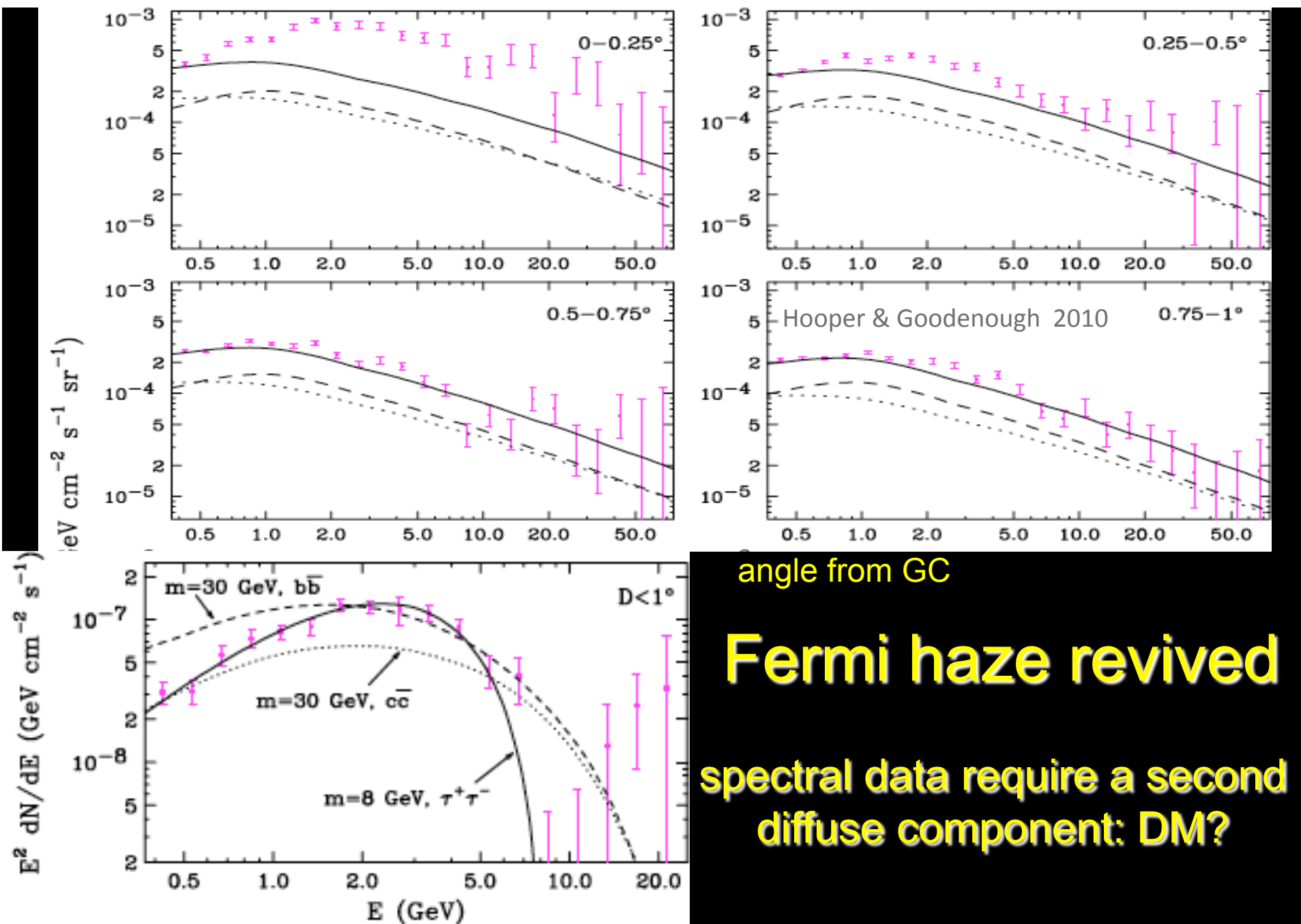


Fermi haze is inverse Compton of e^+e^- on interstellar radiation

Su et al. 2010



Giant gamma ray bubbles
...not dark matter

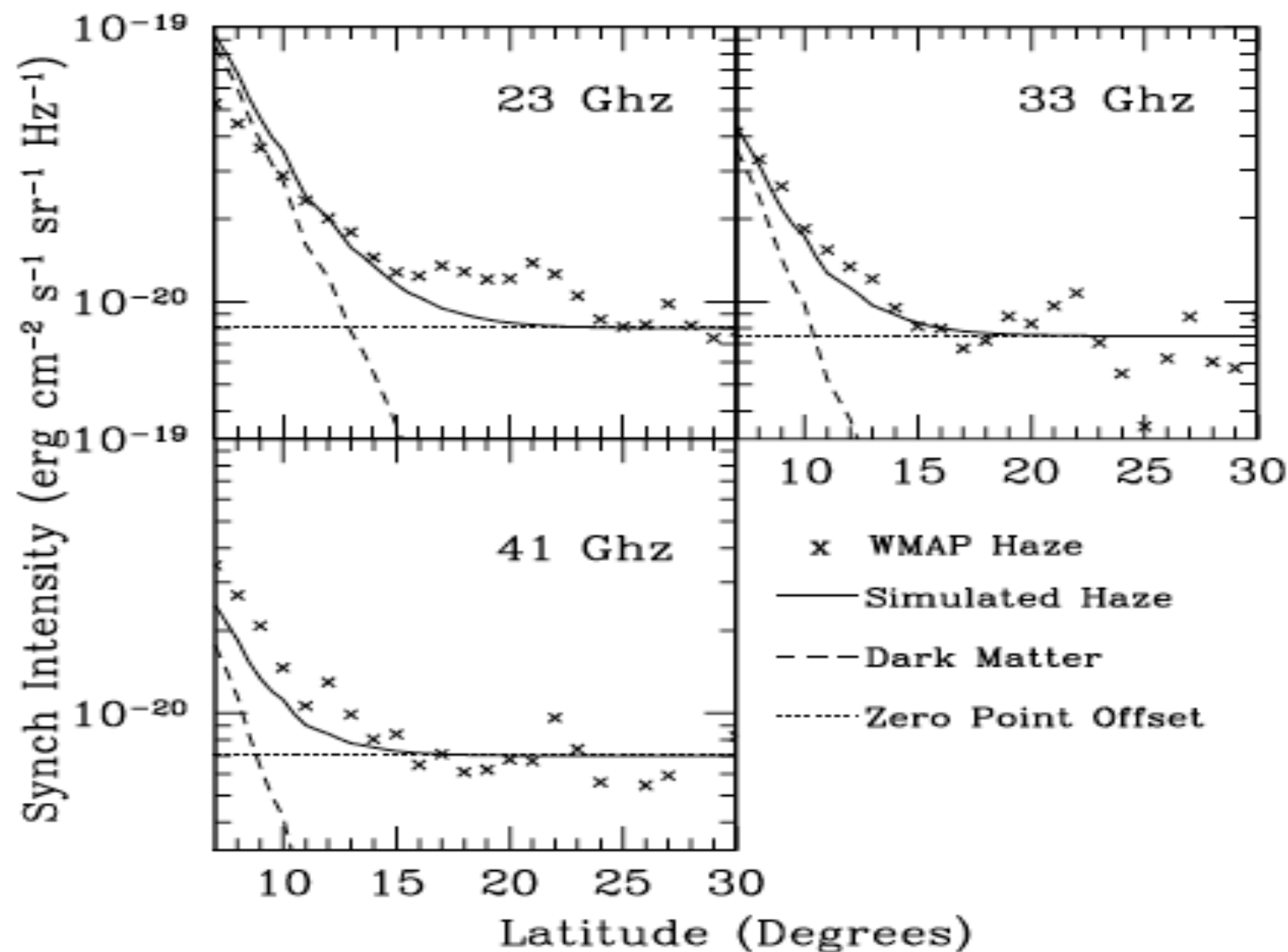


angle from GC

Fermi haze revived

spectral data require a second
diffuse component: DM?

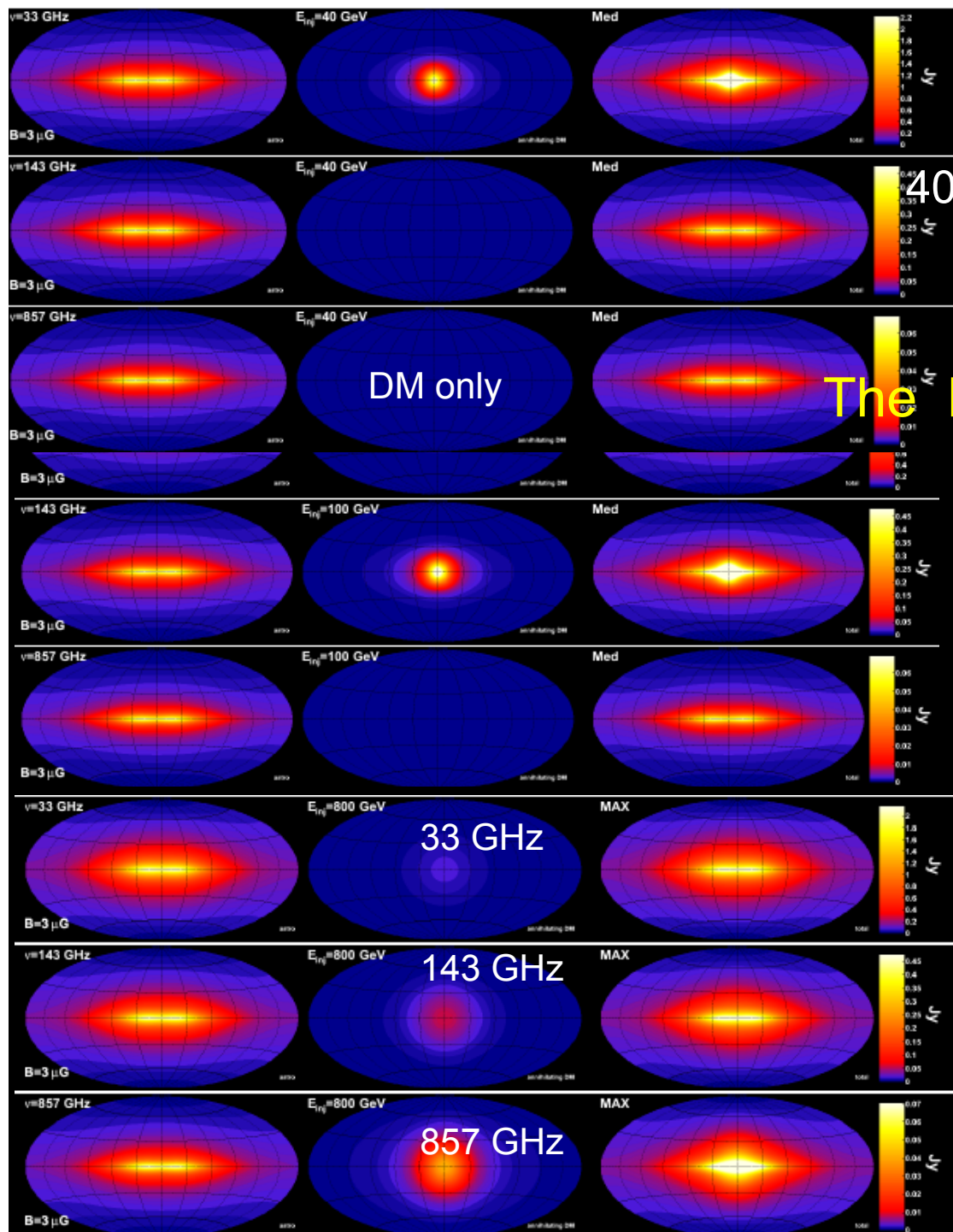
spectral fit: 8 GeV WIMP



Hooper & Linden 2010

WMAP haze revived

due to 8 GeV WIMP annihilations via e, μ, τ and synchrotron radiation



40 GeV

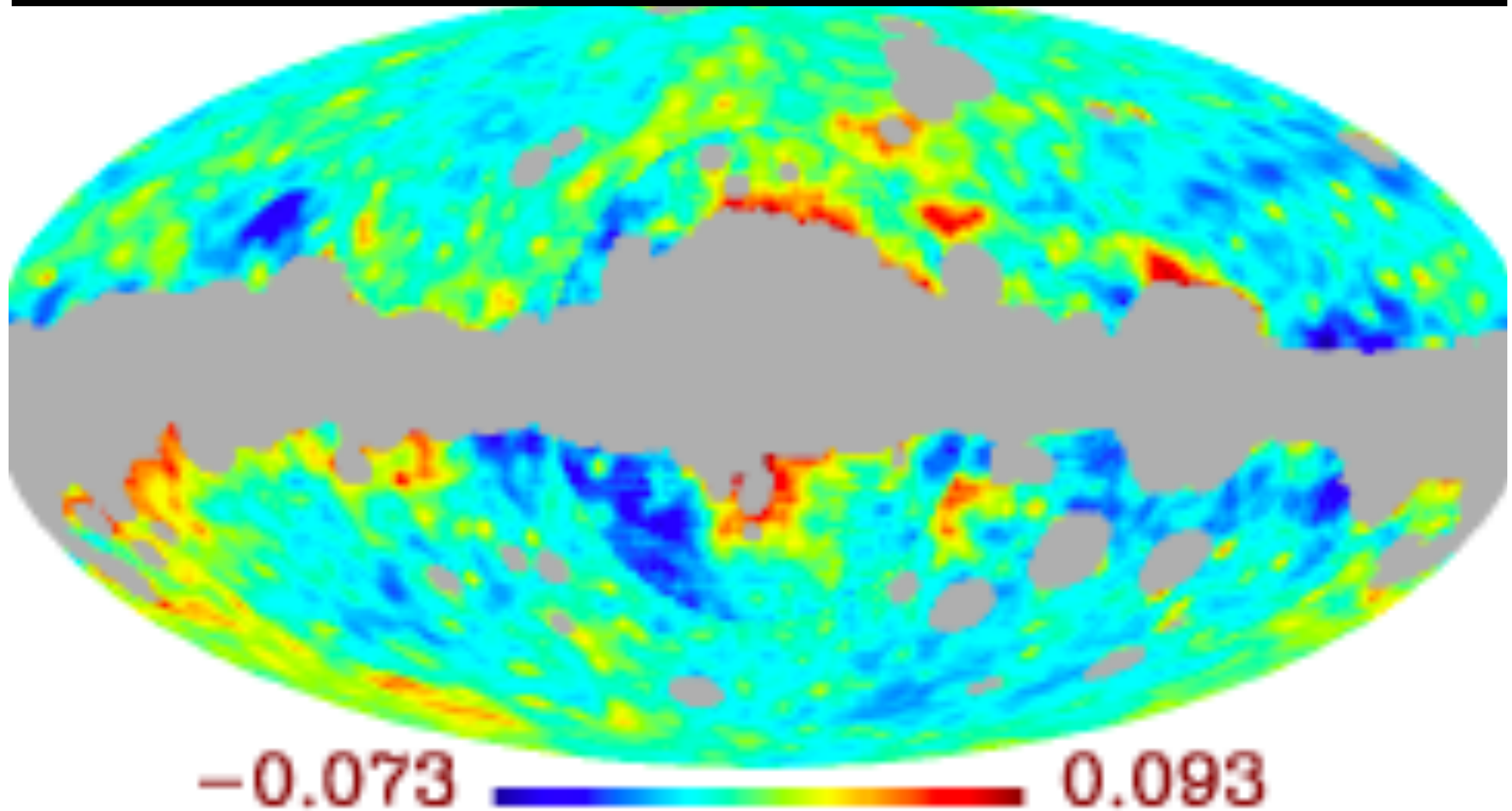
The haze morphology for Planck

100 GeV

Delahaye, Boehm, JS 2011

800 GeV

Spectral index variations in WMAP residual haze

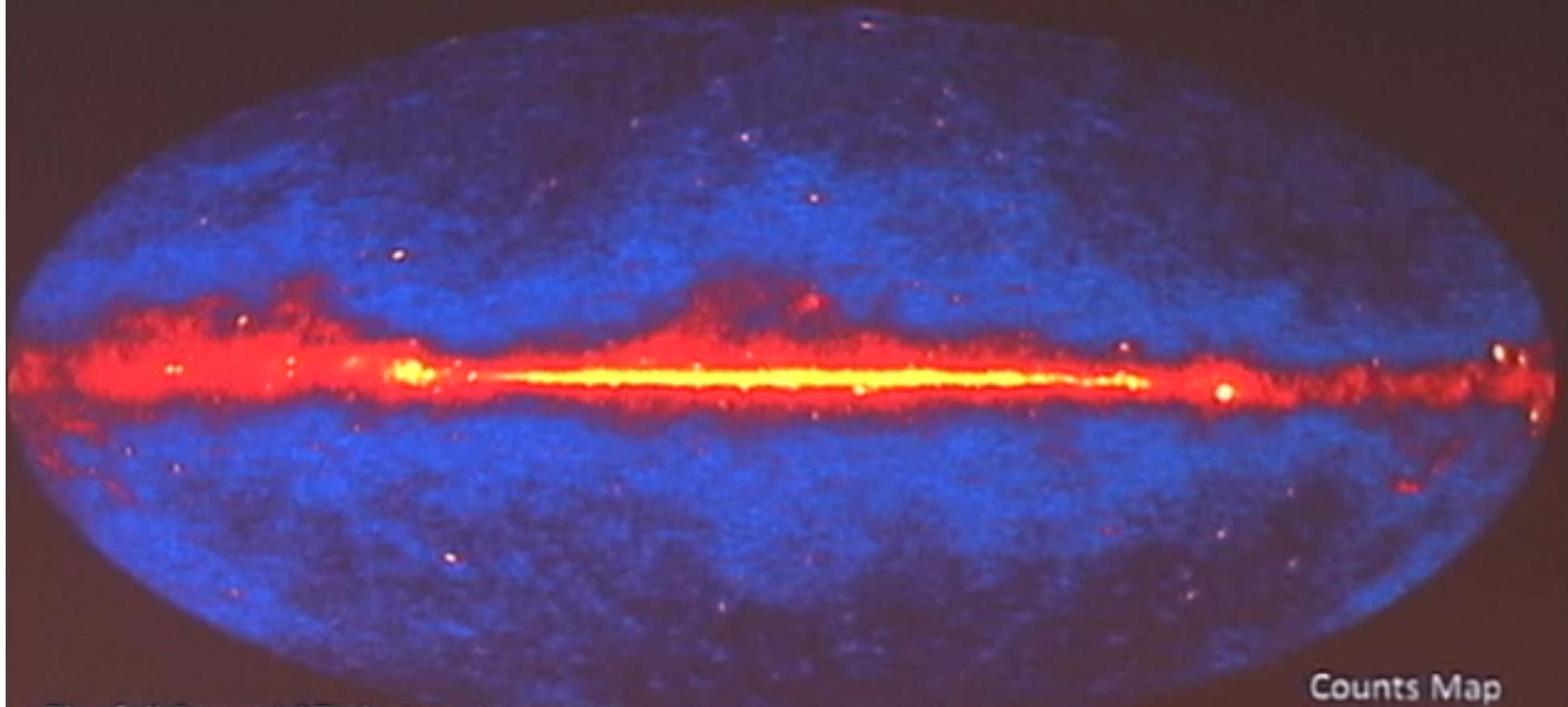


annihilation γ -rays from the centre of the Galaxy ??

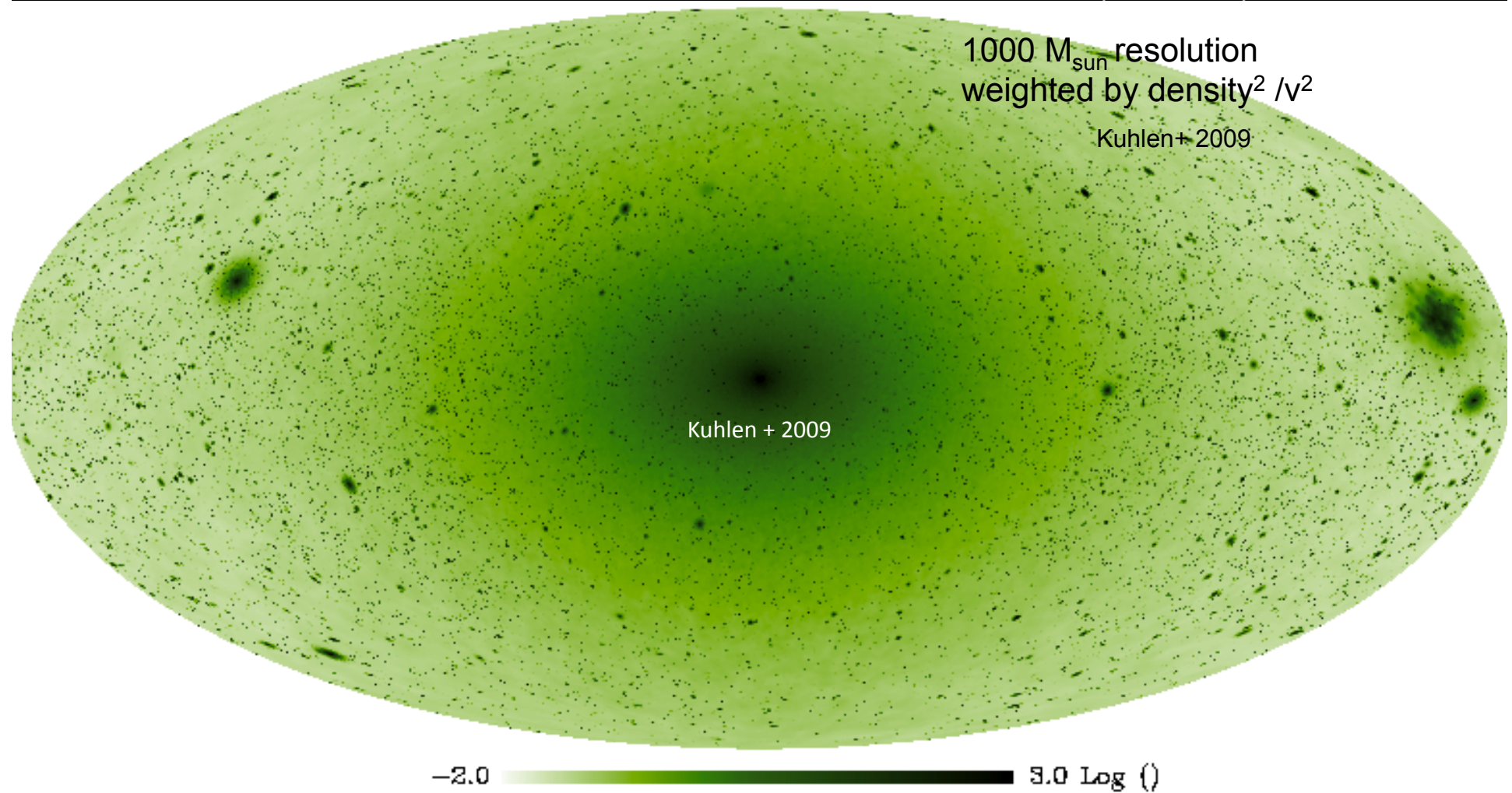
predict γ ray “smoking guns”: e.g. morphology hard spectrum annihilation line

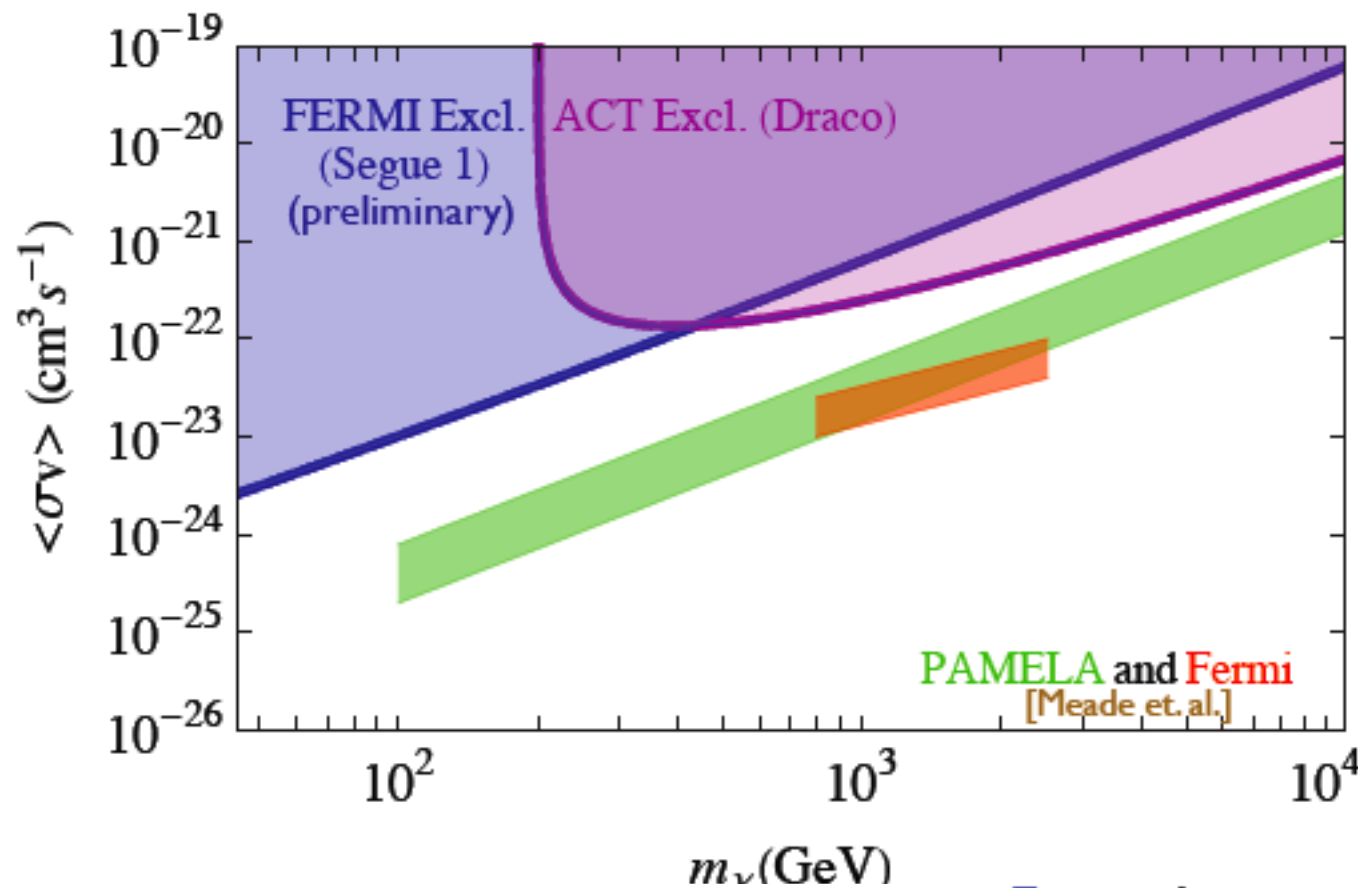
FERMI (2009 launch): 0.02 - 300 GeV, $5^\circ - 5'$, $\Delta E/E \sim 0.1$

2-Year All-Sky Map, $E > 1$ GeV



γ rays from dark matter-dominated dwarf galaxies





Fermi data:

9 months of data

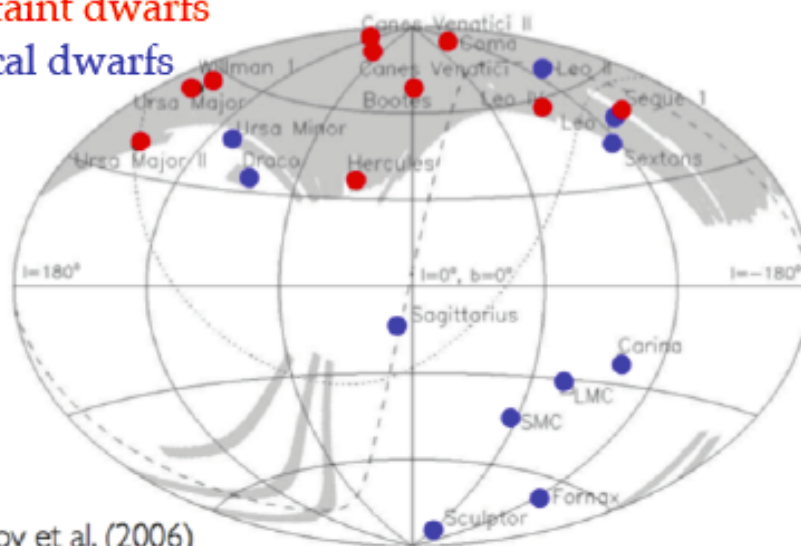
[Farnier, RICAP'09]
[Wang, CINC'09]

ACT data:

VERITAS obs. of
Draco [0810.1913]

PAMELA and Fermi
[Meade et. al.]

- ultra-faint dwarfs
- classical dwarfs



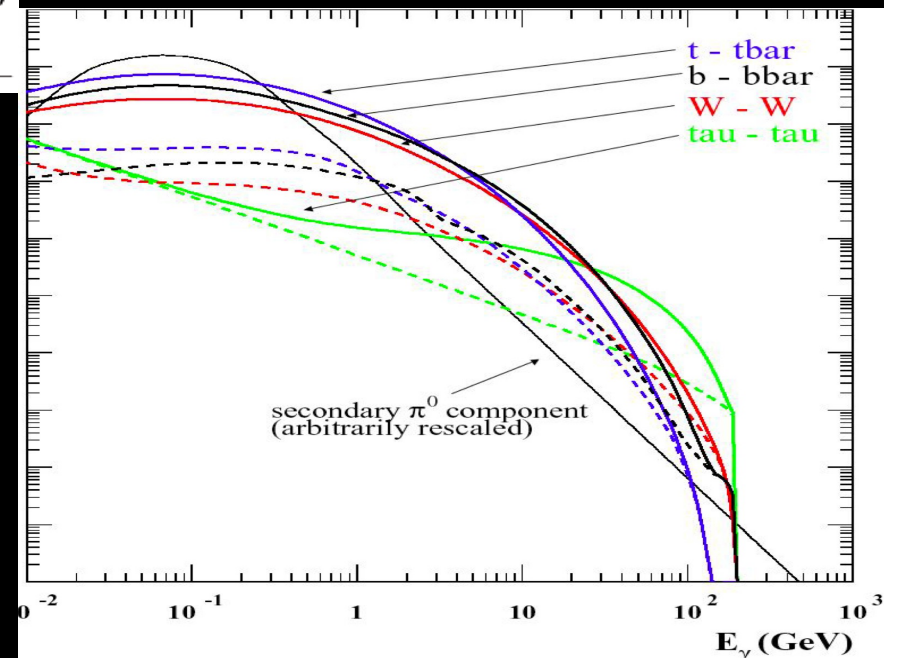
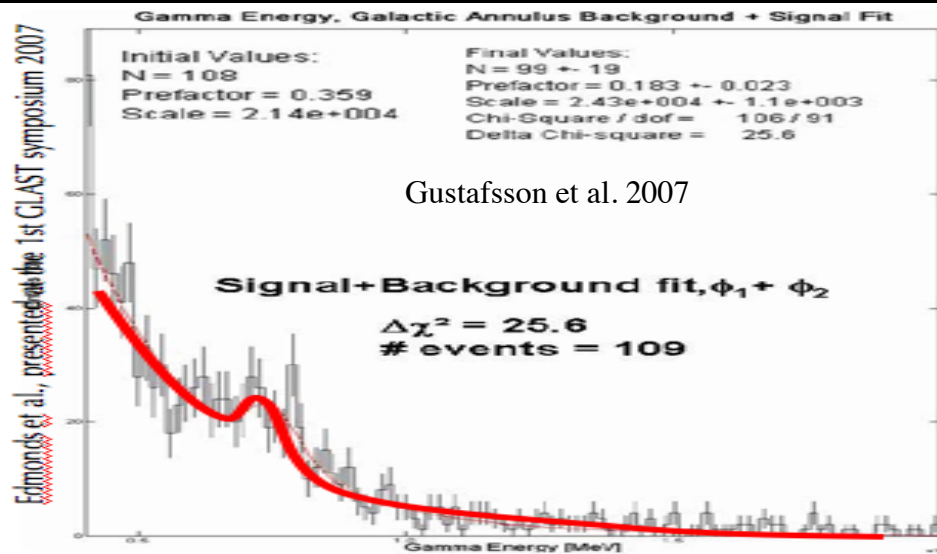
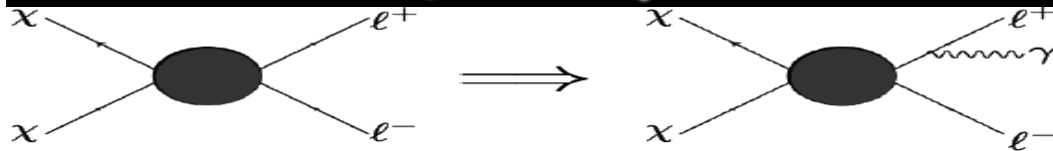
Belokurov et al. (2006)

Fermi better at lower masses,
ACTs at higher masses

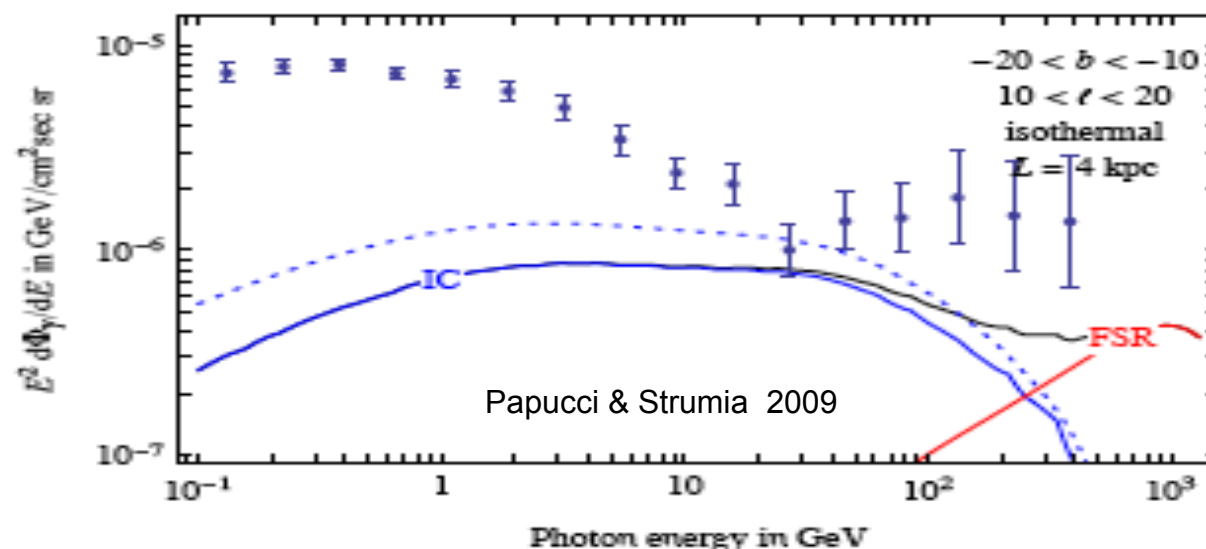
Neelima Sehgal, KIPAC

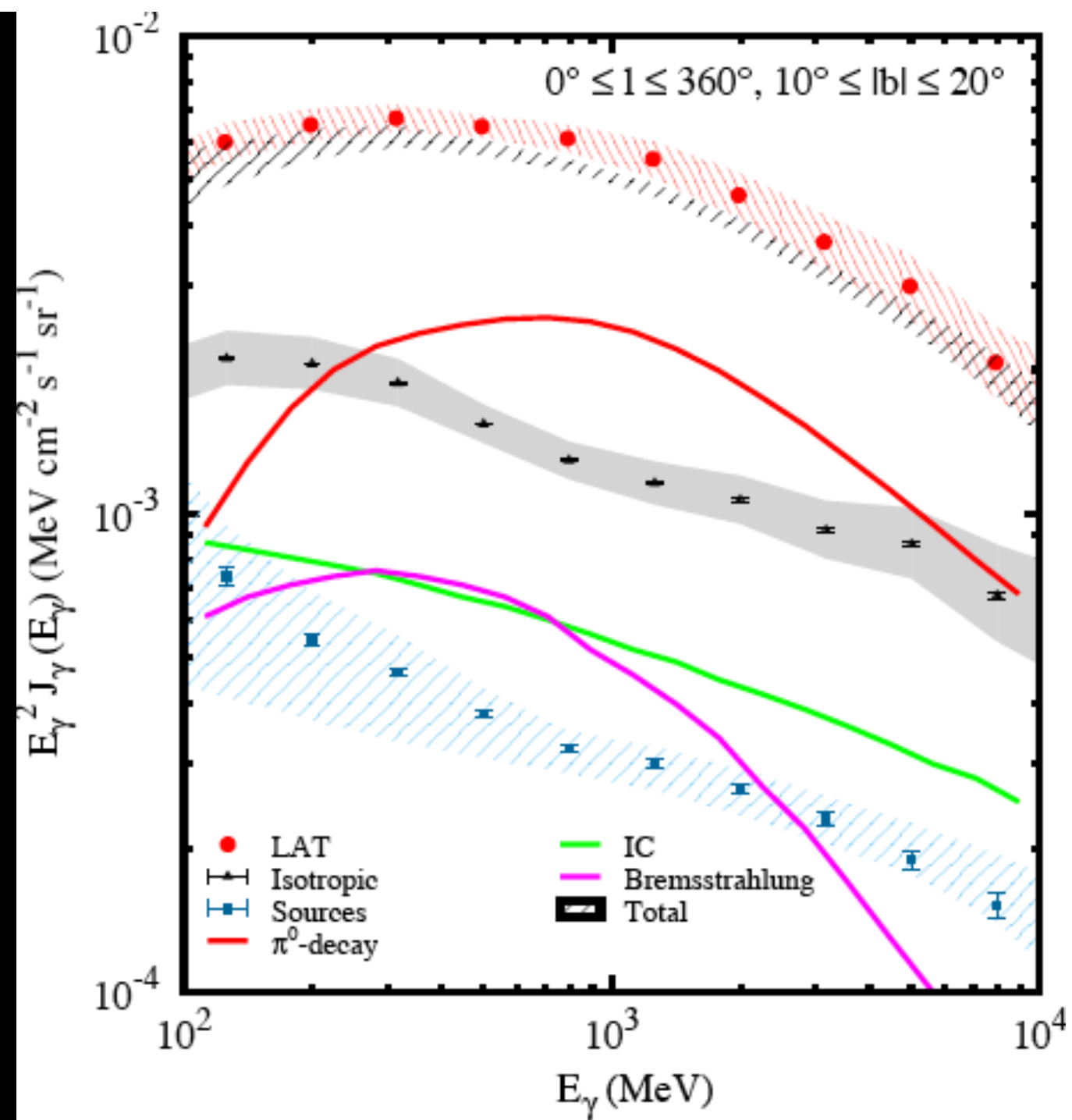
**DWARFS AS A PROBE
only upper limits....**

FERMI/HESS prediction: final state gamma rays

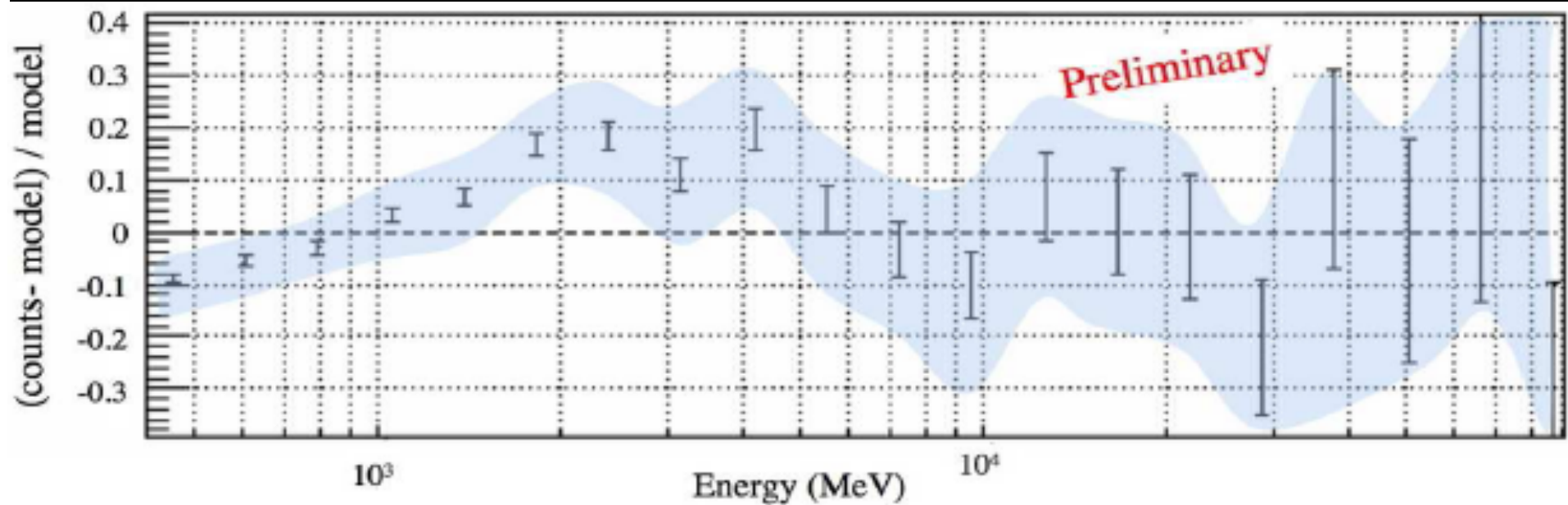


$$\text{DM DM} \rightarrow \mu^+ \mu^-, M = 1.3 \text{ TeV}, \sigma v = 2.8 \times 10^{-23} \text{ cm}^3/\text{s}$$





FERMI galactic centre residuals



Did we prematurely abandon a dark matter contribution in the Galactic Centre?

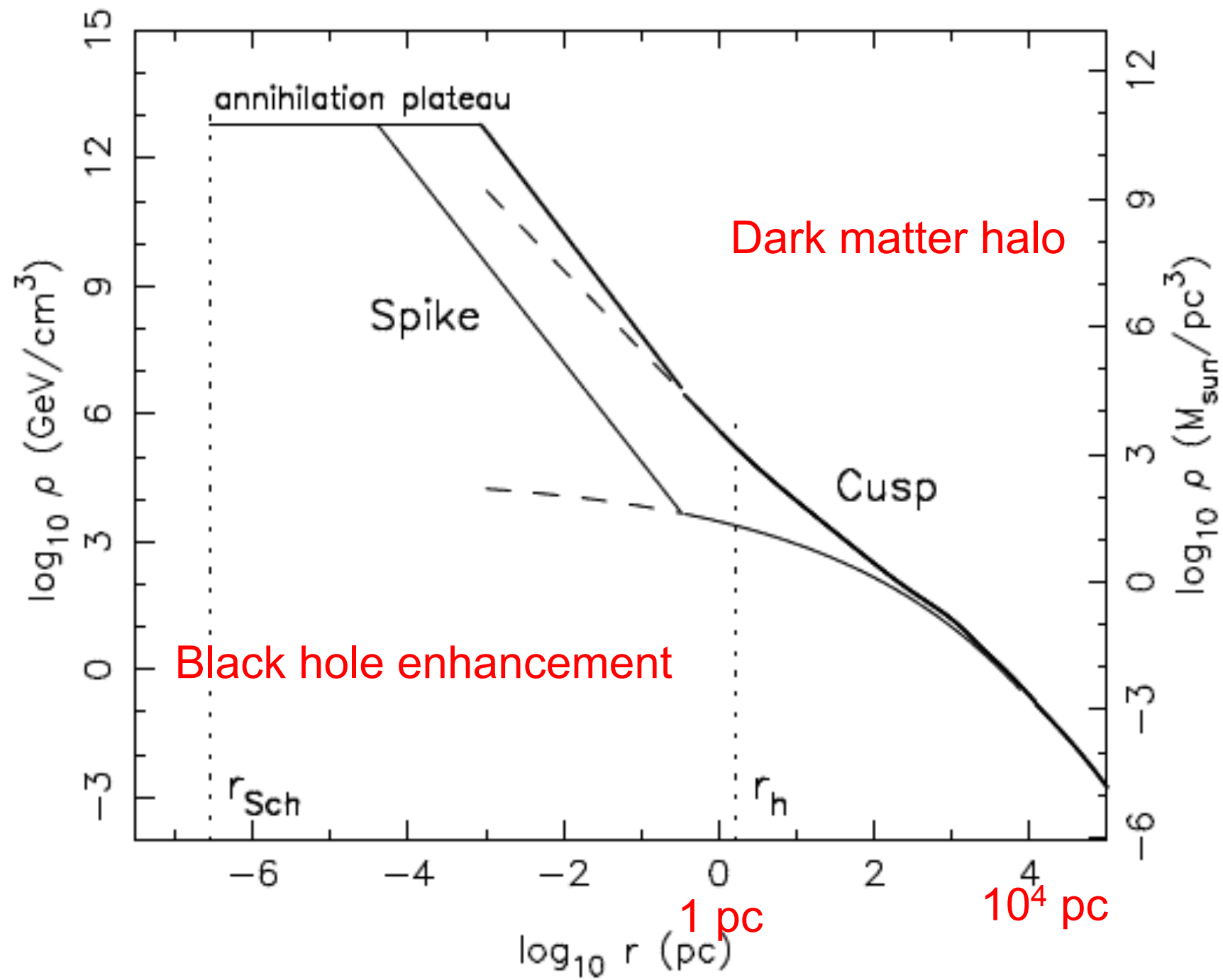
CDM cusp steepens by adiabatic growth
of IMBH: $\rho \propto r^{-\gamma} \Rightarrow \rho \propto r^{-\gamma'}$, with $\gamma' = \frac{9-2\gamma}{4-\gamma}$

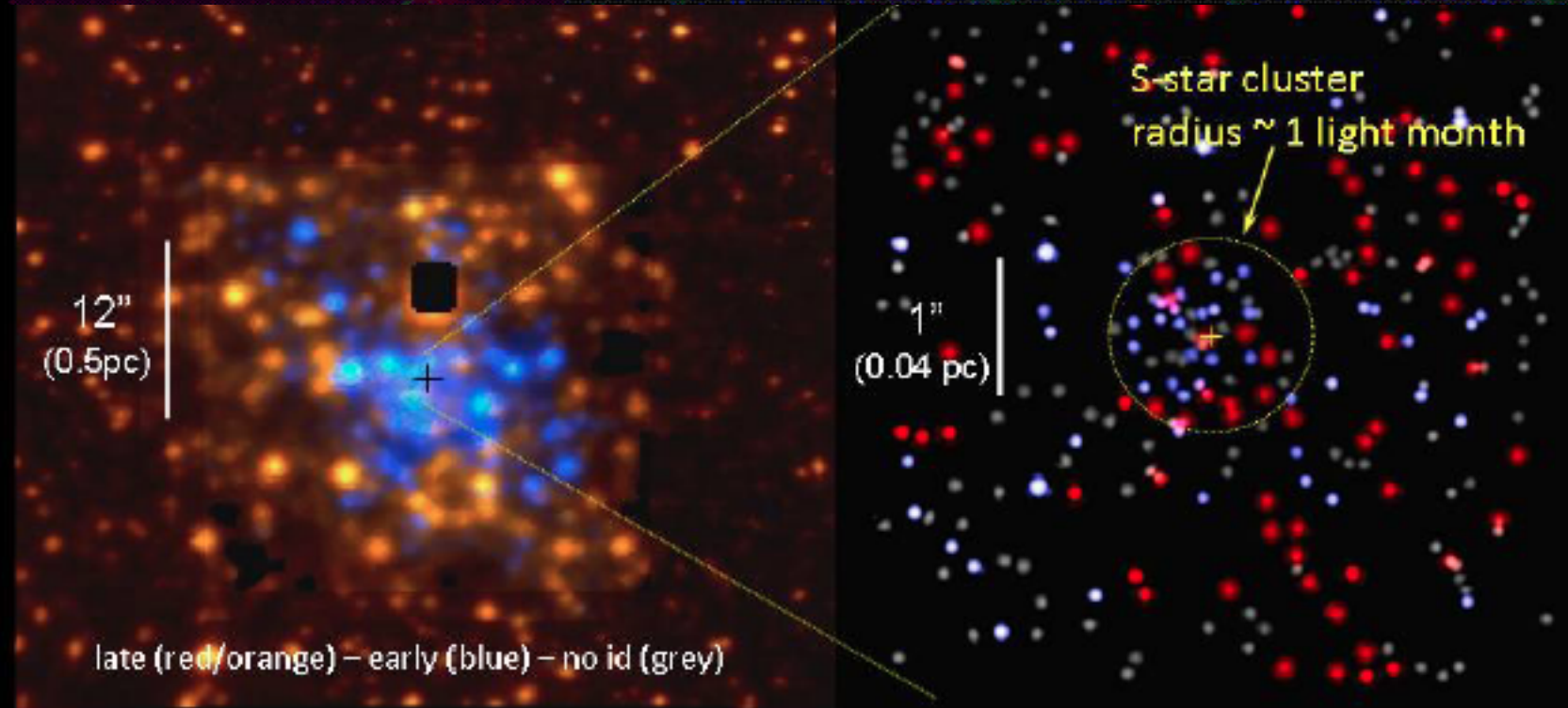
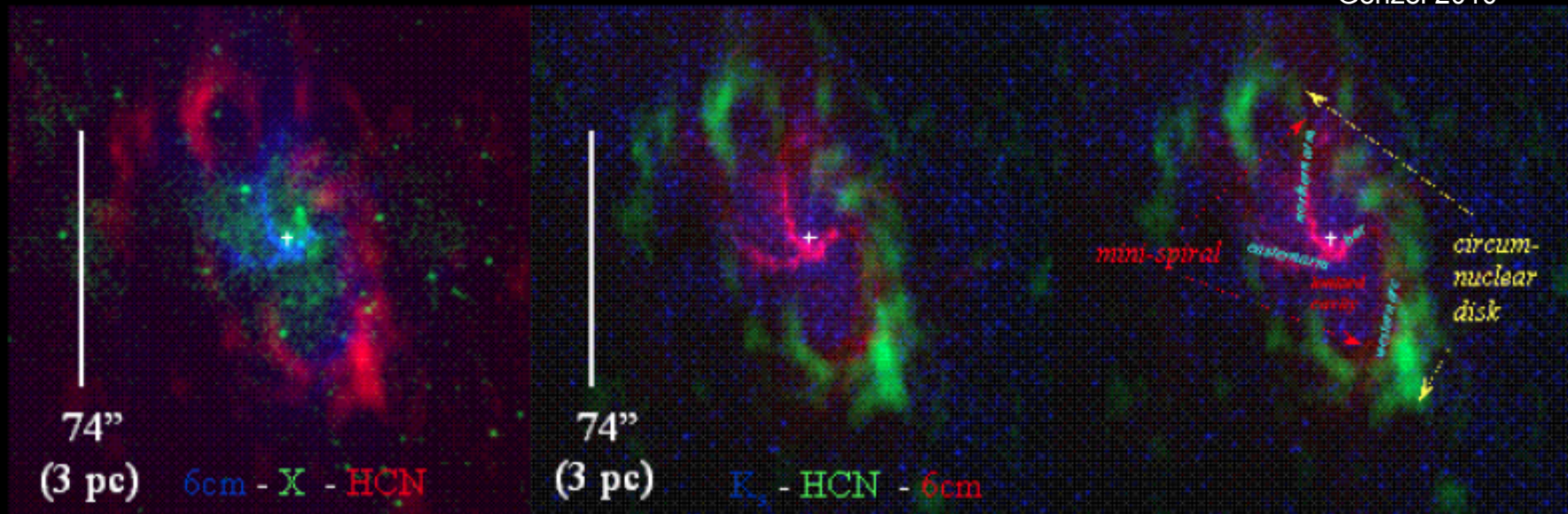
Annihilation rate is amplified within a
radius $GM_{bh}/\sigma^2 \sim 0.003(M_{BH}/10^5 M_\odot)\text{pc}$

a local boost is natural in gravitationally bound
spike around Sag A* black hole $4 \times 10^6 M_{\text{sun}}$

Dynamical heating reduces peak density

DM predicts exponential cut-off + no variability





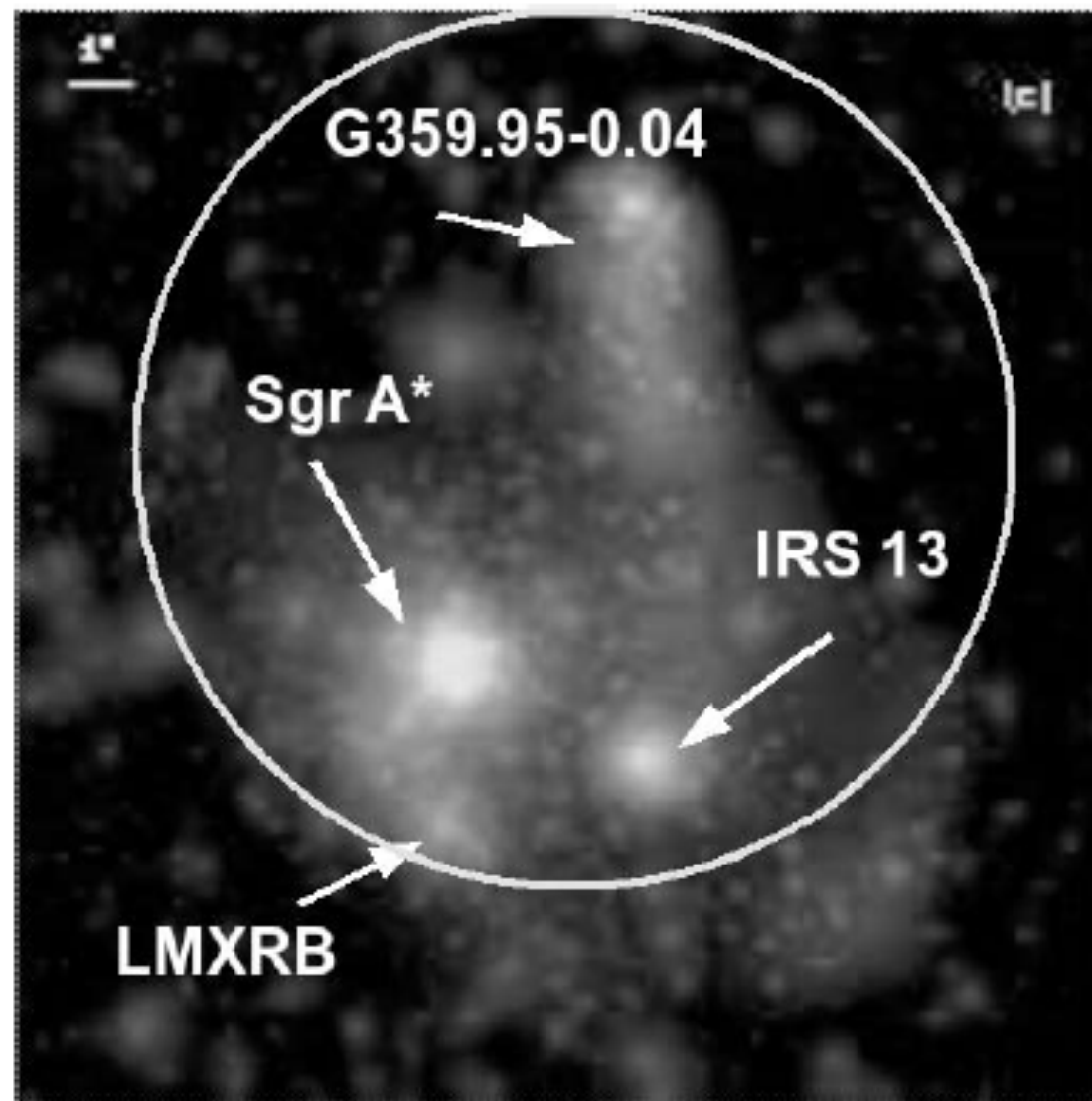


FIGURE 1. Chandra X-ray and NACO Near-infrared Composite of the Galactic center region [4]. The circle marks the systematic (and therefore irreducible) H.E.S.S. uncertainty region of 6".

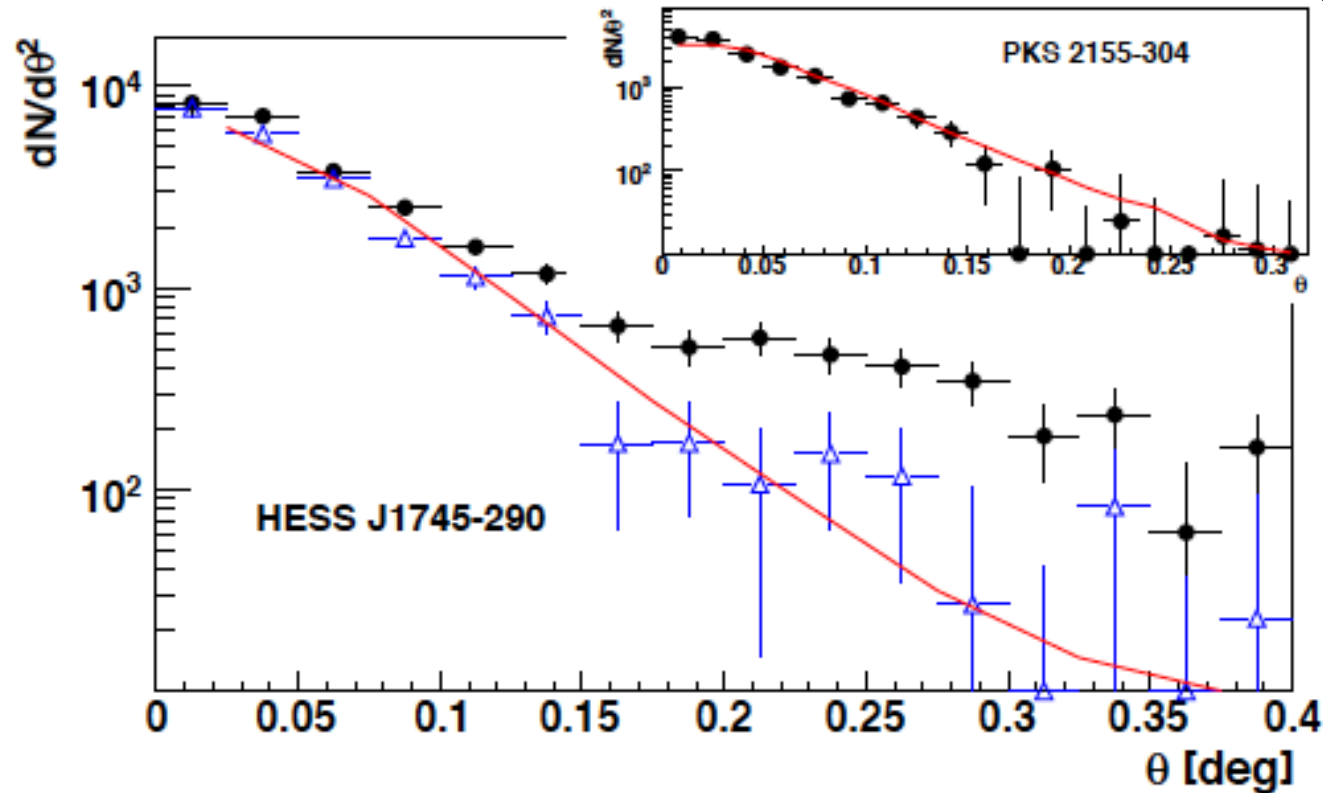
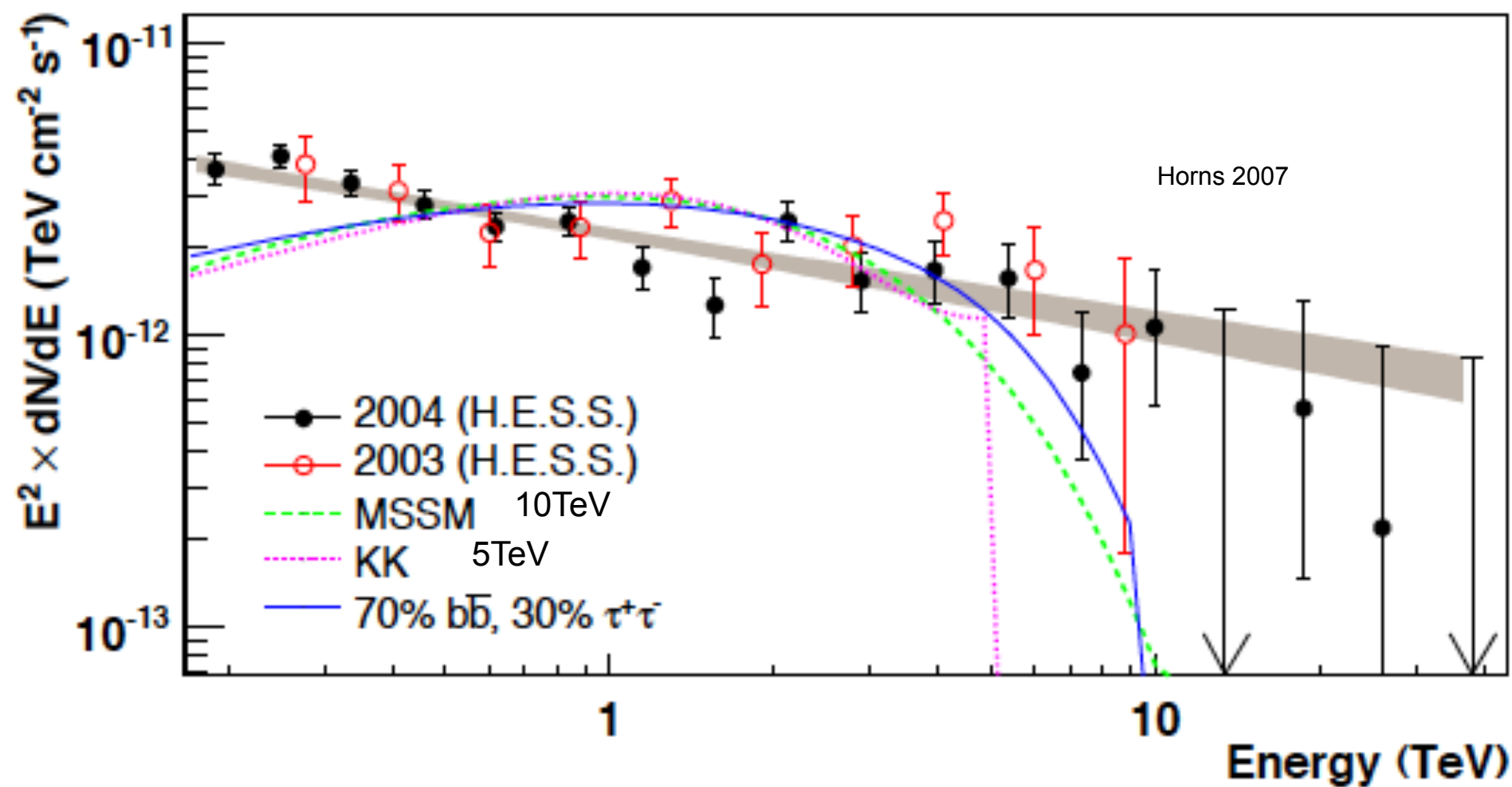


Fig. 2. Radial surface brightness profile of the gamma-ray emission (number of gamma-ray events per solid angle) from the Galactic center: The solid points indicate the number of gamma-ray events detected from the Galactic center and the environment up to an angular separation of $\theta = 0.4^\circ$ while the open points show the surface brightness after subtracting off the diffuse emission from the Galactic ridge. The solid line represents the expected distribution of gamma-rays for a point-like source taking into account varying zenith angles of the observation. As an example for an observation of a point-like source, the signal obtained from the Active Galactic Nucleus PKS 2155-304 is shown in the inlaid figure.



The Galactic Centre black hole:

exponential spectrum preferred?

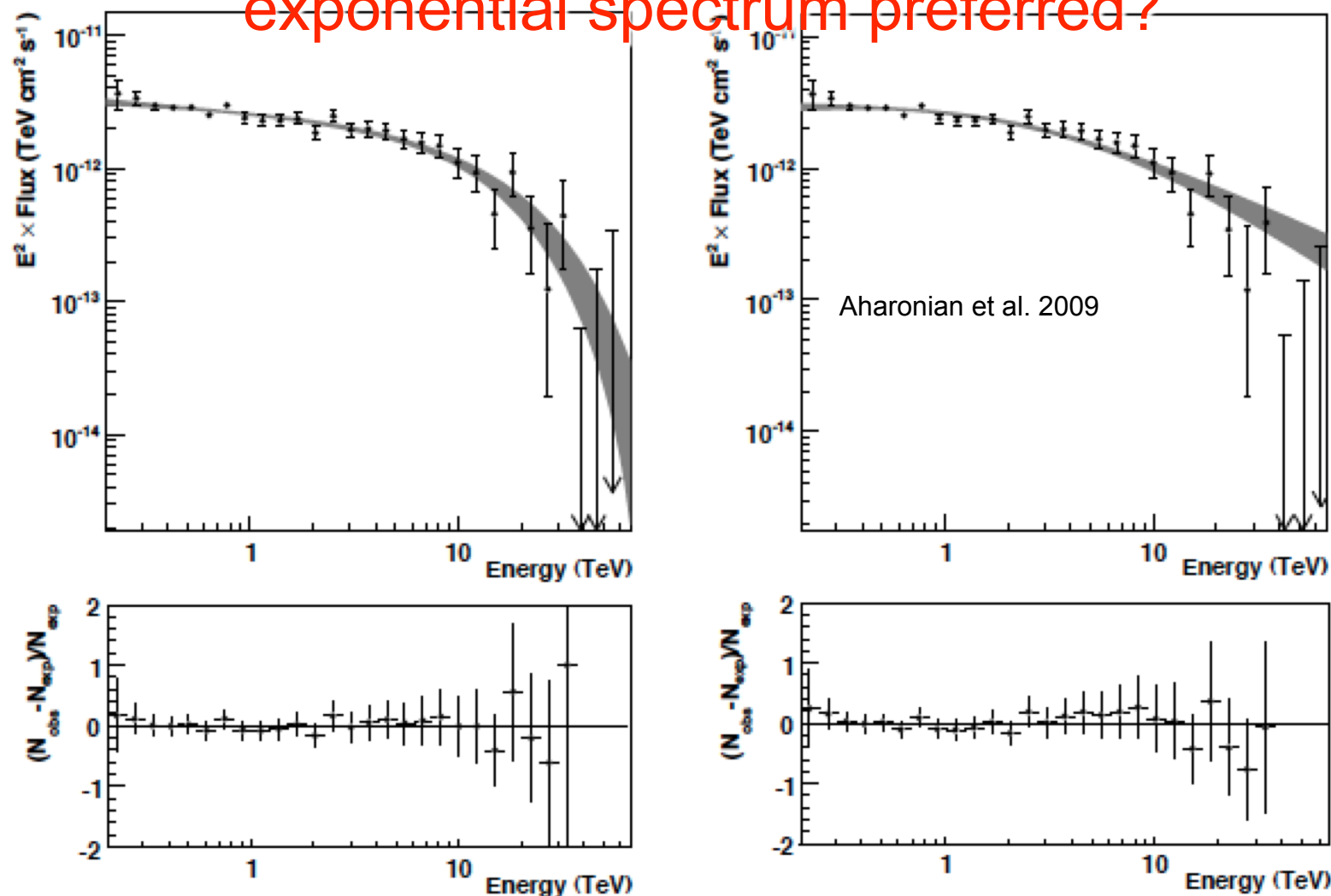
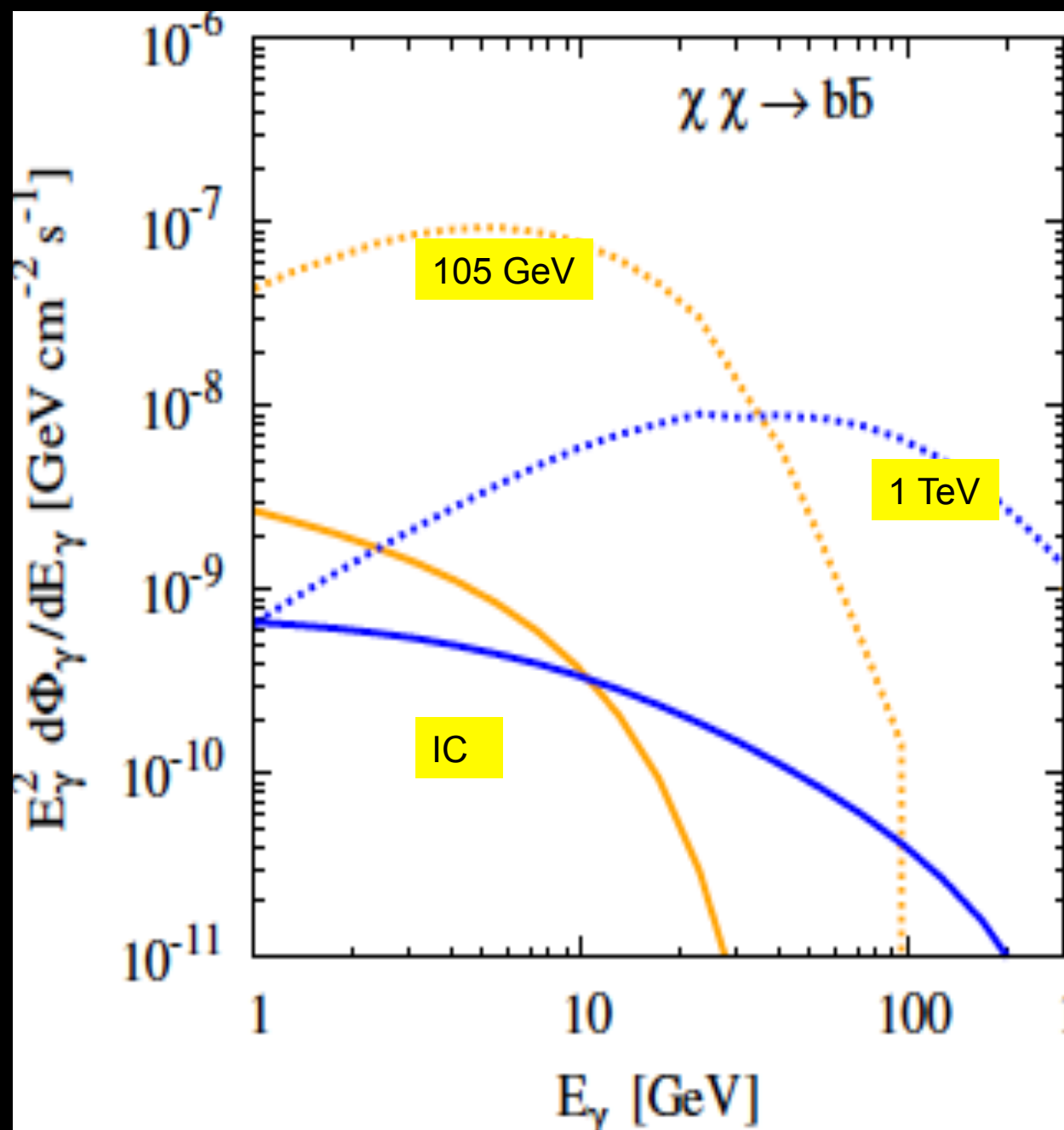
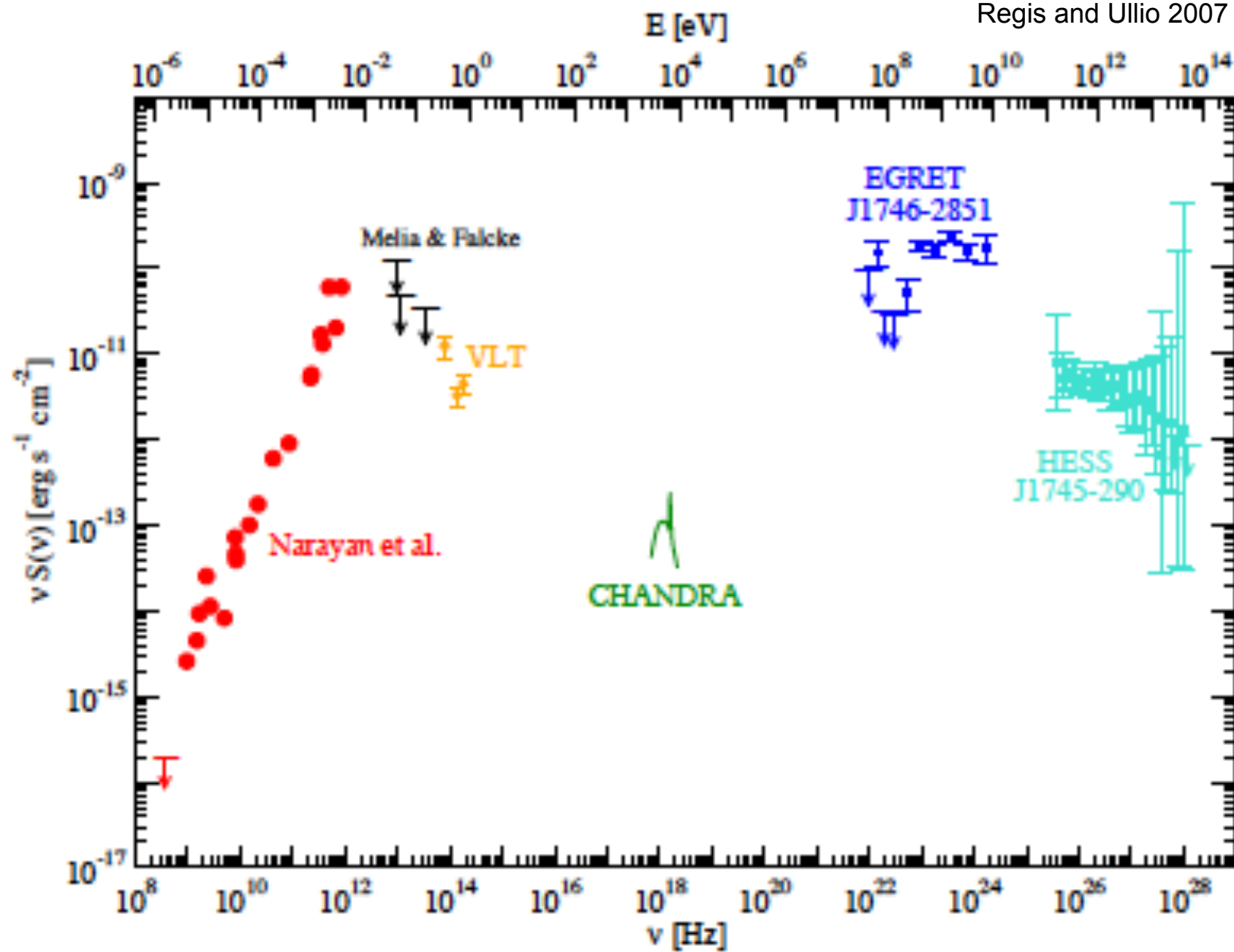
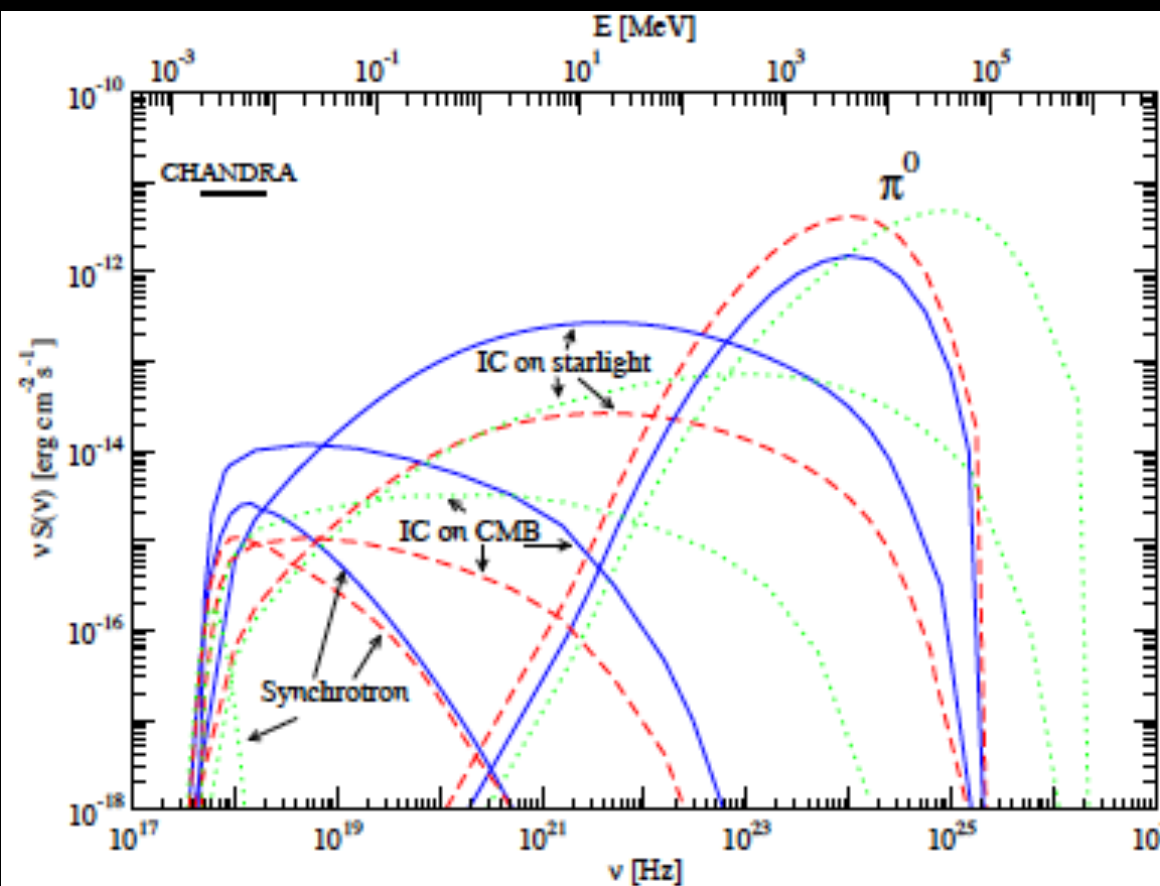


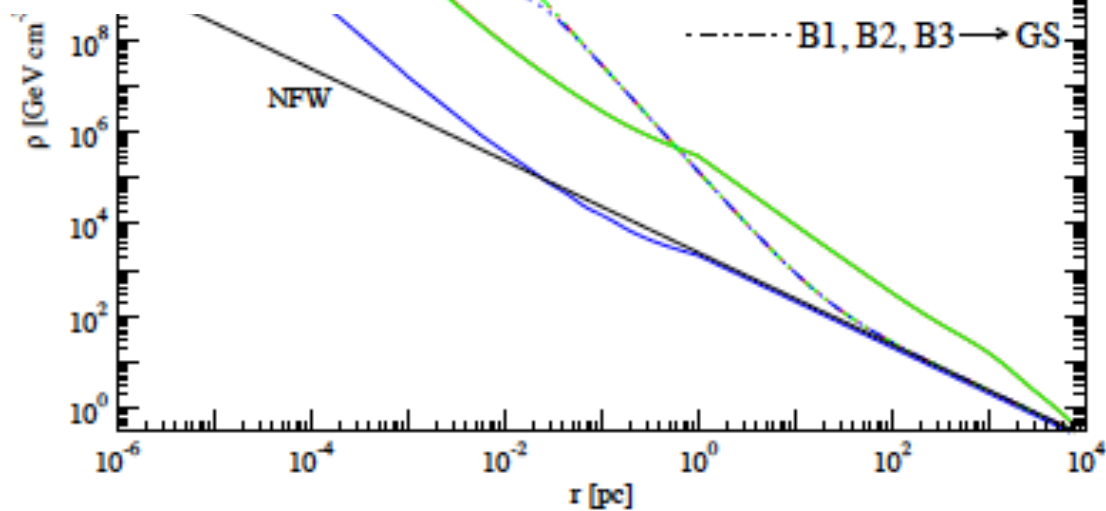
Fig. 2. HESS J1745–290 spectra derived with the combined Hillas/Model analysis for the whole H.E.S.S. GC dataset covering the three years 2004, 2005 and 2006. The shaded areas are the 1σ confidence intervals for the power law with an exponential cut-off fit (left) and the smoothed broken power law fit (right). The last points represent 95% confidence level upper limits on the flux. The fit residuals corresponding to the respective fits are shown on the lower panels.



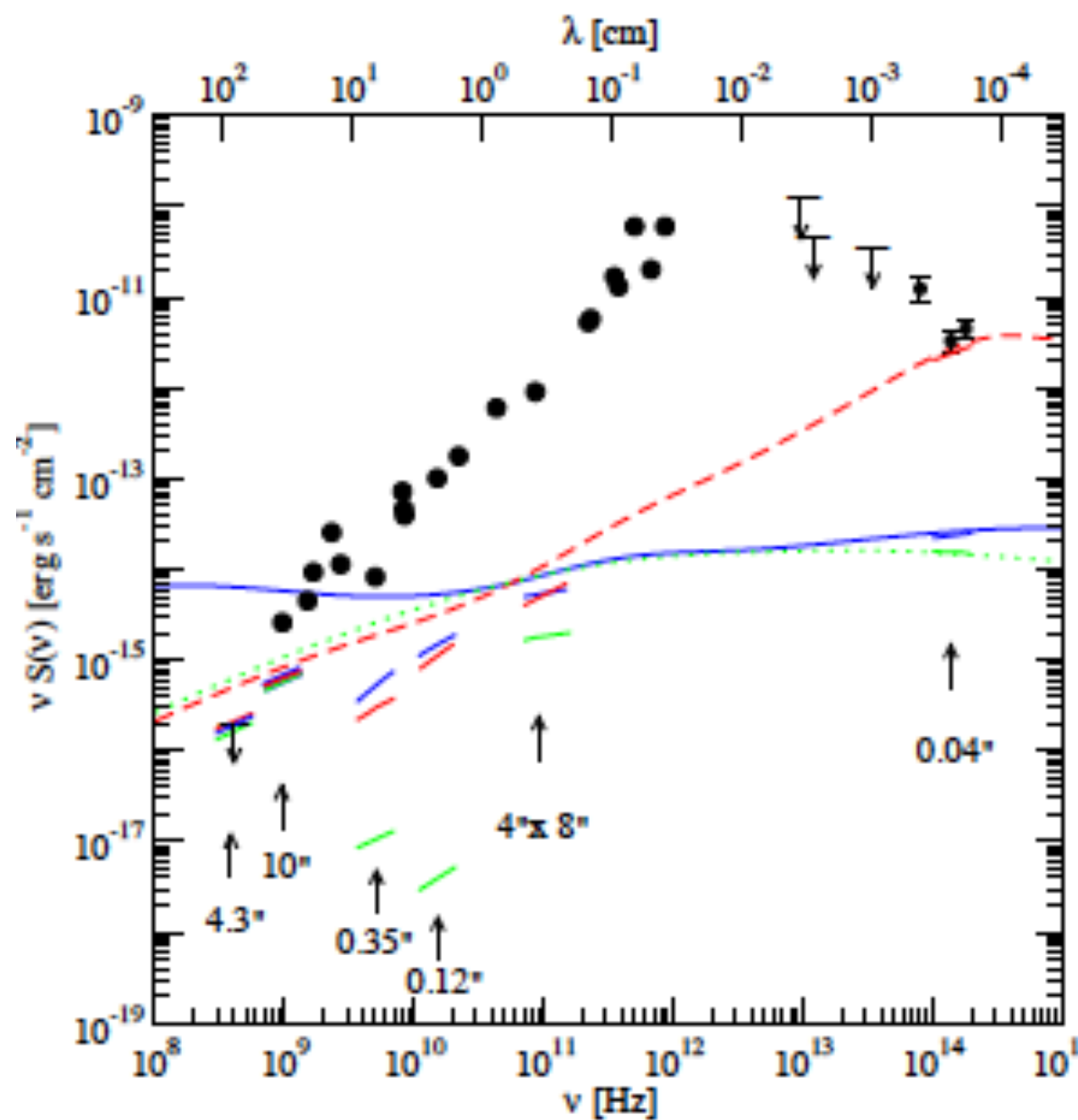




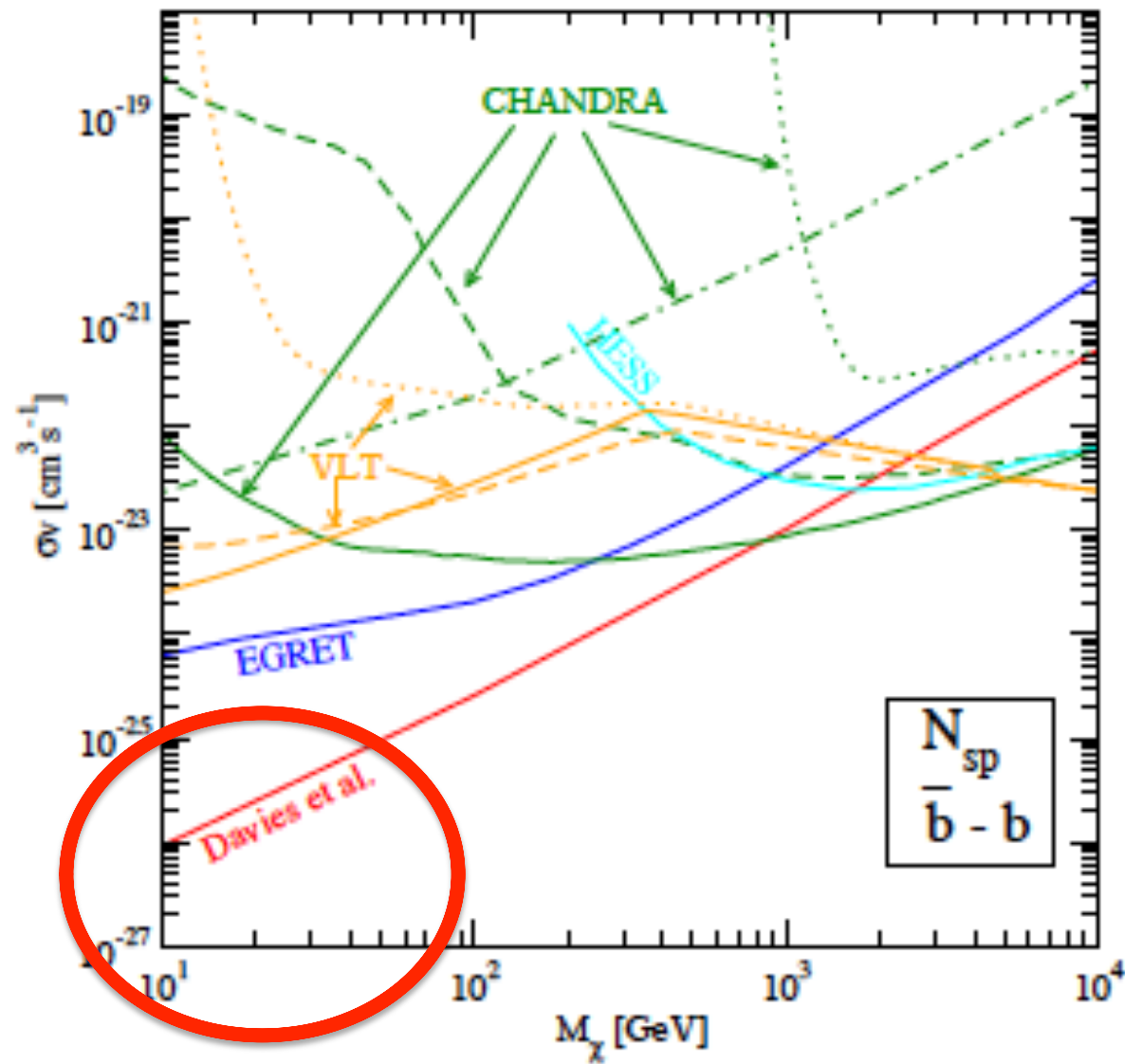
- B1: $N_{sp}, M_\chi = 100 \text{ GeV}, \sigma v = 2 \cdot 10^{-25} \text{ cm}^3 \text{ s}^{-1}$
 B2: $A_{sp}, M_\chi = 100 \text{ GeV}, \sigma v = 6 \cdot 10^{-30} \text{ cm}^3 \text{ s}^{-1}$
 B3: $A_{sp}, M_\chi = 1 \text{ TeV}, \sigma v = 2 \cdot 10^{-28} \text{ cm}^3 \text{ s}^{-1}$



Regis & Ullio 2007



Spike convolved with radio beam



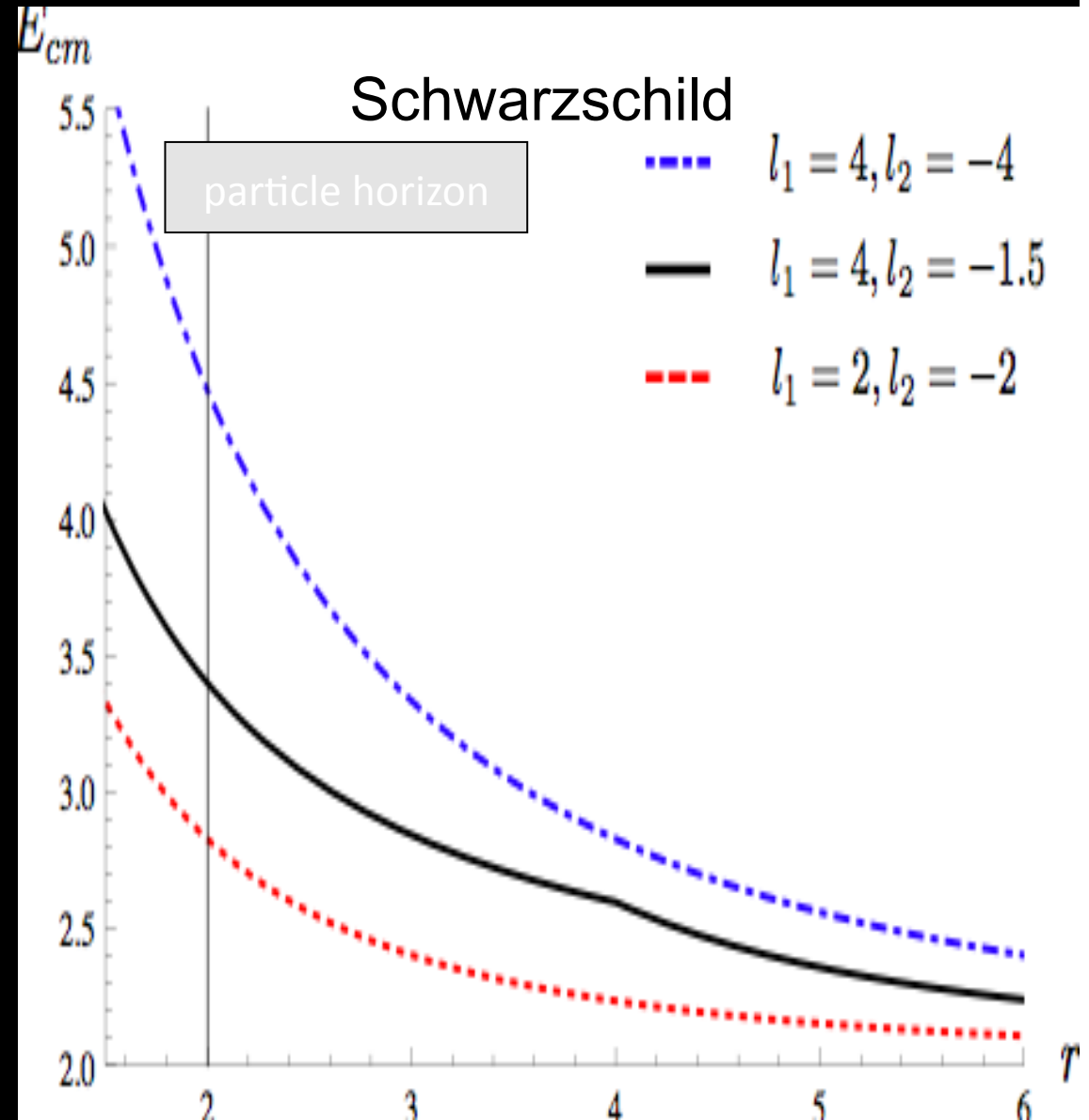
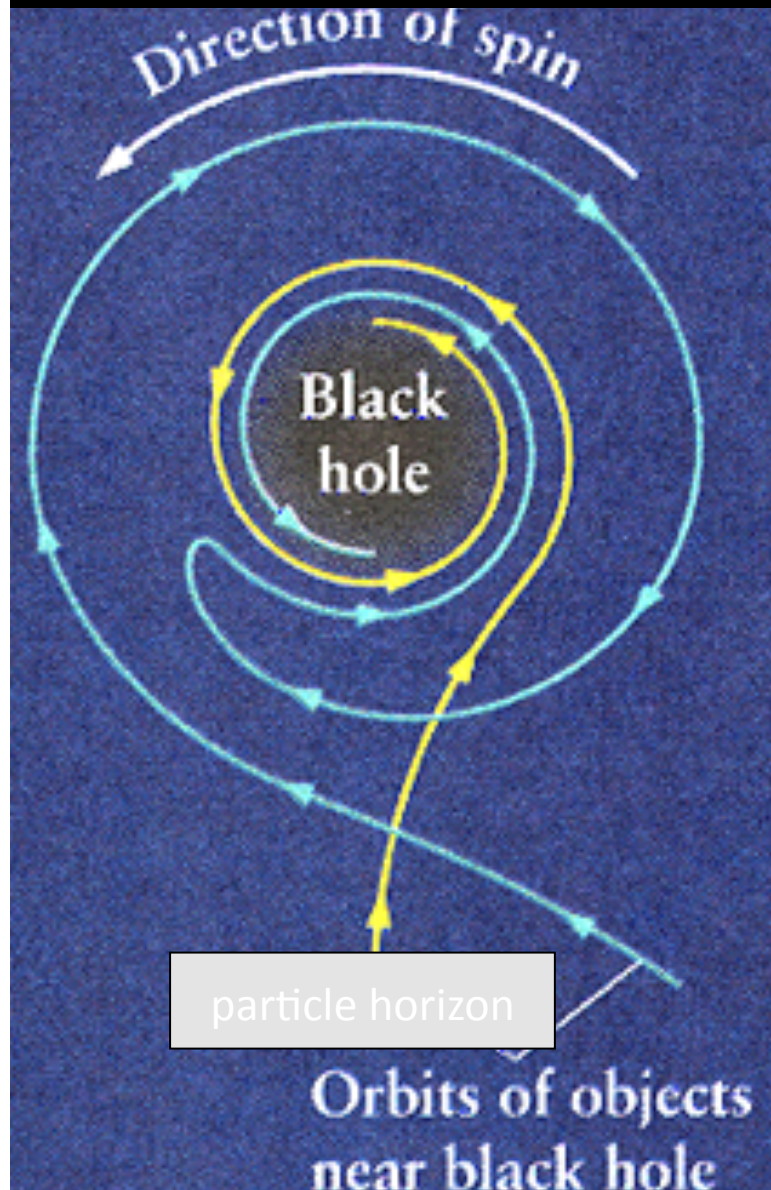
x-ray keV limit

radio GHz limit

Regis & Ullio 2007

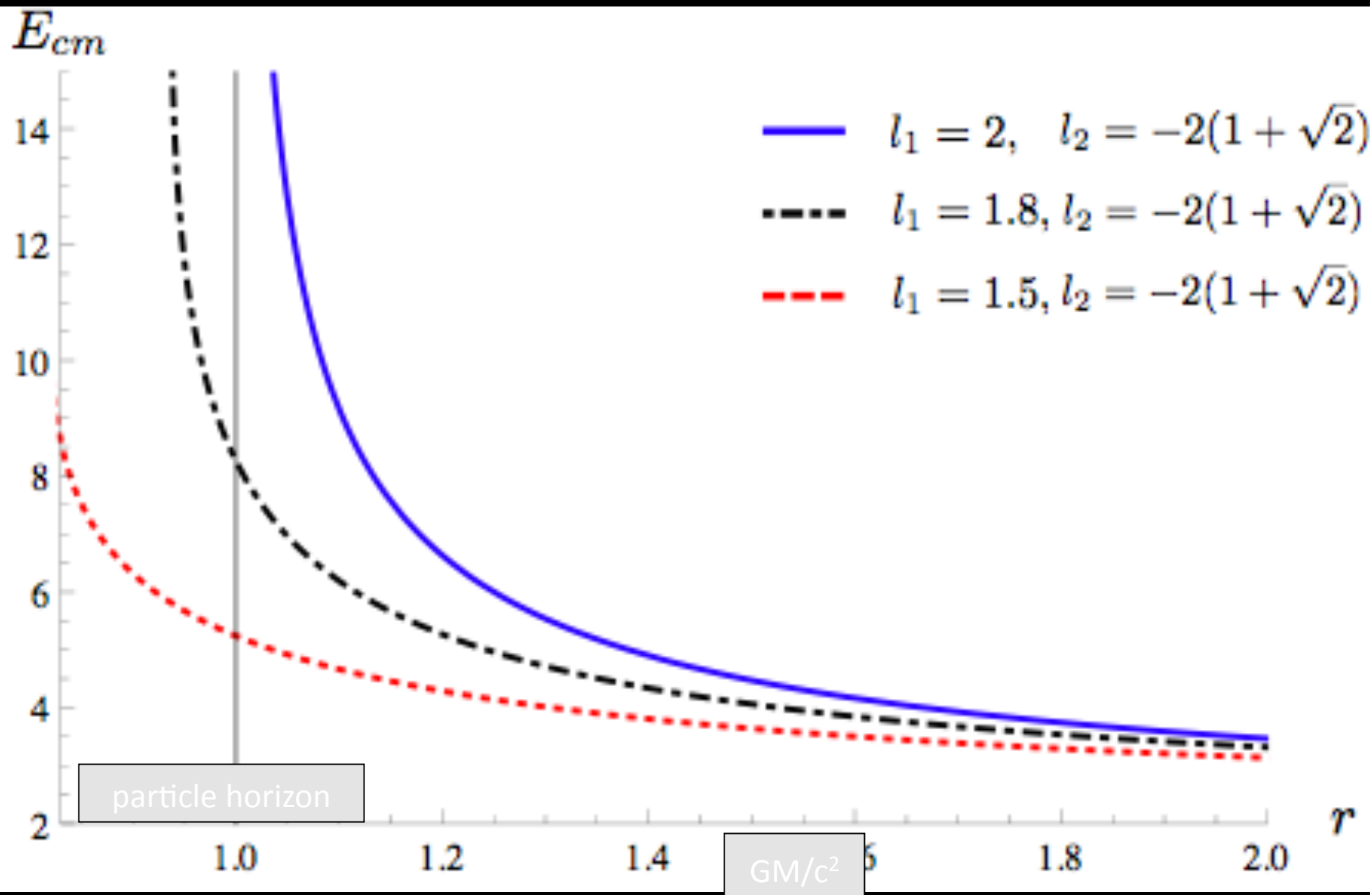
MORE EXOTIC APPLICATIONS TO THE GALACTIC CENTRE

THE ULTIMATE PARTICLE ACCELERATOR: dark matter cusp around black hole

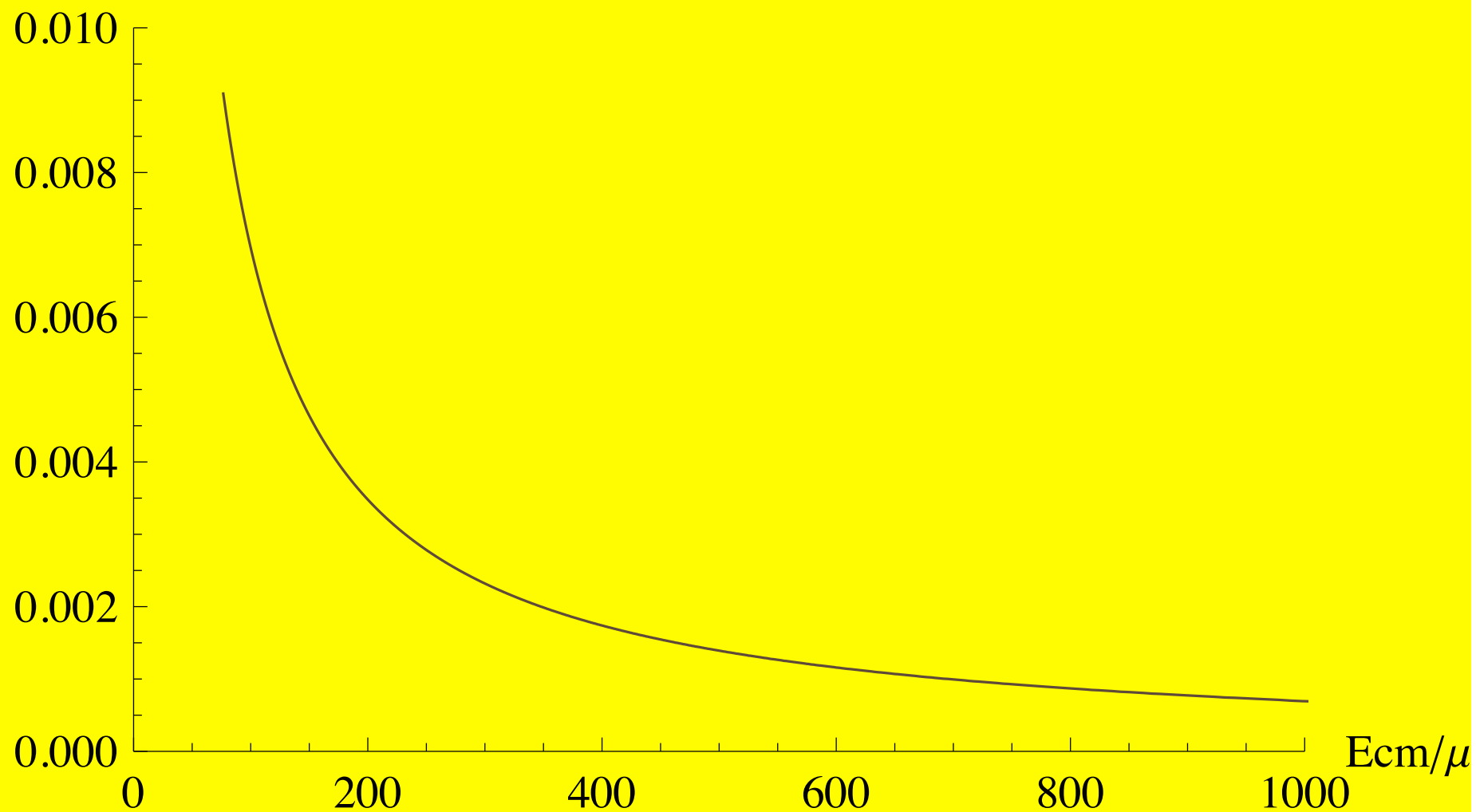


Kerr black hole

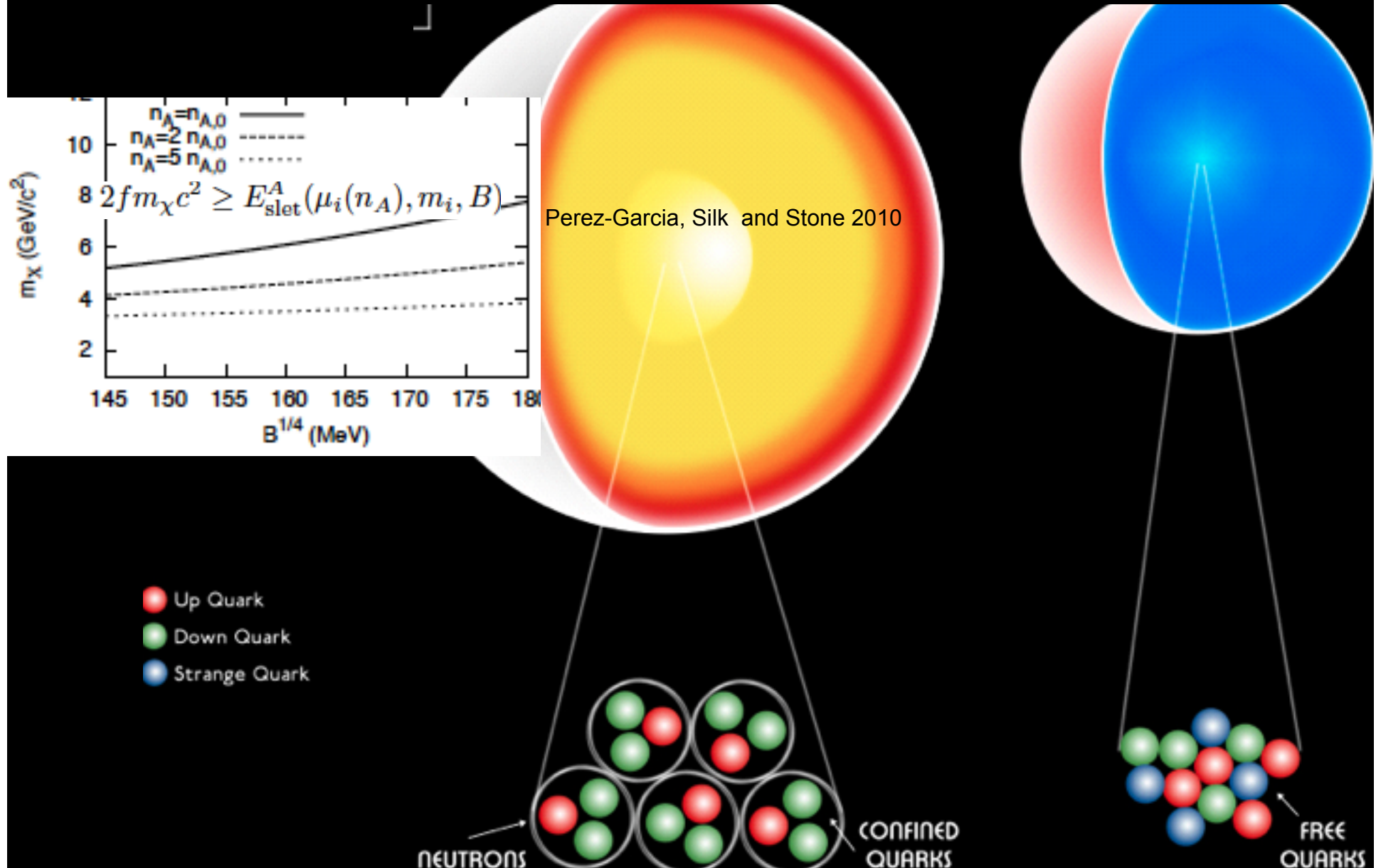
Banados, West, JS 2009



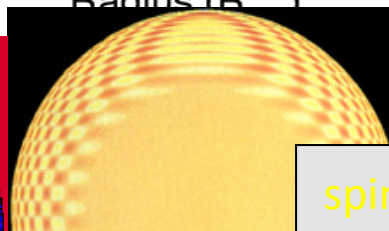
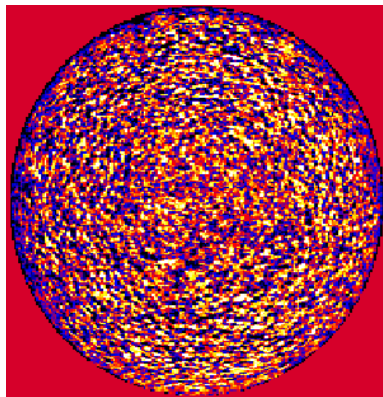
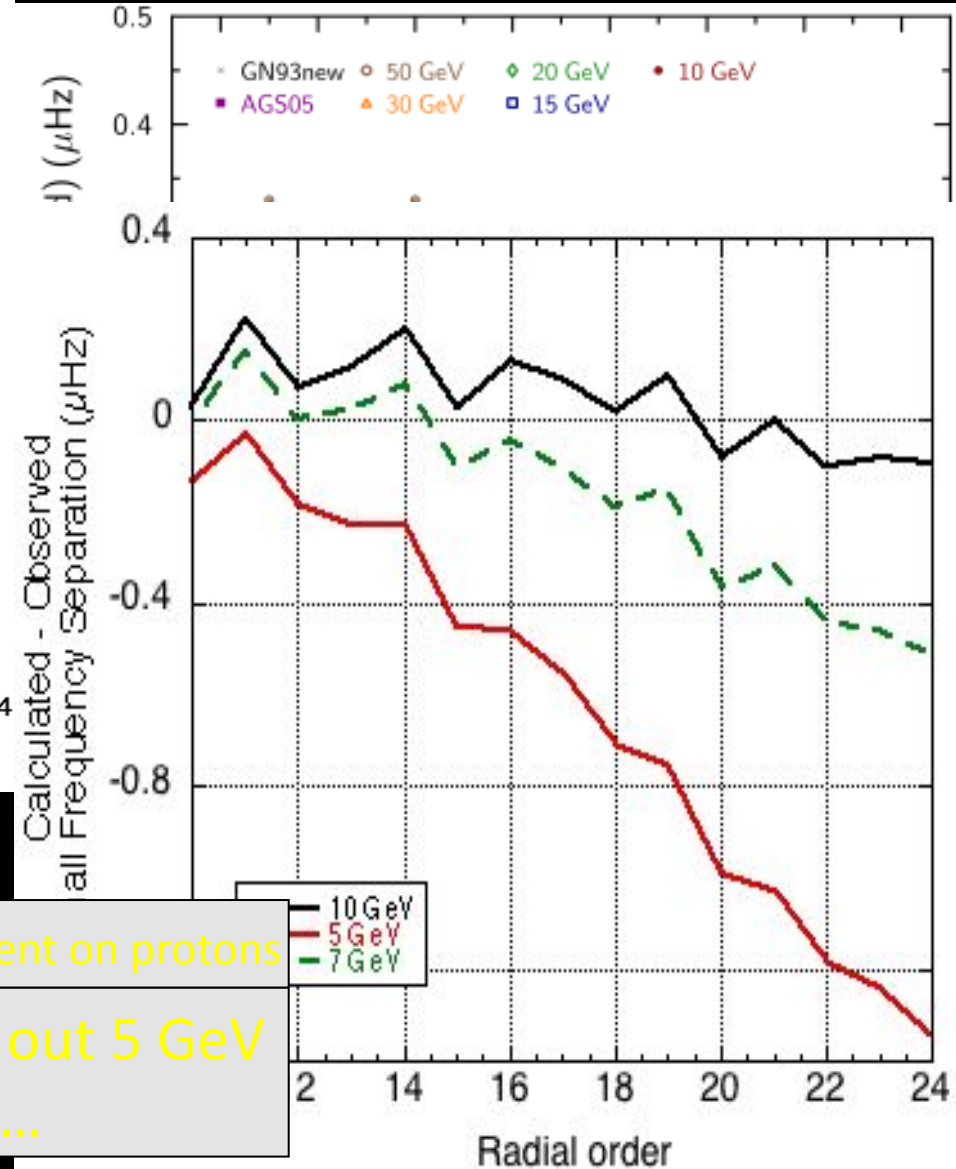
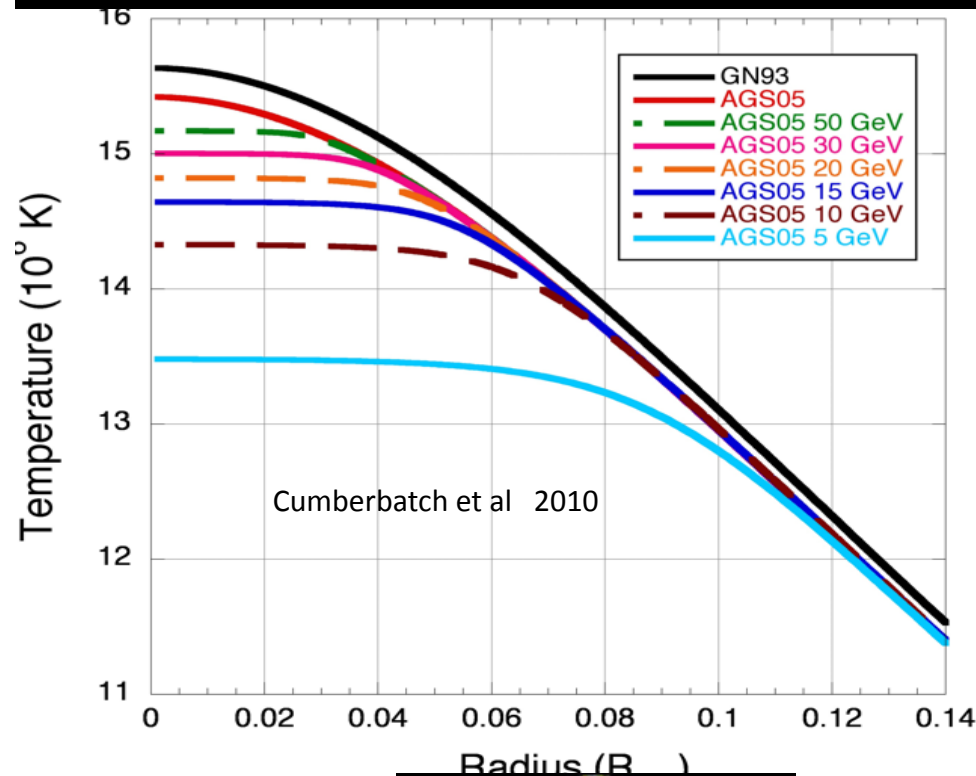
Escape Fraction (EF)



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



low mass ($m_\chi \sim 5\text{-}10\text{ GeV}$) WIMPS are trapped and fill the solar core.... and modify $T(r)$

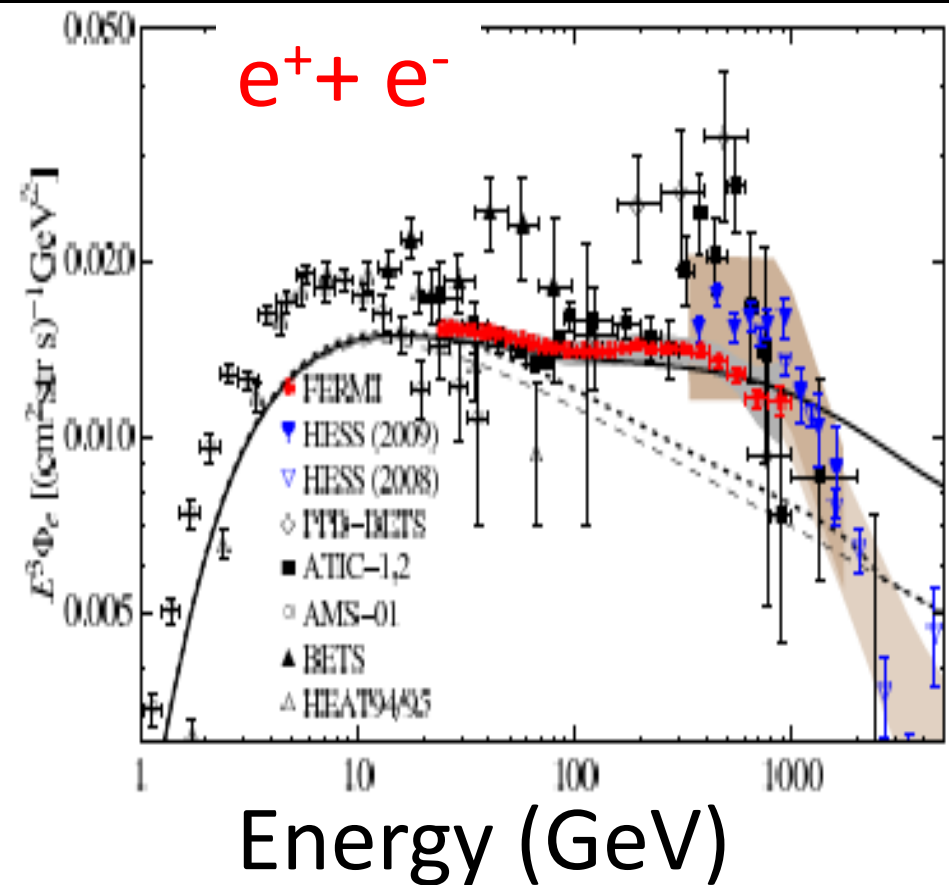
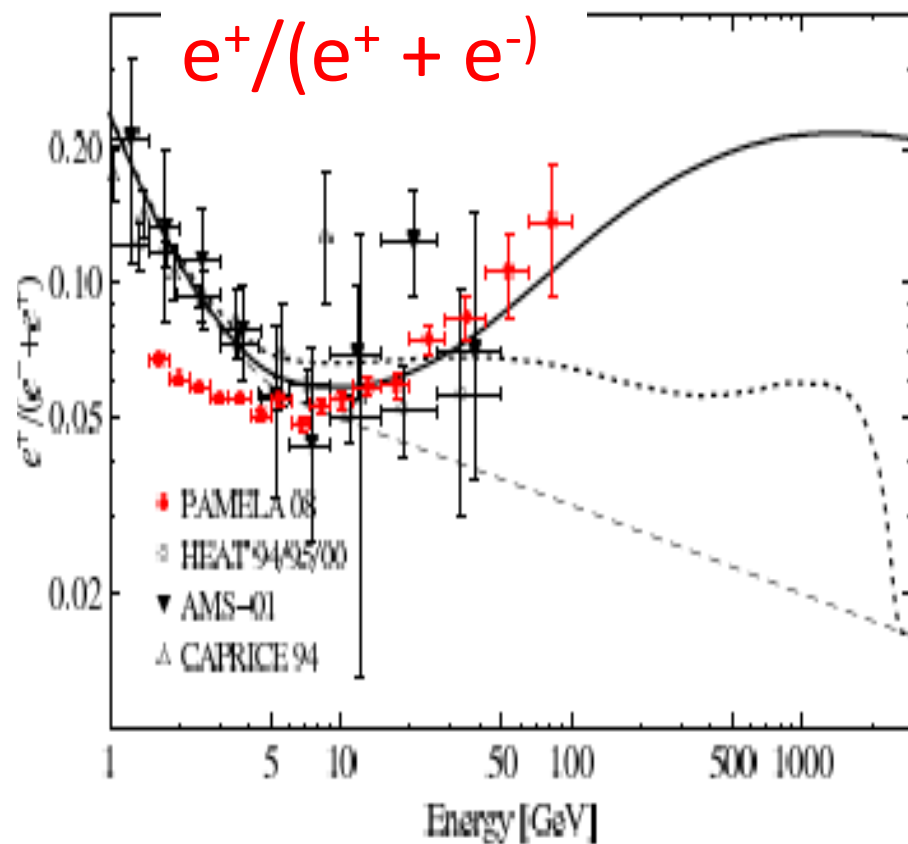


spin-dependent on protons

helioseismology rules out 5 GeV
in some cases...

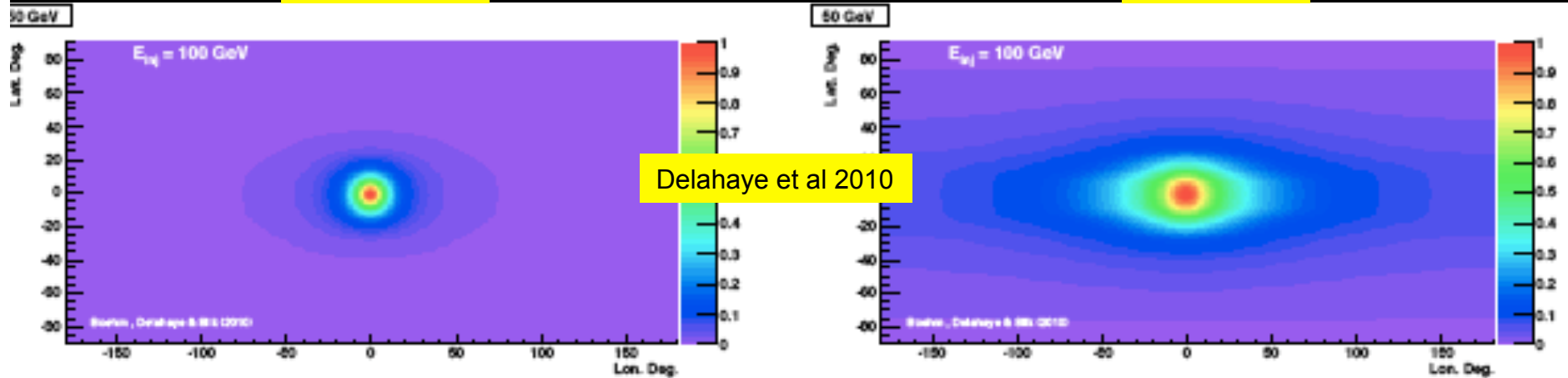
DECAYING DARK MATTER

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

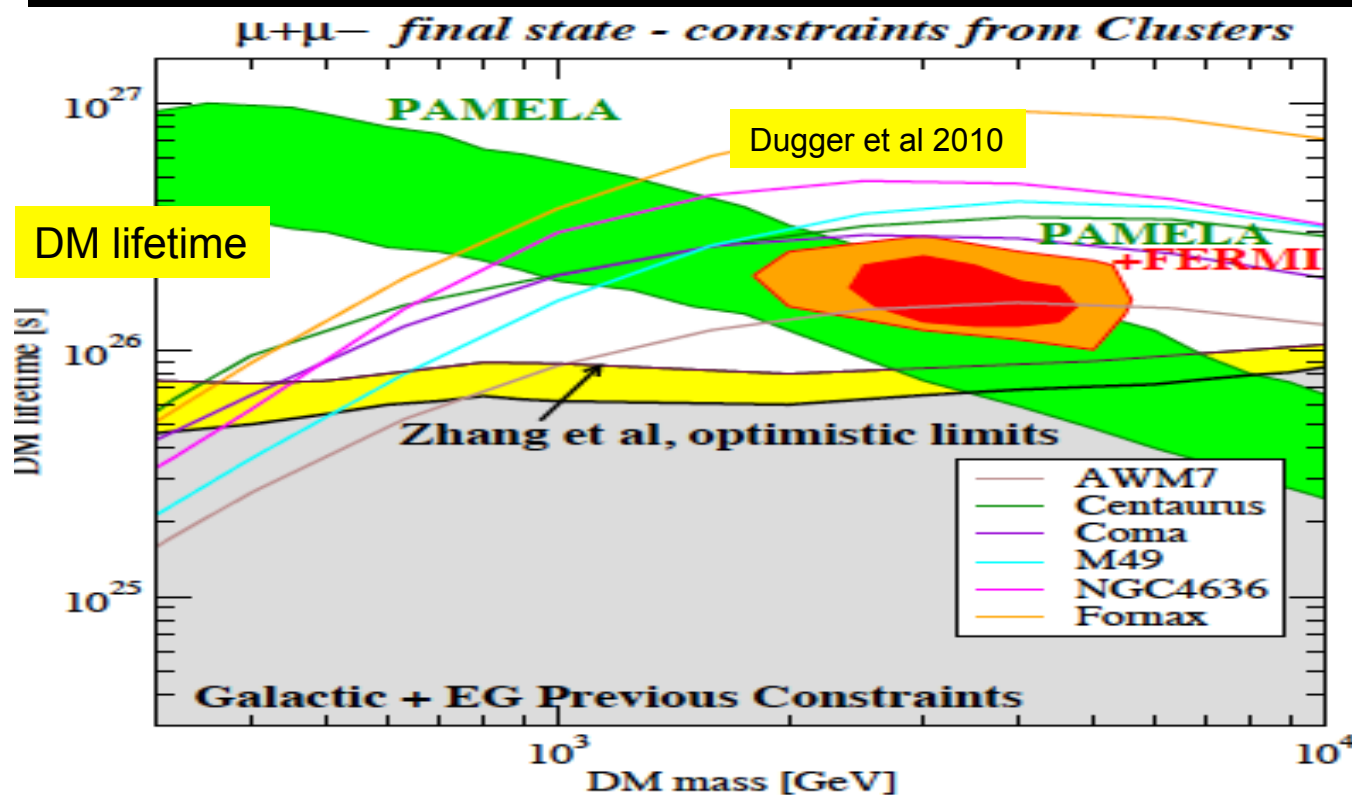


DENSITY²

DENSITY



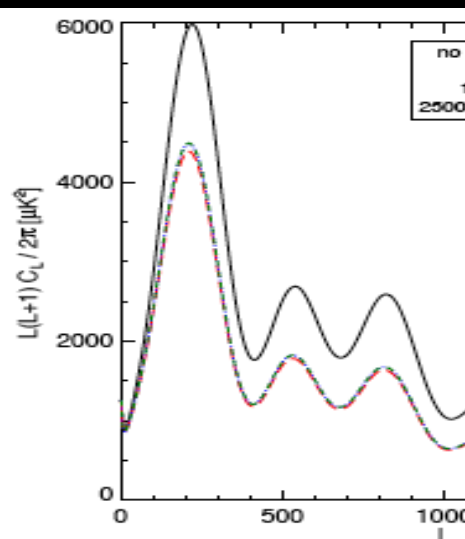
DECAYING DARK MATTER: GALAXY CLUSTERS ARE BEST PROBE



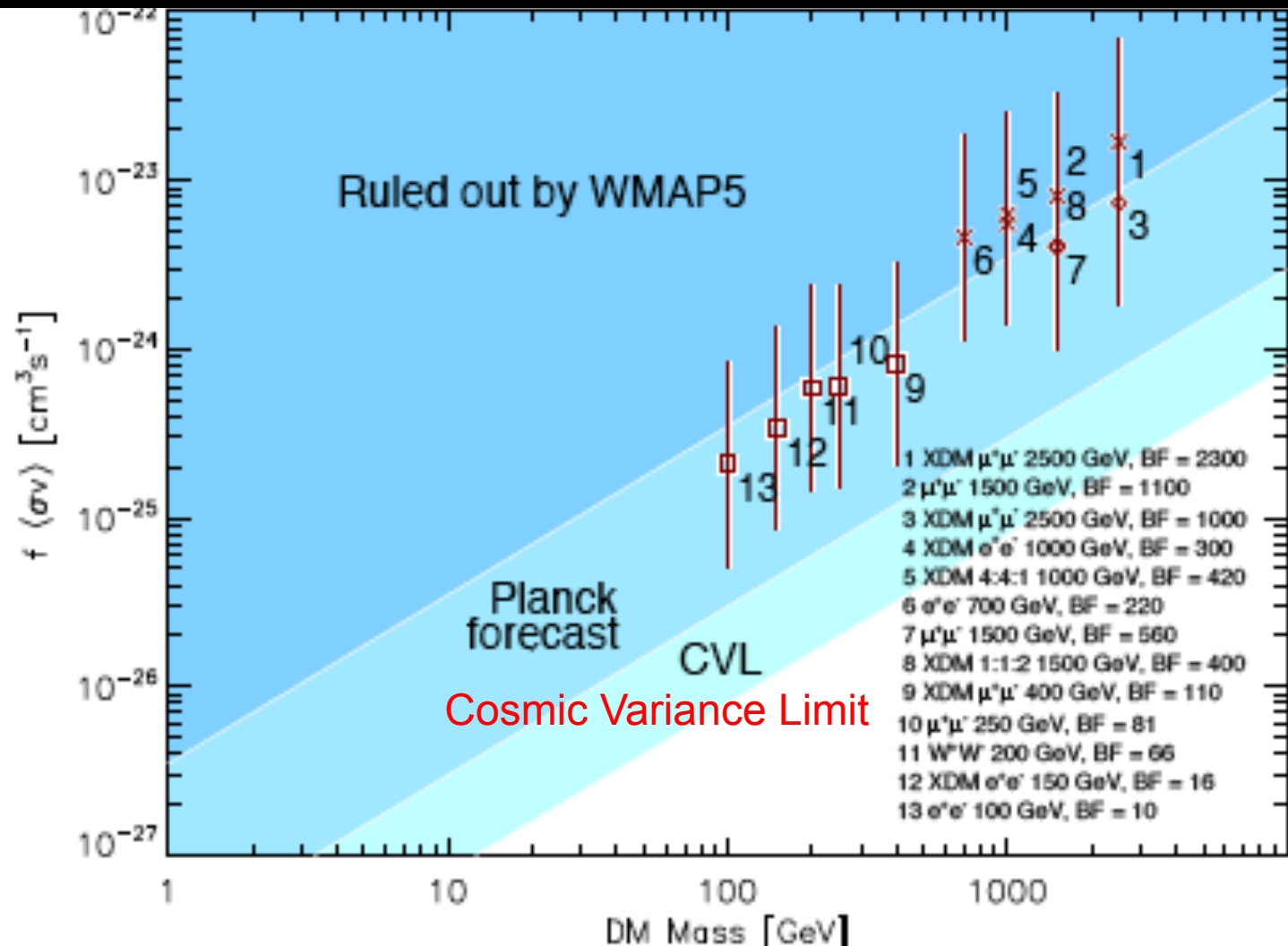
FERMI constraints

THE FUTURE FOR DARK MATTER SEARCHES

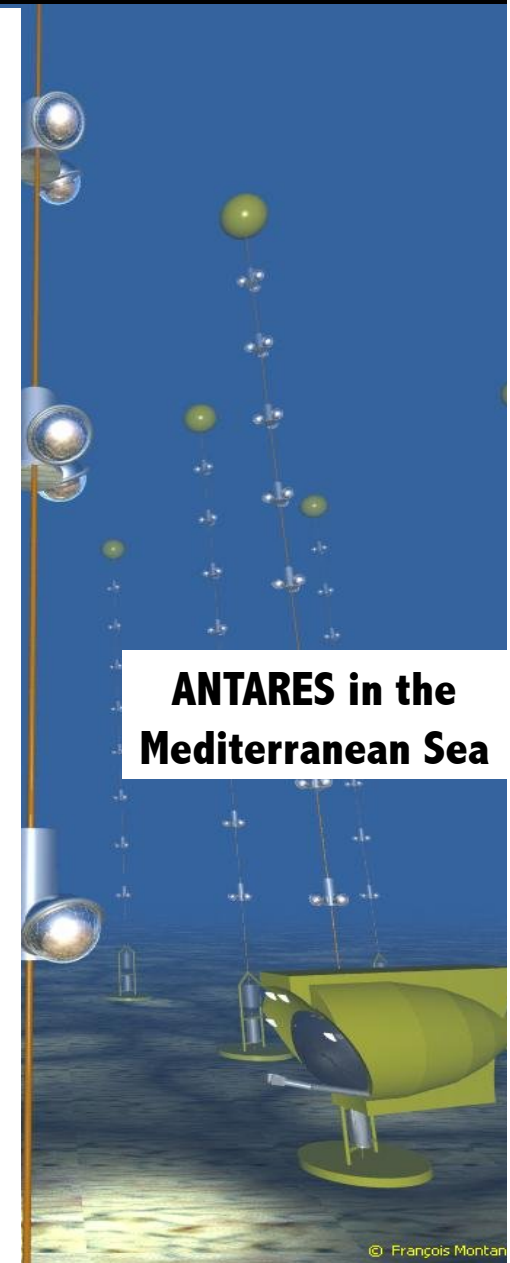
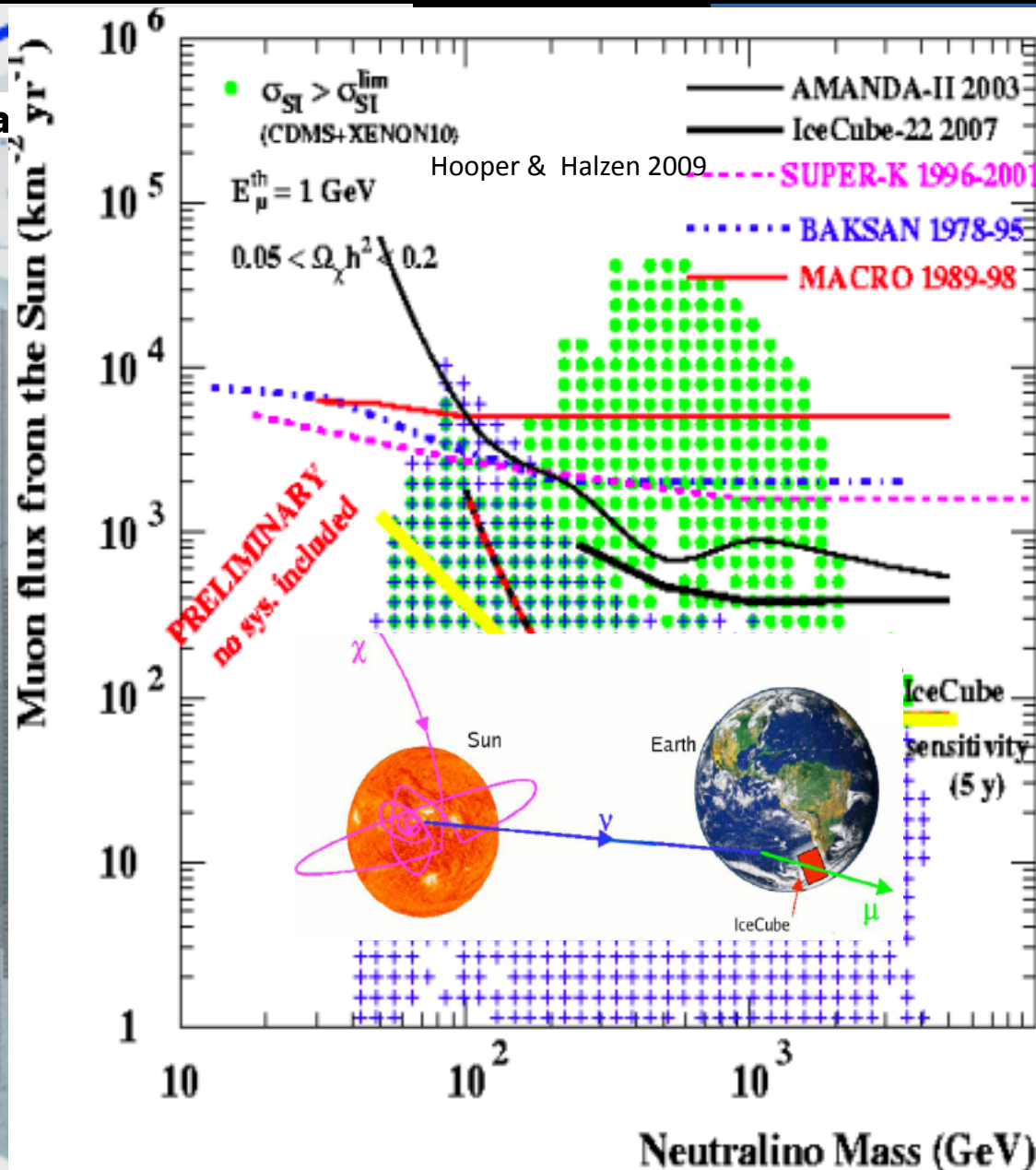
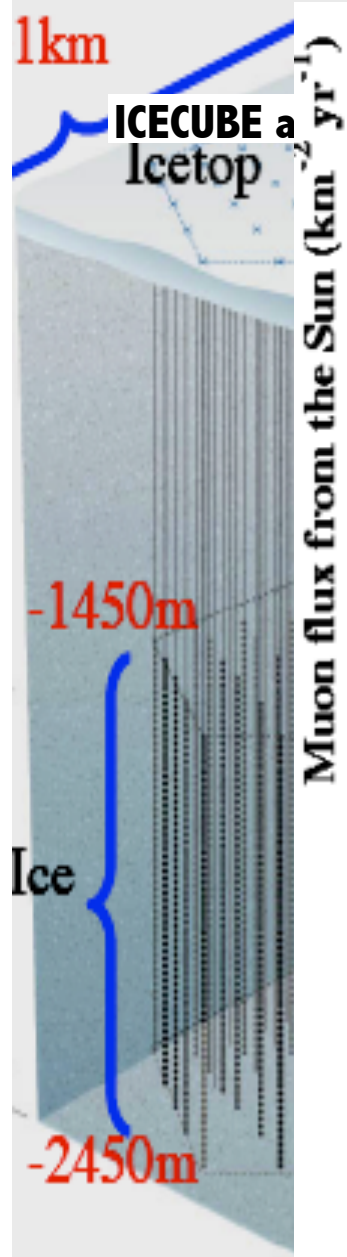
Cosmic microwave background temperature fluctuations: DAMPING BY ENHANCED IONIZATION FROM DARK MATTER ANNIHILATIONS

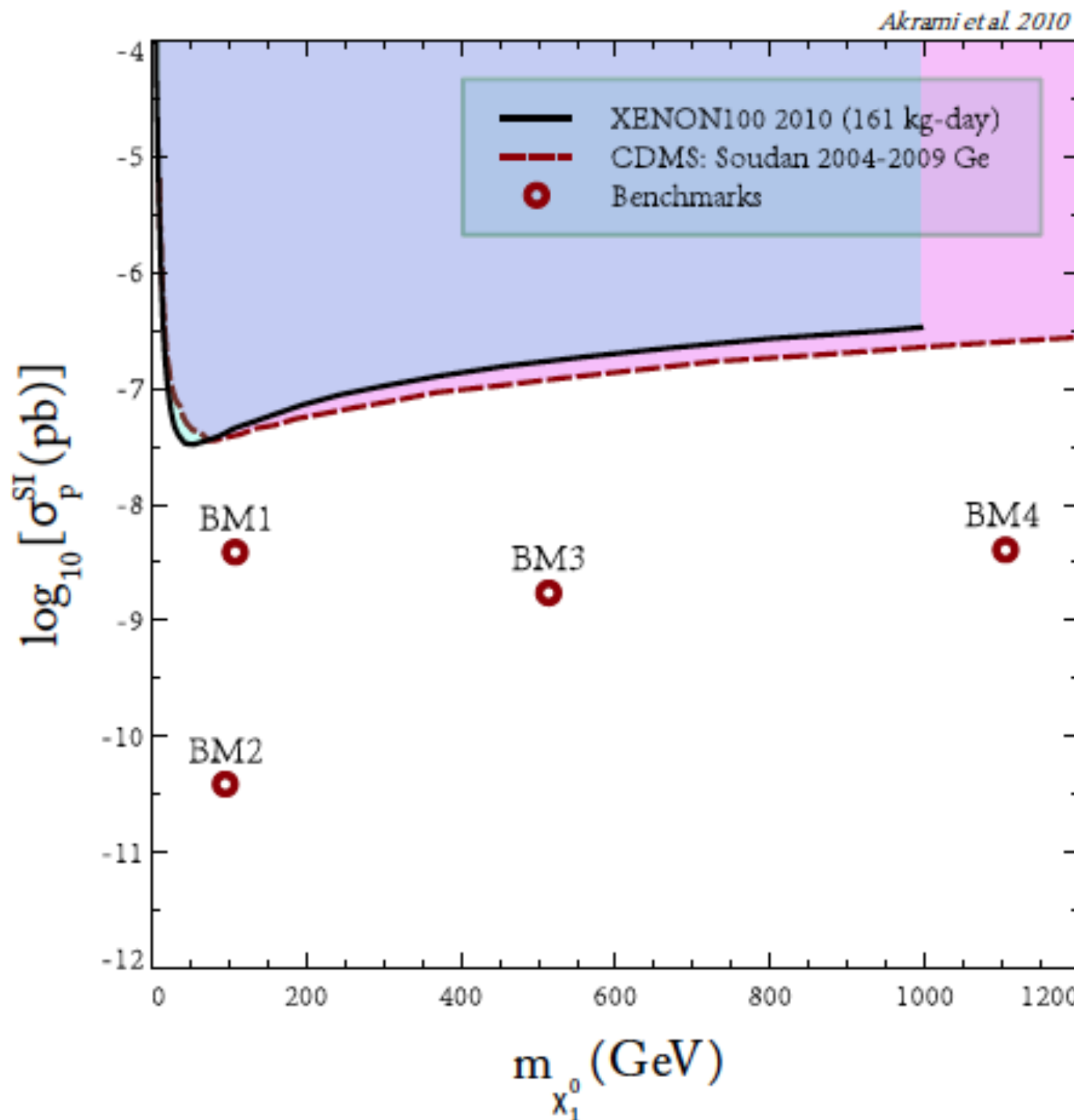


Galli + 2009



ENERGETIC NEUTRINOS FROM WIMPs TRAPPED IN THE SUN

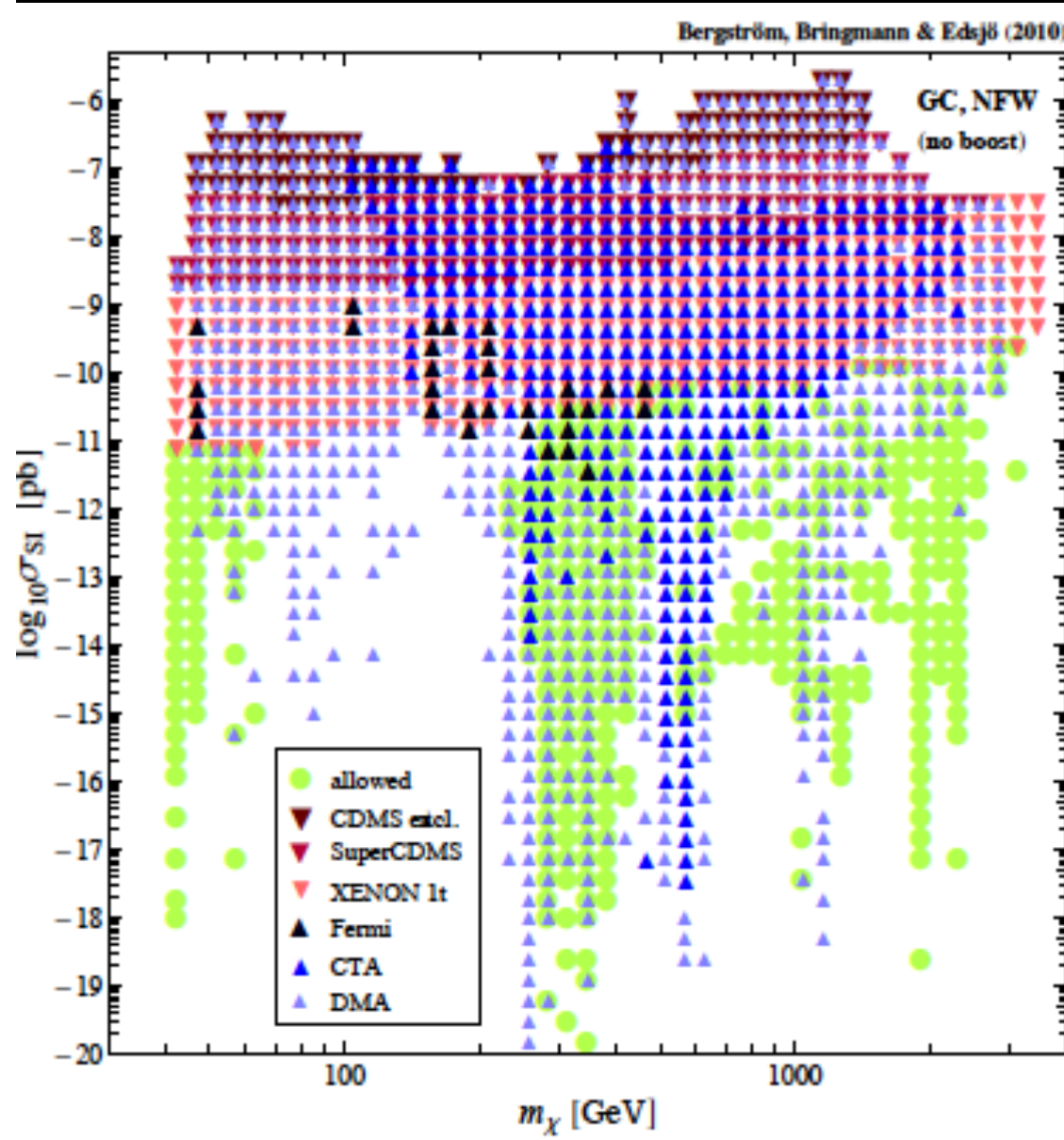




HOW
LOW
DO WE
NEED
TO GO?

ton-scale detectors

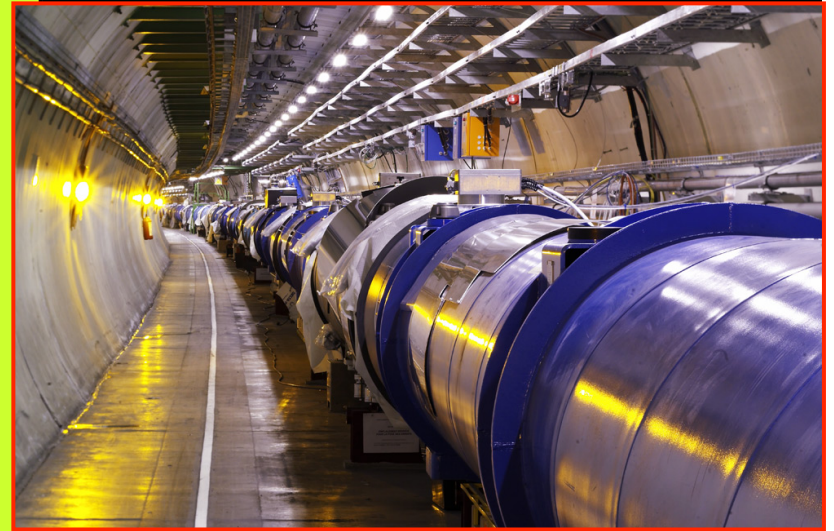
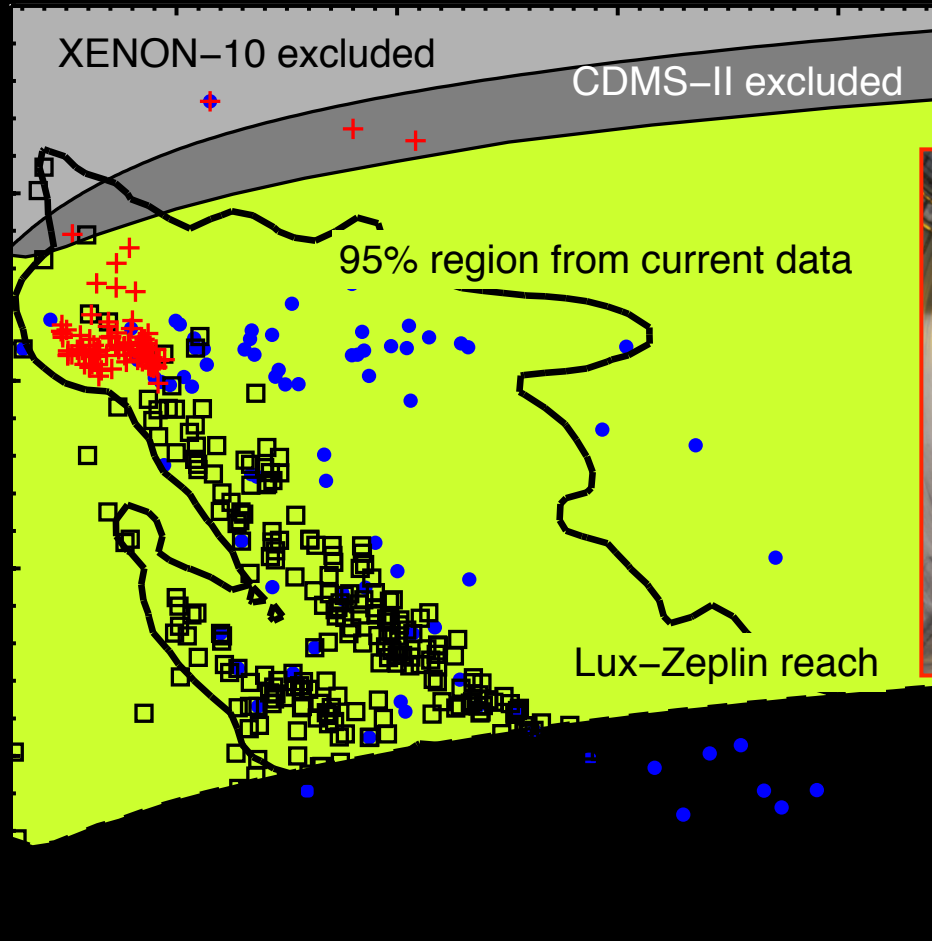
Gamma rays: THE AIR CERENKOV FACTOR



●
+

1 1/fb at 14 TeV energy

WMAP mean with 5- σ Planck uncertainty
5- σ for 1 yr of 80 strings data



WE MAY HAVE A PROBLEM

on < 10 kpc scales

Simulation

Galaxy



TOO MANY DWARF GALAXIES

ADD BARYONS

to make more realistic galaxies

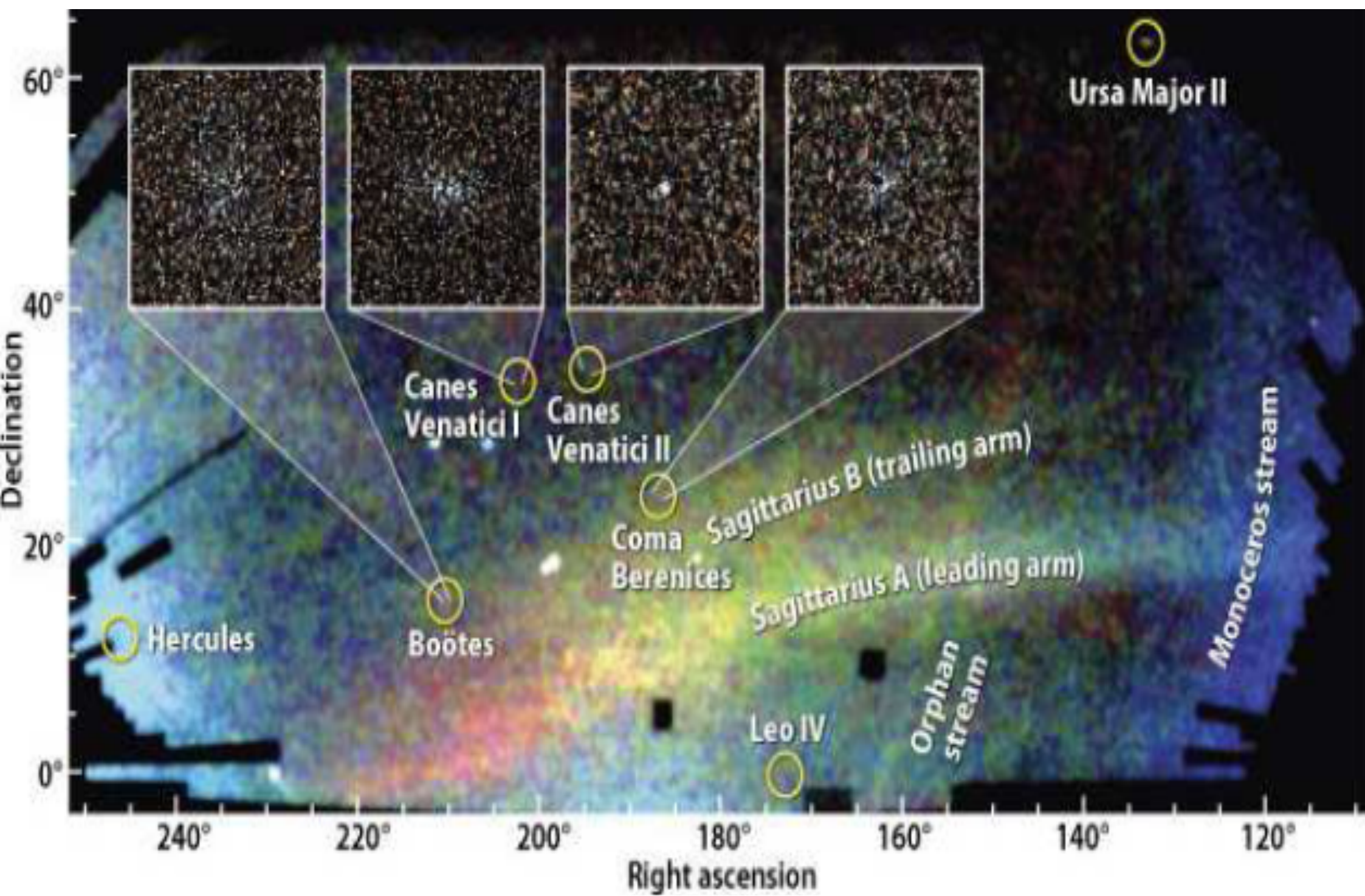
But this creates more problems, e.g.

too many small galaxies, too many big galaxies, too few in the past....

ADD FEEDBACK

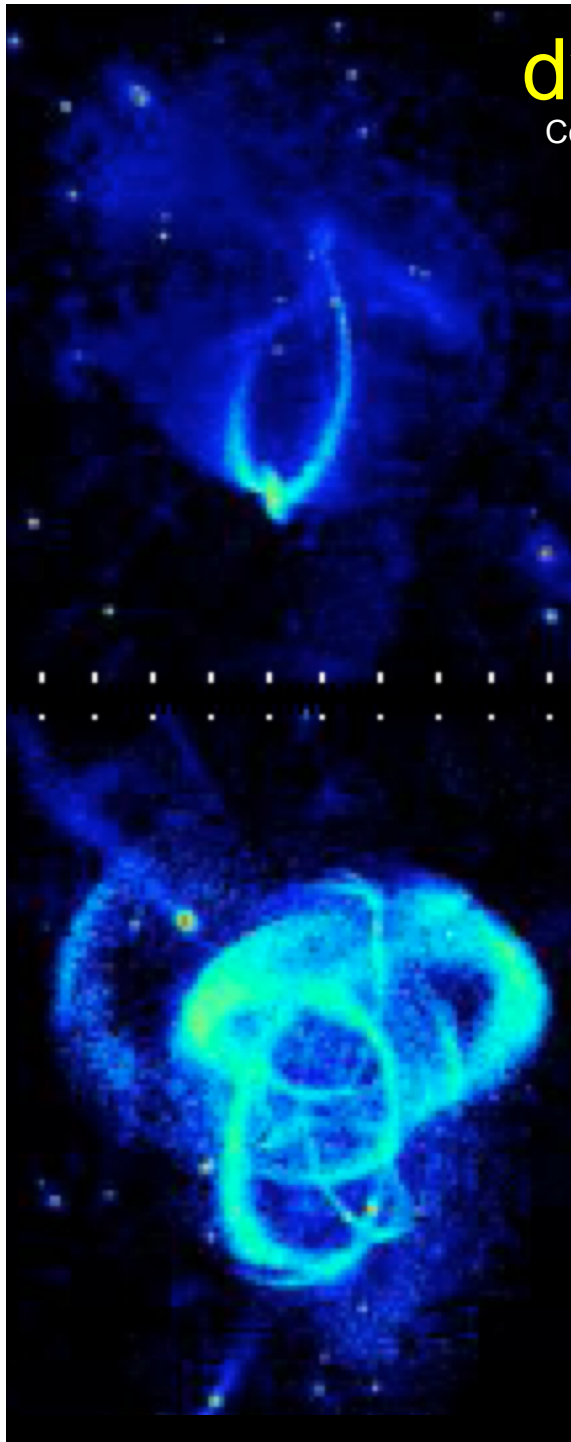
Need reionization, supernovae, tidal disruption, supermassive black holes.....

ABOVE ALL, WE DO NOT
UNDERSTAND STAR FORMATION



dynamical feedback

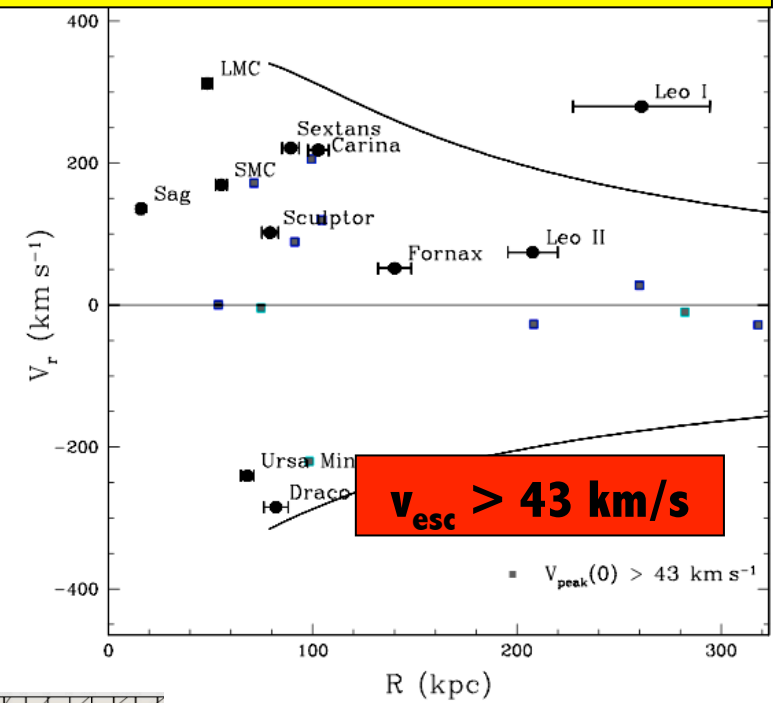
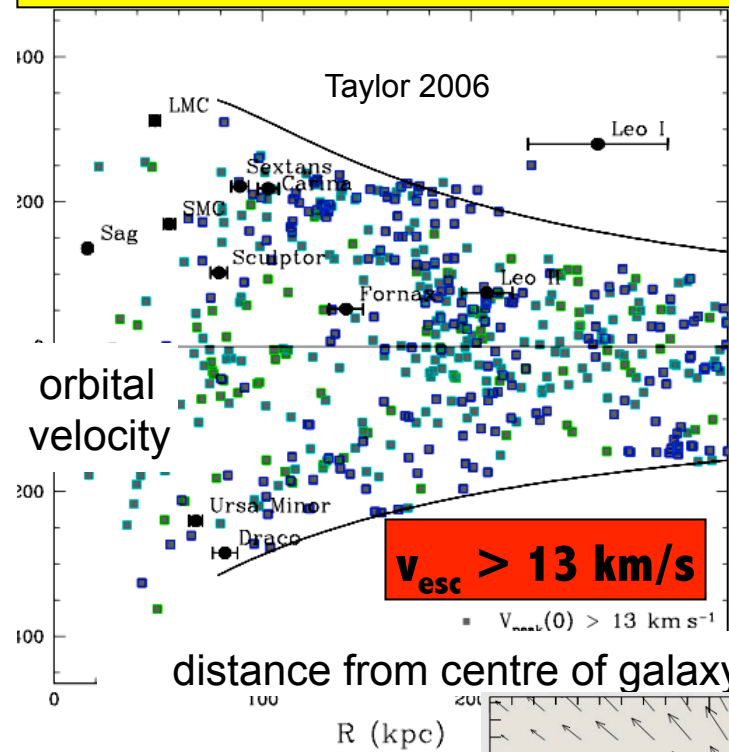
Cooper et al 2010



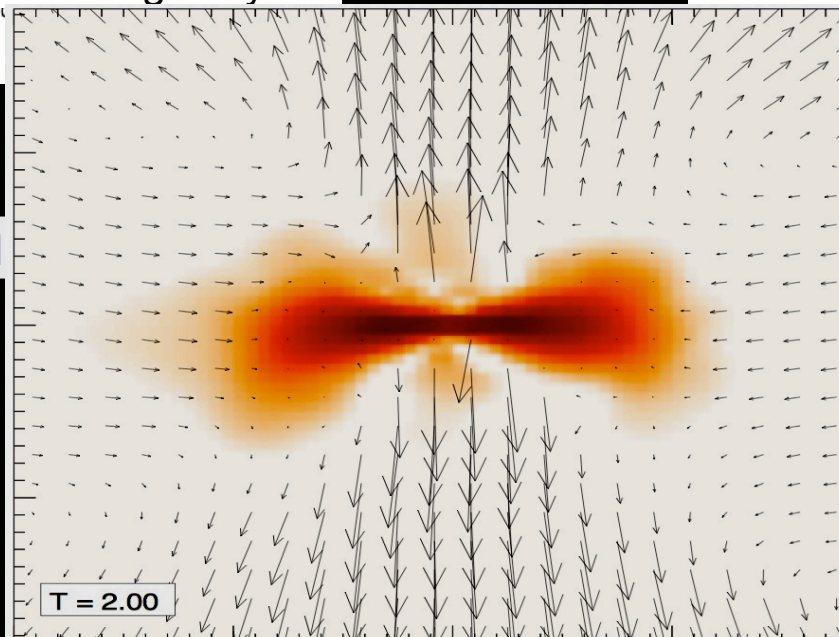
Martínez-Delgado et al 2008



supernova feedback



supernova-driven wind

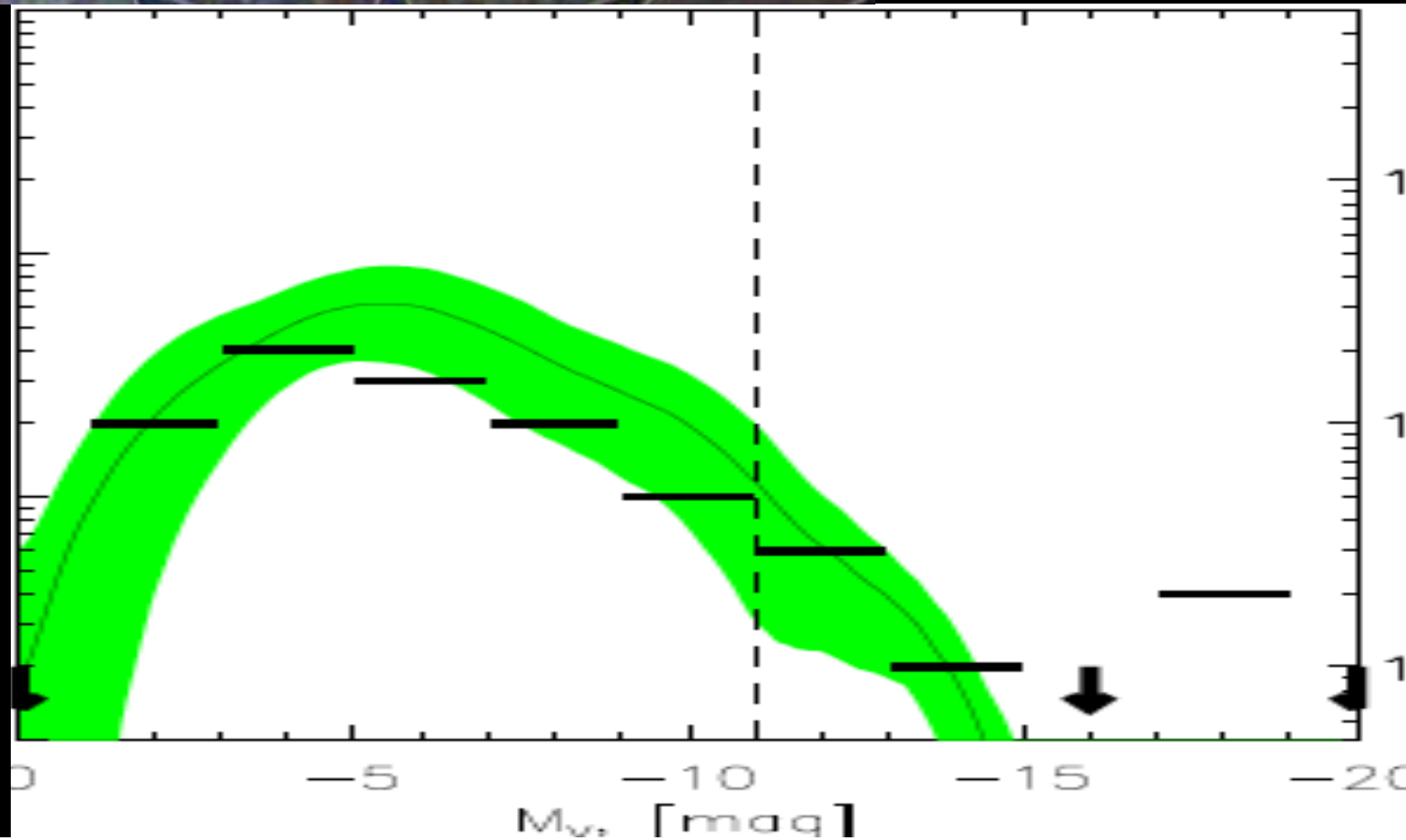


Springel and Hernquist 2003

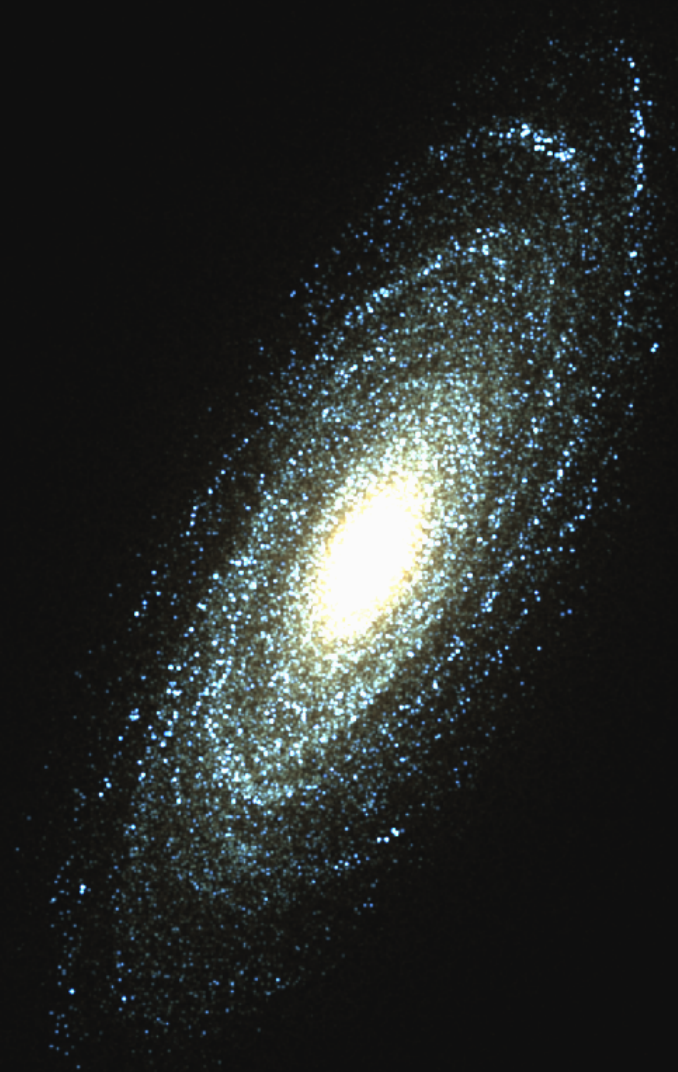
low mass galaxy luminosity function



Koposov et al 2009



can we form galaxies? not yet!



A state of the art simulation at high resolution
with star formation but no feedback
(but too many baryons!)

Taysun Kim 2011

DARK MATTER IS AN URGENT PROBLEM

DETECTION IN MULTIPLE WINDOWS IS ESSENTIAL

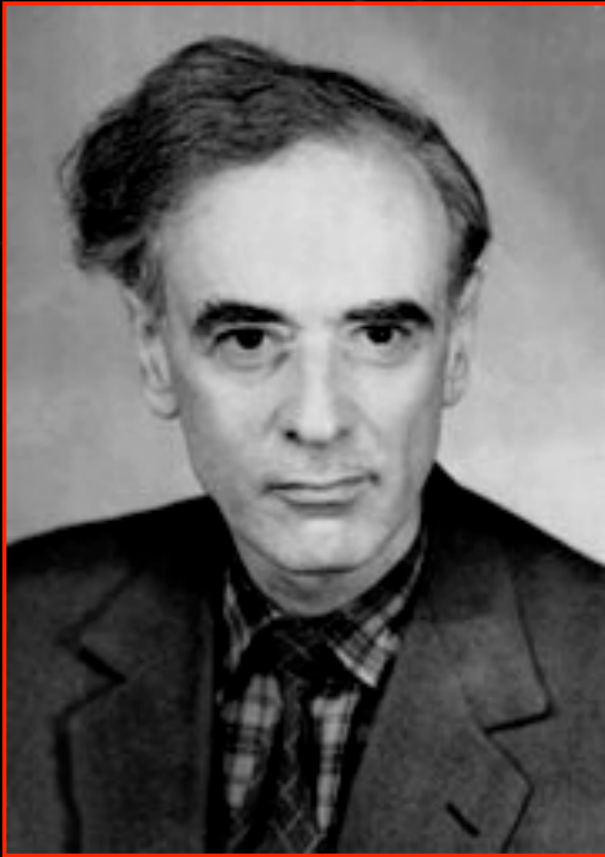
IF WE DETECT IT, RESURRECTION VIA ASTROPHYSICS

- COMPLEXITY OF FEEDBACK NEEDED FOR GALAXY FORMATION

IF WE FAIL, RESURRECTION VIA NEW FUNDAMENTAL PHYSICS

- MODIFYING THE NATURE OF DARK MATTER
- MODIFYING GRAVITY

Landau on Cosmologists



**Often in Error,
Never in Doubt!**

claims require extraordinary evidence.
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A cartoon illustration of Bart Simpson, a yellow-skinned boy with a tall, square head, wearing his signature red t-shirt and black-rimmed glasses. He is standing on the right side of the frame, pointing his right index finger towards the text on the chalkboard. The chalkboard is green and filled with the repeated phrase "claims require extraordinary evidence." in a white, handwritten font. A small white eraser is visible on the bottom edge of the chalkboard.