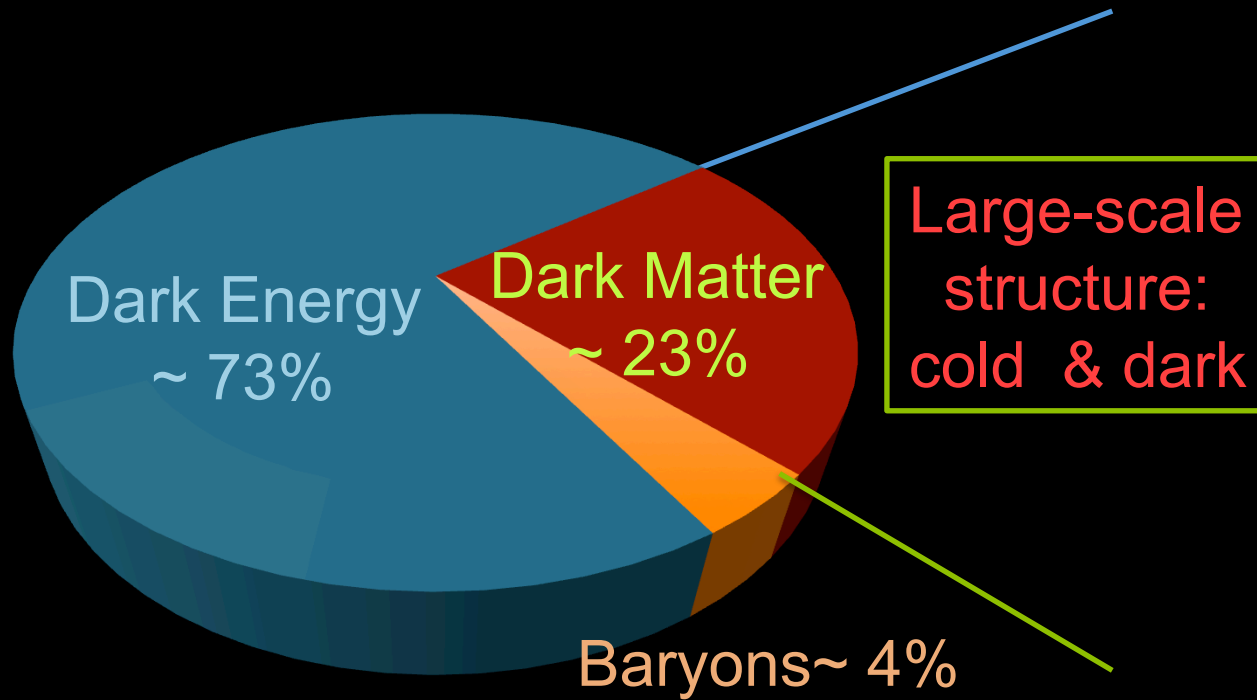


SIGNATURES OF PARTICLE DARK MATTER

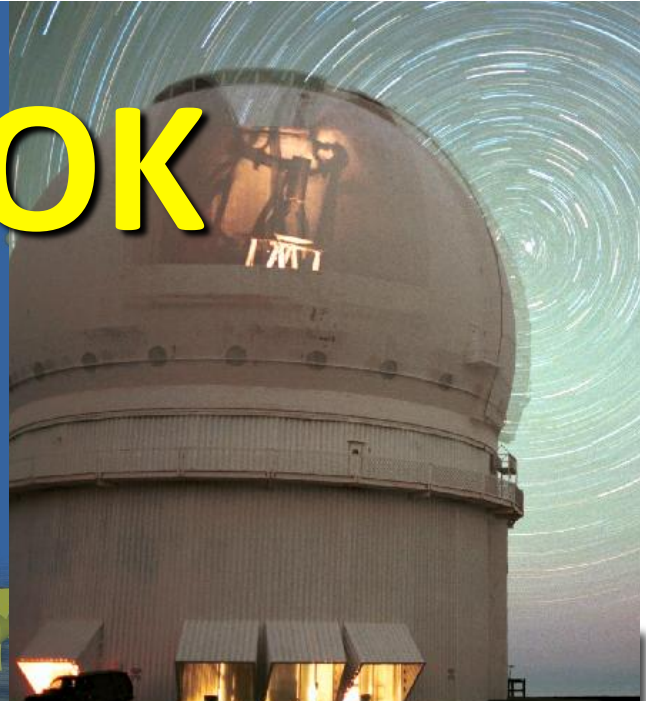
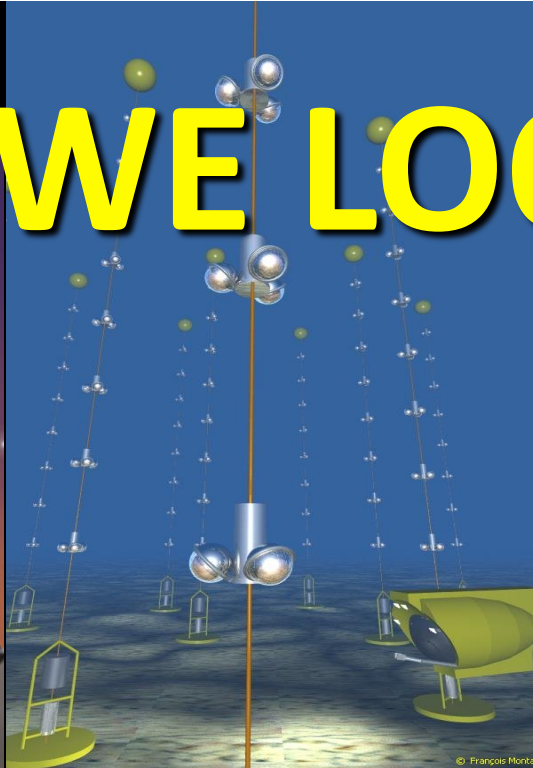
Joe Silk

IAP

29 May 2012



HOW WE LOOK



DARK MATTER DETECTION

- **Direct detection**

DAMA/Libra, CDMS, XENON, CoGeNT, Edelweiss...

- **Production at colliders**

LHC

- **Indirect detection**

γ from annihilations in galactic halo, galactic centre, dwarfs + secondary inverse Compton, radio synchrotron using Fermi, HESS, radio telescopes...

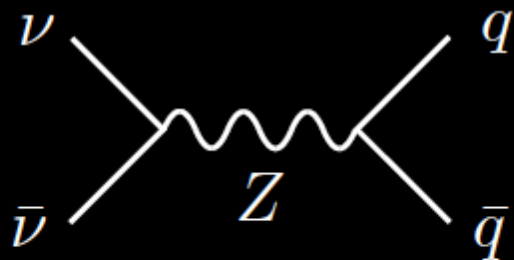
e^+ from annihilations in galactic halo, galactic centre, using PAMELA, Fermi, HESS, AMS...

p bar from annihilations in galactic halo, , using PAMELA, Fermi, HESS, AMS...

ν , $\bar{\nu}$ from annihilations in the sun, earth, using ICECUBE, SuperK....

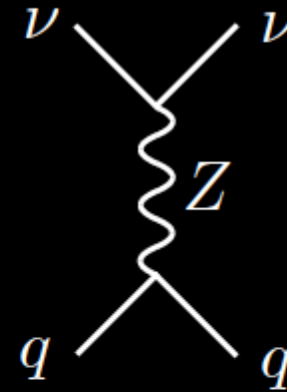
INDIRECT versus DIRECT DETECTION

Annihilation $\nu\bar{\nu} \rightarrow q\bar{q}$



Crossing

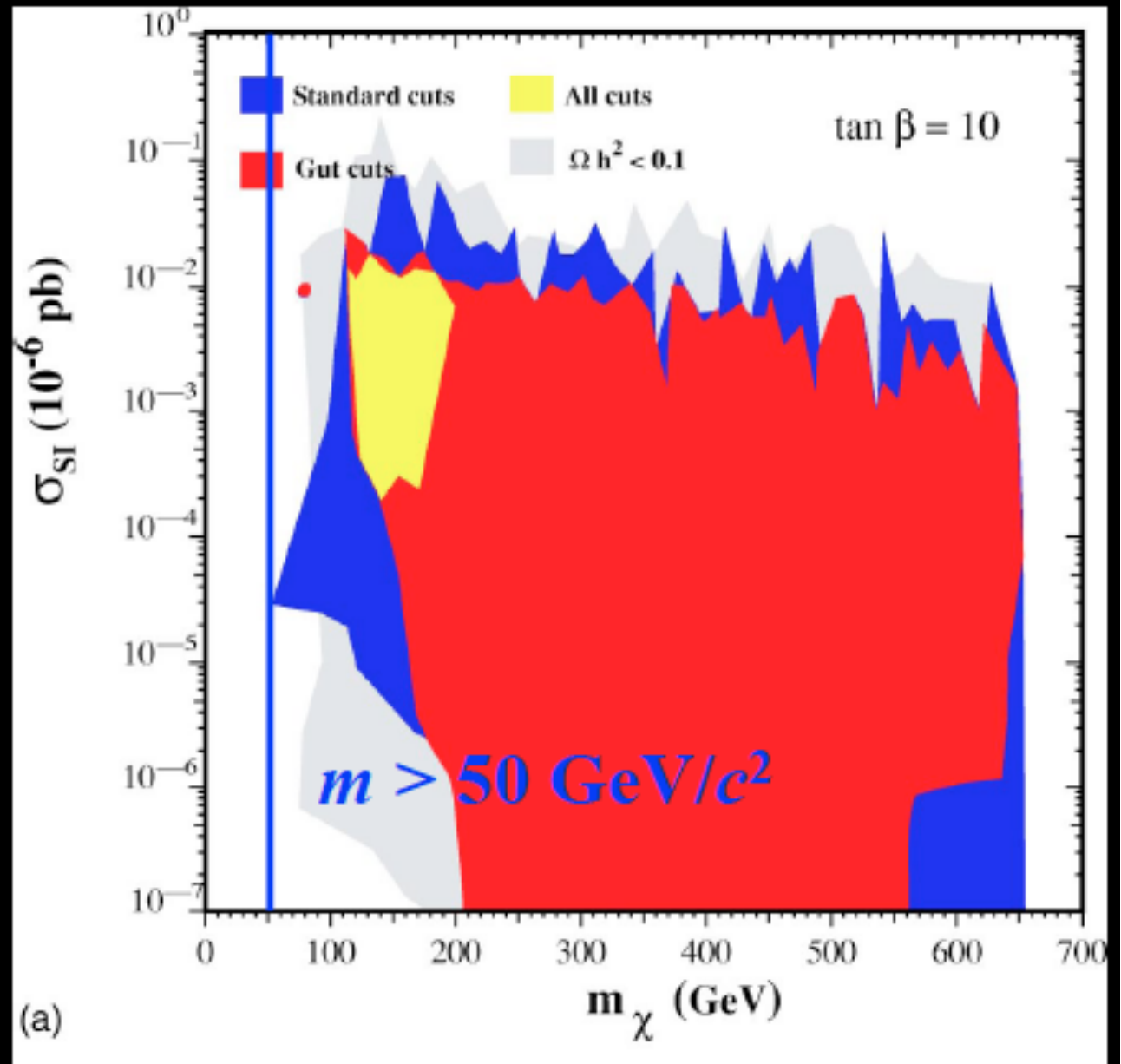
Scattering $\nu q \rightarrow \nu q$



For example, for a $\sim 4 \text{ GeV}/c^2$ dark matter neutrino, the scattering cross section is

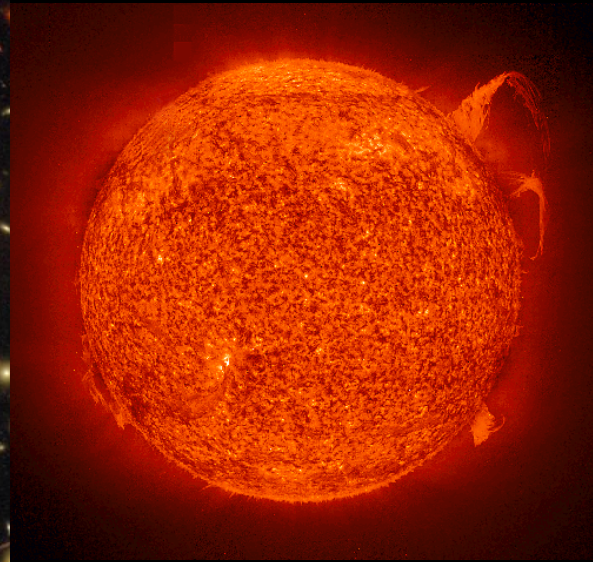
$$\sigma_{\nu n} \simeq 0.01 \frac{\langle \sigma v \rangle}{c} \simeq 10^{-38} \text{ cm}^2$$

SUSY models



Ellis, Ferstl, Olive, Santoso 2003

WHERE WE LOOK



THE SCALES WE PROBE

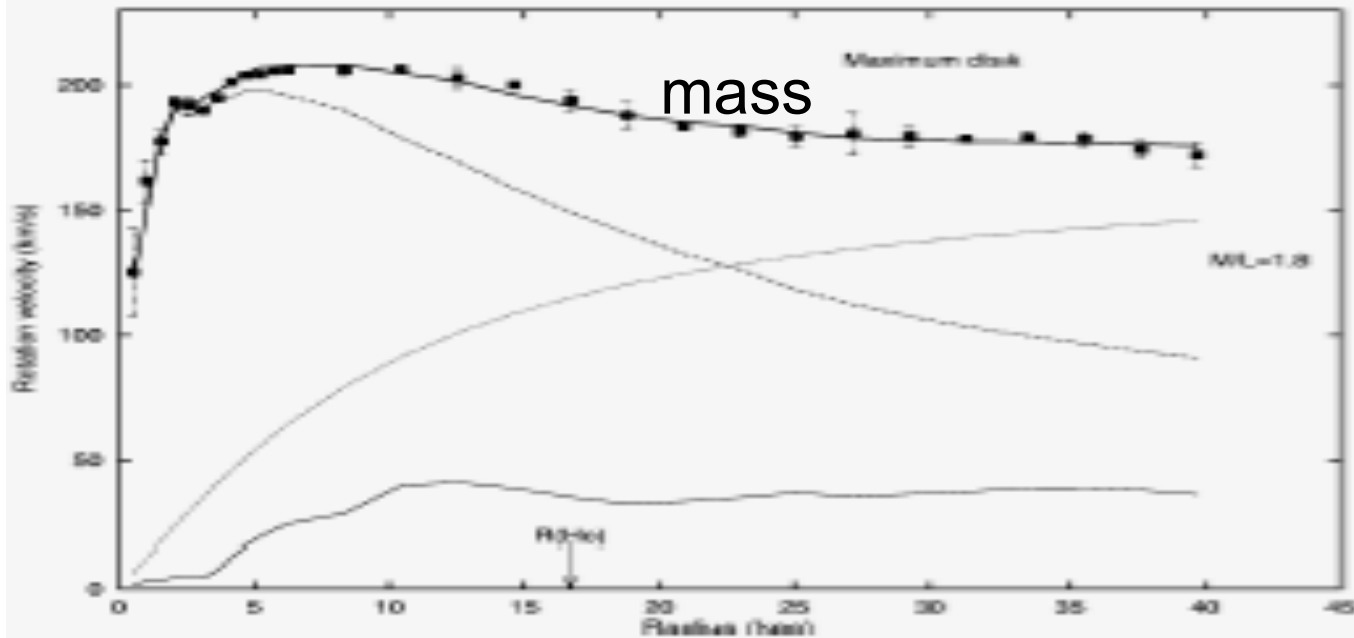
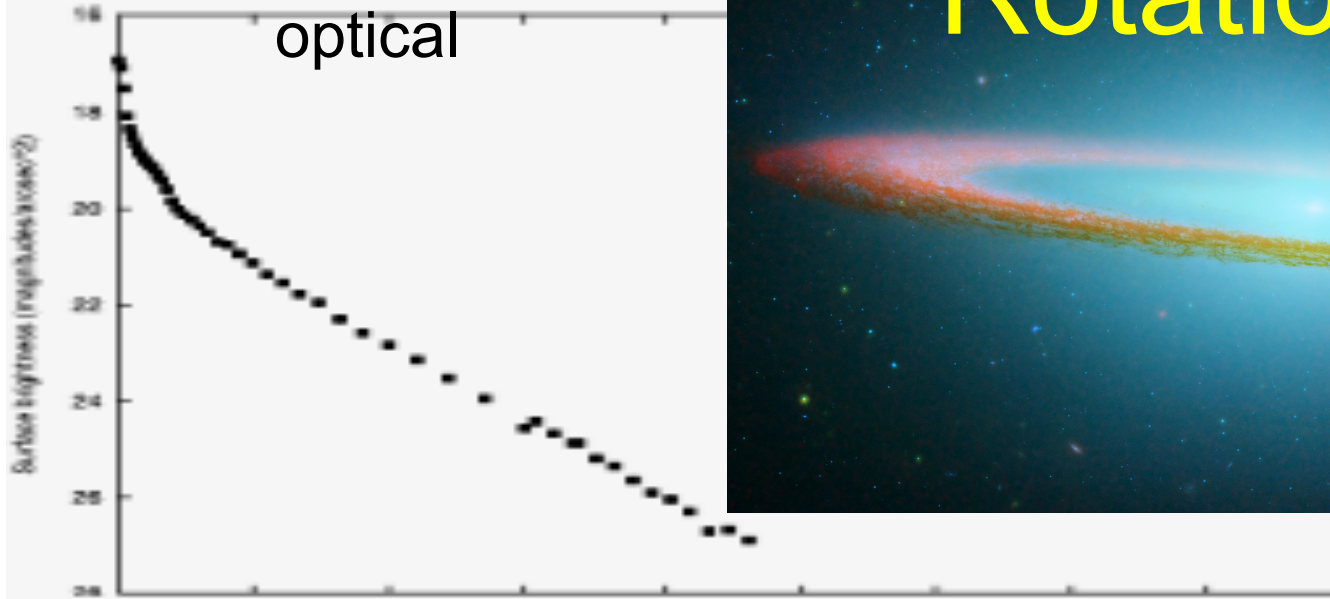
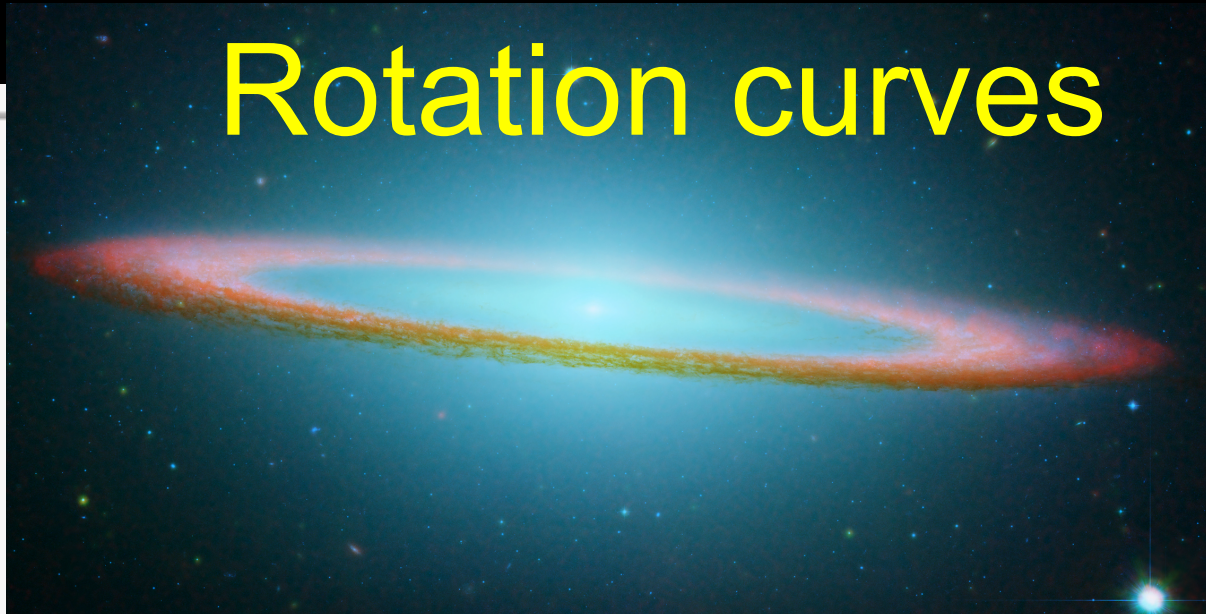
100 kpc rotation curves

1 Mpc cluster lensing

10 Mpc redshift space distortions

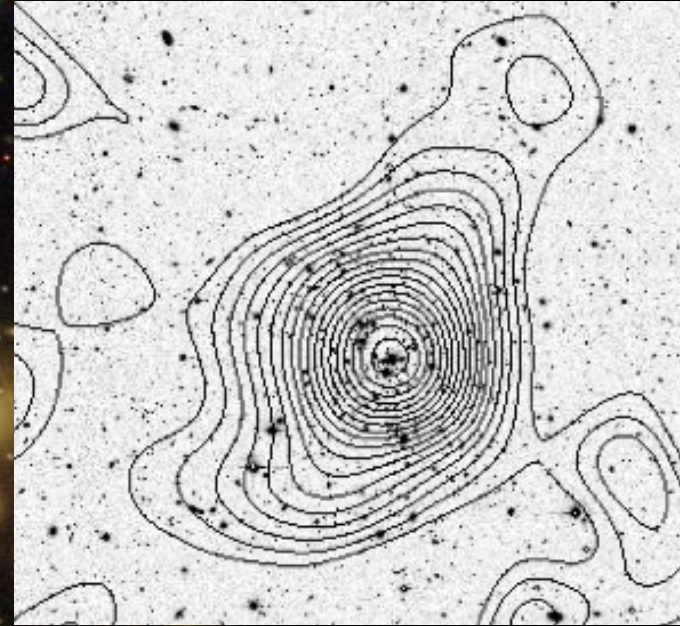
100 Mpc baryon acoustic oscillations

Rotation curves

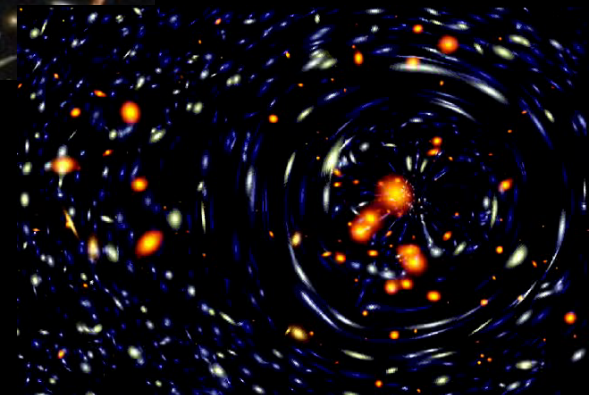


100 kpc

Gravitational lensing

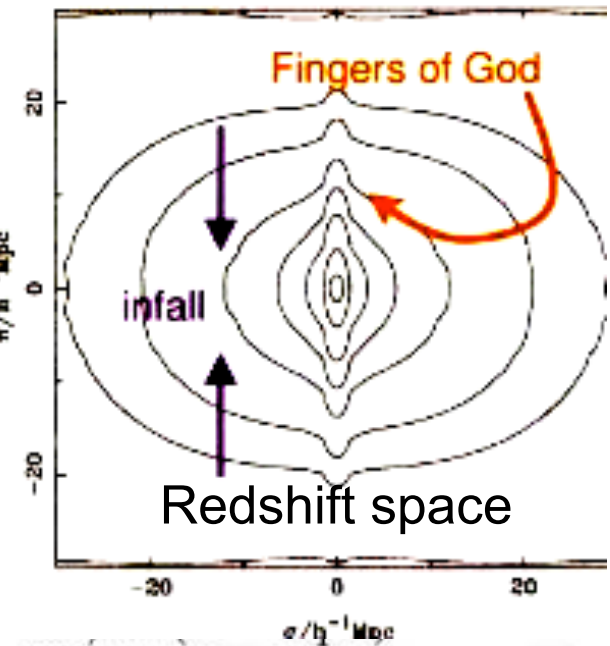
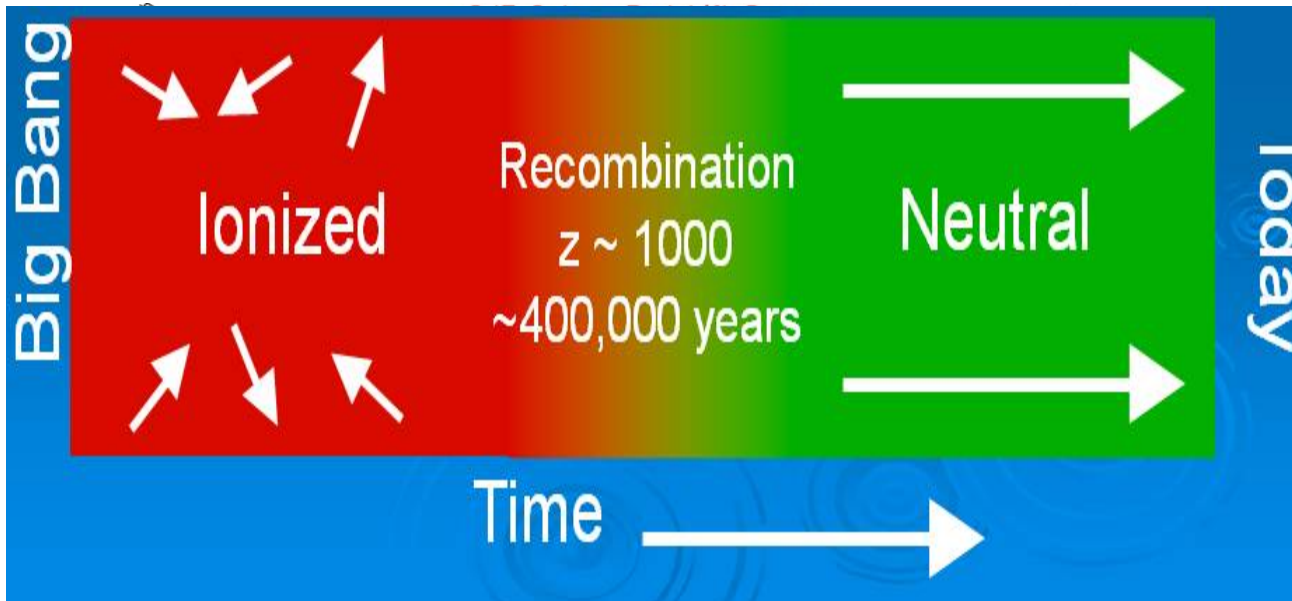


1 Mpc

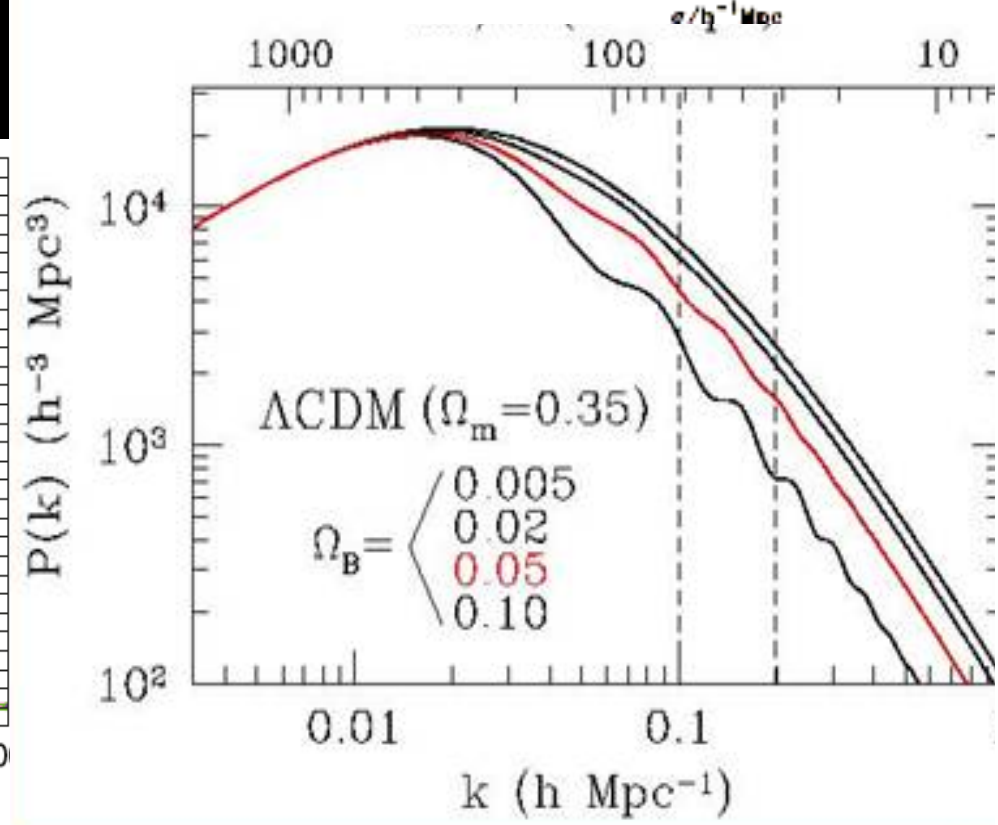
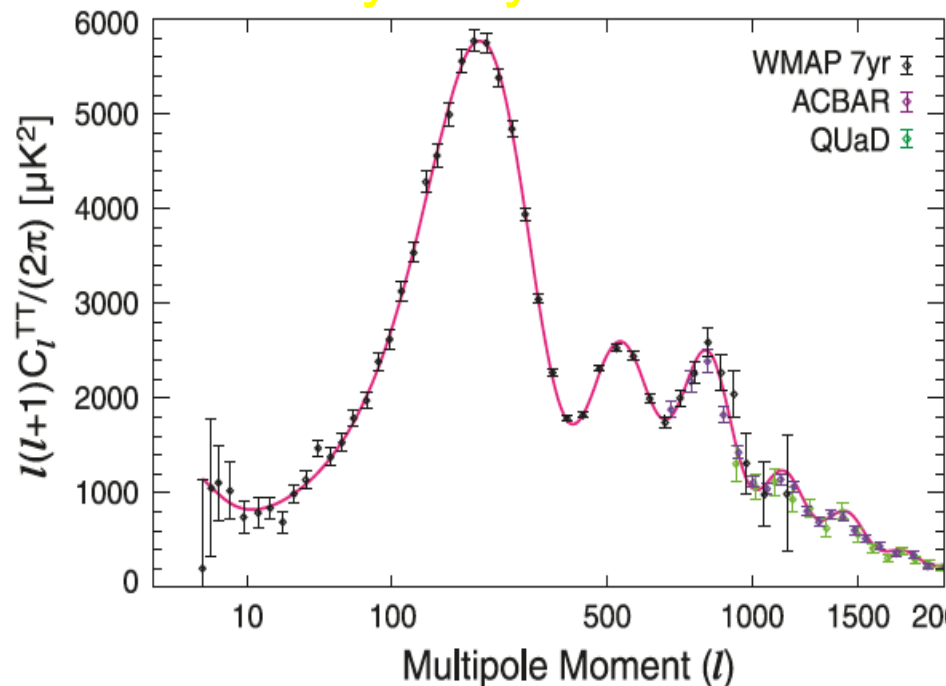


DARK MATTER IS RELATIVELY SIMPLE!

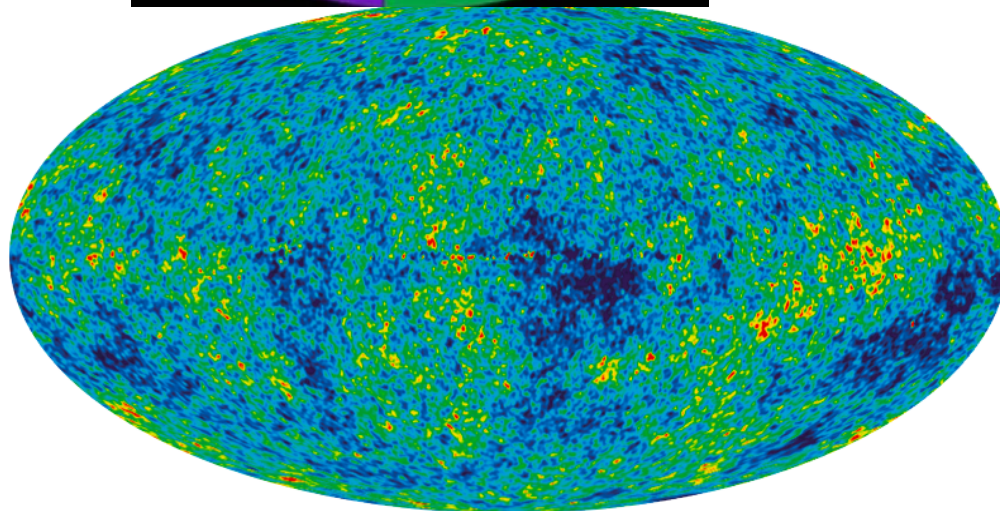
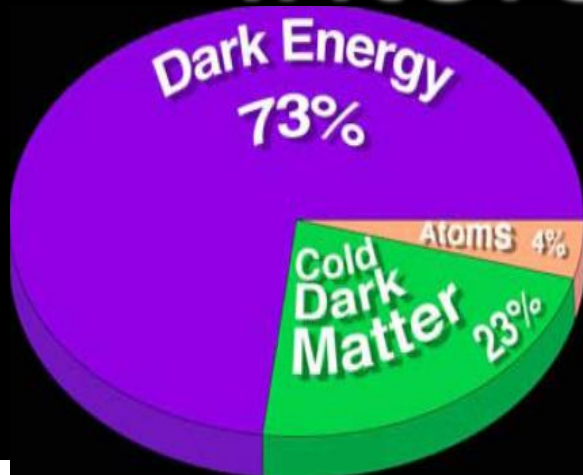




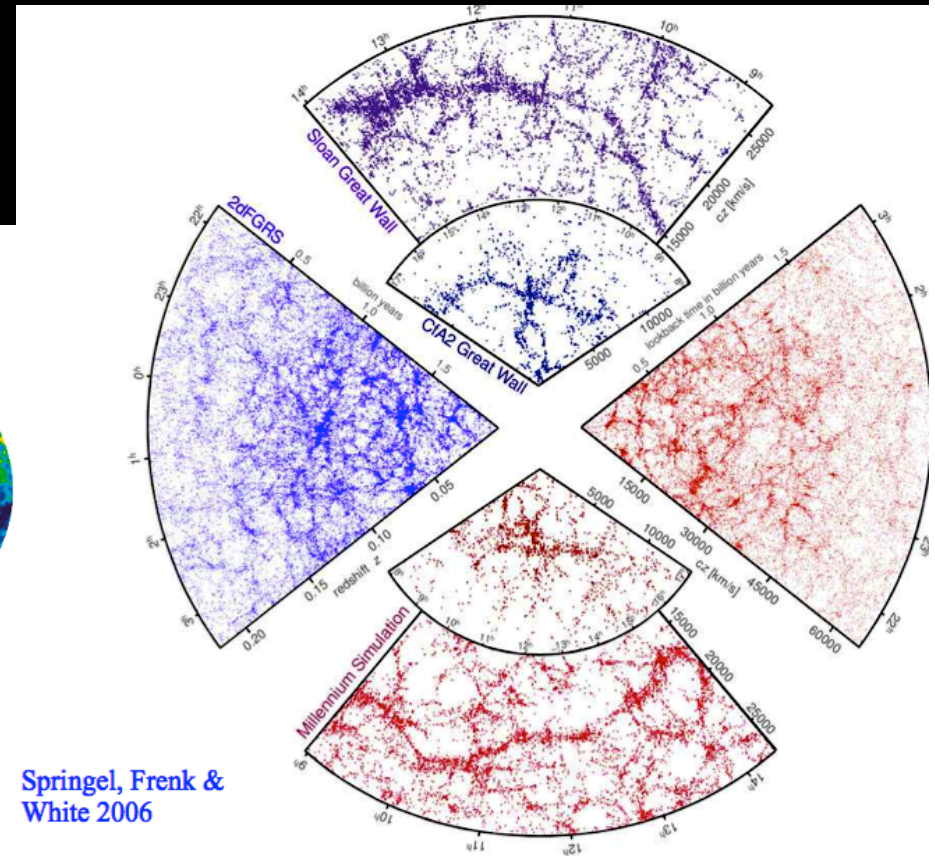
Baryon acoustic oscillations controlled by baryon/DM ratio



Dark Matter is weakly interacting & cold

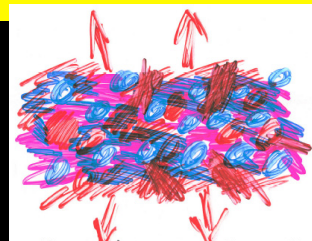


-200 T(μ K) +200 WMAP 5-year



Springel, Frenk & White 2006

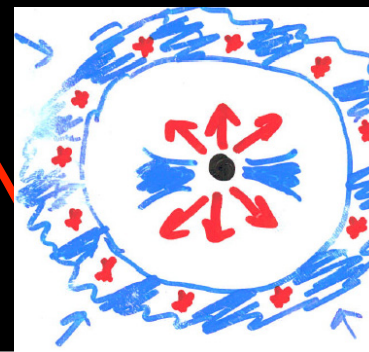
THE MISSING DWARF & GIANT PROBLEMS



theory (CDM-motivated)

observations

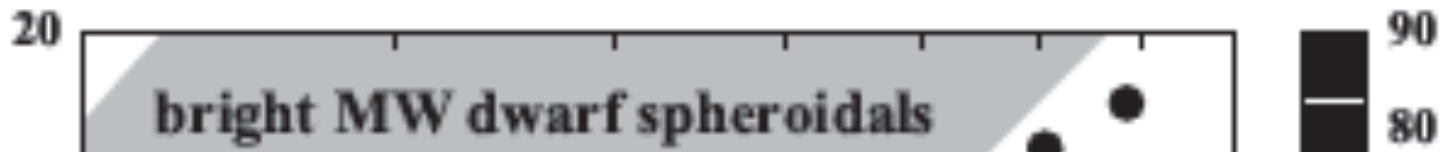
Model matches data



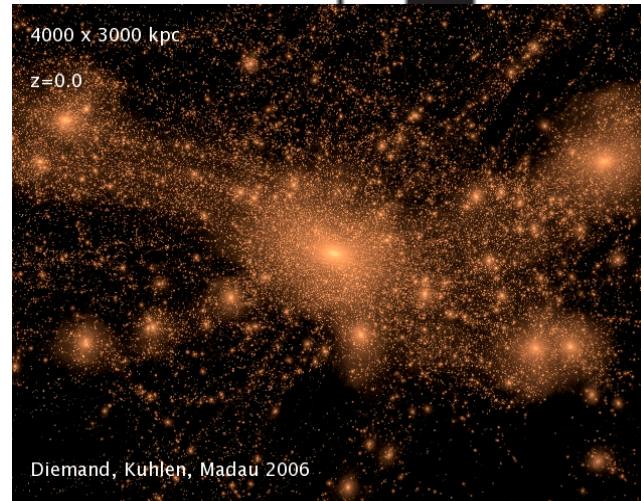
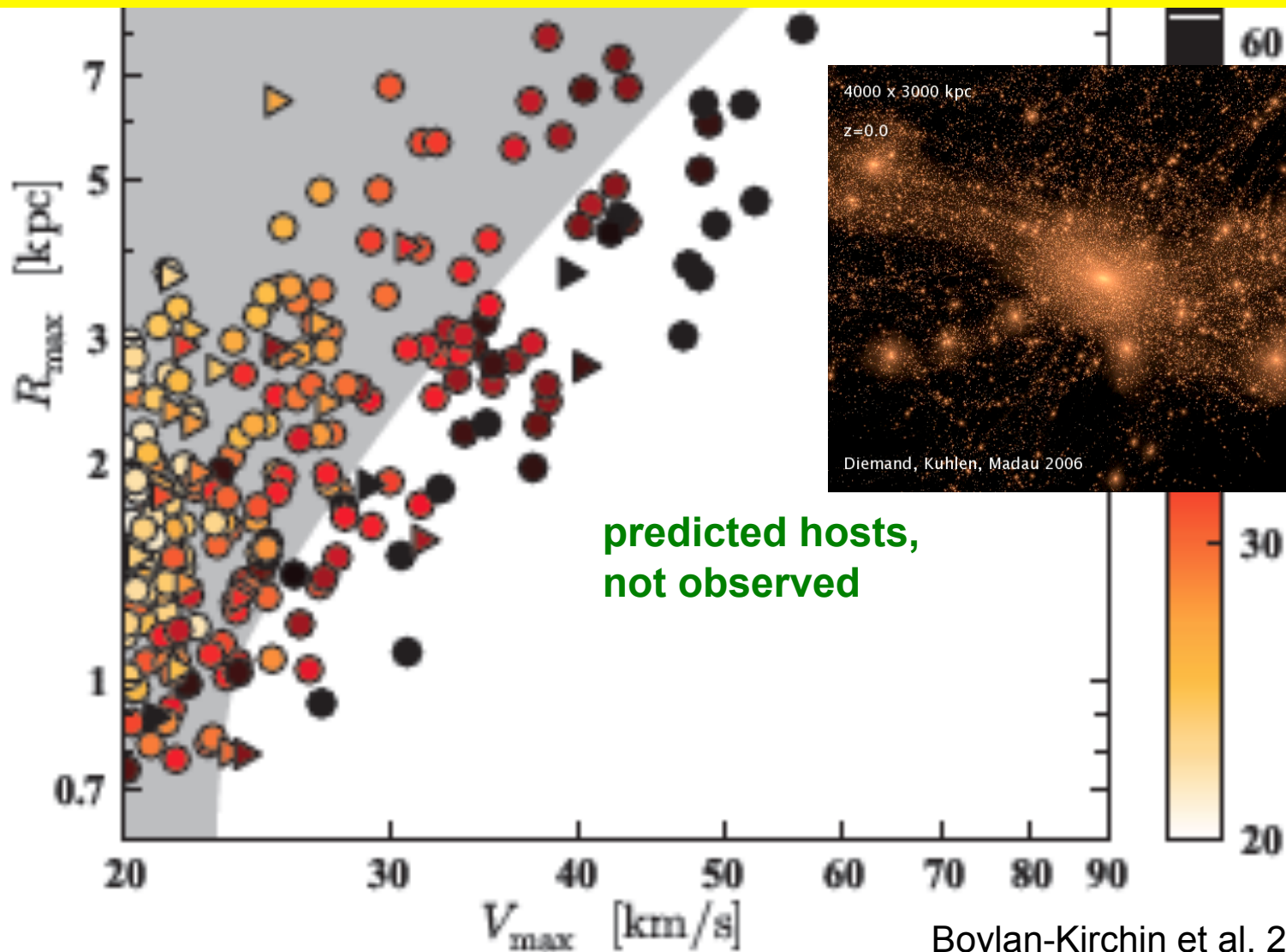
Galaxy luminosity/mass

SN

AGN



THE TOO BIG TO FAIL PROBLEM



Boylan-Kirchin et al. 2011

primordial neutrinos as hot dark matter

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

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

$$\Omega_\nu < 0.20$$

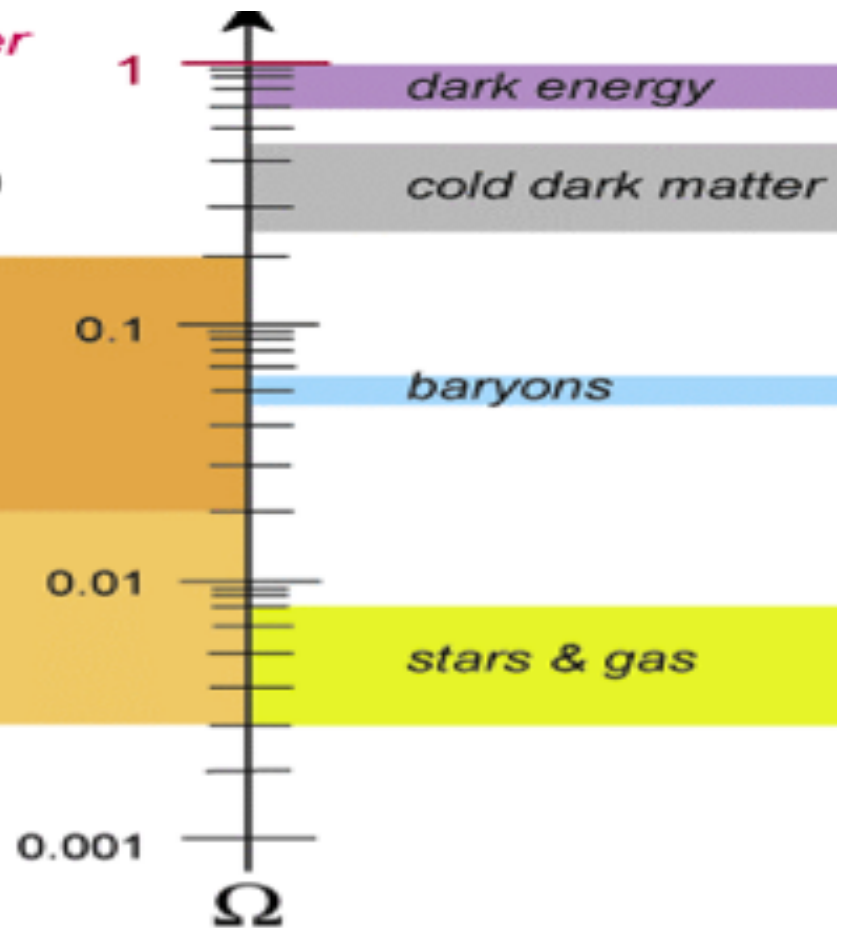
*structure formation
tritium experiments*

$$\Omega_\nu < 0.02$$

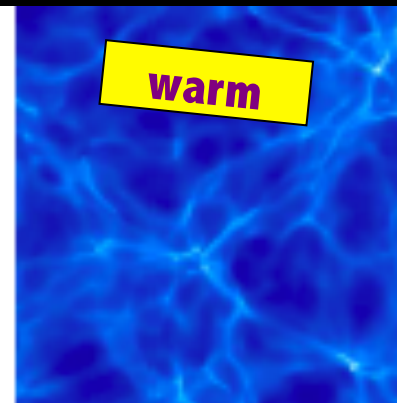
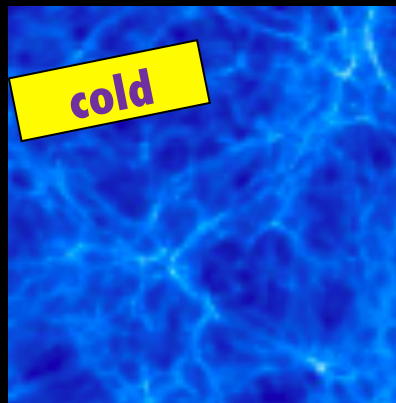
KATRIN sensitivity

$$\Omega_\nu > 0.003$$

Super-Kamiokande



Dark matter is not neutrinos

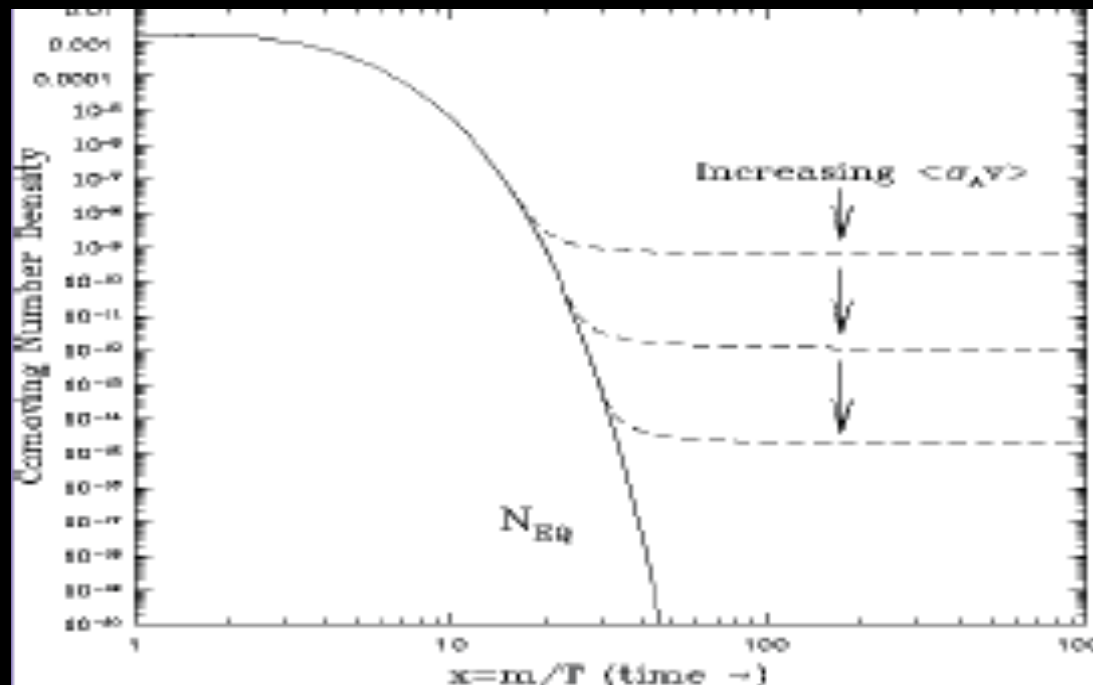


Dark matter “most likely” is a weakly interacting (massive?) particle

Eg WIMP (or LSP) motivated by theory of supersymmetry

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

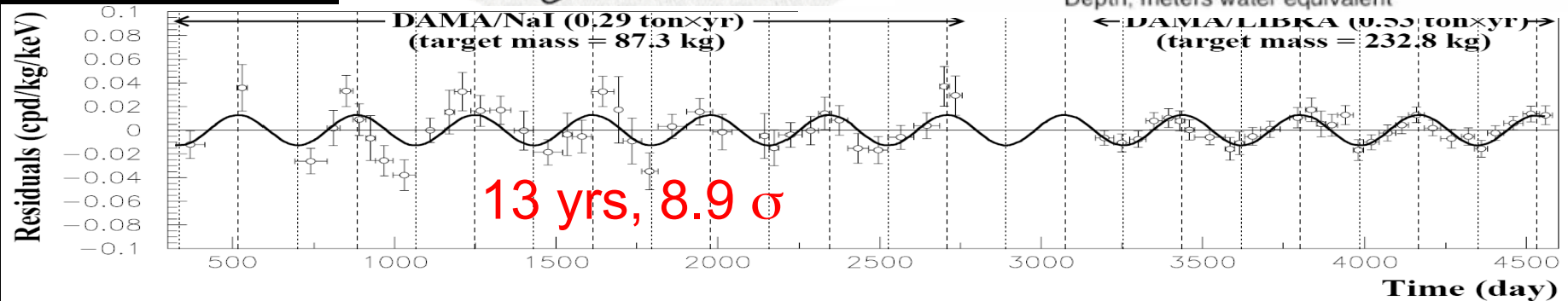
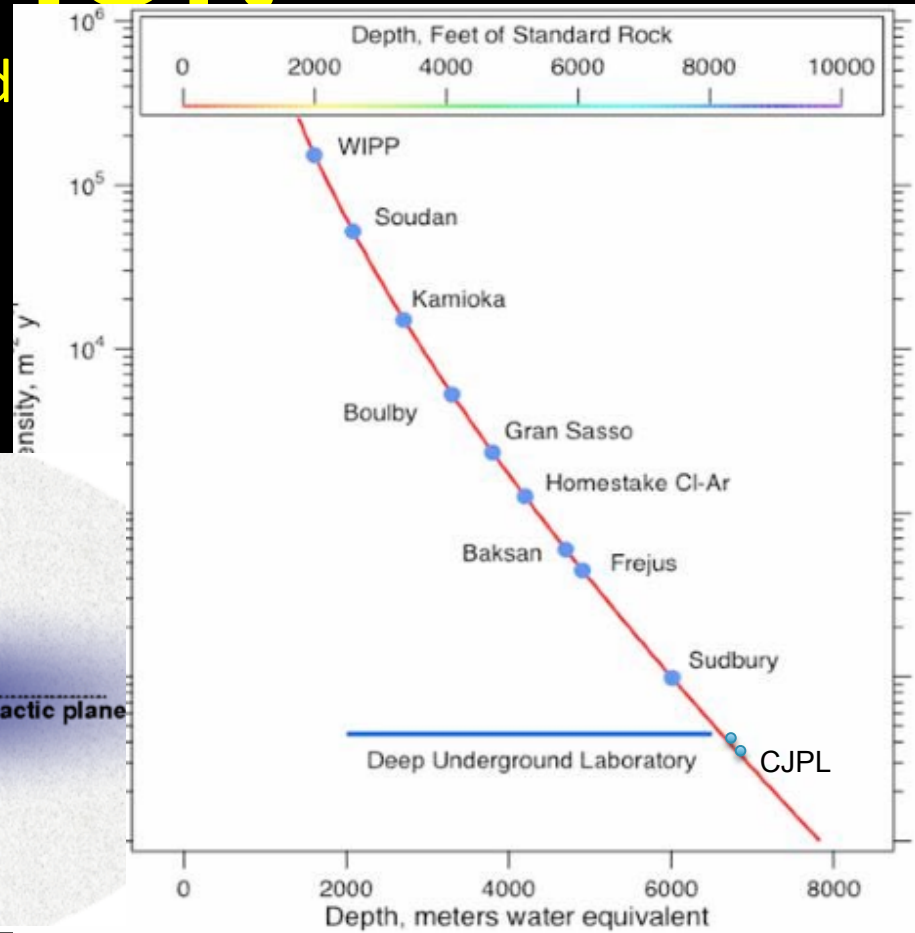
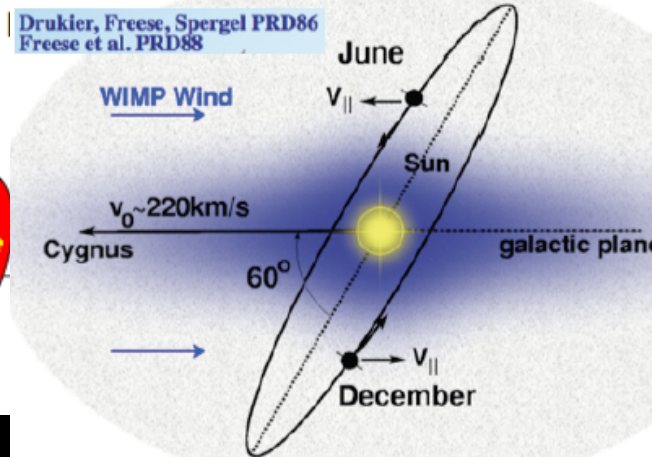
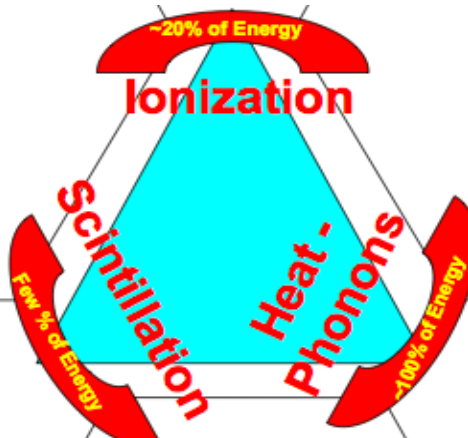
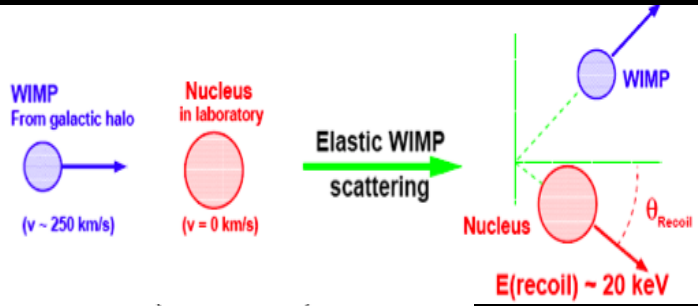
The WIMP miracle: relic abundance if $\langle\sigma v\rangle\sim 3\times 10^{-26}\text{ cm}^3/\text{s}\sim 1/\Omega_x$



Astrophysical probes complement collider experiments

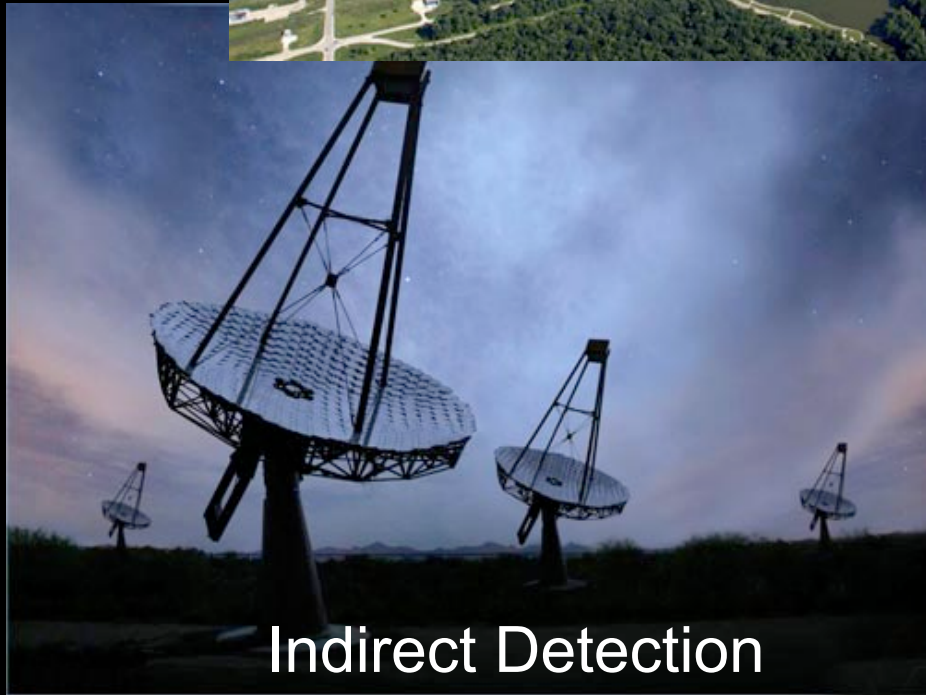
DIRECT DETECTION

many WIMPs pass through per second





WIMP Production



Indirect Detection

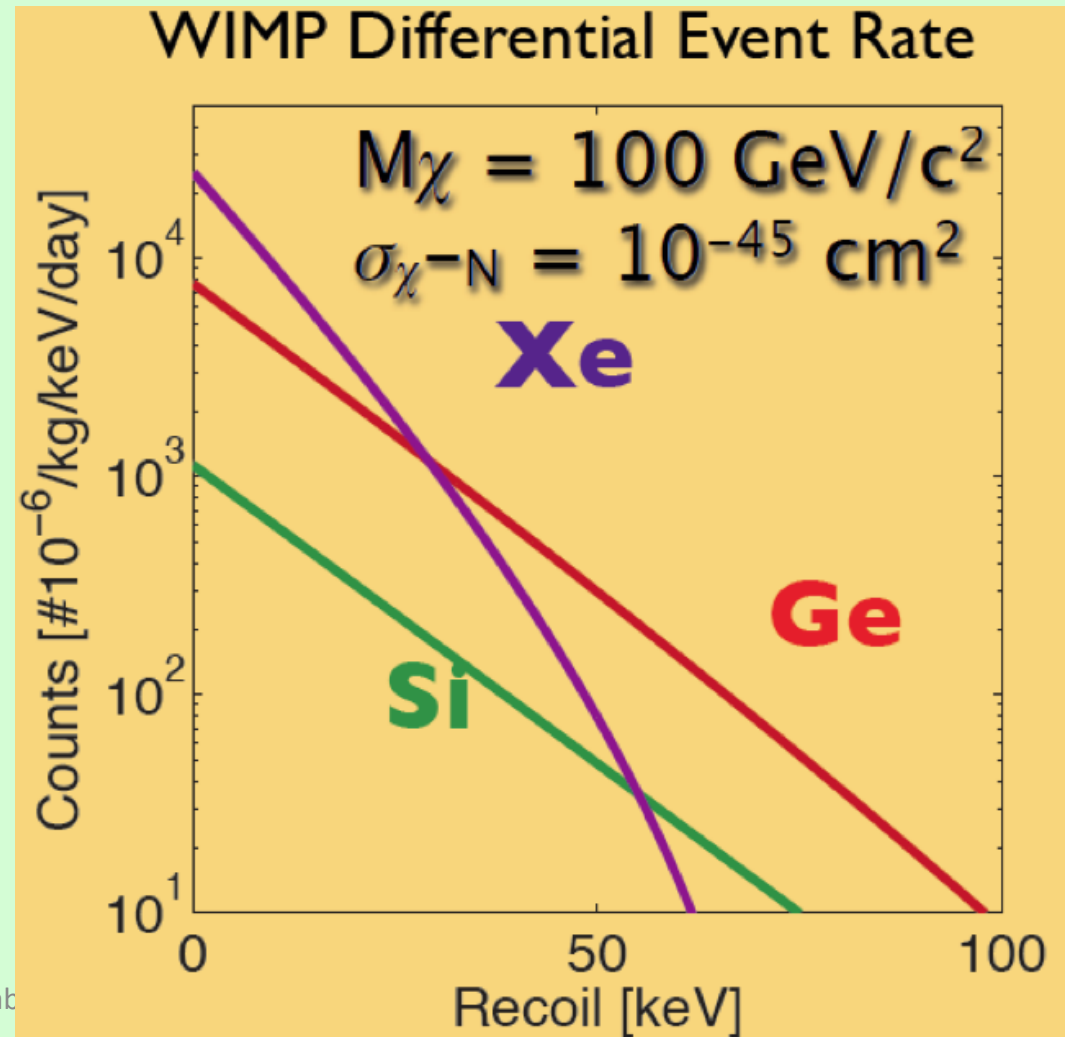


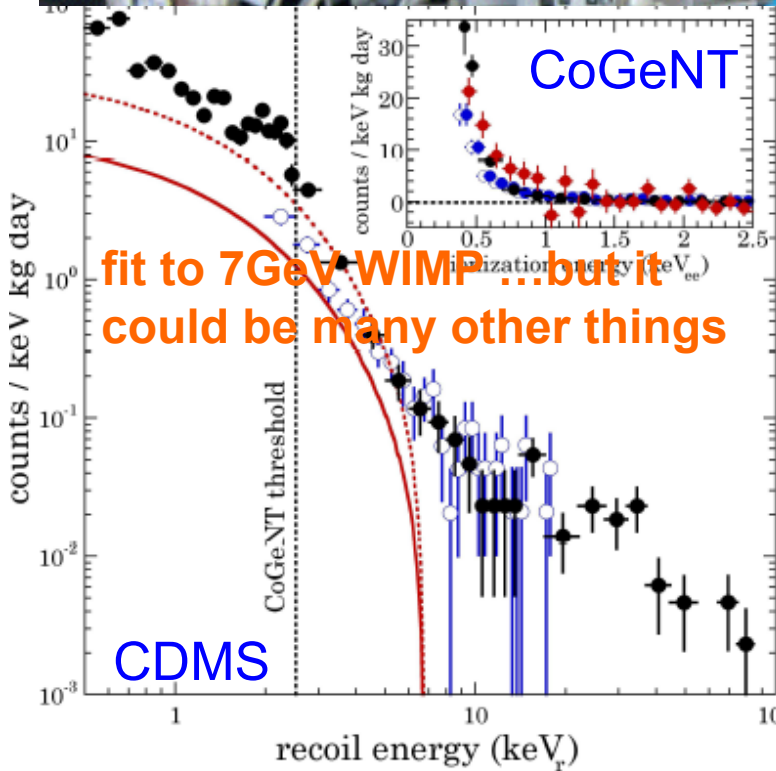
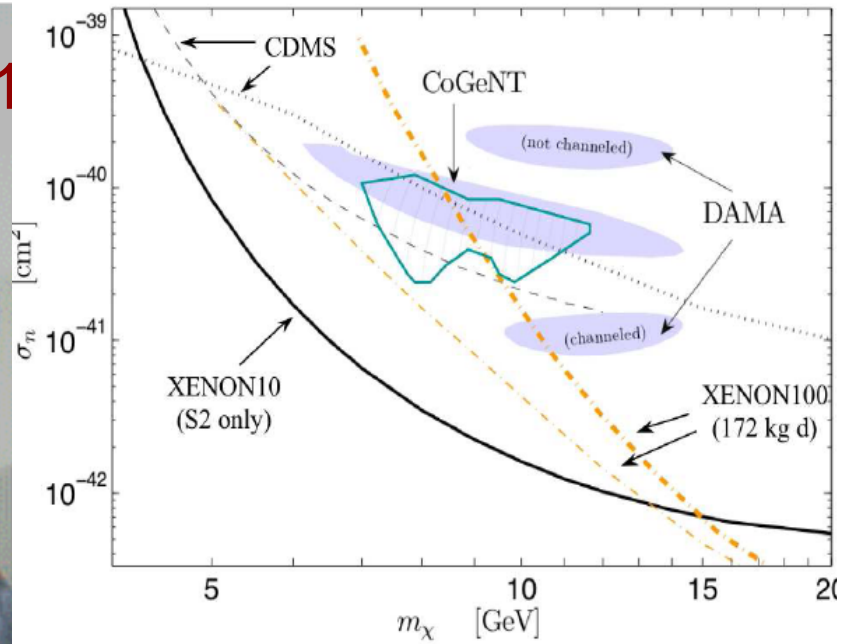
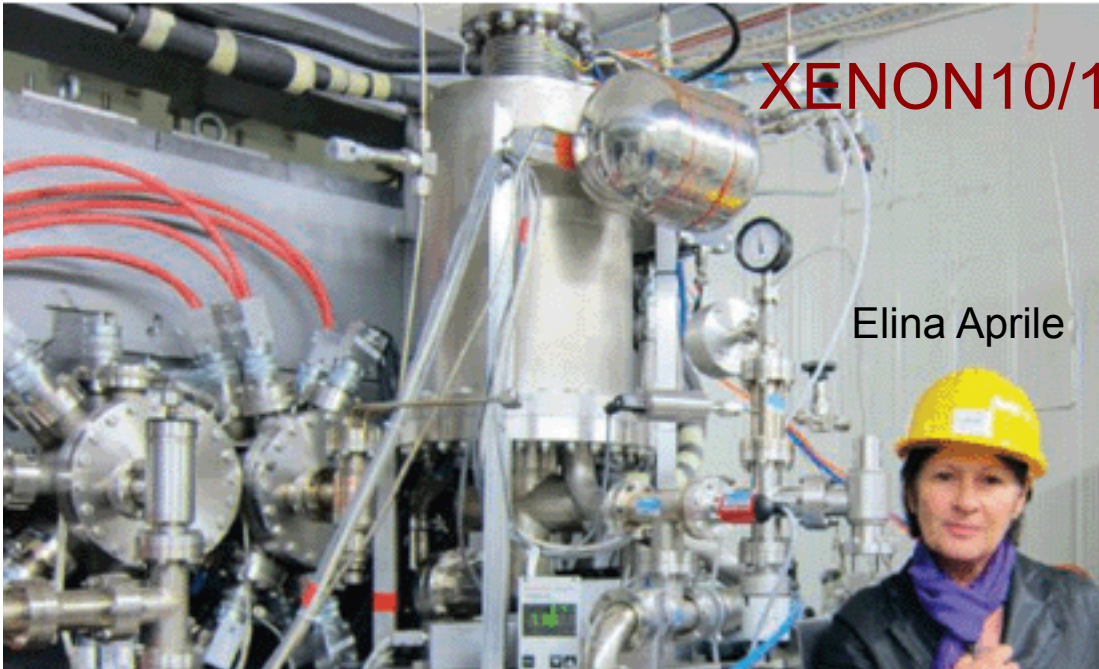
Direct Detection

Direct Detection of Dark Matter by elastic scattering

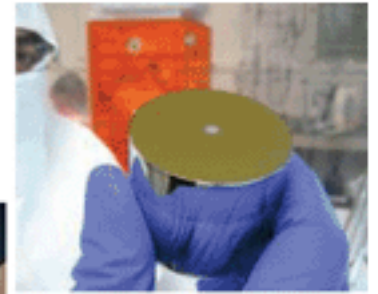
$$1\text{ GeV} - 10\text{ TeV}$$
$$\sigma_{\text{SI}} < 10^{-44}\text{ cm}^2$$
$$\sigma_{\text{SD}} < 10^{-36}\text{ cm}^2$$

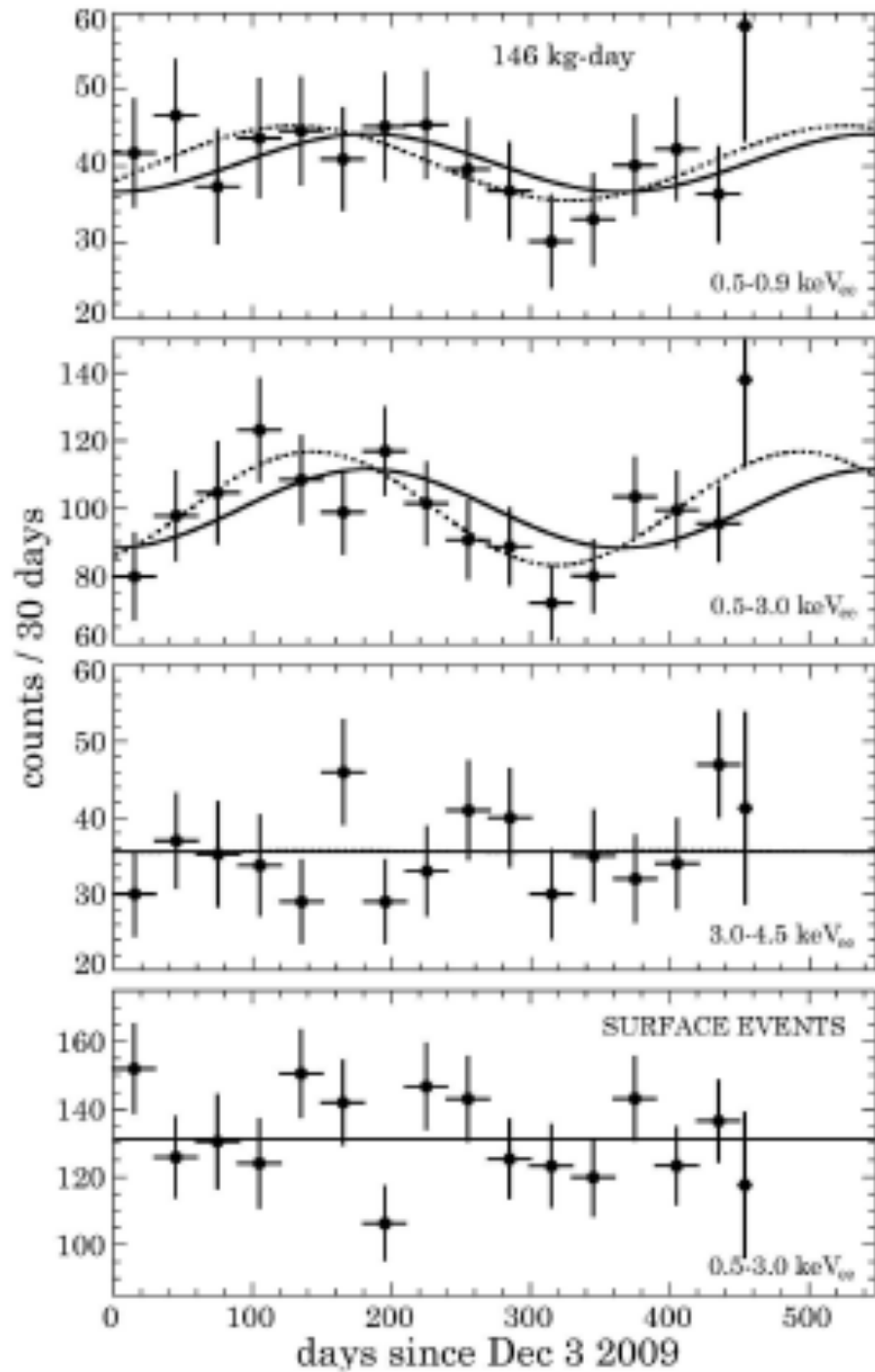
- Low background
- Materials selection
- Shielding
- Discrimination



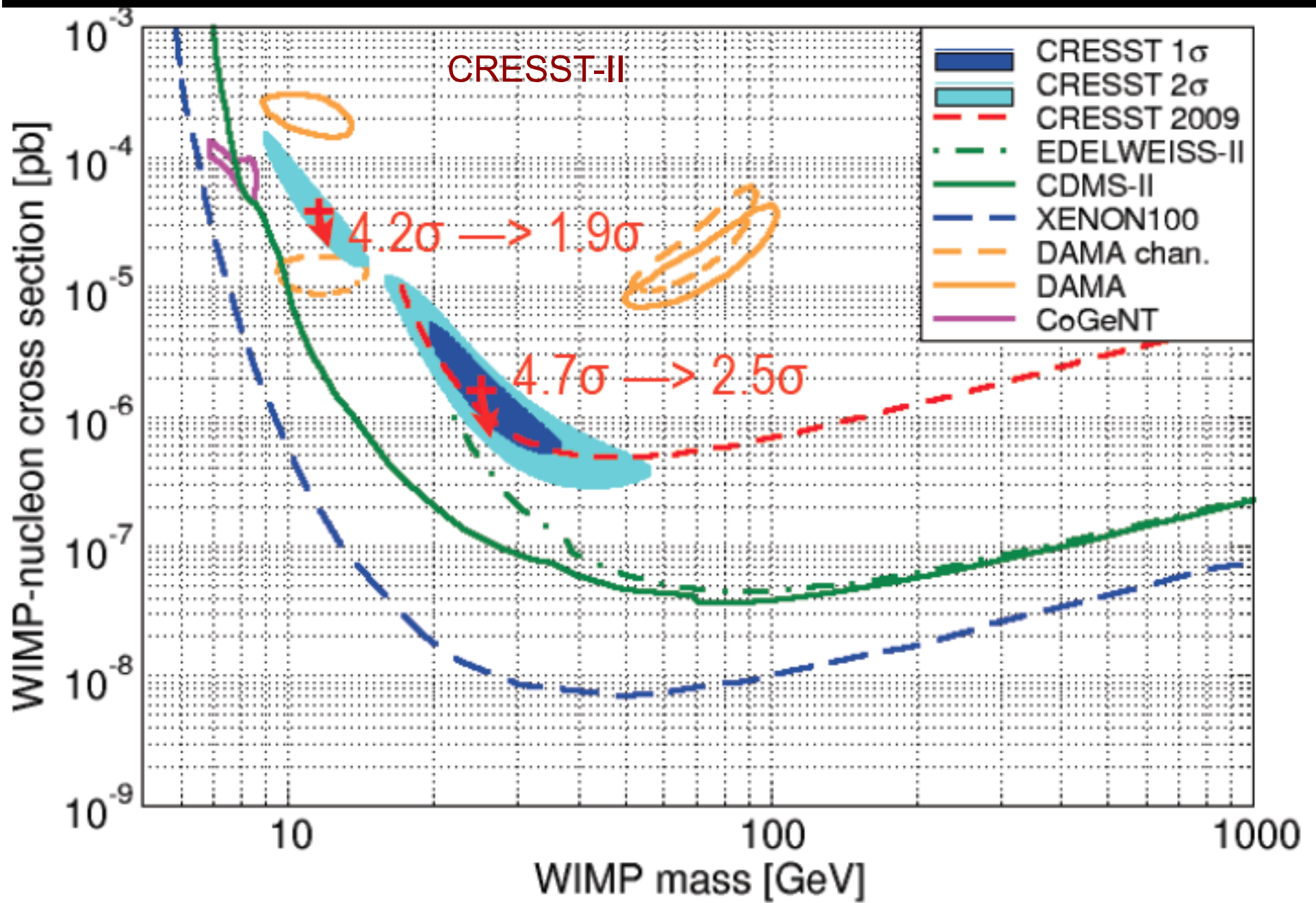


CoGeNT





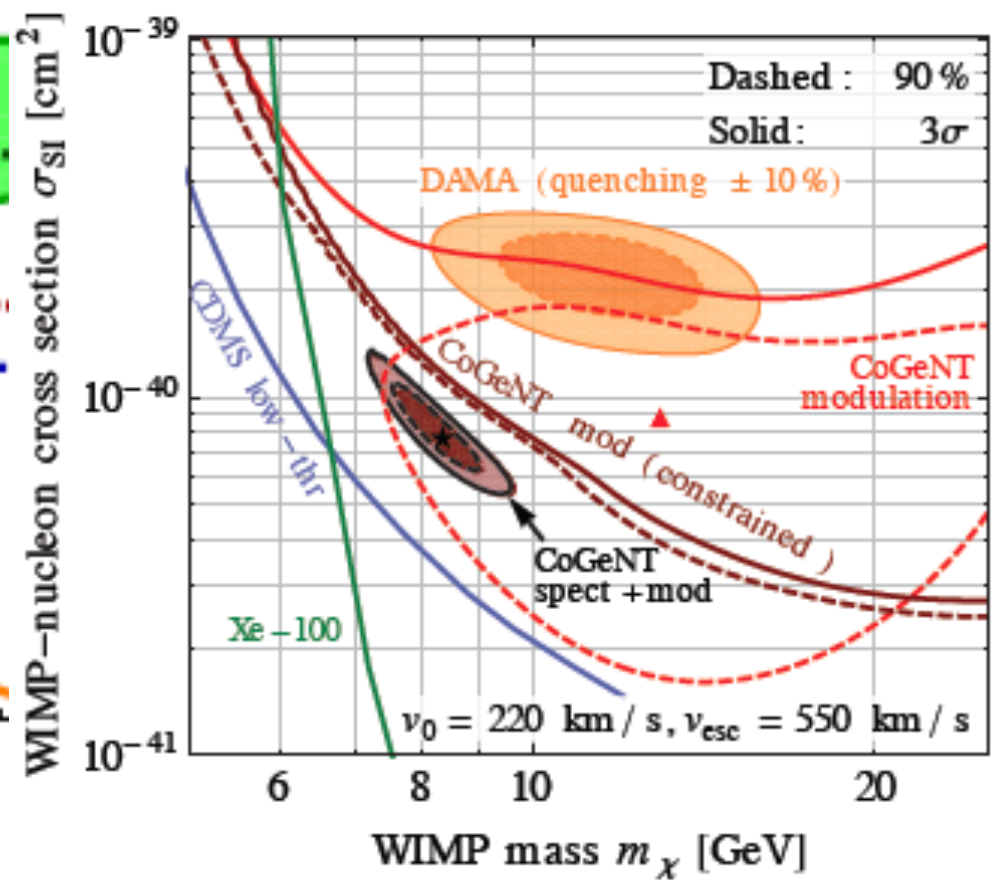
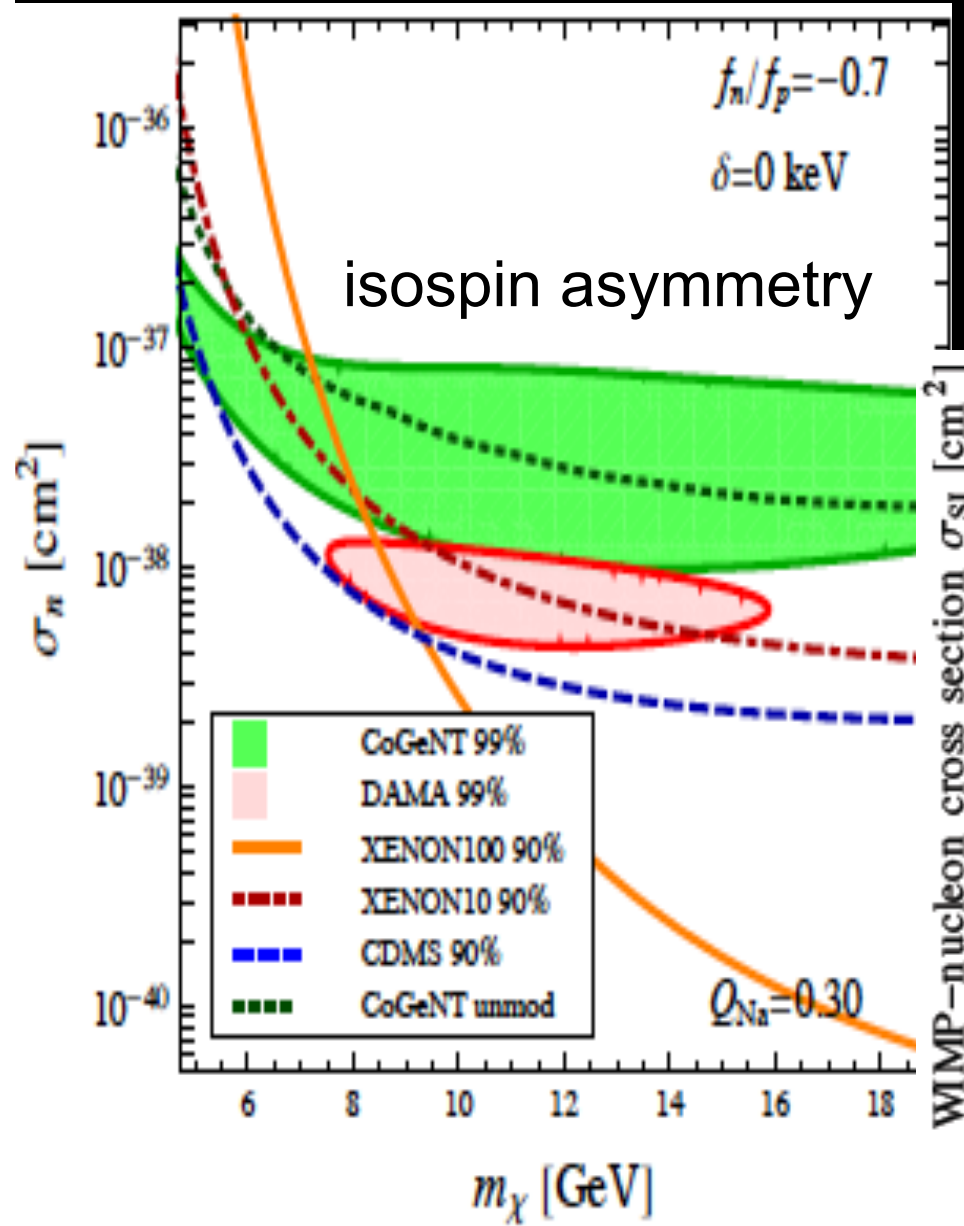
CoGeNT reports
a 2.8σ annual modulation
consistent in phase, amplitude?,
and period (2011)



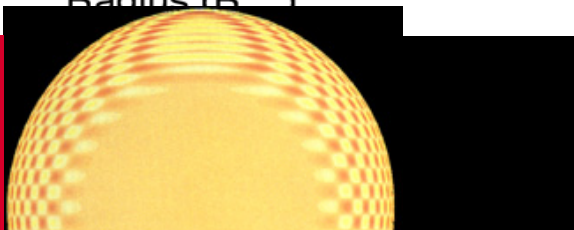
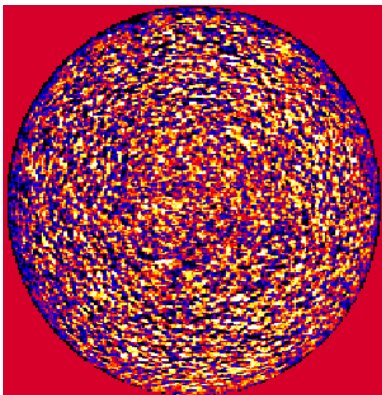
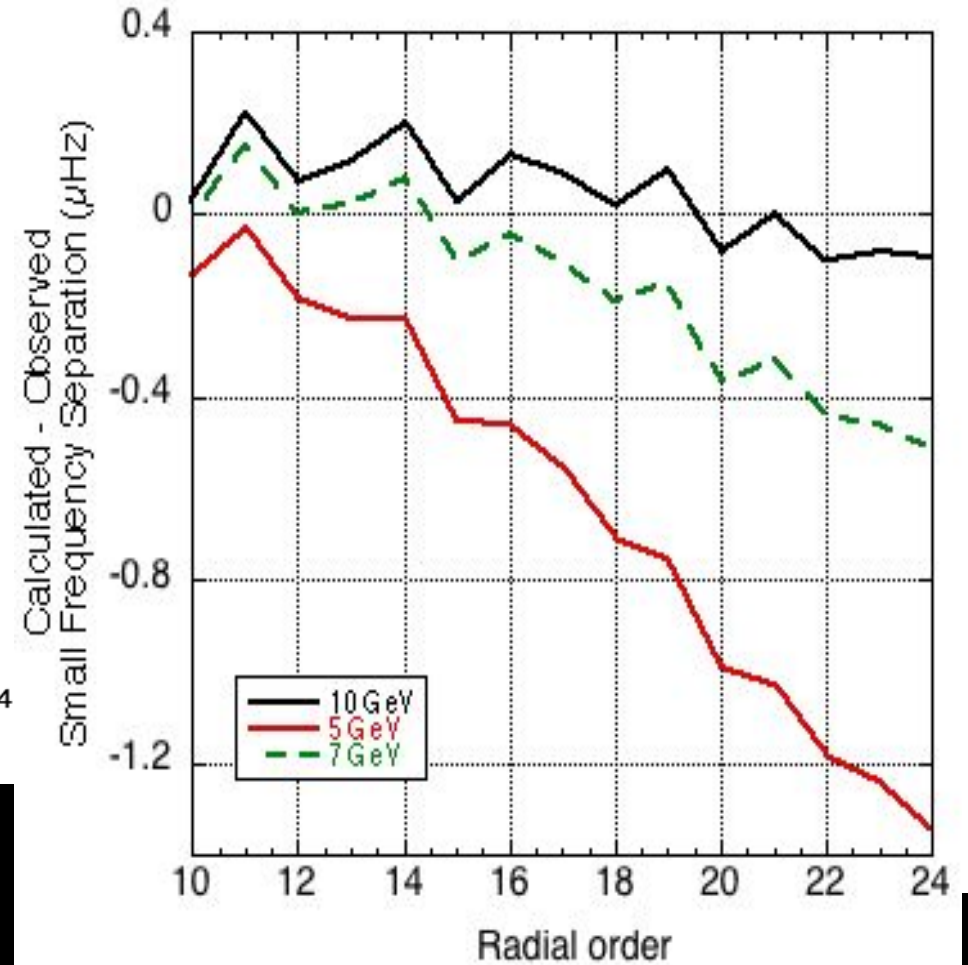
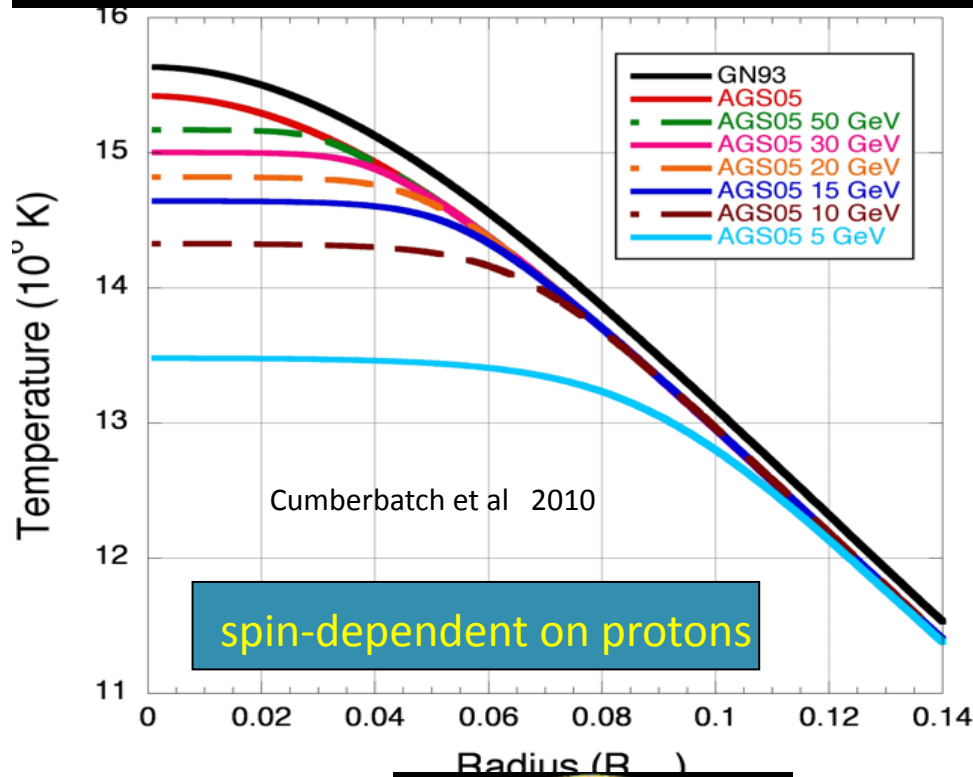
and models can be found for a ~ 7 GeV WIMP...possibly non-annihilating

Frandsen et al. 2011

Fox et al. 2011



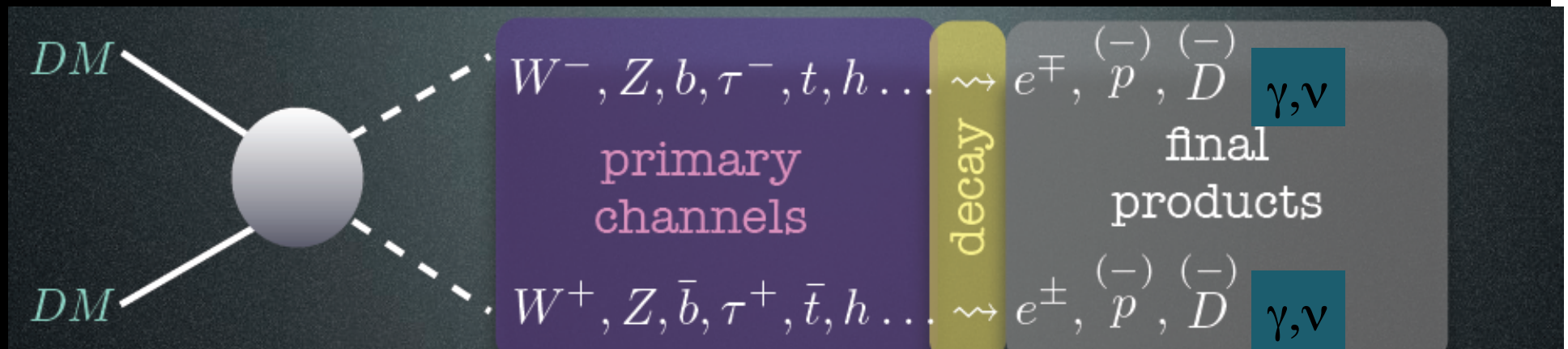
low mass ($m_x \sim 5-10$ GeV) WIMPS are trapped, fill the solar core.... and modify $T(r)$ if non-annihilating



helioseismology rules out 5 GeV in some cases...

INDIRECT DETECTION

halo WIMPS occasionally
annihilate today



into energetic particles

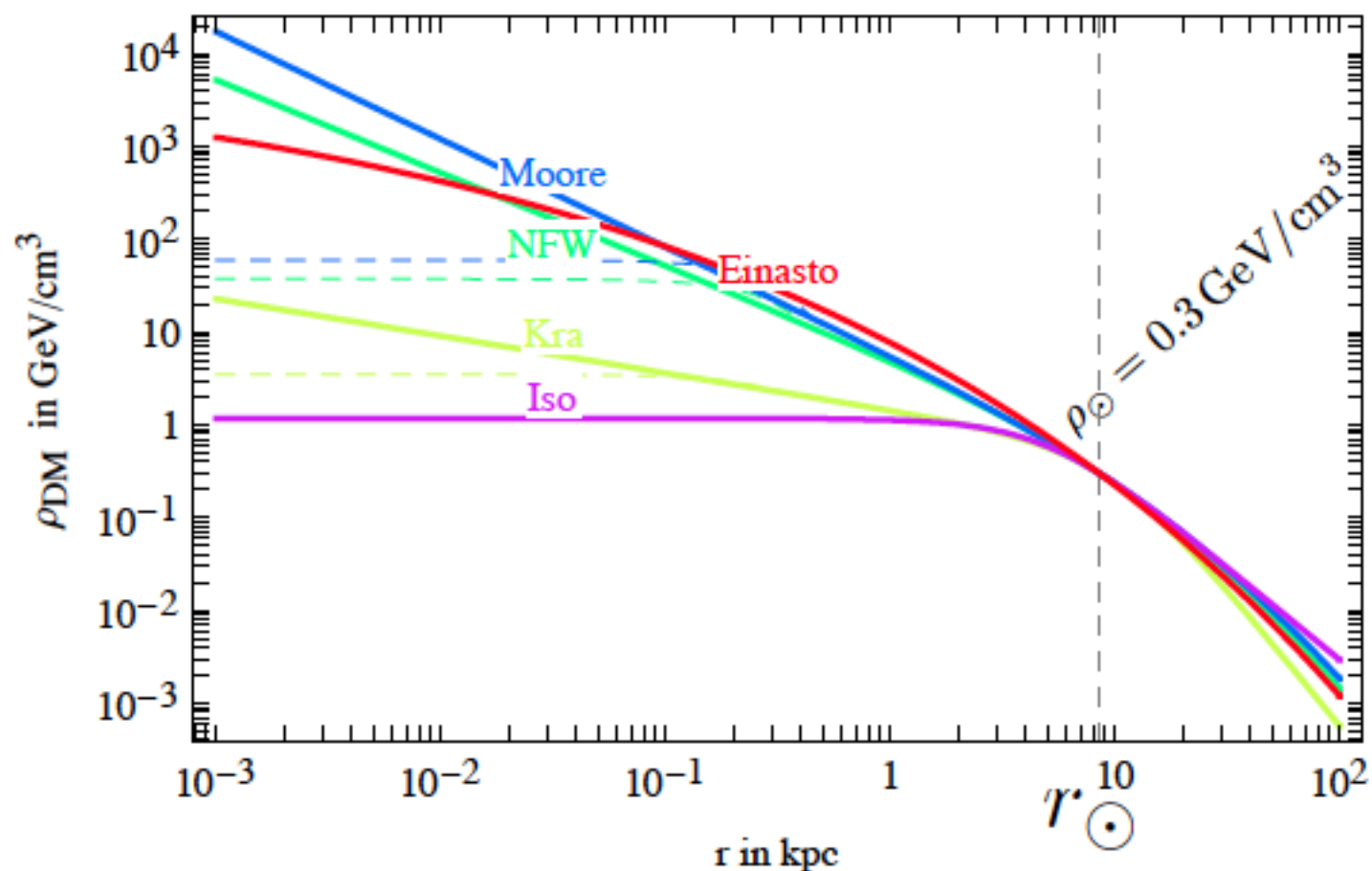
UNCERTAINTIES

Dark matter distribution
profiles, streams, clumps, velocity distribution

Cosmic ray propagation
diffusion, solar modulation, energy losses

Particle physics issues
fragmentation codes

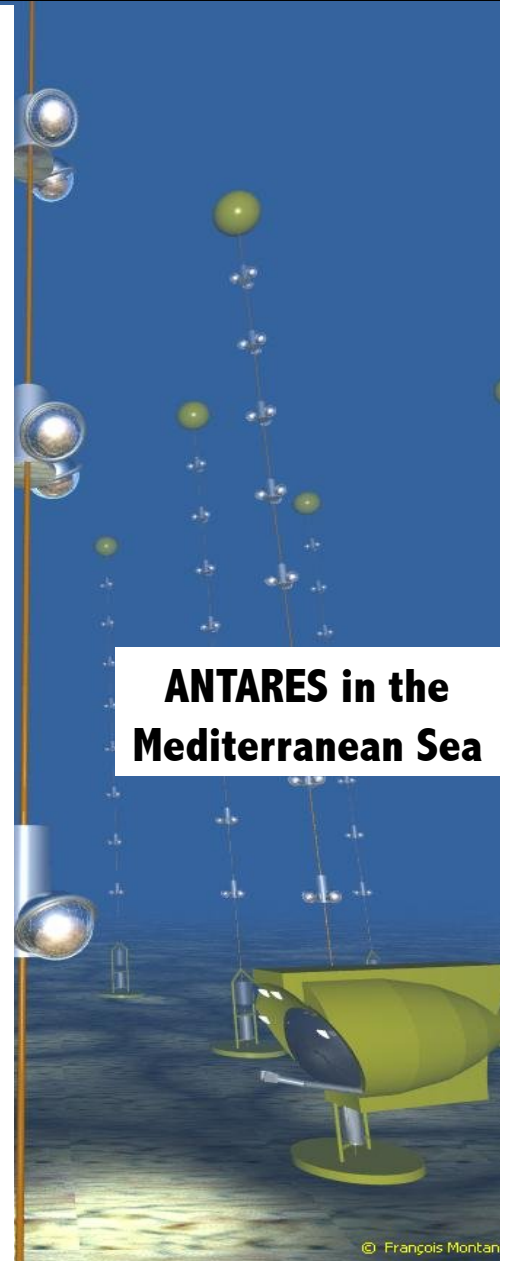
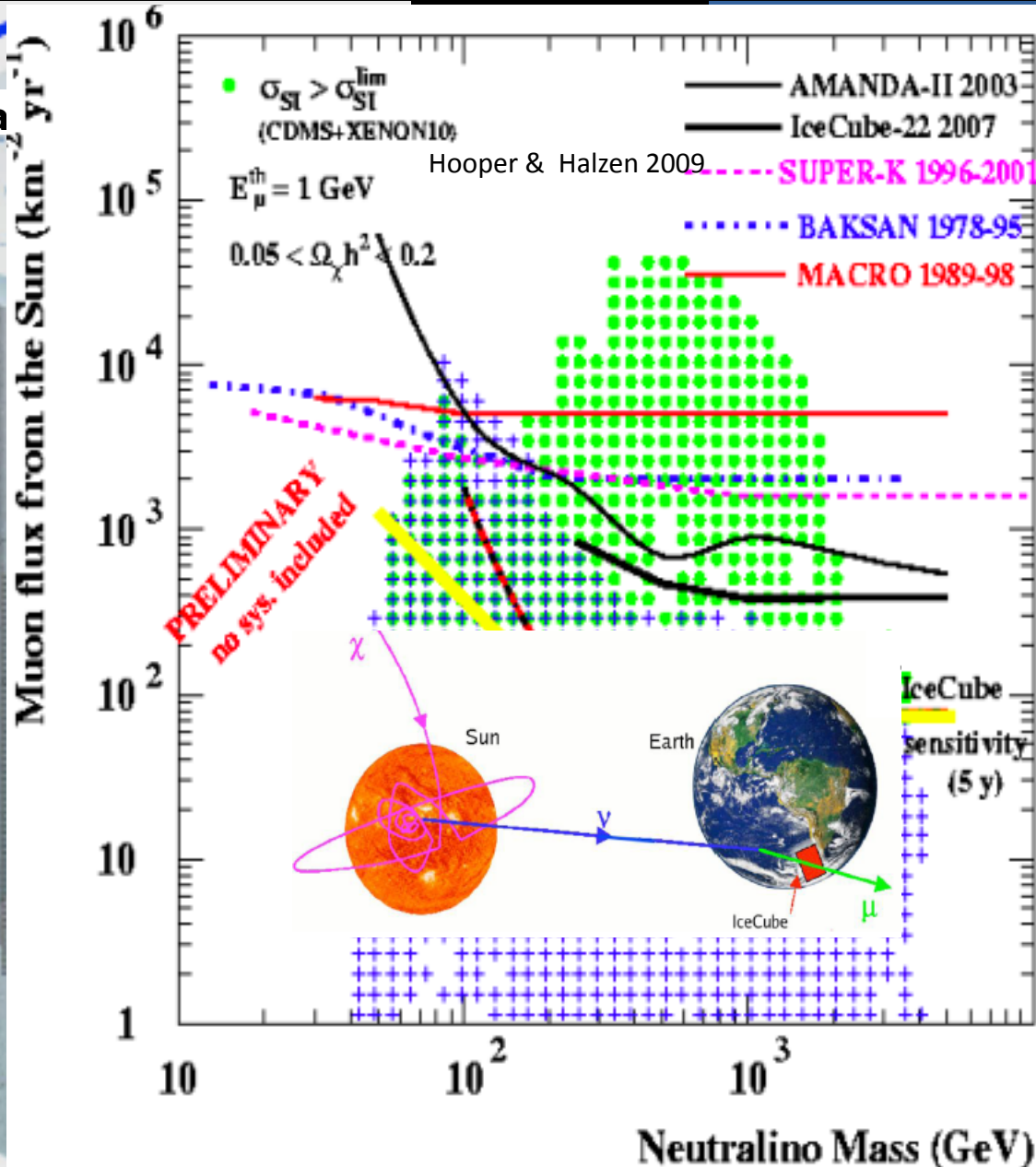
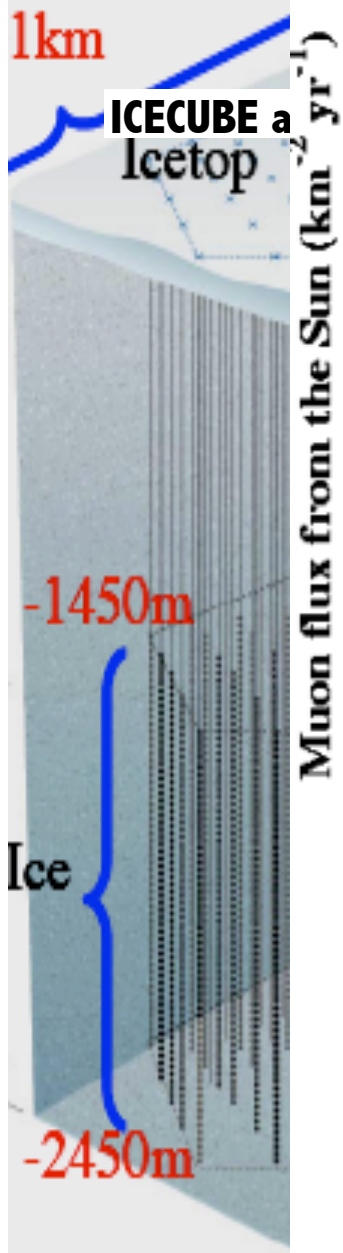
Dark matter profiles

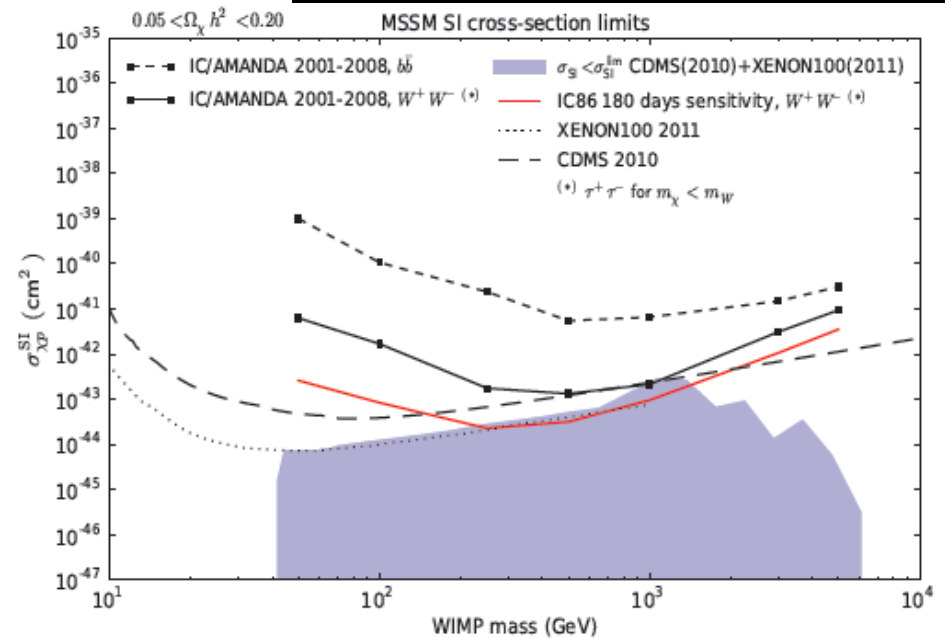
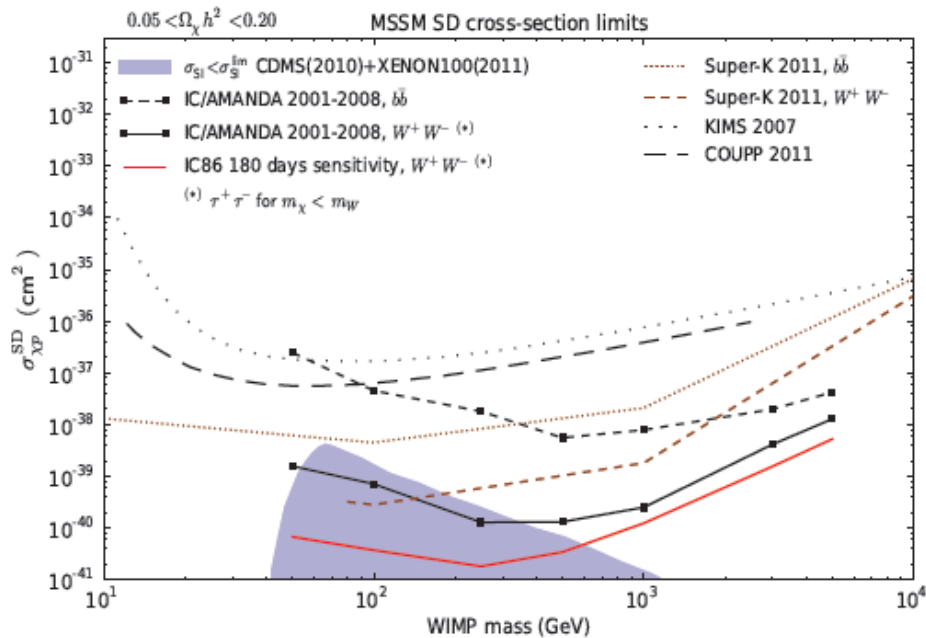
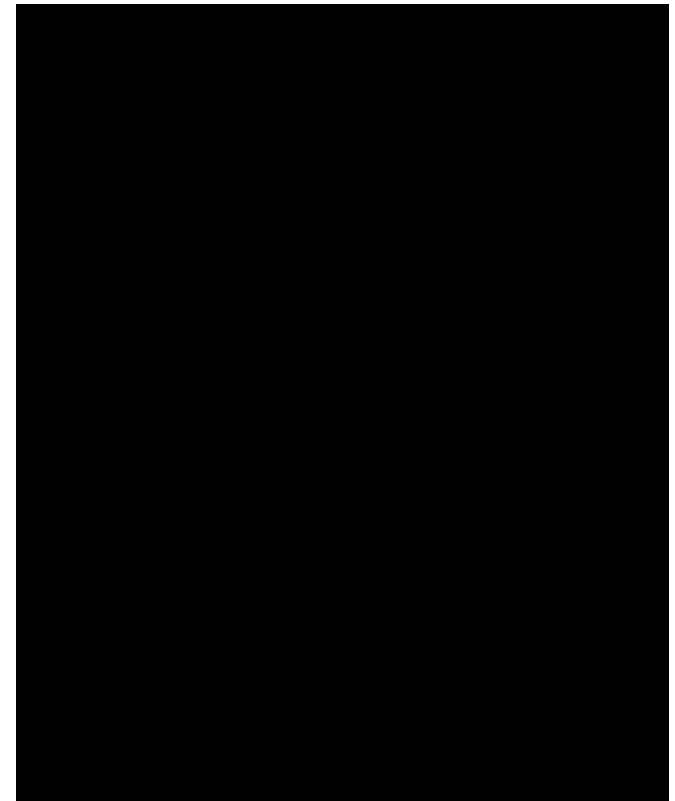
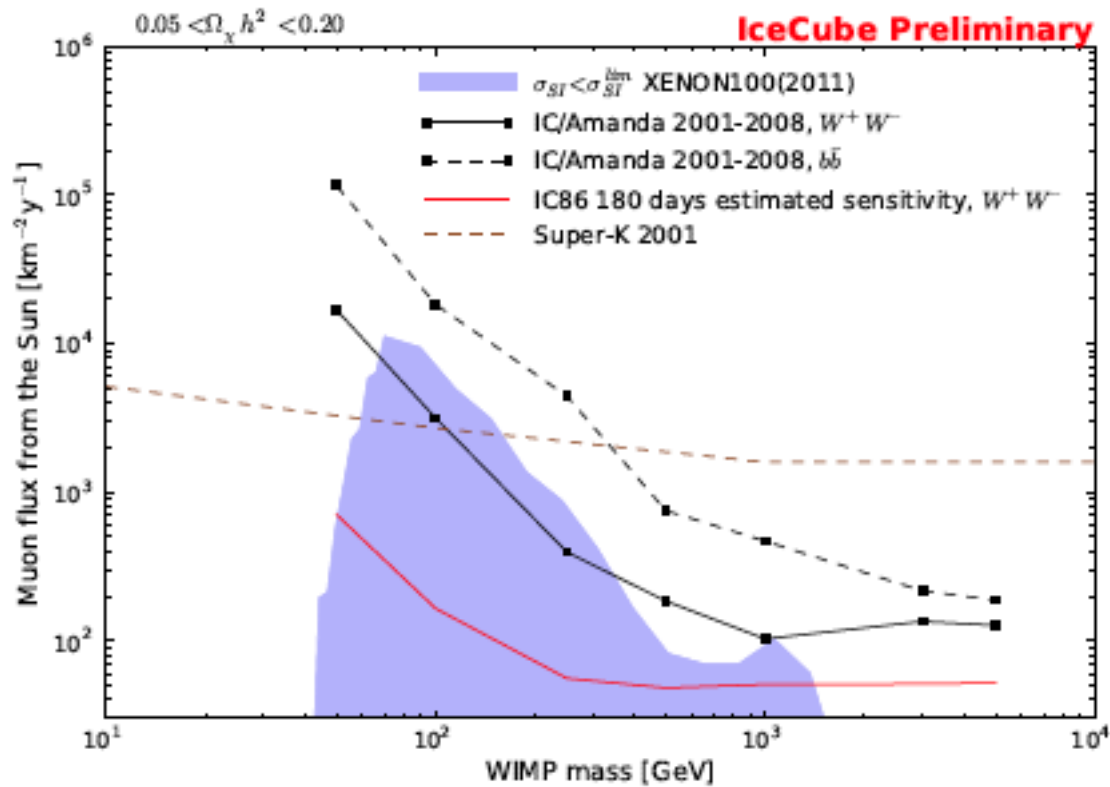


is at TeV scales

backgrounds

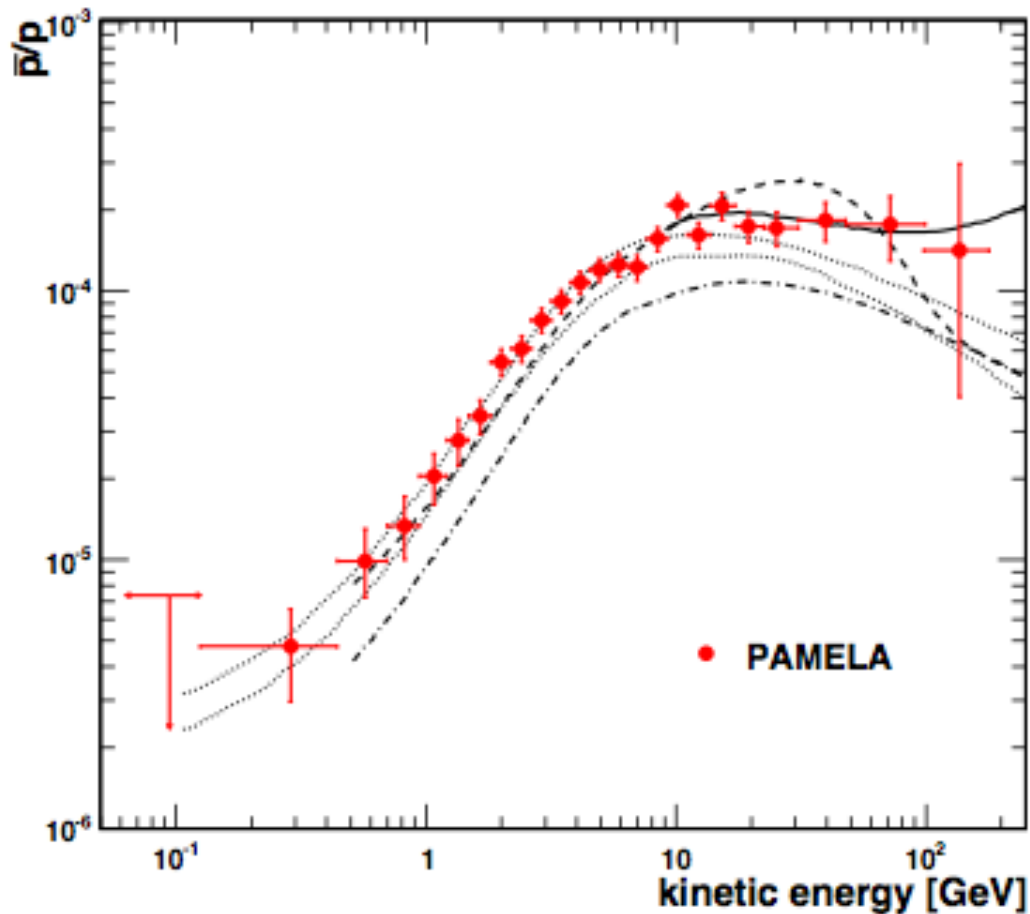
ENERGETIC NEUTRINOS FROM WIMPs TRAPPED IN THE SUN





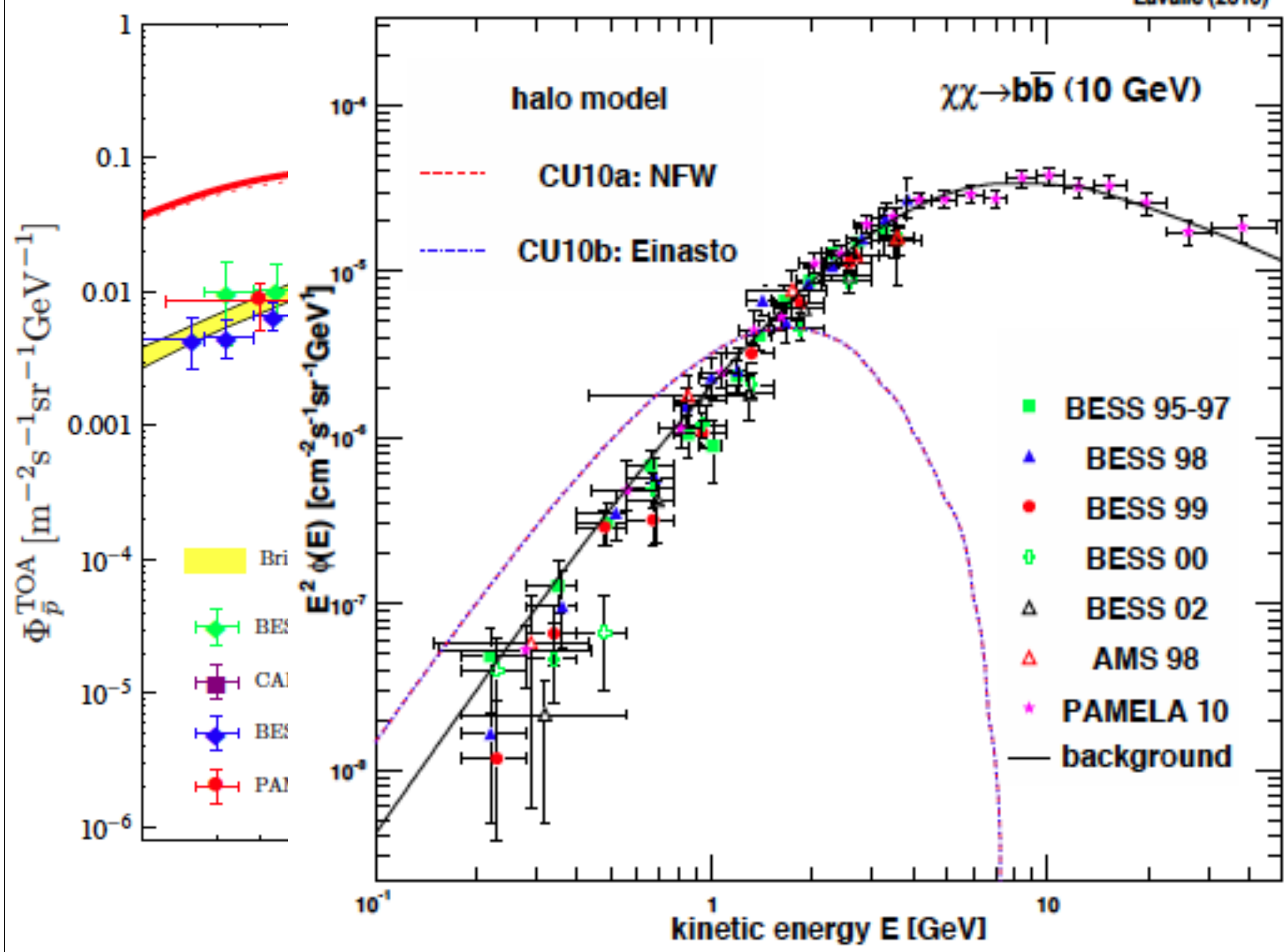
COSMIC RAYS

search for antiprotons



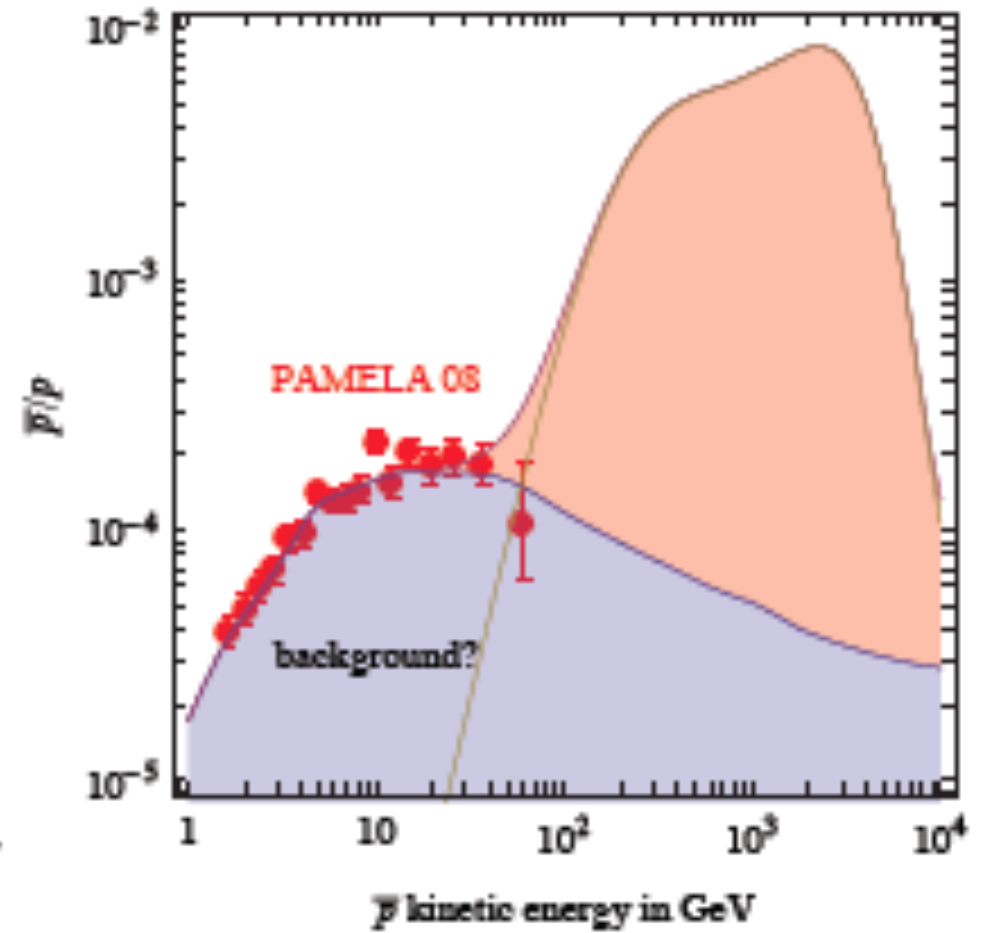
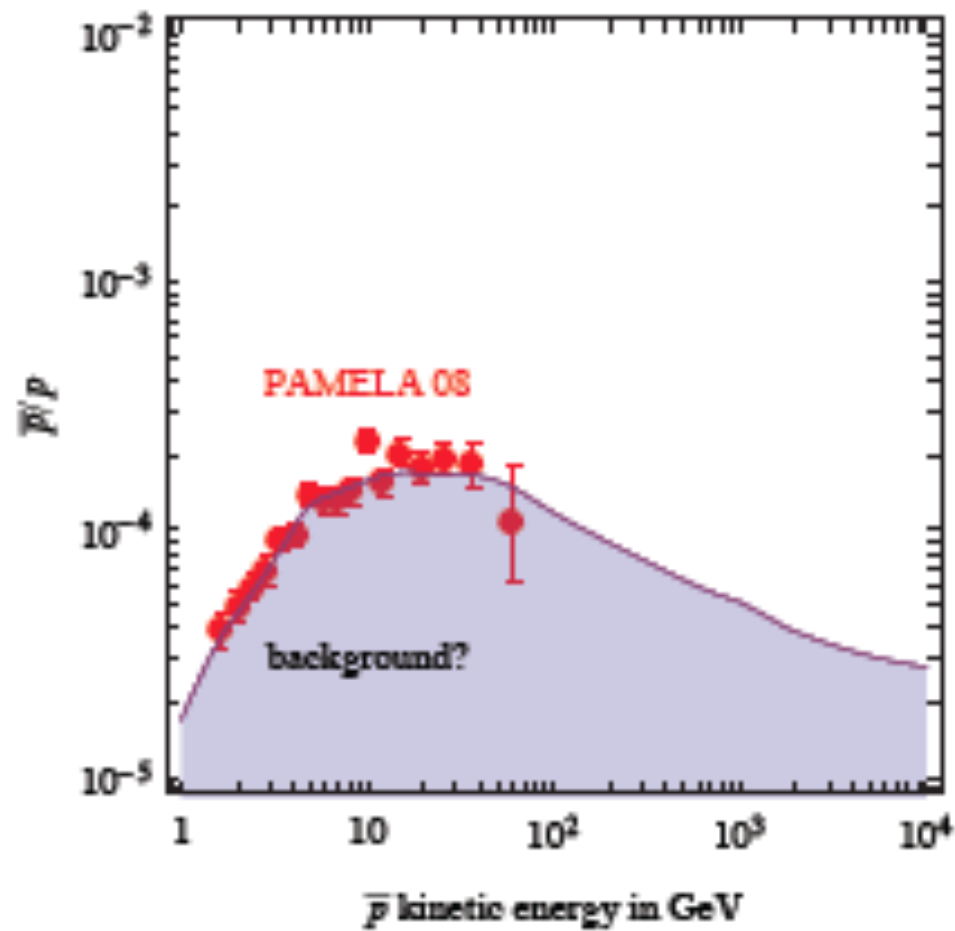
No surprises so far!

...waiting for AMS-02

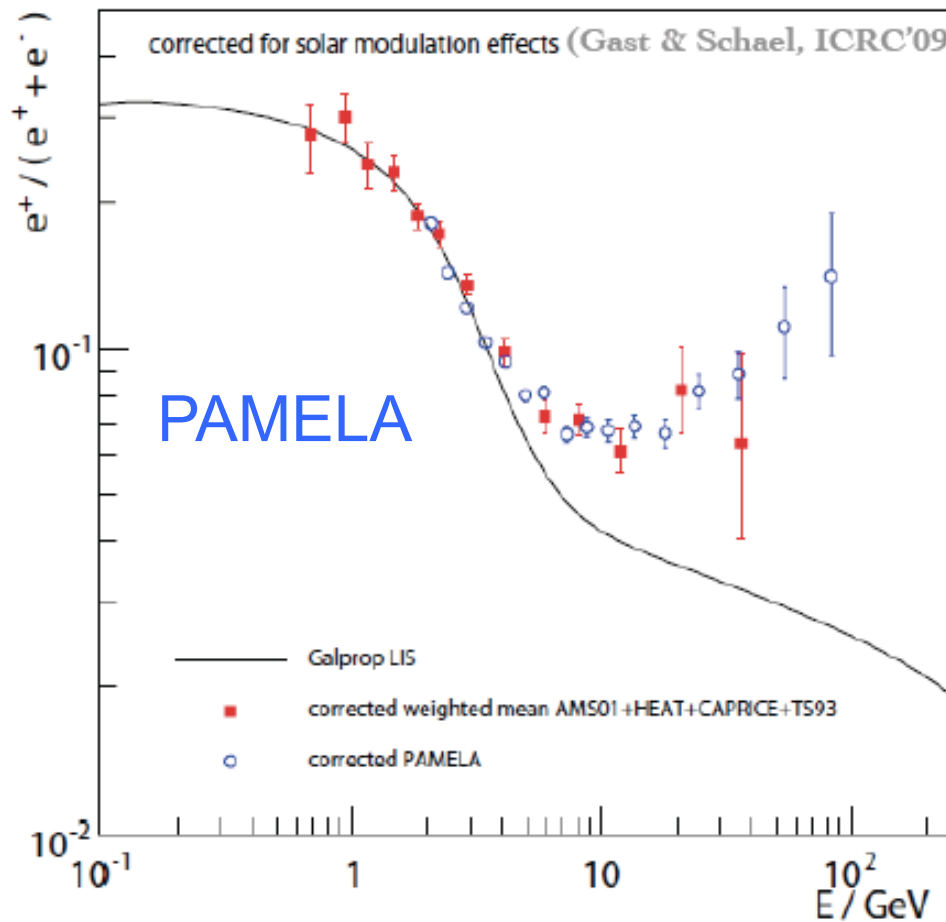


DM with $M = 1$ TeV that annihilates into $\mu^+\mu^-$

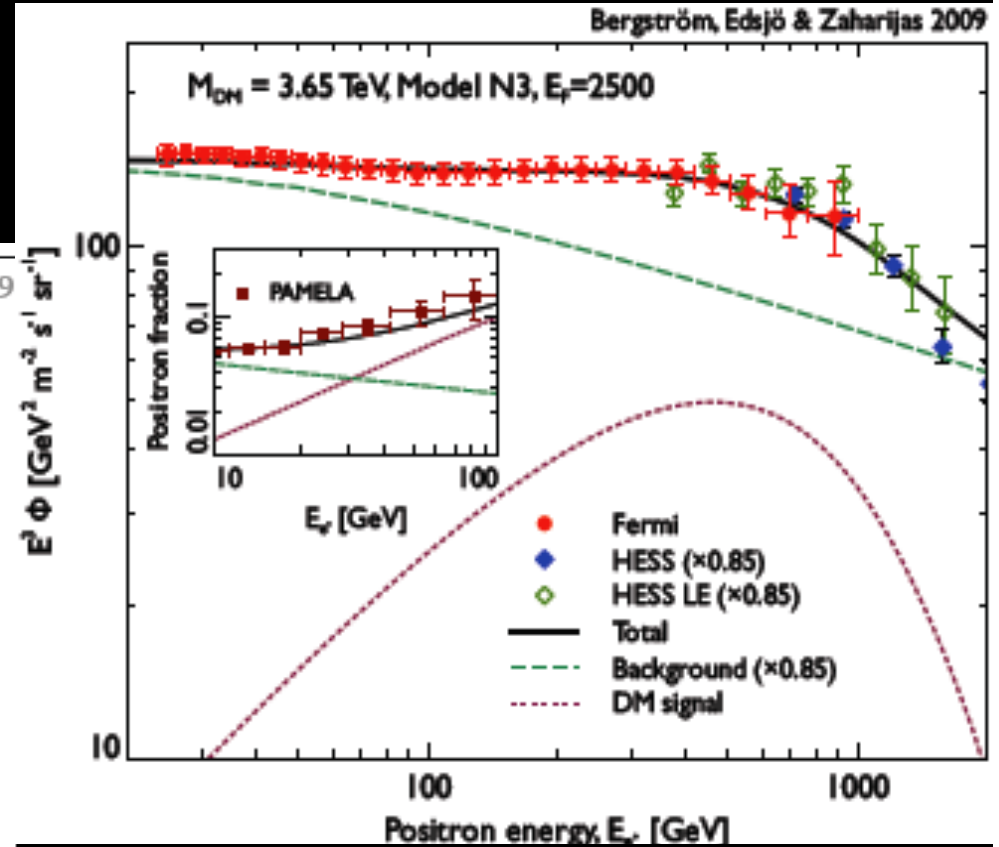
DM with $M = 10$ TeV that annihilates into W^+W^-



High energy positrons



Adriani *et al*, Nature 458:607,2009



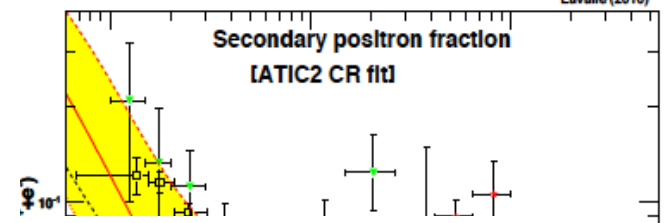
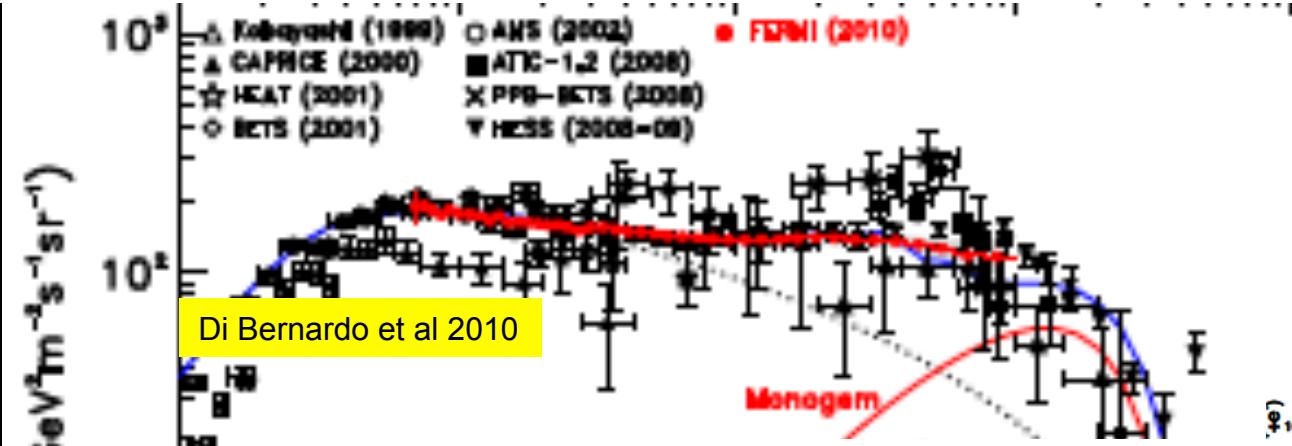
Need boost ~ 100 flux $\sim \rho^2/m_x^2$

Sommerfeld effect: $S=S_0[1+(v_{esc}/v)^2]$
 due to DM light mediator

Arkani-Hamed *et al* 2009, Lattanzi and JS 2009, March-Russell and West 2009

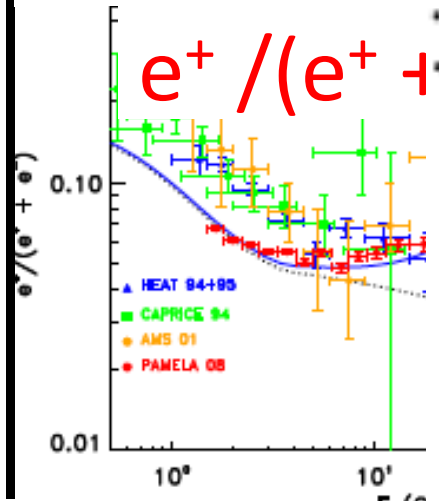
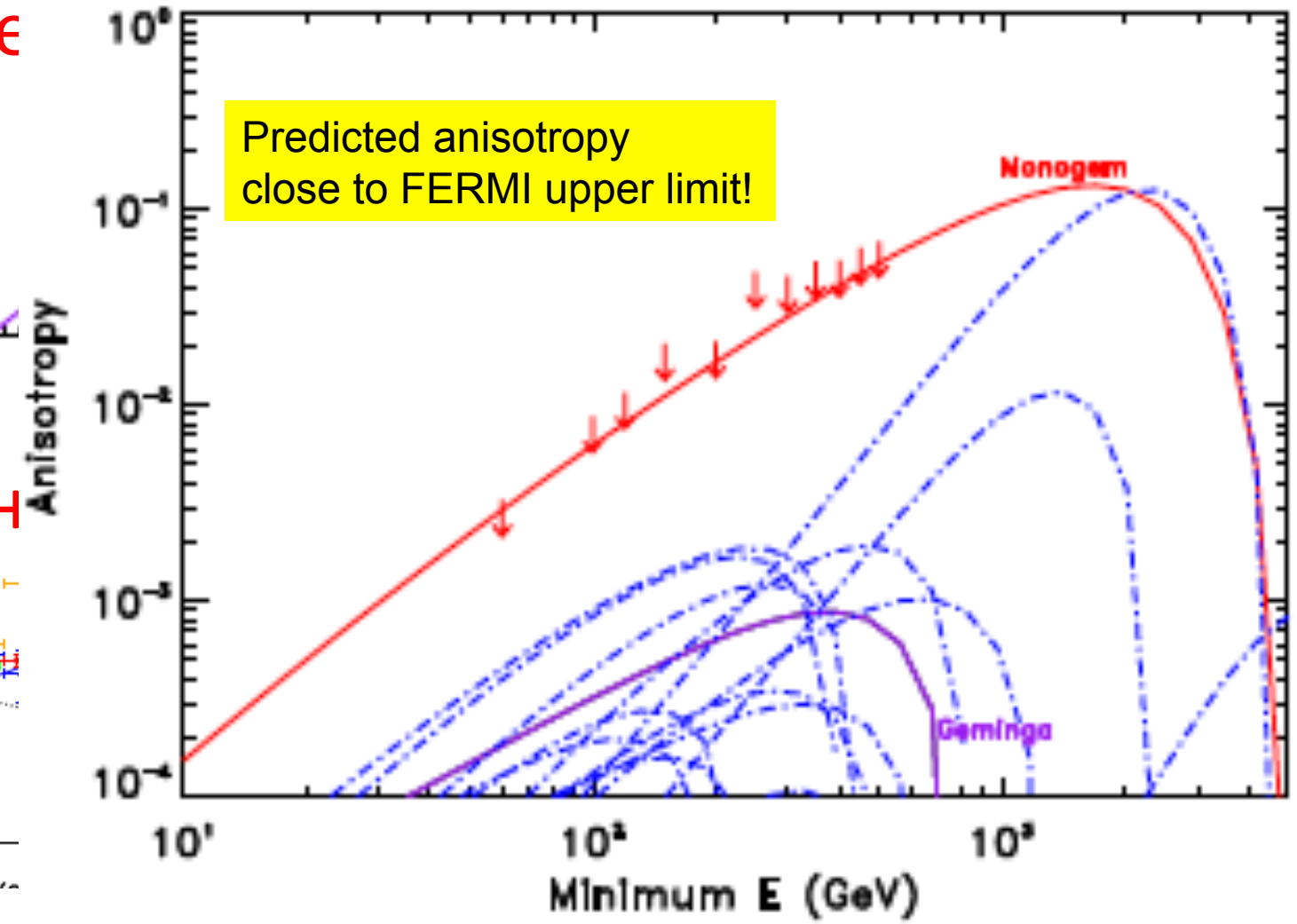
astrophysical origin?

PULSAR WIND



ϵ

Predicted anisotropy close to FERMI upper limit!



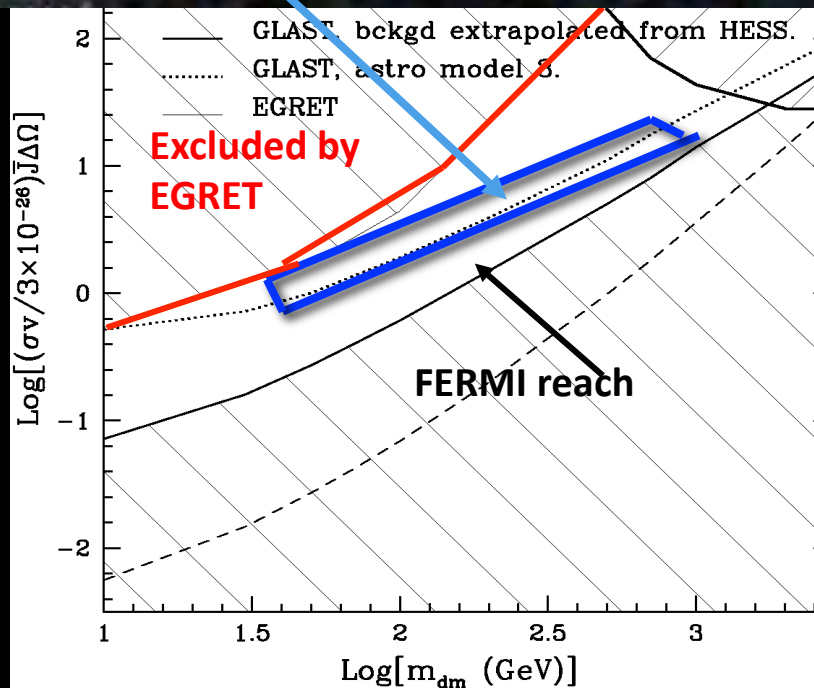
Radio synchrotron emission

The WMAP microwave haze

Finkbeiner 2007

Hooper and Zaharias 2007

predicted γ flux

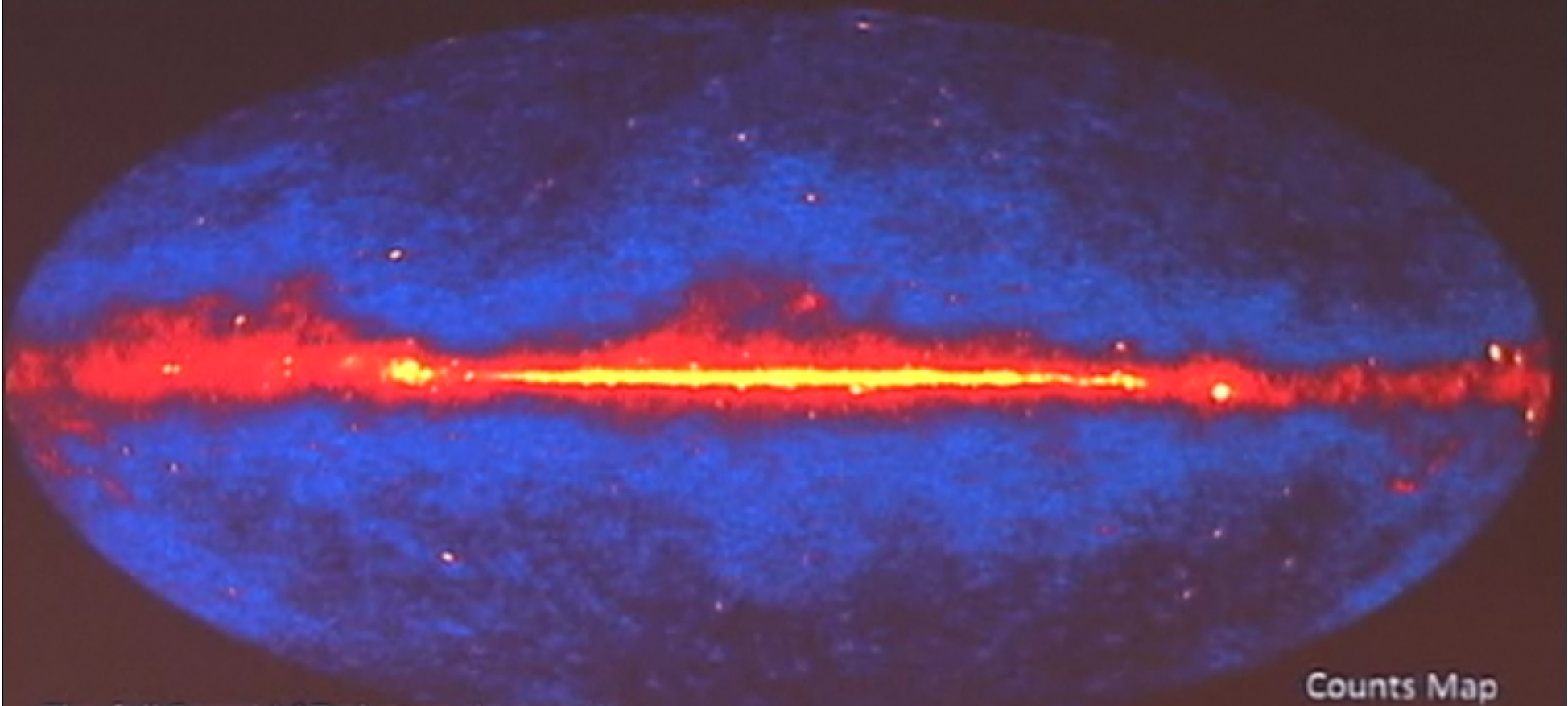


Diffuse gamma rays

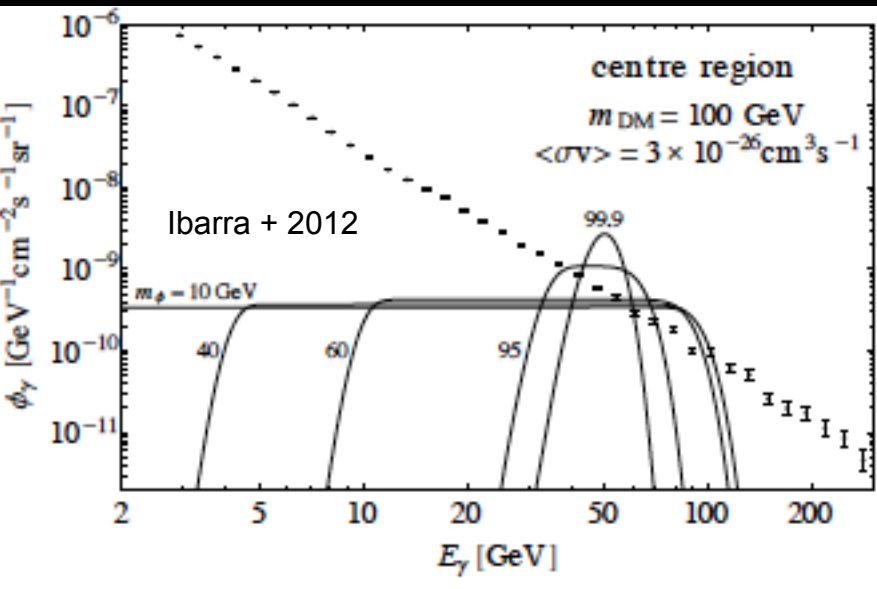
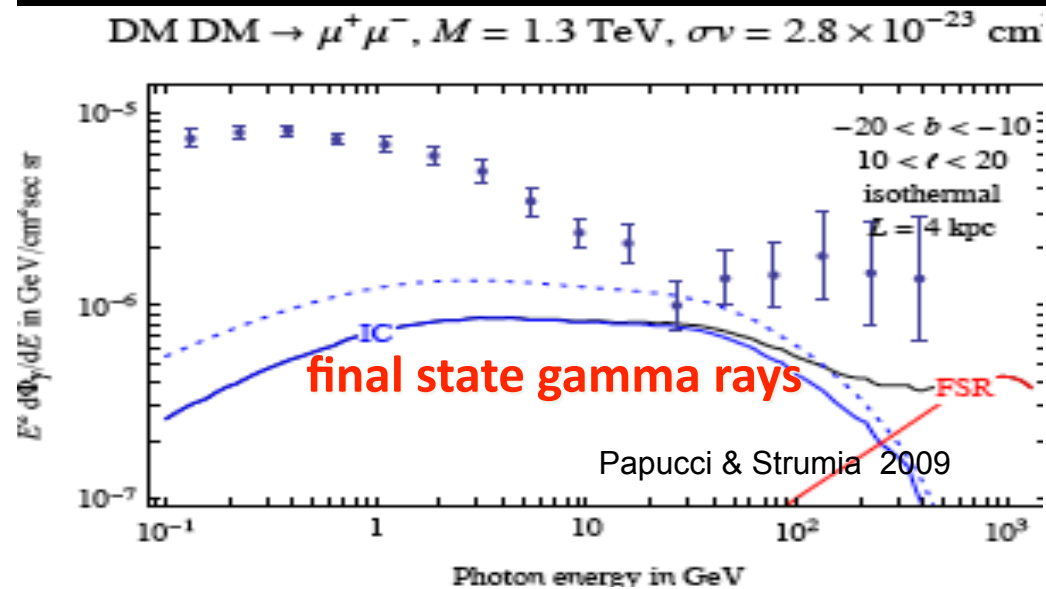
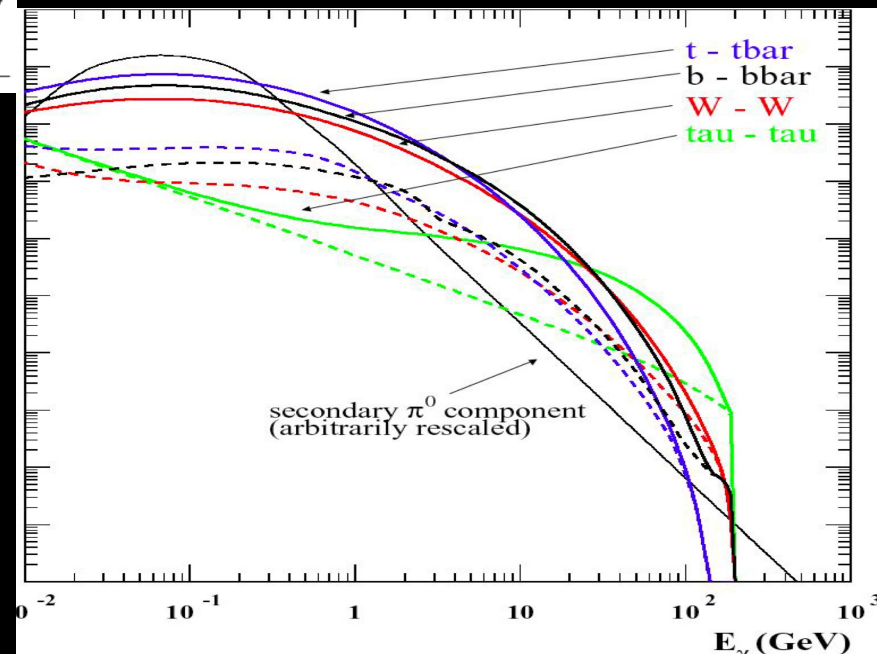
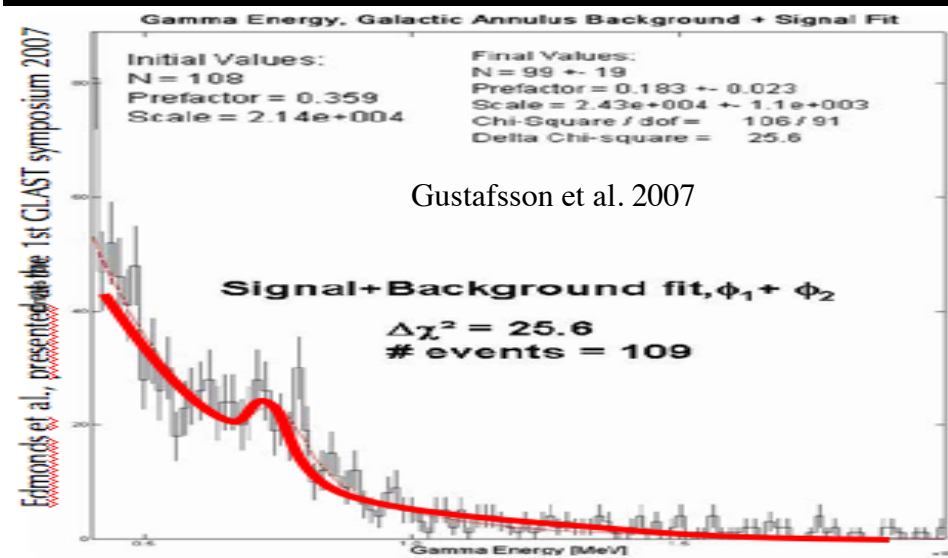
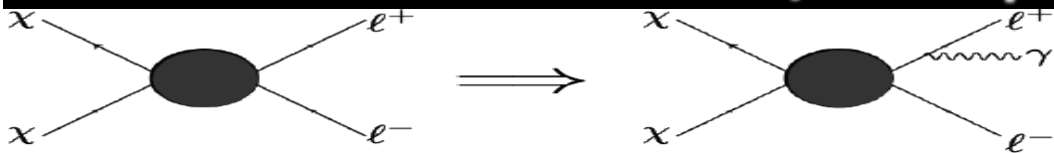
“smoking guns”: e.g. spectral features ...morphology of haze

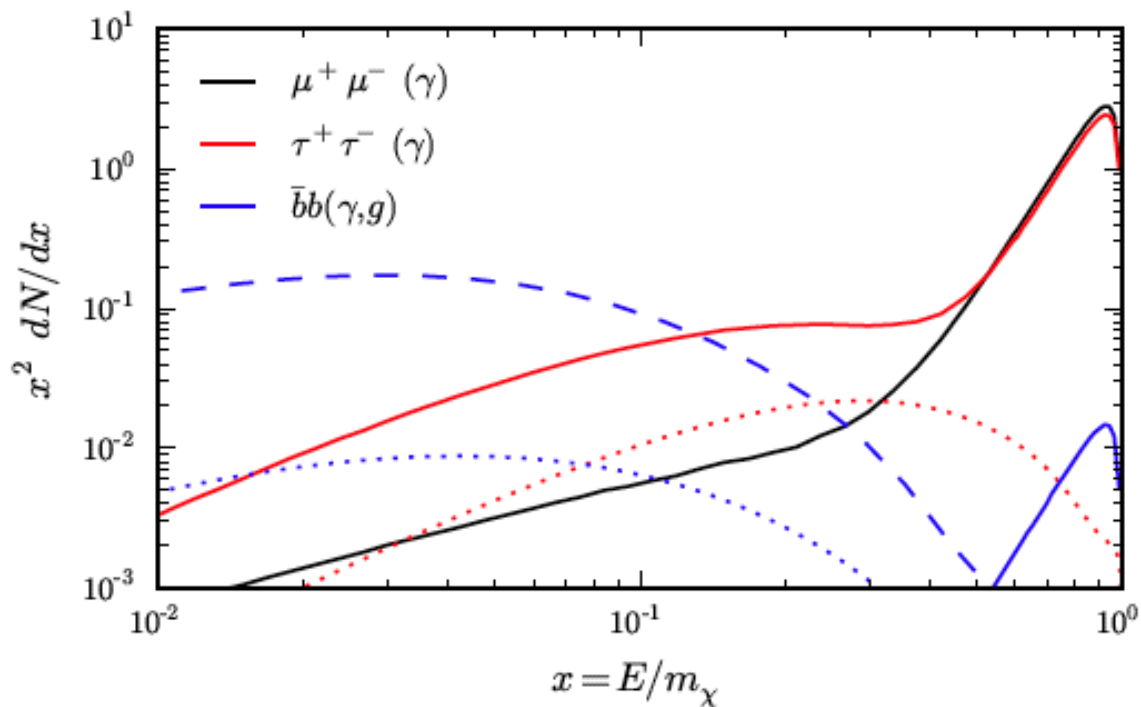
FERMI: 0.02 - 300 GeV, $5^\circ - 5'$, $\Delta E/E \sim 0.1$

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

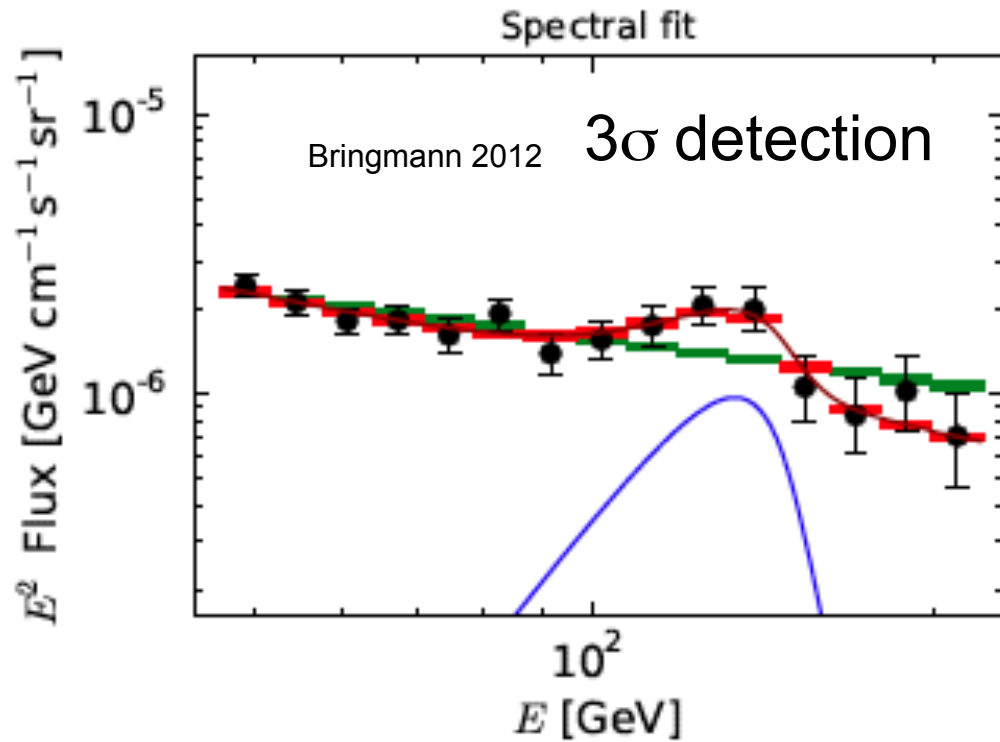
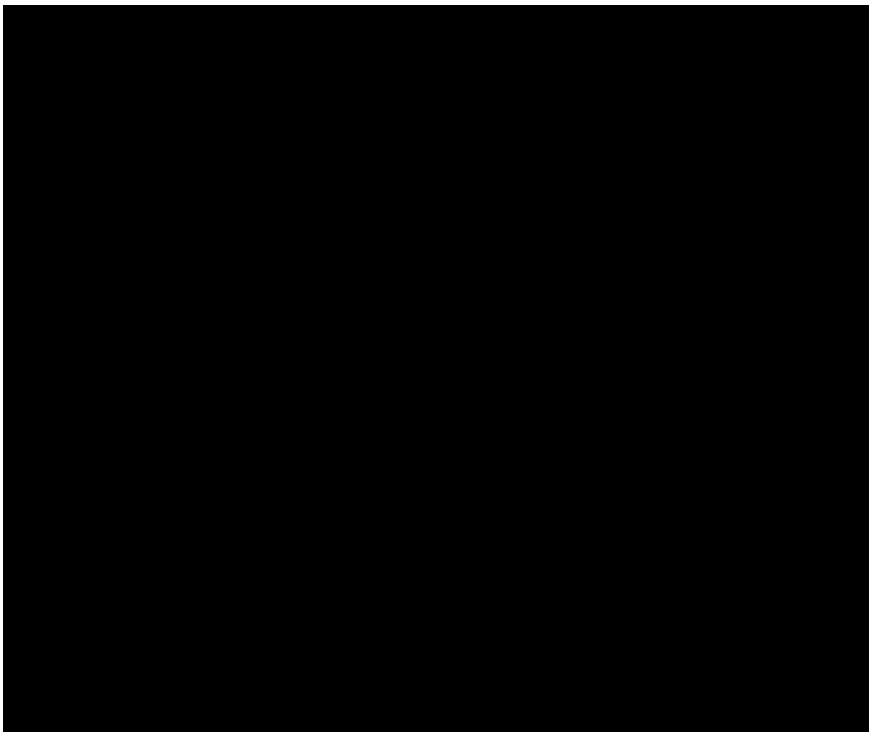


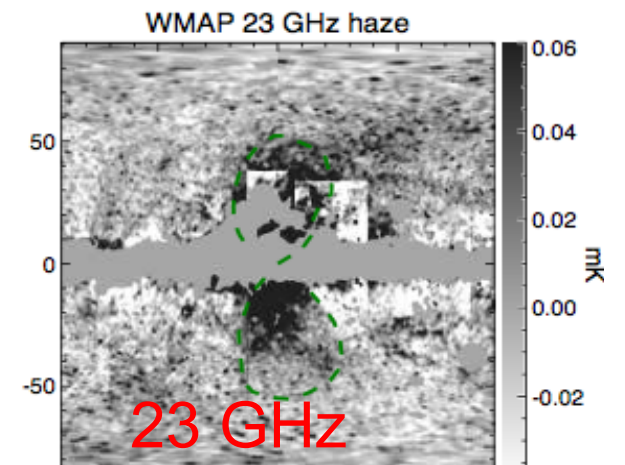
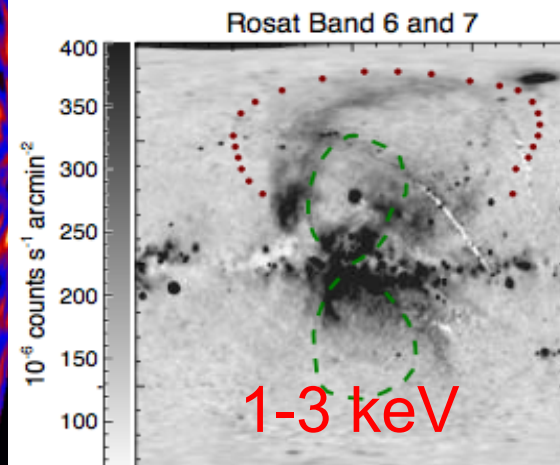
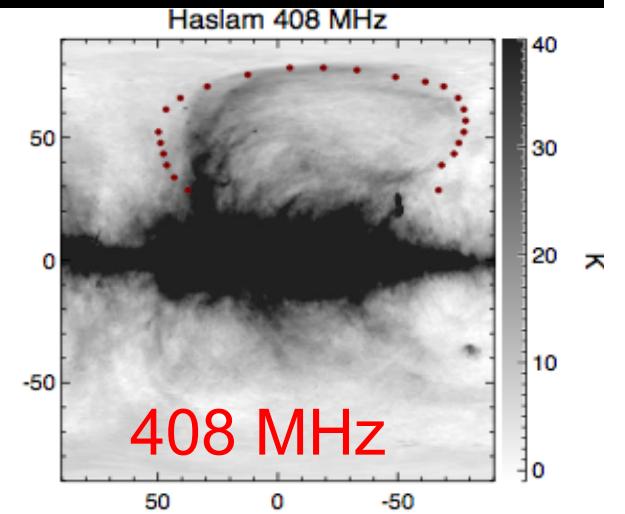
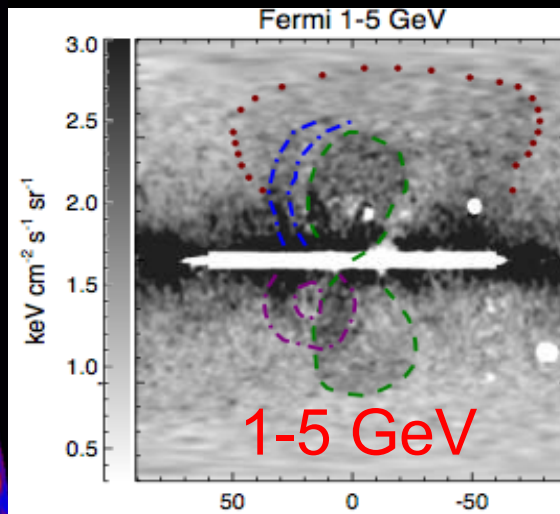
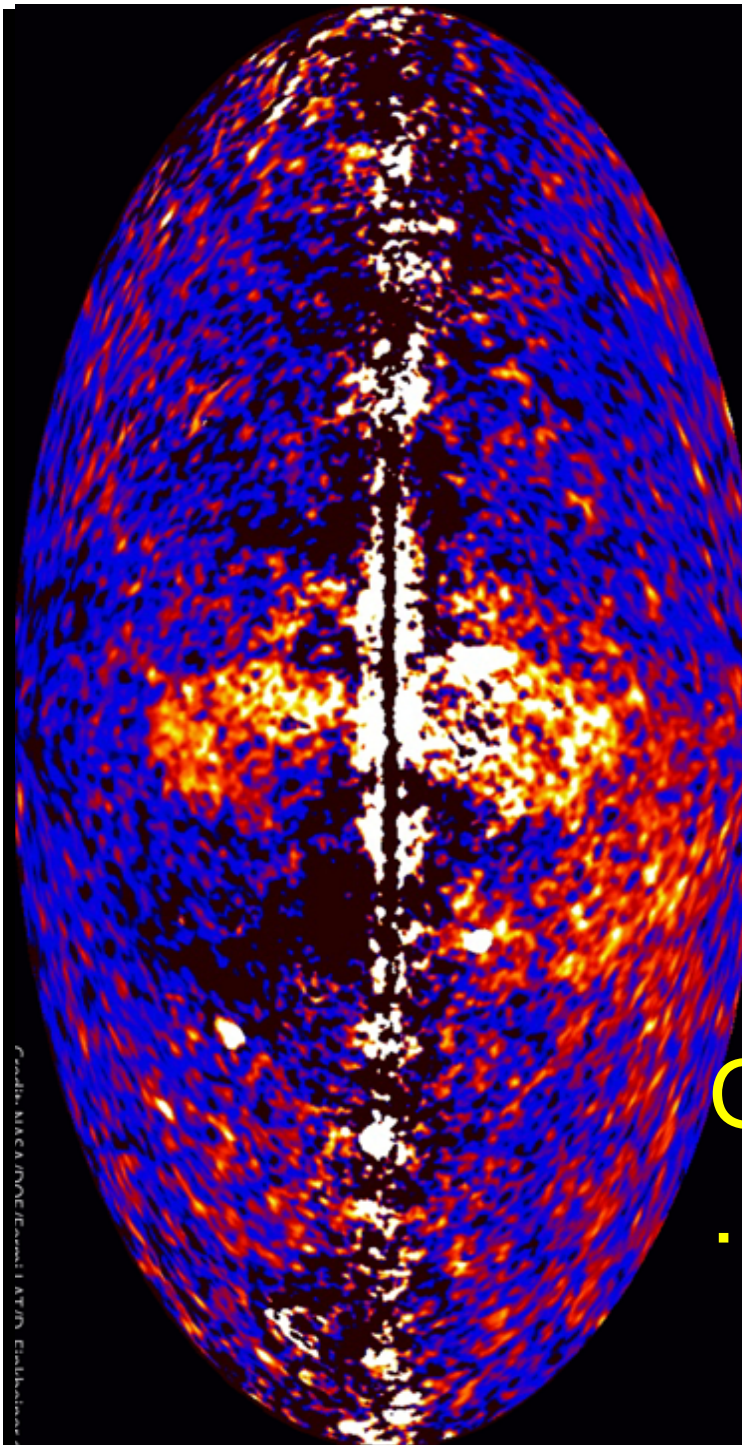
FERMI/HESS prediction:





130 GeV line?





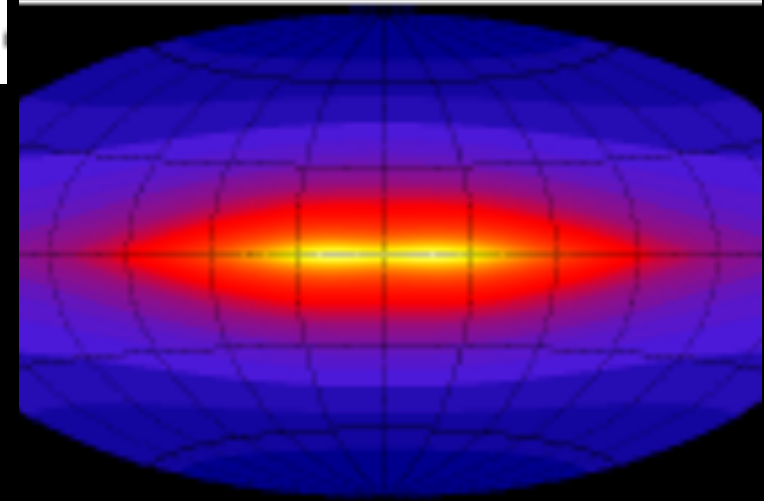
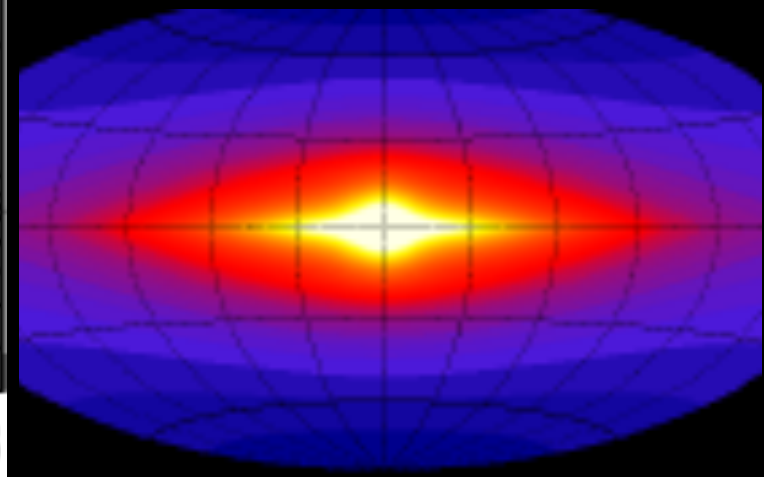
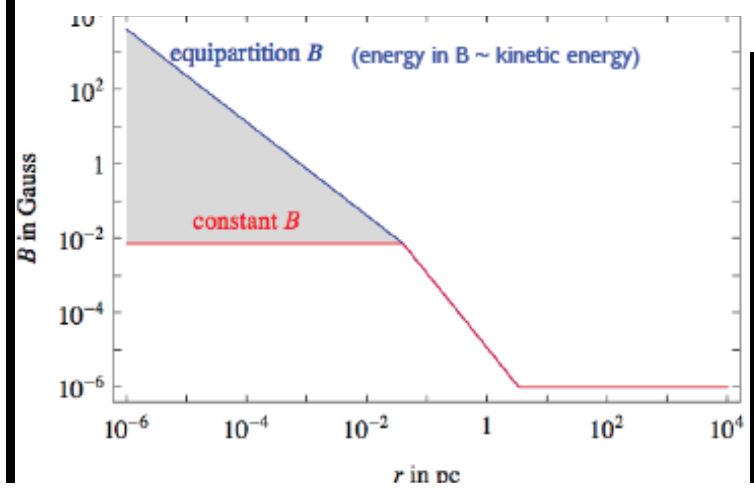
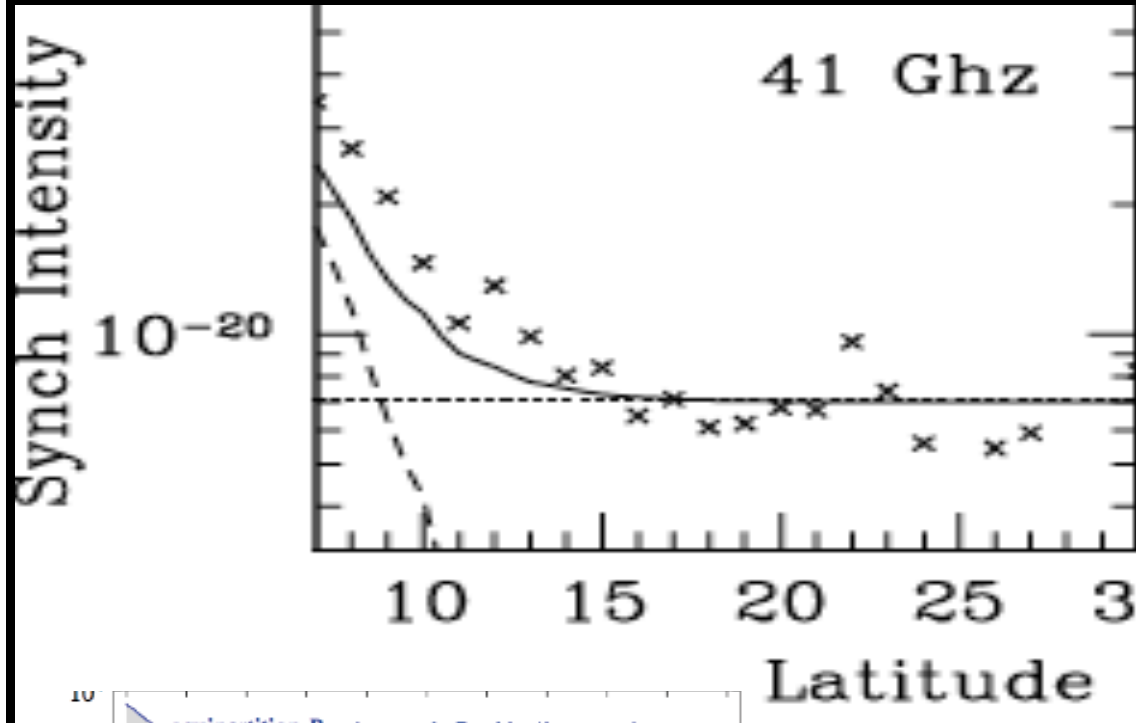
Giant gamma ray bubbles ...not dark matter

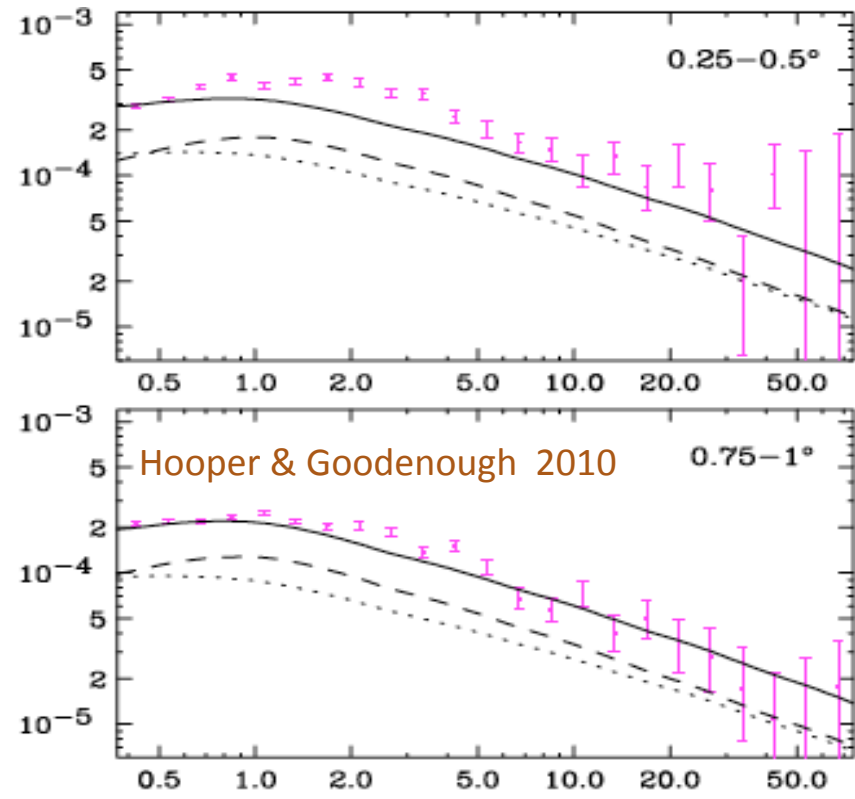
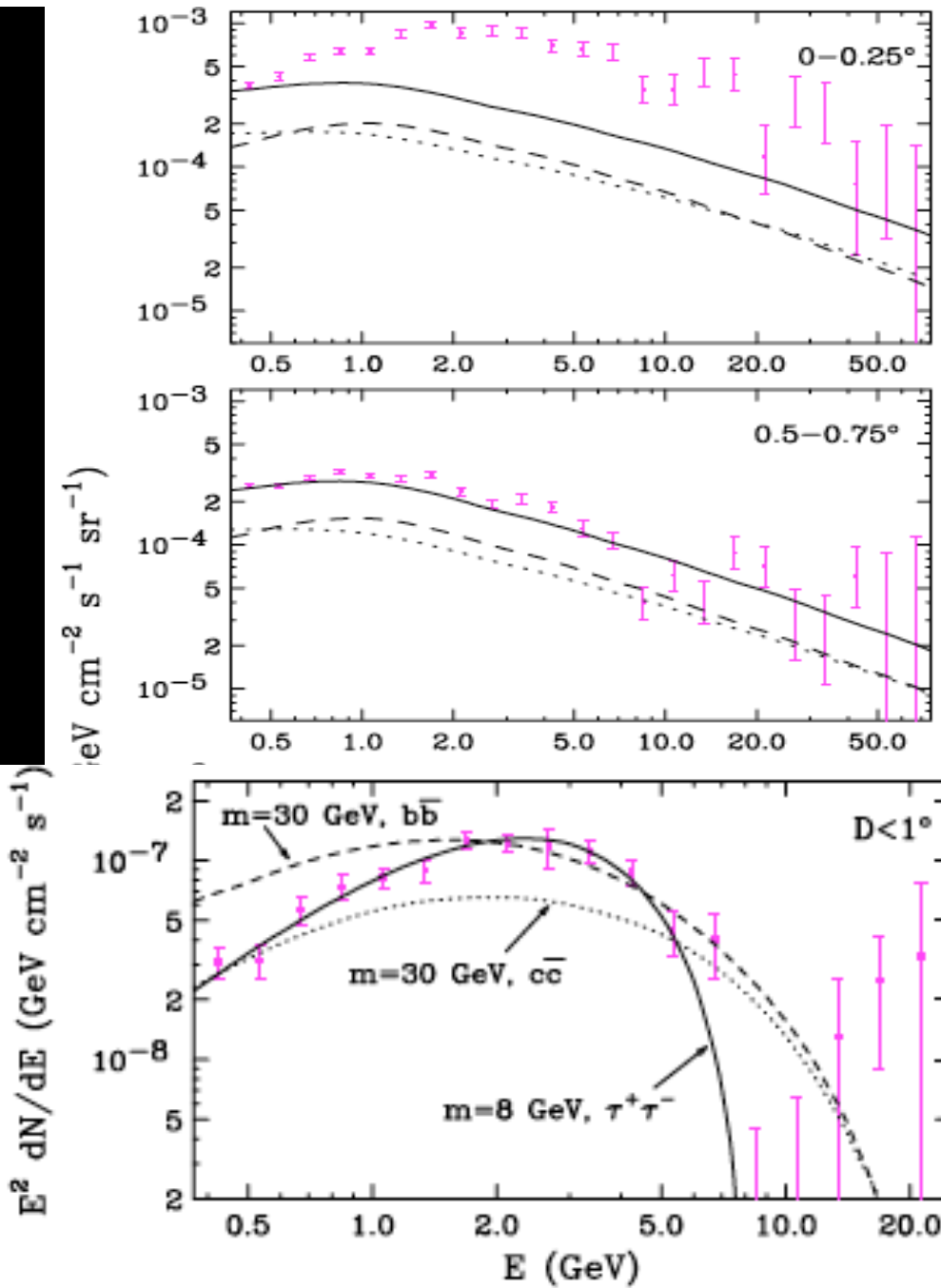
Fermi haze is inverse Compton of e^+e^- on interstellar radiation

WMAP haze revived for 8 GeV WIMP annihilations

Hooper & Linden 2010

Predictions for PLANCK: CMB temperature fluctuations





angle from GC

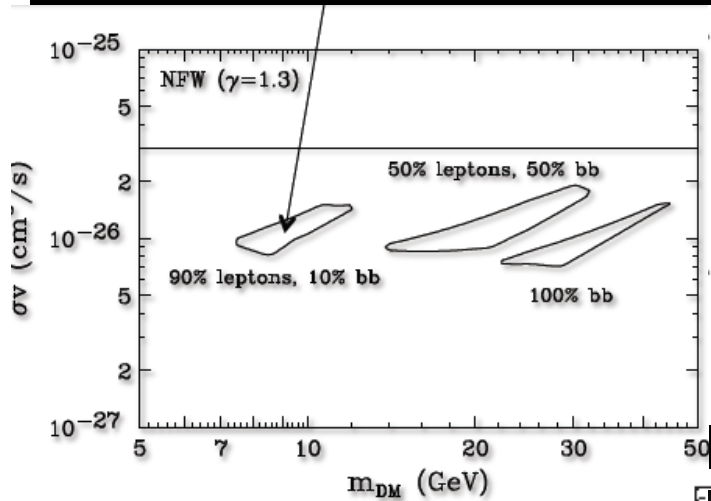
Fermi haze revived

spectral data require a second diffuse component: DM?

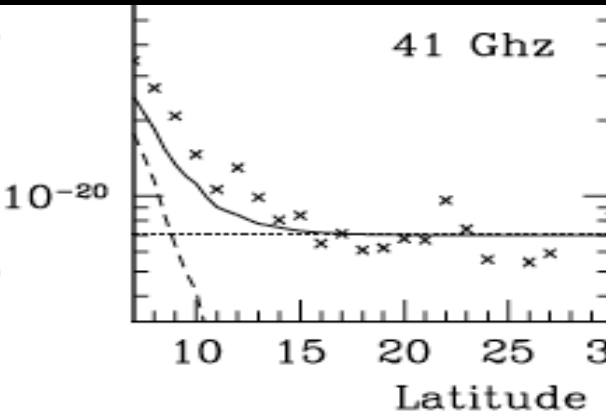
spectral fit: 8 GeV WIMP

The case for low mass WIMPS: 7-12 GeV

Fermi diffuse GC: 0.3-10 GeV

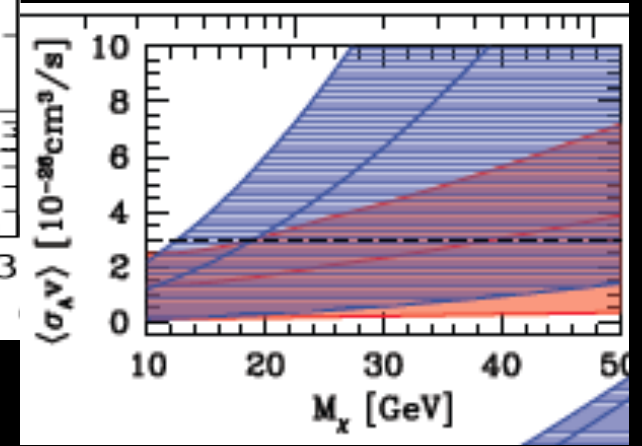


WMAP haze

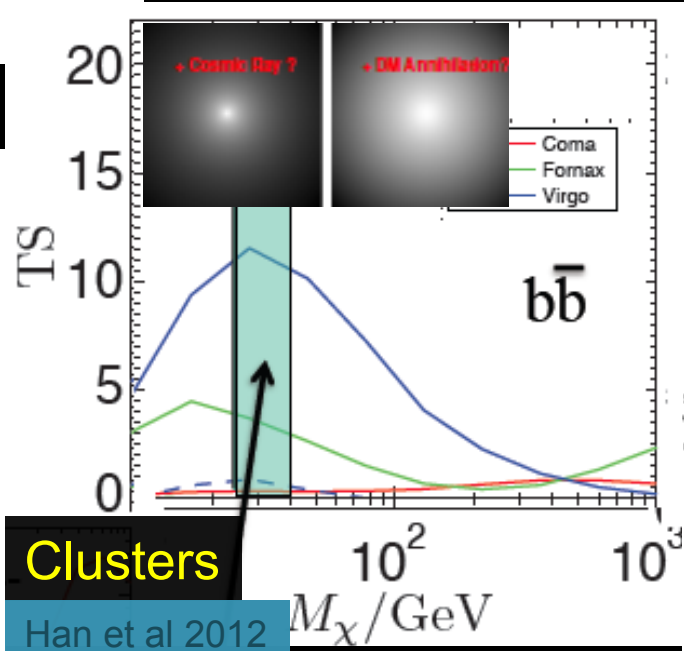
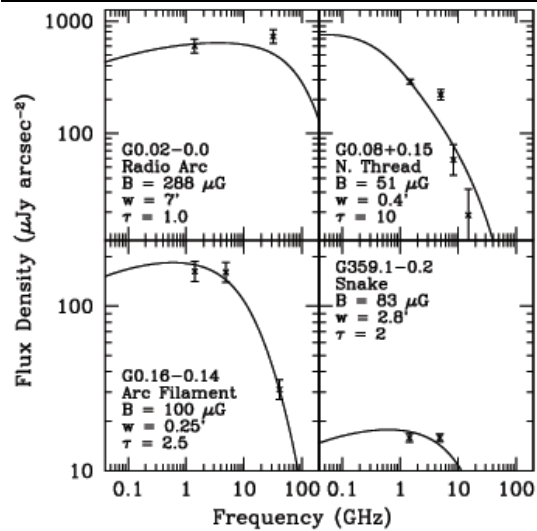


Fermi dwarf limits

Geringer-Sameth & Koushiapas 2011



Radio arcs in GC

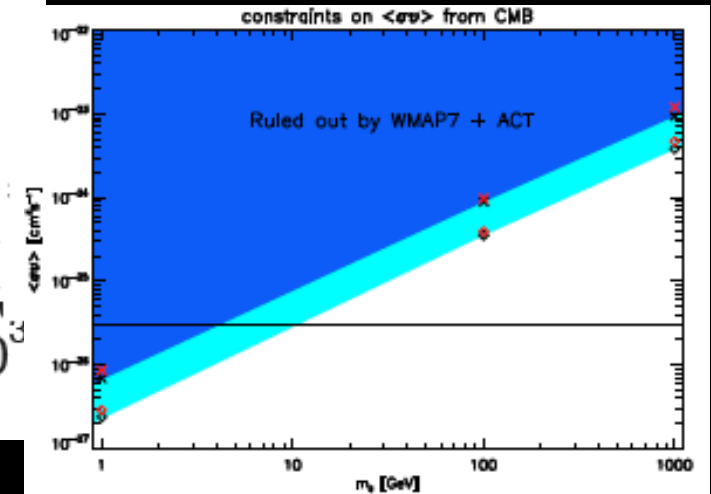


Clusters

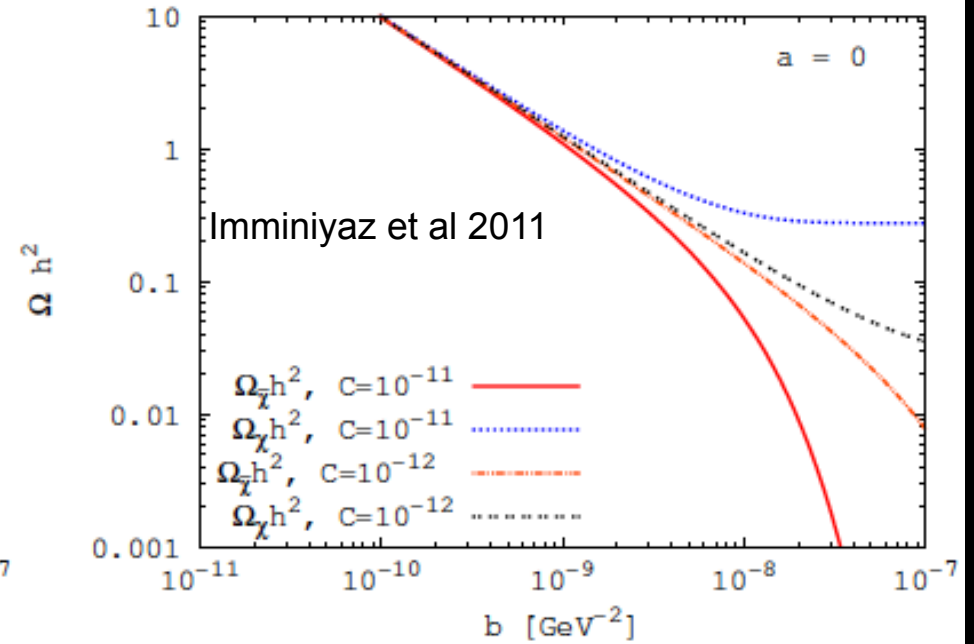
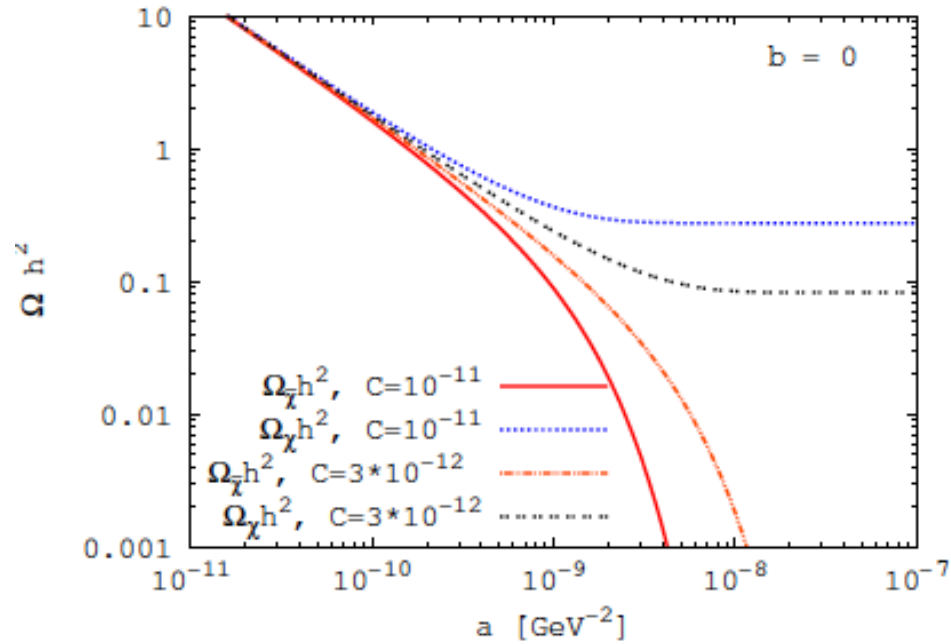
Han et al 2012

CMB limits

Galli et al 2011

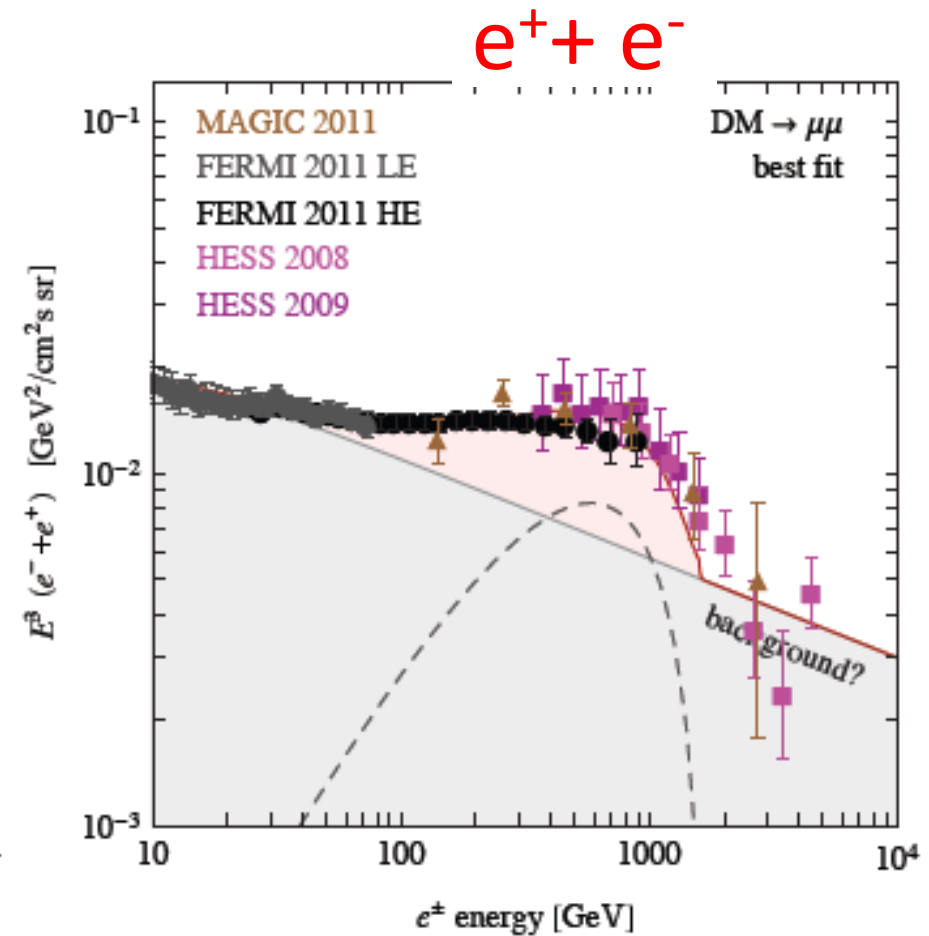
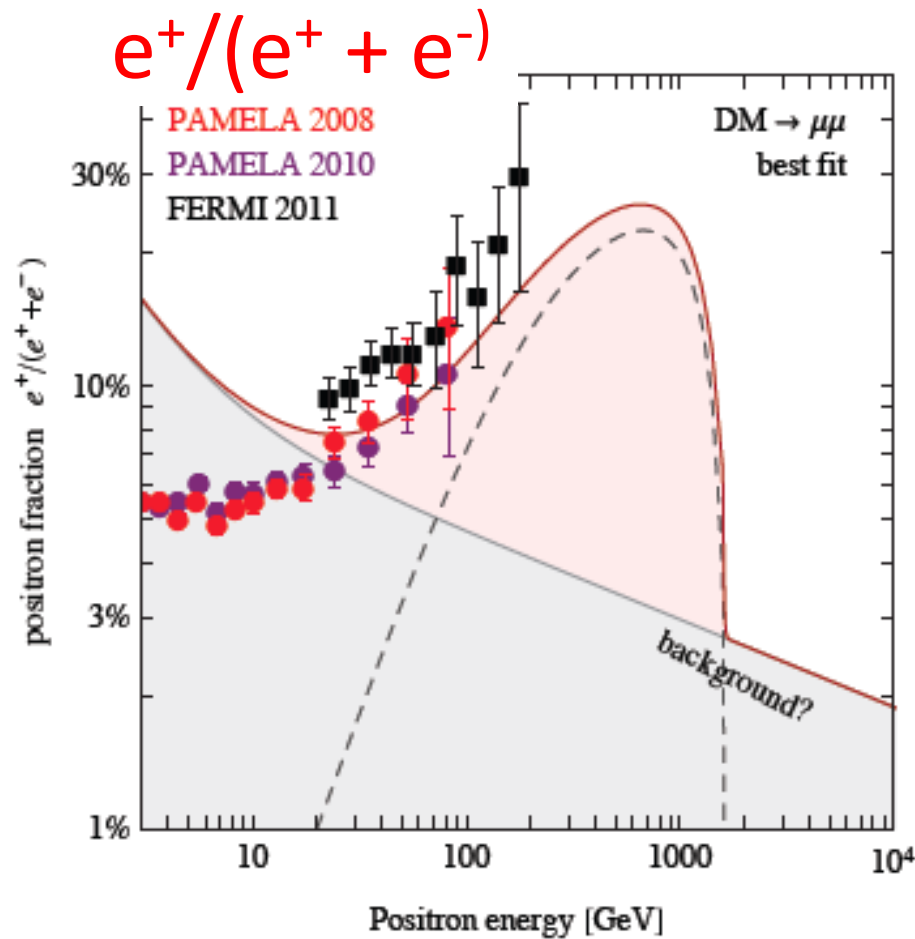


But there is room eg if DM is (partly) asymmetric....



DECAYING DARK MATTER

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

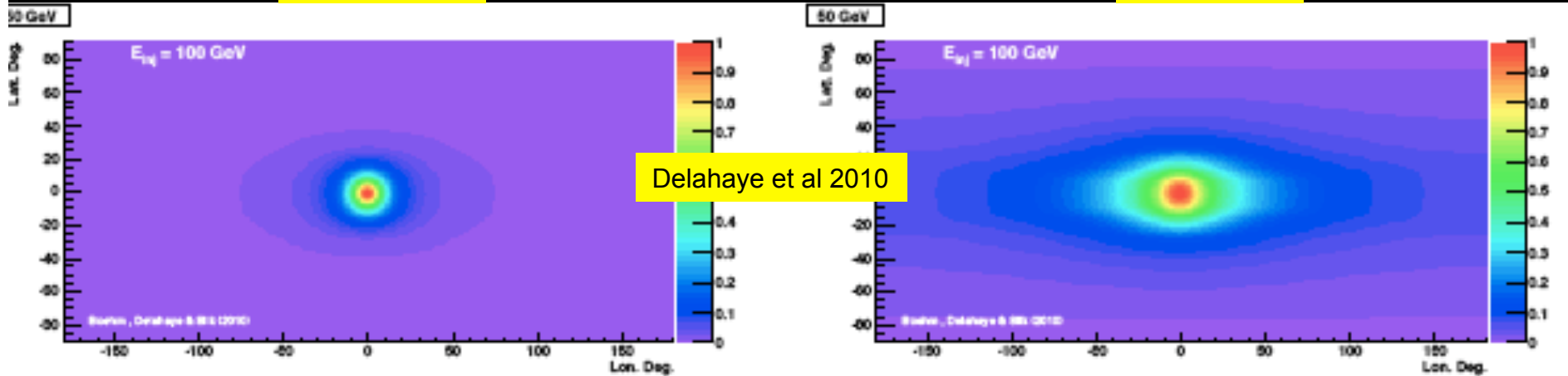


Energy (GeV)

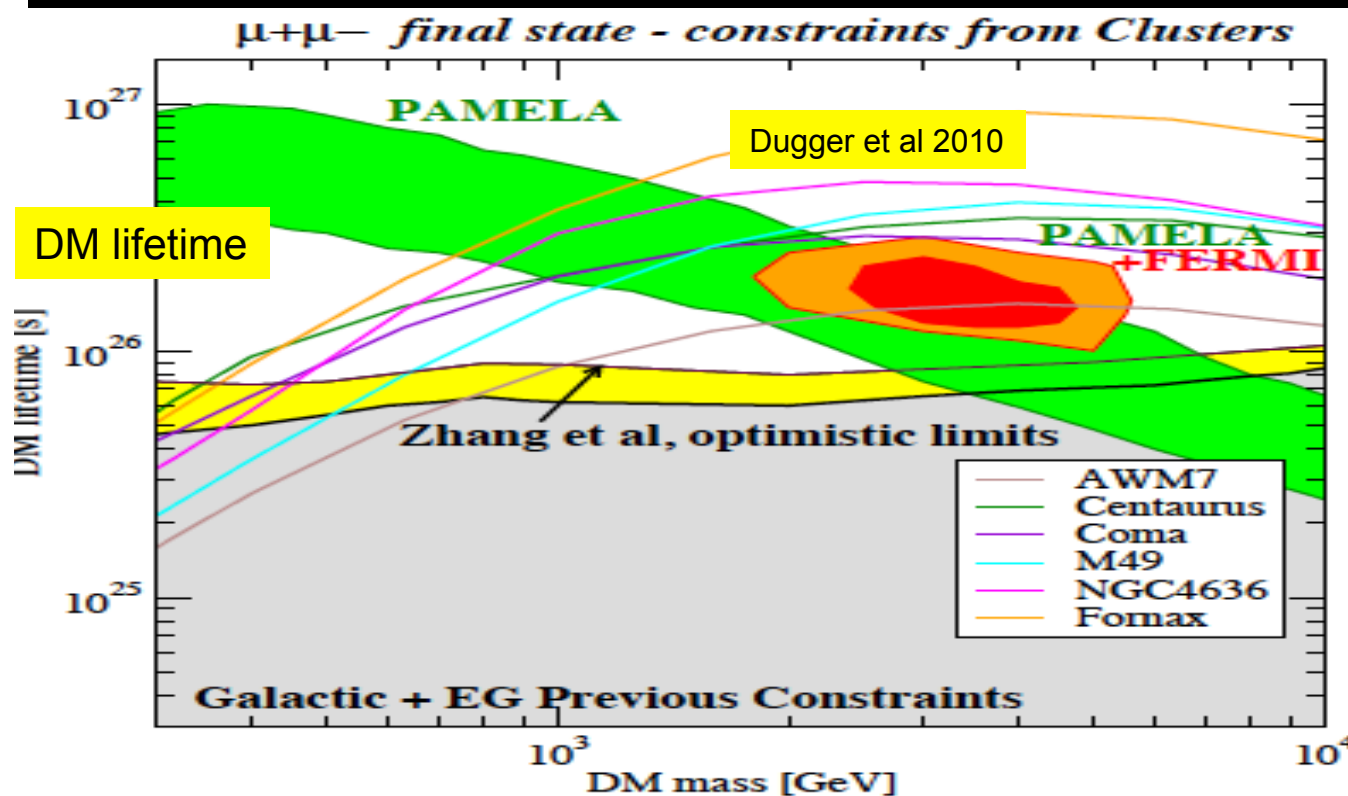
Cirelli + 2012

DENSITY²

DENSITY



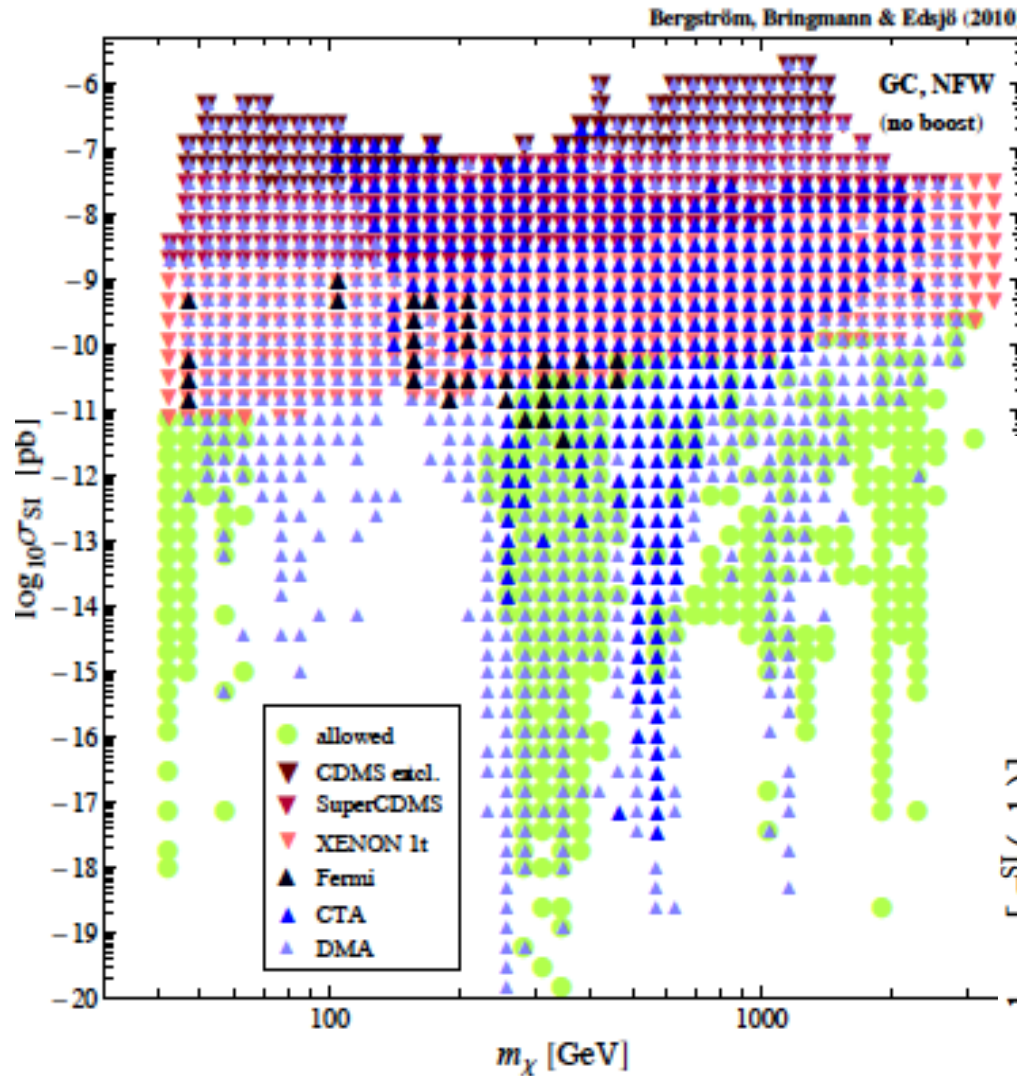
DECAYING DARK MATTER: GALAXY CLUSTERS ARE BEST PROBE



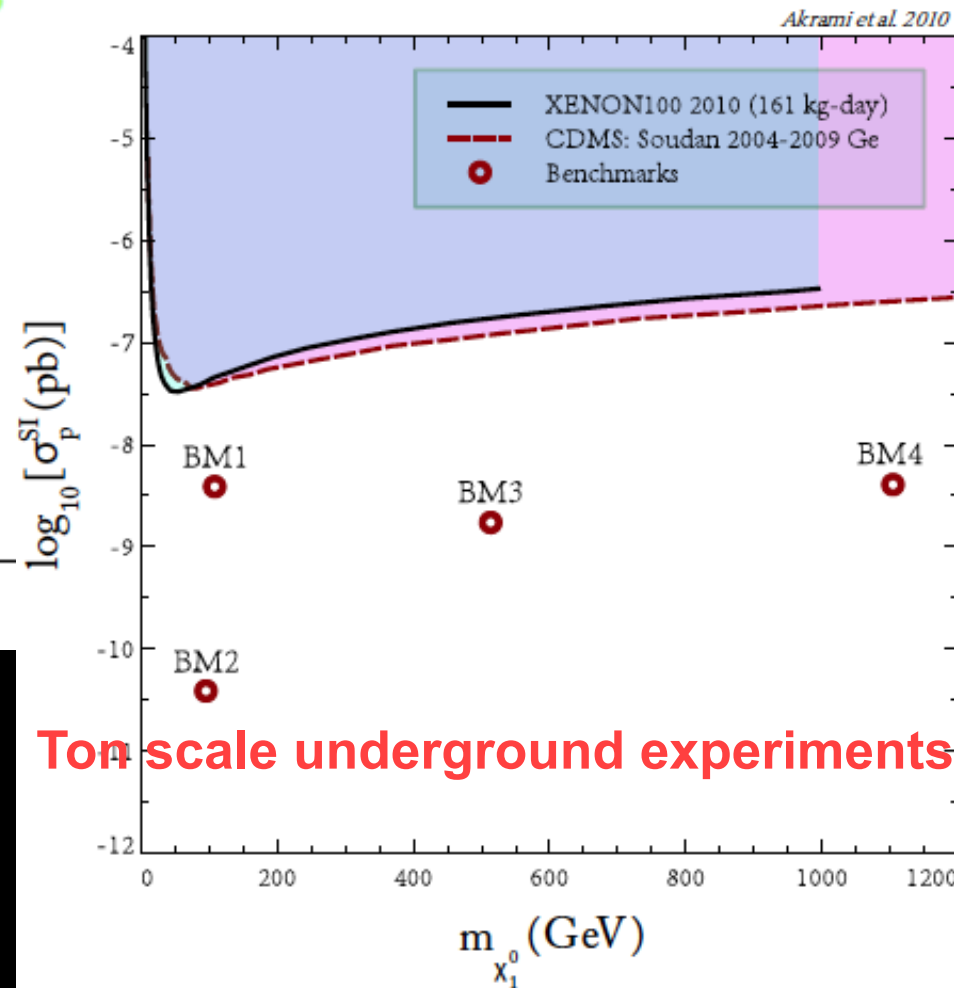
FERMI constraints

HOW LOW CAN YOU GO?

Gamma rays and direct detection



Air Cerenkov telescopes



Ton scale underground experiments

Model building

Cirelli 2009

- Minimal extensions of the SM:
heavy WIMPS (Minimal DM, Inert Doublet)

Cirelli, Strumia et al. 2005-2009

Tytgat et al. 0901.2556

- More drastic extensions:
New models with a rich Dark sector

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUKD DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - E.Ponton, L.Randall, 0811.1029: Singlet DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-G.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: Su3y B-L DM - S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - Gogoladze, R.Khalid, Q.Shaf, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrra baryons - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

- Decaying DM

Ibarra et al., 2007-2009

Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

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

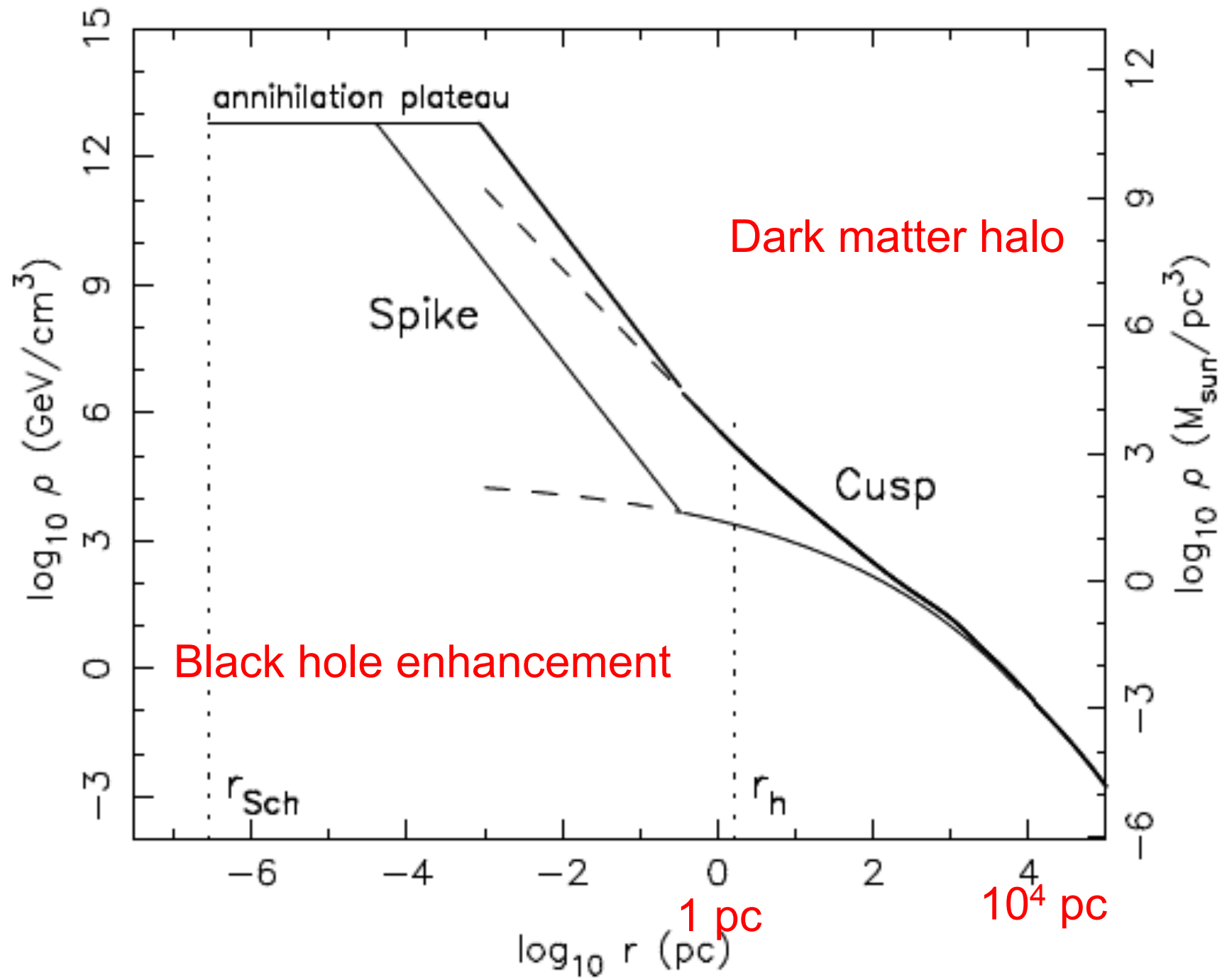
CDM cusp steepens by adiabatic growth
of IMBH: $\rho \propto r^{-\gamma} \Rightarrow \rho \propto r^{-\gamma'}$, with $\gamma' = \frac{9-2\gamma}{4-\gamma}$

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 $4 \times 10^6 M_{\text{sun}}$

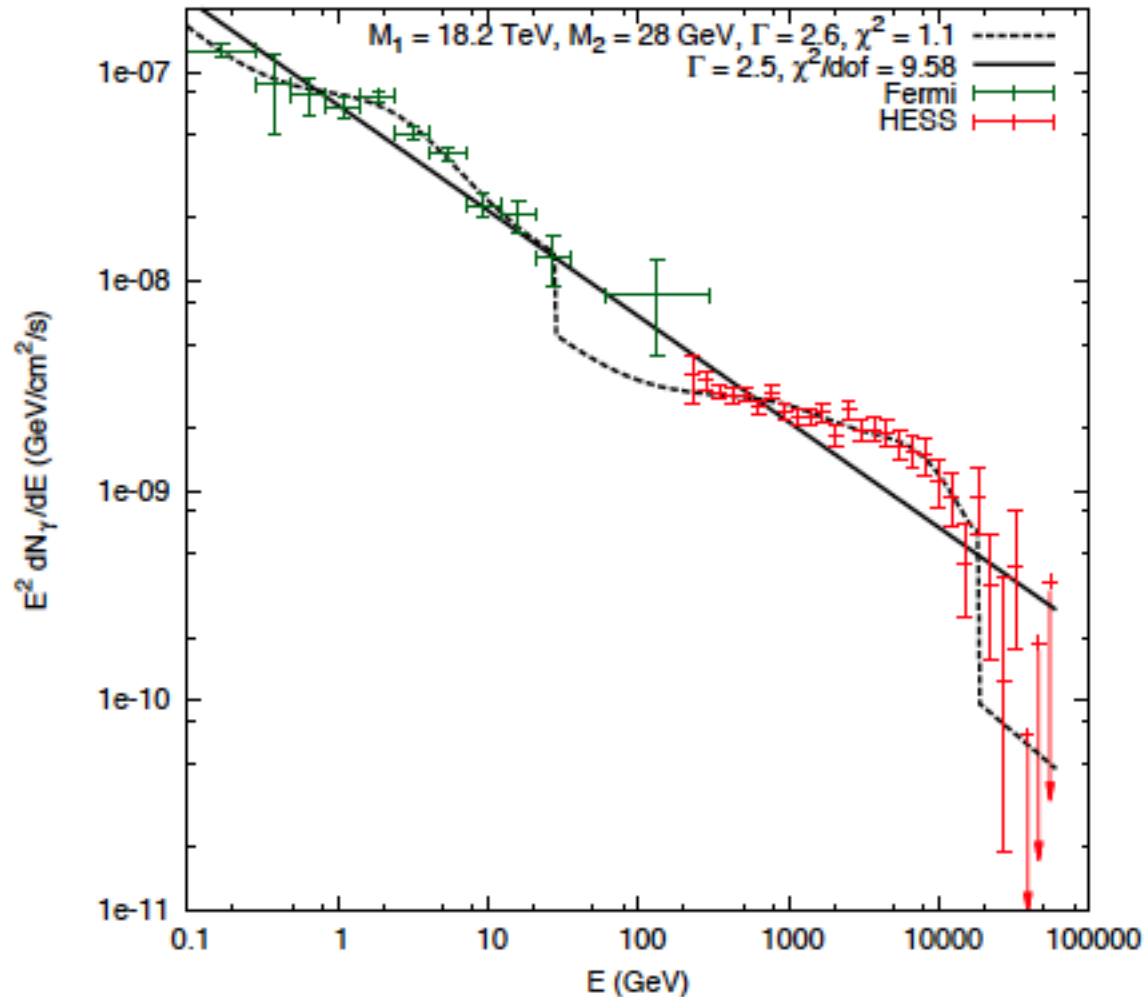
Dynamical heating reduces peak density

DM predicts exponential cut-off + no variability



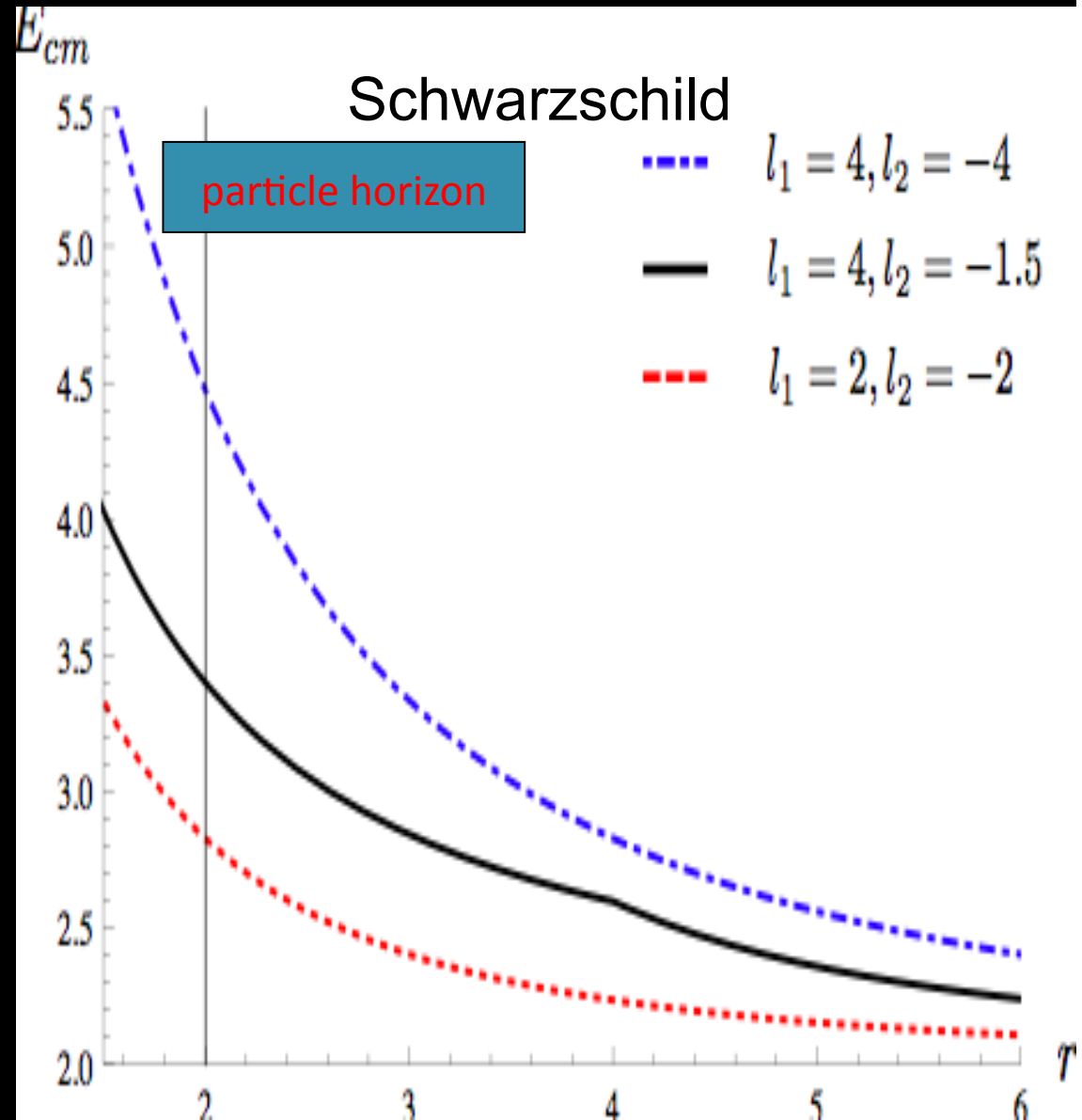
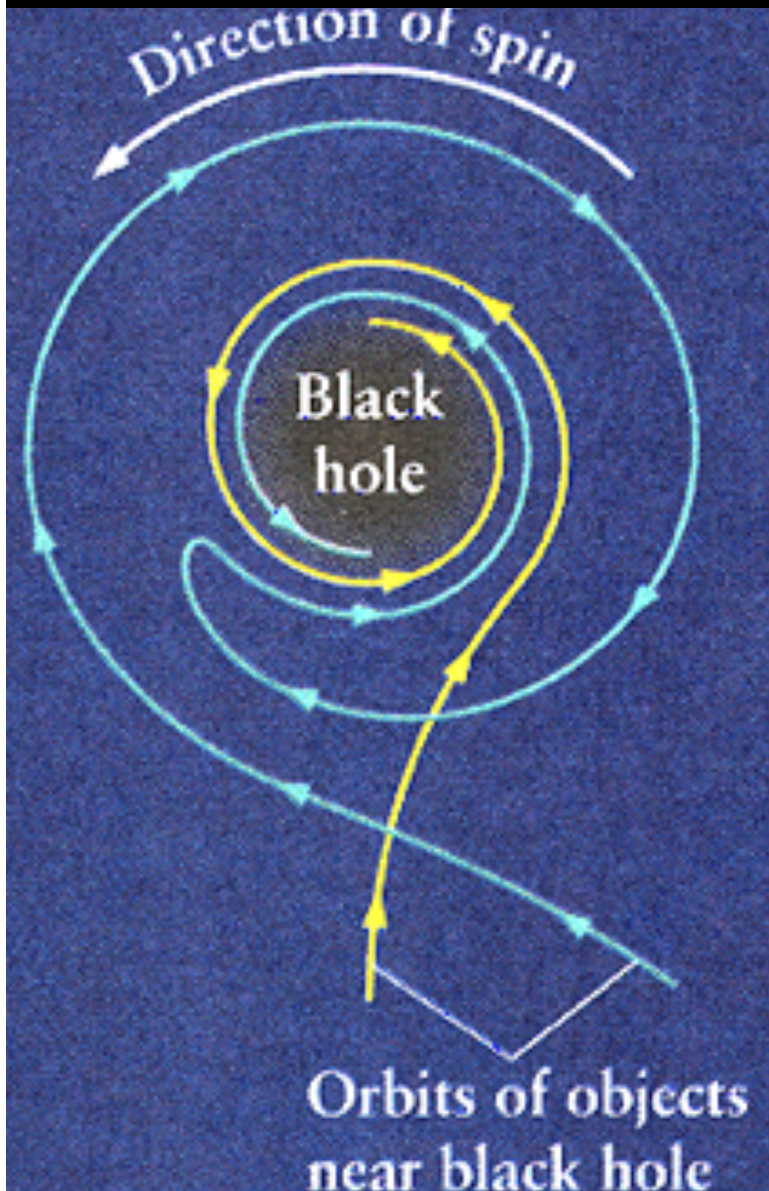
The Galactic Centre black hole

exponential spectrum preferred



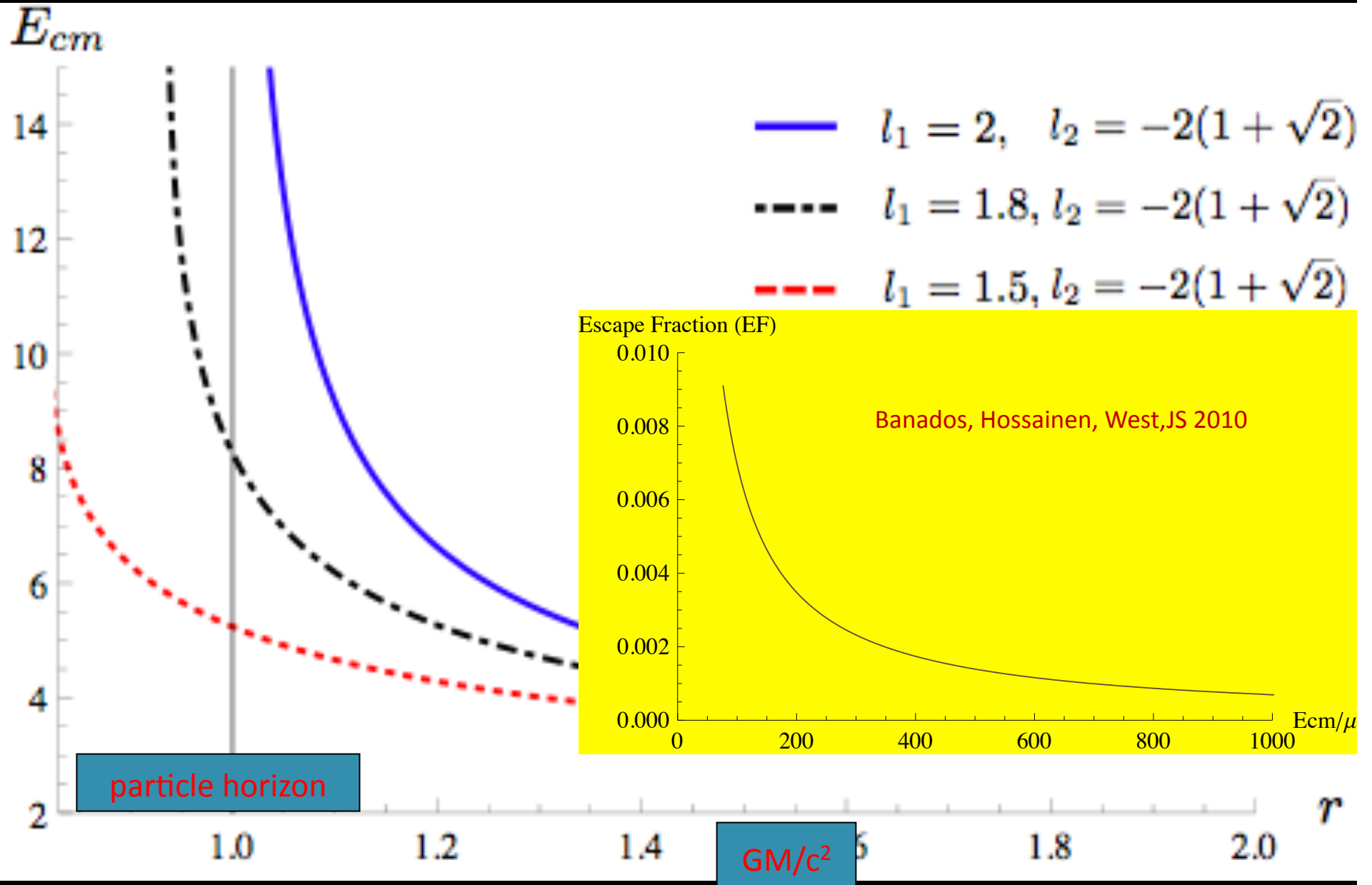
Belikov et al 2012

THE ULTIMATE PARTICLE ACCELERATOR: dark matter cusp around black hole

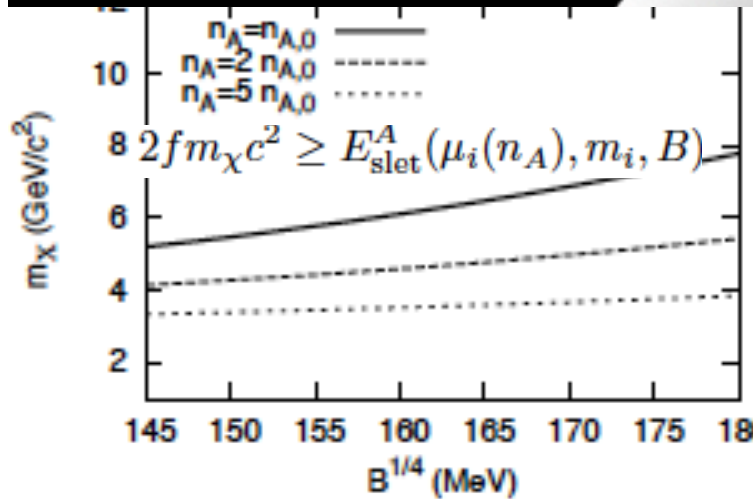


Kerr black hole

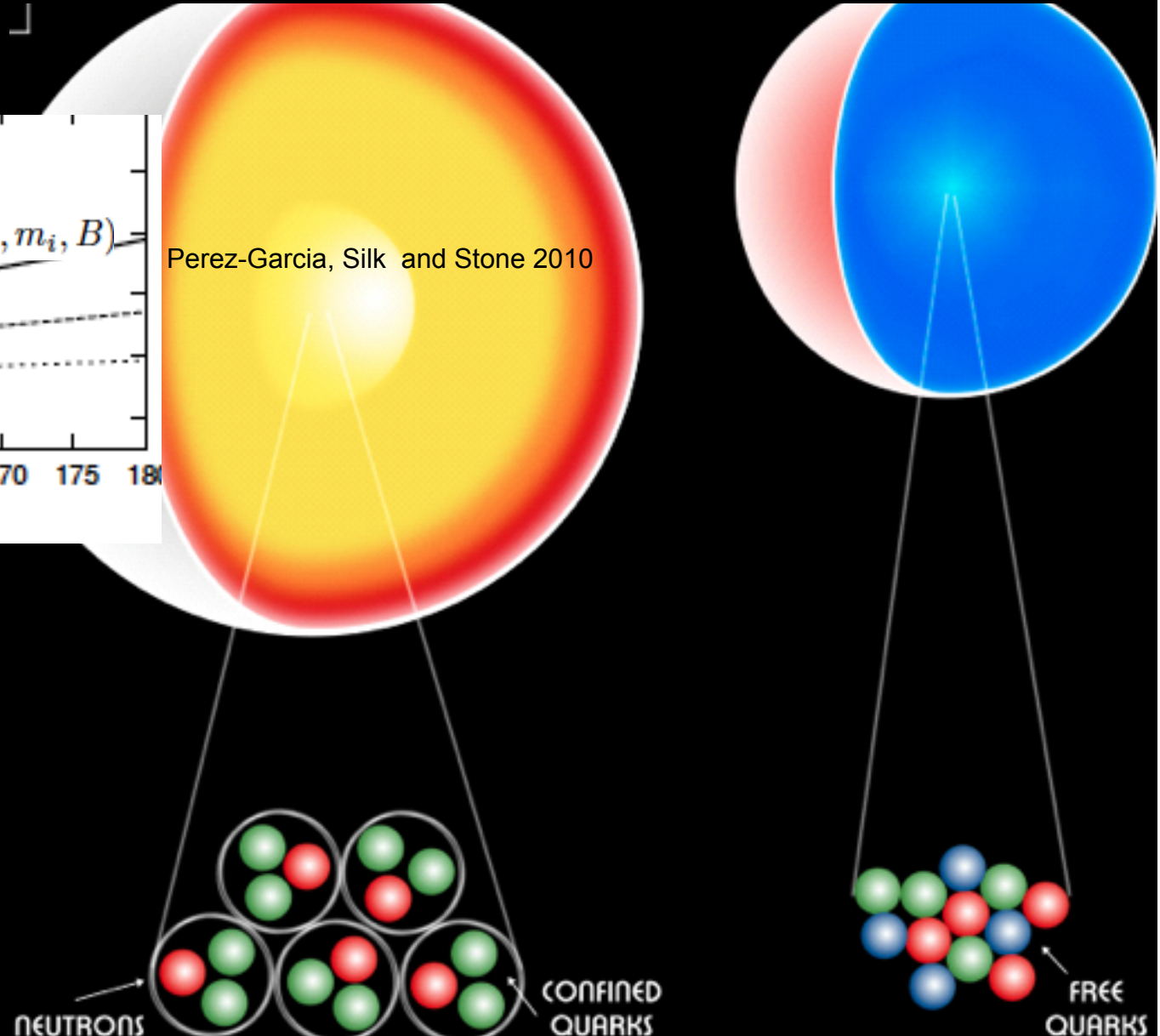
Banados, West, JS 2009



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



Perez-Garcia, Silk and Stone 2010



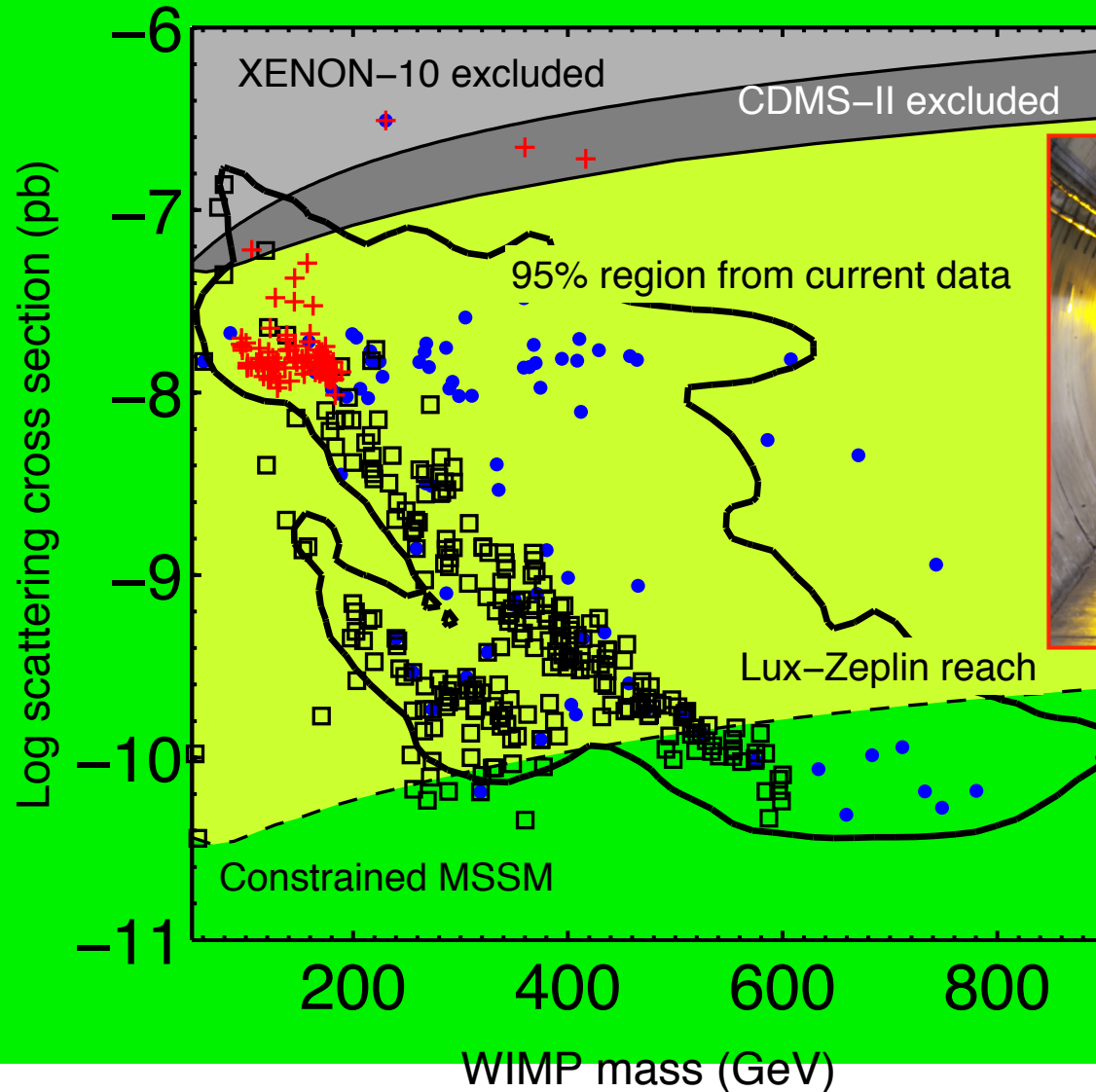
LHC reach

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

1 1/fb at 14 TeV energy

WMAP mean with 5- σ Planck uncertainty

5- σ for 1 yr of 80 strings data



extraordinary claims require extraordinary evidence.
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