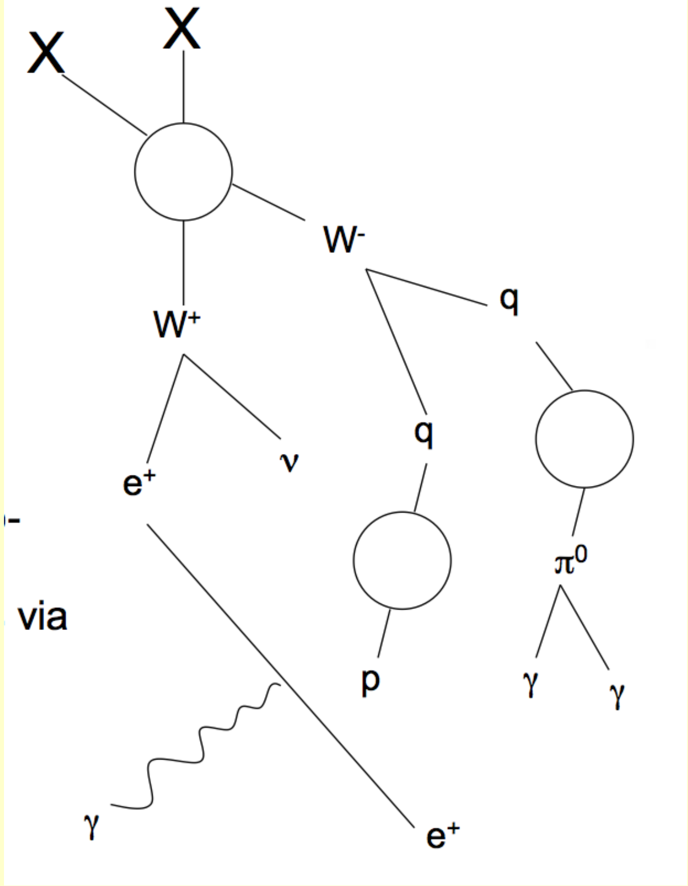


Ciemna materia

- Ciemna materia: przesłanki astronomiczne
- Detekcja bezpośrednia: czy cząstki ciemnej materii rozpraszają się na jądrach atomowych ?
- Detekcja pośrednia: czy promieniowanie gamma pochodzi (częściowo) z anihilacji ?

Dark matter (DM)

- There are few times more DM than baryons (rotation curves, lensing, W models)
- No more than 10-20% DM in the Galactic halo can have the form of MACHOs
- Axions?
- WIMPs?
- ???

[(***) arXiv:1701.01840]:

Status of dark matter in the universe

Katherine Freese

*Based on a presentation at the Fourteenth Marcel Grossmann Meeting on General Relativity, Rome, July 2015.

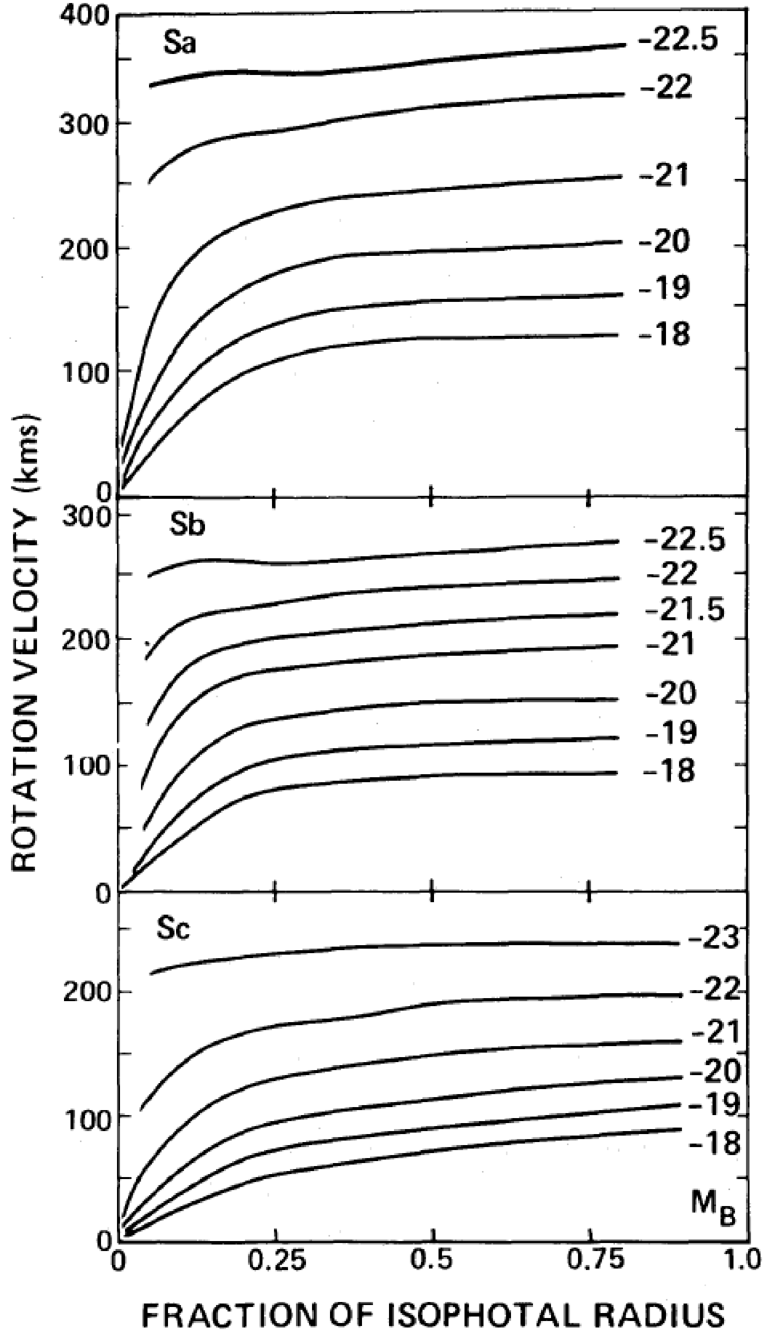
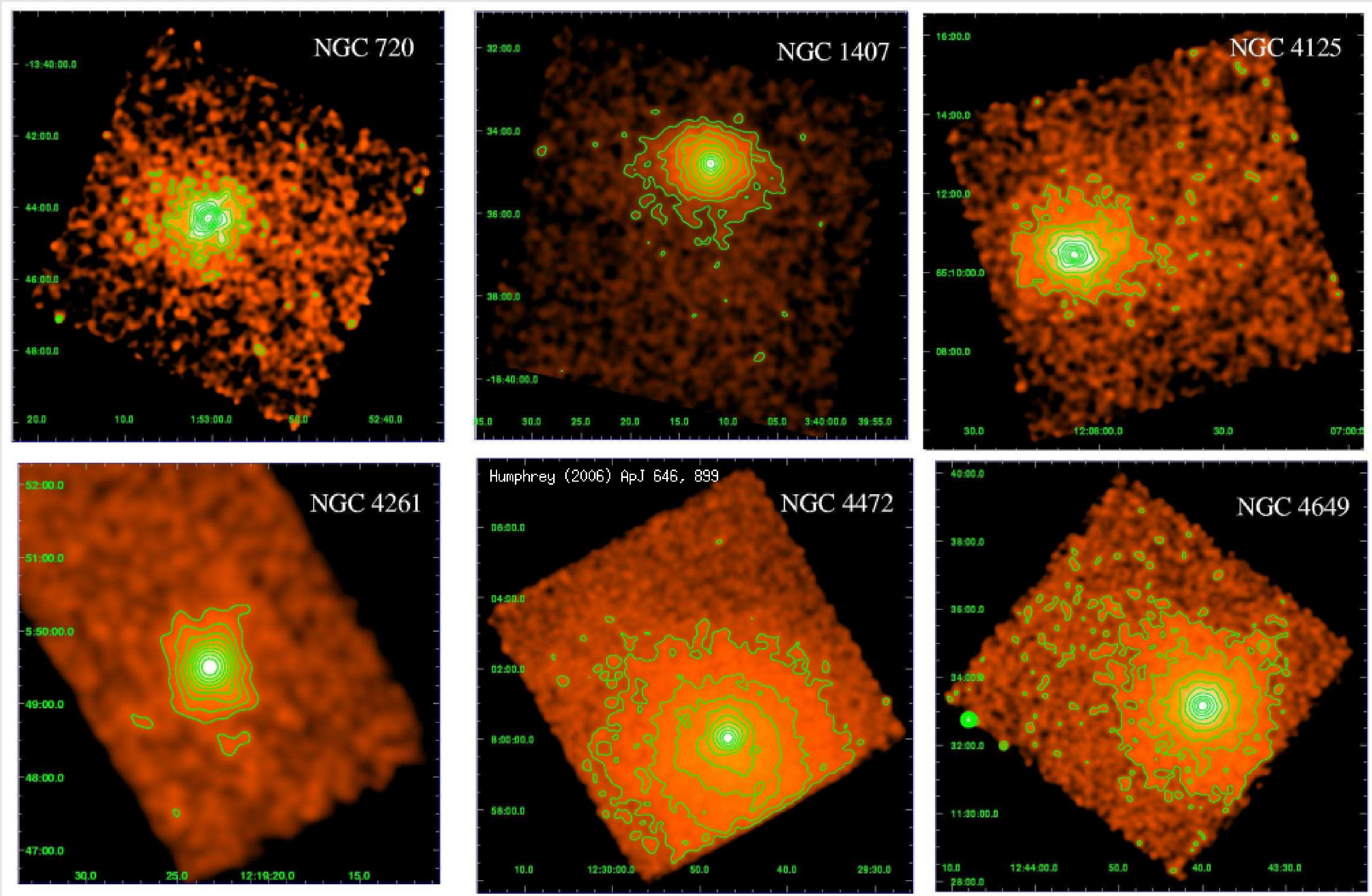


FIG. 4.—Synthetic rotation curves showing average smoothed rotation velocity as a function of fraction of isophotal radius, R_{25}, for (*top*) Sa galaxies of successive luminosities, (*middle*) Sb galaxies, and (*bottom*) Sc galaxies. The procedure for synthesizing these curves is described in Appendix B.

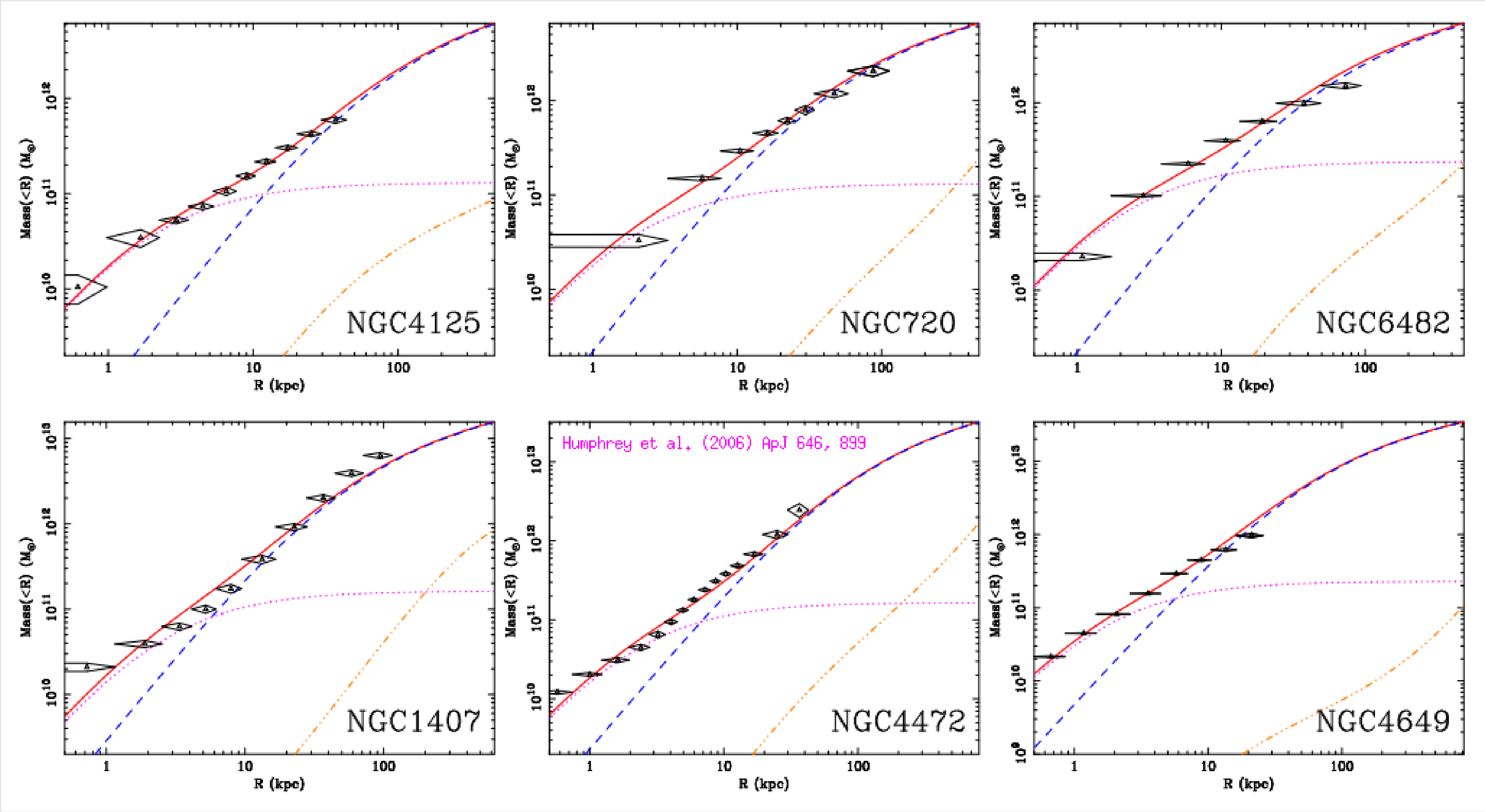
Rubin et al. (1985) ApJ, 289, 81

Promieniowanie X gal. eliptycznych



Kolejne przykłady map rentgenowskich (izofoty) nałożonych na optyczny obraz nieba

Promieniowanie X gal. eliptycznych



---- DM ...... gwiazdy -...-...-... gaz

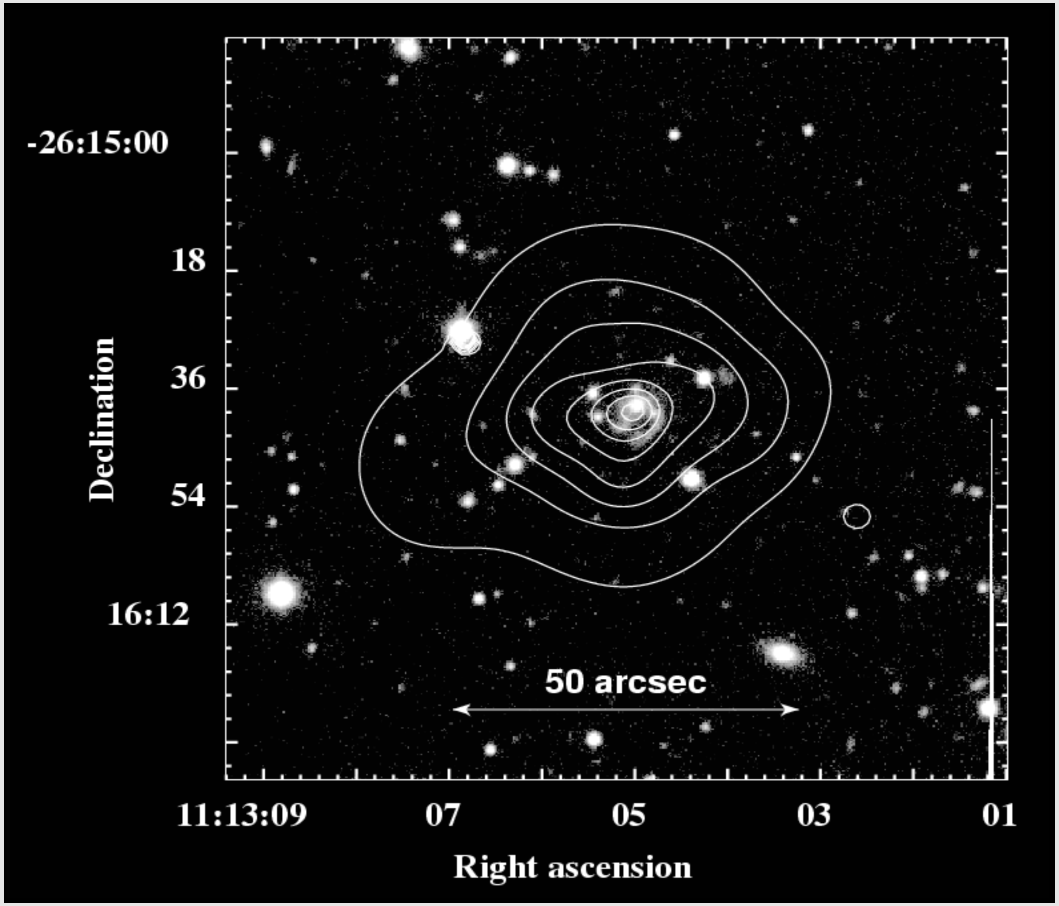
Te wykresy przypominają te dla spiral: ocena całkowitej masy w funkcji promienia oparta jest na interpretacji obserwacji X. Rozkład masy gazu i gwiazd też opiera się na obserwacjach, natomiast rozkład ciemnej materii to dedukcja: rozkład brakującej masy.

Galaxy clusters

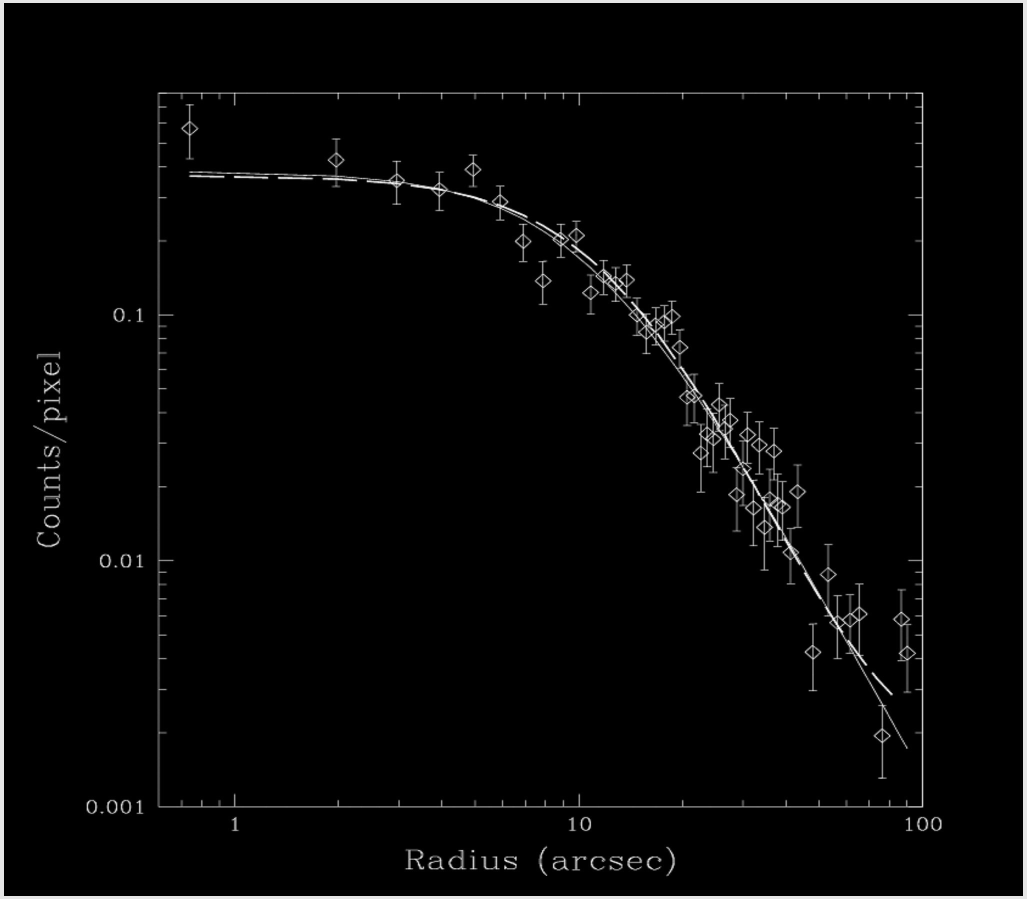
$$\rho_g \sim r^{-\beta} \Rightarrow I_X \sim R^{-(2\beta-1)}$$

$$\frac{dP_g}{dr} = -\rho_g \frac{GM_{tot}(r)}{r^2}$$

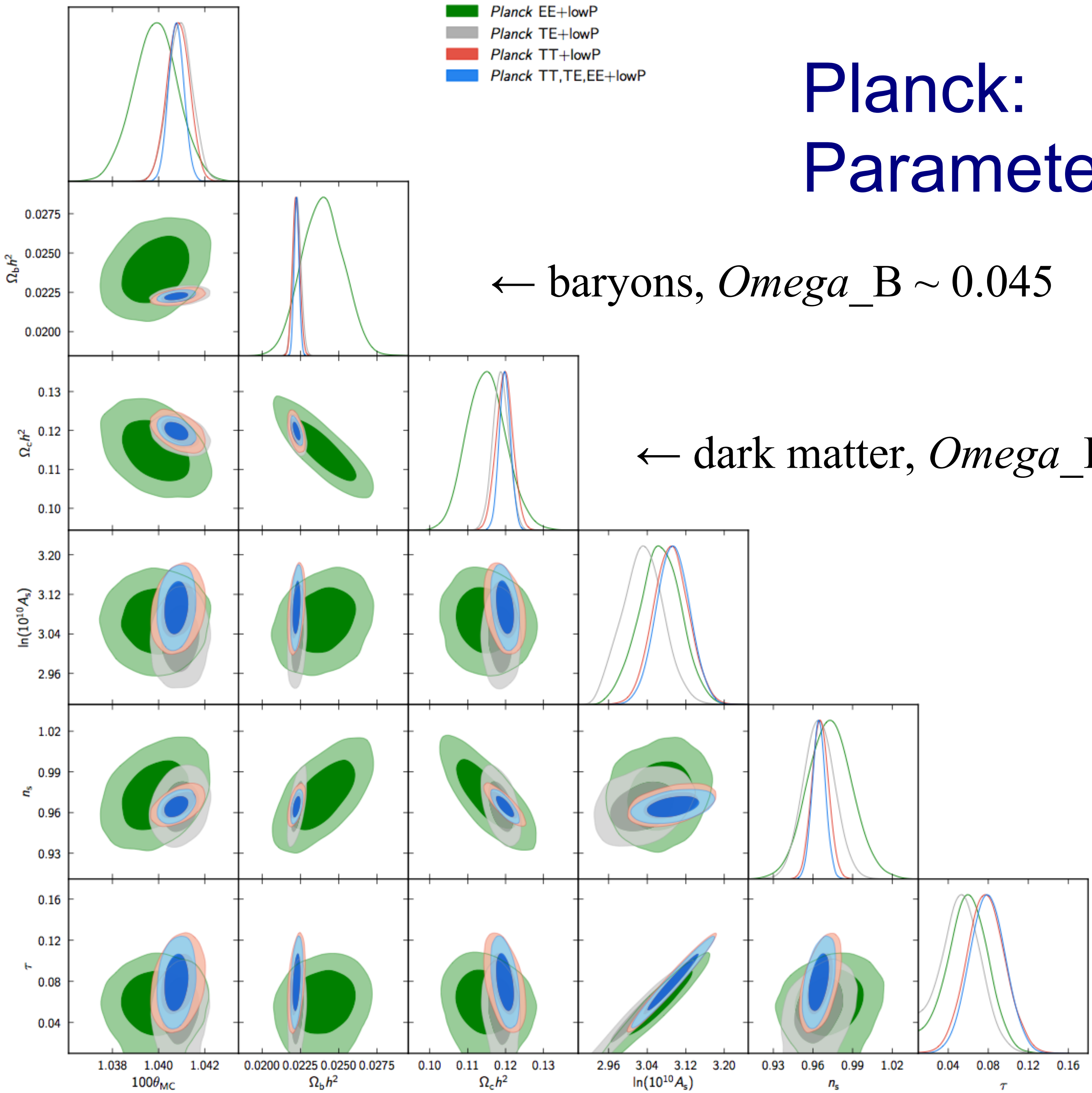
$$\Rightarrow M_{tot}(r) = \frac{\beta k T_g}{G\mu} r$$



Typical X-ray intensity profile →



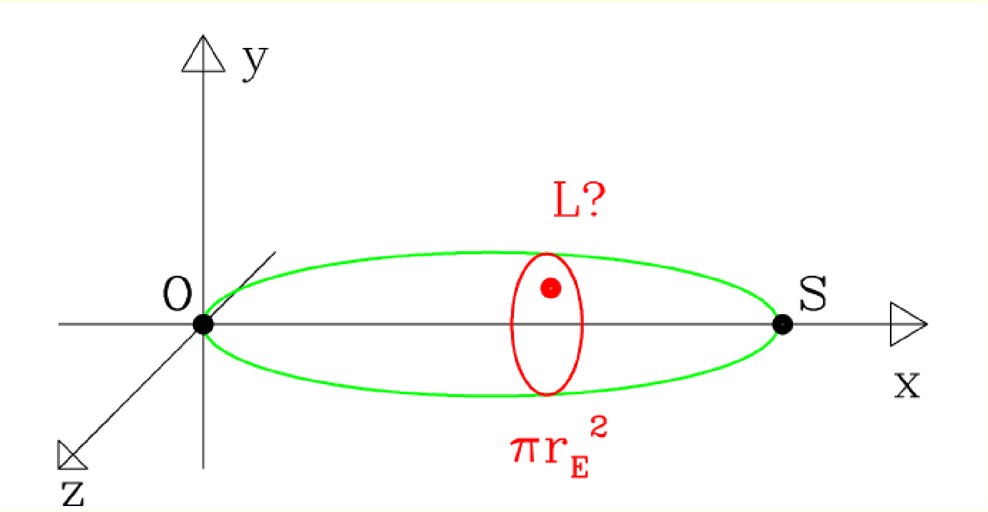
Planck: Parameters



← baryons, *Omega*_B ~ 0.045

← dark matter, *Omega*_DM ~ 0.24

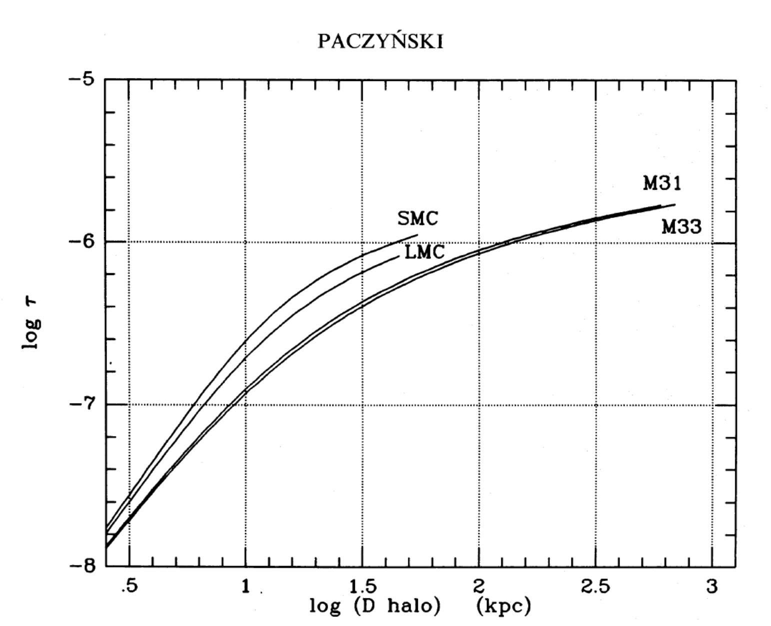
MACHOs or WIMPs?
Lensing probability: theory and estimates



$$\tau = \int_V n\, dV = \int_0^{d_{OS}} n \pi r_E^2 dl$$

$$= \int_0^{d_{OS}} \frac{\rho}{M} \frac{4GM}{c^2} \frac{l(d_{OS}-l)}{d_{OS}} dl$$

$$= \frac{4\pi G d_{OS}^2}{c^2} \int_0^1 \rho(x)\, x(1-x)\, dx$$



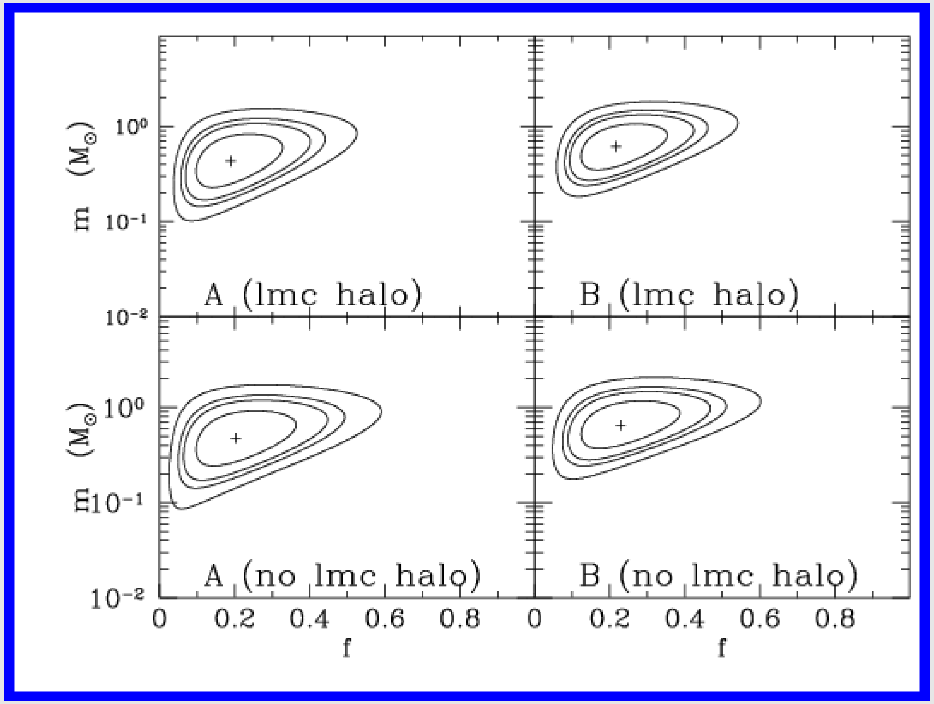
Only MACHO's

density = concentration*mass

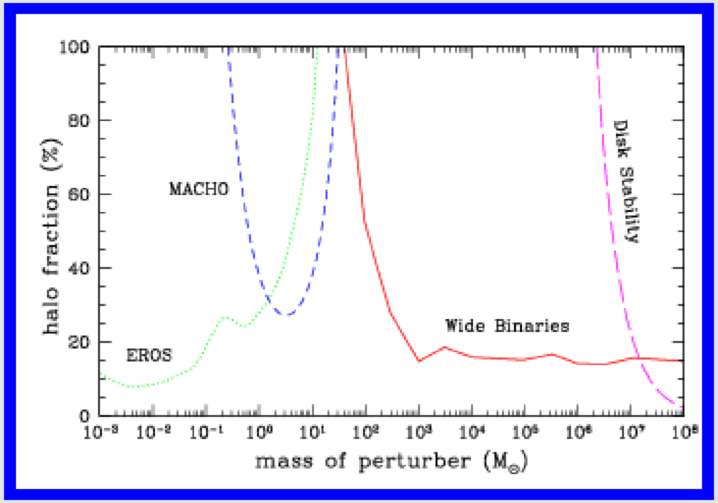
is important

[Paczyński (1986) ApJ, 304, 1]

MACHO, OGLE, EROS....



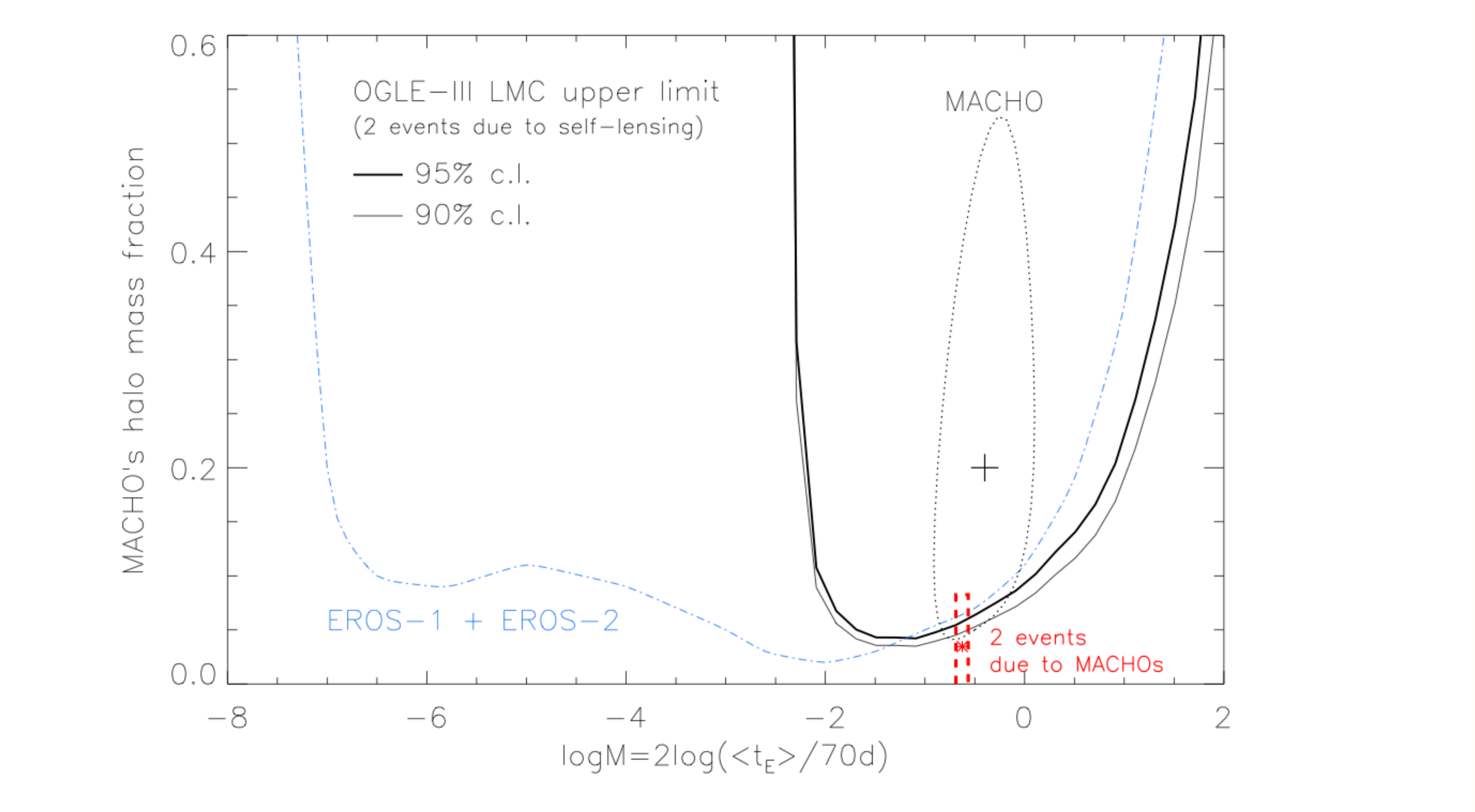
Alcock (+MACHO team) 2000: typical masses of microlenses and their possible contribution to Galaxy halo mass



Limits on MACHOs contribution to halo mass (Gould +)

WIMPs rather than MACHOs ?

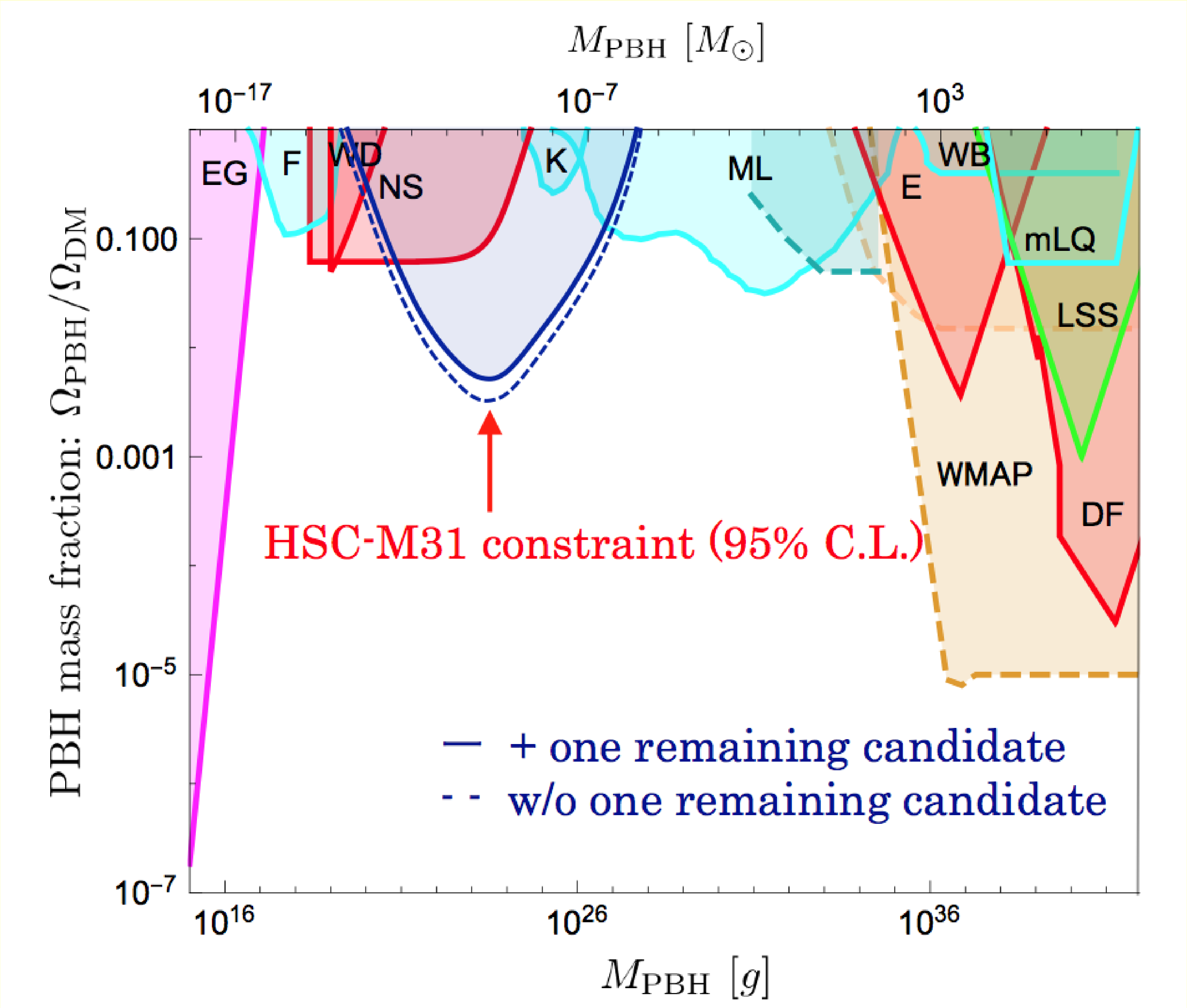
MACHOs: fraction of halo mass



Fraction of the halo mass contained in the dark matter compact objects as derived from MACHO, EROS and OGLE-III

Wyrzykowski et al. (2011) MNRAS, 413, 493
(based on OGLE observations 2001 – 2010)

DM does not consist of MACHOs



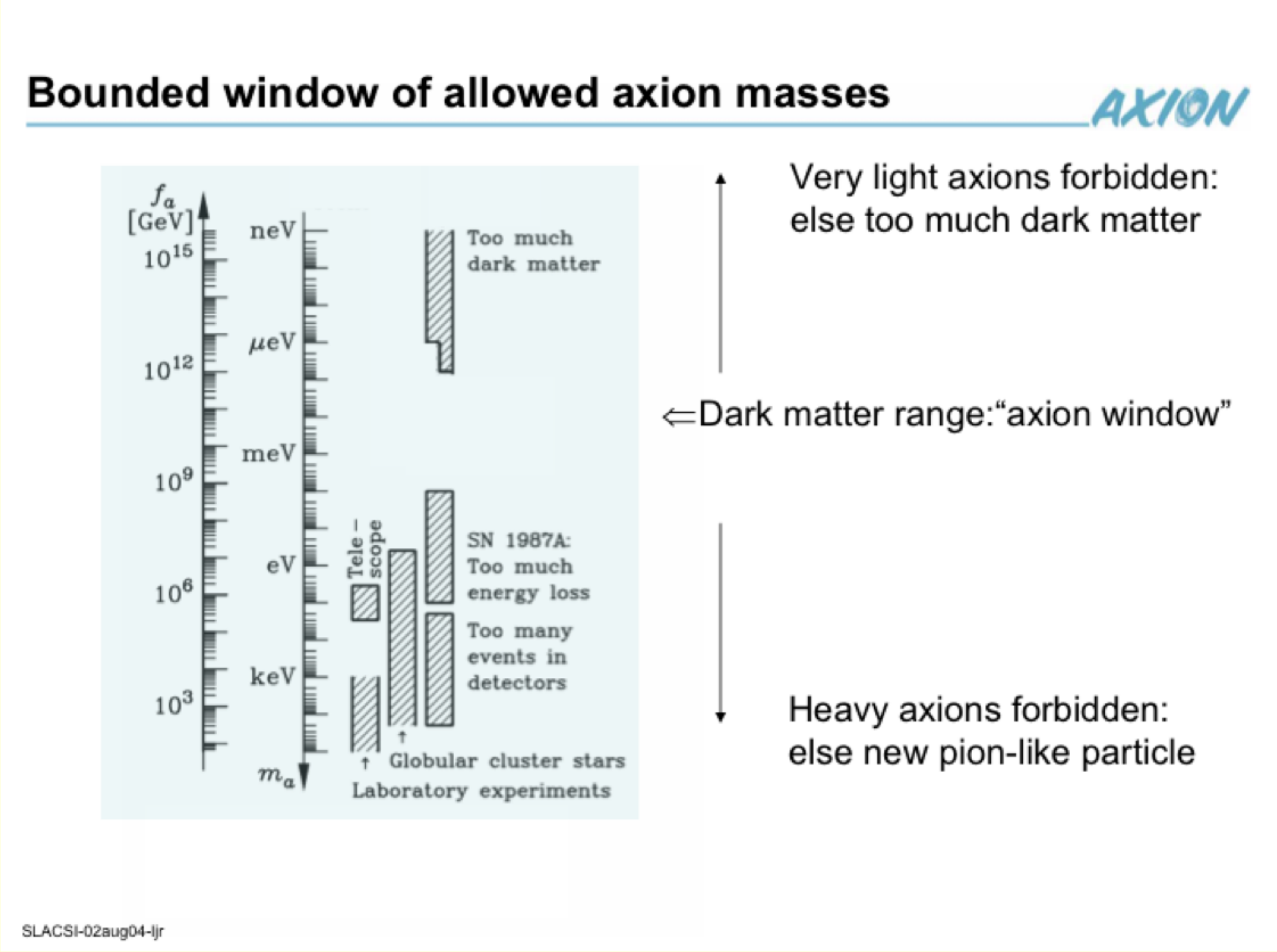
[Niikura et al. ArXiv:1701.02151; Subaru ulensing M31]

DM detection?

(not including gravitational field)

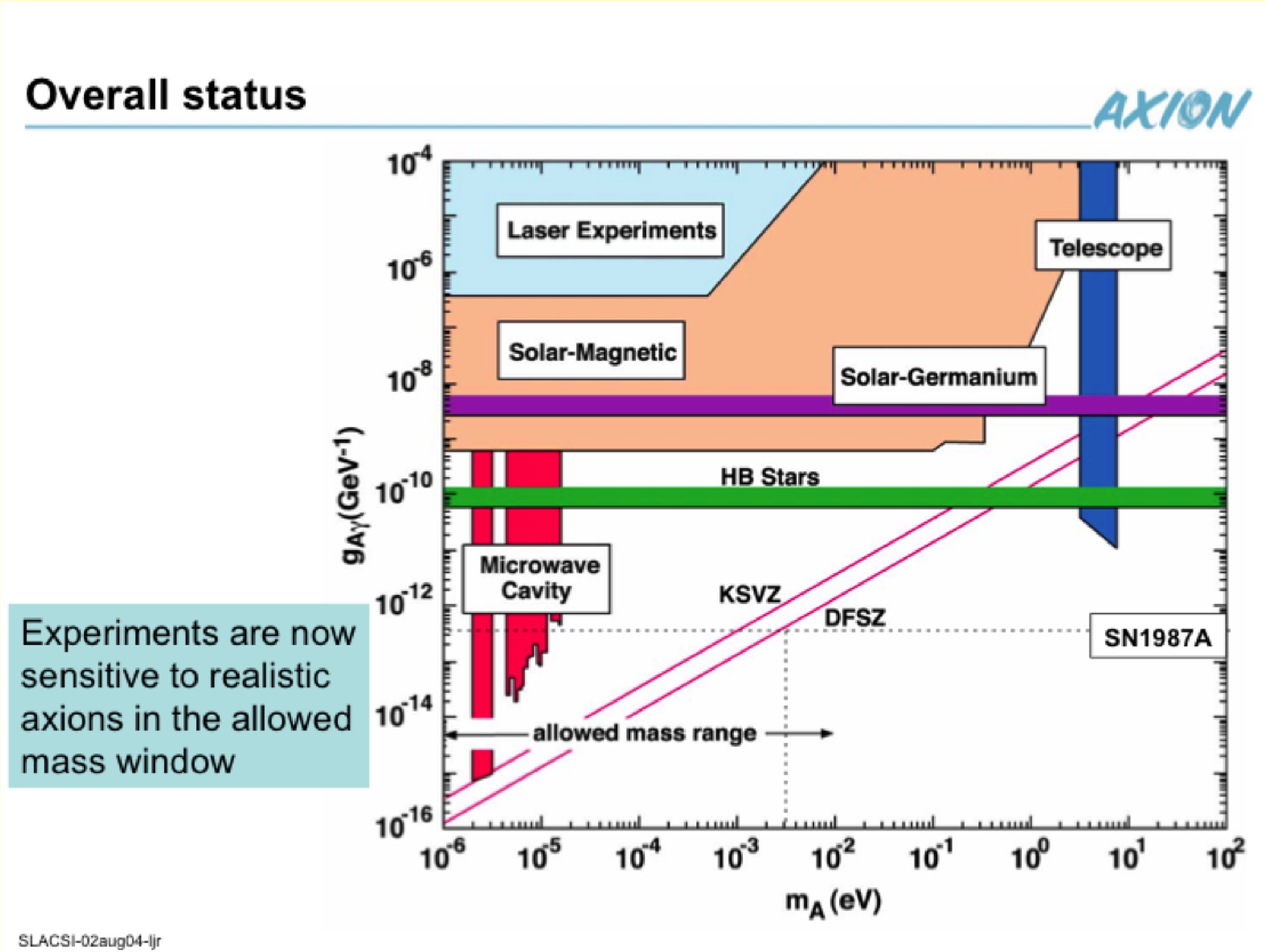
- Axions
- LHC
- Interactions with baryons? (Xe, Ar,I,Ge, … nuclei)
- Annihilation in regions with high DM density → radiation from centers of galaxies and clusters (but: is DM really involved ?)

Axions: hypothesis



QCD: CP symmetry breaking allowed
Peccei – Quinn mechanism: symmetry CP is connected to a field. At low energies symmetry is broken, cases of CP symmetry breaking are possible, but very rare, *axions* are the relic of this field

Axions: limits

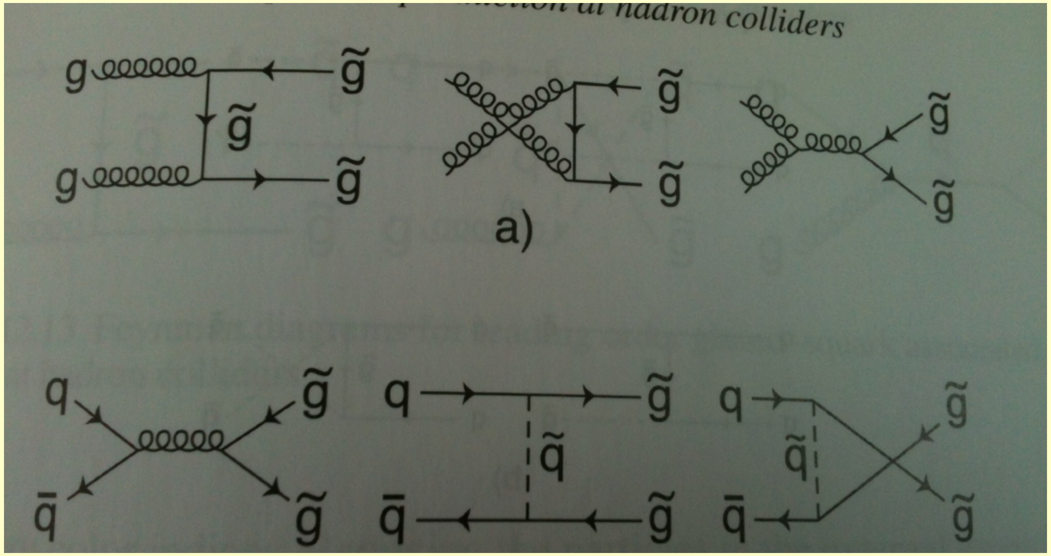


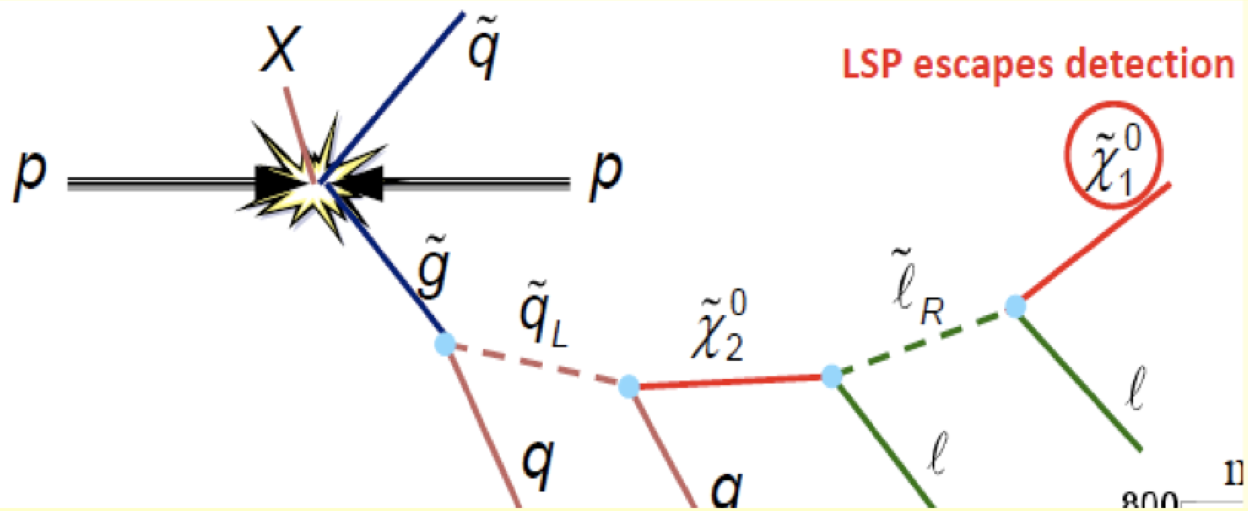
LHC

- Collisions of 7 TeV protons could be producing something dark
- There are many hypothetical particles with masses in the range of LHC (SUSY theories)
- DM particles leave the place of collision with no track – energy and momentum of registered particles are not conserved
- Up to now: exclusion of some SUSY variants

LHC

SUSY: a possibility of producing super-symmetric partners ? (squark, gluino?)





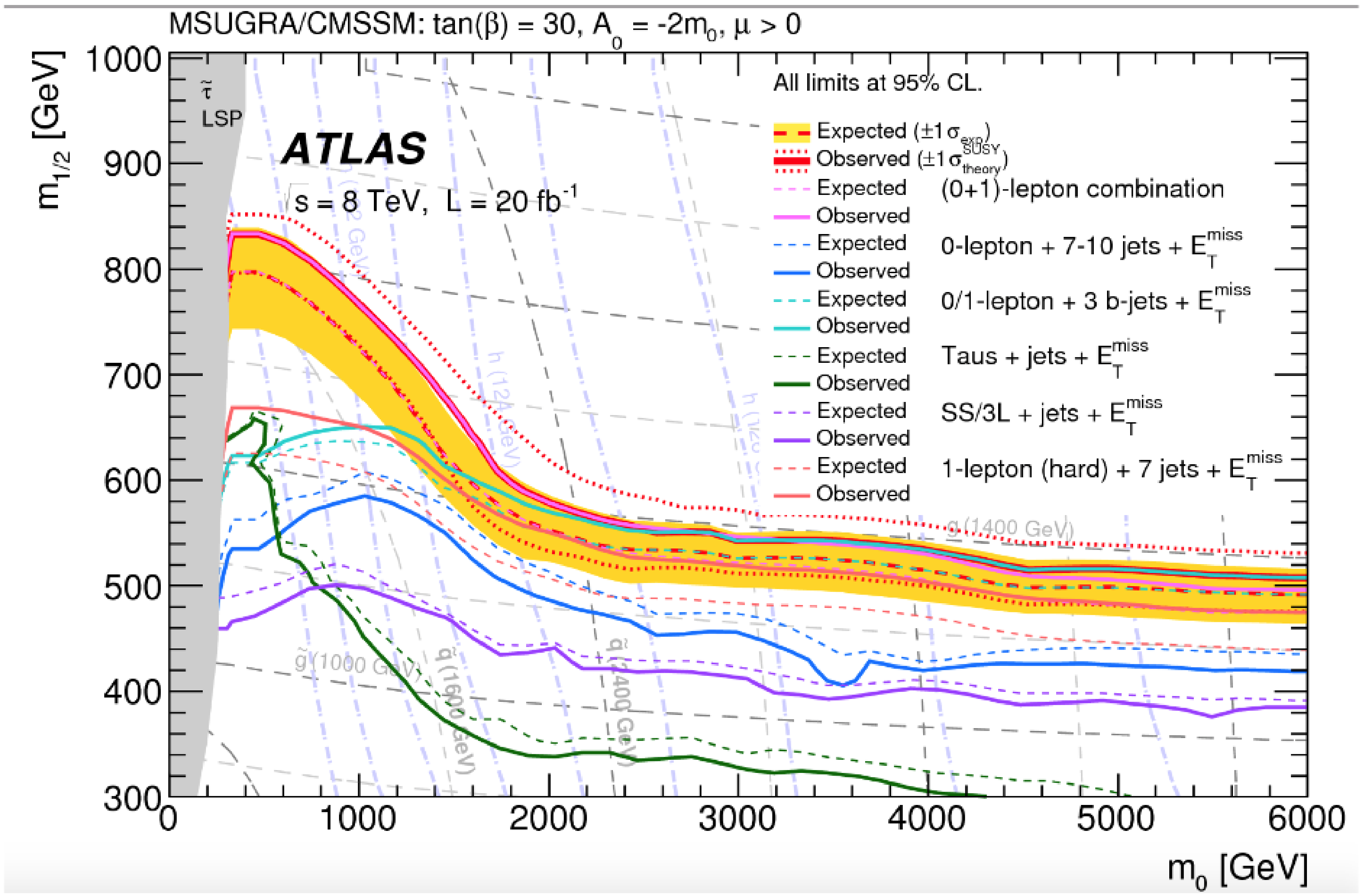


Fig. 6. Bounds on MSUGRA/CMSSM from 8 TeV ATLAS data. The remaining allowed parameter space is above the lines.

[***]

Direct detection? Nuclei scattering

$$\langle E\rangle = m_A \frac{\langle v^3\rangle}{\langle v\rangle}\left(\frac{m_X}{m_X+m_A}\right)^2 \approx 1.6A \text{ keV}\left(\frac{m_X}{m_X+m_A}\right)^2$$

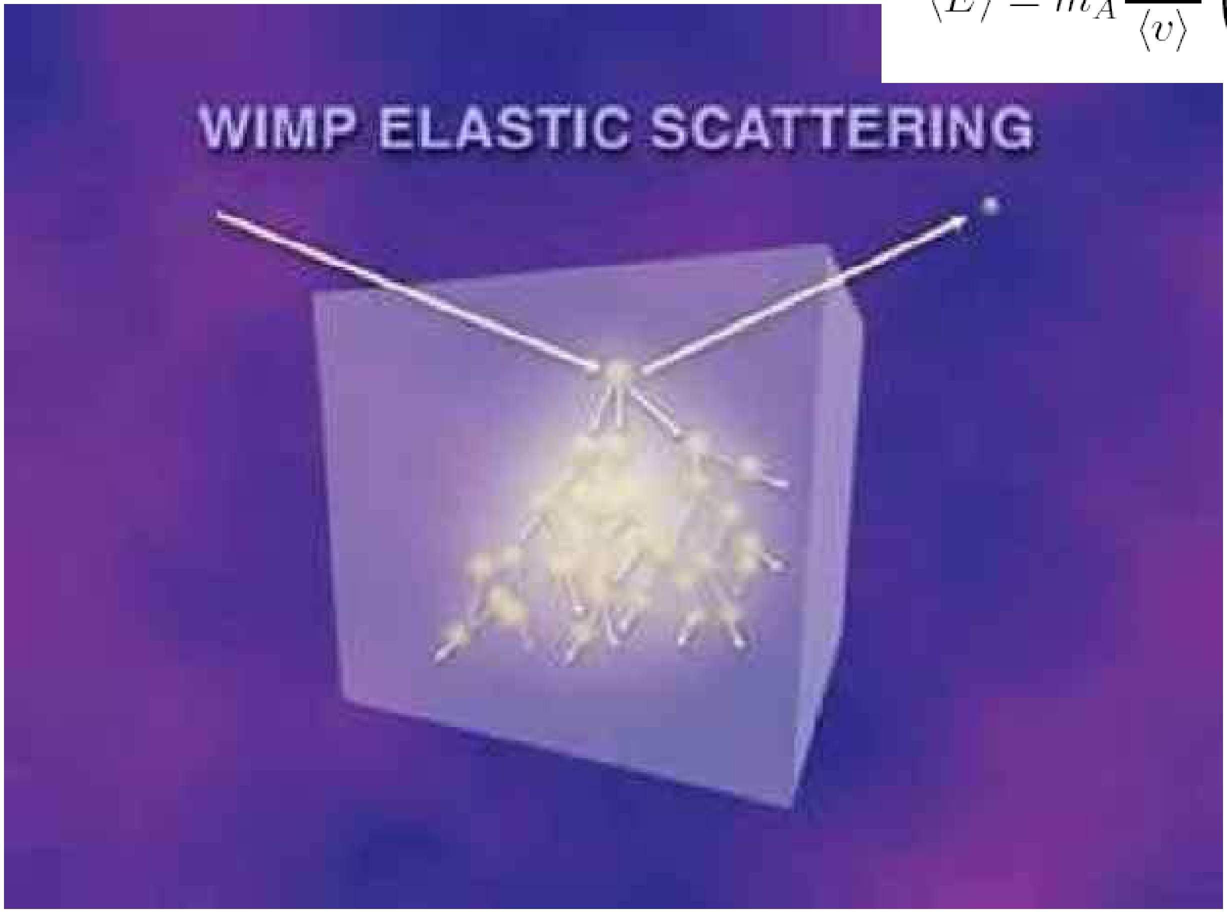


Fig. 3. Schematic principle of a WIMP direct detection experiment. A WIMP scattering induces a low energy (a few keV to a few tens of keV) nuclear recoil, which can be subsequently detected by the phonon, charge or light signals produced in the target material.

Detection attempts

Cold Dark Matter Search
[CDMS]
Soudan Underground Laboratory,
Minnesota
Depth ←→ equivalent to 2080 m
thick water layer

Fig. 5. A SuperCDMS detector, 7.5 cm in diameter, and 2.5 cm thick. The WIMP target mass is 640 g for a Ge, and 250 g for a Si crystal. The phonon collection area was increased by a factor of two relative to CDMS ZIPs, and new H-a-Si electrodes suppress the charge back diffusion.

Dielectrics at T → 0 have thermal capacity ~T^3; T~mK +
energy ~keV ←→ measurable temperature changes

Detection attempts

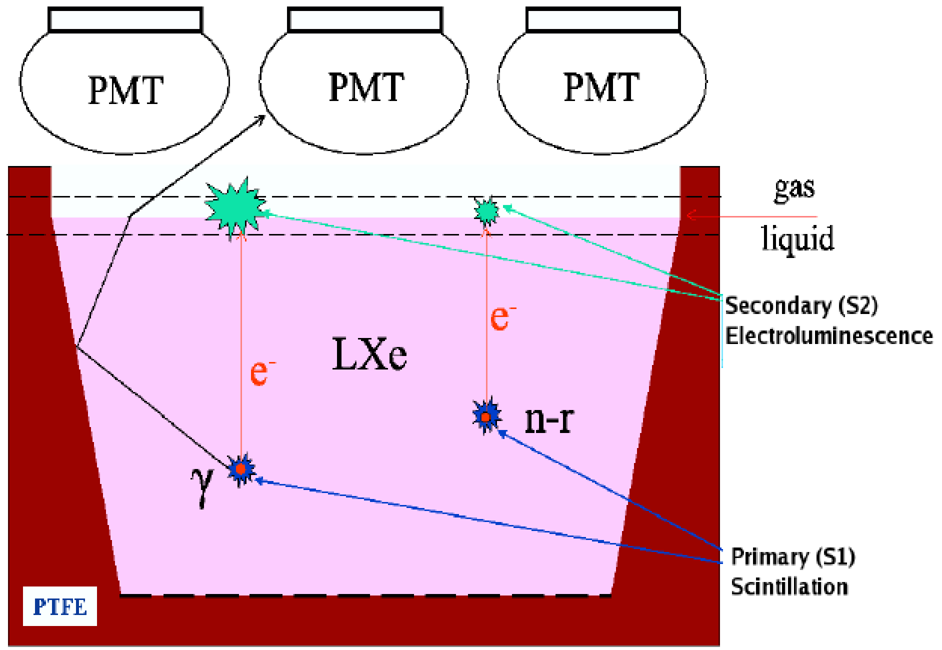
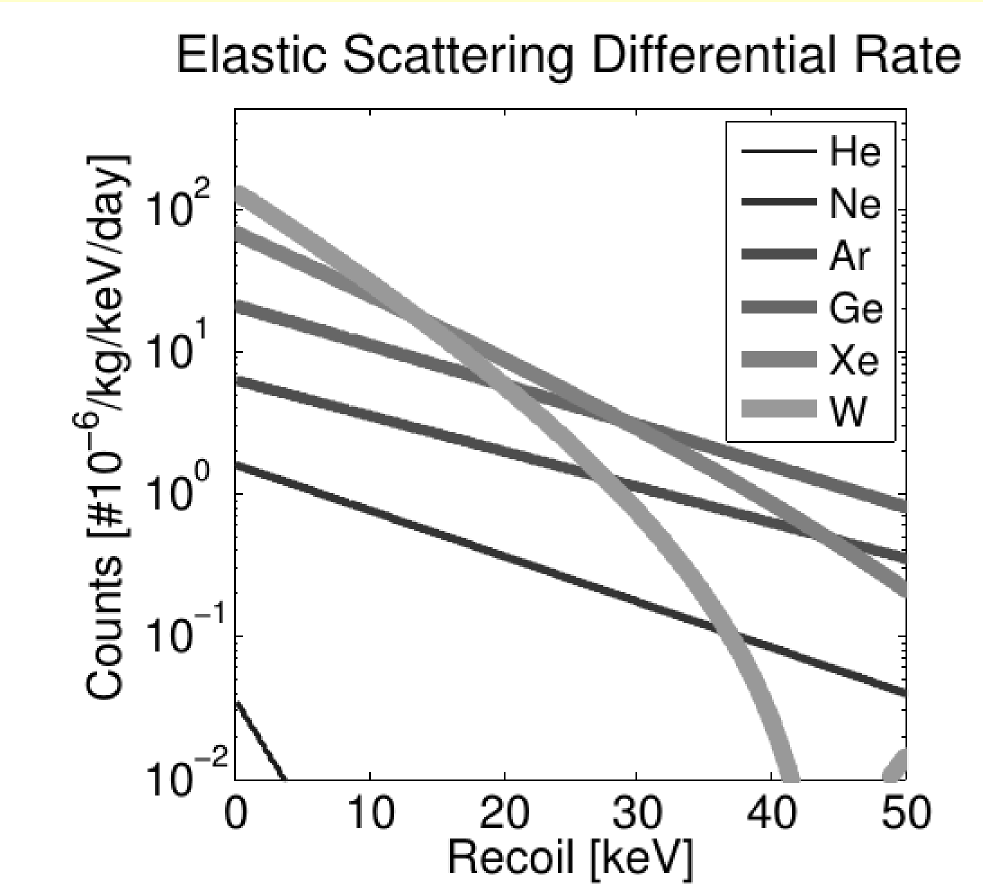
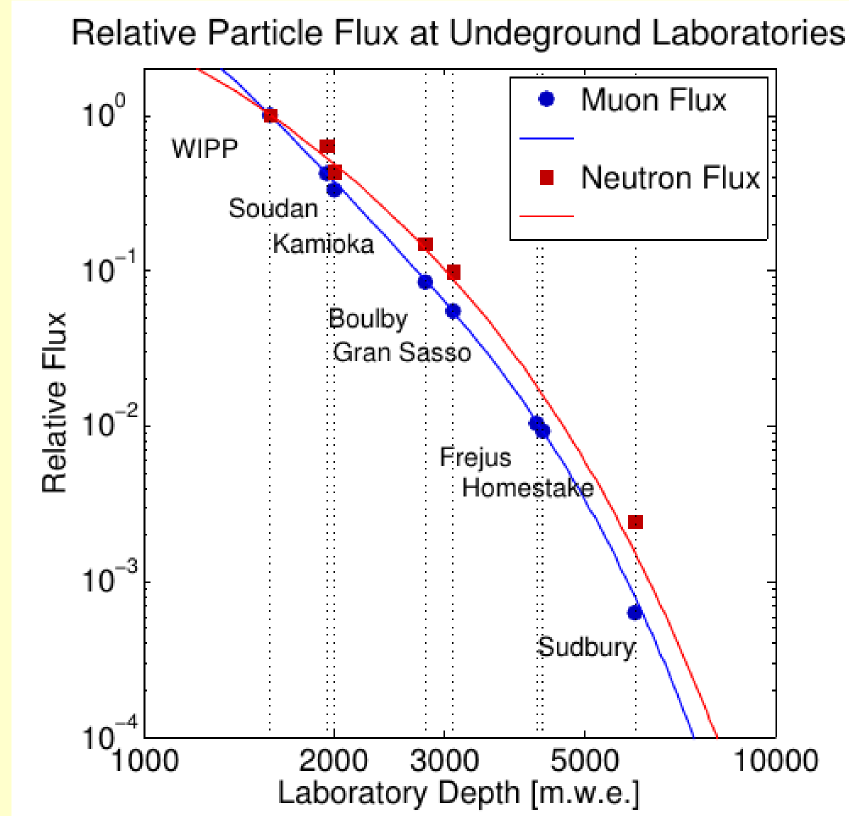


Figure 6: *Schematic of Zeplin II [15]. Particles entering the tank will first interact in the liquid Xe producing a primary scintillation light signal. The secondary electrons are then drifted by an electric field to the Xe gas layer. Here the electrons give off a secondary electroluminescence. Both of these signals are read out by seven PMTs of five-inch diameter located at the top of the detector. The parent reaction can be identified as a nuclear or electron interaction by comparing the two signals.*

Fig. 9. The array of 31 2" PMTs of the ZEPLIN-III experiment, which is currently under operation at the Boulby Lab in the UK (Figure from [26]).

Scattering on nuclei





Expected number of events in a detector depending on its material. Parameters: \sigma=10^{-45}cm^2, m_X= 100 GeV/c^2. Xenon is a good choice

[Saab arXiv:1203.2566]

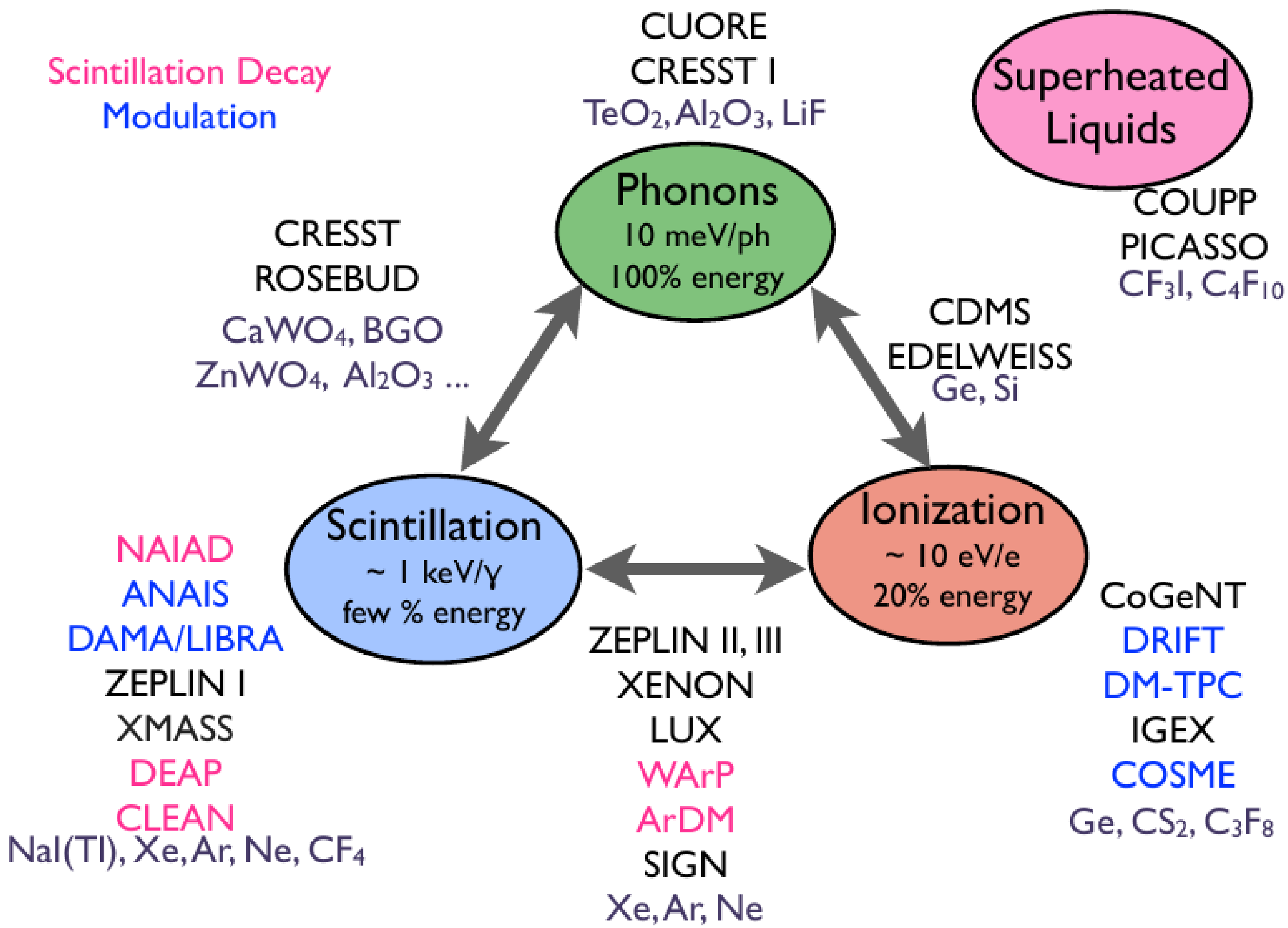


Fig. 2. The corners of the triangle correspond to common energy readout channels. Experiments are listed near the main readout channel, or between the two channels used for discrimination.

[Saab arXiv:1203.2566]

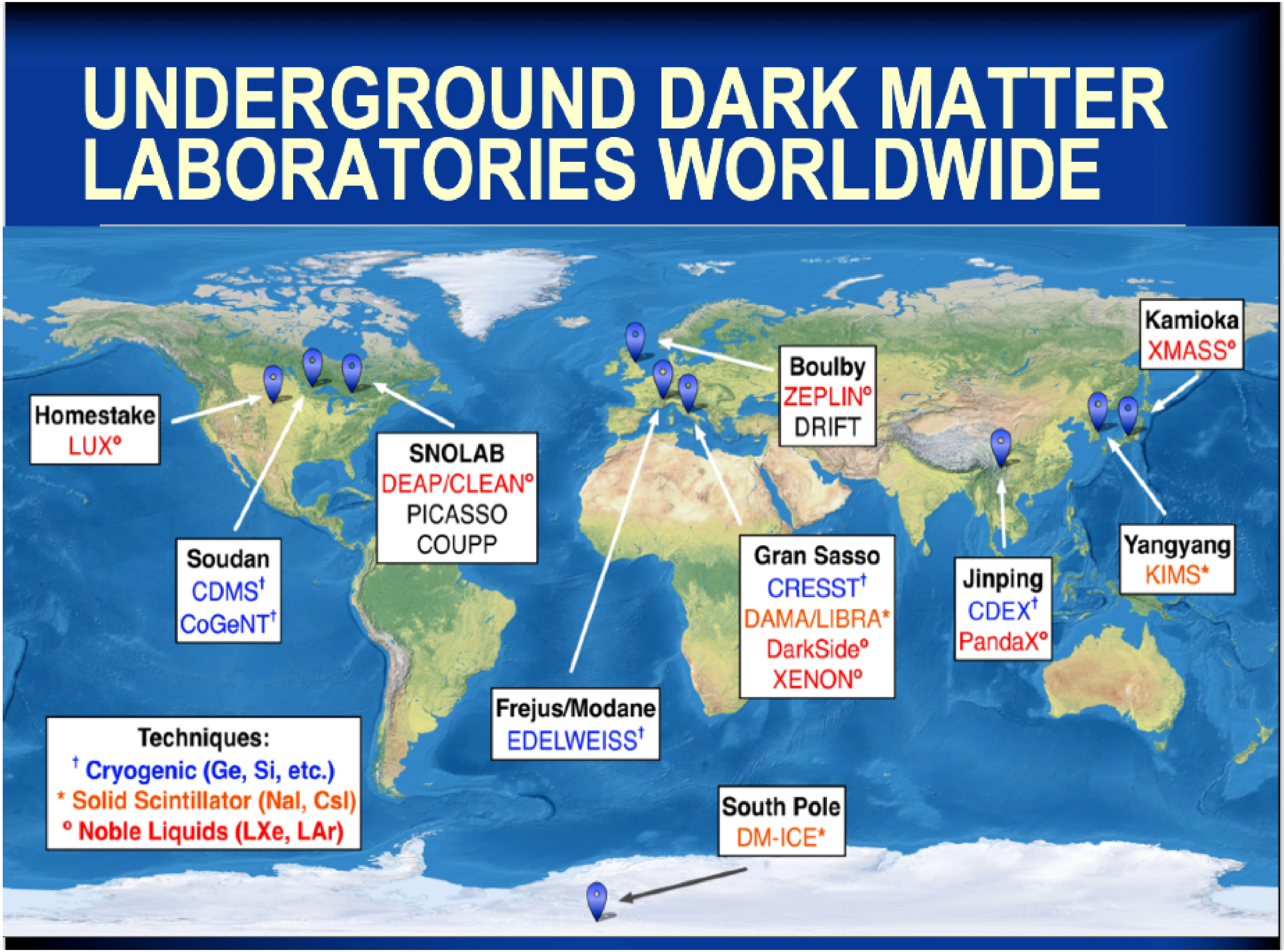
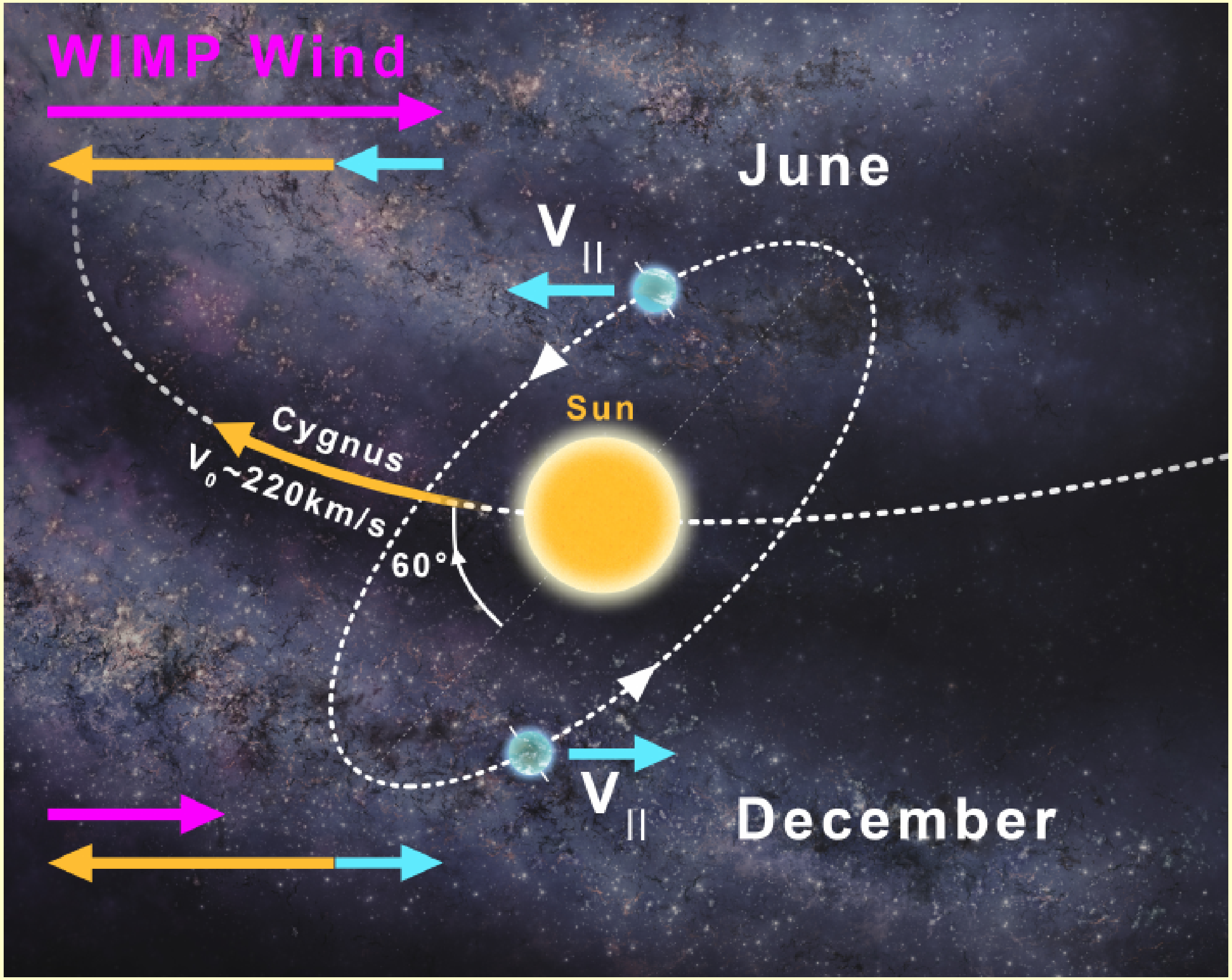


Fig. 7. Underground dark matter laboratories worldwide (courtesy of M. Tripathi and M. Woods). The CanFranc underground laboratory in Spain is missing from the figure.

Annual modulation ?
(a scheme)



James Josephides. *WIMP Wind Infographic*. Swinburne Astronomy Productions, Swinburne University of Technology. 2019 (Unpublished figure).

Annual modulation ?

DAMA (Gran Sasso)

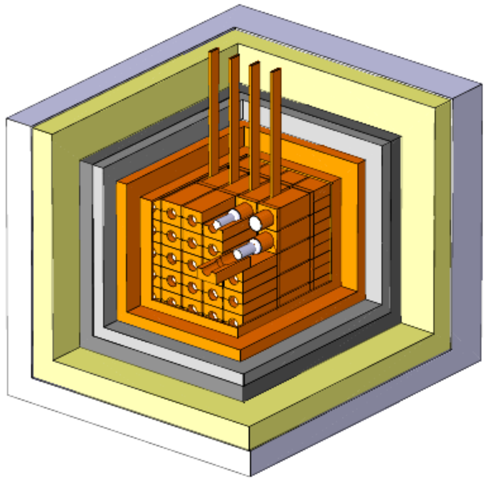


Figure 1: Schematic view of the DAMA/LIBRA apparatus. The 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix), housed in the sealed copper box continuously maintained in High Purity Nitrogen atmosphere, within low-radioactive passive shield are visible. Mostly outside the installation, the DAMA/LIBRA apparatus is also almost fully surrounded by about 1 m concrete made of the Gran Sasso rock. The copper guides of the calibration system are also shown. For details see Ref. [1].

NaI(Tl) scintillators, well screened, with anticoincidence systems, register events...

[Bernabei et al. ArXiv:1308.5109]

Annual modulation ?

DAMA (Gran Sasso)

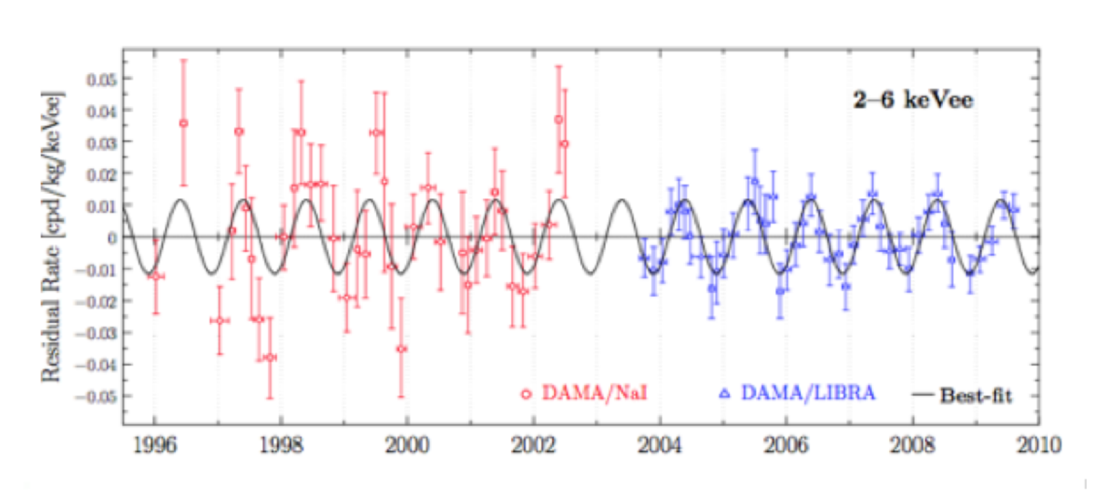


Fig. 8. DAMA data (including DAMA/LIBRA) has a 9 σ detection of annual modulation consistent with WIMPs.[66]

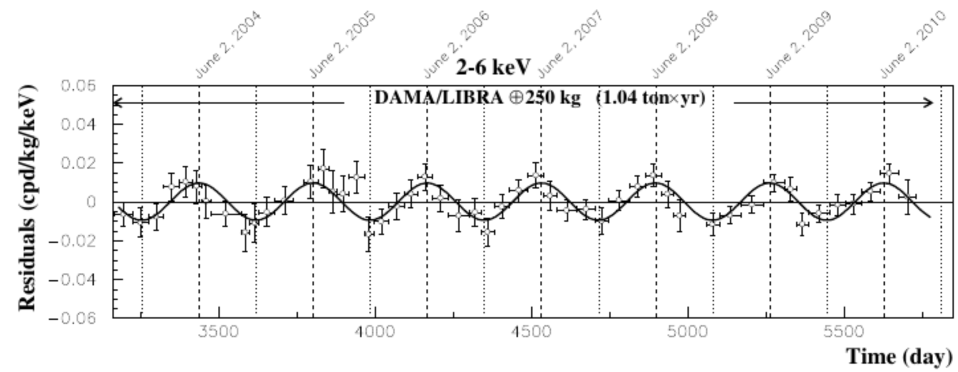
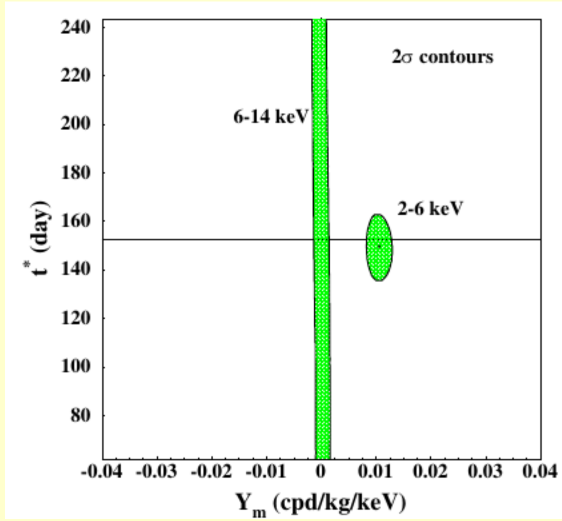


Figure 2: Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–4), (2–5) and (2–6) keV energy intervals as a function of the time. The time scale is maintained the same of the previous DAMA



Annual modulation present. Maximum in agreement with the maximum velocity relative to the DM in Galactic halo in the range 2-6 keV

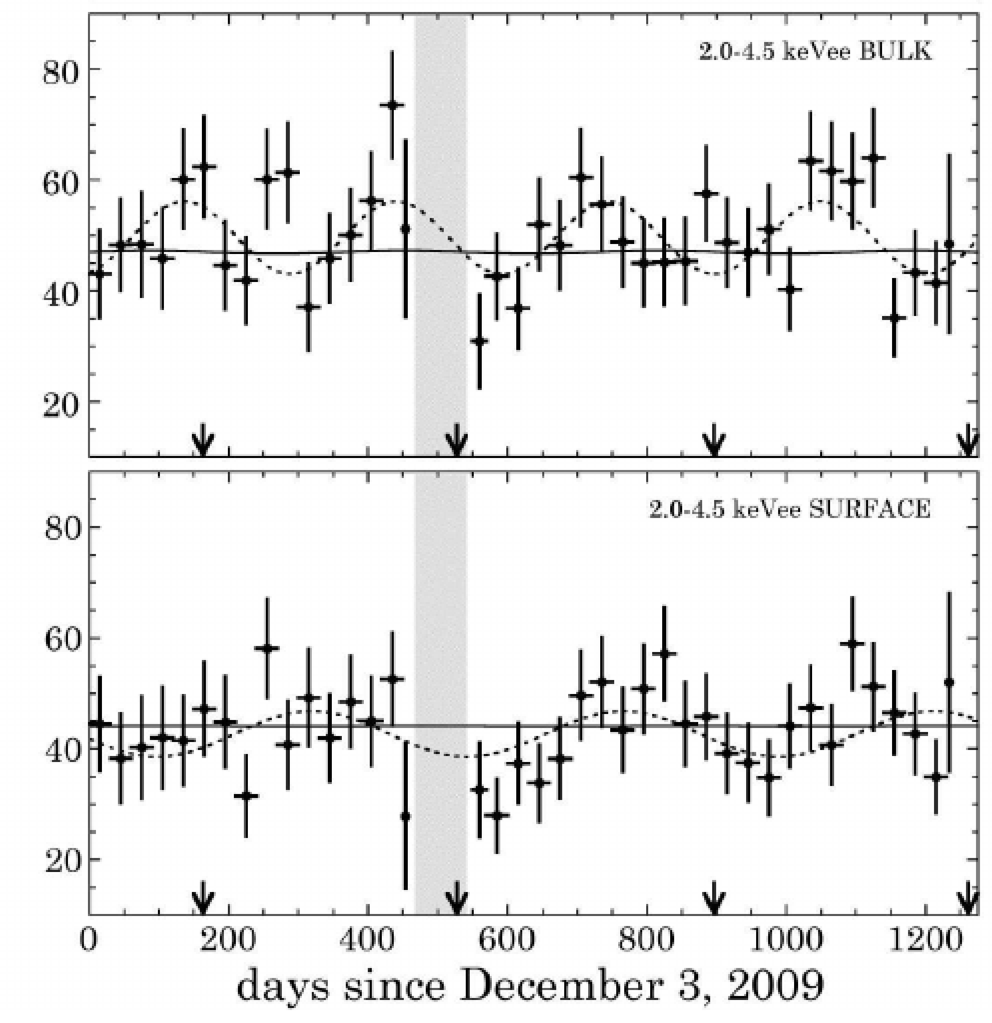
No effect above 6 keV

[Bernabei et al. ArXiv:1308.5109]

Annual modulation ?

CoGeNT (Soudan Underground Laboratory)

Germanium detectors
Is the annual modulation observed by DAMA real ?
It is (2.2 sigma), the phase is also correct but the background is not fully understood.
To verify DAMA results one needs ~5 years observations with NaI detectors optimized for WIMPs in the 10/80 GeV energy range (SABRE, COSINE-100, KIMS, DM-ICE?)



[Aalseth et al. ArXiv:1401.3295]

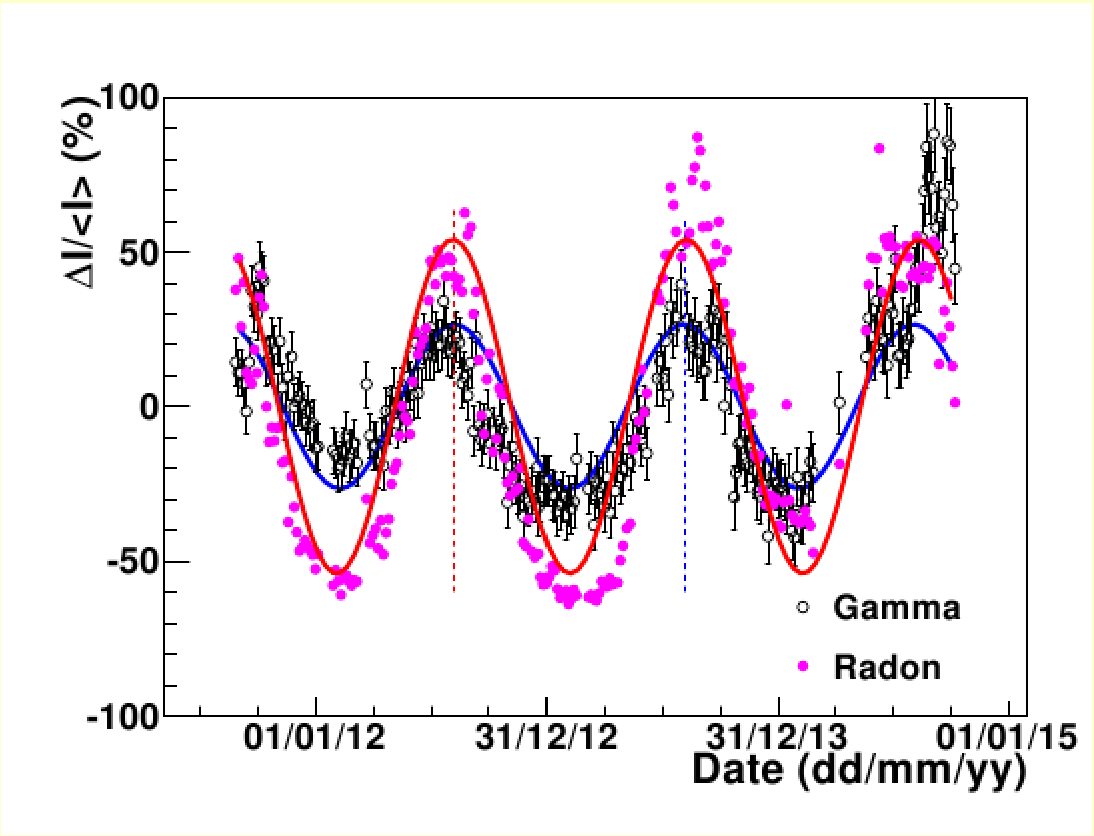
Observation of annual modulation induced by γ rays from (α, γ) reactions at the Soudan Underground Laboratory

Ashok Tiwari,[1] C. Zhang,[1] D.-M. Mei,[1,2,*] and P. Cushman[3]

[1] *Department of Physics, The University of South Dakota, Vermillion, South Dakota 57069, USA*
[2] *School of Physics and Optoelectronic, Yangtze University, Jingzhou 434023, China*
[3] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, 55455*

(Dated: July 25, 2017)

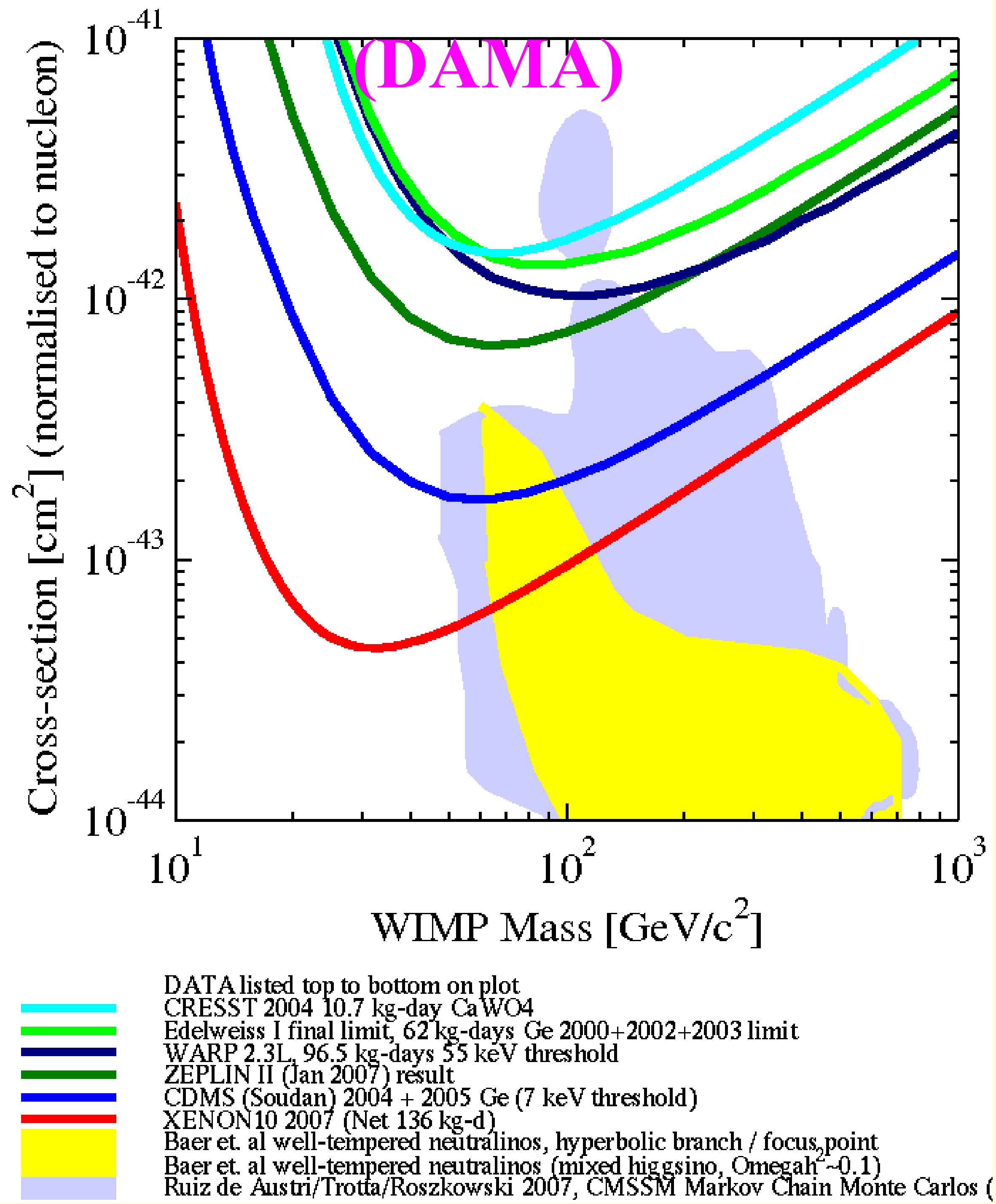
Annual modulation of γ rays from (α, γ) reactions in the Soudan Underground Lab has been observed using a 12-liter scintillation detector. This significant annual modulation, measured over 4 years, can mimic the signature for dark matter and can also generate potential background events for neutrinoless double-β decay experiments. The measured annual modulation of the event rate



Detection attempts: limits

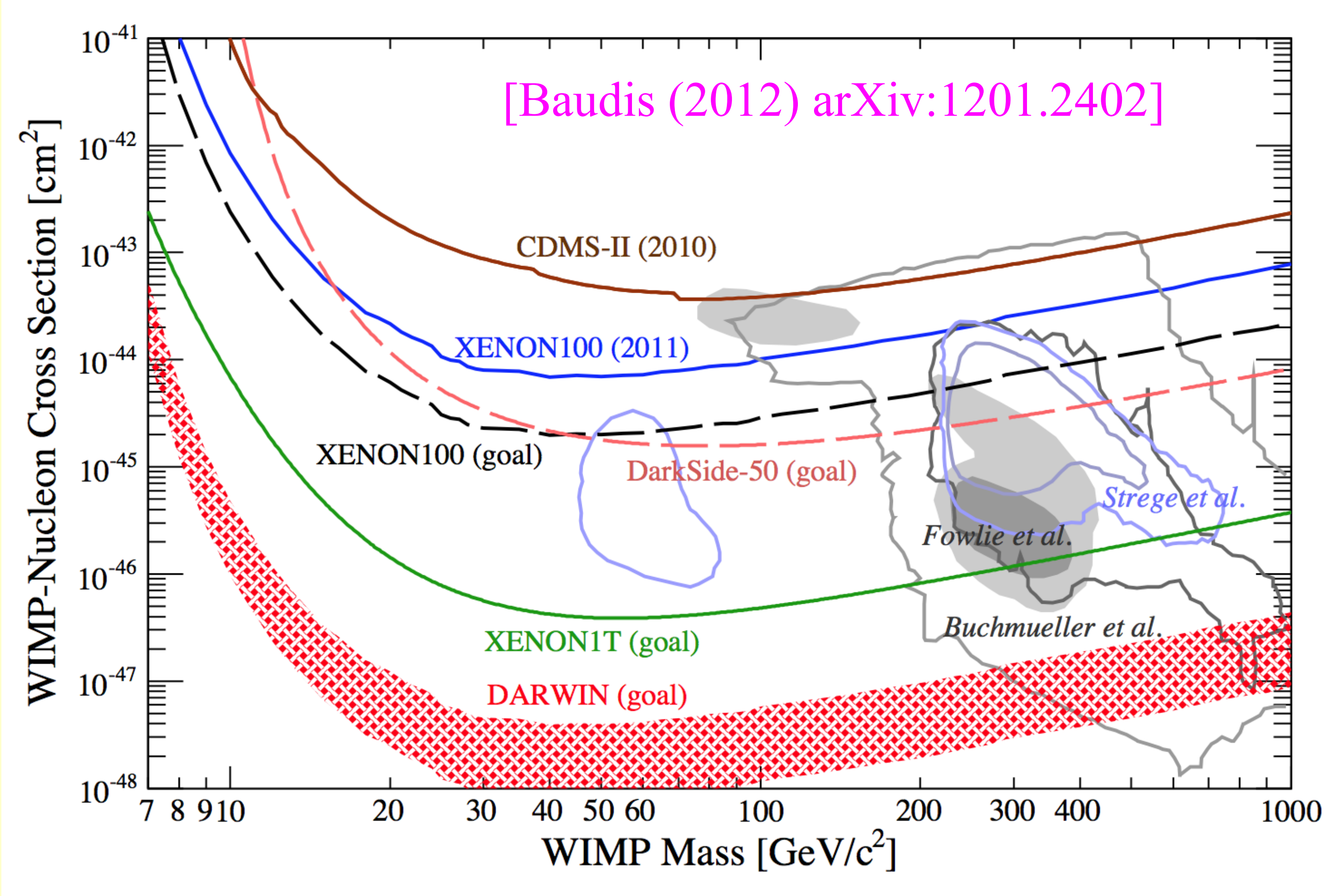
Failed detections give upper limits ...
(in disagreement with DAMA results)

Gray regions: theoretical predictions of SUSY (~100 free parameters)



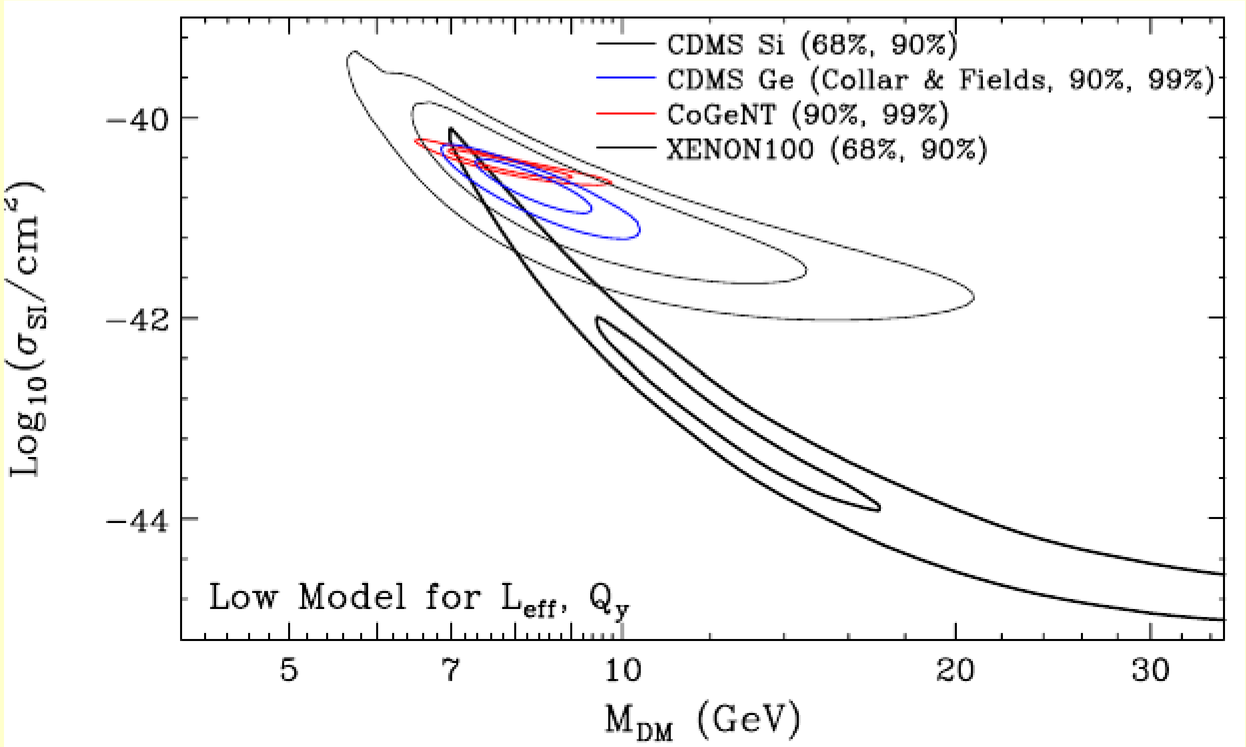
[Baudis (2007) astro-ph/0711.3788]

DARWIN: studium



DARWIN (dark matter wimp search with noble liquids) is a design study for a next-generation, multi-ton dark matter detector in Europe. Liquid argon and/or liquid xenon are the target media for the direct detection of dark matter candidates in the form of weakly interacting massive particles (WIMPs). Light and charge signals created by particle interactions in the active detector volume are observed via the time projection chamber technique. DARWIN is

Detection ?



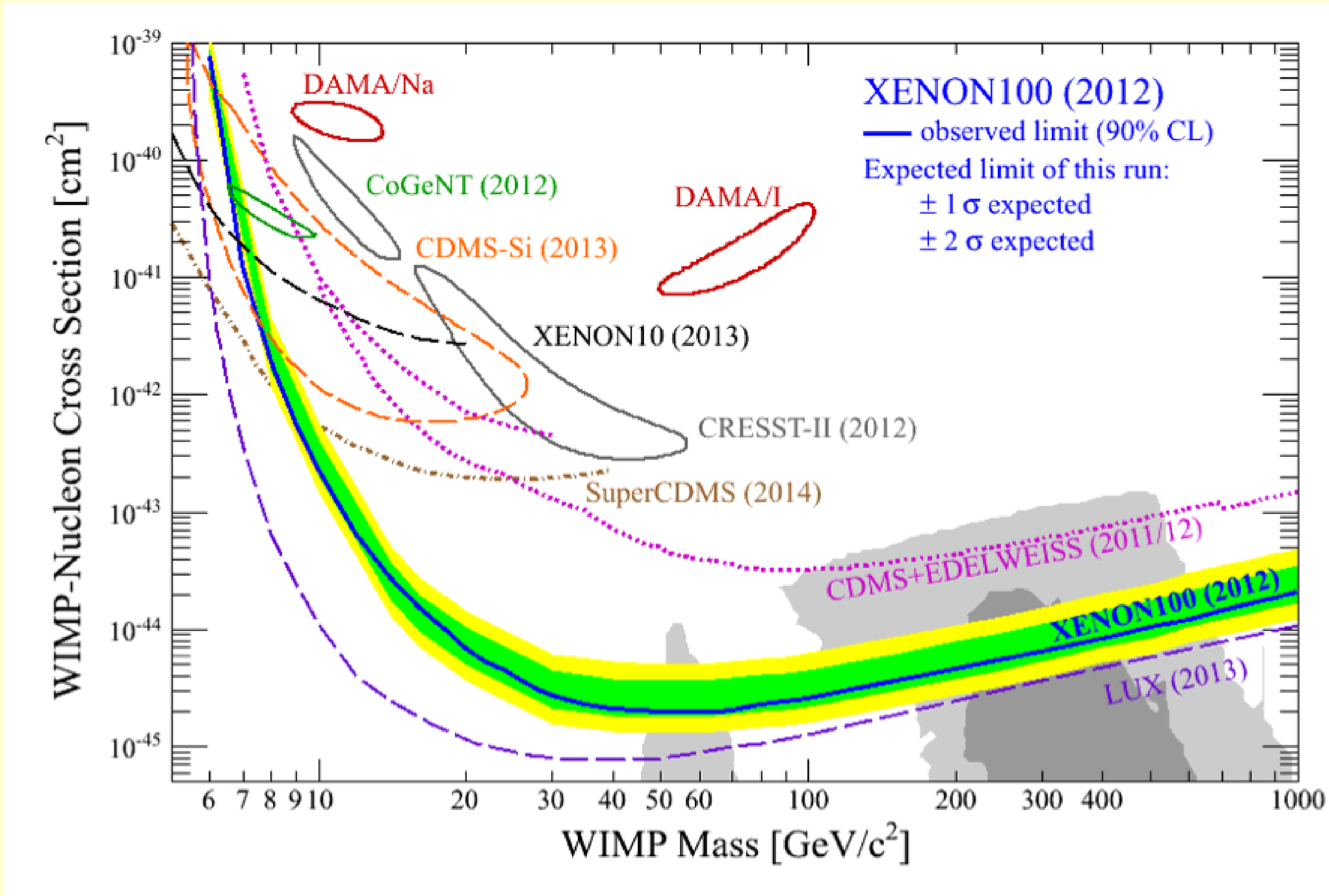
Some of the groups have observed single events which might be related to DM. If so, the plot above shows the preferred DM particle mass and cross-section for elastic nuclei scattering

(XENON100 – this experiment has a different detector)

[Hooper arXiv:1306.1790]

Direct Dark Matter Search with XENON100

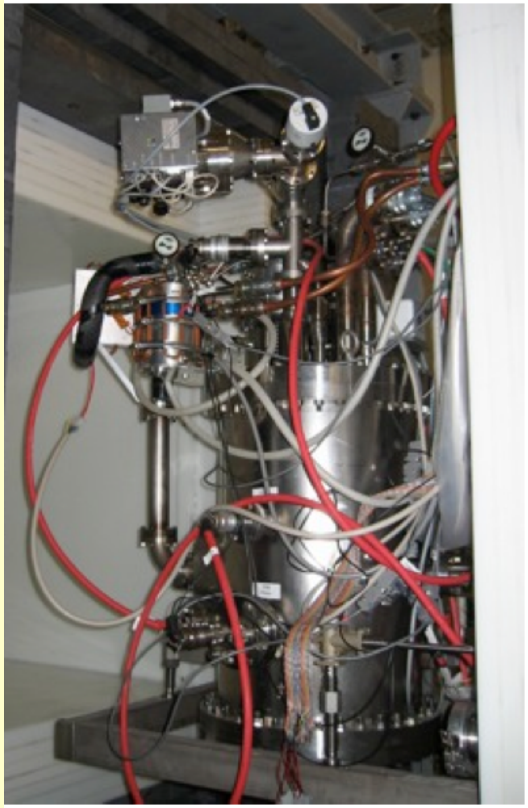
S.E.A. Orrigo[1,a,b]

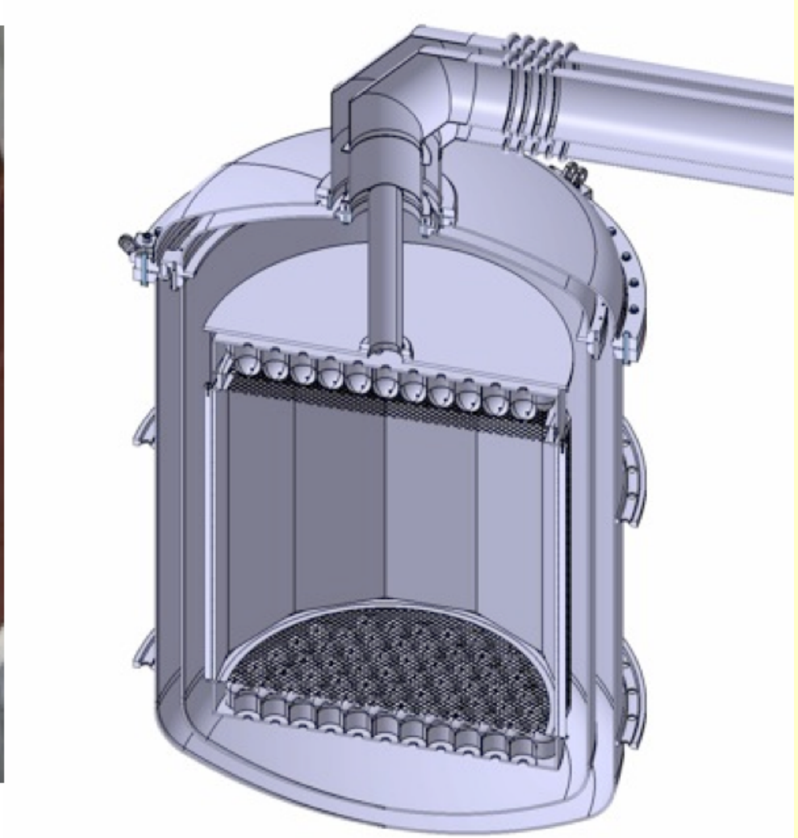


Xenon – I 2015

The XENON Dark Matter Program

past (2005 - 2007)	*current* (2007-2012)	*future* (2012-2017)





XENON10

Achieved (2007) σ_{SI}=8.8 x10^{-44} cm^2

XENON100

Achieved (2011) σ_{SI}=7.0 x10^{-45} cm^2

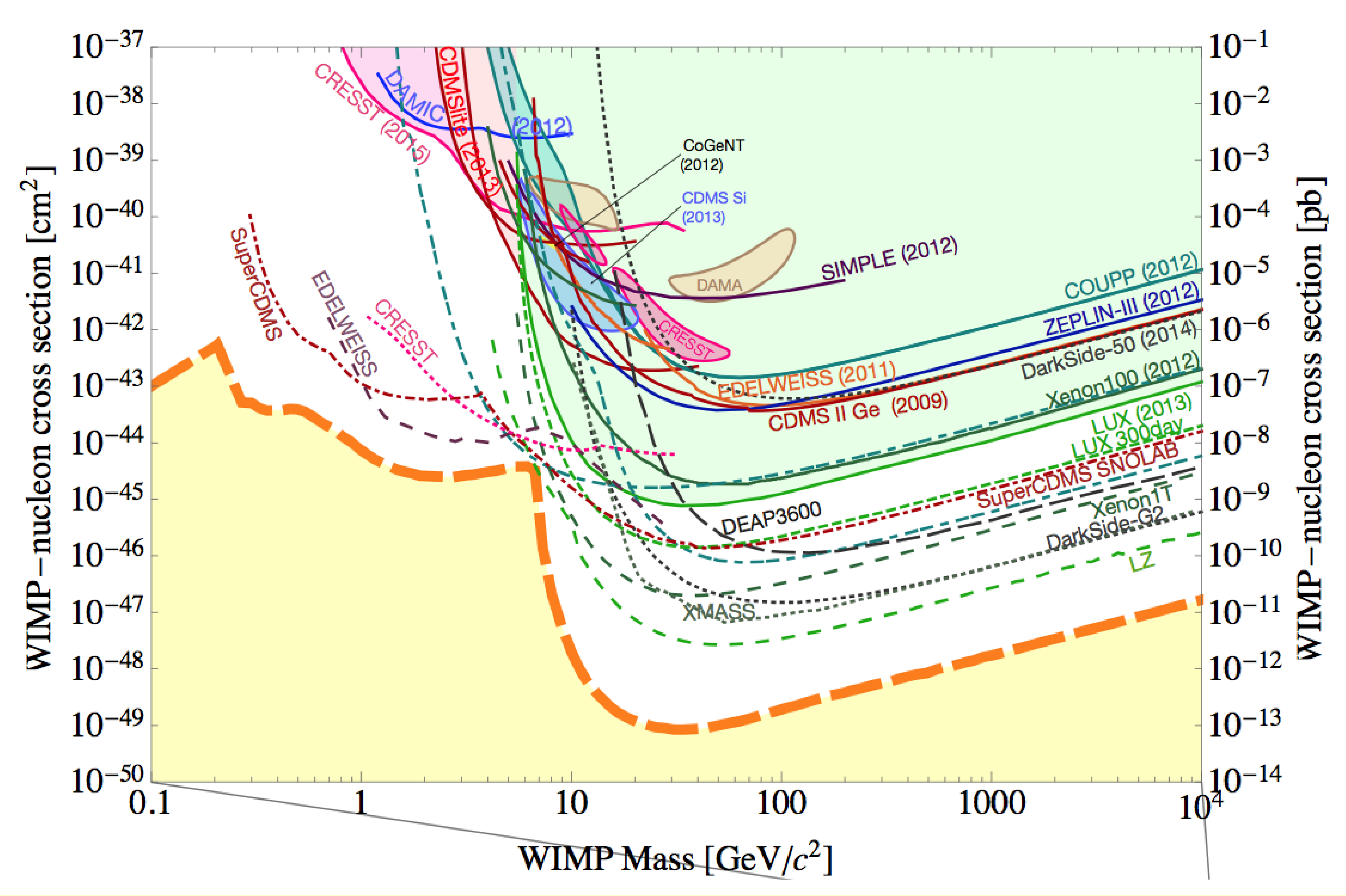
Projected (2012) σ_{SI}~2x10^{-45} cm^2

XENON1T

Projected (2017) σ_{SI} ~10^{-47} cm^2

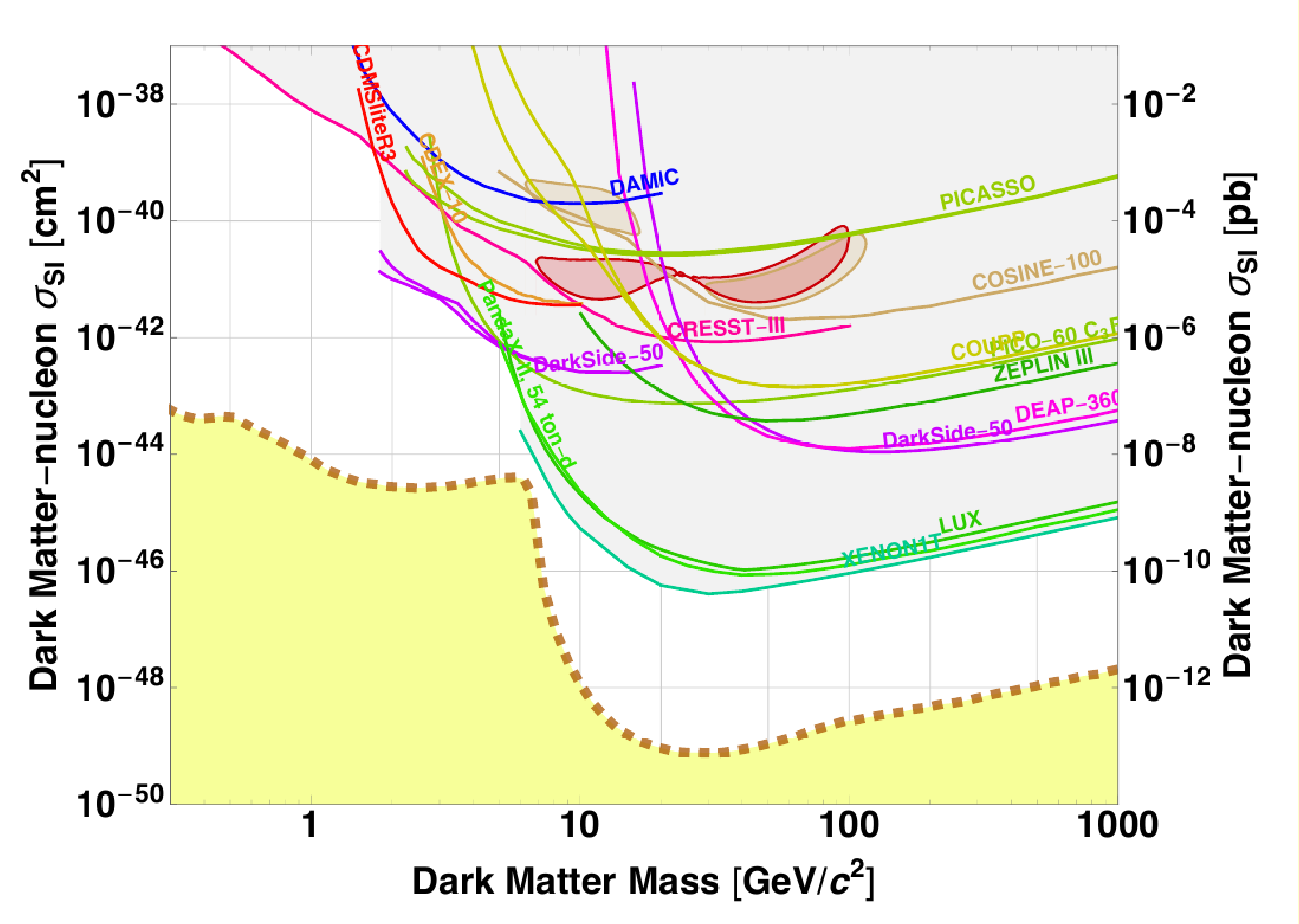
Limits from different Collaborations

[Figueroa-Feliciano, 34th Int. Cosmic Rays Conf. 2015]



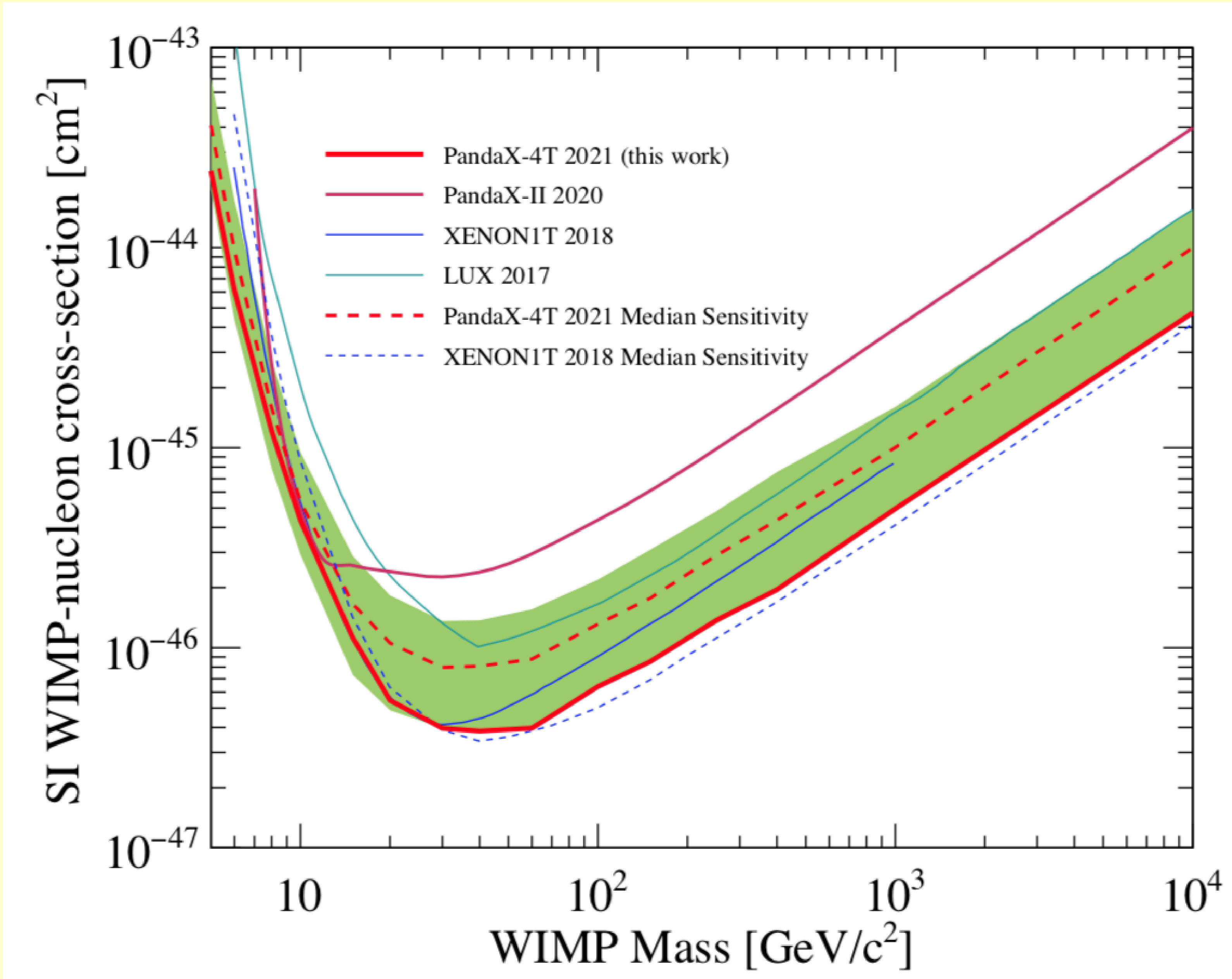
Limits from different Collaborations (~2019)

[https://supercdms.slac.stanford.edu/dark-matter-limit-plotter]



Dark Matter Search Results from the PandaX-4T Commissioning Run

Yue Meng,[1,2] Zhou Wang,[1,2,3] Yi Tao,[1,2] Abdusalam Abdukerim,[1] Zihao Bo,[1] Wei Chen,[1] Xun Chen,[1,2] Yunhua



Indirect methods

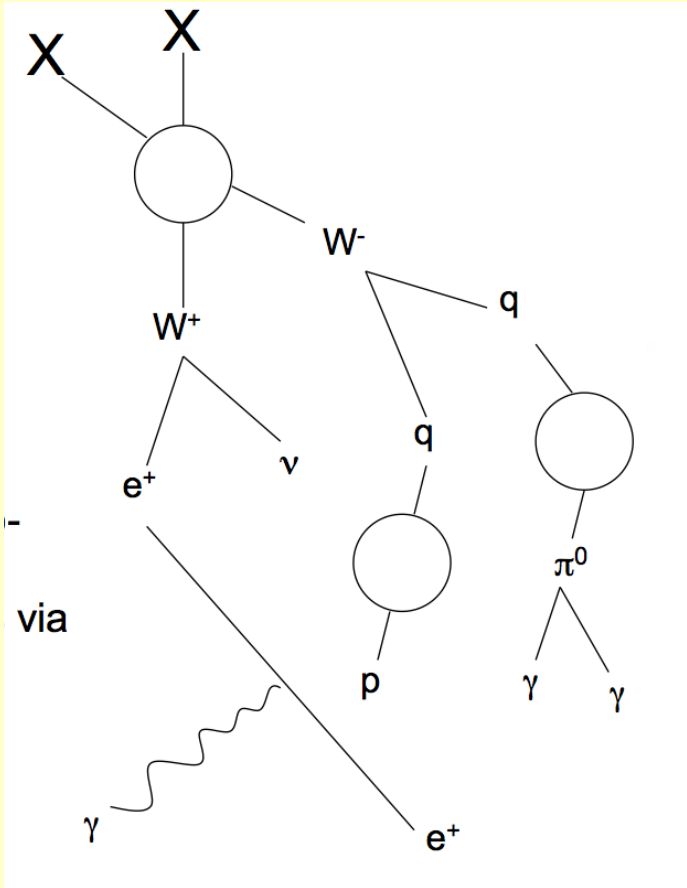
• DM may annihilate or decay (hopefully not too fast)
• The (final) product may be in the form of observable particles (photons, cosmic rays, neutrinos)
• The main problem is the proof that what we observe has anything to do with DM (No alternative? Our model-expected spatial and/or energy distribution of products?)

Anihilacja DM?

WIMPs may annihilate / decay producing cascades of other particles (some not dark, we hope) Stable interacting products may be observed

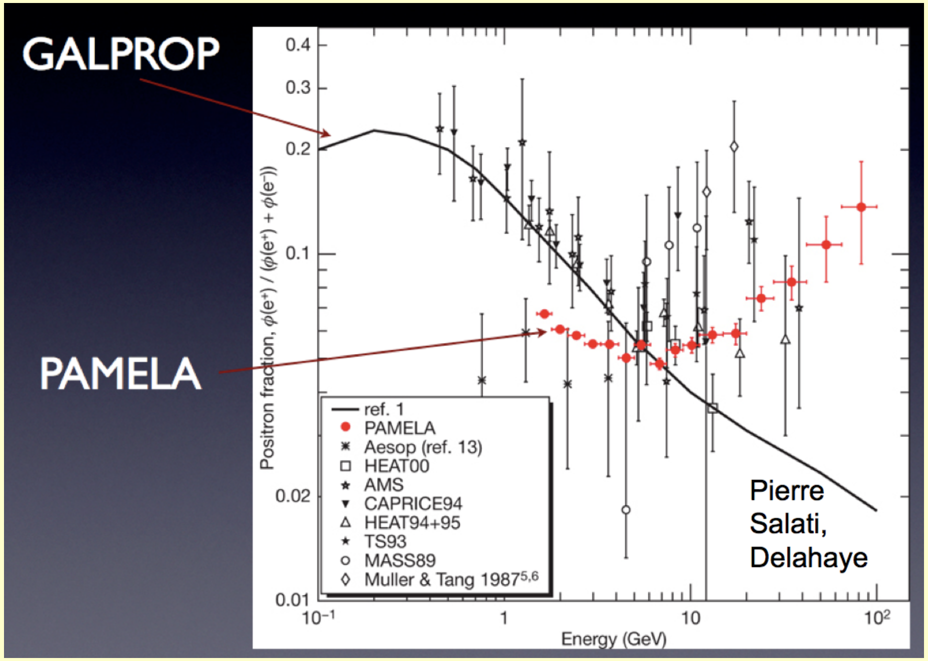
Possible also: synchrotron and inverse Compton with energetic product-particles

On the right: an example of a hypothetical cascade

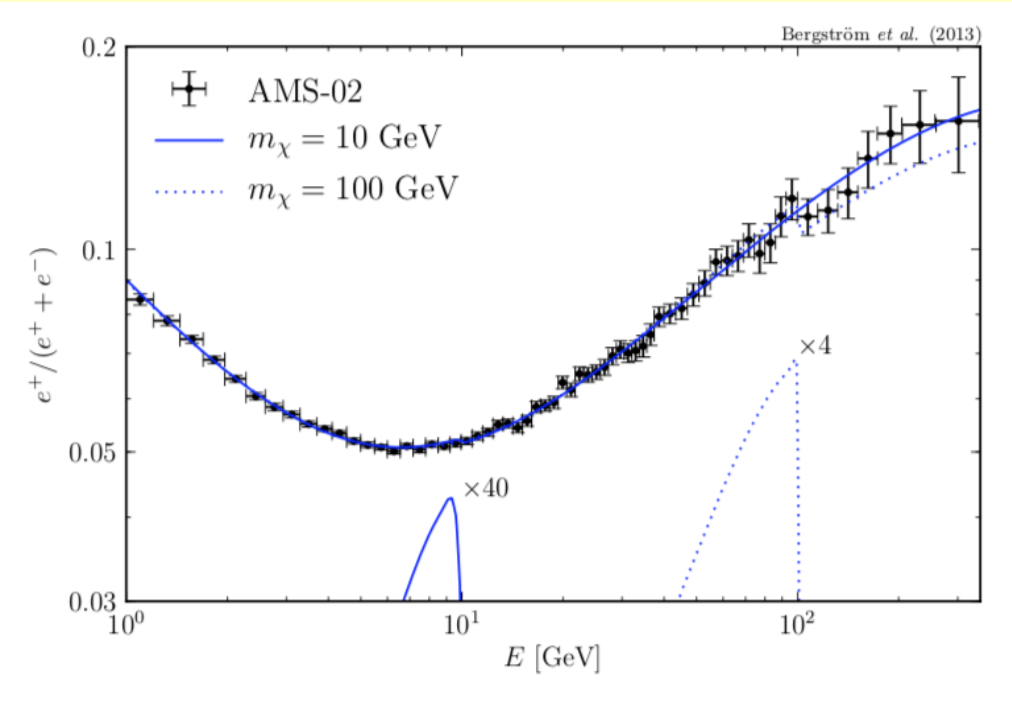


DM annihilation ?

"PAMELA excess" -
Excess of positrons in cosmic rays spectrum as compared to expectations based on the model of their propagation through the Galaxy



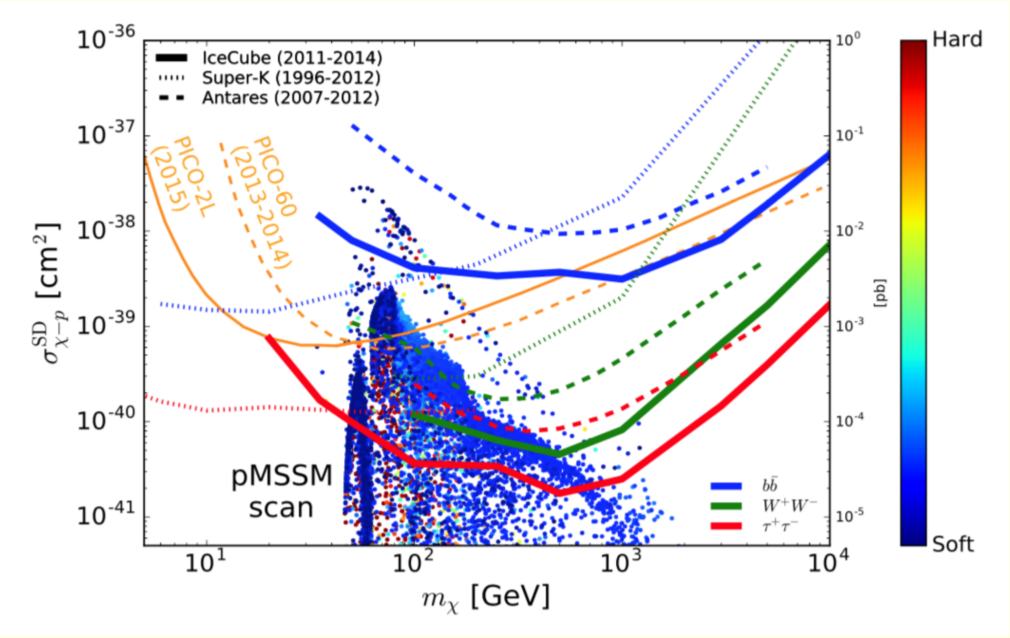
Perhaps these are positrons produced by pulsars? (Geminga is emitting photons >> TeV ← → inverse Compton producing energetic positrons?)



If from annihilation we should observe neutrinos as well (IceCube)

DM annihilation ?

DM annihilation should produce (among other particles) neutrinos of very high energies in numbers depending on process details



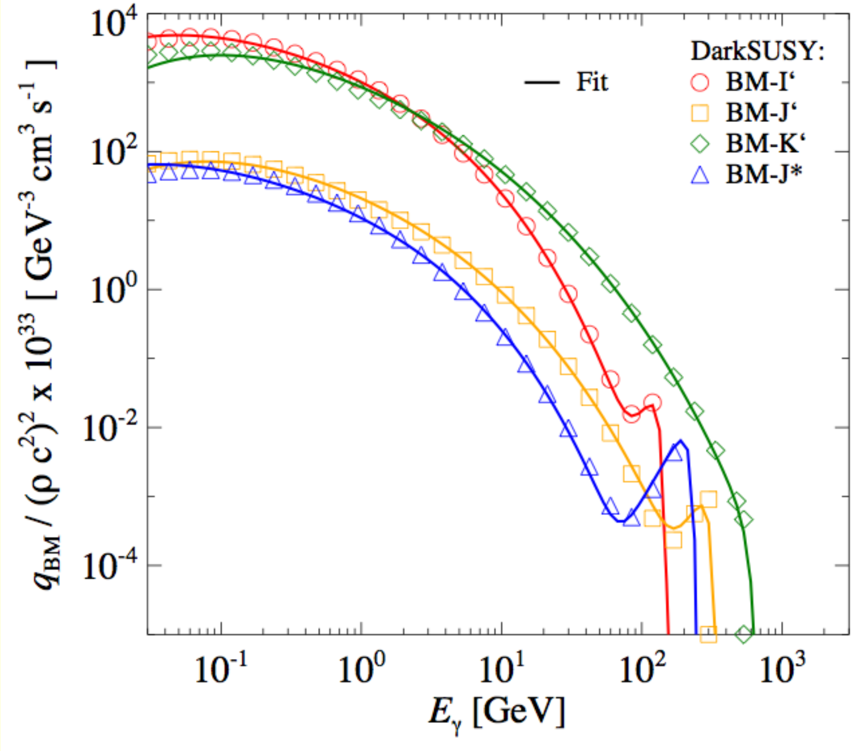
Lack of such IceCube observations gives the limits shown in the figure.

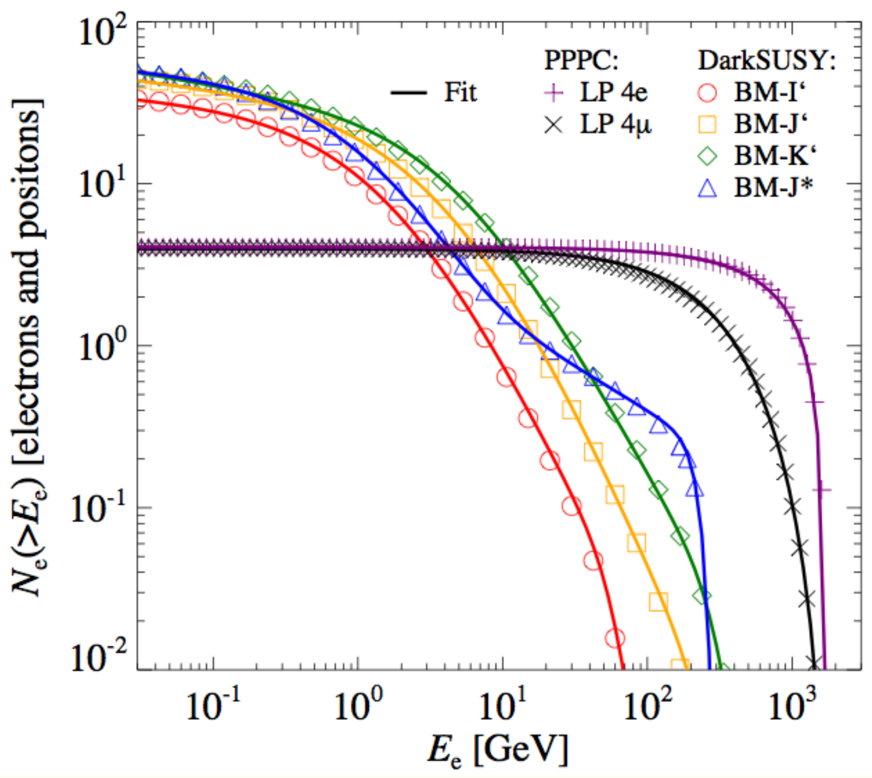
(See also the slides at the end of the lecture for different interpretation of more recent IceCube data)

[241] M. G. Aartsen et al. (IceCube), Eur. Phys. J. **C77**, 146 (2017), 1612.05949

DM annihilation ?

BM	m_χ [GeV]	$\Omega_\chi h^2$	$\langle \sigma v \rangle$ [$cm^3\ s^{-1}$]
I′	140	0.09	4.0×10^{-27}
J′	315	0.12	3.3×10^{-28}
K′	570	0.10	4.4×10^{-26}
J*	234	0.09	8.9×10^{-29}





THEORY:
4 examples of annihilation scenarios, their cross-sections, spectra of produced gamma photons and ultra-relativistic electrons
("leptophiilic" & "supersymmetric" DM)

[Pinzke et al.(2011)arXiv:1105.3240]

DM "creation"

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle \left(n^2 - n_{\rm eq}^2 \right)$$

$$\langle \sigma_{\rm eff} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}}.$$

$$v_{ij} = \frac{\sqrt{(p_i \cdot p_j)^2 - m_i^2 m_j^2}}{E_i E_j}.$$

Crucial parameter: $\langle \sigma_{\rm eff} v \rangle$

[Gondolo i in (2004) JCAP, 0407, 008]

DM particles concentration was established as an effect of "frozen" annihilation. ("Frozen" for reason similar to setting the n/p ratio before primordial nucleosynthesis.) Concentrations fall down because of annihilation and Hubble expansion. At some moment annihilation stops because the free path of DM particles becomes longer than the length scale in the Universe and the ratio DM/photons is established. In an expanding Universe DM particles will never meet. The value of the cross-section defines the residual concentration ↔ \Omega_DM

DM as a remnant from early epochs

Approximate calculation with many simplifications gives the following condition for the annihilation crosssection which ensures the right DM density in the present Universe:

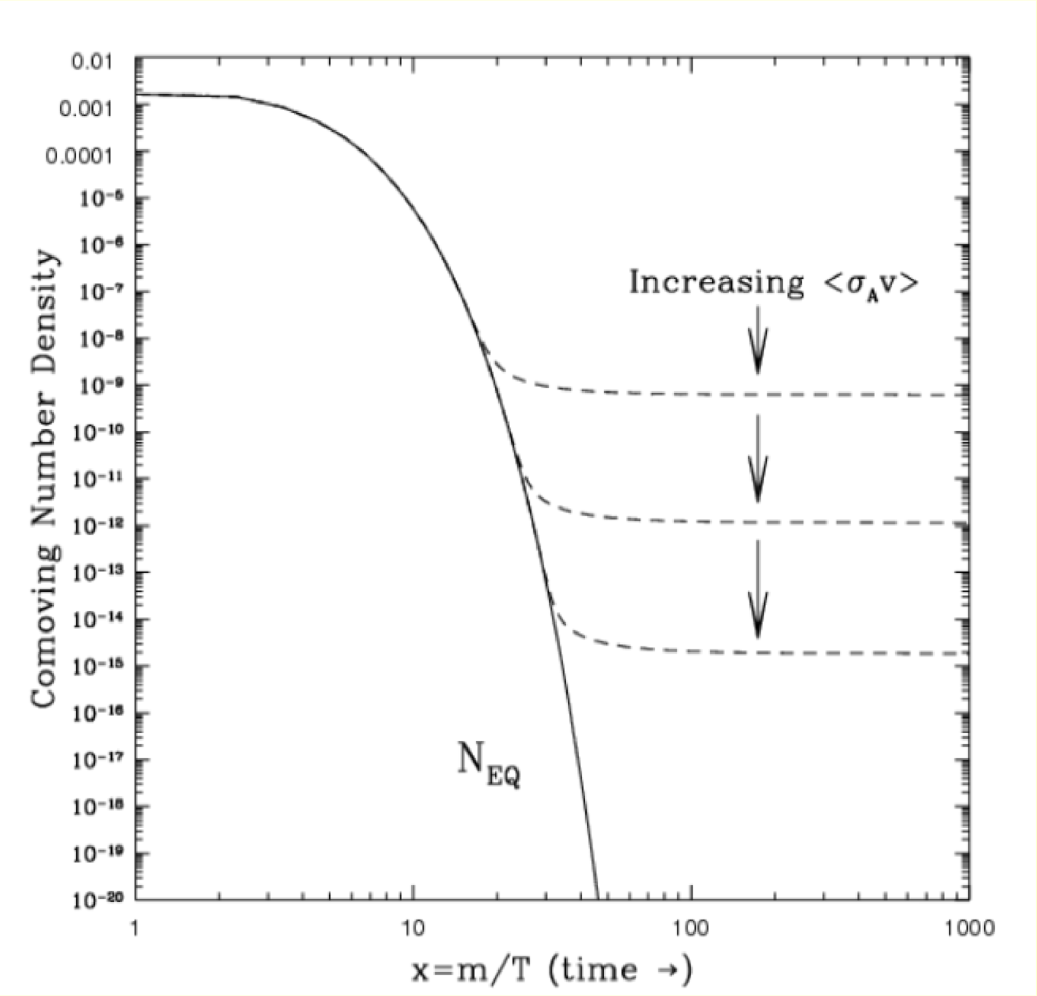
$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \ (n^2 - n_{eq}^2)$$

$$\Omega h^2 \approx \frac{3 \cdot 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$ ~ 0.1

With <\sigma*v> ~ 3*10^{-26} cm^3/s, one gets the observed DM density.

[Bertone et al. (2005) Phys.Rept. 405, 279; Jungman et al. (1996) Phys.Rept. 267, 195]

DM as a remnant from early epochs



D. Hooper (2018) arXiv: 1812.02029

Emission rate

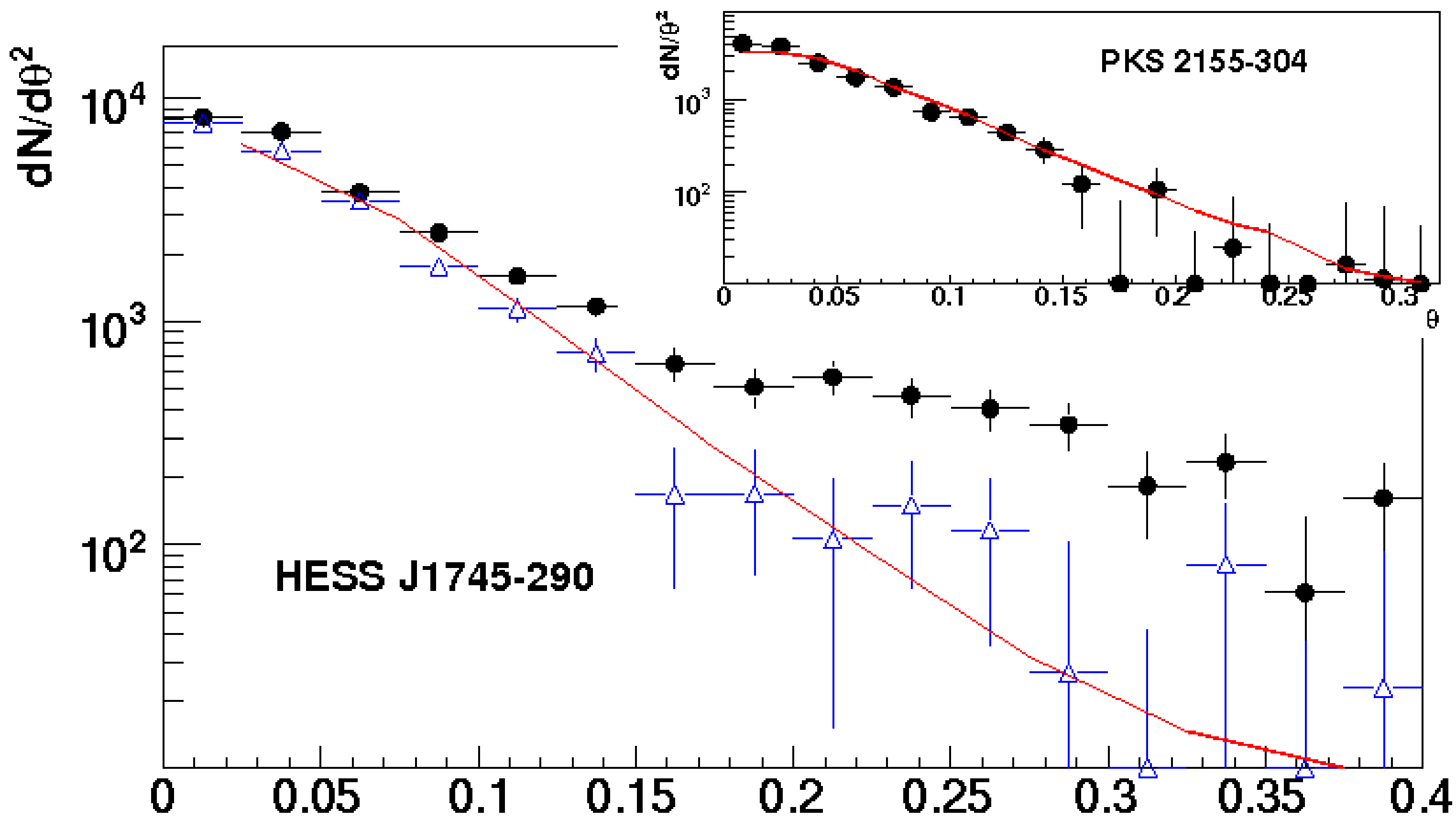
The intensity of annihilation radiation is given as an integral of annihilation rate along the line of sight:

$$\begin{aligned} I(E,\theta) =& \frac{dN}{dA dt d\Omega dE} \\ =& \frac{\langle \sigma v \rangle}{8\pi(1+z)^2} \frac{dN_{ann}((1+z)E)}{d(1+z)E} \int ds \left(\frac{\rho_{DM}(r(s,\theta))}{m_{DM}} \right)^2 \end{aligned}$$

($I(..)$ in gamma-astronomy convention). $r(s,\theta) = \sqrt{s^2 + d^2\theta^2}$, where d is the (angular diameter) distance to the source. The dependence of intensity on the direction θ is directly related to the spatial distribution of DM, which is modeled for instance as:

$$\begin{aligned} \rho_{NWF}(r) =& \frac{\rho_s}{(r/r_s)(r/r_s+1)^2} \\ \rho_E(r) =& \rho_e \exp\left\{ -d_n \left[\left(\frac{r}{r_e} \right)^{1/n} - 1 \right] \right\} \end{aligned}$$

Annihilation of dark matter ?



[Horns +HESS (2007) astro-ph/0702373]

H.E.S.S. telescope registers photons with energies > 100 GeV. The plot of gamma intensity inside 0.4 deg from our Galaxy center is less steep than the plot for PKS 2155-304 – a strong blazar (a point like source) . Perhaps we observe also radiation from an extended component, possibly from DM distribution around the center

(Is this in agreement with DM distribution in the Galaxy ?)

Galaxy Center 2012:

THIS distribution agrees with DM distribution in Galaxy

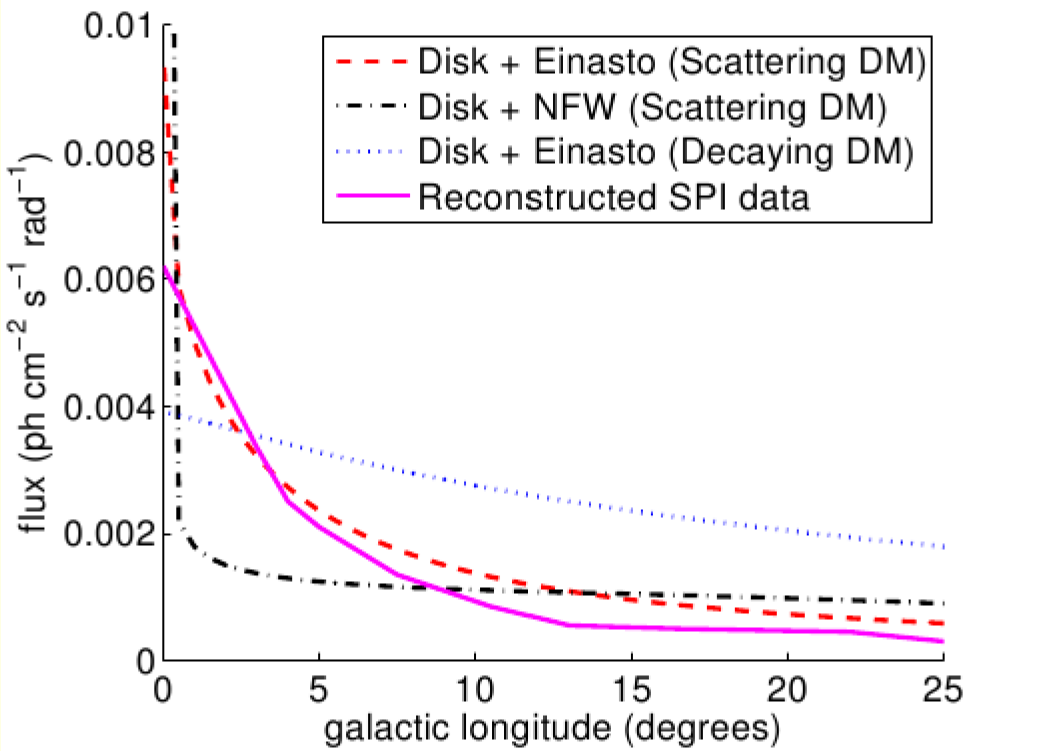
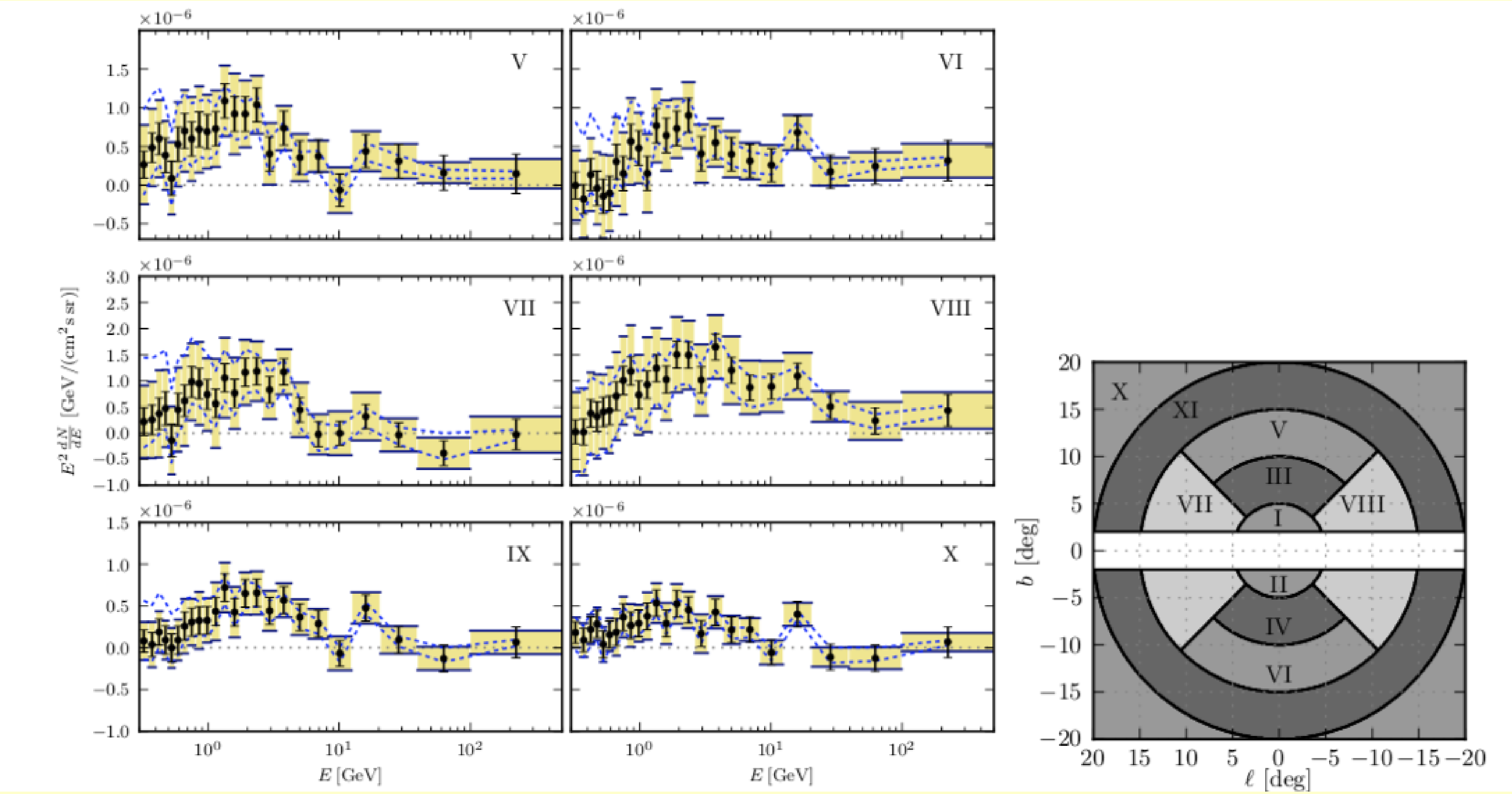


Figure 2: Longitudinal dark matter profiles for the three dark matter models considered, including the disk component from radioactive isotopes. Fluxes are integrated over galactic latitudes $-15° < b < 15°$. “Scattering” refers to either scattering multistate dark matter or annihilating light dark matter. The solid magenta line is left-right averaged, reconstructed SPI data from [6], taken from the skymaps of [36].

[Vincent i in (2012) arXiv:1201.0997]

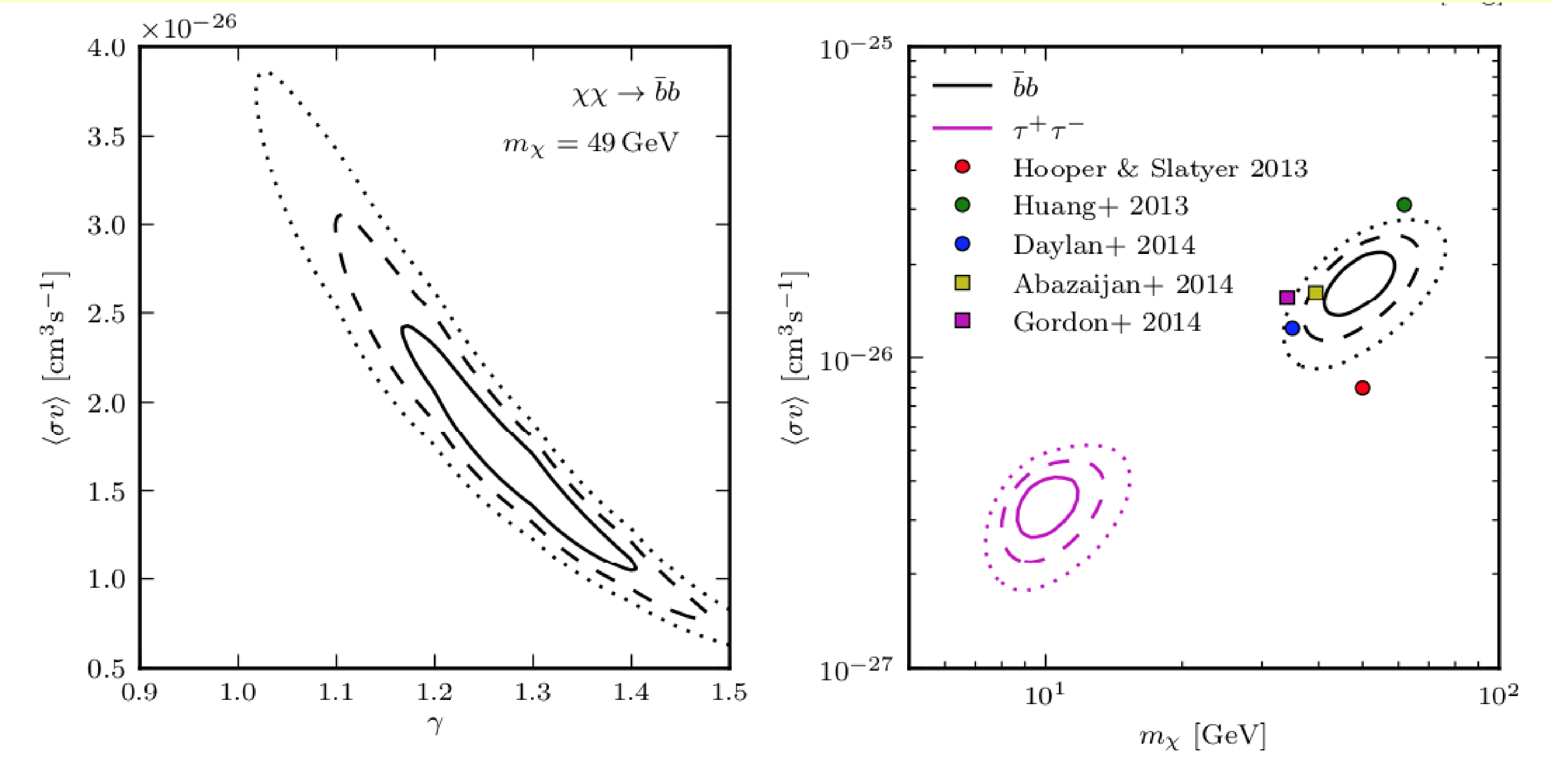
Galaxy Center 2018:



In different regions around the Galaxy Center there are “excess radiation” at energies ~few GeV

D. Hooper (2018) arXiv: 1812.02029

Galaxy Center 2018:



If the radiation excess is interpreted as a result of DM annihilation, than, depending on the postulated chanel of reactions, one gets the above fits for the cross-section and particle masses

D. Hooper (2018) arXiv: 1812.02029

PHYSICAL REVIEW D **103,** 063029 (2021)

Characteristics of the Galactic Center excess measured with 11 years of *Fermi*-LAT data

Mattia Di Mauro*

GCE = Gal.Cen.excess
IEM = interstell.emiss.model

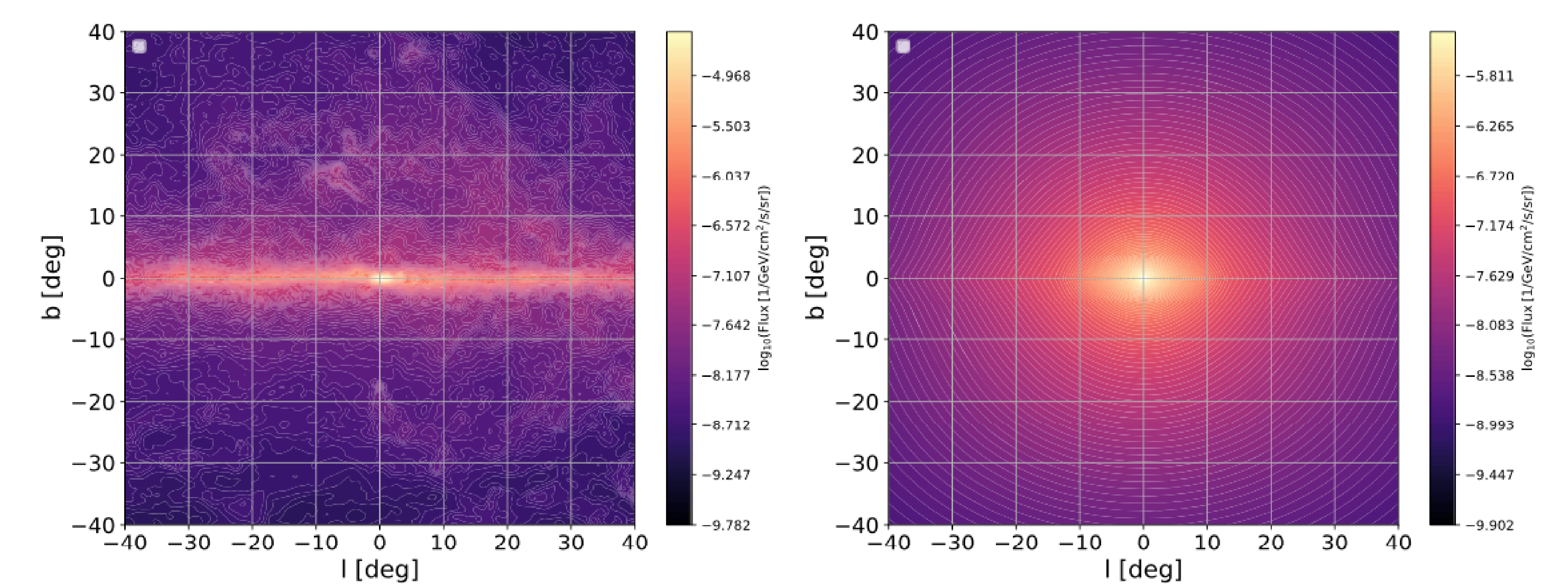


FIG. 1. Map of the flux calculated at 1 GeV for the γ-ray emission produced for bremsstrahlung and π^0 from cosmic-ray protons (left panel) and for inverse Compton scattering from electrons and positrons injected from the galactic center (right panel). The color bar

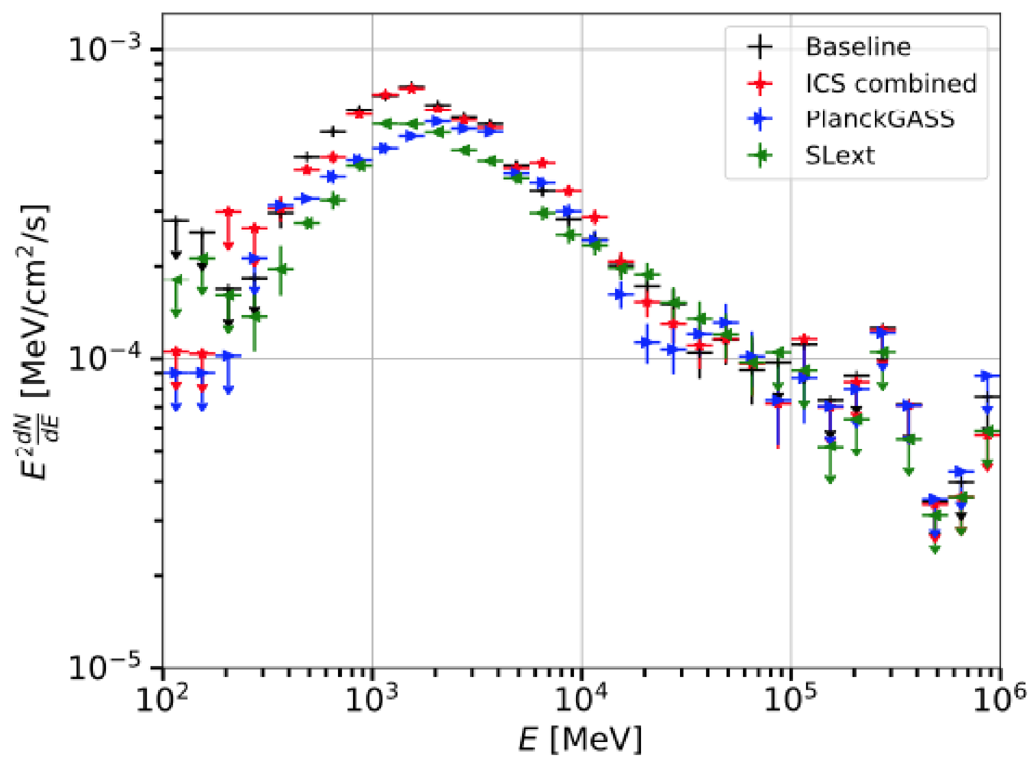
(Two examples of IEMs)
GCE = data - IEM

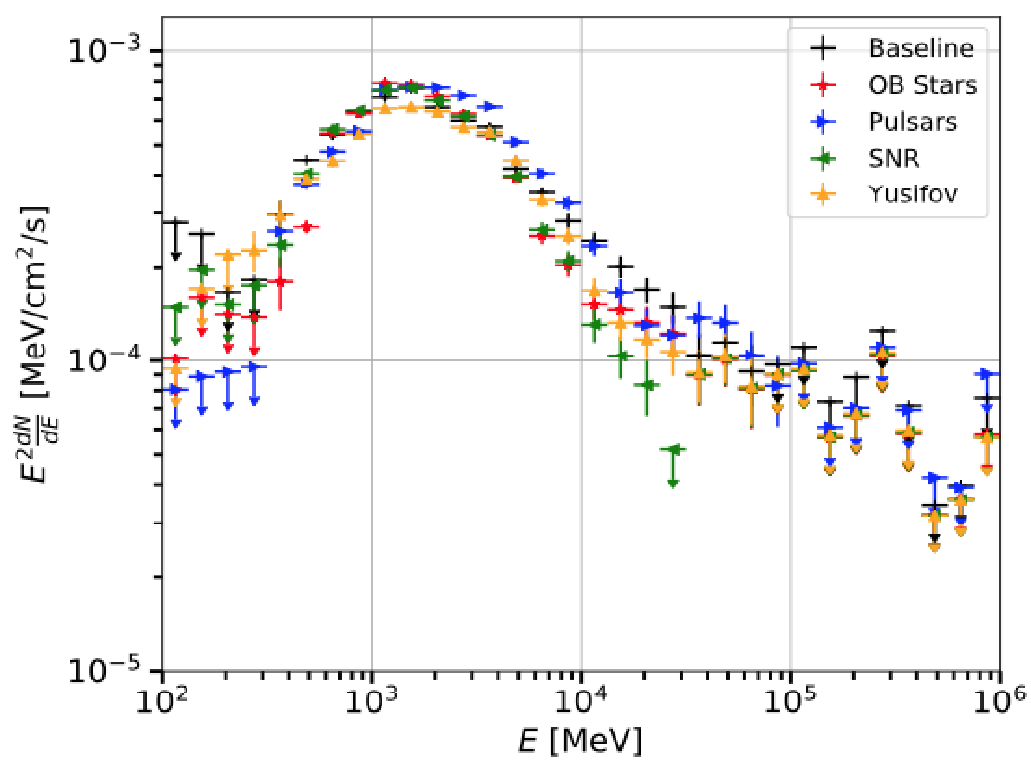
PHYSICAL REVIEW D **103,** 063029 (2021)

Characteristics of the Galactic Center excess measured with 11 years of *Fermi*-LAT data

Mattia Di Mauro*

GCE spectra for different IEMs

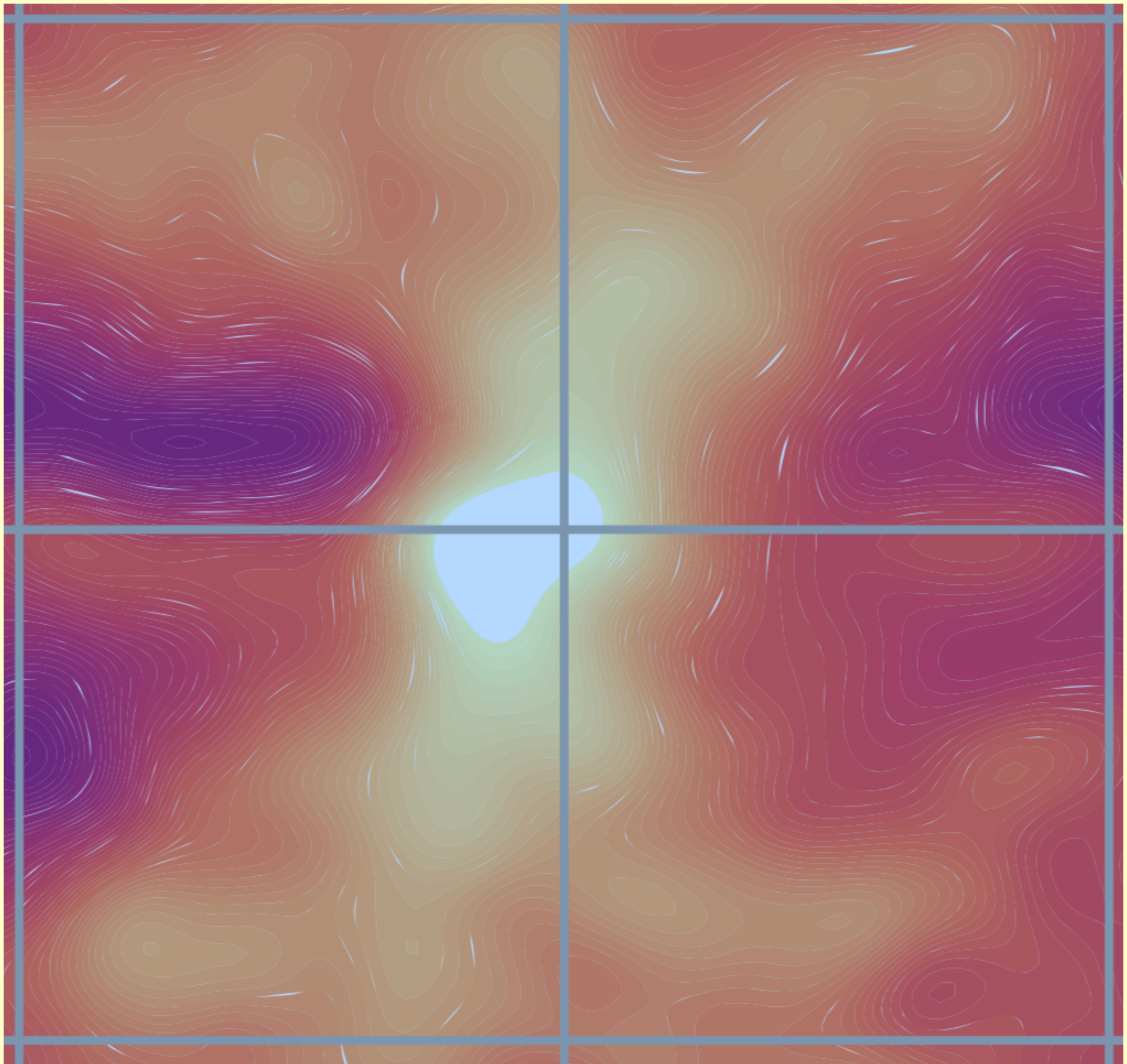


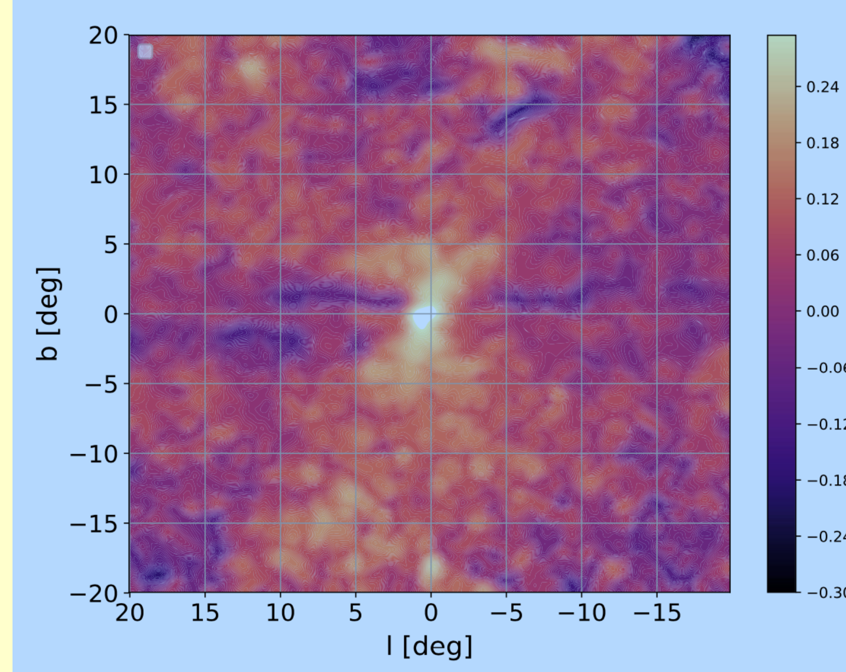


PHYSICAL REVIEW D **103**, 063029 (2021)

Characteristics of the Galactic Center excess measured with 11 years of *Fermi*-LAT data

Mattia Di Mauro*





GCE + residuals
10x10 deg map on the left

Dark matter annihilation and the Galactic Centre Excess

Robert J. J. Grand[1,2★], Simon D. M. White[3]

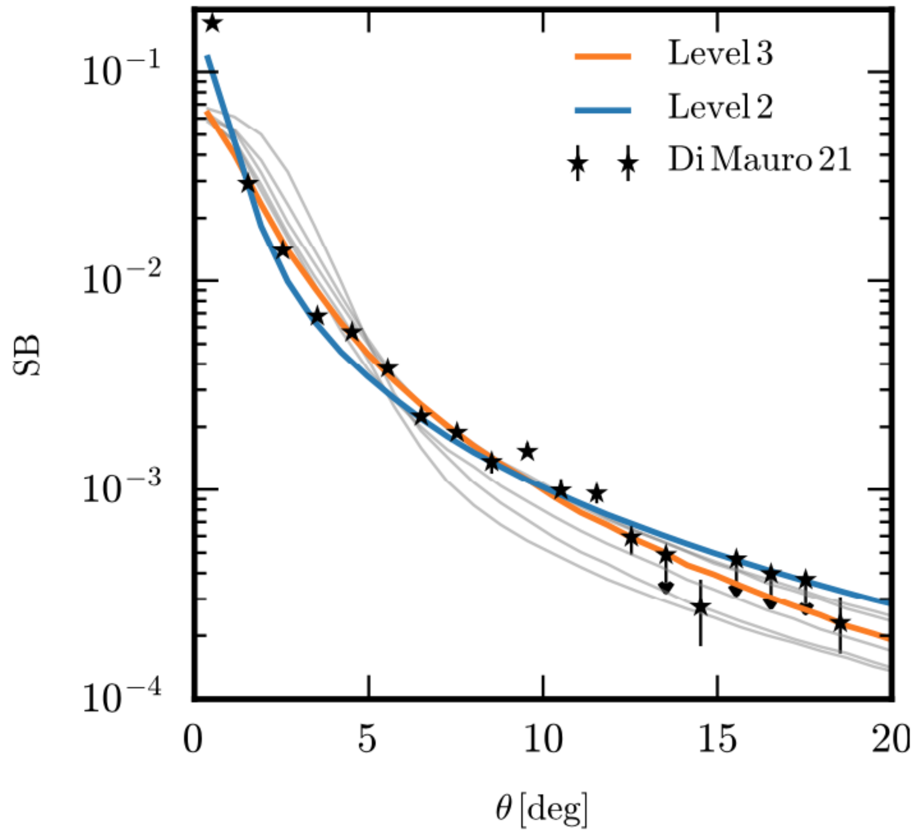
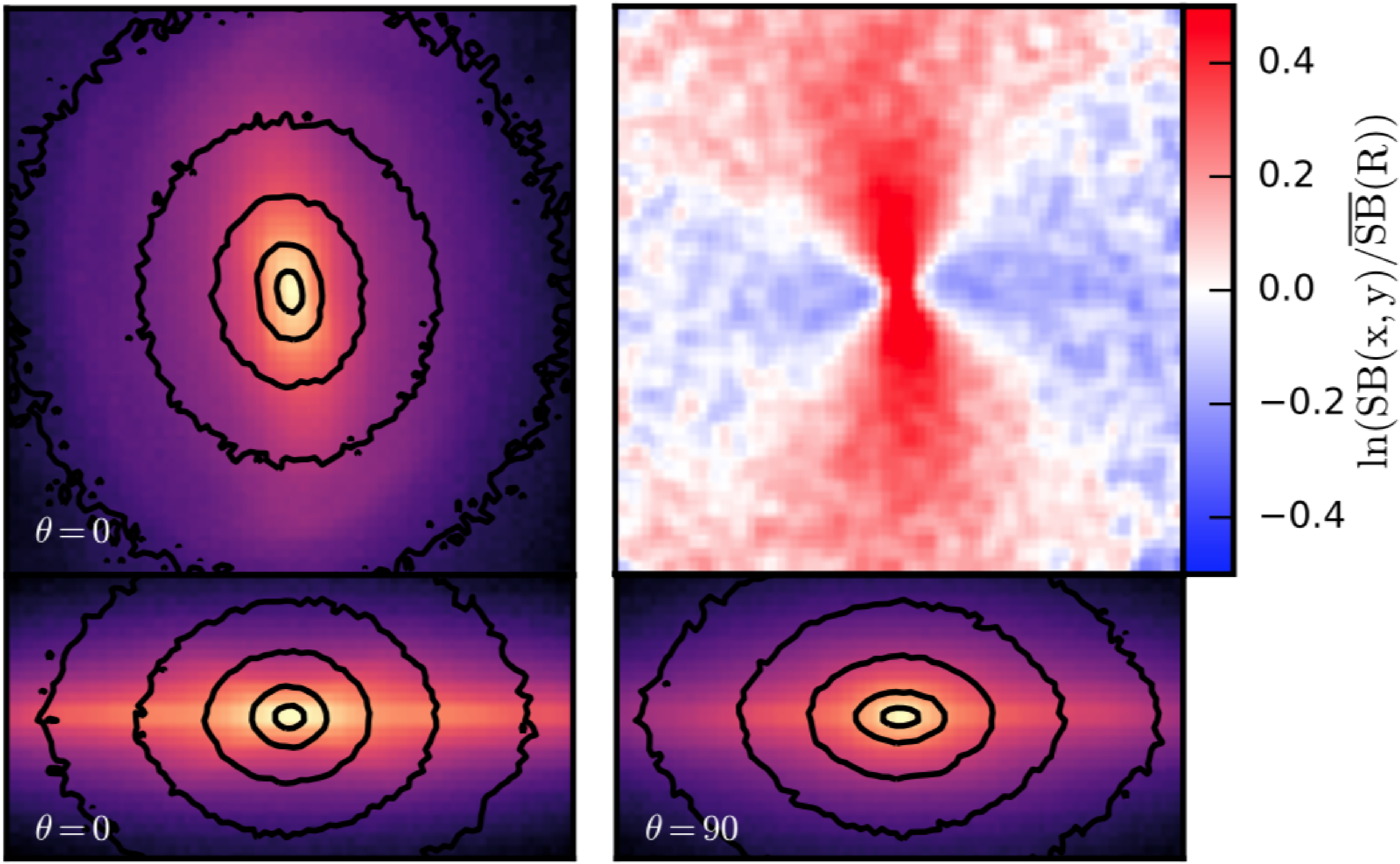


Figure 1. Mean angular surface brightness profiles of the emission produced by dark matter annihilation for our simulated haloes (solid curves) in the full physics runs (left panel) and in the dark-matter-only runs (right panel), together with the observed profile of the Galactic Centre Excess (star symbols, note that four of these are upper limits) from the 11 year Fermi-LAT dataset (Di Mauro 2021). The profile of our highest resolution (level 2) simulation is coloured blue and its lower resolution (level 3) counterpart is coloured orange; the other five level 3 simulations are coloured grey.

Dark matter annihilation and the Galactic Centre Excess

Robert J. J. Grand[1,2]*, Simon D. M. White[3]



Authors: DM annihilation possible source of GCE

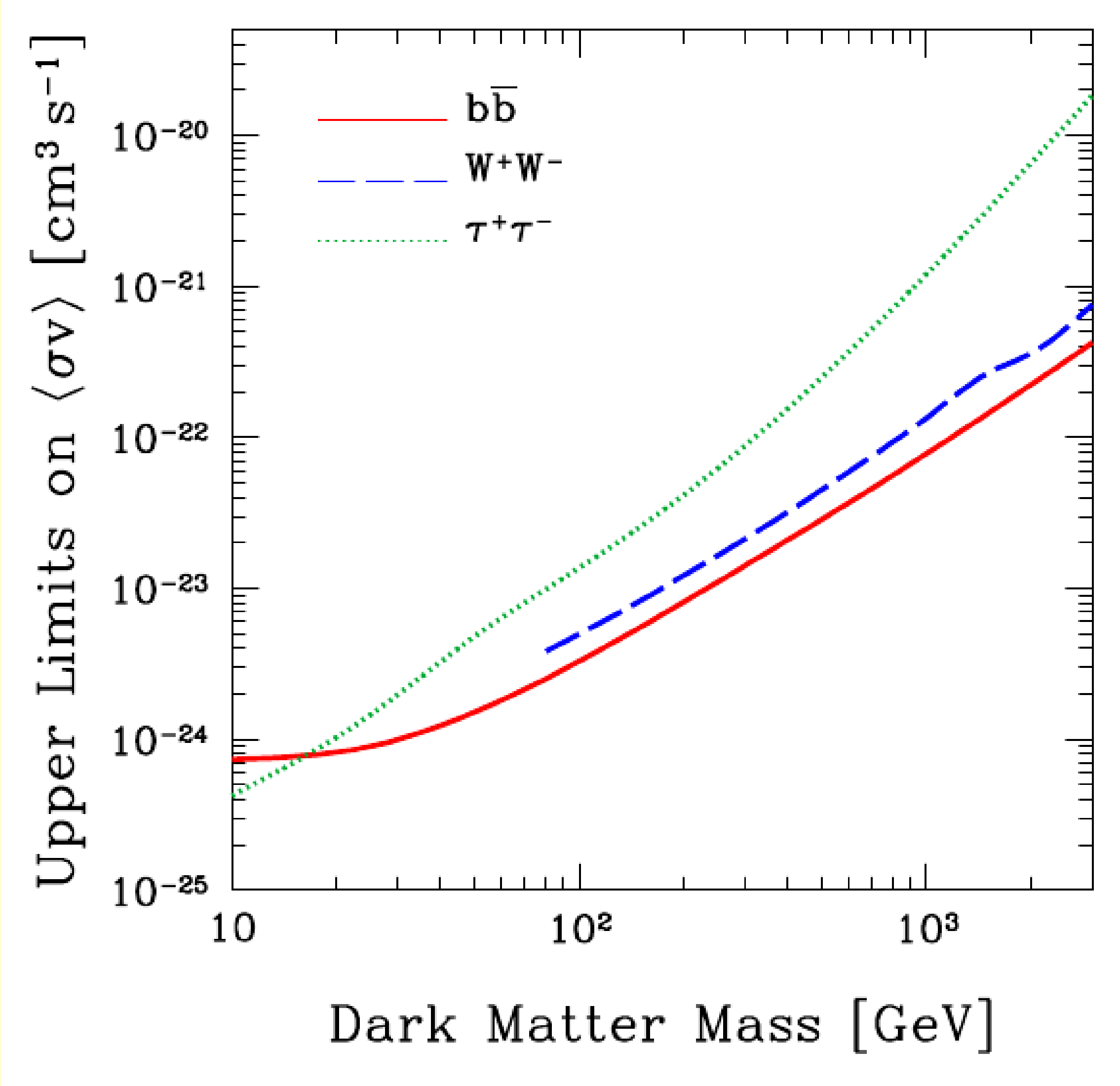
Galaxy clusters observations

Cluster	l (°)	b (°)	z	$M_{\rm vir}$ ($10^{14} h^{-1} M_\odot$)	$r_{\rm vir}$ (h^{-1} Mpc)	$F_{\rm lim}(> 1\,{\rm GeV})$ (10^{-9} cm^{-2} s^{-1})	$F_{\rm DM}/F_{\rm lim}$
A2142	44.23	48.69	0.0904	16.86	2.33	1.93	0.15
A3266	272.09	−40.17	0.0602	12.57	2.15	2.23	0.23
A2029	6.50	50.55	0.0779	12.05	2.10	4.39	0.07
A401	164.18	−38.87	0.0743	12.04	2.10	1.42	0.22
Centaurus	302.41	21.56	0.0499	3.19	1.37	2.93	0.08
Coma	58.09	87.96	0.0232	9.60	2.01	2.79	1.00
Fornax	236.72	−53.64	0.0046	1.17	1.01	0.54	21.51
Hydra	269.63	26.51	0.0114	2.31	1.26	3.77	0.89
M49	286.92	70.17	0.0044	0.60	0.80	0.93	7.54
NGC4636	297.75	65.47	0.0037	0.16	0.51	1.25	2.48

Reversed argument: assuming some DM distribution in the central parts of clusters (which follow observations of galaxy velocity dispersion, X-rays, and possibly lensing) one can calculate the expected flux of gamma radiation for given DM annihilation cross-section. On the other hand the flux can be measured / upper-limited. In most cases the expected gamma flux is too small to be observed (full table contains 49 objects) but in some cases there is a contradiction. In Fornax Cluster one would expect much more gamma photons than observed. This gives an upper limit On cross-section / DM particle mass.

[Ando & Nagai (2012) arXiv:1201.0753]

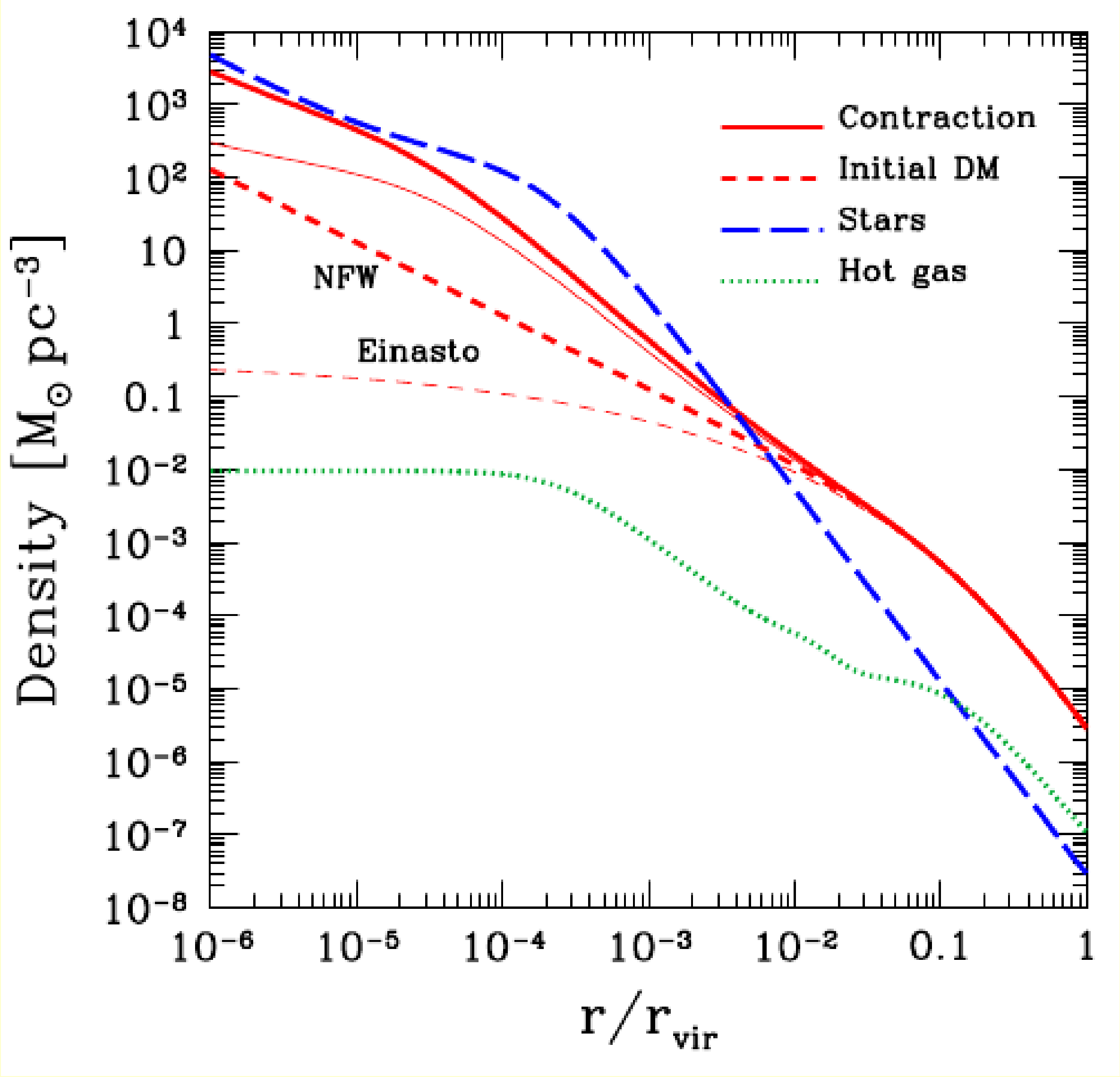
Observations of galaxy clusters



Upper limits on cross-sections as function of particle mass for different annihilation scenarios. Based on Fornax cluster observations, assuming NFW mass profile.

[Ando & Nagai (2012) arXiv:1201.0753]

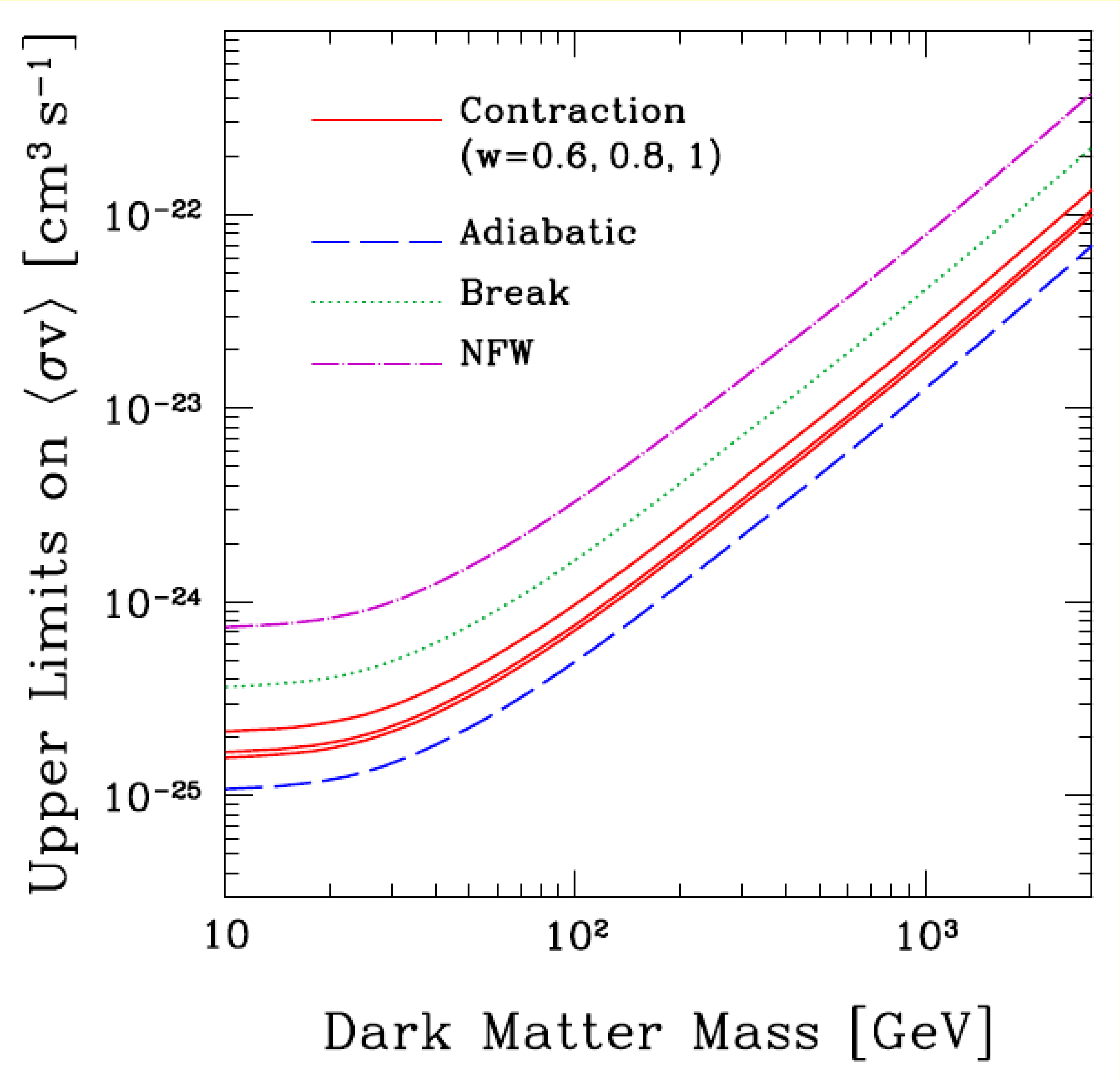
DM density increase due to infalling baryon matter (gas + stars)



Baryons (being dissipative) fall into gravitational well of DM. The well becomes deeper and the density of DM increases as compared to initial conditions just after DM halo formation. This mechanism gives a higher expected rate of DM annihilation.

[Ando & Nagai (2012) arXiv:1201.0753]

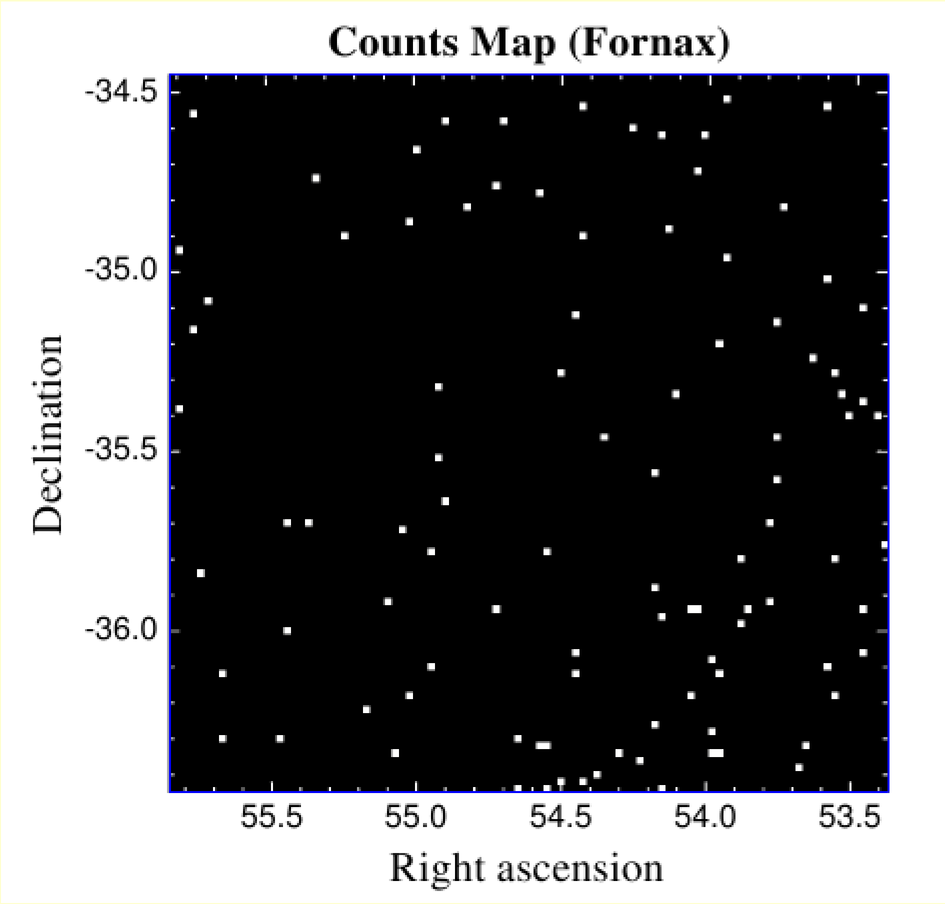
Observations of galaxy clusters

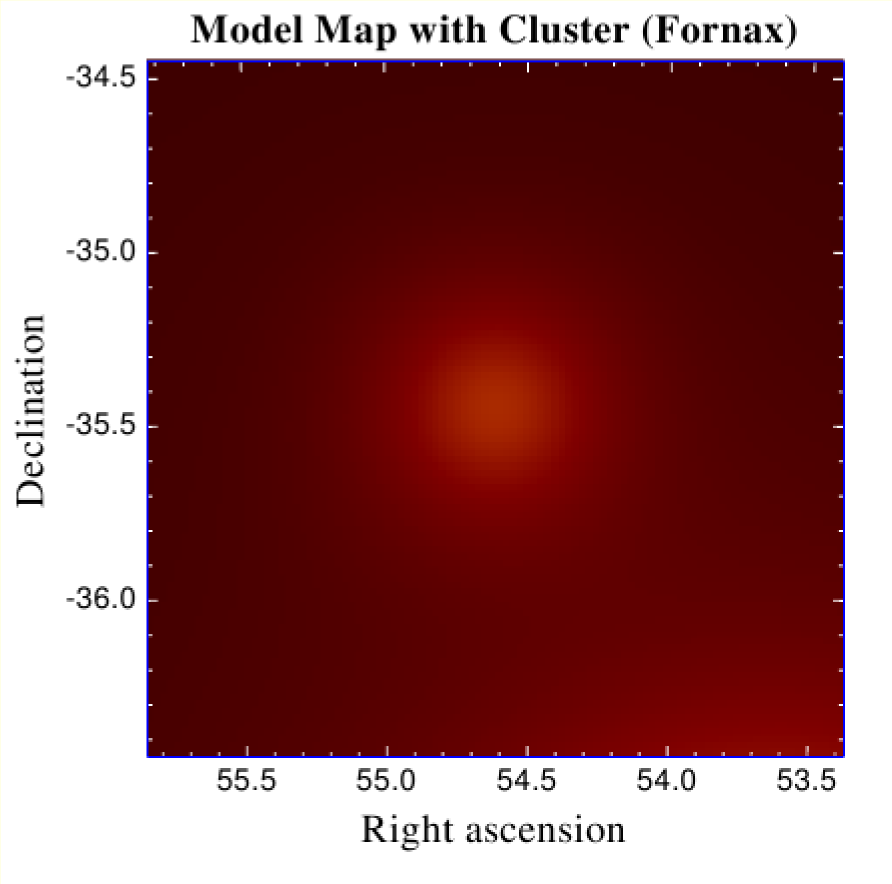


Taking into account the infall of DM into the potential well under baryons attraction allows to tighten the upper limits on annihilation cross-section

[Ando & Nagai (2012) arXiv:1201.0753]

Observations of galaxy clusters

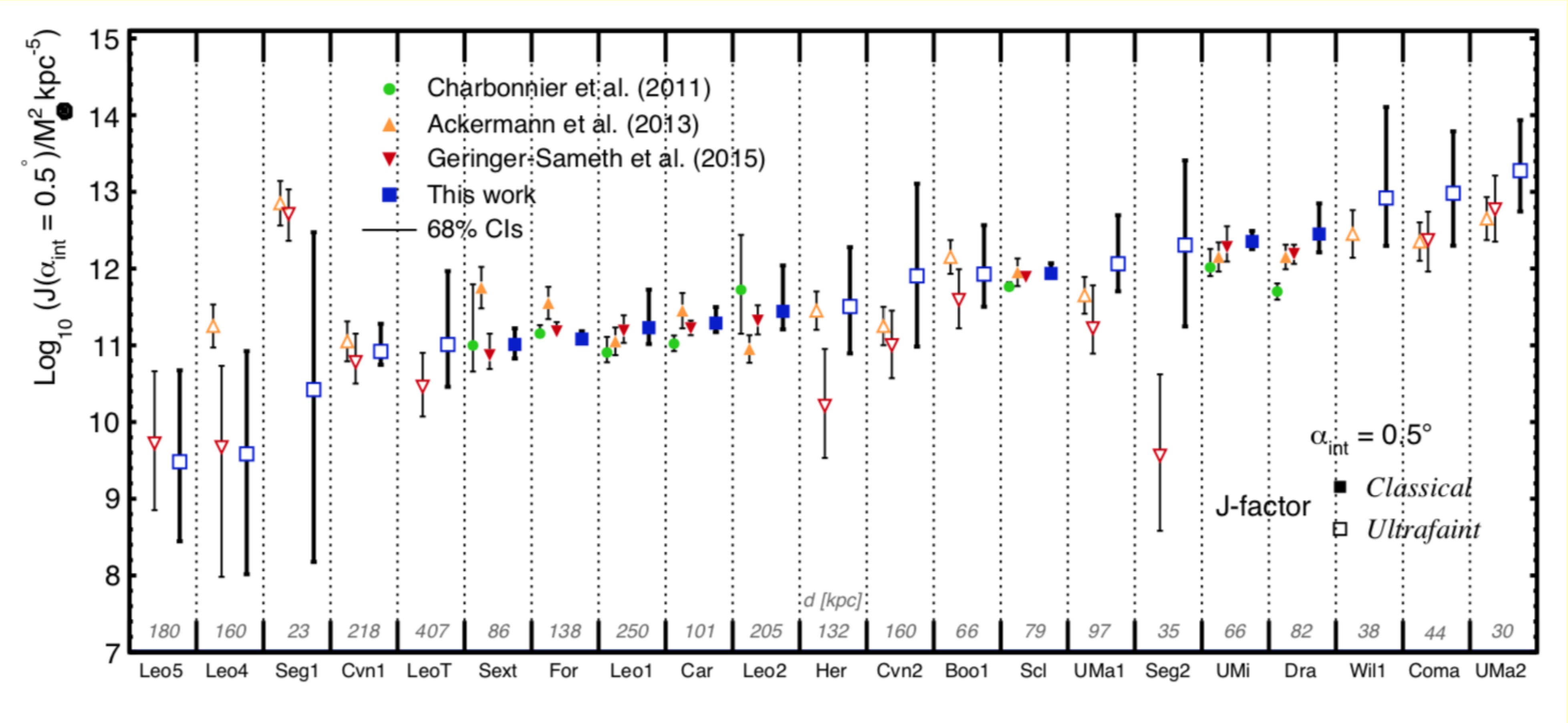




Observations (left) and simulated map of gamma ray intensity in the range 1 – 100 GeV (right). (Simulation for m_X=100 GeV and <\sigma v> = 3*10^{-24} – 100 times larger than the cardinal value.)

[Ando & Nagai (2012) arXiv:1201.0753]

Dwarf galaxies 2018:



$$\Phi_\gamma(E_\gamma, \Delta\Omega) = \frac{1}{2}\frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle}{4\pi m_X^2}\int_{\Delta\Omega}\int_{los}\rho_X^2(l,\Omega)dl d\Omega,$$

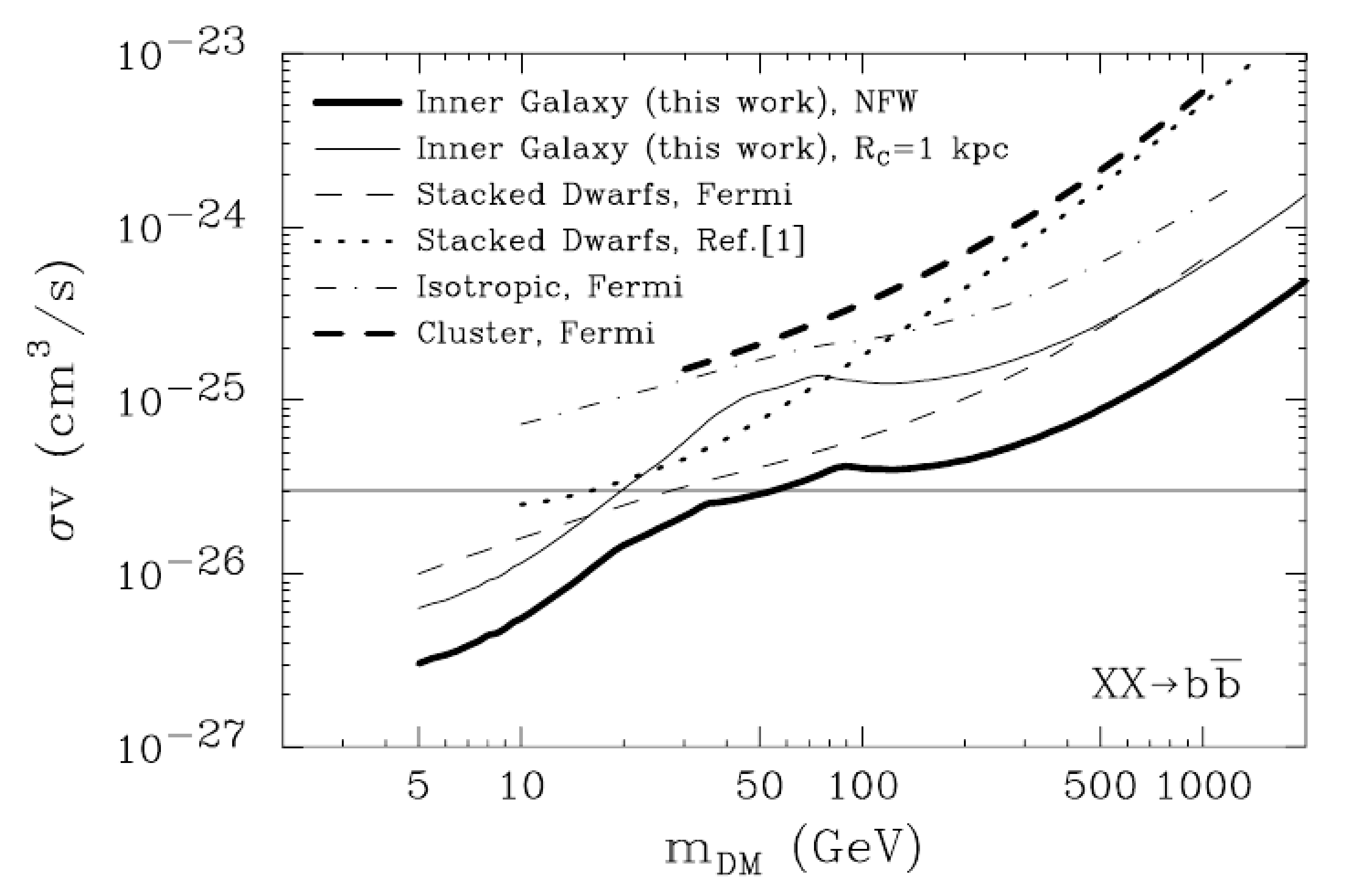
$$J \equiv \int_{\Delta\Omega}\int_{los}\rho_X^2(l,\Omega)dl d\Omega \simeq \frac{4\pi r^3 \rho_X^2}{3d^2}$$

Flux of energy from annihilation is proportional to the integral of DM density squared along the line of sight. It may be estimated for chosen dwarfs.

D. Hooper (2018) arXiv: 1812.02029

Fermi satelite: limits summary

[Hooper et al. (2012) arXiv:1209.3015]

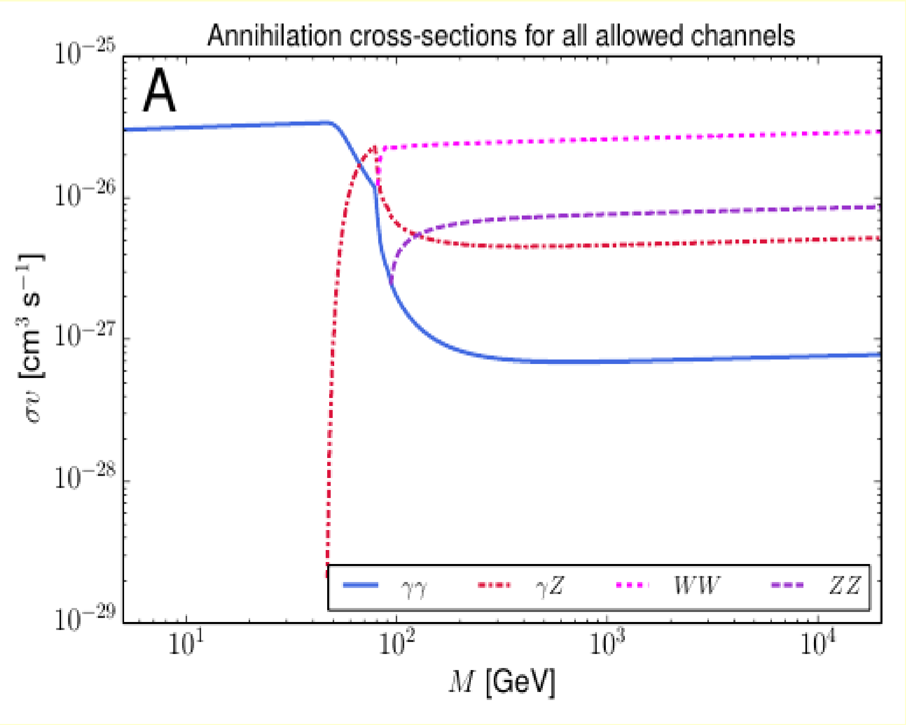


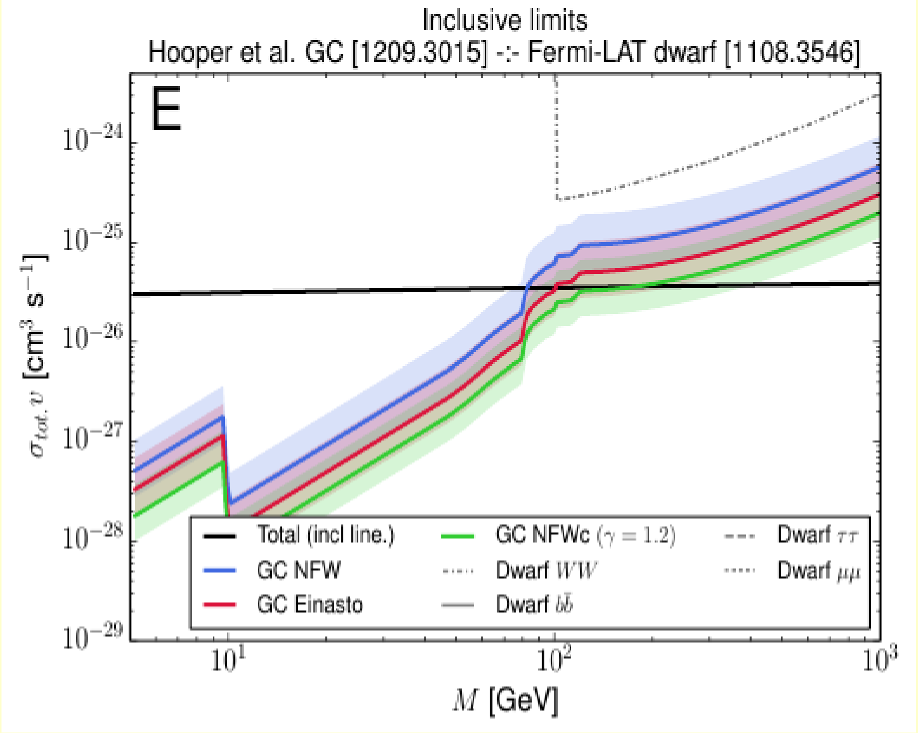
$L \sim 1/m\_X$!

$$\mathcal{L} = 2m_X c^2 \langle \sigma v \rangle n_X^2 = 2m_X c^2 \langle \sigma v \rangle \left(\frac{\rho_X}{m_X} \right)^2$$

Limits on different annihilation chanels

[Fedderke et al. arXiv:1310.6047]

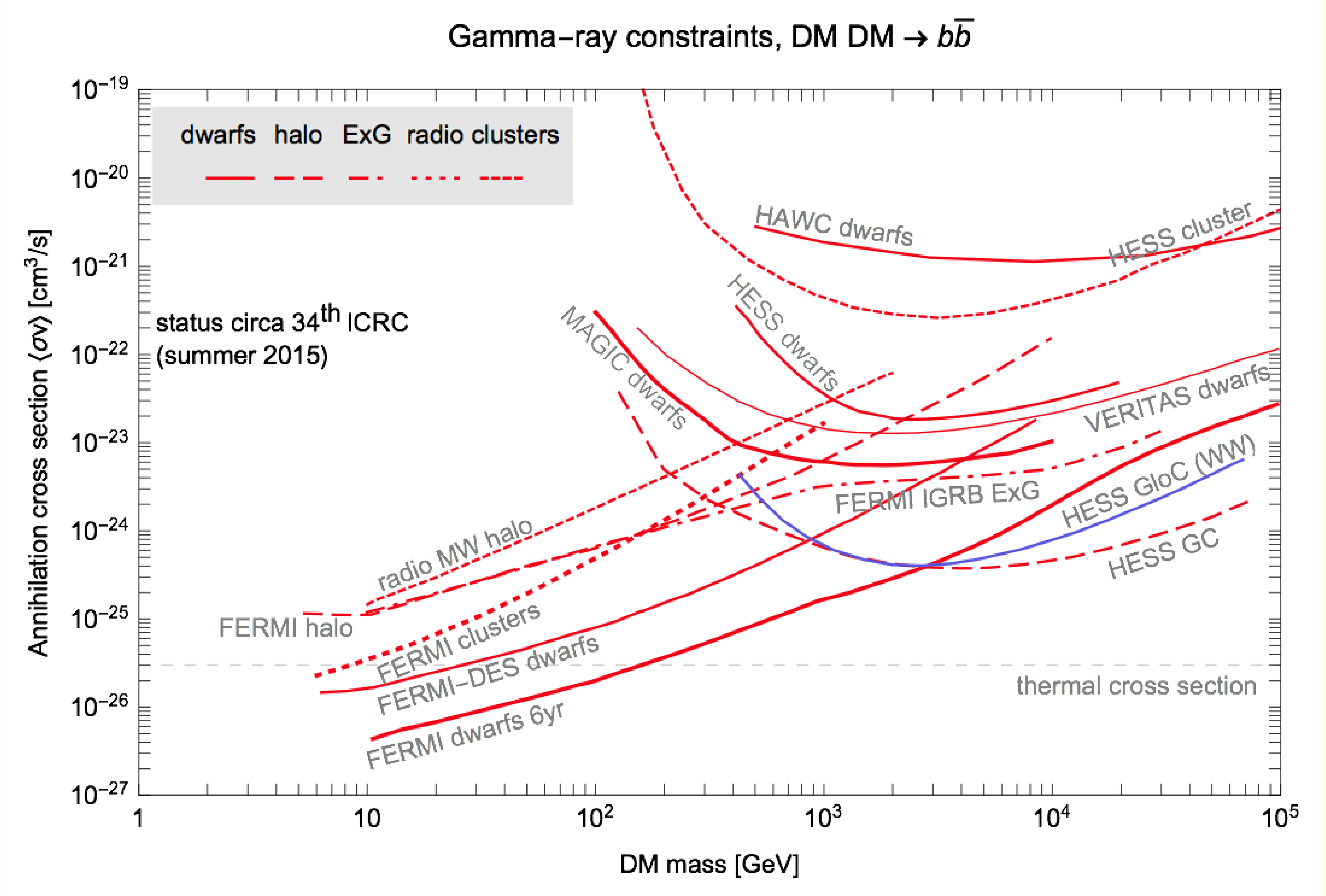




Example above ("operator VI-3"). There are >30 other. Limits are based on Fermi-LAT and HESS observations. In many cases: m_X>100 GeV/c^2

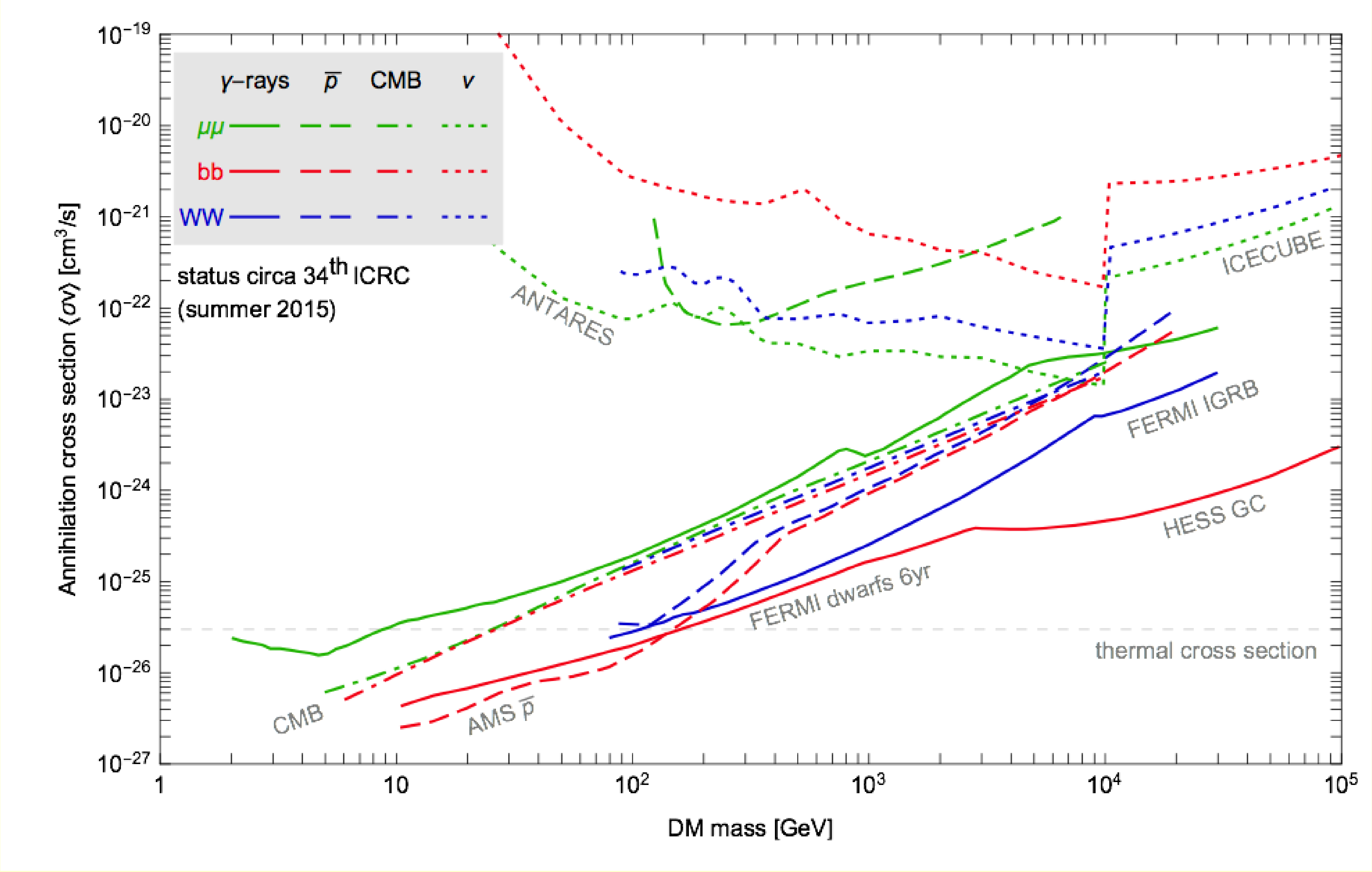
Limits based on different observations

[Cirelli, 34th Int. Cosmic Rays Conf. 2015]

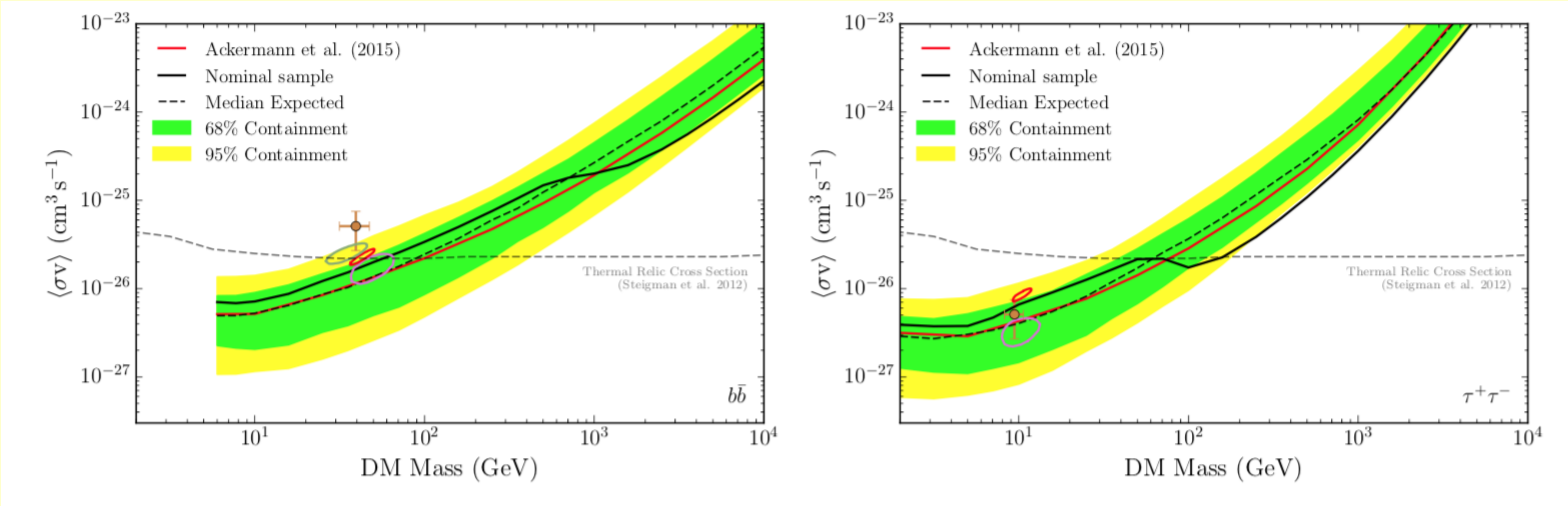


Limits for different annihilation chanels

[Cirelli, 34th Int. Cosmic Rays Conf. 2015]



Dwarf galaxies 2018:



Upper limits on cross-section as function of the DM particle mass. For masses < 60 GeV DM could not have been produced in the required amount.

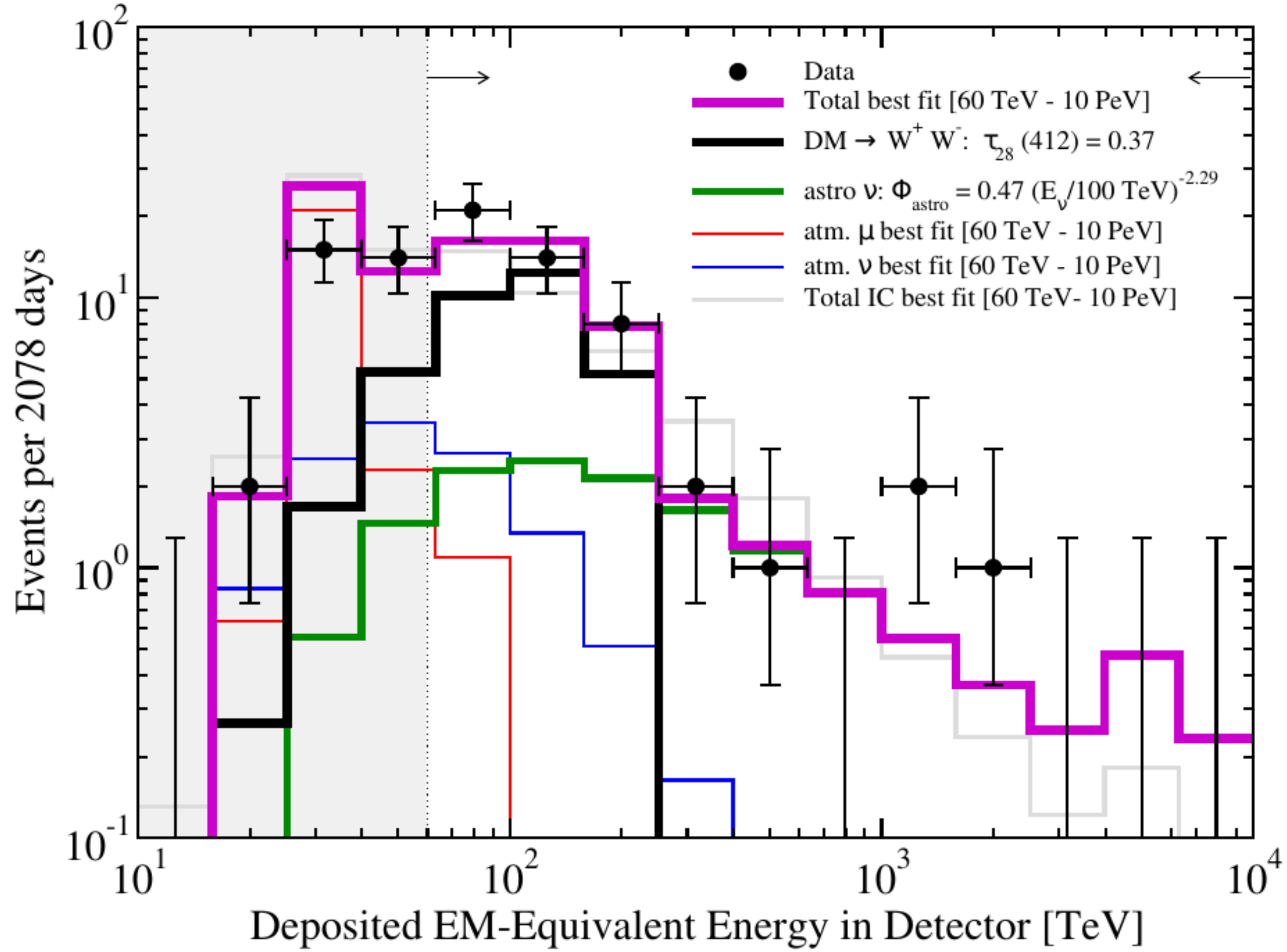
D. Hooper (2018) arXiv: 1812.02029

Ice Cube, PeV neutrinos and DM aspect

Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data

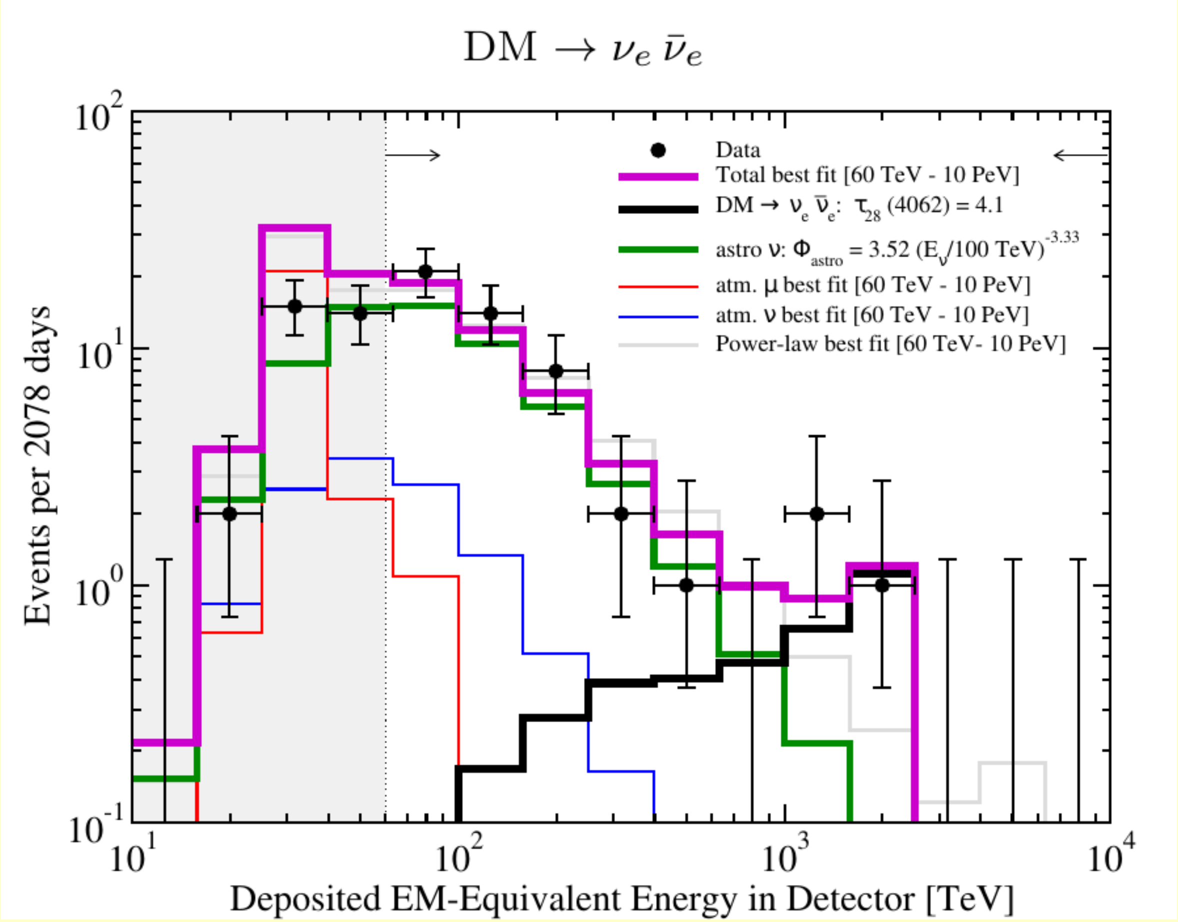
Atri Bhattacharya,[a] Arman Esmaili,[b] Sergio Palomares-Ruiz,[c] Ina Sarcevic.[d,e]

$\mathrm{DM} \to W^+ W^-$



Ice Cube has been active for ~8 years
Neutrinos with up to PeV energies have been detected in small numbers. Authors claim that the fit “astrophysical sources (power law) + decaying dark matter” is better than a power law alone.

Ice Cube, PeV neutrinos and DM aspect



Same idea, another example of possible decay chanel.
Using these scarce data one can show that some product of DM decay are better than other. Statistically differences are not significant but data is accumulating …
Similar schemes considering “astrophysics + DM annihilation” are also discussed ...

DM annihilation why?

- DM must have been produced
- Creation nad annihilation are similar processes
- If DM is a remnant of thermal process in the early Universe, the cross-section for annihilation is crucial: the observed amount of DM today corresponds to a well defined value:

  <\sigma*v> ~3*10^{-26} cm^3/s
- Average DM density is much too low to allow for any observable annihilations today
- Places with much higher DM density (galaxies, clusters) may allow for annihilation
- CTA observations will solve the problem ?

DM detection ?

- Direct: different detectors (different construction, different location) should give consistent results (crosssection, mass)
- Indirect: more than one annihilation chanel in single source ?
- Investigations are under way ...