Indirect DM (→WIMP) detection
(~mid 2013)

Gabrijela Zaharijas

ICTP & INFN Trieste

Invisibles workshop, Durham, 2013.

- a WIMP?

  - connects new physics @ electroweak scale with the observed DM abundance in a simple framework (known to work for SM species) + has all the right properties for DM (caveats... C. Frenk's talk)
  - theoretical bias: "a simple, elegant, compelling explanation for a complex physical phenomenon" (R. Kolb)

- ***Bulk of the current experimental effort and of this talk!*** *(Disclaimer: subjective approach; but the field is much richer -- we'll hear some of ideas here too)*

Sasha's, Michel's ... talks

- WIMP hypothesis is predictive:

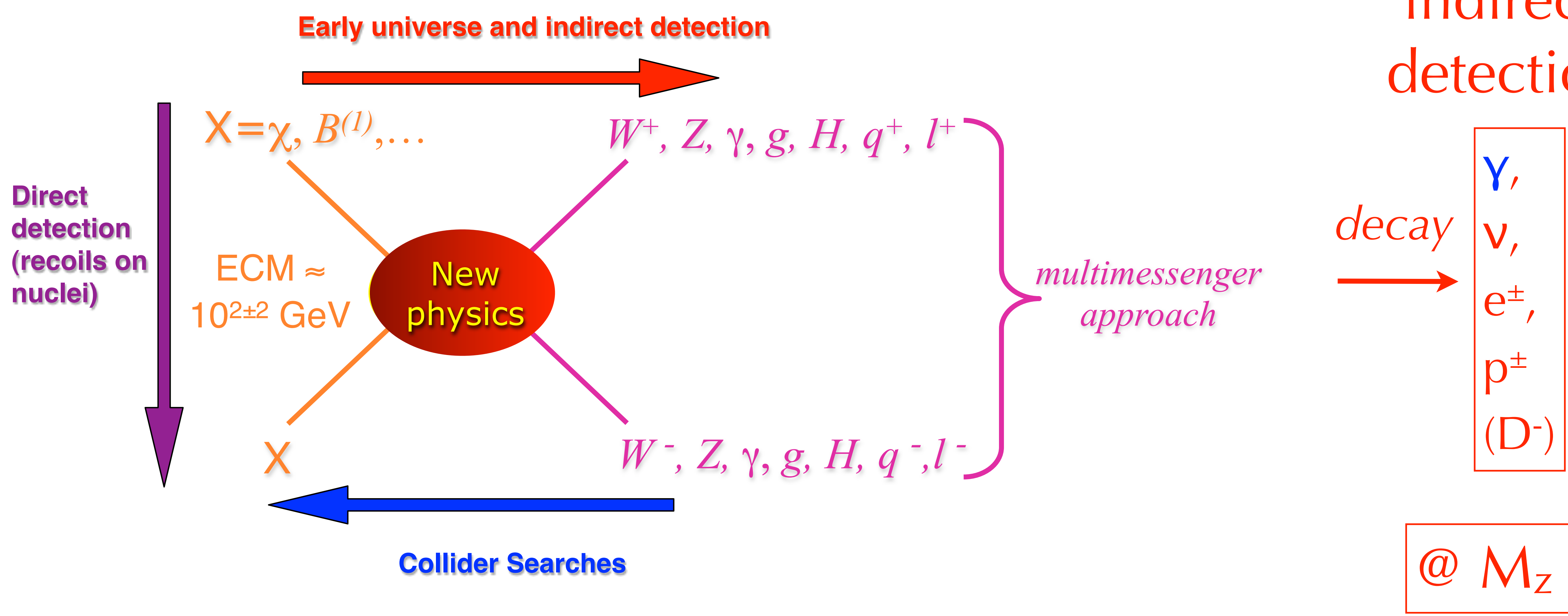
Dark Matter Abundance from Thermal Production

$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

Cosmological Measurement

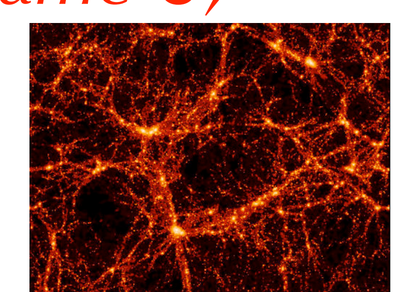
Weak Scale Physics

‘indirect’ detection



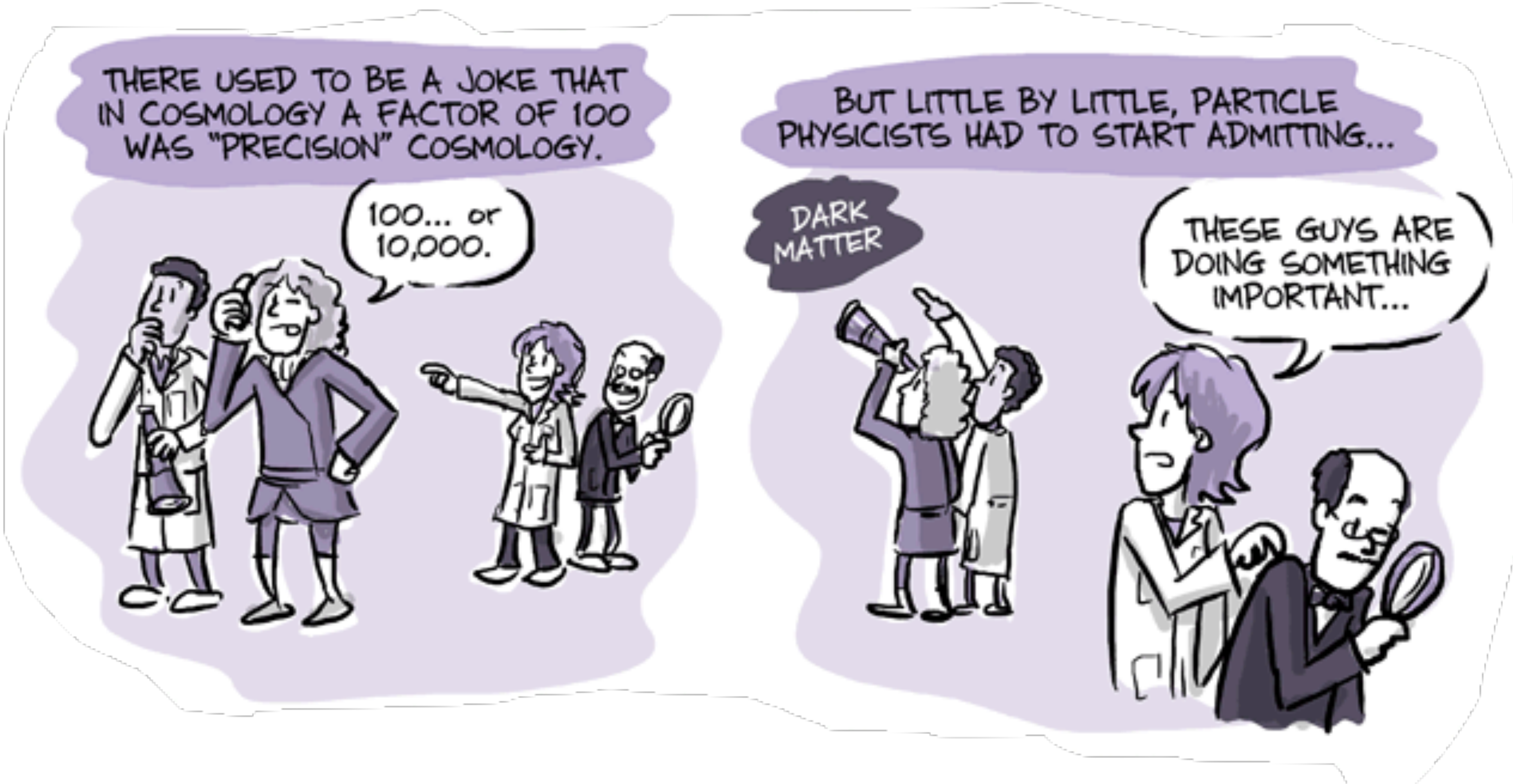
In the Early Universe: DM kept in equilibrium w SM by self-annihilations (σ).

Today, DM expected to annihilate with the same σ, in places where its density is enhanced!

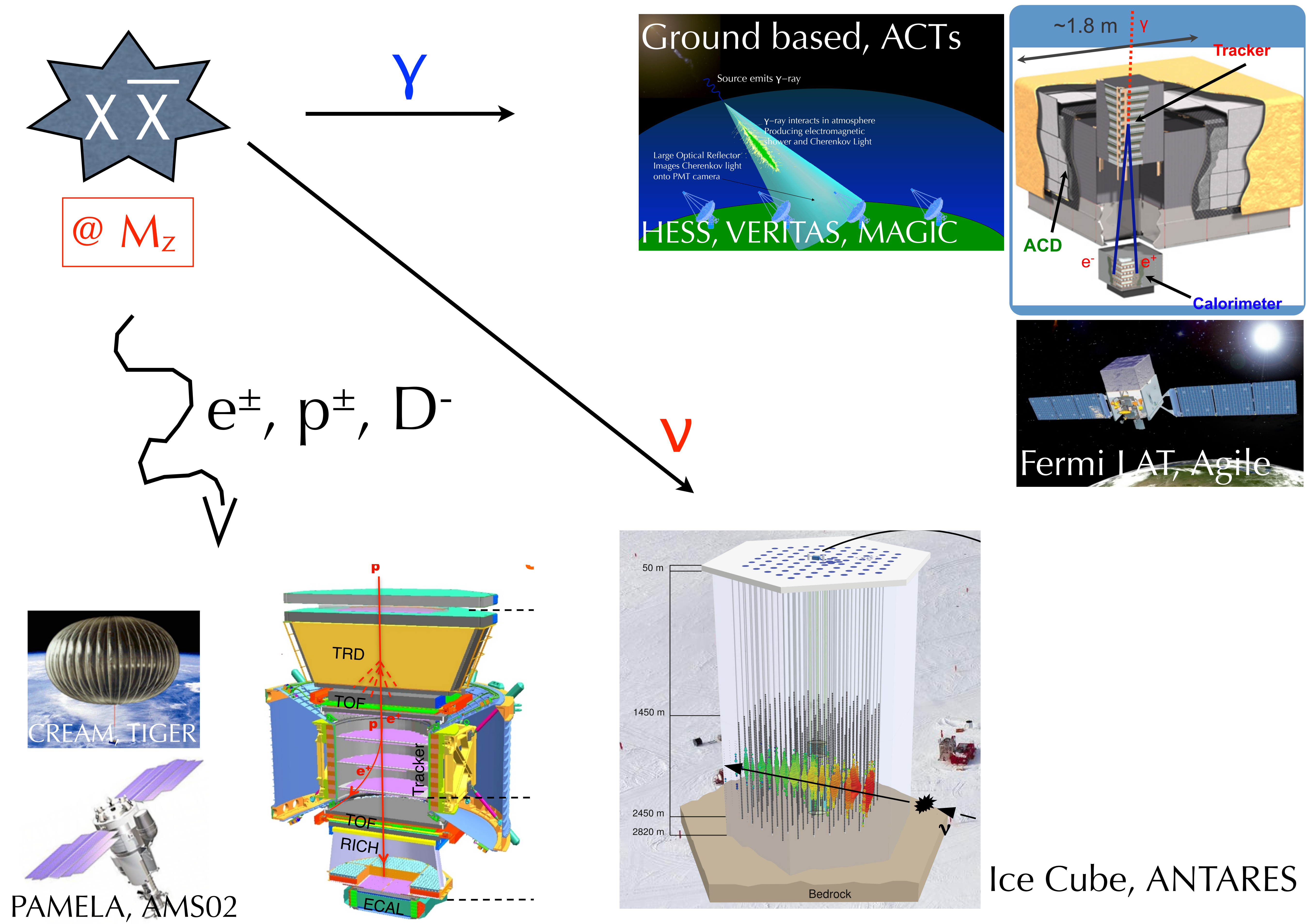


in astrophysical systems - *remotely*

- Why indirect searches?
    - 'backgrounds' are astrophysics not a 'controlled' lab system
- However, it is important:
    - to detect/measure DM remotely/in places where it was discovered
    - annihilation cross section provides **a direct link** to early universe physics
    - ideally: detect it in the Lab AND astrophysical objects. Multiple handle on its properties.



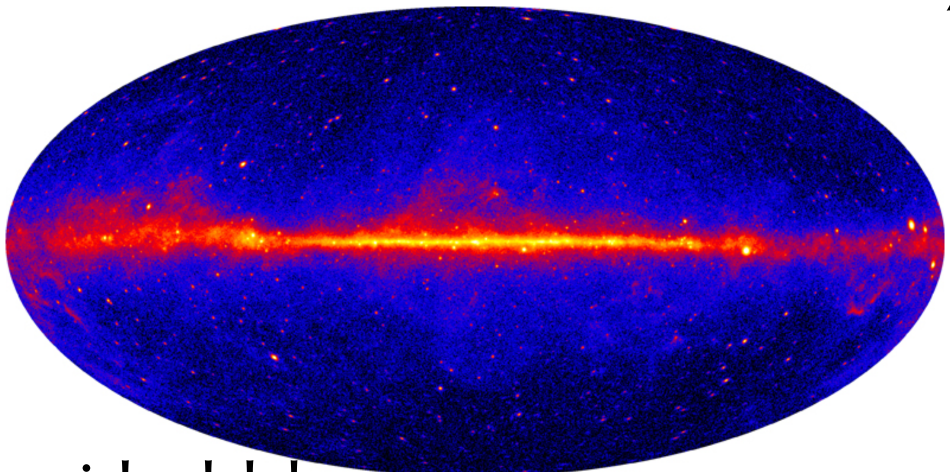
and now we have these powerful tools



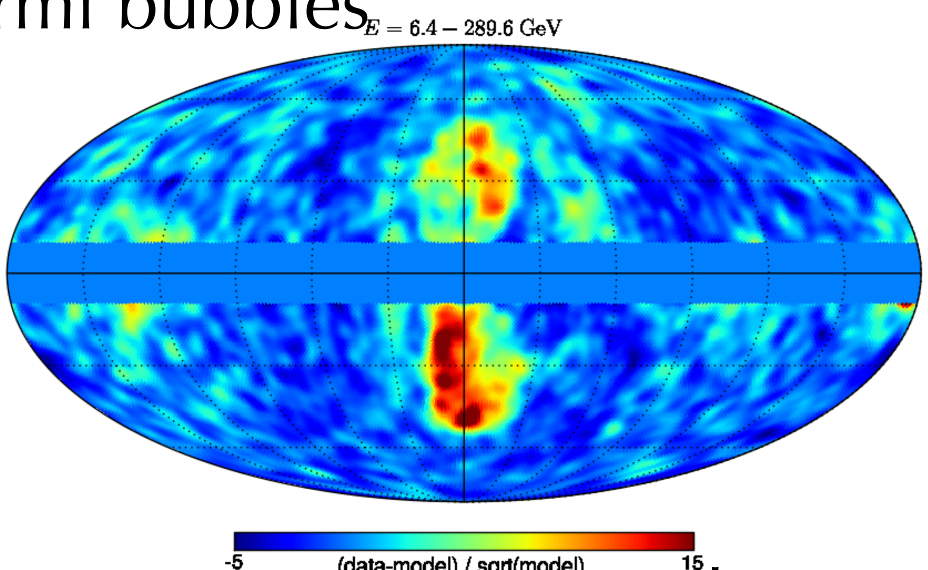
Astrophysical experiments: multipurpose experiments w rich scientific program --> discovering the sky @>~Mz energies/highlights

γ

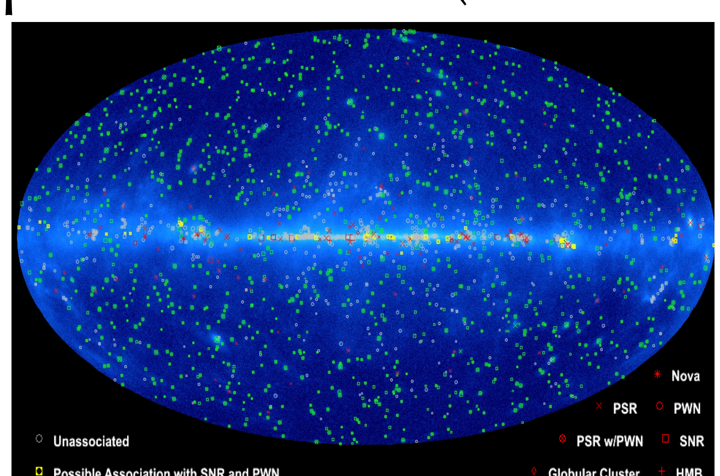
diffuse emission from our Galaxy:



Fermi bubbles

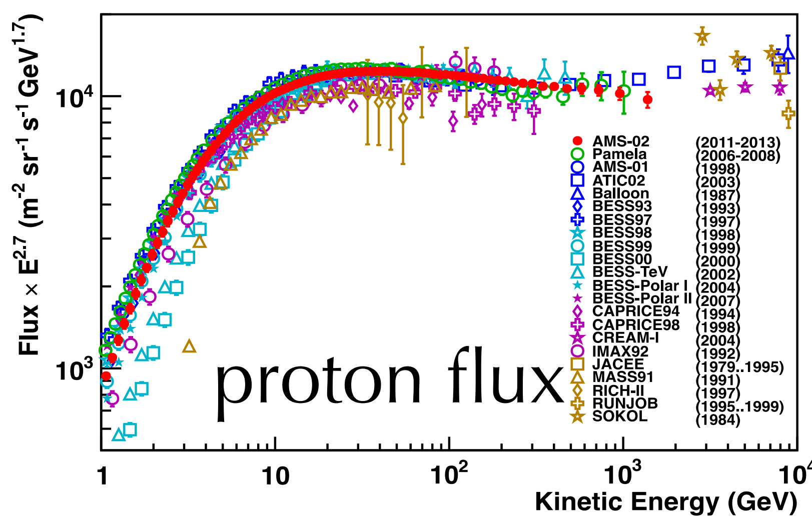


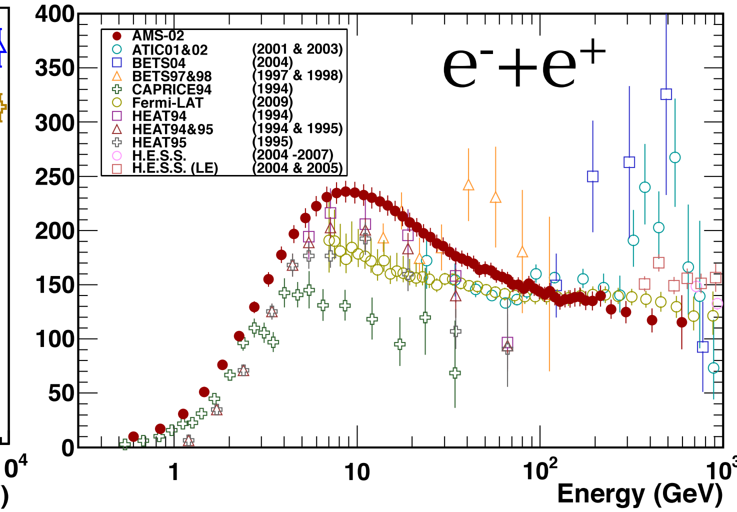
~2000 point sources (Galactic and extraGal):



charged cosmic rays

New AMS results:



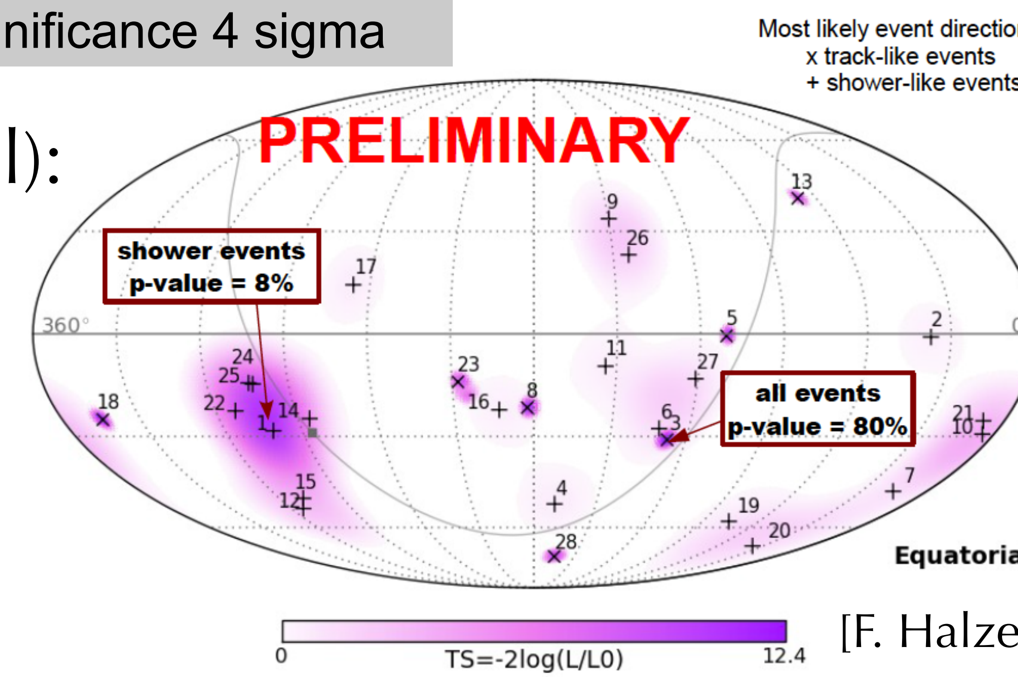


[S. Ting, ICRC 2013]

ν

First detection of astrophysical neutrinos!

- 28 events above 10 TeV
- significance 4 sigma



[F. Halzen, ICRC 2013]

- What are we after:

- γ and ν propagate in a straight line, unaffected by Galaxy

$$\boxed{\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}} \times \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \times \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$

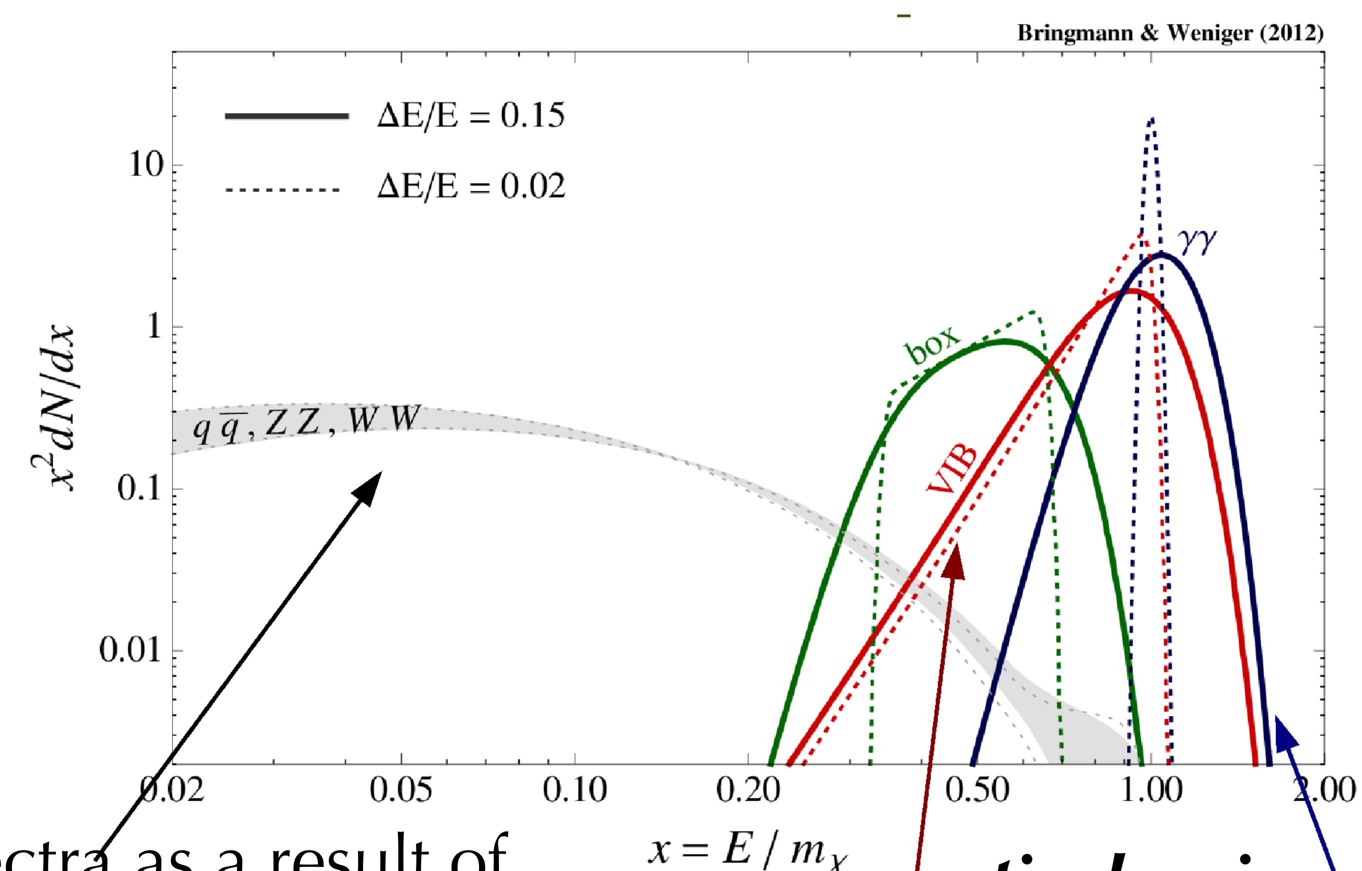
Particle physics: sets **spectrum** and **overall normalization**

DM clustering: **morphology** and **overall normalization**

- What are we after:

- γ and ν propagate in a straight line, unaffected by Galaxy

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\, m_\chi^2}} \times \boxed{\sum_i \mathrm{BR}_i \frac{dN_\gamma^i}{dE_\gamma}} \times \boxed{\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\, \rho^2(s,\Omega)}$$



quasi-universal spectra as a result of fragmentation/hadronization and subsequent pion decays.

Determines early universe decoupling.

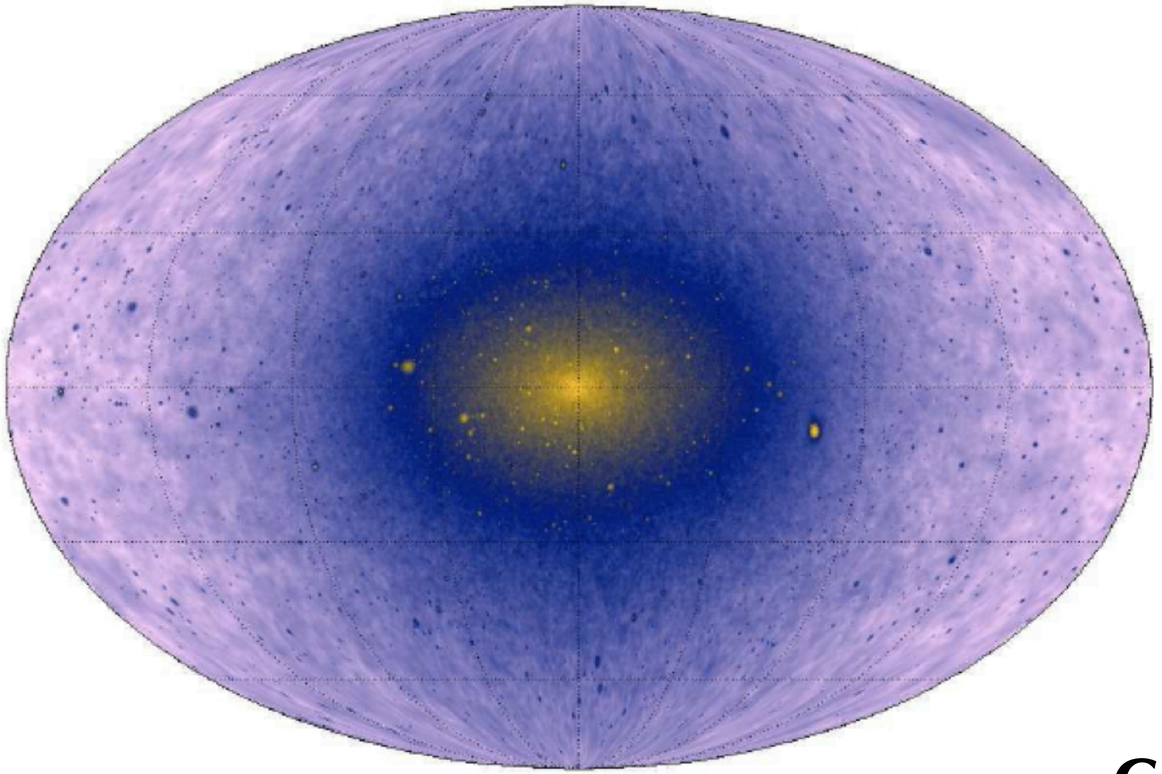
particular signatures predicted intensity model dependent, but hard to mimic with astrophysics.

- What are we after:

- γ and ν propagate in a straight line, unaffected by Galaxy

$$\boxed{\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma}} = \boxed{\frac{1}{4\pi}\,\frac{(\sigma_{\mathrm{ann}} v)}{2\,m_\chi^2}} \; \mathrm{X} \; \boxed{\sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}} \; \mathrm{X} \; \boxed{\int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} \mathrm{d}s\, \rho^2(s, \Omega)}$$

-> **Where to look?** DM clustering map is a good guide to observational targets.



[Diemand+, APJ, astro-ph/0611370]

Simulations: find **cuspy halos with numerous substructure**; ***small halos or baryon dominated regions*** **cannot (yet) be probed reliably.**

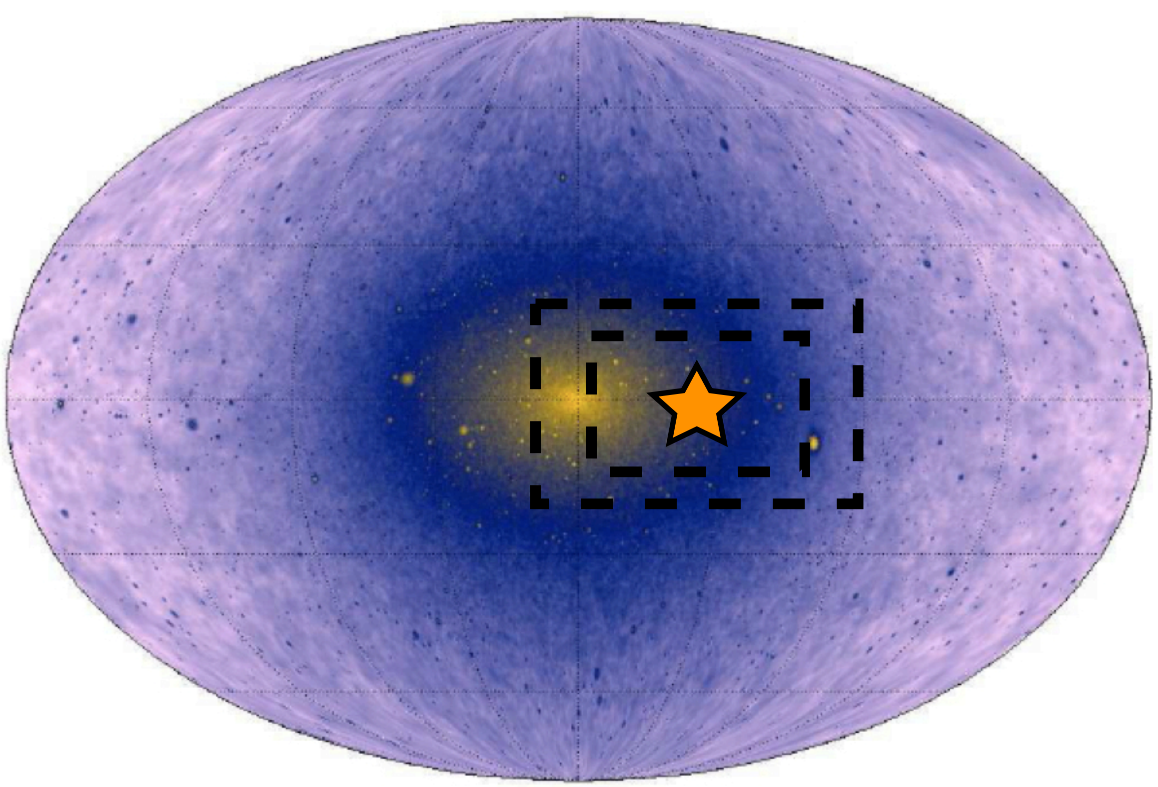
Observations: measure tracers of gravitational potential: again, fail in ***small halos or baryon dominated regions.***

Considerable uncertainties for most of searches.

- charged CR:
- a more complicated story/ less ‘clean’ channel: CRs propagate diffusively entangled in Galactic magnetic fields.
- signal depends also on conventional astrophysics → *diffusion/energy losses/* in the Galaxy.

DM signal = (particle physics X DM clustering)

astrophysics

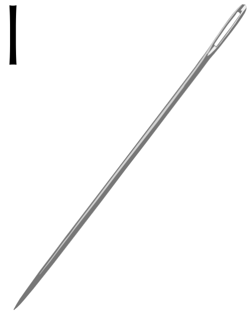


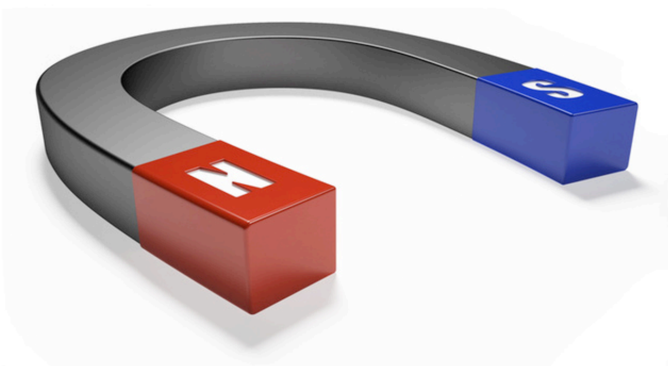
[Diemand+, APJ, astro-ph/0611370]

- probe local volume
- Strategy: *look for **anti particles** as the backgrounds are lower!* (DM produces equal numbers of particles&anti-p)

Challenge:

look for an uncertain signal swapped in the uncertain backgrounds.





[J. Siegal-Gaskins talk@Sackler colloquium 2012]

Possible detection paths:

A) look for ***smoking guns***:

➡ 'zero' astro backgrounds, but need luck -- expected signals (for vanilla DM) low

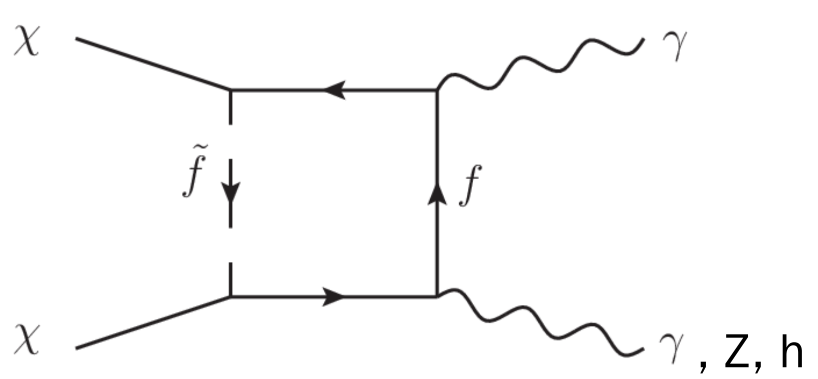
- spectral line features
- dwarf galaxies
- anti-deuterium
- (Sun (neutrinos) - elastic cross section)

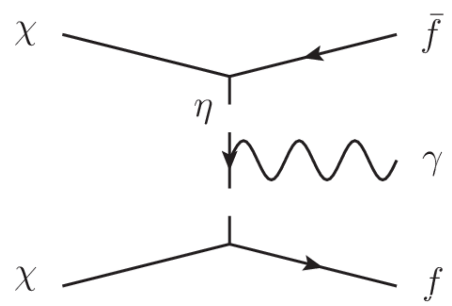
B) search for **standard WIMP signatures** and **use rich astro data to model the backgrounds**

➡ current experimental sensitivity in the right ballpark for vanilla models, but due to the confusion with astro backgrounds possible hints NEED confirmation across the range of ***wavelengths/messengers/targets***

- raising positron fraction;
- Galactic Center gamma ray data

Gamma ray line:

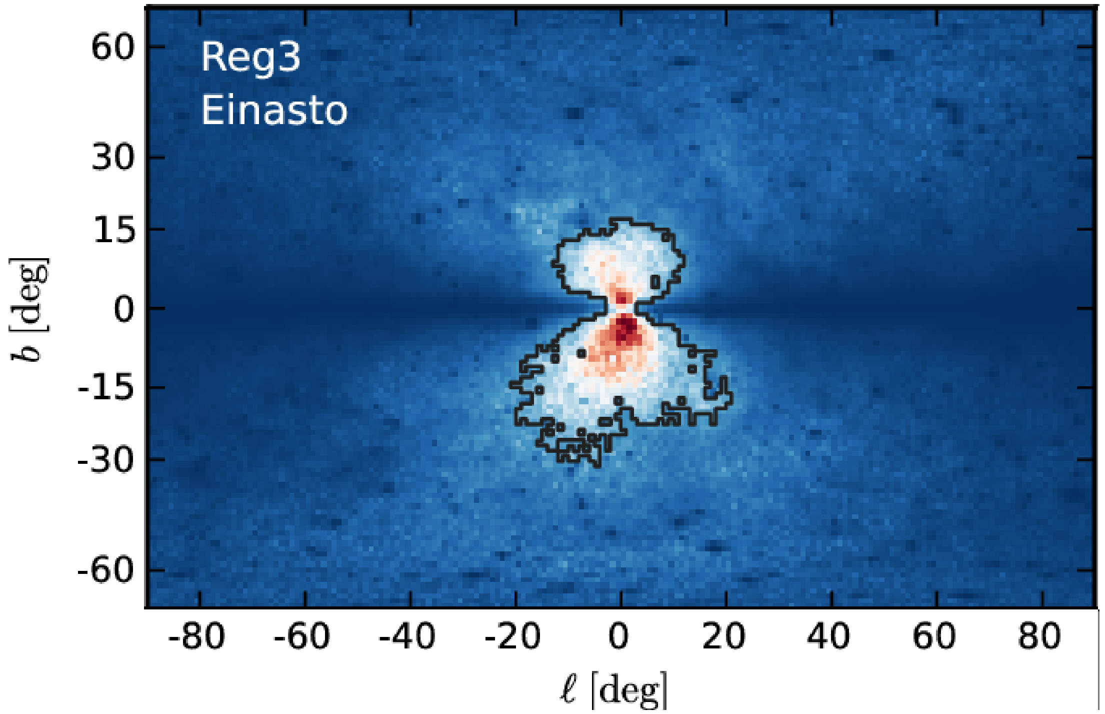




t-channel annihilation

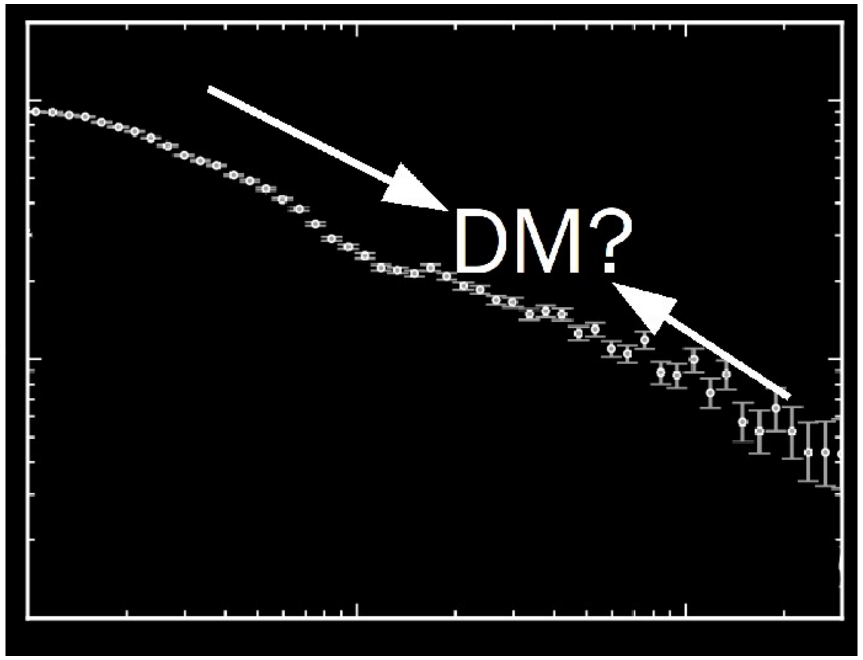
How to look for a spectral feature?

I) Identify target region



blind or maximize S/N assuming a DM density profile

II) Spectral analysis



extrapolate measured spectrum from a larger energy range and look for 'line-like' features.

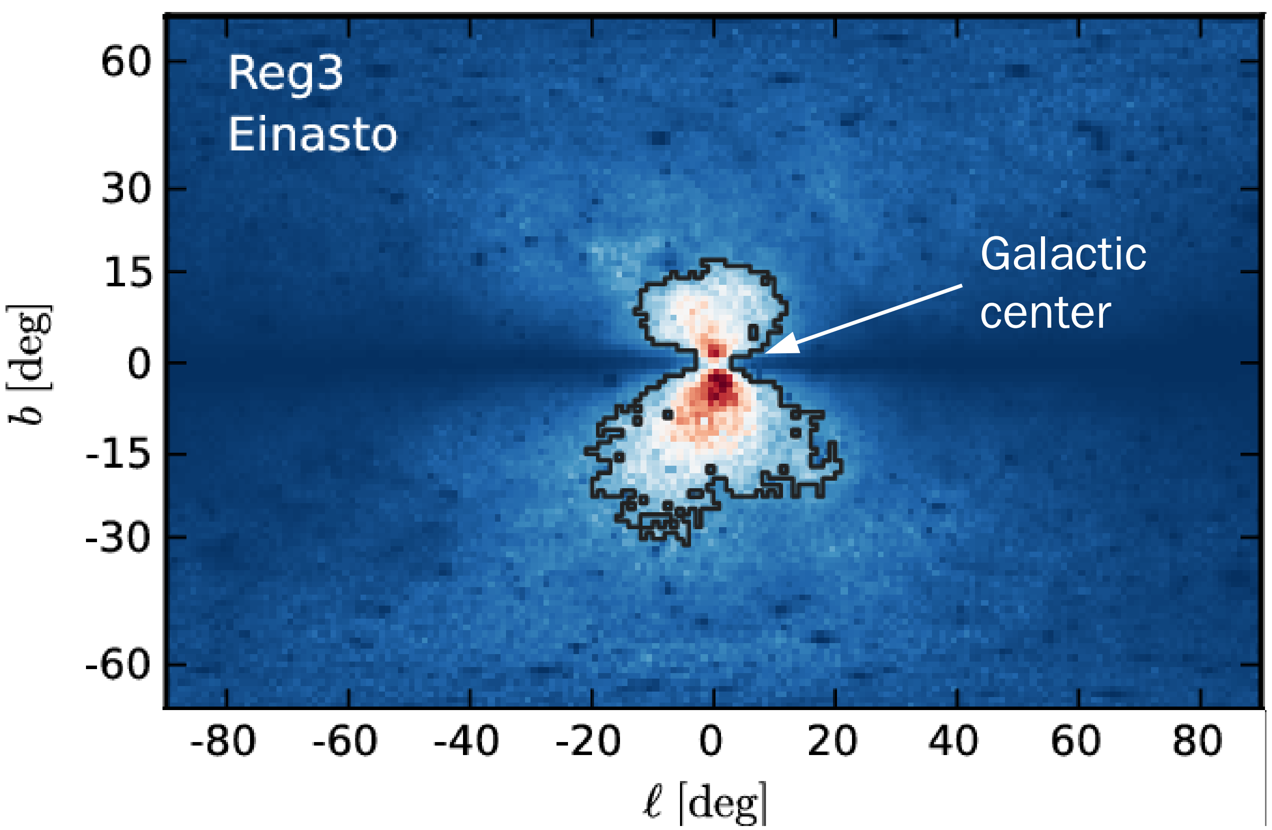
Gamma ray line

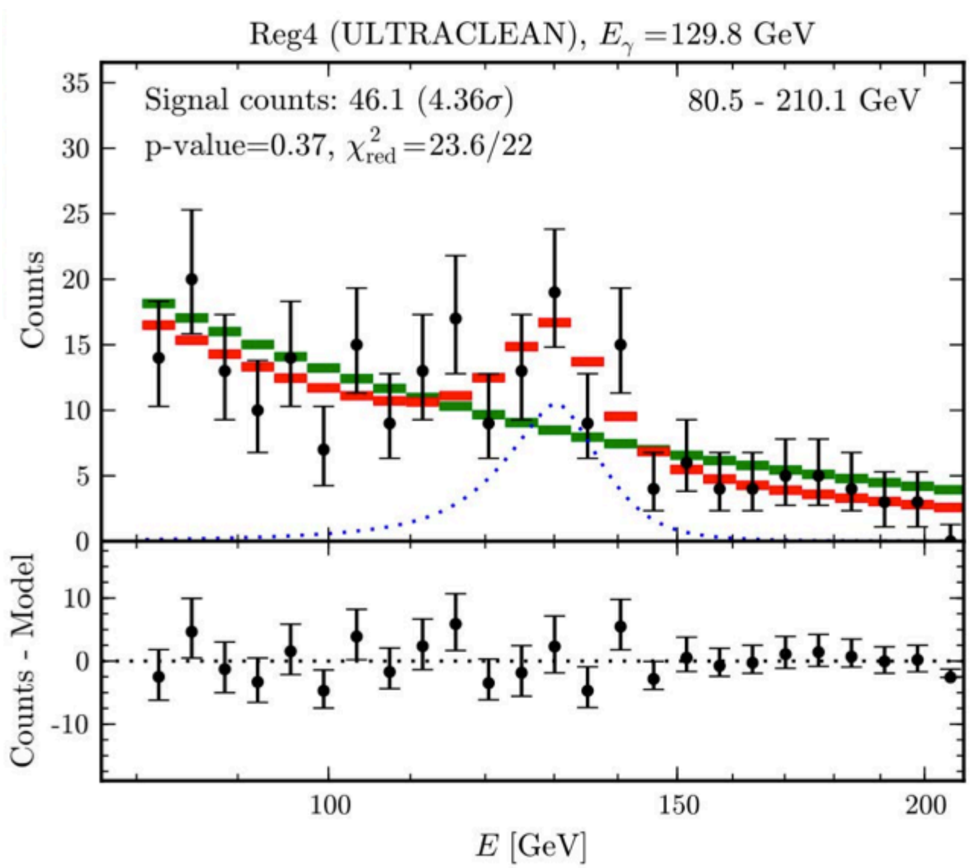
Weniger+ 2012:

Evidence for a narrow spectral feature in 3.5 yr data near 130 GeV in optimized ROIs near the Galactic center.

Some indication of double line (111 &130 GeV), Su+, 2012.

- Signal is particularly strong in 2 test regions (cuspier profiles) with S/N> 30%-60%.





C. Weniger JCAP 1208 (2012) 007, 1204.2797

Gamma ray line

Fermi LAT's line search

(1305.5597)

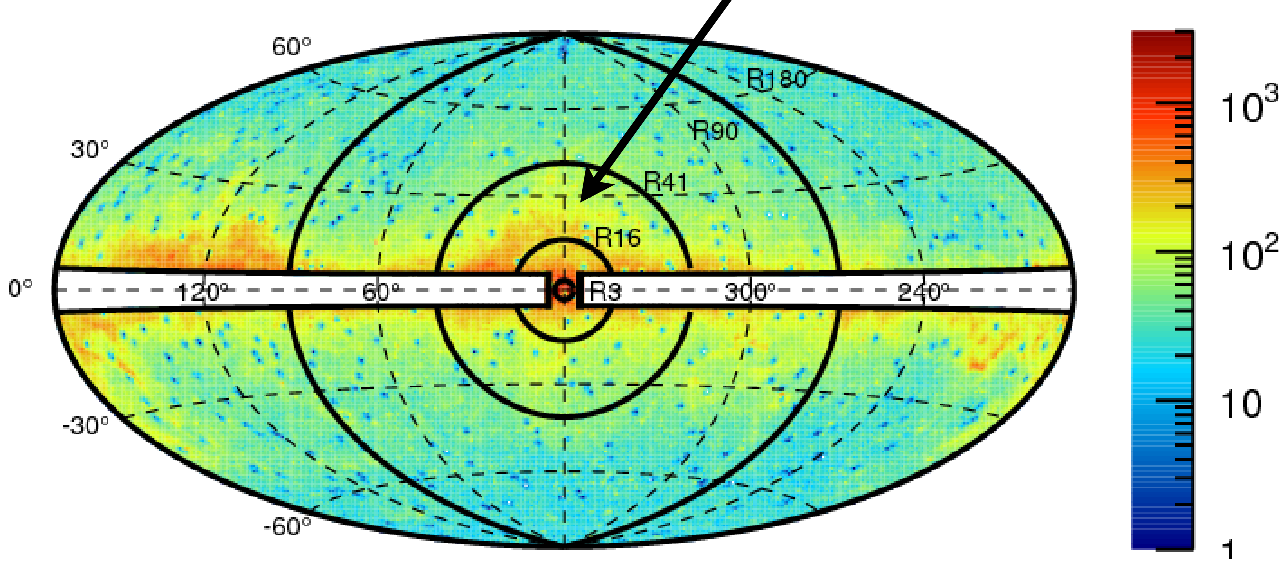
1) Optimize ROI

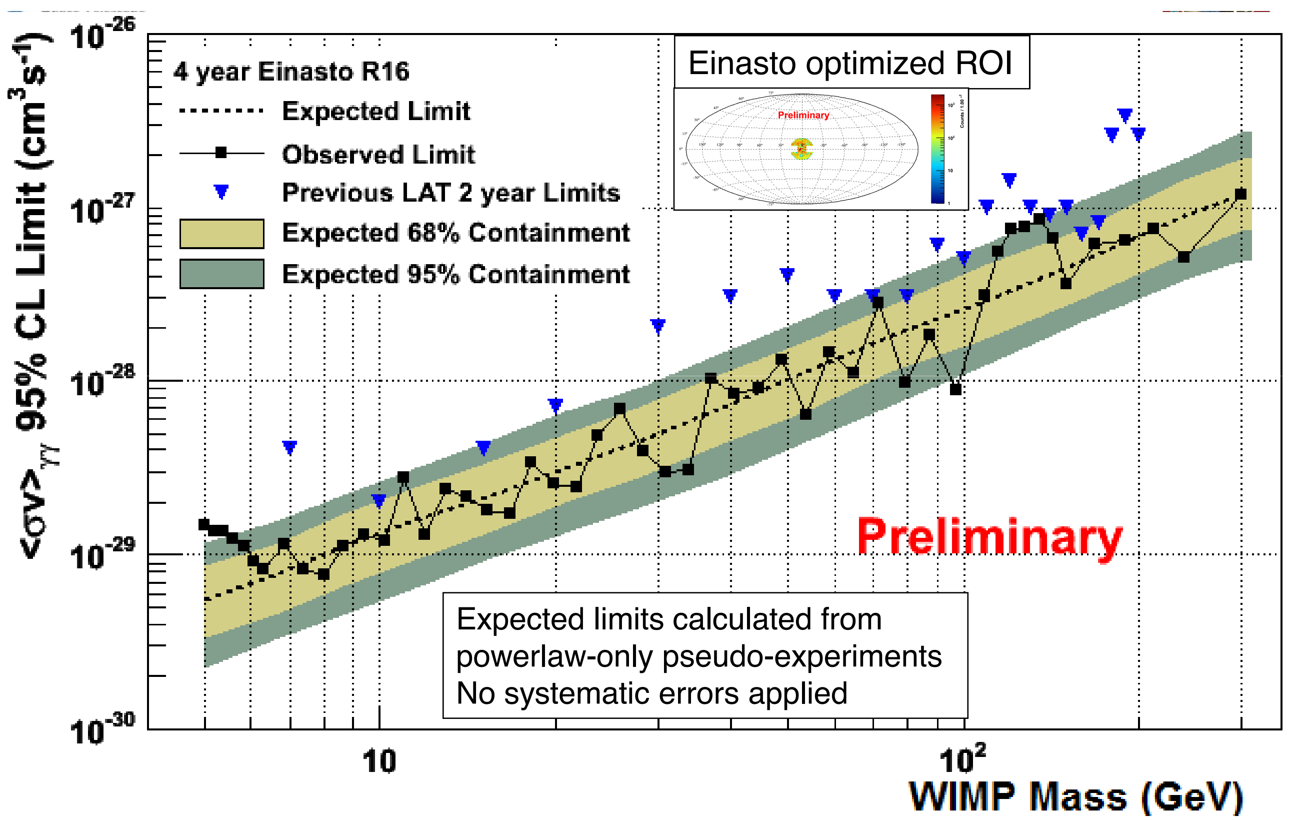
2) Improved Energy Resolution Model

3) Data Reprocessed with Updated Calibrations

No signal found in a blind search.

Einasto profile





Weniger+ signal not ruled out by 95% CL on $\Phi_{\gamma\gamma}$.

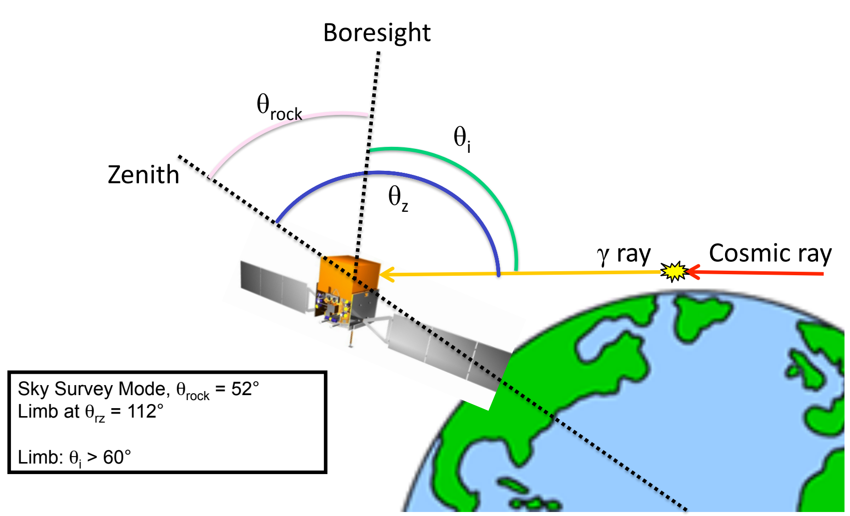
Gamma ray line

Fermi LAT's line search

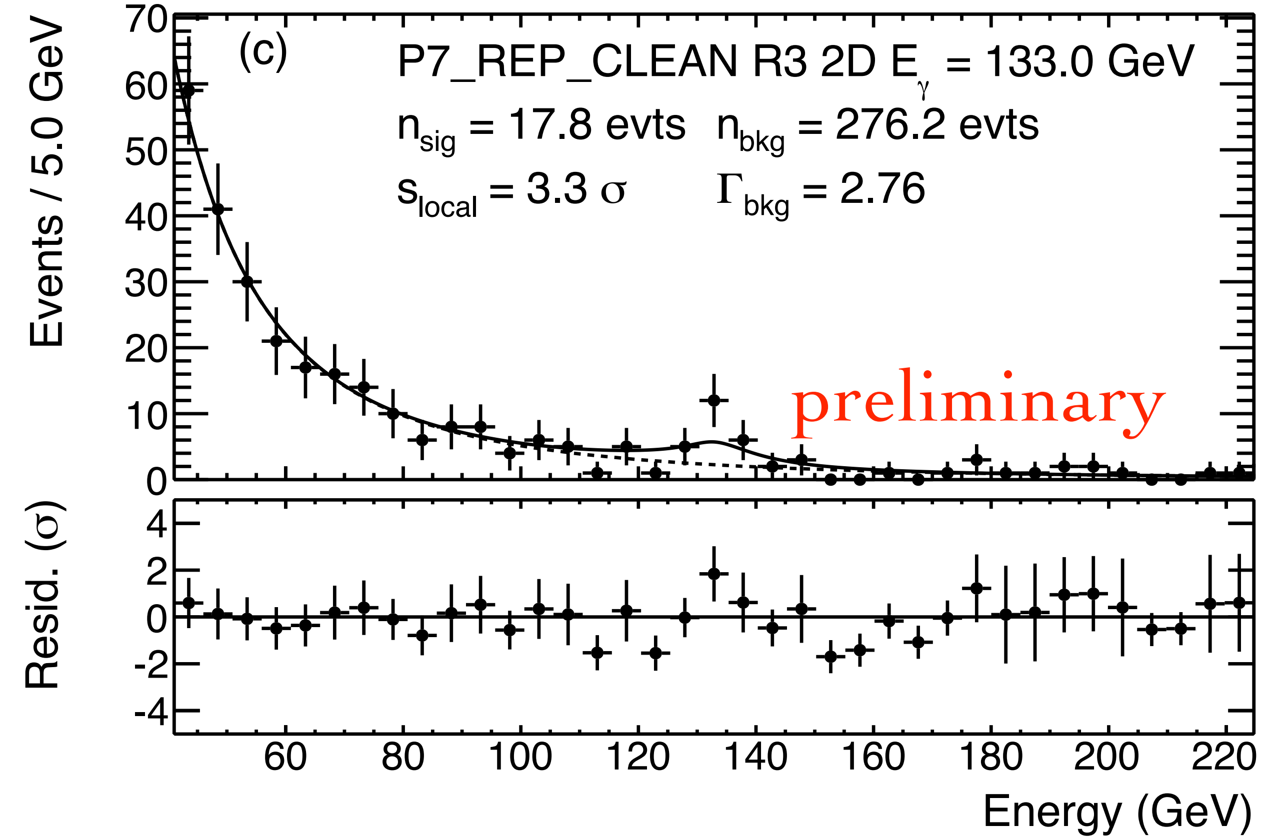
Inspection of a signal @ 133 GeV: 3.3σ (local) <2σ global significance after trials factor; S/N~60%

In addition, weak hint of a spectral line in the limb data, S/N~30%.

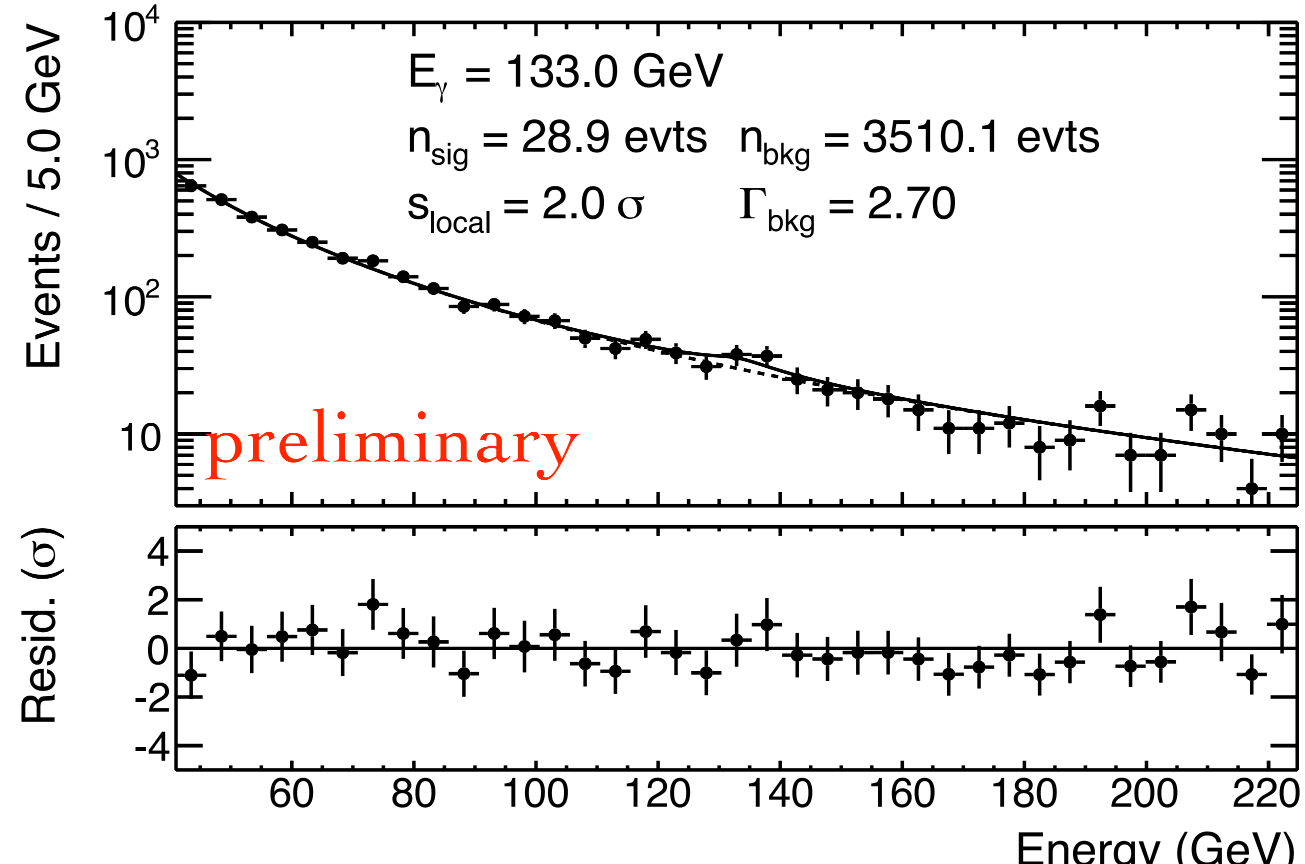
Red flag for an instrumental effect.



R3 Galactic Center region



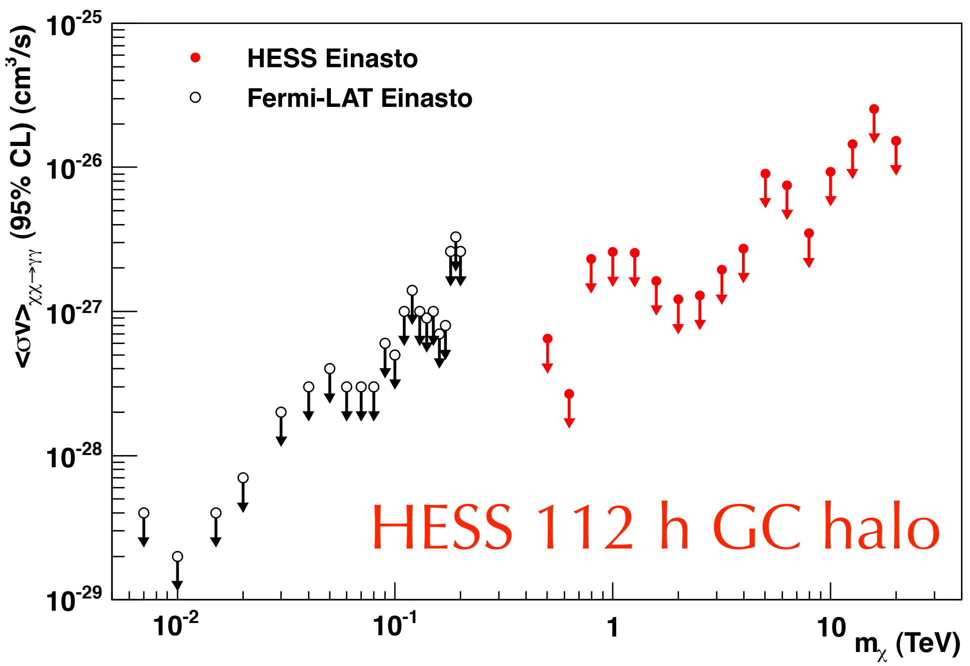
Earth limb data



Gamma ray line

Jury still out:

- Fermi LAT scheduled weekly limb observation, to examine a possible instrumental effect.
- increase statistics:
  - proposed changes in observational strategy (favor GC region) being reviewed AND
  - a NEW independent event selection pass8 (better energy resolution + CAL only events will increase statistics)
- other experiments: HESS 2 taking data! 50 hours of GC observation enough to rule out signature or confirm it at 5 sigma (if systematics are under control)



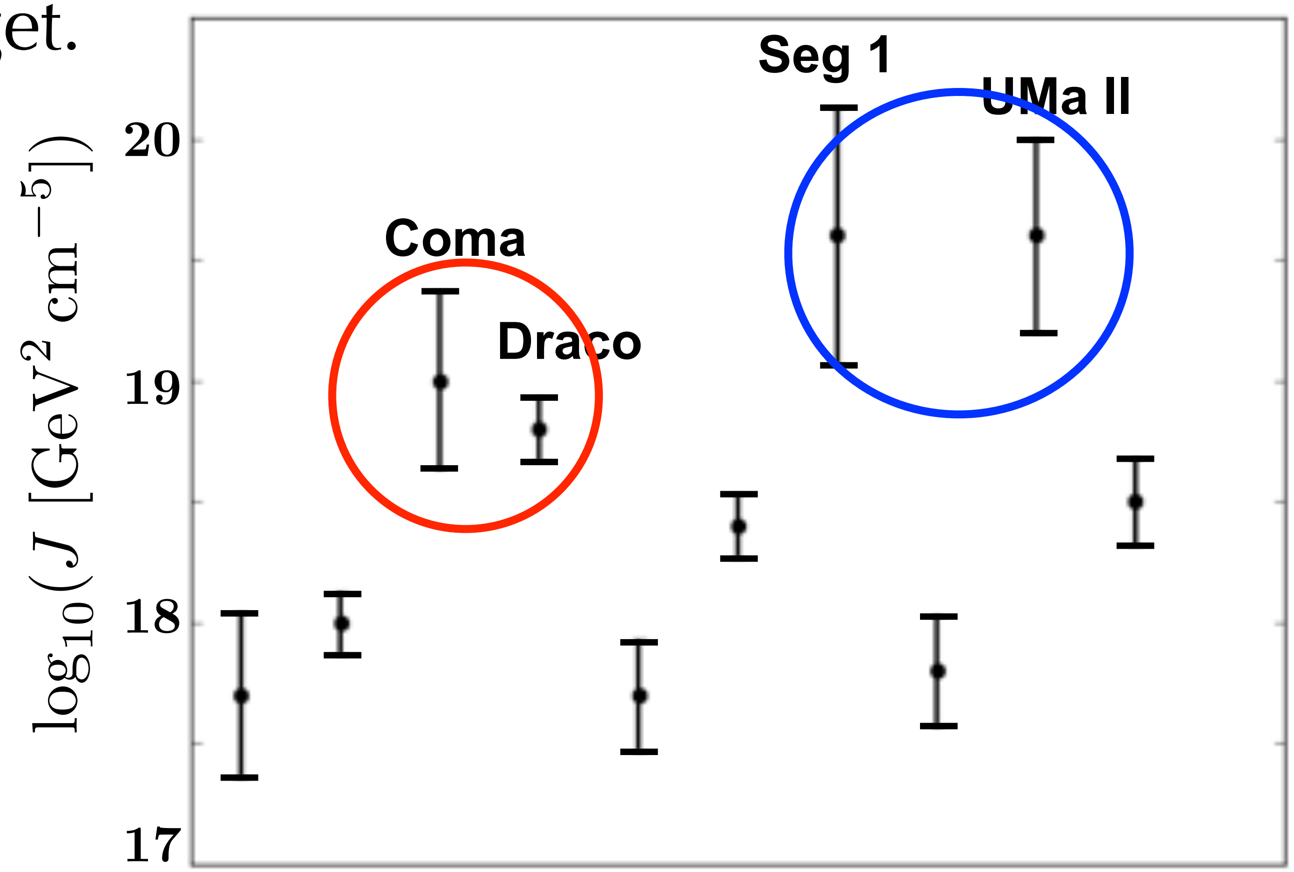
[HESS coll., Phys.Rev.Lett. 2013]

Dwarf spheroidal satellite Galaxies

- Not yet observed in gamma rays! No recent star formation and little gas to serve as target material for cosmic-rays.
- Dark matter dominated systems, mass-to-light ratio up to a few hundreds &within ~ 100 kpc of the Earth

- DM content determined from stellar velocity dispersion
  - Classical dwarfs: thousand stars
  - Ultra-faint dwarfs: <~ 100 stars -- considerable uncertainties

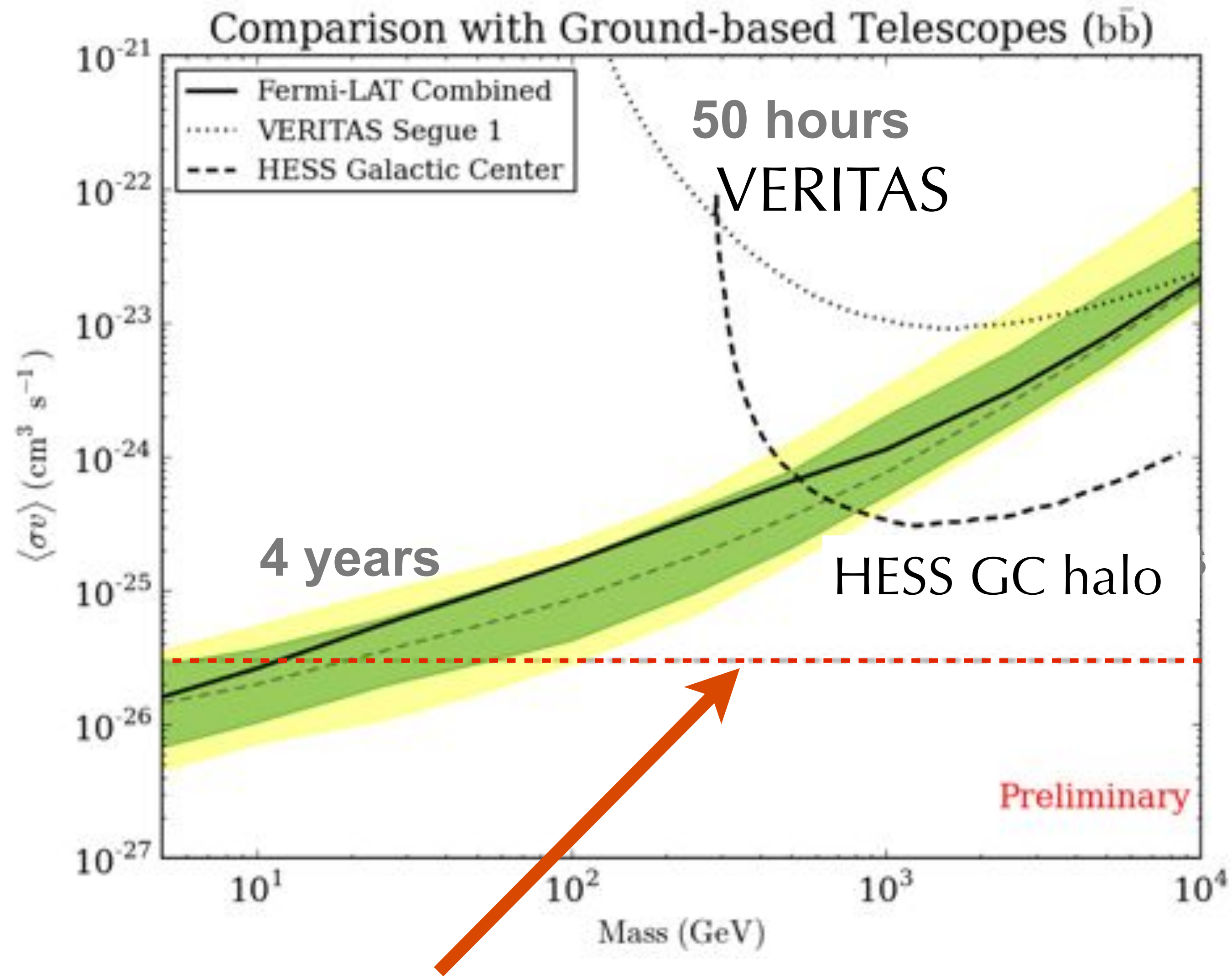
  -> the biggest uncertainty for this target.



[A. Drlica-Wagner, Fermi Symposium 201
(see also Geringer-Sameth+, 1108.2914
Strigari+, 0902.4750, 1007.4199; Magic
coll., 1103.0477; HESS coll., 1012.5602)

Dwarf spheroidal satellite Galaxies

- Fermi LAT analysis of 10 dsph Galaxies using a joint likelihood approach.
- ***systematics* (due to determination of DM content of dwarf Galaxies) *folded in the limits!***



Thermal Relic Cross Section

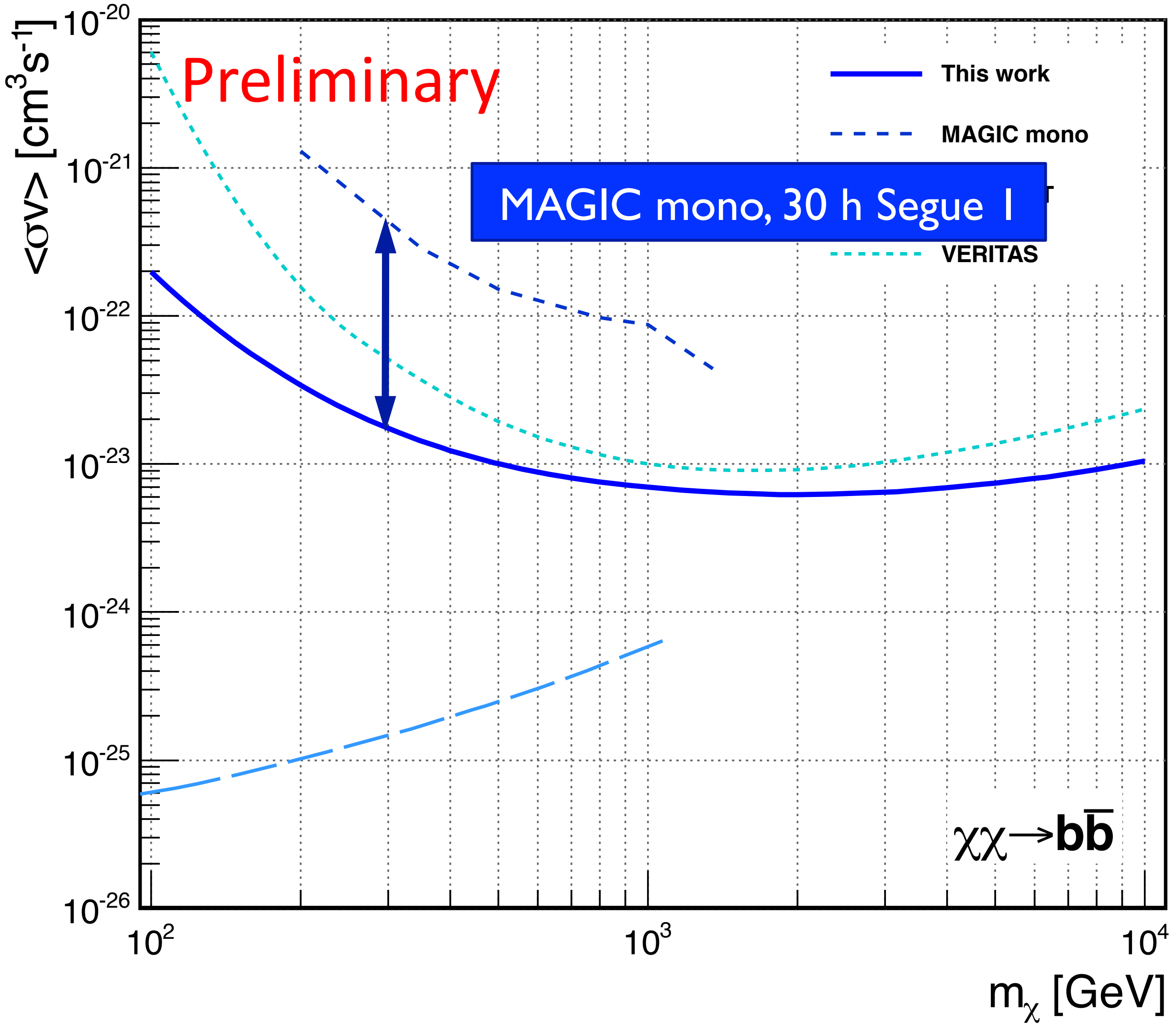
$$\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3\, \mathrm{s}^{-1}$$

One of the strongest limits on generic WIMPs to date: Constrain the conventional thermal relic cross section for a WIMP with mass < 30. GeV annihilating to $b\bar{b}$ or $\tau^+\tau^-$.

[A. Drlica-Wagner, Fermi Symposium 2012]
(see also Geringer-Sameth+, 1108.2914 Strigari+, 0902.4750, 1007.4199; Magic coll., 1103.0477; HESS coll., 1012.5602)

Dwarf spheroidal satellite Galaxies

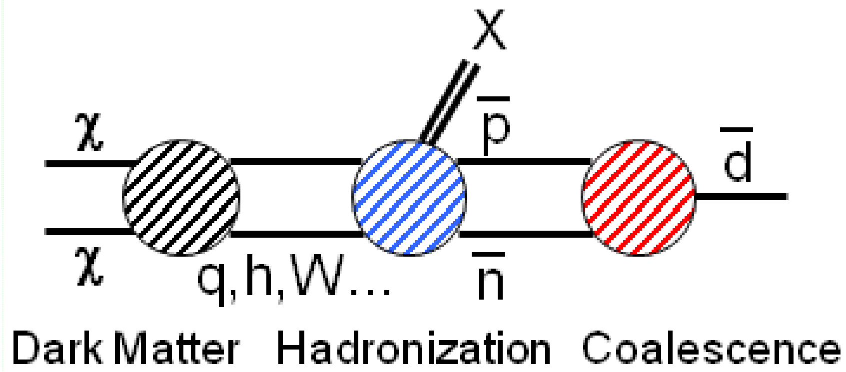
- **MAGIC**: new limits from **Segue 1** based on their stereo system (in place since 2009 (upgrade 2012), all limits based on mono data)
- Total effective observation time:**157.9h**. The deepest survey of any dSph by any IACT! The strongest limits from heavy (~TeV) DM from dwarf Galaxies.

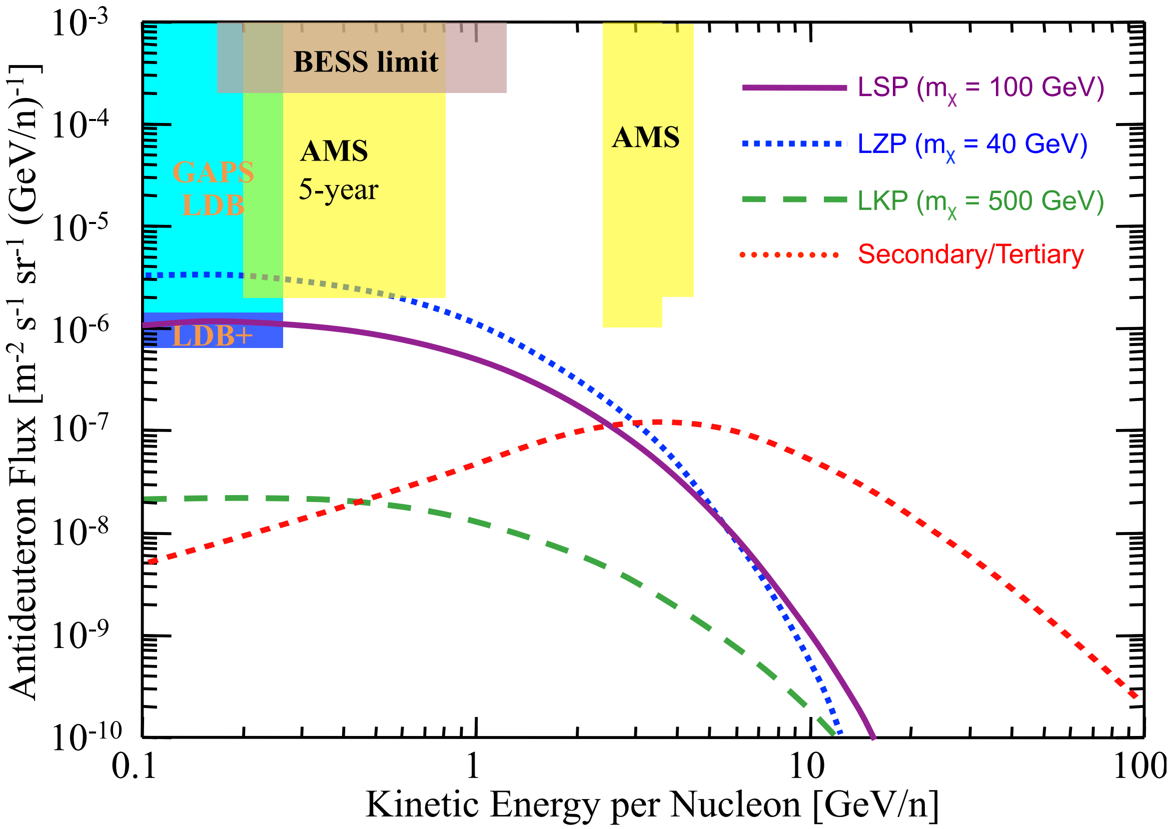


[J. Aleksic, ICRC 2013]

anti-deuterons ($\bar{p}$ $\bar{n}$)

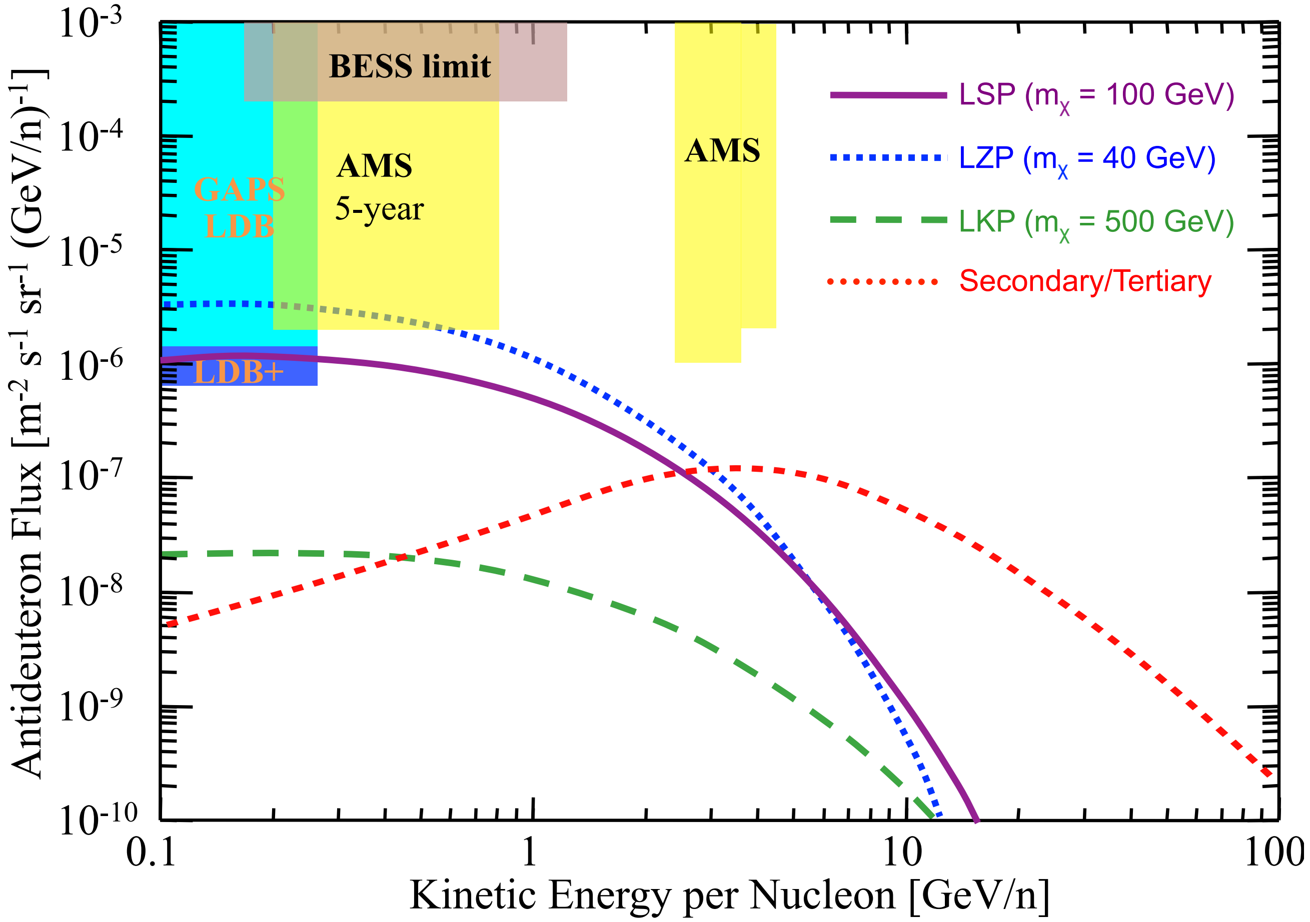
- not detected yet;
- in DM ann/decays produced via the coalescence of an $\bar{p}$ and an $\bar{n}$ originating from an annihilation event
- astro: spallation of high energy cosmic ray protons on the interstellar gas at rest pH or pHe
- ***DM signals*** flatter than astro backgrounds for ***<2,3 GeV/n***: detection of ~1 pn at <1 GeV a smoking gun -- A generic signature with essentially zero conventional astrophysical background





[Ibarra+, 1301.3820, Fornengo+, 1306.4171]

- AMS in its second year & pGAPS finished a prototype flight! Plan for an initial GAPS flight in winter 2017/2018.
- Exciting time coming up for anti-deuteron searches!



[K. Perez's talk at ICRC & arXiv:1303.1615]

2. When astrophysics (can) mimics DM signal:

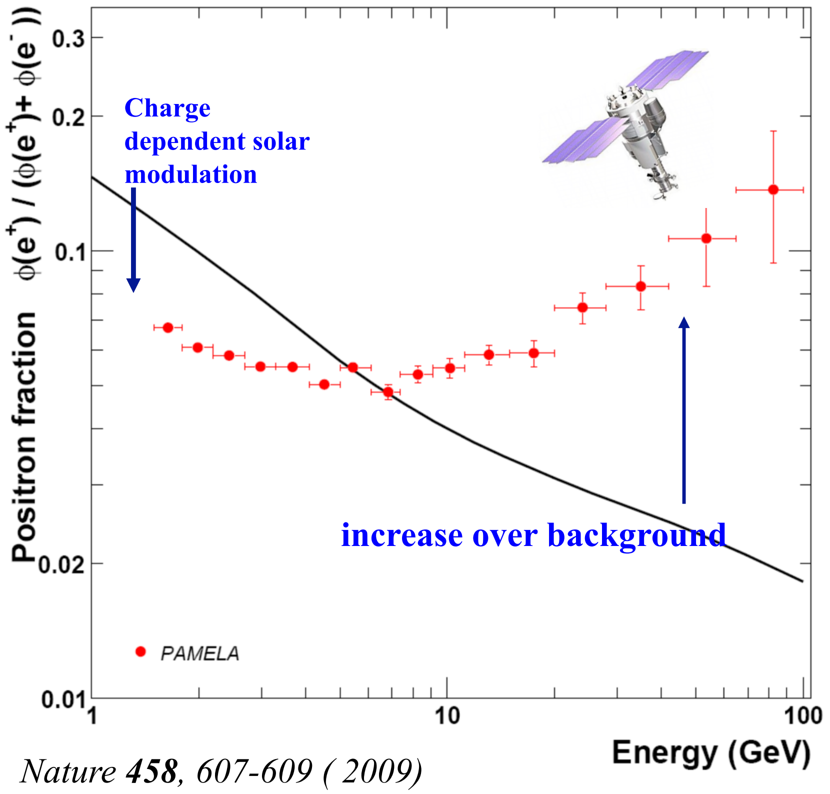
New experiments often reveal ***residuals*** with respect to commonly assumed backgrounds.

Some resemble a DM signal (as we witnessed in recent years).

Rely on multi-wavelength/messenger/target cross checks:

- example: a positron fraction rise.
- review most stringent constraints on WIMP models and illustrate ***complementarity*** of various indirect detection strategies in testing the DM discovery hints.

- Measurement: positron fraction.



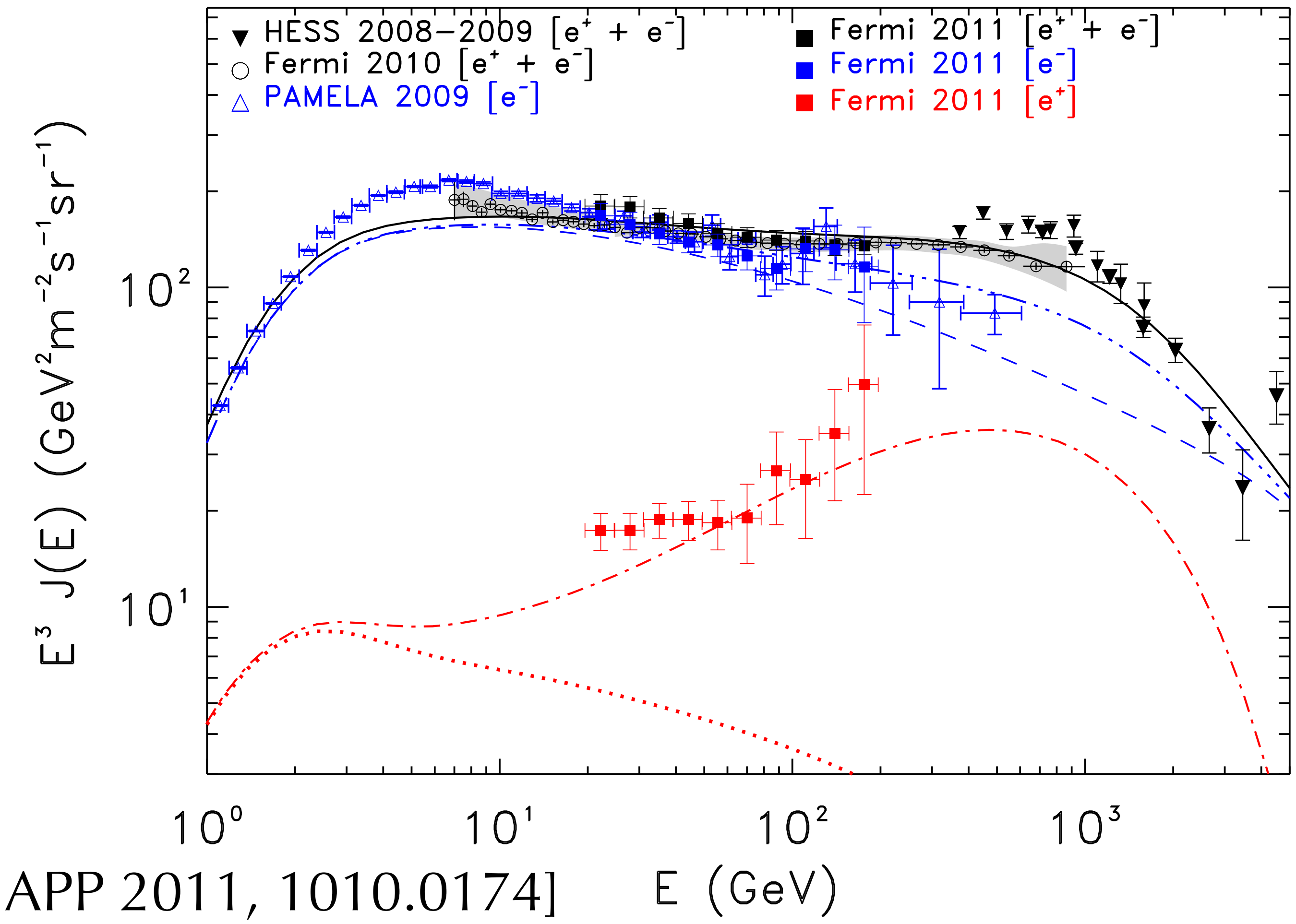
Nature ***458***, *607-609 (2009)*

Measured by PAMELA and confirmed by Fermi LAT and recently by AMS.

- fraction of secondary positron fraction of secondaries falls with energy
- A new source needed to explain the rise!
- ***Could be local CR sources or a DM***.

[see also Fermi LAT coll., PRL 2012; AMS coll., PRL 2013]

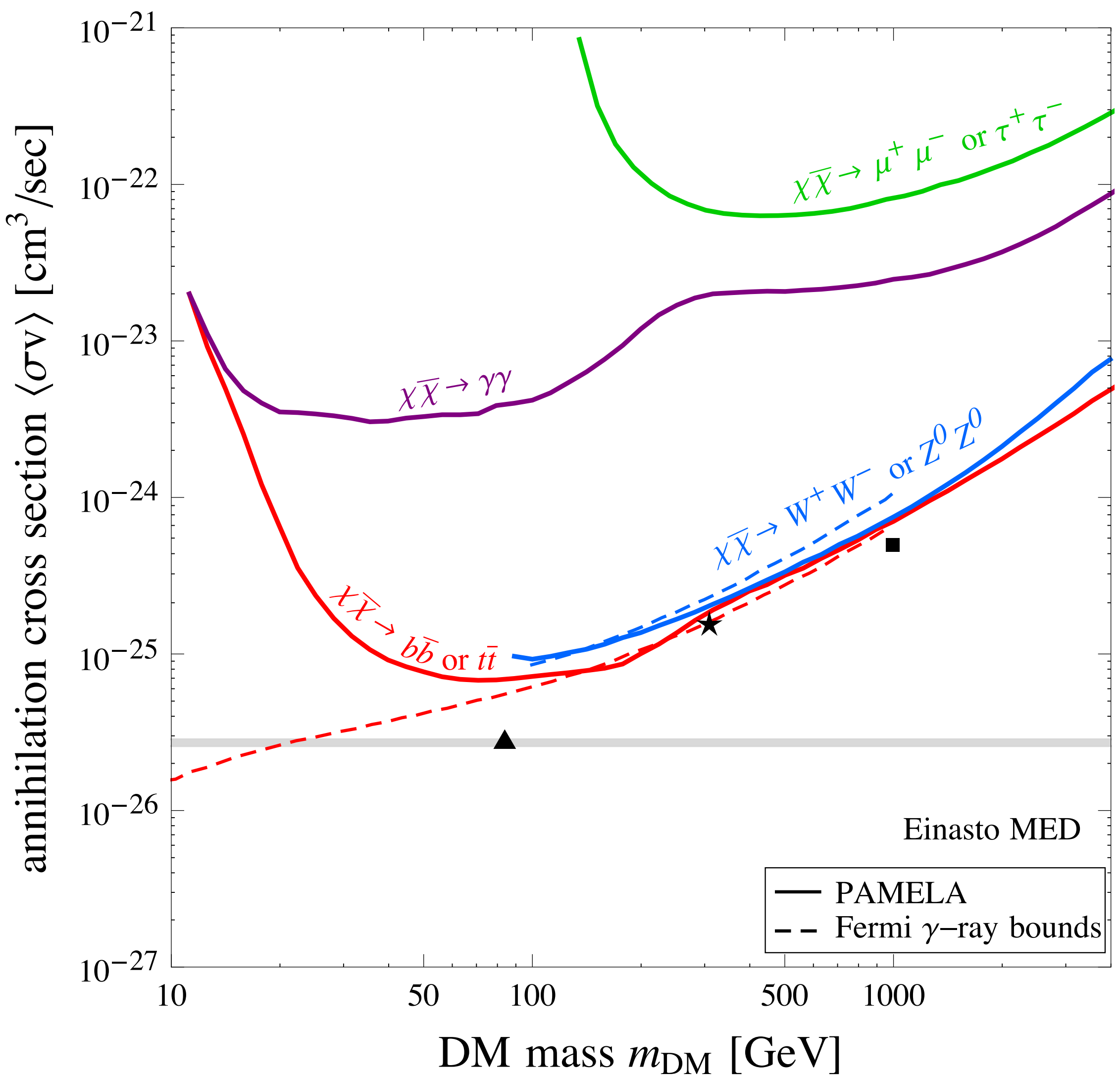
- a new el+pos source consistent with the electron measurements by Fermi LAT and PAMELA.



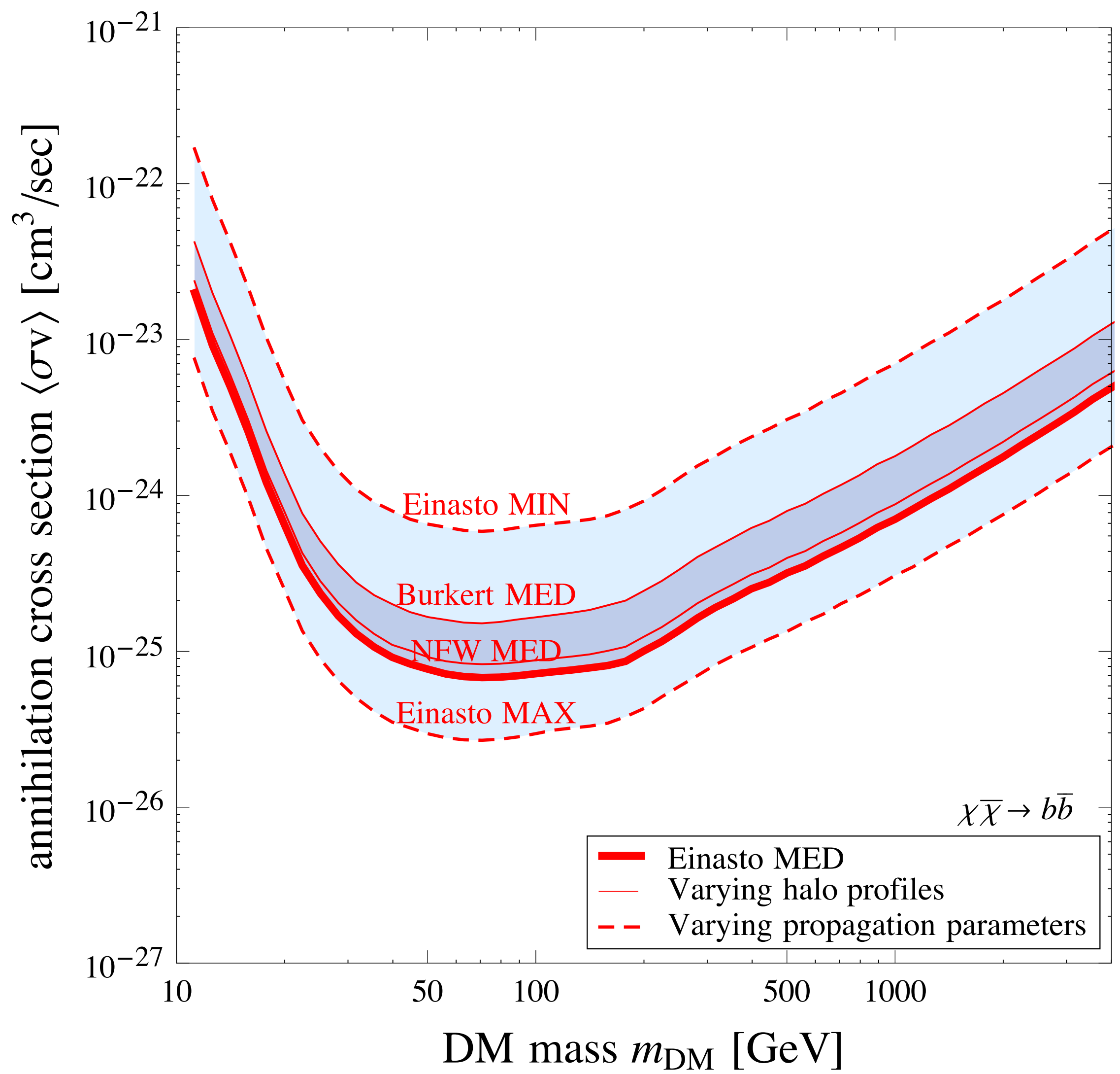
[Bernardo+, APP 2011, 1010.0174]

- DM constraints: CR (anti)protons
  - measurements consistent with purely secondary production of antiprotons in the galaxy
    - tight constraints set on DM annihilation

Annihilation constraints from antiproton flux



Astrophysical uncertainties on the constraints

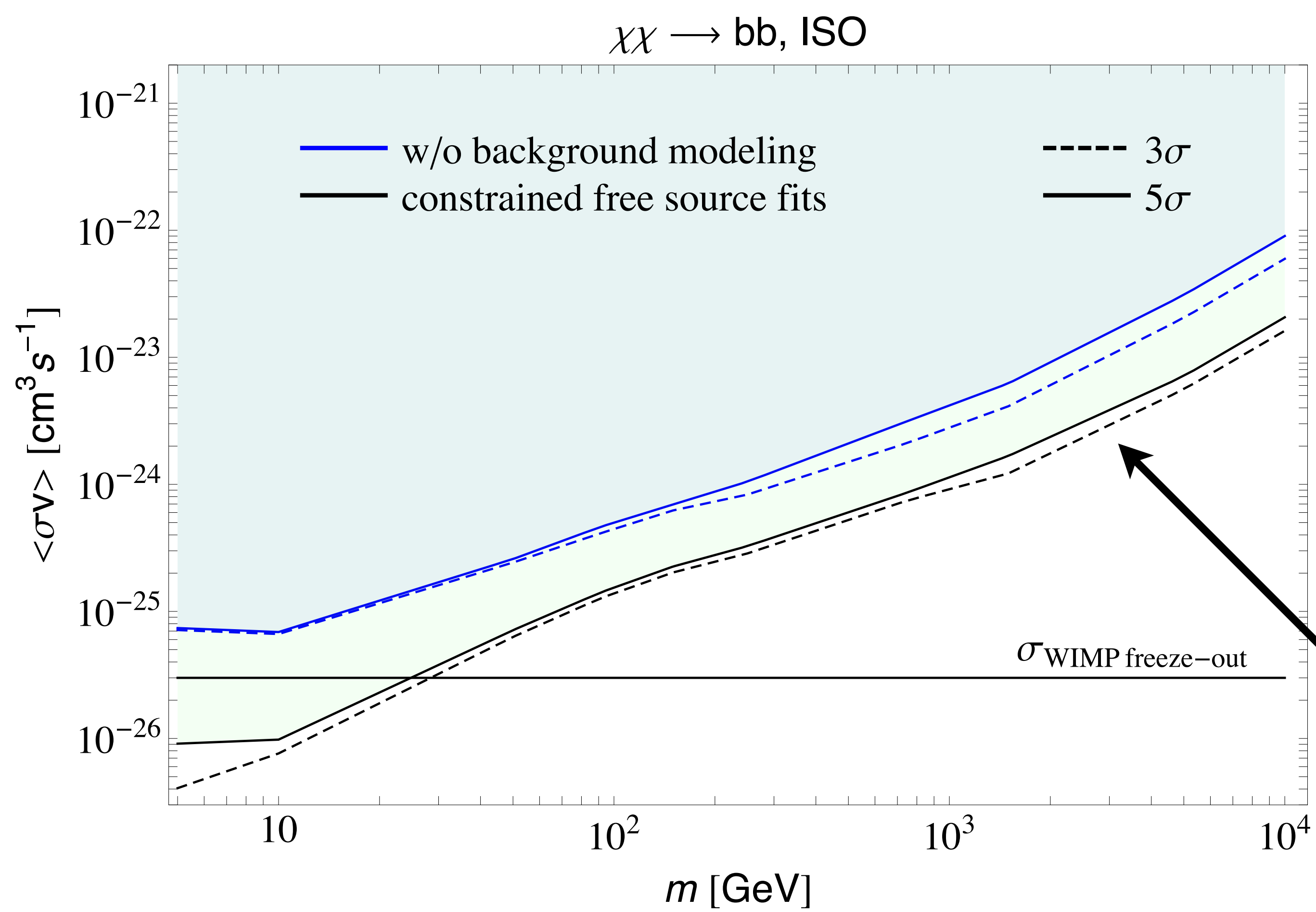


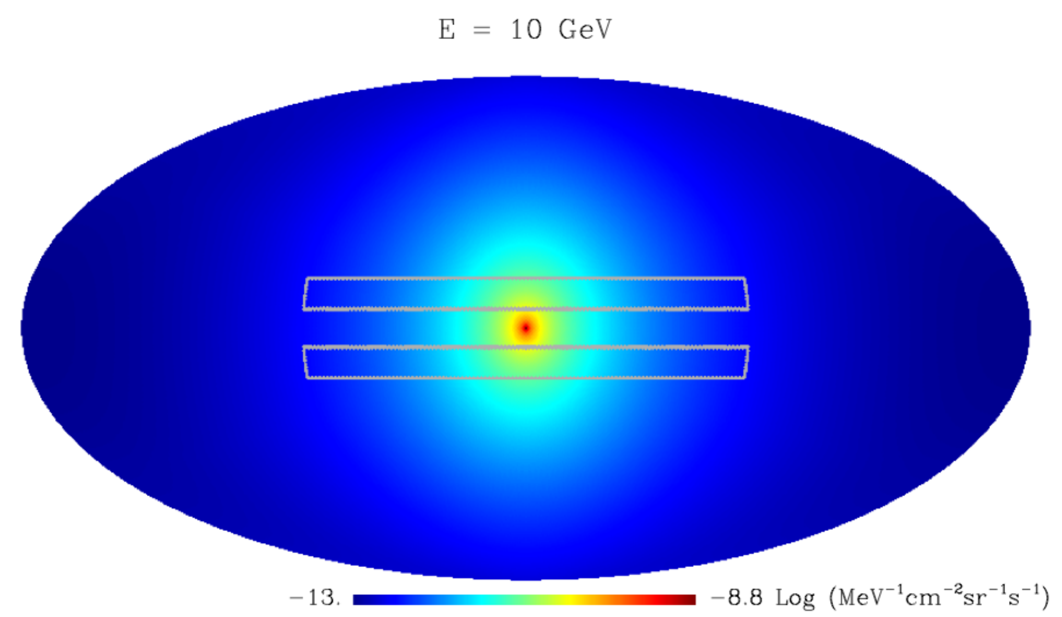
If it is to explain the e+ data DM would have to be:

- **leptophilic**
- **have enhanced cross section, BF~1000.**

[Cirelli+, 1301.7079] (see also Evoli+, 1108.0664 , Donato+, PRL09; Bringmann, 0911.1124...)

- DM constraints: gamma-rays: Fermi LAT/MW halo
  - MW halo a good target for DM search. Going away from the GC, uncertainties in the DM clustering are smaller.
  - Analysis of the Fermi LAT whole sky data.
  - vanilla WIMP models (bb channel) probed at low masses!



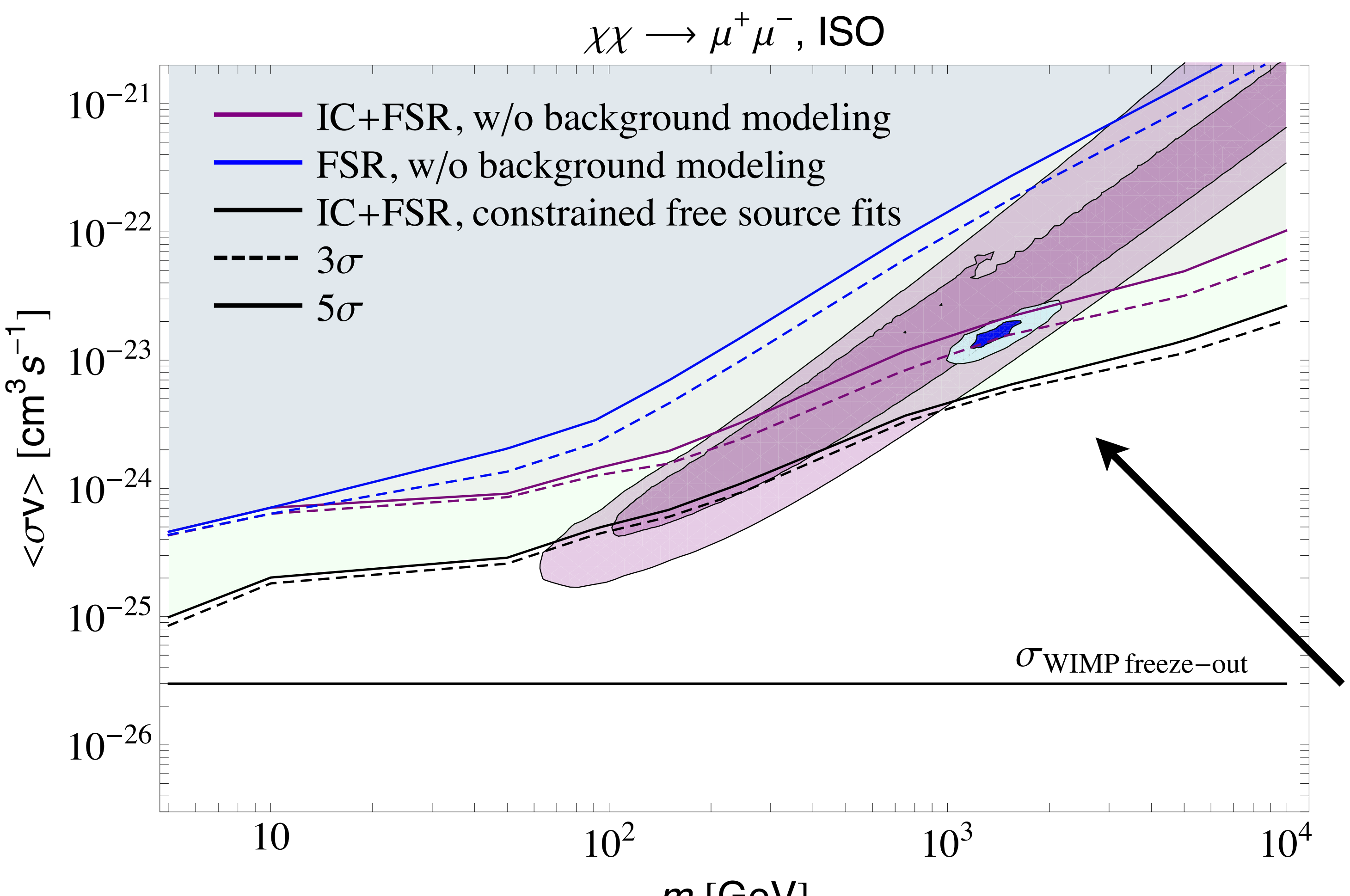


Conventional backgrounds subtracted away

[Ackermann+, APJ 2012, 1205.6474]
(see also Cirelli+, 0912.0663; Papuci+,0912.0742; Baxter+,1103.5779)

marginalized over astrophysical uncertainties!

- DM constraints: gamma-rays: Fermi LAT/MW halo
  - if DM annihilates dominantly to leptons with high sigma-> **strong Inverse Compton emission in the inner galaxy**
  - gamma ray constraints from the IC emission
  - challenge the DM interpretation of the el/positron measurement for ANN DM.



[Ackermann+, APJ 2012, 1205.6474]
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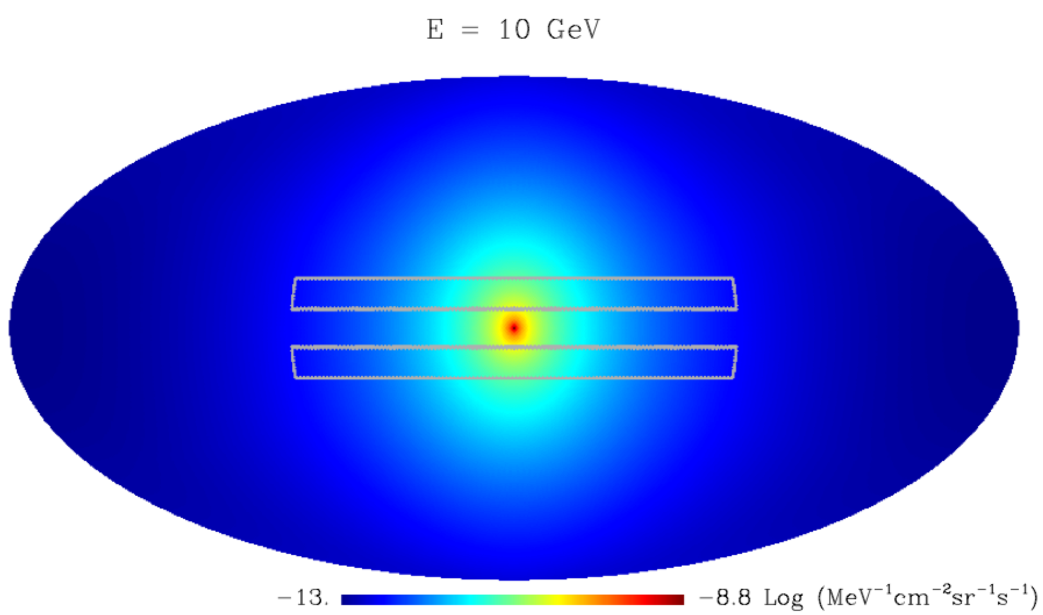
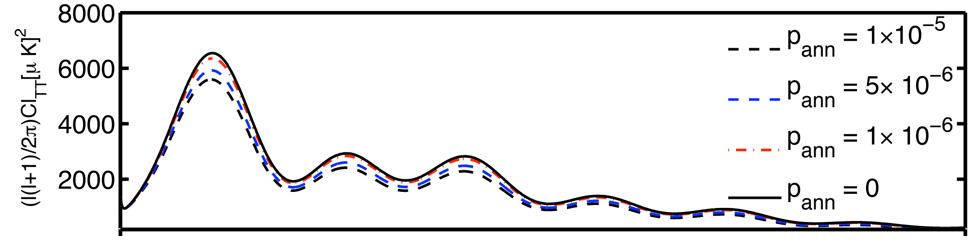


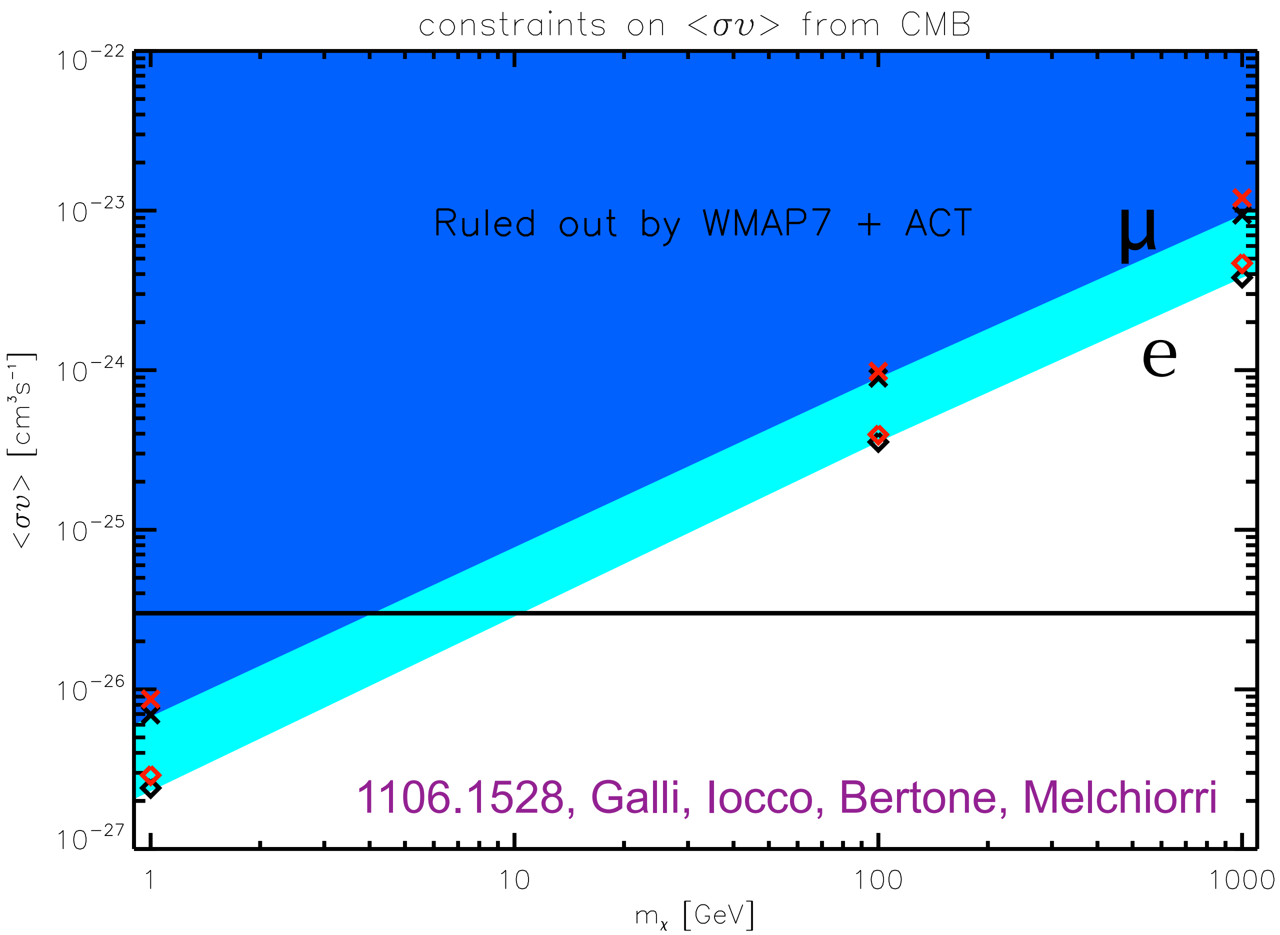
Conventional backgrounds subtracted away

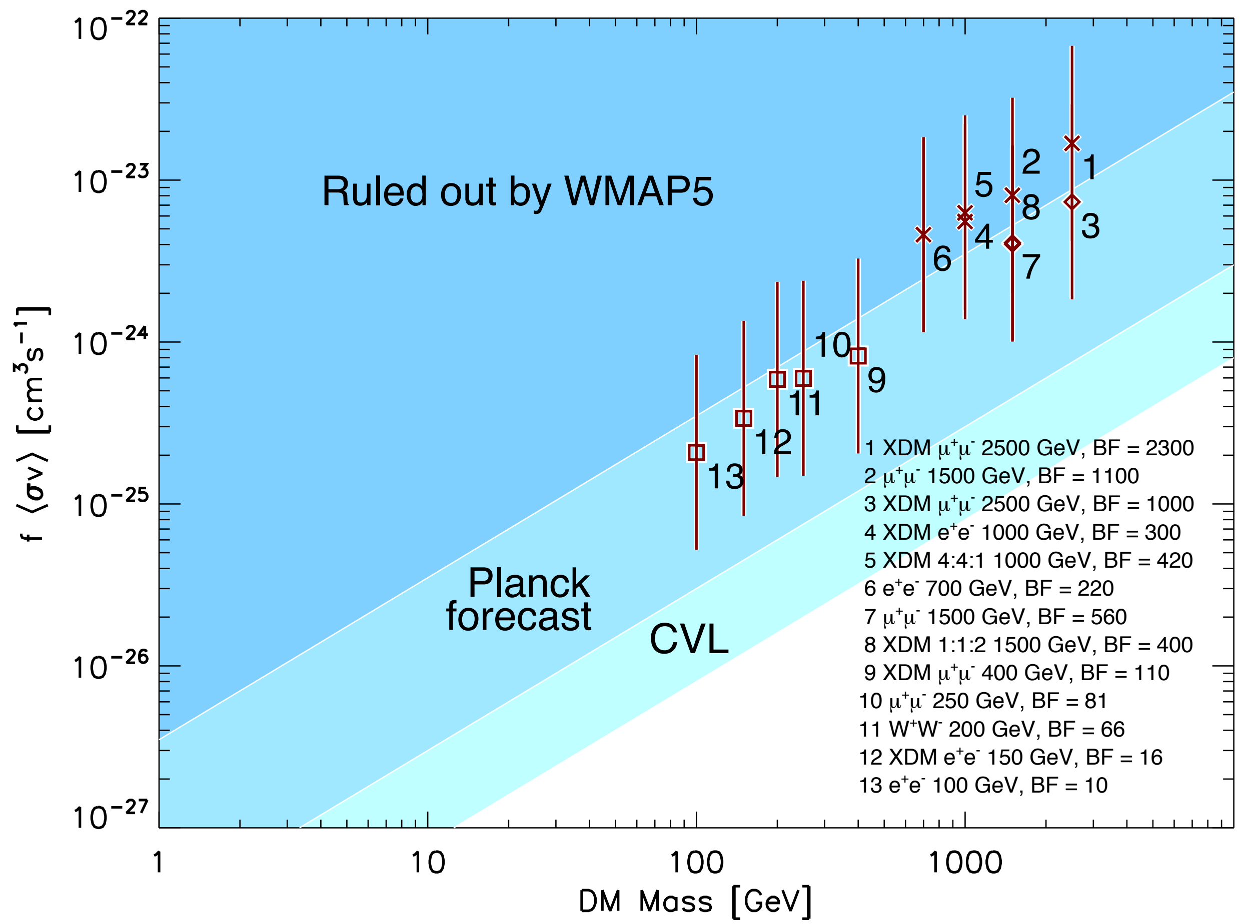
marginalized over astrophysical uncertainties!

- DM constraints: CMB
  - DM annihilations inject energy and energetic particles in the primordial medium, and therefore affect its evolution (i.e. fraction of free electrons).
  - DM in the linear regime/*robust to DM clustering uncertainties*!



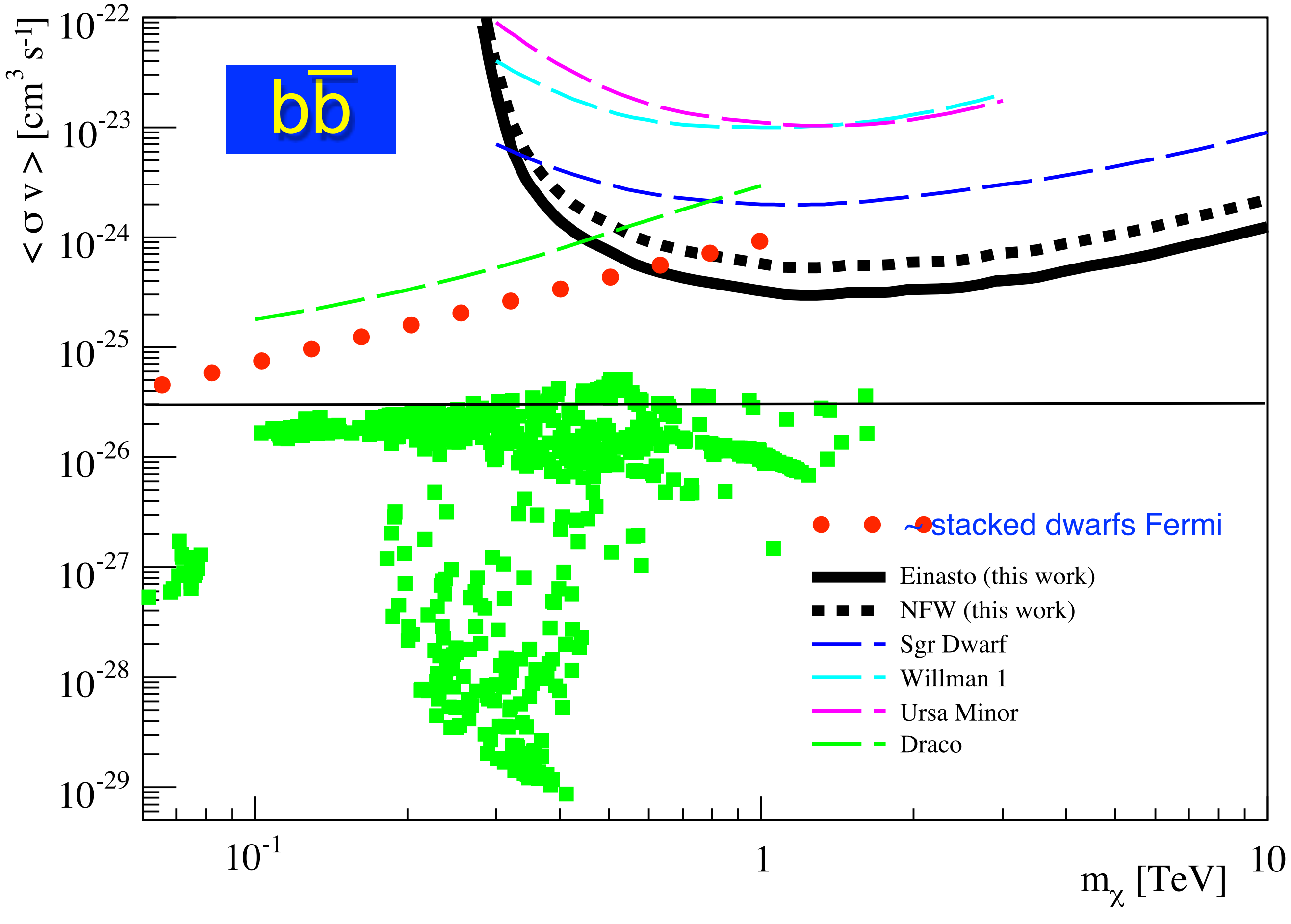
CMB anisotropy for different DM annihilation power.





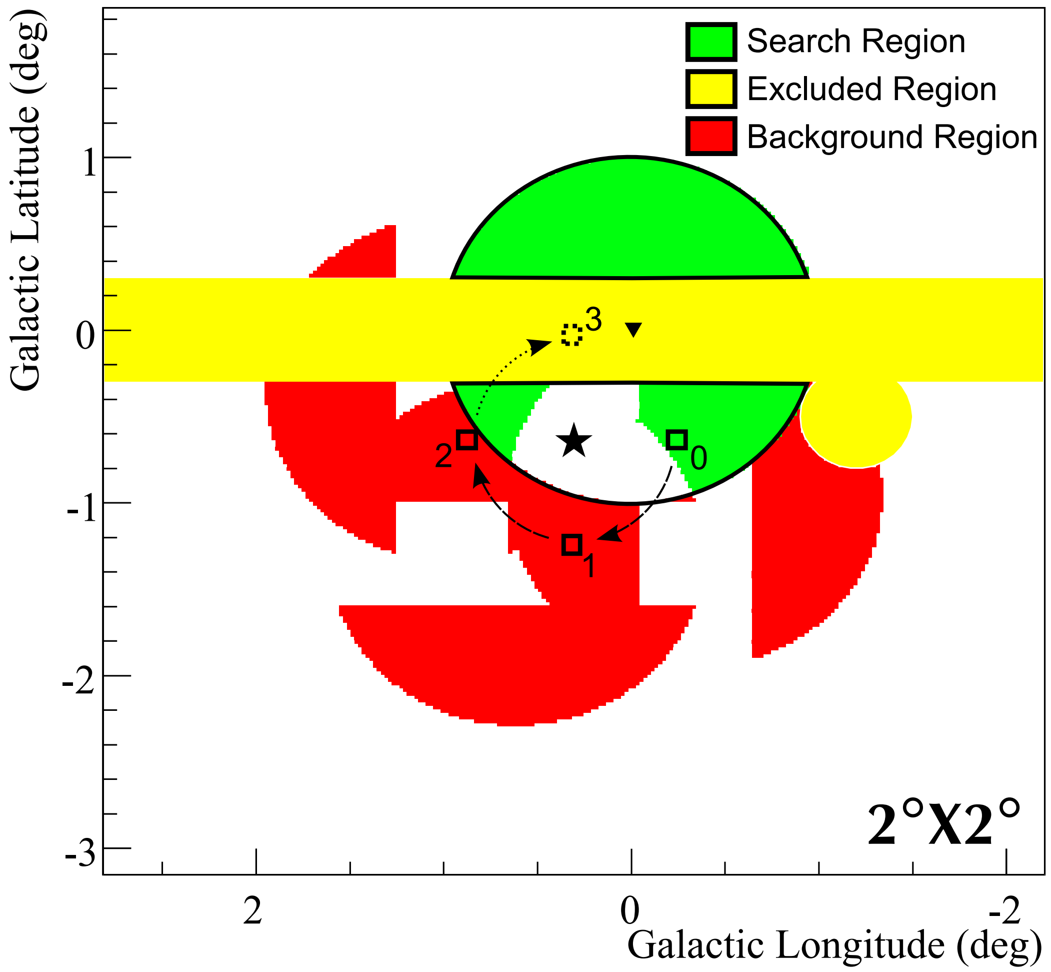
[Slatyer+, PRD 2009, 0906.1197, (see also Cline & Scott, ’13; Weniger et al. `13)]

- DM constraints: gamma-rays: HESS/GC halo
  - HESS analyzed a smaller region around the GC (at angular distances between 0.3°-1.0°) producing one of **the strongest constraints on heavy DM** to date.



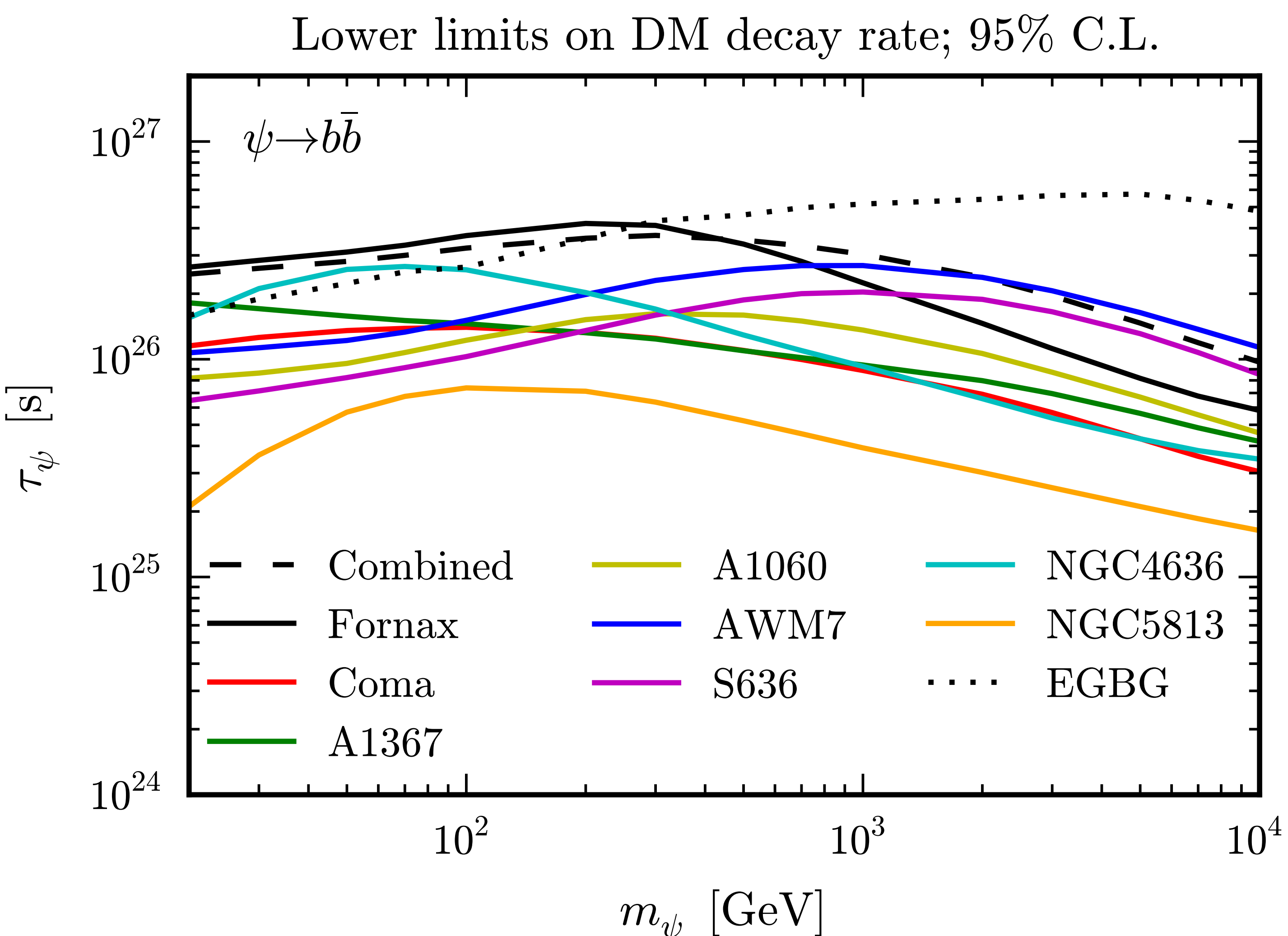
[Abramowski+, PRL, 2011, 1103.3266]

on-source/off-source technique
-> ***not applicable for cored DM profiles***



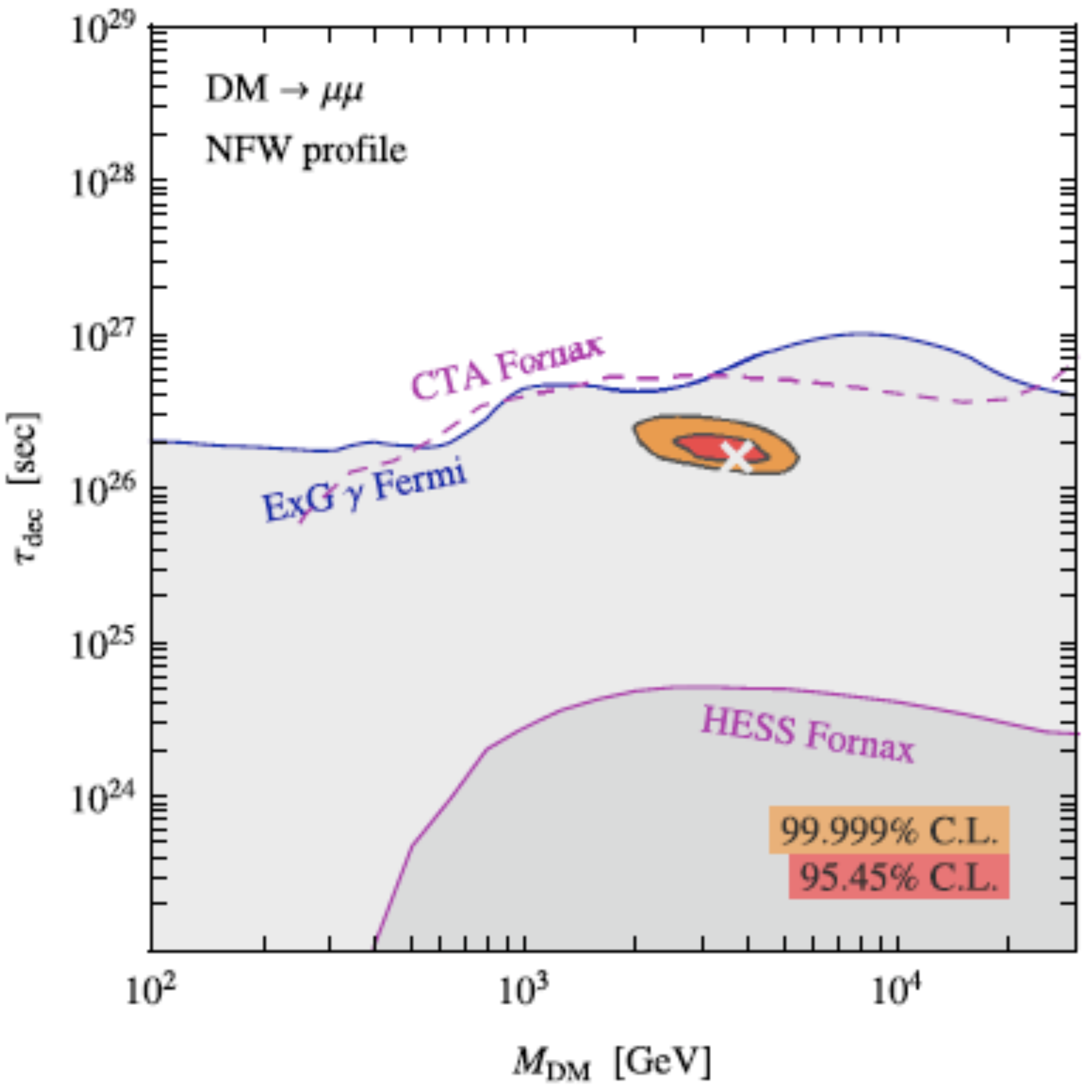
- DM constraints: gamma-rays: decaying DM
  - for decaying DM ‘large volume’ targets most constraining (highest S/N)
    - clusters: the most massive structures yet to form
    - the whole Universe (isotropic signal): for decaying DM does *not depend on DM clustering properties* (only on total amount of DM)

Galaxy Clusters



[Huang+, JCAP, 2012, 1110.1529]

extragalactic DM/isotropic signal; robust to DM clustering uncertainties!



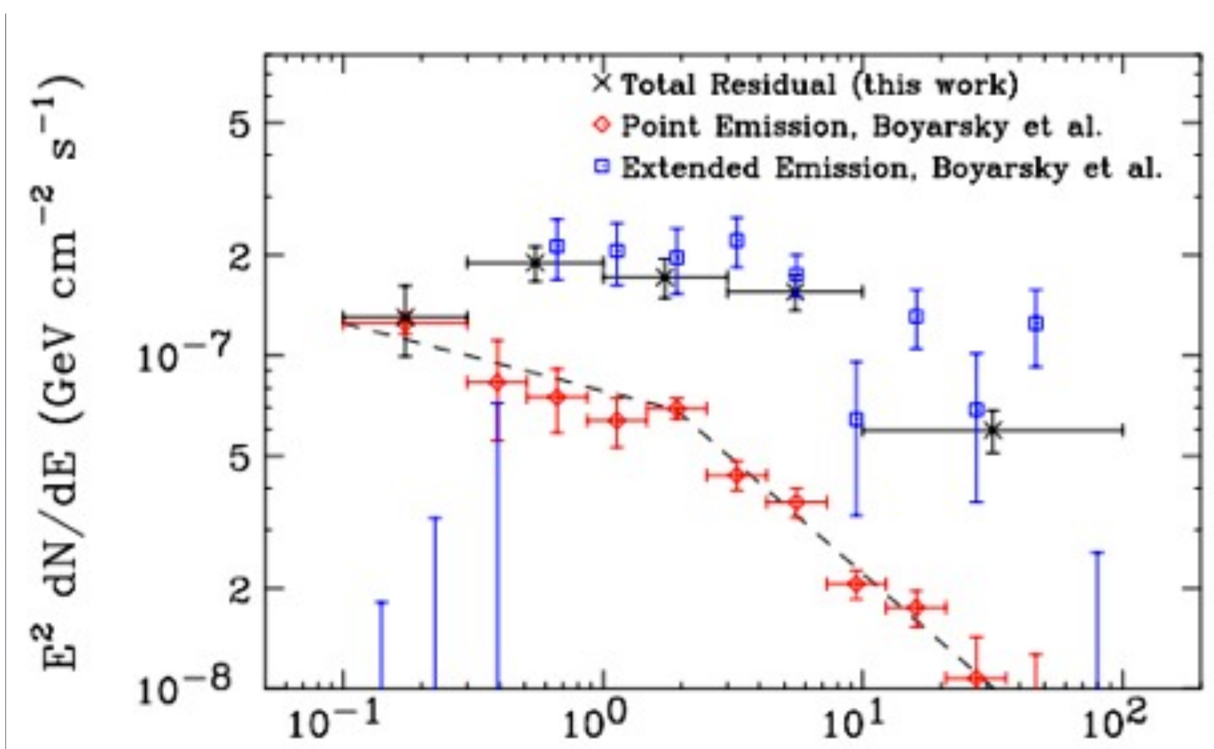
[Cirelli+, PRD 2012, 1205.5283]

- ➡ lessons learned: multi-target approach severely challenged the DM interpretation of the positron rise. Important limits derived along the way.
- recent developments: the new AMS positron fraction and electron data still remain to be studied in terms of DM interpretation.

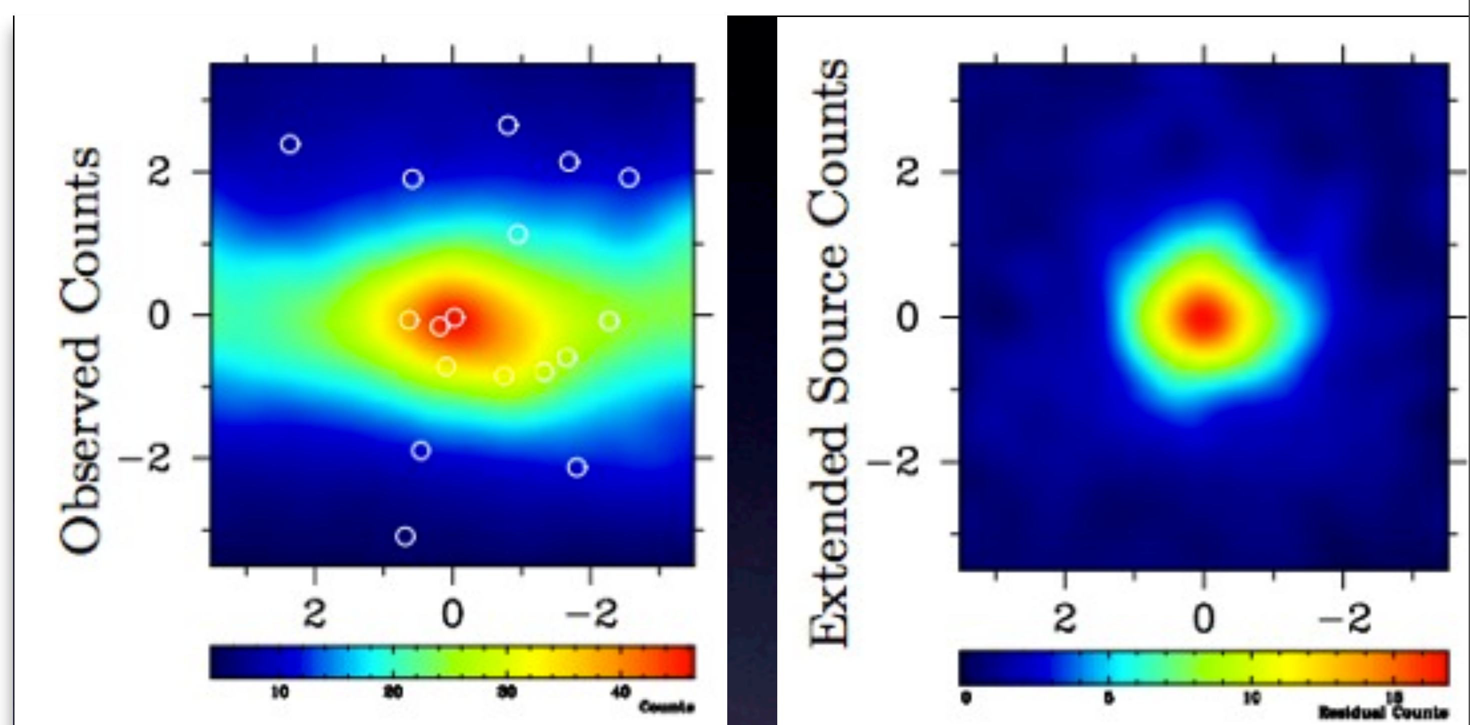
When astrophysics can mimic the DM signal (02)

Galactic Center gamma ray signal

- the Galactic Center region hard to model in the ~ GeV energy range
- **point source confusion with the diffuse emission** (the Fermi LAT resolution ~0.5 deg)
- **possibly unique (and poorly unconstrained) CR propagation and energy loss conditions in this region** (Fermi bubbles...)
- several independent groups reported suspicious residuals in this region, Both 1) In the inner few degrees of the Galaxy



Hooper & Linden 2011

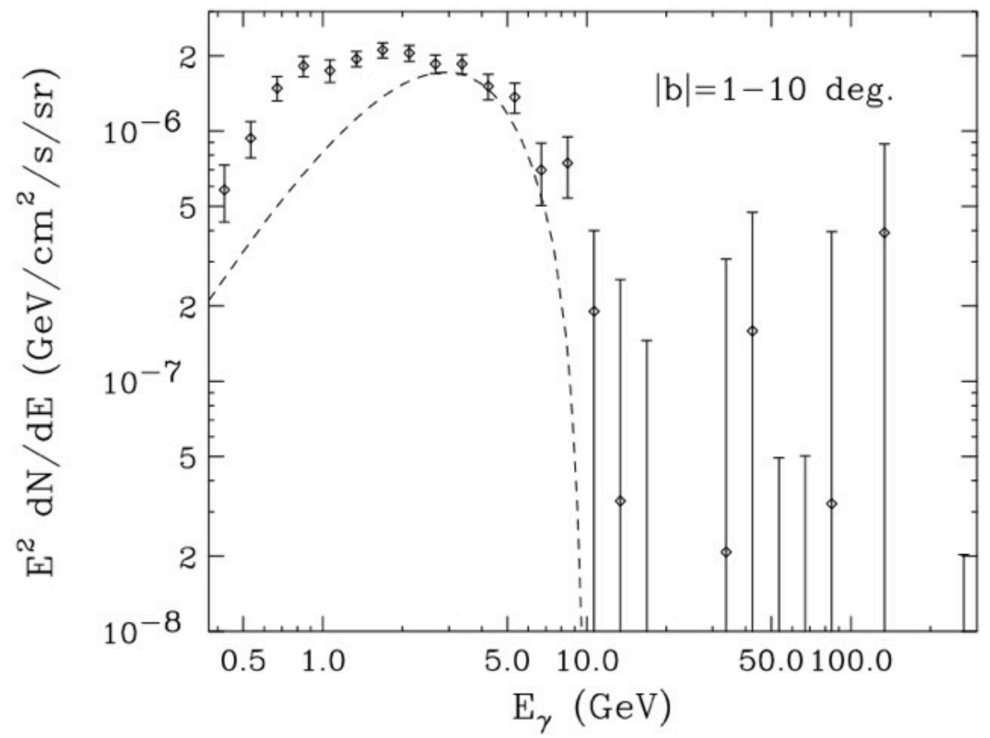


Abazajian & Kaplinghat 2012

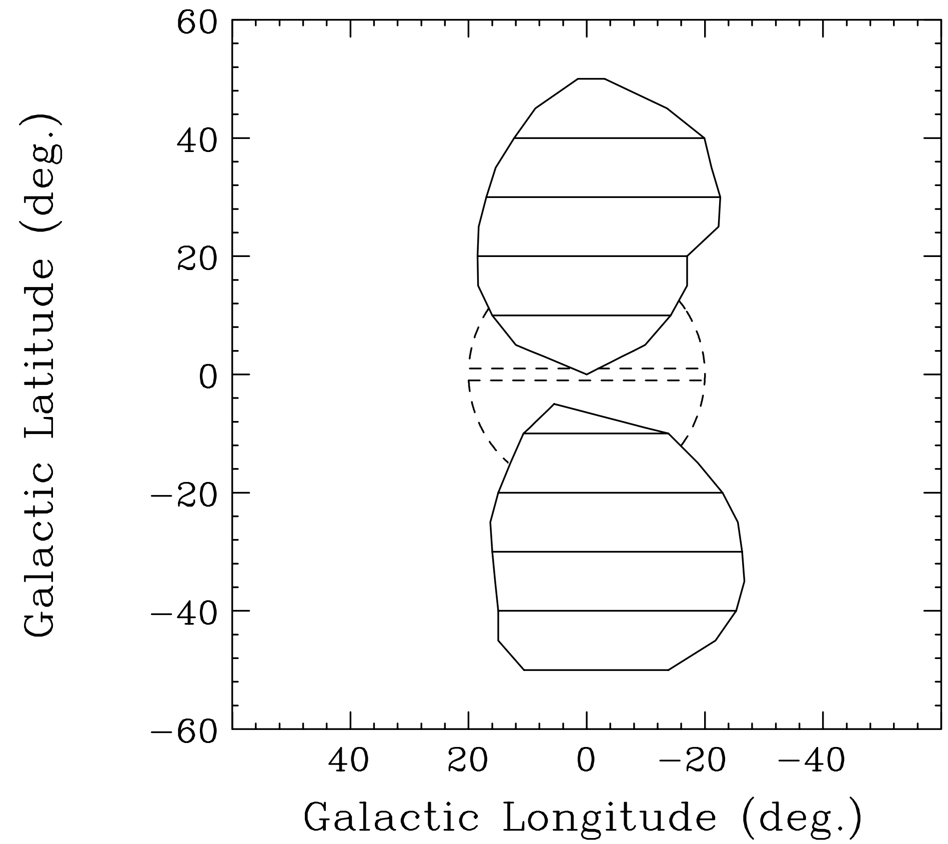
When astrophysics can mimic the DM signal (02)

Galactic Center gamma ray signal

- the Galactic Center region hard to model in the ~ GeV energy range
- **point source confusion with the diffuse emission** (the Fermi LAT resolution ~0.5 deg)
- **possibly unique (and poorly unconstrained) CR propagation and energy loss conditions in this region** (Fermi bubbles...)
- several independent groups reported suspicious residuals in this region, or 2) a larger spread out region ~10-20 degs.



Dashed line = 10 GeV DM annihilating to taus, chosen to fit GC excess (no free normalization), extrapolated outward with squared modified NFW profile with inner slope $r^{-1.2}$.



[Hooper+, 1302.6589]

When astrophysics can mimic the DM signal (02)

Galactic Center gamma ray signal

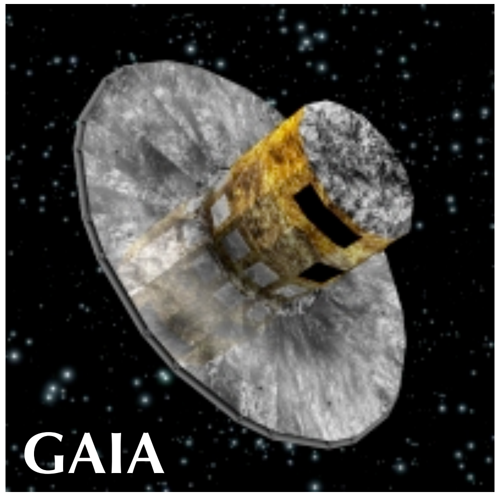
- if confirmed the signal consistent with
  - ~50 GeV DM going to bb, distributed with a steep 1.2 inner slope, with ~10^{-26} cm^3/s, almost thermal, relic cross sections (~vanilla DM!)
  - pulsars have similar spectra, but harder to fit the cuspy yet extended profiles derived from the data
- Bare in mind, it is **very challenging to quantify the exact properties of the residuals**!
- confusion between many templates&point sources -- *important work to study the inner Galaxy ahead!*
- Fermi LAT collaboration paper by the end of the year + possible changes in the observation strategy to study this fascinating region.

Near term improvements:

- Look for ***smoking guns*** (need to get lucky! - increase sensitivity)
- or '***know your nemesis***':
  - The field of astrophysics is being re-defined by high-quality data, extending over a larger dynamical range.

Optical surveys: DM density profiles, discovery of dwarf Galaxies, Galactic dust maps

- pan-STARRS: Hawaii, PS1 started operating in 2008.
- DES: Chile, started 2012.
- Gaia: launch October 2013.



X-ray: GC environment, Fermi bubbles, pulsars, AGNs, star burst Galaxies

- nuSTAR: launched 2012.

Radio: pulsars, CR propagation, DM signatures

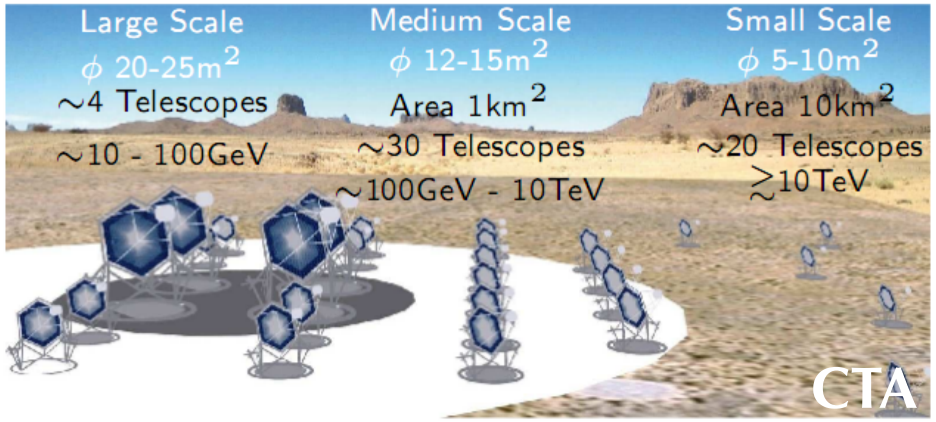
- SKA: construction 2016; to be built in South Africa and Australia.

Gamma rays/charged CRs:

- CTA
- Gamma-400

Neutrinos:

- km3net



- Outstanding effort of humanity for over 50 years: ‘now the tools are there and they are in the right region’!
- Great times for good high-energy astrophysics! -> DM signal might just as well show up on along the way.

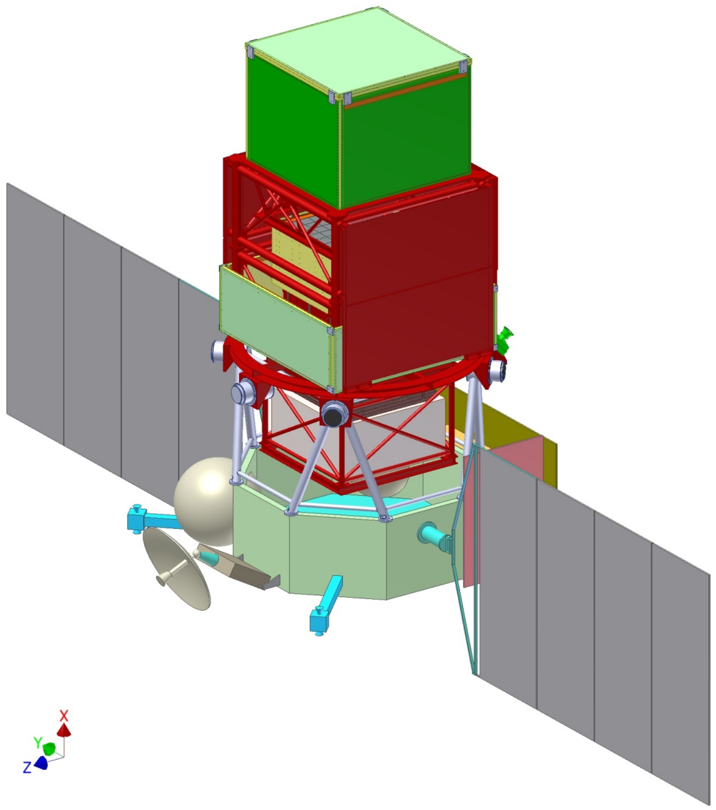
Extra slides

Next generation gamma ray experiments

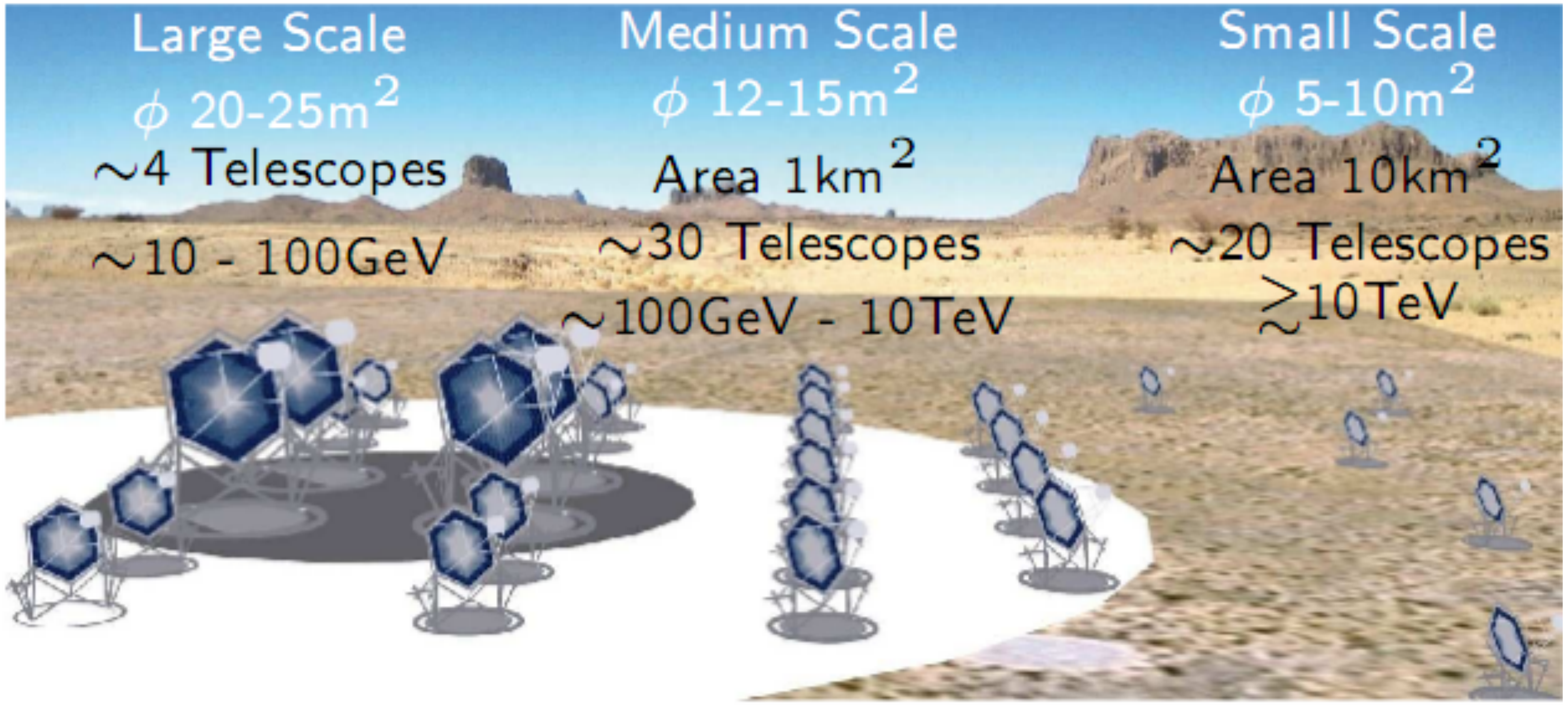
– CTA: a **km^2 array of Atmospheric Cherenkov telescopes**! Sensitivity about a factor 10 better than current ACTs; an energy coverage from a ~10 GeV --~10 TeV, field of view of up to 10° (vs 2°-5°); angular resolution could be as low as 0.02°

– Gamma-400: **satellite with better angular and energy resolution in gamma rays + high precision charge particles detector up to several TeV for e- and PeV for protons!** Funds for launch and basic design secured at a moment!

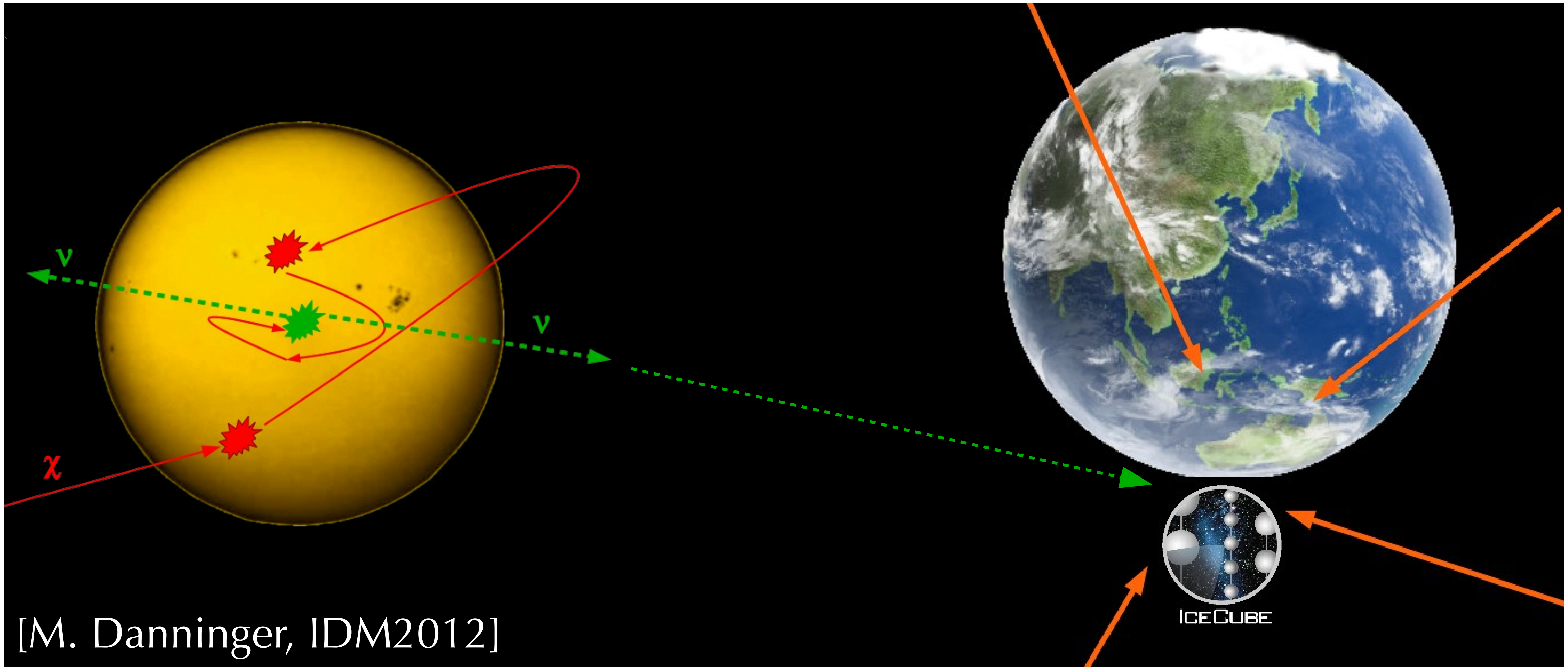
launch planned for 2018.



currently in design phase foreseen to be operative a few years from now.



High energy neutrinos from annihilation in the Sun



In equilibrium all captured DM particles annihilate, potential neutrino signal relates to the elastic (capture) cross section!

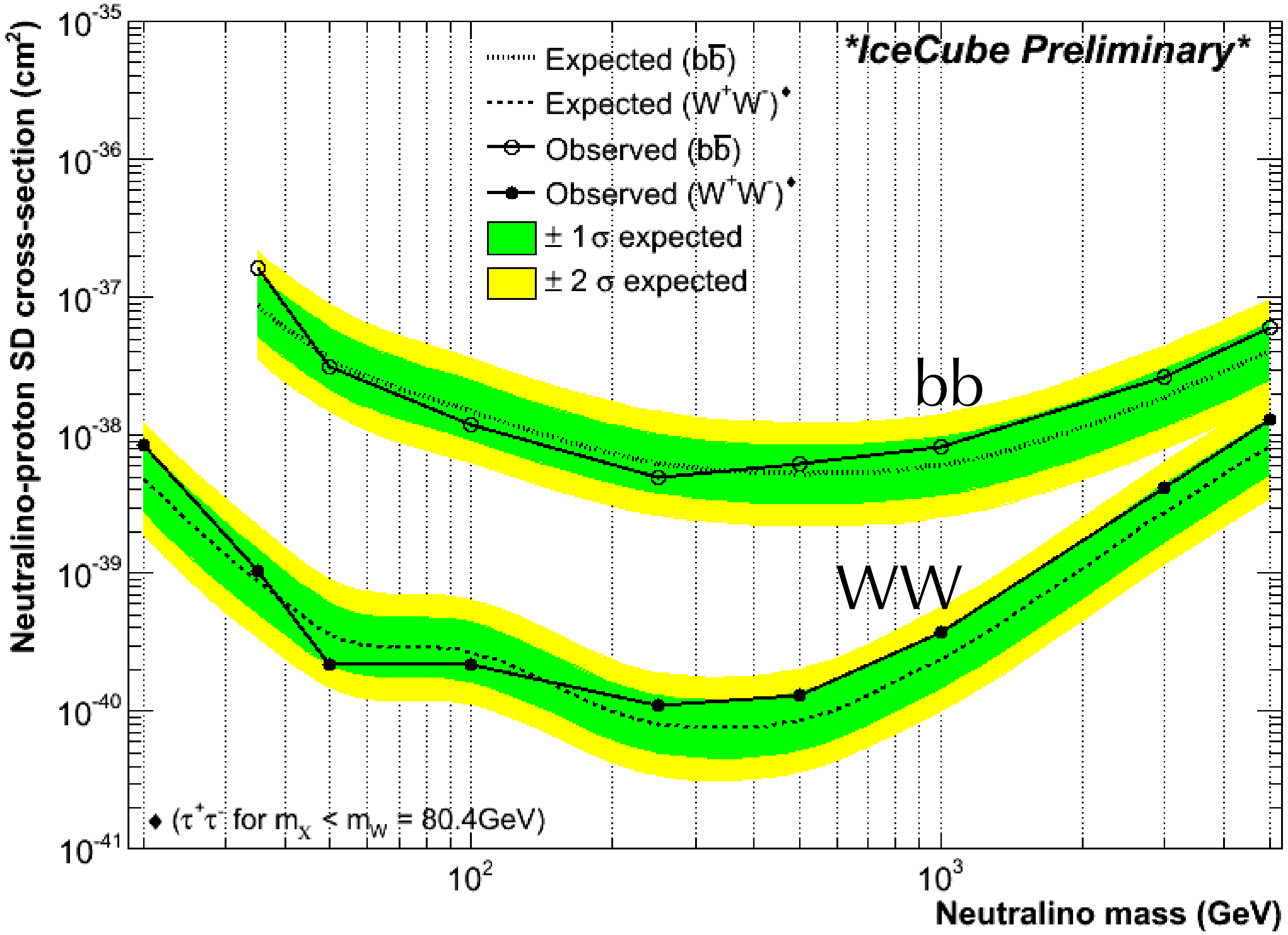
Backgrounds due to neutrinos from nuclear fusion processes BUT @ low <1 GeV energies - detection of a signal- smoking gun.

High energy neutrinos from annihilation in the Sun

Sun is made of p! Limits on spin dependent cross section stronger wrt direct detection experiments!

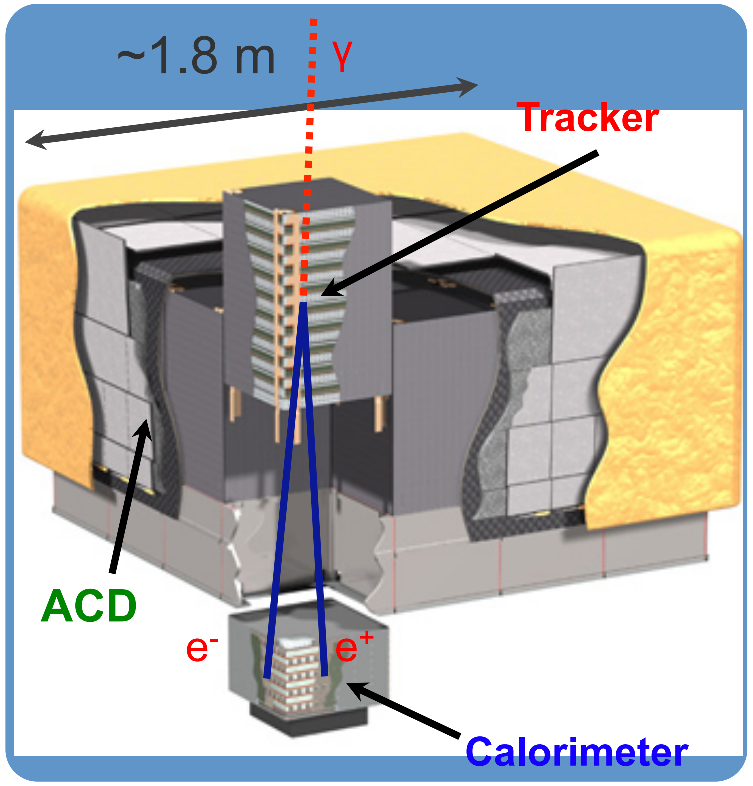
- New results from ***79-string*** data (~1y livetime)
- First Dark Matter analysis including ***DeepCore*** -> constrain low masses >20 GeV and use ***full year***-round IceCube data!

SD scattering



[Aartsen+, PhysRevLett, 131302.]

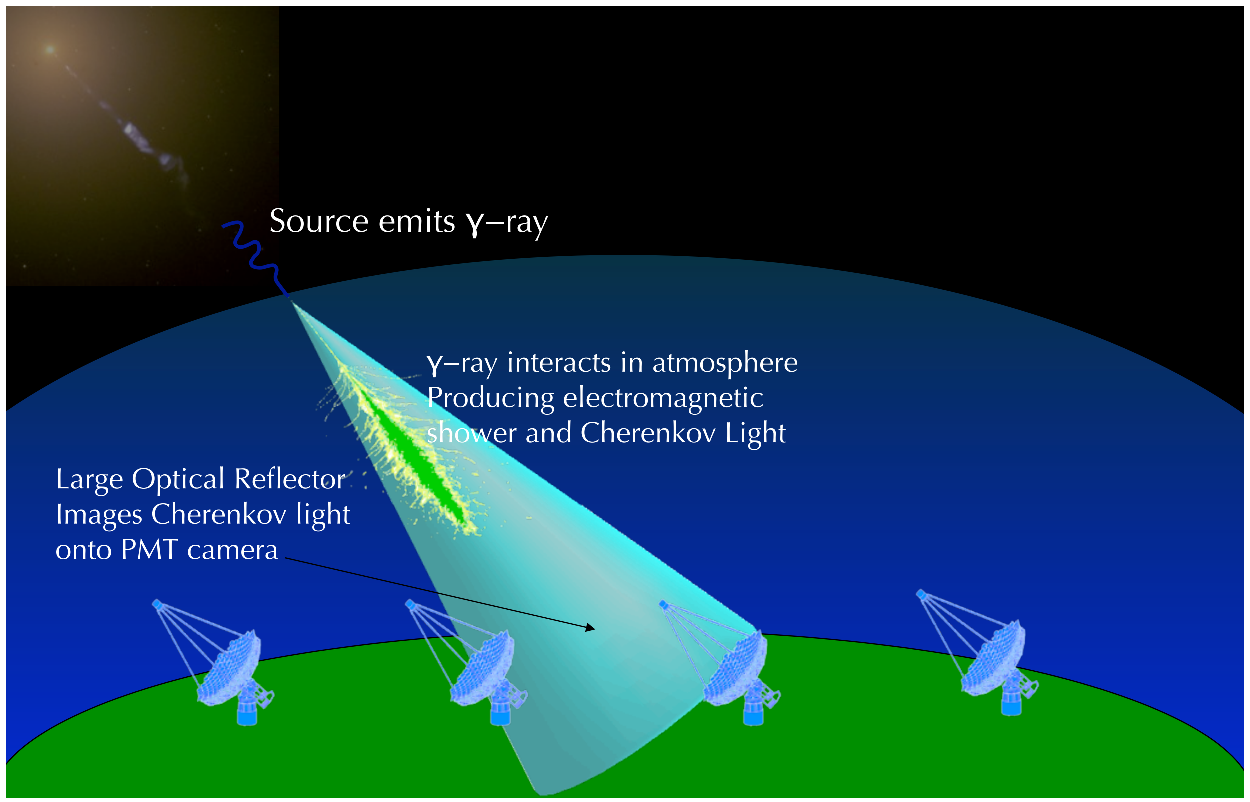
- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments (@~Mz range): *mostly gamma rays (bulk of emission), but lower frequencies (Xray, radio, microwave) relevant too.*
  - satellites (Fermi LAT, AGILE):

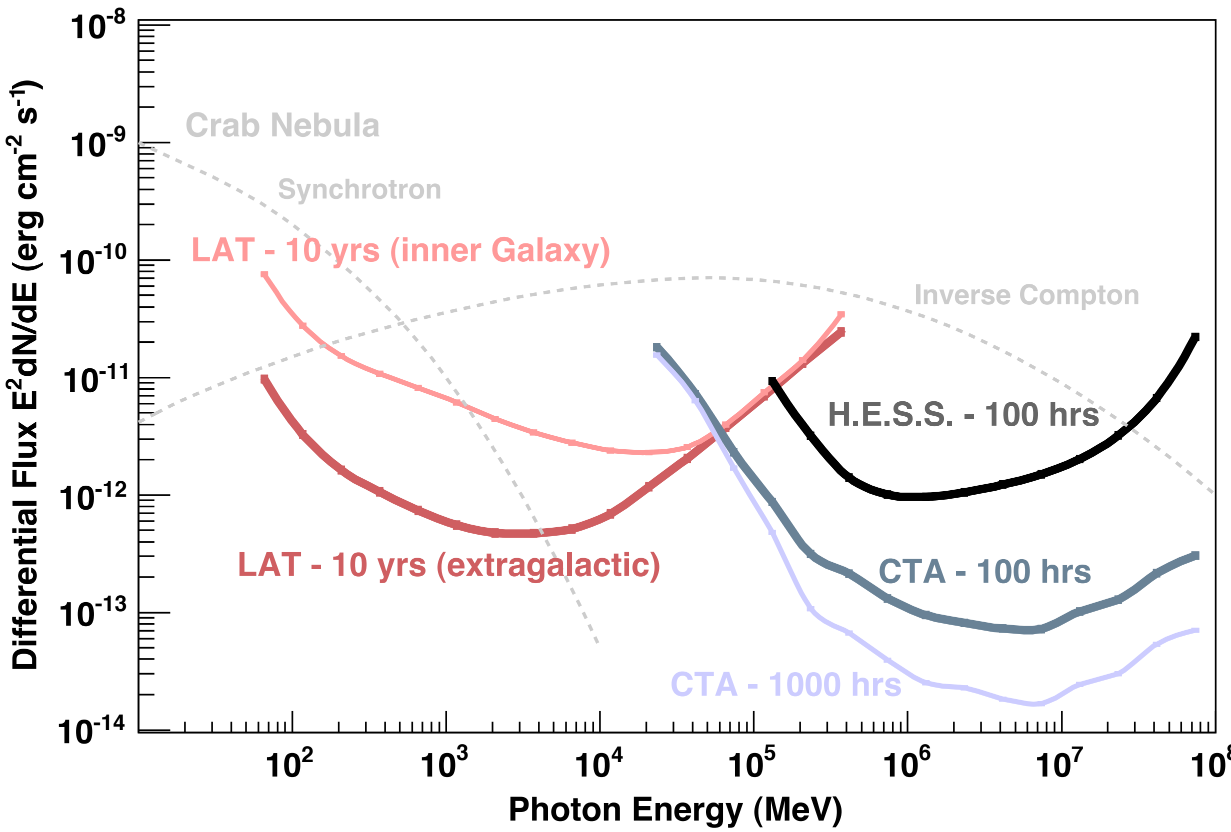


Atwood et al., ApJ 697, 1071 (2009)

- a pair conversion instrument
- ***wide field of view***, 20% of the sky at any instant.
- energy range ***20 MeV-300 GeV*** (encompassing nicely EW scale)
- ~***1 m²*** effective area
- anti-coincidence system → good charge particle rejection → LAT can ***identify*** the relatively rare gamma rays

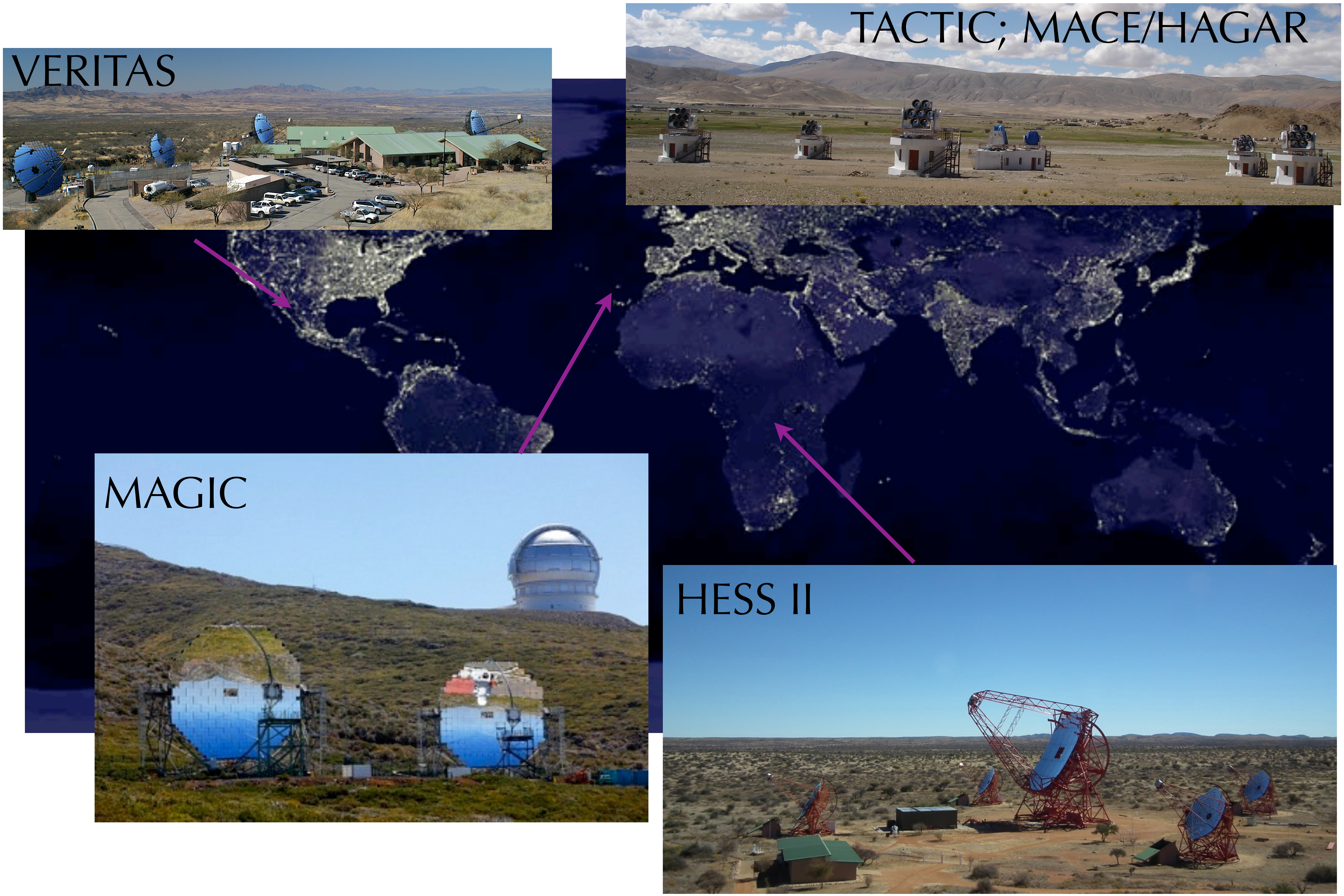
- messengers (γ, ν, e±, p±, D-) /experiments (@~Mz range):
  - Imaging Atmospheric Cherenkov telescopes (HESS, MAGIC, VERITAS, TACTIC, CANGAROO III,...)





- use atmosphere as a calorimeter (increase detection area at high energies)!
- → higher energy range (***100 GeV-100 TeV***); smaller field of view (***2°-5°***), large effective area (***10^5 m²***).
- but, have no anti-coincidence detector: ***irreducible charge particle contamination*** → *hard to measure signals flat over the ROI*
- ***complementarity*** between the two techniques!

- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments (@~Mz range):
  - IACTs (current: HESS, MAGIC, VERITAS,...):

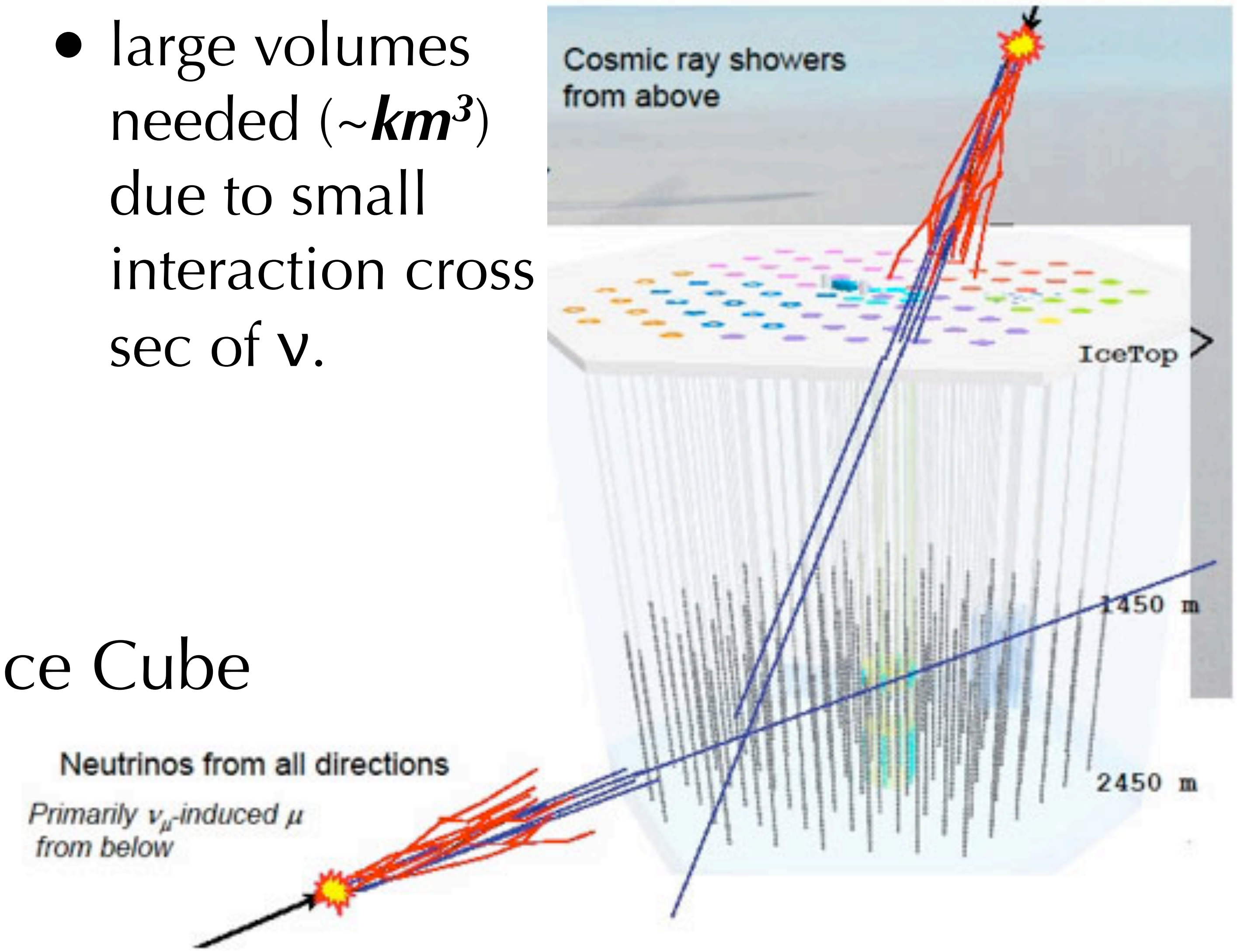


- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments (@~Mz range):
  - ICE CUBE, ANTARES, Baikal

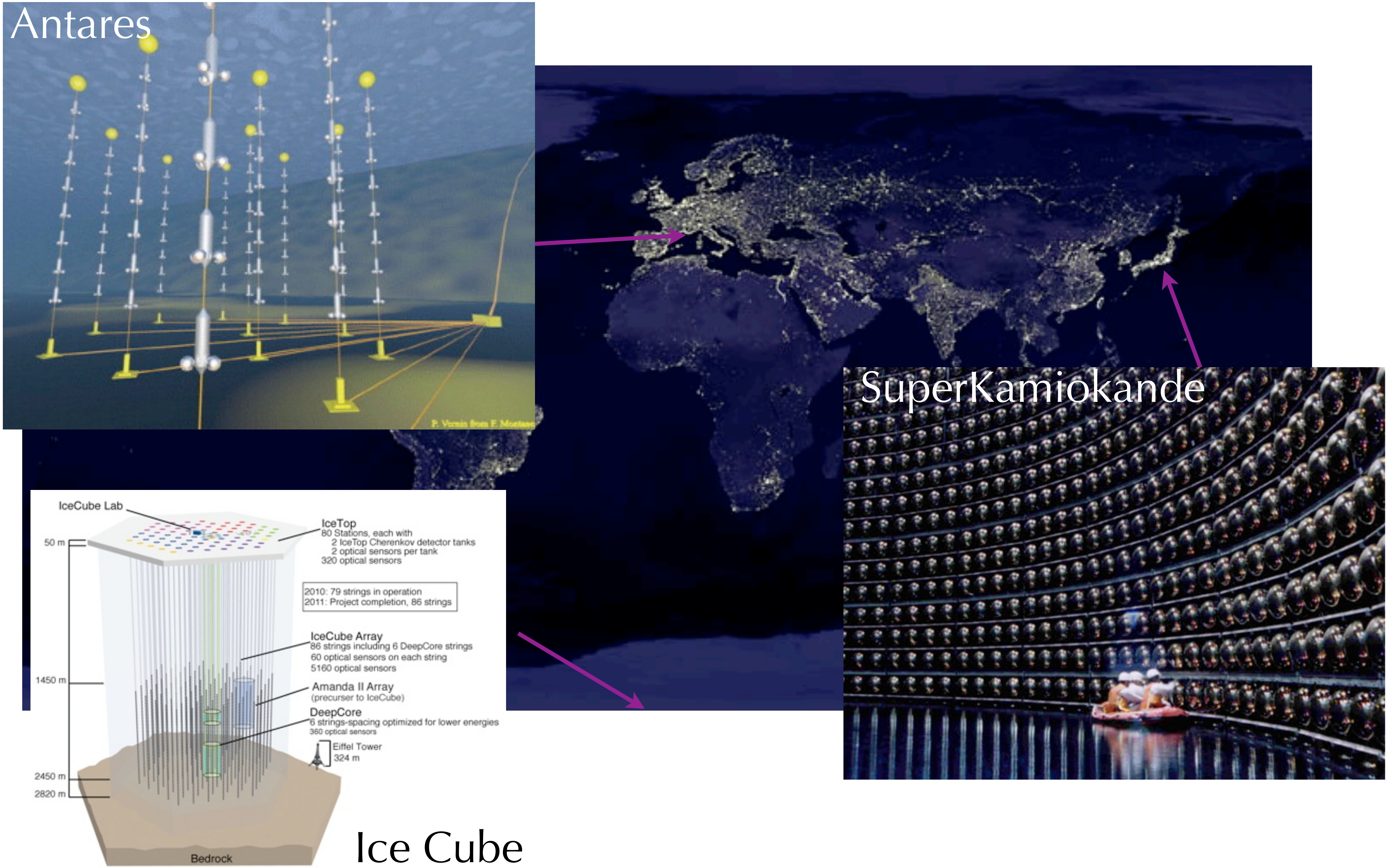
- >~***1 TeV*** (>~ 10 GeV Deep Core)
- muons produced in charged current interactions emit Cerenkov light (in ice/water) → detected by strings of photomultiplier tubes.
- background: *CR muons* → select upward going events or use detector edge as an anticonicidence detector or *atmospheric neutrinos*.
- taus, electrons...

- large volumes needed (~***km³***) due to small interaction cross sec of ν.

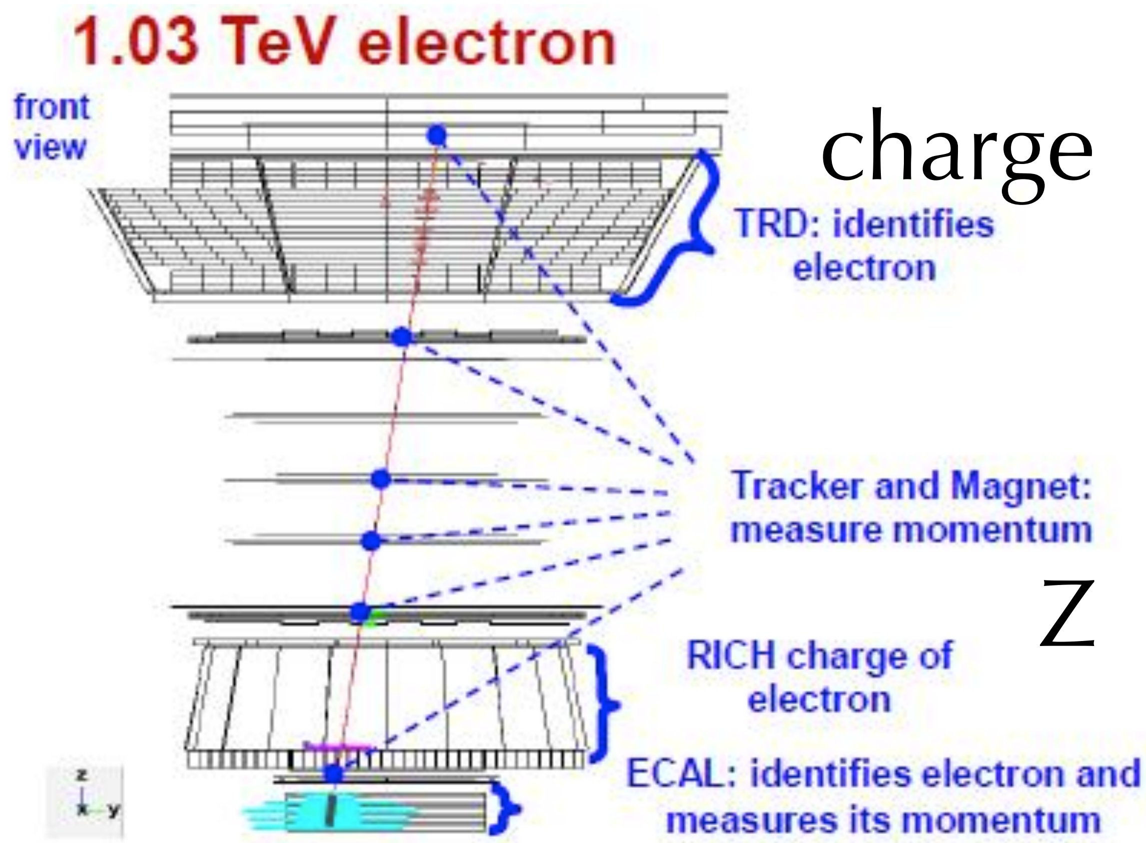
Ice Cube

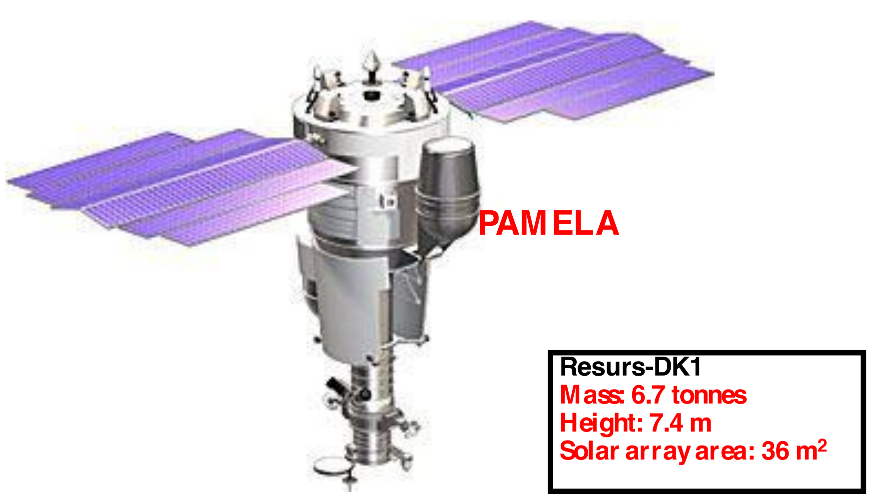


- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments (@~Mz range):
  - Super Kamiokande, ICE CUBE, ANTARES



- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-},...) /experiments (@~Mz range): N. Mori's talk
  - satellites (PAMELA, AMS, ...)/balloons (CREAM, ATIC...):



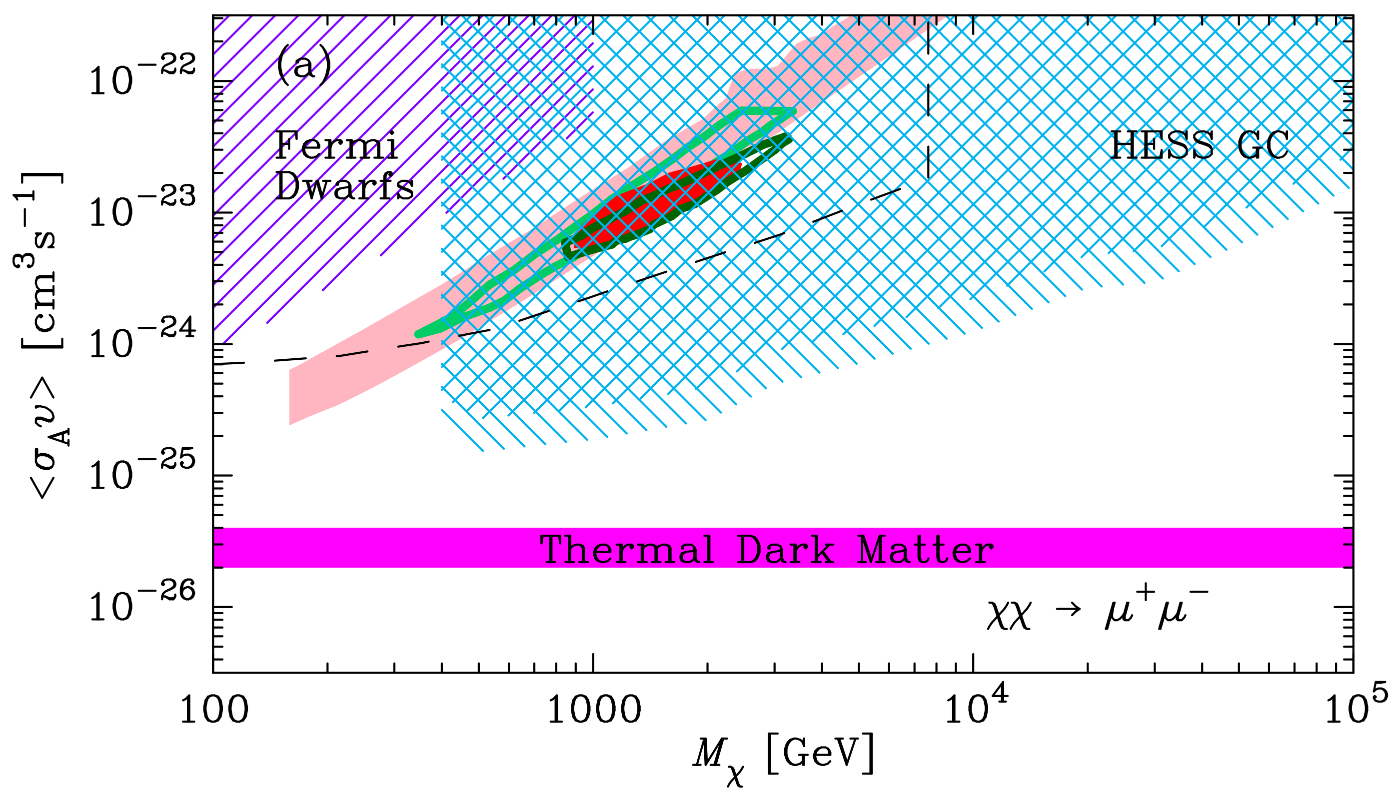


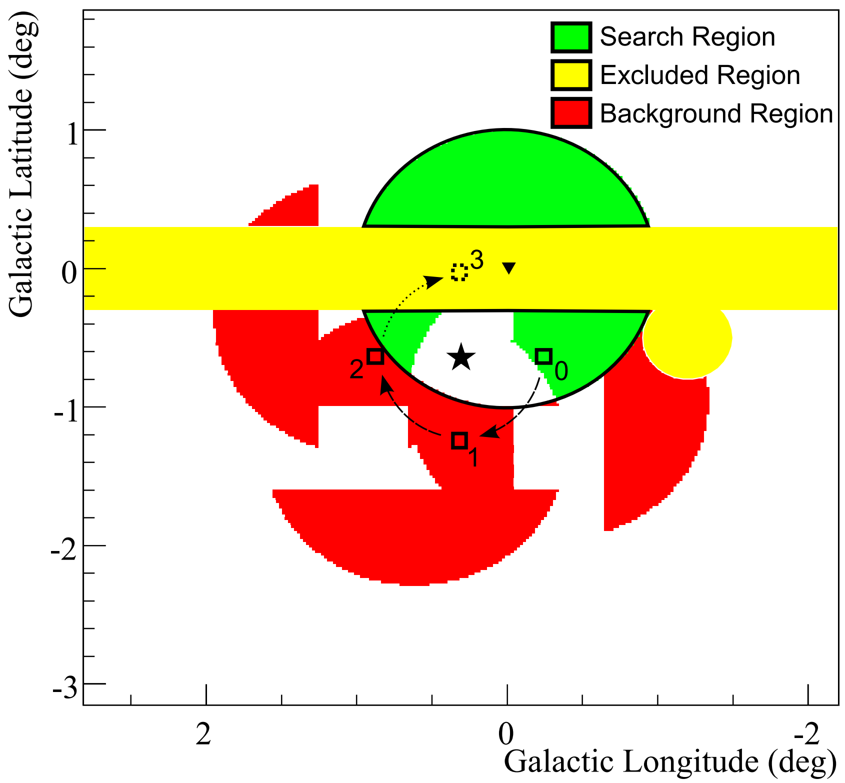
- unlike gamma-ray experiments, ***magnets*** and are further optimized to distinguish charge and Z study e^+/e^-; p^+/p^-
- AMS, launched May 16, 2011, operating at the ISS,
- PAMELA in orbit till the end of 2013.

B) Rely on multi-wavelength/multi target cross checks for an additional handle:

C. Weniger's talk

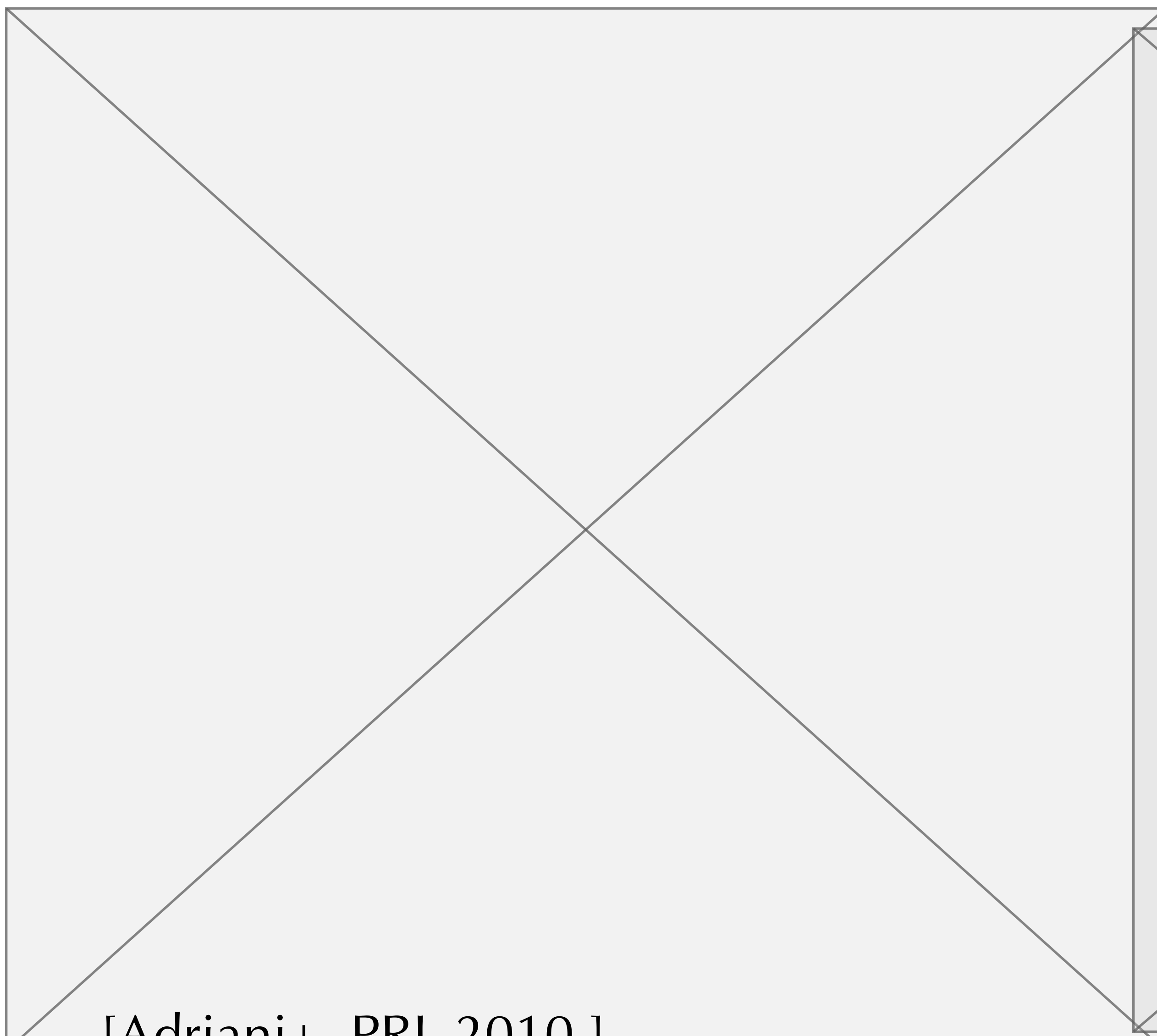
- gamma rays: HESS/MW halo: HESS analyzed a smaller region around the GC producing one of the strongest constraints on heavy DM to date.



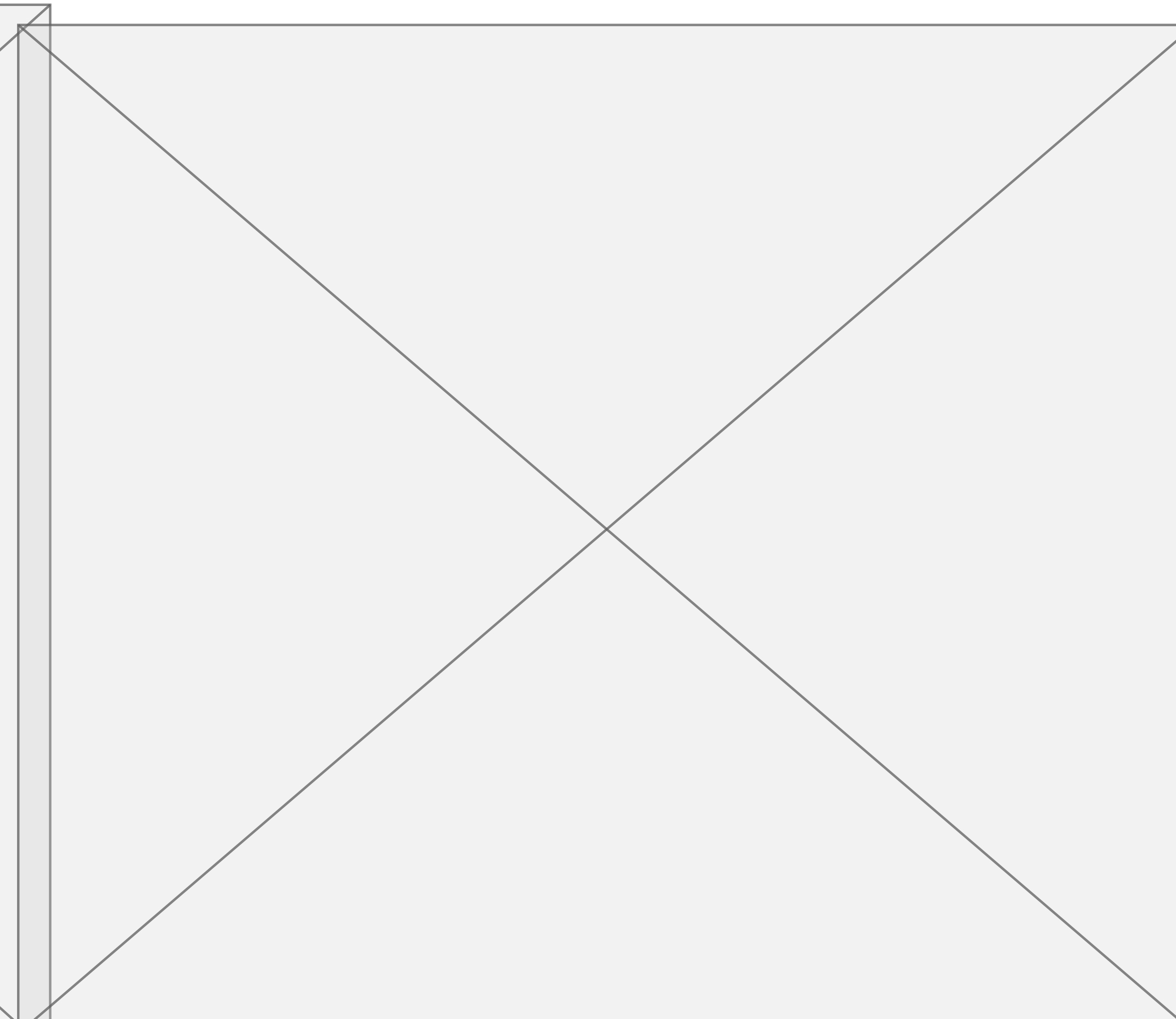


[Abazajian+, JCAP, 2012, 1110.6151]

- measurement: CR (anti)protons
- The measurements consistent with purely secondary production of antiprotons in the galaxy



[Adriani+, PRL 2010.]



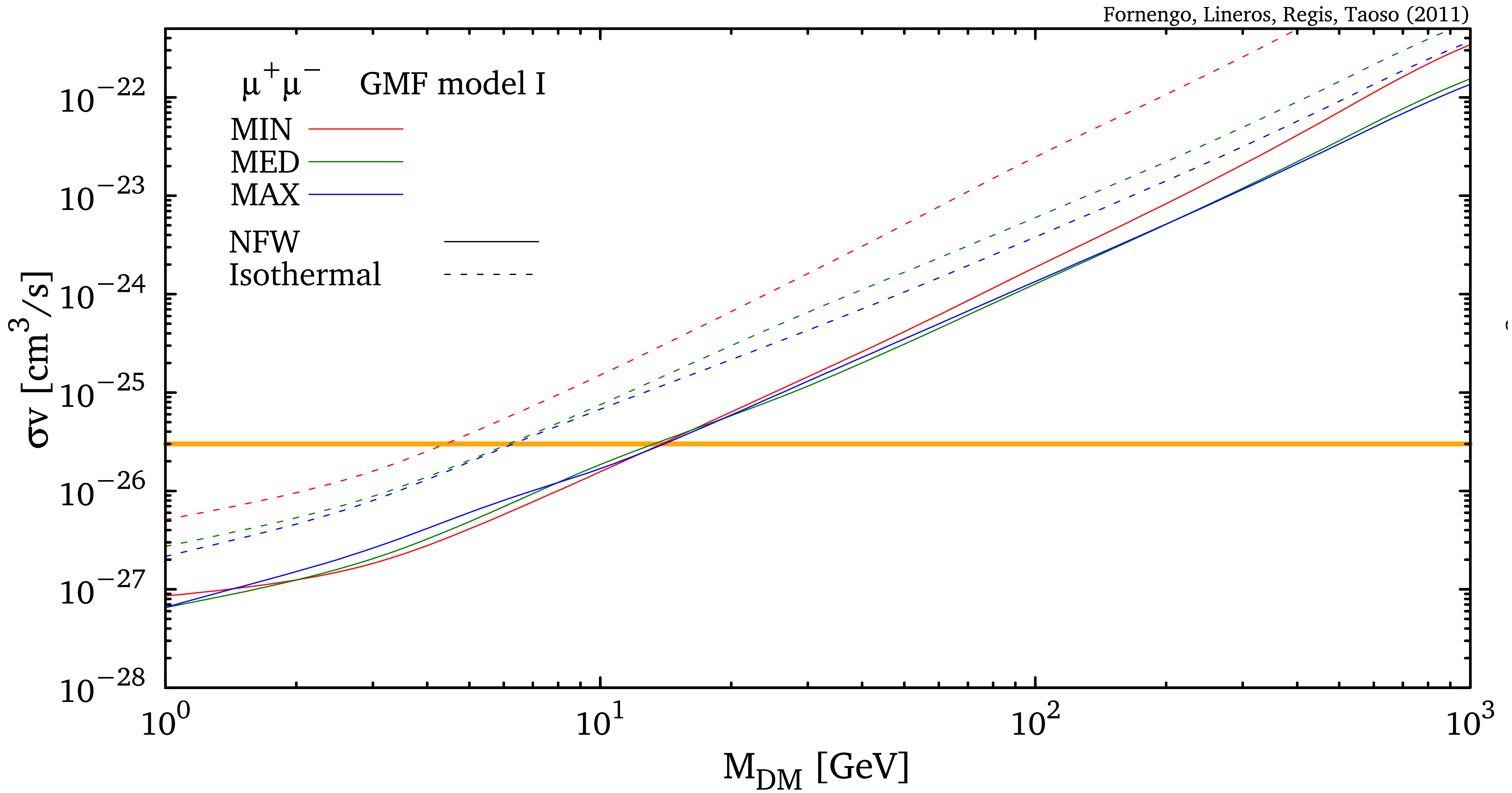
B) Rely on multi-wavelength/multi target cross checks for an additional handle:

C. Weniger's talk

- positron fraction: prime example (few_k papers; 615X2) and a demonstration of a method!

2. multiwavelength/multi target cross checks:

- gamma rays: radio, GC region



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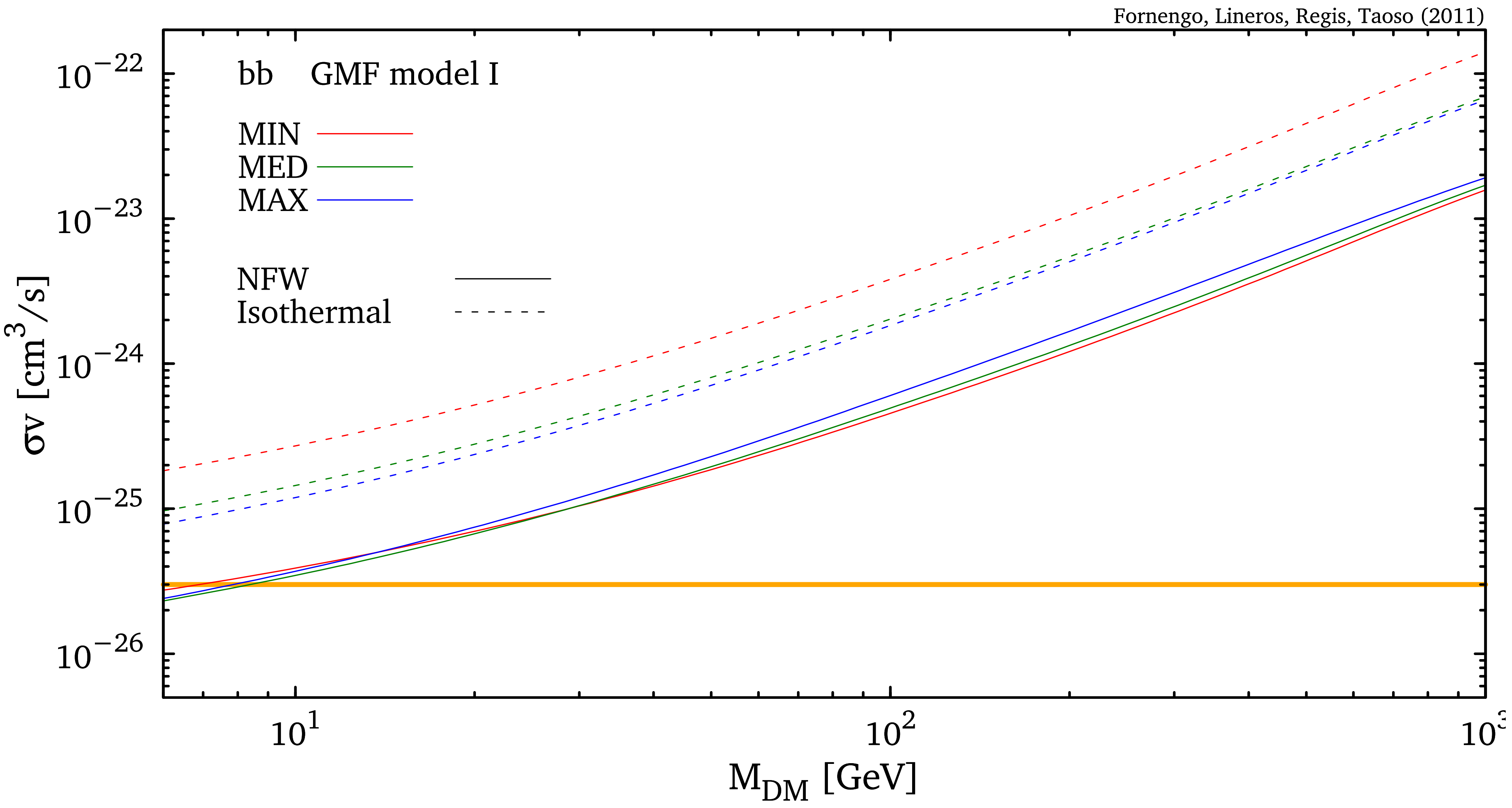
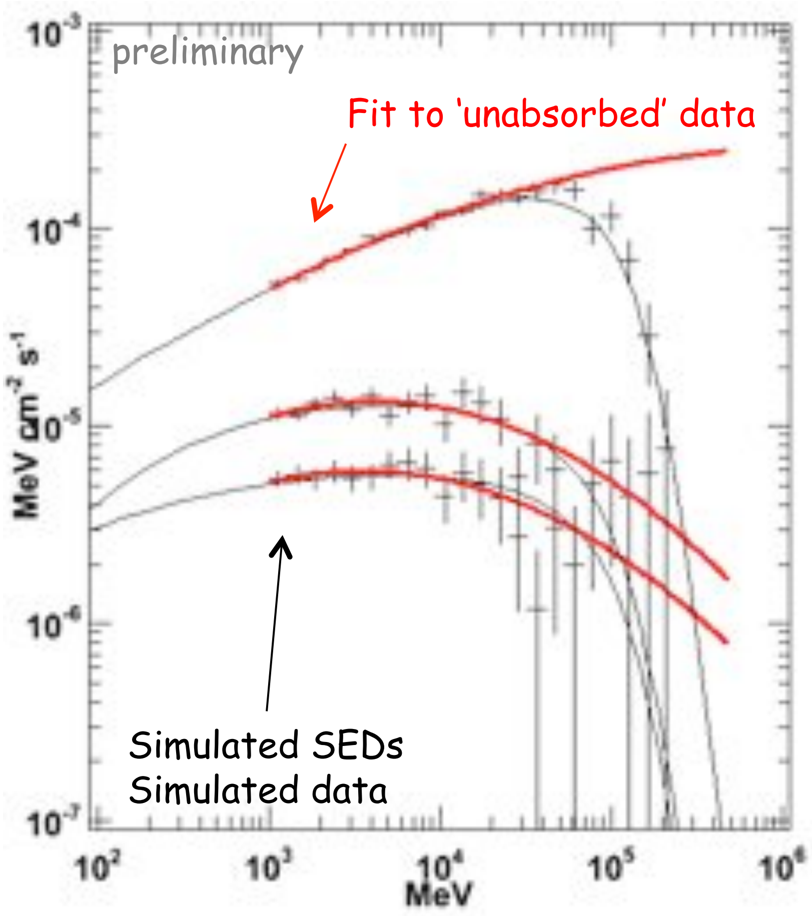


[Lineros+,]

Highlights from astrophysics:

- point sources: sufficient numbers for population studies
- diffuse emission: Galactic/extraGalactic
- CR spectral breaks



$$F(E)_{absorbed} = F(E)_{\text{int}\,rinsic} \cdot e^{-b\cdot\tau_{\text{mod}\,el}}$$

- also significant progress with ACT's (J. Knapp's talk)

- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments:
  - balloons (CREAM, ATIC, ...):

?

many balloon flights, measuring CR nuclei and electron spectrum.
The CREAM mission has had five successful flights: 2004-2010.
ATIC:

- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}) /experiments (@~Mz range):

$\chi + \chi \rightarrow WW \rightarrow e + \nu\text{'s} + \ldots$

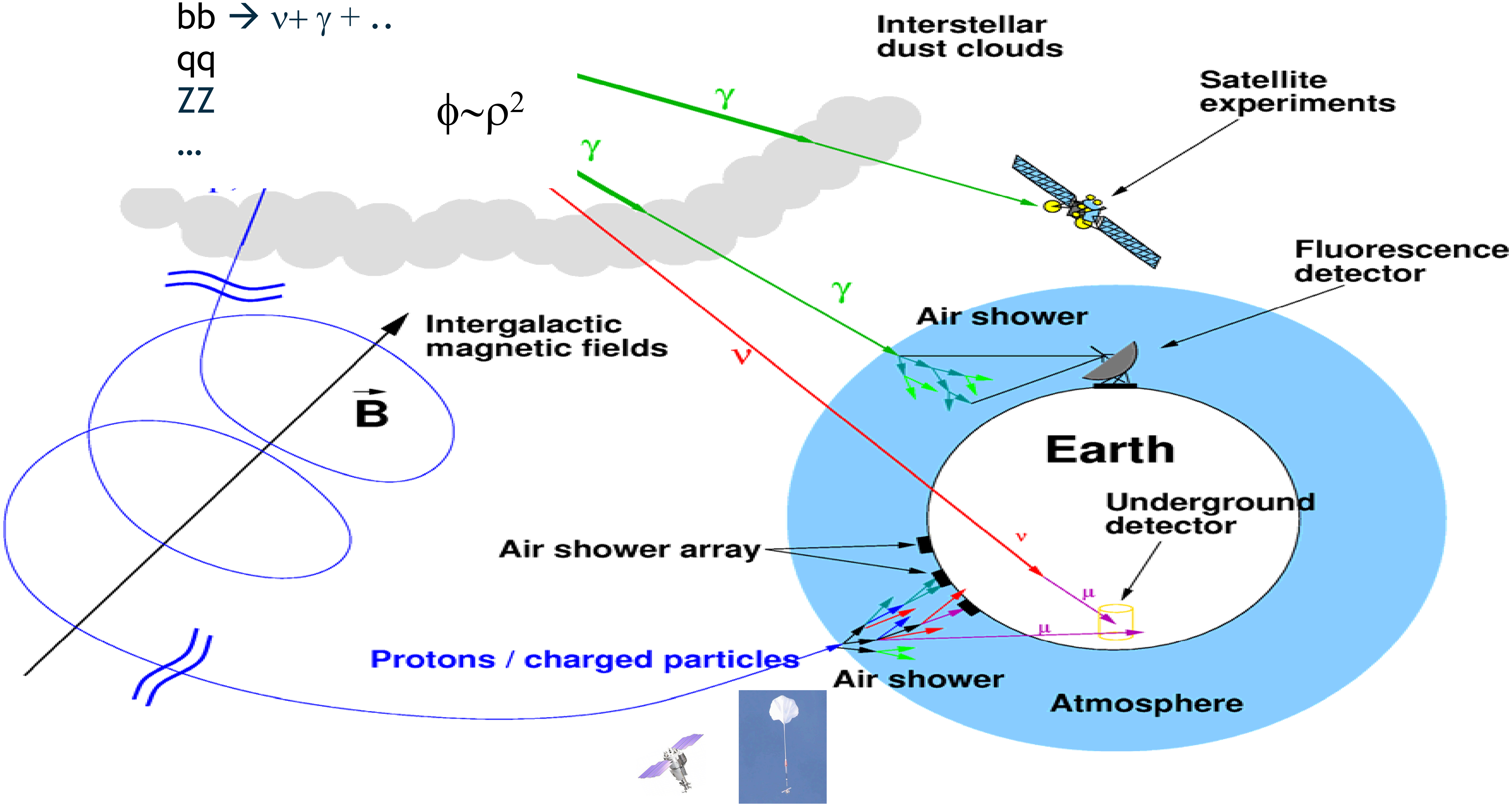
$b\bar{b} \rightarrow \nu + \gamma + \ldots$

qq

ZZ

...

$\phi \sim \rho^2$



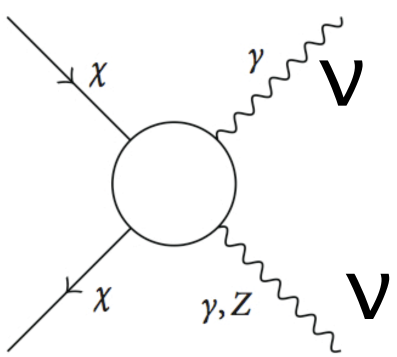
[C. Rott, SnowPACK 2012.]

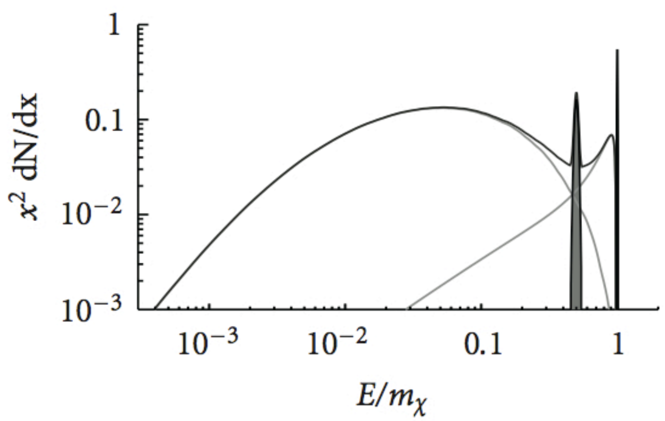
- What we can ~reliably predict:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi}\,\frac{(\sigma_{\rm ann} v)}{2\,m_\chi^2}\,\mathrm{X}\,\boxed{\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}}\,\mathrm{X}\,\int_{\Delta\Omega} d\Omega \int_{\rm los} ds\,\rho^2(s,\Omega)$$

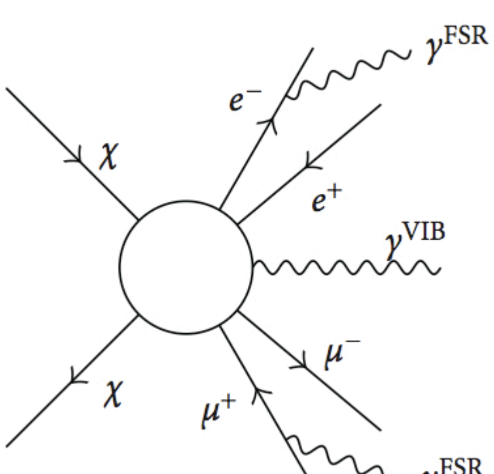
- *The (prompt) spectrum of SM particles* resulting from DM annihilation/decay→ Fixed when DM mass and branchings are set!
  - feature-full: for a given set of SM final states are quasi-universal spectra as a result of fragmentation/hadronization and subsequent pion decays.

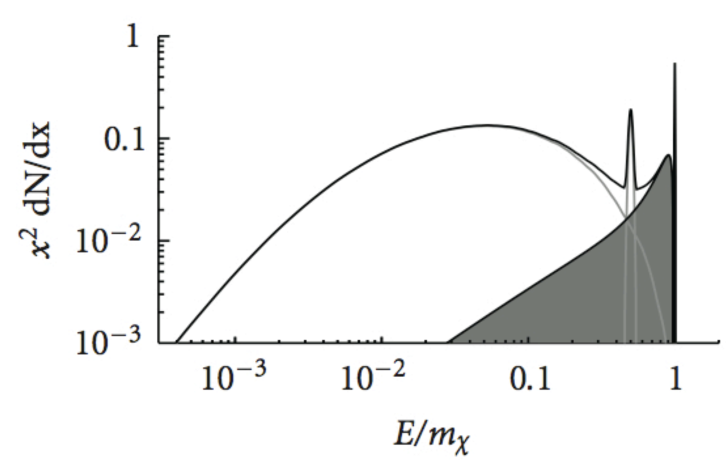
Line signal (loop level $\mathcal{O}(\alpha^2)$)



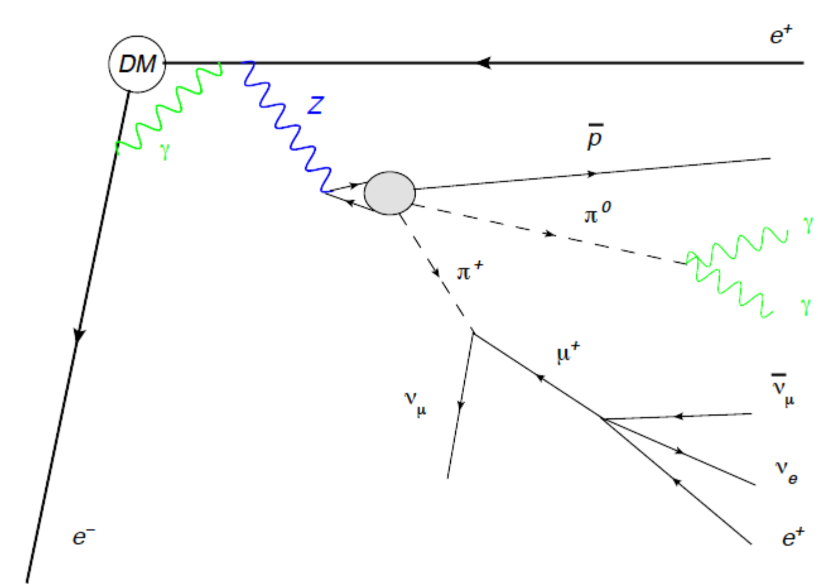


Internal bremsstrahlung $\mathcal{O}(\alpha)$





[M. Kuhlen, AA, 2010.]



For heavy DM also ElectroWeak bremstrahlung relevant [Ciafaloni, JCAP 2011, 1009.0224].

- What are we after:

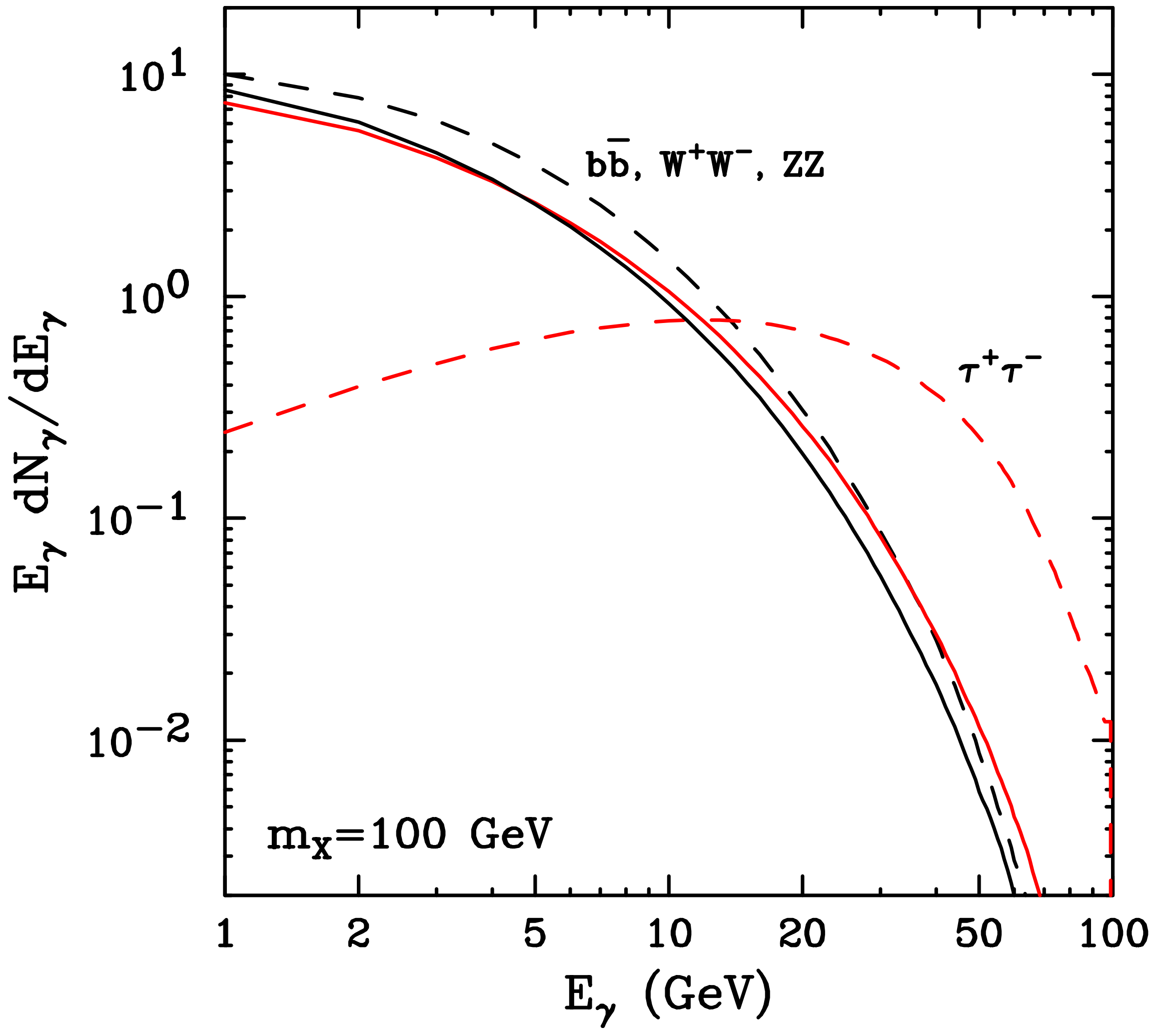
DM signal = particle physics X DM clustering

- charged CRs: are entangled with the magnetic fields in our Galaxy.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle \sigma v \rangle_{\rm ann}}{8\pi m_\chi^2} \times \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \times \int d^3r\, \rho^2(\mathbf{r})$$

- What are we after:

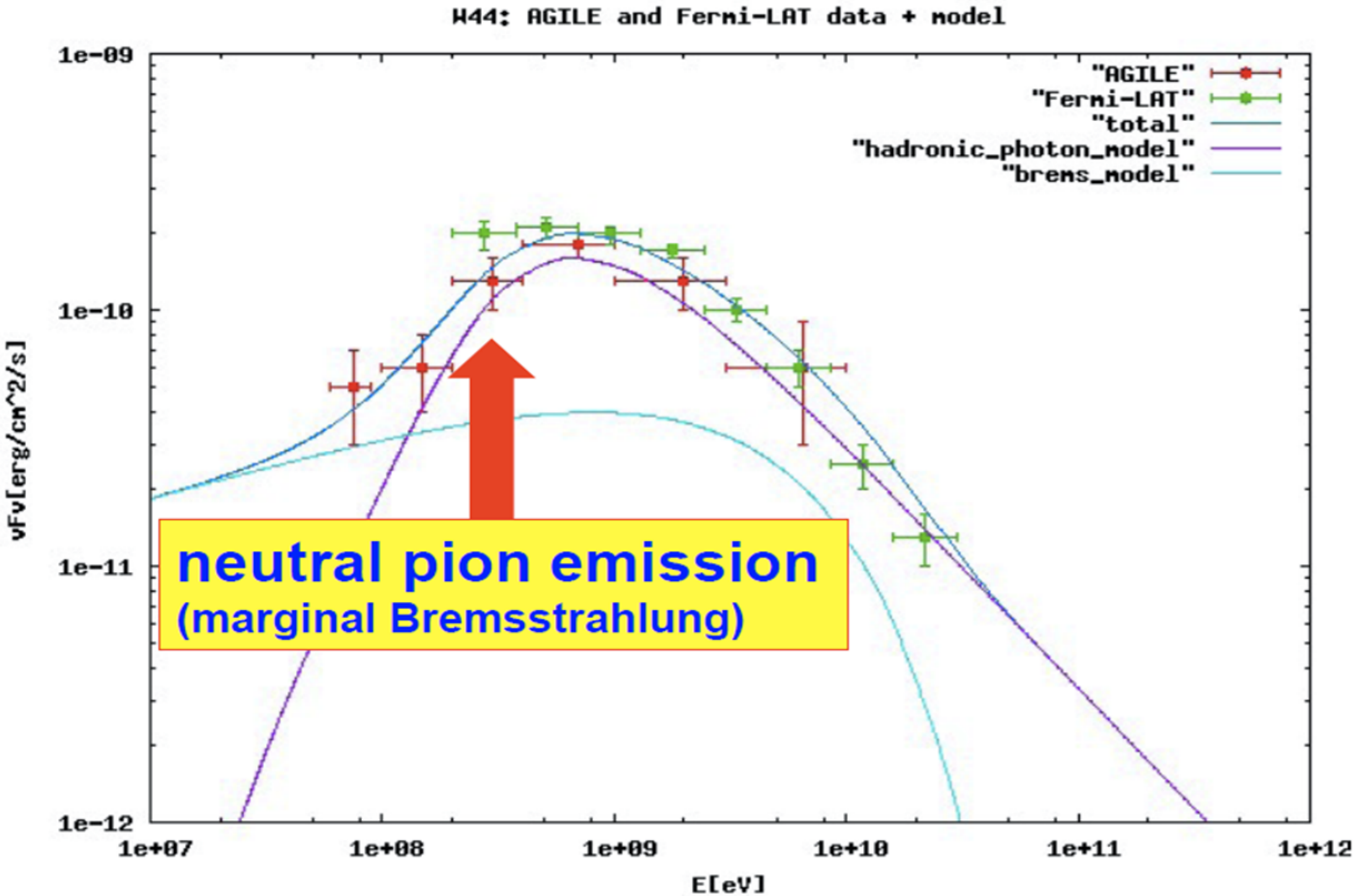
- What we can ~reliably predict: The (prompt) spectrum
  - for a given set of SM final states are quasi-universal spectra as a result of decays/fragmentations

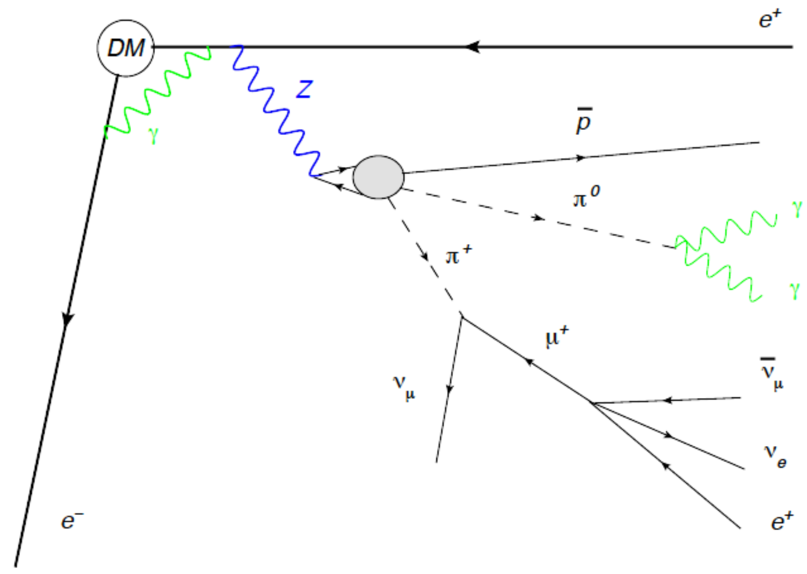


$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2} \times \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \times \int d^3r\,\rho^2(\mathbf{r})$$

- messengers (γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-} @~Mz scale)
  - gamma rays: bulk of emission produced close to the particle mass! highest S/N (background low)
  - but lower frequencies too!
  - microwaves
  - radio: Electrons and protons produced in dark matter annihilations in the Galactic Center region will emit synchrotron radiation

(Giuliani, Cardillo et al. 2011)





For heavy DM relevant also ElectroWeak bremstrahlung

[Ciafaloni, JCAP 2011, 1009.0224].

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \frac{\langle \sigma v \rangle_{\rm ann}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \cdot \int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\rm l.o.s} d\ell(\psi) \rho^2(\mathbf{r})$$

$$\simeq \left(D^2 \Delta\psi\right)^{-1} \int d^3r\, \rho^2(\mathbf{r})$$

$$\frac{\partial \psi}{\partial t} - \nabla \cdot (D\nabla - v_c)\psi + \frac{\partial}{\partial p} b_{\rm loss} \psi - \frac{\partial}{\partial p} K \frac{\partial}{\partial p} \psi = q_{\rm source}$$