# Indirect Searches for Dark Matter: Signal candidates & Constraints

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NWO

# Indirect searches for WIMP annihilation products

Injection rate of DM annihilation products

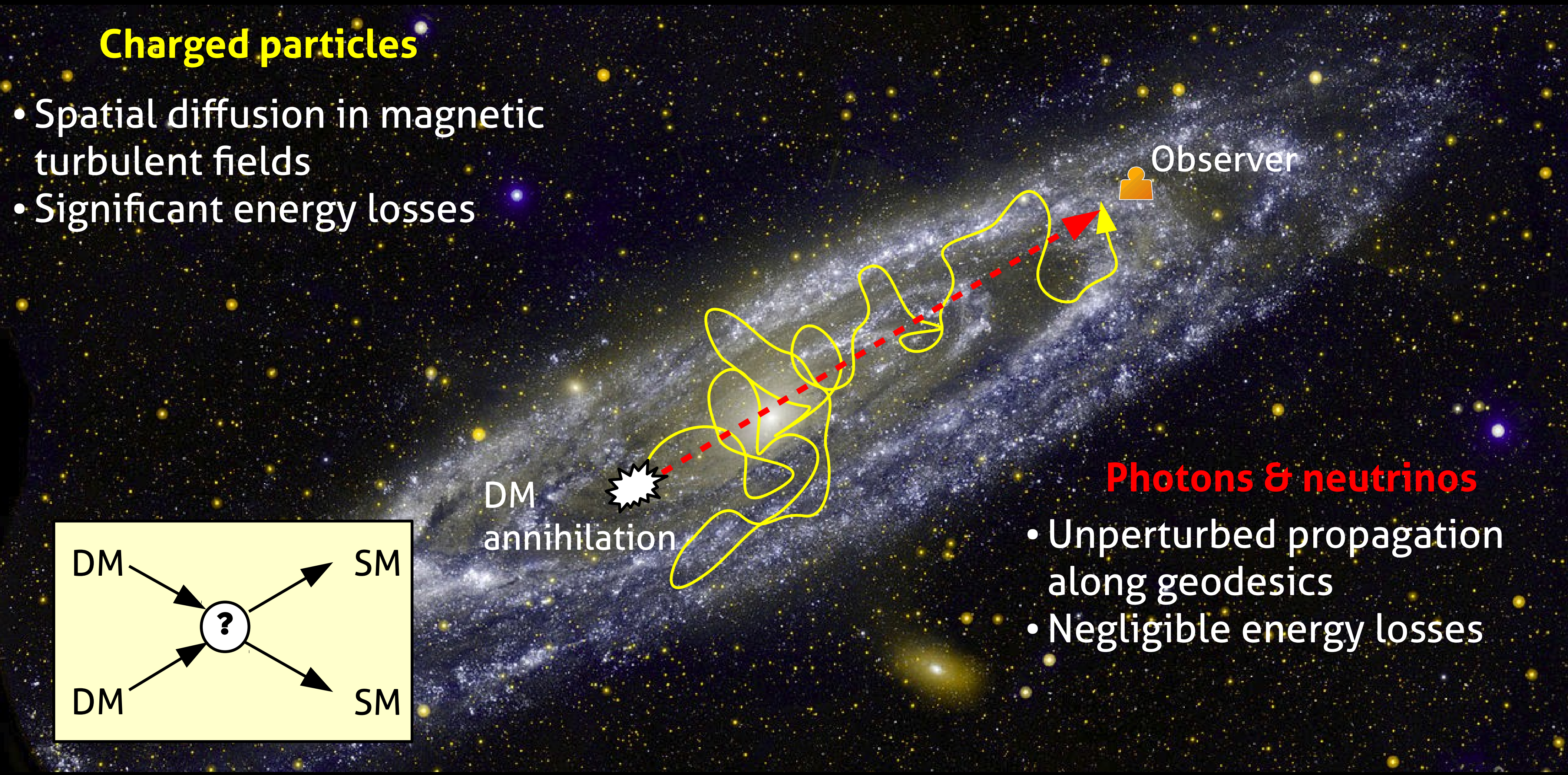
$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle \sigma v \rangle \rho_{\rm DM}^2}{2 m_{\rm DM}^2} \frac{dN_X}{dE}$$

Self-annihilation cross section

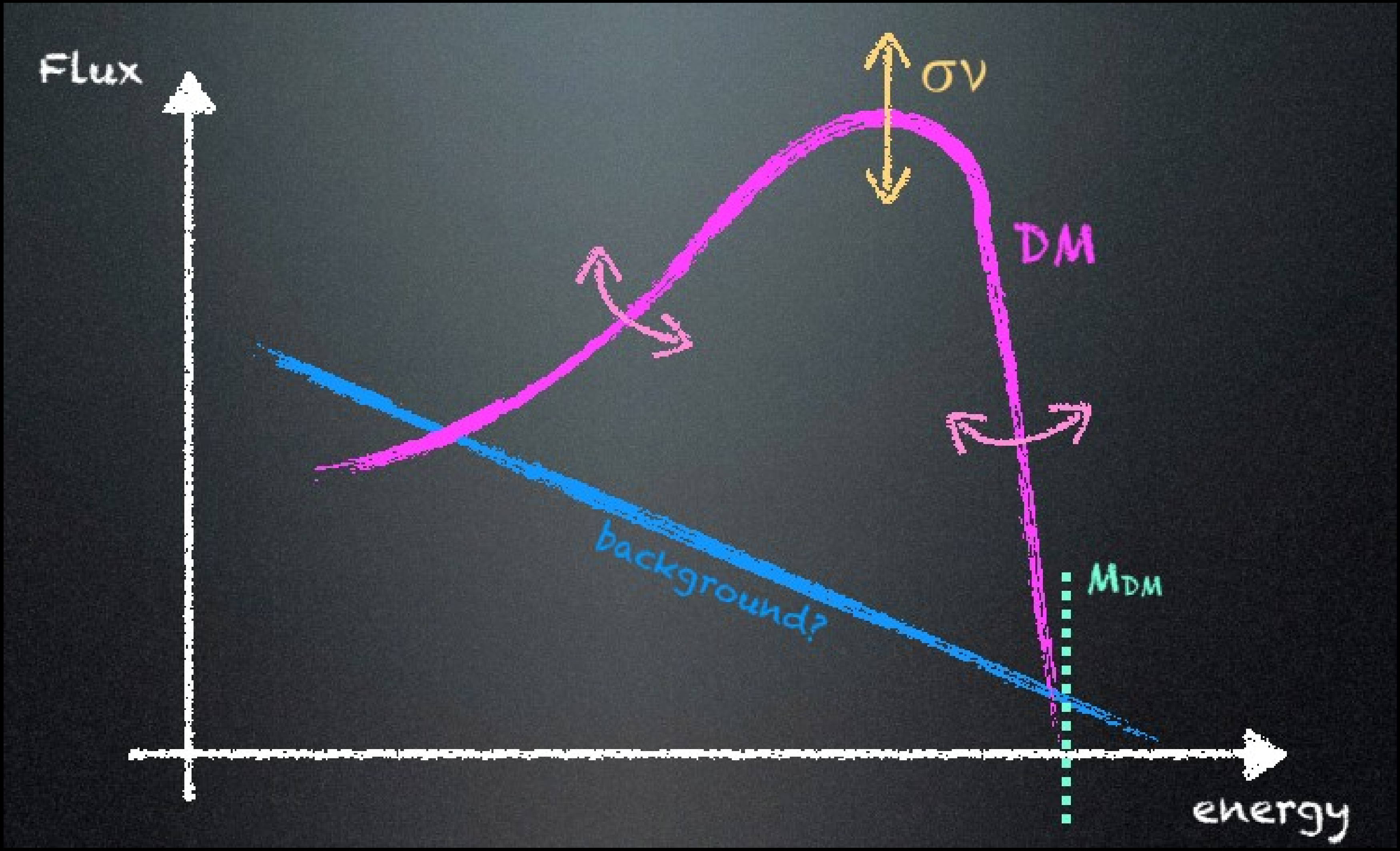
mass density of DM

DM mass

Energy spectrum



# Goal: Find excess above astro background




Credit: M. Cirelli

**Relevant parameters**

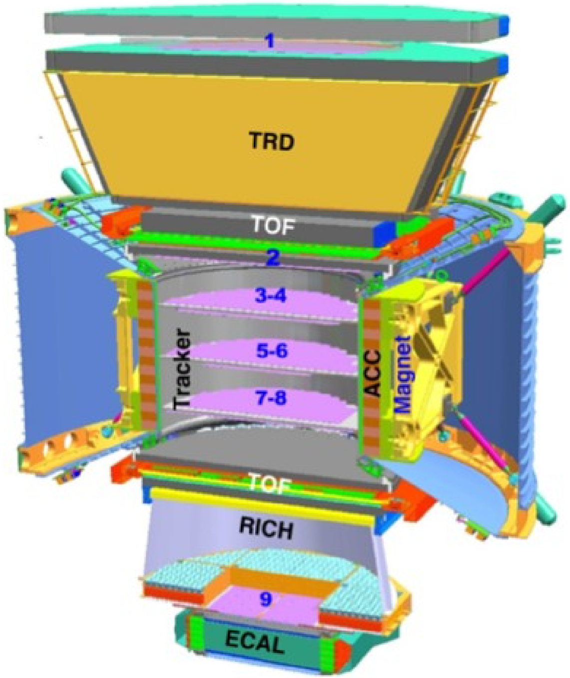
- Background parameters
- Annihilation cross-section
- DM mass
- Annihilation channels

# On The Menu

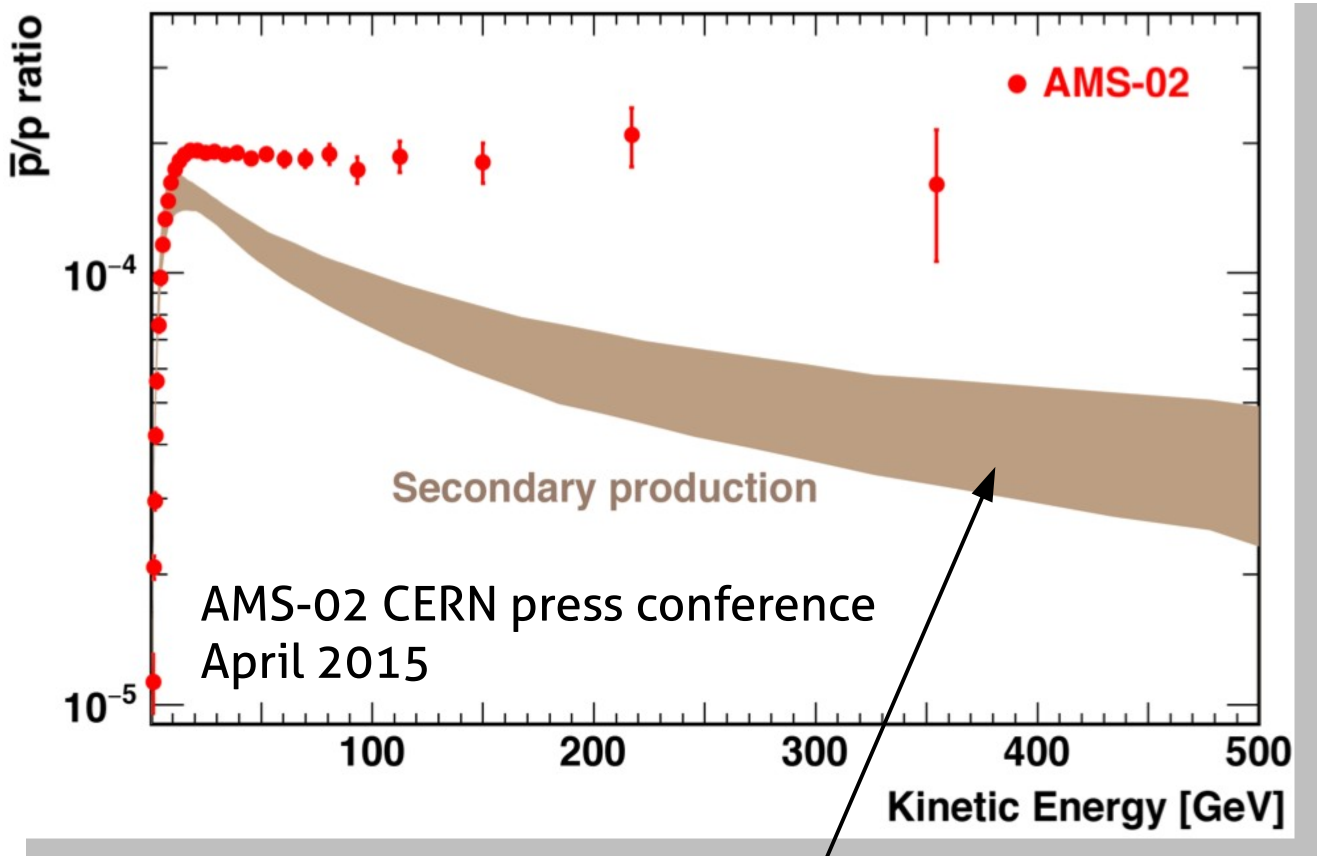
- *Updates*
  - *Anti-protons*
  - *Positrons and CMB*
  - *Gamma-ray dwarfs*
  - *Gamma-ray lines*
  - *Neutrinos from the Sun*
- *The Fermi GeV excess*
- *Outlook & Conclusions*

# Searches with Antimatter

# Finally! Anti-protons from AMS-02




AMS-02
Taking data since 2011



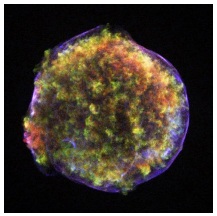

**Preliminary anti-proton to proton ratio**

- Up to 350 GeV – Syst. + stat. error bars?
- Compatible with previous results by PAMELA, though with significantly smaller error bars at high energies
- Shown as excess above the expectations from secondary production (ICRC 2015: "**Theoretical prediction based on pre-AMS knowledge of cosmic ray propagation**")

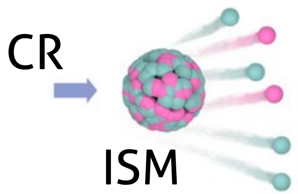
Samuel Ting

# The “grammage” matters

Two sources for cosmic rays

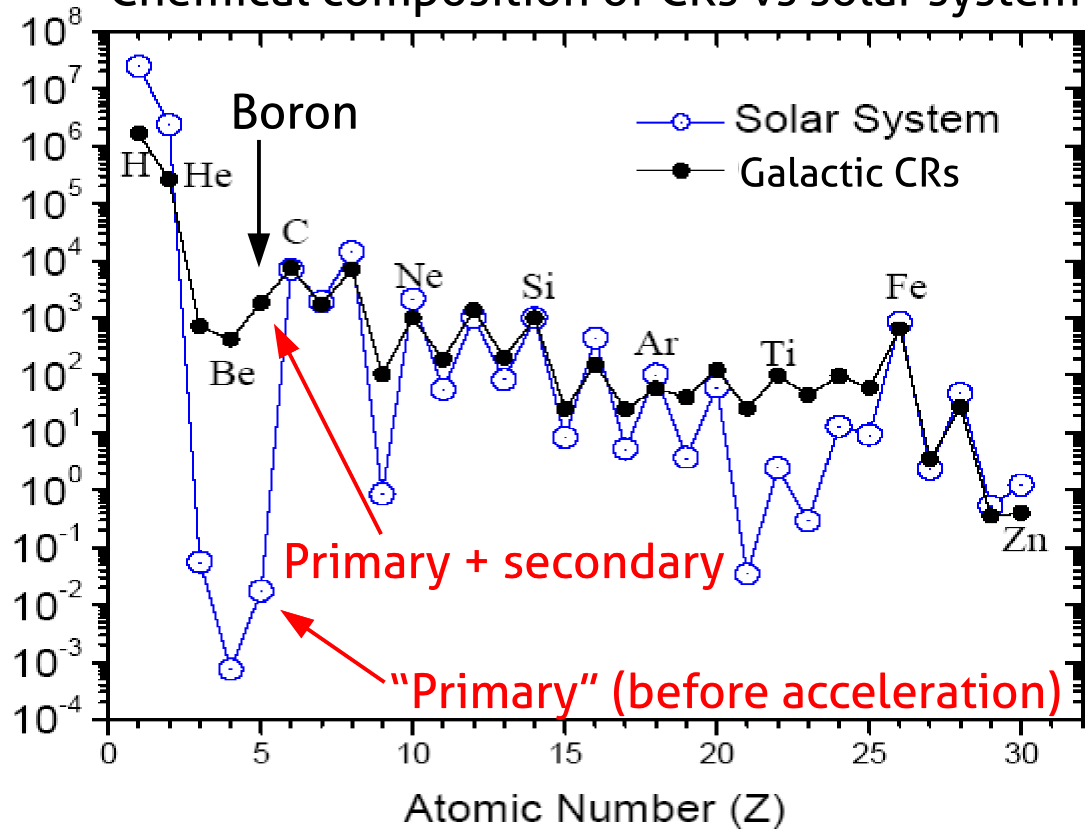


**Primary cosmic rays**
from supernova remnants (likely)




**Secondary cosmic rays**
from spallation etc

Chemical composition of CRs vs solar system



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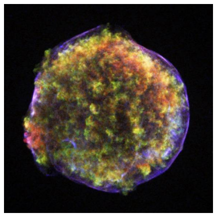

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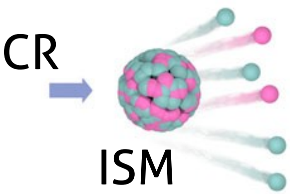
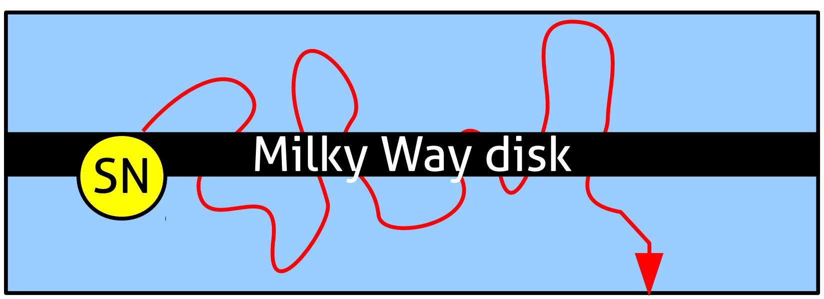
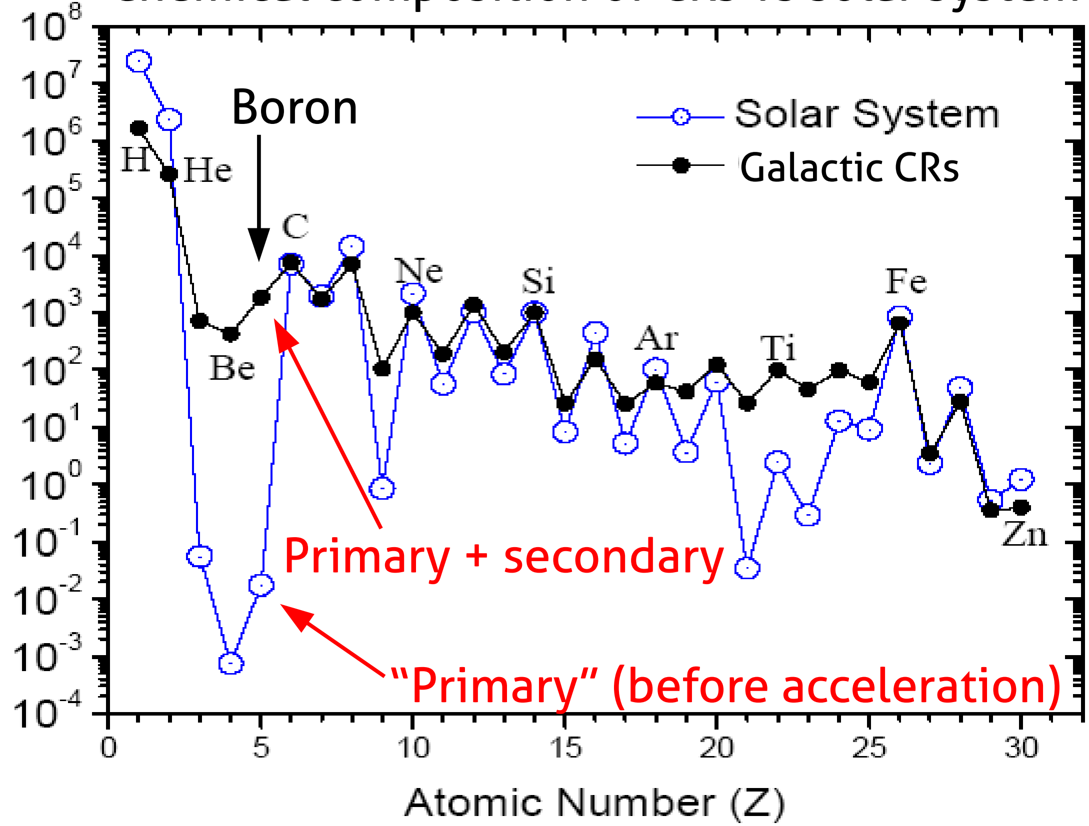



**Secondary cosmic rays** from spallation etc

Diffusion in a box




Chemical composition of CRs vs solar system



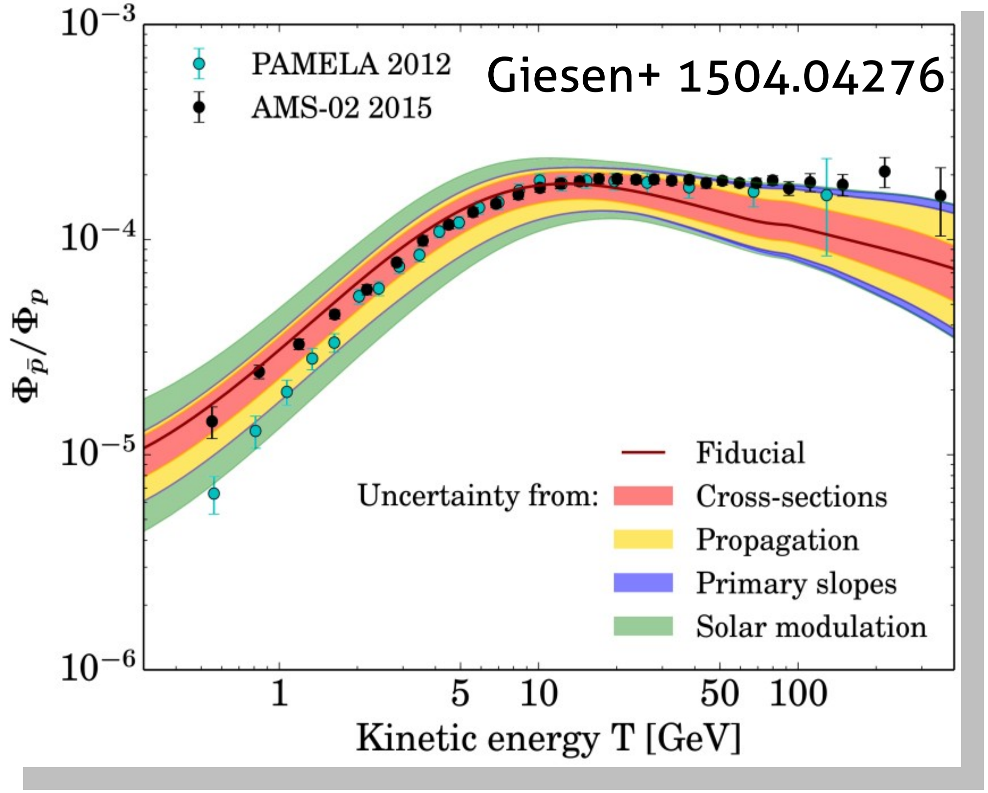

**Total grammage** (column density along propagation path)

$$G_{\text{total}} = n_{\text{crossings}} G_{\text{disk}} \sim \mathcal{O}(10\ \text{g cm}^{-2})$$

Secondary Boron: $n_B = n_C \sigma(C \to B) \cdot G_{\text{total}} \quad \Rightarrow G_{\text{total}}$

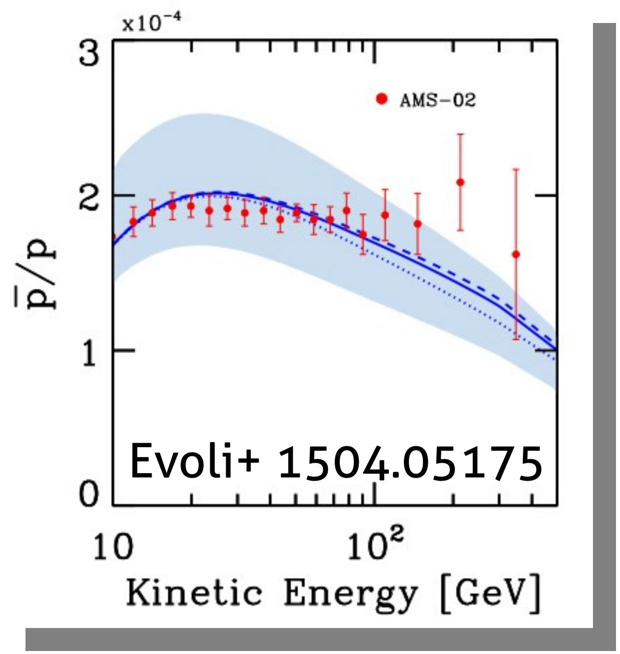
Secondary antiprotons: $n_{\bar{p}} = n_p \sigma(p \to \bar{p}) \cdot G_{\text{total}} \quad \Rightarrow n_{\bar{p}}$

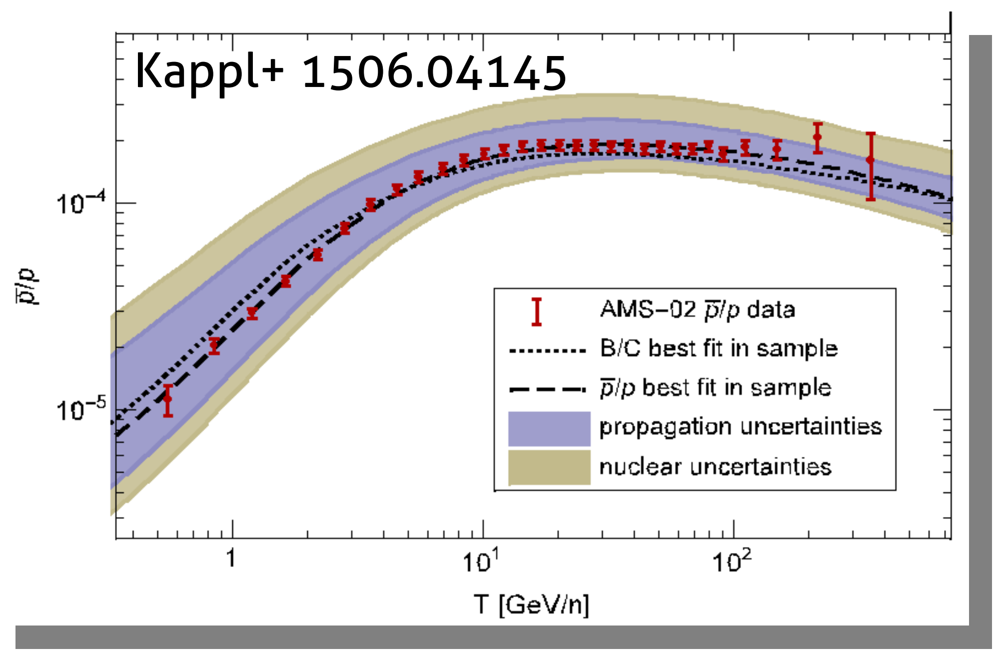
# No excess above secondary backgrounds




**Relevant uncertainties for CR BG**
- pbar production cross-section
- spectrum of CR primaries
- CR propagation
- solar modulation (below ~10 GeV)

**Situation**
- **No excess** observed above astrophysical background, when all uncertainties are taken into account
  → Only upper limits



# No excess above secondary backgrounds

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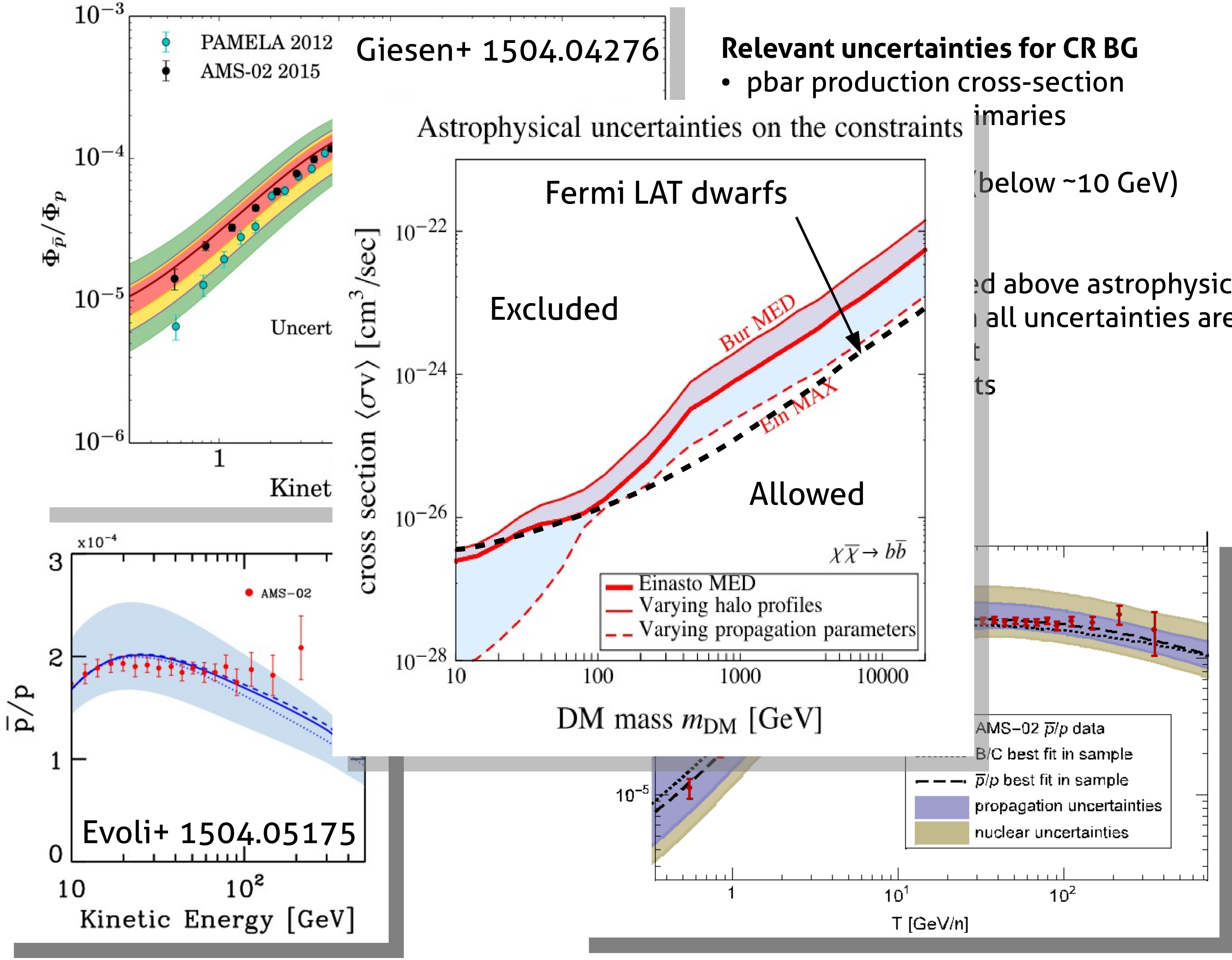
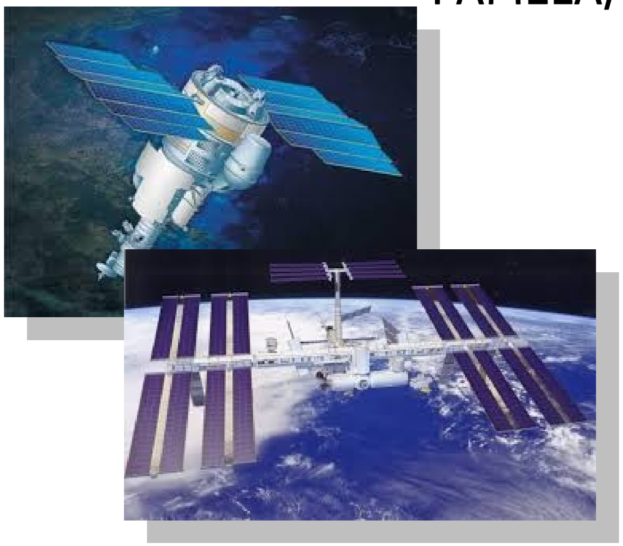
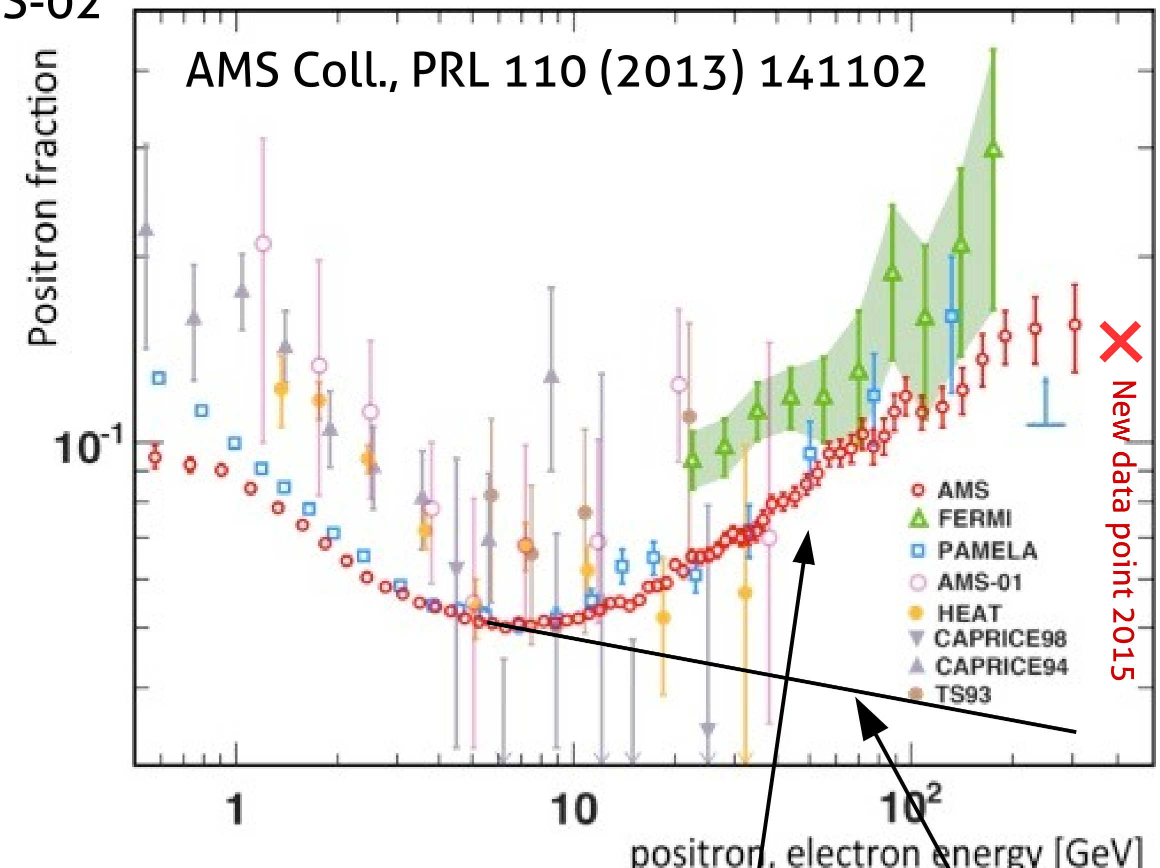


# Dark Matter searches with positrons

PAMELA, AMS-02

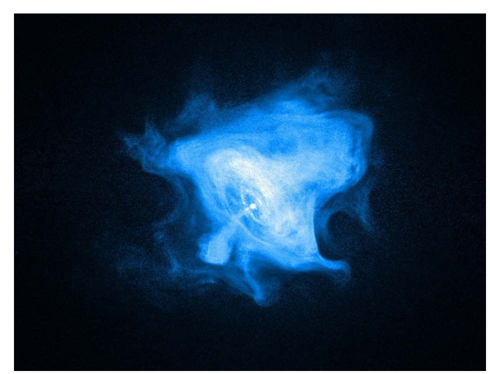





Positron fraction in cosmic rays $\frac{\Phi_{e^+}}{\Phi_{e^\pm}}$

Pulsars or DM?

Secondary production



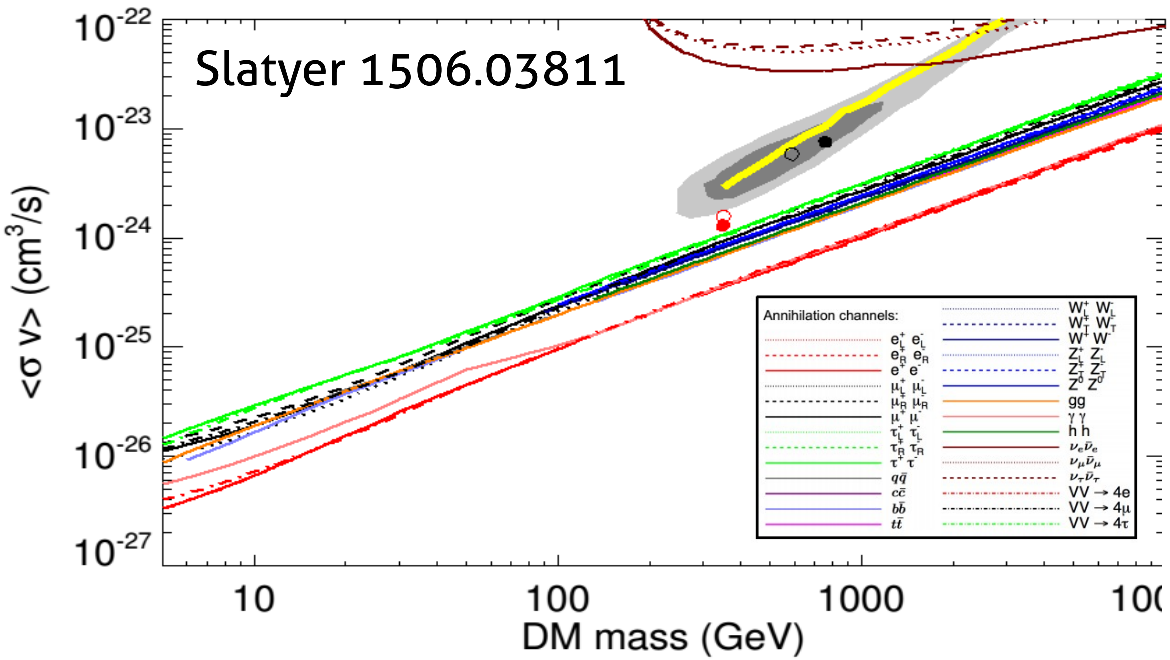
**What is new?**

- AMS-02 presented additional data point at high energies

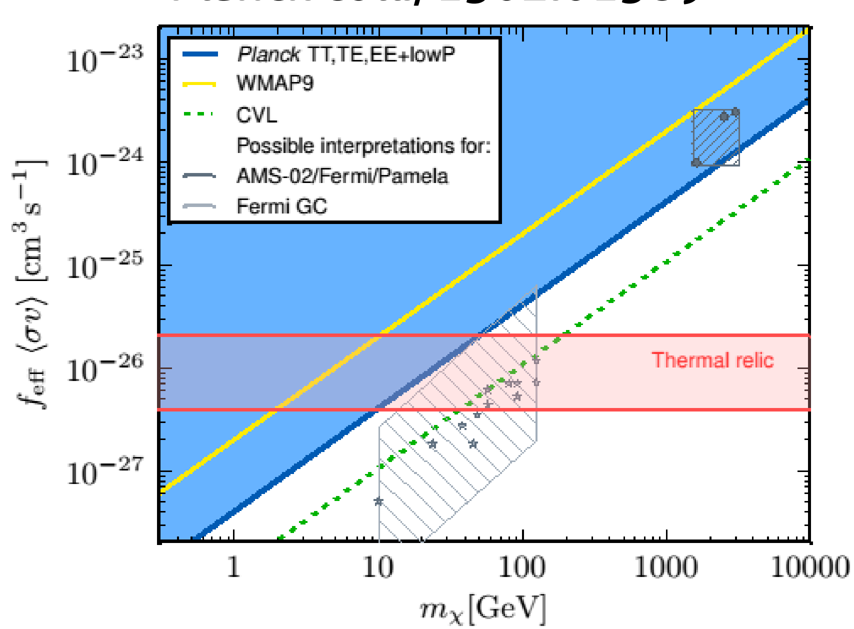
# Remember: Many DM interpretations ruled out by CMB

**Summary**

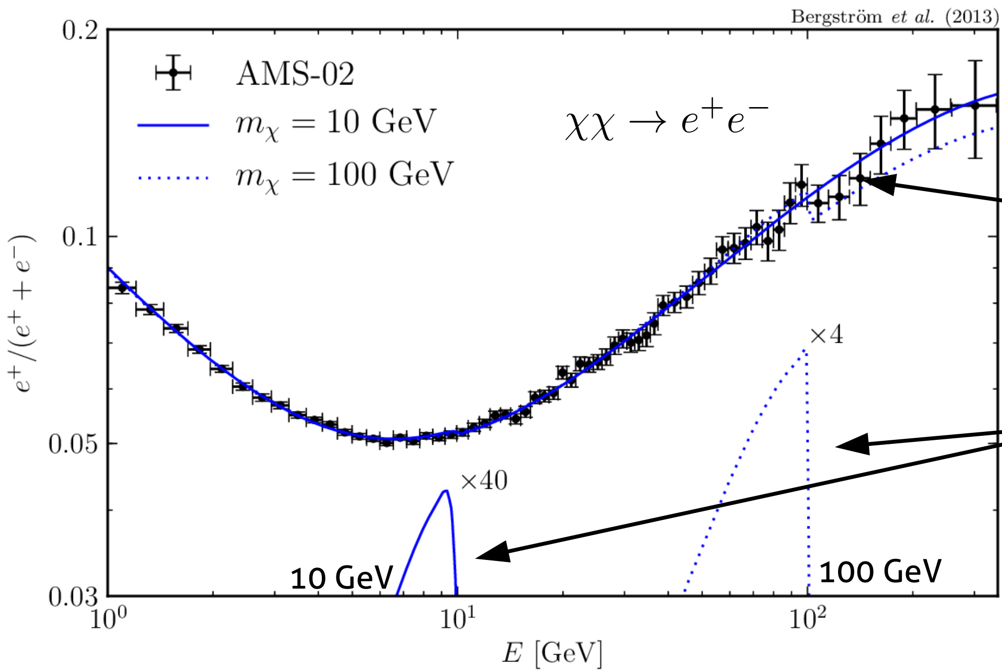
- The positron excess (AMS-02 e+ & PAMELA e+ & Fermi e+- & HESS e+-) can be explained e.g. with leptonic DM annihiation, masses around 1 TeV and cross-sections 100x – 1000x larger than thermal
- This is in general conflict with e.g. gamma-ray observations (except for cored profiles)
- For s-wave annihilation, this is excluded for all models of interest (1506.03811) by the non-observation of a broadening of the last scattering surface due to the injection of ionizing particles




Planck coll., 1502.01589



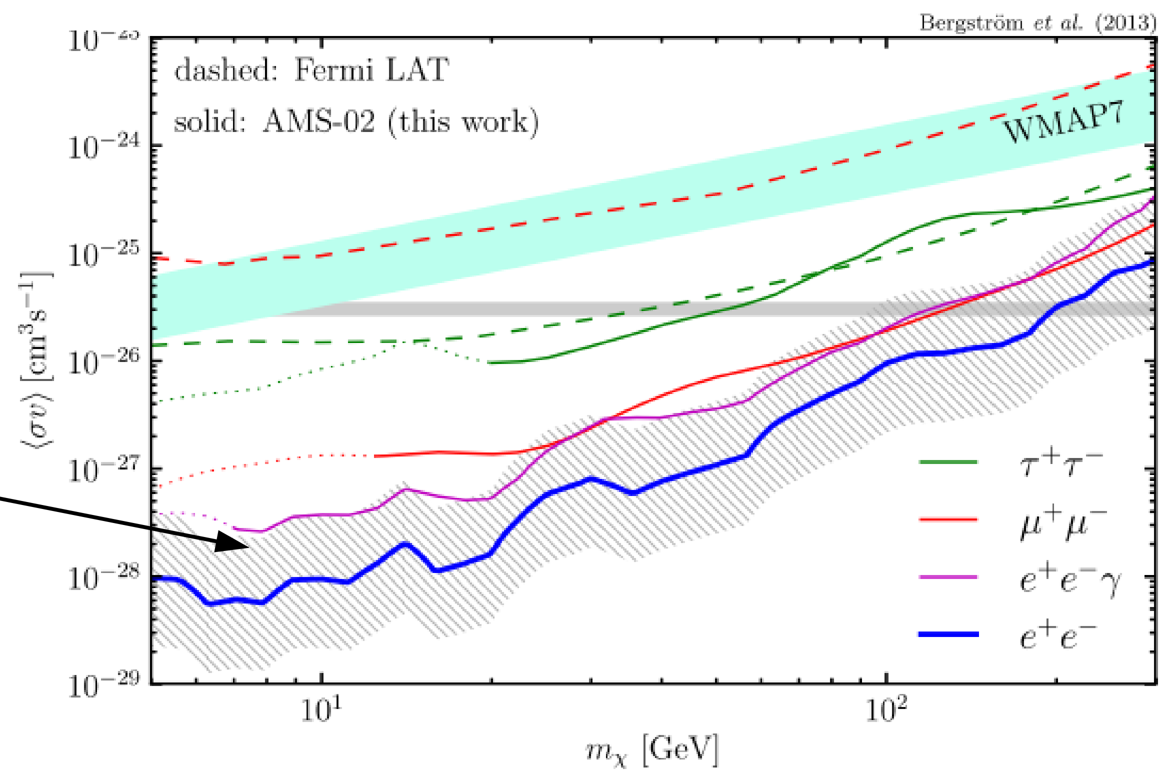
# But: Data provides extremely sensitive probe for light DM




Measured spectrum is **smooth** (no sharp features)

Expected annihilation signal after energy losses for

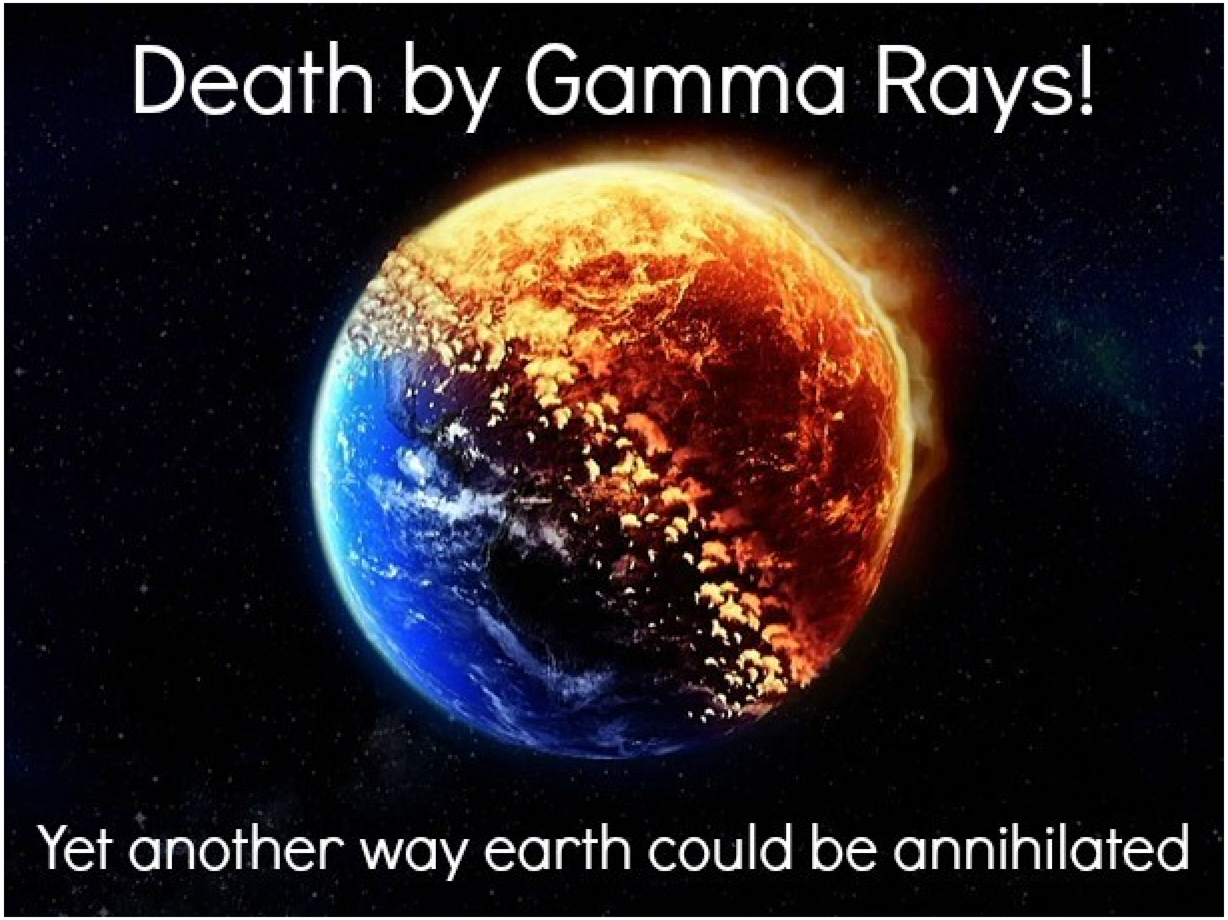
$$\chi\chi \to e^+e^-$$




The non-observation of spectral features give **extremely** stringent constraints on DM annihilation into leptonic final states.

Bergström, CW+, PRL 1306.3983

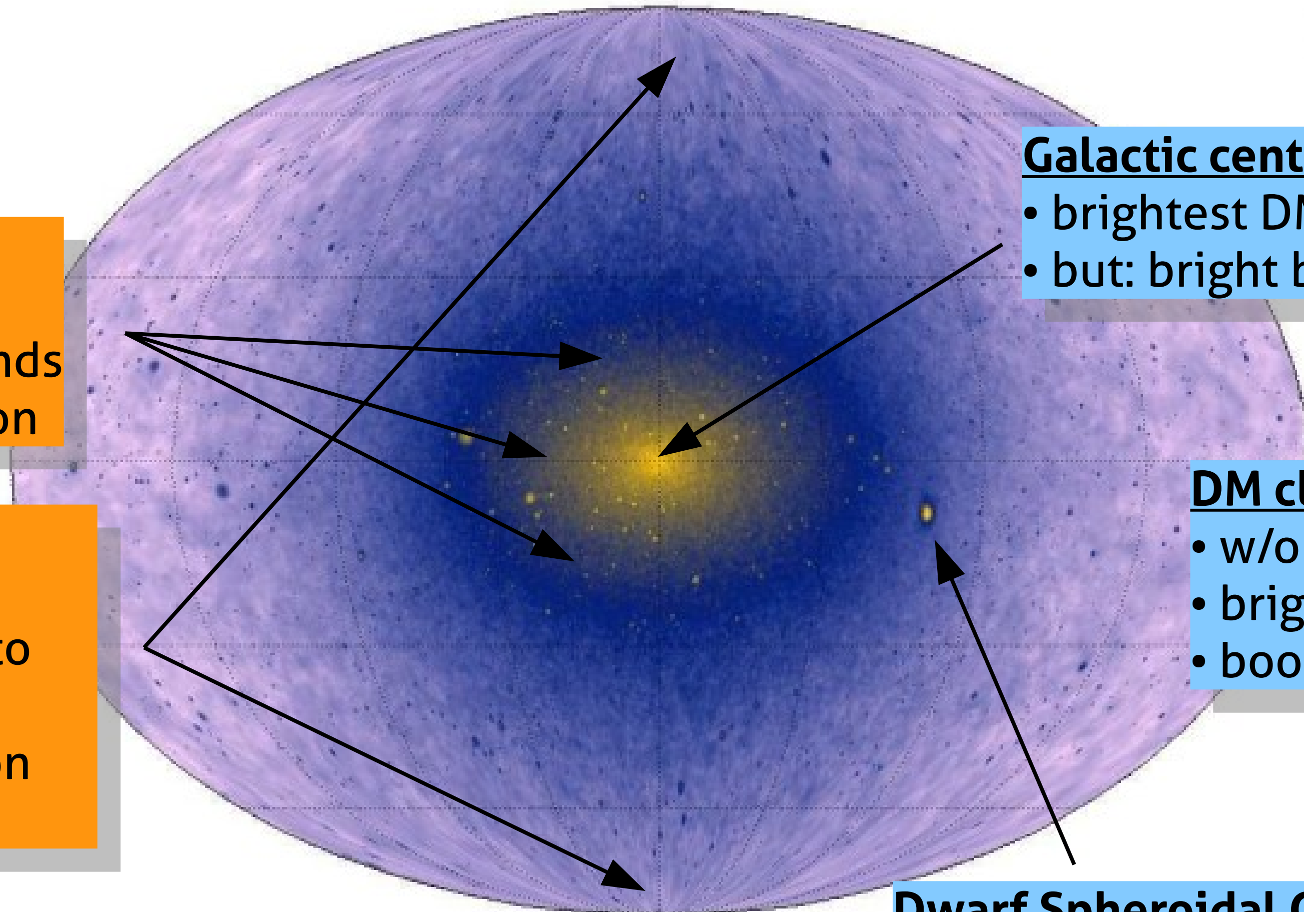
# Searches with gamma rays



# Many potential targets

Signal is approximately proportional to column square density of DM

$$\frac{d^2\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$



**Galactic DM halo**
- good S/N
- difficult backgrounds
- angular information

**Extragalactic**
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

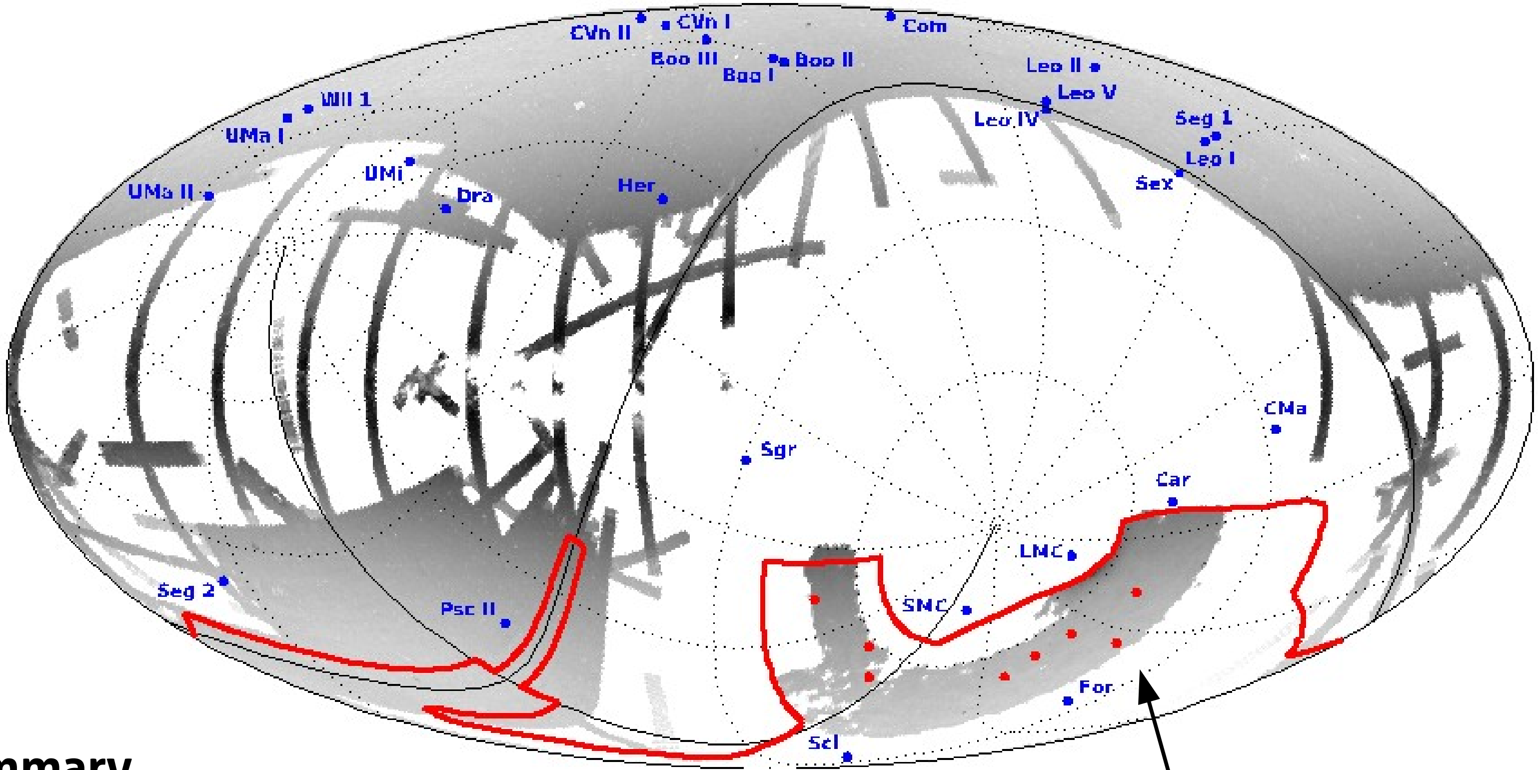
**Galactic center (~8.5 kpc)**
- brightest DM source in sky
- but: bright backgrounds

**DM clumps**
- w/o baryons
- bright enough?
- boost overall signal

**Dwarf Spheroidal Galaxies**
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

# New candidates for dwarf spheroidals!




DES footprint
5000 deg^2

**Summary**

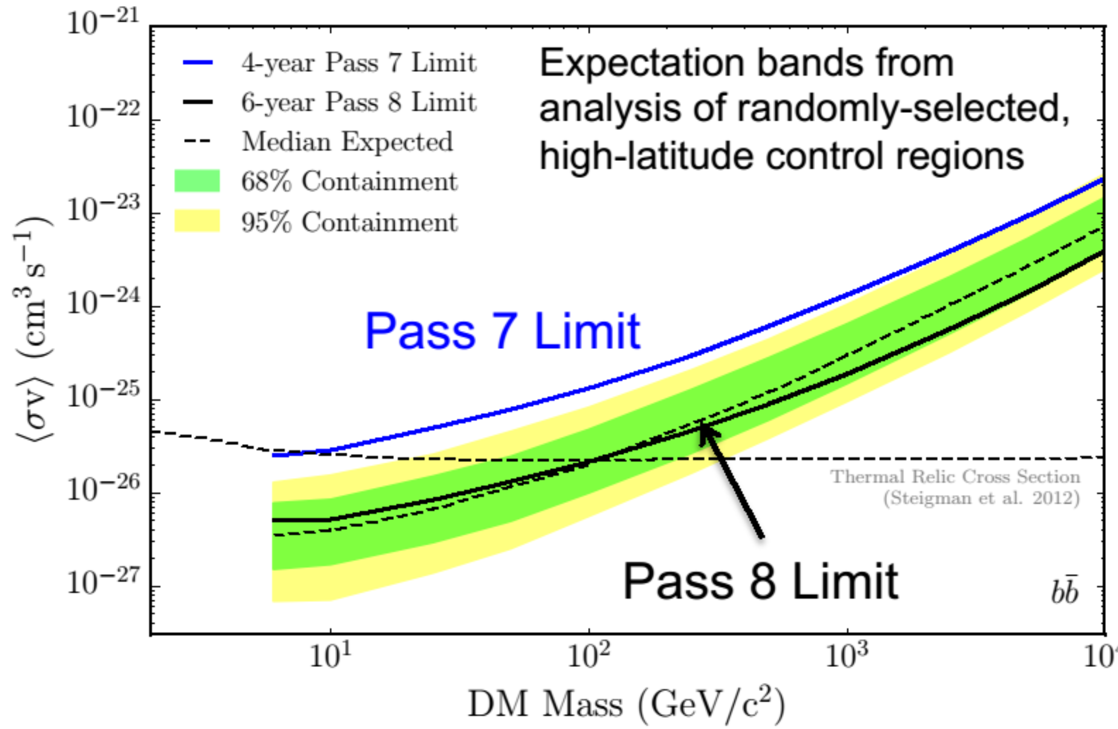
- Dwarf spheroidals and candidates
  - 12 classical dSphs
  - LMC + SMC
  - 15 ultra-faint dSphs (SDSS)
  - **8 new dSph candidates from DES Y1A1** (1503.02584, 1503.02079)
  - 5 more dSph candidates from other searches (1503.05554, 1503.08268, 1506.01021, 1503.02079)
  - 8 new dSph candidates from DES Y2 (1508.03622)
- J-values for new dSph candidates only known for Reticulum II (1504.07916, 1504.03309)
- Maybe hundreds of additional dSphs left to discover

# Current situation

**Limits based on 15 dSphs (not including DES candidates)**

- Pass 8: Released June 24 this year!
- Improvements:
  - 4 → 6 years data
  - Pass 7 → pass 8
  - Including PSF quality in fit
- Limits in very good agreement with expectations → no indication for signal from

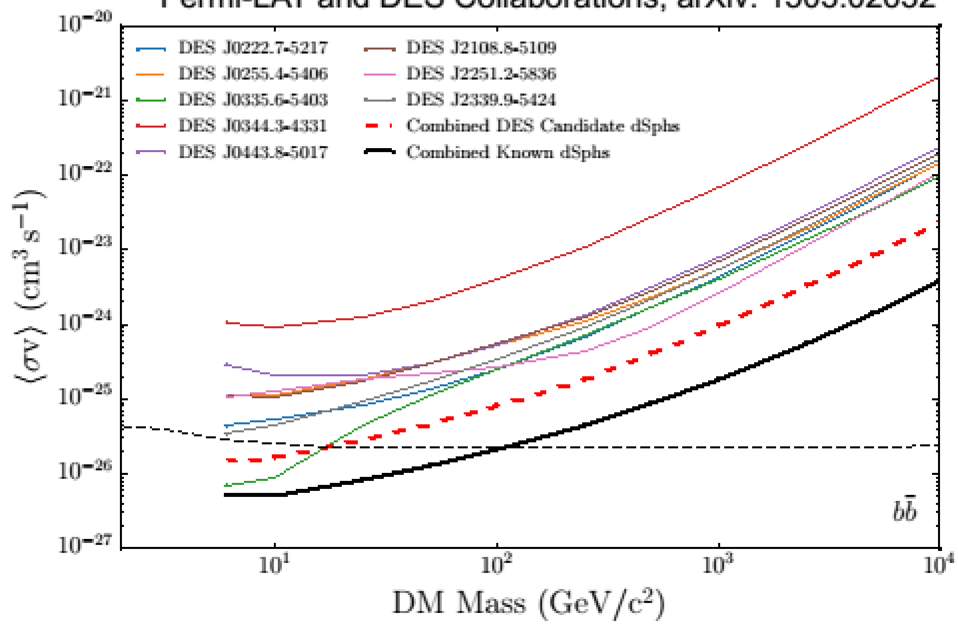
Ackermann et al. 2015, arXiv:1503.02641



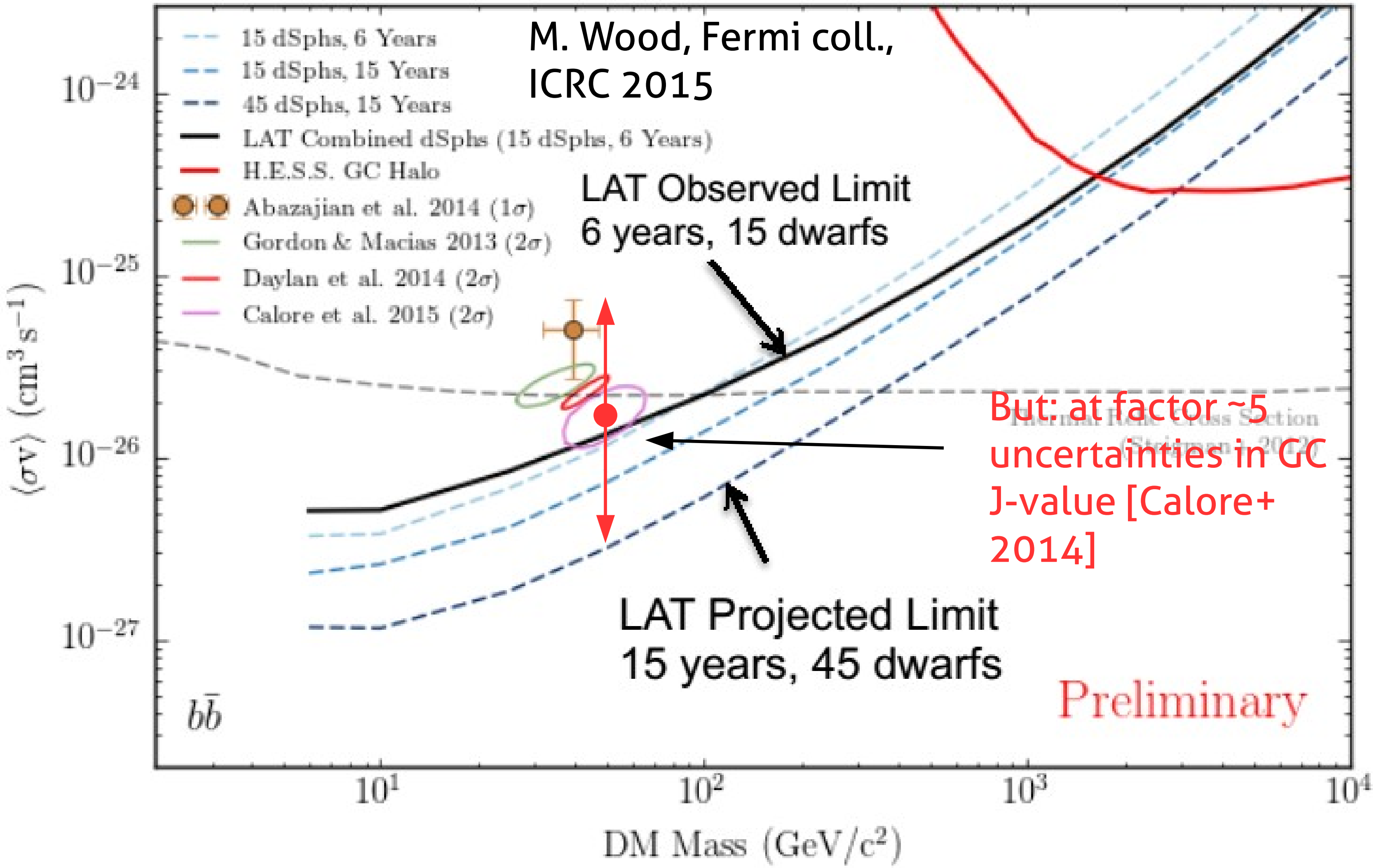

**DES candidate dSphs**

- Analysis with 6 years of pass 8 data shows no evidence for gamma-ray emission from the 8 new DES candidates (Fermi coll. 1503.02632)
- Largest excess in Reticulum II (2.4 sigma local significance)
- Independent analysis (Geringer-Sameth+ 1503.02320, Hooper+ 1503.06209) with pass 7 report somewhat larger significance in Reticulum II

Fermi-LAT and DES Collaborations, arXiv: 1503.02632



# Comparison and future predictions




**Future possible improvements**

- More data: Up to 15 years (until 2023, formally approved until 2016)
- 3x more dwarfs
  → would lead to factor ~4 improvement of limits
  → strong enough to probe GC excess even for pessimistic DM profiles

# Preliminary HESS-I results (and HESS-II projections)

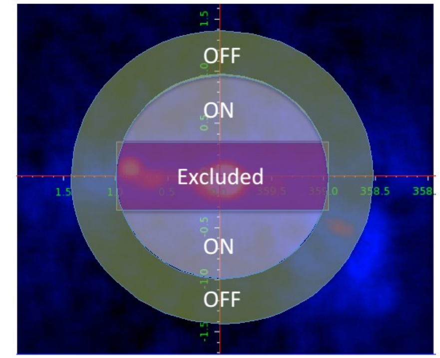
**Results**

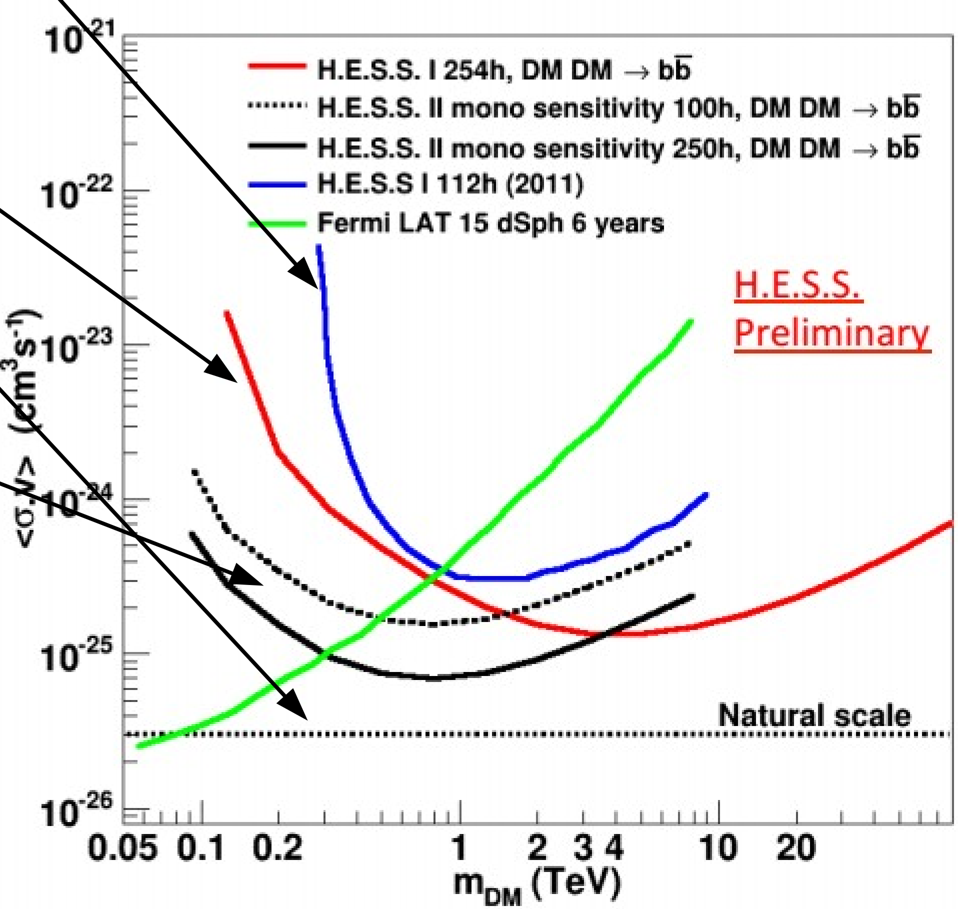
- Previous results: 2011 PRL (112h), using Tasitiomi signal spectrum
- **Now**:
  - 254h
  - full 2D spectra + spatial likelihood
  - realistic signal spectra

→ Significant improvement of limits
→ tau+ tau- limits reach thermal cross-section

- **Projections for HESS-II**
  - Improvement by factor 5 and more below 1 TeV

On & Off regions




Lefranc+, HESS coll., ICRC 2015

# HESS-II results on gamma-ray lines

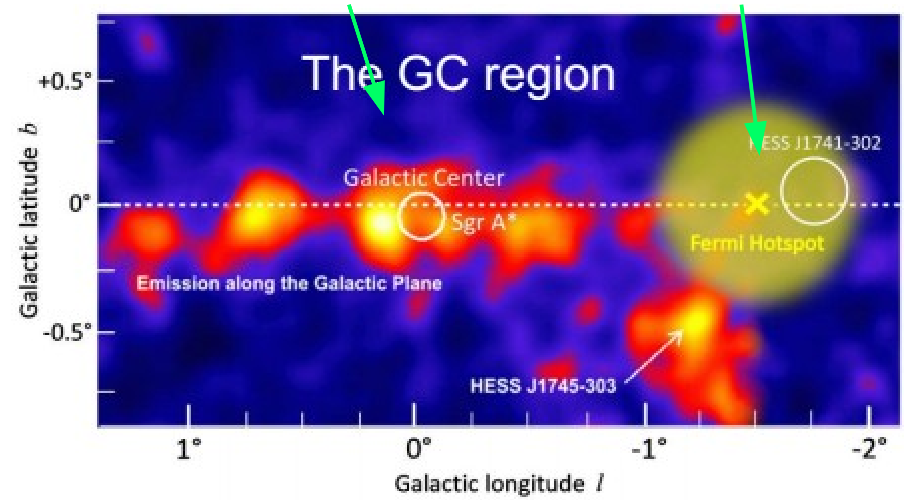
**Previous results**
- HESS-I upper limits 500 GeV – 25 TeV

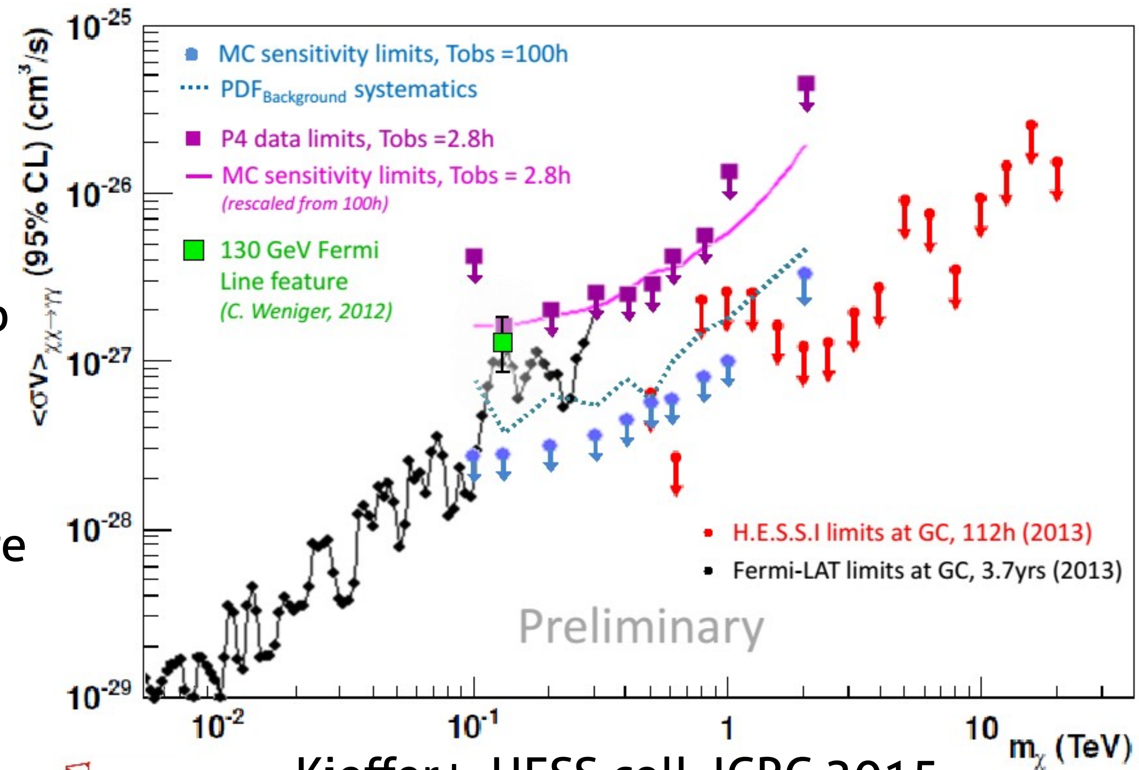
**New preliminary HESS-II results**
- Search in "Fermi hot spot" (l=-1.5 deg ; b=0 deg) 100 GeV – 2 TeV
- Preliminary results using 2.8h data (20h available in total)
- Unbinned spectral analysis
- "Off-region" for BG estimates is Galactic center

- Upper limits come close to "Fermi line"
- Projected 100h limits will "close gap between HESS-I and Fermi limits"

**Remember**
- DM interpretation of 130 GeV feature already in strong conflict with Fermi LAT pass 8 data (> 3 sigma)

Off-region On-region




Kieffer+, HESS coll. ICRC 2015

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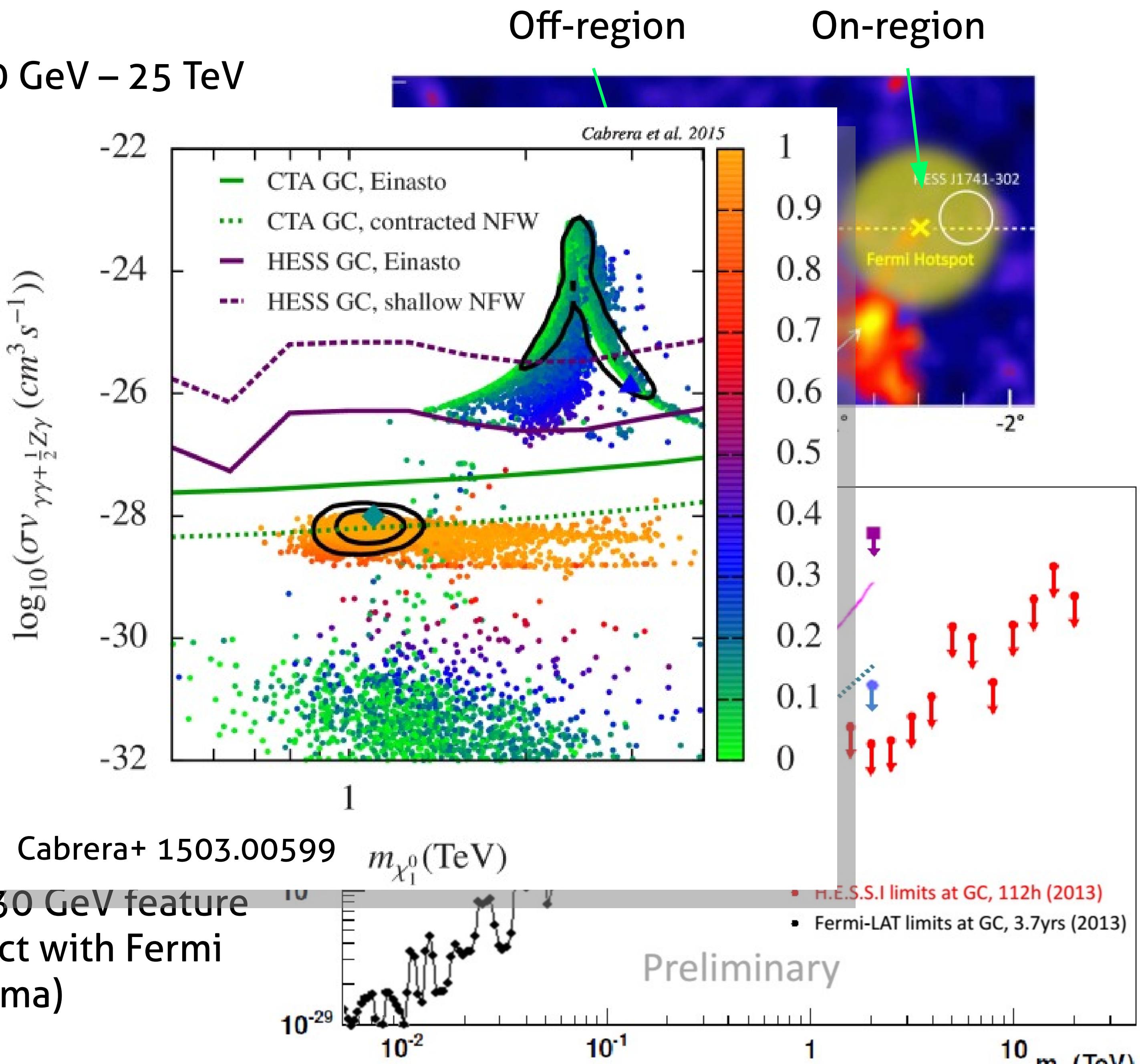
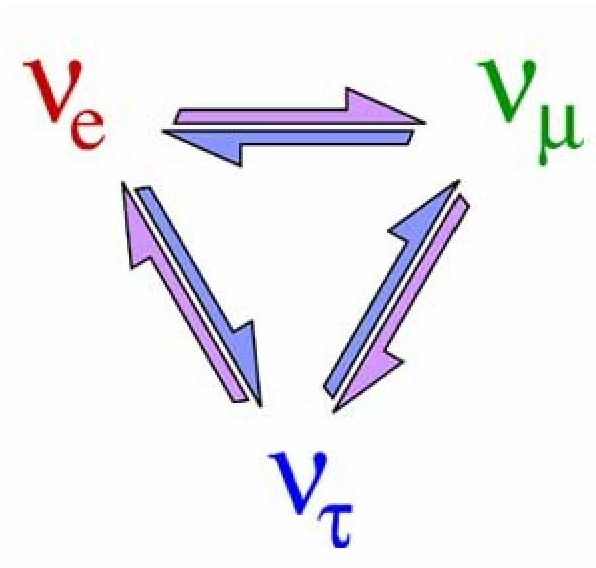


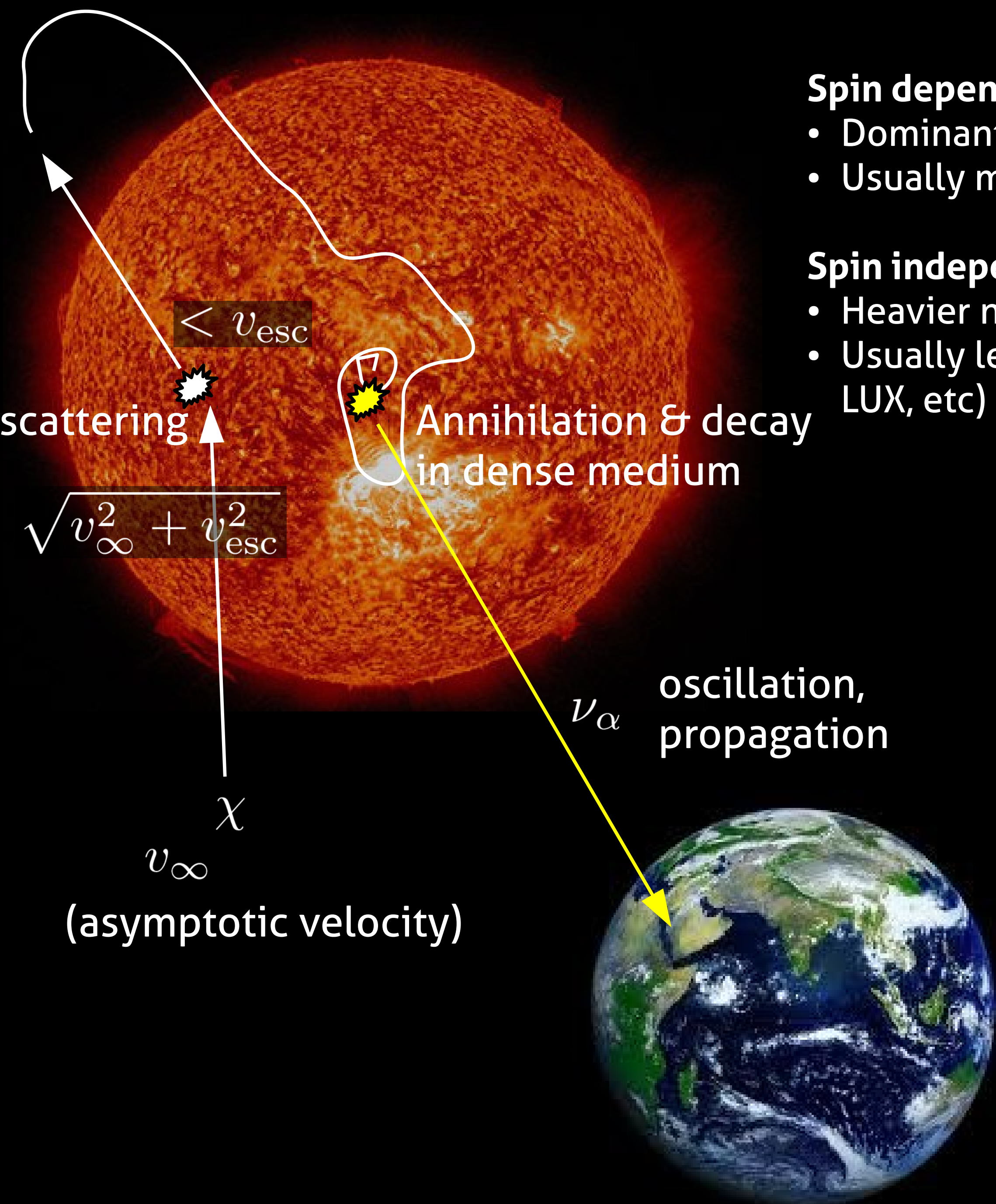

Cabrera+ 1503.00599

Kieffer+, HESS coll. ICRC 2015

# Searches with Neutrinos (from the Sun)



# Neutrinos from the Sun




**Spin dependent scattering**

- Dominant contribution from scattering on hydrogen
- Usually more constraining than direct searches

**Spin independent scattering**

- Heavier nuclei contribute
- Usually less constraining than direct searches (XENON, LUX, etc)

$$\dot{N} = C - C_A N^2$$

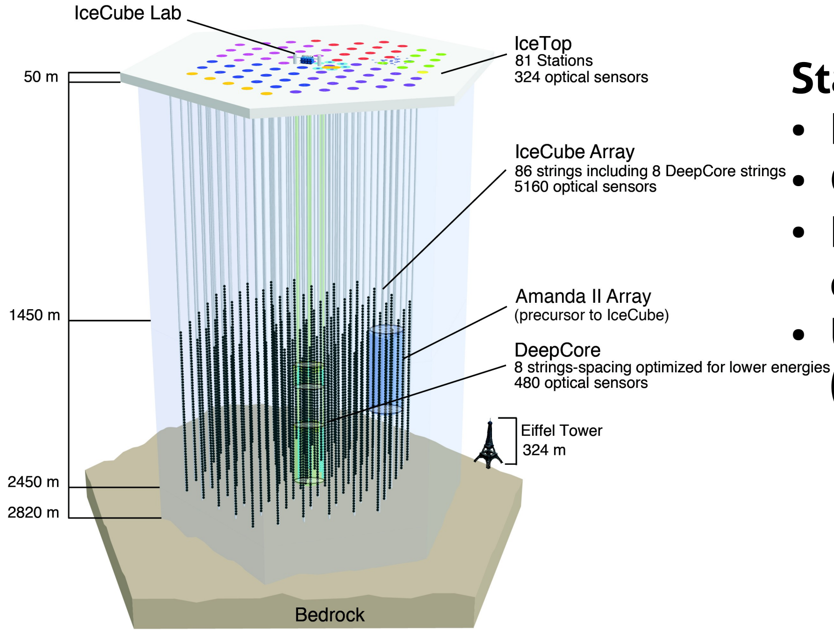
Capture rate ($C$); Annihilation rate ($C_A$); Number of WIMPs ($N$)

$$C \propto \sigma \rho_\chi$$

In equilibrium, the annihilation rate is fully determined by the capture rate:

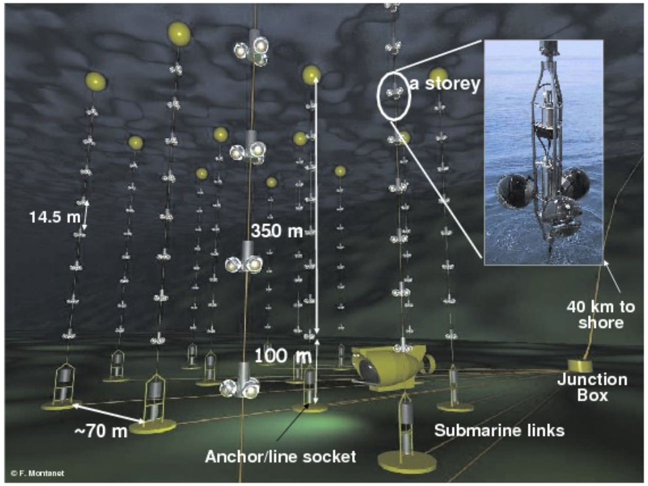
$$\Rightarrow \Gamma_A = \frac{C_A}{2} N_{\rm eq}^2 = \frac{C}{2}$$

# Neutrino detectors



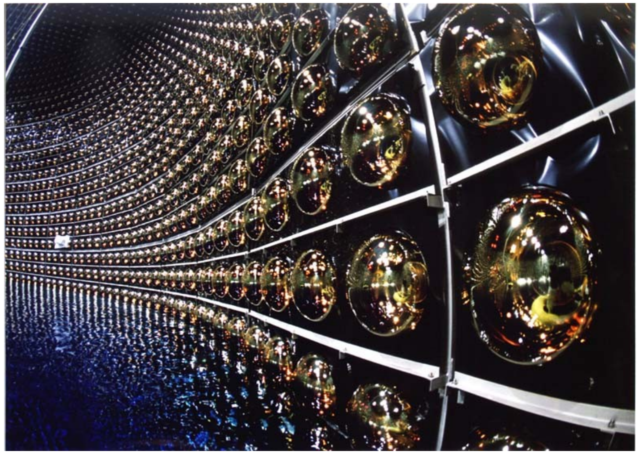

### Status IceCube

- Located at geographic south pole
- Completed (IceTop+IceCube+DeepCore) since 2011
- Effective area for muon neutrinos O(mm$^2$ - m$^2$), depending on energy and analysis details
- Updated results on Sun neutrinos shown at ICRC 2015 (341d livetime, IC86)




### Status ANTARES

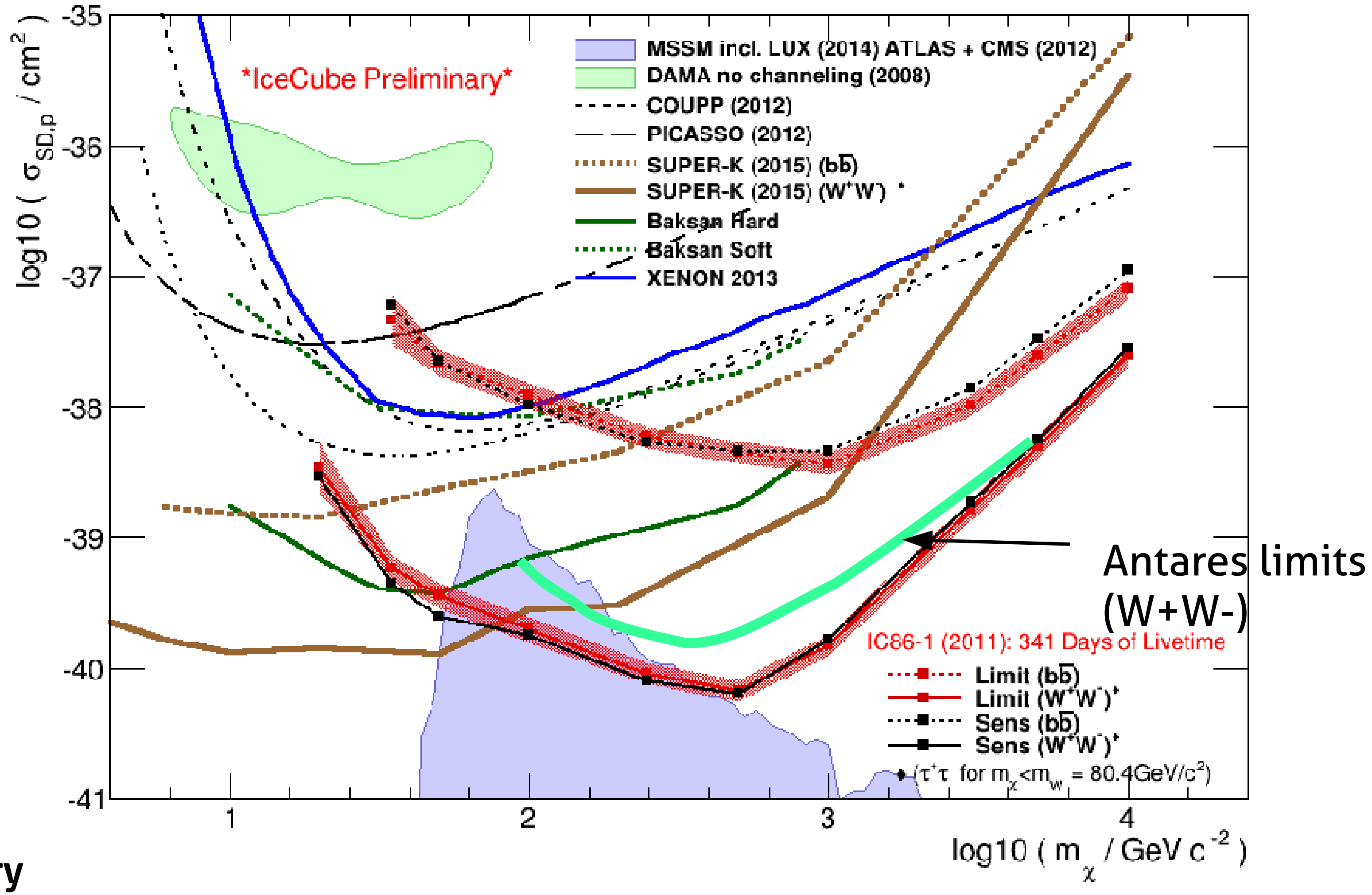
- Located in the Mediterranean Sea
- Completed in 2008
- Effective area O(mm$^2$ - cm$^2$)
- Updated results on Sun neutrinos shown at ICRC 2015



### Status Super-Kamiokande

- Located in Mozumi Mine, Japan
- SK-IV completed in 2008
- Gives rise to best limits at low WIMP masses
- Updated results from 2015 (Sun neutrinos, 1503.04858)

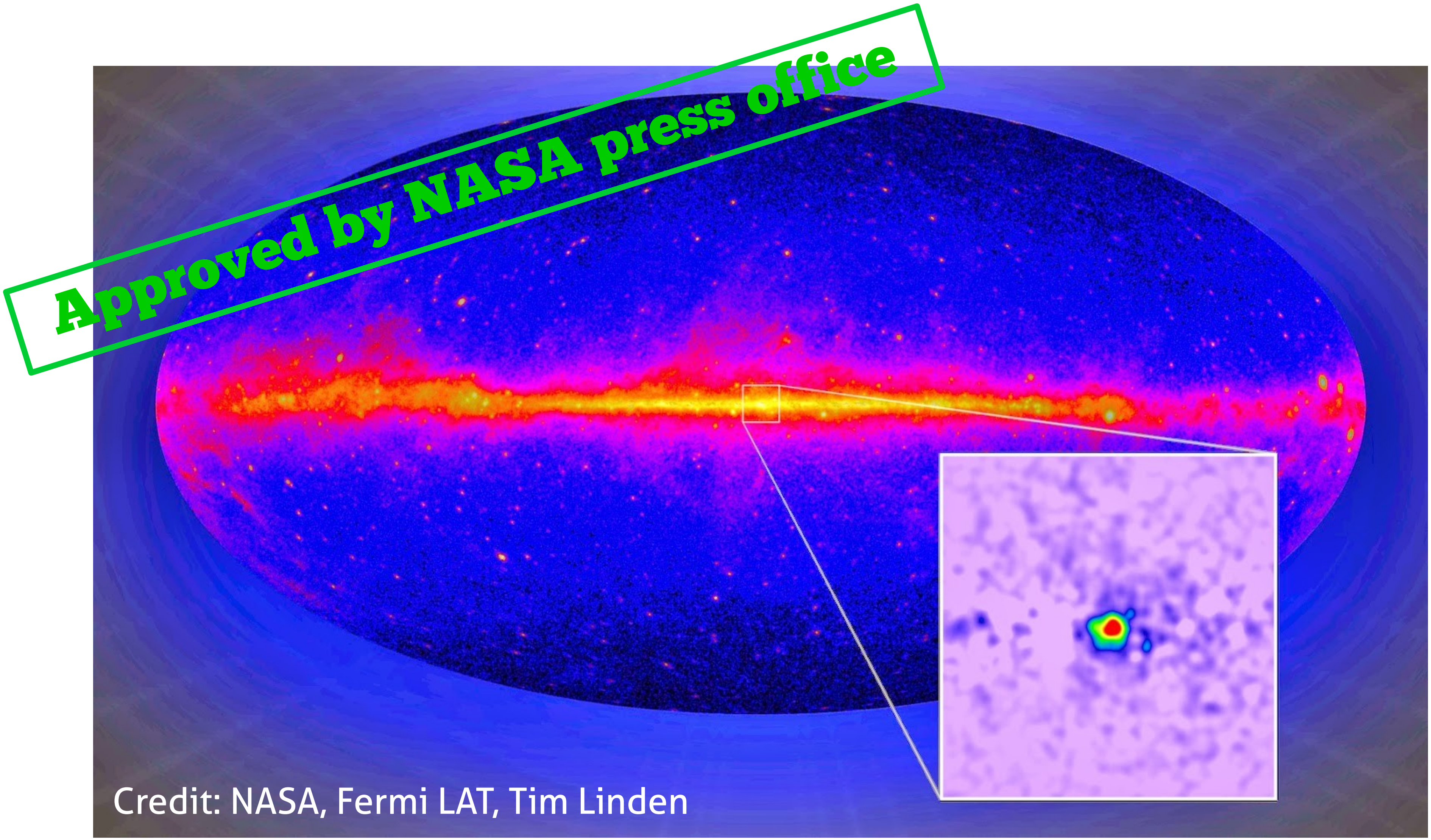
# Upper limits




**Limits summary**

- IceCube (preliminary IC86-1 results at ICRC 2015)
  - Mostly austral winter data, through-going muons, search for clustering of neutrinos around Sun
  - Improves previous IC79 results by factor up to 4 at TeV DM masses
- Antares limits (preiminary resulst at ICRC 2015)
  - Based on 1321 days of data (2007 – 2012) comparable to IceCube
- Super-K (1503.04858, based on ~4000d of data)
  - Using contained events for the first time → Significant improvement below 200 GeV
  - Strongest limits below DM masses of ~100 GeV

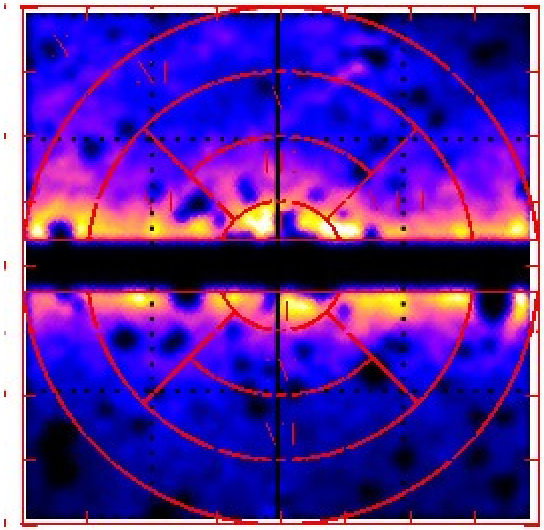
# The Fermi Galactic center excess




Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+ 2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero+ 2015

# Dark Matter annihilation works just fine

Calore, Cholis, CW 1409.0042

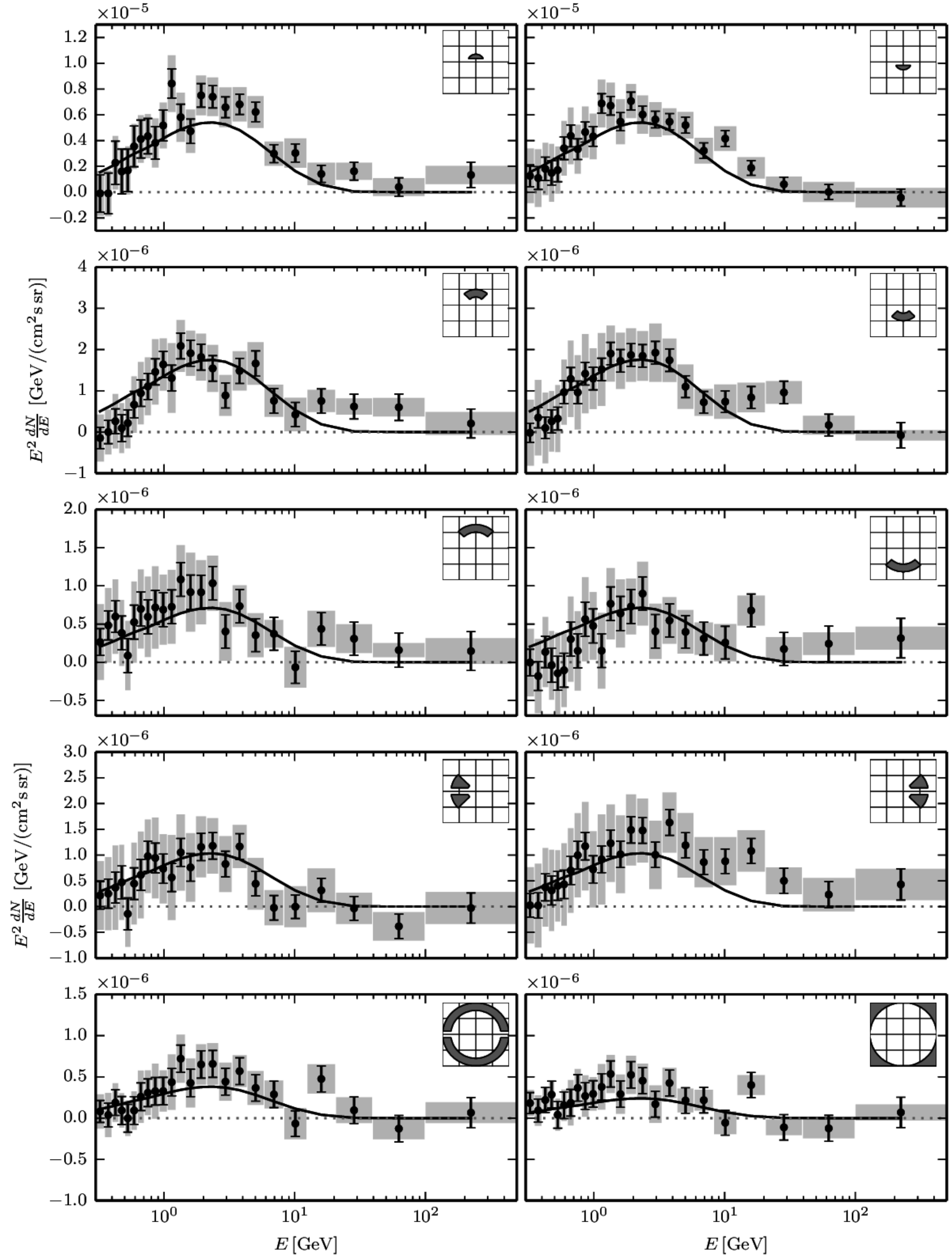


$$2^\circ \leq |b| \leq 20^\circ \quad \text{and} \quad |\ell| \leq 20^\circ$$

Good fits are obtained with DM spectra and slightly contracted NFW profile

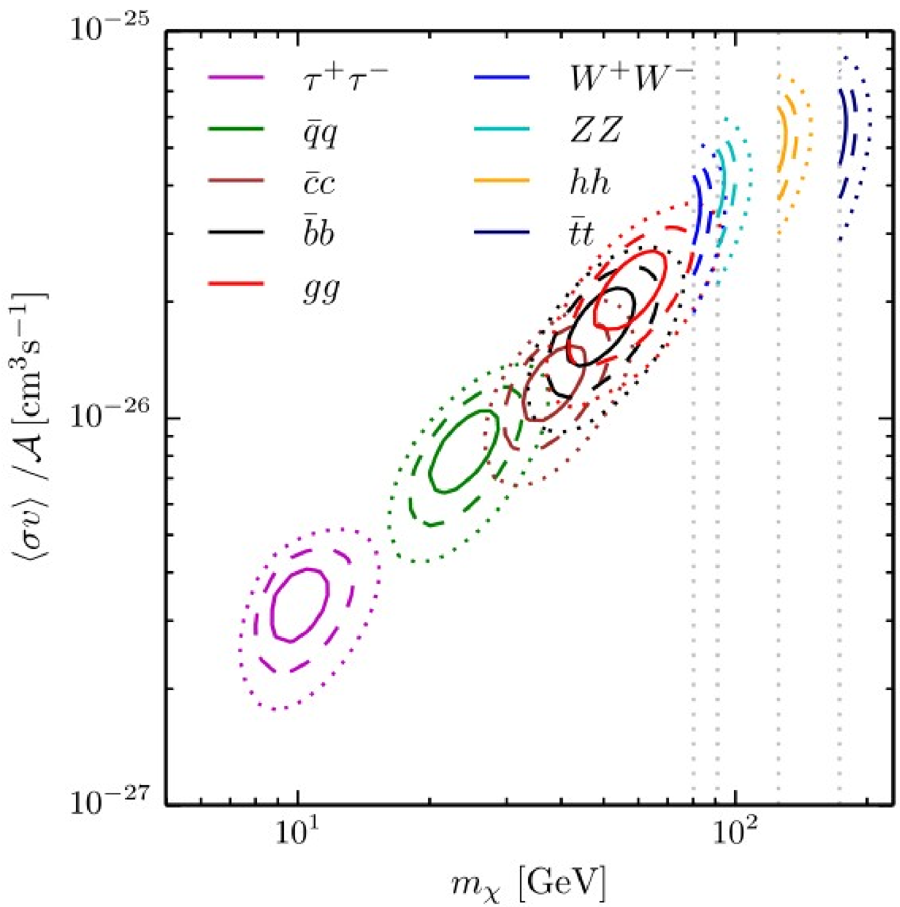
$$\rho_{\rm DM} = \frac{1}{r^\gamma (r_s + r)^{2-\gamma}}$$

$$\gamma \simeq 1.26$$

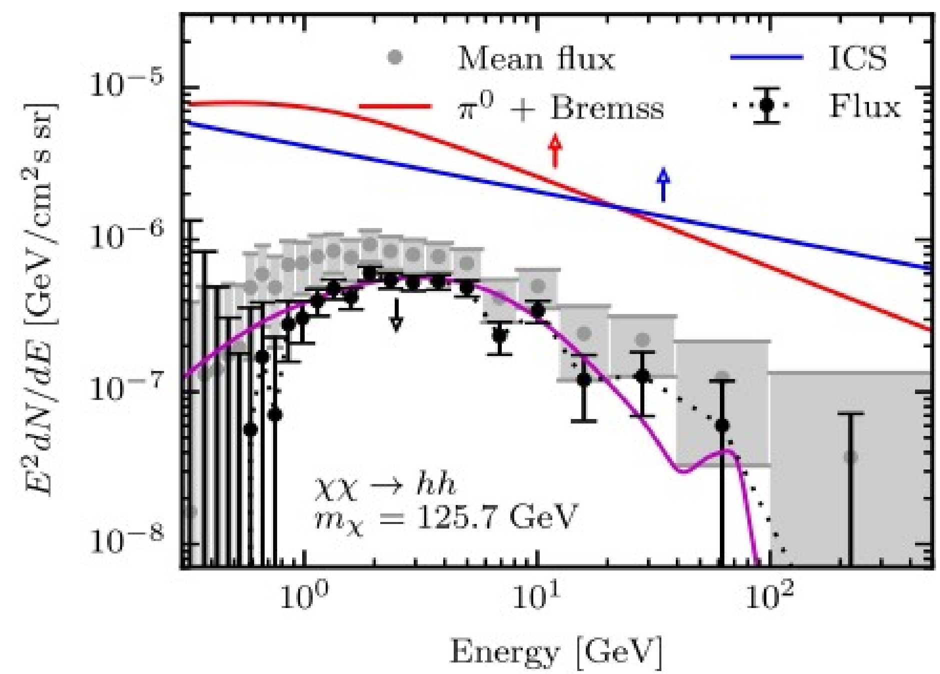


# Fits with dark matter annihilation spectra

Calore, Cholis, McCabe, CW 2014




| Channel | $\langle \sigma v \rangle$ ($10^{-26}$ cm$^3$ s$^{-1}$) | $m_\chi$ (GeV) | $\chi^2_{\min}$ | $p$-value |
|---|---|---|---|---|
| $\bar{q}q$ | $0.83^{+0.15}_{-0.13}$ | $23.8^{+3.2}_{-2.6}$ | 26.7 | 0.22 |
| $\bar{c}c$ | $1.24^{+0.15}_{-0.15}$ | $38.2^{+4.7}_{-3.9}$ | 23.6 | 0.37 |
| $\bar{b}b$ | $1.75^{+0.28}_{-0.26}$ | $48.7^{+6.4}_{-5.2}$ | 23.9 | 0.35 |
| $\bar{t}t$ | $5.8^{+0.8}_{-0.8}$ | $173.3^{+2.8}_{-0}$ | 43.9 | 0.003 |
| $gg$ | $2.16^{+0.35}_{-0.32}$ | $57.5^{+7.5}_{-6.3}$ | 24.5 | 0.32 |
| $W^+W^-$ | $3.52^{+0.48}_{-0.48}$ | $80.4^{+1.3}_{-0}$ | 36.7 | 0.026 |
| $ZZ$ | $4.12^{+0.55}_{-0.55}$ | $91.2^{+1.53}_{-0}$ | 35.3 | 0.036 |
| $hh$ | $5.33^{+0.68}_{-0.68}$ | $125.7^{+3.1}_{-0}$ | 29.5 | 0.13 |
| $\tau^+\tau^-$ | $0.337^{+0.047}_{-0.048}$ | $9.96^{+1.05}_{-0.91}$ | 33.5 | 0.055 |
| $[\mu^+\mu^-$ | $1.57^{+0.23}_{-0.23}$ | $5.23^{+0.22}_{-0.27}$ | 43.9 | $0.0036]_{\text{ICS}}$ |




- Large *correlated* uncertainties affect the best-fit spectrum
- Large number of different final states possible
- **Even annihilation into W+W- not excluded,** when uncertainties in predicted spectra are taken into account (Achterberg+ 1502.05703)
- Formally best fit: **broken power law**

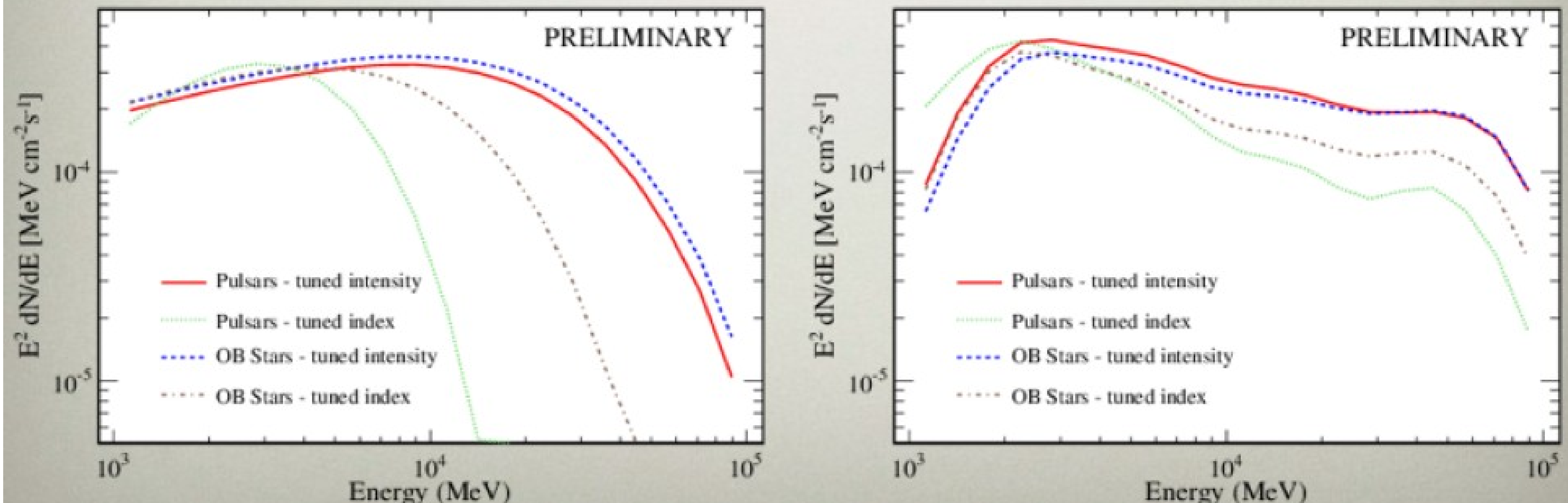
S. Murgia, slides from Fermi Symposium 2014, Nagoya

# Additional Templates

- We test the possibility that an additional component centered at the GC contributes to the data (2D gaussians, Navarro-Frenk-White, or a gas-like distribution as proxy for unresolved sources)
- Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement for the four variants of the foreground/background models. IC ring 1 contribution ~2-3x smaller than without additional component and HI ring 1 contribution is ~2-5x larger

➡ The predicted spectrum depends on the foreground/background models.

**Integrated flux in 15°x15° ROI, NFW component**



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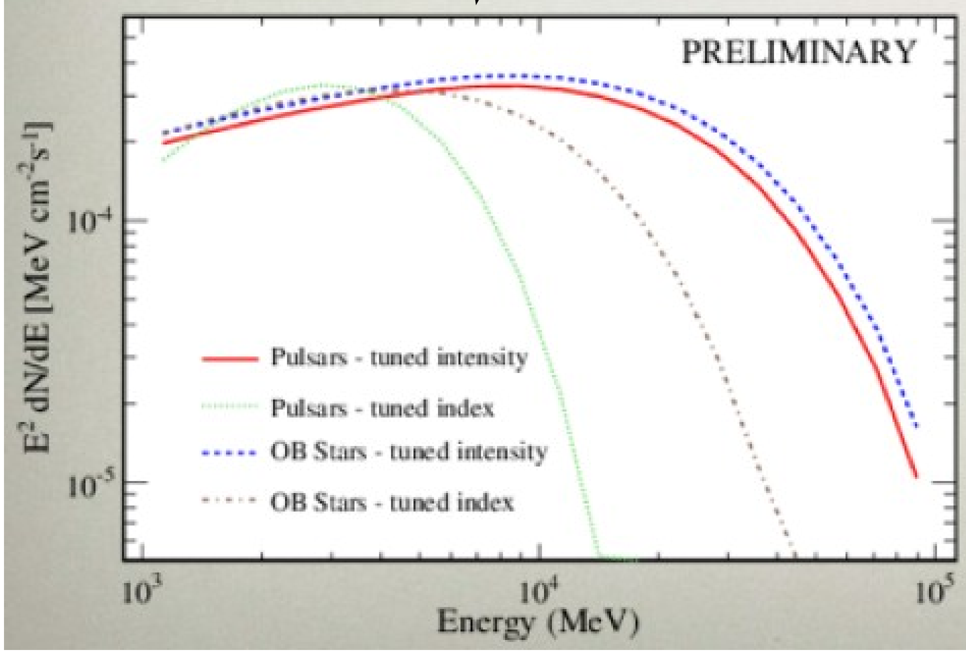
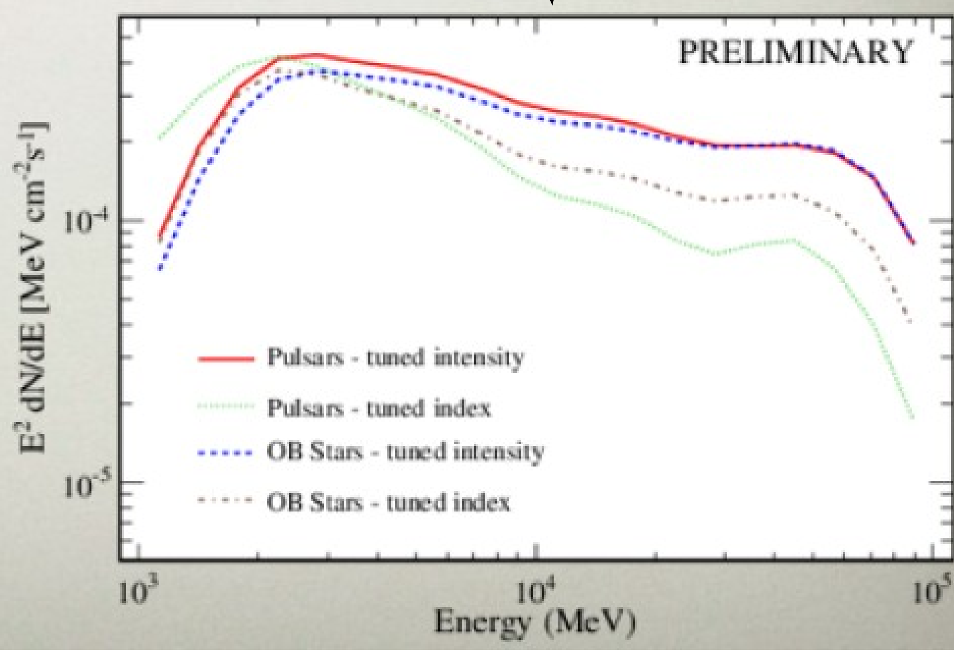
Parametric fits (PL + exp cutoff) to excess energy spectrum

Non-parameteric fits to excess energy spectrum

Integrated flux in 15°x15° ROI, N… component



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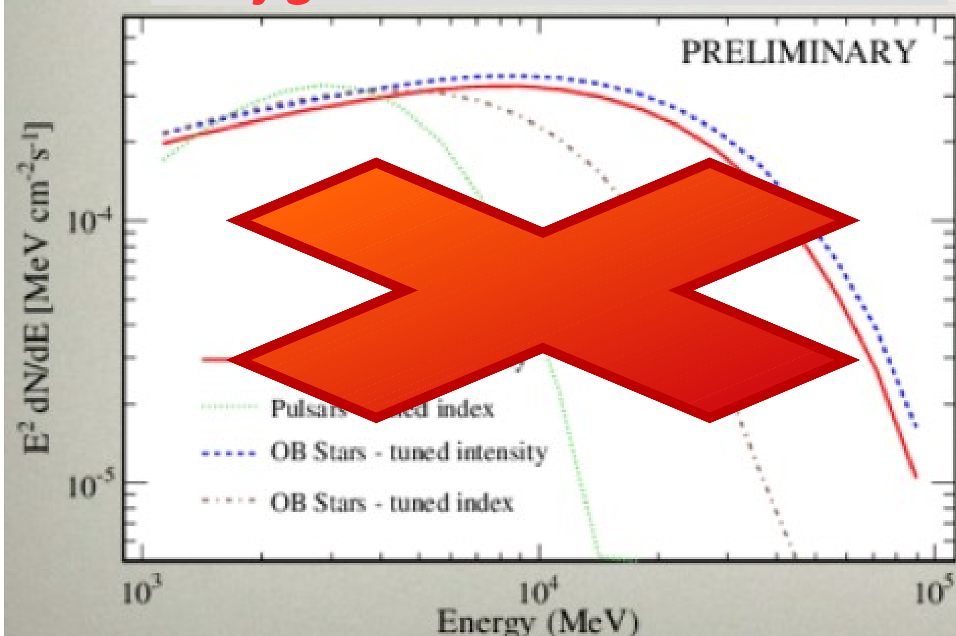
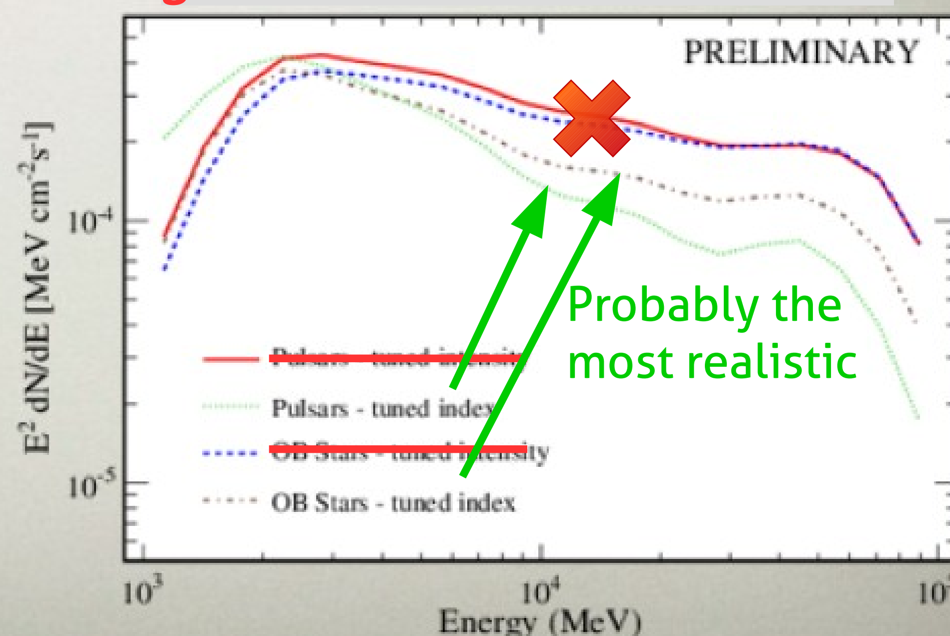
Using suboptimal parametrization likely gives biased results.

Using non-tuned CR index likely gives biased results.



S. Murgia, slides from Fermi Symposium 2014, Nagoya

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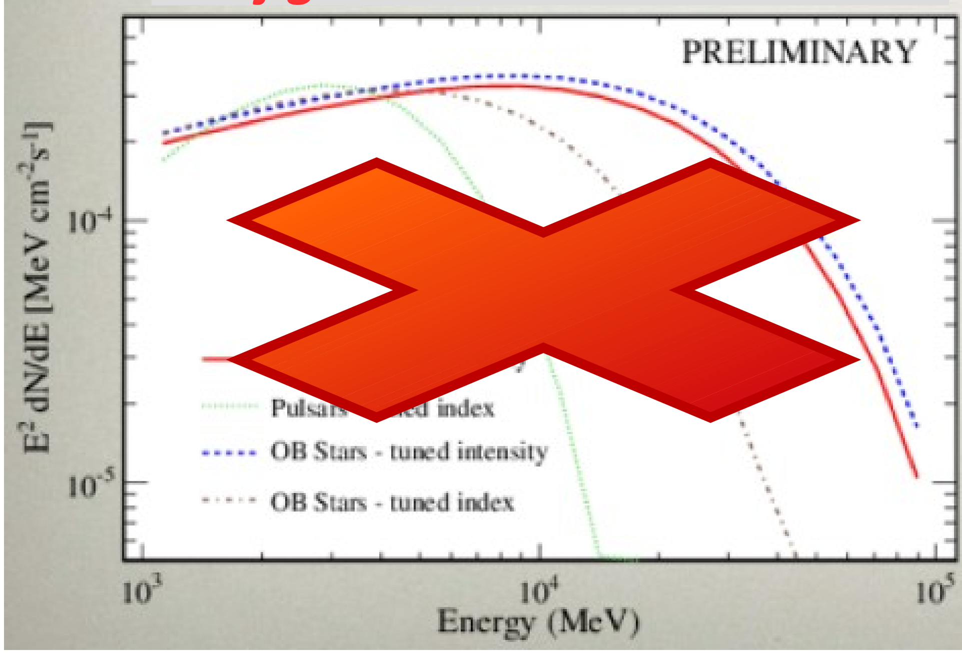
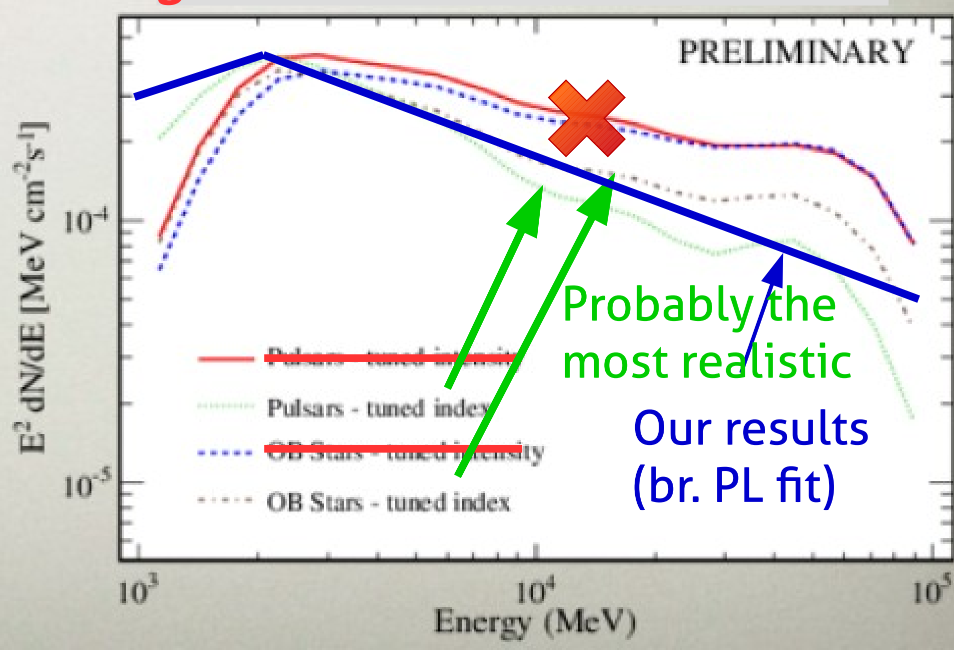


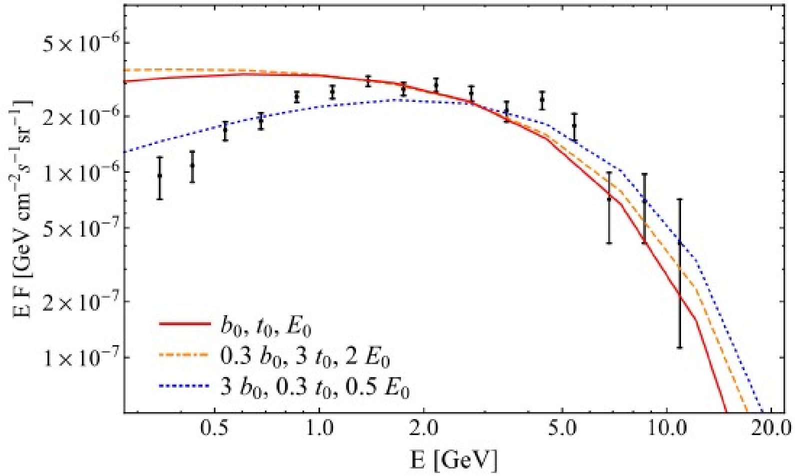



# Astrophysical interpretations

**Leptonic activity at the Galactic center:**

Petrovic+ 2014; Cholis+ 2015

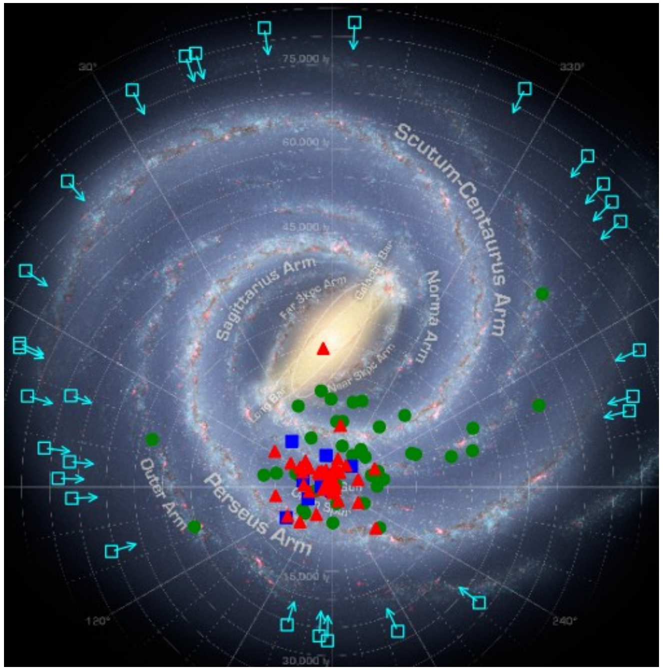
- Recent injection of hard electrons at Galactic center, ~1 Myr ago
- Diffusion → approx. spherical profile & emission
- Can potentially explain peaked spectrum
- The morphology, especially emission above 10 deg (1.5 kpc) is hard to reproduce, since the energy loss time of electrons is < 1 Myr.




**Millisecond pulsars (MSPs):**

Wang+ 2005; Abazajian 2011; Gordon & Macias 2013; Hooper+ 2013; Yuan & Zhang 2014; Hooper+ 2013; Calore+ 2014; Cholis+ 2014, Petrovic+ 2014

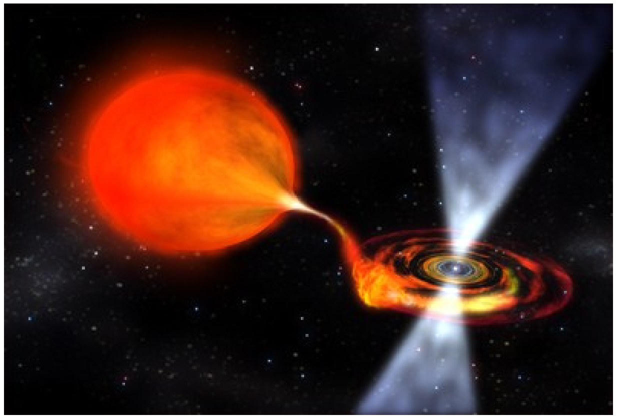
- Spectrum of known MSPs agrees reasonably well with claimed GCE spectrum (except at sub-GeV energies)
- Observed luminosity function is claimed to be incompatible with GCE (we don't see resolved MSPs at GC) Hooper+; Calore+; Cholis+ 2013
- Compatible with distribution of low-mass X-ray binaries (possible MSP progenitors)

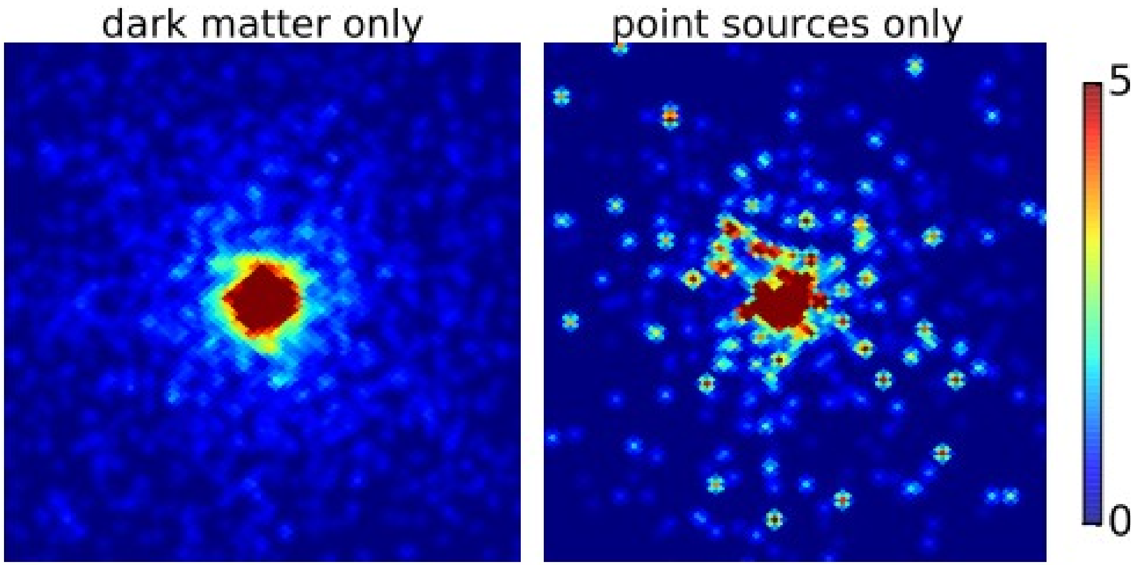


# An observational challenge

**Point sources or diffuse emission?**

- A signal composed of point sources would appear more "**speckled**" than a purely diffuse signal






(Credit: Lee+ 2014)

**Proposed methods**

- *One-point statistics*
  - Random contribution of point sources to individual pixels leads to non-Poissonian noise [Lee+ 1412.6099] (successfully used at high latitudes by Malyshev & Hogg 1104.0010)
  - **BUT**: Requires modeling / subtraction of backgrounds → Subject to systematics
- *Local maxima of normalized wavelet transform:*
  - *"Wavelet transform":* spatially constrained Fourier transform. Filters out structures of a specific size, like point sources. Removes diffuse emission.
  - *"Normalized":* Null hypothesis is equivalent to smoothed Gaussian random field → Largely independent of modeling of diffuse backgrounds

# Wavelet transform of inner Galaxy data

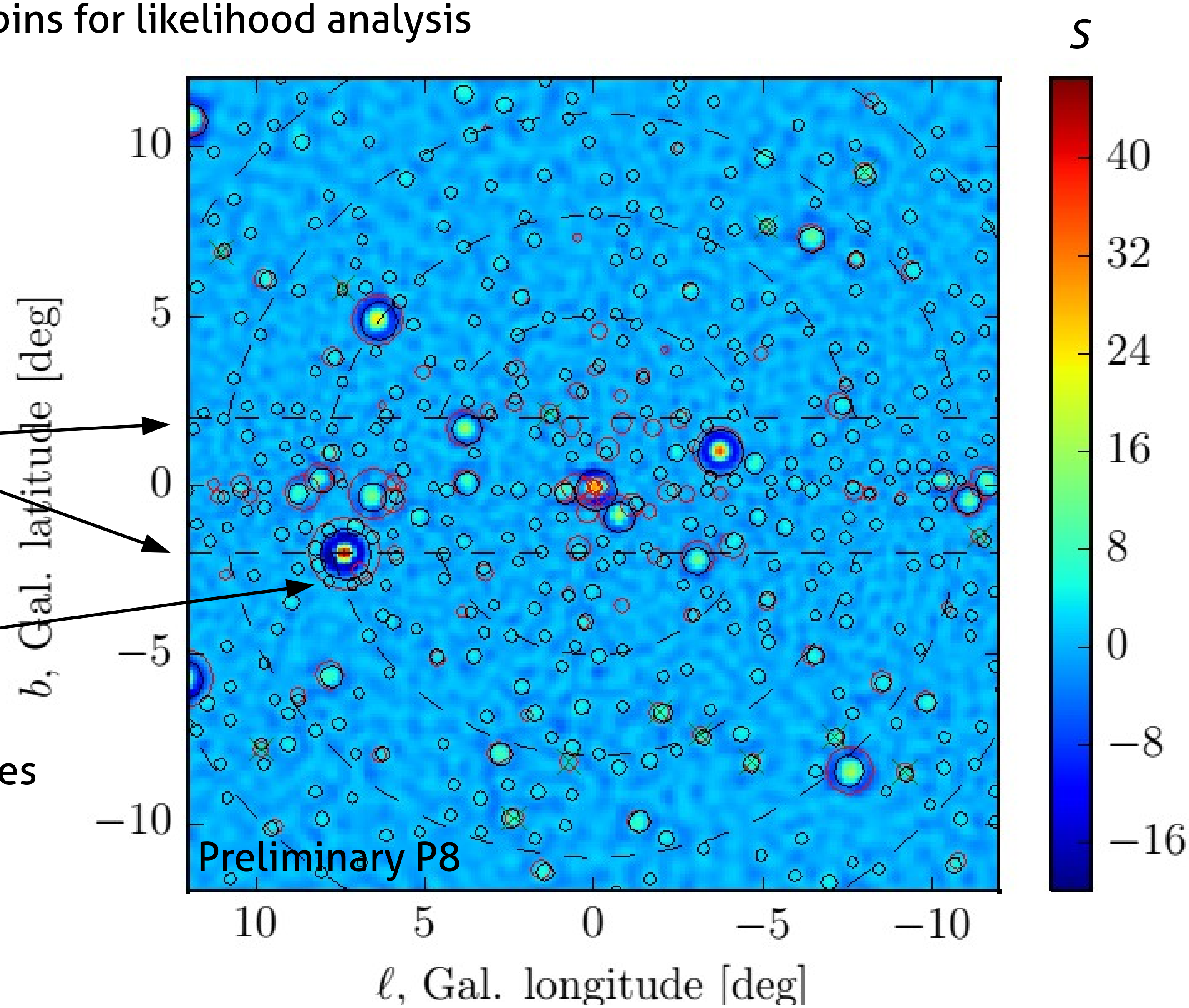
**Image color:** Value of normalized wavelet transform
**Black circles**: Wavelet SNR peaks with values above 2 (circle area ~ *S*)
**Red circles**: 3FGL sources for comparison (circle area ~ sqrt(TS) in 1-3 GeV band)
**Green crosses**: Unmasked sources (MSP-like)
Dashed lines: Spatial bins for likelihood analysis

Based on:
Pass8 Fermi LAT data
Ultraclean events
Front+back converted
6 ½ years of data
1-4 GeV range

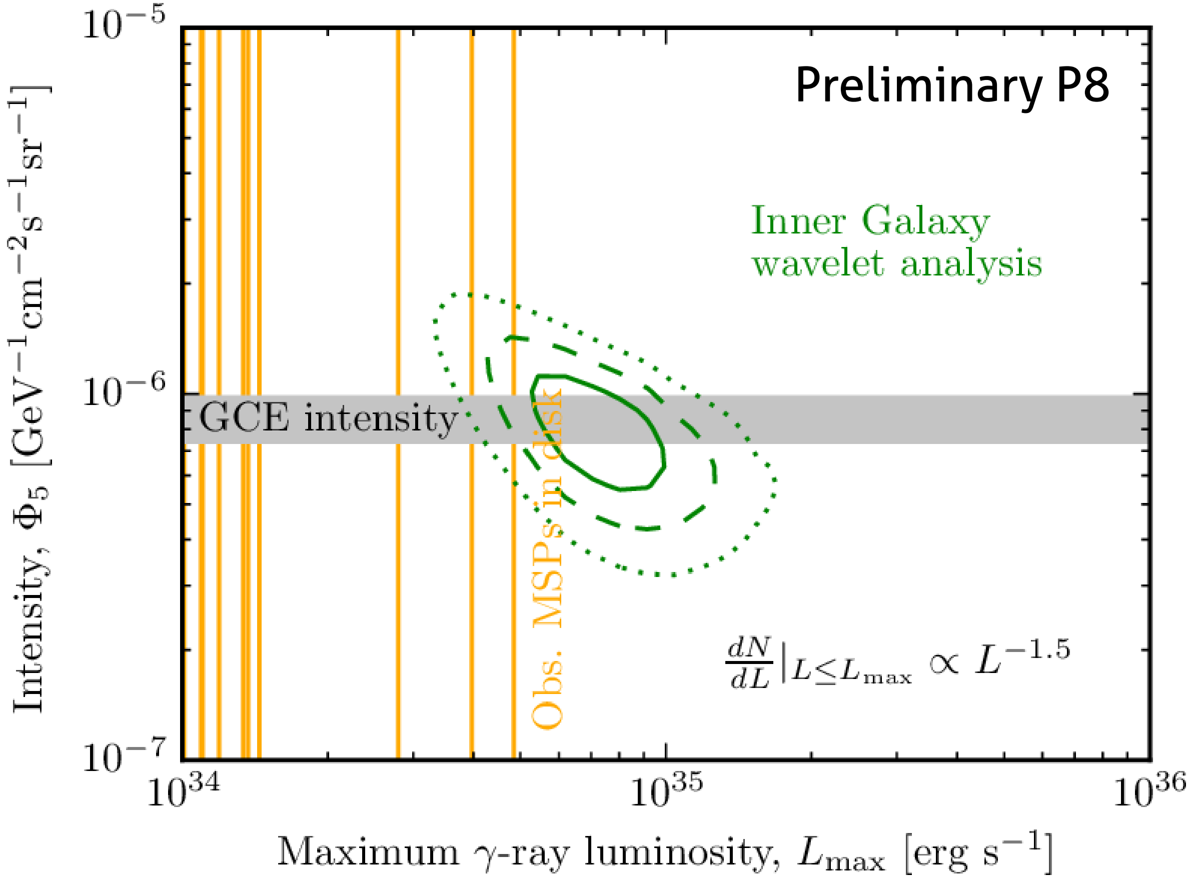
Masked disk
|b|>2 deg

Artifacts around bright sources (removed in later analysis)

→ Except for bright sources (where noise estimates includes source flux), we find good agreement between sqrt(TS) and S.



# Best-fit contours agree with MSP expectations



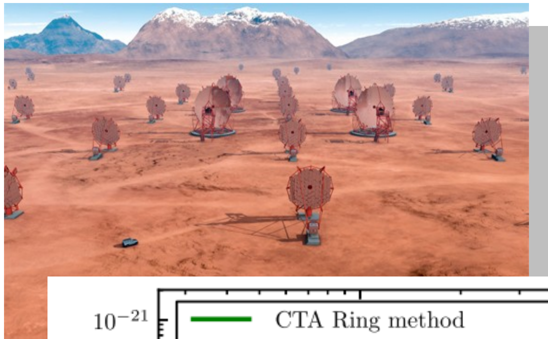

**Results**

- For a luminosity function index around 1.5, a MSP population with the best-fit normalization would reproduce 100% of the excess emission
- The best-fit cutoff luminosity is compatible with gamma-ray emission from detected nearby MSPs (beware of large uncertainties due to uncertainties in the distance measure, Petrovic+ 1411.2980, Brandt & Kocsis 1507.05616)

Lee+ 1506.05124 come to similar conclusions (with different technique, though they find a slightly different luminosity function)

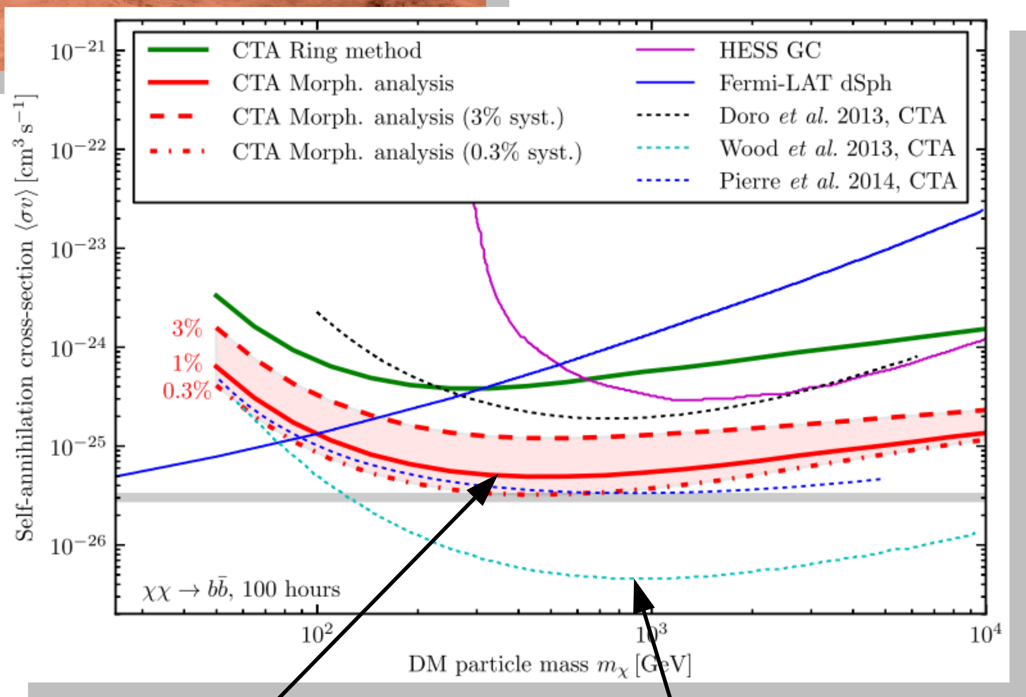
# Future

# Indirect detection prospects for the next years



cherenkov telescope array

Tens of GeV – 100 TeV

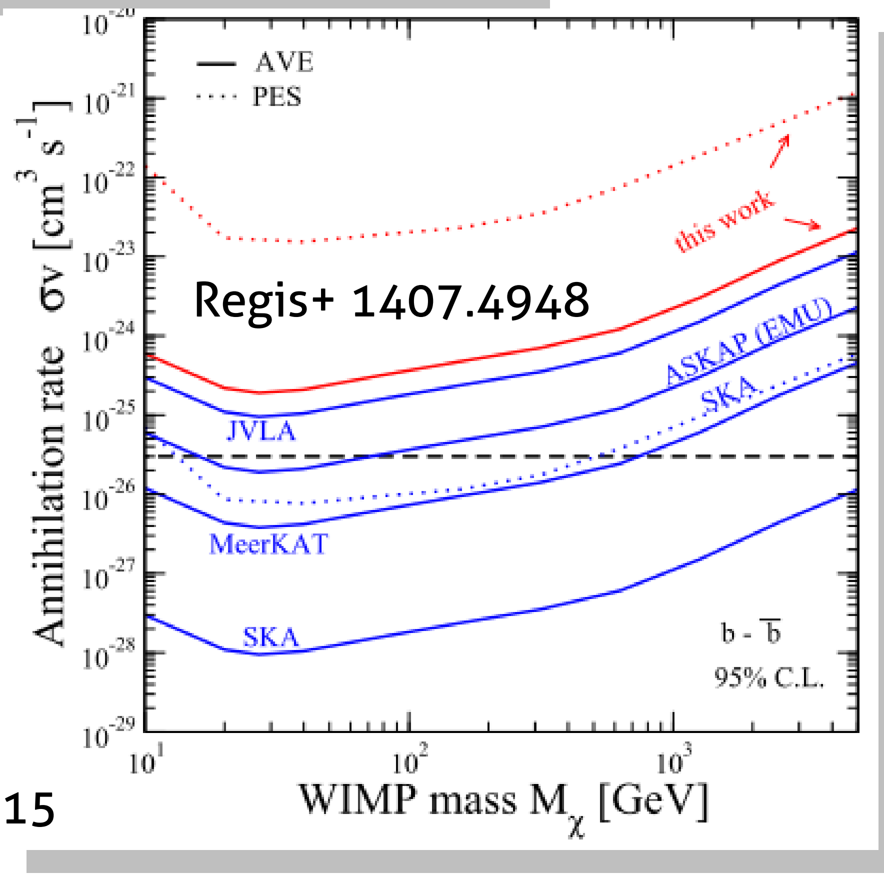



Silverwood+ 1408.4131
(1% uncorr. systematics)

CTA coll. (stat. only)
Wood+ 1305.0302
Similar to J. Carr ICRC 2015

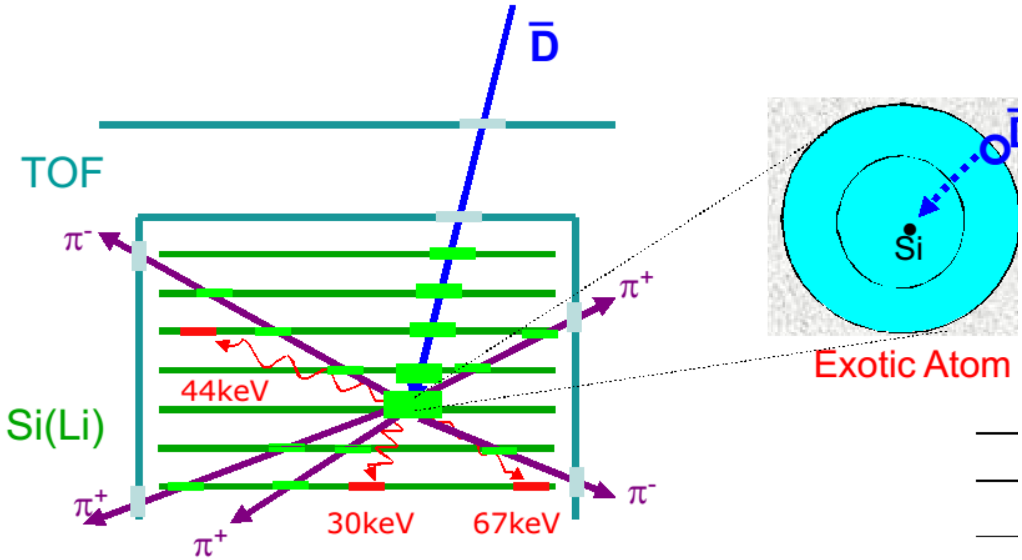
SQUARE KILOMETRE ARRAY

50 Mhz – 14 GHz




Note: Real instr. systematics are *correlated*, detailed studies are ongoing in CTA coll.

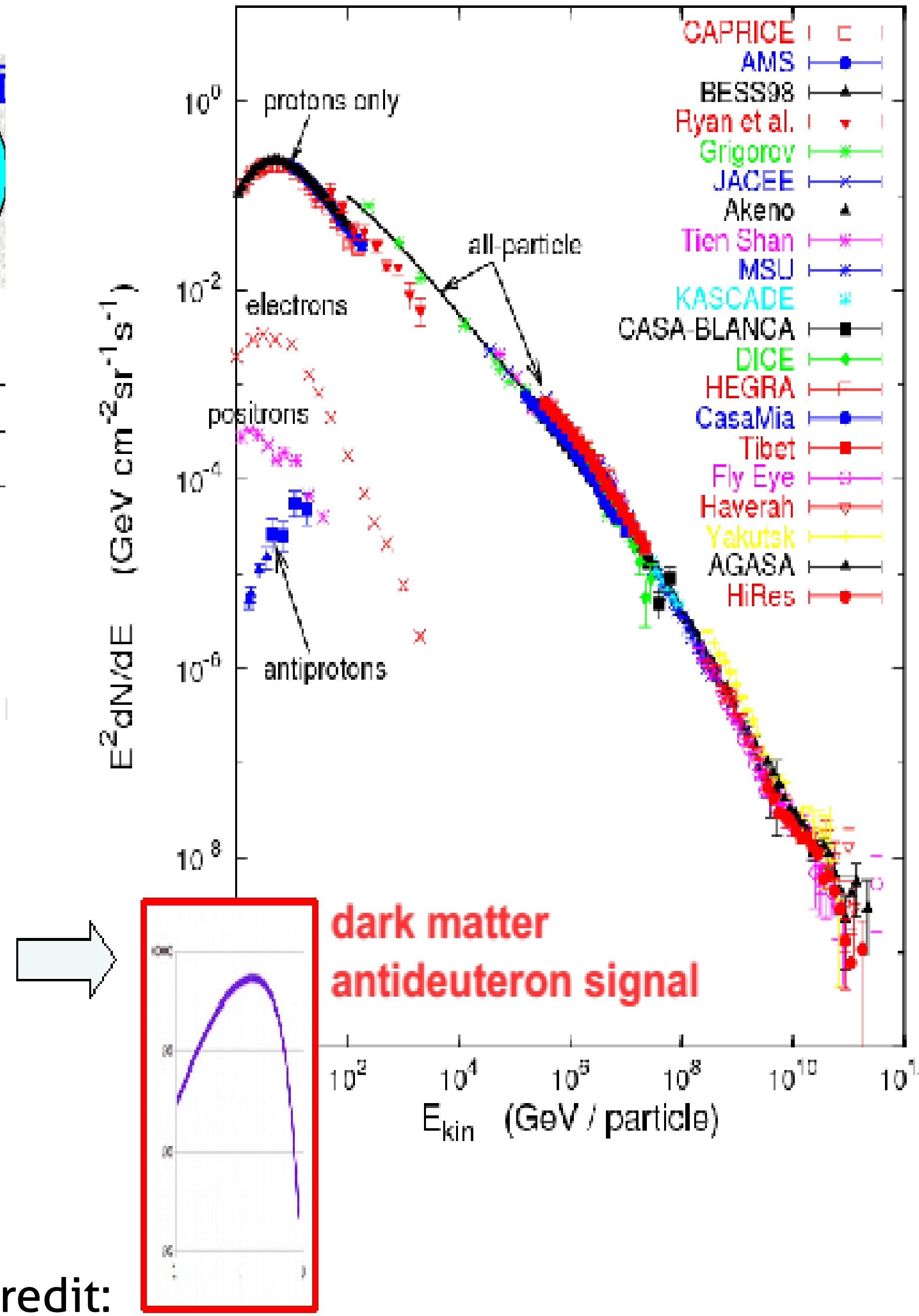
# Anti-deuterons




Detection technique based on generation of exotic atoms and observation of annihilation products.

**Anti-deuterons as indirect search channel**

- Anti-deuteron flux about 10 orders of magnitude below proton flux
- BG free channel!
- Can be sensitive to WIMP models close to thermal cross-section
- AMS-02: analysis is ongoing
- GAPS: LDB flights from Antarctica proposed to NASA




Credit:
ICRC 2015, GAPS coll., Von Doetichem

# Conclusions

- Progress on all fronts:
  - AMS-02 antiprotons
  - Dwarf limits (Fermi pass 8 & numerous new dSph candidates from DES)
  - Searches for gamma-ray lines and halo signal (HESS-I)
  - Neutrinos from Sun (IceCube IC86, Super-K and ANTARES )
- Next future
  - HESS-I & II results on gamma-ray lines and halo
  - More dSphs, improved Fermi limits
  - Antideuteron from AMS-02
- The Galactic center excess
  - Resembles impressively well a DM annihilation signal
  - Most plausible alternative explanation is MSPs (supported by searches for unresolved sources)
- Future outlook: SKA, CTA, GAPS, …