Indirect Dark Matter searches with charged cosmic rays and sub-GeV photons

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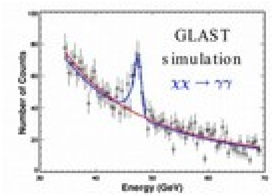
Different searches, different challenges

Number of 'control regions'

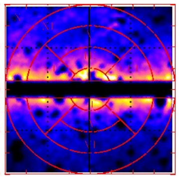
dwarf spheroidals

dark matter subhalos

gamma-ray lines, etc



extragalactic background

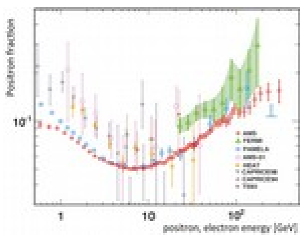


Galactic bulge/center

HARD

galactic neutrinos

anti-proton cosmic rays



positron cosmic rays

anti-deuteron cosmic rays

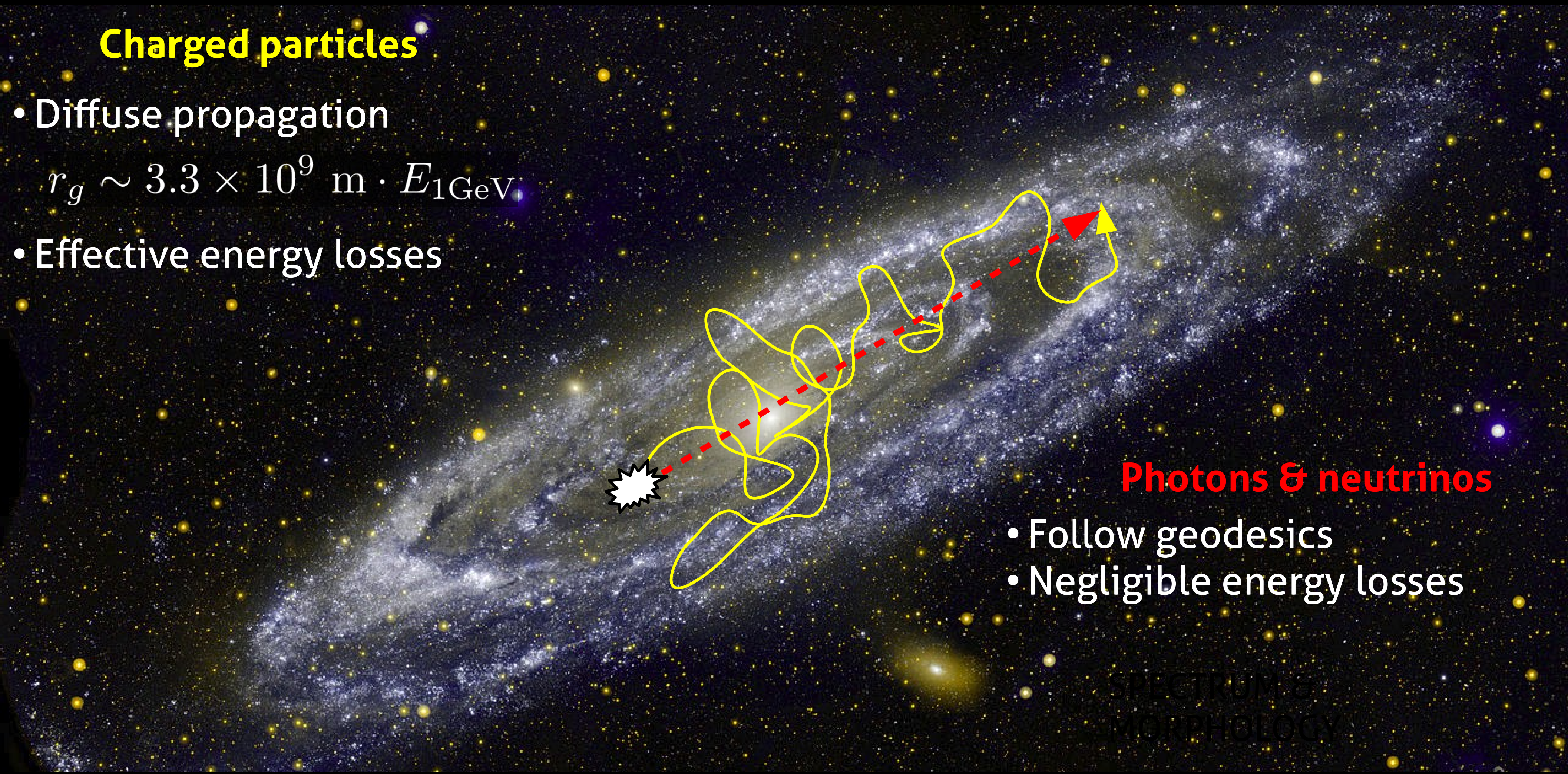
solar HE neutrinos

Background modeling complexity

Propagation of messengers from DM

Differential emissivity of DM annihilation products

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



Charged particles

- Diffuse propagation

  $r_g \sim 3.3 \times 10^9\ \mathrm{m} \cdot E_{1\rm GeV}$

- Effective energy losses

Photons & neutrinos

- Follow geodesics
- Negligible energy losses

Diffusion-reacceleration model for CR transport

D: **Diffusion parameter**
v_c: **Convection velocity**

Reacceleration

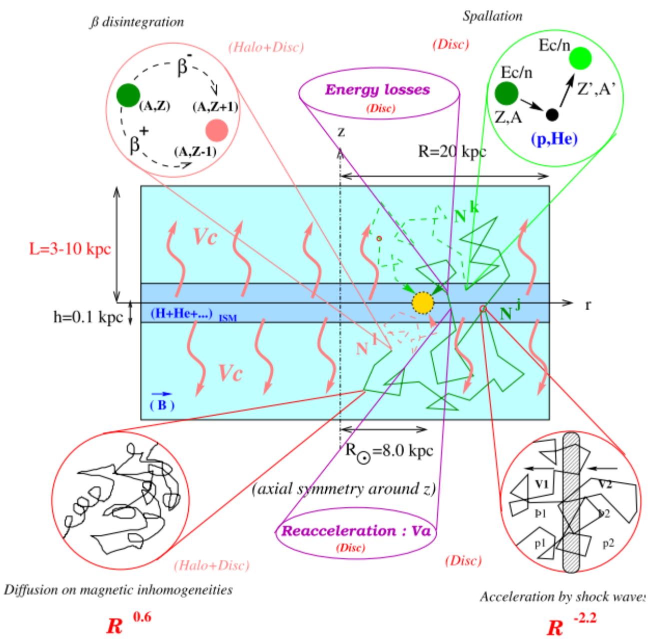
$$D(E) = D_0 \beta (\mathcal{R}/1\mathrm{GV})^{\delta}$$

$$\frac{\partial N_i}{\partial t} - \nabla \cdot (D\nabla - \boldsymbol{v}_c) N_i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot \boldsymbol{v}_c\right) N_i - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{N_i}{p^2} =$$

$$= Q_i(p, r, z) + \sum_{j>i} c\beta n_{\mathrm{gas}}(r, z)\sigma_{ji} N_j - c\beta n_{\mathrm{gas}} \sigma_i^{\mathrm{in}}(E_k) N_i \ ,$$

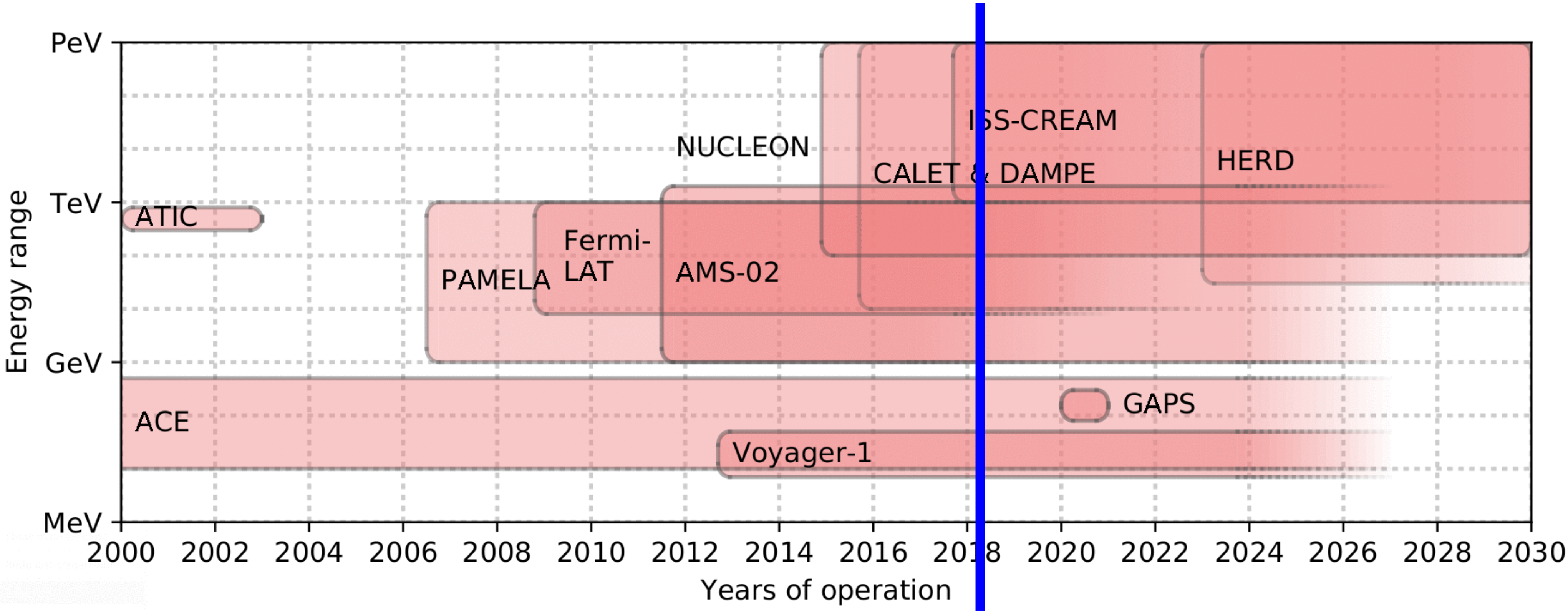
Primary sources

ISM interaction



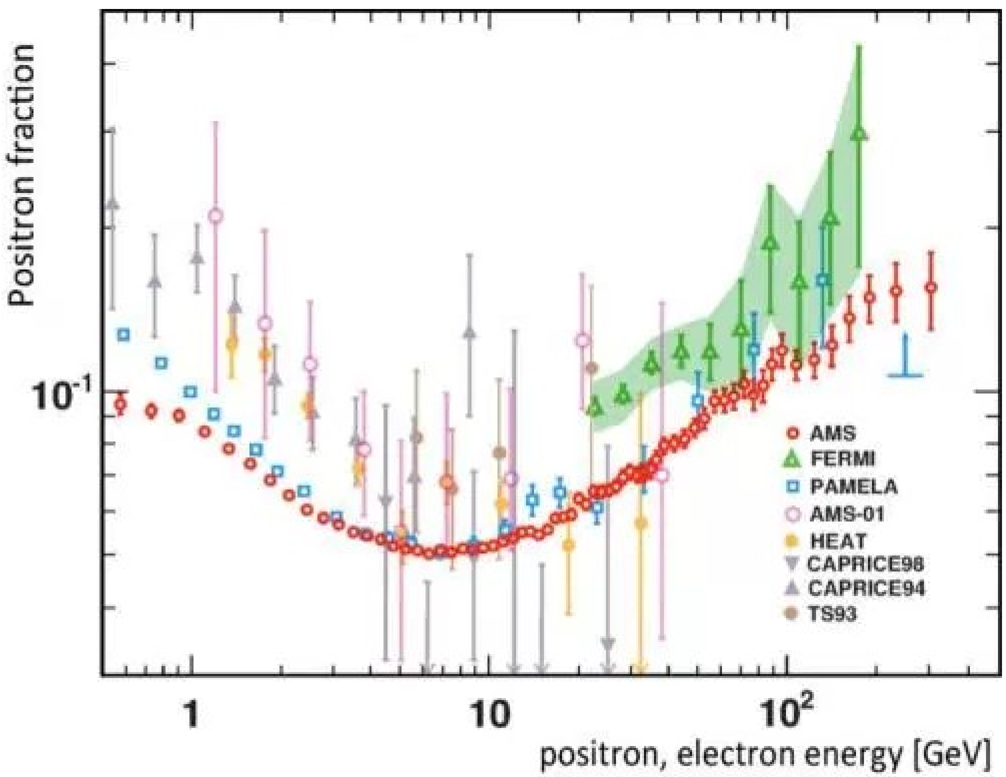
[see e.g. Evoli et al. (2012) and refs therein; Lavalle & Salati (2012); Strong, Moskalenko and Ptuskin (2007)]

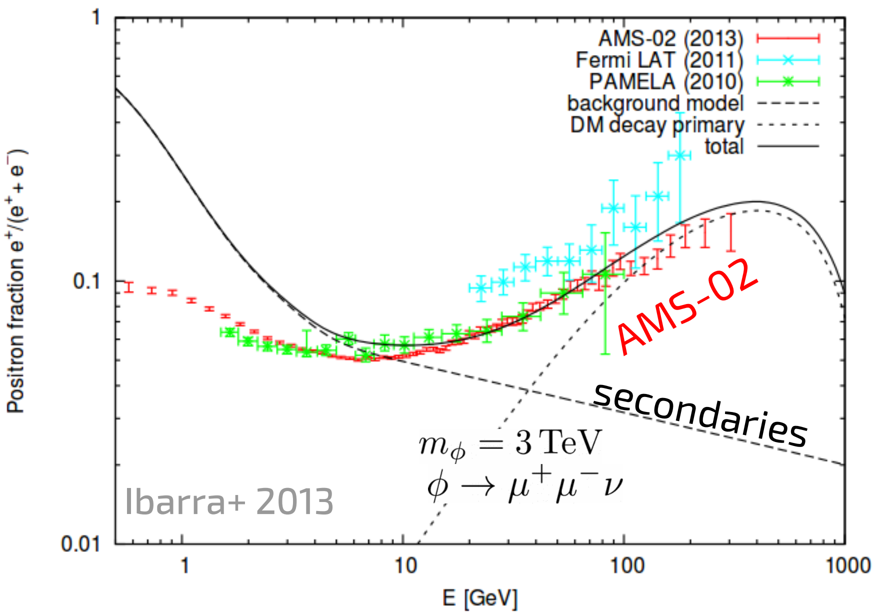
Instrumental panorama – Charged cosmic rays



- GeV – TeV: AMS-02 higher statistics, more analyses
- TeV – PeV: Various new satellite experiments will significantly improve statistics
- sub-GeV: GAPS

The CR "positron excess"

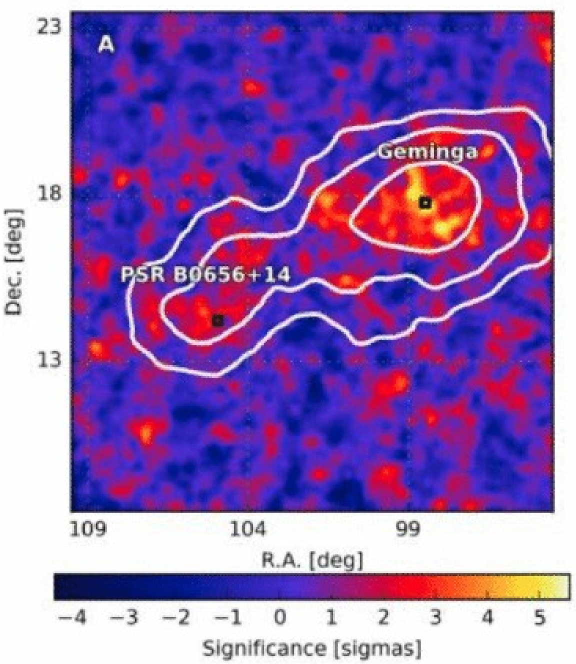


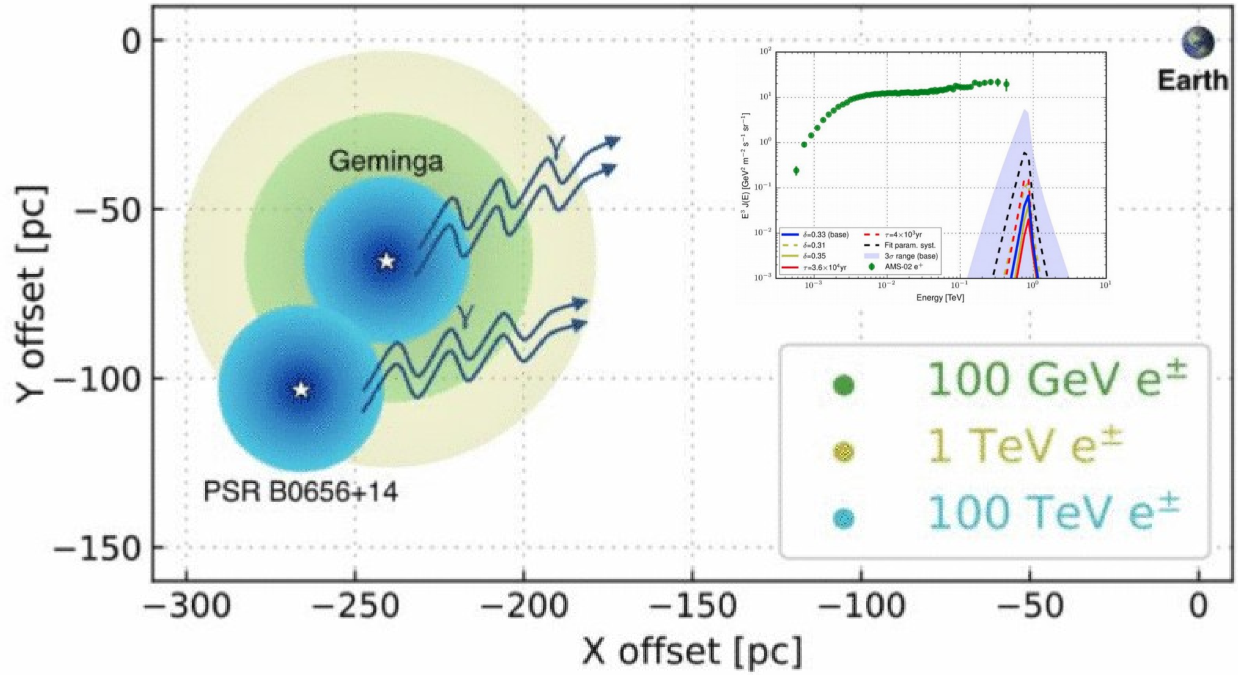


Status

- Excess above generic secondary expectations (e.g. Delahaye+ '10, Kappl & Reinert '16)
- Explaining 100% of the excess with DM is largely excluded (nothing in gamma, CMB, pbar etc) (e.g. Papucci & Strumia '10, Cirelli+ '10, Ibarra+ '13, Slatyer '15)
- Pulsar origin is possible, but also, e.g., microquasars, SNRs (secondary production in primary sources), dark matter, …

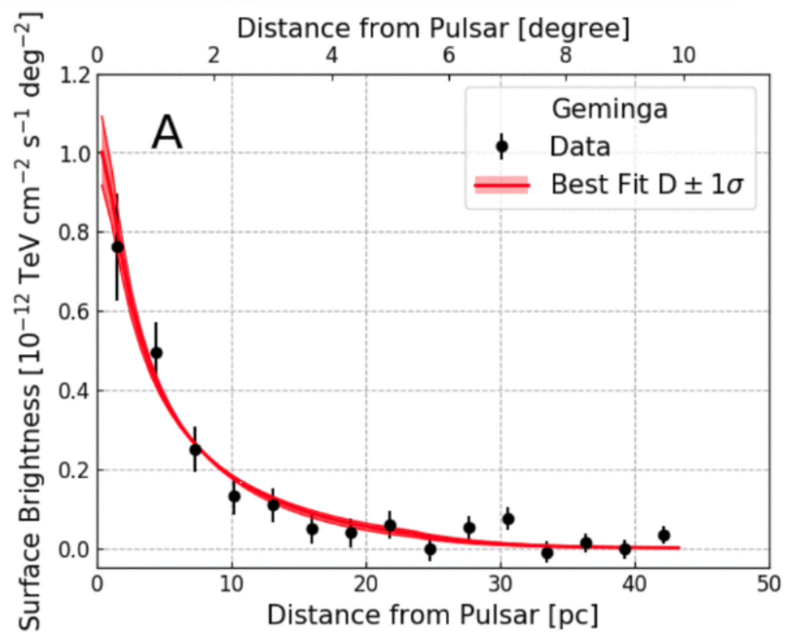
Do pulsars contribute to the positron excess?



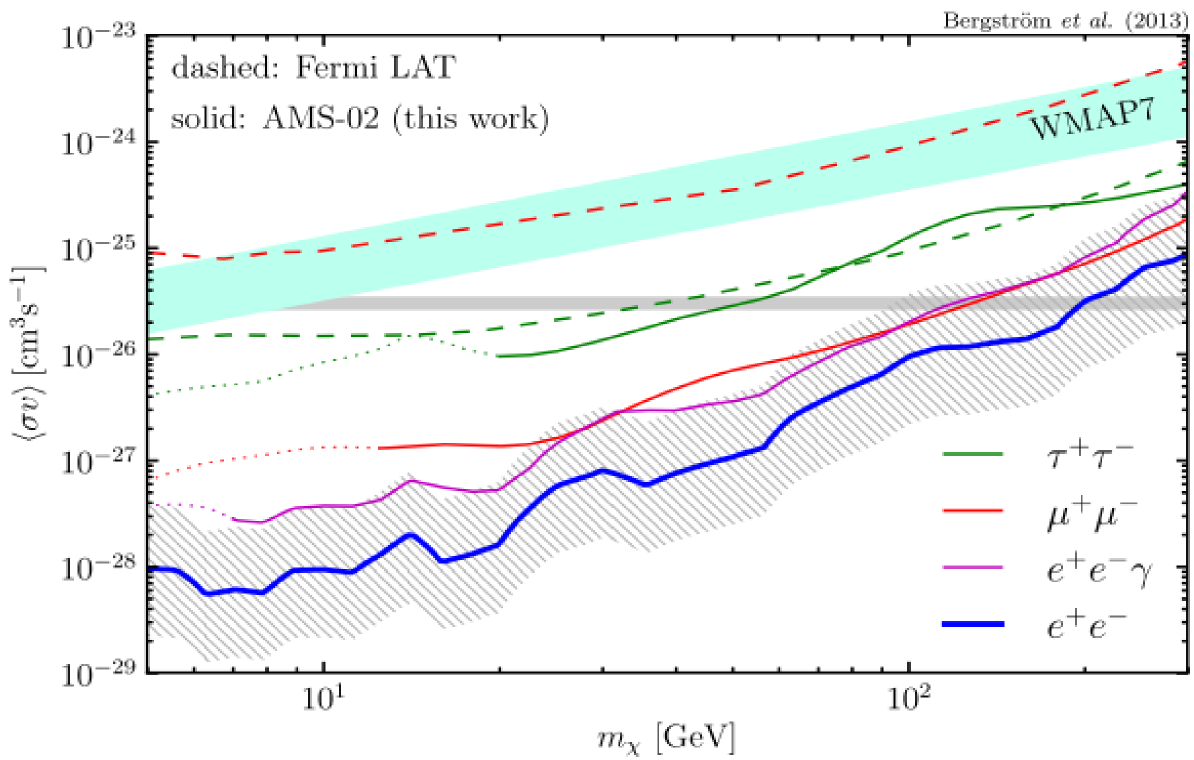


HAWC observations of Geminga and PSR B0656+14 (Monogem)

- Observations of compact TeV emission halo → extremely low diffusion coefficient (x100 times lower than from B/C) → Monogem/Geminga do not contribute to positron excess
- But: last step relies on adopting low diffusion coefficient for entire (local) ISM, which seems to be in conflict with general observation of ~10 TeV electrons (Hooper & Linden 17, see also Lopez-Coto & Giacinti 17)



No spectral features in positron flux

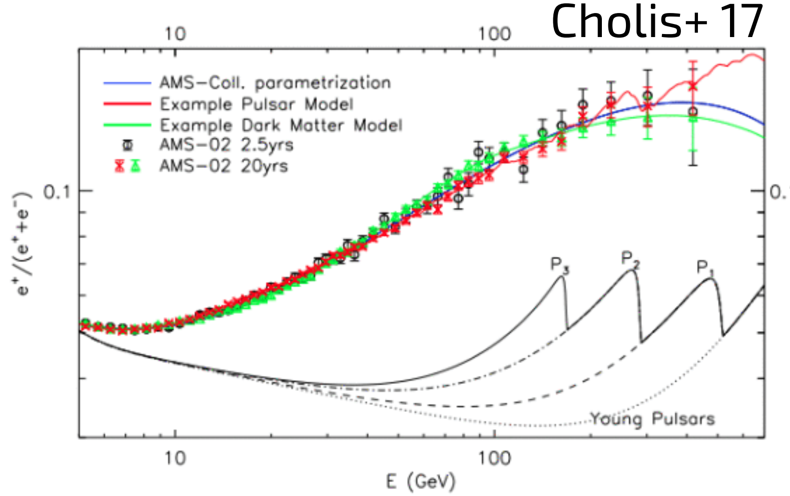


AMS-02 positron spectrum rather smooth

- strong upper limits on light DM annihilation from non-observation of spectral signatures in positron flux

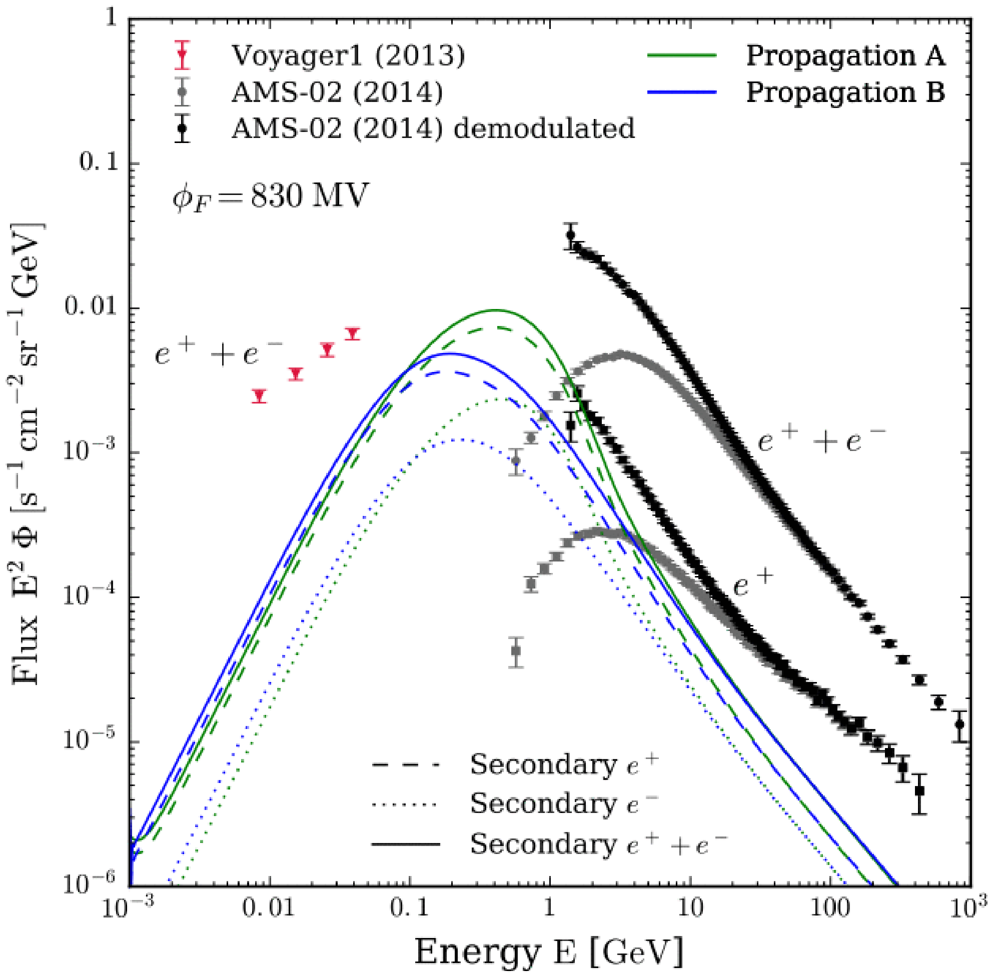
BBCHW 2013, Ibarra+ 2013

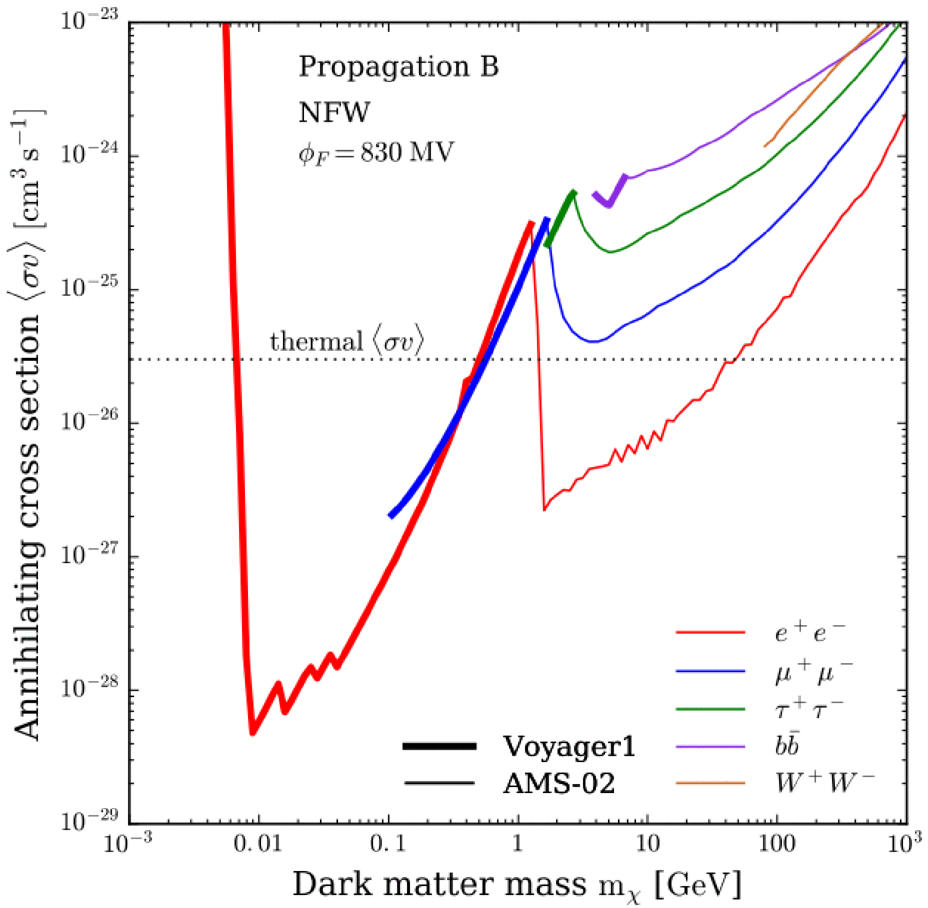
Cholis+ 17



Pulsar-related wiggles in positron spectrum can potentially be detected in AMS-02 (10 yrs) or DAMPE (3 yrs) data (Cholis+ 17).

sub-GeV electrons from Voyager-1

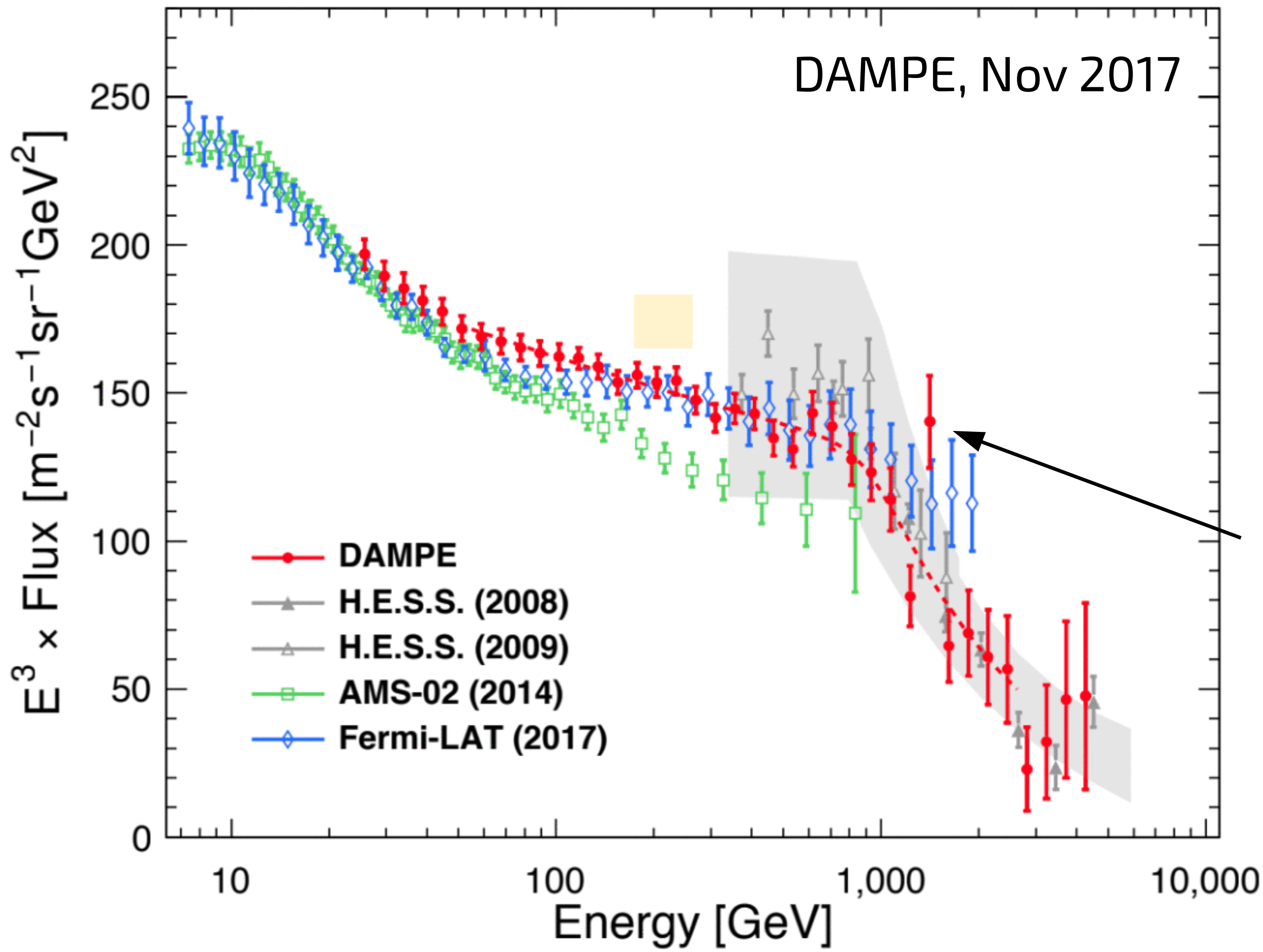




- Voyager 1 crossed heliopause 2012
- Measured electron+positron spectrum unaffected by solar modulation
- → Limits on MeV DM annihilation (for p-wave annihilation stronger than CMB)

Boudau+ 17

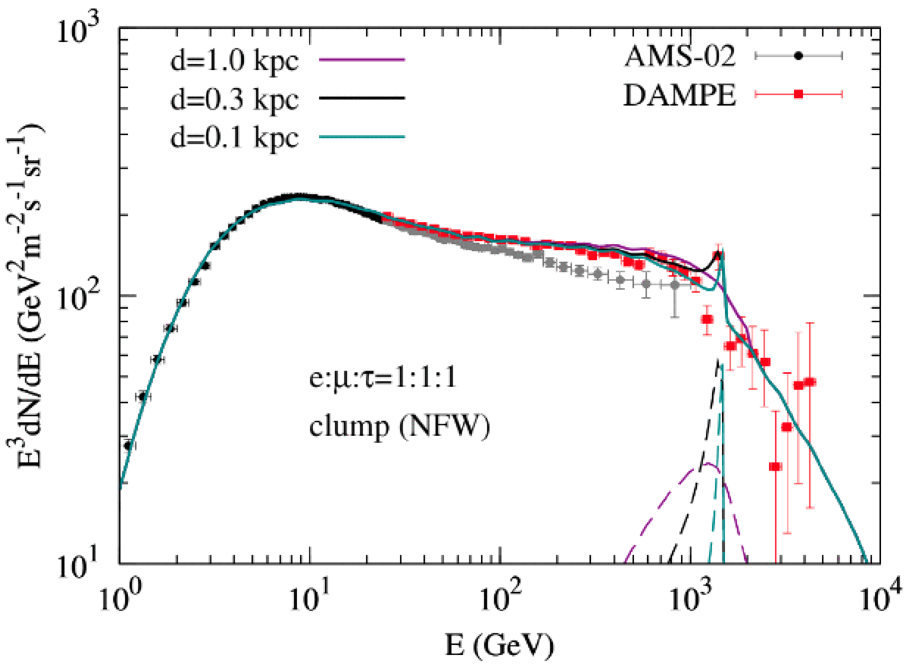
Positrons + electrons with DAMPE



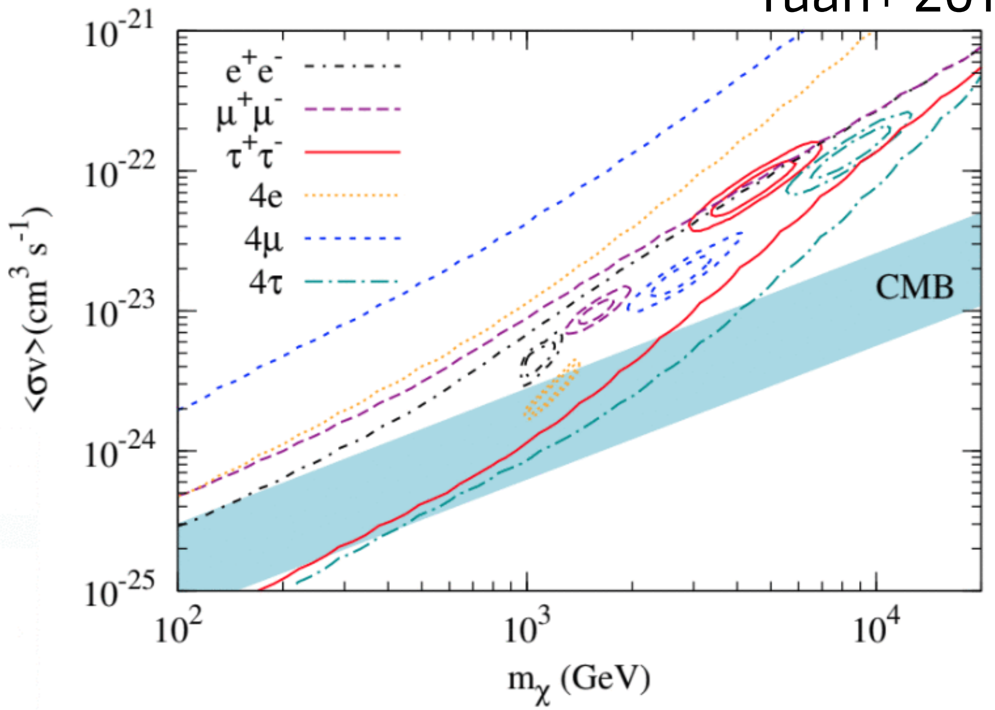
1.4 TeV line?
2.3 global significance
(Fowlie 2017)

- Spectral break measured by HESS clearly confirmed
- A suggestive peak at 1.4 TeV (~3 papers/week)
- Energy resolution is better than 1.2% @ > 100 GeV

Interpretations of DAMPE result



Yuan+ 2017



Interpretations of the 1.4 TeV feature

- Statistical fluctuation
- Cold, ultra-relativistic e+e- pulsar wind
- DM annihilation into monoenergetic e+e- pairs. This requires local (< 1 kpc) DM clump to switch off effects of cooling which would distort spectrum. Very small probability that such a clump is there (VL).

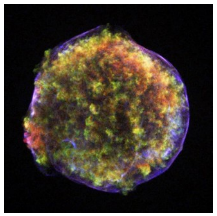
Interpretations spectral cutoff

- Dark matter annihilation (TeV masses, the usual very large cross-sections)
- Maximum acceleration limits of sources

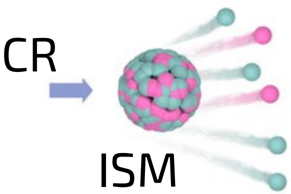
See also: Athron+ 17, Duan+ 17, Fan+ 17, Gu 17 (also 3.5 keV line!), Yang+ 17, many others

The “grammage” matters

Two sources for cosmic rays

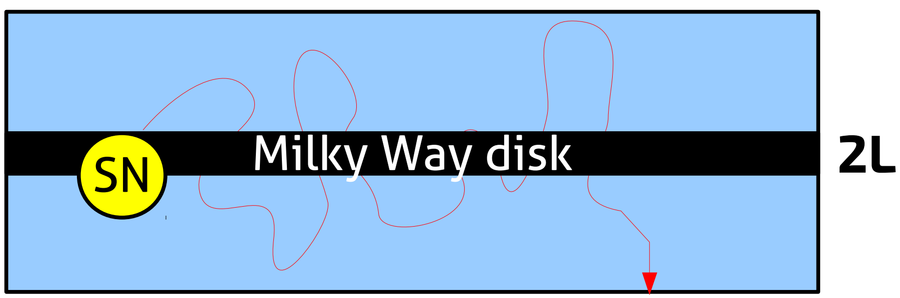


Primary cosmic rays from supernova remnants (likely)

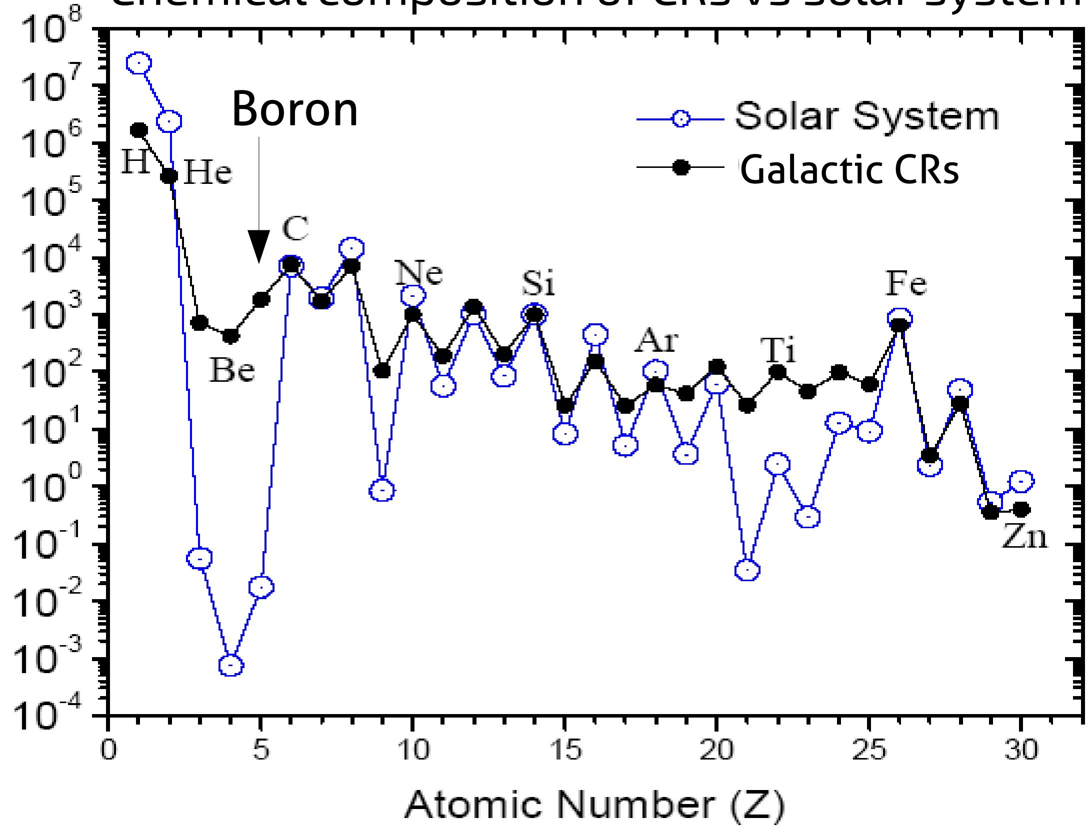


Secondary cosmic rays from spallation etc

Diffusion in a box



Chemical composition of CRs vs solar system



Total grammage

(column density along propagation path)

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

Input: Boron/Carbon ration $\quad n_B \sim n_C \sigma(C \to B) \cdot G_{\rm total} \Rightarrow G_{\rm total}$

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

Leaky box & spectral indices

Diffusion and escape:

$$\frac{dN}{dt} = \dot{Q} - \frac{N}{\tau_p}$$

Diffusion distance

$$\langle x \rangle \simeq \sqrt{6D\tau} \sim L$$

L: Extend of diffusion region

Implied escape time

$$\tau_p \sim \frac{L^2}{6D}$$

Spectrum of primaries: $\mathscr{R} = \mathbf{p}c/Ze$ is rigidity

$$\dot{Q} \propto \mathcal{R}^{-\gamma}$$

Source spectrum

$$D \propto D_0 \mathcal{R}^{\delta}$$

Diffusion parameter

$$N_{\rm prim} \propto \frac{L^2}{D_0} \mathcal{R}^{-\gamma-\delta}$$

Steady state solution

Spectrum of secondaries:

$$\dot{Q}_{\rm sec} \propto N_{\rm prim}/L$$

$$N_{\rm sec} \propto \frac{L^3}{D_0^2} \mathcal{R}^{-\gamma-2\delta}$$

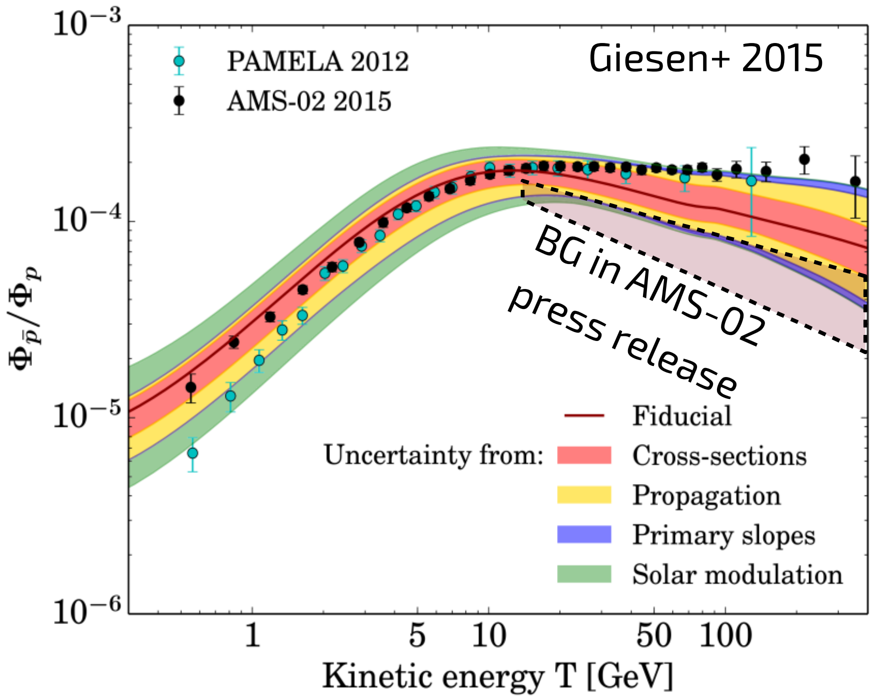
$$\frac{N_{\rm sec}}{N_{\rm prim}} \propto \frac{L}{D_0} \mathcal{R}^{-\delta}$$

Consequences

Secondary-to-primary ratios probe *slope* and *normalization* (times 1/L) of diffusion parameter

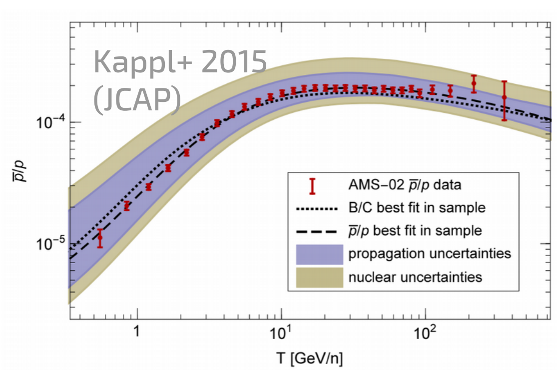
AMS-02 anti protons – ~100 GeV

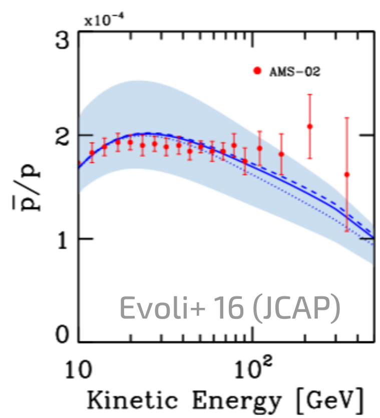
Hadronic annihilation/decay channels contribute to cosmic-ray anti protons. No clear excess is observed above backgrounds



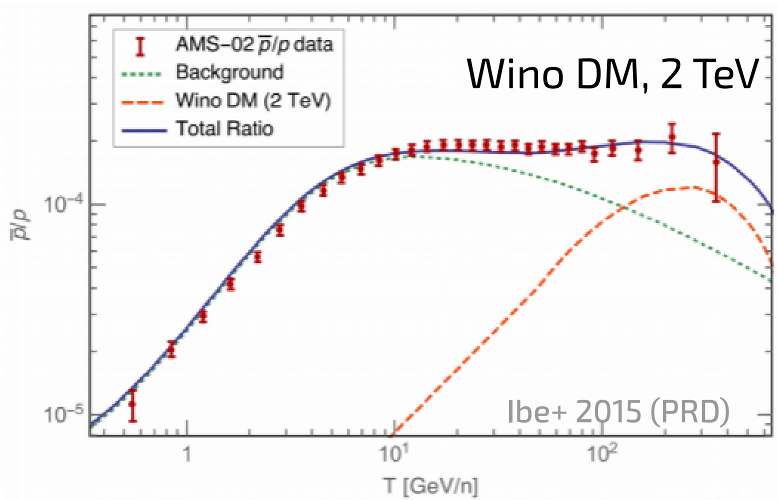
Situation

- Background of secondary anti-protons can be predicted within factor of a few
- Measurements marginally consistent with secondary background (Giesen+ 15; Evoli+ 15)
- Hard to exclude astro explanation for excesses above secondaries (e.g. nearby SNR; e.g. Kachelriess+ '15, non-universal diffusion, etc)

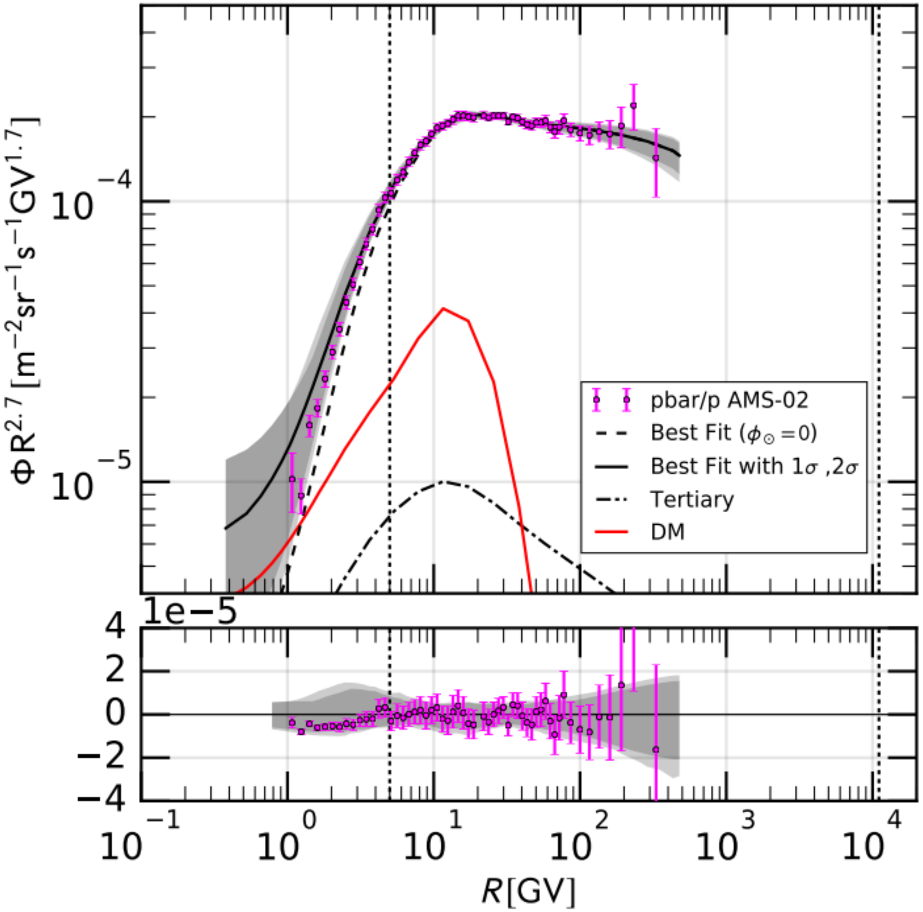


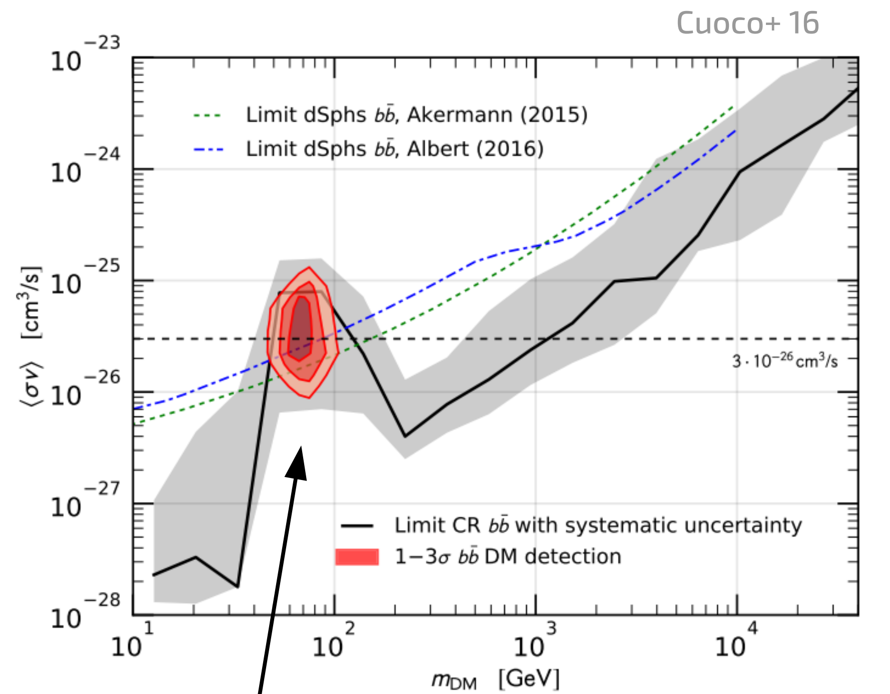


But: DM fit is possible



AMS-02 anti-protons - ~ 10 GeV



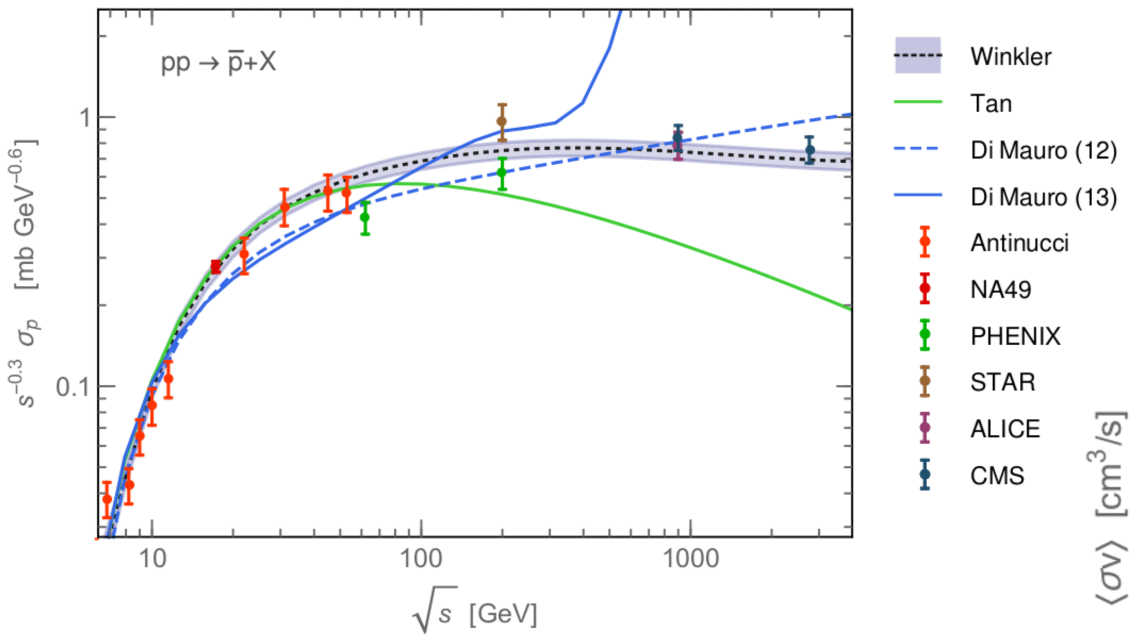


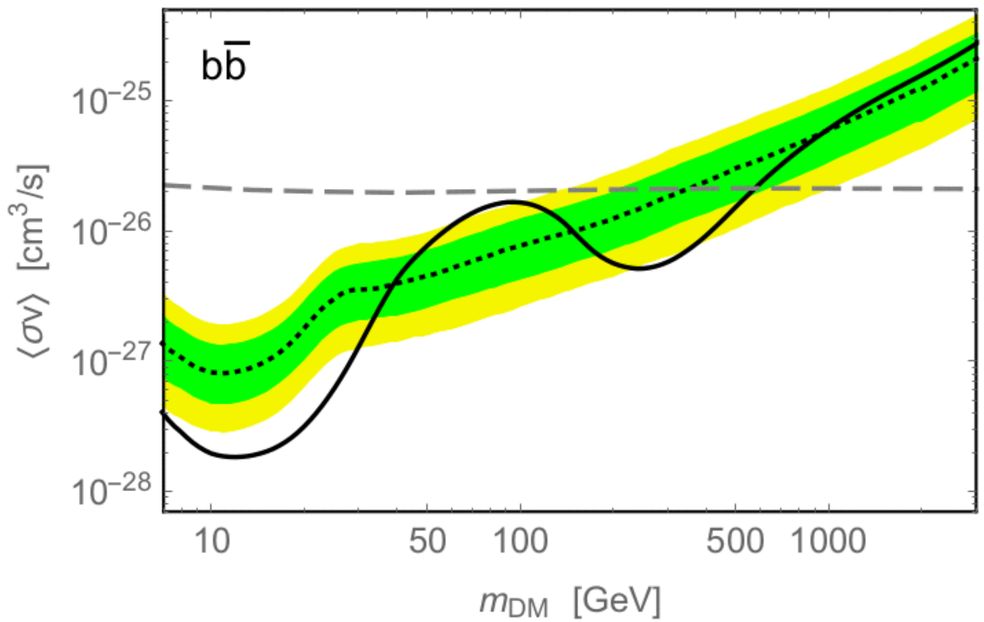
Indications for an excess around 10 GeV (Cuoco+16, see also Cui+ 16)

- Formally ~5 sigma preference for DM contribution, mass & flux compatible with GCE
- But: Simple propagation scenarios are insufficient to explain *all* CR data (and DM does not help) → Extraction of reliable limits or signal becomes a huge challenge

See also: Winkler+ 17; Carlson+14; Cirelli+14; Jin+15; Ibe+15; Hamaguchi+15; Lin+15; Kohri+15; Balazs&Li15; Doetinchem+15; Fornengo+13

Effect of various systematic uncertainties





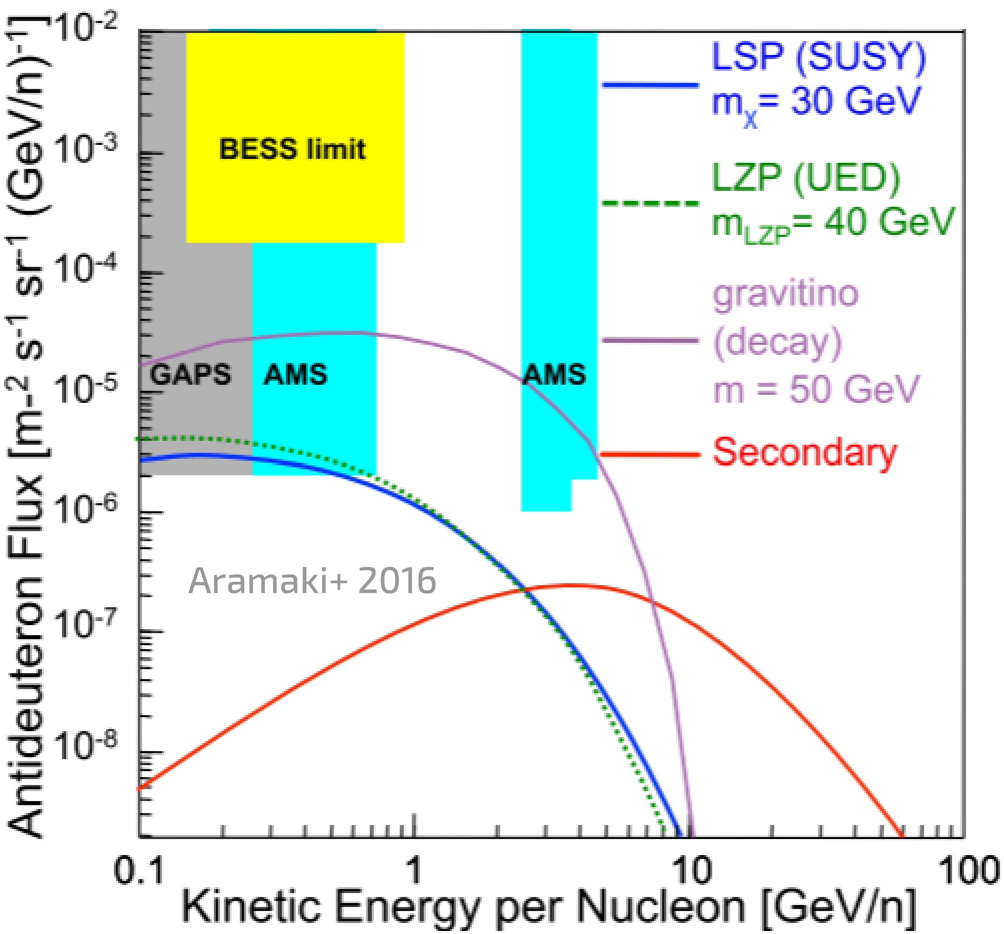
Accounting for covariances of various systematics (Reinart & Winkler 2017)

- Refitting nuclear spallation data for Boron production from Carbon, Oxygen, Nitrogen, etc
- Charge-dependent solar modulation
- Refitting primary cosmic ray measurements
- → Reasonable fit to B/C and pbar data with universal diffusion-reacceleration model
  → Significance for ~80 GeV DM contribution drops to below 2 sigma
  → Very strong limits on DM annihilation at low and higher DM masses

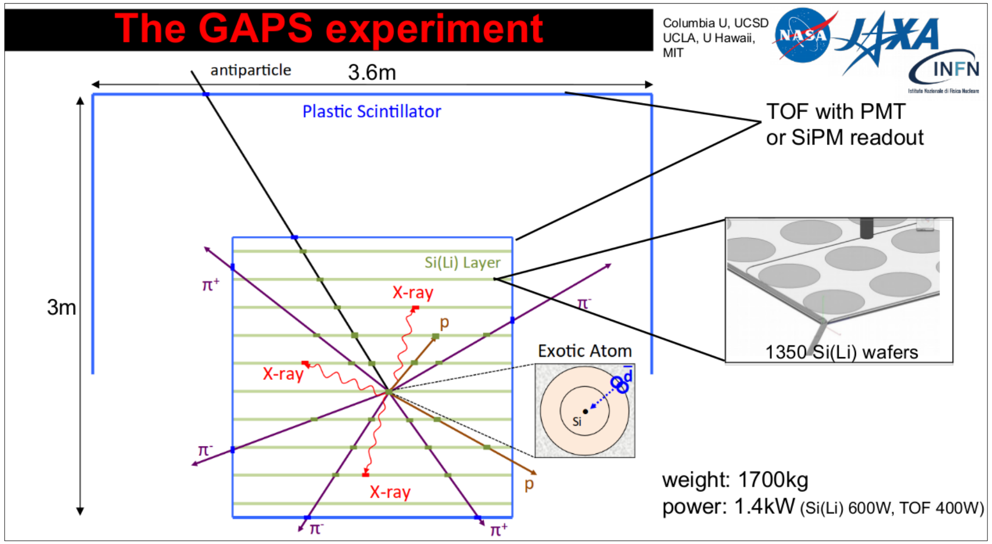
General AntiParticle Spectrometer (GAPS)

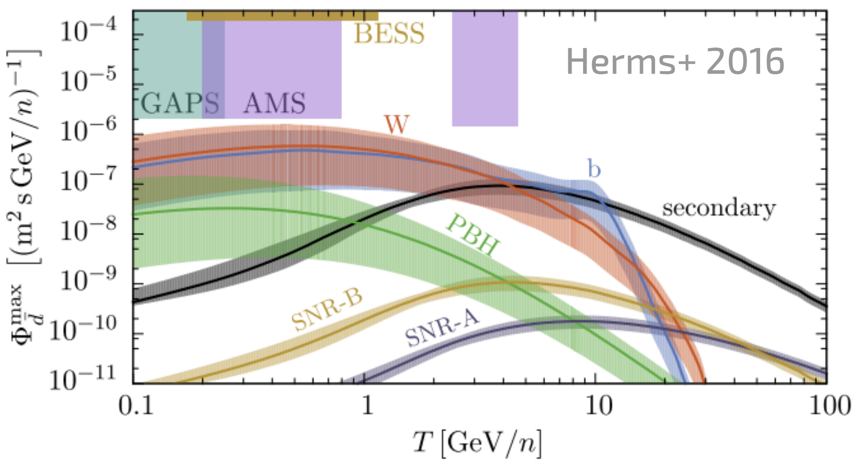
Searches for **anti-deuterons** with exotic atom formation

Funded by NASA & JAXA. First flight planned for ~2020.



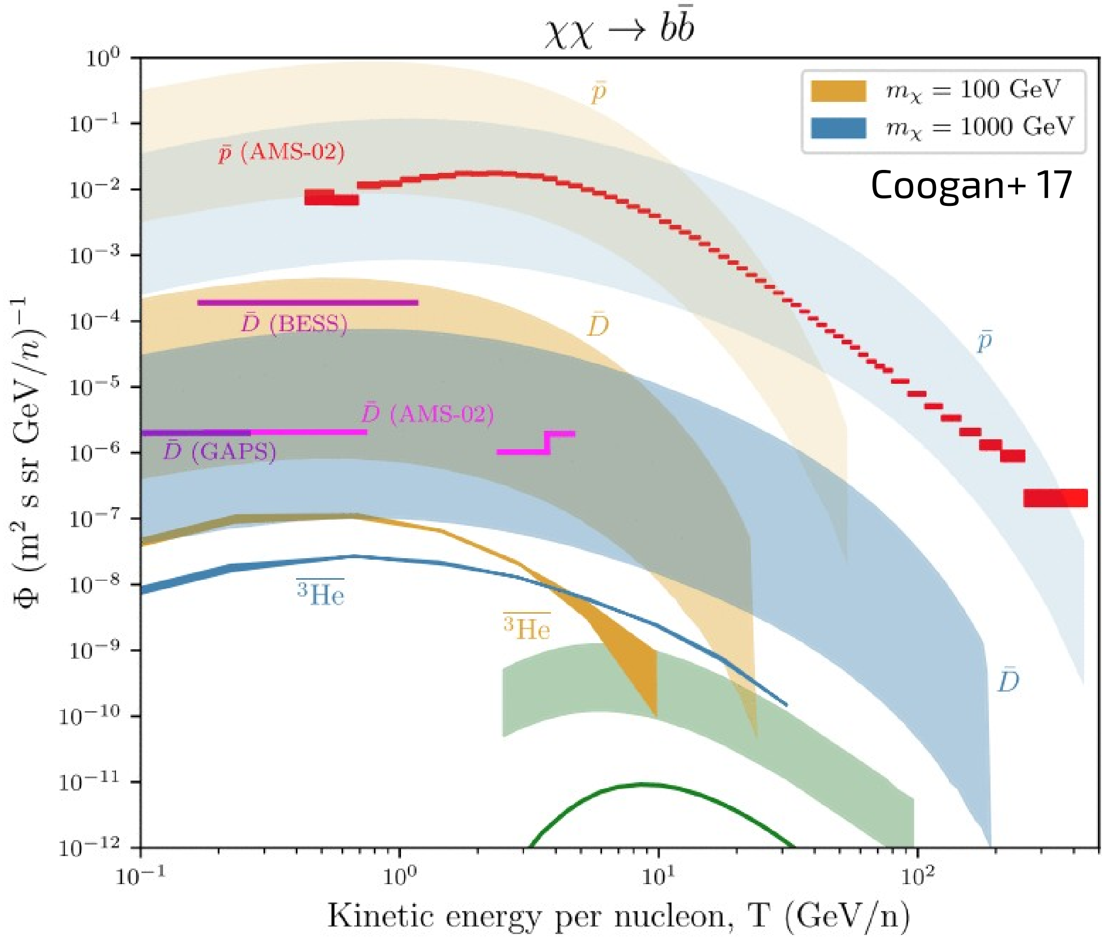
Credit: P. von Doetinchem

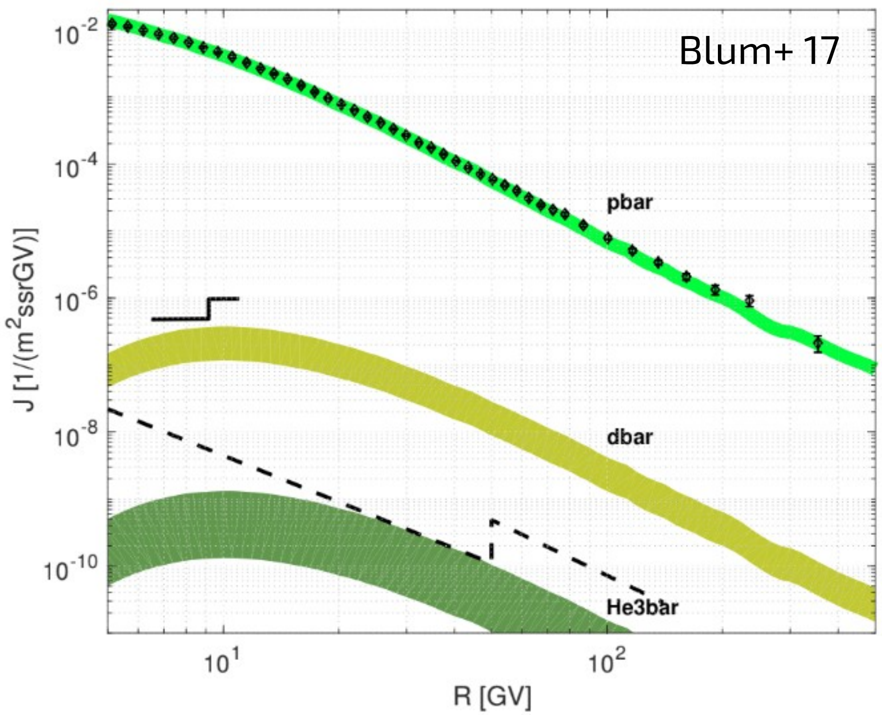




Sever constraints on the range of detectable models comes from AMS-02 anti-protons.

Dark matter searches with anti-^{3}He



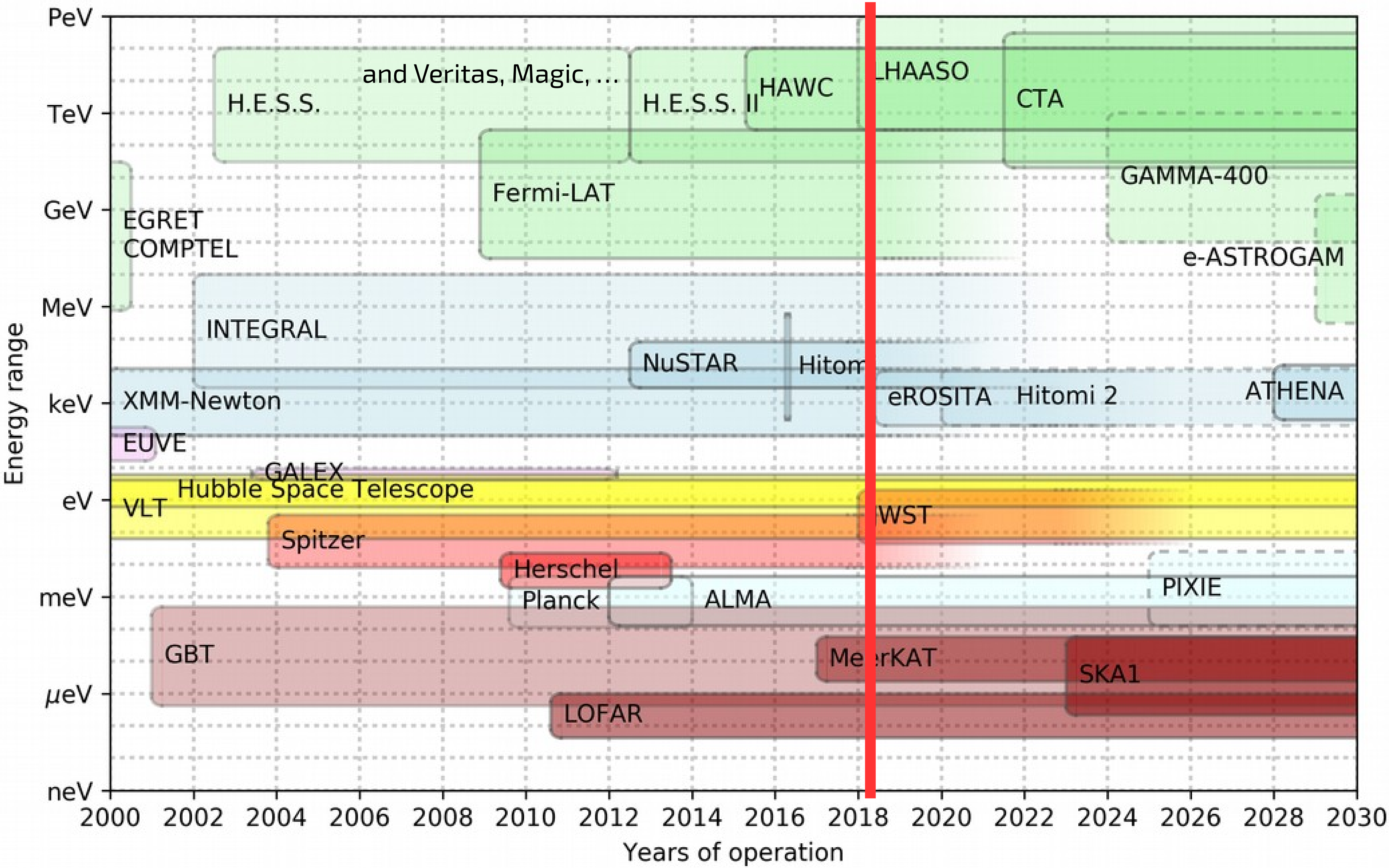


Ong+ 17; Blum+ 2017; Coogan+ 2017

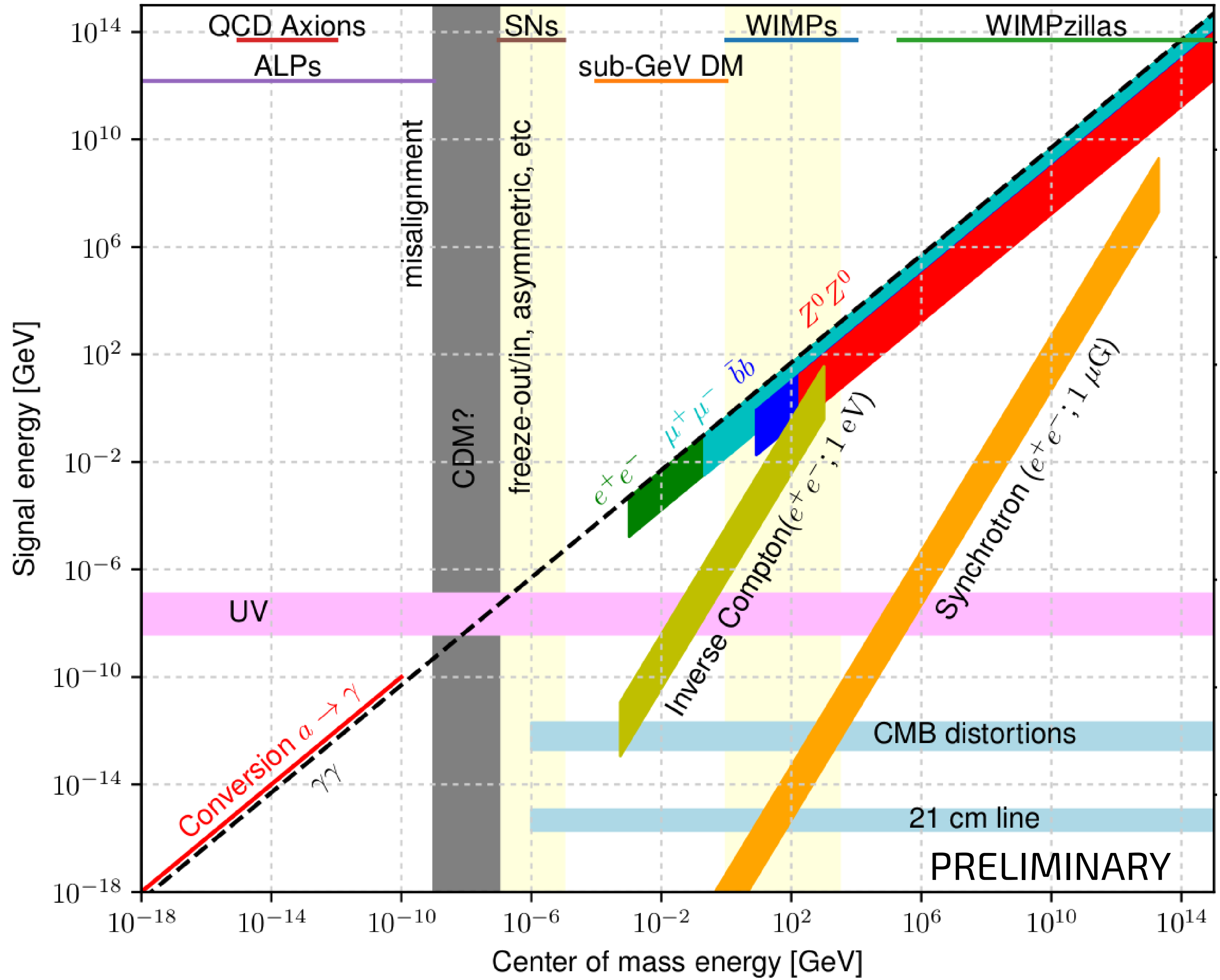
Searches for anti-^{3}He

- Recently considered by Carlson+ 14, Cirelli+ 14
- Smaller rates than anti-deuteron signal, but thought to be even cleaner than anti-deuteron
- However, new estimates indicate secondary anti-^{3}He background might be larger and in reach of AMS-02 (Blum+ 2017)
- Ting (Dec 2016 CERN): Few ^{3}He candidates in AMS-02 data, will take years to confirm
  → Secondary? Dark matter?

Instrumental panorama – Photons



DM center of mass energy → Photon energy



CSW, in prep

UHECRs

Gamma rays

X rays

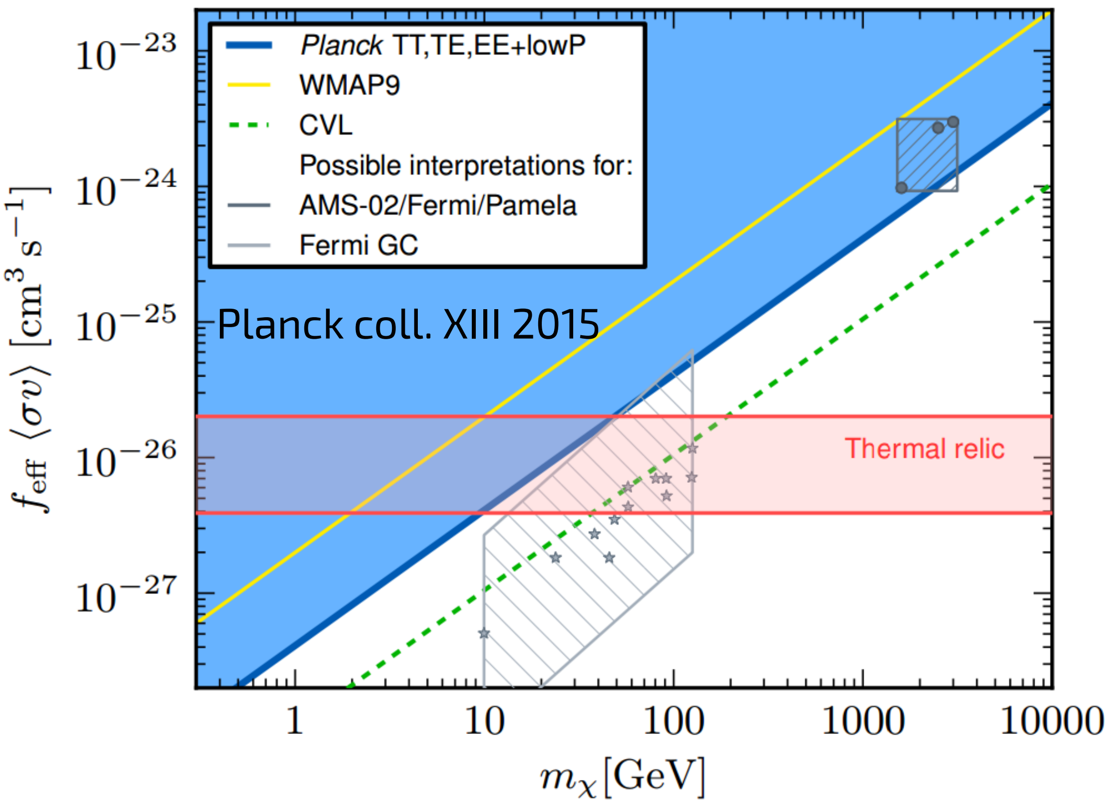
UV

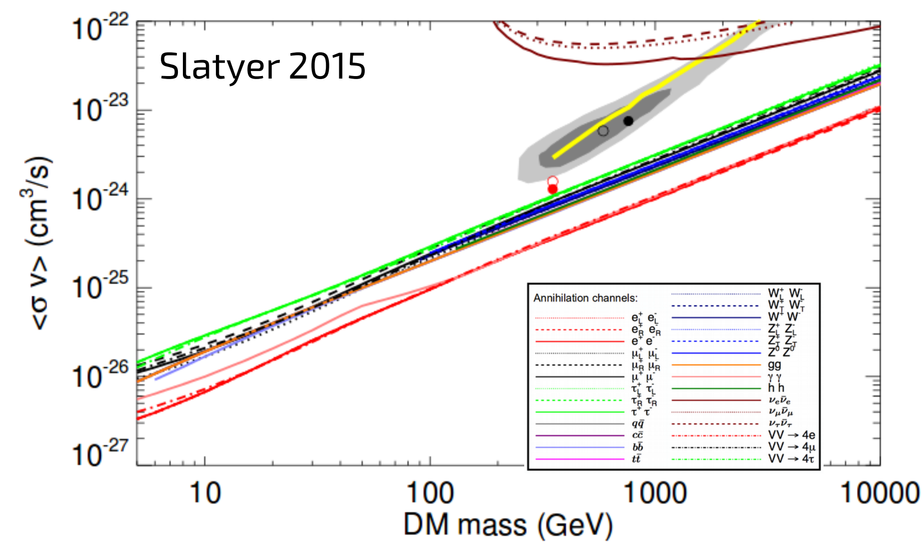
Optical/IR

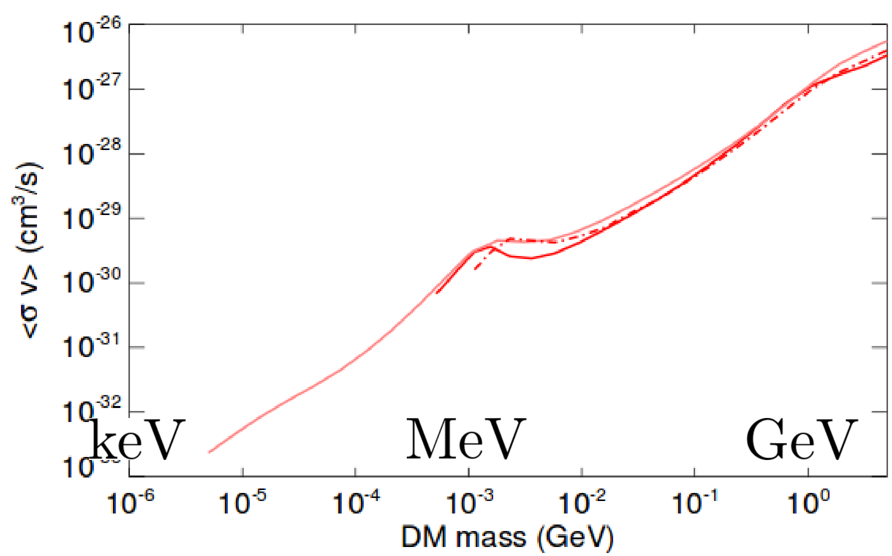
CMB

Radio

Bounds on DM from Planck observations







Status

- Bounds depend on effective energy deposition (f_{eff}), otherwise *very* robust
- Exclude s-wave annihilation below m~10 GeV unless annihilation into neutrinos dominates

$$\langle\sigma v\rangle \lesssim (1-4)\times 10^{-27}\left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)\mathrm{cm^3\,s^{-1}}$$

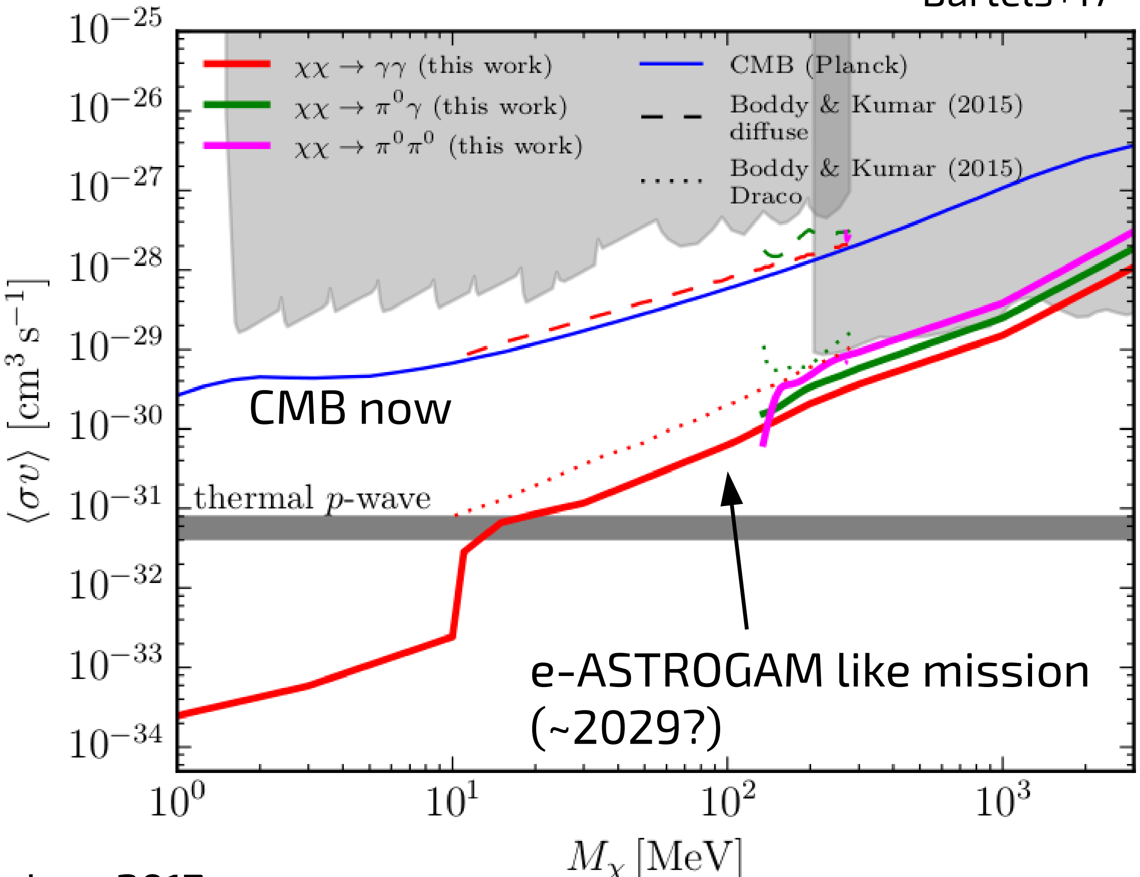
see also Ali-Haimoud+15; Liu+16; Chluba+16; Cline&Scott 13; Galli+13; Madhavacheril+13

The MeV – GeV sensitivity gap

Situation

- Spectral features play an important role for DM annihilation/decay at low energies (e.g., Boddy & Kumar, 15)
- Any of the proposed future missions (e-ASTROGAM, AMEGO) are expected to have very good energy resolution, greatly improving DM search prospects
- For leptonic channels, in-flight annihilation plays an important role (Bartels+ 17)

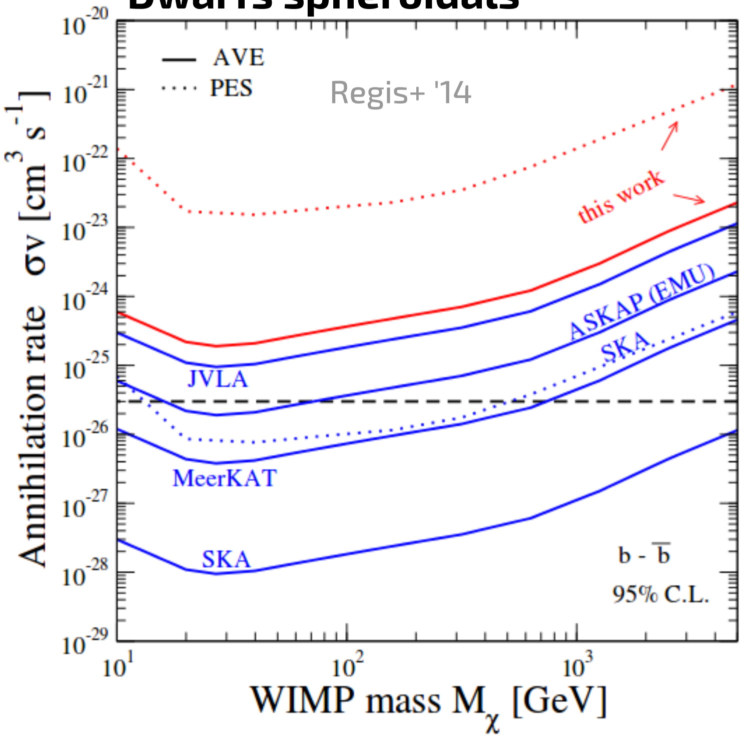
Bartels+17

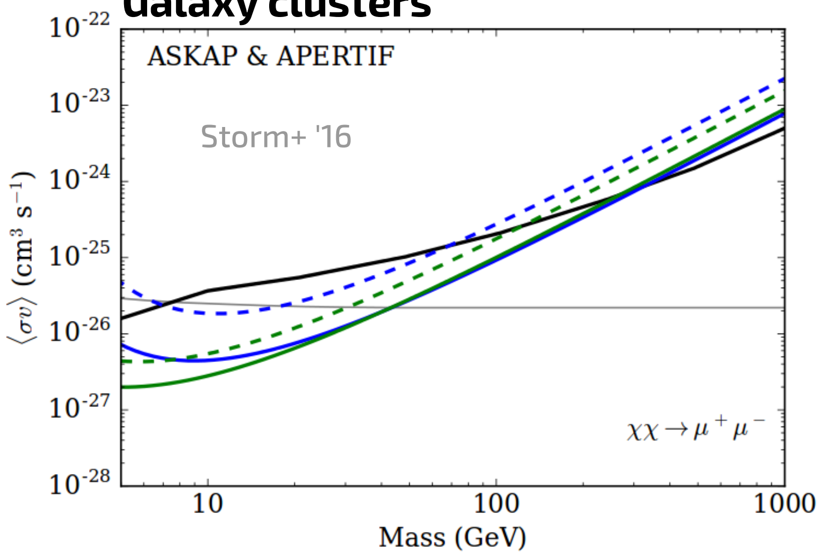


See also: Gonzales-Morales+ 2017

Radio searches for WIMP dark matter

CR electrons/positrons from DM generate **synchrotron radiation in radio**



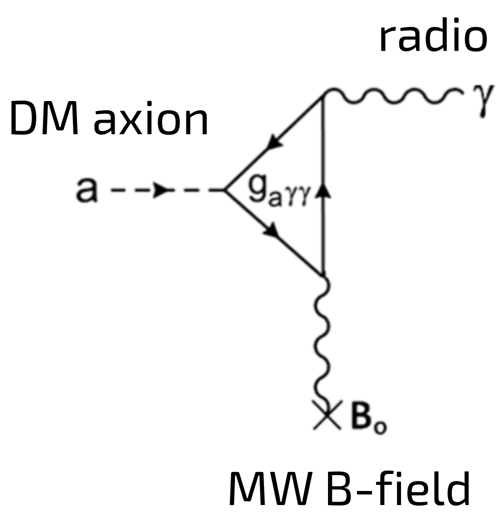


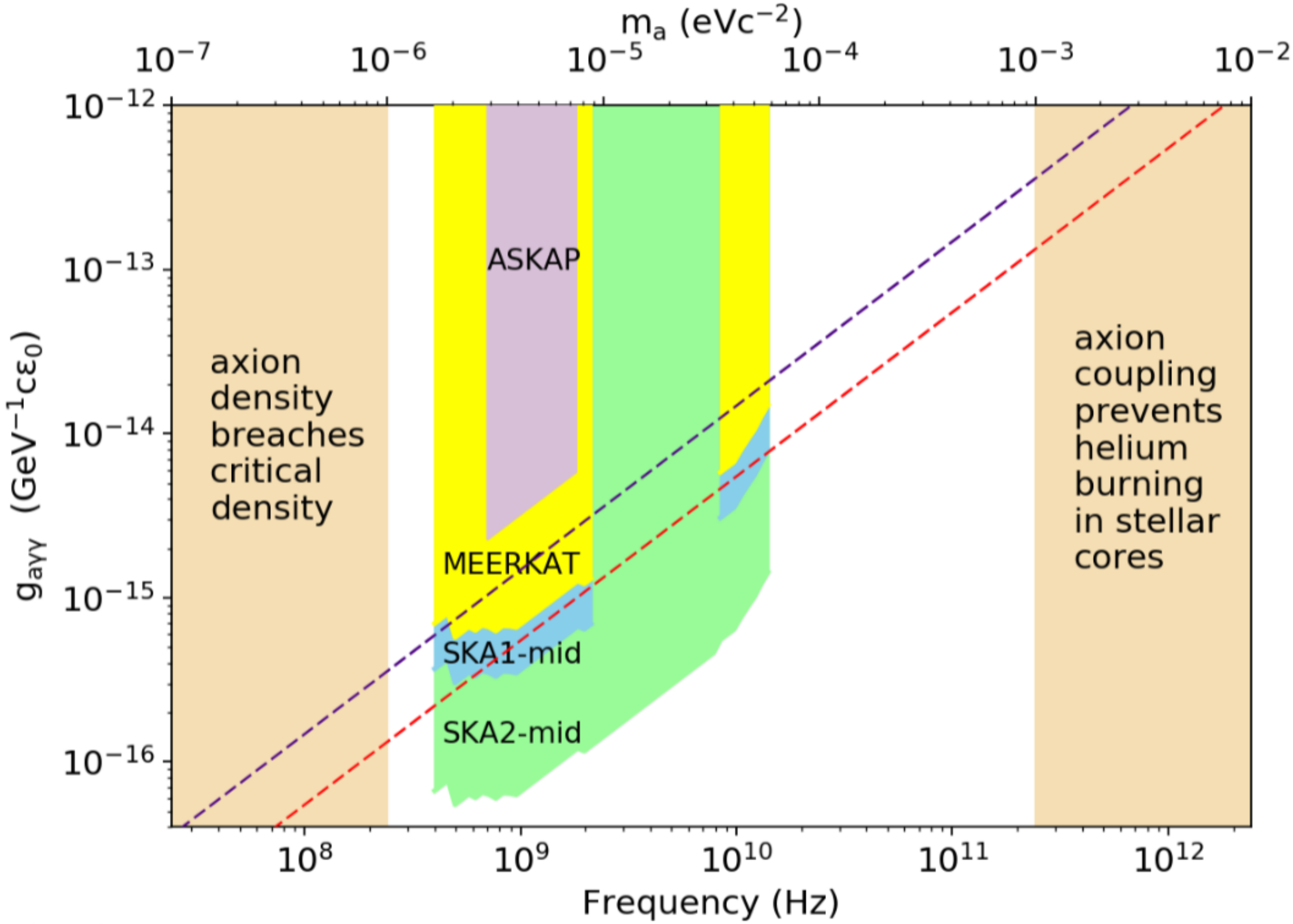
Bright future for radio astronomy

- Several new and upcoming telescopes (LOFAR, MeerKAT, ASKAP, SKA, …) improve current sensitivities by several orders of magnitude
- Prospects for WIMP searches *might* be excellent
- Turbulent and regular B-fields need to be better understood

see also: Crocker+10; Linden+11; Fornengo+11; Valdes+12; Storm+13; Spekkens+13; Bringmann+14; Cholis+14; Evoli+14; Tashiro+14; Fang&Linden 15; Cirelli&Taoso 16

Axion DM conversion in MW B-field?





Flux **very** uncertain: Need to know turbulence of Galactic B-field at meter scale...

$$\Gamma \propto |B(k = m_a)|^2$$

Kelley & Quinn 2017

Radio searches for bulge MSPs

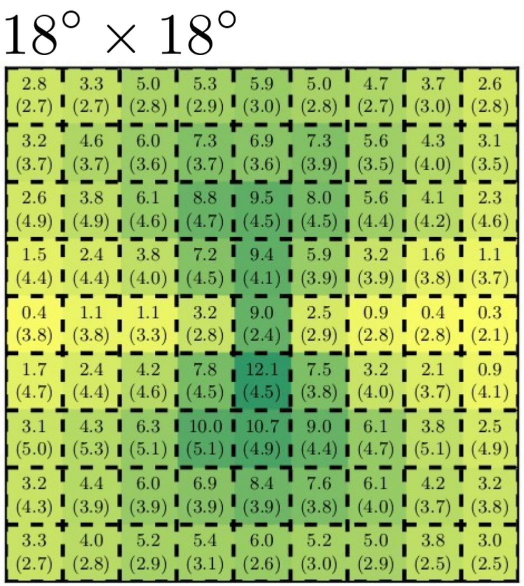
Radio detection prospects (CDDHW 16)

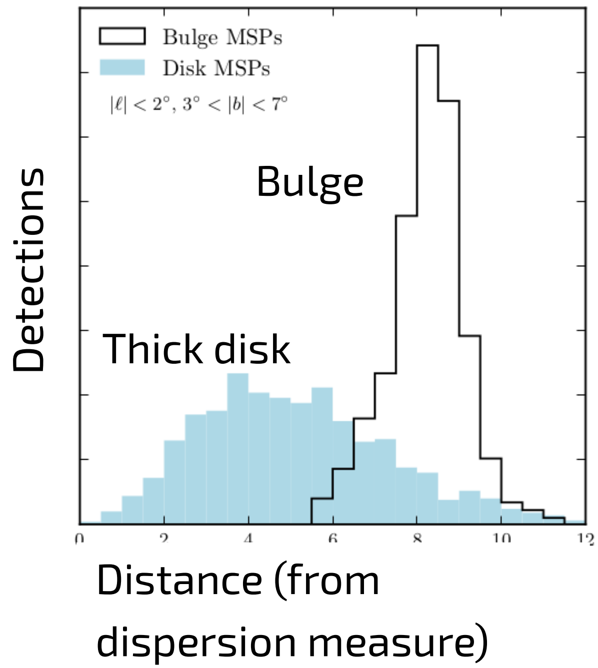
(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

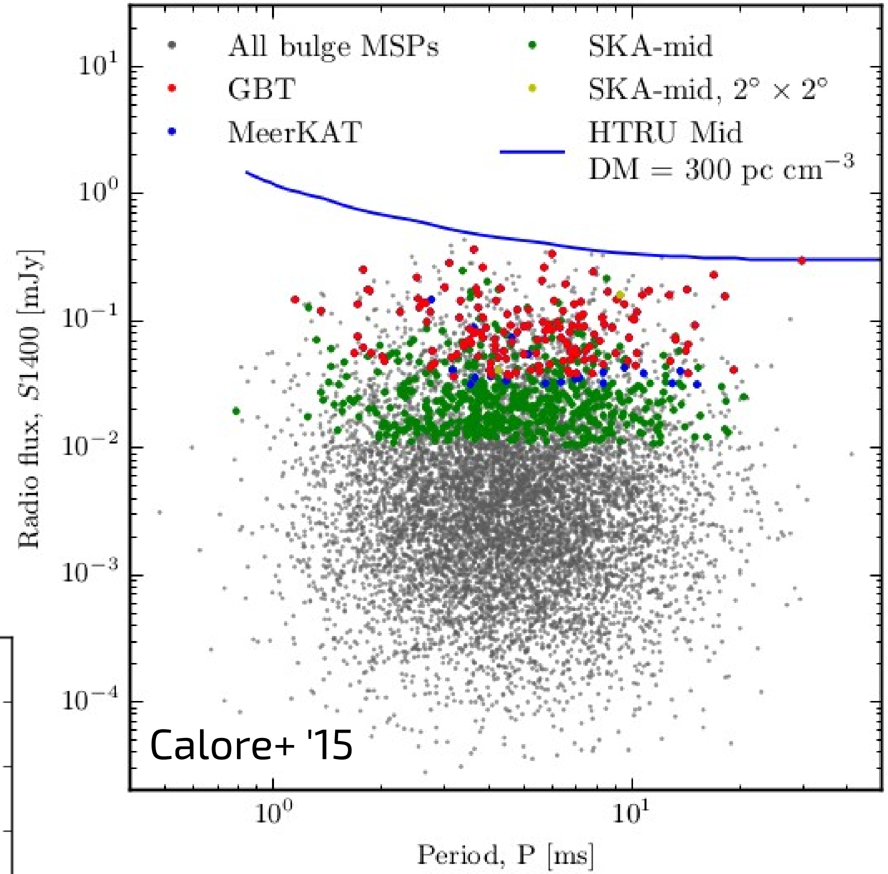
- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Our plans for the near future

- We teamed up with MeerKAT TRAPUM → plans for dedicated survey in 2019







Conclusions

- Indirect dark matter searches are 20% about killing dark matter models, and 80% about scrutinizing dark matter signal hints

  Might be frustrating from outside, but it is a sign that progress is made
- Prospects for WIMP searches
  - Anti-proton constraints are strong (although weaker in GeV excess region), more work required to make them as robust as possible
  - Origin of positron excess still unclear (HAWC might help to constrain pulsar emission), more data needed for DAMPE 1.4 TeV feature
  - In the mid-term future, synchrotron emission searches could be key to improve WIMP limits
- Other searches
  - Great experimental progress at X-ray and radio energies expected in upcoming years; great for sterile neutrino searches, maybe axions
  - Searches for bulge MSPs with MeerKAT (2019?) will probe Fermi GeV excess and might provide strong evidence for a pulsar origin.

Thank you