Indirect searches for particle dark matter

GRAPPA

GRavitation AstroParticle Physics Amsterdam

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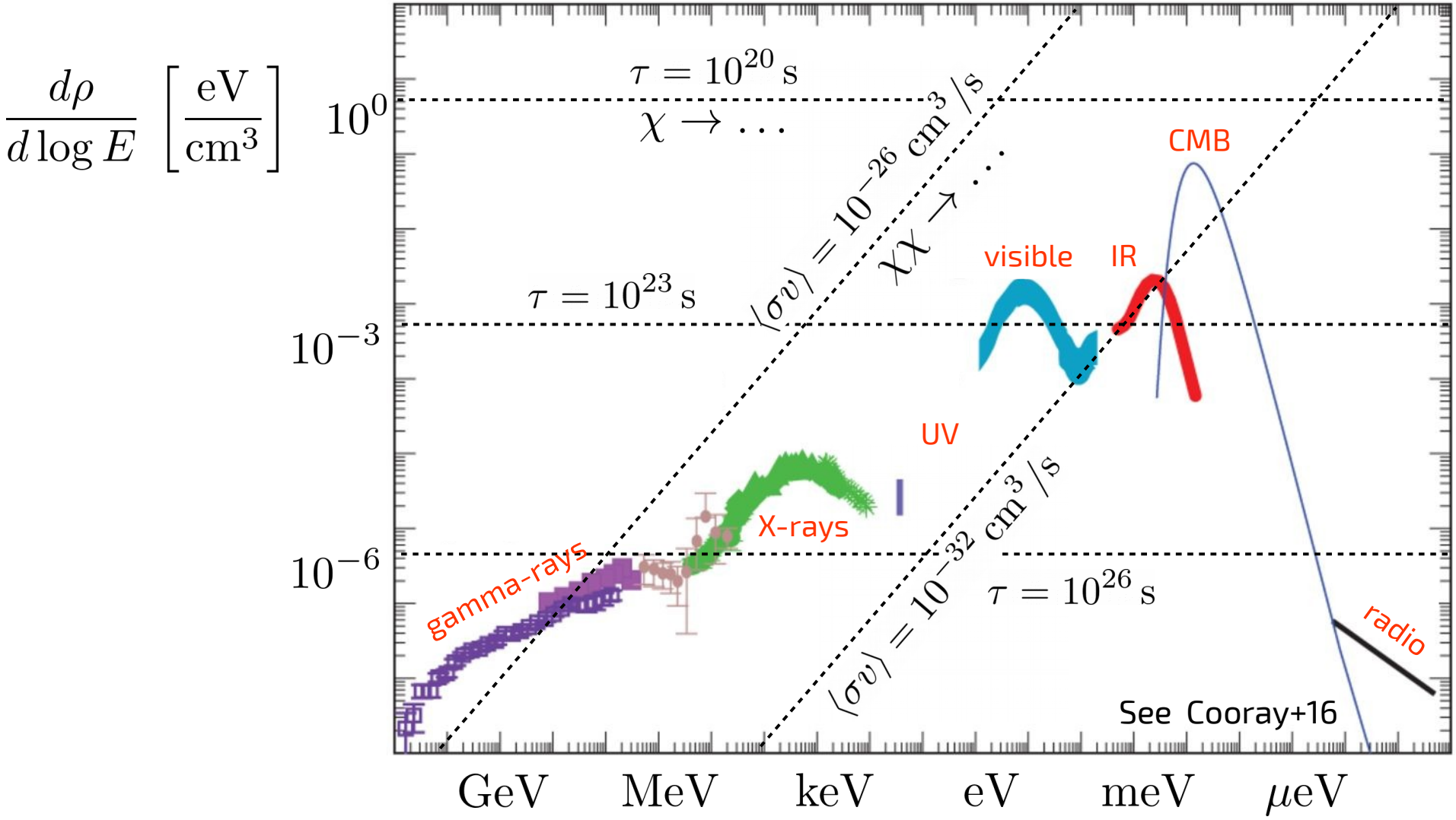
NWO

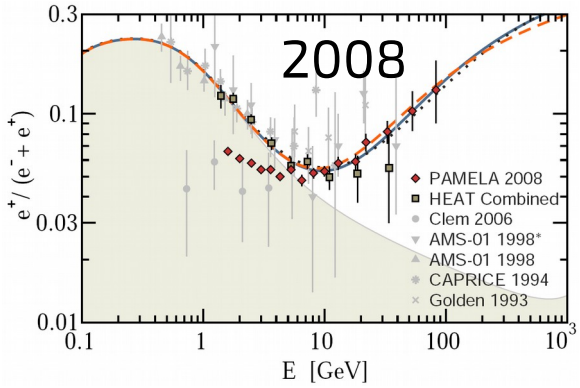
Average energy densities in today's Universe

Dark matter energy density >> Radiation energy density

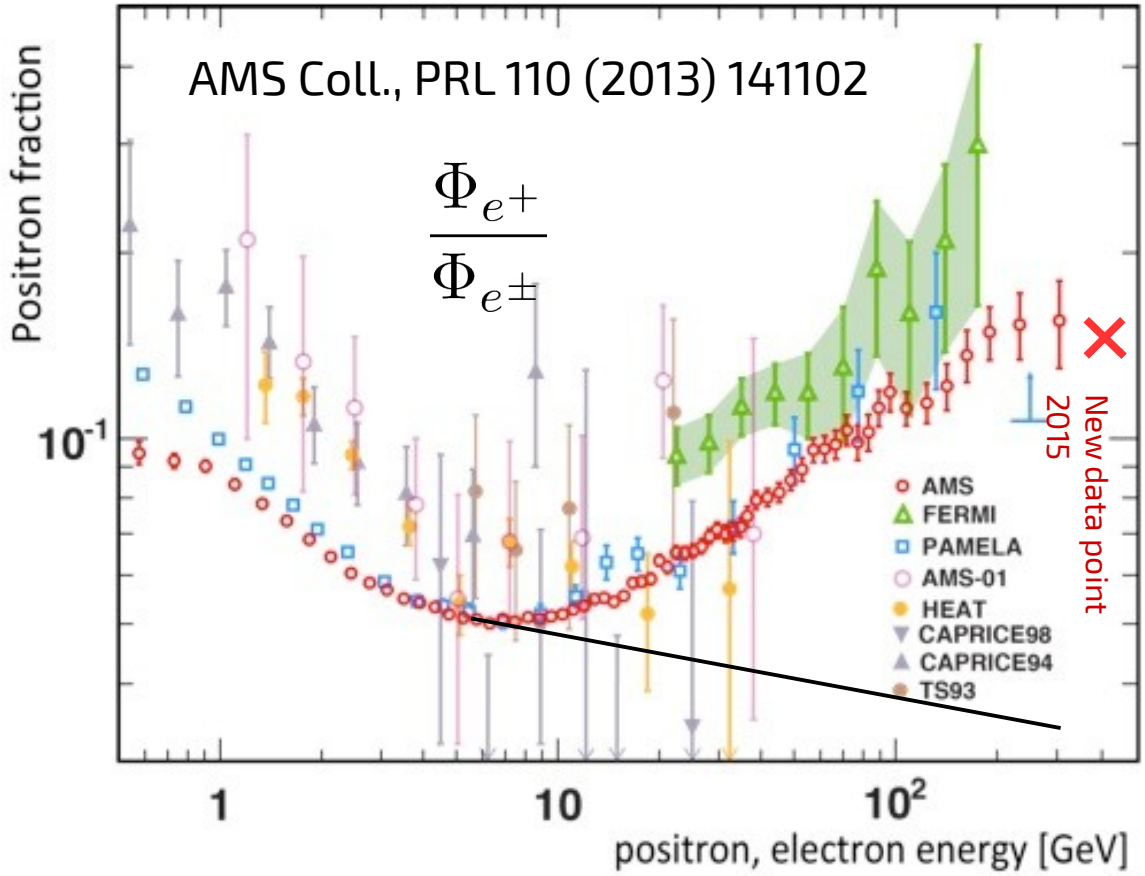
$$\rho_{\rm dm} \sim 1.3 \times 10^3 \frac{\rm eV}{\rm cm^3} \qquad \rho_{\rm rad} \sim 1 \frac{\rm eV}{\rm cm^3}$$



The good ol' days PhD: The PAMELA excess



Back in 2008: ~1 paper/day explaining the "PAMELA excess"



Pair production in pulsars:

- Pro: Pulsars exist
- Pro: Pulsars produce e+ e- and accelerate them to high energy
- Con: Detailed injection not well constrained

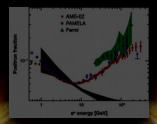
Dark matter annihilation / decay:

- Pro: Would be amazing if true
- Con: Positron channel strongly contaminated with astro backgrounds
- Con: No corresponding anti-proton / gamma-ray excesses

No shortage of excesses

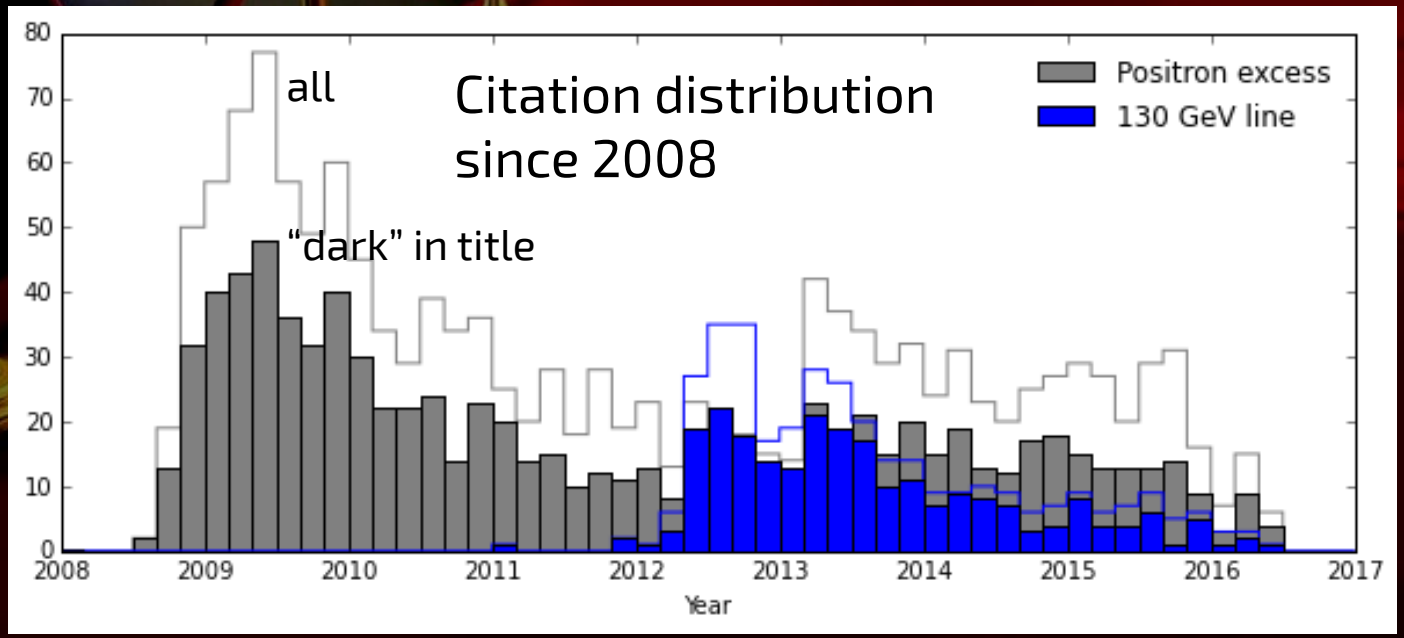
The top six

- Positron excess (~1800)
- Fermi GeV excess (~510)
- 130 GeV line (~430)
- 3.5 keV line (~300)
- 511 keV line
- WMAP/Fermi haze



Honorable mention

- Galactic center TeV source
- ATIC bumps
- X-ray signal from Sun
- EGRET excess
- ARCADE excess
- Virgo excess
- Reticulum II excess



Overview

Non-photon probes

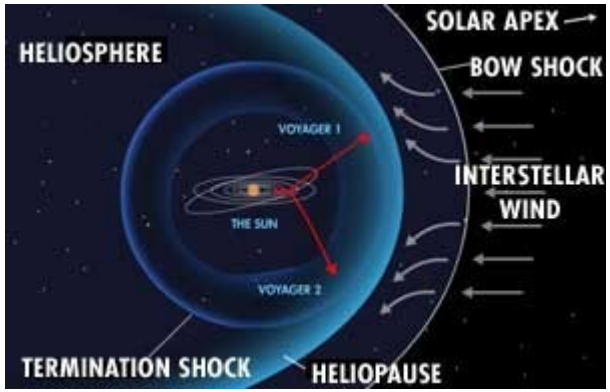
Fermi GeV excess

Searches from radio to gamma-rays

Differential Fisher information

Conclusions

Antimatter cosmic rays

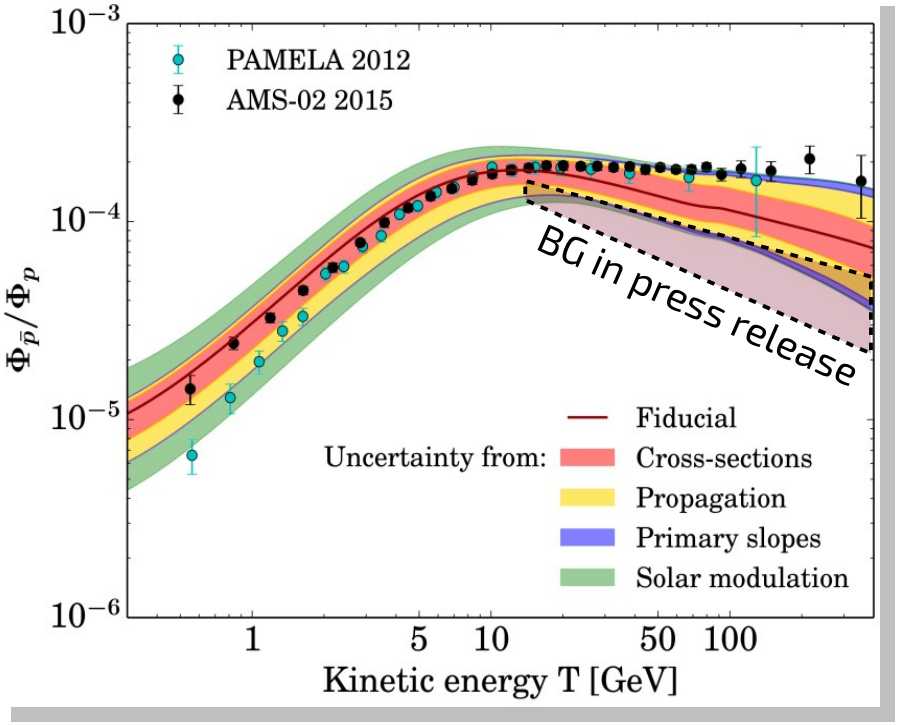


Available or future data

- Positrons (0.5 – 300+ GeV)
- Anti-protons (0.8 – 350+ GeV)
- *Searches for anti-deuterons*

Instruments

- PAMELA
- Fermi, HESS
- AMS-02
- DAMPE (2015)
- CALET (2015)
- *HERD (~2020)*
- *GAPS (~20??)*



Possible interpretations

- Secondary anti-proton systematics (e.g. Cirelli+14)
- room for DM (e.g. Wino DM, also positrons?) (e.g. Hamaguchi+15)
- room for contributions from nearby supernova remnant (e.g. Kachelriess+15)

Carlson+14 (PRD); Cirelli+14 (JHEP); Giesen+15 (JCAP); Evoli+15 (JCAP); Jin+15 (PRD); Ibe+15 (PRD); Hamaguchi+15 (PLB); Lin+15; Kohri+15 (PTEP); Kachelrieß+15 (PRL); Balazs&Li15 (JHEP); Doetinchem+15 (PoS); Fornengo+13

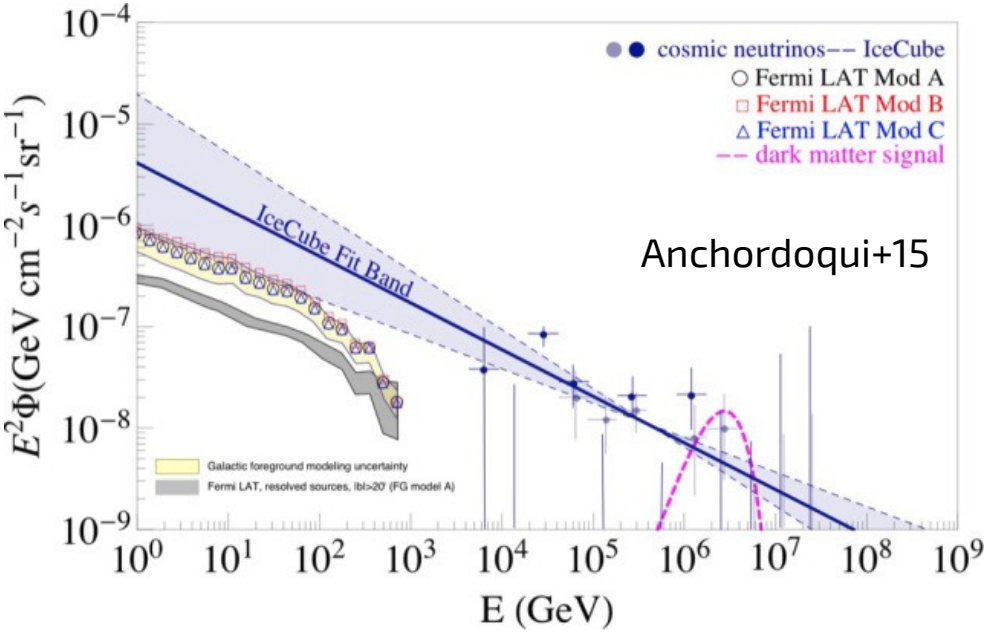
Neutrinos

Available data from

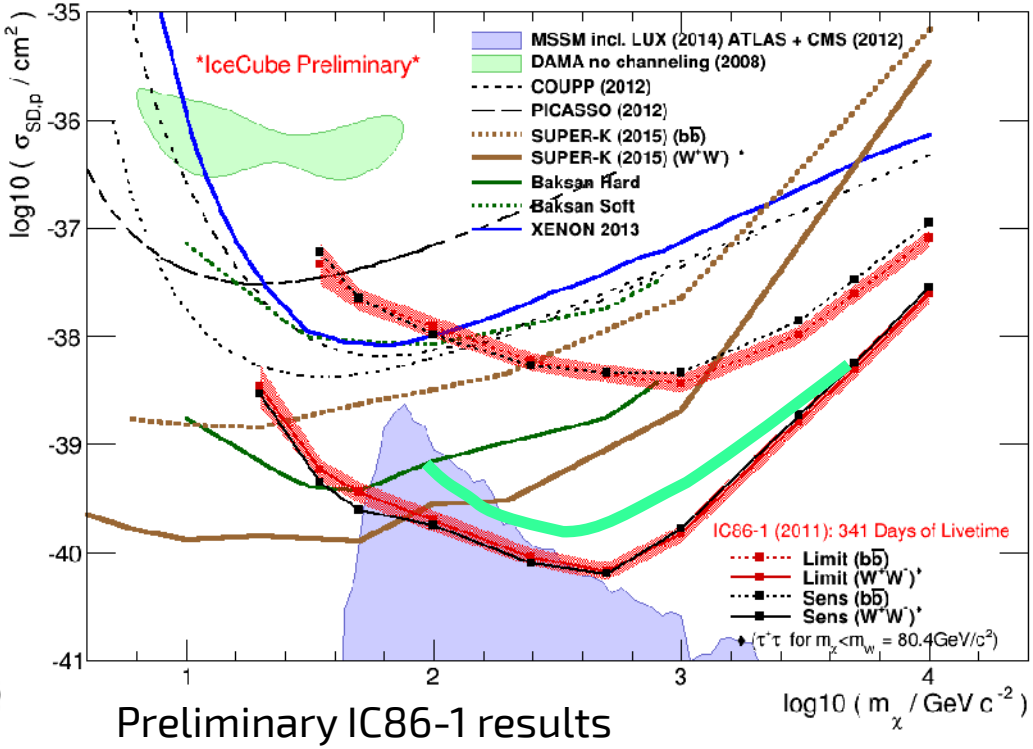
- IceCube
- Antares
- Super-K

No HE neutrinos from Sun → Limits on DM scattering cross-section

Decaying DM origin of IceCube PeV neutrinos?



Anchordoqui+15



Preliminary IC86-1 results

ICRC 2015

e.g. Esmaili&Serpico 13; Anchordoqui+ 2015; Bai+ 13; Queiroz+16; Feldstein+13

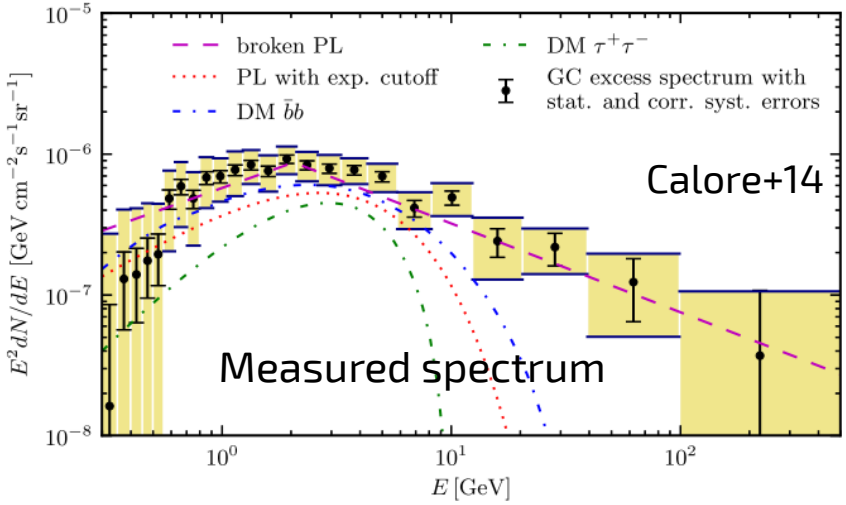
Photons

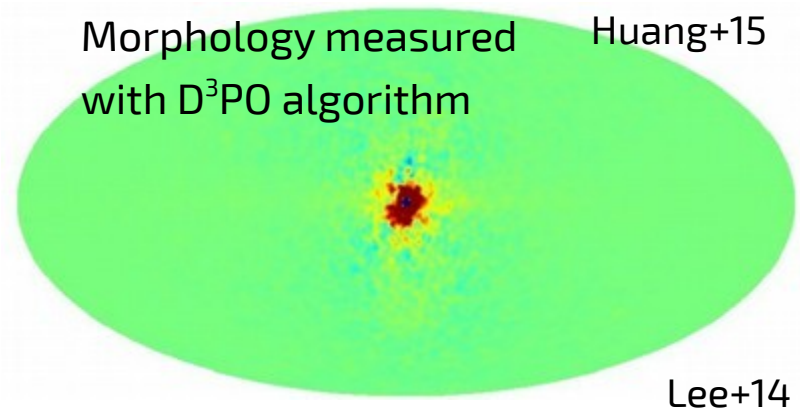
Nebra sky disk
1600 BC

The Fermi LAT GeV excess

Characteristics

- Excess of ~1–3 GeV photons at Galactic center
  Goodenough & Hooper 2009; Hooper & Goodenough 2011; Hooper & Linden 2011; Boyarsky+ 2011; Abazajian & Kaplinghat 2012; Gordon & Macias 2013; Macias & Gordon 2014; Abazajian+ 2014; Daylan+2014
- Excess with similar spectrum at mid-latitude (up to ~15 deg)
  Hooper & Slatyer 2013; Huang+ 2013; Zhou+ 2014; Daylan+ 2014

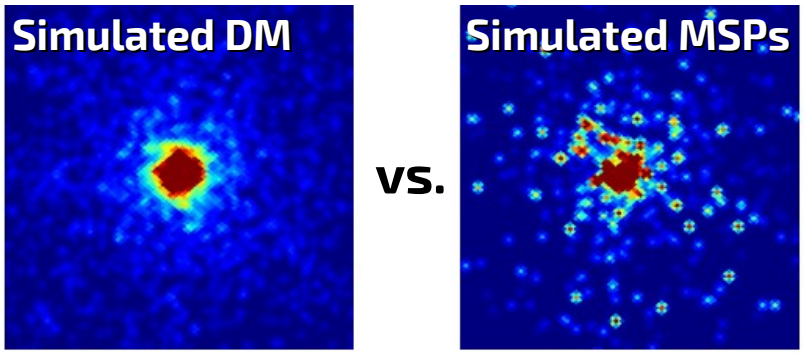




Interpretations

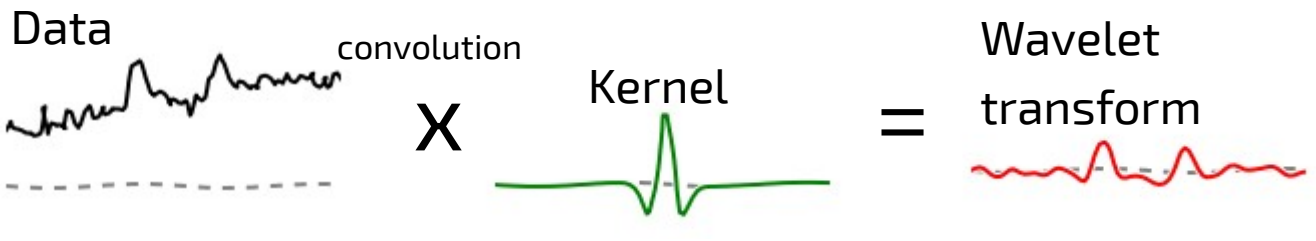
- Annihilation of ~50 GeV WIMPs into bb
- Star formation in central molecular zone
  Carlson+15
- Past activity of central black hole
  Cholis+15; Petrovic+13
- Young pulsars
  O'Leary+15
- Millisecond pulsars
  Abazajian 11; Brand & Kocsis 15

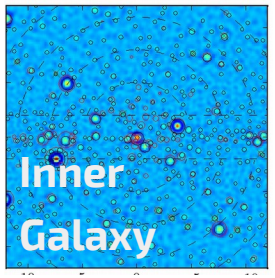
Lee+14



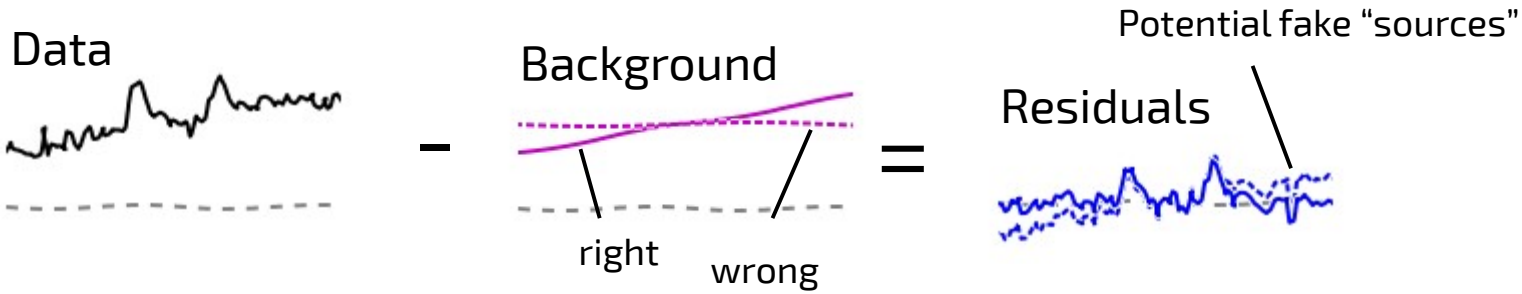
Wavelet fluctuation analysis supports MSPs

Bartels+15 (PRL): Analysis of variations in the wavelet transform:



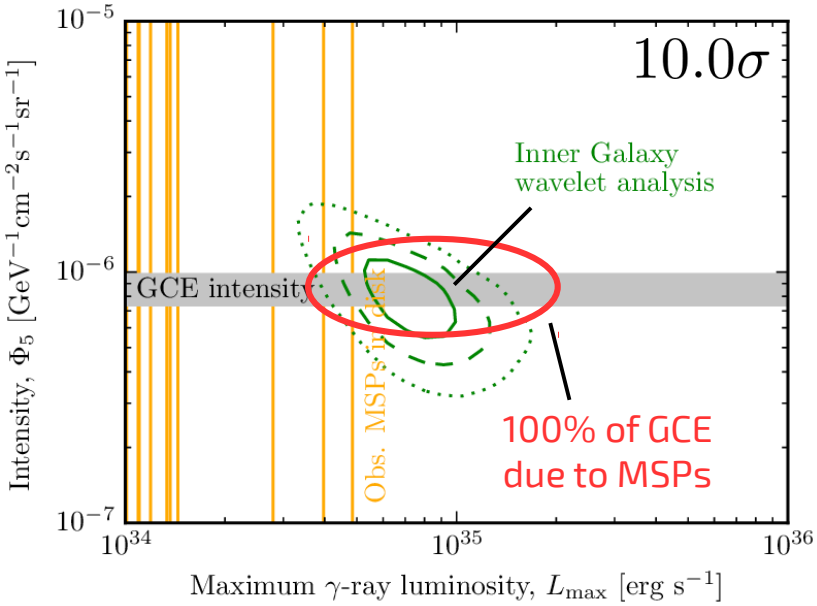


Lee+15 (PRL): Analysis of variations w.r.t. background model:



Wavelet approach is robust and simple

- No background modeling required
- Build-in source localization
- Extremely fast (allowed careful Monte Carlo tests of the results)



Millisecond pulsar mythbuster

The claim:

"(Millisecond) pulsars cannot account for the Inner Galaxy's GeV Excess"

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer 2013

See also: Cholis+14; Linden 15; Petrovic+14; Abazajian+14

"They are not abundant enough in the Galactic bulge"

Come on. Who knows? Only MSPs at O(1 kpc) distances can be observed easily. Dynamical models actually suggest that MSPs are distributed similar to what the GeV excess suggests.

"Their progenitor systems (LMXB) are not abundantly observed in the bulge"

True, but the life-cycle of LMXBs are far from understood.

"Their observed gamma-ray spectrum is not compatible with the GeV excess"

Wrong. We showed (Calore+13) that the spectrum is not well enough constraint for this statement.

"Bulge MSPs should have been seen as individual sources, but they haven't"

2x wrong. We showed (Bartels+15) that gamma-ray observations are not only compatible with the MSP hypothesis, but prefer it with high statistical significance.

"The wavelet fluctuation signal is just gas"

Most likely wrong. The power spectrum of the gas distribution (as traced by dust) at low angular scales is far too low to explain the observations

"The brightest bulge MSPs should have been seen in radio"

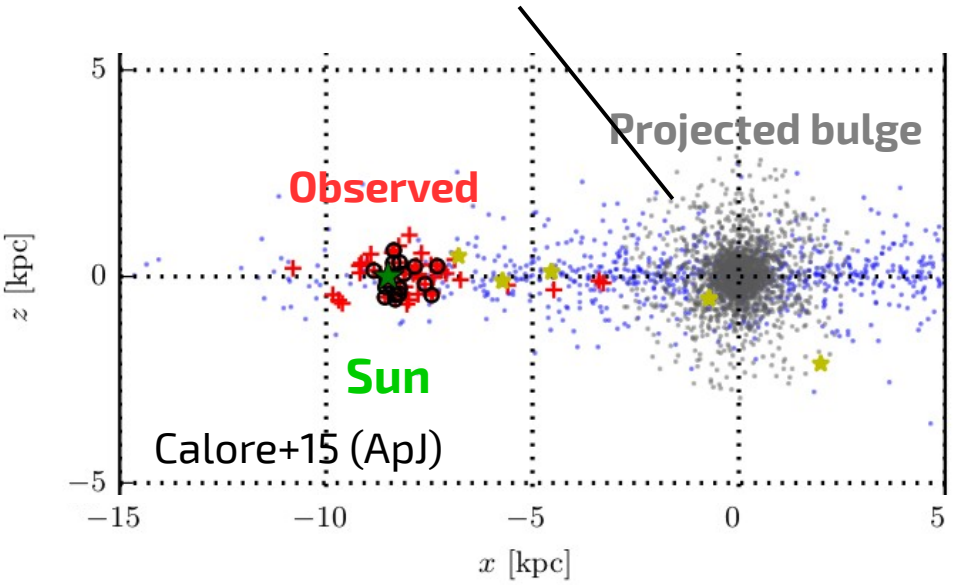
Wrong. We showed (Calore+15) that they are juts around the corner.

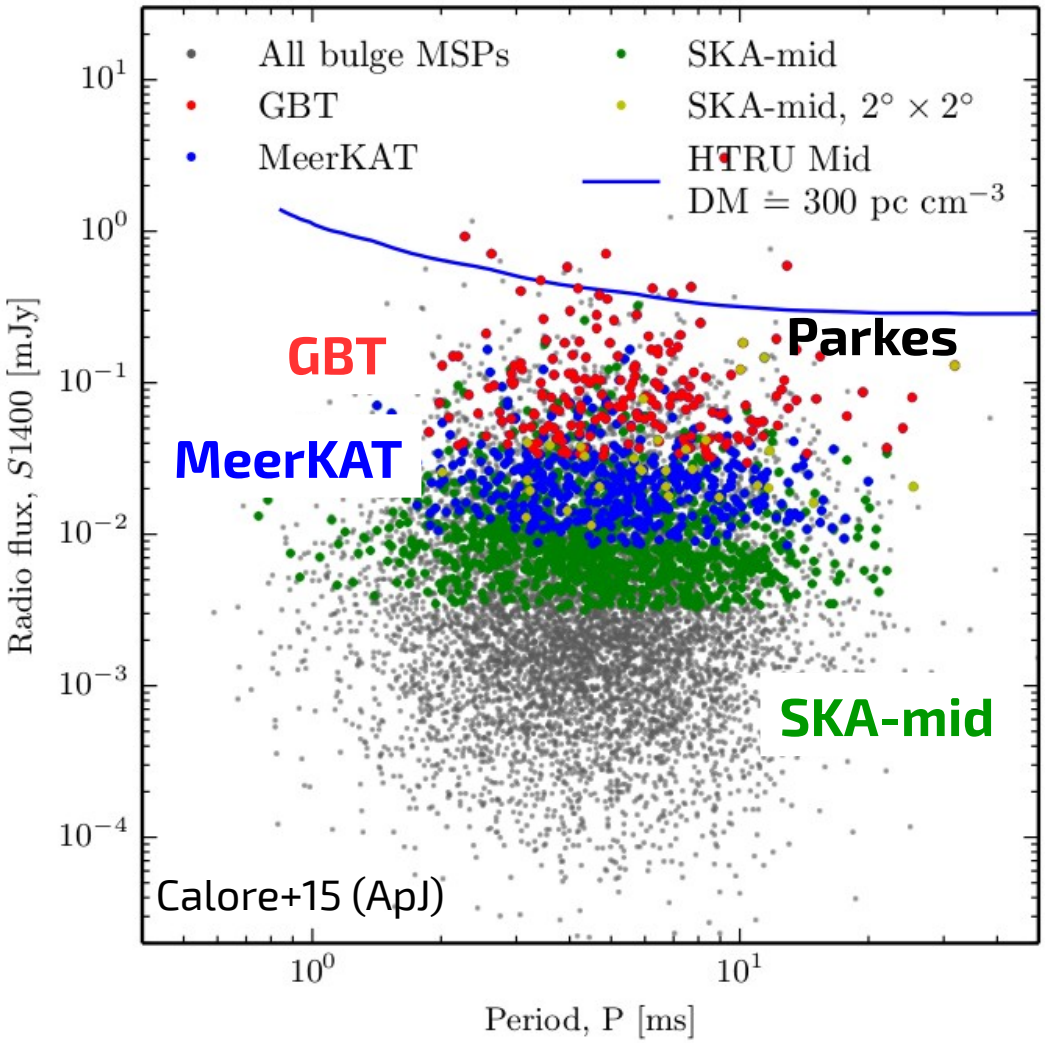
BUSTED

Prospects for radio searches

Projected bulge distribution

~3000 radio-bright ($S_{1.4\ GHz}$ > 10 μJy) sources

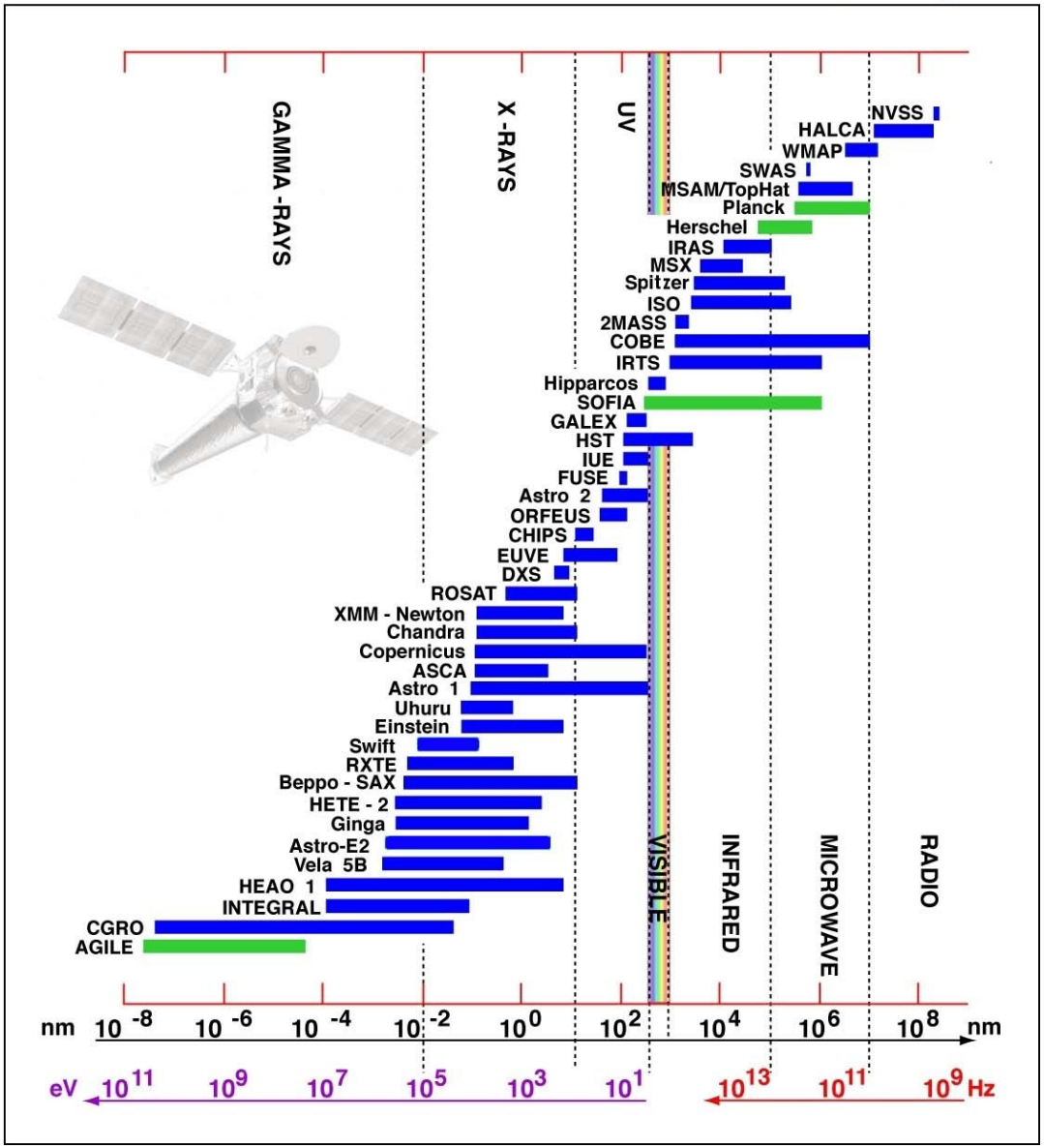




Radio detection prospects

- Below previous survey sensitivities
- Dedicated GBT campaign: ~3
- Dedicated MeerKAT survey: ~15
- With VLA we will search for young pulsars (later this year!)

From gamma rays to radio

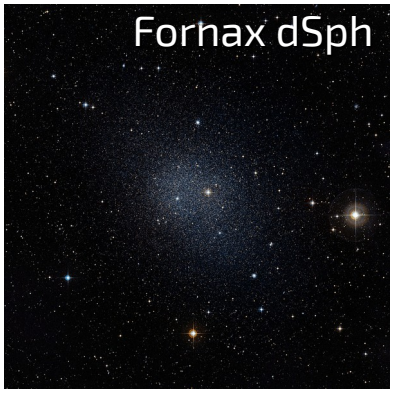


http://nssdc.gsfc.nasa.gov/astro/astrolist.html

Emission mechanisms:

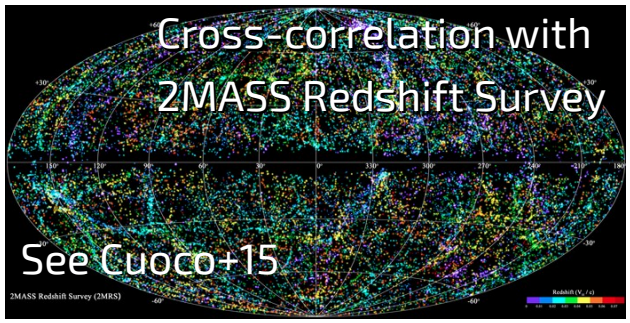
- Prompt (e.g. WIMP $\chi\chi \rightarrow \bar{q}q$ annihilation)
- Inverse Compton

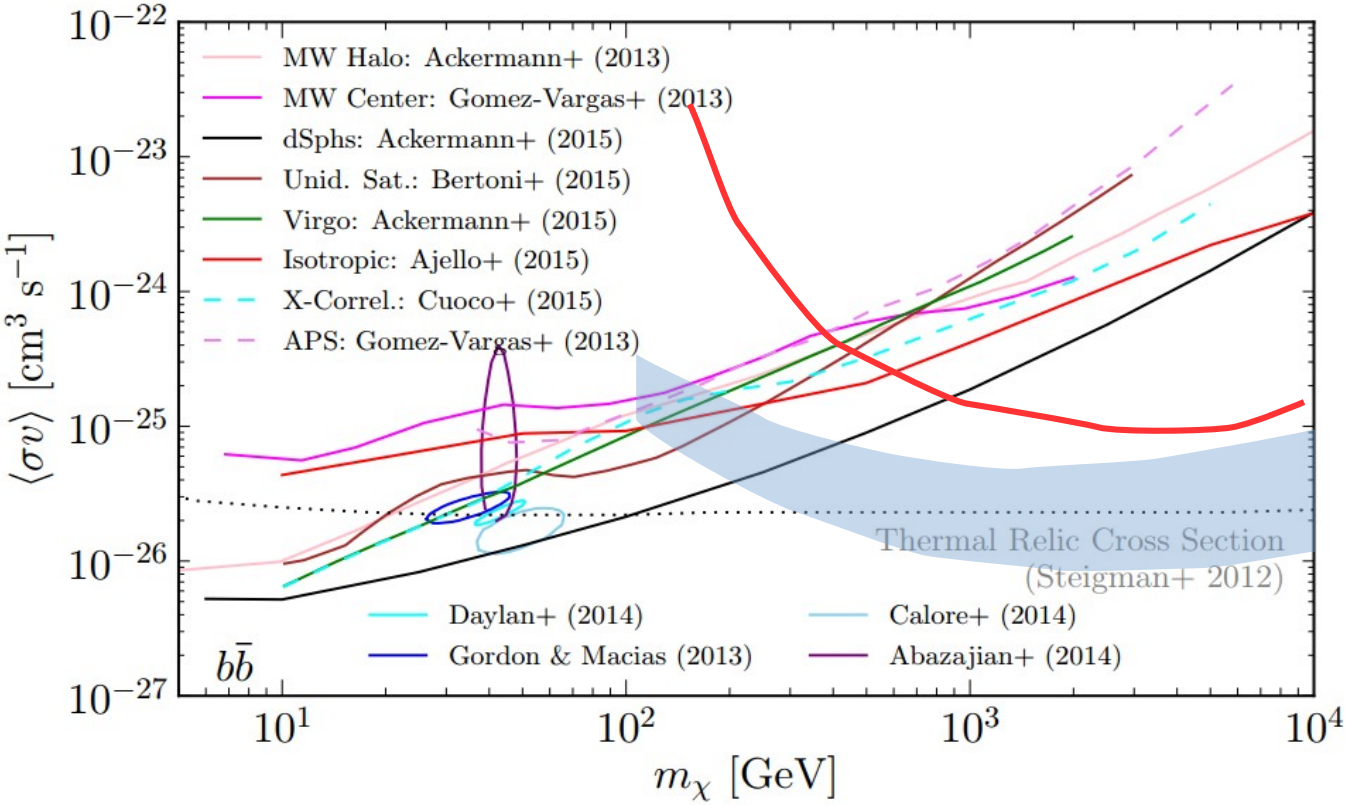
$$e^+\gamma_{eV} \rightarrow e^+\gamma_{GeV}$$



Traditional

Future?





e.g. Charles+16; Silverwood+15 (JCAP); Geringer-Sameth+15; Bringmann&CW 12; Bonnivard+15; Ando&Komatsu 13; Ando&Ishiwata 16

Instruments

- Fermi LAT, H.E.S.S., Veritas, Magic
- *CTA (~2019)*
- *AstroGam?*
- *GRIPS, Pangu?*
- *Gamma-400?*

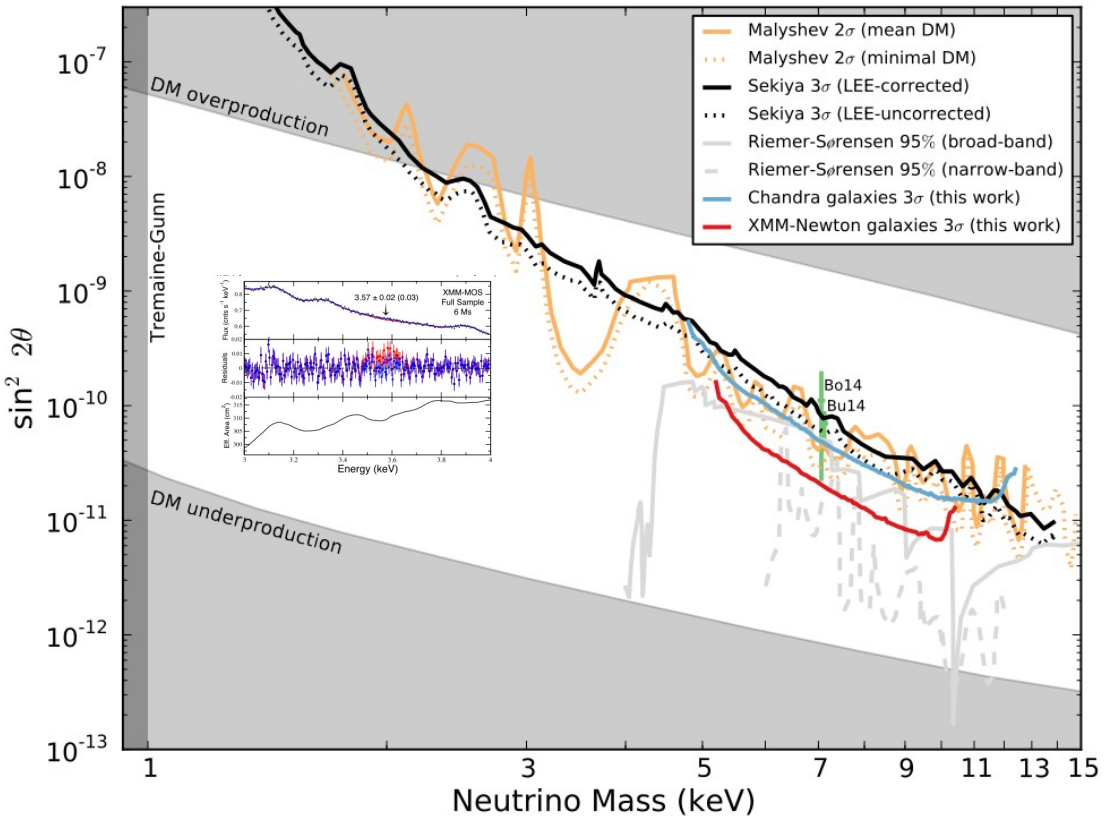
See talk by Andrzej Hryczuk

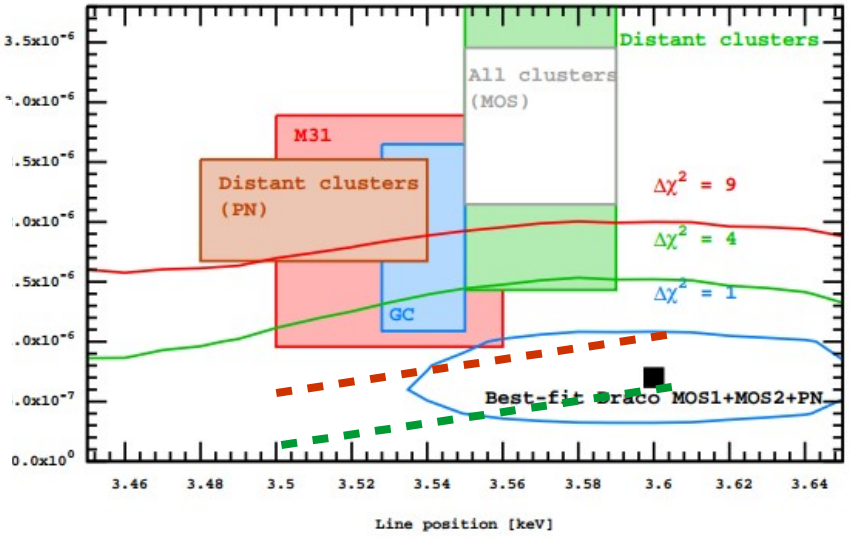
Emission mechanisms:

- Prompt (e.g. sterile neutrinos) $\chi \to \gamma\nu$
- Inverse Compton
- Hidden sector 21cm line, exited DM

Instruments

- XMM-Newton, Suzaku
- *Micro-X (2016), HXMT (2016)*



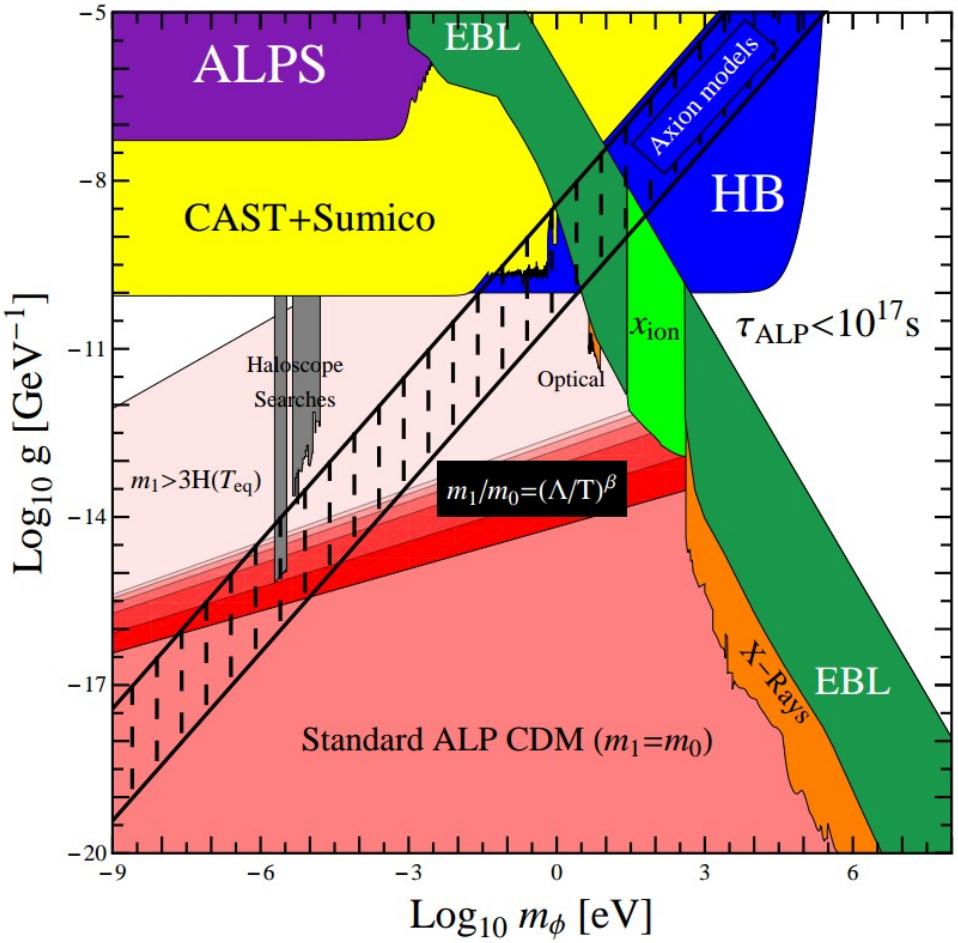


Astro-H tragedy

e.g. Bulbul+14; Boyarsky+14; Anderson+14; Jeltema&Profumo 12 (MNRAS); Jeltema&Profumo 14 (); Carlson+14 (); Malyshev+14 (); Ruchaysky+15 (); Jeltema&Profumo 15 (); Urban+14; Boyarsky+12; Zavala+11; Figueroa-Feliciano+15

Emission mechanisms:

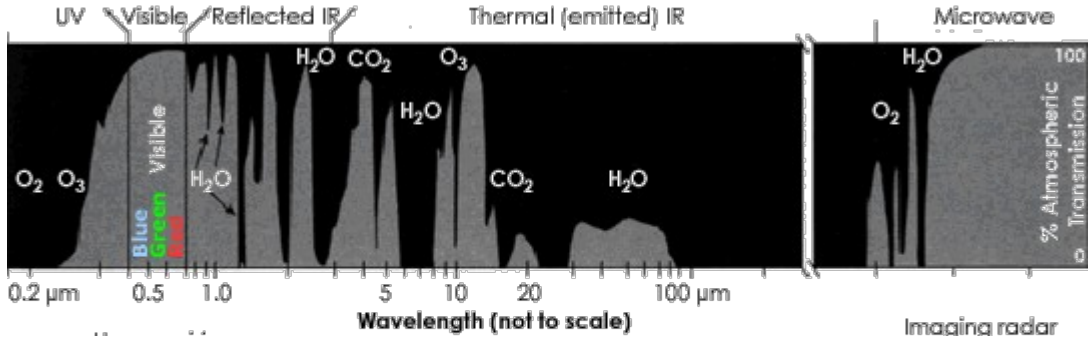
- Decay of bosonic DM (WISPs) $\chi \rightarrow \gamma\gamma$
- Maybe atomic dark matter $\chi^* \rightarrow \chi\gamma$



Instruments

- GALEX, HST
- Astrosat (2015)

For UV one has to go to space



Overduin+04 (PR); Cline+12 (PRD); Arias+12 (JCAP); Cline+14 (PRD);

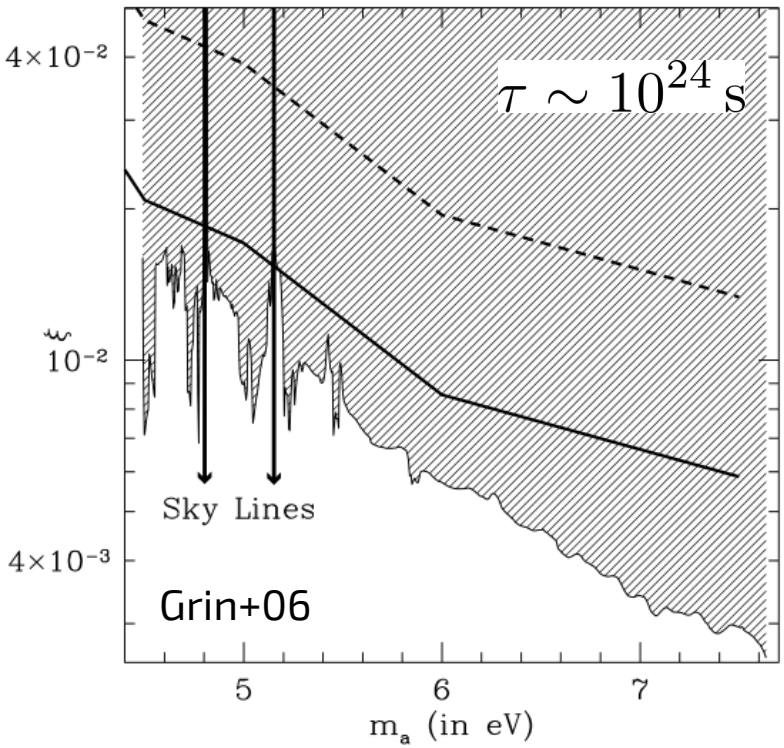
See talk by Jörg Jäckel for WISPy DM

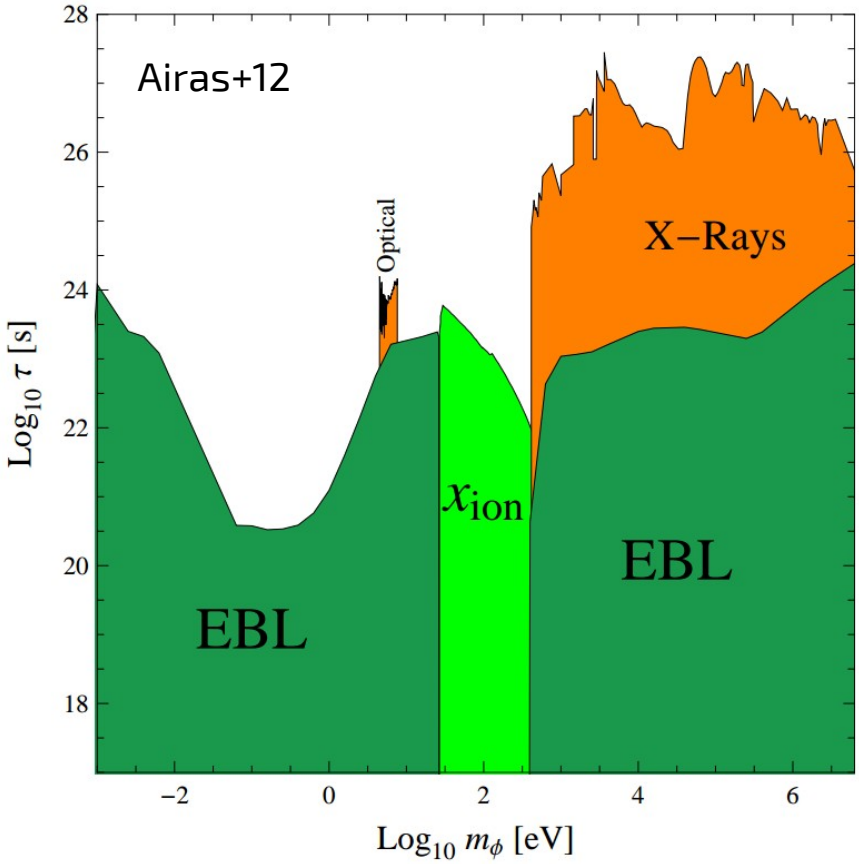
Emission mechanisms:

- WISPy dark matter
- Hot axions $\chi \rightarrow \gamma\gamma$

Instruments

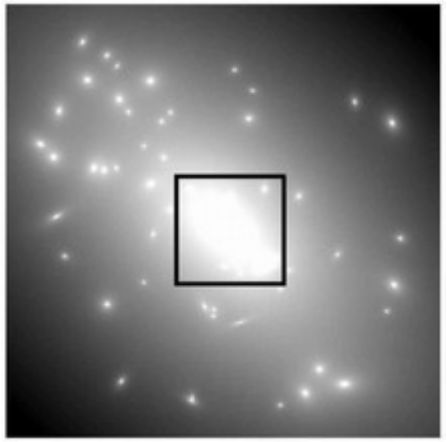
- VLA (VIMOS)





Image

Lensing mass map



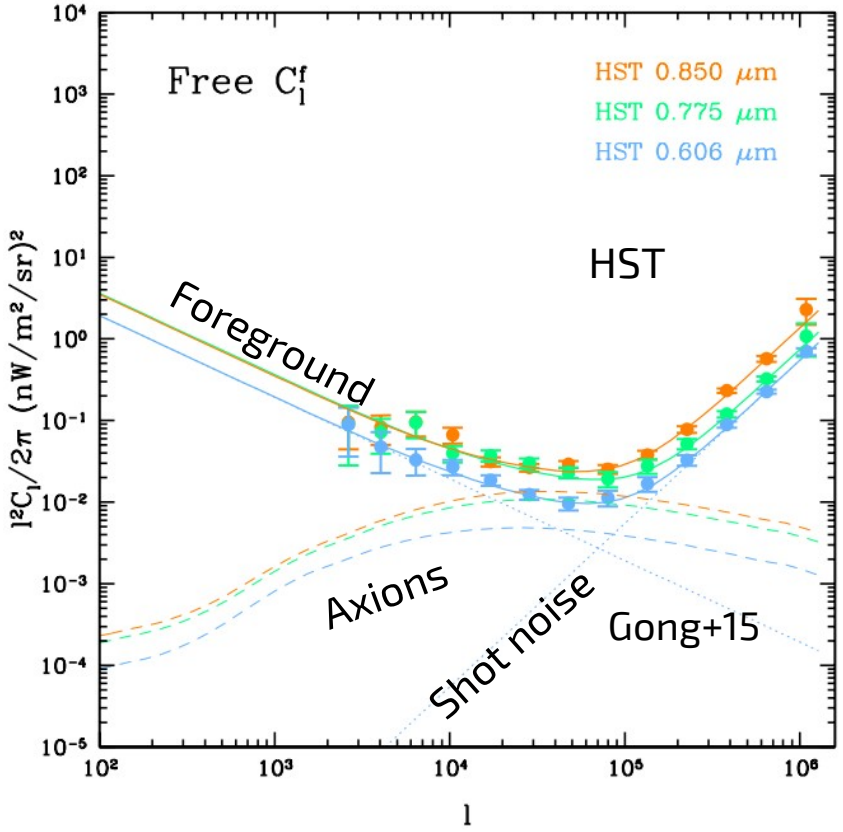
Not much: Ressell 91; Bershady+91; Grin+06 (PRD); Airas+12 (JCAP)

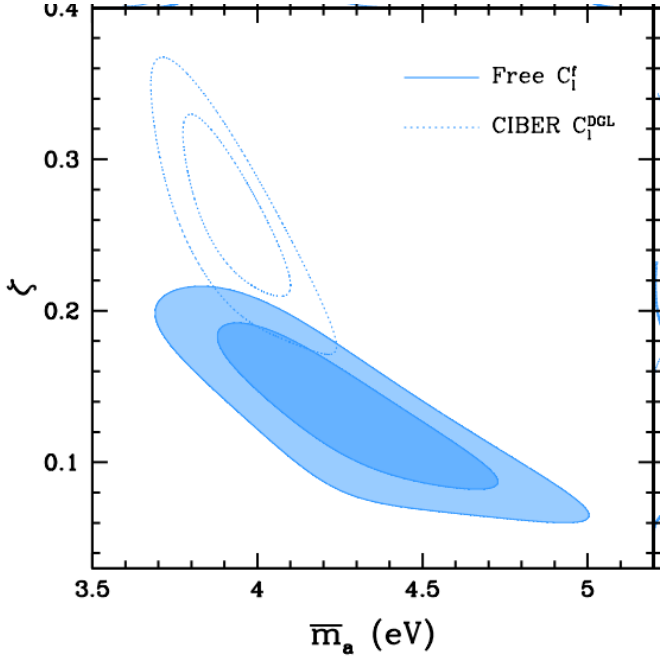
Emission mechanisms:

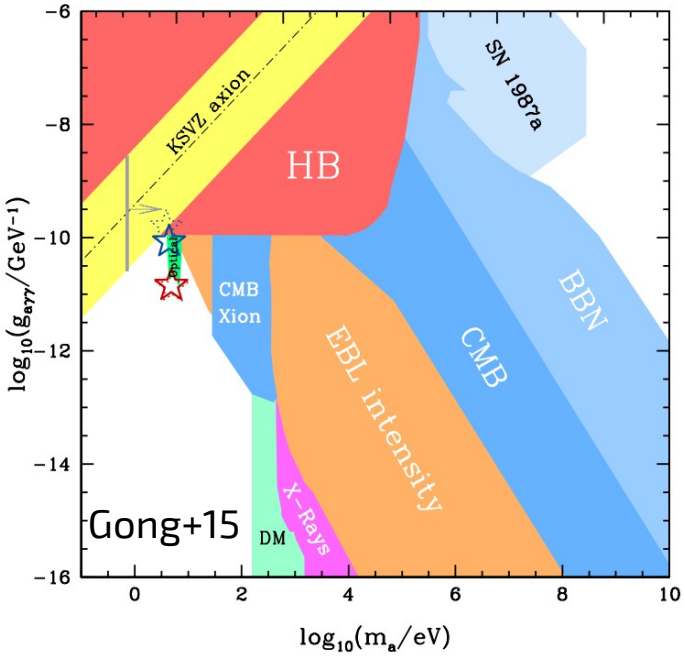
- Decay $\chi \rightarrow \gamma\gamma$
- WISPy dark matter
- Hot axion dark matter:

Instruments

- HST, CIBER, Spitzer, …



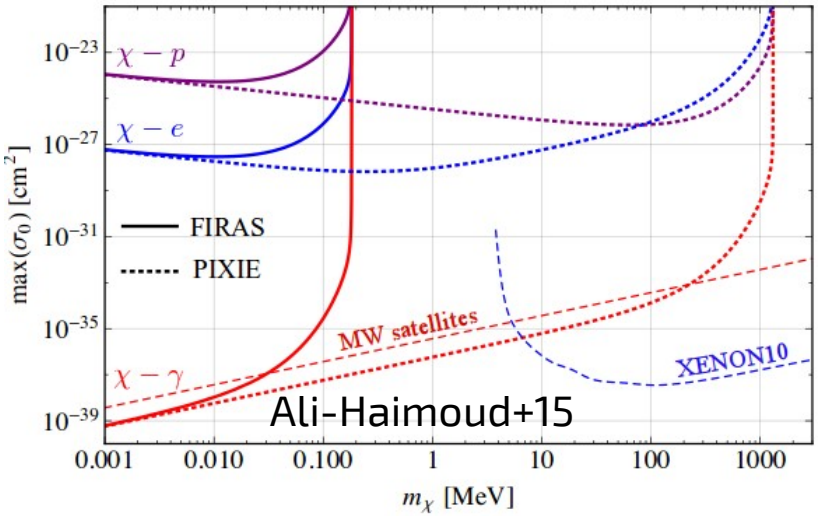


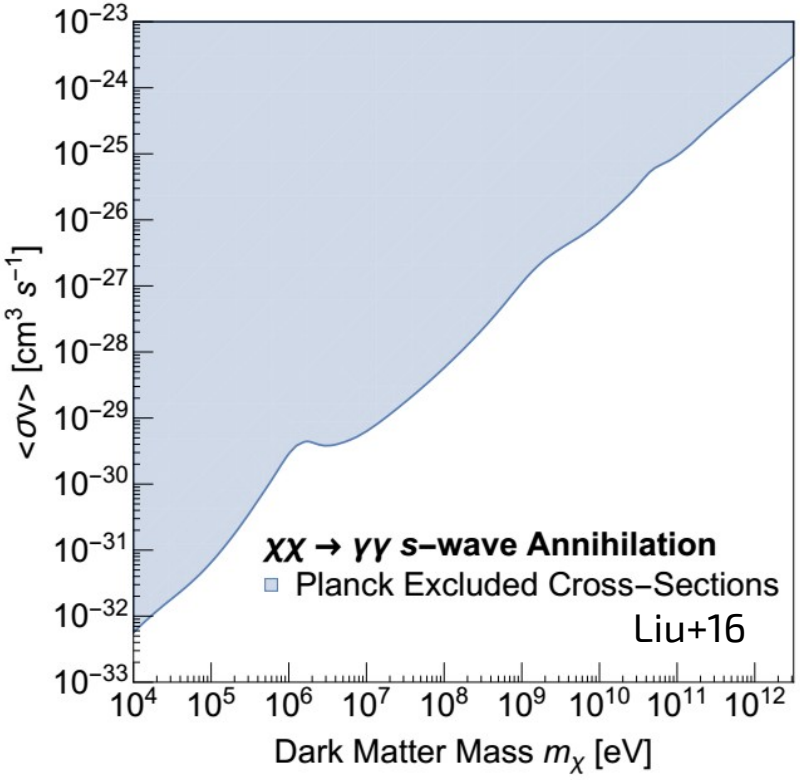


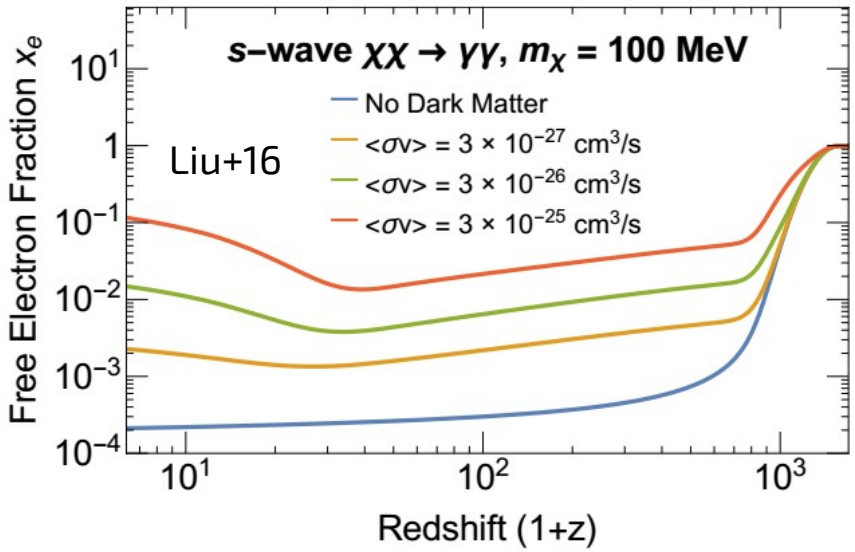
Not much: Gong+15 (ApJ)

Constraints from:

- Broadening of surface of last scattering → less fluctuations at small scales
- Spectral distortions







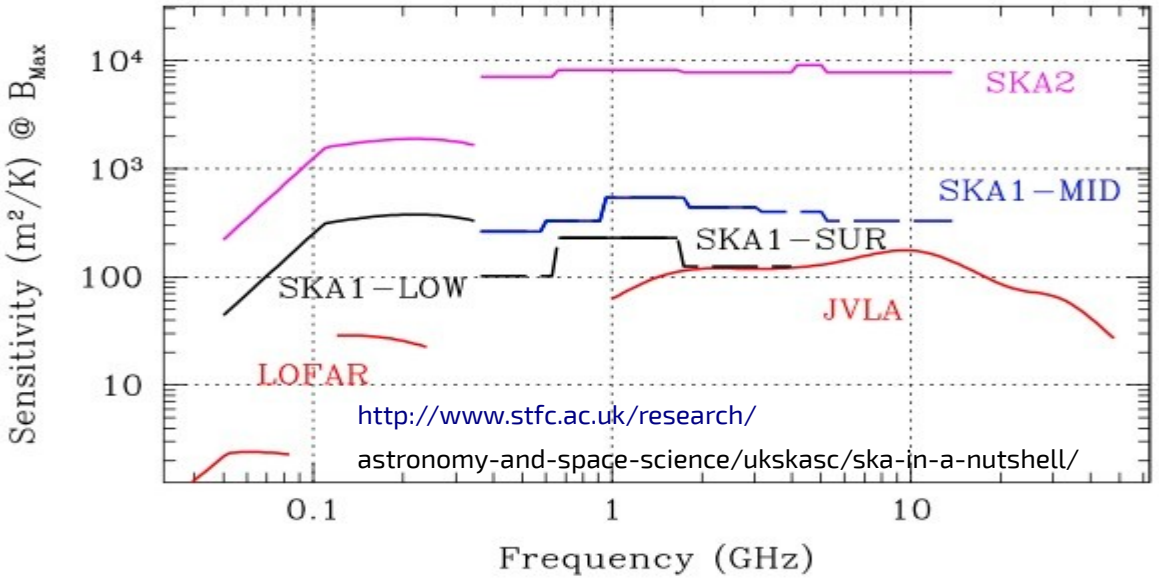
e.g. Planck 15; Ali-Haimoud+15 (PRL); Liu+16; Chluba+16; Cline&Scott 13; Galli+13; CW+13; Madhavacheril+13

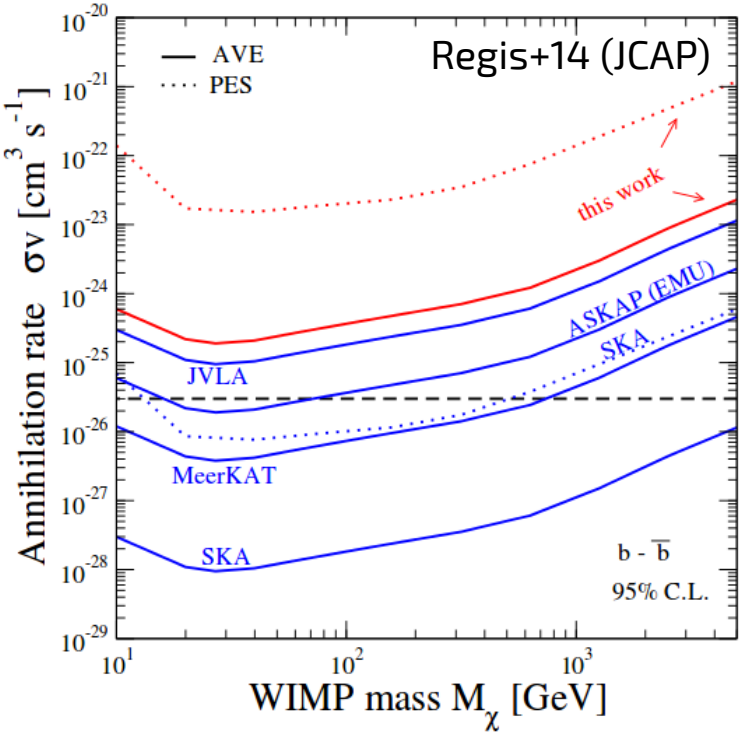
Emission mechanisms:

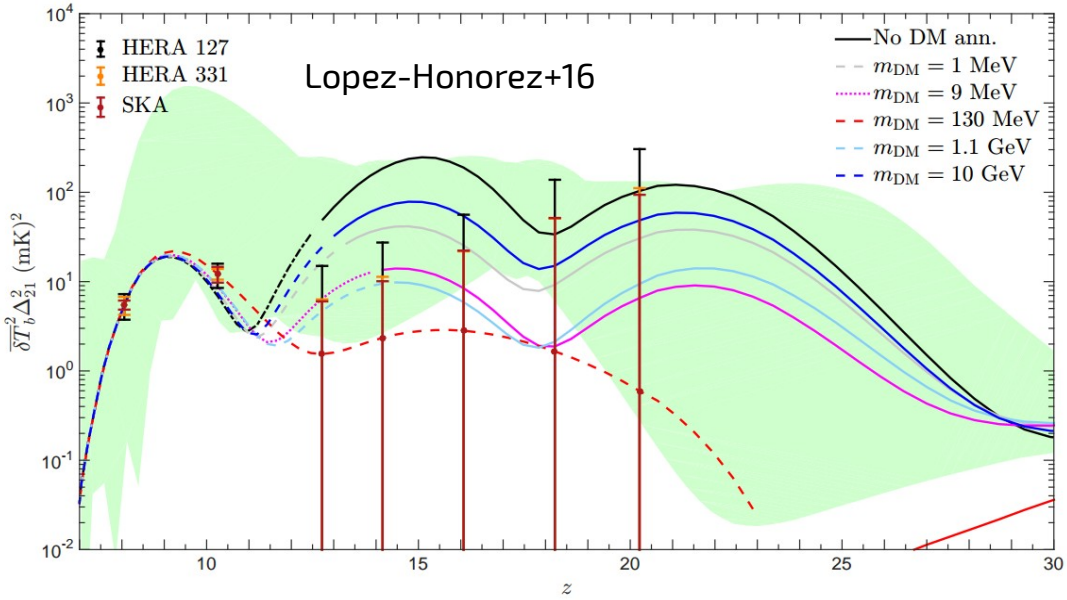
- Synchrotron emission

$$e^{\pm}\gamma^{*} \rightarrow e^{\pm}\gamma$$

- 21 cm tomography



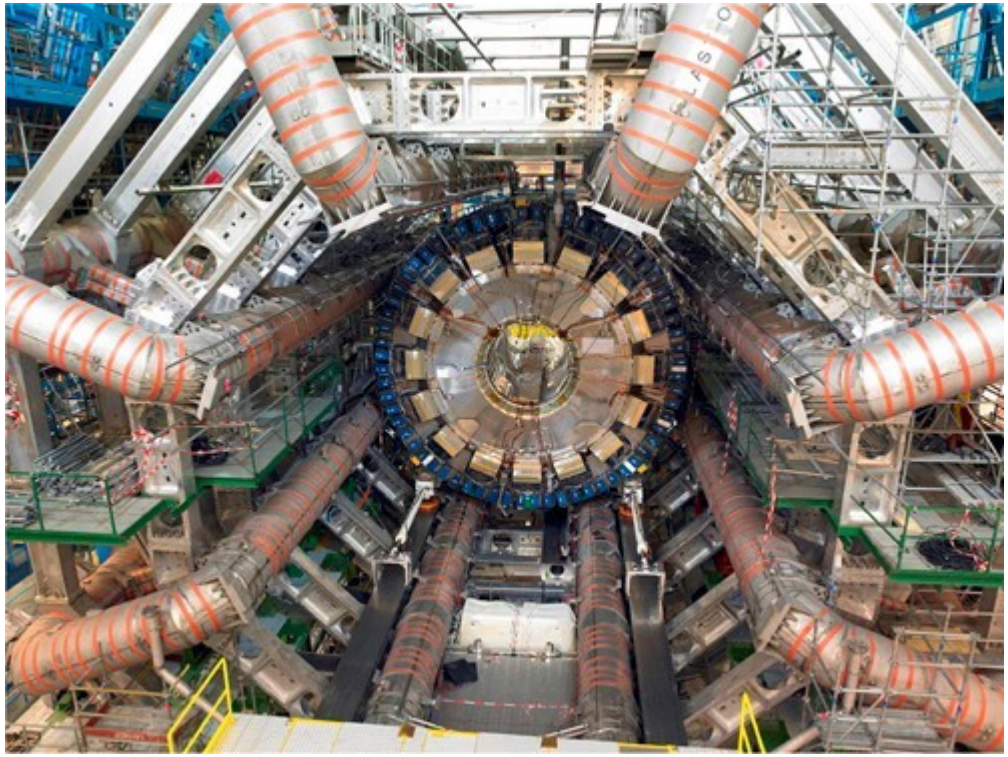




Crocker+10 (PRD); Linden+11 (ApJ); Fornengo+11 (PRL); Valdes+12 (MNRAS); Storm+13 (ApJ); Spekkens+13 (ApJ); Bringmann+14 (PRD); Regis+14 (JCAP); Cholis+14 (PRD); Evoli+14 (JCAP); Tashiro+14 (PRD); Fang&Linden 15 (PRD); Cirelli&Taoso 16

Different types of problems

Searching for the Higgs



complex.

Searching for Dark Matter

WICKED.

DM searches as wicked problem

Strategy development for (indirect) DM searches is a "wicked problem"*

*https://en.wikipedia.org/wiki/Wicked_problem

- ***Hard to develop optimal strategies.***
  Need to know particle properties of DM beforehand.
- ***No clear stopping rule.***
  "When should we stop searching in target X?"
- ***Strategies are neither wrong nor right.***
  They are at most good or bad.
- ***Strategies are usually one-shot operations.***

Is there a method to...

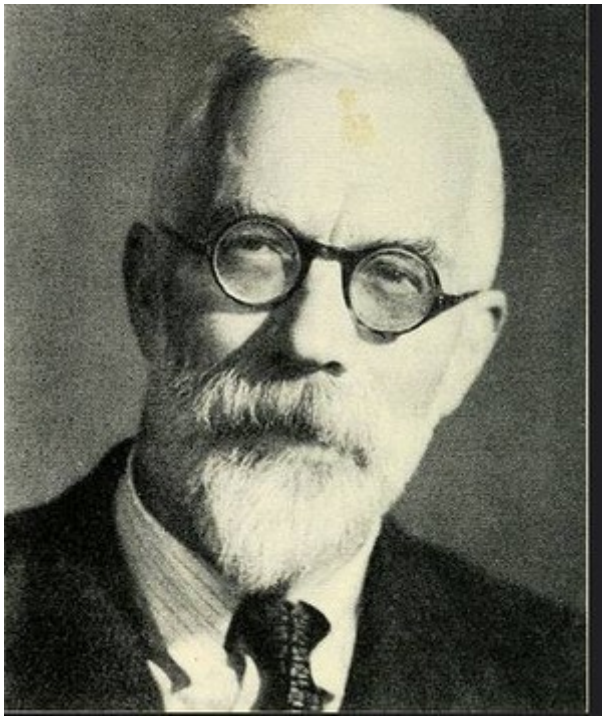
...coherently describe the reach of various methods?

...estimate how far we are away from the ultimate reach (for a given experiment)?

...identify optimal strategies for non-standard & exotic DM scenarios at one glance?

Is there a top-down approach for strategy development?

Sir Ronald Aylmer Fisher (1890 – 1962)



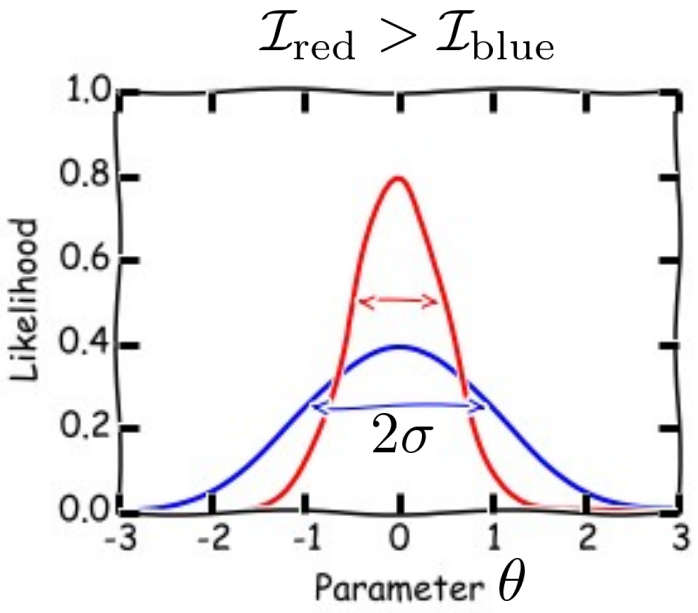
Fisher information

- is the expected "observed information"

$$\mathcal{I} \equiv -\left\langle \frac{\partial^2}{\partial\theta^2} \ln \mathcal{L}(\theta|\mathcal{D}) \right\rangle$$

- can be understood as inverse of the measured parameter variance

$$\mathcal{I} \overset{\text{norm}}{=} \frac{1}{\sigma^2}$$



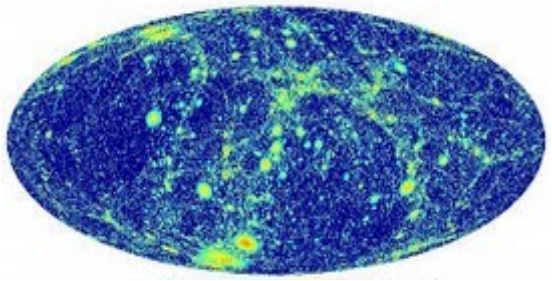
Fun with Differential Fisher information I

The most simple case:

(backgrounds well understood)

$$\mathcal{I} = T_{\rm obs} A_{\rm eff} \int_{\rm ROI} d\Omega \, \frac{\left(\frac{\partial}{\partial\theta}\Phi_{\rm sig}\right)^2}{\Phi_{\rm bg}}$$

Possible signal



Possible background

Note:

- Depends on the **square** of the signal flux:
  Signal more pronounced → easier to detect
- This describes **the optimum one can do**
  (encompasses ***all*** possible analysis techniques)

Simple sum rules

- Targets $\mathcal{I} = \mathcal{I}_{\rm Draco} + \mathcal{I}_{\rm M31+...}$
- Redshifts $\mathcal{I} = \int_0^\infty dz \, \frac{d\mathcal{I}}{dz}$
- Mass ranges $\mathcal{I} = \int_0^\infty dM \, \frac{d\mathcal{I}}{dM}$

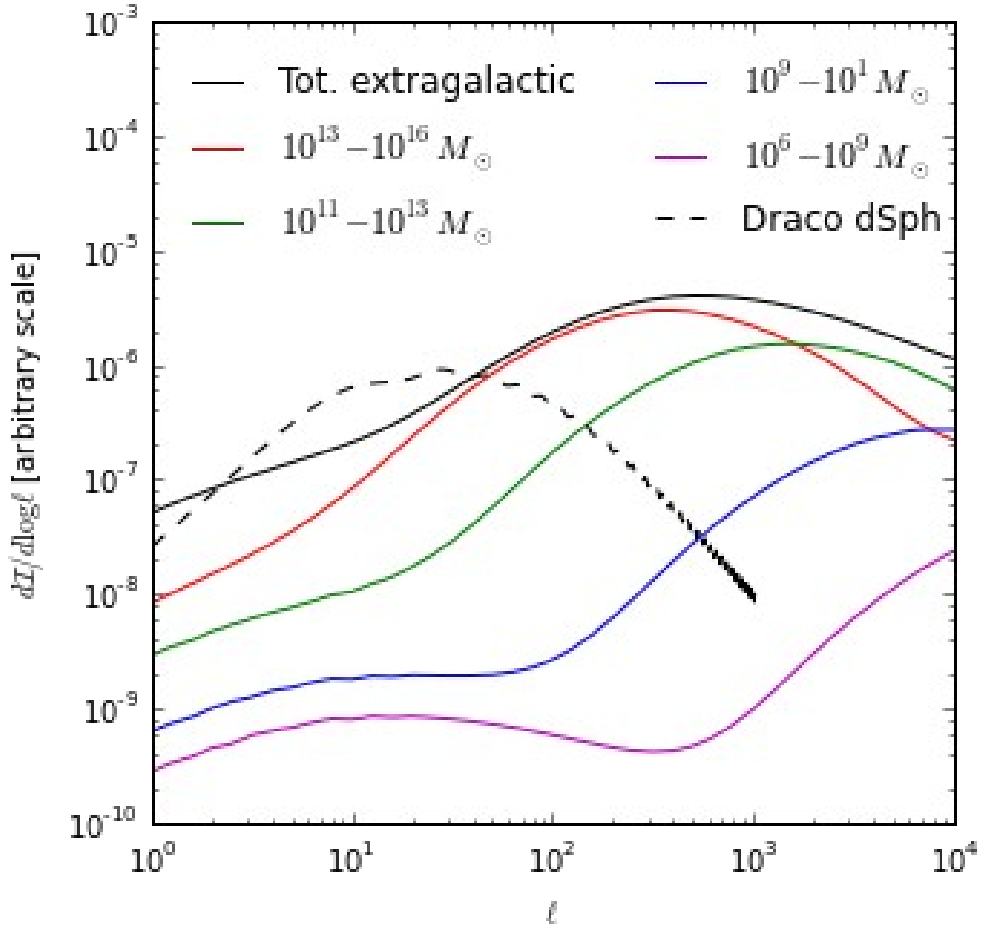
Fun with Differential Fisher information II

Decomposition in different angular scales

$$\mathcal{I} = \int_0^\infty d\log\ell \, \frac{d\mathcal{I}}{d\log\ell}$$

Details:

- 3.5 keV sterile neutrino signal
- integrated over 3.4 to 3.6 keV
- assuming isotropic background



Edwards, CW+, in prep

see also Zandanel+15

Python packages in the making

~~Greek mythology~~

~~Planets & Stars~~

~~Famous scientists~~

Star Wars!

Names containing "D"

Virtual

Atlas for

Dark matter

Engendered*

Radiation

*cause or give rise to

- Probabilistic catalog of DM halos
- Based on galaxy & cluster catalogs, local group observations
- Subhalo MC
- Works with *many* particle physics models
- Allows modeling of backgrounds
- Very high resolution thanks to hierarchical healpix format

Yield

Optimization for the

Dark matter

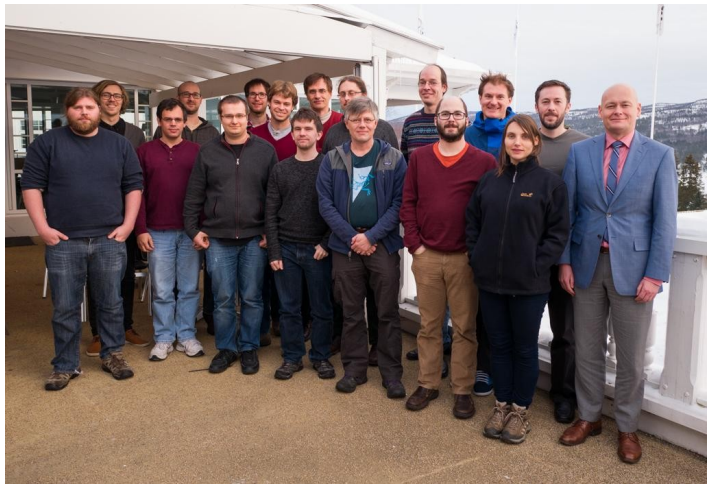
Anarchist

- Set of helper tools for Fisher matrix analysis
- Makes useful plots

GAMBIT: The Global And Modular BSM Inference Tool

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White,
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	J. Conrad, R. Trotta
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, S. Hoof, F. Kahlhoefer, A. Krislock, A. Kvellestad, M. Pato, F. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White



27 Members, 9 Experiments, 4 major theory codes, 10 countries

This Summer!

Conclusions

- Indirect searches for dark matter are one of the fundamental windows to probe DM properties (lifetime, annihilation cross section)
- Lots of data. Experiments are often, but not always, for “free”.
  - Fermi LAT, AMS-02, CALET, DAMPE, Astrosat, Micro-X, …
- Lots of excesses. Good sign that the community is alive and working.
  - There is growing evidence that Fermi GeV excess is caused by MSPs in the bulge. Excellent prospects to find the in radio in the upcoming years, if we do it right.
  - Situation with 3.5 keV line remains confusing. No supporting evidence from 1.5 Msec of Draco observations. Strong constraints from stacked galaxies.
- Lots of theoretical models.
  - Usually build around excesses. It would be great to have a systematic study of what signatures are possible in general.
- Fisher analyses are one honking great idea – let's do more of those!

Thank you!