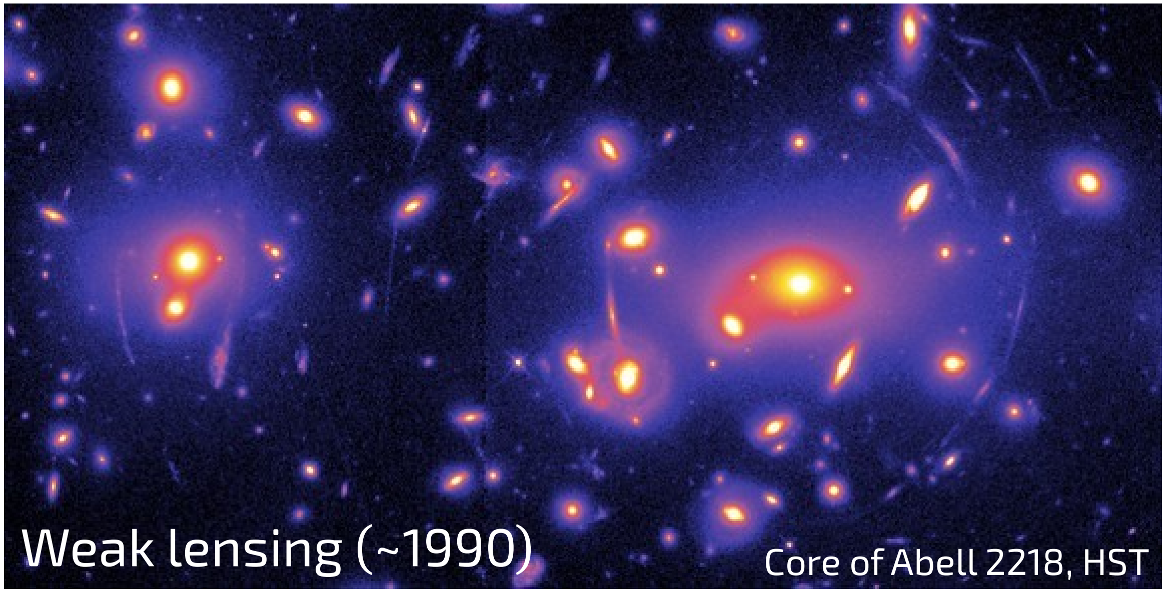
Indirect dark matter searches
Status and perspectives

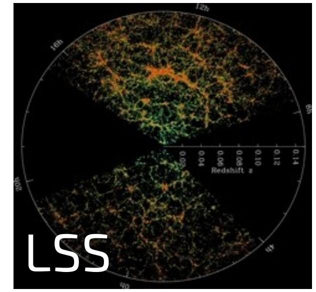
TeVPA 2016, CERN
14 Sep 2016

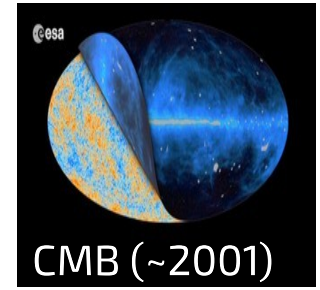
Christoph Weniger
University of Amsterdam

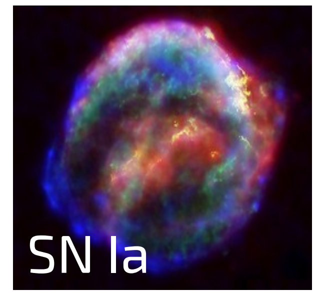
Indirect searches in a nutshell

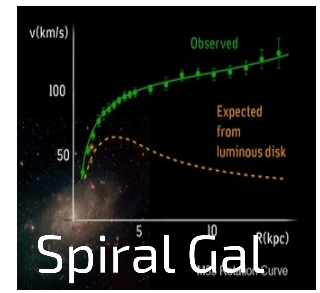
Evidence for dark matter in the Universe











Is dark matter really dark?

Self-annihilation of dark matter particles

$$\chi\chi \to \mathrm{SM\,stuff}$$

Decay of dark matter particles

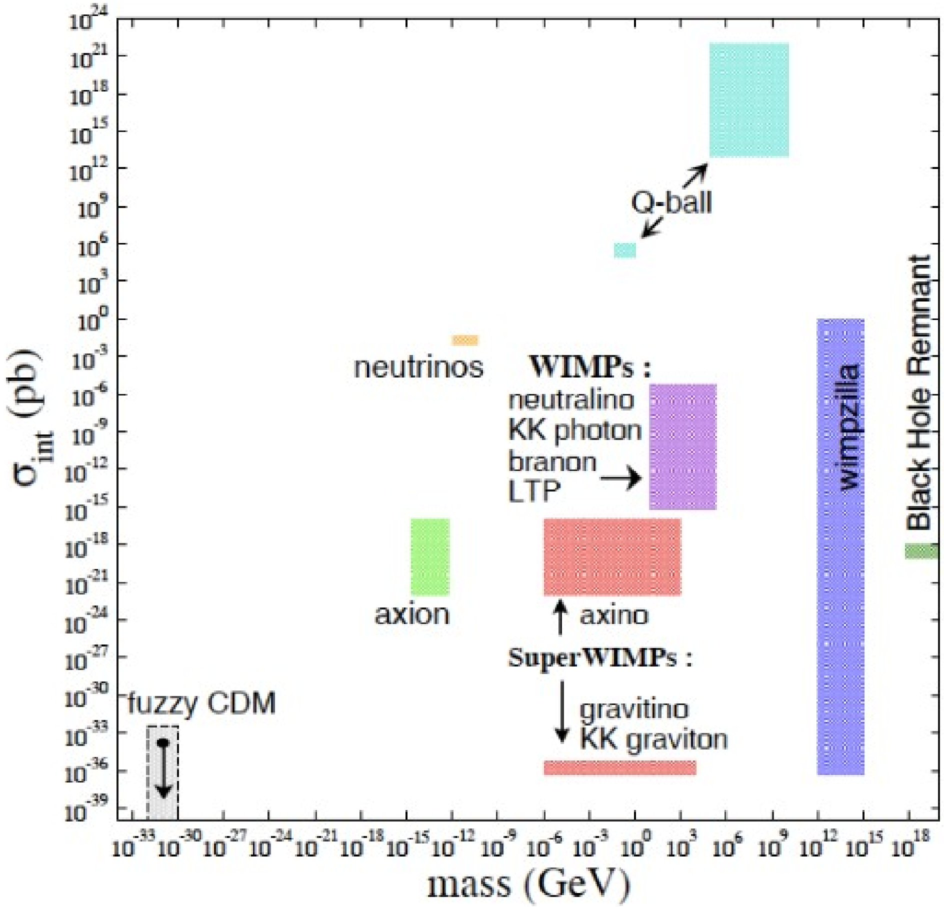
$$\chi \to \mathrm{SM\,stuff}$$

Photons, Neutrinos
Anti-matter, ...

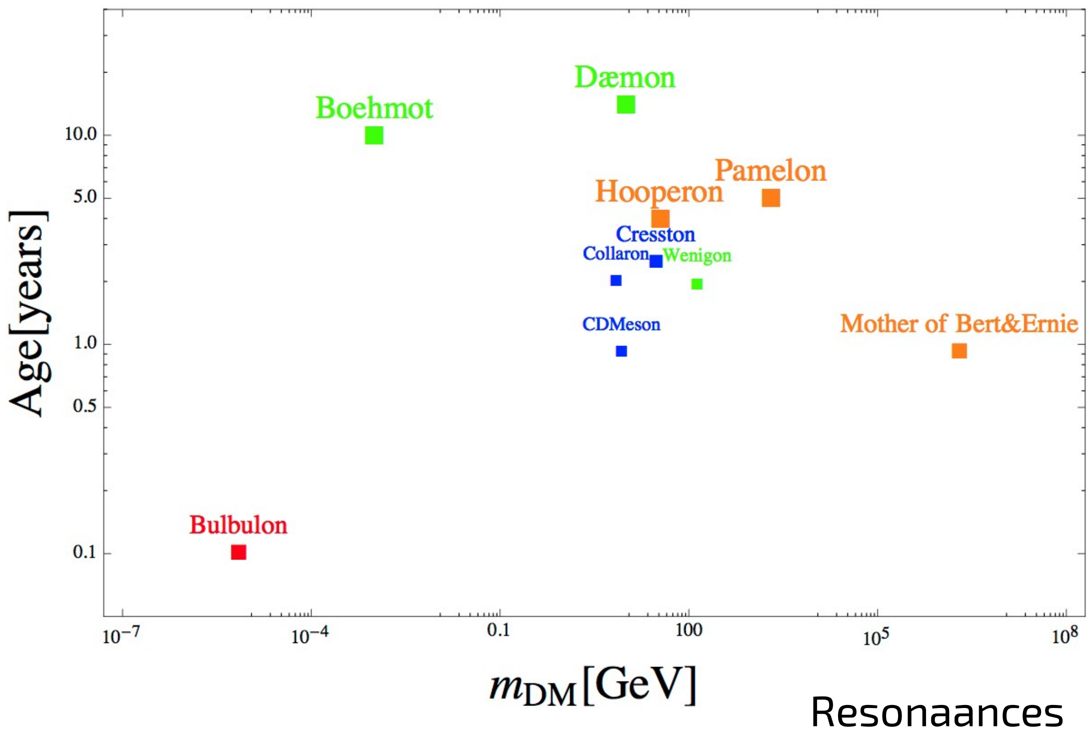
Candidates for particle dark matter

Mass-scales and interactions are suggested by

- Theoretical arguments → Various incarnations of **WIMPs, Sterile neutrinos, Axions, …**
- Hints in the data → **positron excess, 511 keV line, Fermi GeV excess, PeV neutrinos, …**

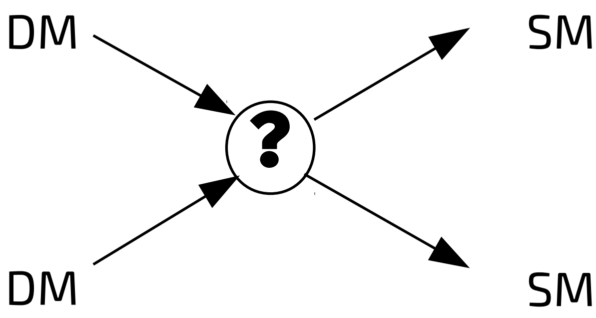


E-K Park 2007



Resonaances

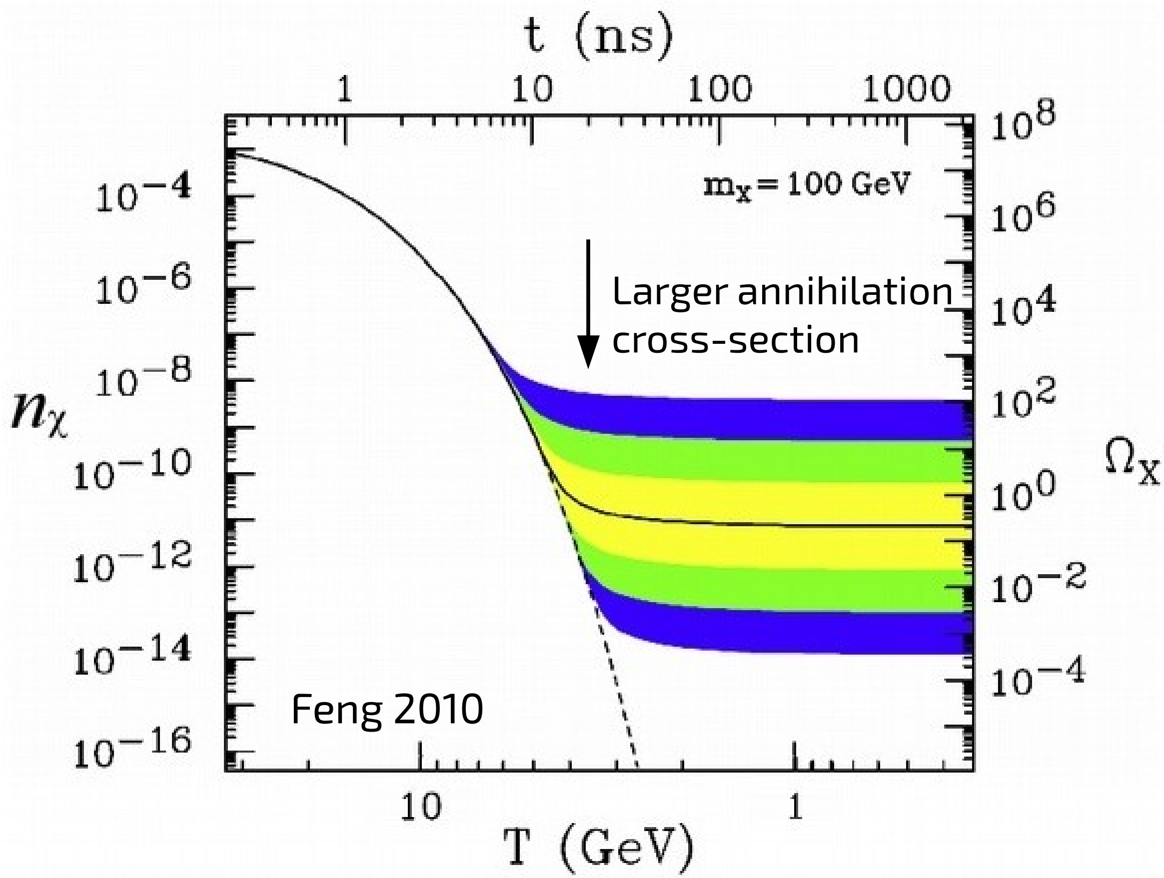
Freeze-out of WIMP dark matter



Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\text{eq}}^2 \right]$$

Velocity-averaged annihilation cross-section in early Universe is fixed by observed mass density of DM



$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle}$$

This is very close to experimental sensitivities!

This provides a rough estimate for annihilation rate of DM particles today.

How would a dark matter signal look like?

Spatial characteristics

(for prompt photons from DM annihilation)

- Signal proportional to column square density
- Contributions from MW center, subhalos, nearby galaxies and galaxy cluster, the distant Universe

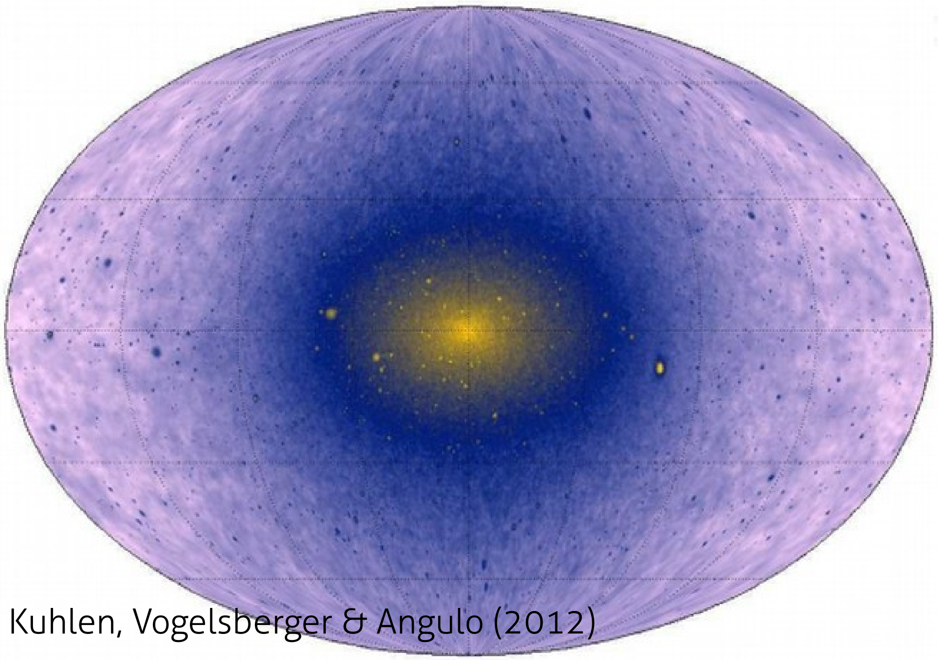
Spectral characteristics

- In most cases bumped, with a bumpiness hierarchy like

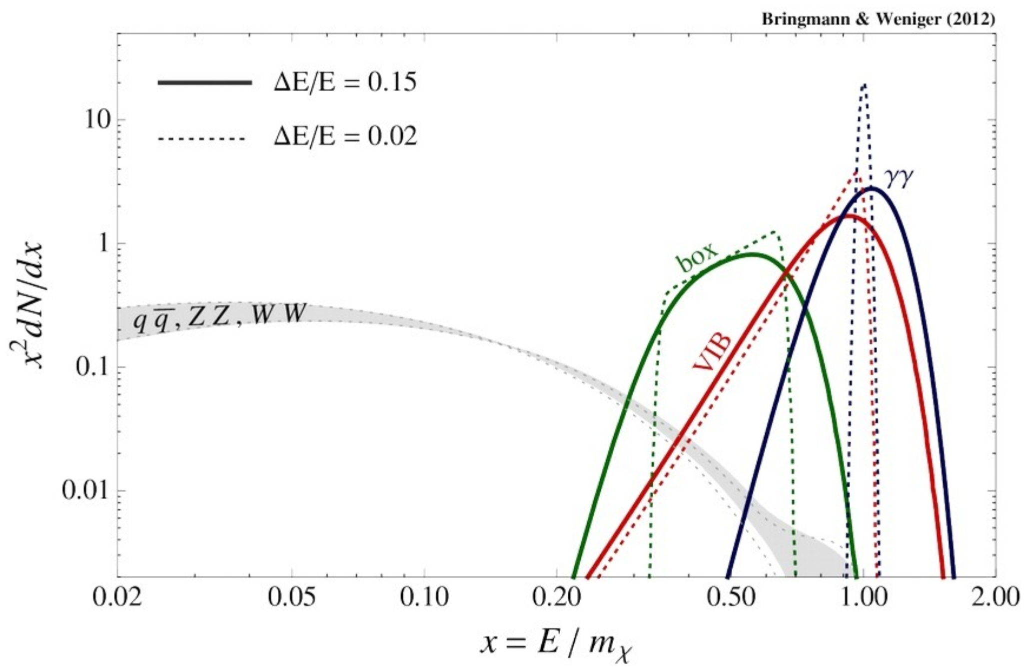
  hadronic < leptonic < lines

- *Not* like typical astronomical thermal or non-thermal (PL-like) spectra

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



Kuhlen, Vogelsberger & Angulo (2012)



An incomplete list of relevant instruments

Space based

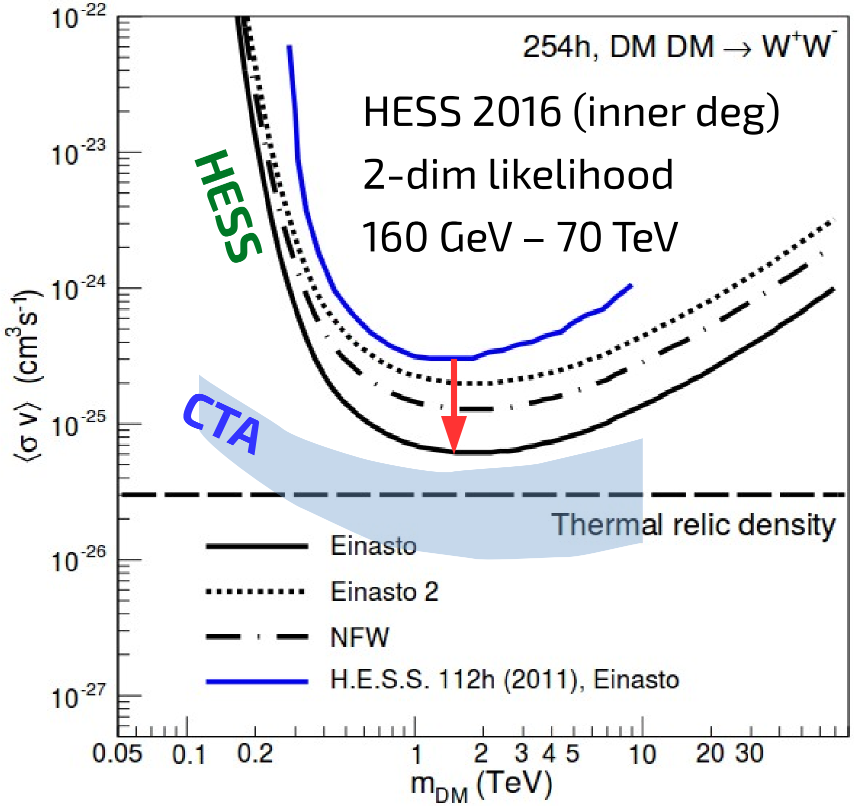
- gamma ray & cosmic rays: **Fermi LAT**, **AMS-02, PAMELA**, **Integral, Comptel**, **CALET, DAMPE**, *HERD*, *E-Astrogam*, *PANGU*, *GAPS*, ...
- X-ray: **XMM-Newton**, **Chandra**, **Hitomi / Astro-H**
- visible: **Galex**, **HST**, Astrosat
- microwave: **FIRAS**, **COBE**, **WMAP**, **Planck**, Pixie

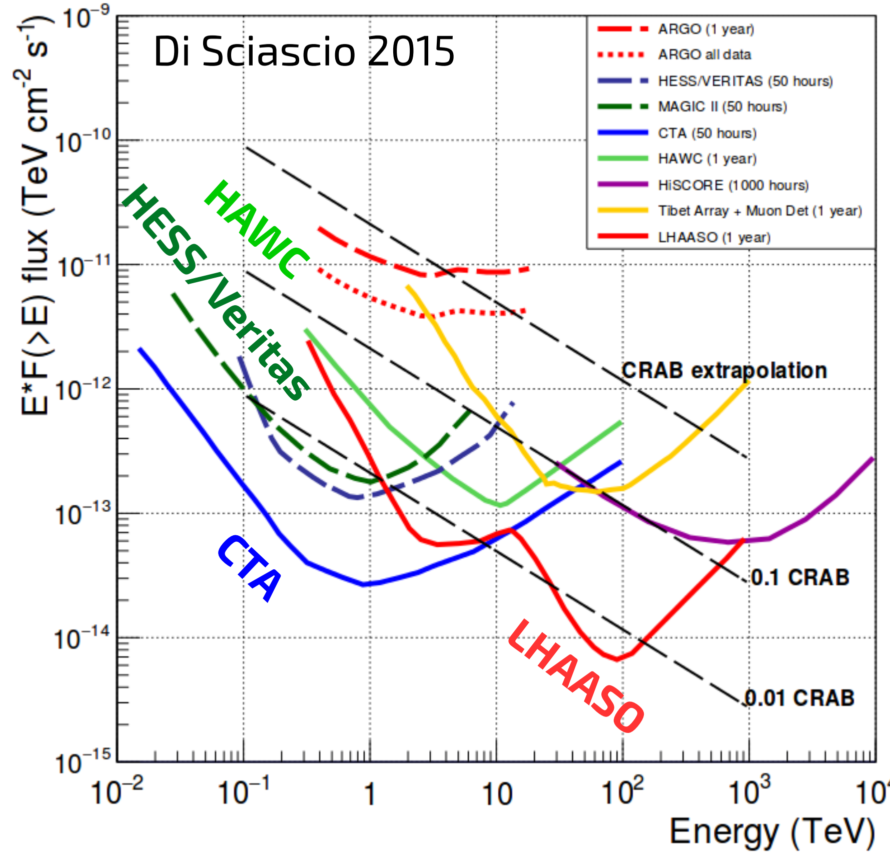
Ground based

- gamma ray & cosmic rays: **HESS**, **MAGIC**, **Veritas**, *CTA*
- X-ray: *Micro-X*
- visible: **SDSS**, **DES**, LSST
- microwave: **BICEP-2**
- radio: **VLA, GBT**, *MeerKAT*, *SKA*

100 MeV to > PeV

Very-high-energy gamma rays





DM searches with Cherenkov telescopes

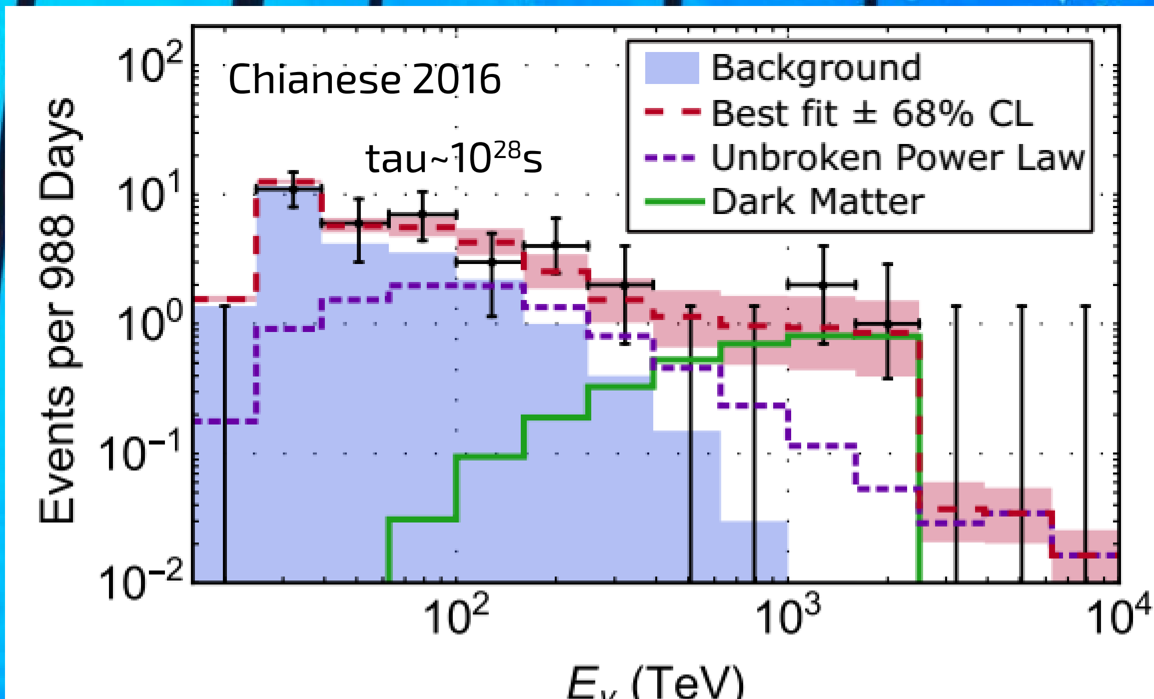
- Large CR backgrounds imply that brightest targets are best → Go for the GC
- Strongest limits from HESS GC halo observations, recent updates use improved stat. method (HESS 2016)
- Relevant limits at ultra-high-energy gamma rays (m>100 TeV) come from IceCube (Murase & Beacom 2012)

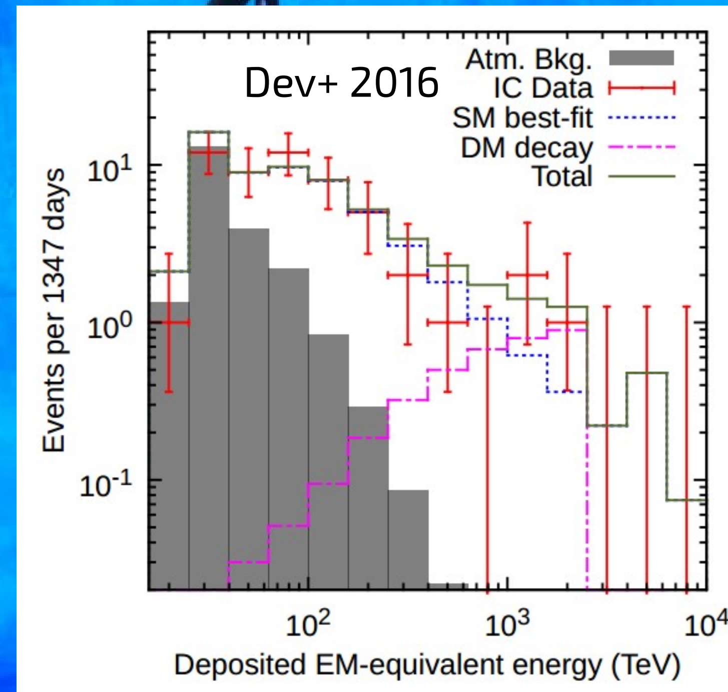
Future **Talks D. Paneque, B. Humensky, J. Linnemann, A. Morselli (Fri)**

- Above m~100 TeV, HAWC will improve limits from observations of dSph & GC (Abeysekara+ 2014; Proper+ 2015)
- LHAASO (~2022) will dominate above m~100 TeV in the long run (e.g. Knödlseder 2016)
- CTA (~2021) will improve HESS limits by factor up to 10 (Silverwood+ 2015, Doro+ 2013, Carr+ 2015, Lefranc+ 2015)

PeV neutrinos from dark matter decay?

The decay of super-heavy DM particles could be responsible for IceCube neutrinos





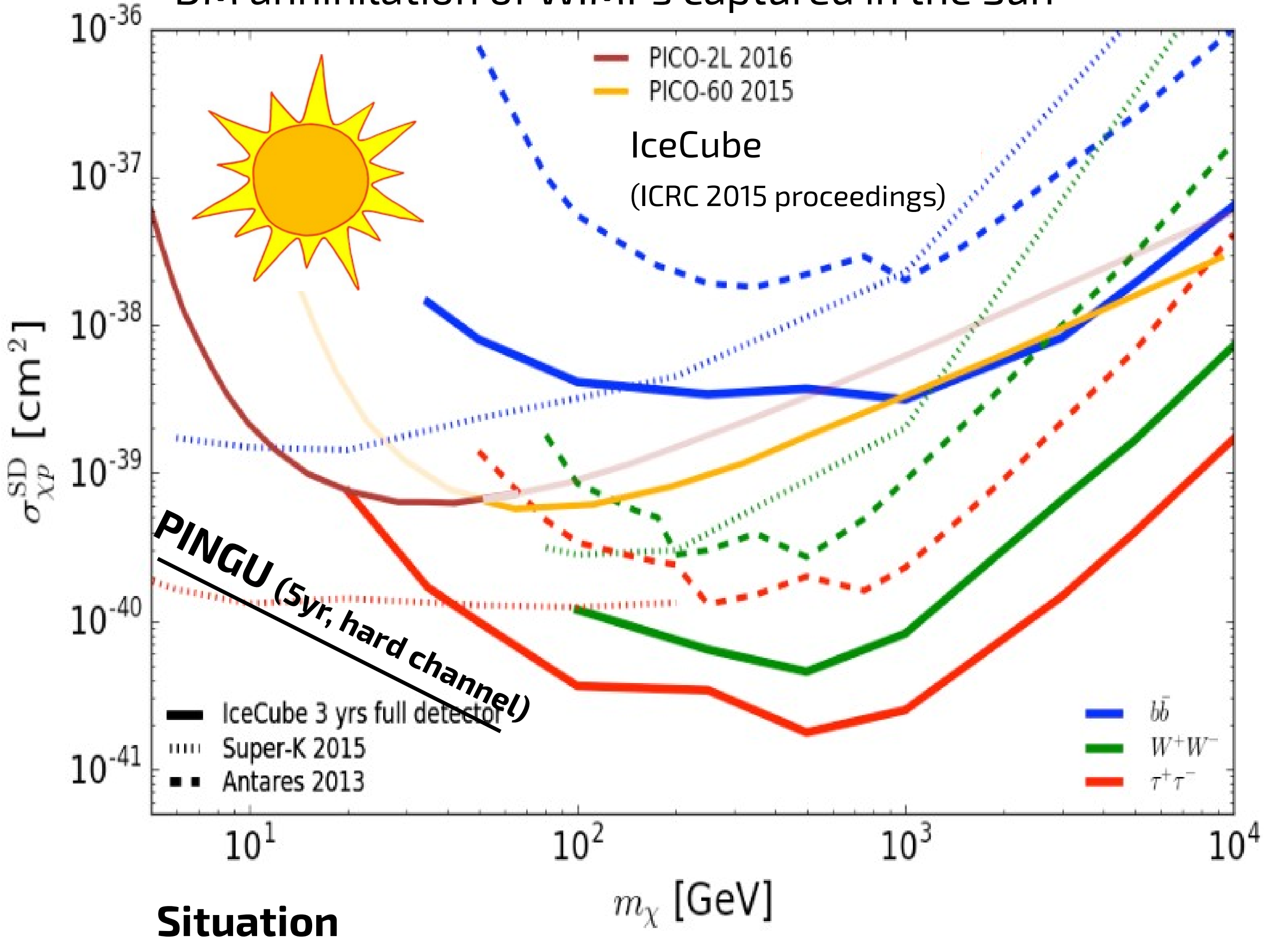
PeV neutrinos from DM

- IceCube neutrinos open new window to study exotic contributions from dark matter
- Apparent abrupt cutoff compatible with typical DM signal spectra
- Dipole-like anisotropy – for decaying DM, a 3 sigma detection takes up to ten years to collect enough data (Esmaili & Serpico 2013)

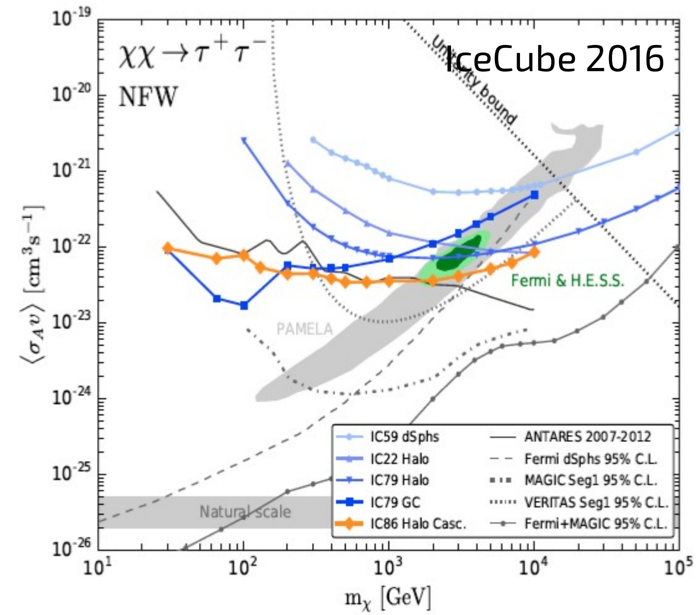
See also Esmaili&Serpico '13/14; Anchordoqui+ 2015; Murase+ 2015

Neutrinos from solar WIMP annihilation

DM annihilation of WIMPs captured in the Sun



DM annihilation in MW



Situation

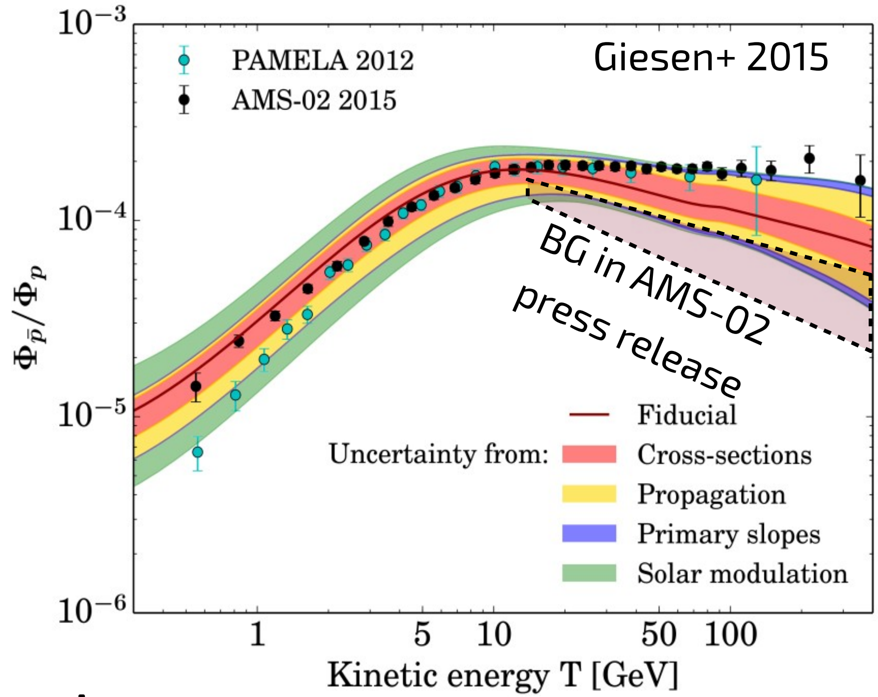
- Most stringent bounds on spin-dependent scattering cross-section in the 10 GeV to multiple TeV range come from neutrino telescopes (IceCube, Super-K)
- "Conventional" searches for signal from GC not very competitive

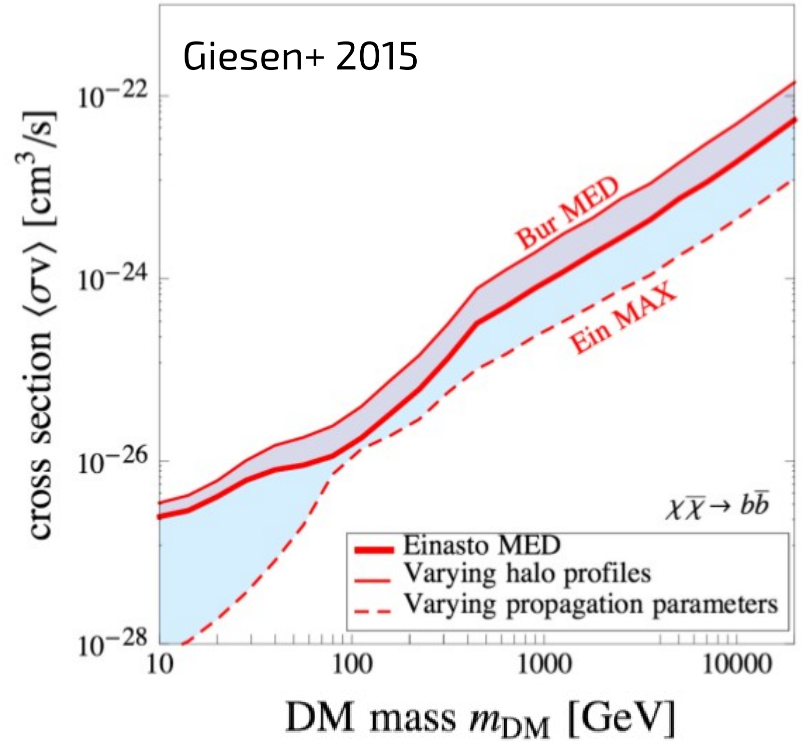
Future **Talks A. Takeda, M. Medici, M. Chianese (Thu)**

- PINGU (~2020?) will improve sensitivity to WIMP masses below 100 GeV significantly
- Hyper-K (~2026): Improvement by x5 at low energies

Cosmic-ray anti-protons

Dark matter annihilation can contribute to anti-proton cosmic rays





Situation

- Background of secondary anti-protons can be predicted within factor of a few
- Measured anti-proton flux marginally consistent with secondary background (Giesen+ 15; Evoli+ 15)
- Limits are around level of gamma-ray dSphs, but more uncertain (diffusion zone height, winds etc)
- Hard to exclude astro explanation for excesses above secondaries (e.g. nearby SNR; e.g. Kachelriess+ '15)

Future Talk F. Donato (Fri), P. Salati (Tue)

- Data at higher energies; but interpreting an excess in anti-protons will remain a challenge
- But: anti-deuterons are a background-free channel! Results awaited from AMS-02, later GAPS

Talk P. Doetinchem, A. Raklev (Tue)

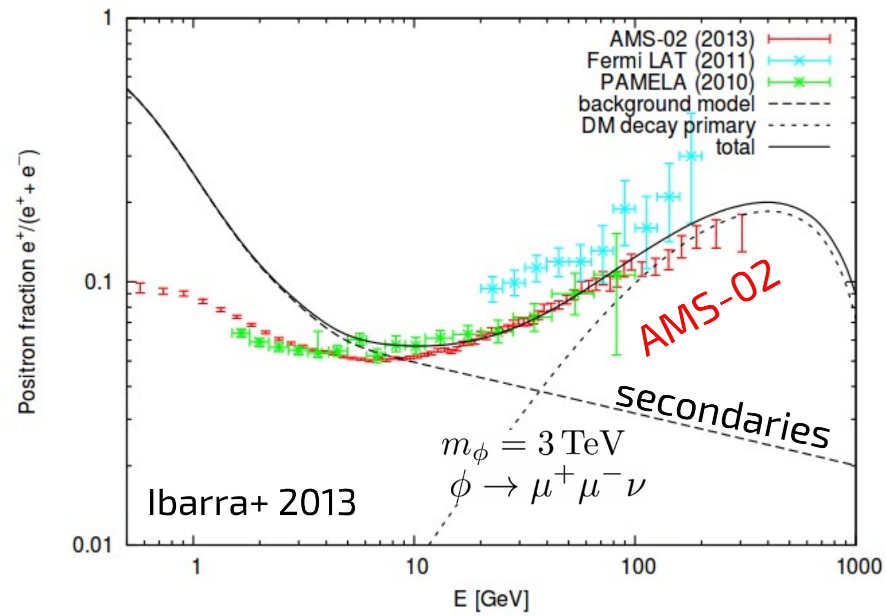
See also: Carlson+14; Cirelli+14; Jin+15; Ibe+15; Hamaguchi+15; Lin+15; Kohri+15; Balazs&Li15; Doetinchem+15; Fornengo+13

Cosmic-ray positrons

Situation (very different from anti-protons)

- There is a clear excess above secondaries (e.g. Delahaye+ '10, Kappl & Reinert '16)
- Explaining 100% of the excess with DM is largely excluded (nothing in gamma, pbar etc) (e.g. Papucci & Strumia '10, Cirelli+ '10, Ibarra+ '13, Slatyer '15)

Talk M. Boudaud (Tue)



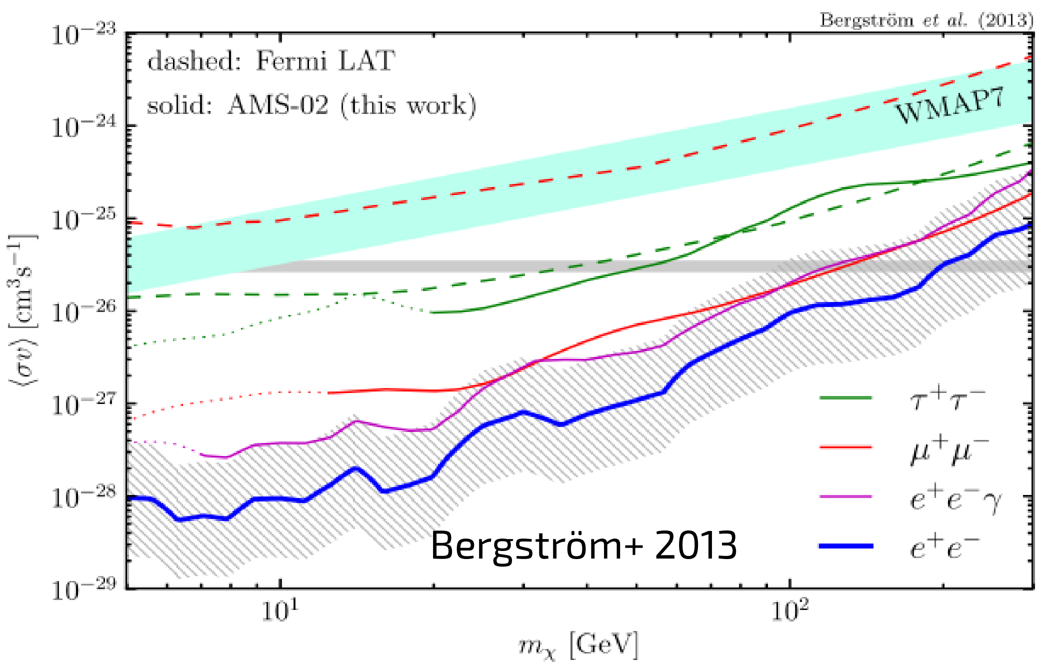
Future

- Still, hope is to see DM contribution as clear cutoff in the positron fraction at > 400 GeV energies
- Even then, recent nearby pulsars could give similar signature (e.g. Pato+ '10)
- High energy-resolution measurements of positrons/electron flux (e.g. CALET)

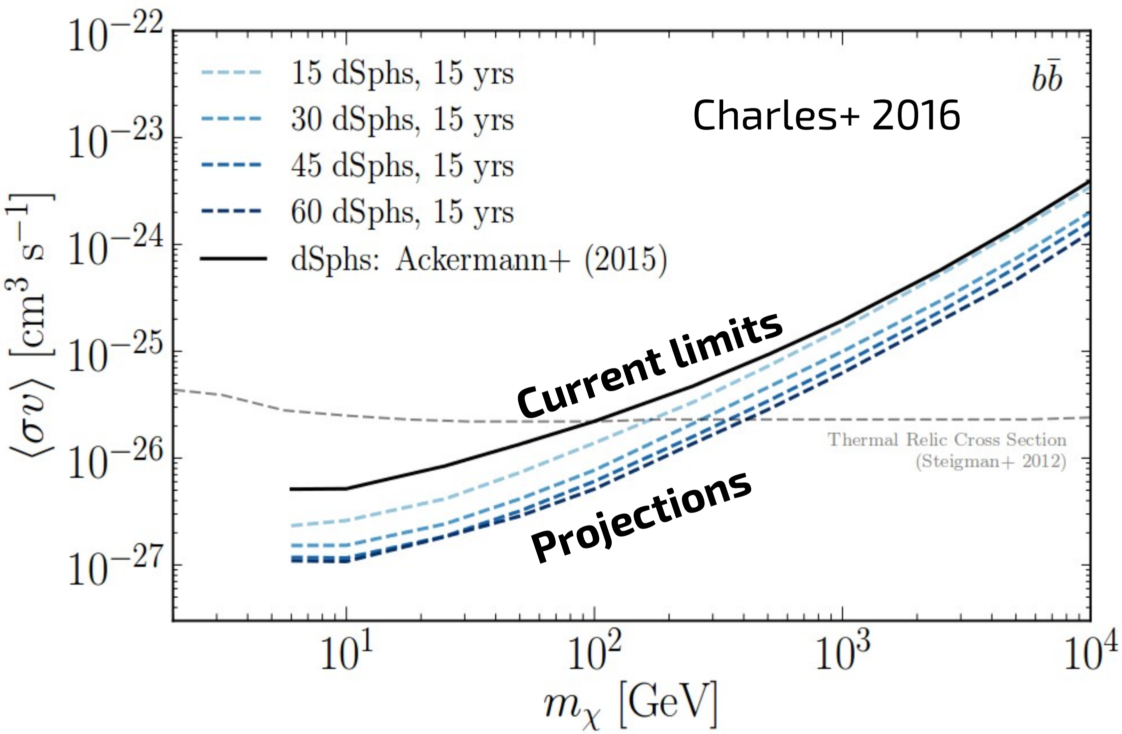
Talk H. Motz (Tue)

Playing it safe

- Assume all of the smooth positron excess is due to pulsars
- Constrain DM annihilation/decay into leptonic channels with (spiked signals!) (Bergström+ '13, Ibarra+ '13)

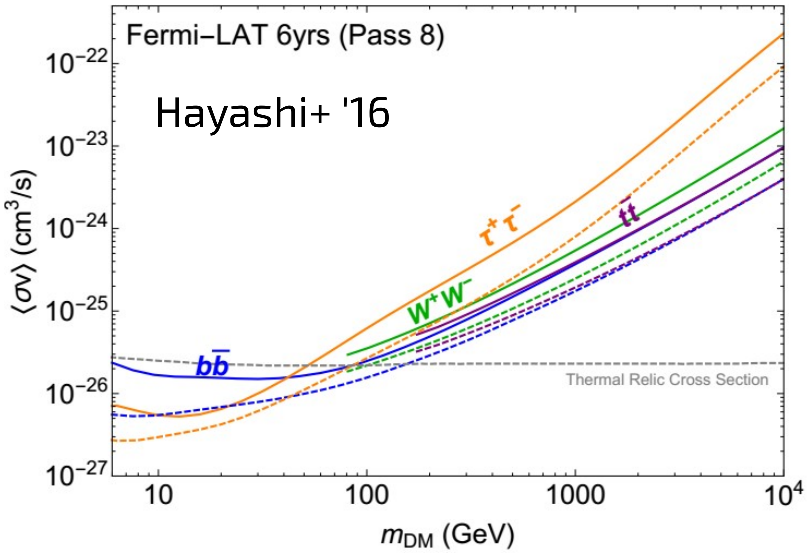


Gamma rays from dwarf spheroidal galaxies



Situation

- Current stacked limits from 15 dSphs cross thermal cross-section at 100 GeV
- Still quite some discussion about J-values in the literature (e.g. Bonnivard+ '15, Geringer-Sameth+ '15, Charbonnier+ '11, Walker+ '11)
- Impact of tri-axiality somewhere around factor 2 (Bonnivard+ '15, Hayashi+ '16)
- Non-parametric approach can reduce J-values by up to factor 4 (Ullio & Valli 2015)
- Still, thanks to combination of sources, limits are likely the most robust ones

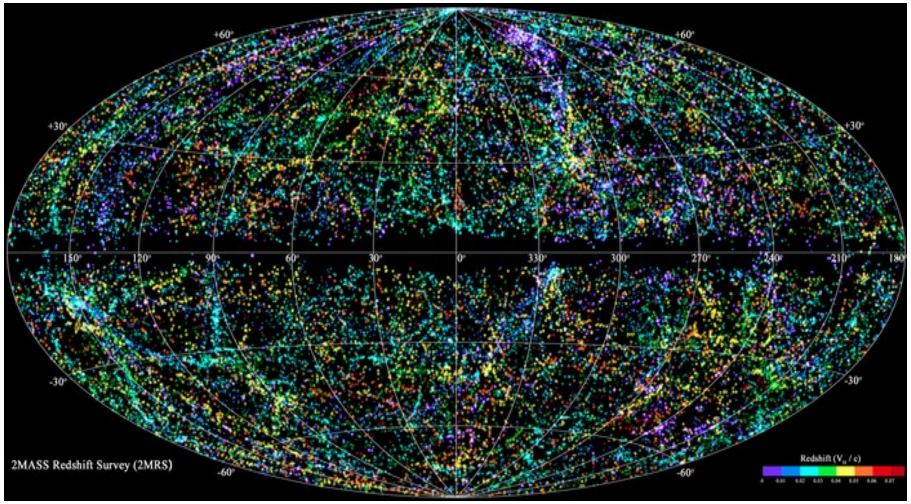


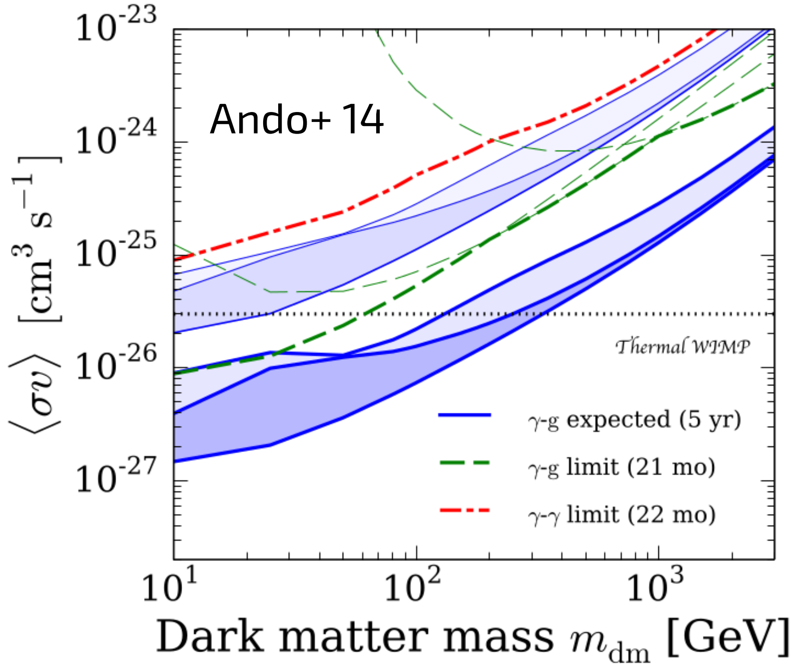
Future Talks K. Ichikawa, A. Chiappo (Mon)

- Fermi will remain best satellite in ~0.3 – ~50 GeV region for the foreseeable future
- Future limits might improve by factor 2-5, depending on how many dwarfs will be found in addition (100s expected from DES, Pan-STARRS, LSST; Hargis, Willman & Peter 2014)

Cross correlation with galaxy catalogs

Cross-correlation with galaxy catalogs



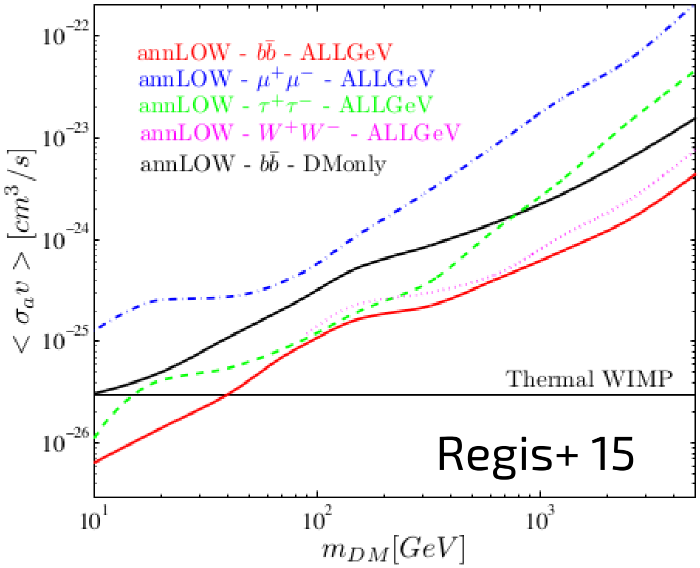


Situation

- DM annihilation predicted to have large correlation with 2MRS galaxies (up to z~0.1)
- Correlation analysis great to reduce "astrophysical backgrounds"
- Predicted sensitivity is comparable with dSph limits (Ando+ 14)
- Correlations with several catalogs detected (2MASS, NVSS, SDSS-QSO, SDSS) (Xia+ '15, Cuoco+ '15)

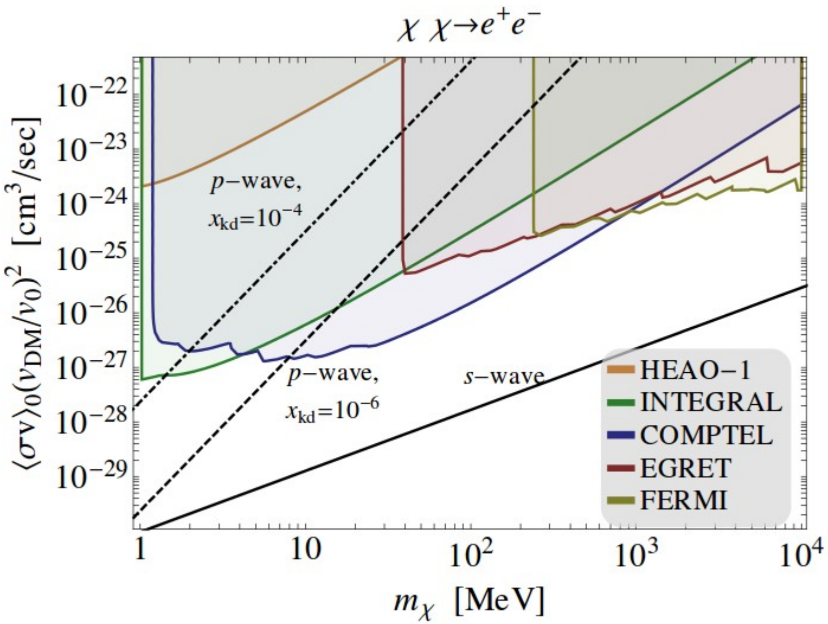
Future

- Combined analysis of wavelet, 1-point fluctuation, 2-point correlations etc



Talk M. Fornasa, M. Regis (Mon)

Future telescopes & the MeV gap



Essig+ 2013;
see also Boddy & Kumar 2015

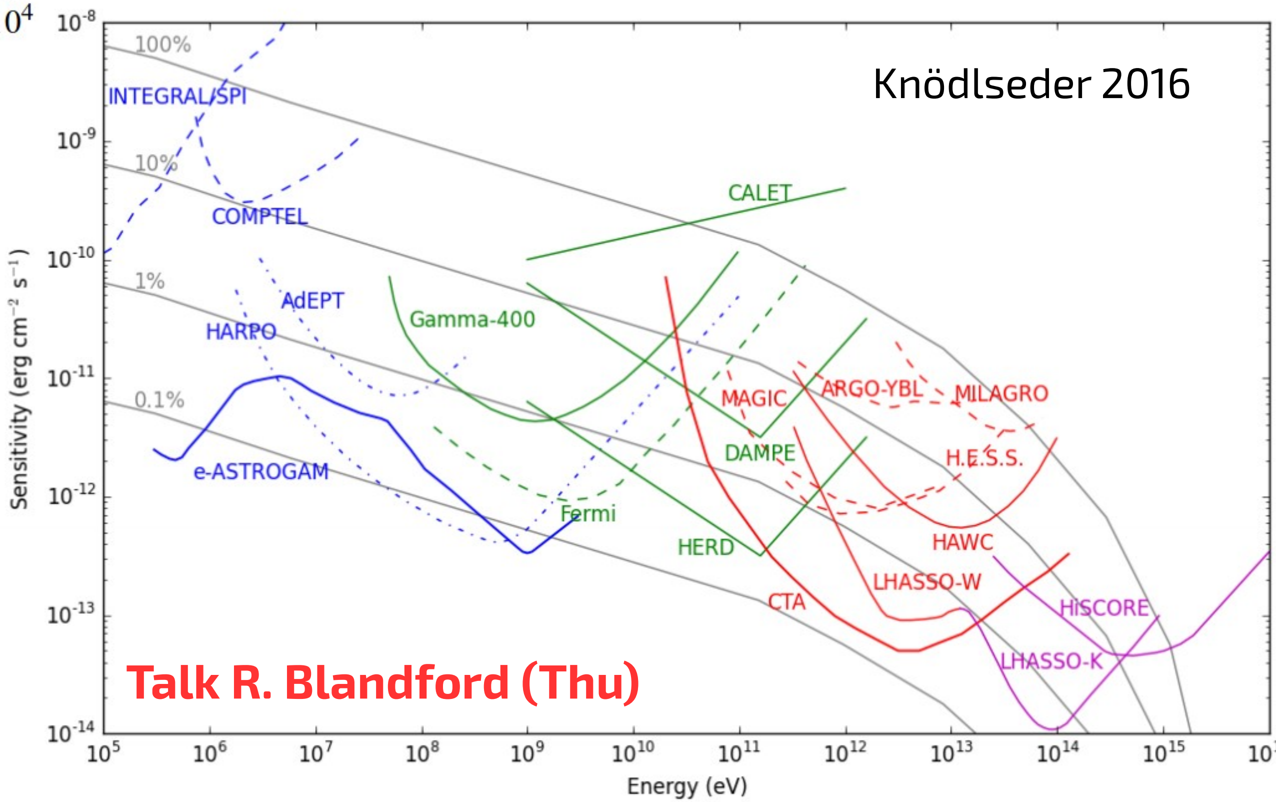
In-flight annihilation important at MeV scale!

Talk R. Bartels

Future gamma-ray telescopes

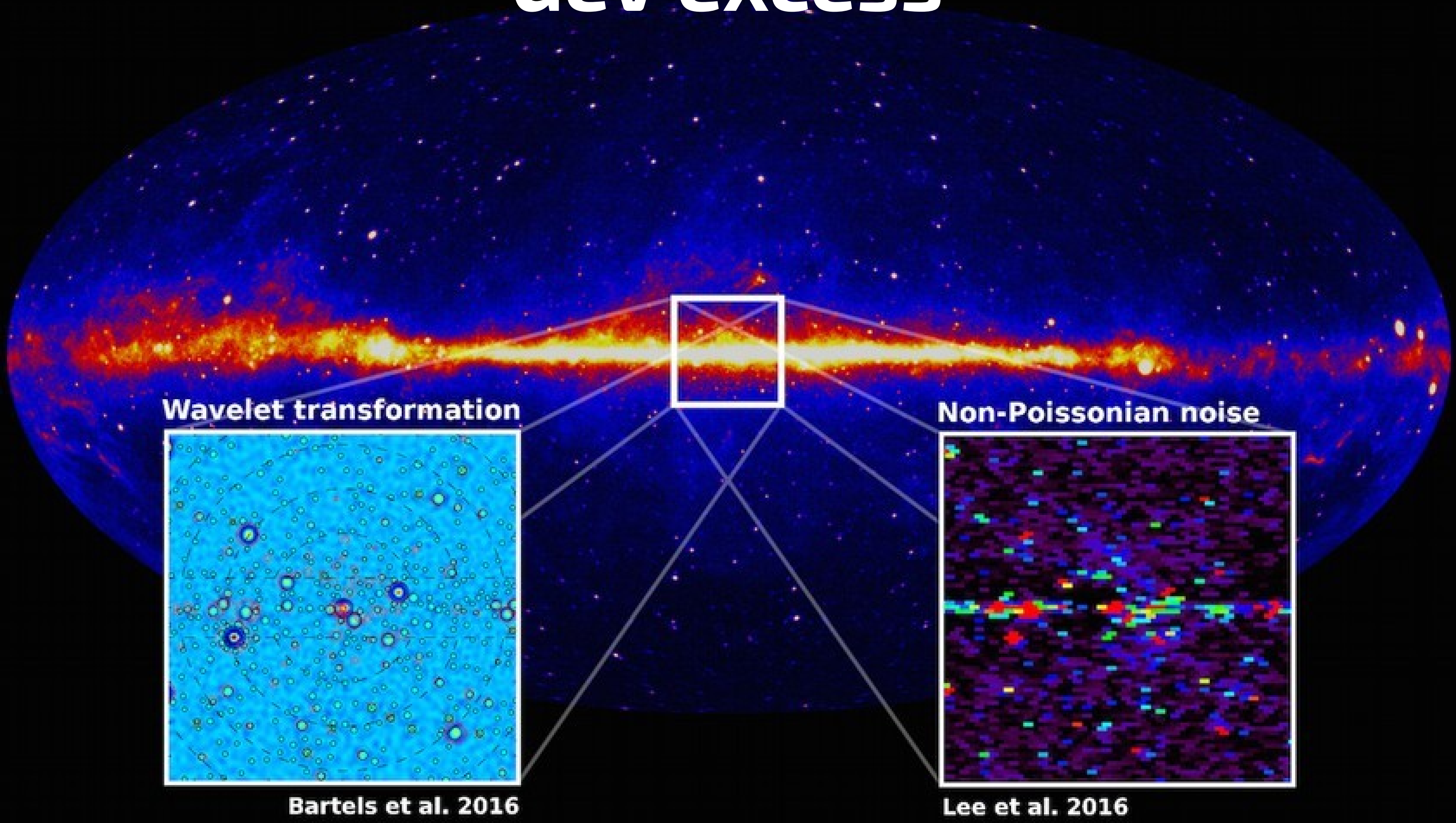
- CALET (in space, ISS) – ΔE/E=2% @ 100 GeV – small A_{eff}
- DAMPE (in space) – ΔE/E=1.5% @ 100 GeV – small A_{eff}
- HERD (~2020?) – 1% energy res. @ 100 GeV
- GAMMA-400 (~2021?) – 0.02 deg resol. @ 100 GeV
- e-ASTROGAM (~2029?) – explore < 100 MeV range
- ComPair (?), PANGU (?)

Talk H. Motz (Tue)



Talk R. Blandford (Thu)

The Fermi Galactic center GeV excess



Point sources or diffuse emission?

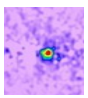
The Fermi Galactic center GeV excess

Various groups found an "excess of GeV photons" that extends from the Galactic center up to mid-latitudes. (Goodenough & Hooper 2009; Vitale & Morselli 2009, …

… Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Cholis+ 15; Bartels+ 15; Lee+ 15, …)

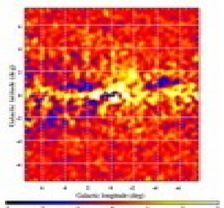
Different groups, different ROIs

$7^\circ \times 7^\circ$

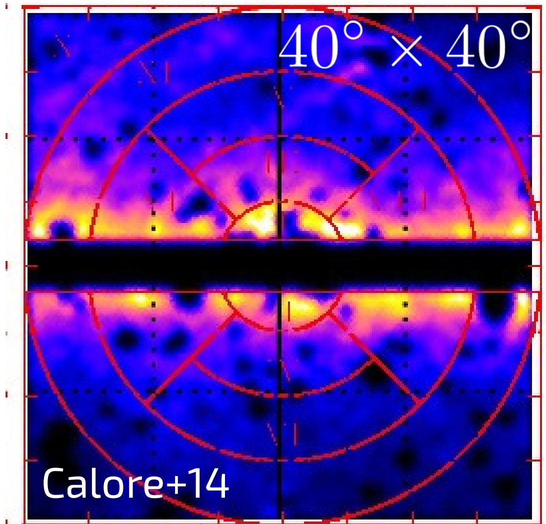


Daylan+ 14 (GC analysis)

$14^\circ \times 14^\circ$

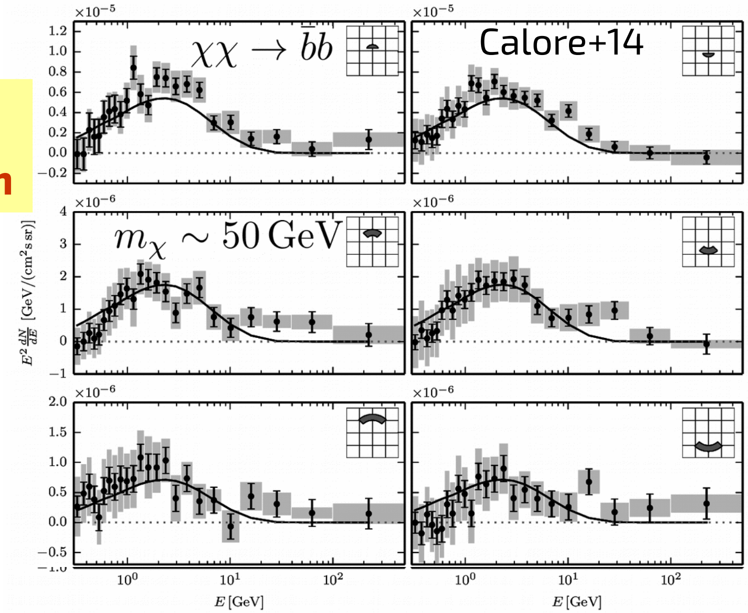


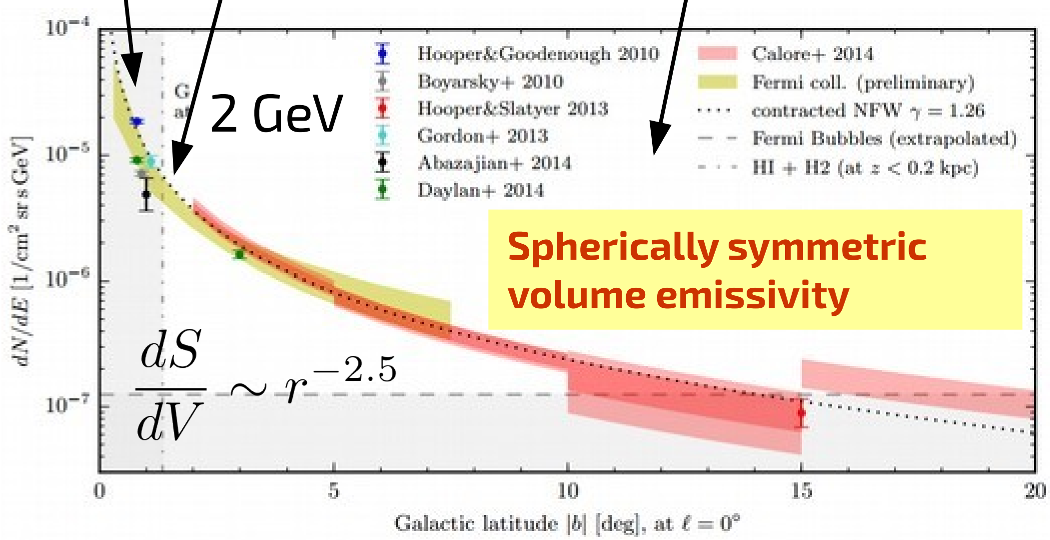
Ajello+15



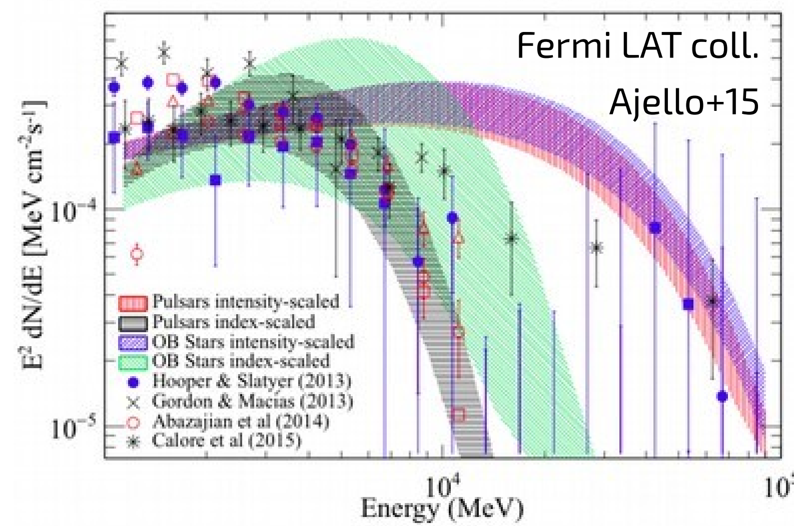
Uniform spectrum

Peaks at 1-3 GeV





Spherically symmetric volume emissivity



Talks E. Bloom, T. Linden, E. Storm, M. Di Mauro, W. De Boer, J. Heisig (Thu)

~~Fermi GC Excess~~ → Galactic bulge emission

Given what is *actually* done in many analyses, it would be more adequate, and much less confusing, to call the "Fermi GeV excess" just

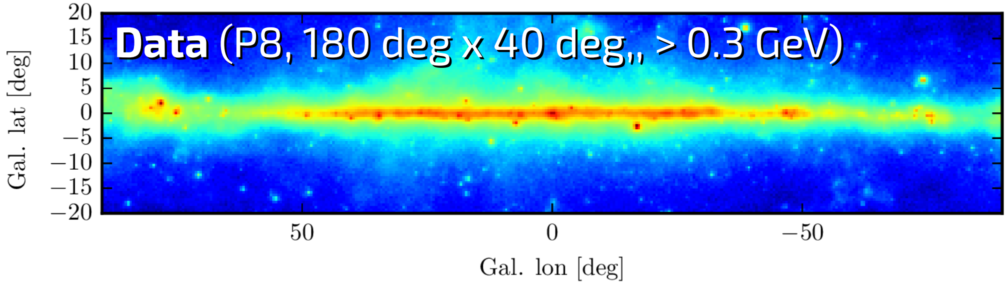
Gamma-ray emission of the Galactic bulge.

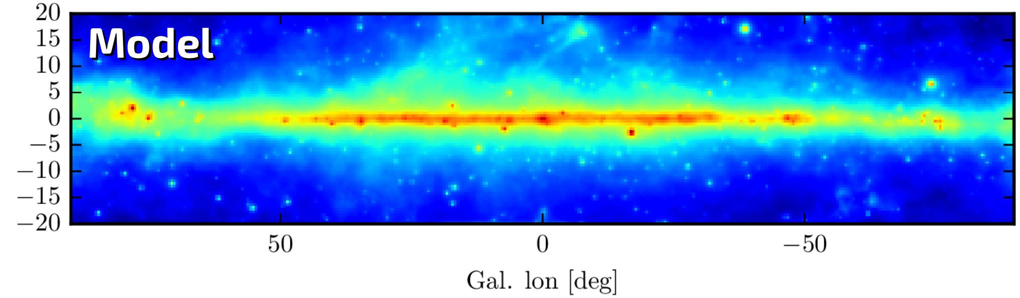
Towards the bulge emission with SkyFACT

SkyFACT: Sky Factorization with <u>Adaptive</u> Constrained Templates

(template regression on steroids)

Talk E. Storm (Thu)



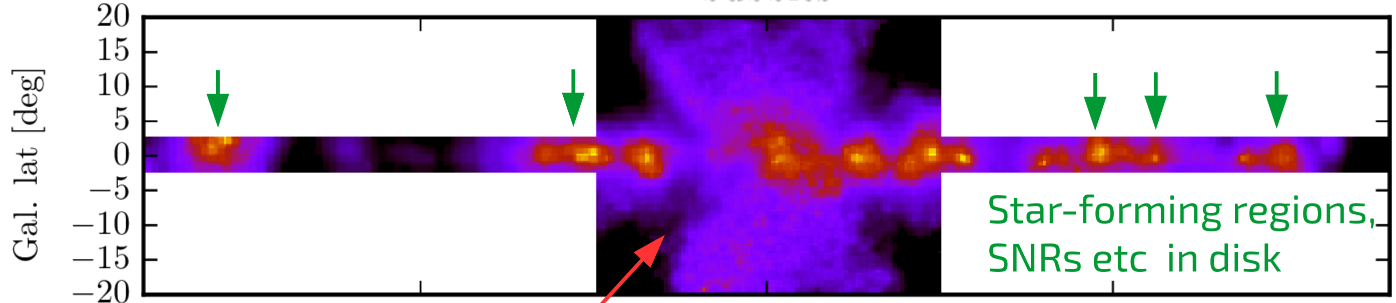


First results from SkyFACT

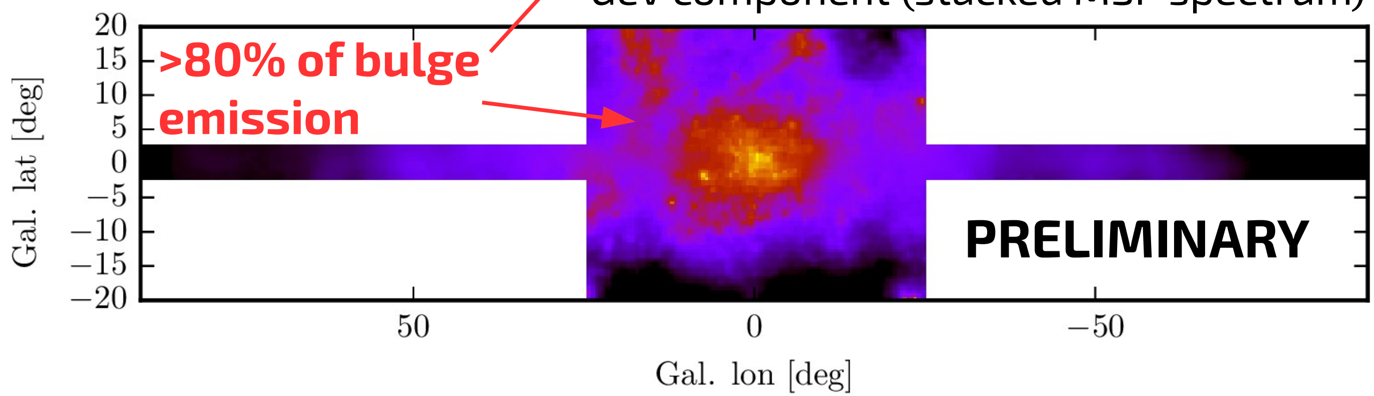
- 180 deg x 40 deg ROI
- Foreground/background modeling
  - All 3FGL sources with free spectra
  - ICS (Dragon/Galprop)
  - pi0 (Galprop/Dragon)
  - No CR sources in GC
  - Almost negligible emission in bulge region
- Bulge emission absorbed with two templates: fixed spectra (bubbles & MSPs) but adaptive morphology
- ~100000 free parameters (sic!)

One possible decomposition of the bulge emission:

Hard component (Fermi bubble spectrum)

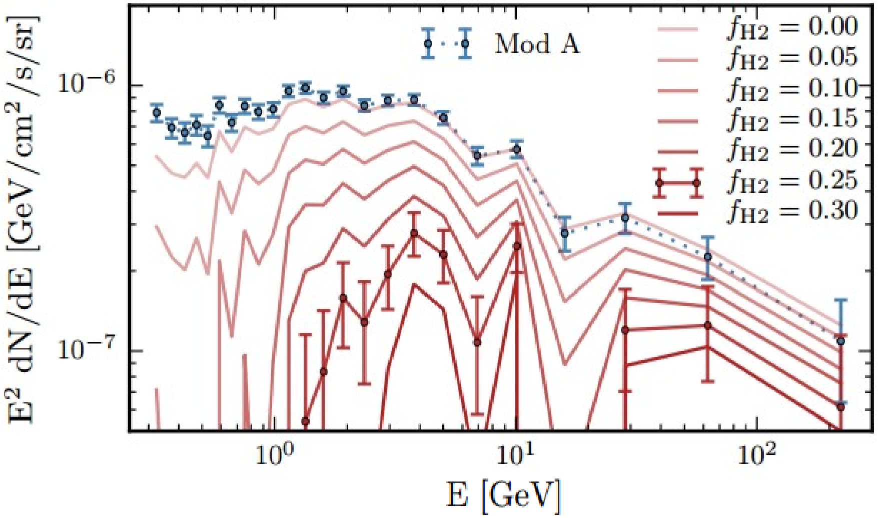


~GeV component (stacked MSP spectrum)

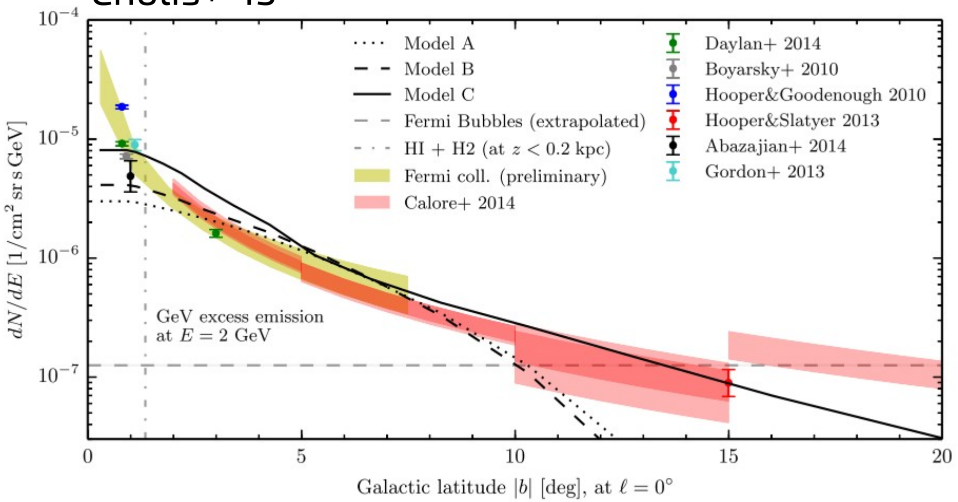


Possible contributions to bulge emission

Carlson+ '15



Cholis+ '15



Expected contributions

- Star formation (Gaggero+ '15, Carlson+ '15)
  - ~O(5%) star formation in the GC provides similar amount of energy in CRs as seen in the GeV bulge emission
- Bubble-related emission (very hard to model)
- Young pulsars (can be reasonably modeled, O'Leary+ '15)
- Millisecond pulsars* (spectrum expected to bump at GeV energies, but not clear how many, how distributed, etc; Abazajian 11; Brand & Kocsis 15)

Speculative contributions

- Dark matter annihilation* (spectrum not exactly known but can bump at ~GeV energies, not clear how strong signal, what shape)
- Past activity of central black hole (cooling effects might in principle explain the observed peaked spectrum; e.g. Cholis+15; Petrovic+13)

*predict extended quasi-diffuse uniform spectrum

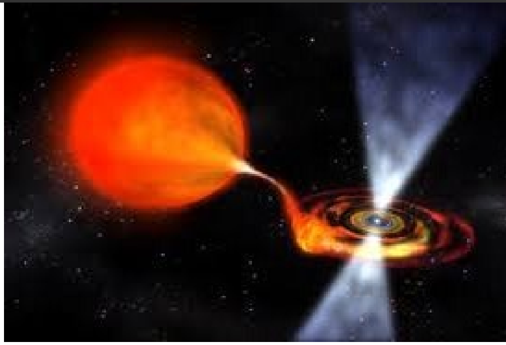
Millisecond pulsar mythbuster

The claim

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

Hooper+ 2013

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



“They are not abundant enough in the Galactic bulge”

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 (Brandt & Kocsis '15)

“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 demonstrated (Calore+13) that systematics are too large 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 that they prefer it with high statistical significance.

“The wavelet fluctuation signal is just gas”

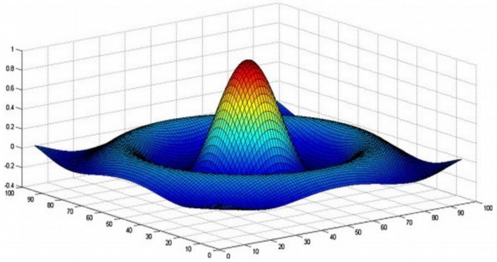
Almost certainly wrong. Masking problematic sky regions with strong gas contributions does not alter results significantly (Bartels+ in prep)

“The brightest bulge MSPs should have been seen in radio”

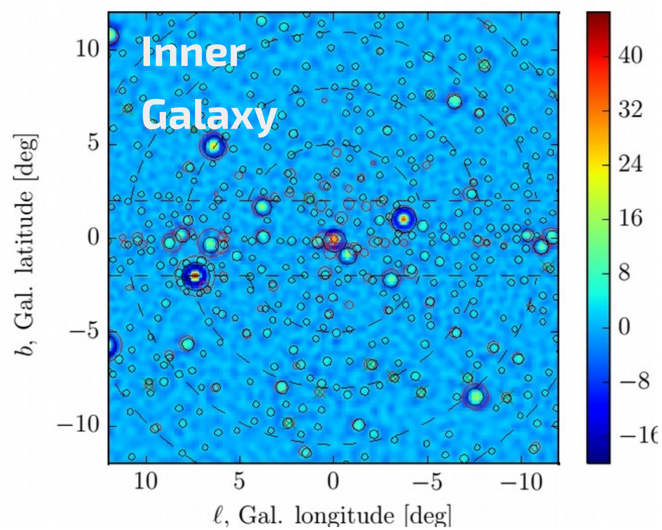
Wrong. We showed (Calore+15) that they are instead just around the corner.

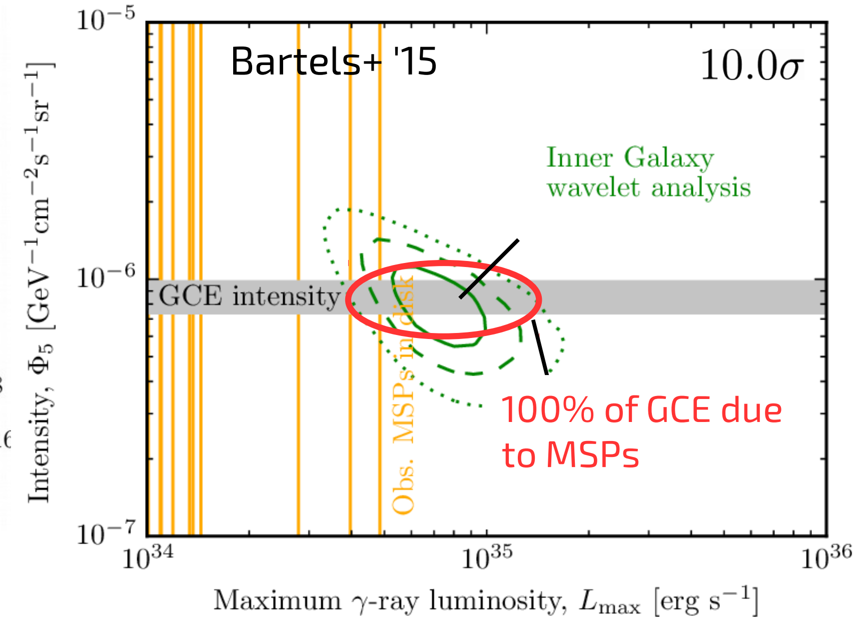
Wavelets! Strong support for MSP hypothesis

Mexican hat wavelet



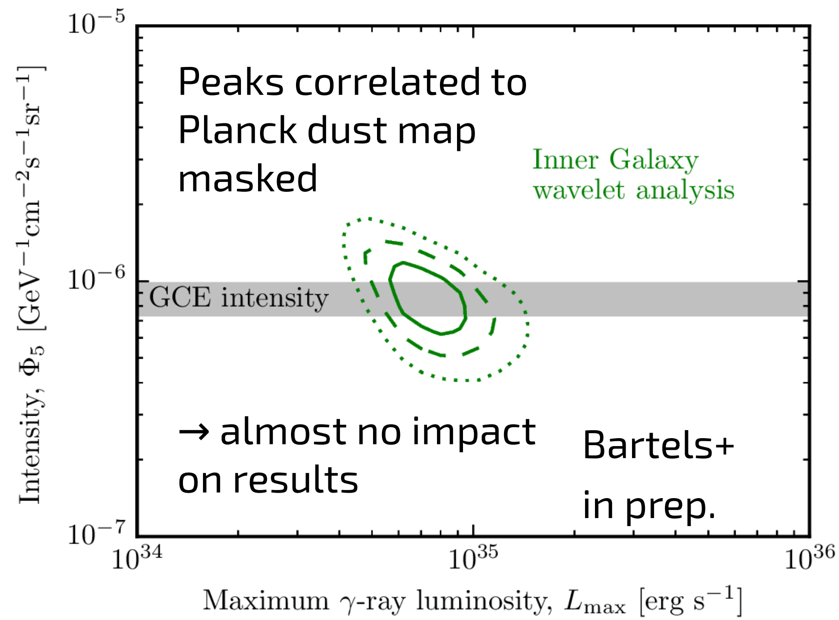
Credit: https://www.researchgate.net





Results

- Number and spatial distribution of 1-10 sigma wavelet peaks in the inner Galaxy point to a large number of unresolved sources in that region
- Assuming that these are MSPs in the bulge (with properties as observed locally), these sources explain 100% of the GeV bulge emission
- We don't find indications for correlation with gas-induced wavelet peaks (Bartels+ in prep); density of "thick disk" sources too low to explain observations (Bartels+ '15)
- **Similar analysis with different method and systematics (Lee+ '15) comes to similar conclusions!**

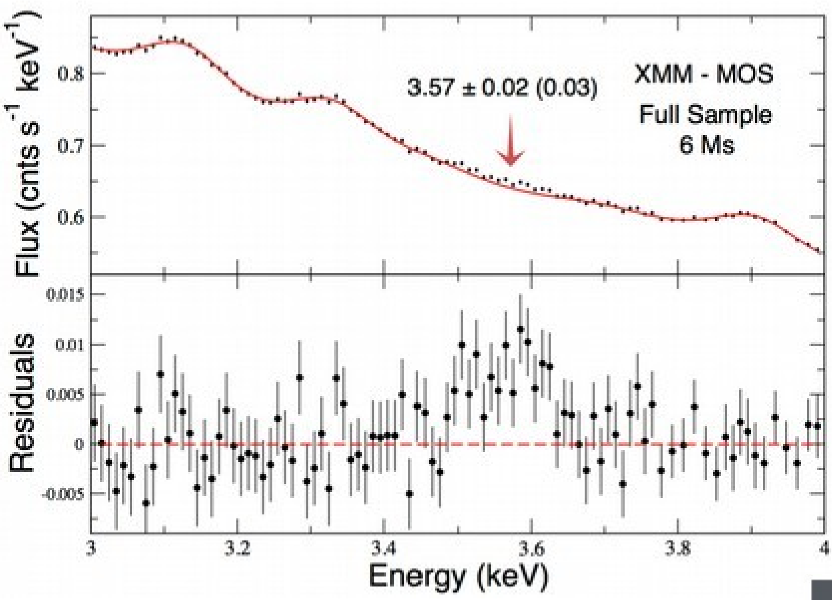


MSPs arguably the most plausible astro explanation for GeV bulge emission

→ Needs to be confirmed with radio searches

1 keV to 100 MeV

The 3.5 keV – Searches in many targets



Bulbul, Markevitch, Foster, Smith, Loewenstein+ 2014

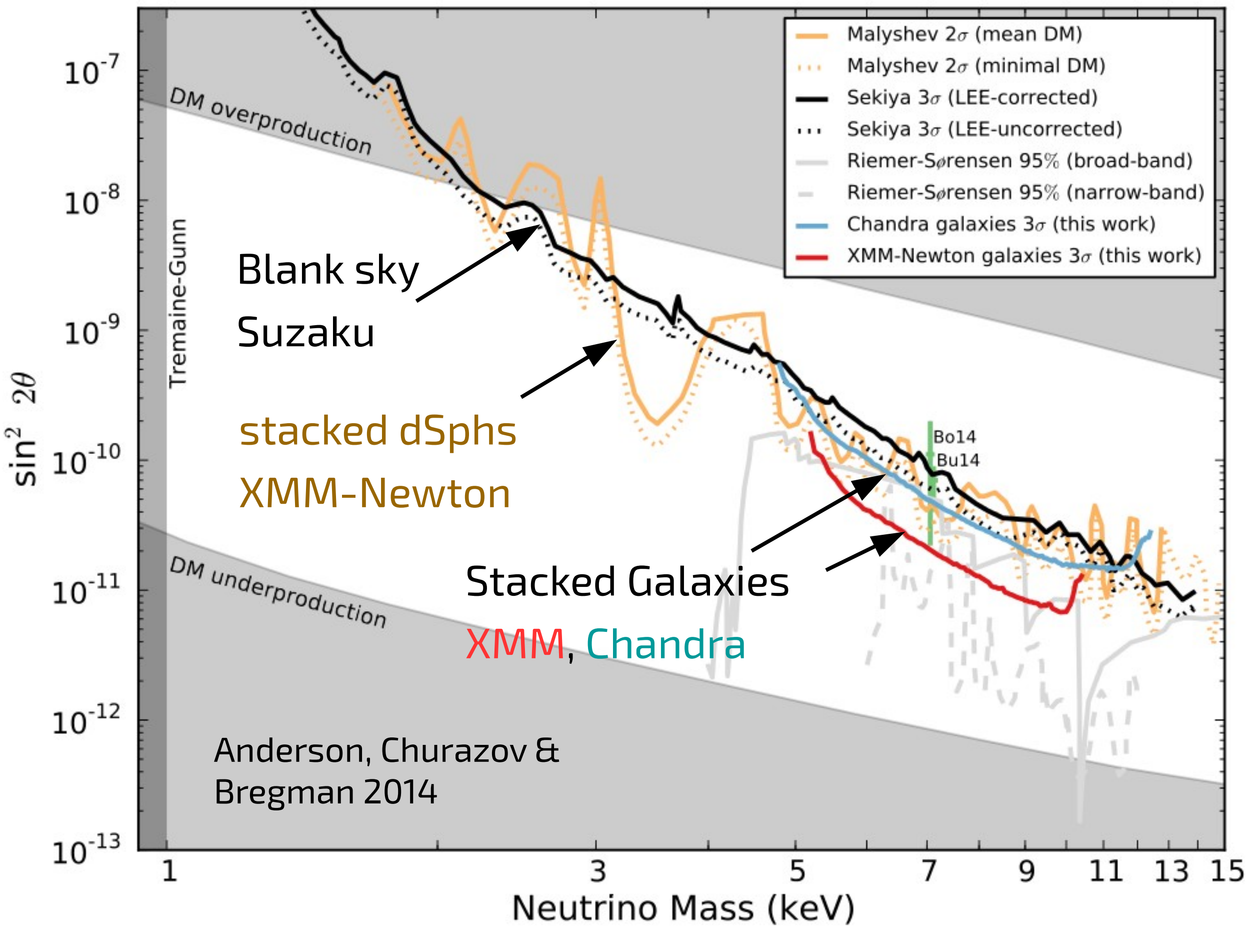
The 3.5 keV line

- First identified in 73 stacked and de-redshifted nearby galaxy clusters (central parts) (Bulbul+ '14)
- Shortly after in M31 and outskirts of Perseus (Boyarsky+ '14)
- Large number of follow-up studies in Galactic center, dSphs, stacked galaxies
- Non-observations seem to disfavor decaying dark matter interpretation
- Debate about Potassium lines, charge exchange lines etc (e.g. Jeltema & Profumo '14)

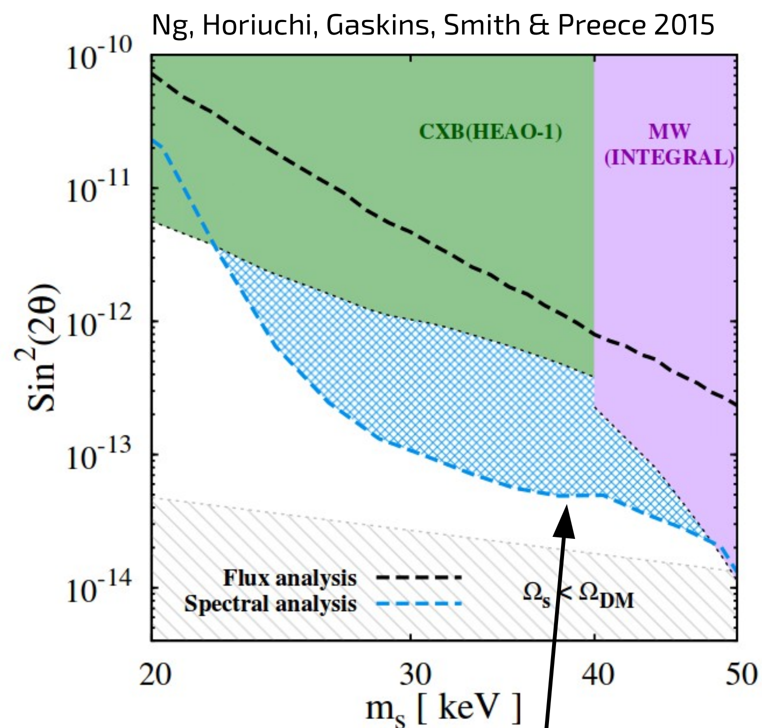
Target	Instrument	Significance (σ)	Reference
M31	XMM-Newton/MOS	3.2	Boyarsky 2014 1402.4119
Perseus Cluster (outskirts)	XMM-Newton/MOS XMM-Newton/PN	2.6 2.4	Boyarsky 2014 1402.4119
Perseus Cluster (center)	Chandra/ACIS	3.5	Bulbul 2014 1402.2301
Perseus Cluster (center)	Suzaku	3	J. Franse (TAUP 2015)
Galactic Center	XMM-Newton/MOS	5.7	Boyarksy 2014 1408.2503
73 Stacked Clusters (z<0.4)	XMM-Newton/MOS XMM-Newton/PN	5 4	Bulbul 2014 1402.2301
8 Stacked dSphs	XMM-Newton/MOS XMM-Newton/MOS	Non-detection	Malyshev et al. 2015 1408.3531
M31	Chandra/ACIS	Non-detection	Horiuchi et al. 2014 1311.0282
Blank Sky	XMM-Newton/MOS	Non-detection	Boyarsky 2014 1402.4119

Table stolen from Keith Bechtol (TeVPA '15)

Summary current limits



Talk M. Drewes (Thu)



4 yr Fermi GBM, NaI detectors, ΔE/E~10%

Sterile neutrino dark matter

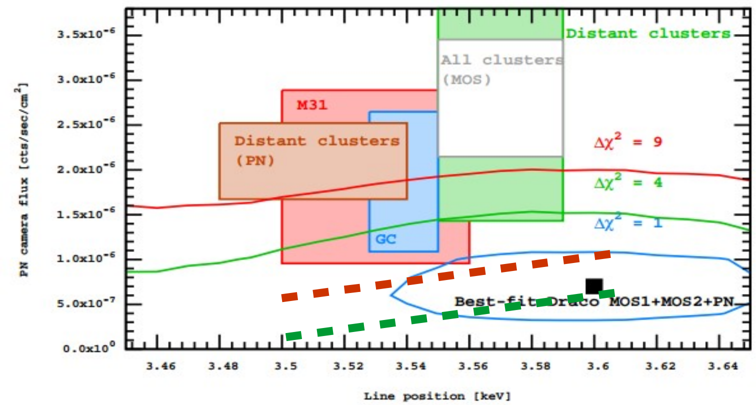
- Upper limit from non-resonant production
- Lower limit from resonant production
- Left limit from phase space arguments (Tremaine & Gunn 1978; e.g. Hannestad 2006)
- Upper-right limits from X-ray line searches

Recent updates & outlook

Draco campaign with XMM-Newton

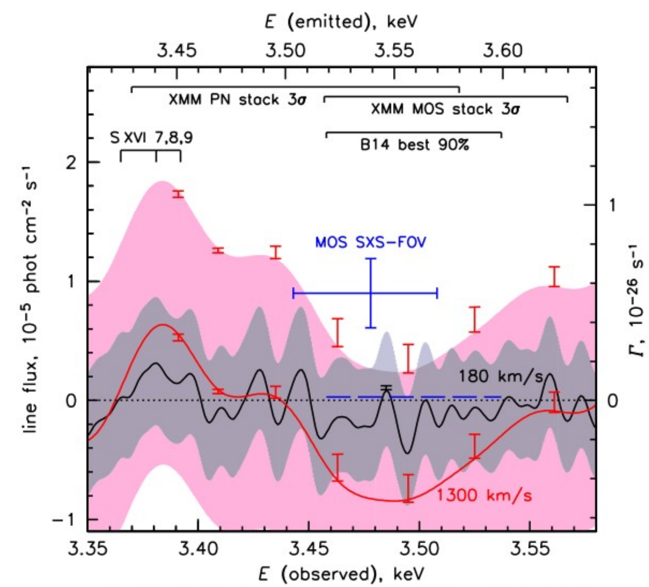
- 1.5 Ms observation time in 2015
- Jeltema & Profumo '15: Claim they can exclude Bulbul line @ 99% CL
- Boyarsky+ '15: Weak hint for line from MOS, lower than expected

  → sterile neutrino interpretation disfavored



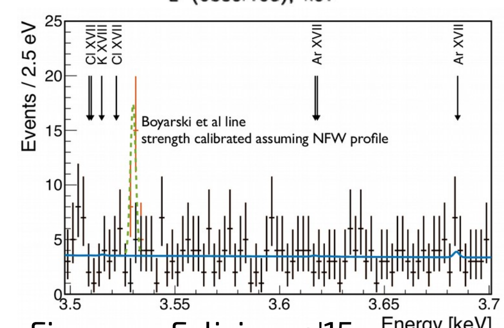
***Hitomi* legacy** (Hitomi coll. 2016)

- First-light observations of Perseus cluster
- Bulbul "all cluster" signal not bright enough
- But XMM MOS observations of Perseus were brighter, could be excluded at >99% CL
- Hints for S XVI line complex – charge exchange?



Micro-X

- Previous XQC analysis marginally constraining
- Short exposure (~5 min), but huge FoV (~0.4 sr)
- No pointing, but excellent energy resolution (~ 3 eV)
- Search for signal from Milky Way halo
- Payload under development; expect flight this/next year

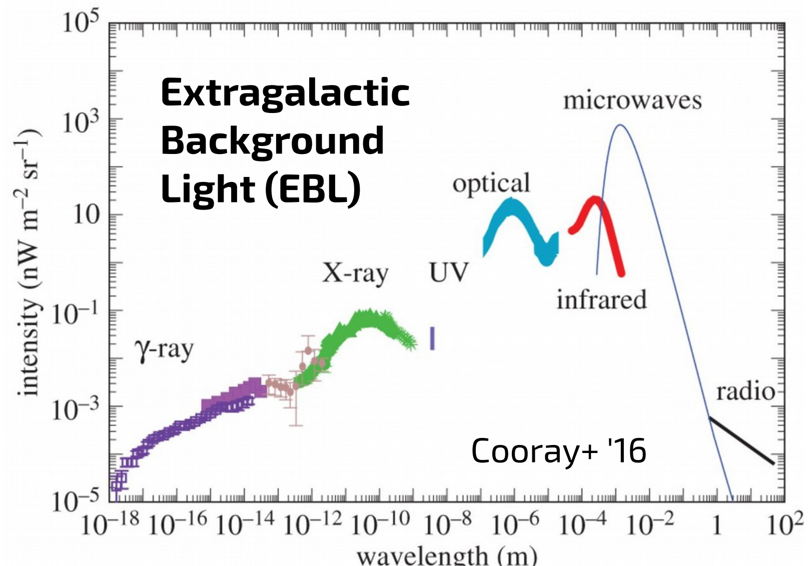


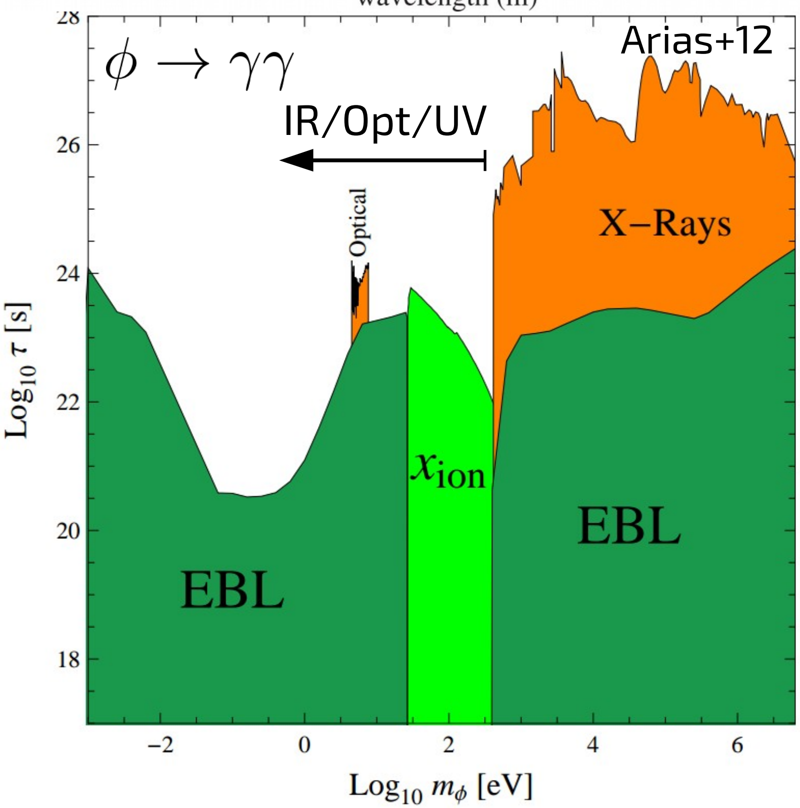
Figueroa-Feliciano+'15

1 meV – 1 keV

gamma ray
& cosmic rays
X-ray
ultraviolet
visible
infrared
microwave
radio

DM searches at IR/Optical/UV frequencies





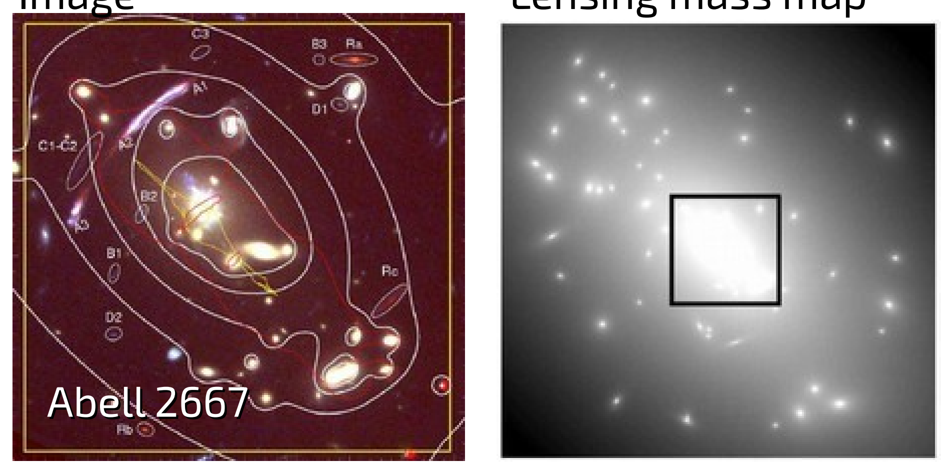
The eV gap (10^{-3} – 10^2 eV)

- Decay of axion-like particle DM could in principle give signals in that range
- Weak broad-band constraints come from extragalactic background light (EBL)
- Dedicated search for decaying DM signals in Abell 2667 only at optical frequencies (Grin+ '06)

Future

- DM theory challenge: any other DM signals predicted/possible in this frequency range?
- Dedicated analyses of archived data in this range might improve existing limits significantly

Image Lensing mass map

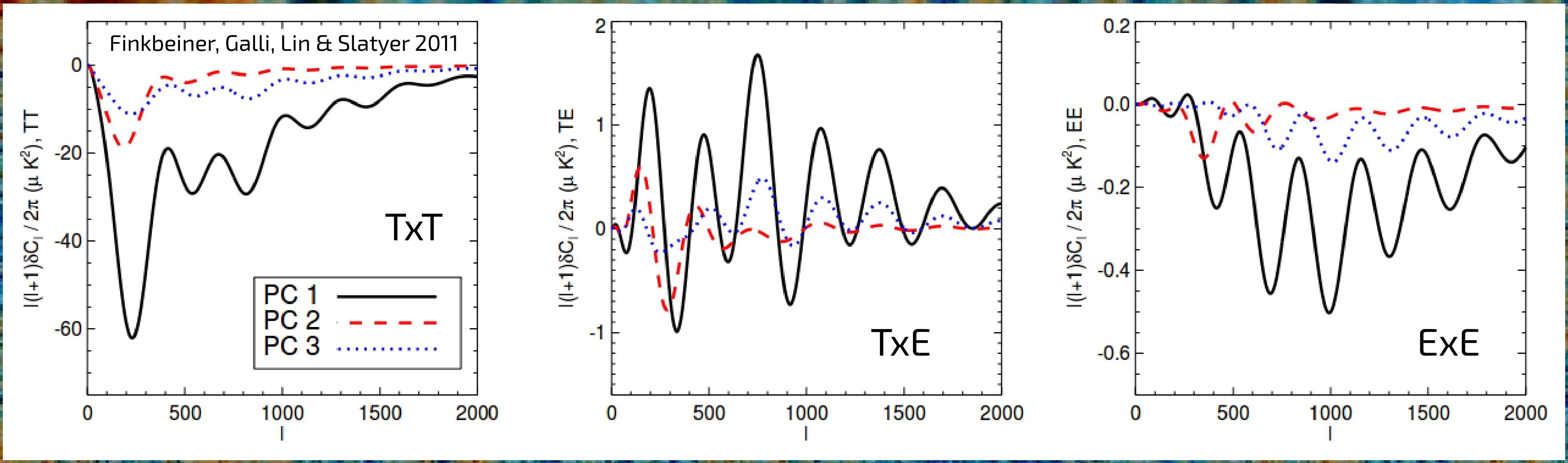


Grin+06

0.01 meV – 1 meV


gamma ray
& cosmic rays
X-ray
ultraviolet
visible
infrared
microwave
radio

DM annihilation can affect the CMB



Bounds on annihilating DM

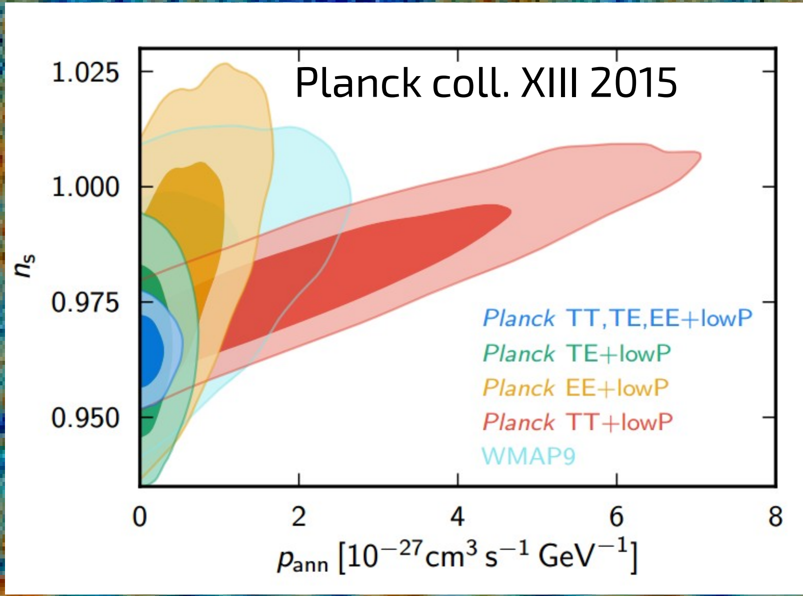
- Energy injection

$$p_{\rm ann}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}$$

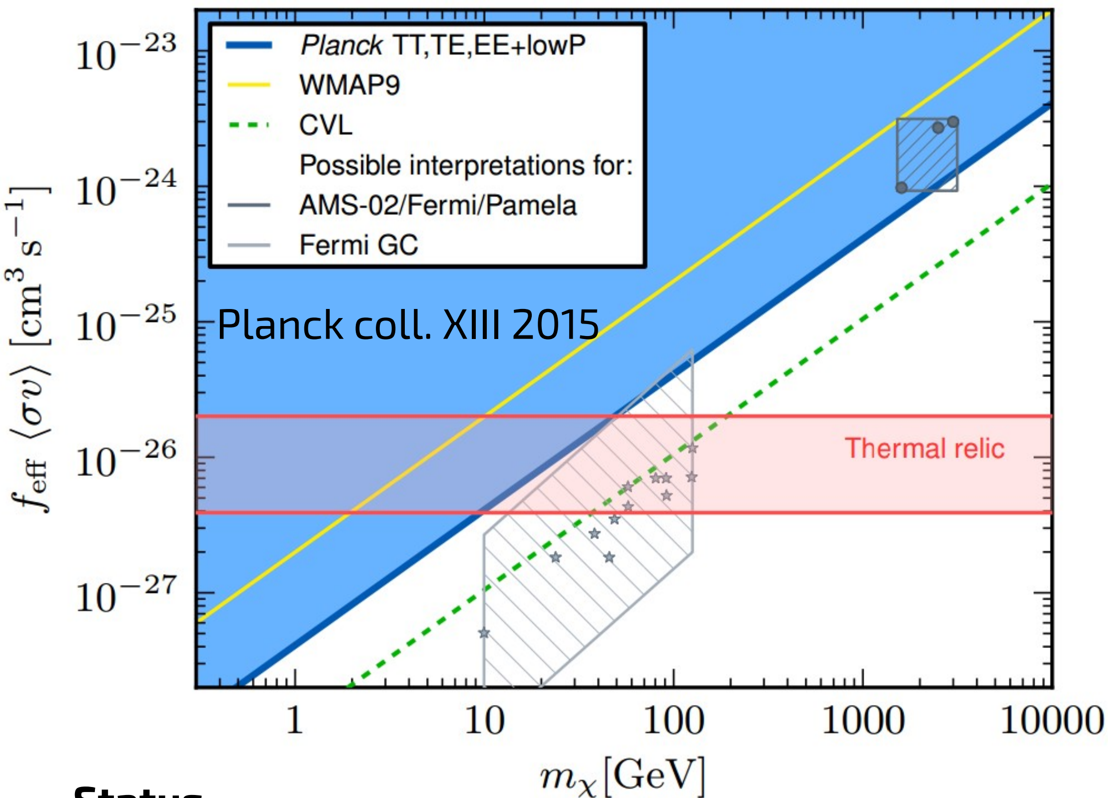
- Energy injection at z~500 – 1000 increases free electron fraction

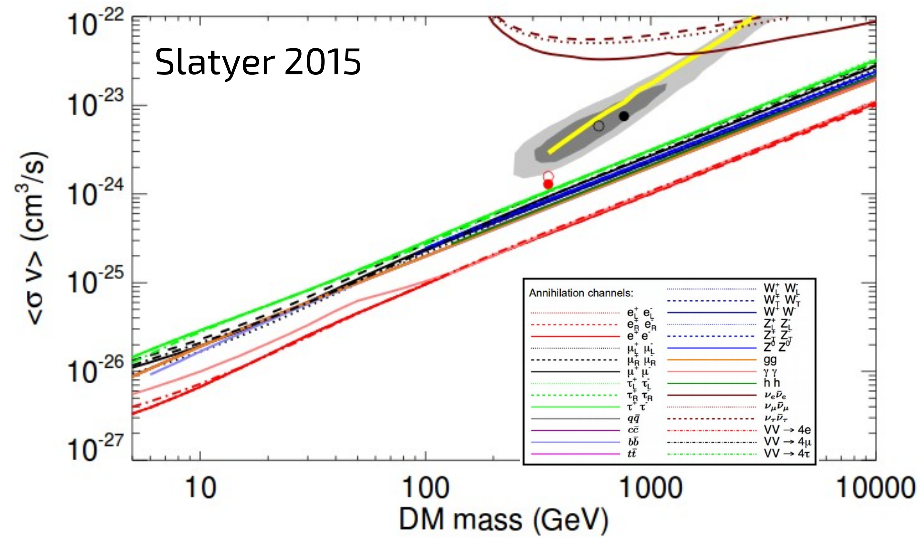
  → broadening of surface of last scattering
  → less fluctuations at small scales

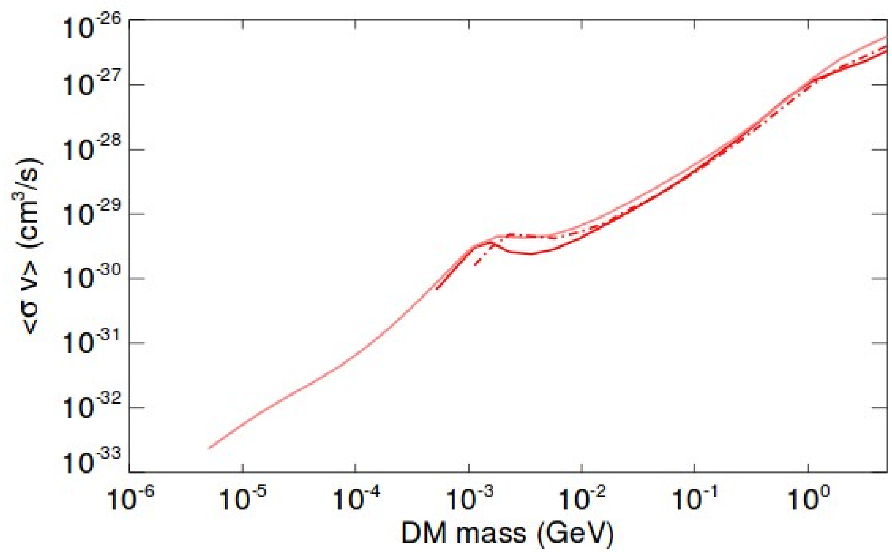
- Insensitive to details of non-linear structure formation



Bounds on DM from Planck observations







Status

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

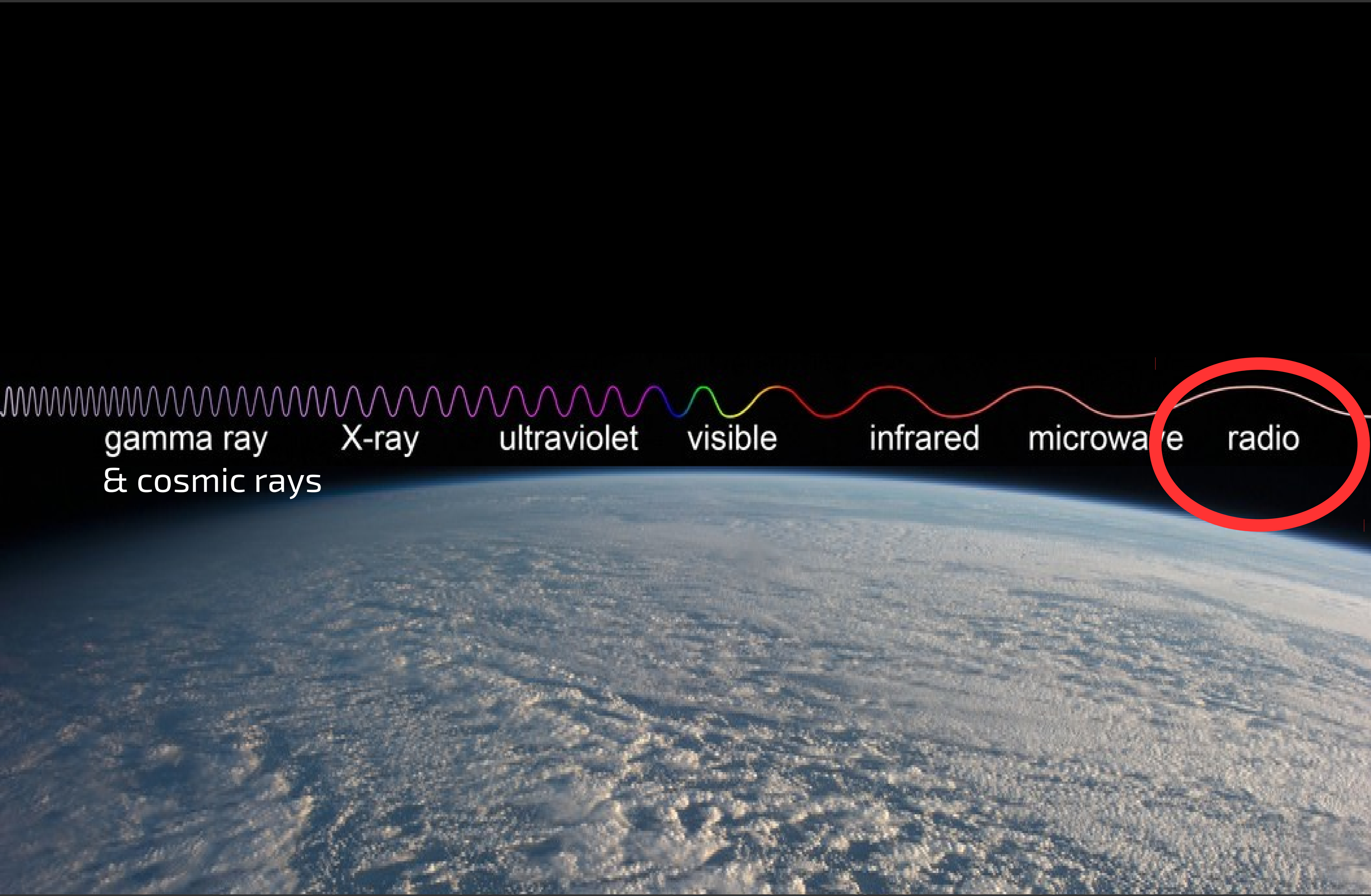
$$\langle\sigma v\rangle \lesssim (1-4)\times 10^{-27}\left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)\mathrm{cm^3\,s^{-1}}$$

Future

- e.g. COrE+ (2030?) → cosmic variance limit EE

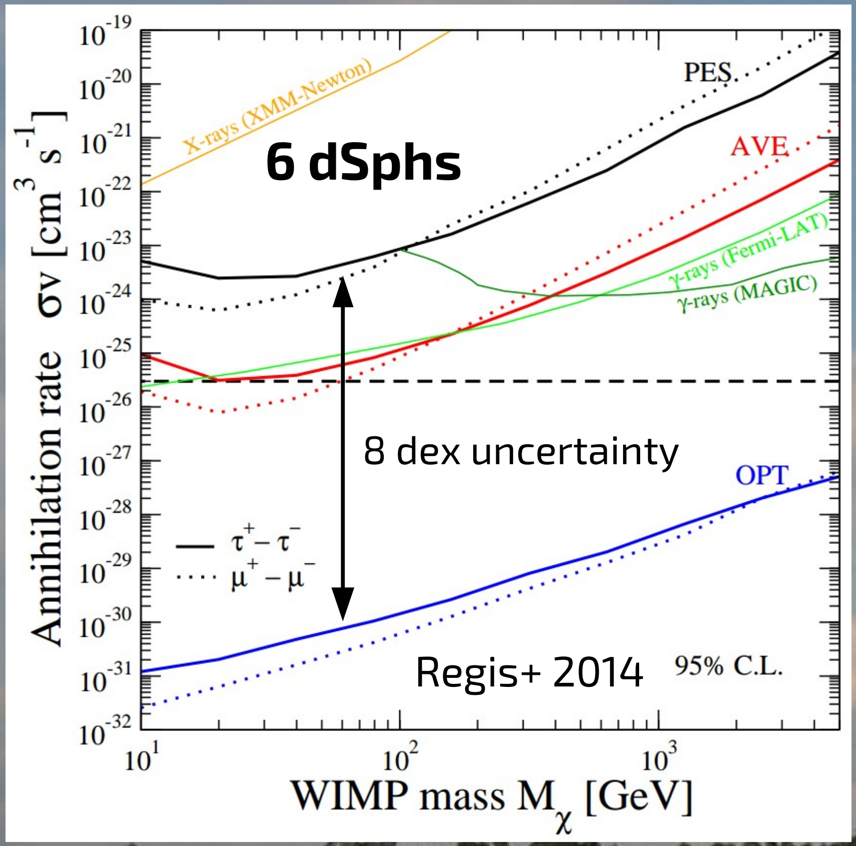
see also Ali-Haimoud+15; Liu+16; Chluba+16; Cline&Scott 13; Galli+13; Madhavacheril+13

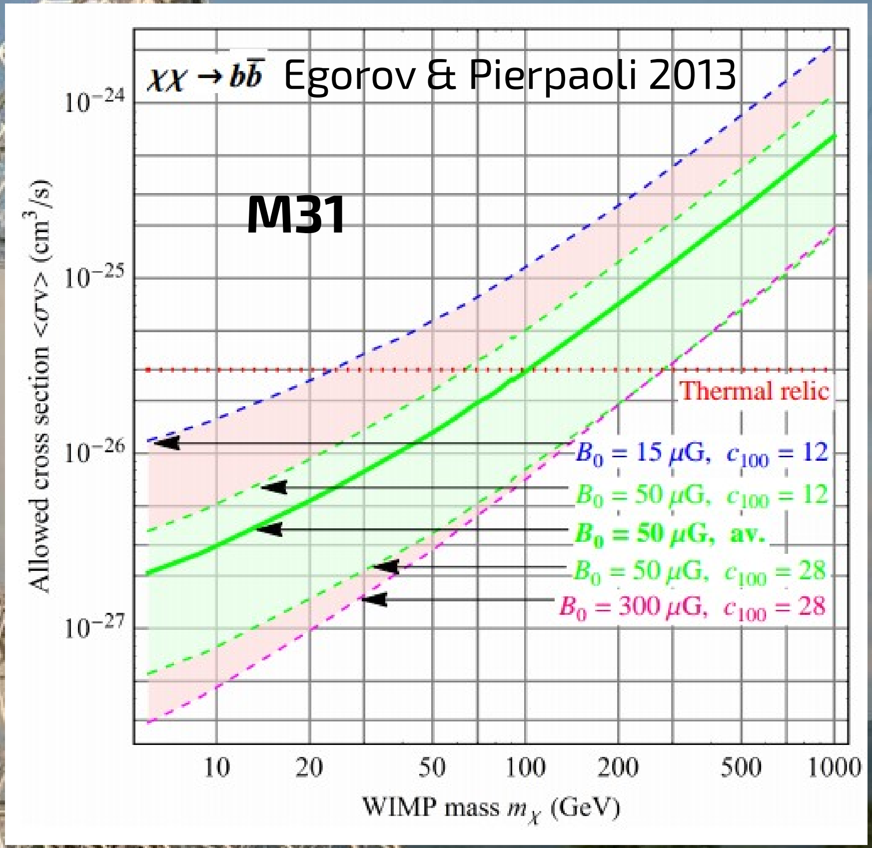
< 0.01 meV


gamma ray
& cosmic rays
X-ray
ultraviolet
visible
infrared
microwave
radio

Radio searches for synchrotron emission from DM

e± from DM annihilation/decay + B-field → Synchrotron radiation

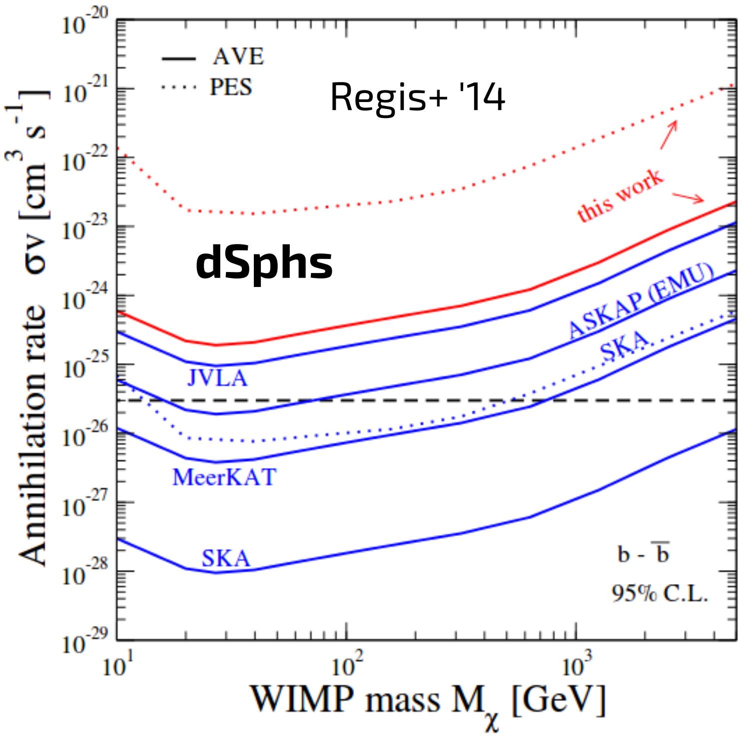


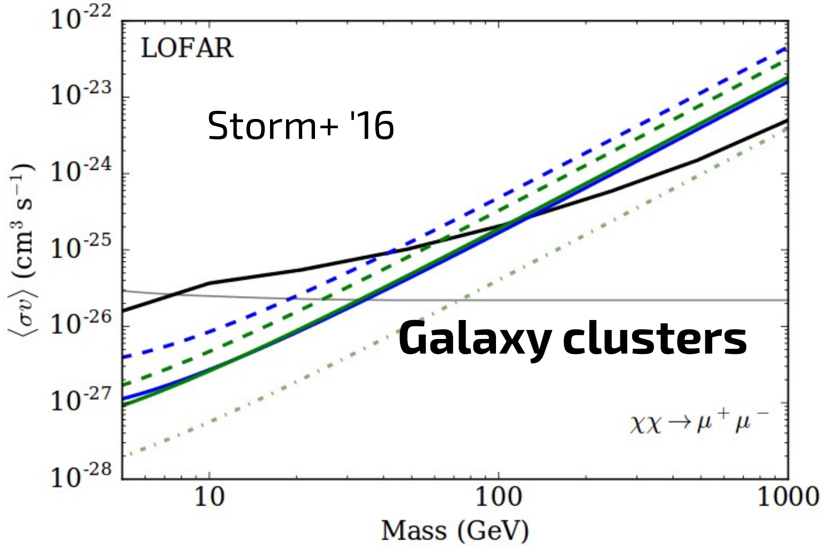


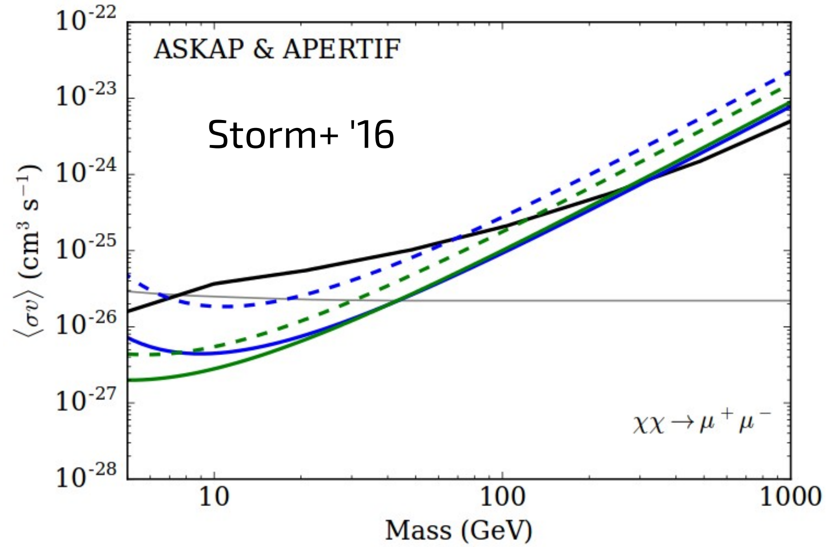
Radio searches for dark matter

- Dark matter annihilation/decay into leptons gives rise to synchrotron emission
- Signal strength depends on magnetic fields → additional, often large, uncertainty for signal flux
- Current limits from dSph and M31 (e.g. ATCA , VLSS, WENSS, NVSS, GB6) are potentially comparable to Fermi dwarf limits, but (much) less robust

Radio searches







Excellent prospects for radio astronomy

- Radio astronomy is entering a "golden age"
- Several new and upcoming telescopes (LOFAR, MeerKAT, ASKAP, SKA, …) improve current sensitivities by several orders of magnitude
- Possibilities for indirect dark matter searches still not fully explored
- Main challenge will be B-fields, but also defining proper analysis techniques

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

Planned radio searches for bulge MSPs

Radio detection prospects (Calore+ '15)

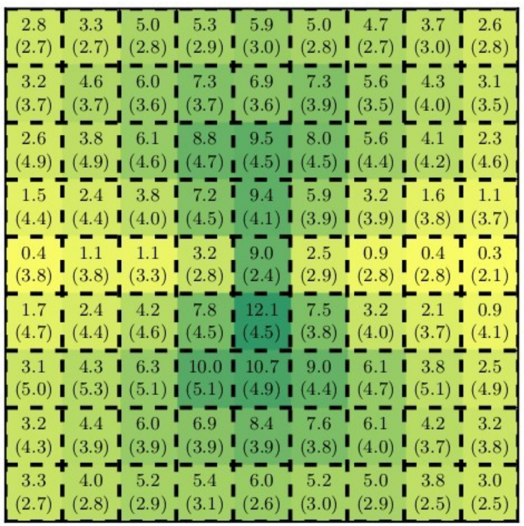
(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

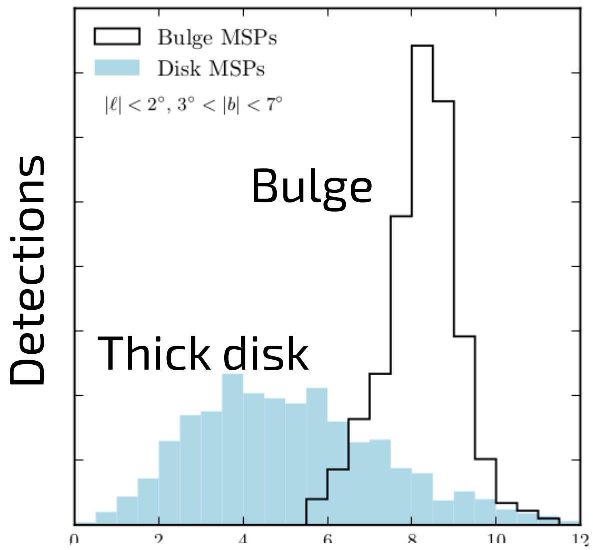
- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Good news! Our plans for the near future

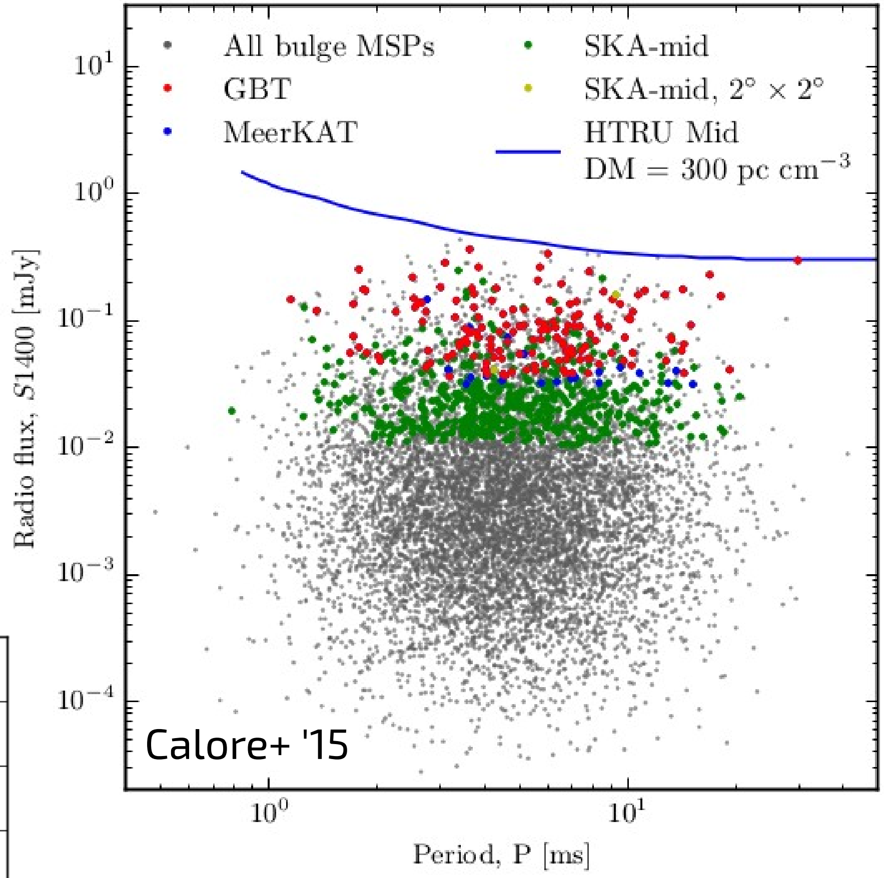
- We teamed up with MeerKAT TRAPUM → dedicated survey planned for **2018** (~**300h**)

$18^\circ \times 18^\circ$





Distance (from dispersion measure)



Wish list for indirect DM searches

1 **Make data (or likelihood functions) public.**

2 **Explore full space of possible DM signatures.**

3 **We have ~25 dex of bandwidth. Let's use them.**

Conclusions

- Anti-matter cosmic-rays
  - No indications for a DM signal right now. Will be hard to prove in the future given that we only have spectra. But: stay tuned for anti-deuteron measurements!
- Gamma-rays
  - Significant improvement of existing searches in the upcoming years, first high energies (HAWC, CTA), later sub-GeV (mabye e-ASTROGAM etc)
  - GeV ~~excess~~ bulge emission probably due to MSPs. Good chances to detect/exclude them in the near future with MeerKAT.
- X-rays
  - 3.5 keV story remains confusing. Look out for Micro-X!
- IR/Optical/UV
  - Appear to be underexplored, both theoretically and observationally
- CMB
  - Provides most robust limits over large DM mass range. Future improvements mild.
- Radio
  - Expected experimental improvement is impressive. It would be a pity if this cannot be used for indirect searches

Thank you!

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

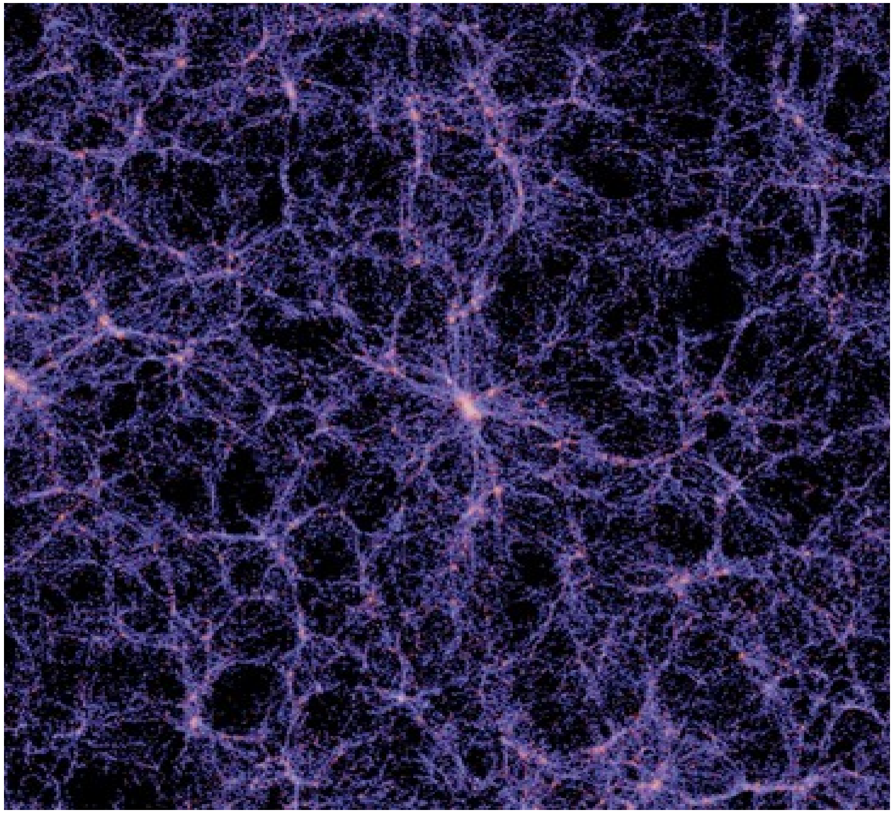
27 Members, 9 Experiments, 4 major theory codes, 10 countries

Coming soon!

Relic density calculations

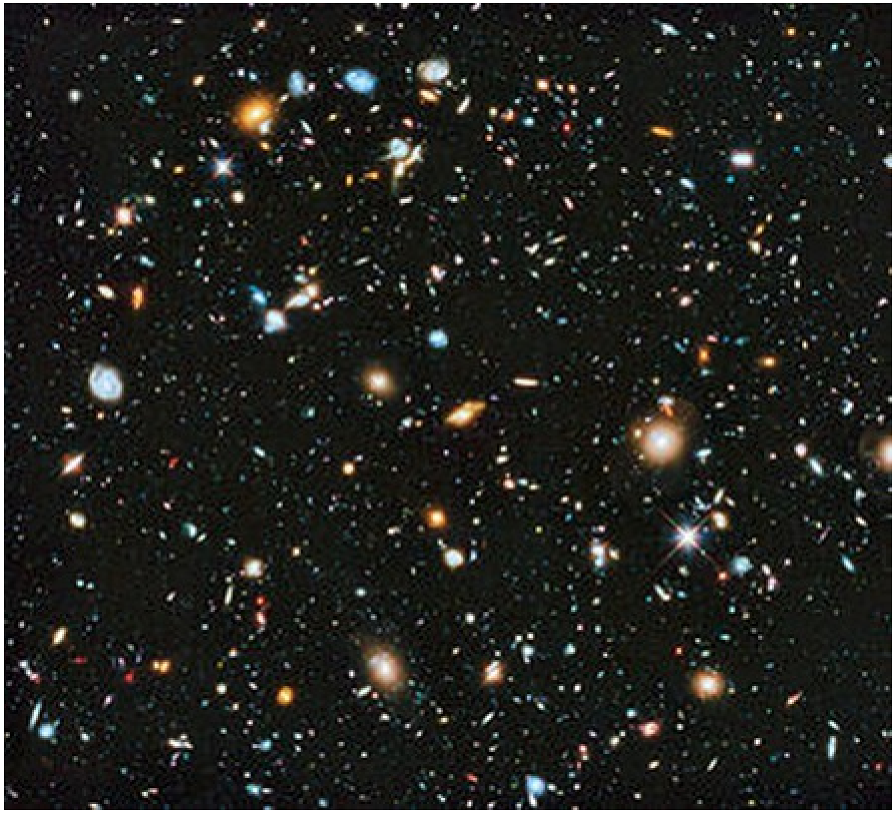
One of the major remaining shortcomings of the Standard Model is used as starting point of all dark matter model building.

Standard Model + CDM Universe



$\eta_B \simeq 0$

Actually observed Universe

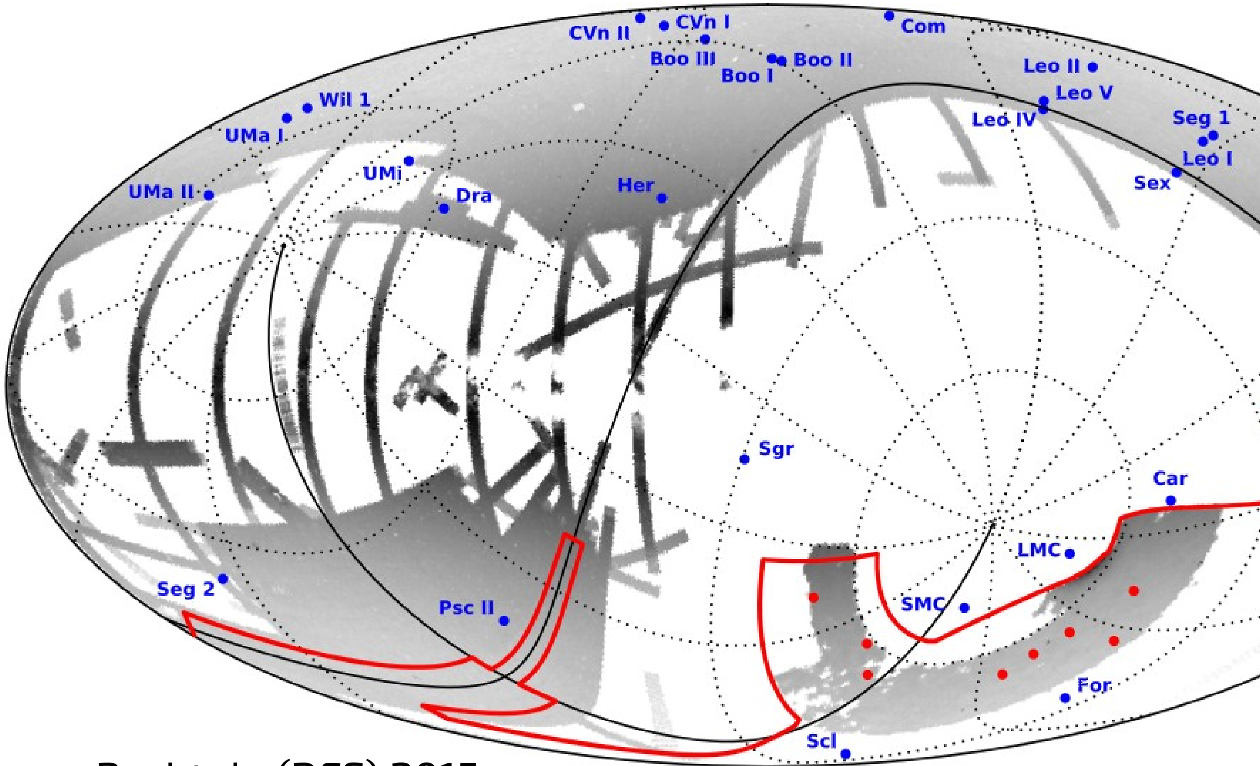


$$\eta_B = \frac{n_B}{s} = (8.8 \pm 0.2) \times 10^{-11}$$

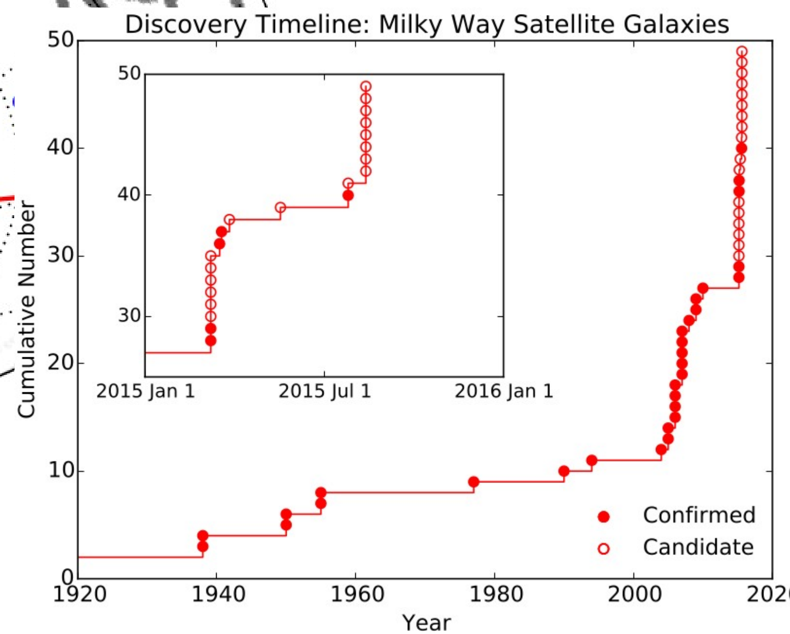
WMAP-5

We really don't know what we are looking for. Good idea to remain agnostic.

Future detections of dSphs



Bechtol+ (DES) 2015



Status

- 9 classical dwarfs; 25 (+8) dSphs used in Fermi LAT seaches up to now
- more than two dozens of ultra-faint dwarfs from SDSS (~25% sky coverage) and DES (~20%) (Bechtol+ '15, Koposov+ '15; Kim & Jerjen '15)

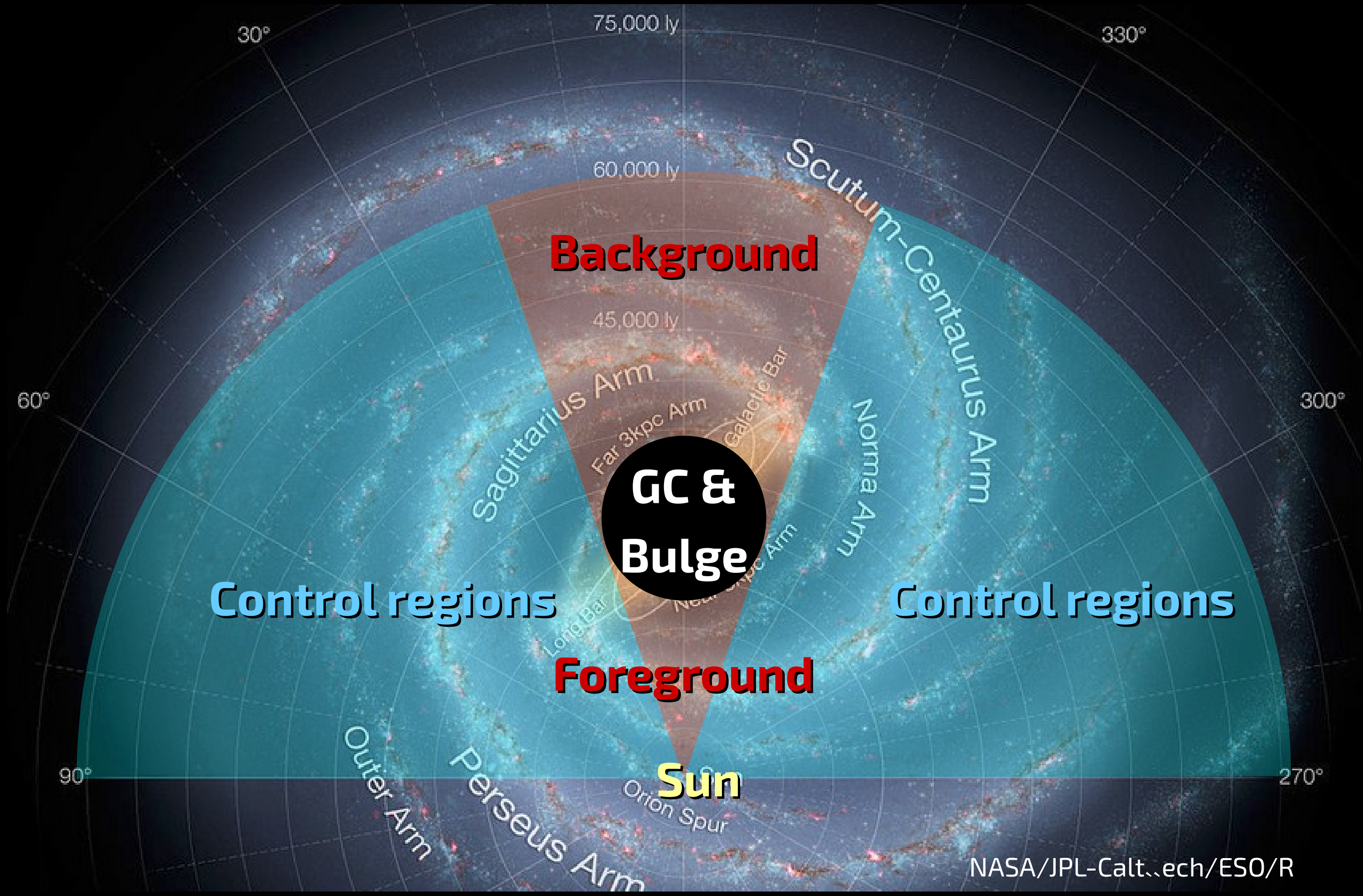
Future

- Expect 100+ regular and hyperfaint dSphs (up to 300 kpc) with DES, Pan-STARRS, SSS, LSST (2019?) (Hargis, Willman & Peter 2014)

~~Fermi GC Excess~~ → Galactic center & bulge emission

Excess = Data – Foreground – Background – Bulge/GC model

Bulge/GC emission = Data – Foreground - Background



Two steps

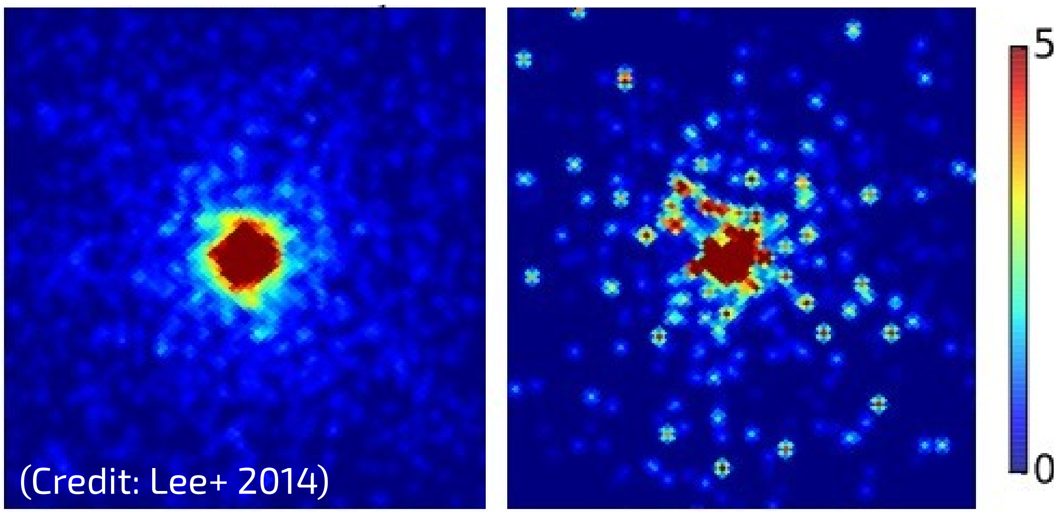
1) Foreground & background subtraction (hard, but we have control regions!) → Bulge emission

2) Modeling of bulge emission (really hard, no control regions, need multi-wavelength, etc)

Taking too many steps at once will likely break your neck

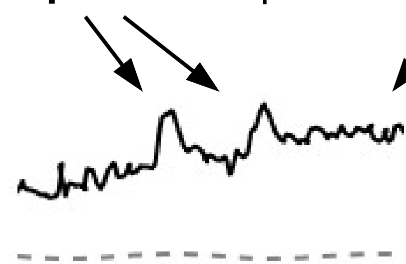
Wavelet fluctuation analysis supports MSPs

Diffuse emission (Unresolved) point sources



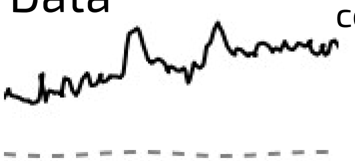
A signal composed of point sources would appear more "speckled" than a purely diffuse signal (like from dark matter annihilation)

Goal: find **peaks** on top of **Poisson noise**



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

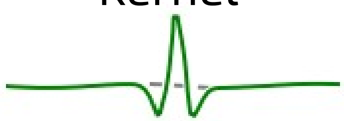
Data



convolution

X

Kernel



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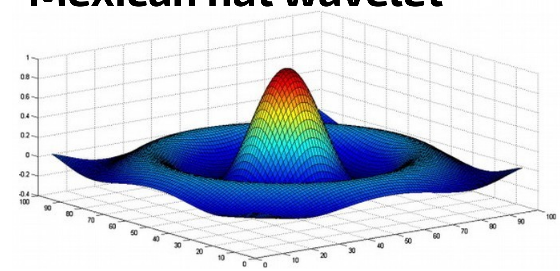
Wavelet transform

Mexican hat wavelet



Credit: https://www.researchgate.net