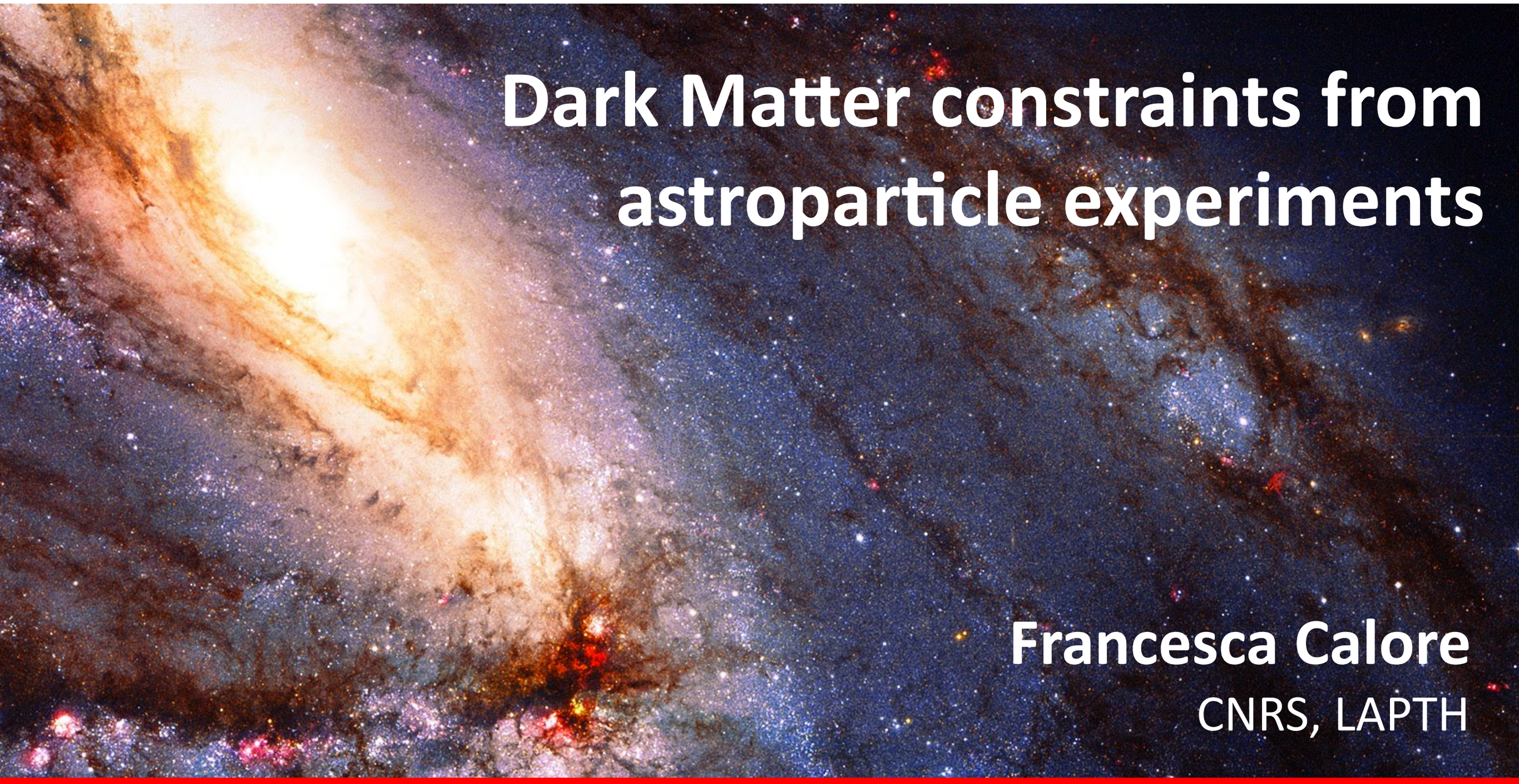


Dark Matter constraints from astroparticle experiments

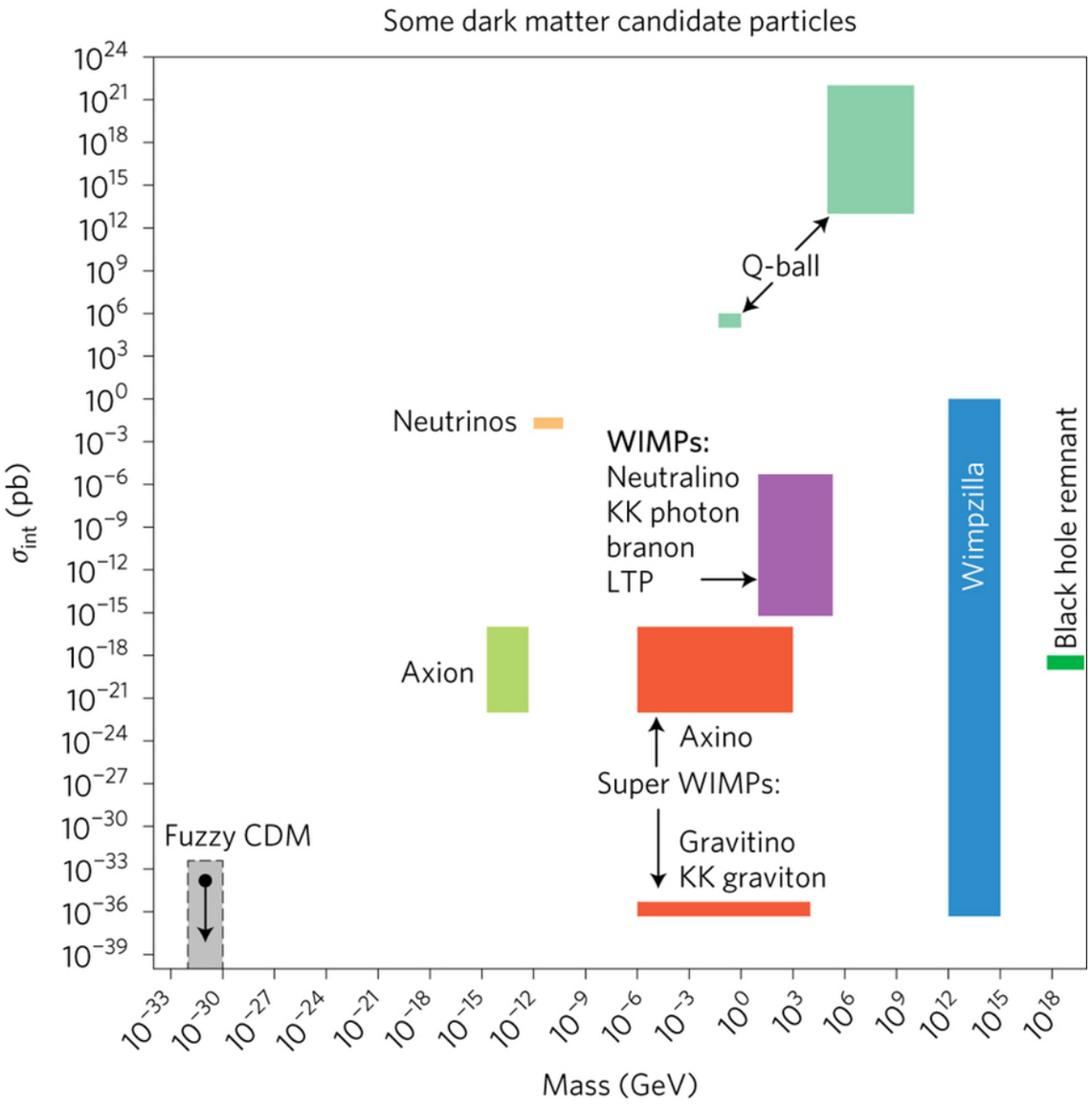
Francesca Calore
CNRS, LAPTH

DESY THEORY WORKSHOP
26 - 29 September 2017

Fundamental physics in the cosmos:
The early, the large and the dark Universe

DESY Hamburg, Germany

The dark matter landscape



Conrad & Reimer, Nature Physics 13 (2017) 224-231

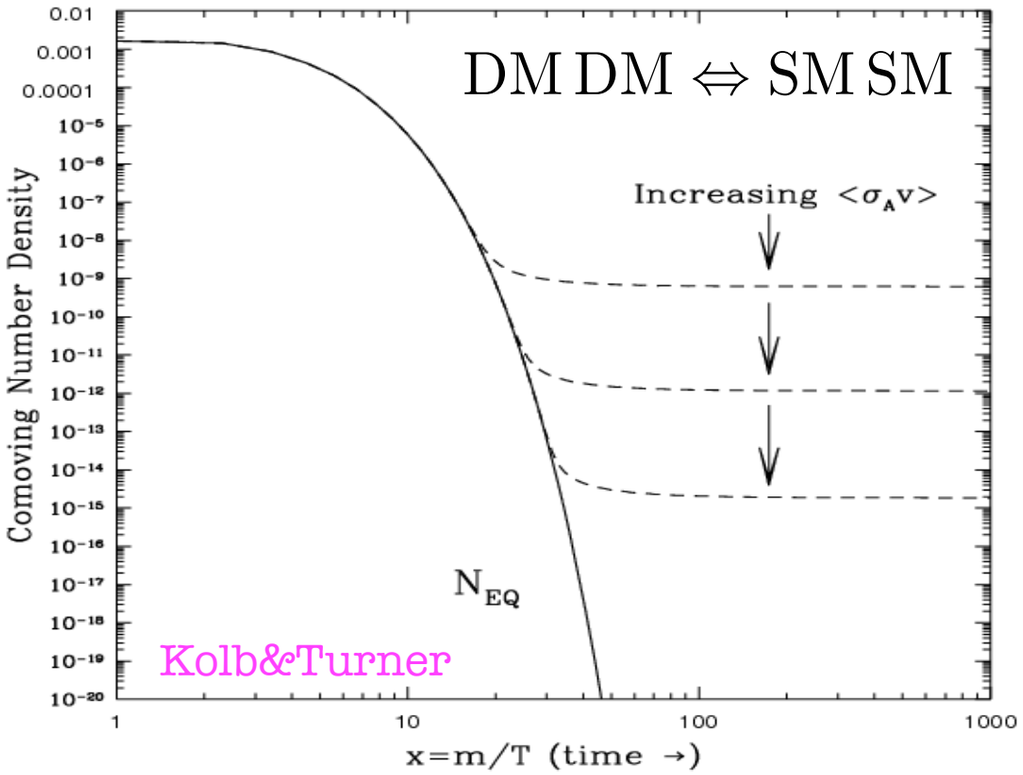
- In order to define a search strategy, we first need to better define the dark matter candidate of interest (input from theory) => **DM zoology**!
- Once the theoretical context is defined, we can engage in identification strategies which can be more or less model dependent
- There is always some theoretical prejudice in DM searches…

This talk: WIMP DM
L. Hui, A. Ringwald, J. Garcia-Bellido
other viable DM candidates

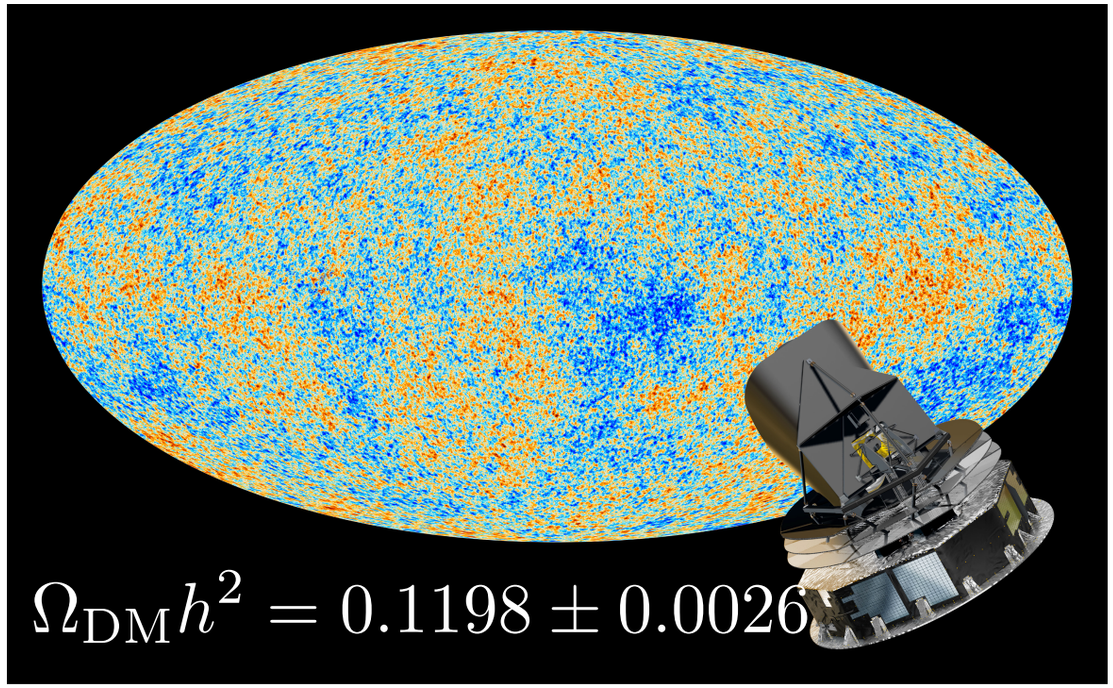
Weakly Interacting Massive Particles (WIMP)

The dark matter landscape

Freeze-out production mechanism



CMB temperature anisotropy



$$\Omega_{\rm DM}h^2 \sim \frac{10^{-27}{\rm cm}^3/{\rm s}}{\langle\sigma({\rm DM\,DM} \to {\rm SM\,SM}){\rm v}\rangle}$$

$$\langle\sigma({\rm DM\,DM} \to {\rm SM\,SM}){\rm v}\rangle \sim 3 \times 10^{-26}{\rm cm}^3/{\rm s}$$

Natural candidates at the weak scale

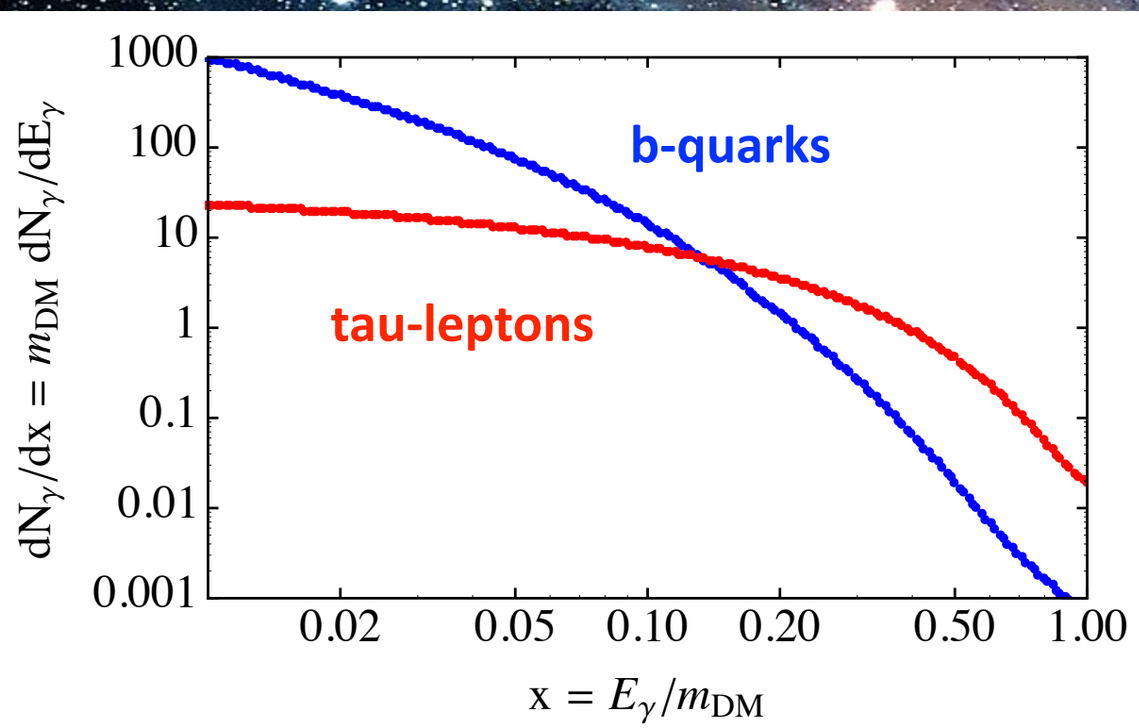
WIMP searches with astroparticle experiments

WIMP searches with astroparticle experiments

Indirect detection

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

Annihilation



+ Contribution from gamma-ray lines

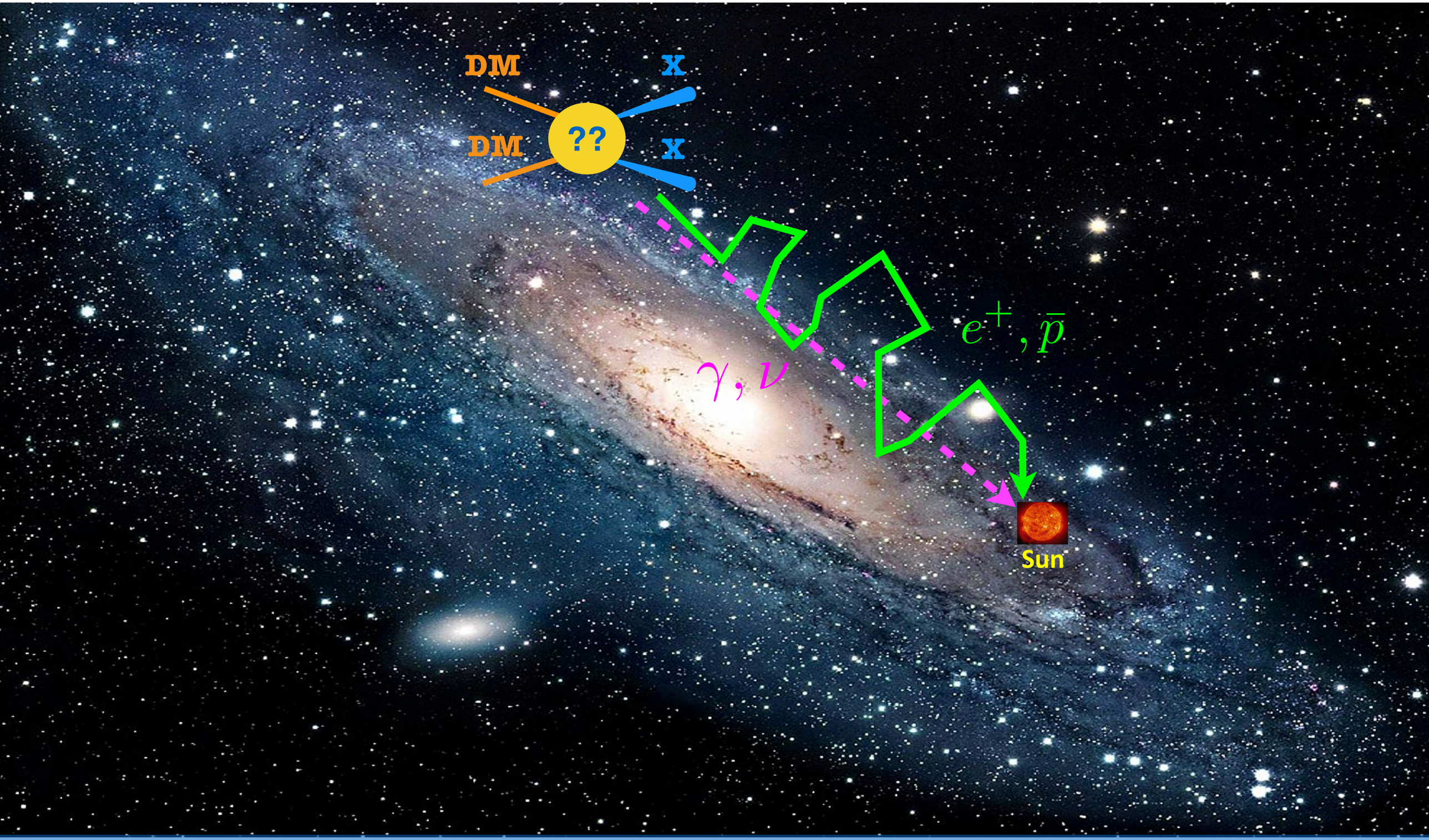
Bergström et al., JCAP'05

+ EM and EW corrections

Bringmann et al., JHEP'08; Ciafaloni et al., JCAP'11; Bringmann & Calore, PRL'14

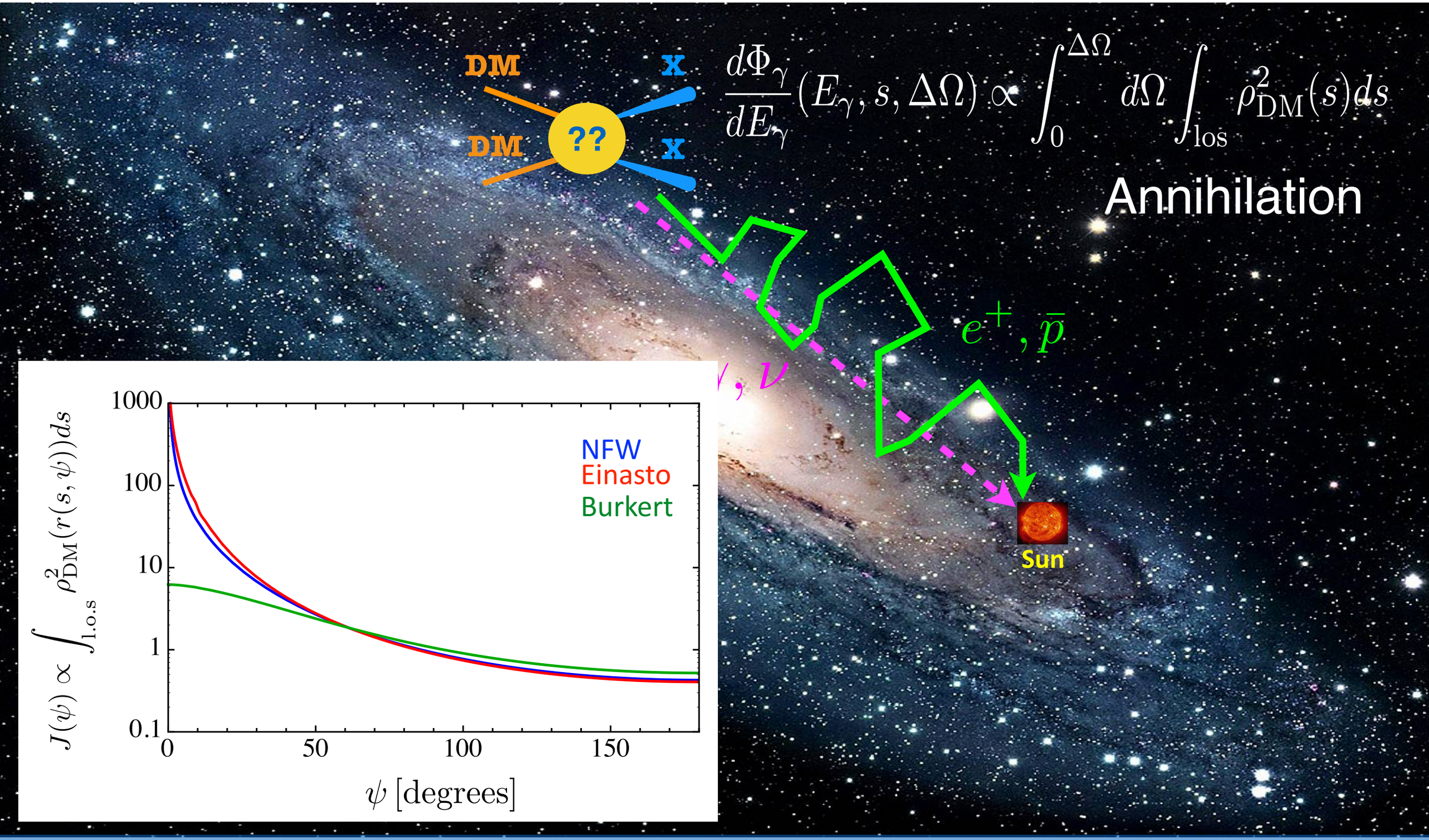
WIMP searches with astroparticle experiments

Indirect detection



WIMP searches with astroparticle experiments

Indirect detection

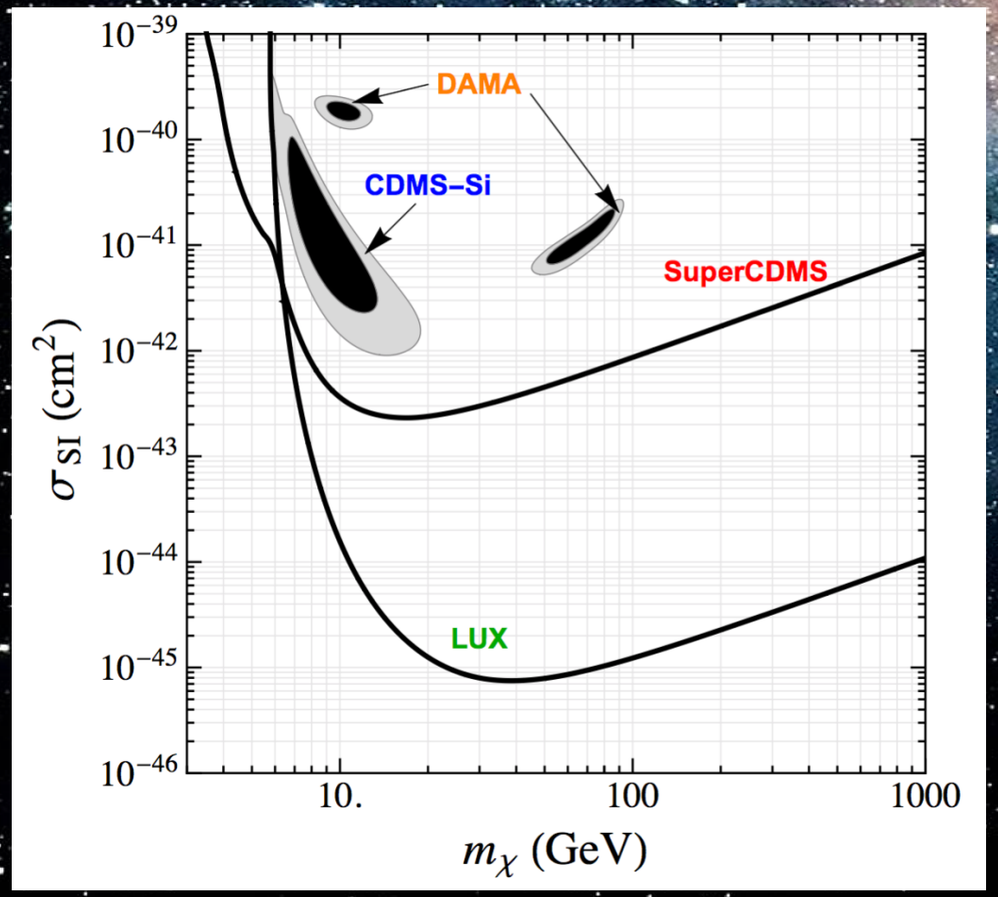


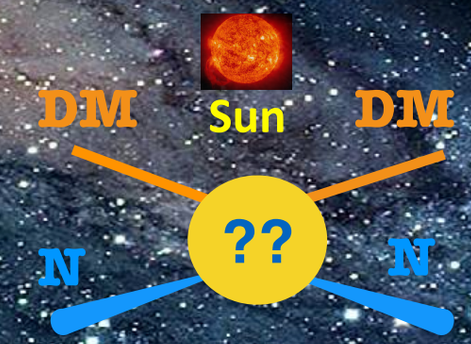
WIMP searches with astroparticle experiments

Direct detection

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_{\rm DM}} \frac{1}{m_A} \int_{v>v_{\rm min}} d^3v \frac{d\sigma_A}{dE_R} v f_{\rm det}(\mathbf{v}, t)$$

DM-nucleus scattering



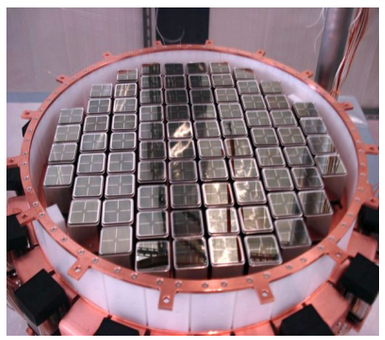


DM astrophysical ingredients and their uncertainties

(1) DM density distribution in the Milky Way $\rho_{\rm DM}(R)$

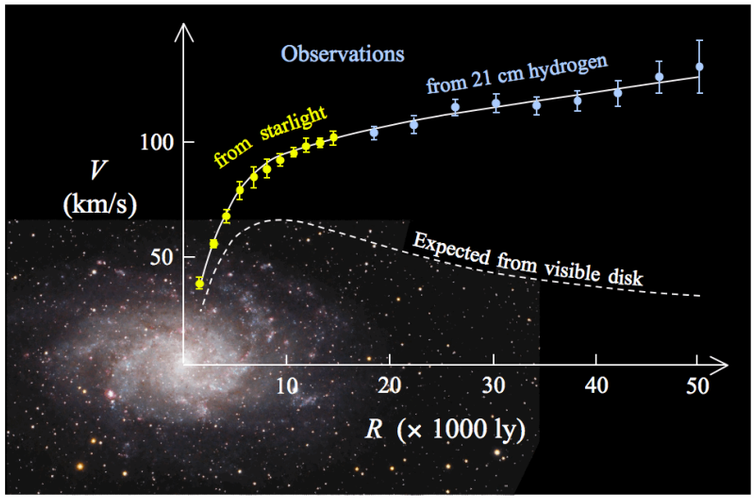
(2) Local DM density $\rho_{\rm DM}(R_\odot) \equiv \rho_\odot$

(3) Local DM velocity distribution $f_{\rm det}(\mathbf{v}, t)$



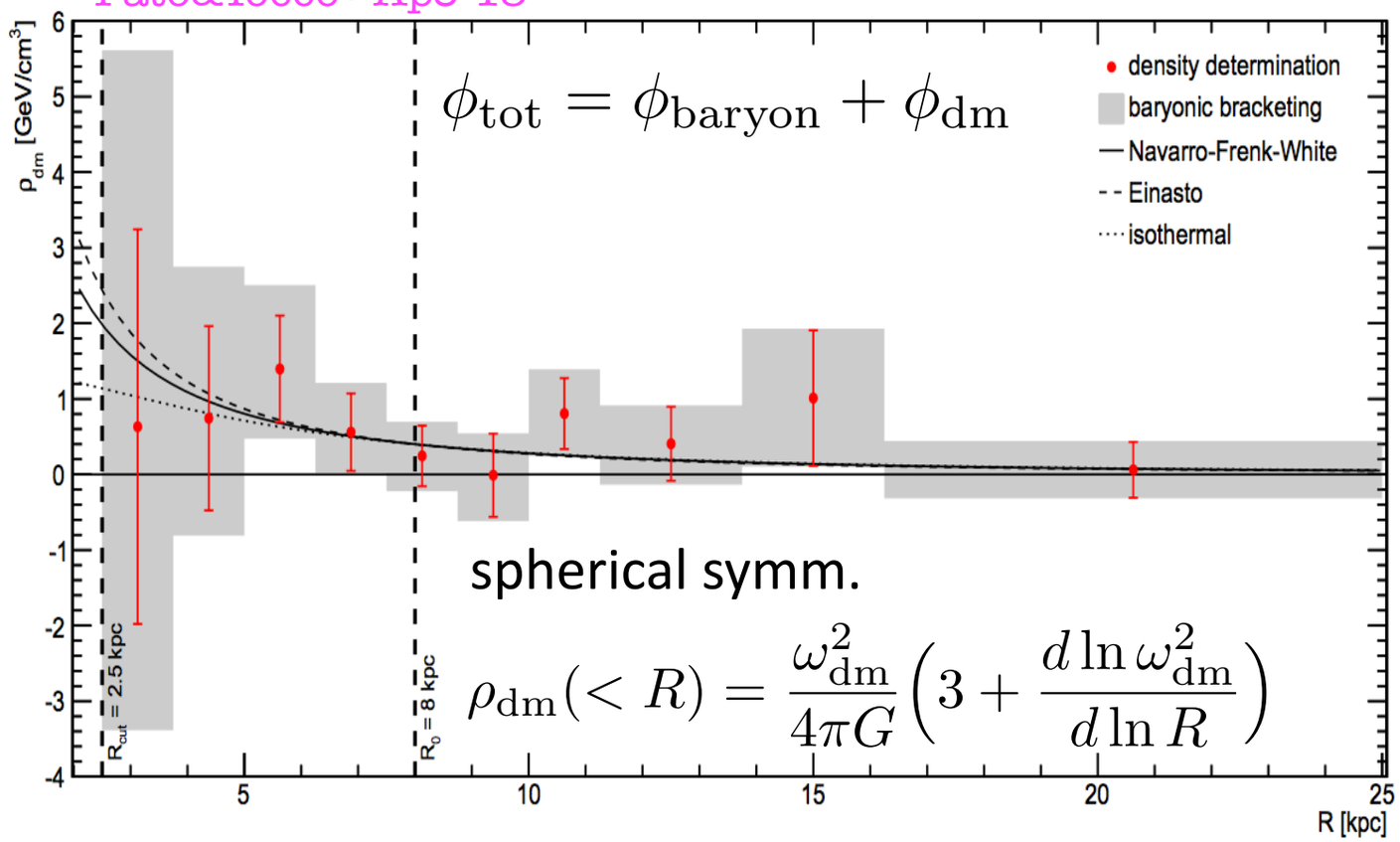
What can we infer from observations?
And where do we need simulations of the Galaxy?

Reconstructing the DM density distribution



Non-parametric reconstruction:
approach free of profile assumptions,
but large uncertainties

Pato&Iocco+ ApJ'15



Parametric reconstruction: strong profile assumptions, and large uncertainties due to baryonic models.

$$\omega^2_{\rm dm} = \frac{G}{R^3}\int_0^R dr\, 4\pi r^2\, \rho_{\rm dm}(r)$$

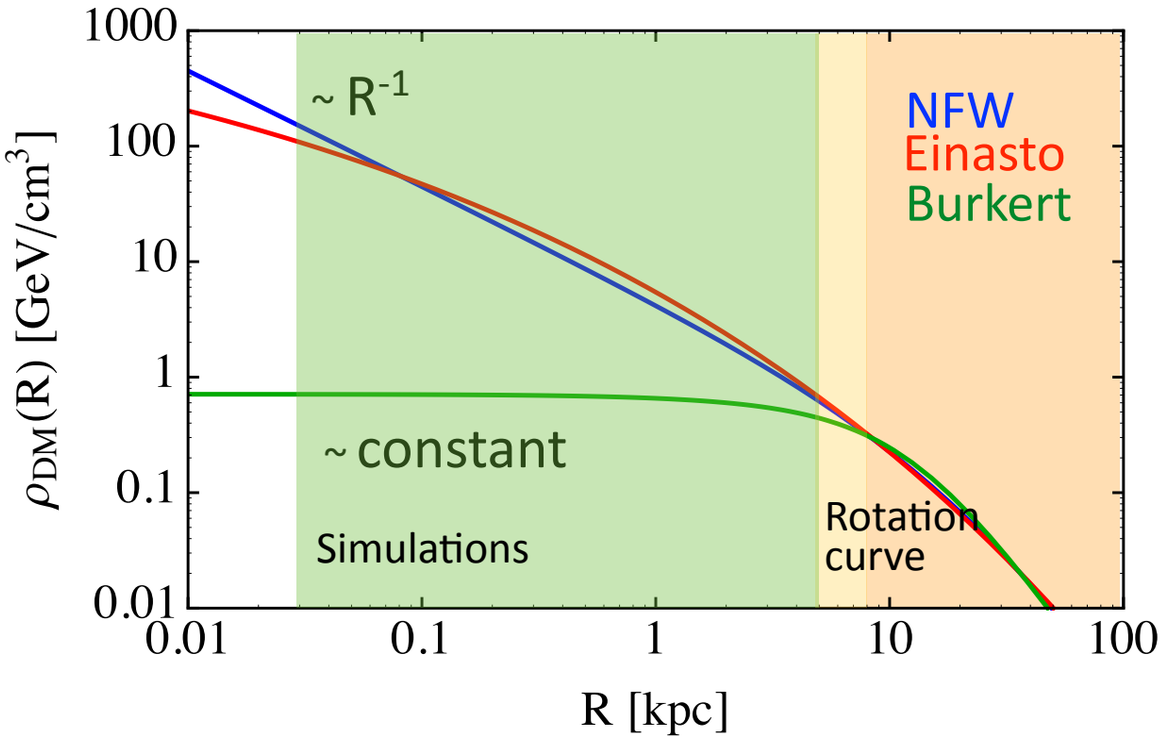
NFW, **Einasto**, etc.

e.g: Pato+ JCAP'15; McMillan+ MNRAS'16; Iocco&Benito PDU'17

Full mass modelling of MW and "global" method to derive **local DM density**.

e.g: Catena&Ullio JCAP '10; Salucci+ A&A'10, Pato&Iocco JCAP'15

The MW dark matter distribution



Rotation curve can only probe DM spatial distribution down to a few kpc.

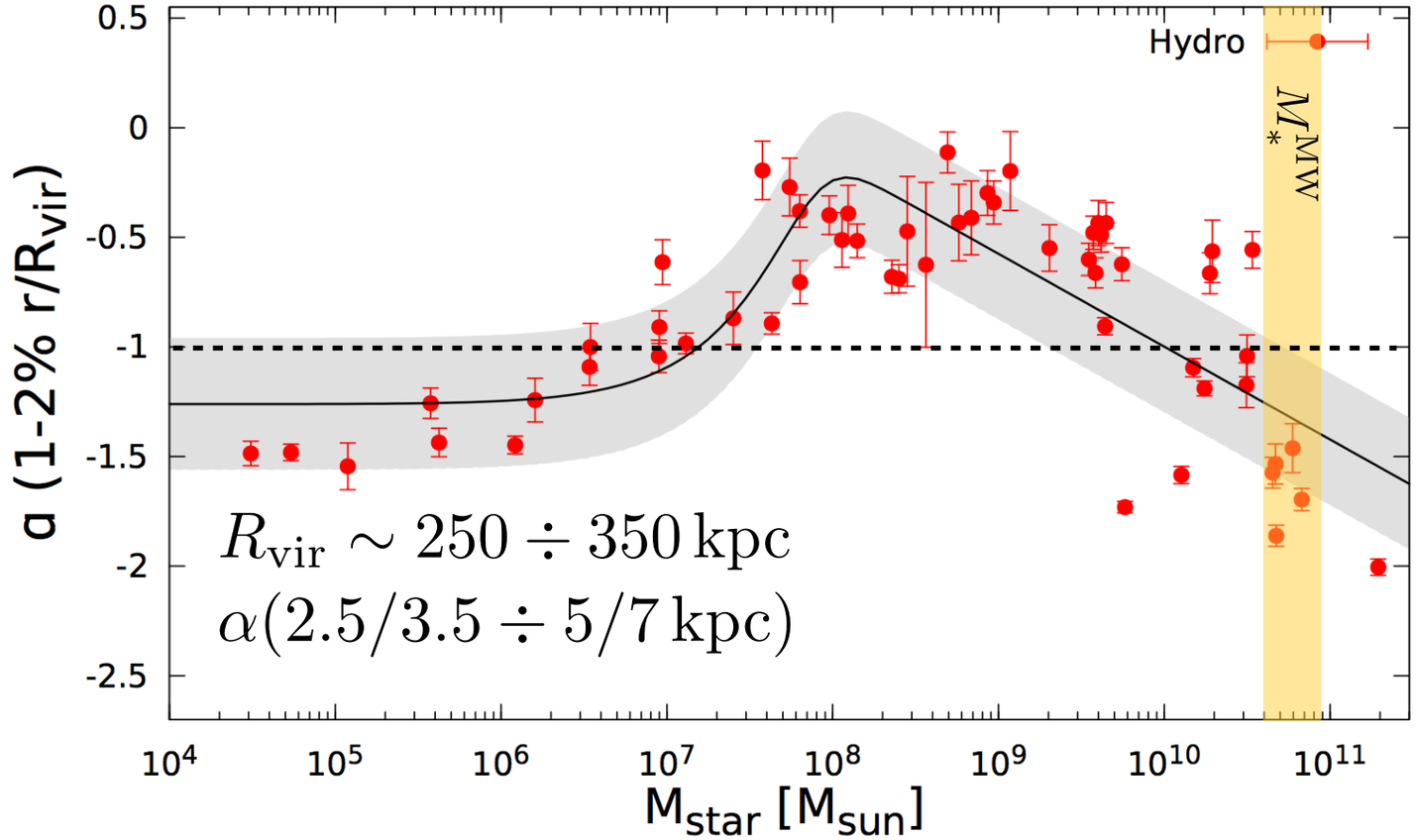
We need simulations of galaxy formation, including baryon effects.

Challenges

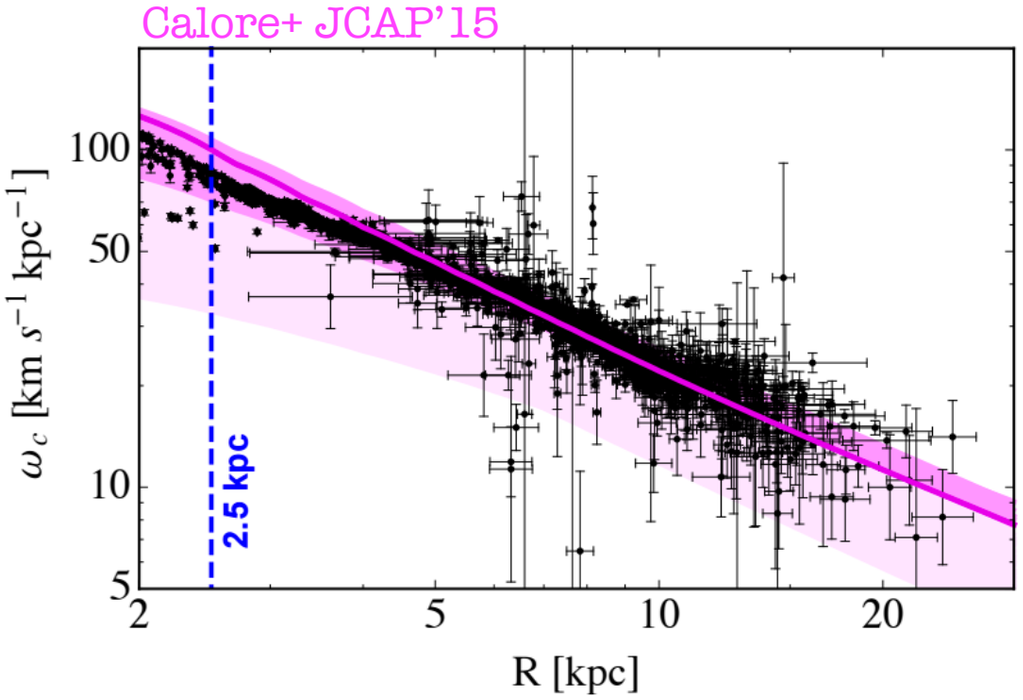
1) How to select a good MW halo candidate?

2) How to extrapolate the profile down to smaller scales?

Tollet+MNRAS'15



Milky-Way like galaxies in EAGLE



Selection of MW-like objects based on 3 criteria:

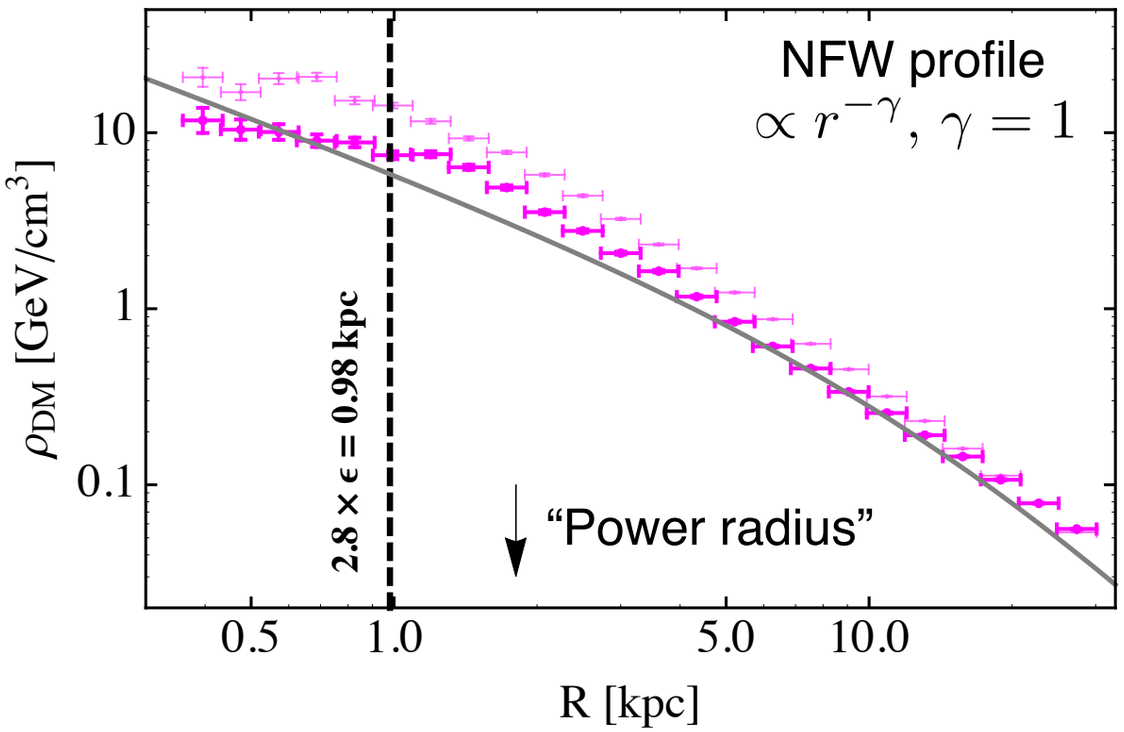
(i) Good fit to observed MW rotation curve.

(ii) Total stellar mass within the 3σ observed MW range.

(iii) Presence of a substantial stellar disc component.

[constrained MW halo, see e.g. Wang+MNRAS'12; Gottloeber+2010]

DM density profile in EAGLE MW-like galaxies



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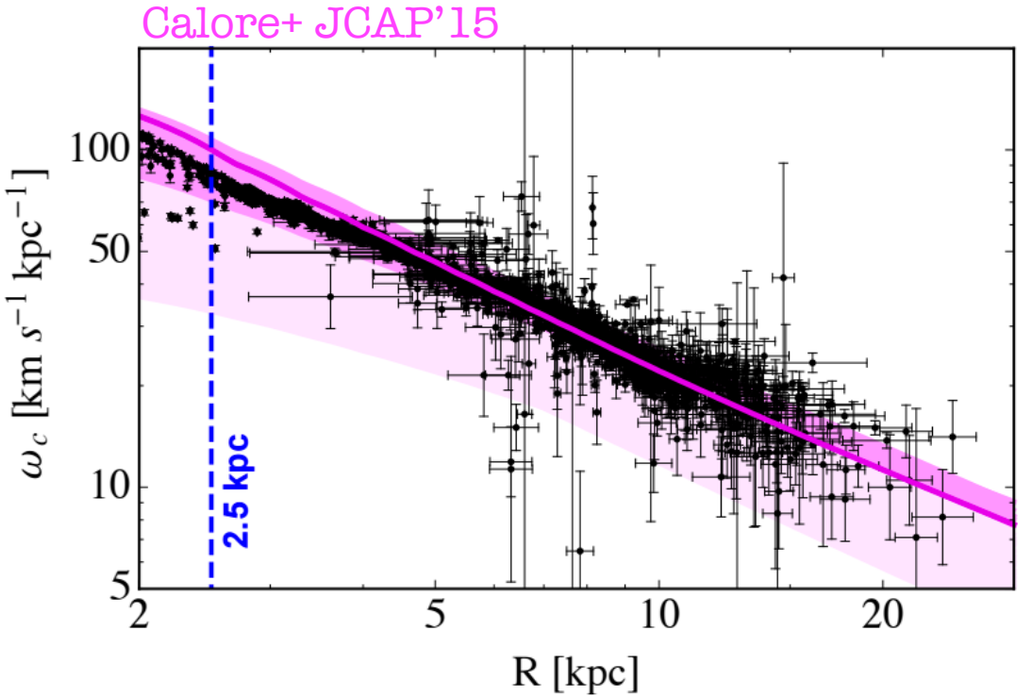

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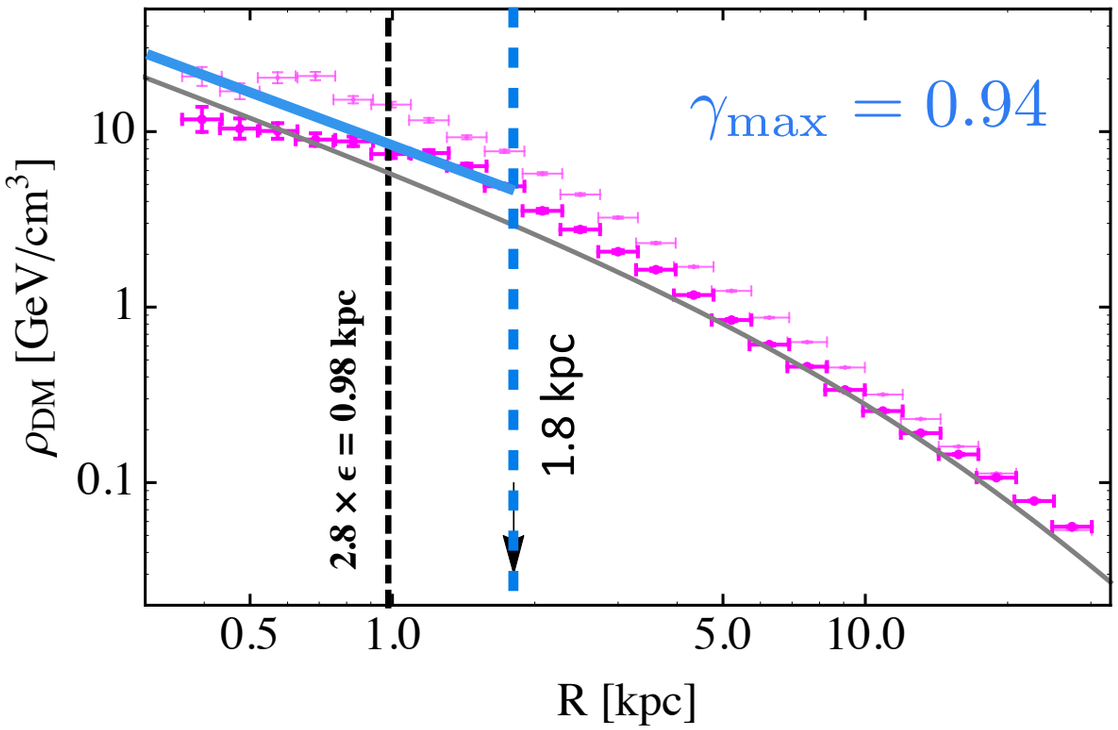


Small scale profile?

Power-law extrapolation with robust upper limit on the inner asymptotic slope at Power radius:

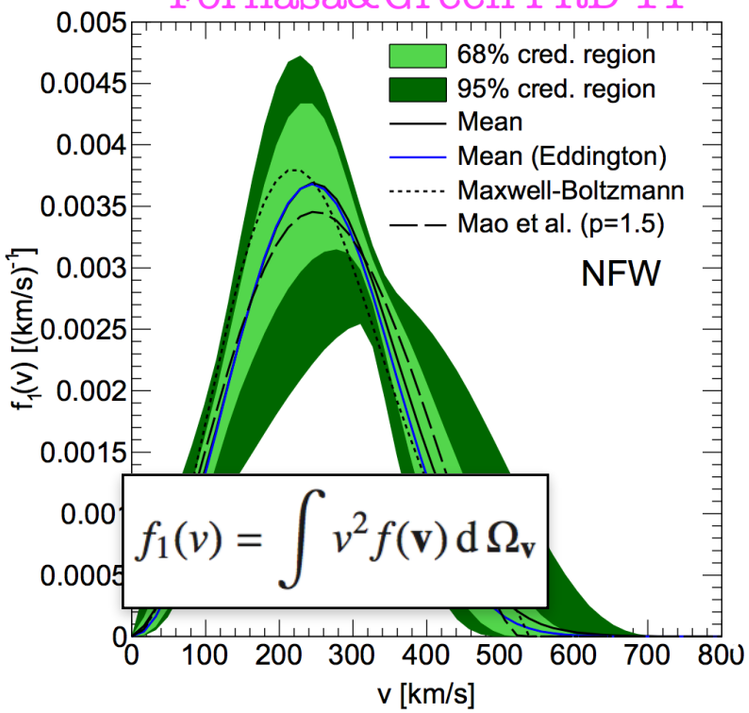
$$\gamma_{\rm max}(r) \equiv 3(1 - \rho(r)/\bar{\rho}(r))$$

$$\gamma_{\rm max} \sim 0.6 - 0.9$$

Reconstructing the local velocity distribution

Mass Modelling

Fornasa&Green PRD'14



$$\mathcal{F}(\mathbf{x}, \mathbf{v})$$

Phase-space density consistent with total gravitational potential

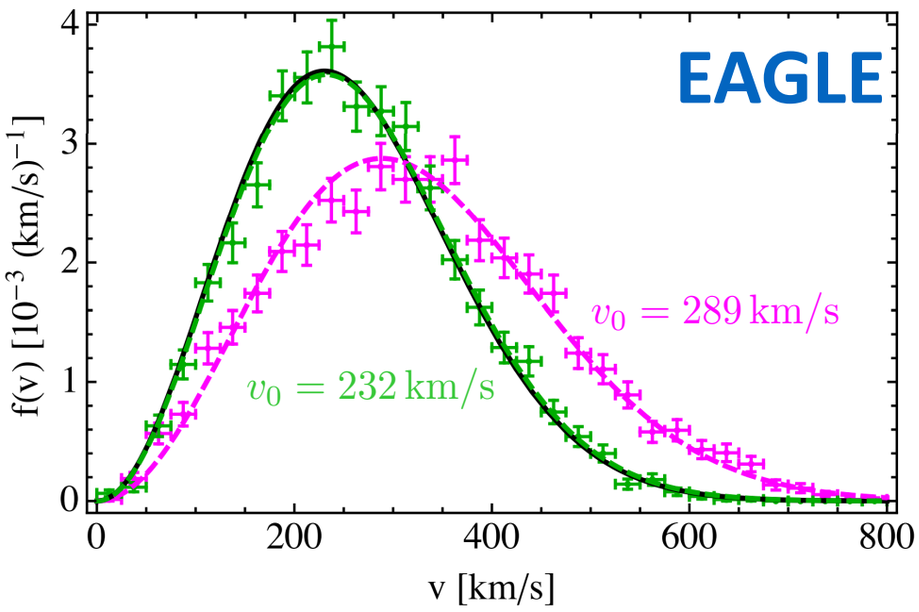
$$f(\mathbf{v}) = \mathcal{F}(\mathbf{x}_\odot, \mathbf{v})/\rho(\mathbf{x}_\odot)$$

Local DM velocity distribution

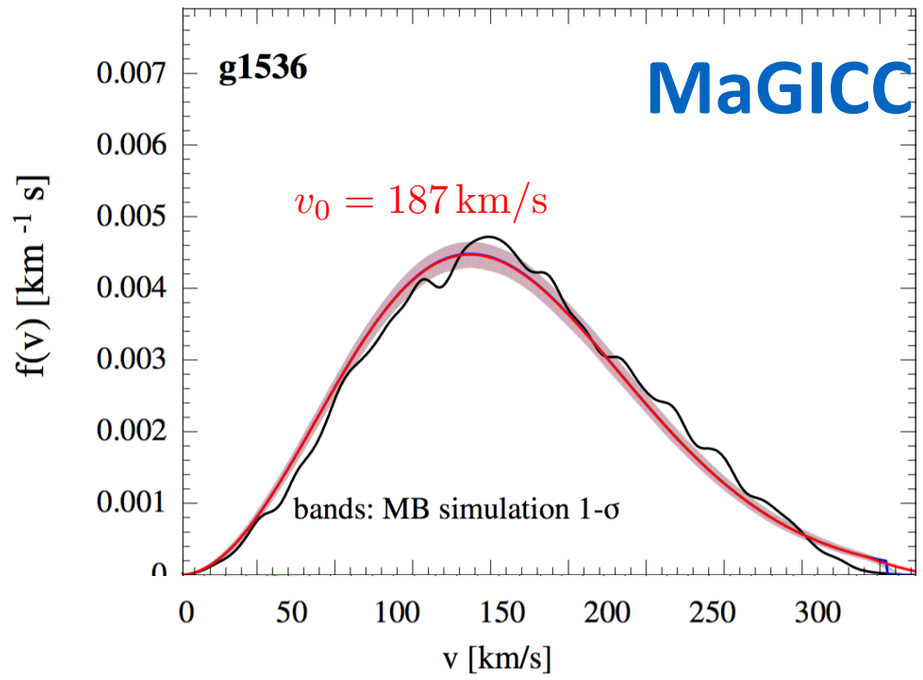
Isotropy & isothermal halo sphere → Standard Halo Model
(Maxwell-Boltzmann v distribution)

Hydro simulations

Bozorgnia, Calore+ JCAP'16



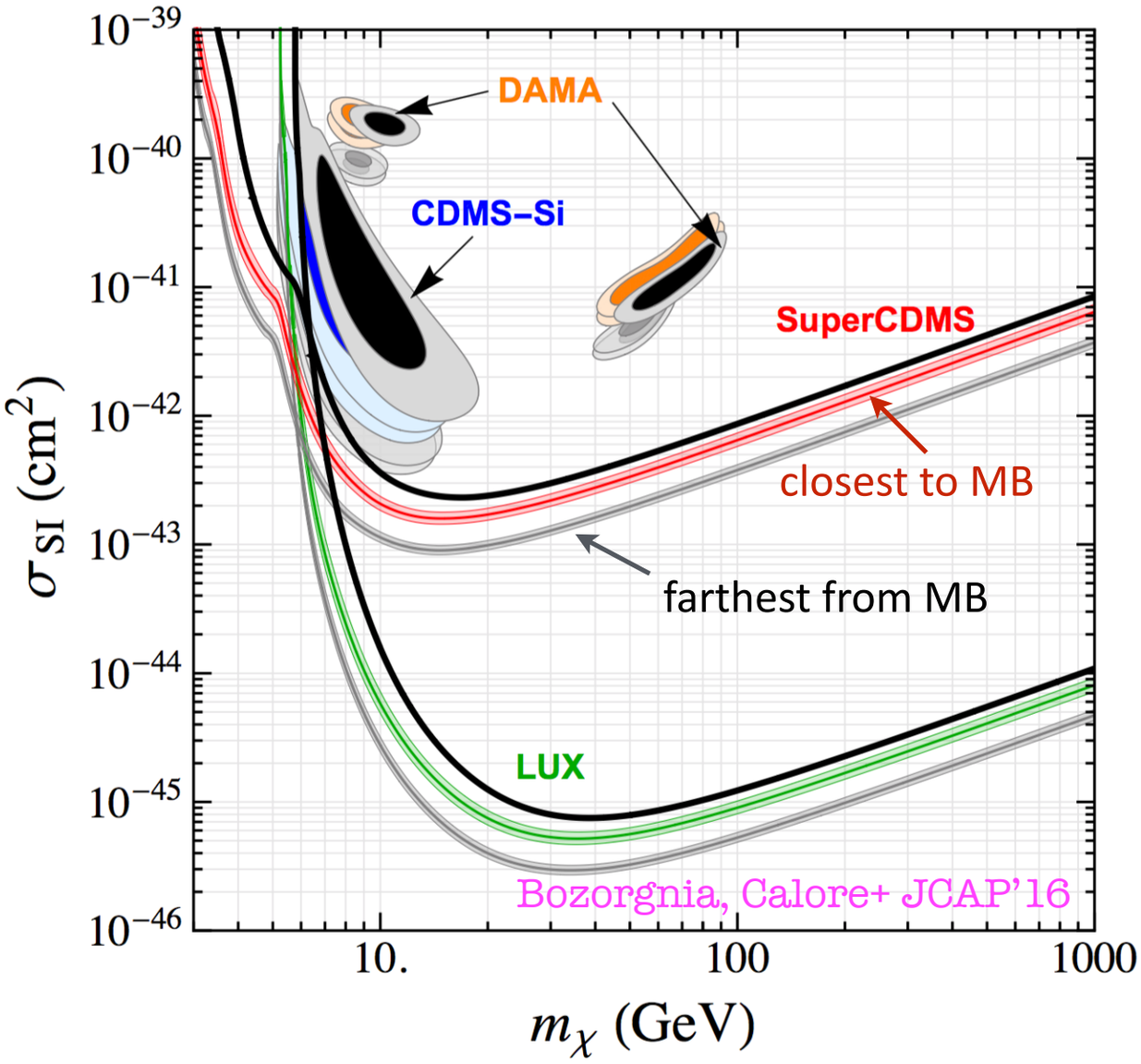
Kelso+ JCAP'16



Typically, a **Maxwellian with free peak v_0** better description for hydro case w.r.to DMO

Impact on DM direct detection limits

$$\eta(v_{\rm min},t) \equiv \int_{v>v_{\rm min}} d^3v \frac{f_{\rm det}(\mathbf{v},t)}{v} \qquad R(E_R,t) \propto \eta(v_{\rm min},t)$$

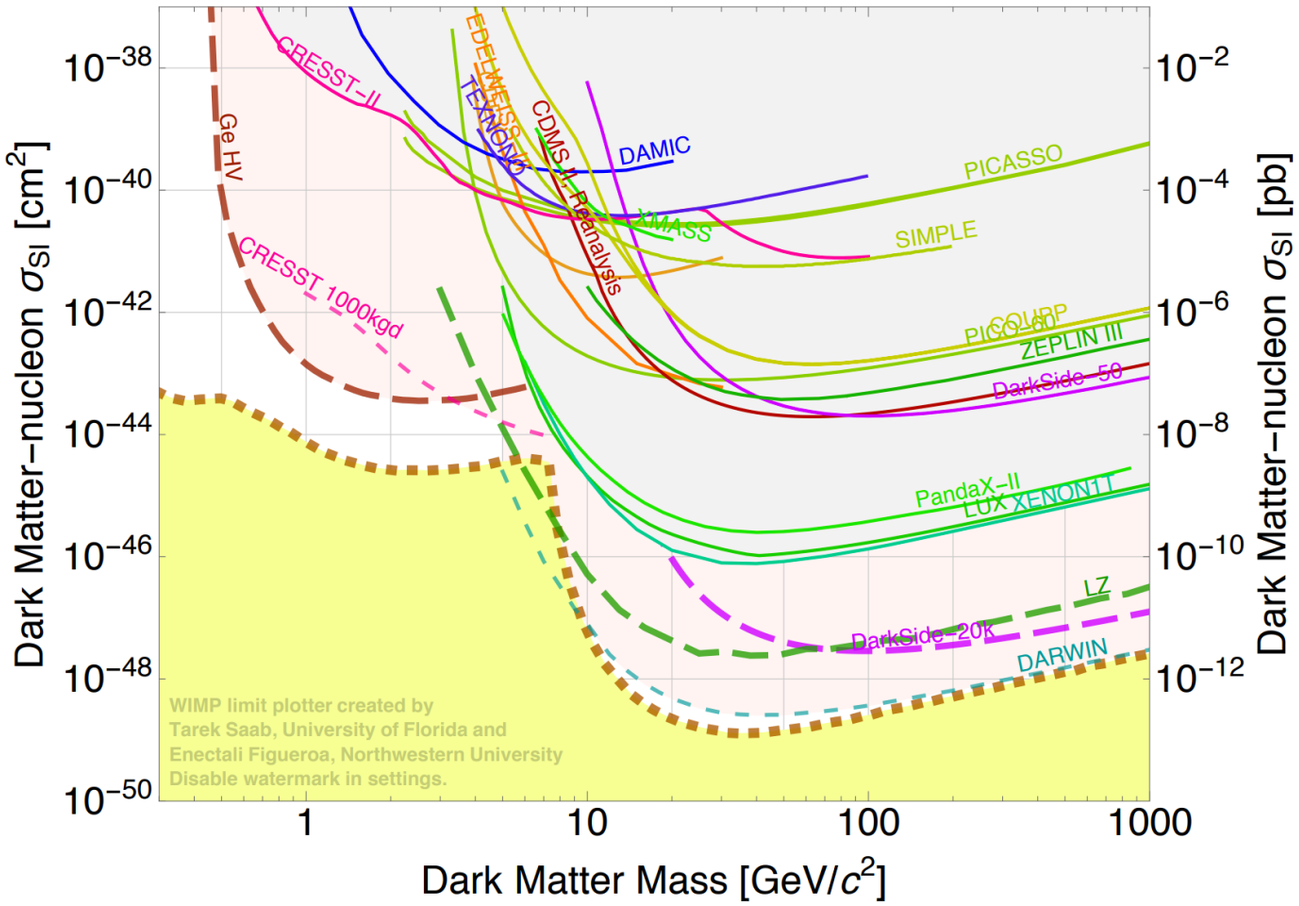


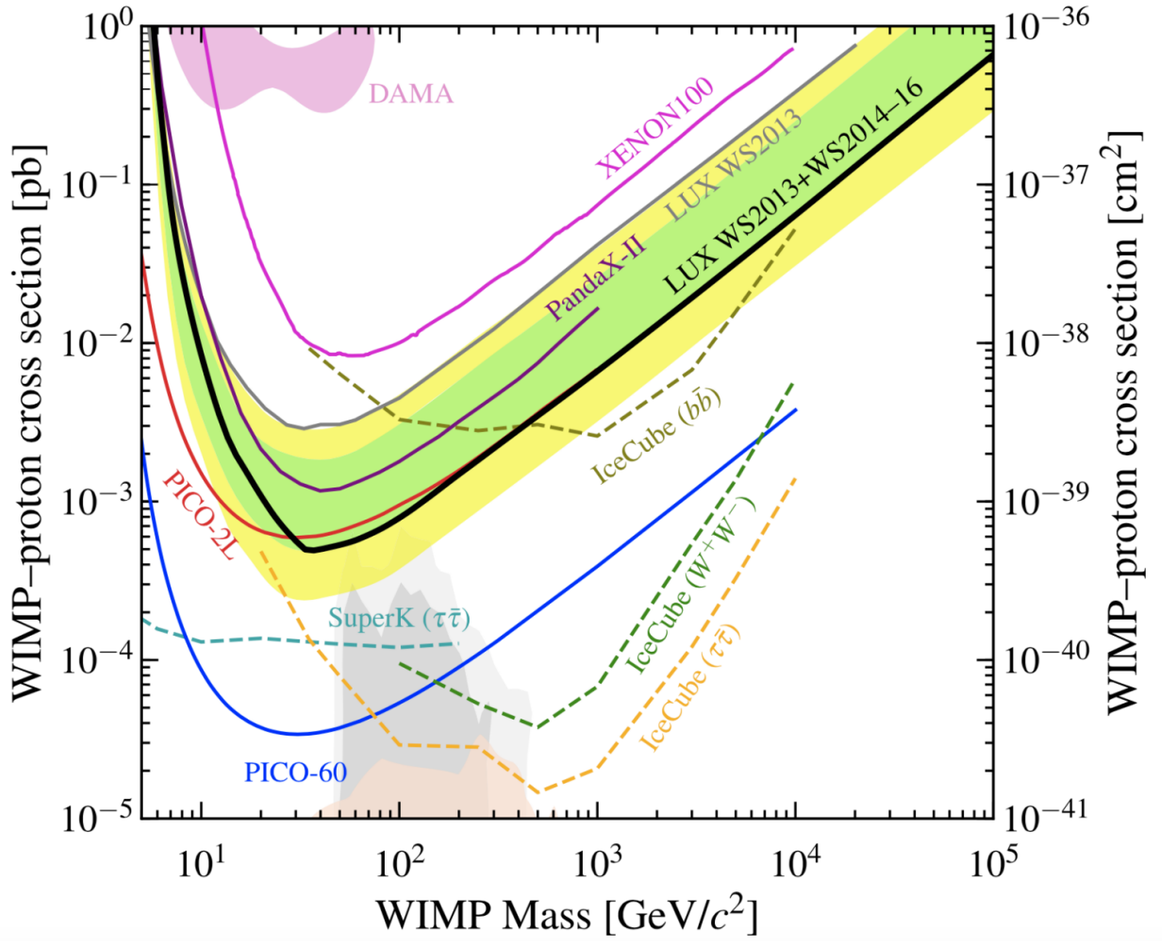
- ✓ Larger effect due to value of local DM density (overall rescaling).
- ✓ Shift of velocity peak implies a shift of allowed regions and limits by a few GeV at low masses (small effect).
- ✓ The compatibility between experiments is not improved.

[for comparing DD experimental results with astrophysical independent method see Fox, Kribs, Tait, PRD'11; Fox, Liu, Weiner, PRD'11; etc.]

[for uncertainties due to Galactic parameters and baryonic morphologies see Benito, Calore+JCAP'16]

Direct detection: Current limits





Spin-independent cross section

$$\sim 10^{-46}\,\mathrm{cm}^2 \,@\, 30\,\mathrm{GeV}$$

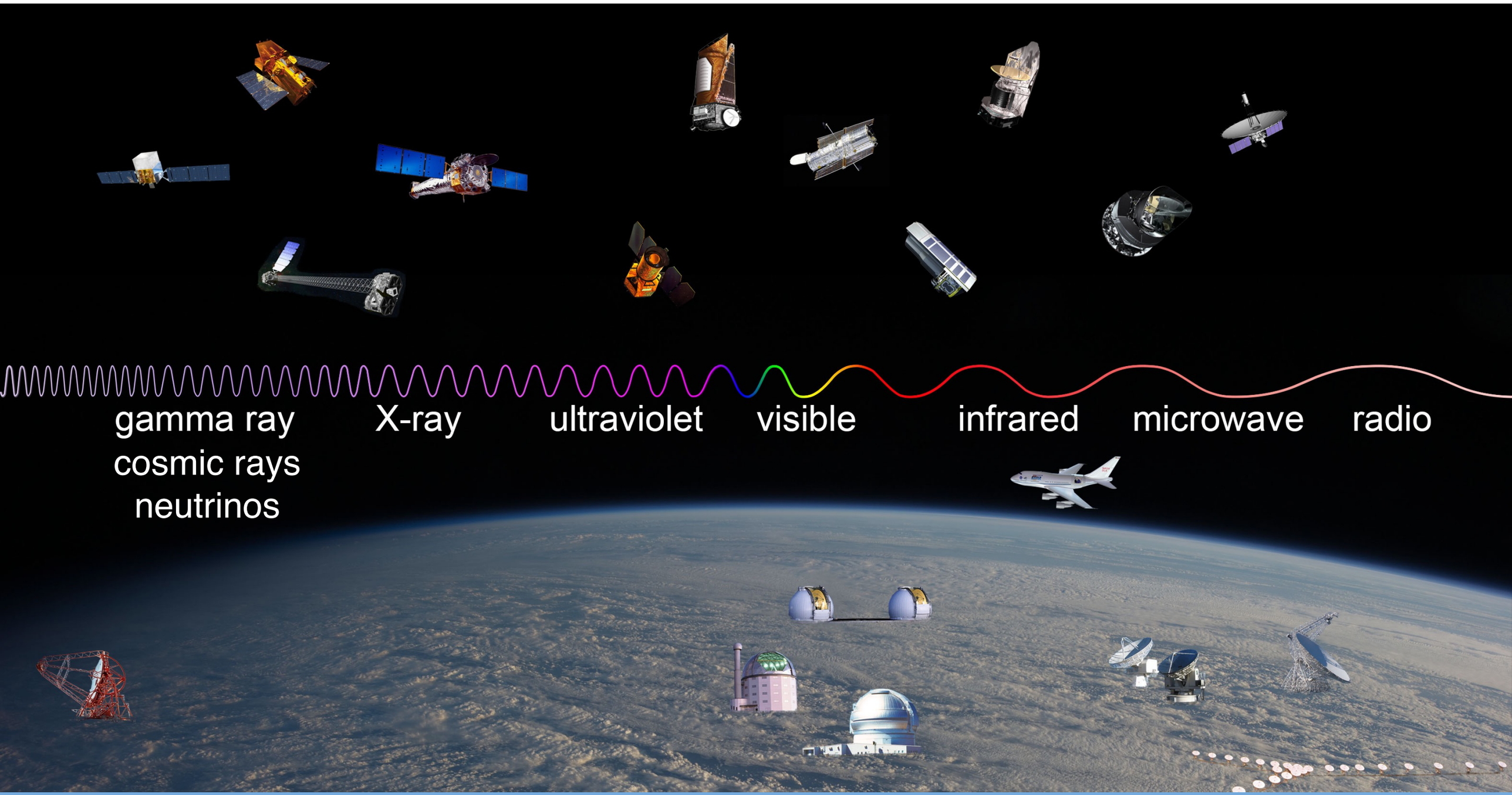
Spin-dependent (p) cross section

$$\sim 3 \times 10^{-41}\,\mathrm{cm}^2 \,@\, 30\,\mathrm{GeV}$$

[Latest results and future prospects presented at: TAUP2017; ICRC2017]

The astronomical data landscape

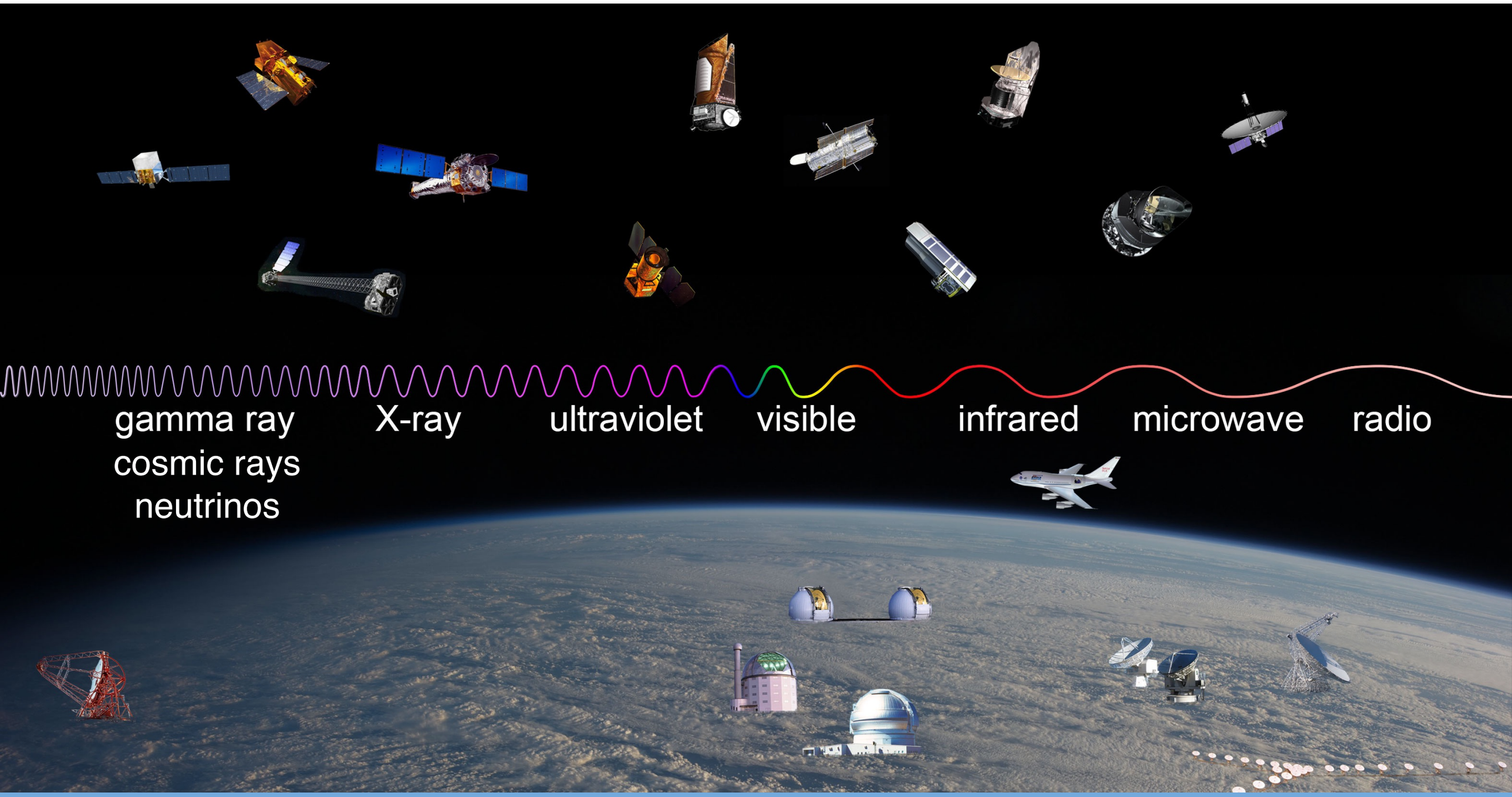
Ground-based telescopes and **spaceborne instruments** dedicated to detection of electromagnetic radiation, cosmic rays (eg: AMS02) and HE neutrinos (eg: ICECUBE, Antares)



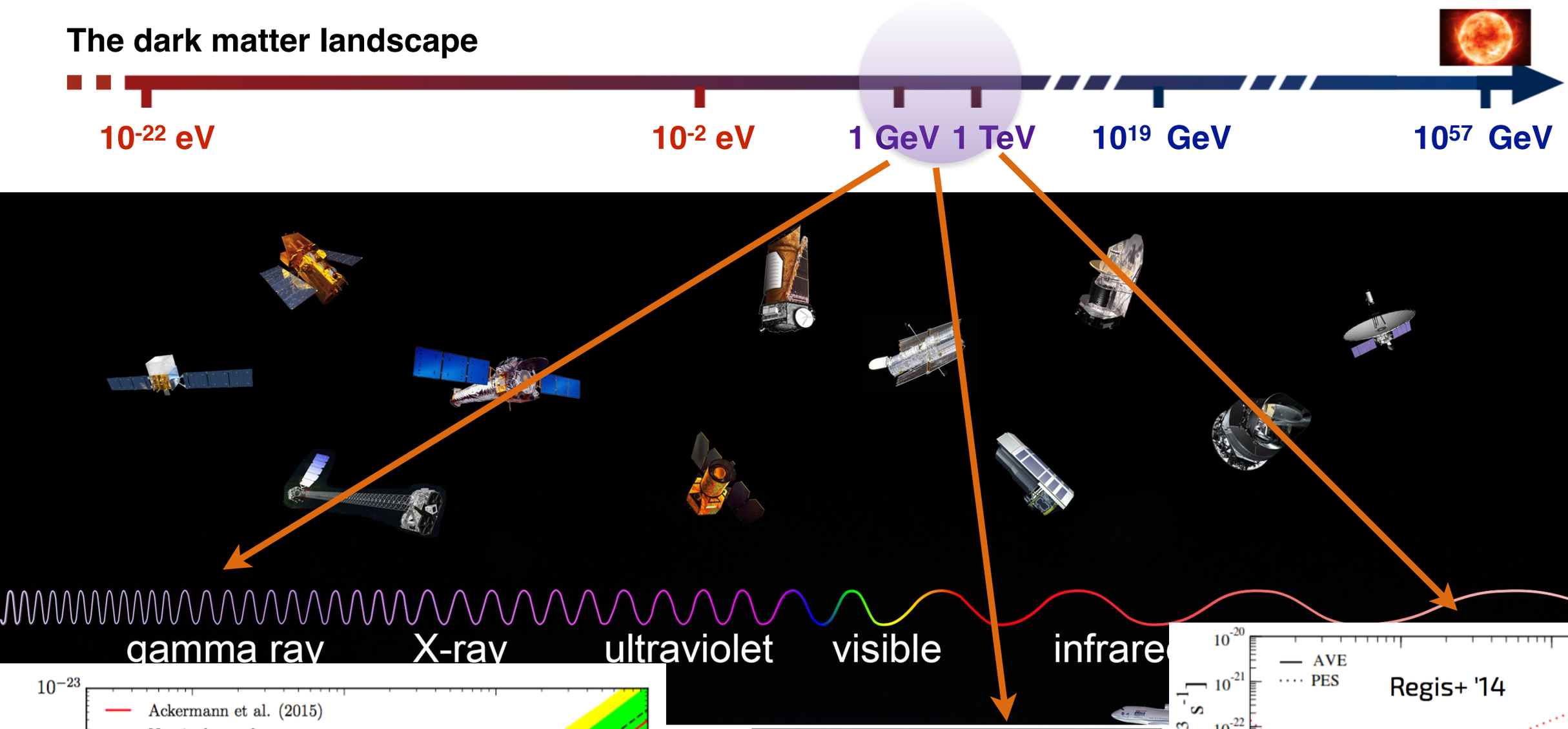
The astronomical data landscape

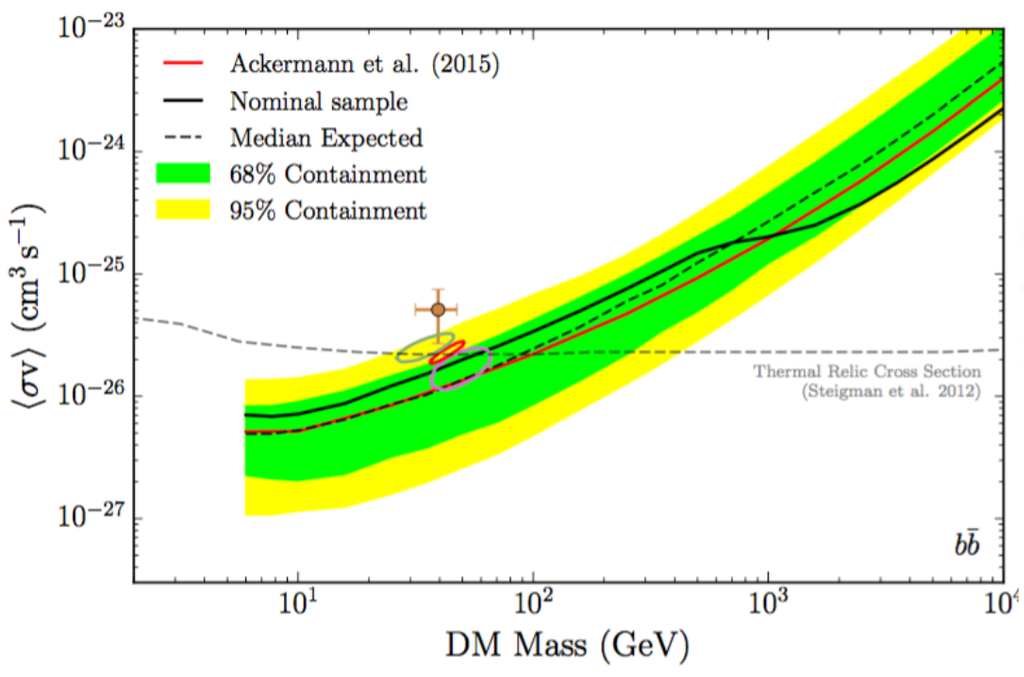
The dark matter landscape

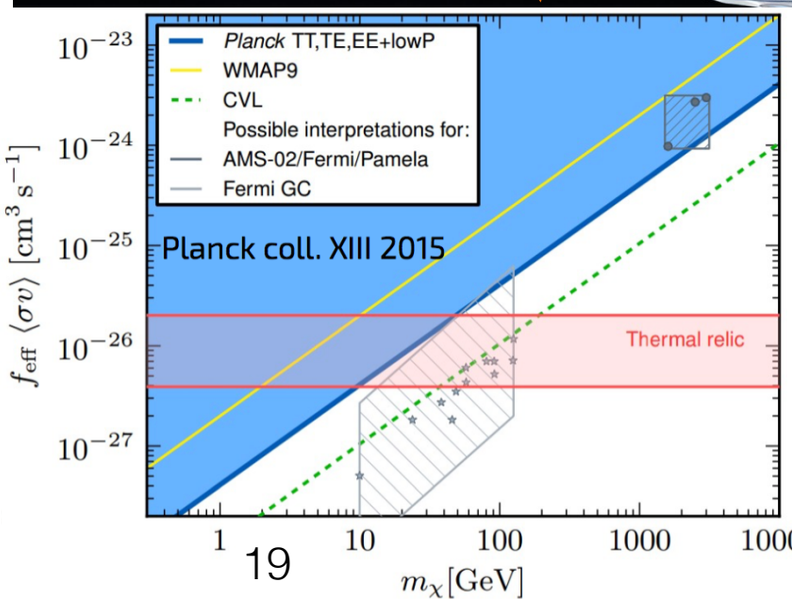
10^{-22} eV — 10^{-2} eV — 1 GeV 1 TeV — 10^{19} GeV — 10^{57} GeV

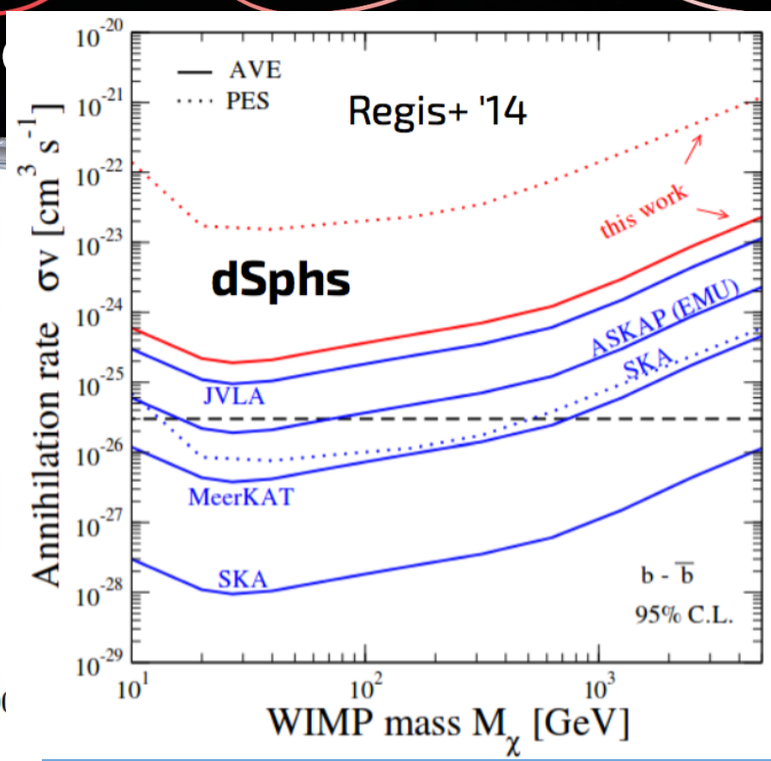


The astronomical data landscape

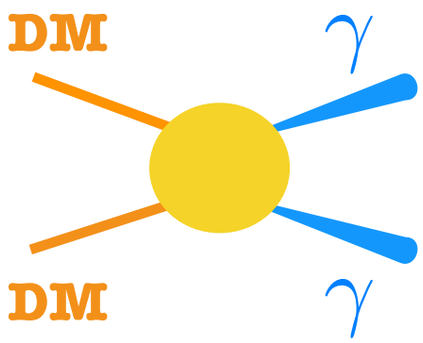






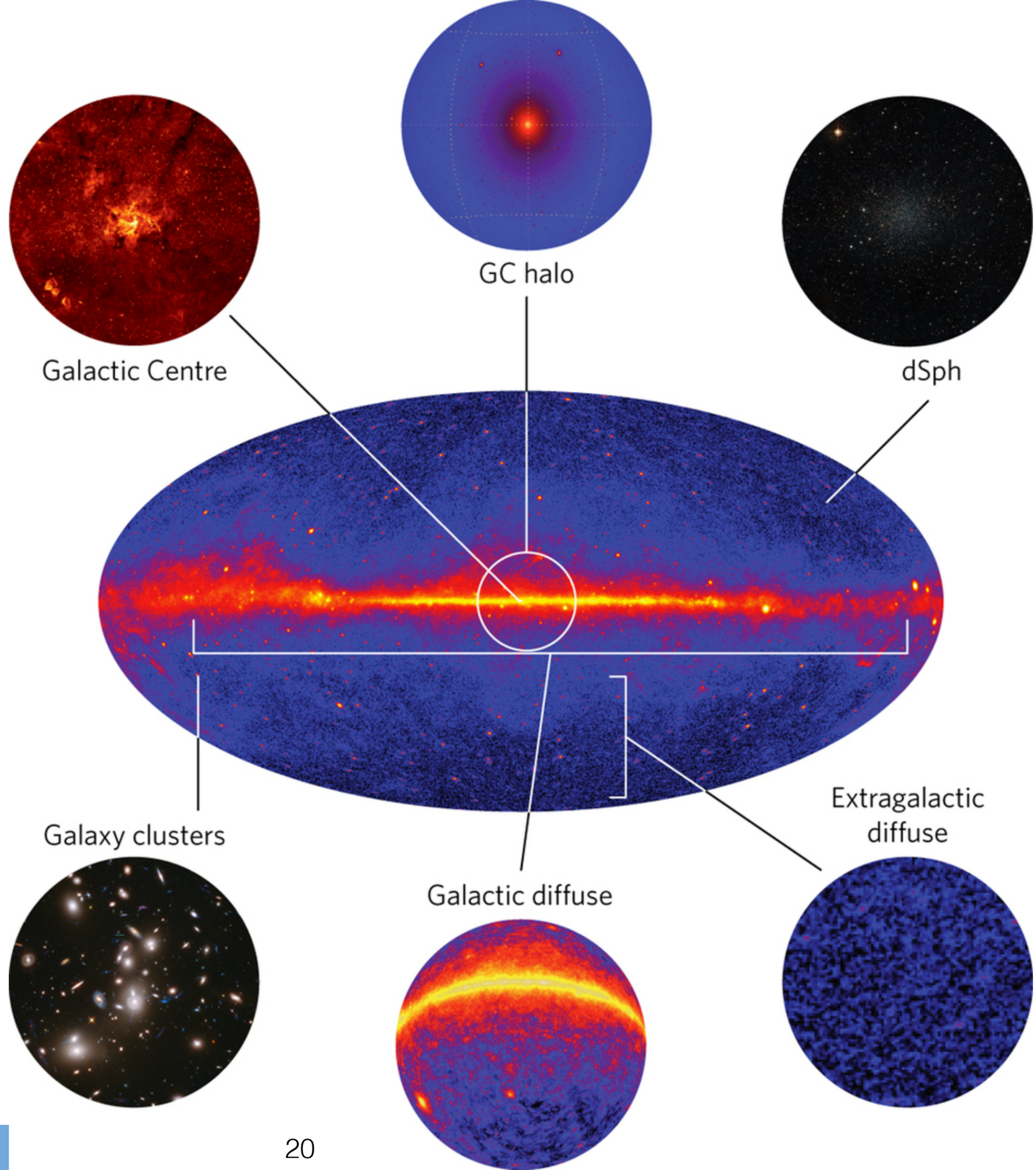


Targets for dark matter gamma-ray searches



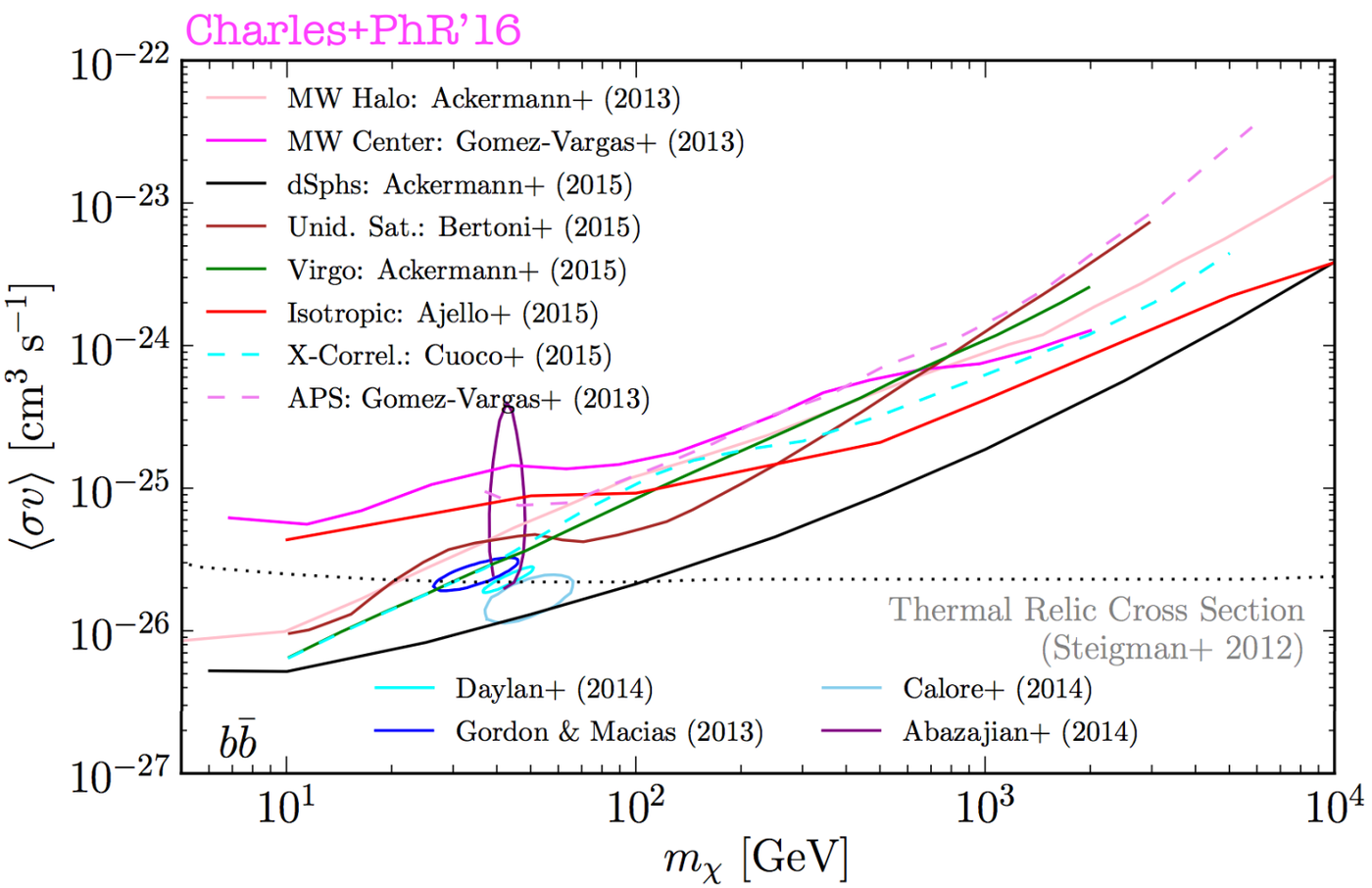
+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

Conrad & Reimer
Nature Phys. 13 (2017)

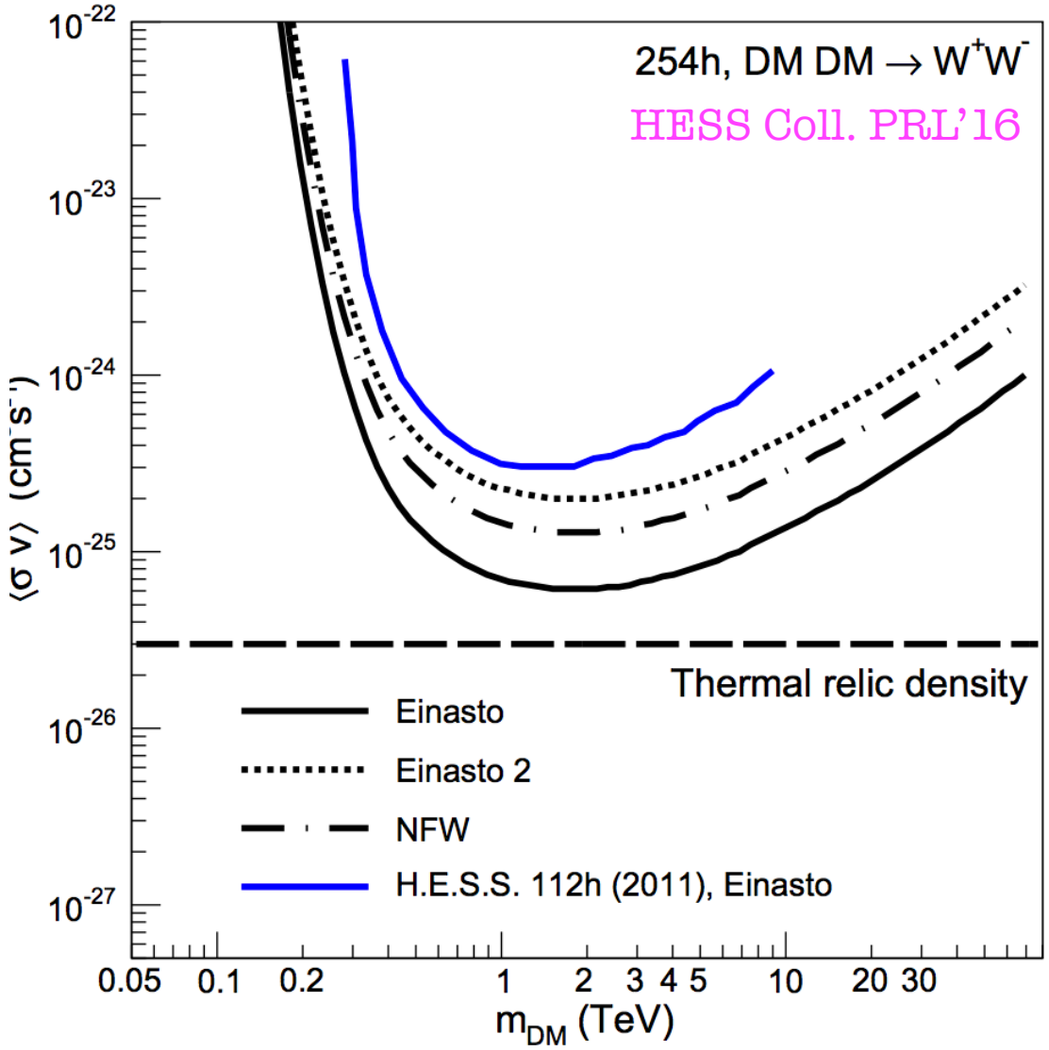


The present of gamma-ray DM searches

Fermi-LAT: most stringent limits from dwarf spheroidal galaxies.



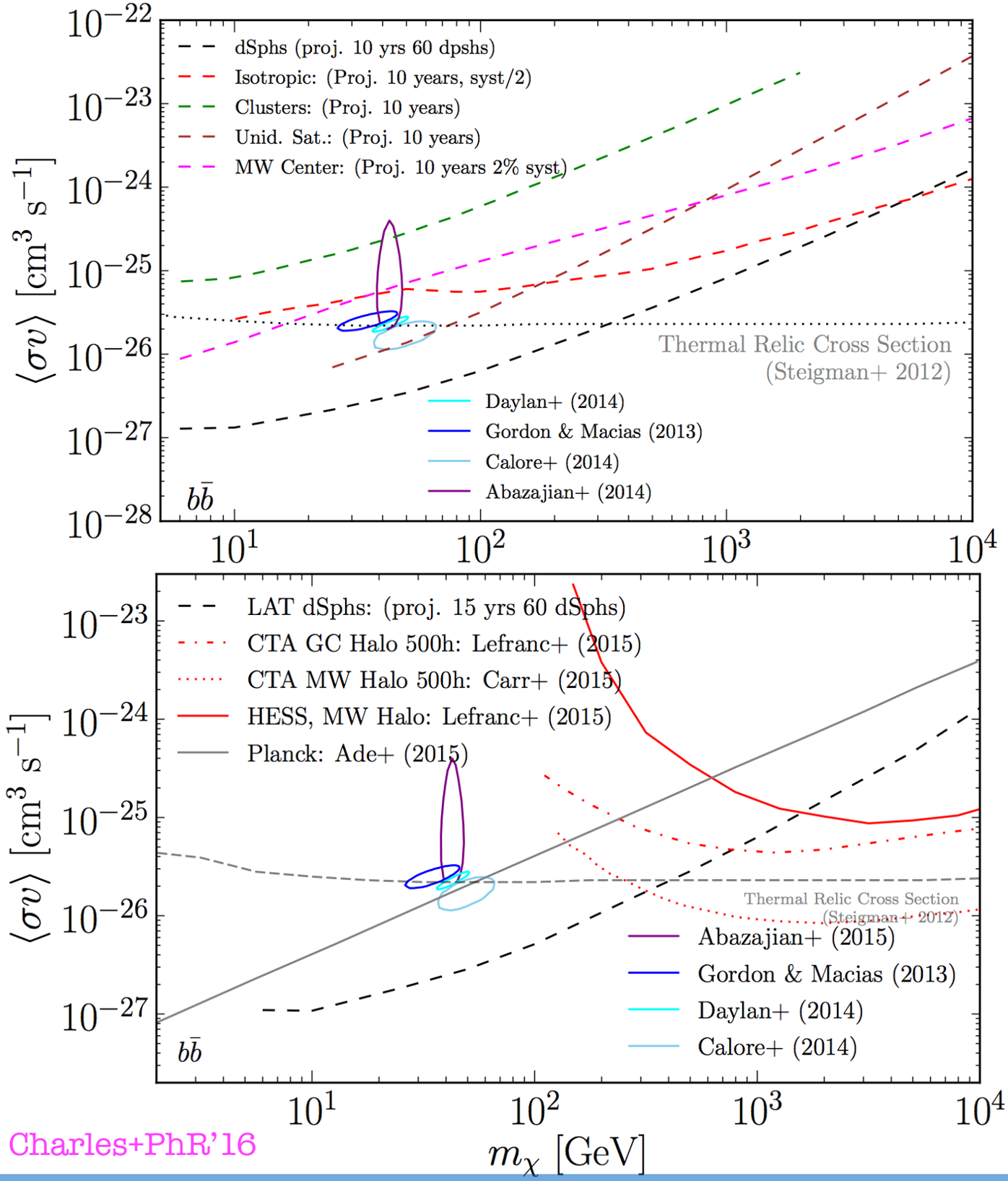
HESS: 10yr observation of the inner Galactic halo



- Comparison with current limits from other Galactic and extragalactic targets.
- Mild tension with GeV excess alleviated by the latest analysis of dwarfs, incl. DES 2yr candidates.

- Most constraining analysis; in the reach of thermal cross-section.
- At E>1TeV competitive with Fermi-LAT.

The future of gamma-ray DM searches



Charles+PhR'16

- **Fermi-LAT** limits improvement depends on target (syst., bkg or signal limited); dwarfs limits might improve by factor 2-5, depending on new dwarfs discovery (DES, Pan-STARRS, LSST).

  Hargis+ ApJL'14
- **HAWC** will improve limits from observations of dwarfs and Galactic centre; **CTA** will improve **HESS** limits by factor up to 10.

  Silverwood+ JCAP'15; Doro+ AP'13; Carr+ 2015; Lefranc+ PRD'15
- Great potential in the unexplored MeV/ sub-GeV range (e.g. **Amego**; **e-ASTROGAM**)

  Bringmann+PRD'17; Bartels+2017
- Future **radio telescopes**: great improvement in sensitivities [e.g. Storm +ApJ'17]

Beyond limits…

…Some signal hint?

The Galactic centre GeV excess

Signal:

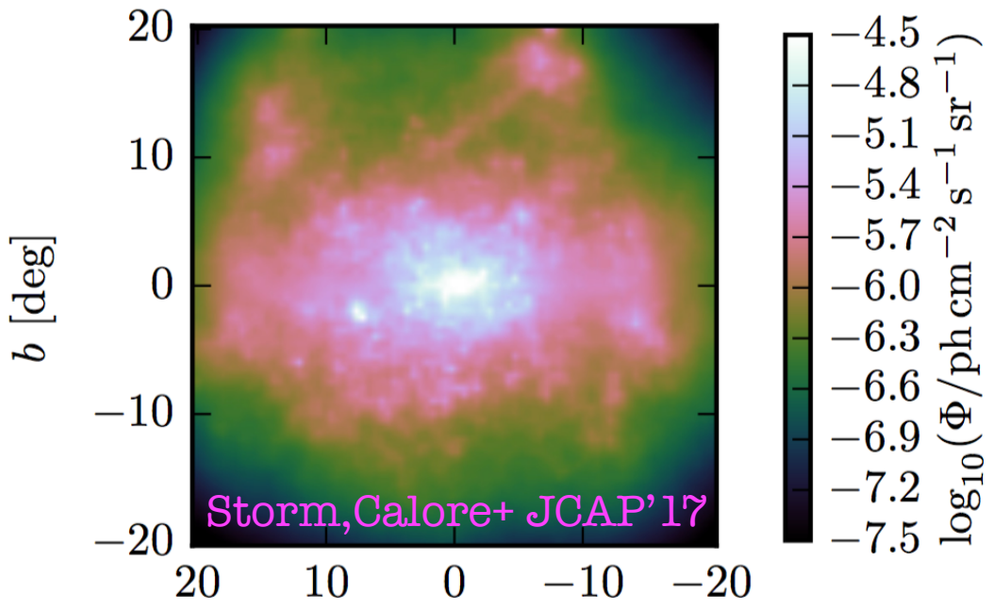
- Excess of GeV photons from inner Galaxy**
- Fermi-LAT
- Galactic centre analysis

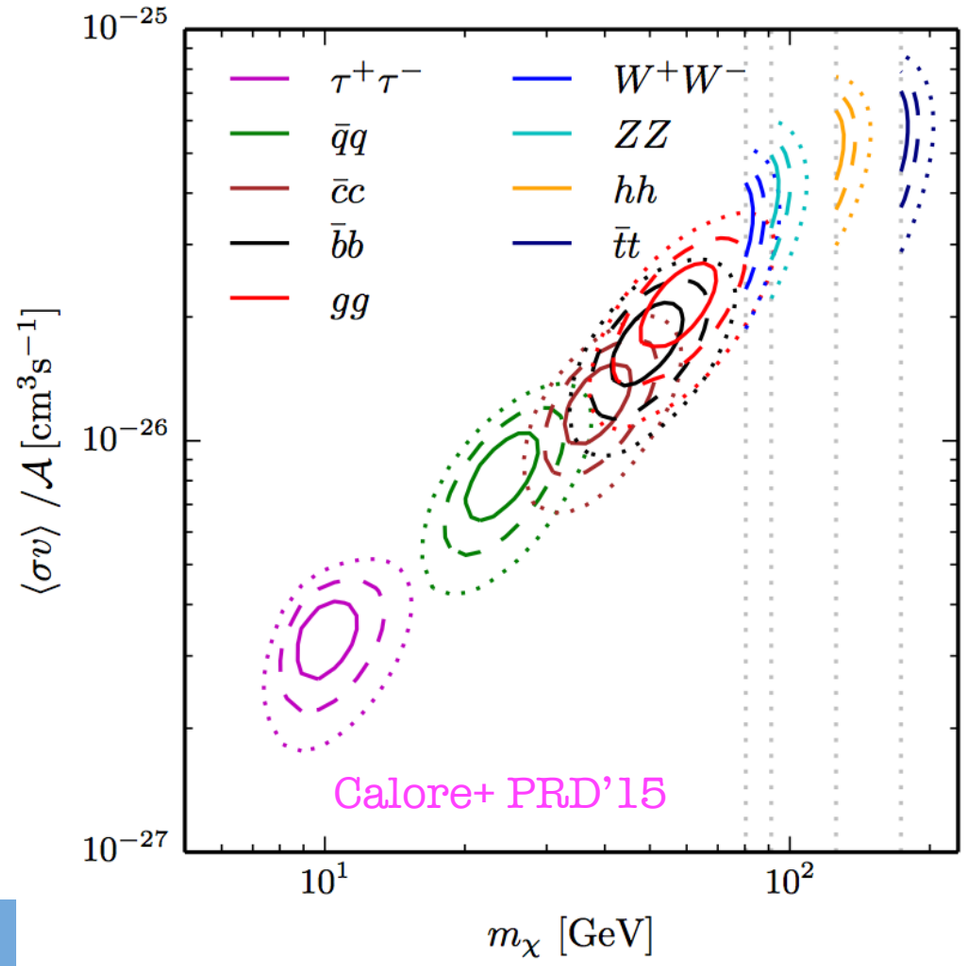
Interpretations:

- Astrophysics: Diffuse emission from electrons/ positrons at the Galactic centre (ehnanced SF or activity GC); Sub-threshold millisecond pulsar-like point sources. Gaggero+ JCAP'15; Carlson+PRD'15, Petrovic+ JCAP'14; Cholis+JCAP'15; Bartels+PRL'16; Lee+PRL'16; Ackermann+'17
- Dark matter annihilation: large freedom in channel/masses thanks to syst. uncertainties

Future: Calore+ PRD'15; Agrawal+JCAP'15

- Upcoming radio telescopes: dedicated surveys with MeerKAT/SKA (> 2018) Calore+ ApJ'16
- Conclusive tension with other targets (eg dSphs)





**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017

Weak excesses in dwarf spheroidal galaxies

Signal:

- < 3σ excesses in dSphs galaxies
- Fermi-LAT + DES targets (Indus II, Reticulum II and Tucana III)

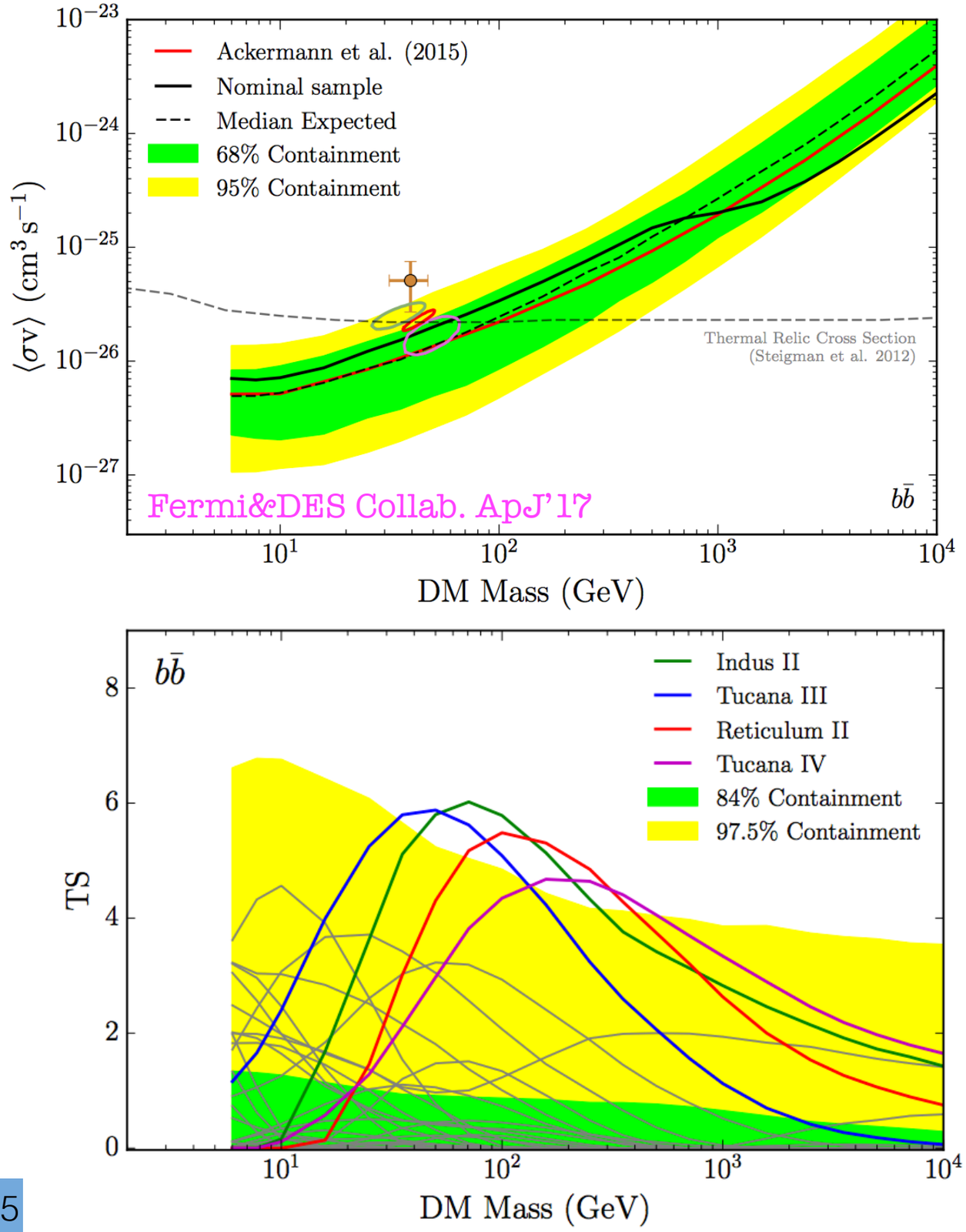
Interpretations:

- Dark matter annihilation with mass ~ 40 — 100 GeV
- Syst. uncertainties on J-factor determination for ultra-faint dSphs

Future:

- New data from Fermi-LAT (improvement by a factor of 3-4)
- New large optical surveys and spectroscopic data (LSST, Maunakea Spectroscopic Explorer)
- Radio searches with ATCA/SKA

Regis+ JCAP'17



X-correlation: Fermi-LAT & Galaxy catalogs

Signal:

- Detection (> 10σ, NVSS) of cross-correlation signal between extragalactic gamma-ray background and galaxy catalogs Cuoco+ ApJS'17
- Fermi-LAT/Galaxy catalogs (NVSS, 2MASS, SDSS-DR12, WISExSuperCOSMOS, 2MPZ, WIxSC)

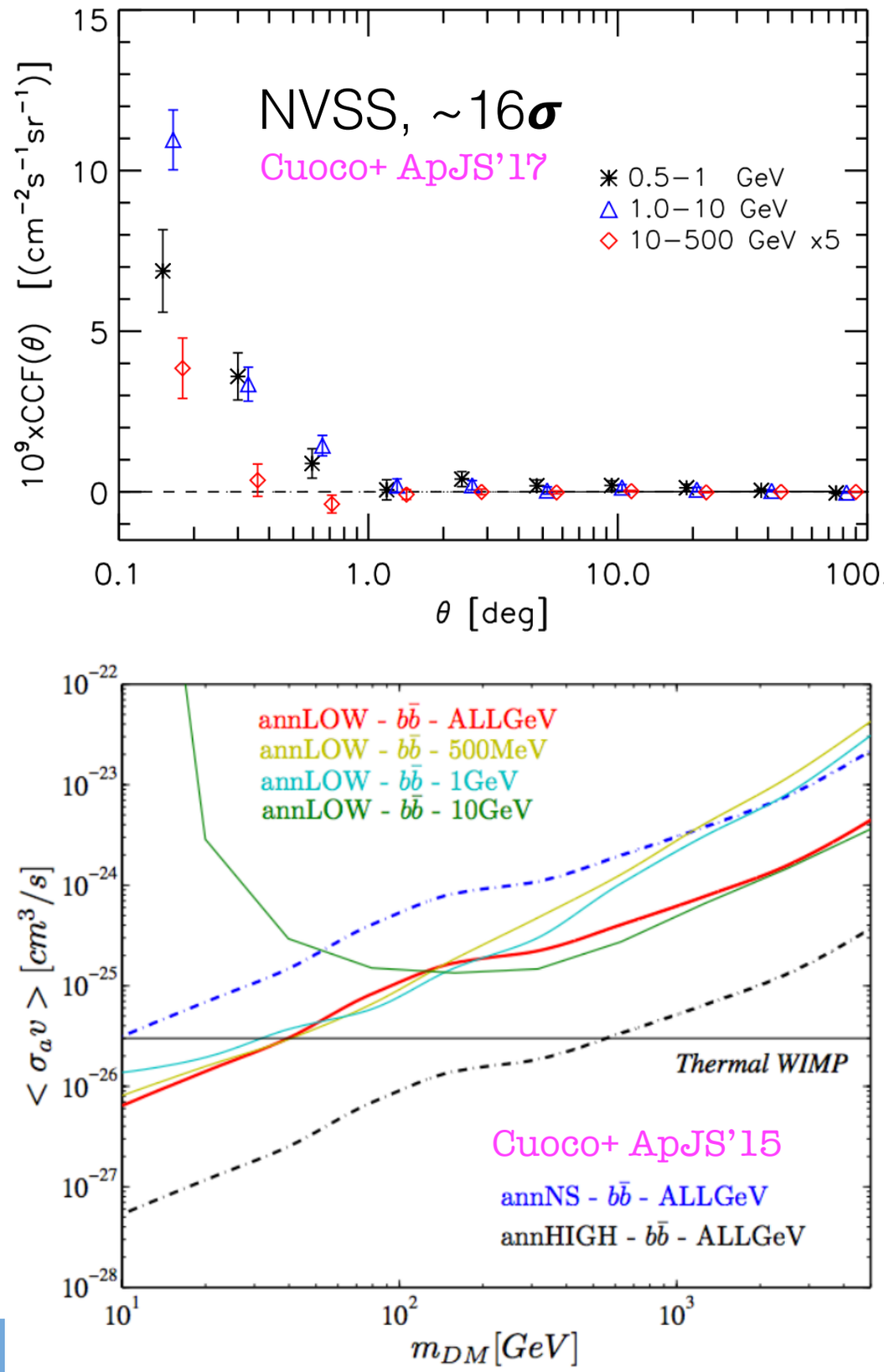
Interpretations:

- Degeneracy between DM interpretation and AGN hosted in big halos (groups or clusters)
- Tomographic approach account for the full redshift distribution of source populations: DM and astro peak at different z Regis+ PRL'15

Future:

- X-correlation with other catalogs, weak lensing and cosmic shear
- Low-z tomography => highest sensitivity to DM

[Detection in X-corr gamma rays with cluster catalogs Branchini+ ApJS'17; no detection with weak lensing data Troester+ MNRAS'17; detection with CMB lensing Fornengo+ ApJ'15]



Low-energy excess in cosmic-ray antiprotons

Signal:

- Excess in cosmic-ray antiprotons @ 10 — 20 GeV
- AMS-02 Cuoco+ PRL'17; Cui+ PRL'17

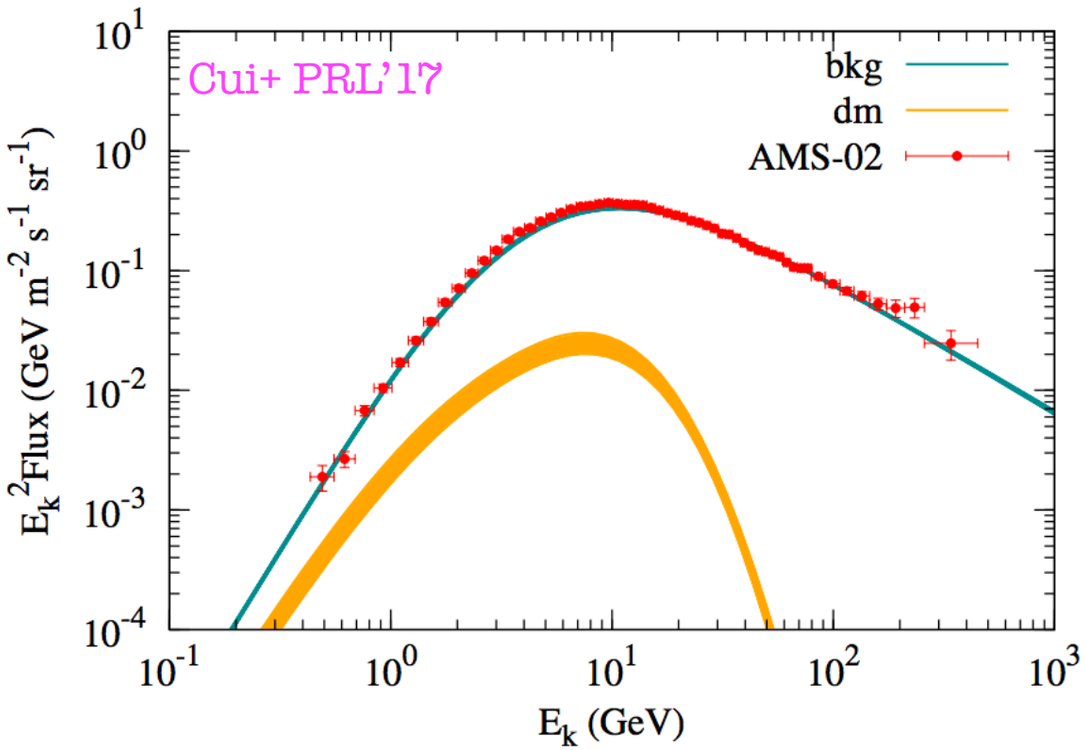
Interpretations:

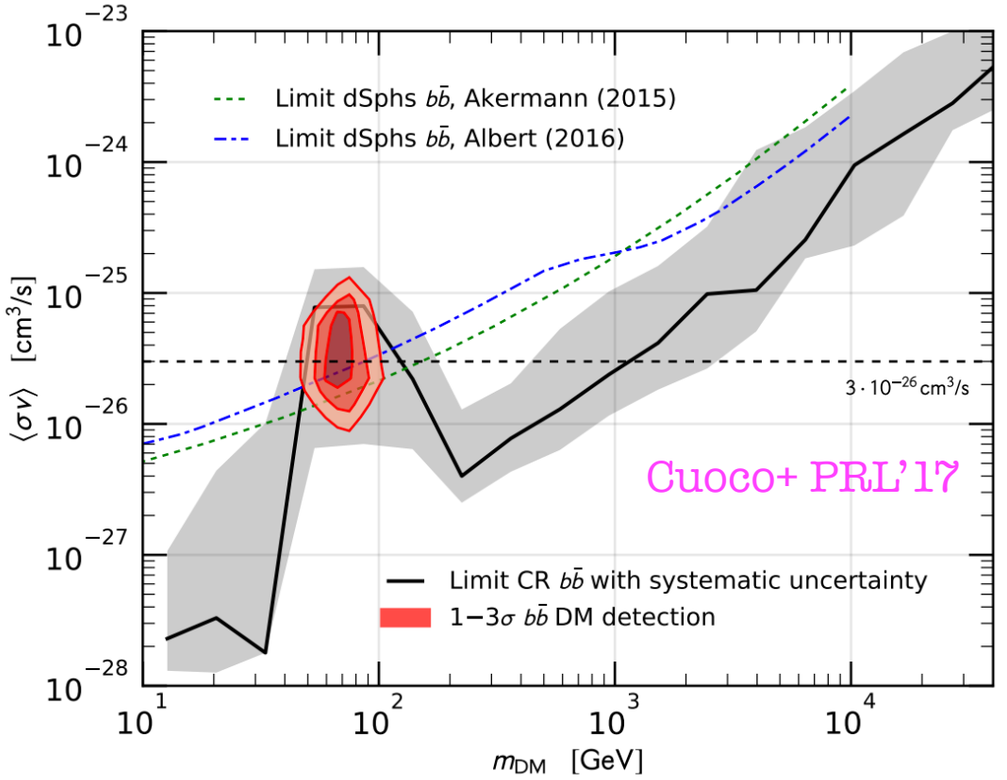
- Dark matter annihilation with mass ~ 40 — 130 GeV (consistent with GeV excess) Cuoco+, 2017
- Syst. uncertainties still large: pbar production cross section; effects of solar modulation; cosmic-ray propagation

Future:

- New low-E data?
- Better constraints on pbar production cross section and its energy dependence

F. Donato, P. Serpico
XSCRC, CERN, March 2017





[Do not forget the rising of the **positron fraction** as perpetual claim of dark matter detection]

3.5 keV X-ray line

Signal:

- 3.5 keV line in X-ray
- XMM-Newton, Chandra, Suzaku
- Multi-target (stacked clusters, Perseus, M31, GC)
- But also null detections…

Bulbul+ ApJ'14; Boyarsky+ PRL'14; Urban+ MNRAS'15

Interpretations:

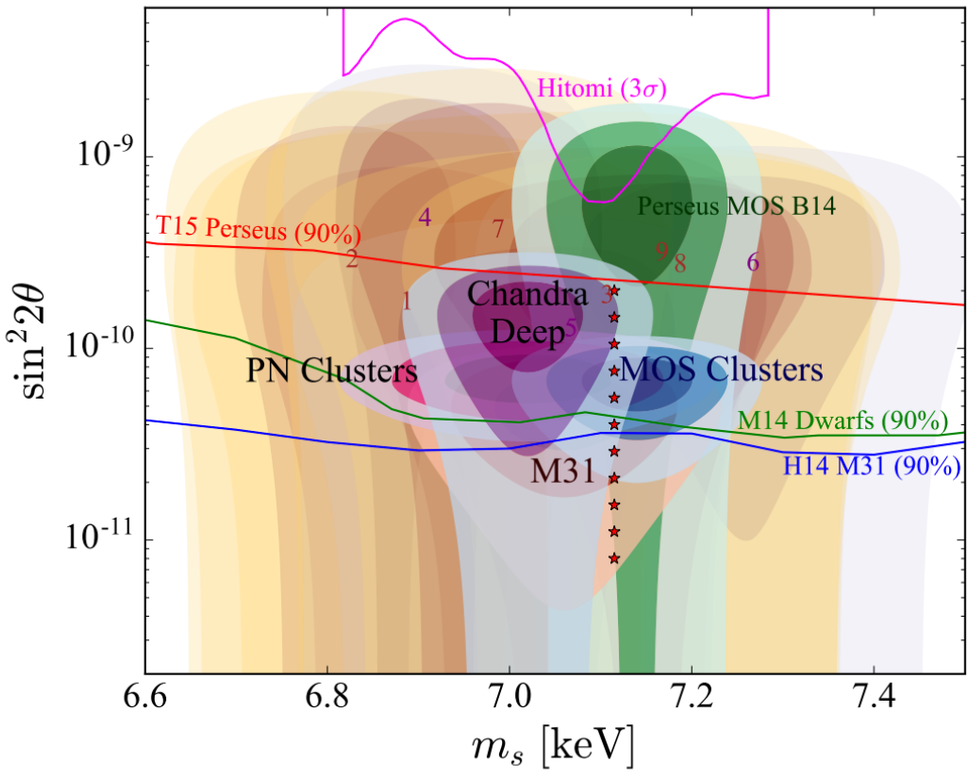
- Astro contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas
- Dark matter: decay of ~7 keV sterile neutrino (not at weak scale…)

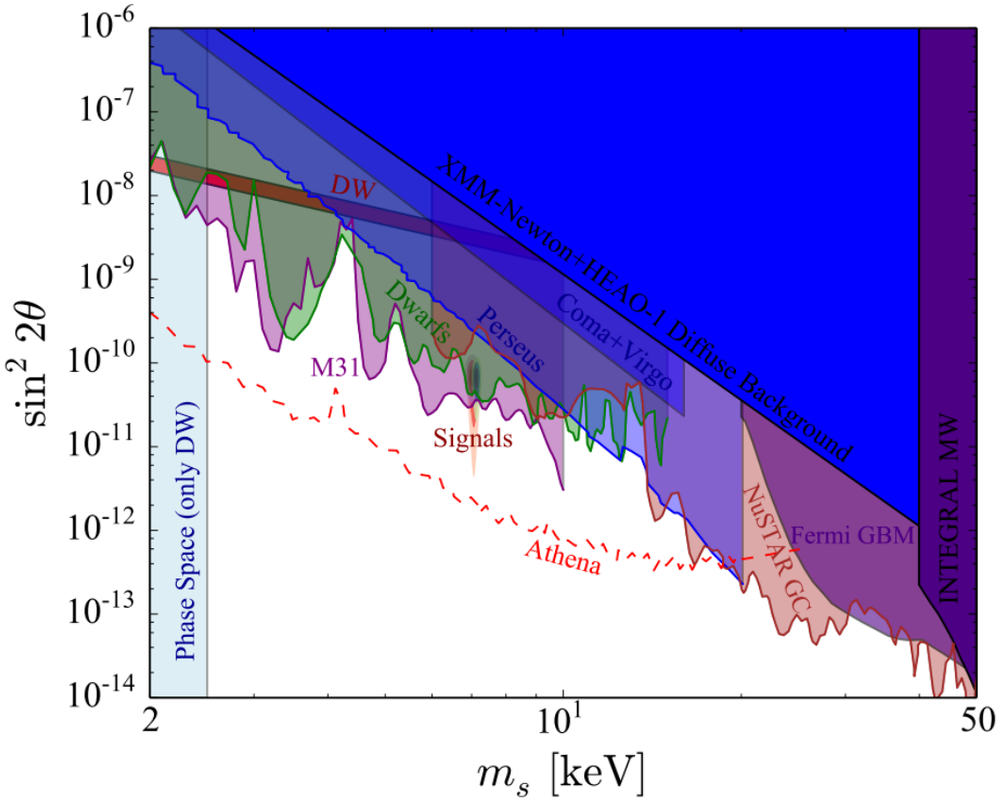
Future:

- Current X-ray telescopes' constraints: NuStar is approaching
- Exploit v distribution of the signal and Doppler shift effects, visible with XARM (March 2021)?
- Micro-X dedicated mission 2019 (~3 keV energy resolution)
- Athena (2028) sensitivity

Abazaijan, Phys. Rep. 2017

Abazaijan, Phys. Rep. 2017



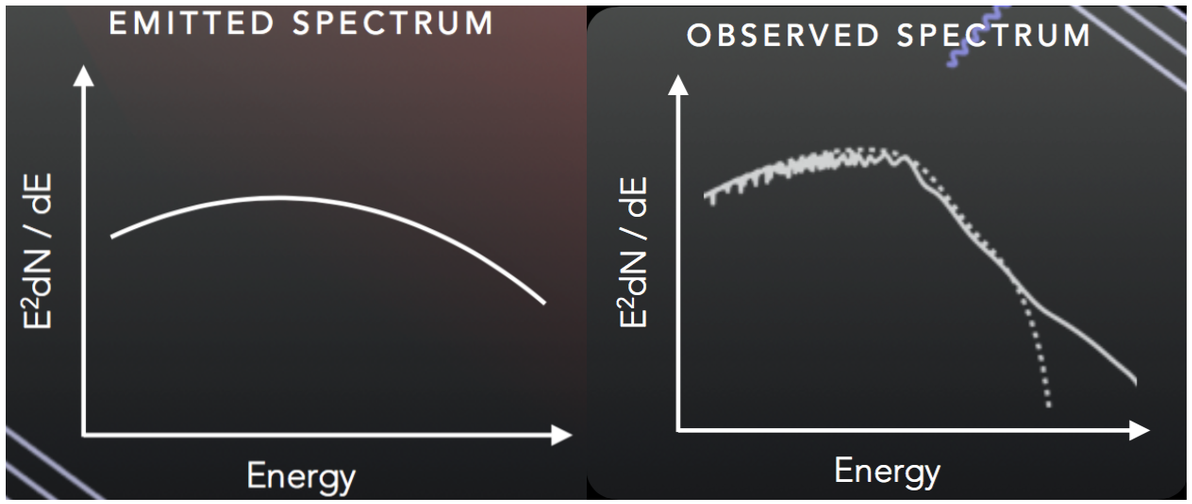


Beyond WIMPs with astroparticle experiments…

…just a taste

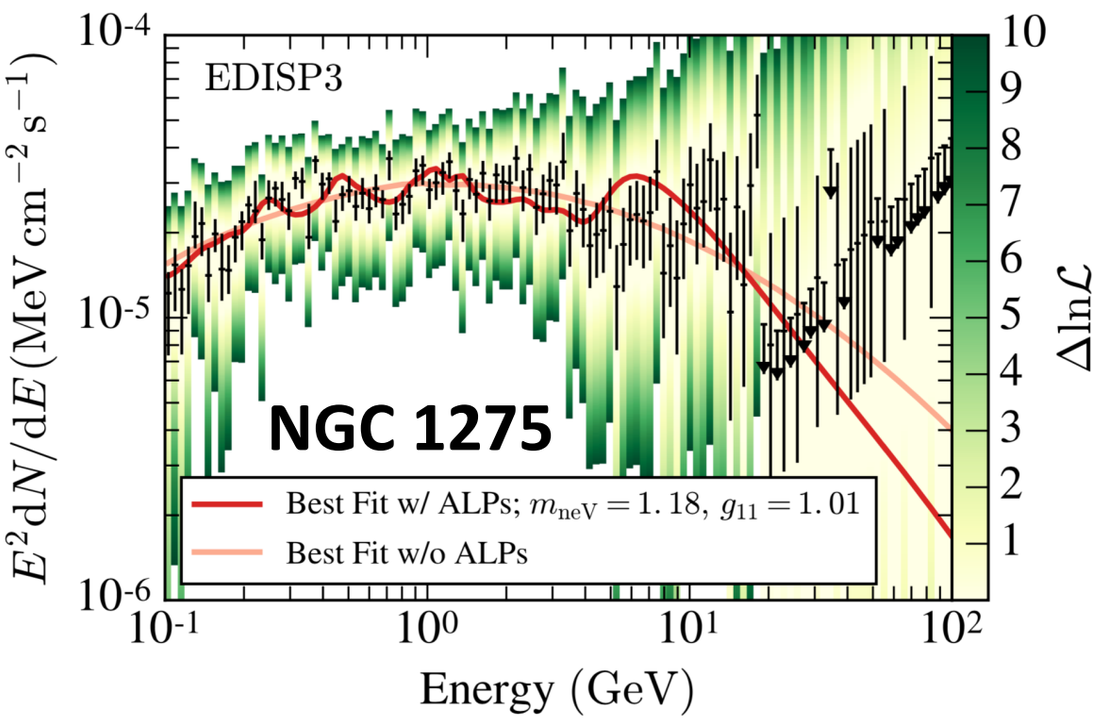
ALPs: gamma-ray spectral distorsions

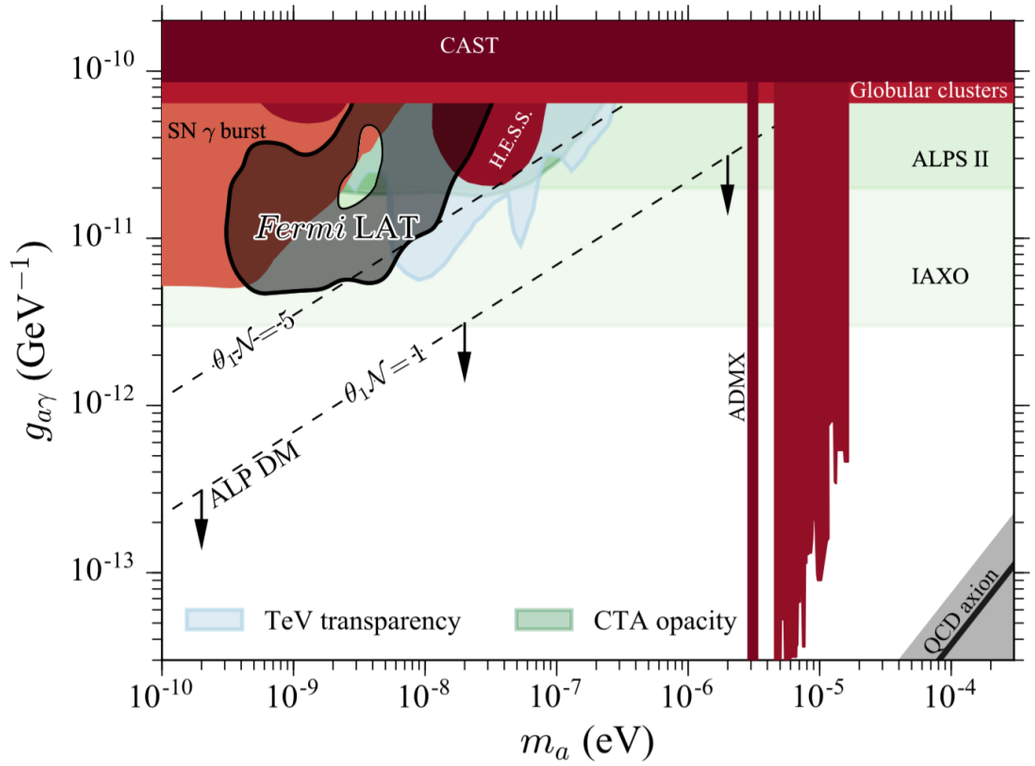
Photon-ALPs oscillation in external and Galactica magnetic fields, due to mixing between ALPs and photon polarization along field direction



1) Oscillations below critical E
2) Reduced absorption (extragal)

Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; M.Meyer et al. 2013, 2014



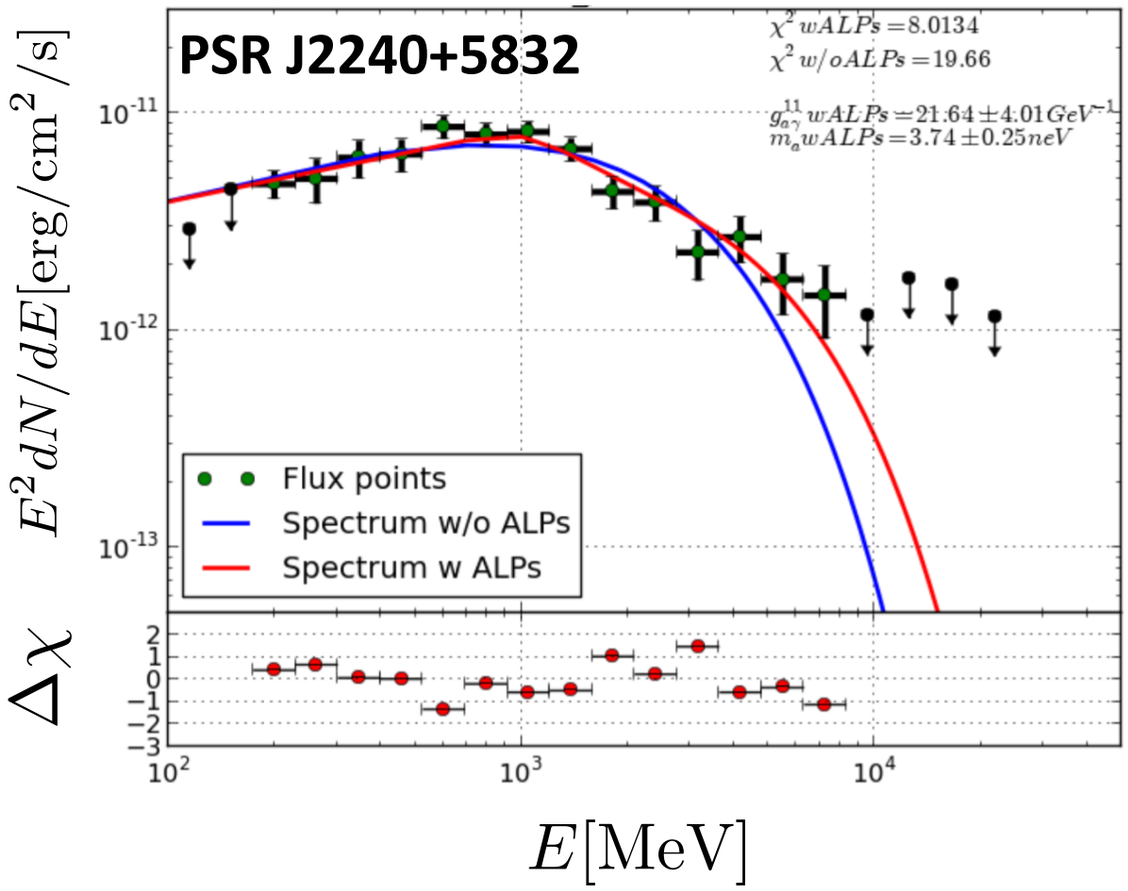


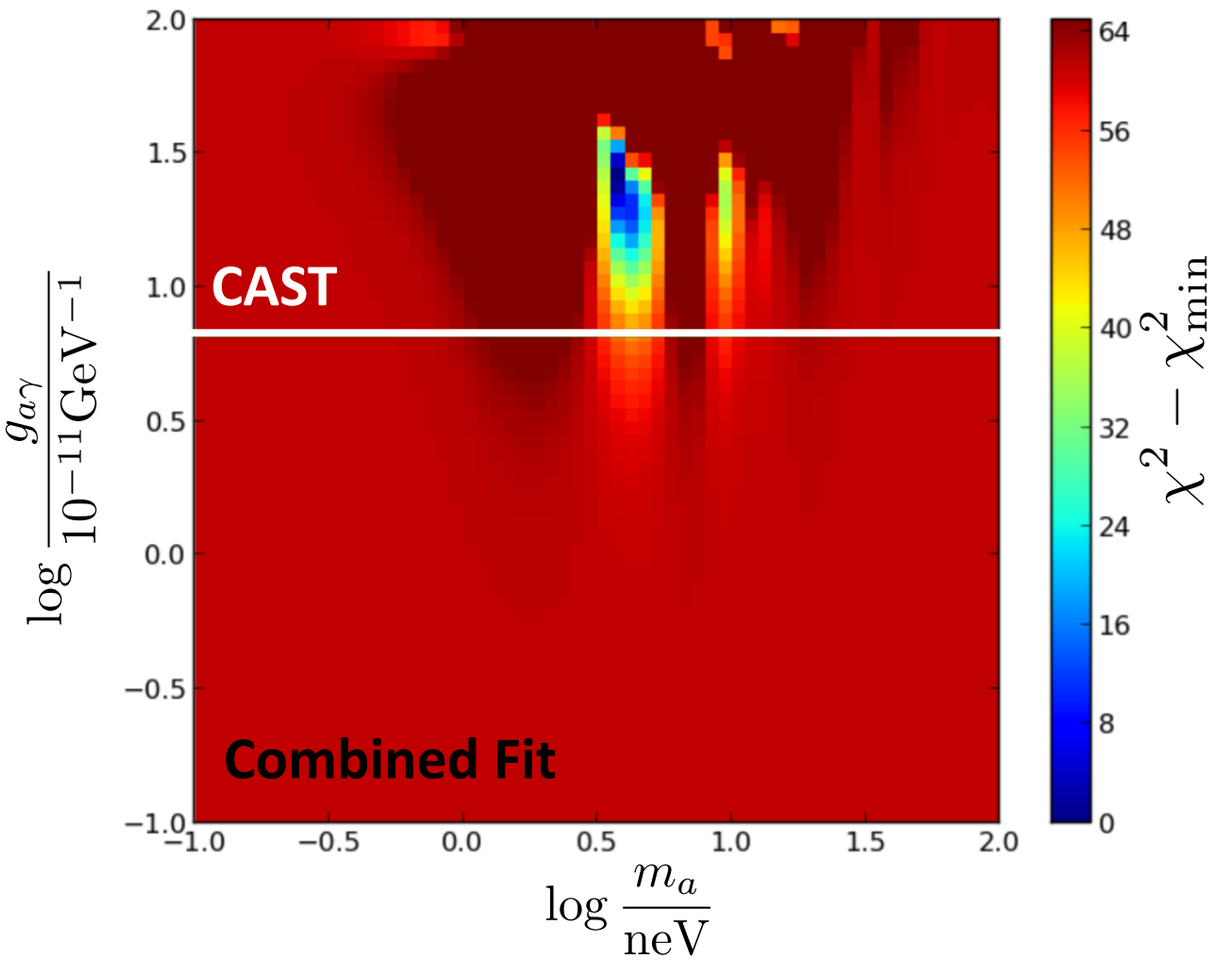
Fermi-LAT Collab. PRL'16

See A. Ringwald's talk

ALPs in Galactic sources

J. Majumdar, F. Calore*, D. Horns, In prep.



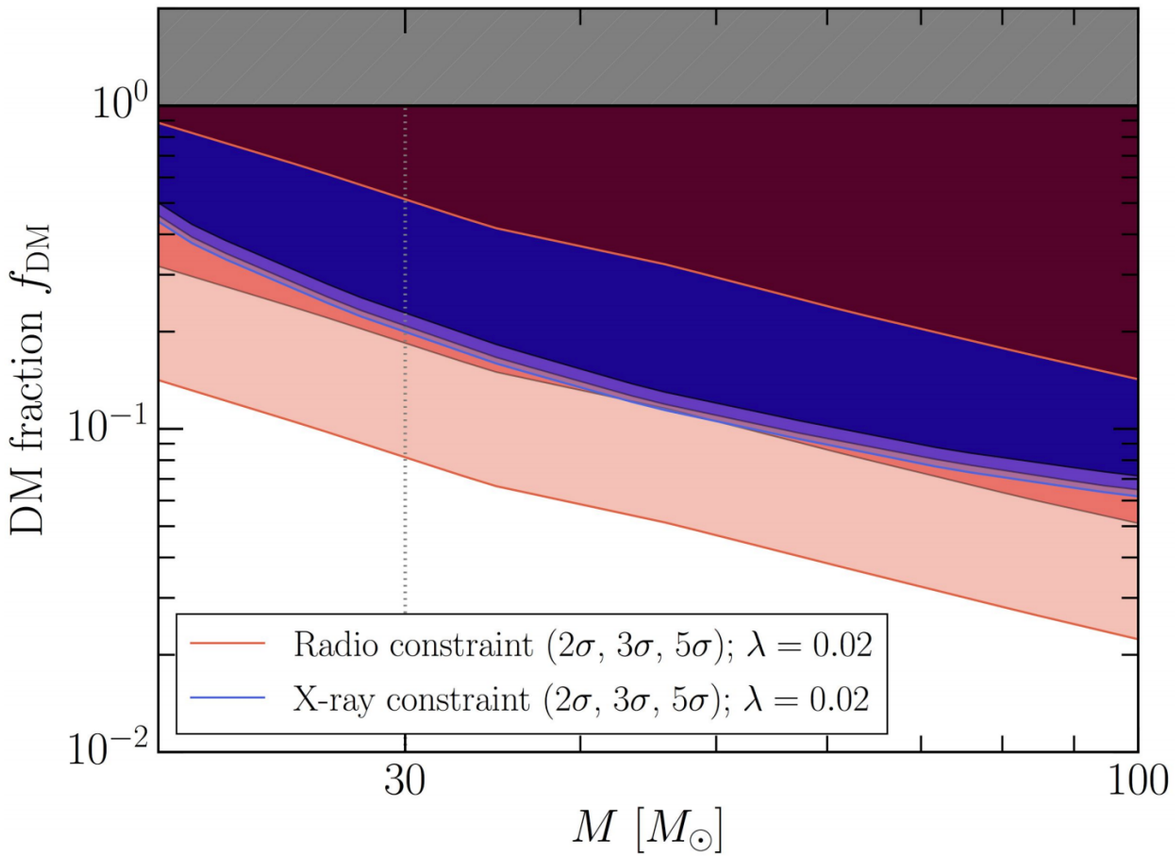


- Oscillation typically below 1 GeV => We can look at the spectra of bright Galactic sources, aka pulsars.
- Selection of six brught gamma-ray pulsars, at different position w.r.to Galactic spiral arms (PASS 8, 8.5yr data)
- Significant improvement in the fit when including ALPs oscillations
- However, best-fit region excluded by CAST limits => Study effect of Galactic magnetic field on the combined best-fit

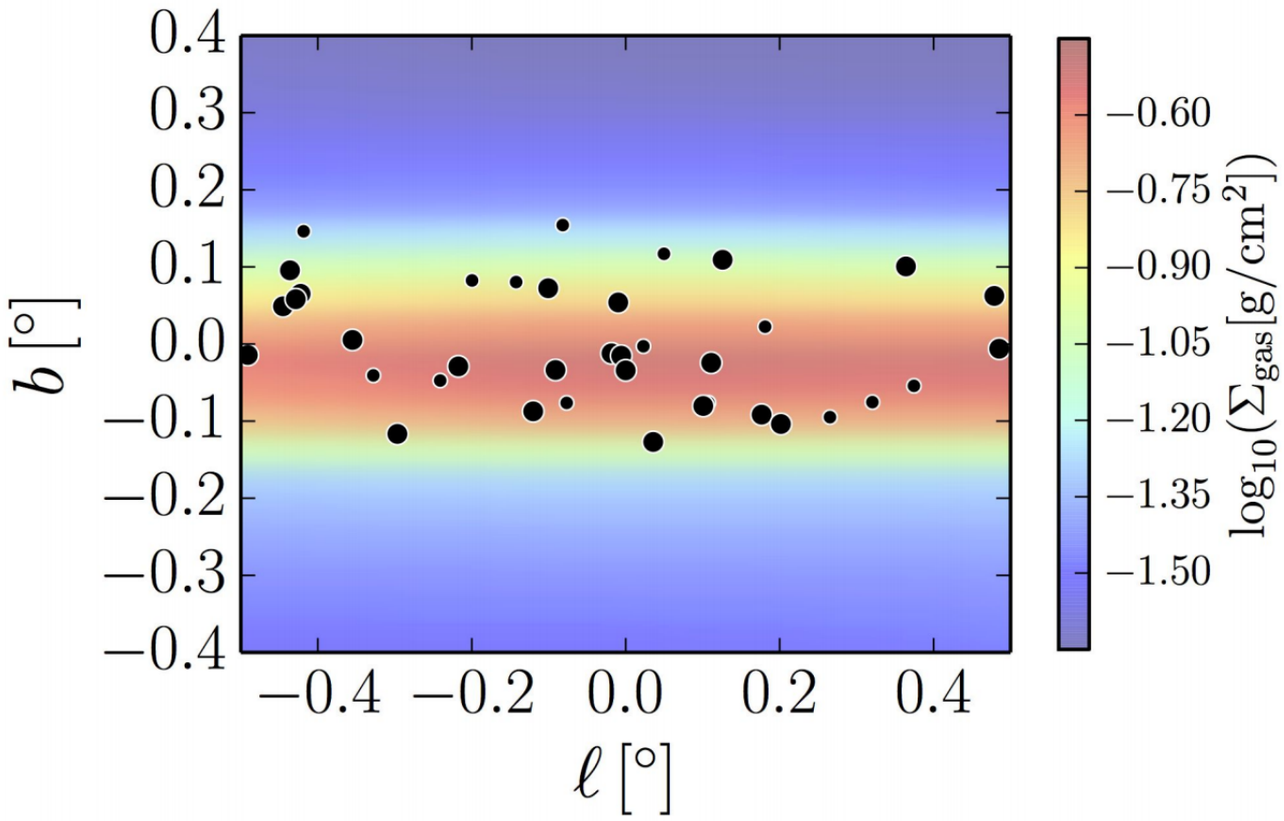
*SFB Fellow 2016

PBH and HE astrophysics

Gaggero, Calore+ PRL'17



VLA detectable sources

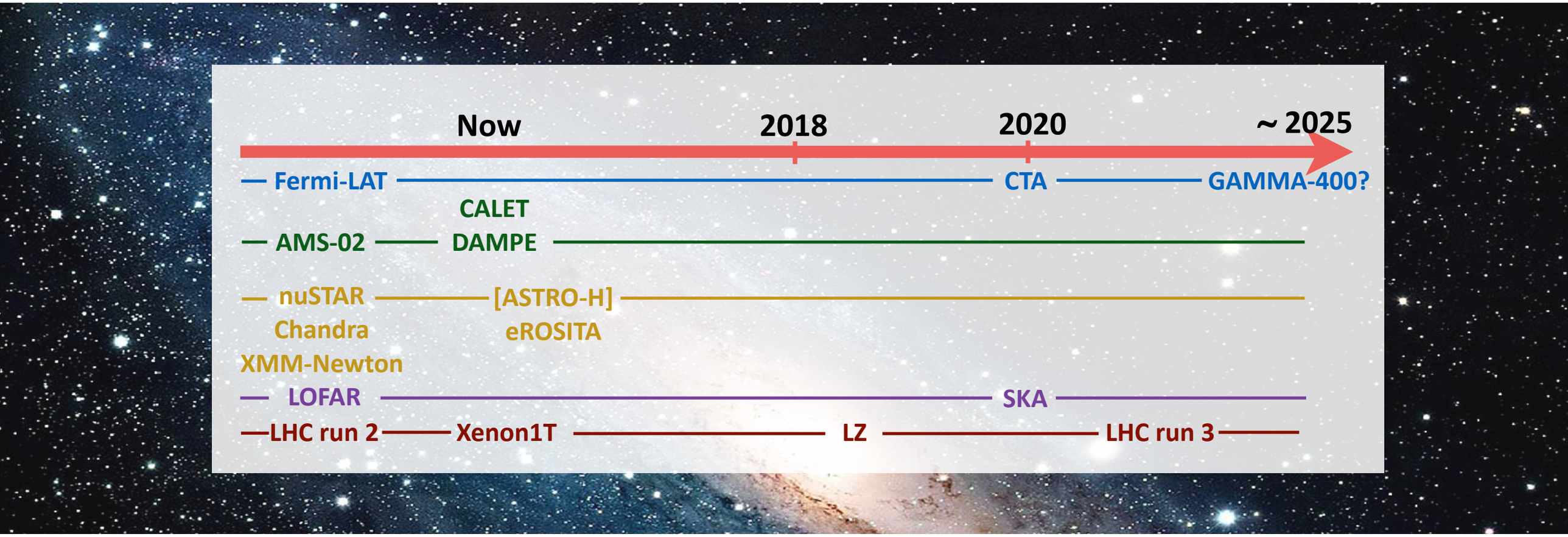


- If PBH are DM => the MW halo should contain 10^{11} 30 M_{Sun} PBH!!
- How can we "see" them? Accretion of gas onto BH
- Constraints from number of observed HE radio and X-ray BH candidates (Chandra/ NuSTAR/VLA), exploiting fundamental plane for accreting (astro) BHs
- Great potential of SKA to detect (or rule out) this population

See J. Garcia-Bellido, S. Clesse talks

[In the same mass window, strongest constraints are the revised CMB limits of Poulin, Serpico, Calore+ PRD'17]

A (multiwavelength) look ahead

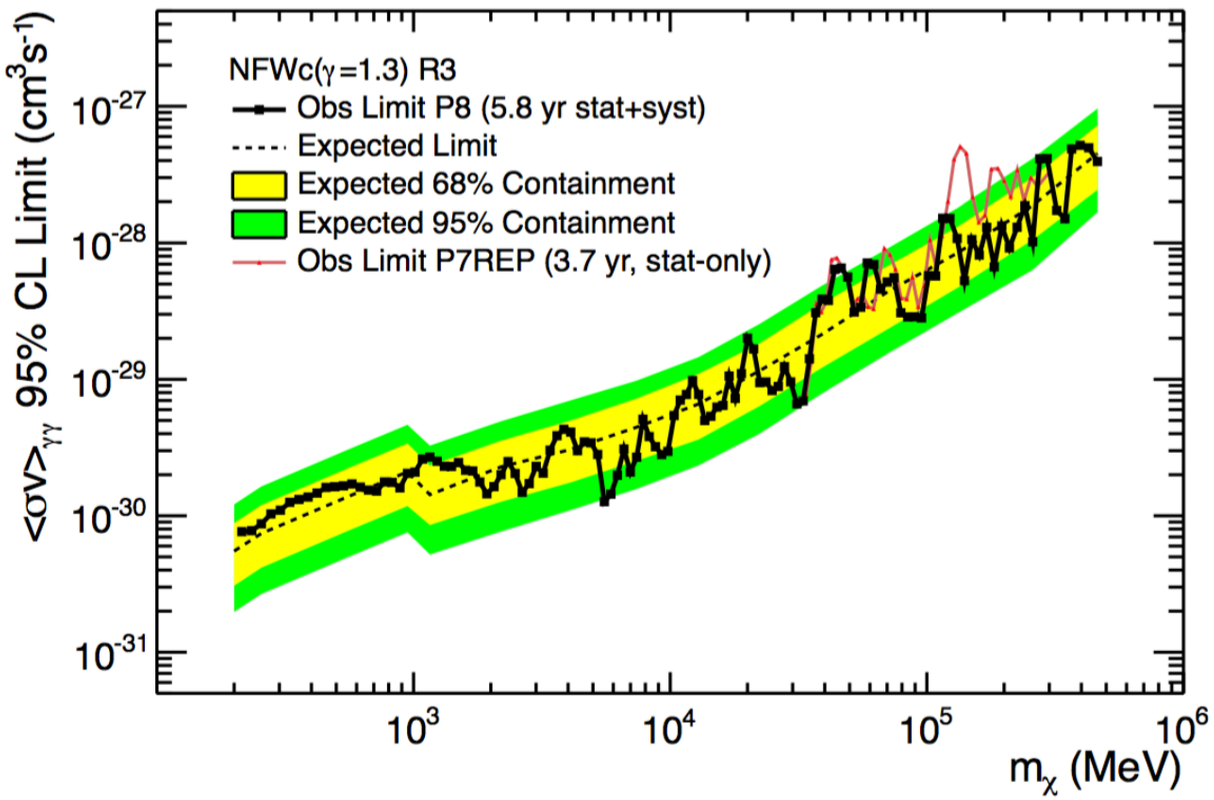


- ✓ Astroparticle experiments represent a powerful probe to test different dark matter models (WIMP, ALPs, primordial BH)
- ✓ Promising way to discover anomalies and new emission processes, mostly with indirect detection so far
- ✓ Relevance of astrophysical uncertainties related to dark matter distribution in the Milky Way

Backup slides

Status of line signal searches in gamma rays

Ackermann+ PRD'15



Abdalla+ PRL'16