

Unveiling the nature of dark matter: A multi-faceted search program

CAHEP 2020 – 26/11/2020

Francesca Calore (CNRS/LAPTh)



Dark matter gravitational evidence

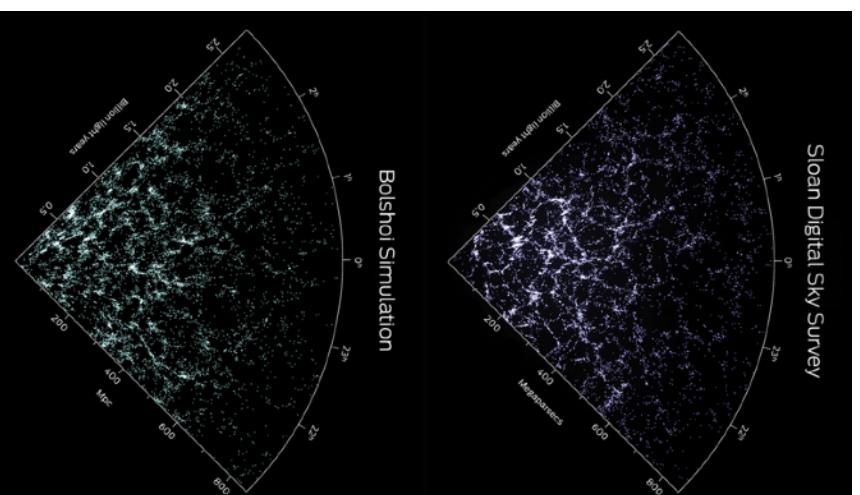
Rotation curves



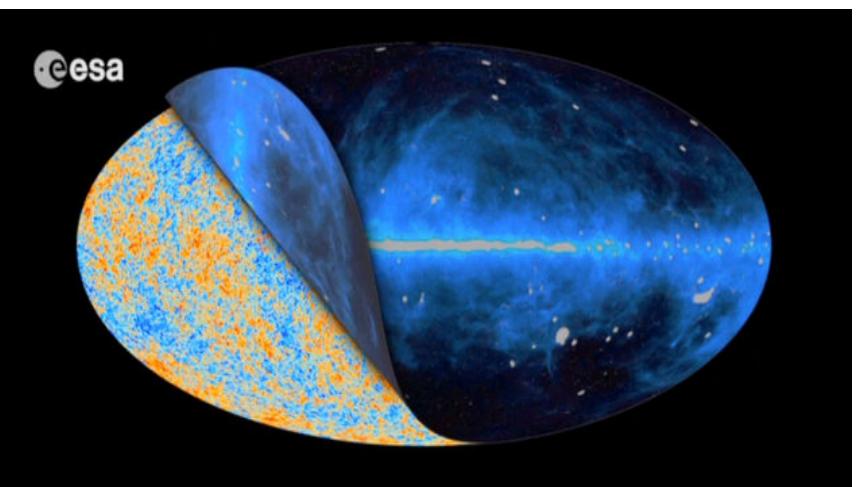
Galaxy clusters



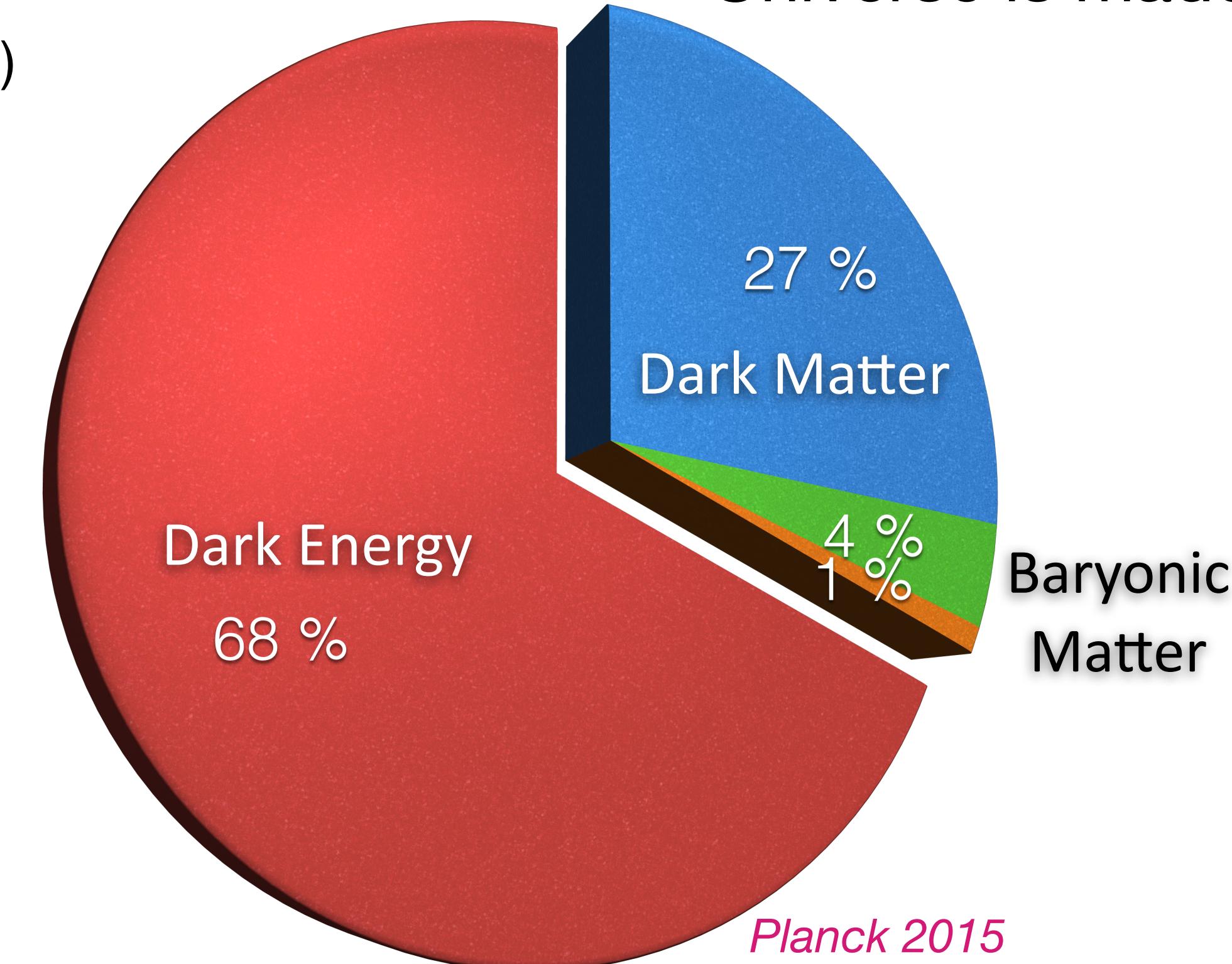
Large Scale Structures



Cosmic microwave background



↓
~kpc
(10^{19} m)
~Mpc
~Gpc



We do not know what most of the Universe is made of!

We add one (or more?) extra-ingredient, which interacts only gravitationally

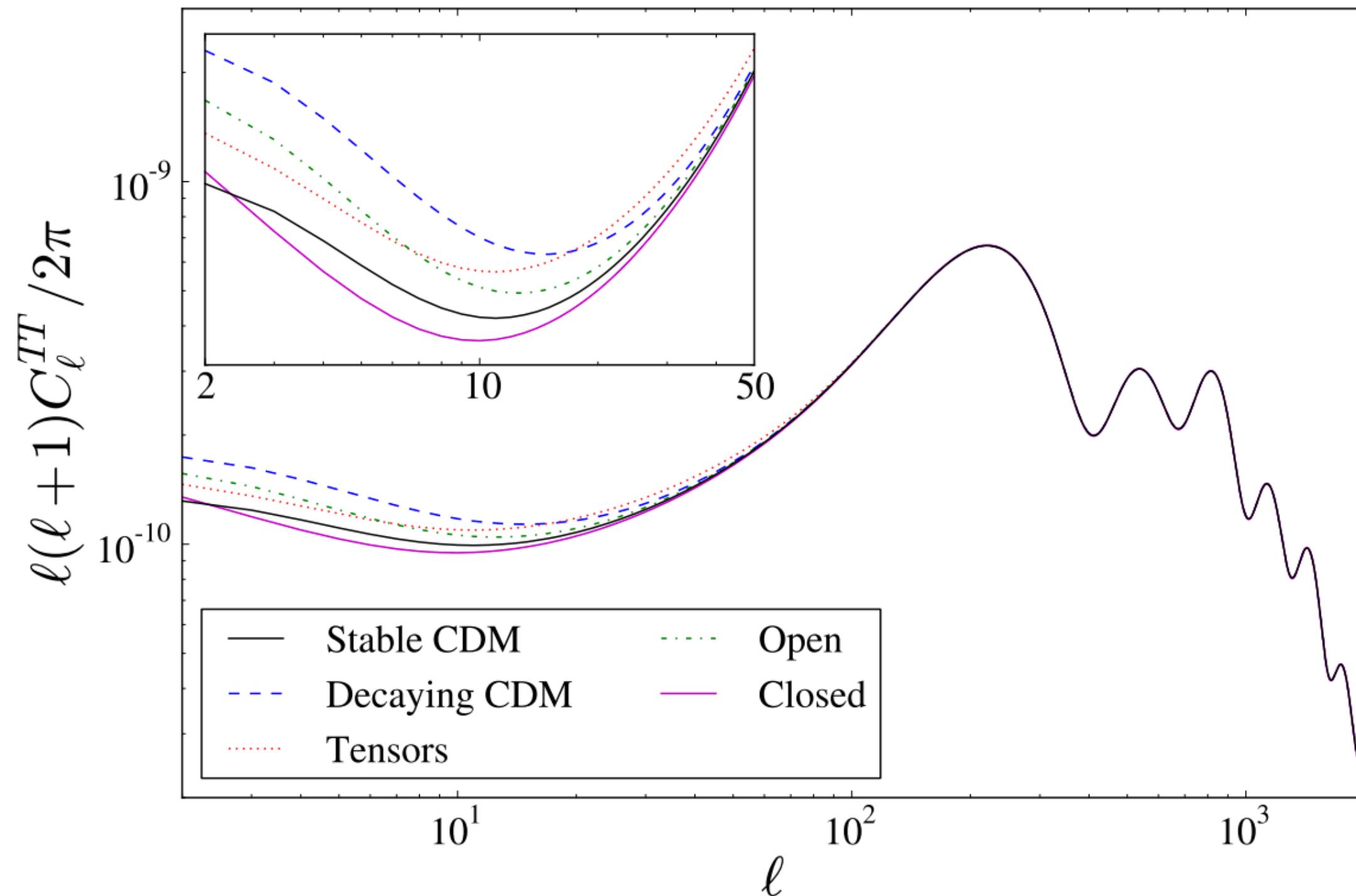
Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]



$\tau \gtrsim 160$ Gyr CMB only
 $\tau \gtrsim 170$ Gyr + other consistent
 data

Audren+JCAP'14; Poulin+JCAP'16

Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]
4. **Sufficiently heavy**, to behave “classically”

$$m \gtrsim 10^{-22} \text{ eV}$$

If bosons, from confinement in dwarf galaxies

$$m > \mathcal{O}(10 - 100 \text{ eV})$$

If fermions, from Pauli exclusion and phase space density conservation

Tremaine & Gunn, PRL'79; Boyarsky+ JCAP'09

If thermally produced (both bosons and fermions)

$$m \gtrsim \text{few keV}$$

Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]
4. **Sufficiently heavy**, to behave “classically”
5. **Smoothly distributed** at cosmological scales

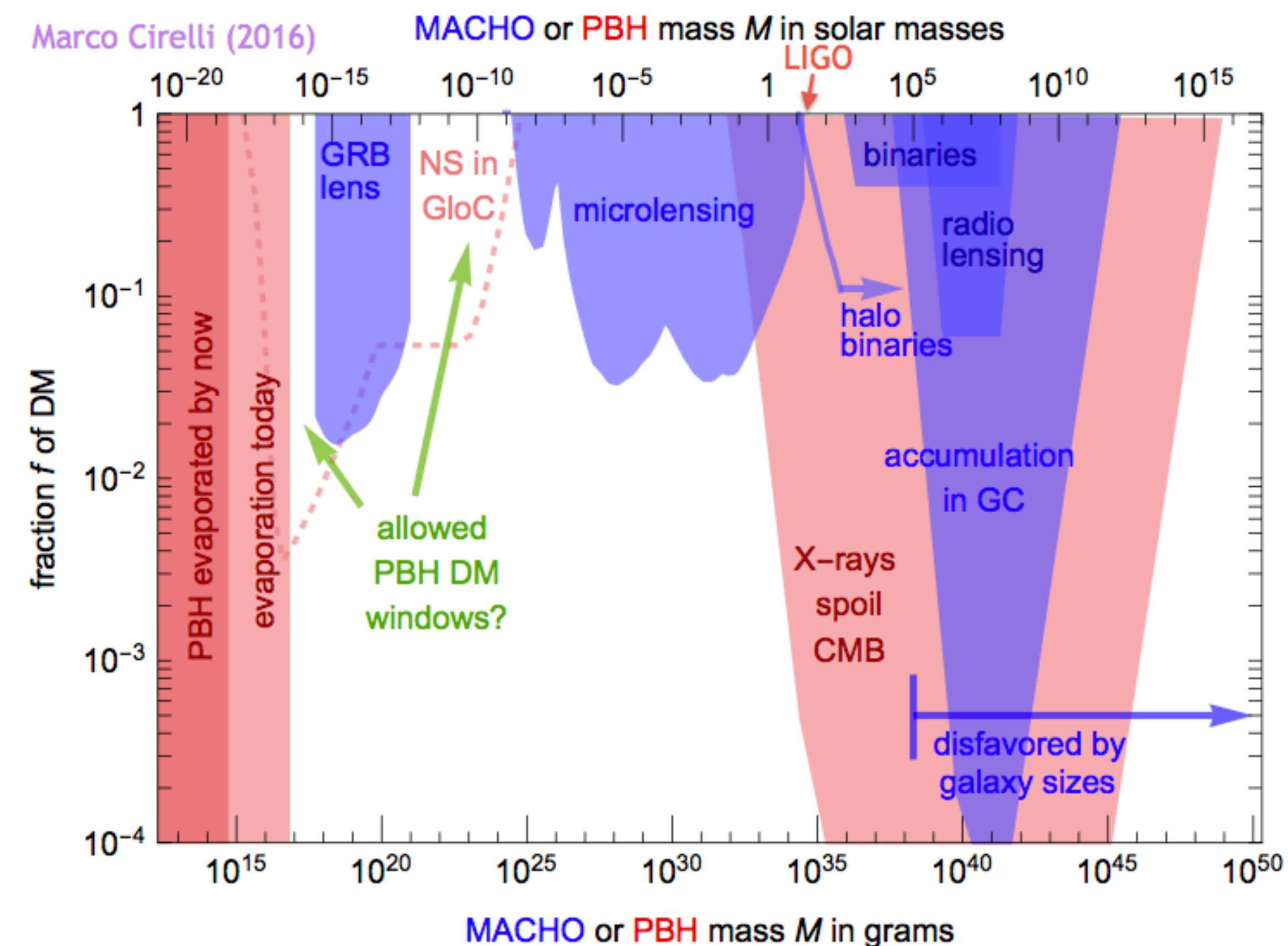
$$m \lesssim 10^{3-4} M_{\odot} \sim 10^{70-71} \text{ eV}$$

Additional Poisson noise in matter PS

Afshordi+ ApJ'03

PBH as dominant DM component are strongly constrained by CMB, dynamics of stellar clusters, X-ray and radio observations. New physics needed from non-minimal inflationary scenarios

Review & Refs in Carr+PRD'16



Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]
4. **Sufficiently heavy**, to behave “classically”
5. **Smoothly distributed** at cosmological scales

6. If thermally produced, **weak interactions w/ SM particles**
7. **Optically dark and dissipationless, very weak e.m. interaction**

Properties of dark matter

What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]
4. **Sufficiently heavy**, to behave “classically”
5. **Smoothly distributed** at cosmological scales

6. If thermally produced, **weak interactions w/ SM particles**
7. **Optically dark and dissipationless, very weak e.m. interaction**
8. **Collisionless or not very collisional**, limits on self-interactions

Slightly smaller σ could also be beneficial to explain clusters dynamics

$$\sigma/m < 1 \text{ cm}^2/\text{g} \sim 1 \text{ barn}/\text{GeV}$$

Kaplinghat+ PRL'16

Properties of dark matter

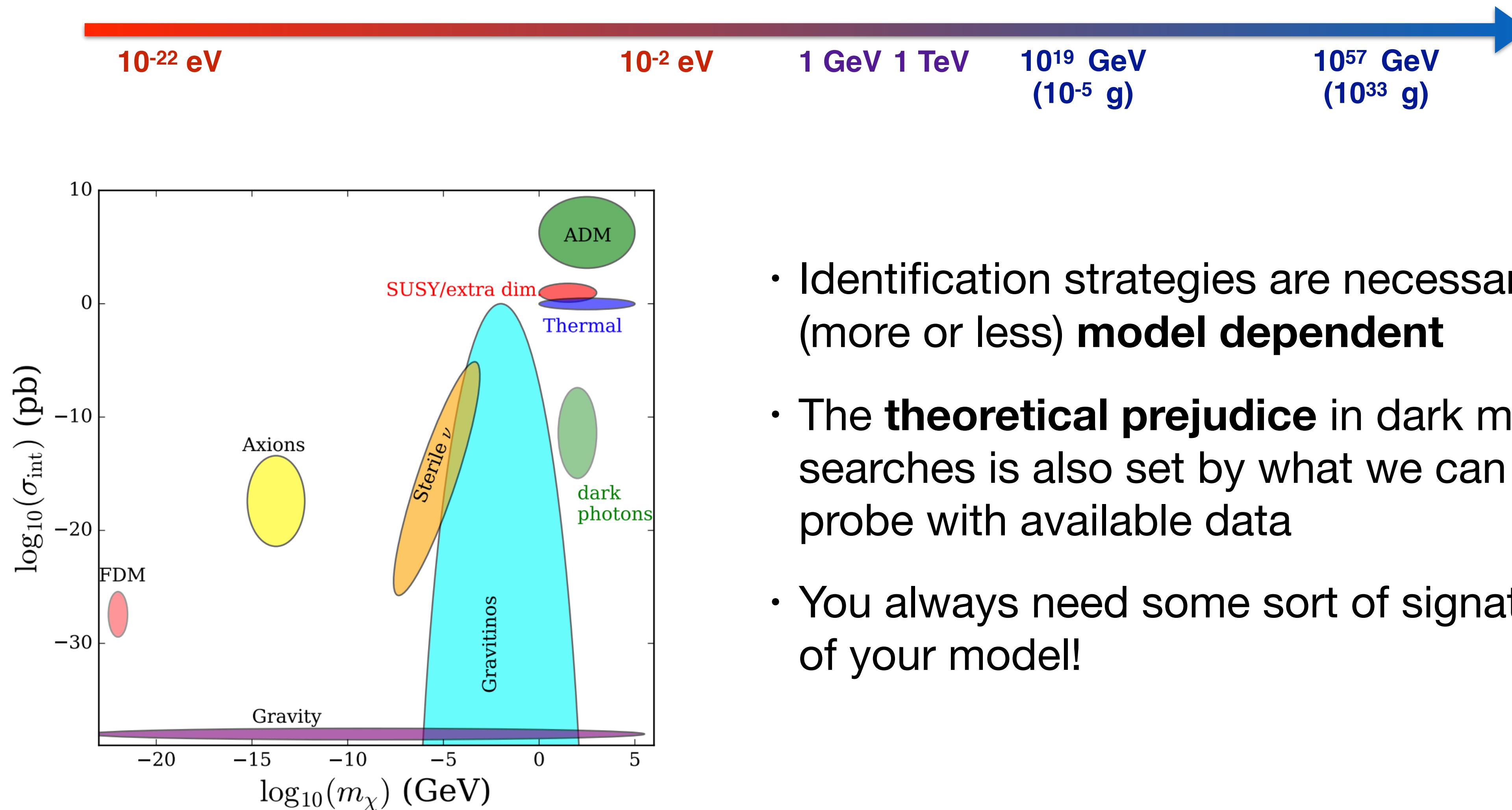
What fundamental properties can we infer from astro/cosmo observations?

1. **Massive, but non-baryonic** [structure formation]
2. Non-relativistic at decoupling, i.e. **cold or close to cold** [CMB peaks, Ly-alpha, structure formation, dwarf galaxy phase space]
3. **Stable or long-lived** [CMB, LSS]
4. **Sufficiently heavy**, to behave “classically”
5. **Smoothly distributed** at cosmological scales

6. If thermally produced, **weak interactions w/ SM particles**
7. **Optically dark and dissipationless, very weak e.m. interaction**
8. **Collisionless or not very collisional**, limits on self-interactions

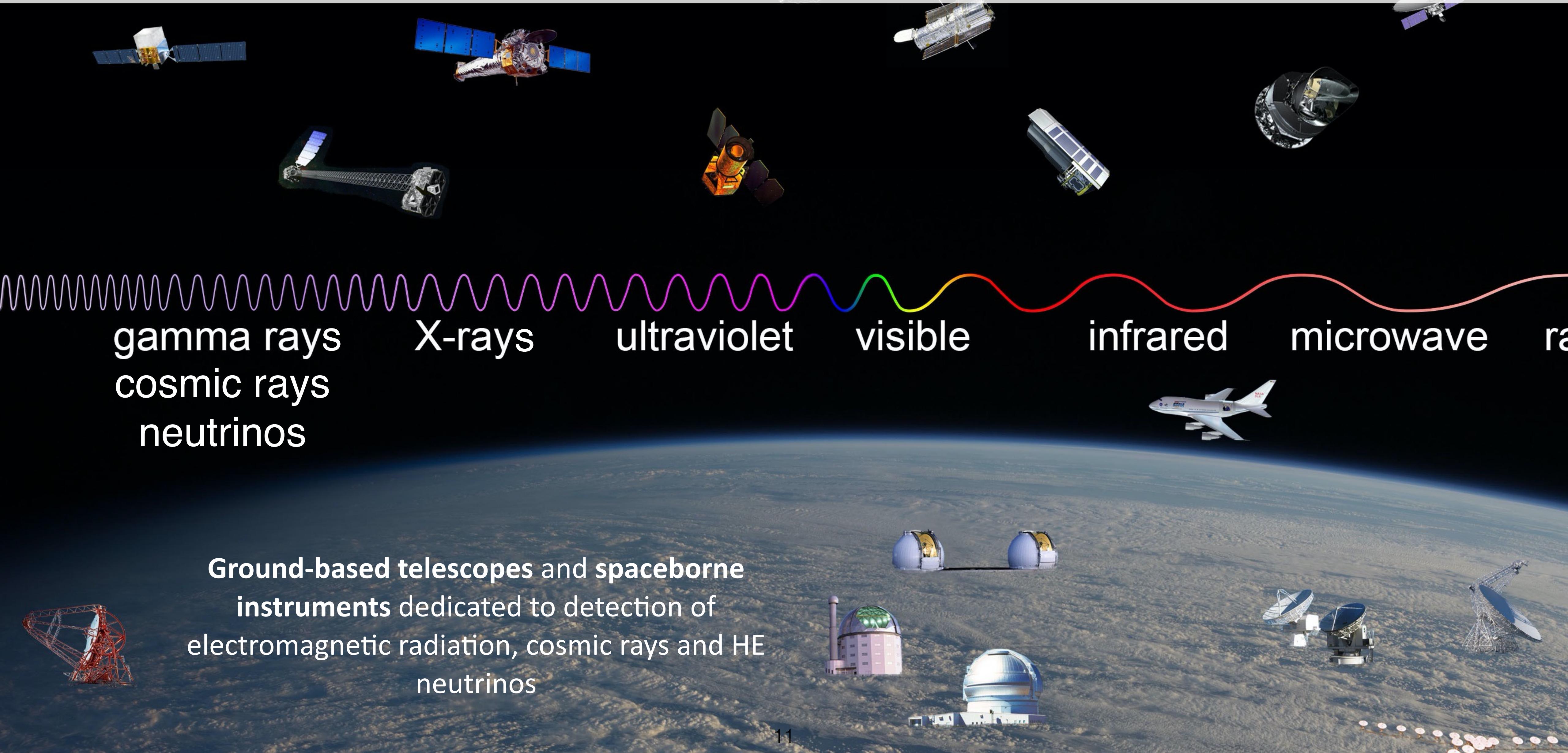
DM evidence requires new physics, beyond current theories
=> new d.o.f., appealing from a particle physics perspective

The dark matter particle landscape



Buckley & Peter, Phys. Report'18

The astronomical data landscape

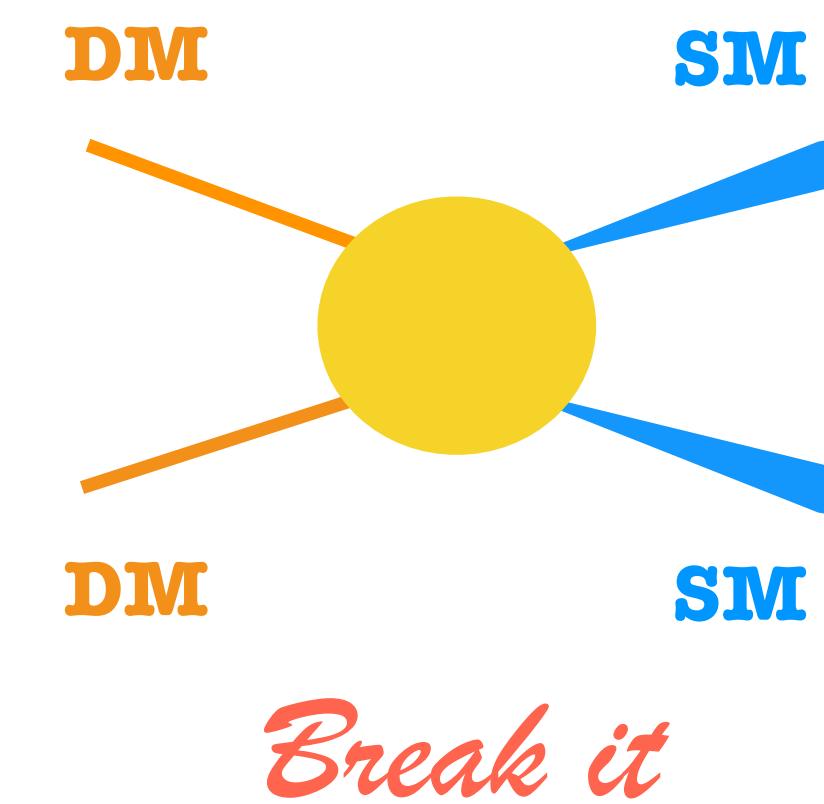


Dark matter indirect detection

How can we use astroparticle experiments to get insight into the DM nature?

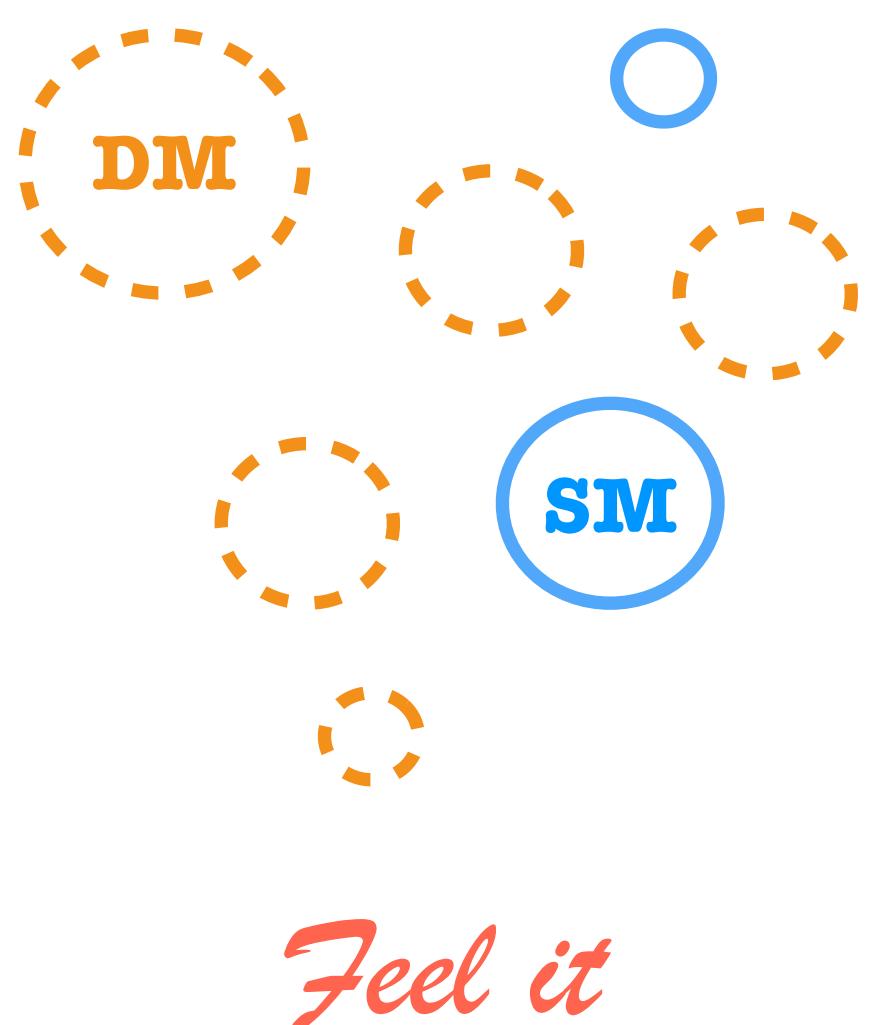
General goal & method:

- * To identify (theoretically) some effects (a.k.a signatures) which yield information about the dark matter nature
- * To carry out data analysis to discover these effects on top of the (often dominating) astrophysical background(s)
- * When data are not available, to actually ask for observation time...



Guaranteed results:

1. Constraints on the dark matter nature
2. A better understanding of the astrophysical background



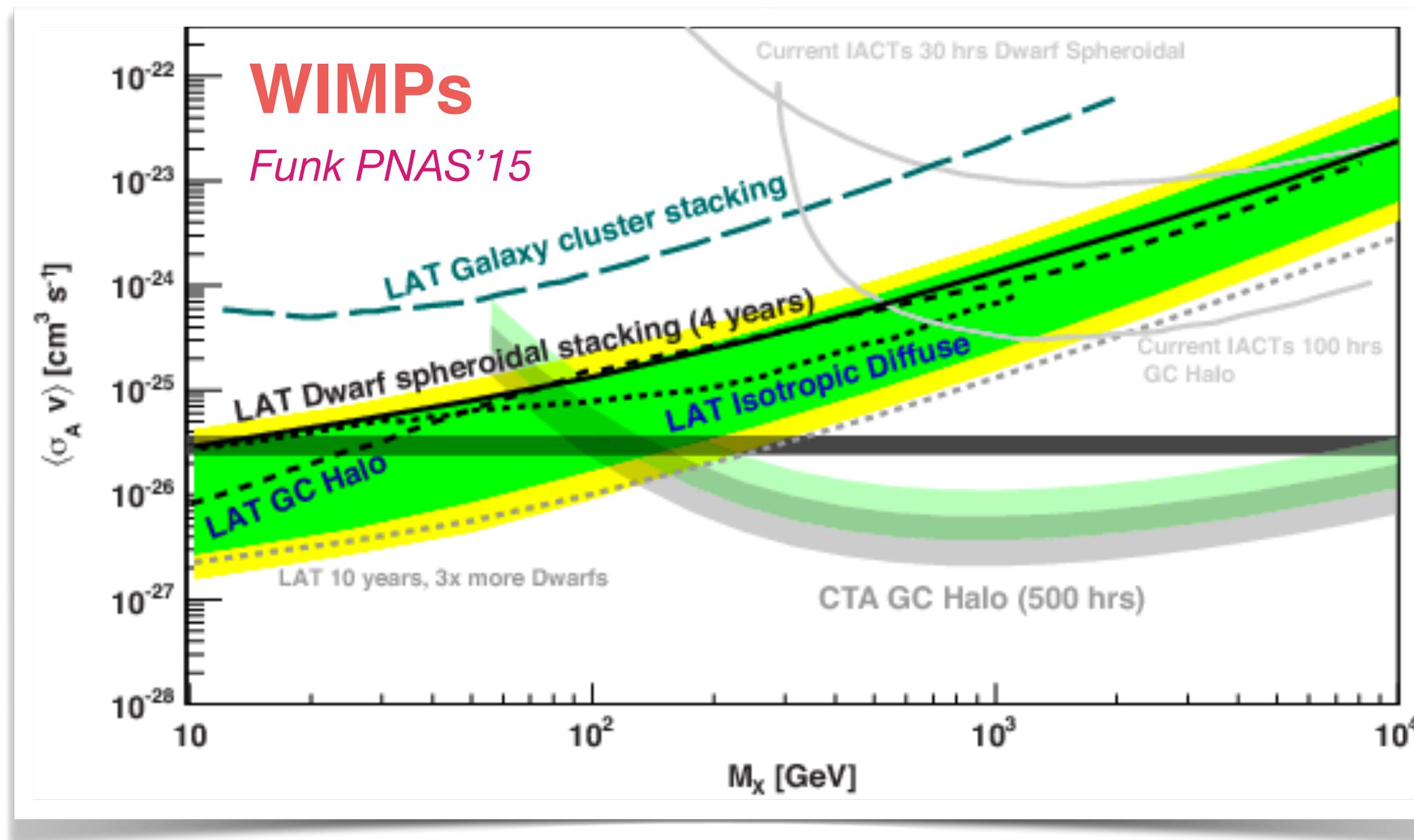
Credit: T. Slatyer, M. Lisanti

What dark matter model?

Any model which can affect the fluxes of observable charged particles and/or photons through **new production mechanisms or distortion effects**.

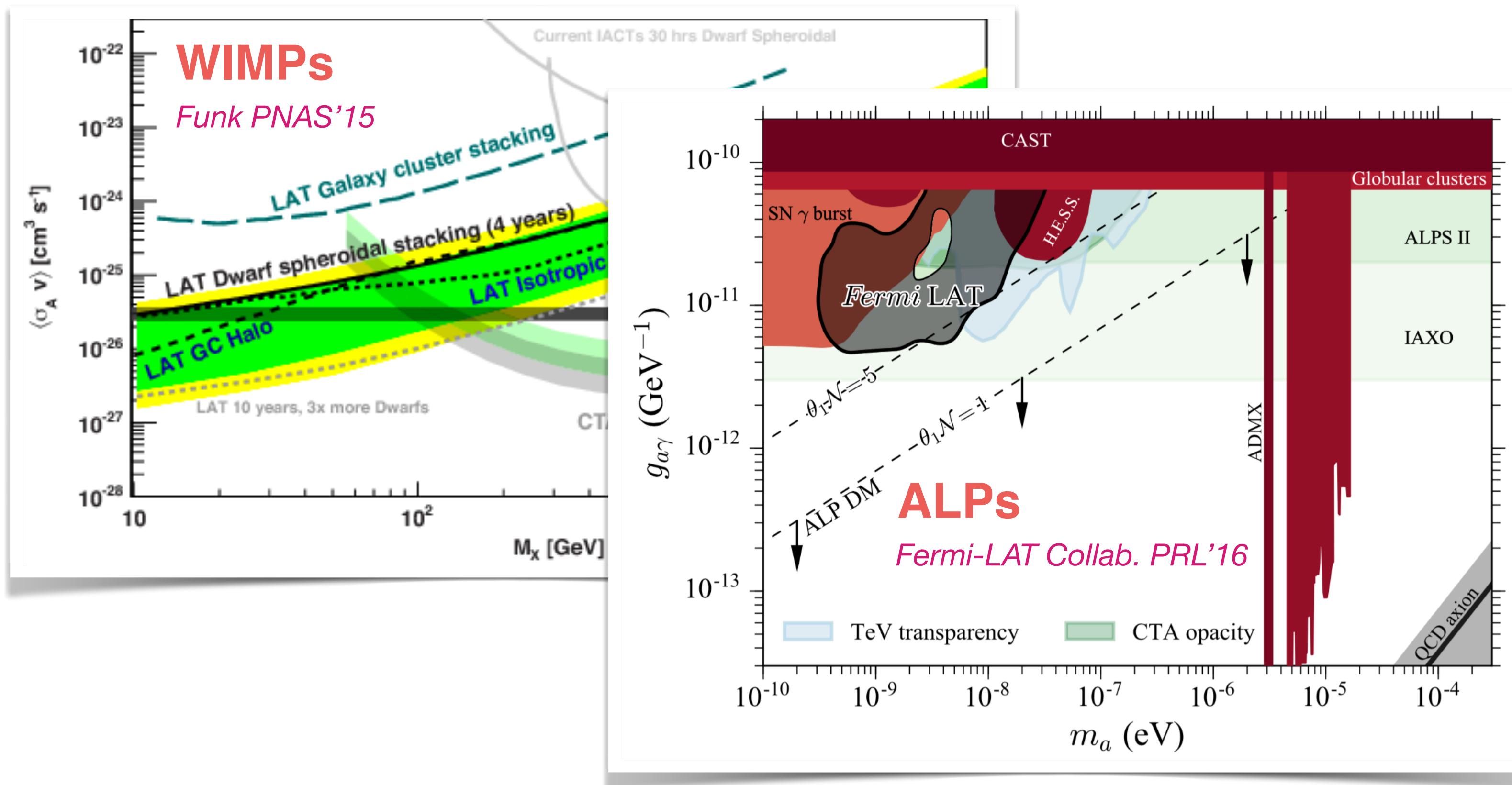
What dark matter model?

Any model which can affect the fluxes of observable charged particles and/or photons through **new production mechanisms or distortion effects**.



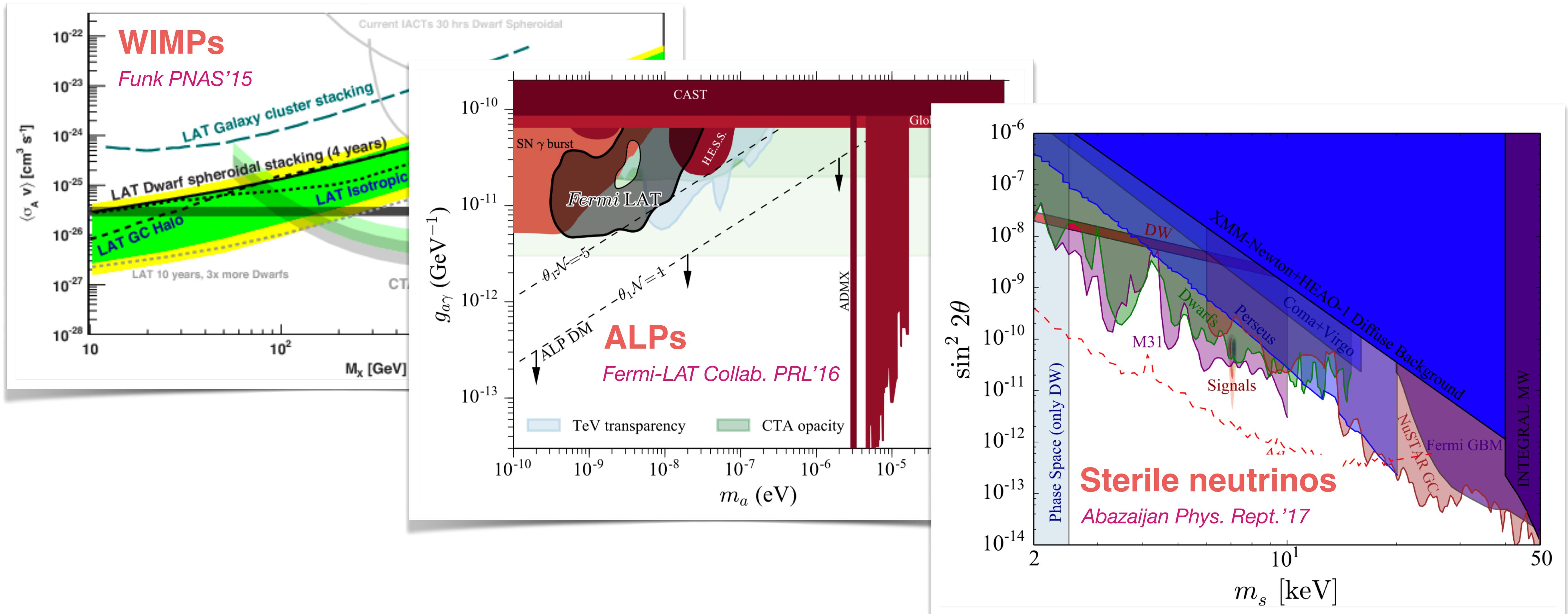
What dark matter model?

Any model which can affect the fluxes of observable charged particles and/or photons through **new production mechanisms or distortion effects**.



What dark matter model?

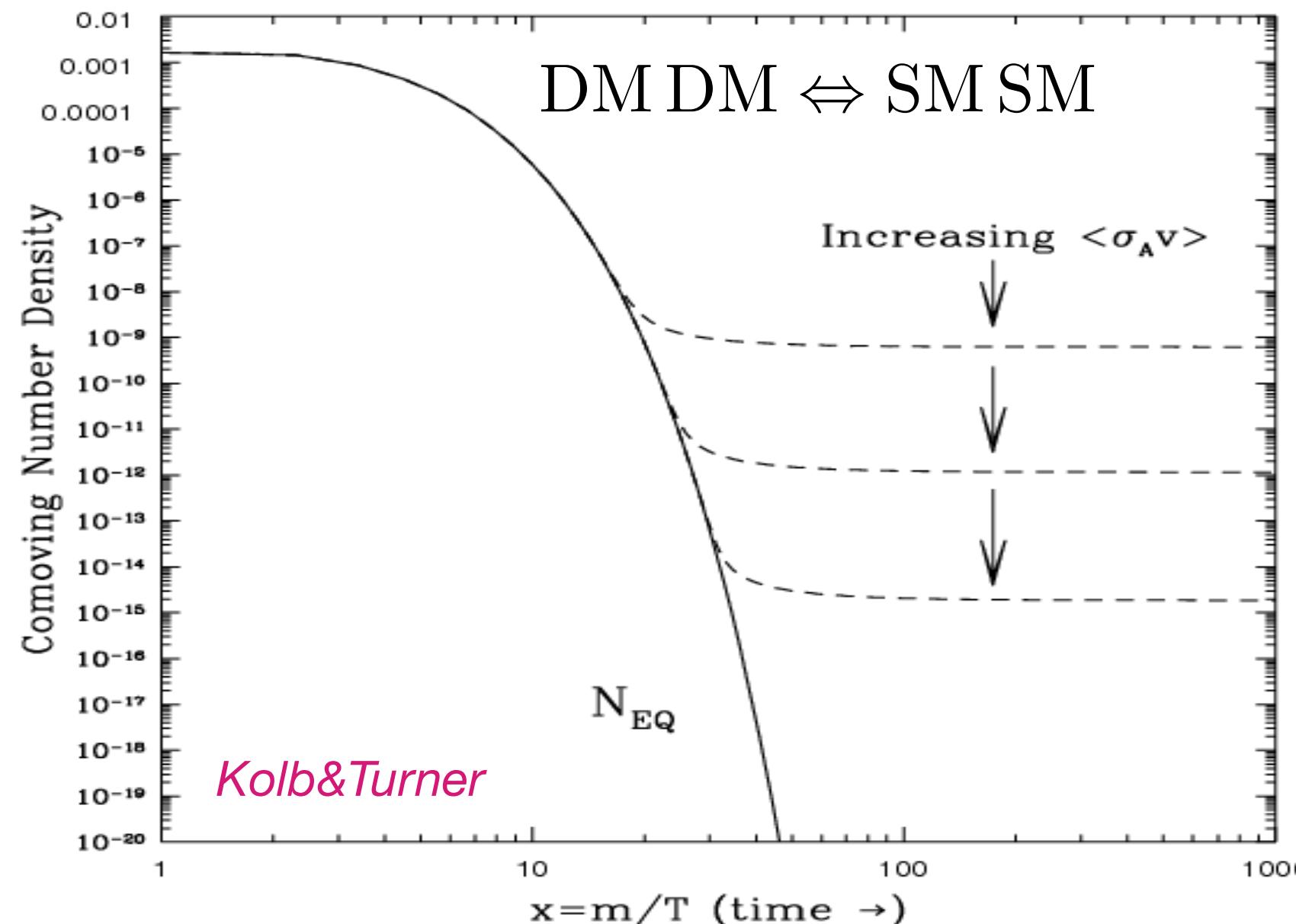
Any model which can affect the fluxes of observable charged particles and/or photons through **new production mechanisms or distortion effects**.



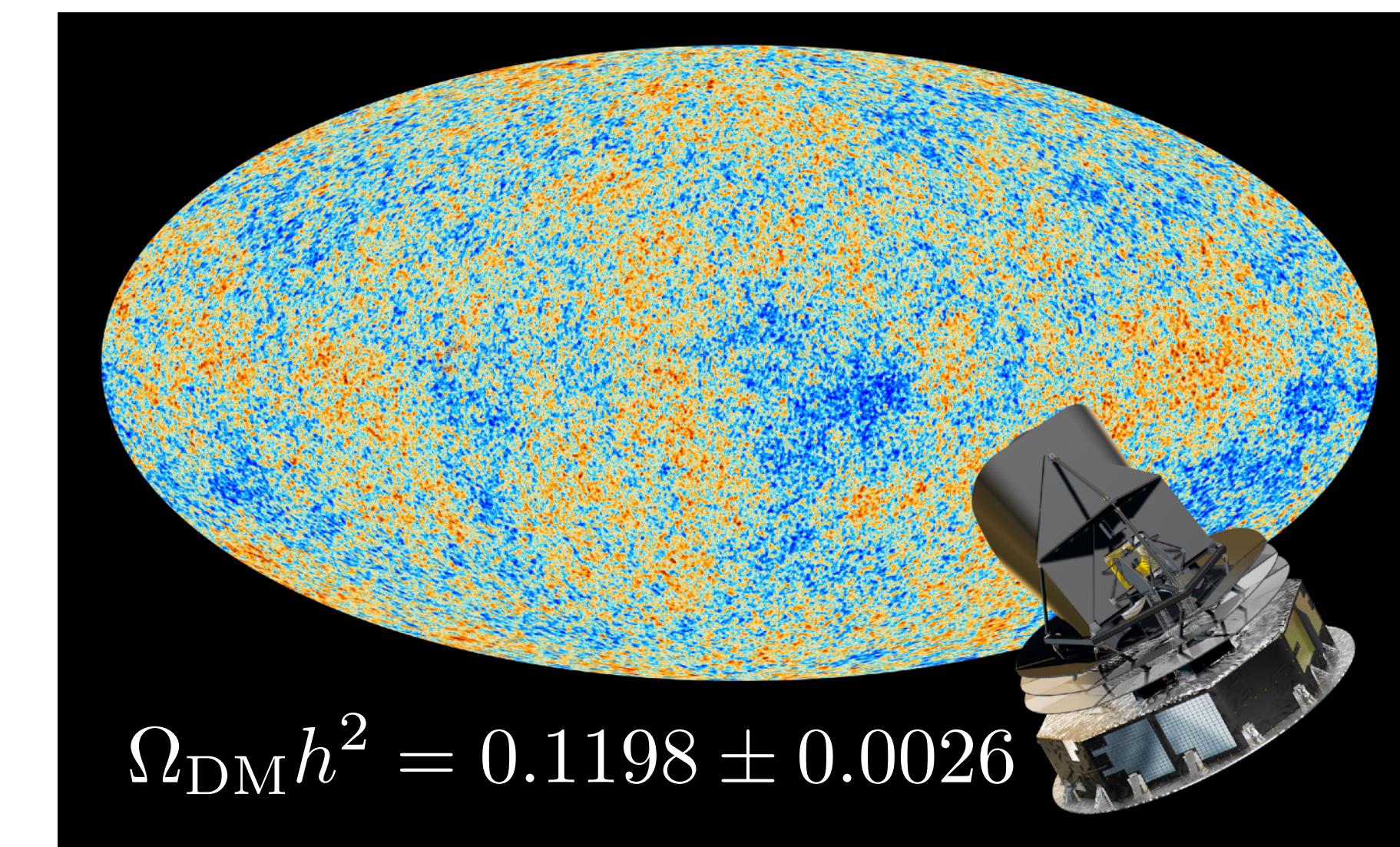
The minimal WIMP



Freeze-out production mechanism



CMB temperature anisotropy

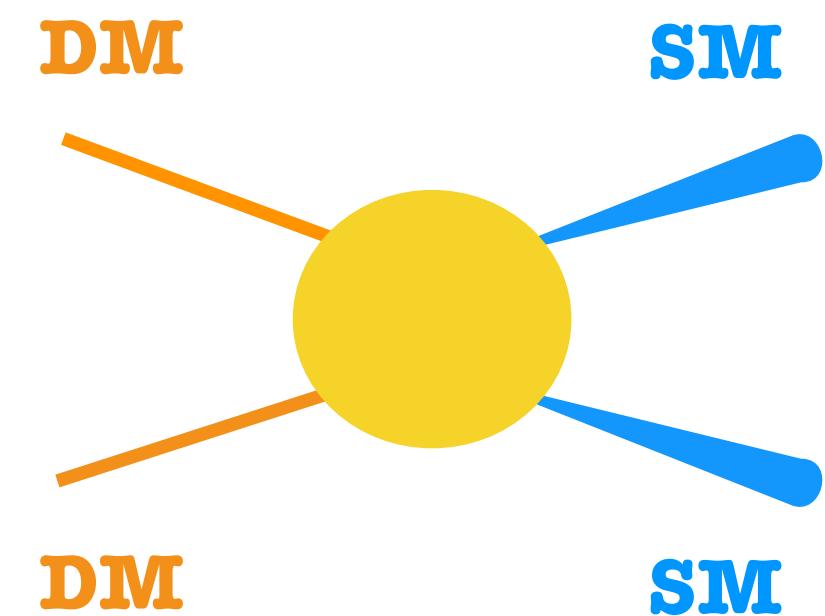


$$\Omega_{DM} h^2 \sim \frac{10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma(\text{DM DM} \rightarrow \text{SM SM})v \rangle}$$

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

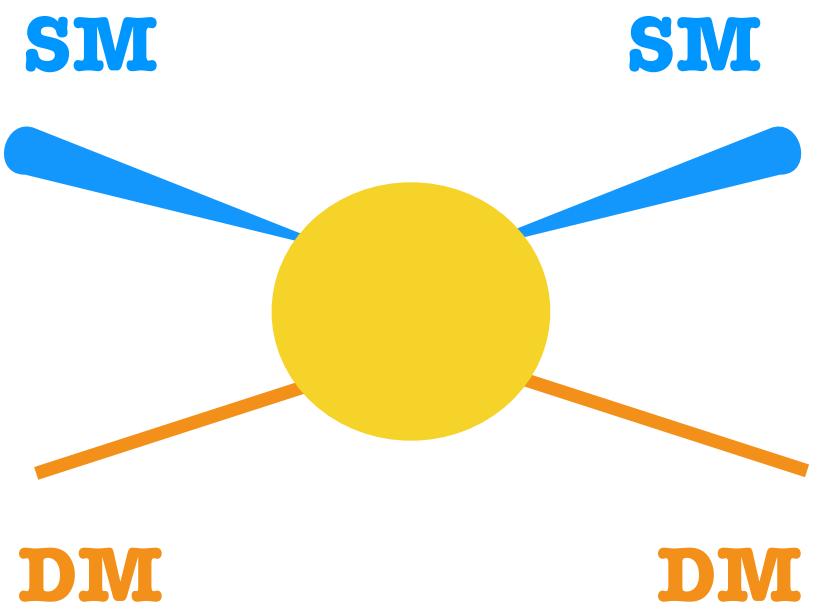
The WIMP search program

More model-independent tests

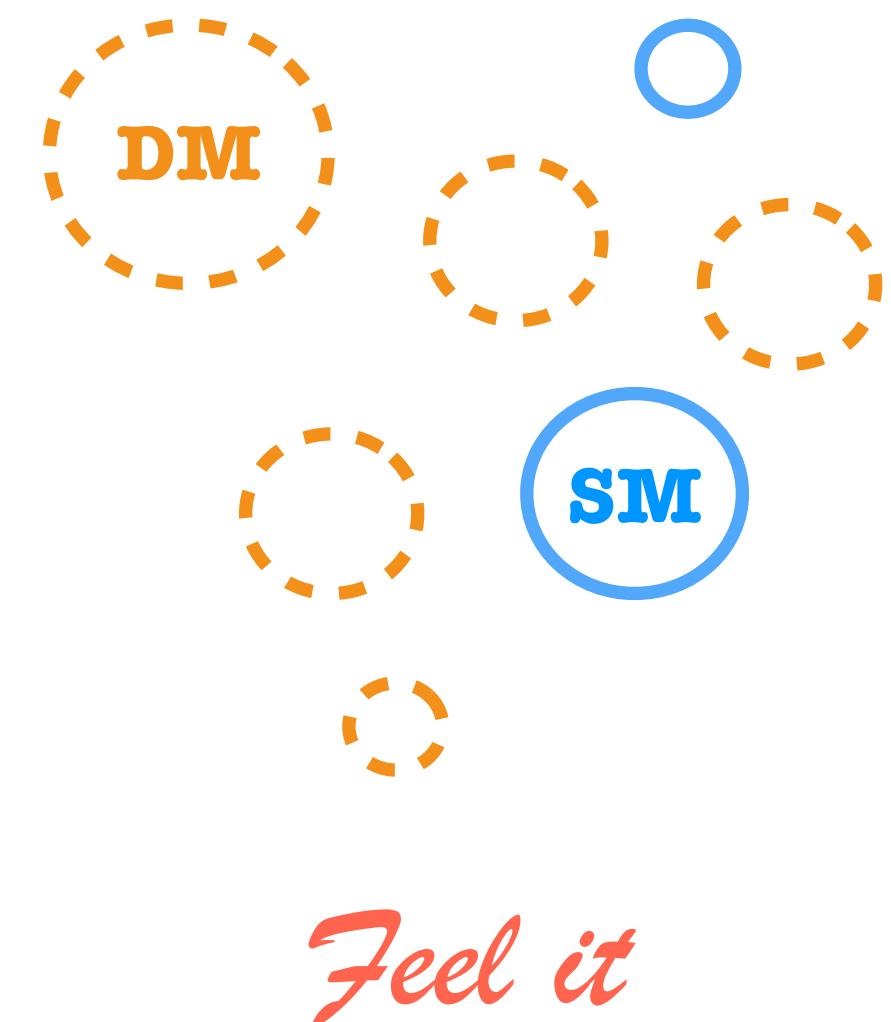


Break it

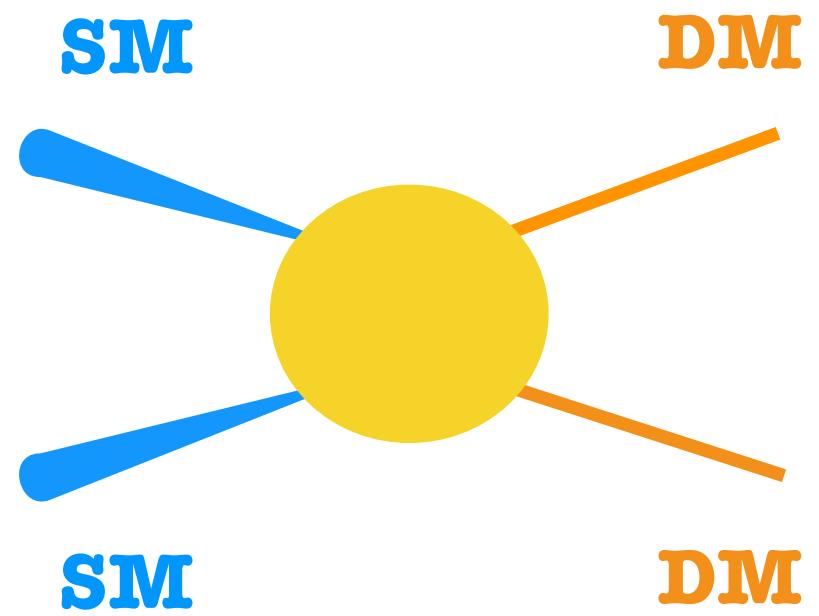
More model-dependent tests



Shake it



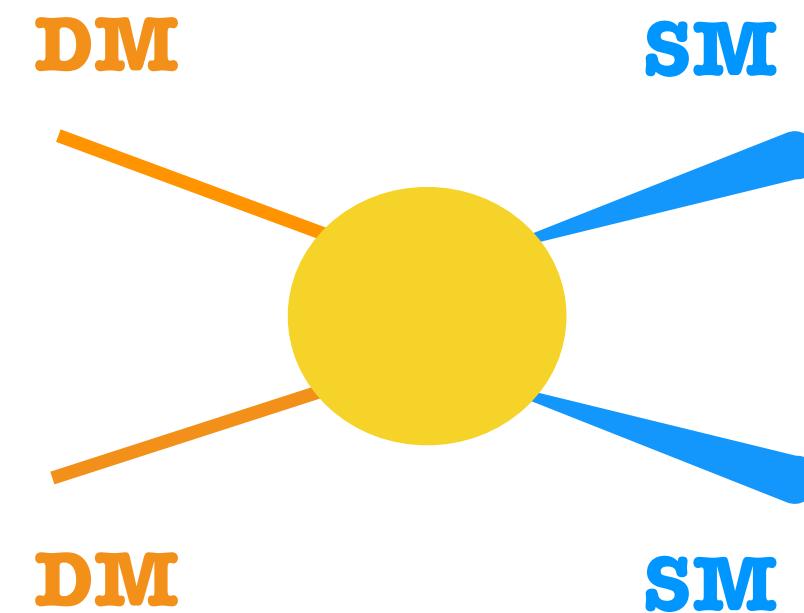
Feel it



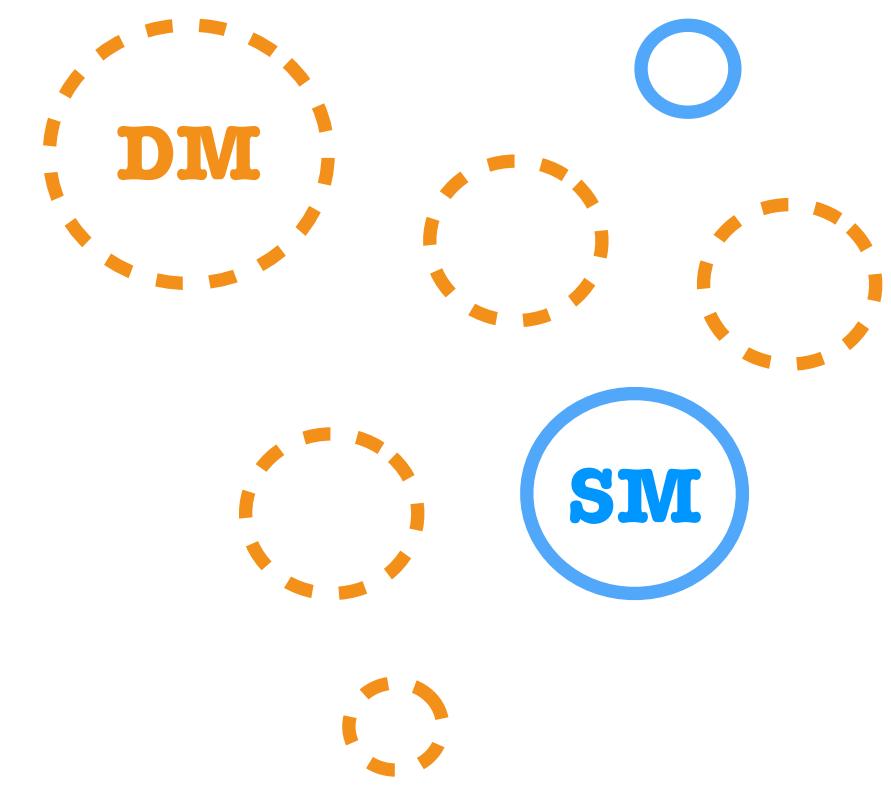
Make it

The WIMP search program

More model-independent tests

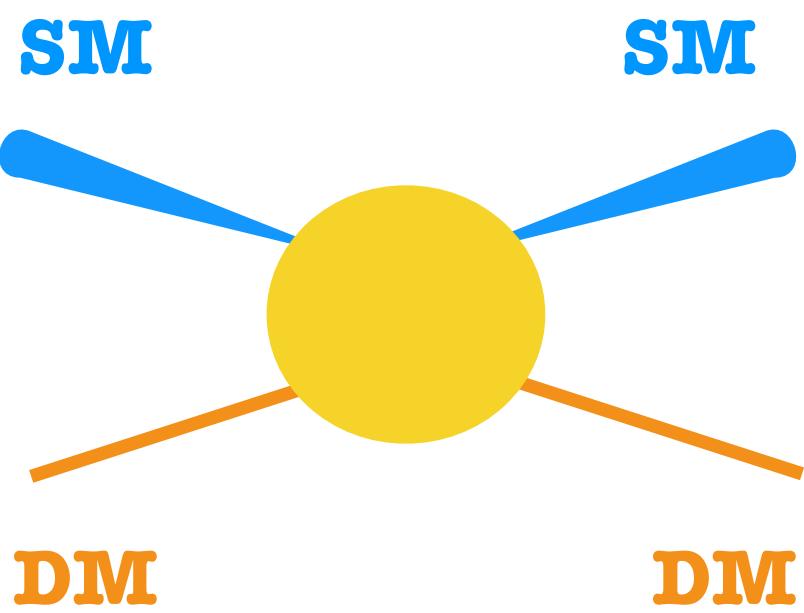


Break it

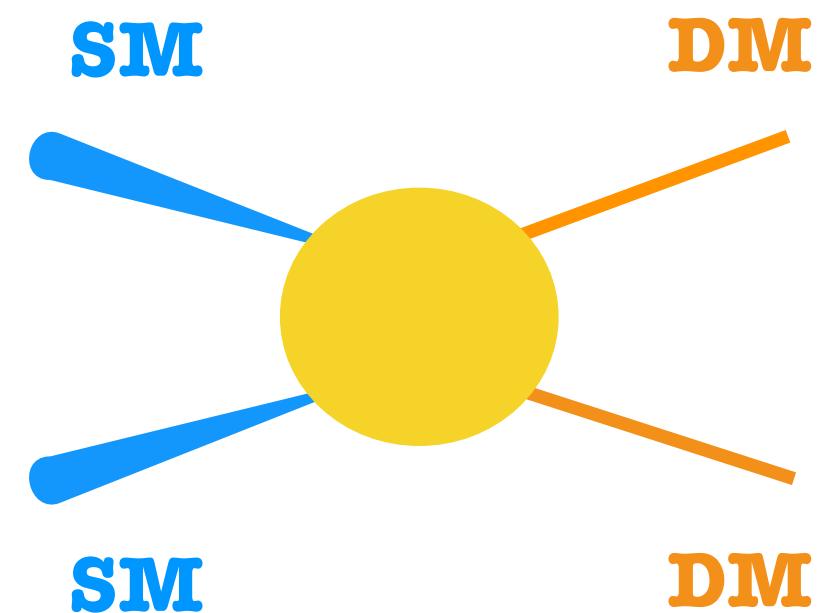


Feel it

More model-dependent tests



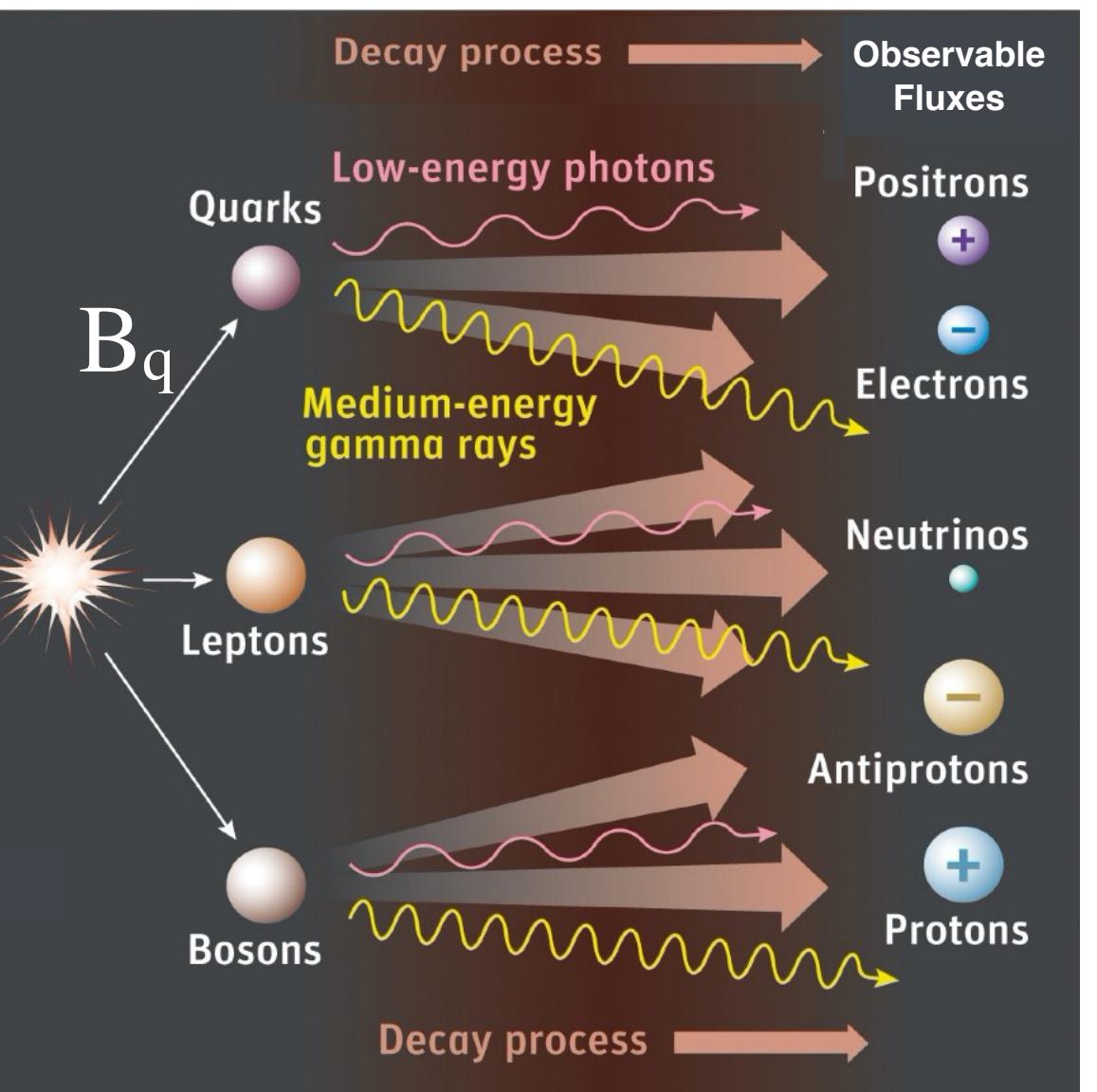
Shake it



Make it

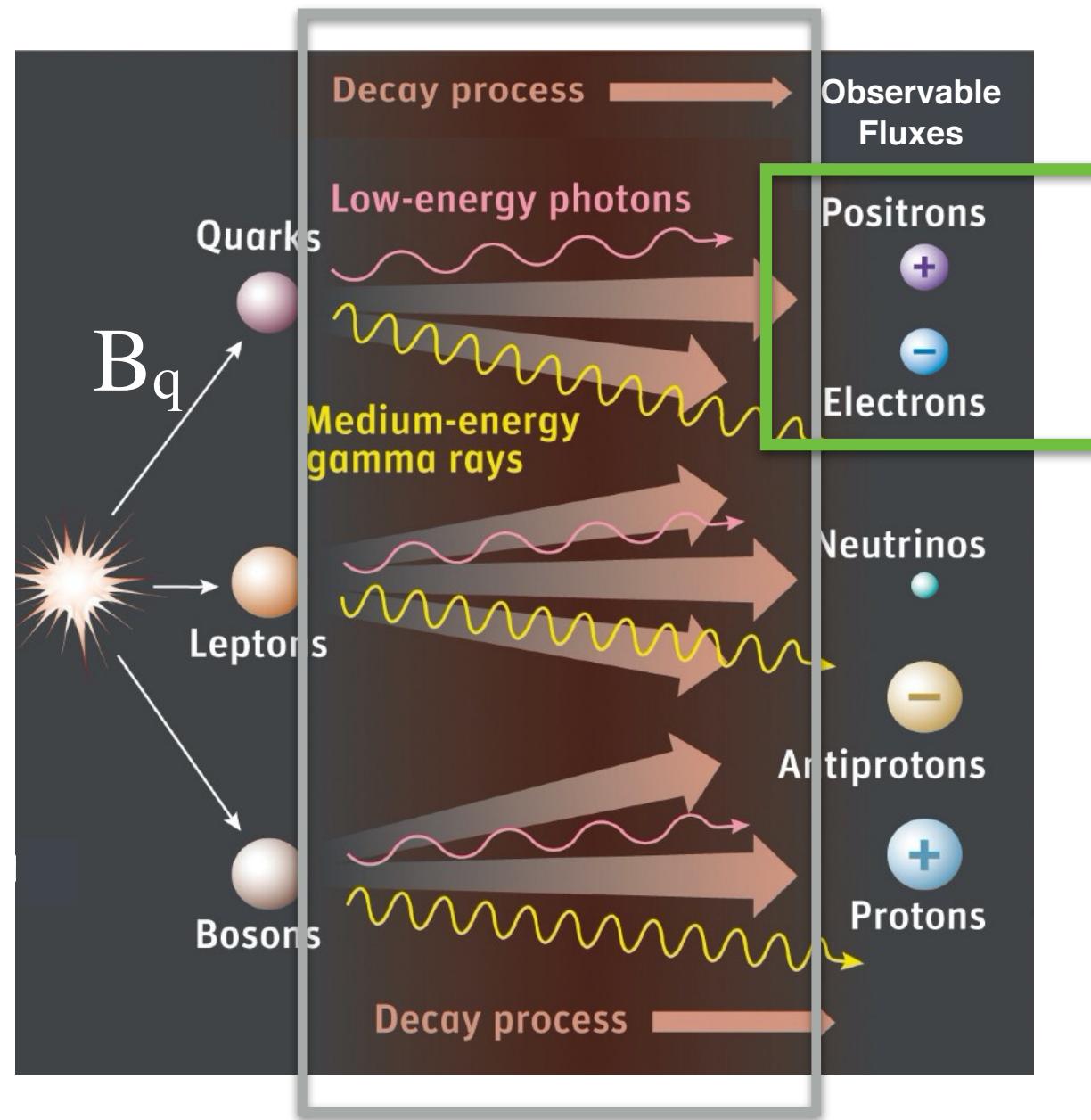
WIMP indirect detection

DM annihilation/decay

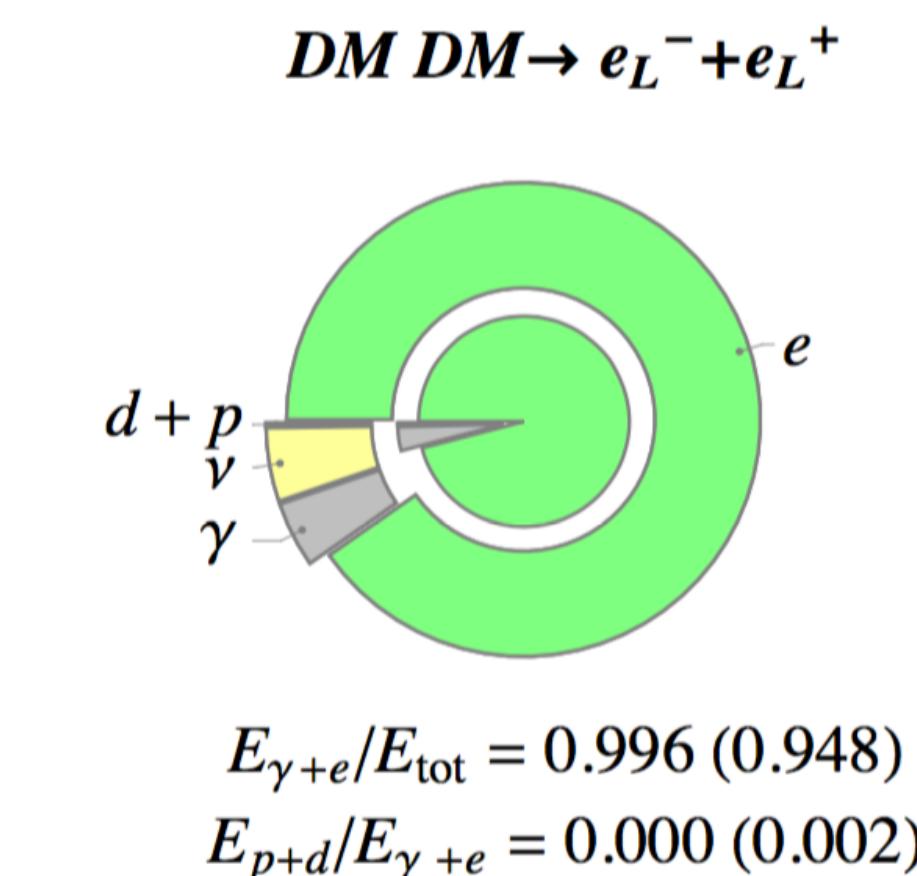
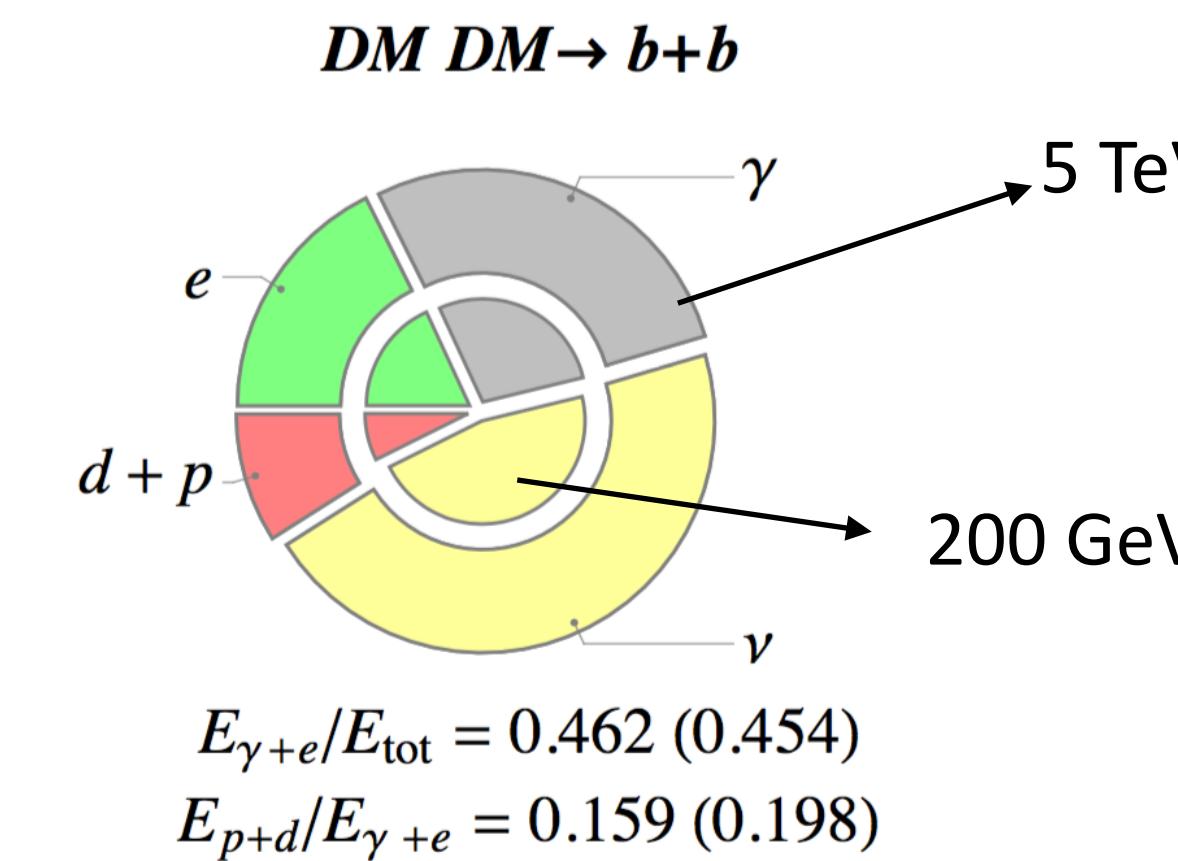


WIMP indirect detection

DM annihilation/ $decay$



Energy distribution into final state particles

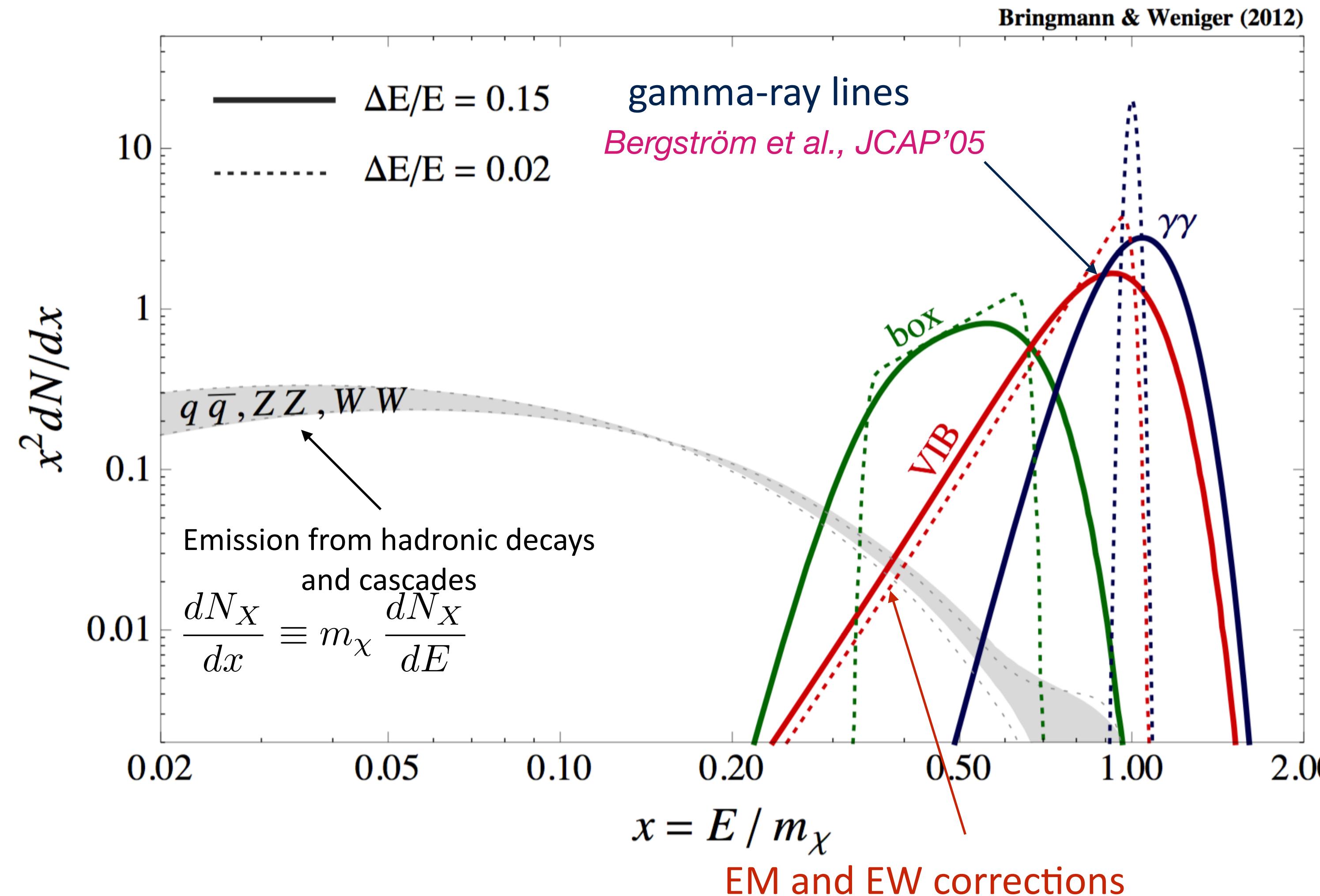


Prompt (or “secondary”) emission of final particles i

$$\sum_f B_f \frac{dN_i^f}{dE}(E)$$

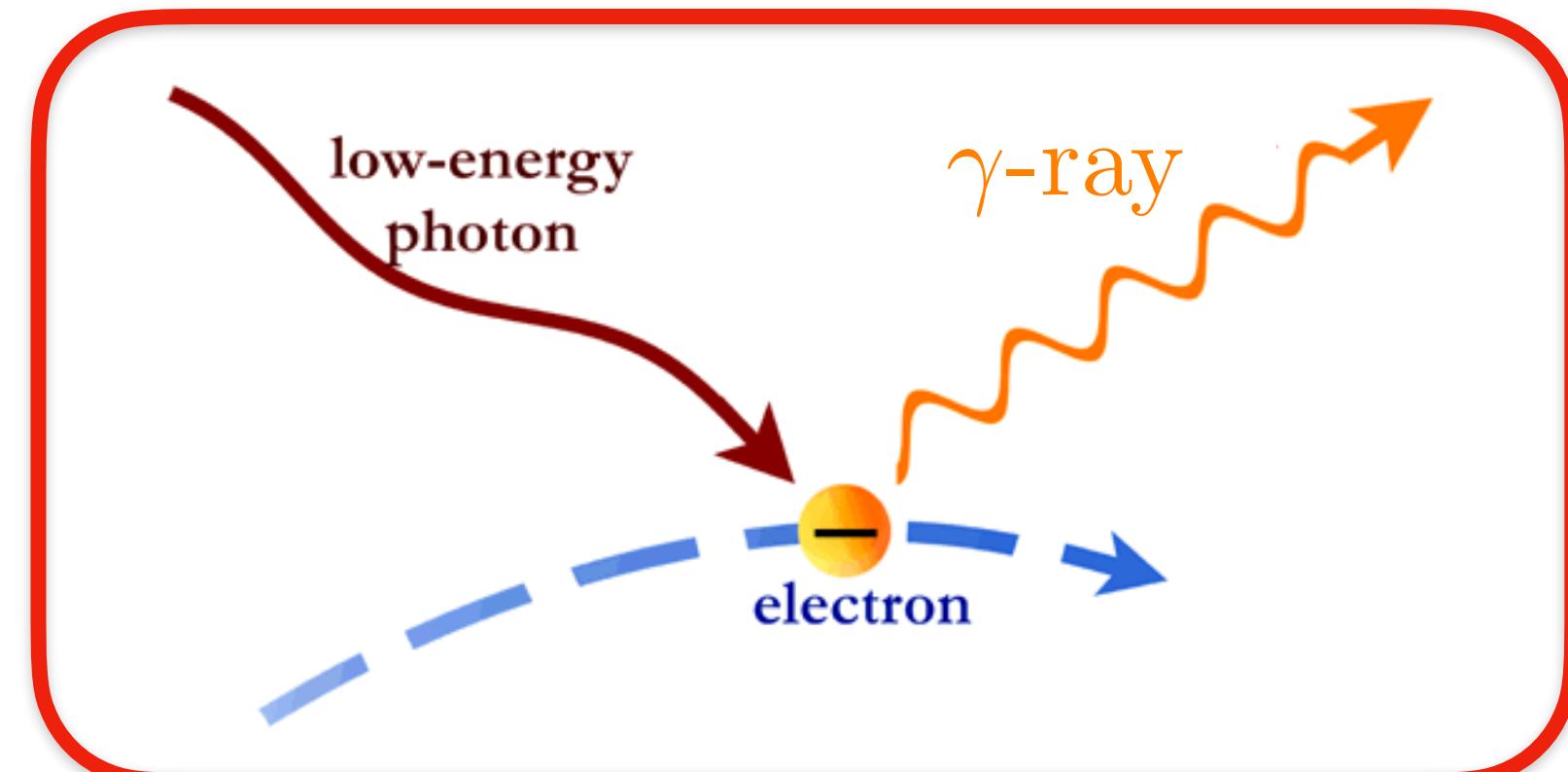
100% branching ratio is usually assumed, independent on PP model

The prompt photon spectrum



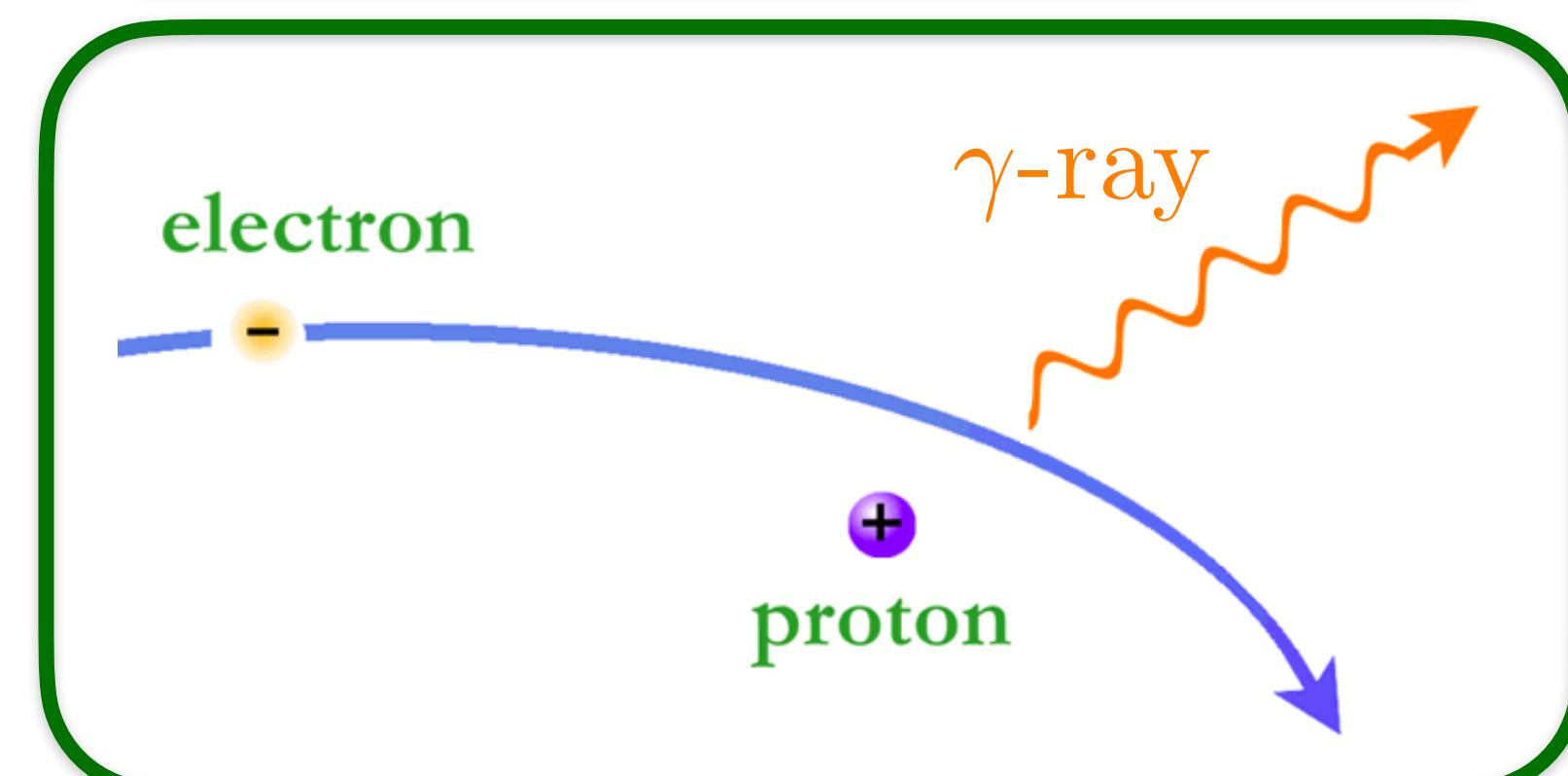
Bringmann, FC+ JHEP'08; Ciafaloni+ JCAP'11; Bringmann&FC PRL'14

Radiative emission from final leptons

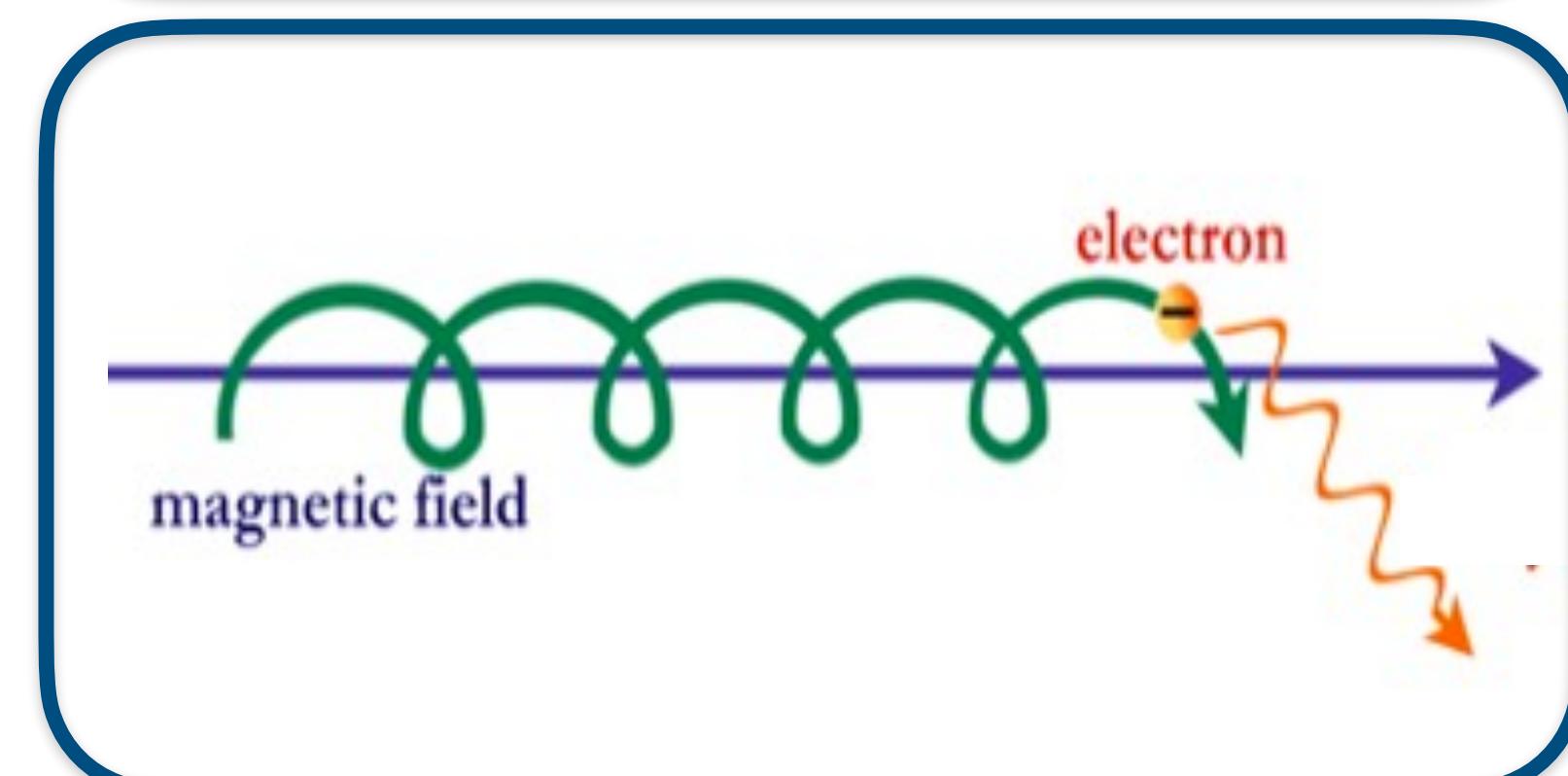


Inverse Compton scattering
on CMB, star-light, infrared-light

$$E_\gamma \simeq 6.5 \left(\frac{E_e}{1\text{TeV}} \right)^2 \left(\frac{\epsilon}{\text{meV}} \right) \text{GeV}$$



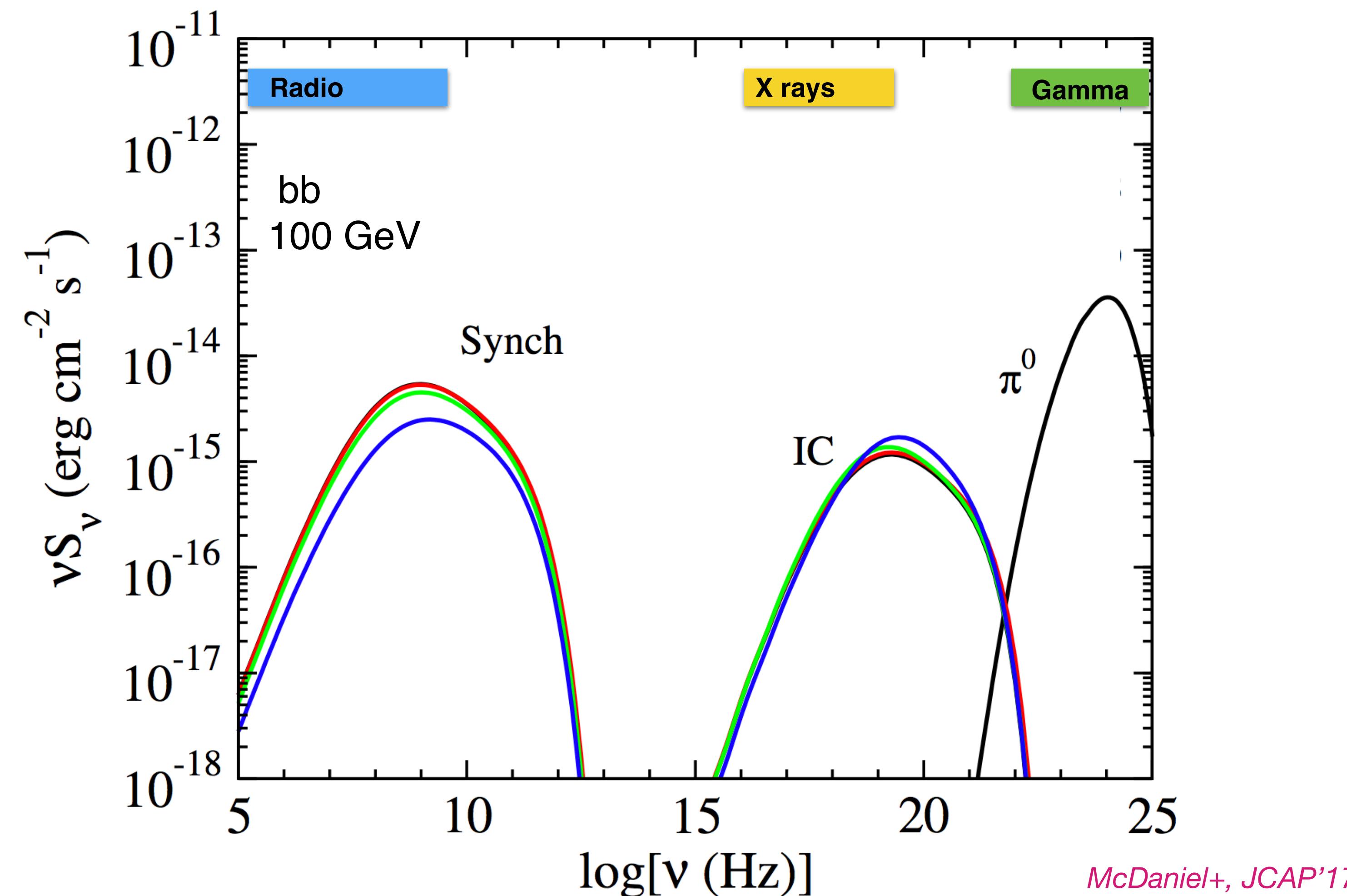
Bremsstrahlung
onto gas of interstellar medium



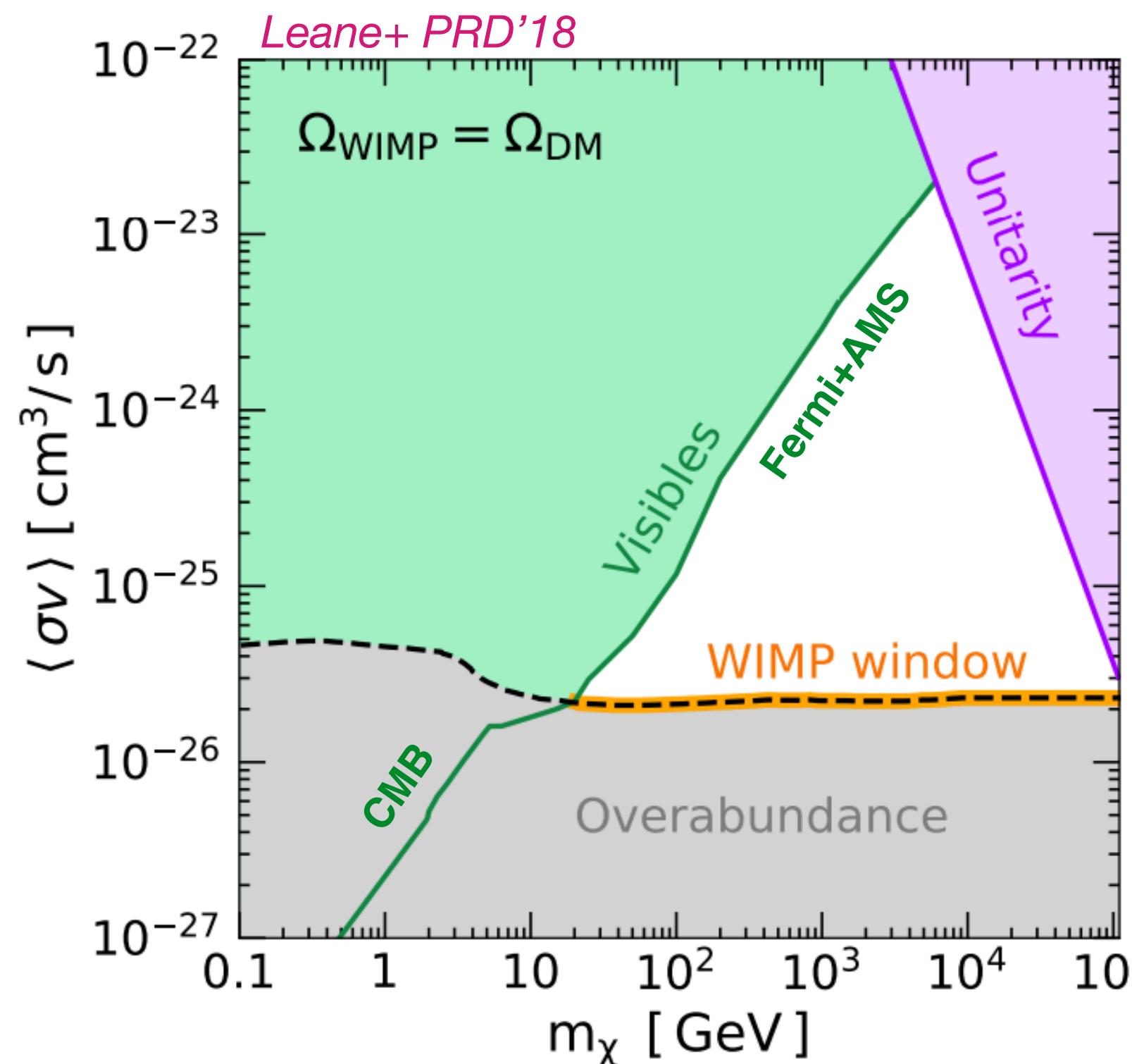
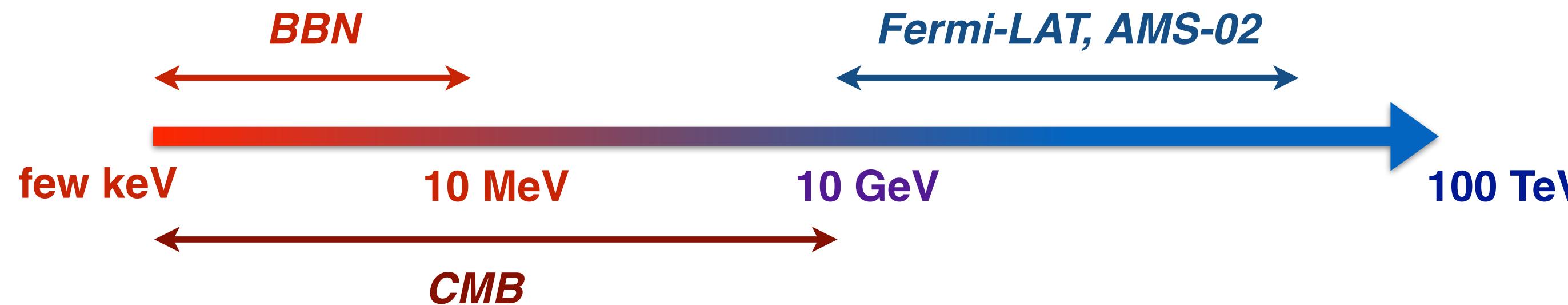
Synchrotron radiation
magnetic field $\mathcal{O}(\mu\text{Gauss})$ for GeV-TeV e^\pm
=> MHz-GHz radio signal

$$E_{sync} \simeq 0.2 \frac{B}{10\mu G} \left(\frac{E_e}{\text{TeV}} \right)^2 \text{eV}$$

Multi-wavelength dark matter spectrum



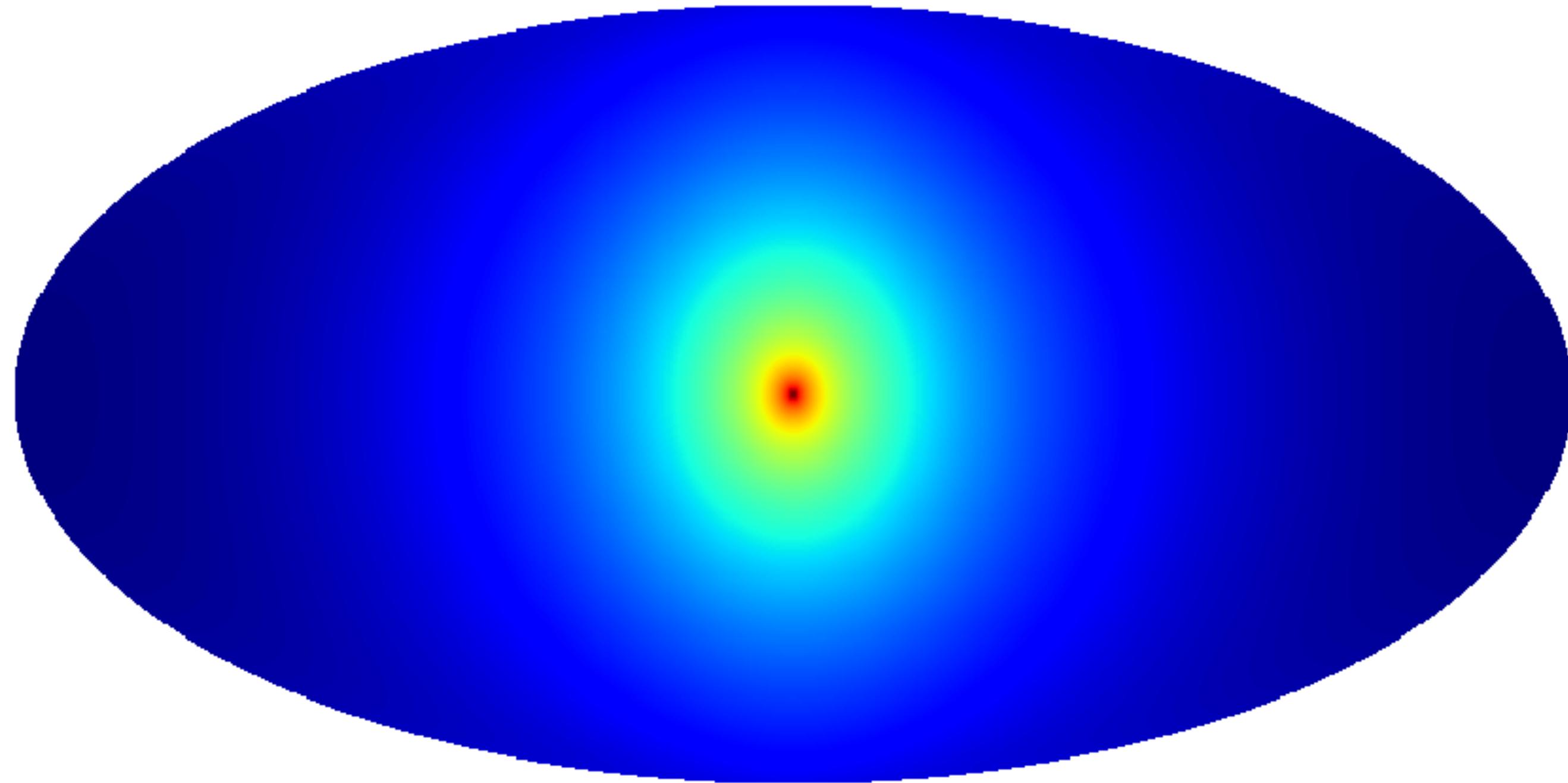
WIMP annihilation constraints



- **Total cross-section sets relic abundance**
 - **Indirect detection provides model-independent UL on annihilation cross-section for a given final state**
- Consistent and conservative interpretation of the data in the context of the generic thermal WIMP

What do we look for?

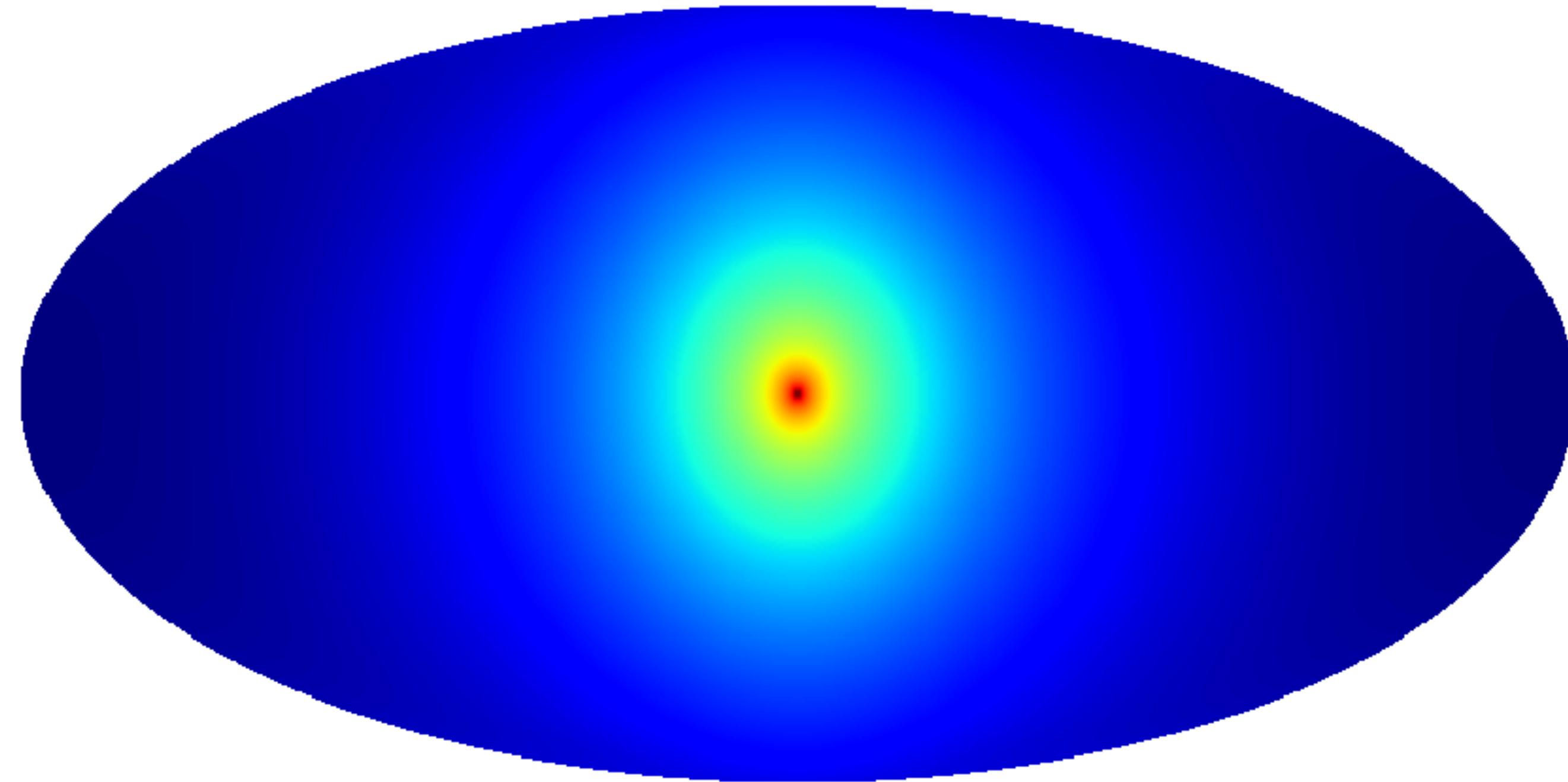
Expected **gamma-ray (prompt) flux** from **dark matter annihilation** in the smooth Galactic halo



$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2$$

What do we look for?

Expected **gamma-ray (prompt) flux** from **dark matter annihilation** in the smooth Galactic halo

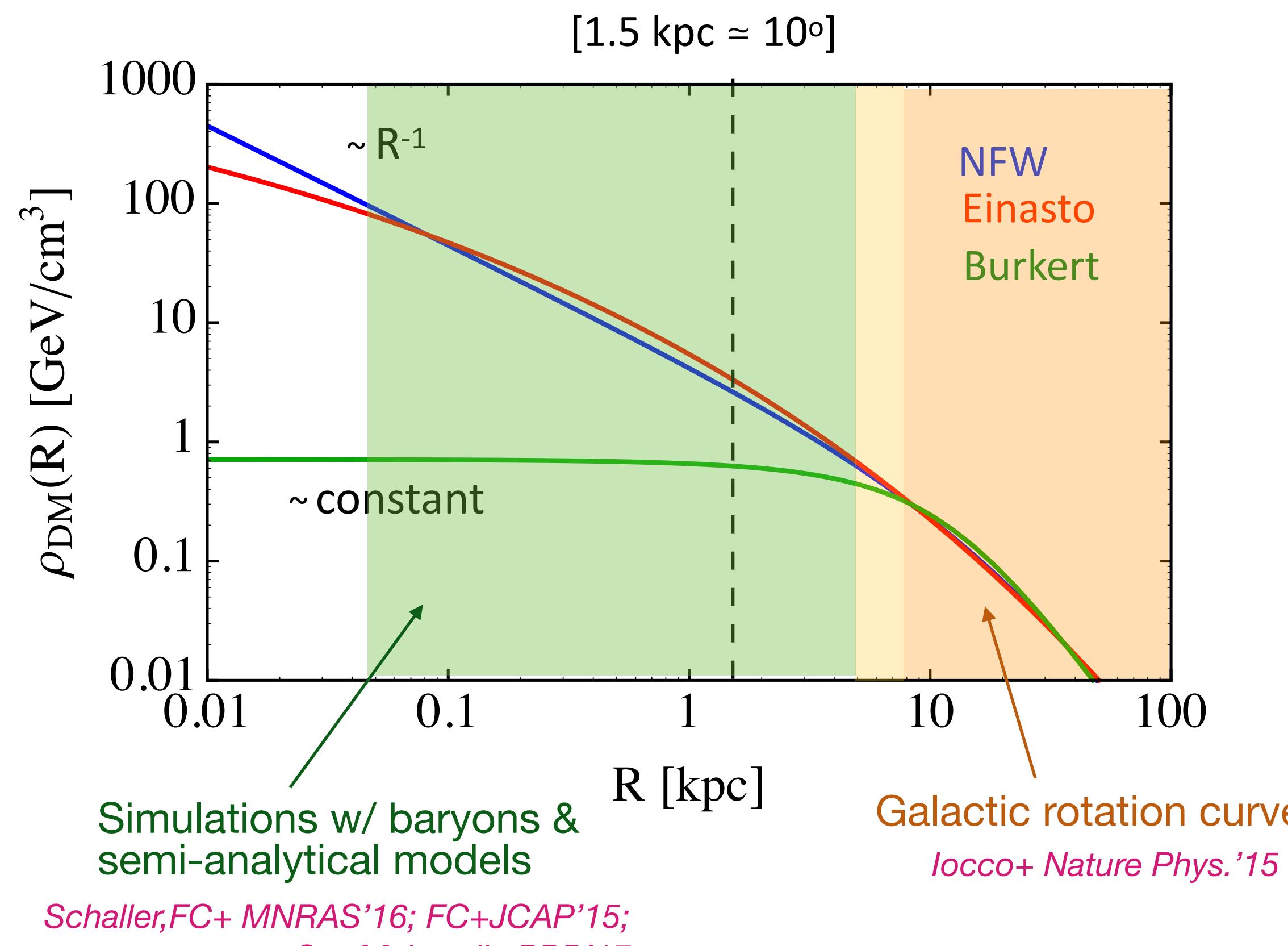


$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2$$

Direct link with cosmology: if the annihilation cross section is not velocity dependent, bounds on σv today are directly connected to the DM relic density

Dark matter spatial distribution

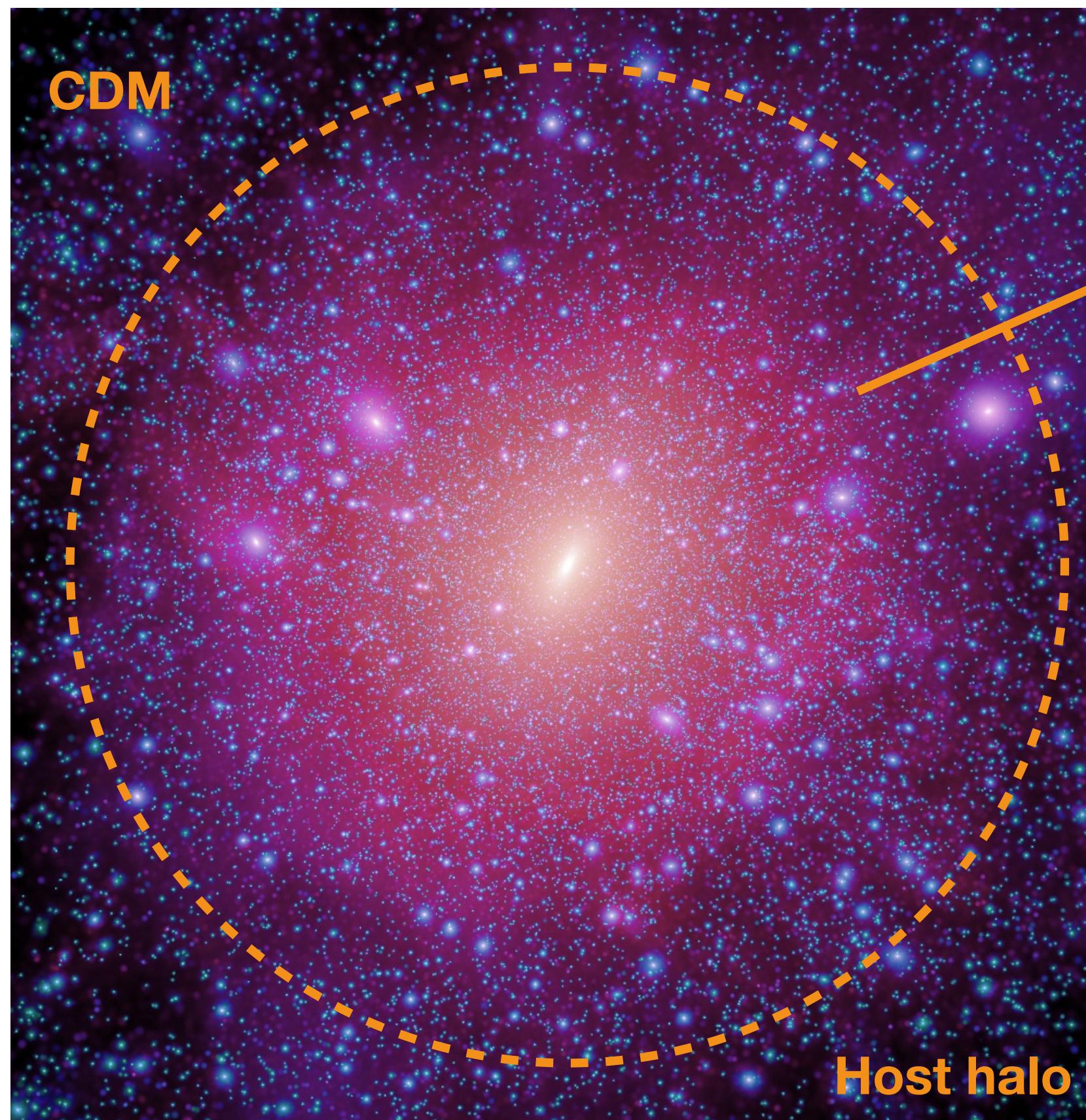
$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2$$



- The distribution of DM in galaxies is affected by large uncertainties
- **Unavoidable modelling uncertainty** to account for when deriving constraints on DM models

Dark matter small-scale structures

Simulations of structure formation allow to predict the distribution and size of haloes in cosmological volumes



Springel+ MNRAS'08

Dark matter sub-haloes or sub-structures

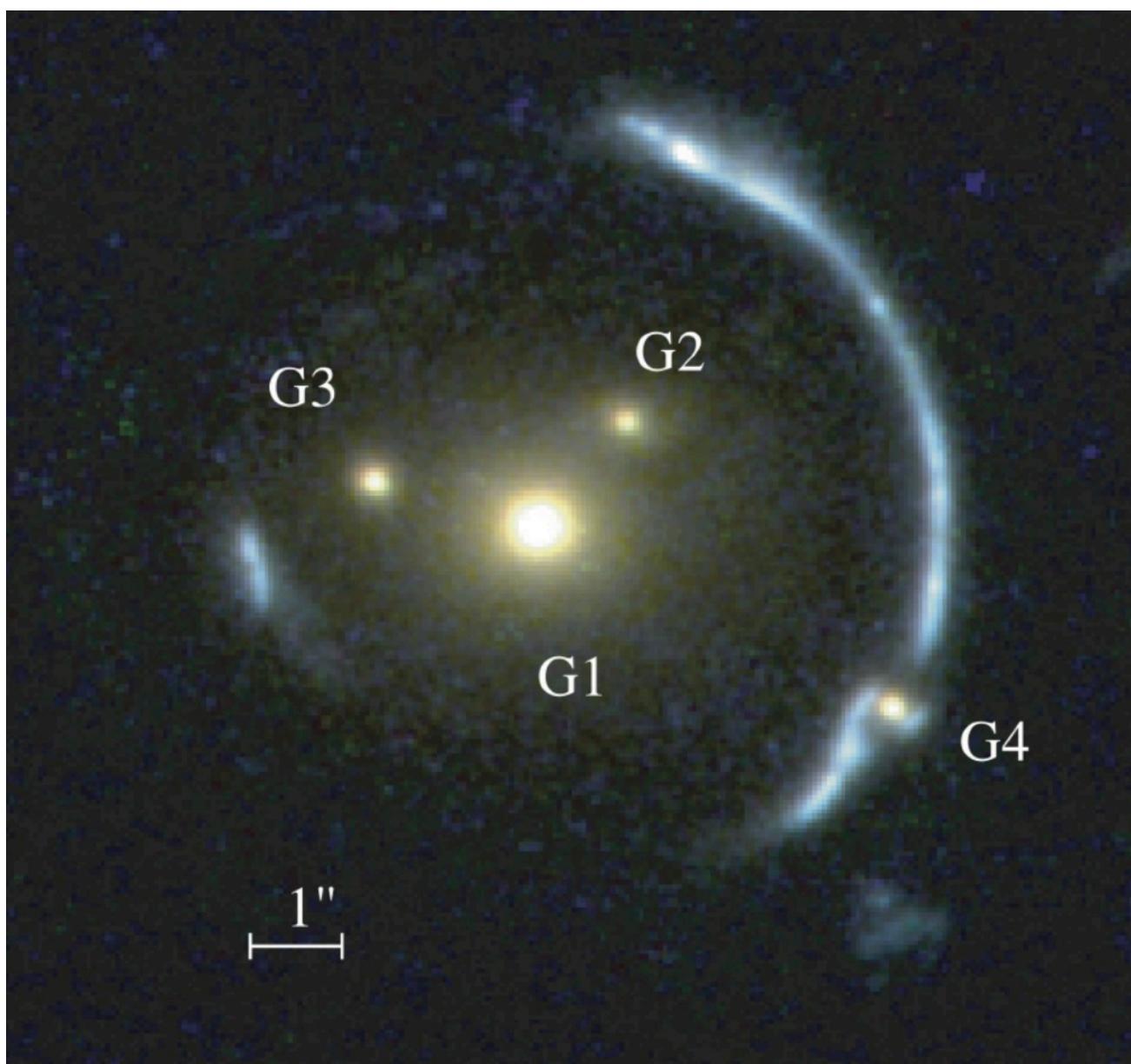
- Low-mass DM haloes, do not trigger star formation => do not contain stars (**dark haloes**)
- Their mass distribution depends on fundamental properties of DM (warm vs cold)
- CDM predicts abundance down to Earth-sized objects ($10^{-6} M_{\text{Sun}}^*$)
- Their distribution leads to specific angular signatures of the DM signal

* In WIMP and non-thermal axion models

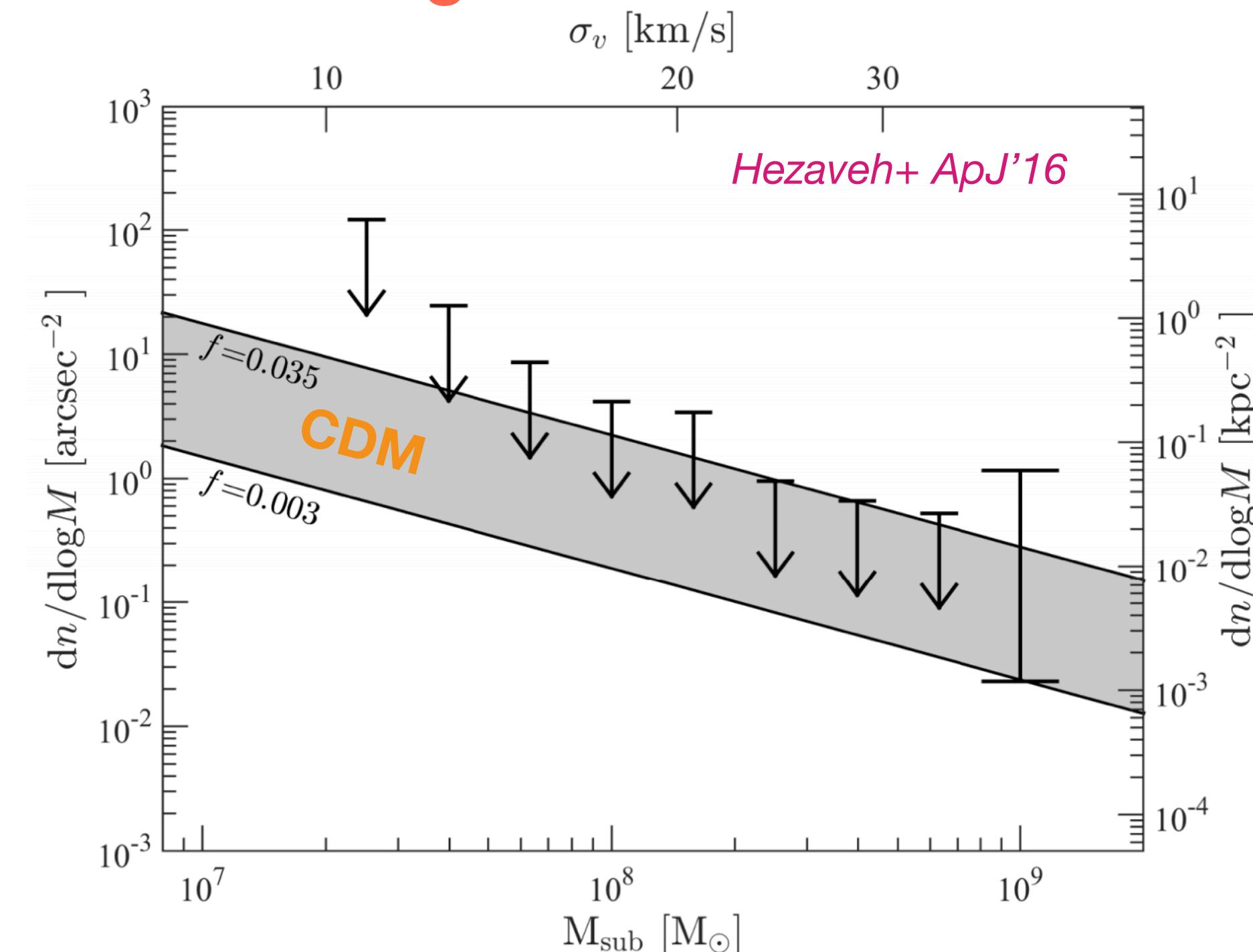
The minimum halo mass

Smallest known galaxies provide a proof of existence for halos of mass
 $\sim 10^8 - 10^9 M_{\text{Sun}}$

Strong gravitational lensing



Vegetti+ MNRAS'10



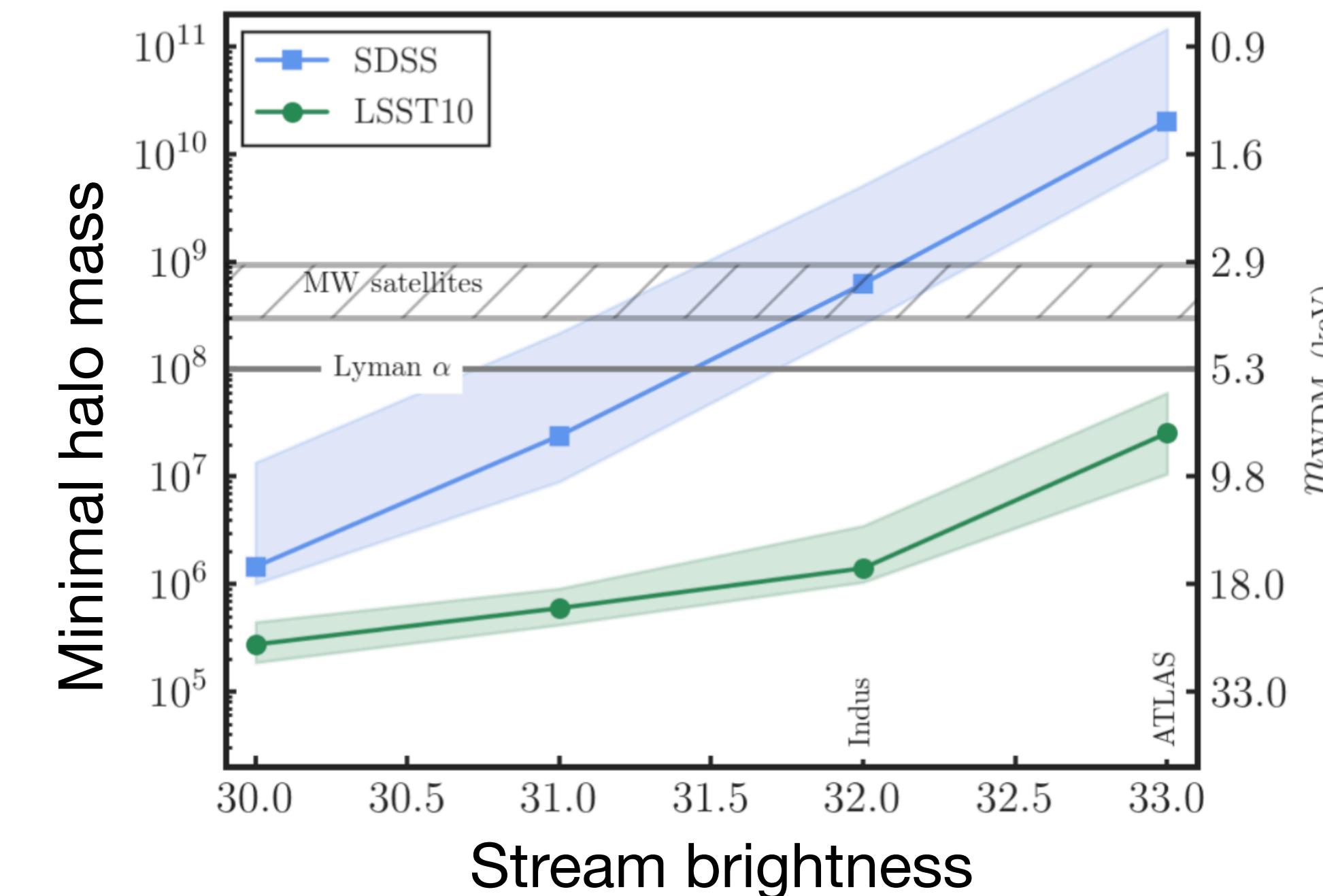
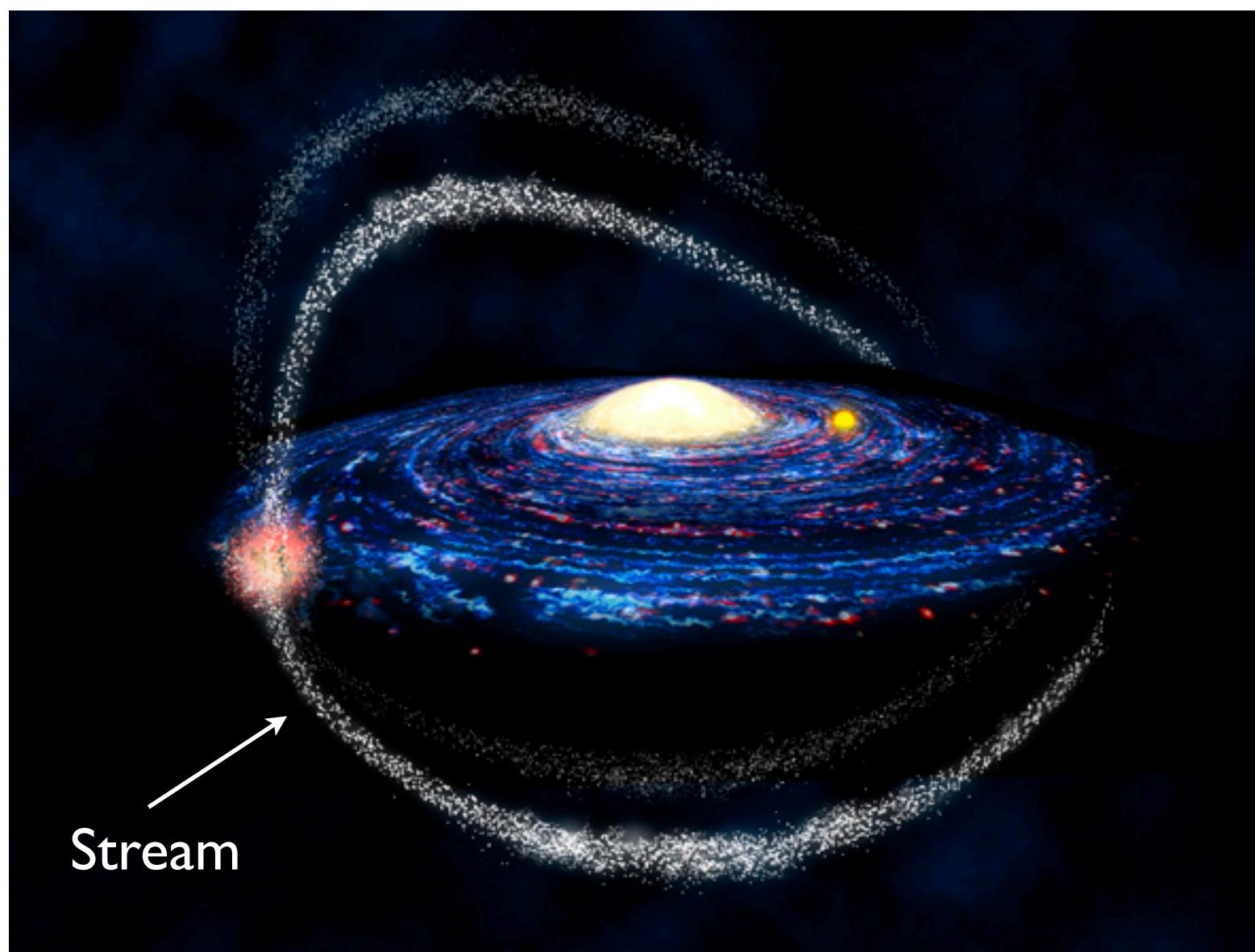
Constraints on subhalo mass function will greatly improve
with LSST and ALMA observations

The minimum halo mass

Smallest known galaxies provide a proof of existence for halos of mass
 $\sim 10^8 - 10^9 \text{ M}_{\text{Sun}}$

Gaps in stellar streams

Drlica-Wagner+1902.01055

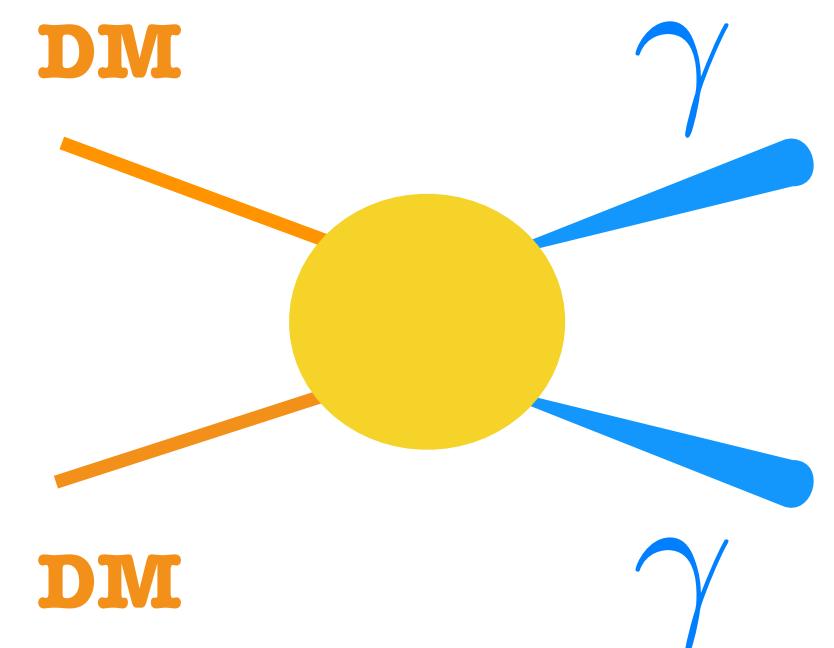


DM subhaloes may induce perturbations of stellar streams
=> Detectable gaps for masses $M_{\text{sub}} \sim 10^5 - 10^6 \text{ M}_{\text{Sun}}$

Ibata et al., 2002; Johnston et al., 2002; Yoon et al., 2011; Carlberg, 2012

Probing the WIMP window with high-energy gamma rays

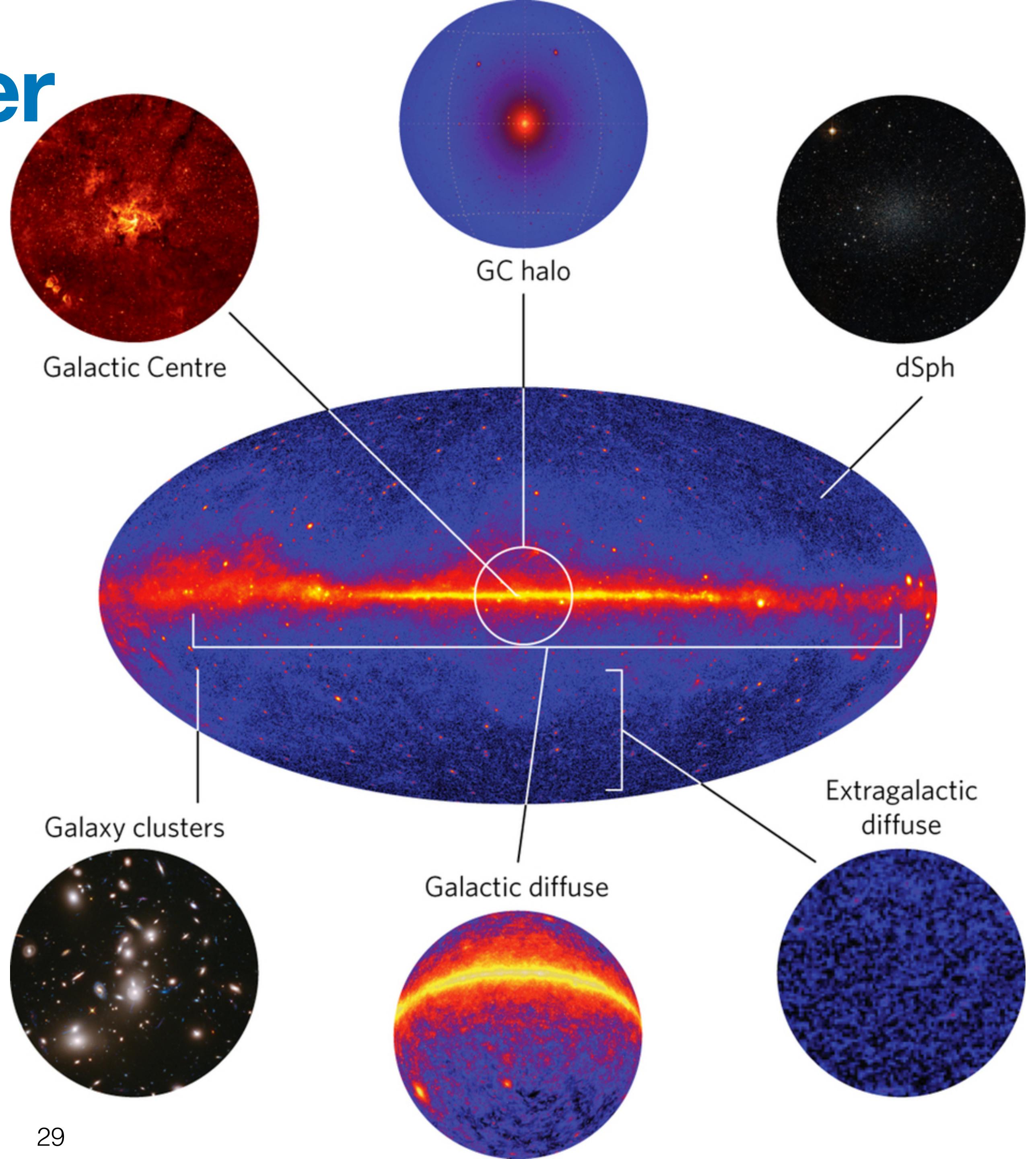
Targets for dark matter searches



$$\mathcal{I} \propto \int d\ell \rho [r(\ell, \psi)]^2$$

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

Conrad & Reimer Nature Phys. 13 (2017)

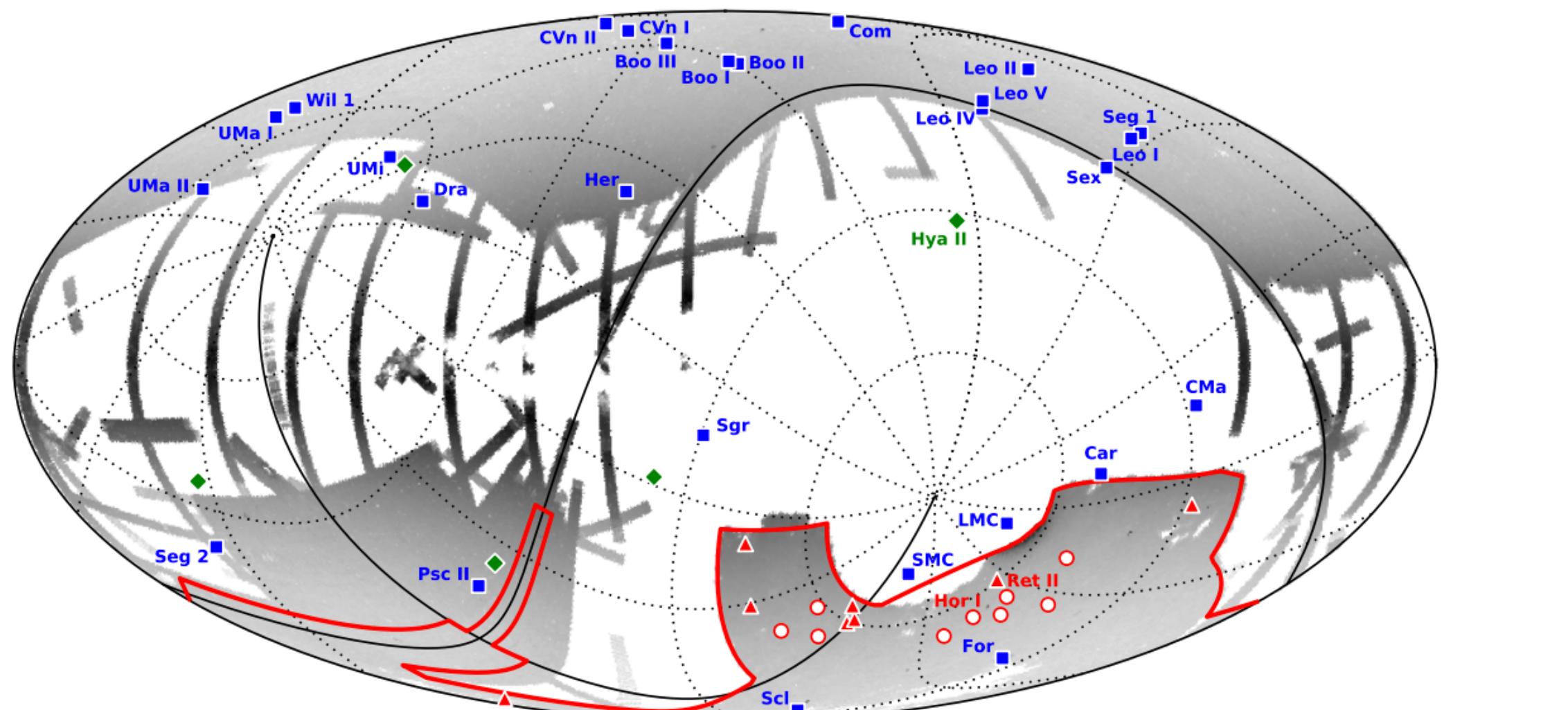


Dwarf spheroidal galaxies

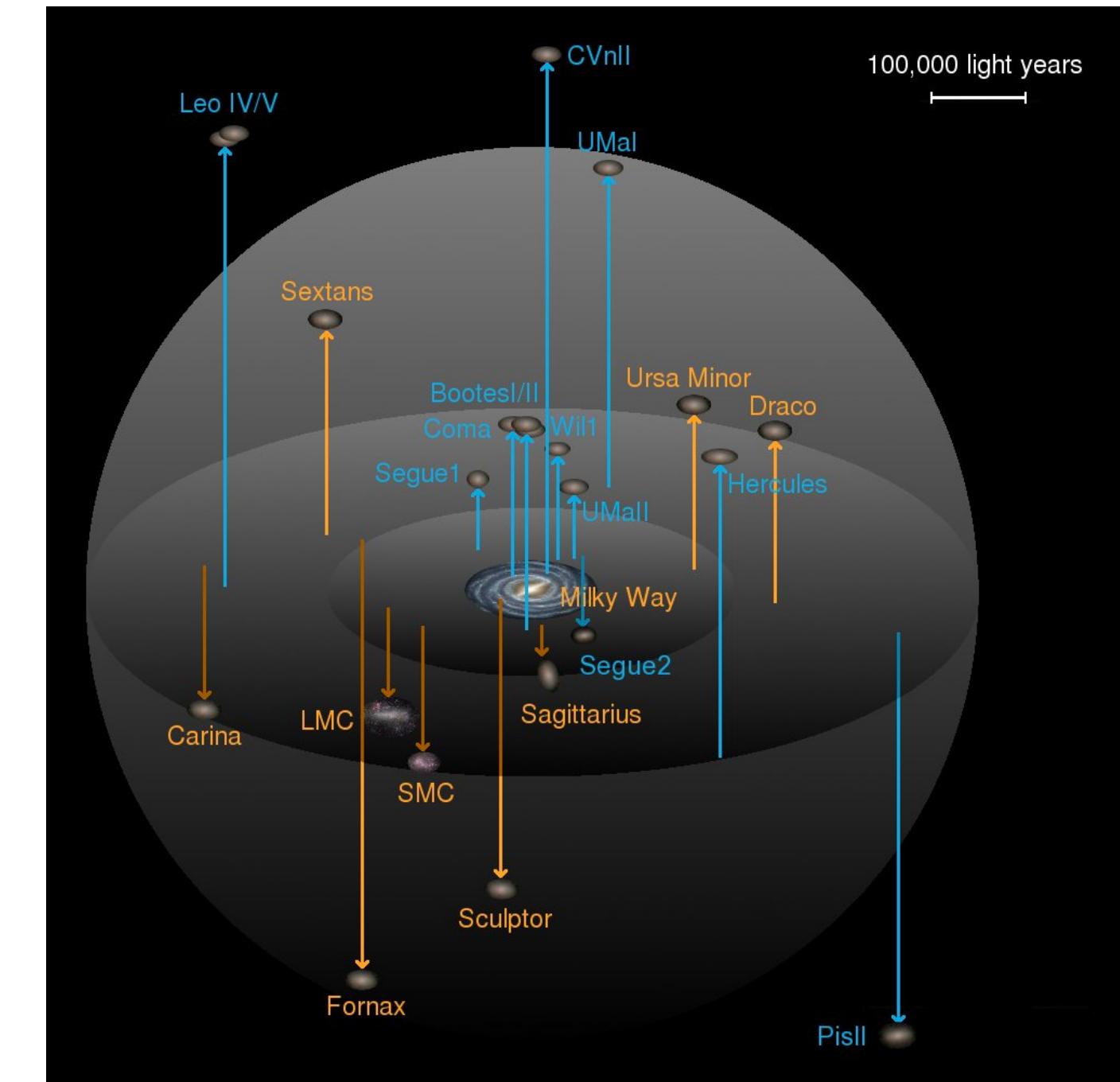
Known satellites of the Milky Way at ~ 100 kpc from Earth

“Clean” target for DM searches, high mass-to-light ratio and no astrophysical emission

Winter+ ApJ'16



Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates

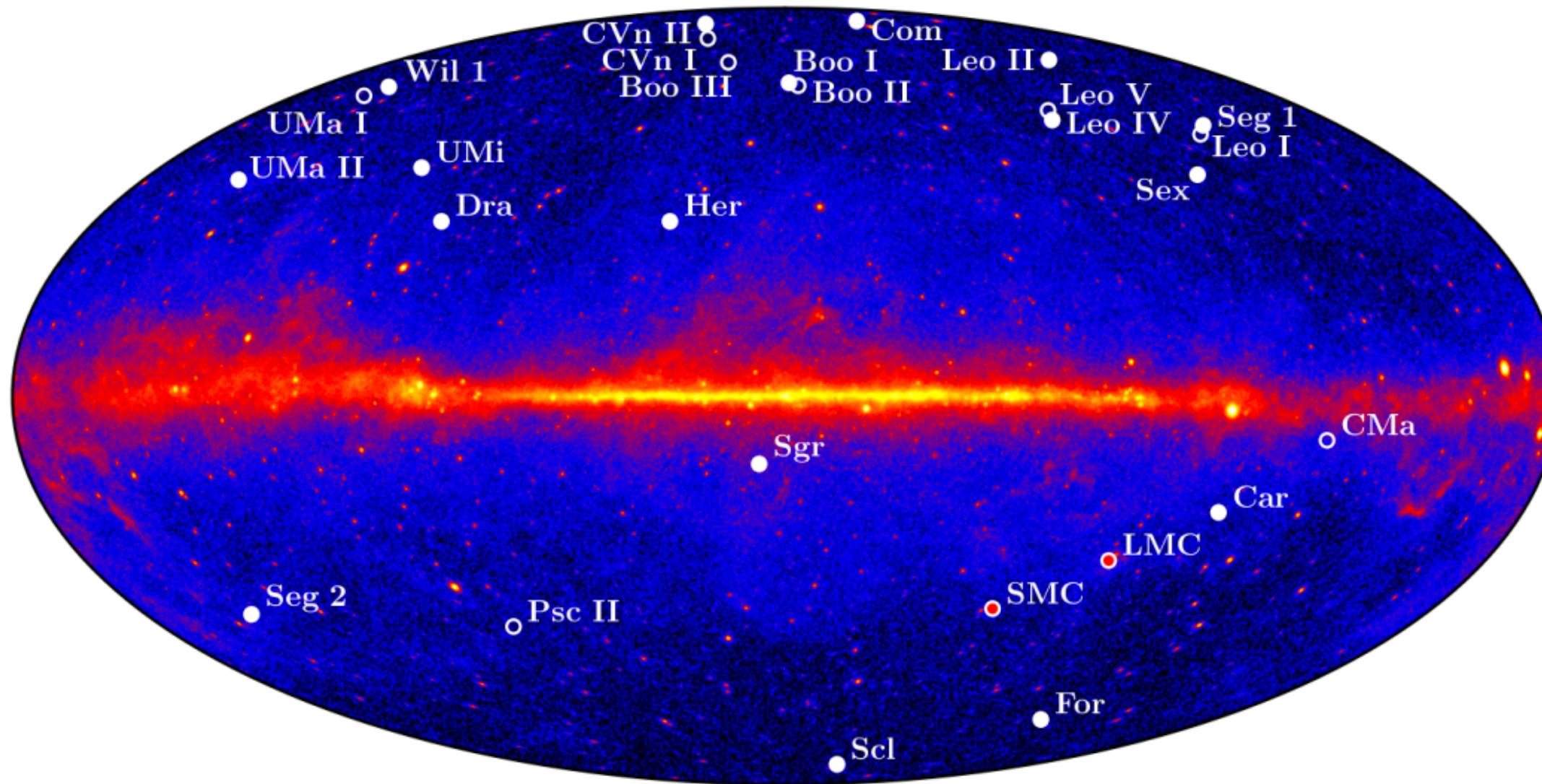


SDSS northern hemisphere, classical + ultra-faint dSphs

DES southern hemisphere, 17 new
Pan-STARRS, 3 new candidates

DES Collaboration, ApJ'15

Limits from dwarf spheroidal galaxies

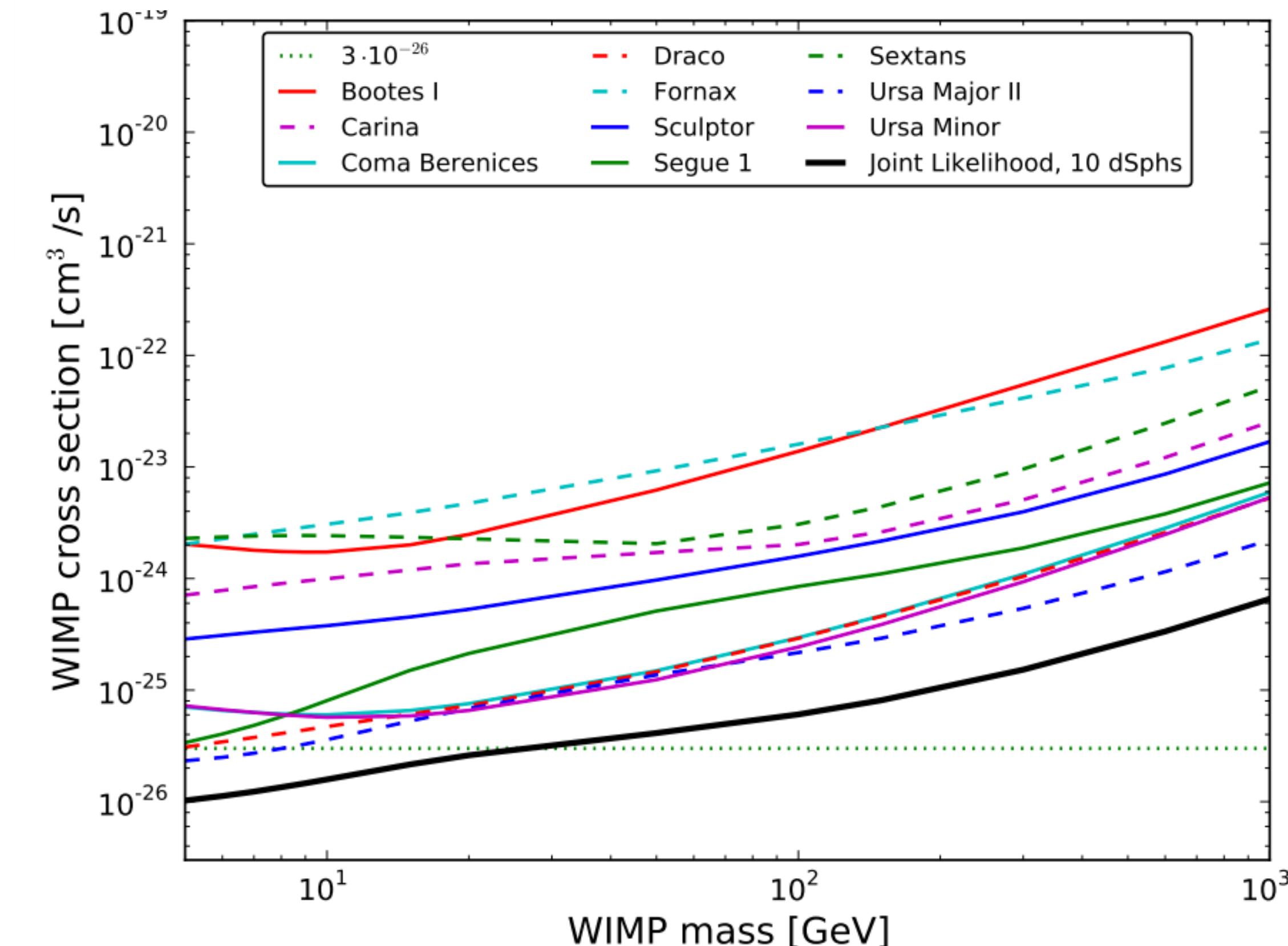


Analysing dSphs as a group results in sensitivity competitive with other targets => **Stacking technique.**

Fermi-LAT Collaboration, PRL'11

$$\mathcal{J} \propto \int d\ell \rho [r(\ell, \psi)]^2$$

$$L(D|\mathbf{p}_{\text{W}}, \{\mathbf{p}\}_i) = \prod_i L_i^{\text{LAT}}(D|\mathbf{p}_{\text{W}}, \mathbf{p}_i)$$
$$\times \frac{1}{\ln(10) J_i \sqrt{2\pi} \sigma_i} e^{-[\log_{10}(J_i) - \overline{\log_{10}(J_i)}]^2 / 2\sigma_i^2}$$



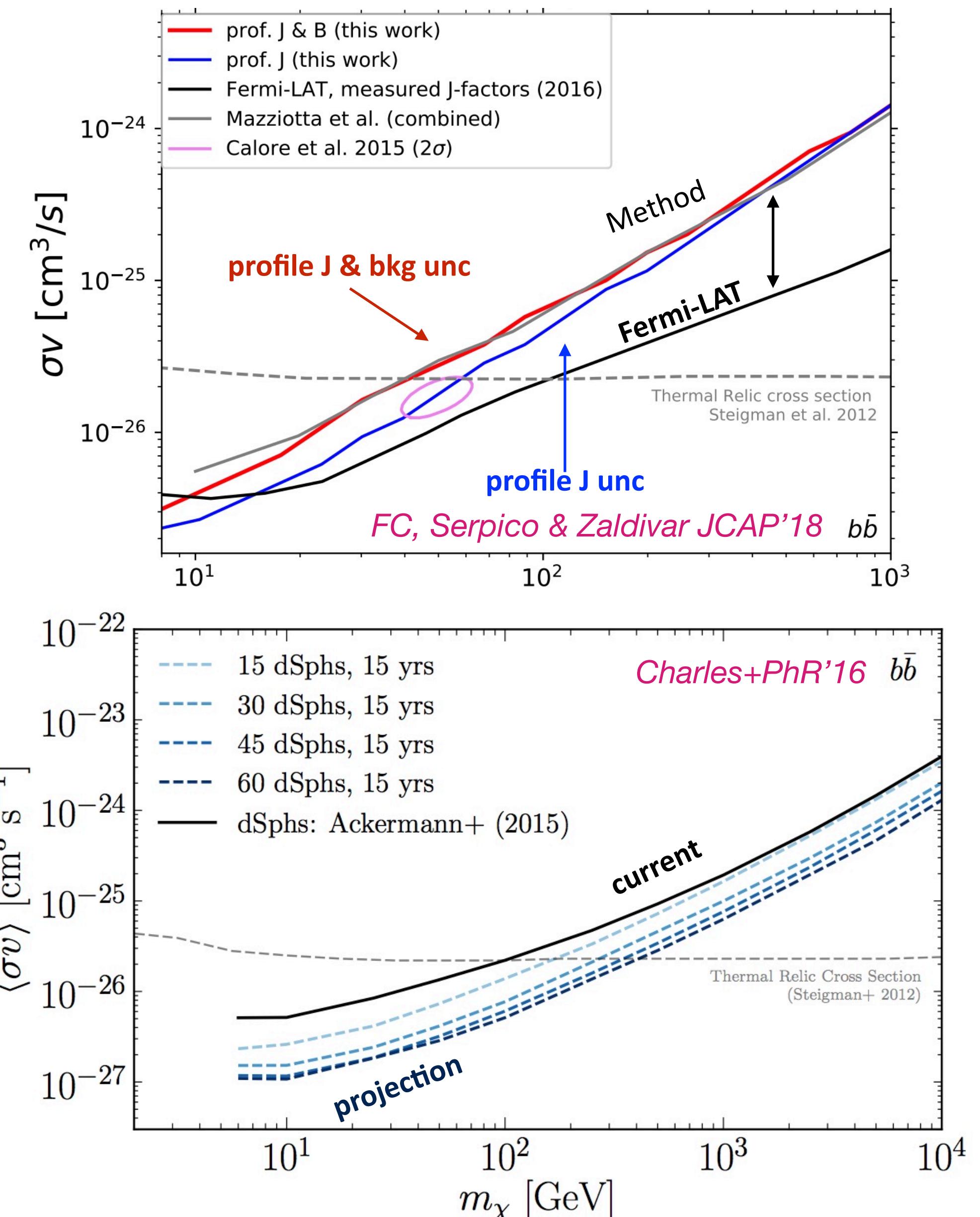
Limits from dwarf spheroidal galaxies

Status:

- Exclude thermal cross section below 100 GeV
(16 dSphs stacking, 6 yr of data) *Albert+ ApJ'17*
- Syst unc J-factor determination for ultra-faint dSphs (tri-axiality, contamination, velocity anisotropy) *Ullio&Valli JCAP'16;*
Hayashi+ MNRAS'16; Klop+ PRD'17
- Syst unc background mis-modelling are important (3x weaker limits) *FC, Serpico & Zaldivar JCAP'18;*
Alvarez, FC+ JCAP'20

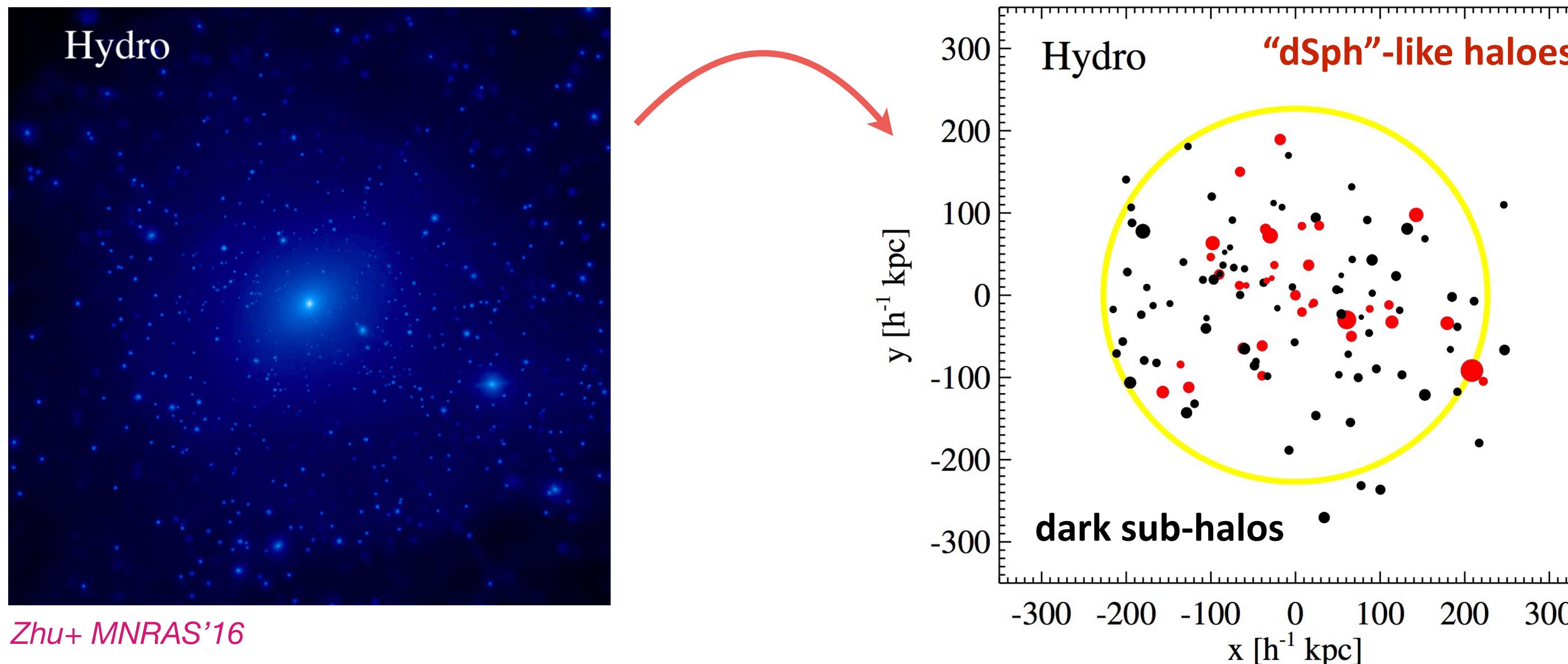
Future:

- New data from Fermi-LAT (improvement by a factor of 2-5)
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019) *Hargis+ApJL'14*
- Competitive bounds from future radio and X-ray telescopes *Regis+, JCAP'14;*
Jeltema&Profumo, MNRAS'12



Searches for dark sub haloes

Simulations of **galaxy formation** allow us to predict the distribution and size of haloes in cosmological volumes and their stellar content



Do we have already detected dark subhaloes among currently unassociated gamma-ray sources?

Bertoni+ JCAP'15; Schoonenberg+ JCAP'16; Hooper&Witte JCAP'17; FC+PRD'17; Coronado-Blazquez+ JCAP'19, Galaxies 20

Limits from dark subhaloes searches

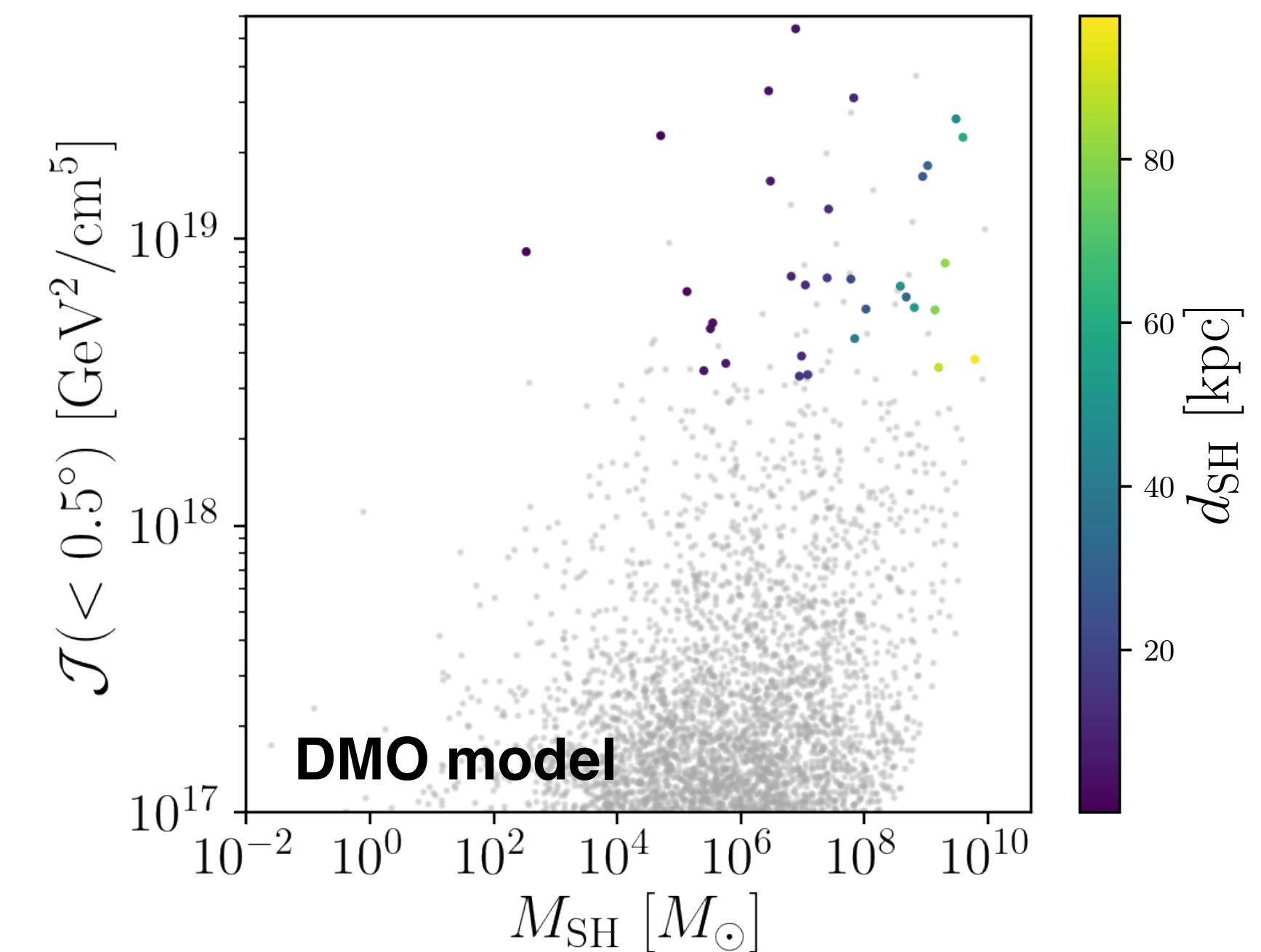
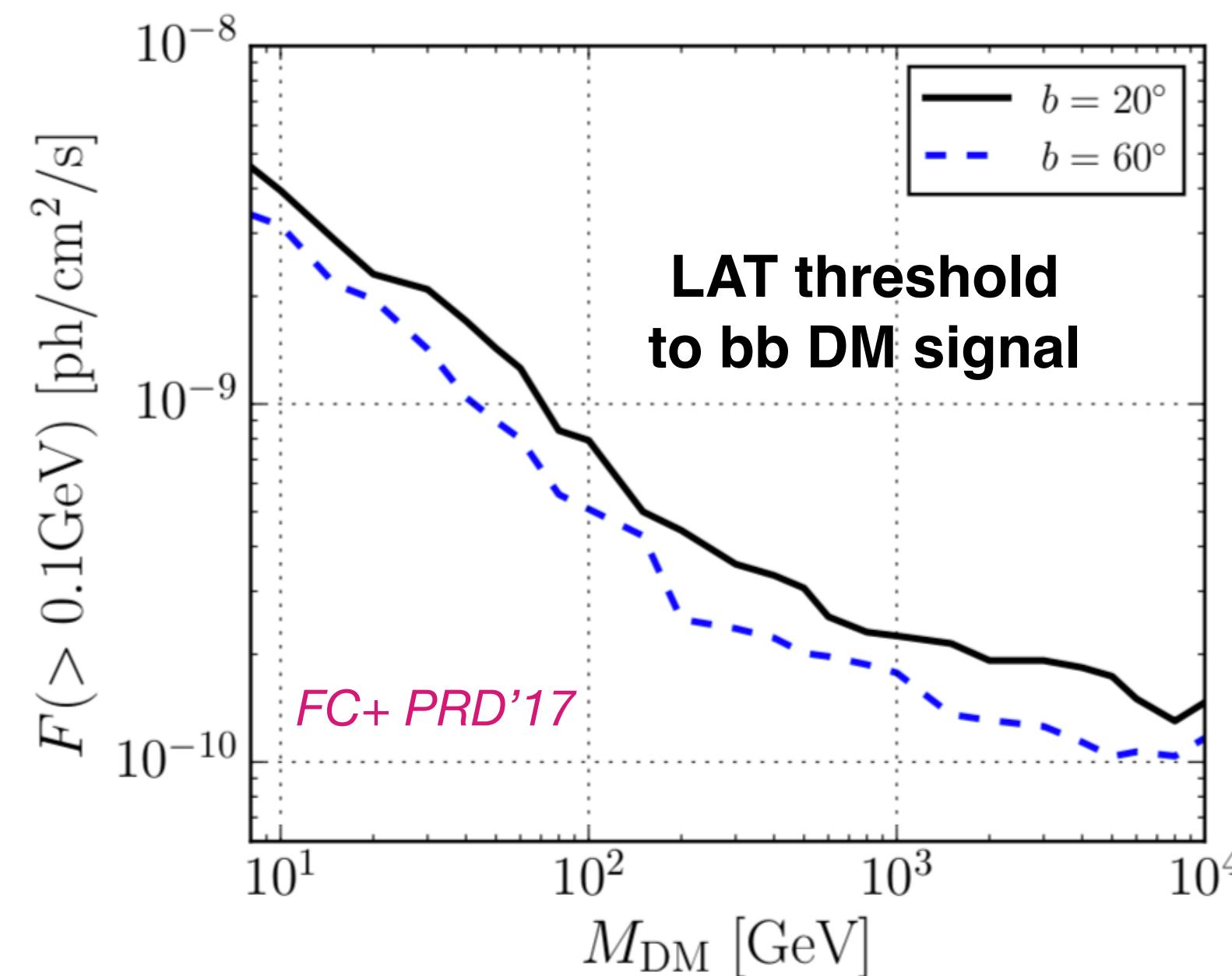
1. Number of gamma-ray DM subhalo candidates from data?

- Classification of Fermi-LAT gamma-ray sources based mainly on spectral properties

Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17; Coronado-Blazquez+ JCAP'19

2. Number of detectable gamma-ray DM subhaloes from models?

- Use sub halo models to infer distribution and number of dark objects in the Galaxy
 - relevant effects of baryonic potential
- Convolve with realistic Fermi-LAT detection threshold to DM sub halo signals



Limits from dark subhaloes searches

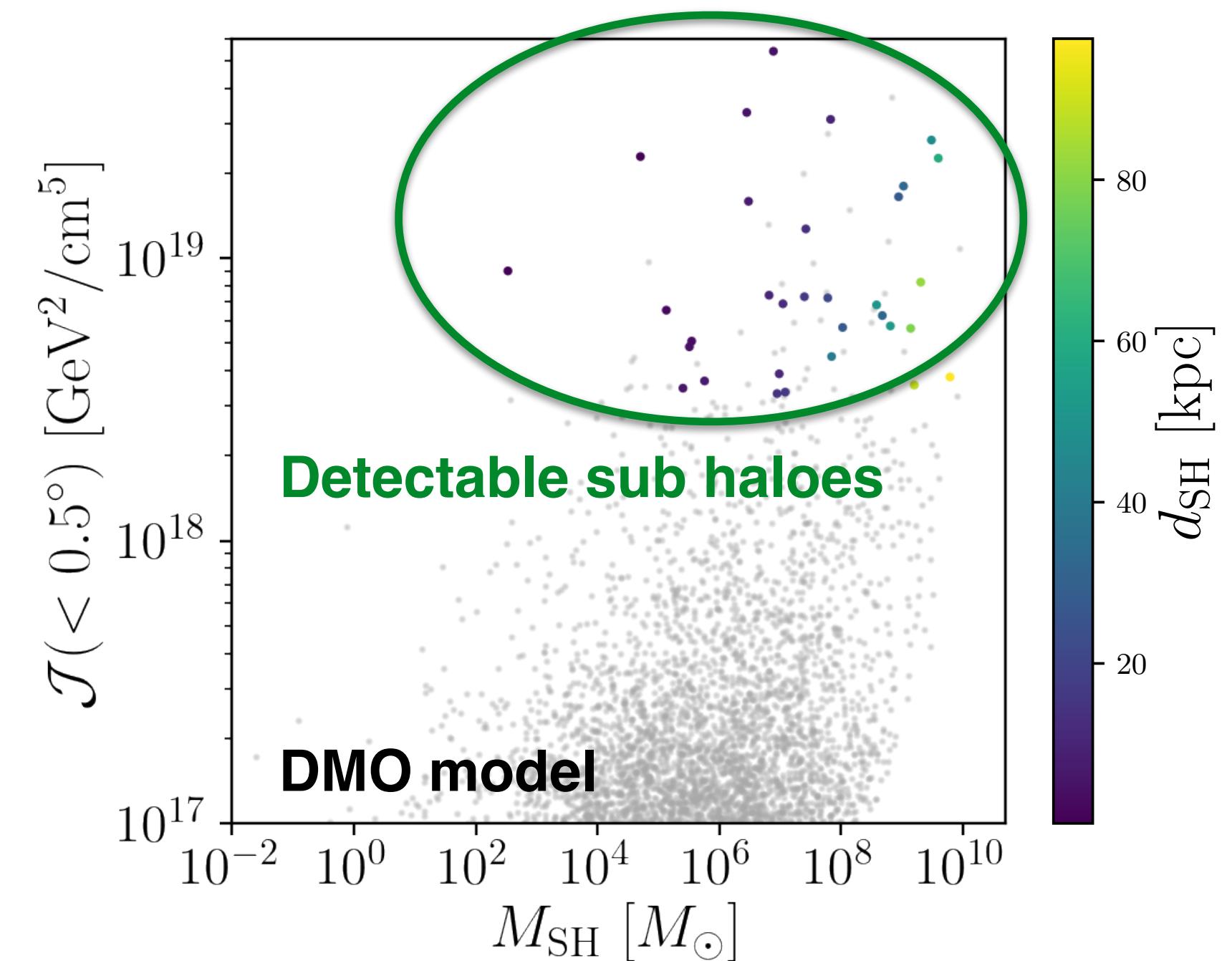
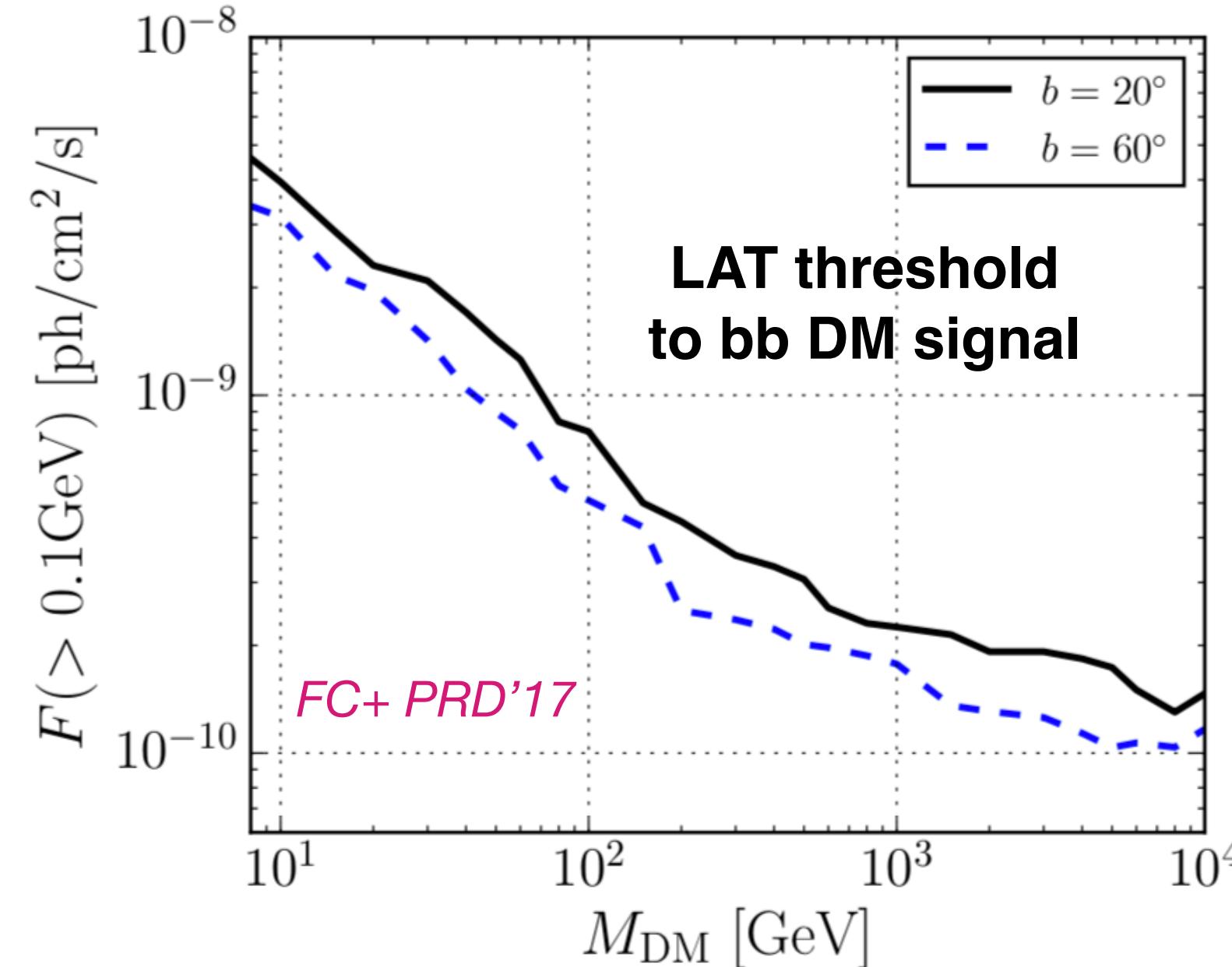
1. Number of gamma-ray DM subhalo candidates from data?

- Classification of Fermi-LAT gamma-ray sources based mainly on spectral properties

Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17; Coronado-Blazquez+ JCAP'19

2. Number of detectable gamma-ray DM subhaloes from models?

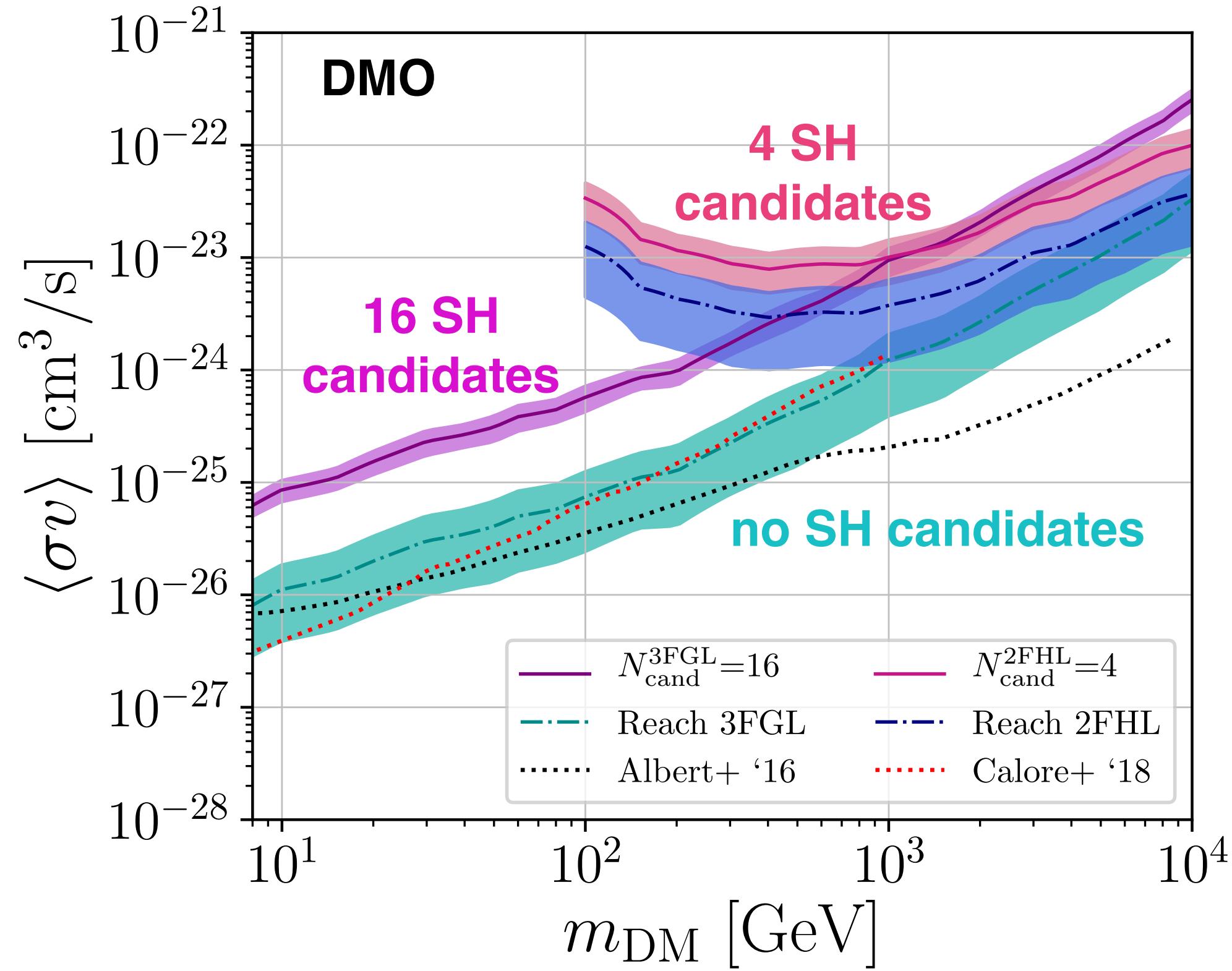
- Use sub halo models to infer distribution and number of dark objects in the Galaxy
 - relevant effects of baryonic potential
- Convolve with realistic Fermi-LAT detection threshold to DM sub halo signals



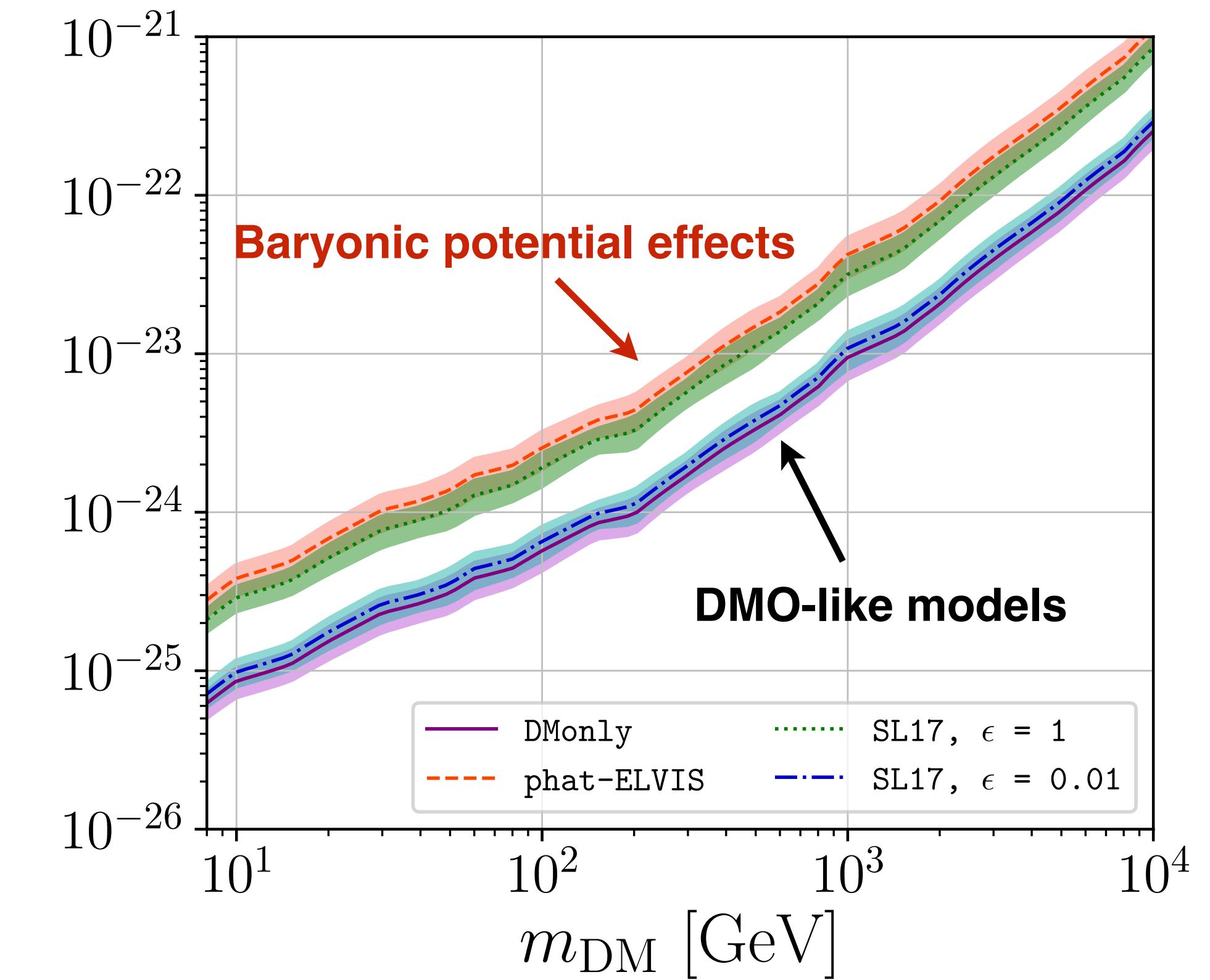
Limits from dark subhaloes searches

- To match (2) with (1), one has to tune the DM particle physics free-parameters
- Limits on DM annihilation cross-section depends on sub halo modelling and sub halo spatial extension

Di Mauro, Stref, FC PRD'20

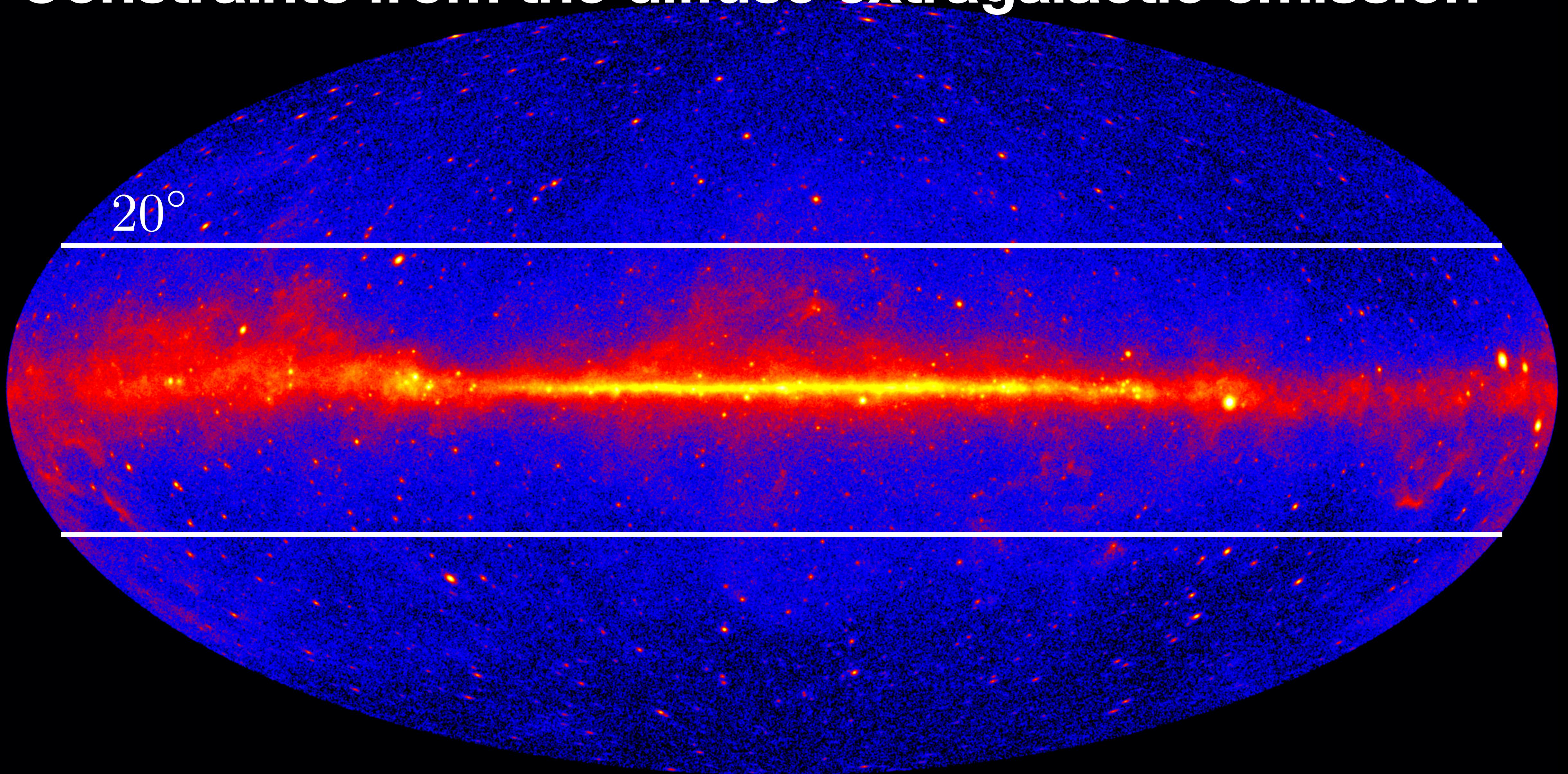


FC+ Galaxies'19

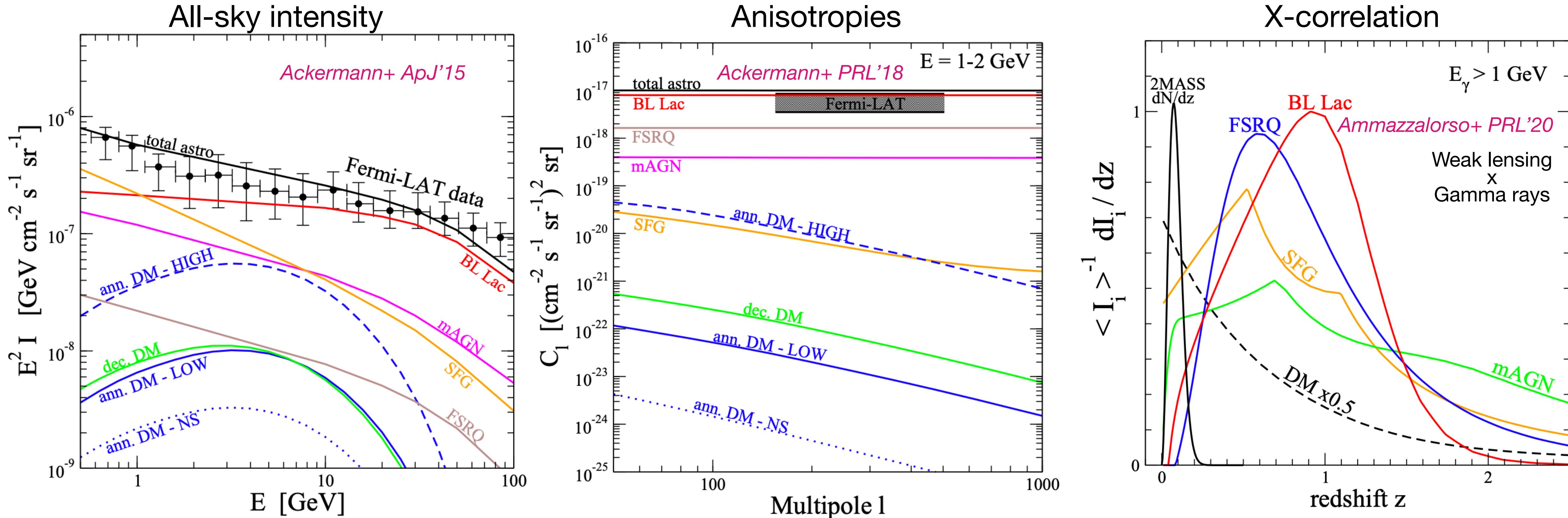
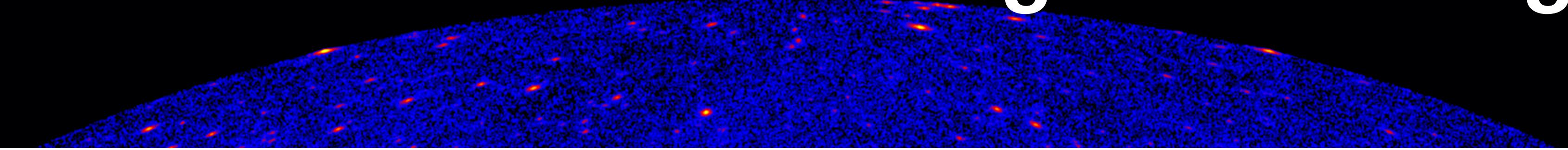


Future: Follow-up observations crucial to reduce the number of subhalo candidates

Constraints from the diffuse extragalactic emission



Constraints from the diffuse extragalactic background

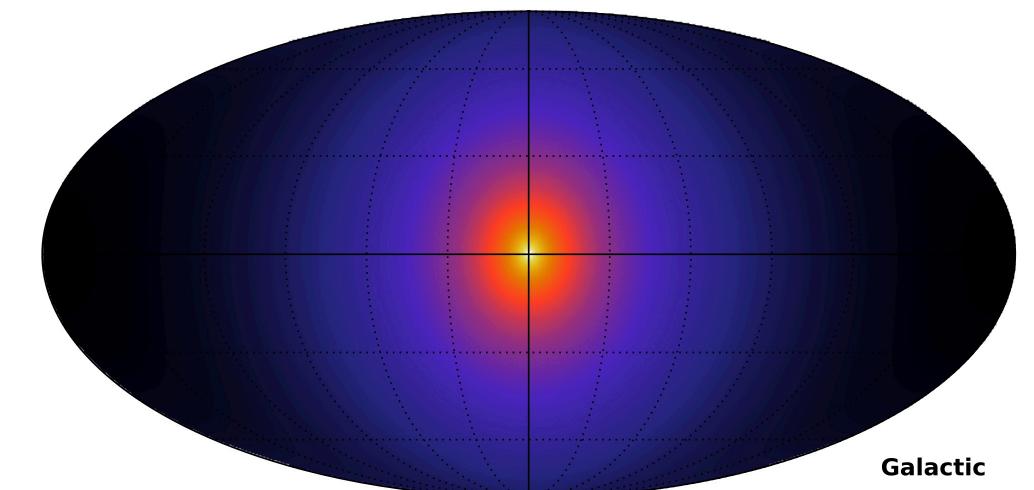


Exploit spatial (redshift) features of DM signals to set constraints

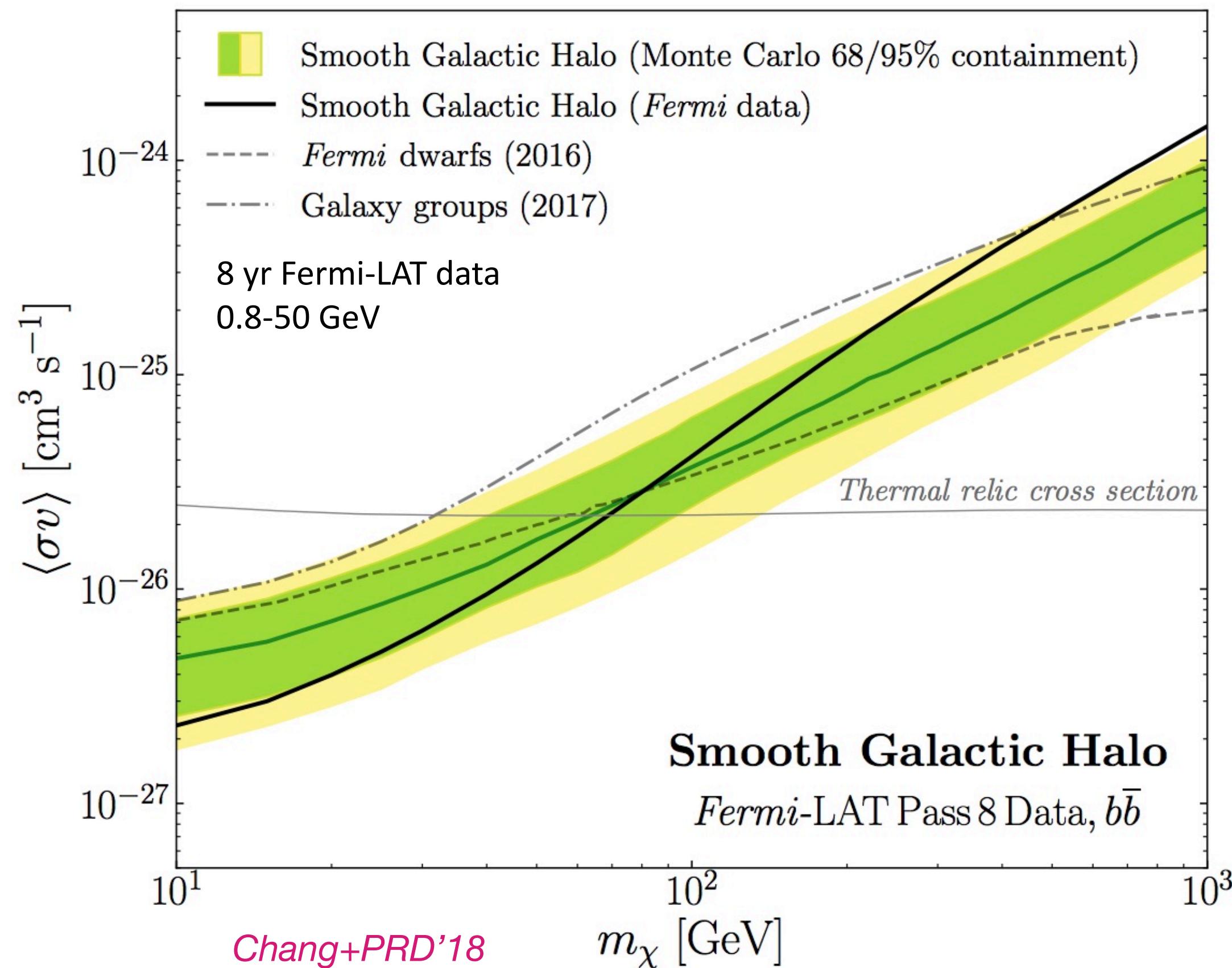
Bringmann+ PRD'14, Chang+ PRD'18, Siegal-Gaskins JCAP'08, FC+ MNRAS'14; Zechlin+ PRD'18; Regis+ PRL'15, Cuoco+ ApJS'15, Camera+ JCAP'15

Limits from dark matter halo searches

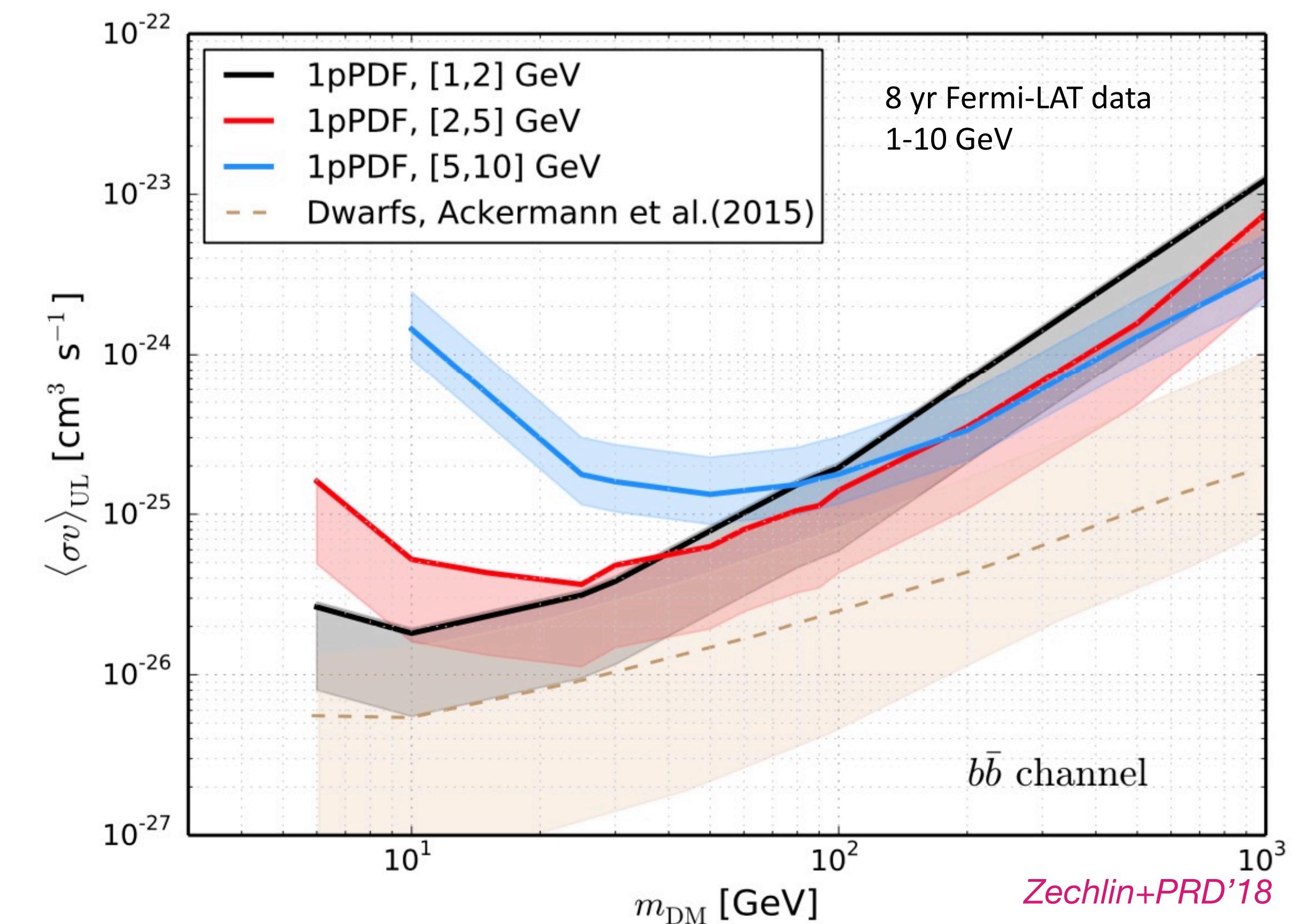
The high-latitude region provides **robust constraints** on annihilating dark matter into hadronic final states



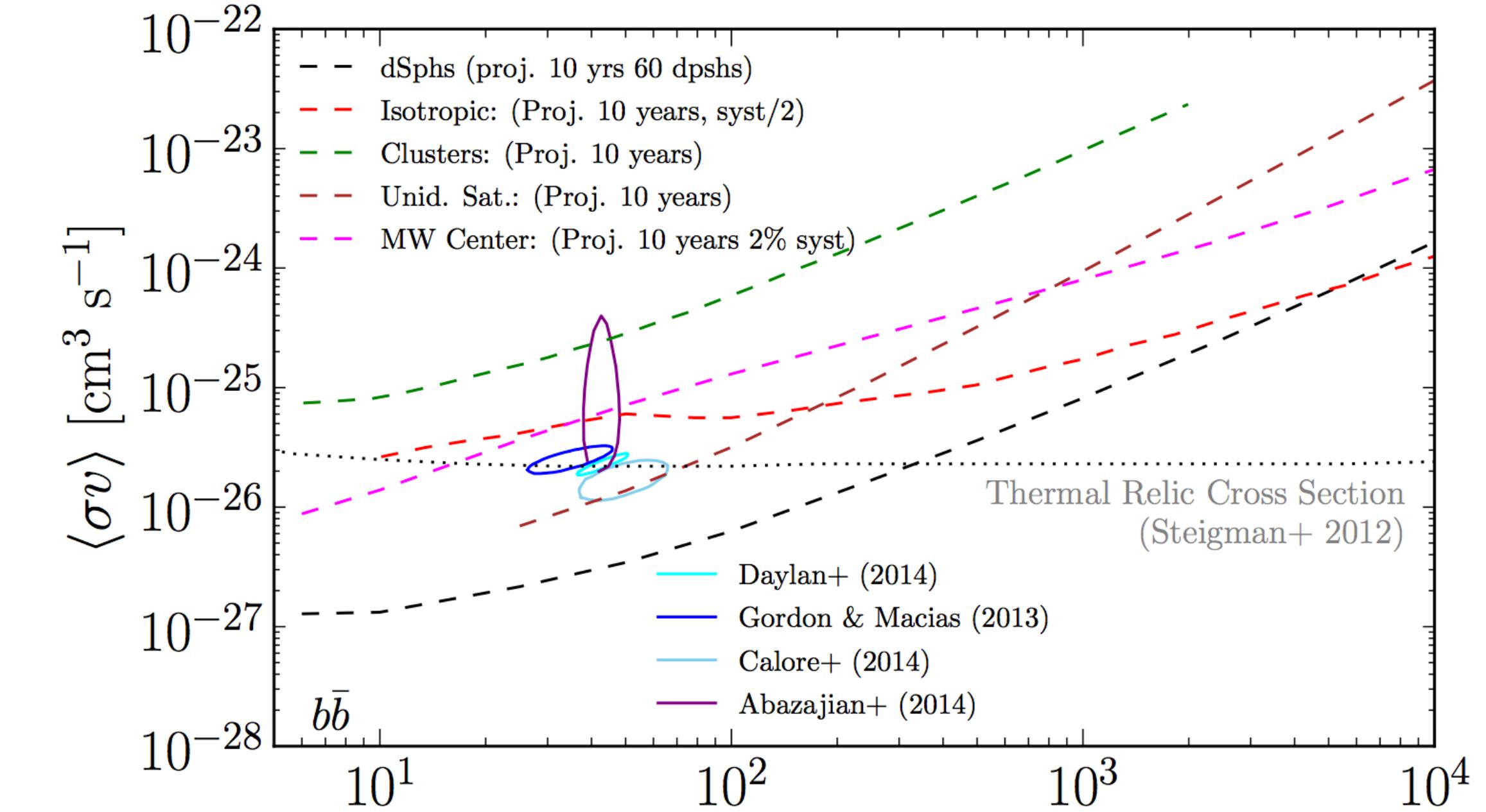
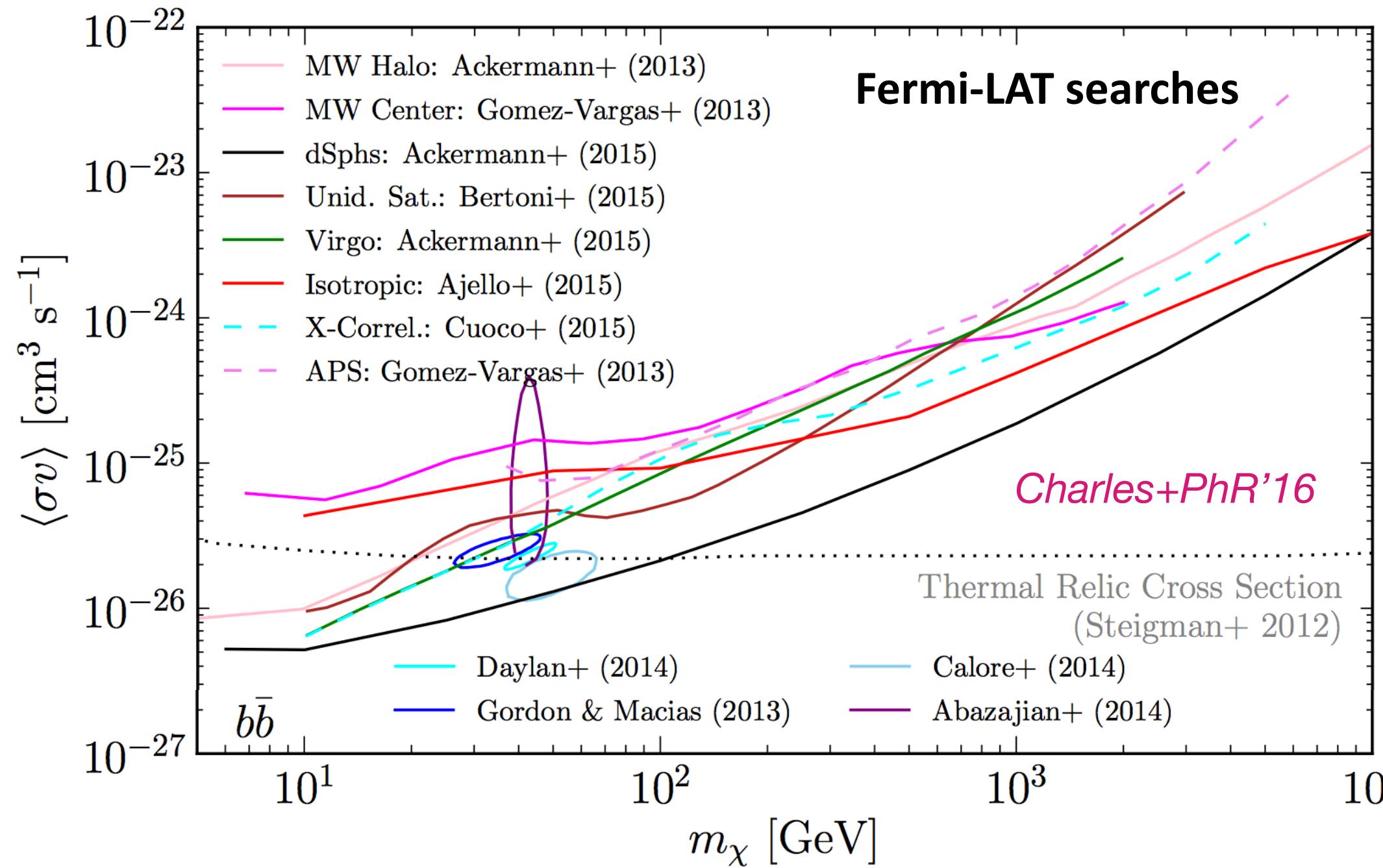
Template fitting



1-point Statistics



GeV photons: multi-target constraints



Status

- Comparison with current limits from other Galactic and extragalactic targets
- Mild tension with GeV excess, but astro unc on dSphs bkg and Galactic DM profile are important
- Powerful limits from galaxy group catalogs

FC+ JCAP'18

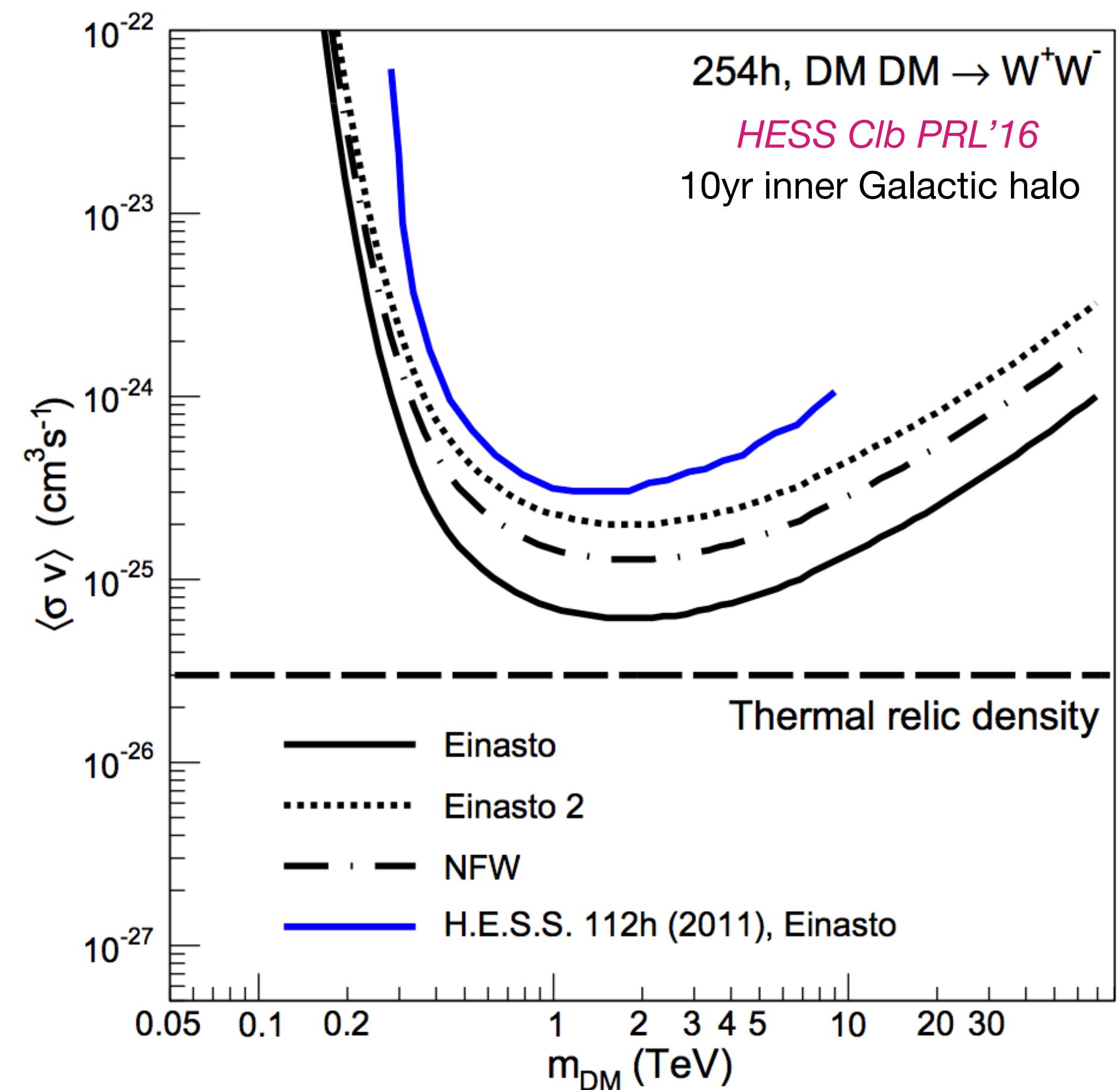
Benito, FC+ JCAP'16; Keeley+ PRD'18

Lisanti+ PRD'18, PRL'18

Future

- Fermi-LAT** limits improvement depends on target (syst., bkg or signal limited)
- Future **radio telescopes**: great improvement in sensitivities [e.g. *Storm+ApJ'17*]

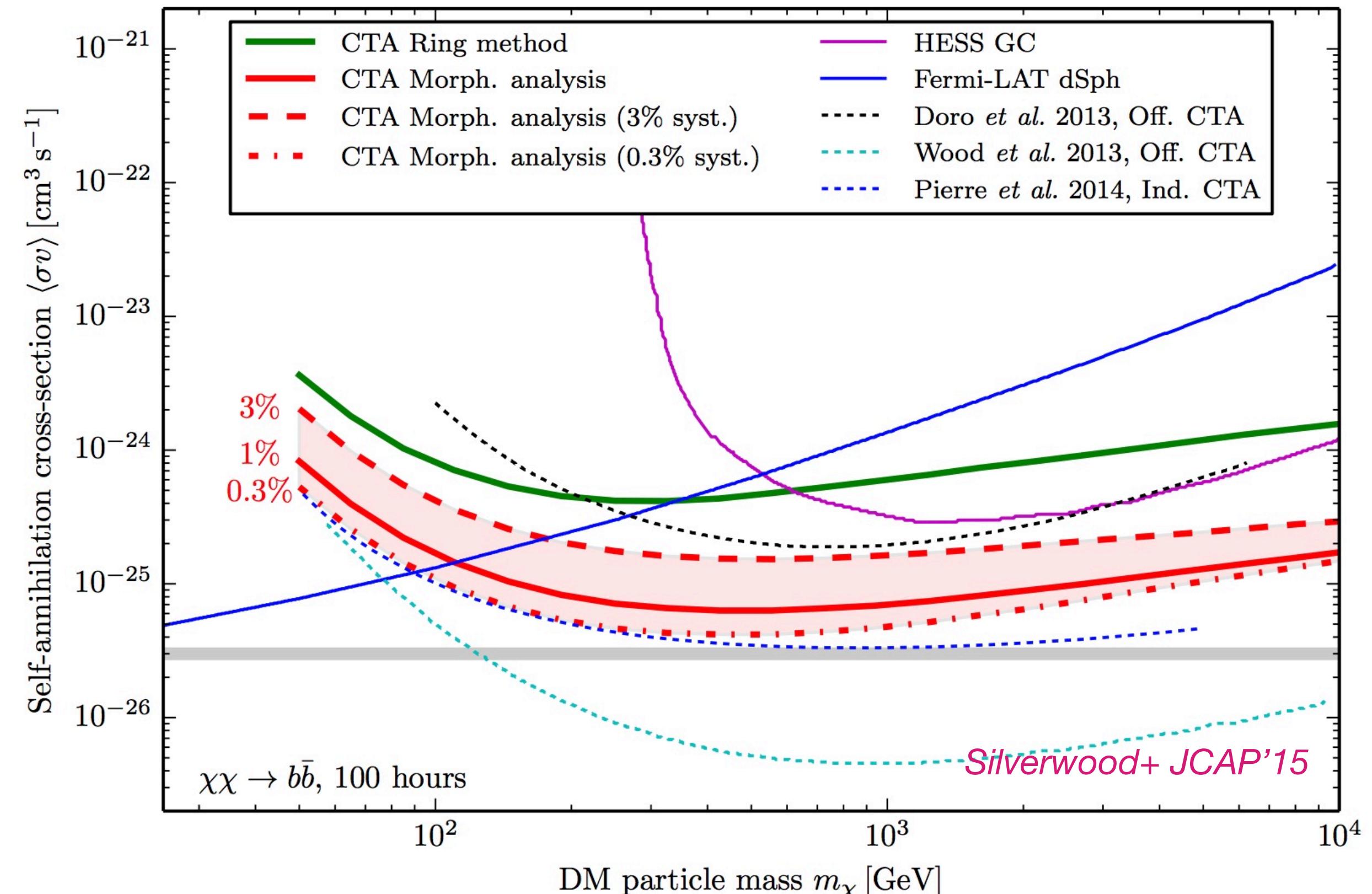
Very high-energy photons



Status

- Most constraining analysis at $E > 1 \text{ TeV}$
- Other relevant targets: combined dSphs
- TeV scale thermal dark matter starts to be challenged

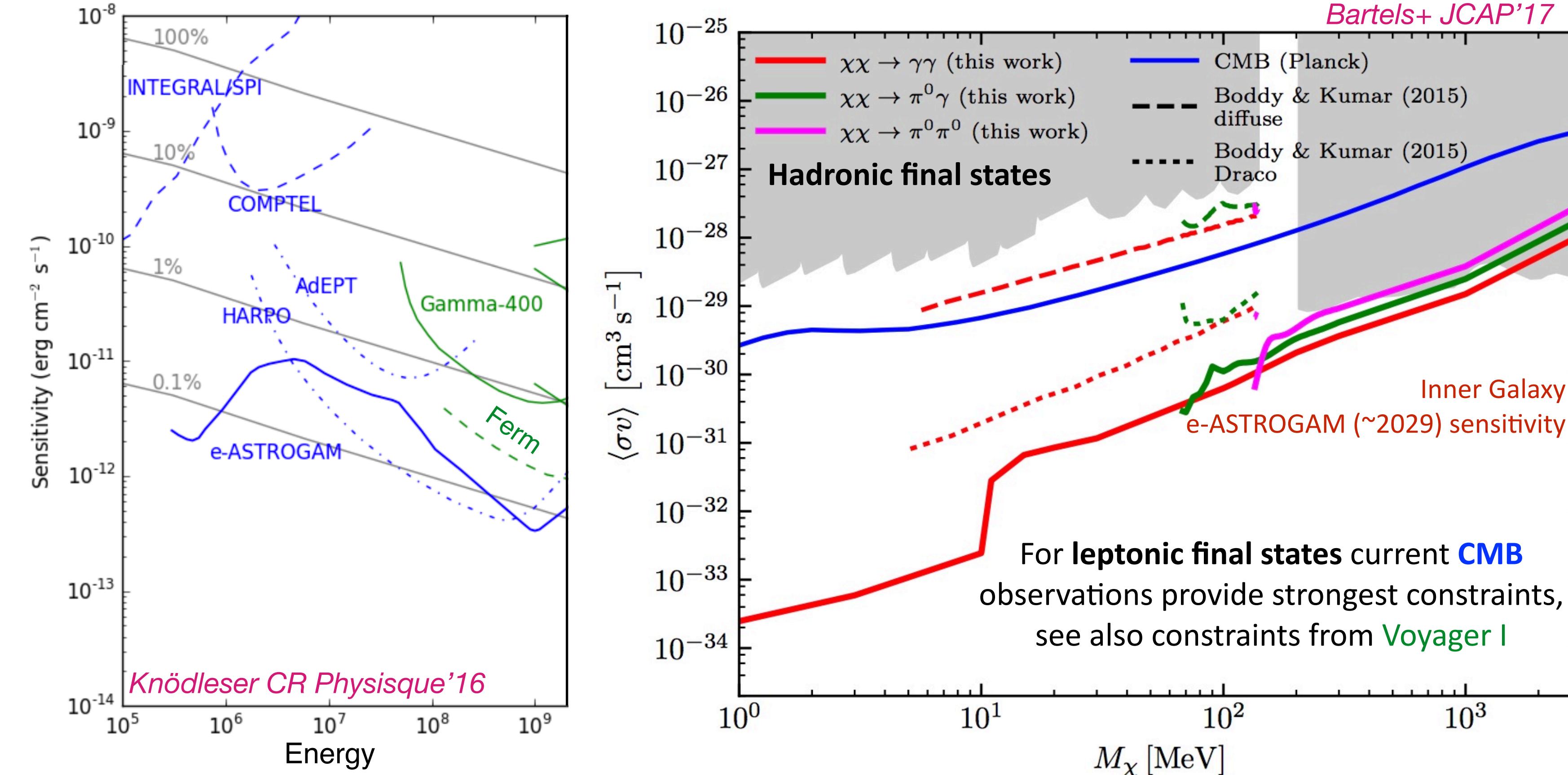
Baumgart+ 1808.08956;
Rinchiuso+ PRD'18



Future

- HAWC** is already improving limits from dSphs ($> 1 \text{ TeV}$) and Galactic centre ($> 100 \text{ TeV}$)
Albert+ ApJ'18; Abeysekara+ JCAP'18
- CTA** (~ 2022) will improve HESS limits by factor up to 10
Silverwood+ JCAP'15; Carr+ 2015; Lefranc+PRD'15

The sub-GeV sensitivity gap



- Great potential in the unexplored MeV/sub-GeV range with new, high energy resolution instruments (e.g. **Amego**; **e-ASTROGAM**)
- Spectral features play an important role at sub-GeV energies
- Greatly improved DM limits prospects and discovery potential

Boddy&Kumar PRD'15

Bringmann+PRD'17; Bartels+JCAP'17; Gonzalez-Morales+ PRD'17; De Angelis+'17

**Beyond limits...
... Hints for dark matter signals?**

The Galactic center GeV excess

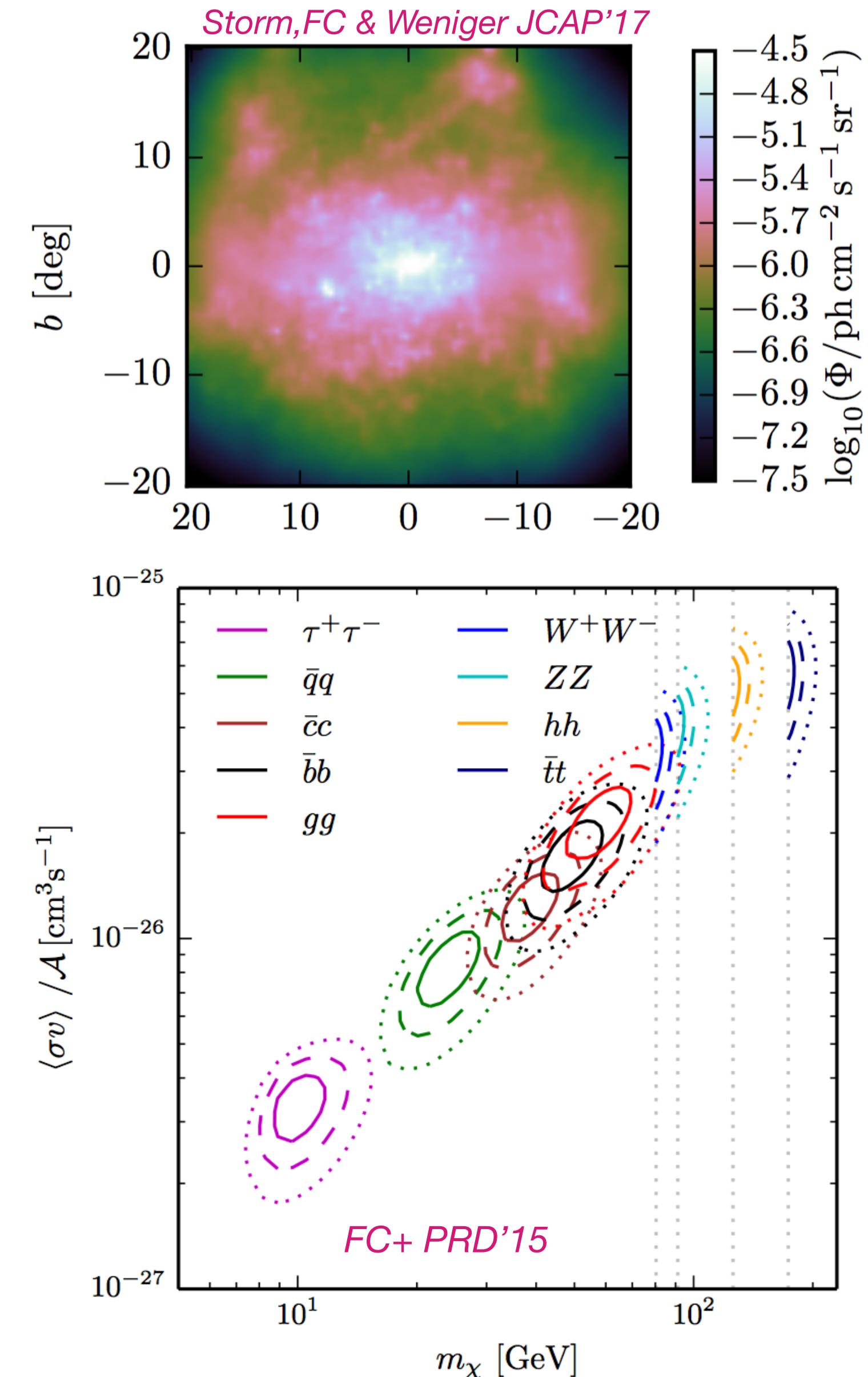
Signal:

- Well-established excess of Fermi-LAT GeV photons from the inner Galaxy^{**}
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~ 10 degrees (~ 1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

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

^{**}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; FC+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Leane & Slatyer'19; Di Mauro PRD'20*



Evidence for the stellar bulge GeV emission

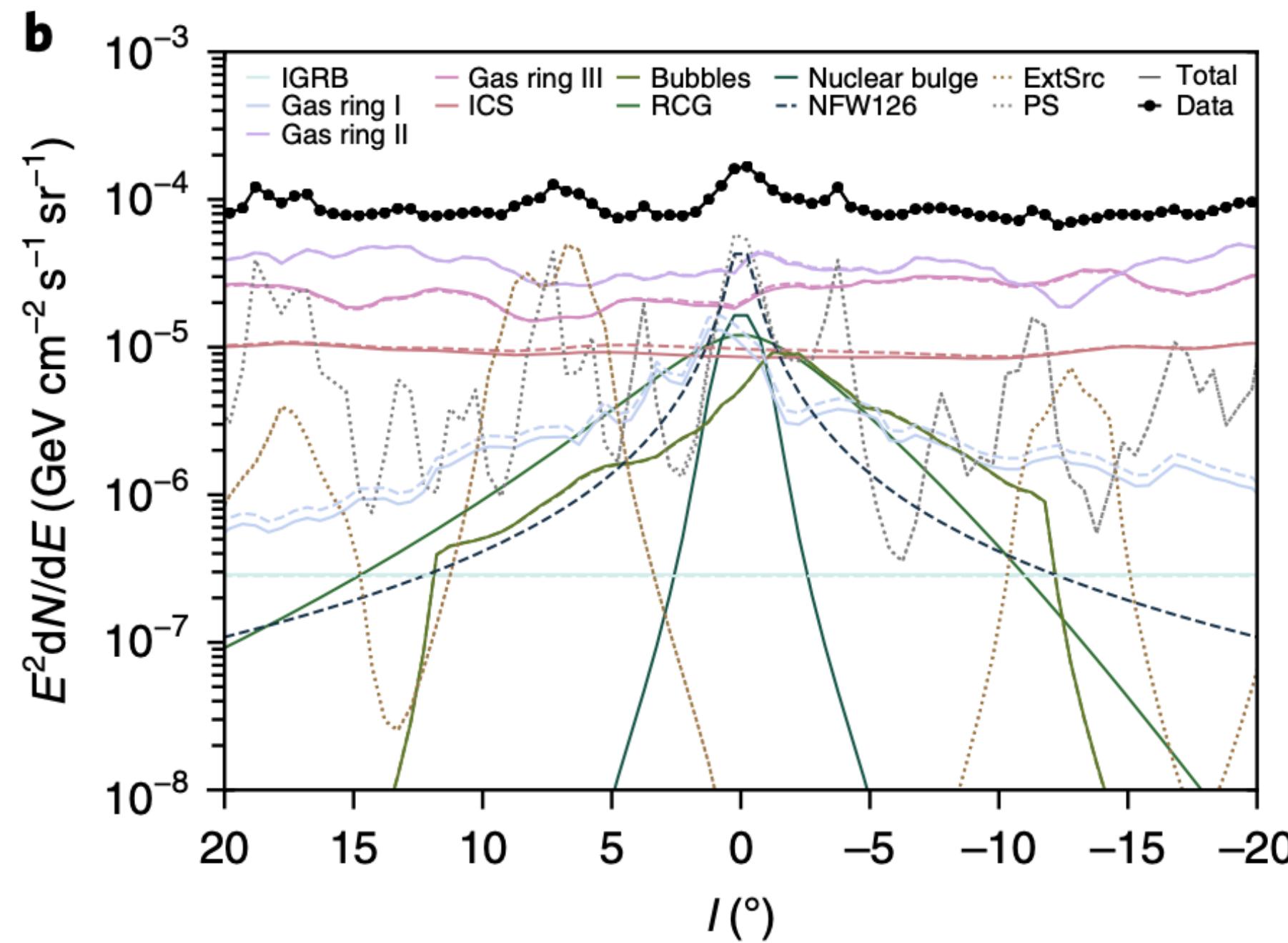
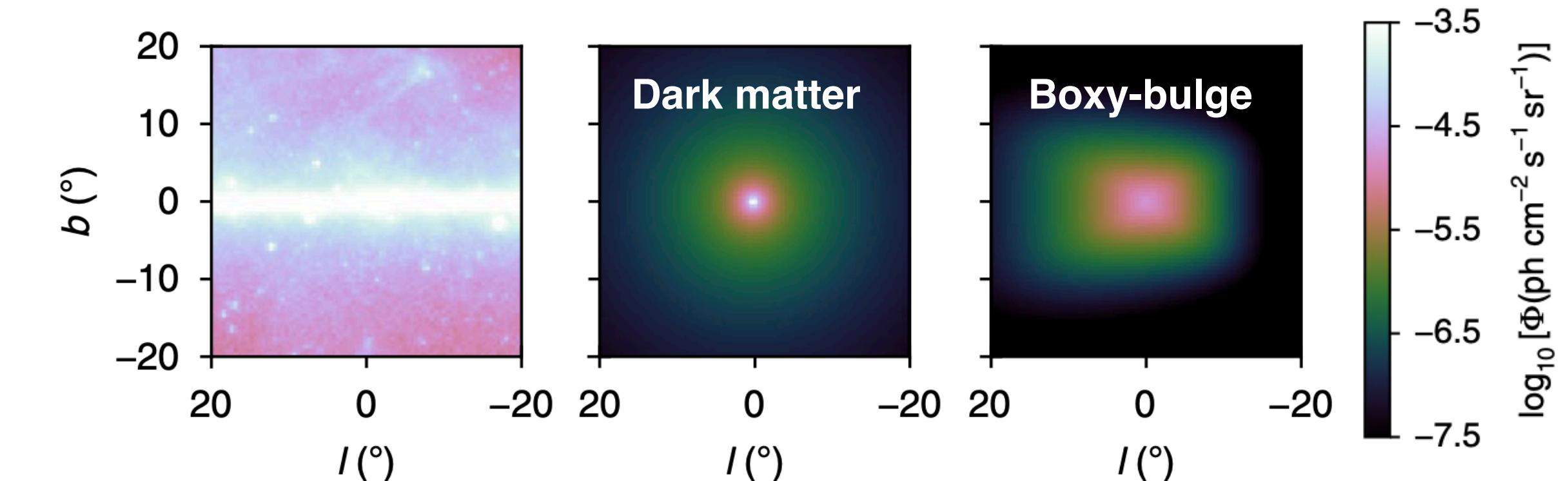
nature
astronomy

ARTICLES

<https://doi.org/10.1038/s41550-018-0531-z>

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels^{1*}, Emma Storm¹, Christoph Weniger¹ and Francesca Calore²

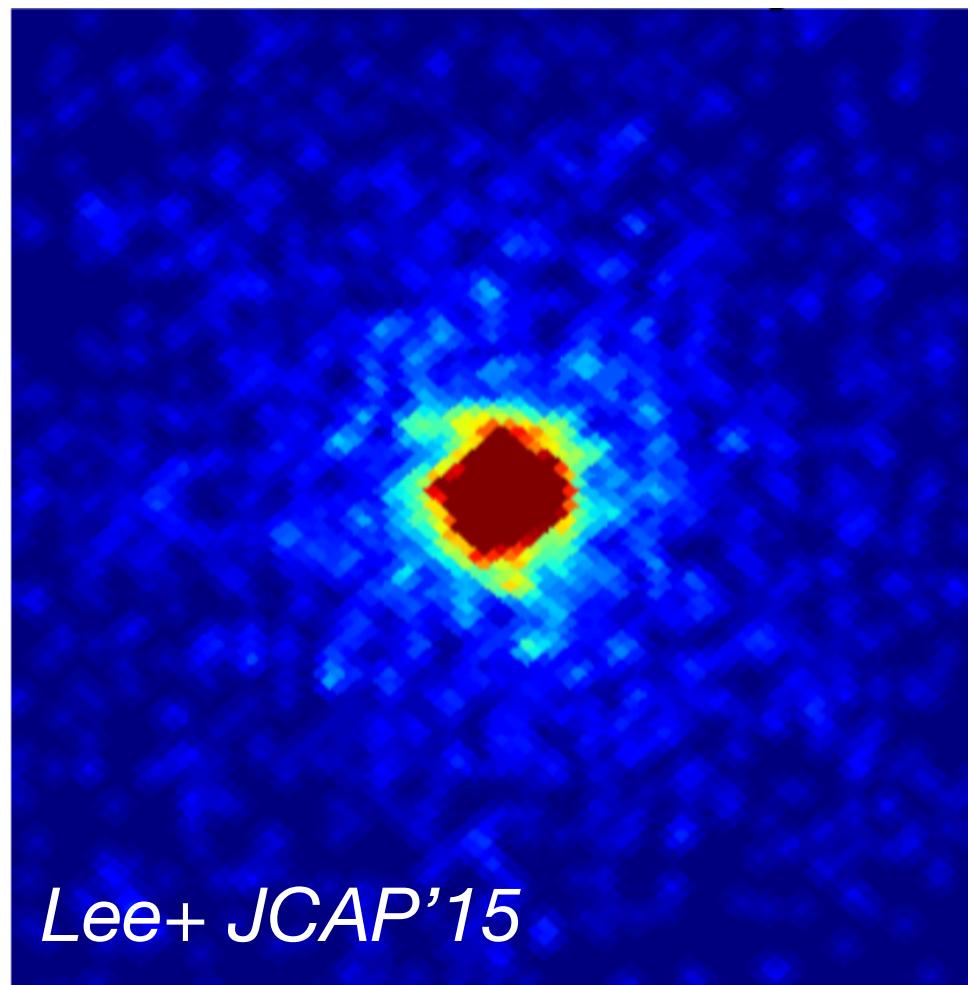


- ✓ **Stellar bulge model: Boxy bulge as traced by red-clump giants + nuclear bulge**
Cao+ MNRAS'13; Launhardt+ A&A'02
- ✓ Strong evidence for additional **stellar bulge model** (16σ); no evidence for additional **DM model** ($< 3\sigma$)
- ✓ Discriminating feature: Asymmetry at ~ 10 deg longitude => **Morphology** of the GCE **more oblate** than what found before

Macias+ Nature Astronomy'18; Macias+ JCAP'19

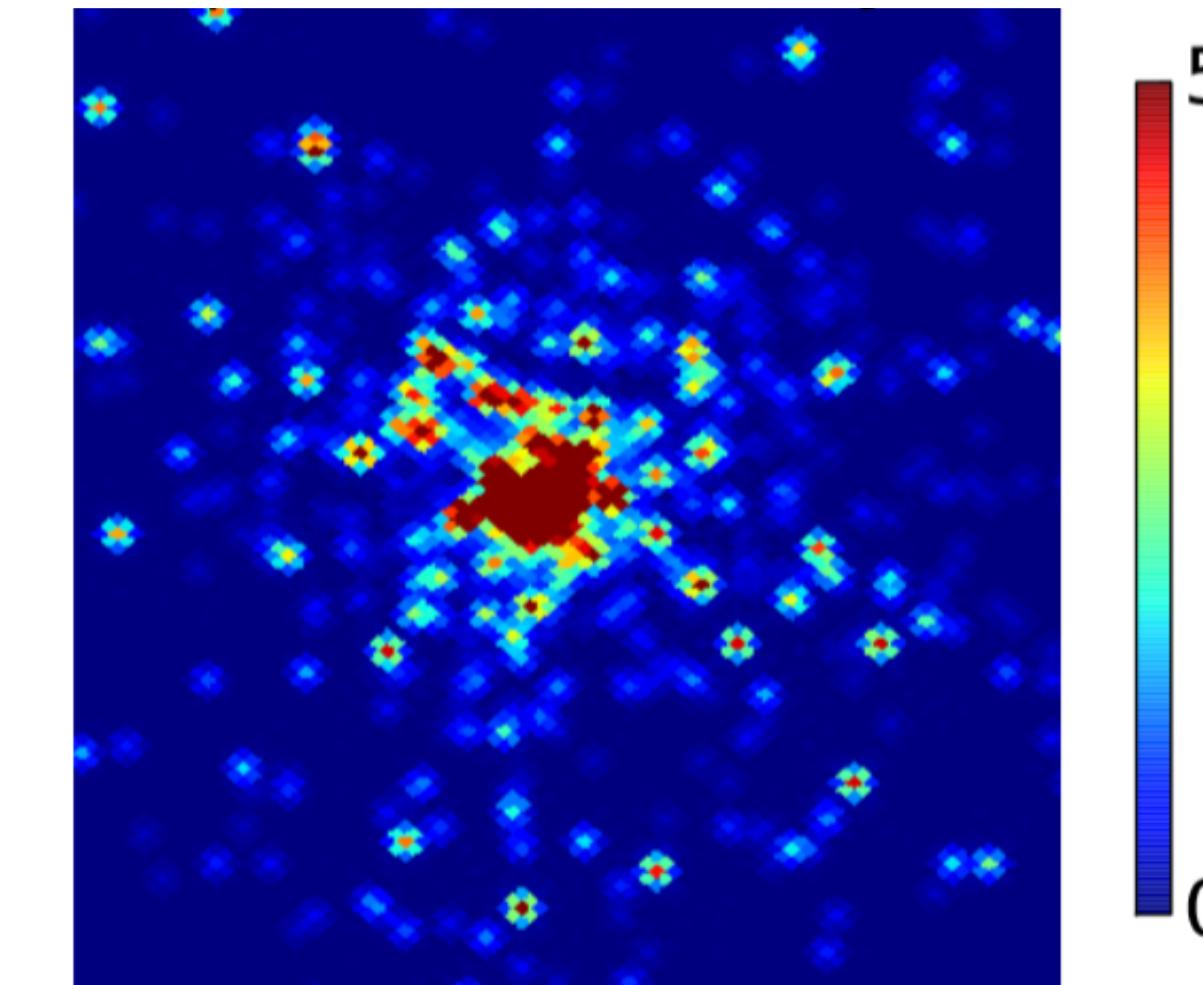
The GeV excess nature

Truly diffuse emission



dark matter,
enhanced star-formation, leptonic bursts

Unresolved point sources



millisecond or young pulsars

Difference in the statistics of the photon counts

Bartels+ PRL'16, Lee+ PRL'16; Zhong+PRL'19; Leane&Slatyer PRL'20, PRD'20; Chang+ PRD'20, Buschmann+PRD'20

Correlations with stellar tracers

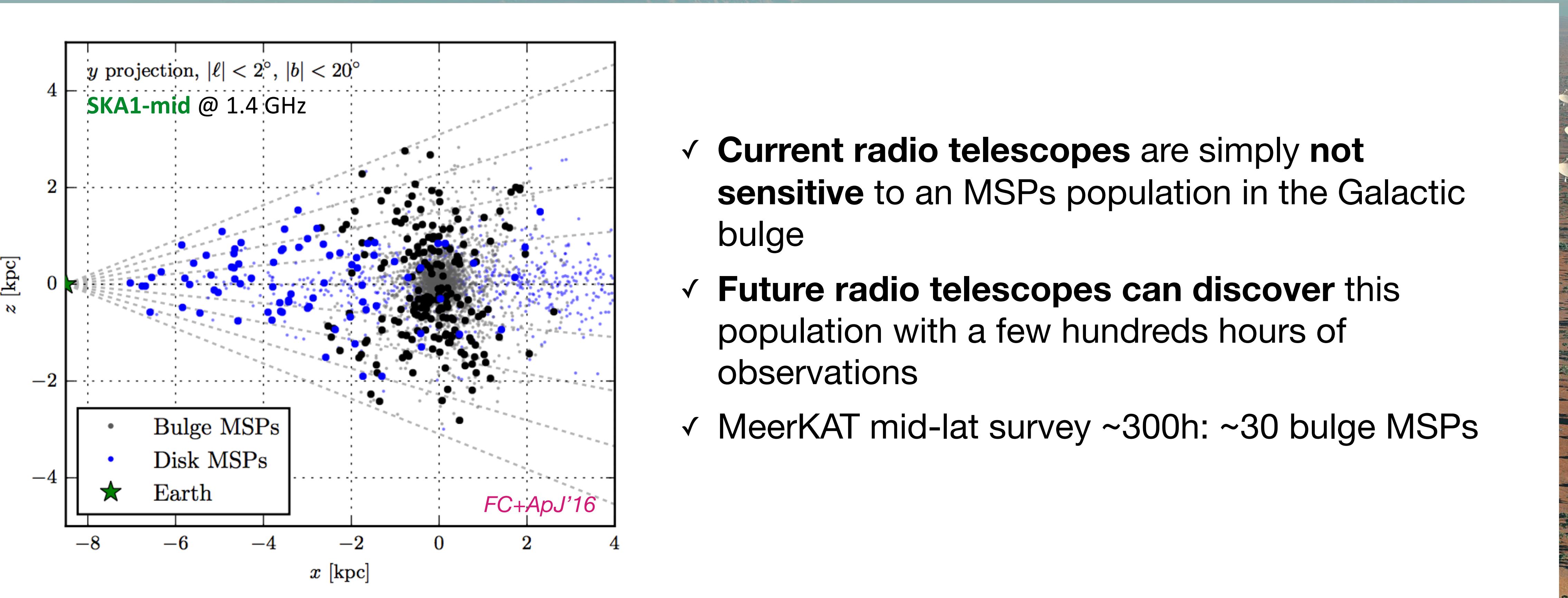
Macias+ Nat. Astron. '18, Bartels, FC+ Nat. Astron. '18

Multi-messenger signals (radio surveys, GW stochastic bkg)

FC+ApJ'16; FC+PRL'19

Multi-messenger tests of the GeV excess

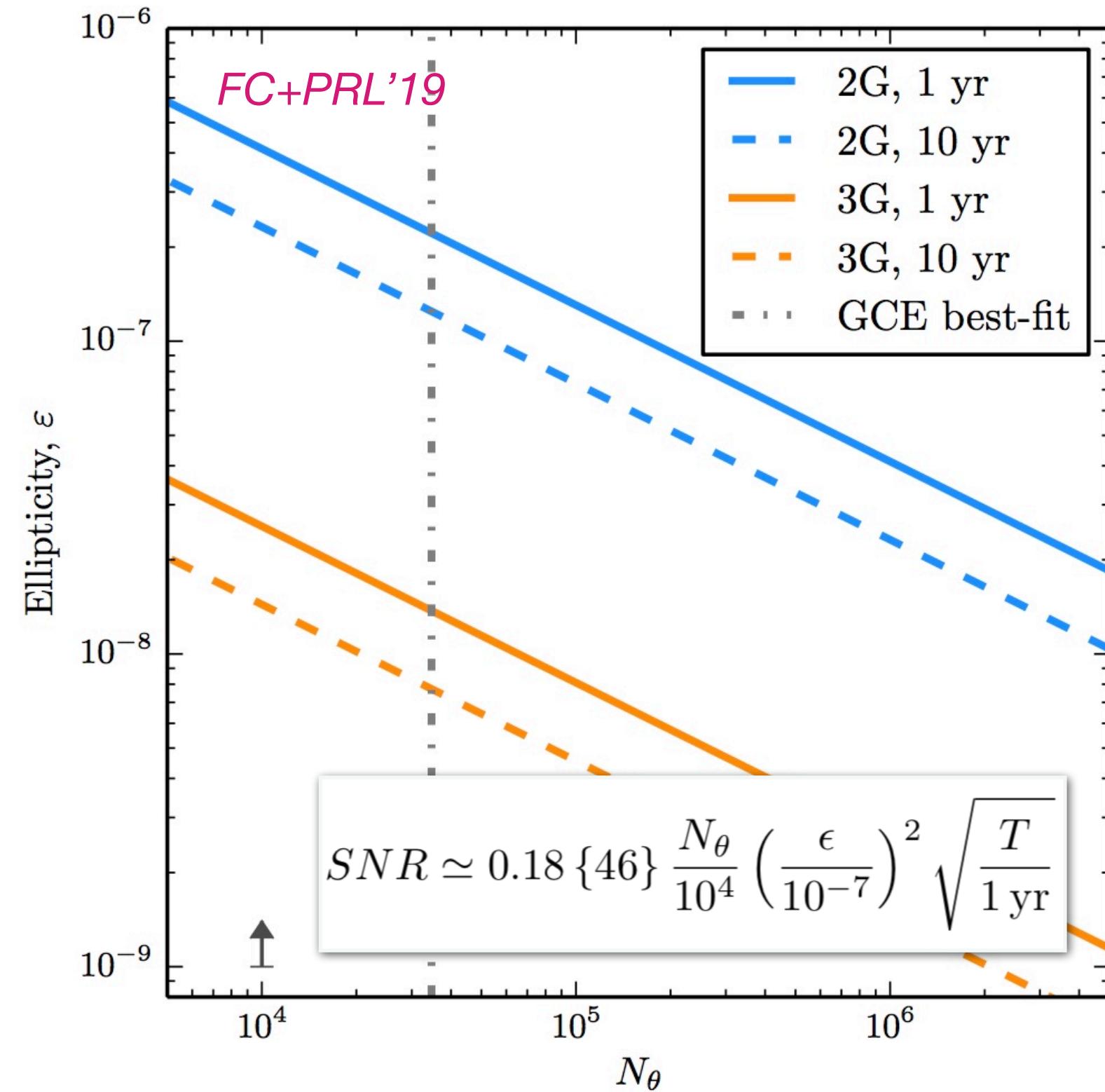
Testing a faint population of millisecond pulsars in the Galactic bulge



- ✓ **Current radio telescopes** are simply **not sensitive** to an MSPs population in the Galactic bulge
- ✓ **Future radio telescopes can discover** this population with a few hundreds hours of observations
- ✓ MeerKAT mid-lat survey ~300h: ~30 bulge MSPs

Multi-messenger tests of the GeV excess

Testing a faint population of millisecond pulsars in the Galactic bulge



- ✓ Neutron stars high rotation velocities make any irregularity (ellipticity) in their shape a **quadrupolar source of GWs**
- ✓ A **population of MSPs in the bulge** represents the **dominant contribution to the stochastic GW background** in the LIGO/Virgo sensitivity range
- ✓ This search can provide **crucial diagnostics for the GeV excess nature**

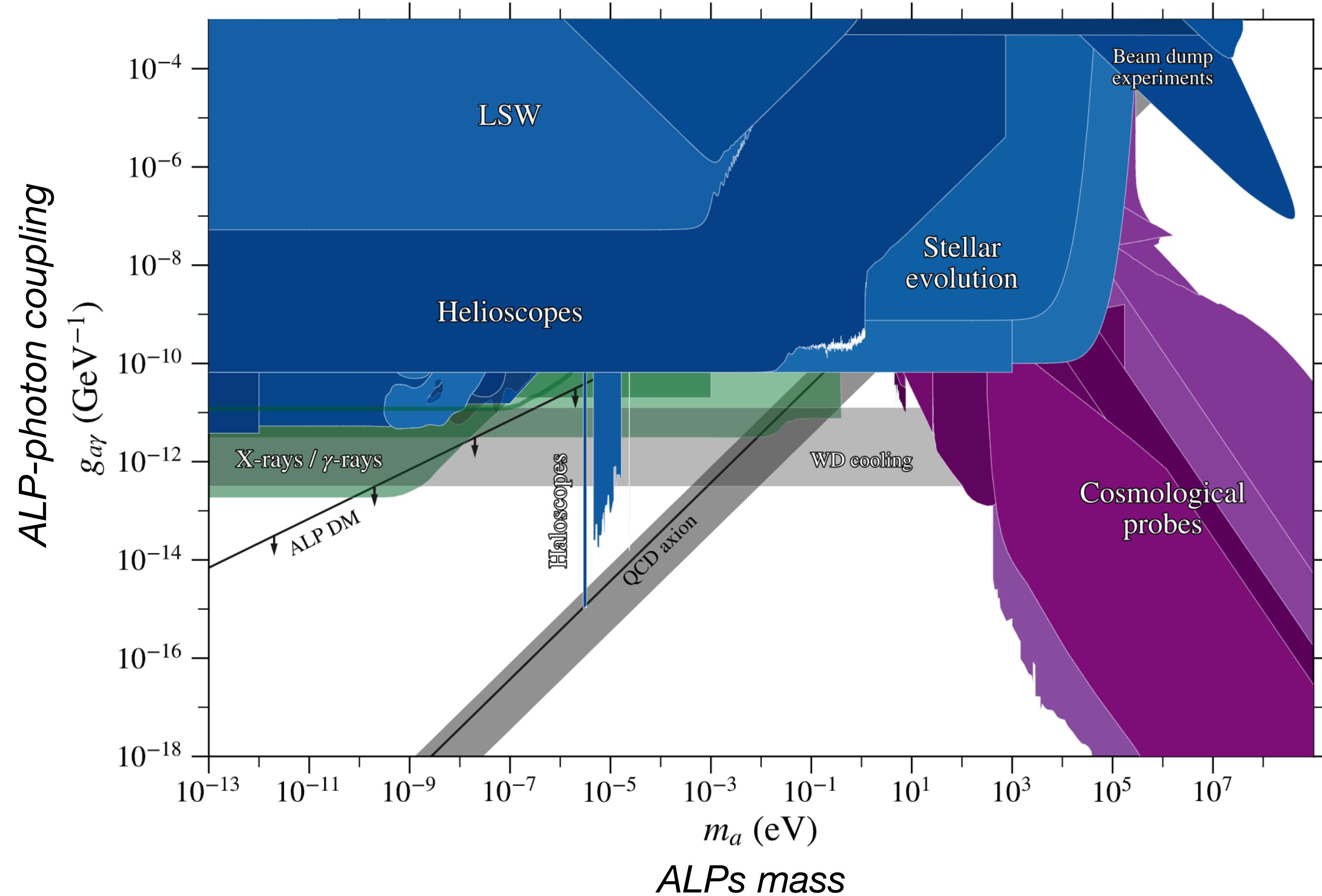
Constraining on axion-like particles with high-energy astrophysics

Axion & Axion-like particles

- Axion as pseudo-Nambu Goldstone boson predicted by the Peccei-Quinn mechanism
Peccei Journal of Korean Physical Society 1996
- ALPs as generalization of the QCD axion
 - Very light pseudo-scalar bosons predicted by multiple extensions of the Standard Model
Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10
 - The mass and the coupling constant of ALPs are completely independent parameters
 - They represent weakly interacting slim (ultralight) particles (**WISPs**)
 - They can be cold dark matter candidates for certain values of mass and coupling*Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10*

The ALP-photon coupling landscape

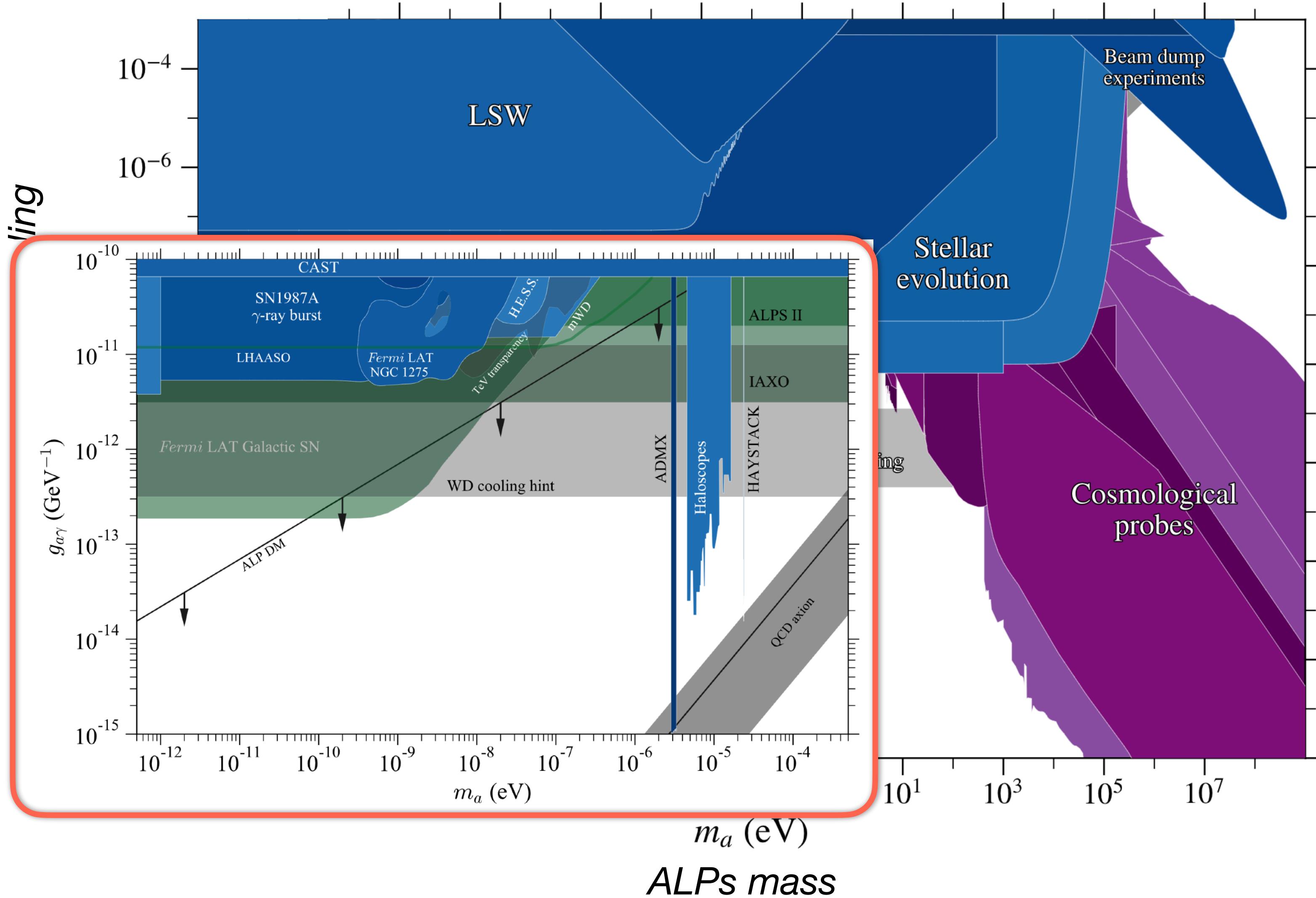
$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma}\mathbf{E} \cdot \mathbf{B}a$$



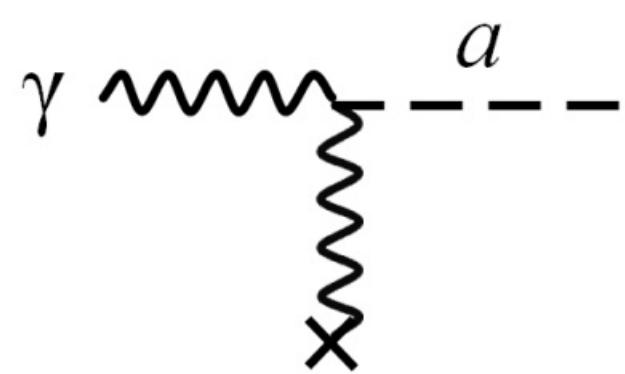
Credit: M. Meyer @ <https://github.com/me-manu/gammaALPsPlot/>

The ALP-photon coupling landscape

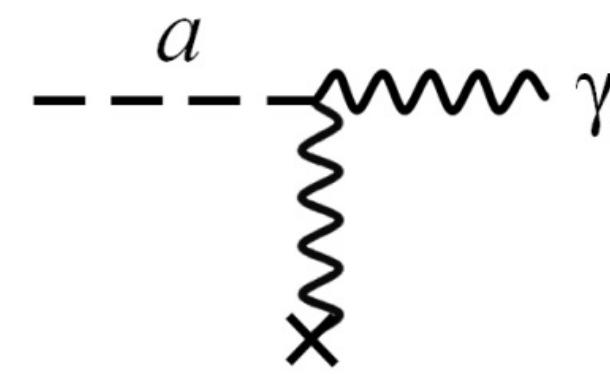
$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a = g_{a\gamma}\mathbf{E} \cdot \mathbf{B}a$$



Credit: M. Meyer @ <https://github.com/me-manu/gammaALPsPlot/>



The ALP-photon mixing



Considering the propagation of photons in a **single magnetic domain d** with a **coherent B-field**, the propagation equations reduce to a 2-dimensional problem:

$$\begin{aligned} P_{\gamma \rightarrow a}^{(0)} &= \sin^2 2\theta \sin^2 \left(\frac{\Delta_{\text{osc}} d}{2} \right) \\ &= (\Delta_{a\gamma} d)^2 \frac{\sin^2(\Delta_{\text{osc}} d/2)}{(\Delta_{\text{osc}} d/2)^2} \end{aligned}$$

Probability for purely polarised photon beam ($A_{||}$) to oscillate into an ALP after distance d

$$\Delta_{\text{osc}} \equiv [(\Delta_a - \Delta_{\text{pl}})^2 + 4\Delta_{a\gamma}^2]^{1/2}$$

Oscillation wave number

$$E_c \equiv \frac{E|\Delta_a - \Delta_{\text{pl}}|}{2\Delta_{a\gamma}}$$

Critical energy

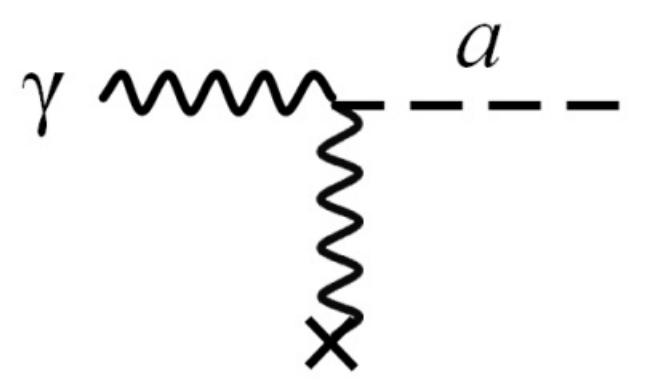
$$\Delta_{\text{osc}} = 2\Delta_{a\gamma} \sqrt{1 + \left(\frac{E_c}{E} \right)^2}$$

$E \gg E_c$ $E \simeq E_c$

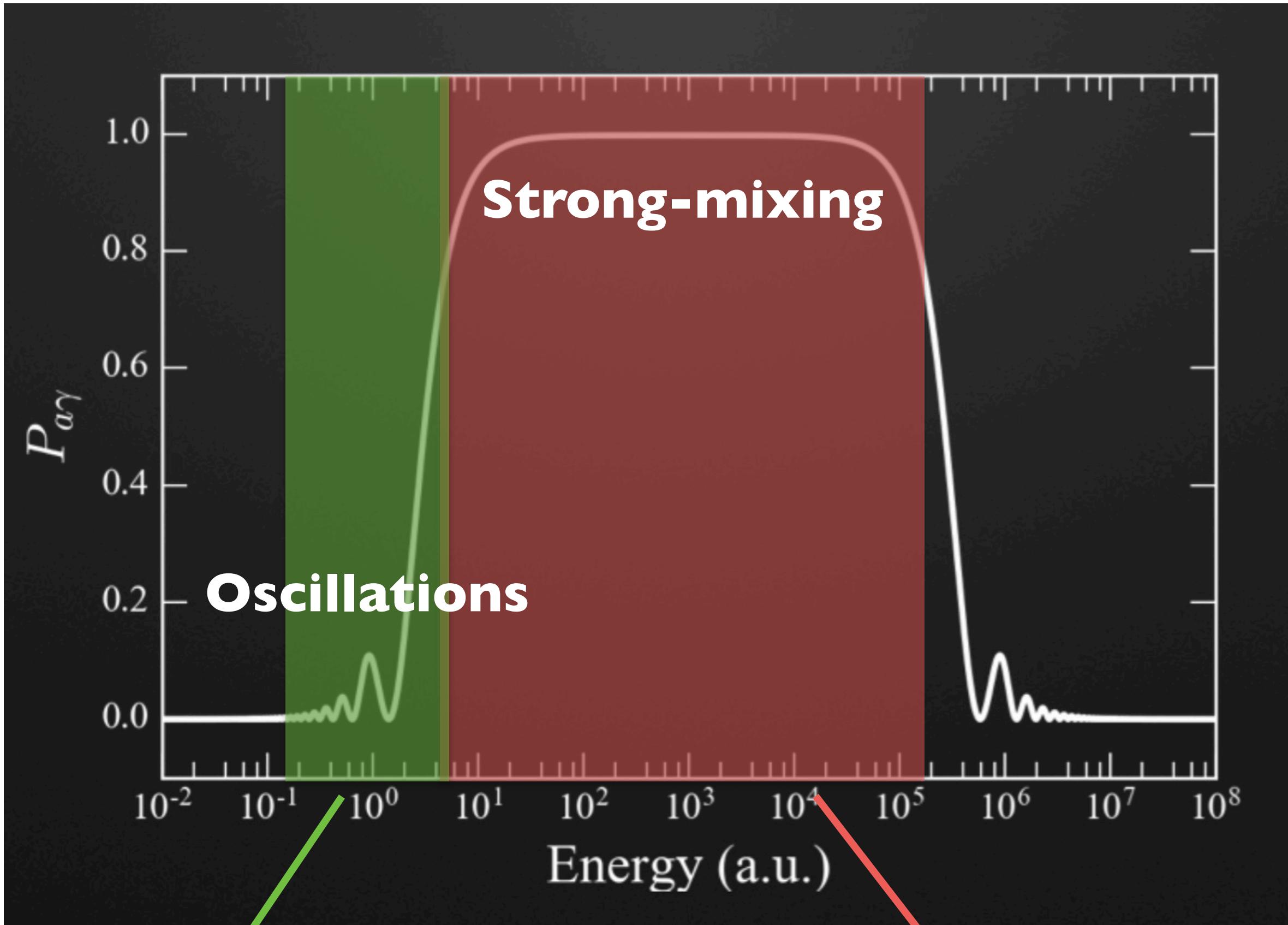
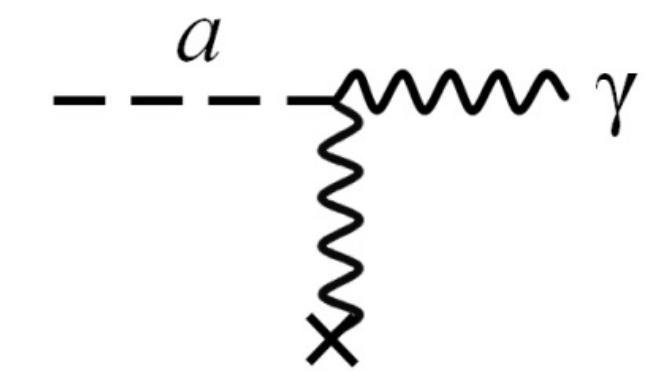
$\Delta_{\text{osc}} \simeq 2\Delta_{a\gamma}$
Strong mixing regime

Oscillation regime

e.g. Mirizzi & Montanino JCAP'09



The ALP-photon mixing



I. Spectral irregularities at $\sim E_c$

II. ALPs do not get absorbed,
enhancing the photon flux

Searches for spectral irregularities

$$E_\gamma \simeq E_c$$
$$E_c \simeq 2.5 \text{ GeV} \frac{|m_a^2 - \omega_{Pl}^2|}{1 \text{ neV}} \left(\frac{B_\perp}{\mu\text{G}} \right)^{-1} \left(\frac{g_{a\gamma\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^{-1}$$

The diagram illustrates the components of the equation. A green arrow points from the term $|m_a^2 - \omega_{Pl}^2| / 1 \text{ neV}$ to a box labeled "ALPs parameters" containing m_a and $g_{a\gamma\gamma}$. A red arrow points from the term $(B_\perp / \mu\text{G})^{-1}$ to a box labeled "Astrophysical environment" containing $\omega_{Pl} = 0.03 \text{ neV} \sqrt{n_e/\text{cm}^{-3}}$ and B_T .

ALPs parameters

 m_a $g_{a\gamma\gamma}$

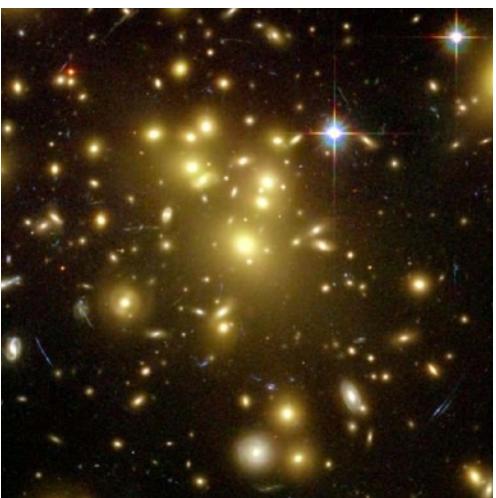
Astrophysical environment

 $\omega_{Pl} = 0.03 \text{ neV} \sqrt{n_e/\text{cm}^{-3}}$ B_T

Searches for spectral irregularities

$$E_\gamma \simeq E_c$$

$$E_c \simeq 2.5 \text{ GeV} \frac{|m_a^2 - \omega_{Pl}^2|}{1 \text{ neV}} \left(\frac{B_\perp}{\mu\text{G}} \right)^{-1} \left(\frac{g_{a\gamma\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^{-1}$$



Galaxy cluster

$$n_e \sim 0.01 \text{ cm}^{-3}$$

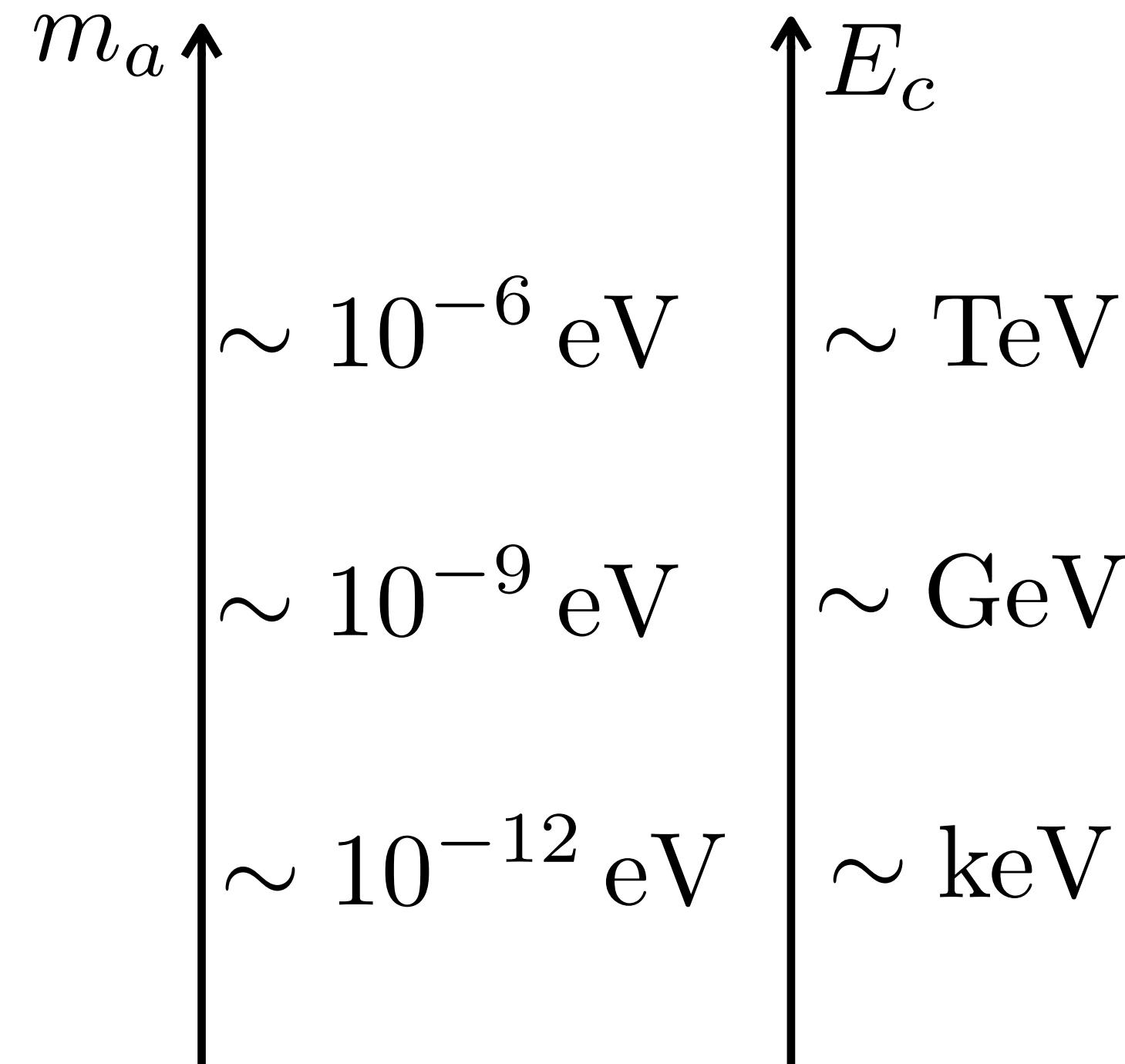
$$B_0 \sim 1 - 10 \mu\text{G}$$



Milky Way

$$n_e \sim 0.1 \text{ cm}^{-3}$$

$$B \sim 1 \mu\text{G}$$

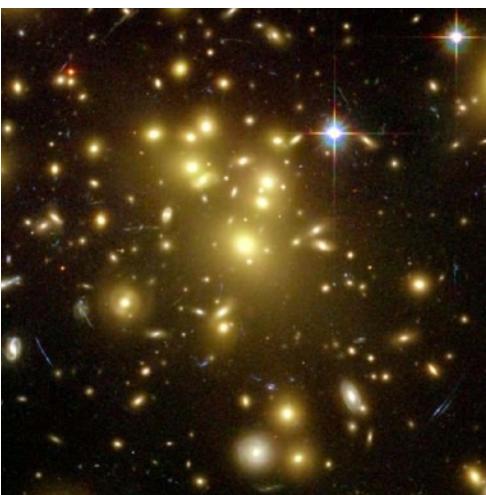


Wouters & Brun ApJ'13; Conlon+ JCAP'17

Searches for spectral irregularities

$$E_\gamma \simeq E_c$$

$$E_c \simeq 2.5 \text{ GeV} \frac{|m_a^2 - \omega_{Pl}^2|}{1 \text{ neV}} \left(\frac{B_\perp}{\mu\text{G}} \right)^{-1} \left(\frac{g_{a\gamma\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^{-1}$$



Galaxy cluster

$$n_e \sim 0.01 \text{ cm}^{-3}$$

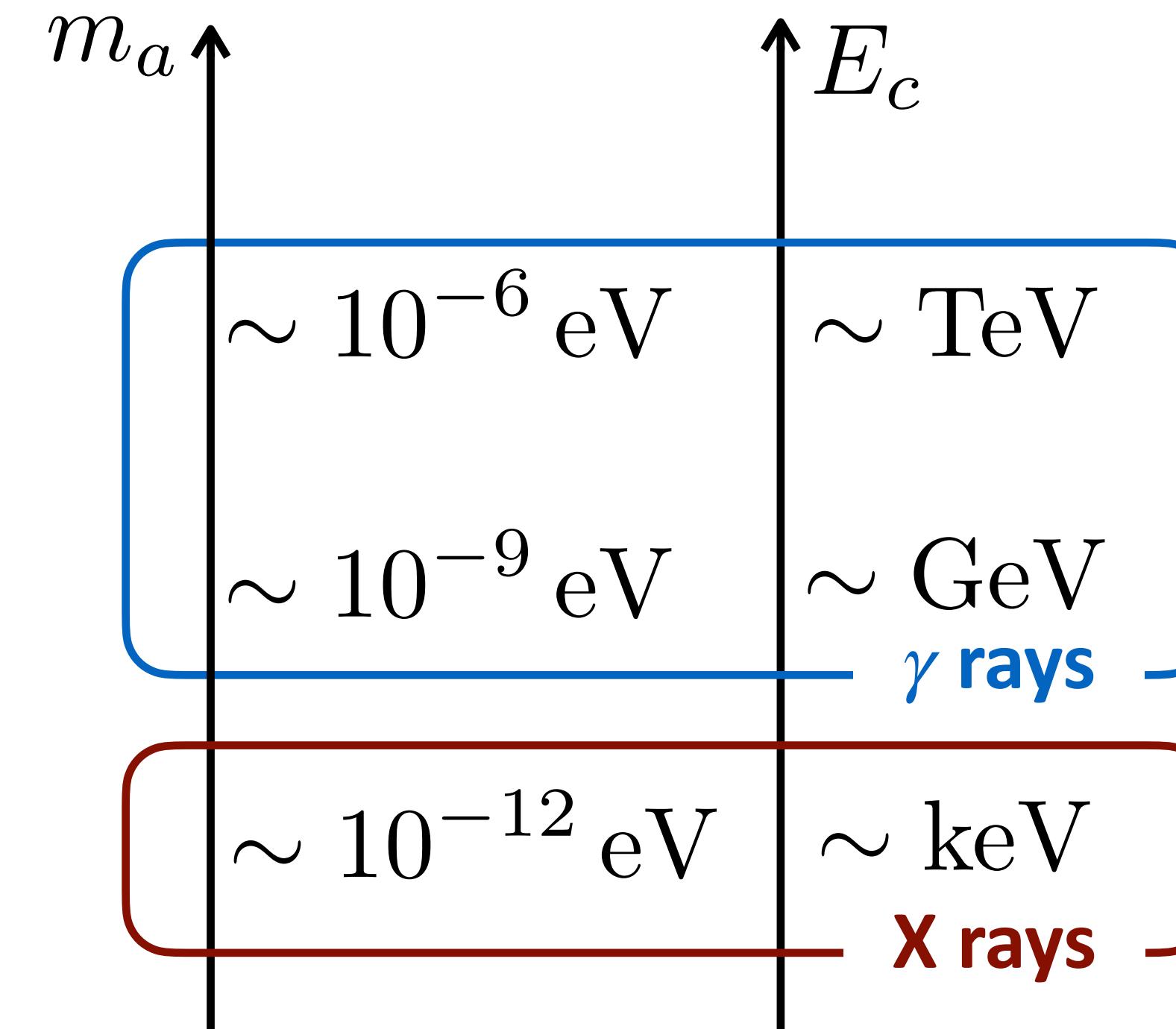
$$B_0 \sim 1 - 10 \mu\text{G}$$



Milky Way

$$n_e \sim 0.1 \text{ cm}^{-3}$$

$$B \sim 1 \mu\text{G}$$



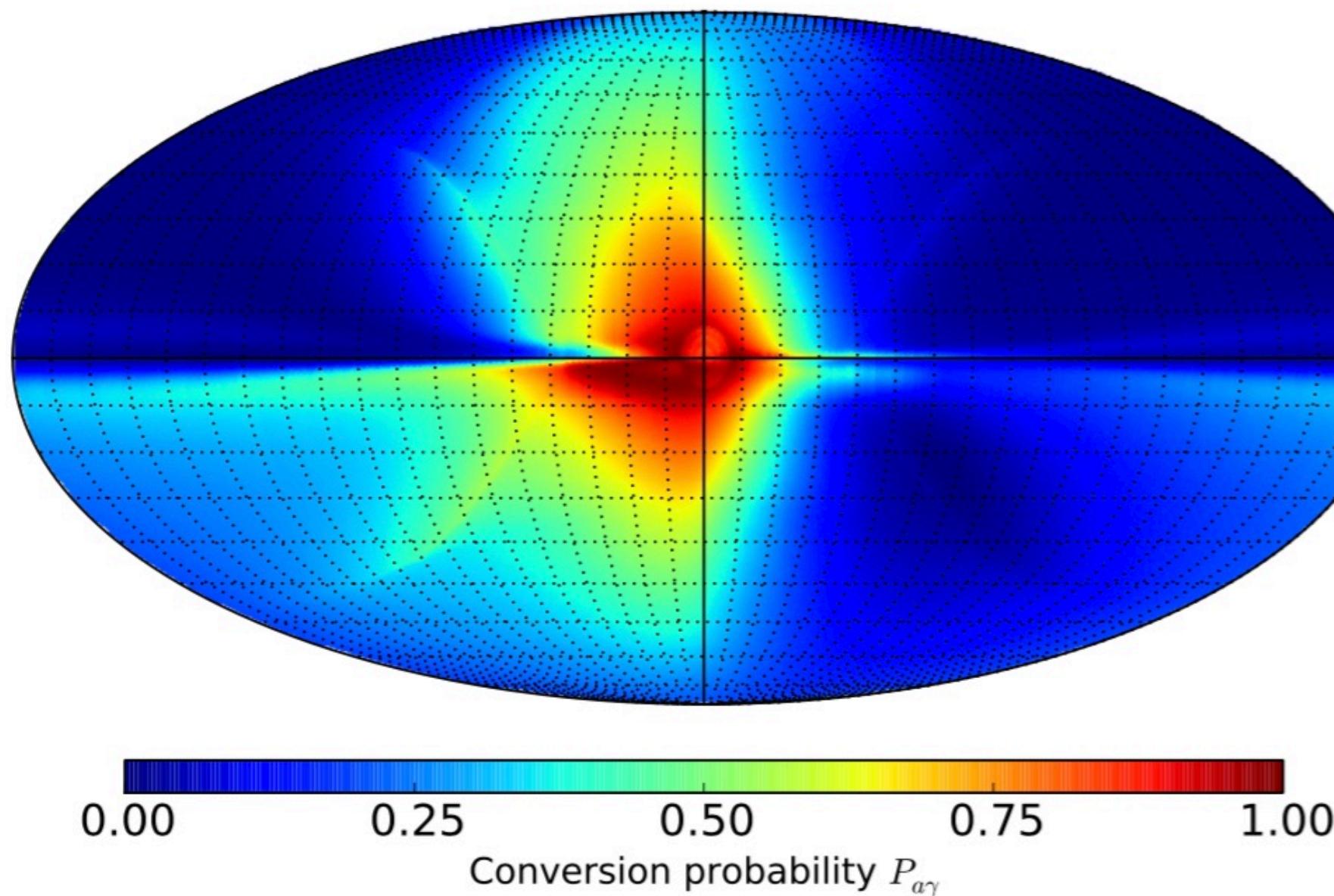
Wouters & Brun ApJ'13; Conlon+ JCAP'17

Searches for spectral irregularities

High-energy gamma rays

Some basic requirement:

- Very **bright gamma-ray sources** → High statistics for a good spectral determination
- Sources far enough and in the **direction of strong transversal B-fields**, e.g. behind or within a galaxy cluster
- Good knowledge of B-field! As ALP searches are sensitive to the product $\mathbf{g}_{a\gamma} \mathbf{B}_T$, the constraint on $g_{a\gamma}$ is only as good as the knowledge of B_T .

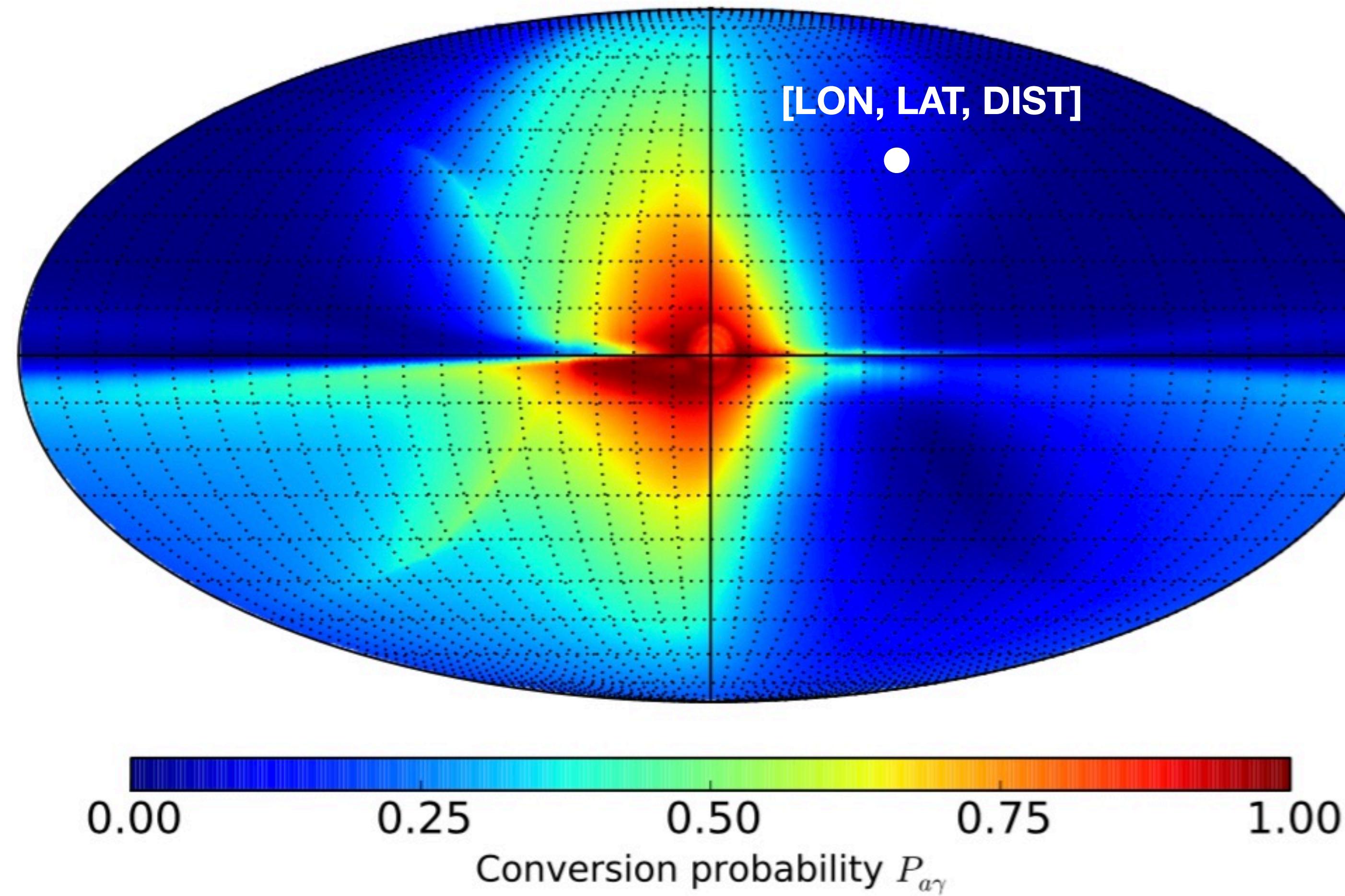


Conversion probability in
Galactic B-field

$g_{a\gamma} = 5 \times 10^{-11} \text{ GeV}^{-1}$
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

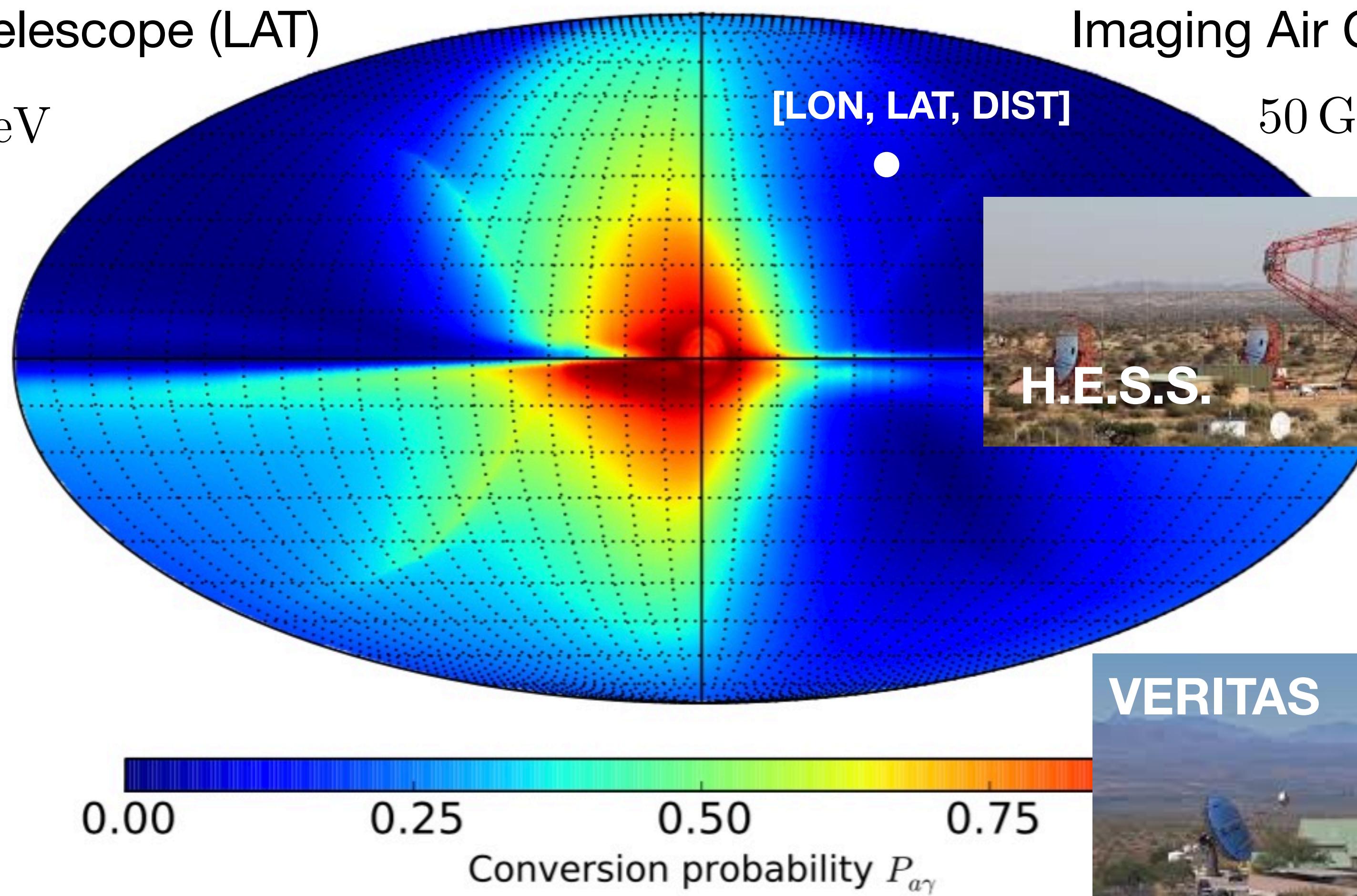


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Fermi Large Area Telescope (LAT)

$30 \text{ MeV} \lesssim E_\gamma \lesssim 1 \text{ TeV}$

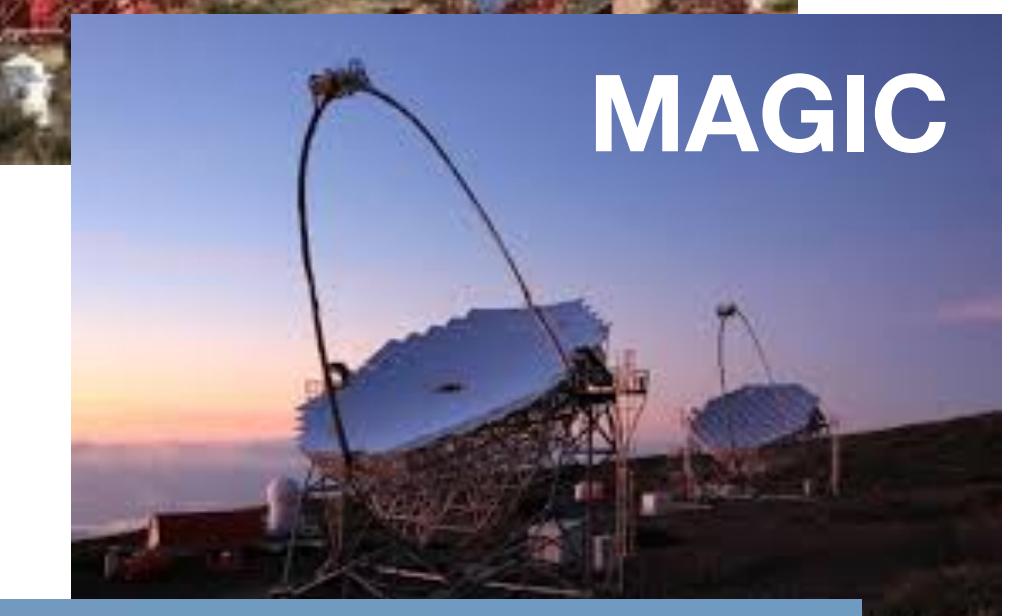


Imaging Air Cherenkov Telescopes

$50 \text{ GeV} \lesssim E_\gamma \lesssim 100 \text{ TeV}$



H.E.S.S.



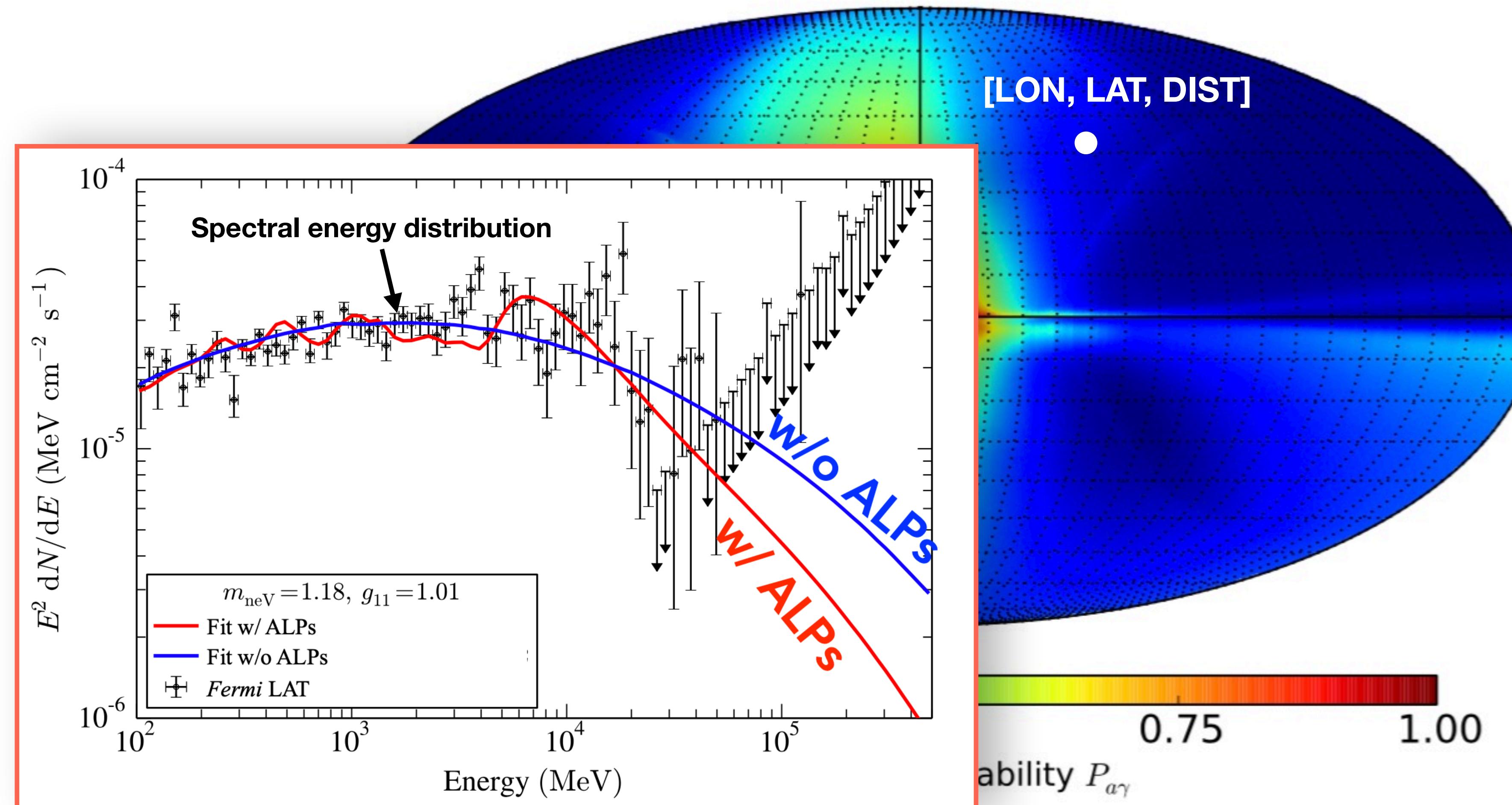
MAGIC



VERITAS

Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

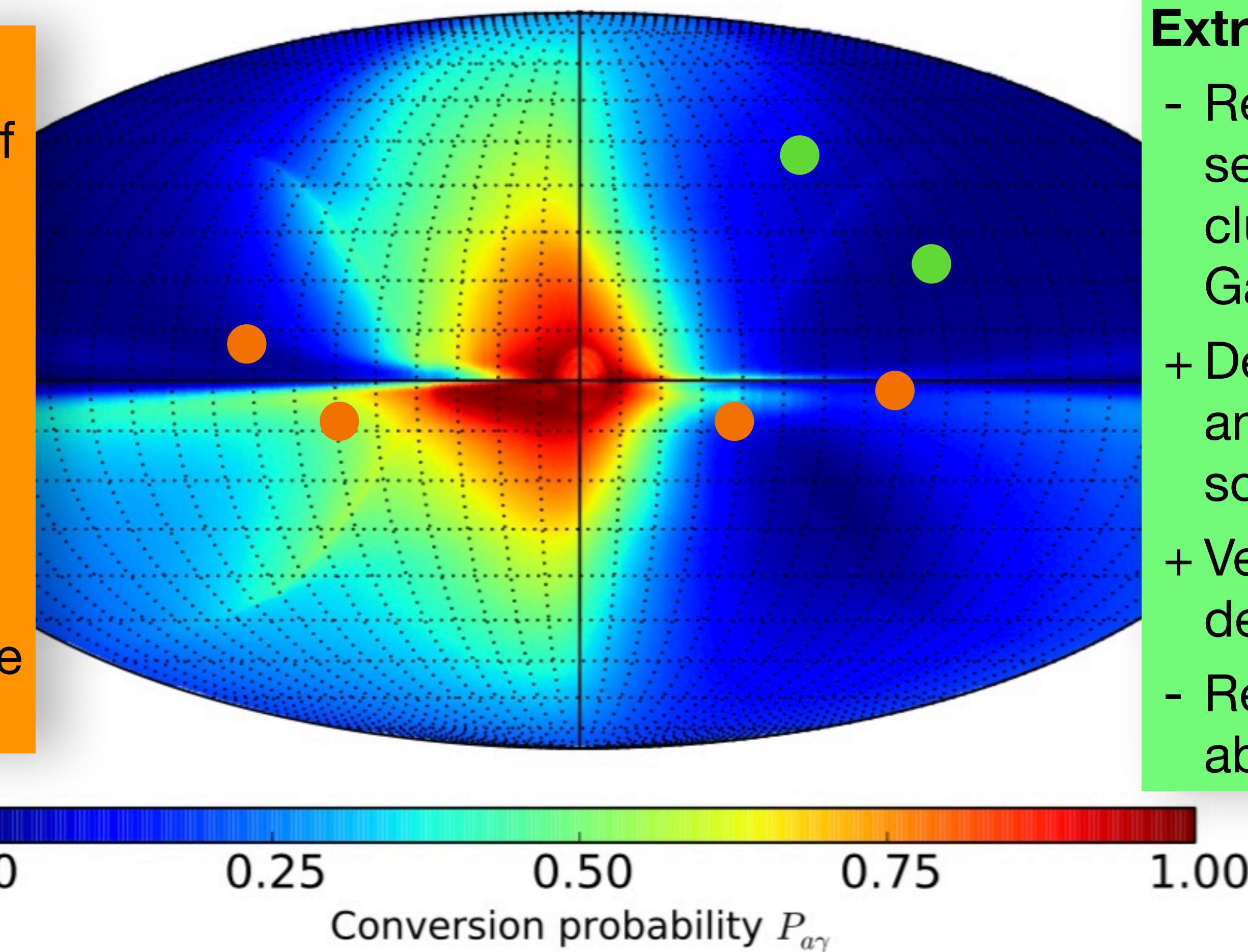


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Galactic targets:

- + Require only modelling of Galactic B field
- Strength of the conversion depends on position in the Galaxy (e.g. beyond spiral arms)
- Larger systematics on spectral determination due to gamma-ray diffuse emission foreground



Extragalactic targets:

- Require modelling of several B fields (intra-cluster, intergalactic, Galactic)
- + Depends only on latitude and longitude of the sources
- + Very accurate spectral determination
- Require modelling of EBL absorption

Signal hints for ALP-photon mixing

Search for spectral irregularities in Galactic targets

- Analysis of **6 bright pulsars** with **Fermi-LAT** *Majumdar, FC & Horns JCAP'18*

✓ **4.6 σ** significance for common ALP-photon mixing

$$m_a = (3.6_{-0.2_{\text{stat.}}}^{+0.5_{\text{stat.}}} \pm 0.2_{\text{syst.}}) \text{ neV} \quad g_{a\gamma\gamma} = (2.3_{-0.4_{\text{stat.}}}^{+0.3_{\text{stat.}}} \pm 0.4_{\text{syst.}}) \times 10^{-10} \text{ GeV}^{-1}$$

✓ 20%-40% spectral variation vs ~3% experimental systematic uncertainty

✓ Systematic theoretical uncertainties on transverse B field and distances

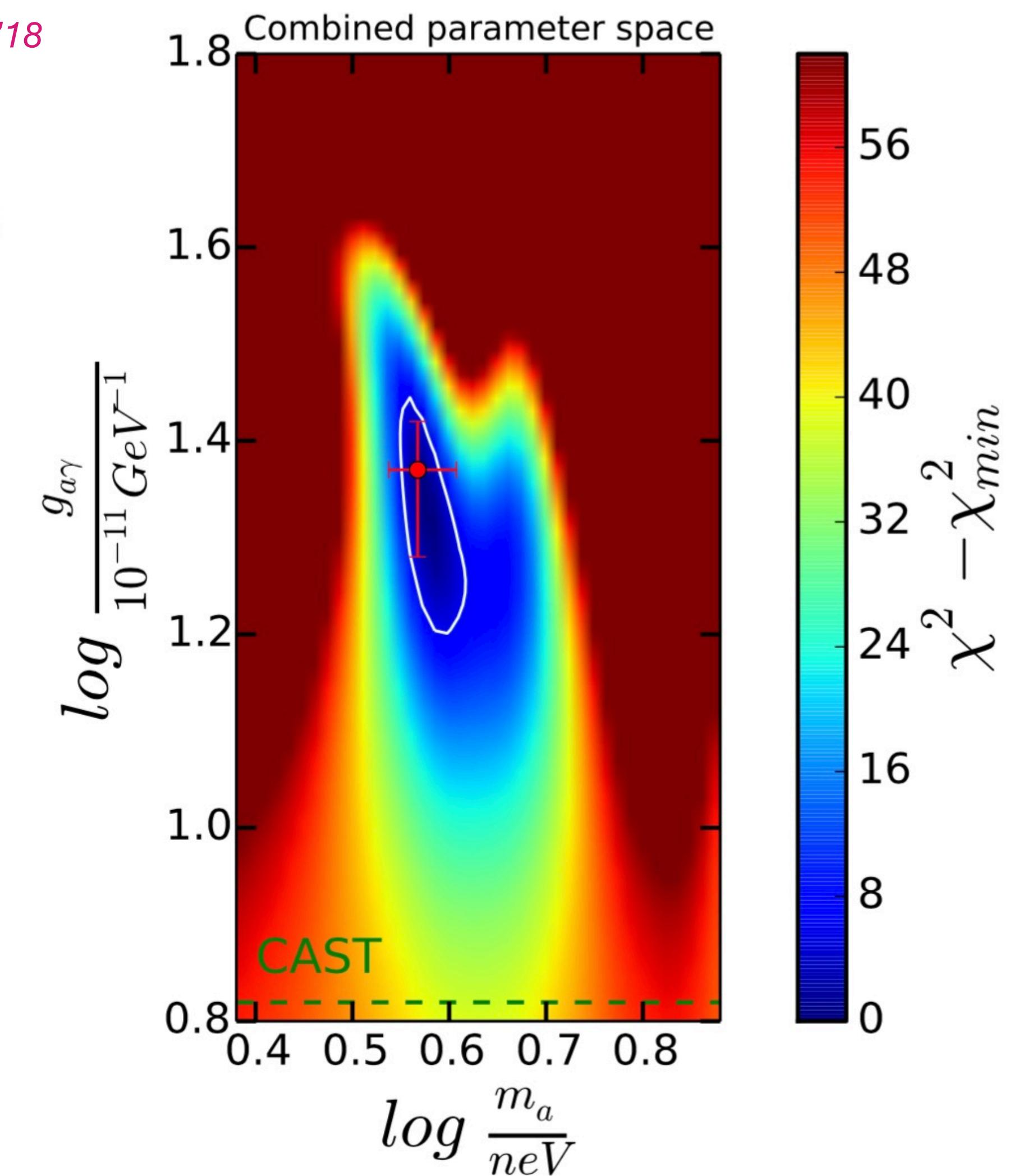
- Analysis of **3 bright SNRs** with **Fermi-LAT** and **HESS/MAGIC/VERITAS** *Xia+ PRD'19*

✓ **3 σ** significance for only one source (IC443)

✓ Large systematic due to GeV-TeV data calibration

- Analysis of **10 SNRs and pulsars** *Liang+ JCAP'19*

✓ No evidence for common ALP-photon mixing



Constraints on ALP-photon mixing

Search for spectral irregularities in extragalactic targets

No evidence for ALP-photon mixing → Strong but **not very robust upper limits**

- Analysis of radio galaxy **NGC1275** (Perseus cluster) with **Fermi-LAT** and **MAGIC**

Ajello+PRL'16, Malyshev+1805.04388

- ✓ Limits very sensitive to modelling of intra-cluster B field
- ✓ Typically, only turbulent component is modelled
- ✓ But, there is evidence for large scale ordered component (better match to Faraday rotation measure and others)
- ✓ With a purely ordered B field limits almost vanish

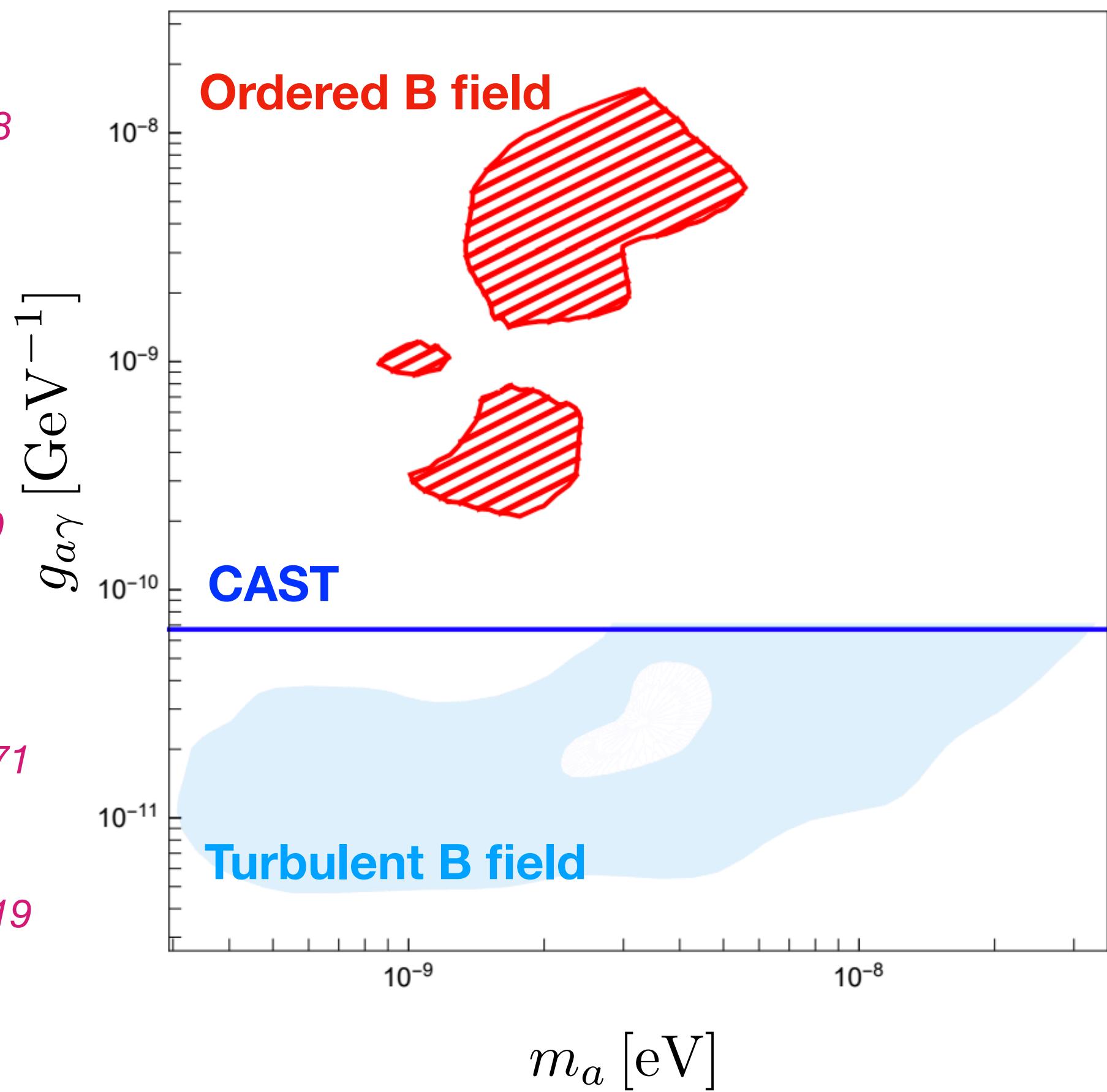
Libanov & Troitsky PLB'20

- Analysis of nearby blazar **PKS 2155-304** with **Fermi-LAT** and **HESS**

Abramowski+ PRD'13, Zhang+ PRD'18; Guo+:2002.07571

- ✓ Only turbulent component of the intra-cluster B field
- ✓ Intergalactic B field RMS usually overestimated
- ✓ Limits can be significantly weakened

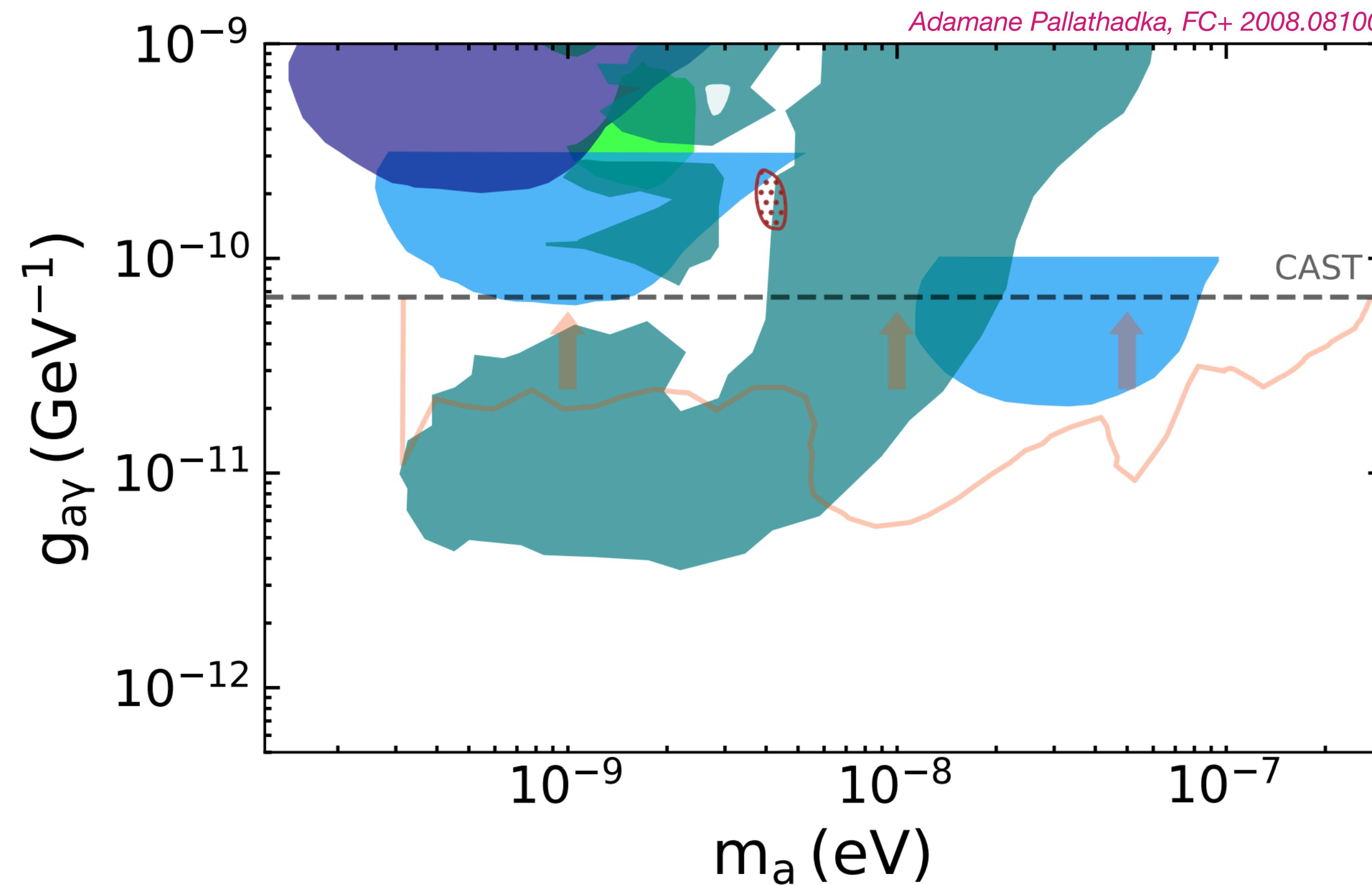
Jedamzik & Saveliev, PRL'19



Libanov & Troitsky PLB'20

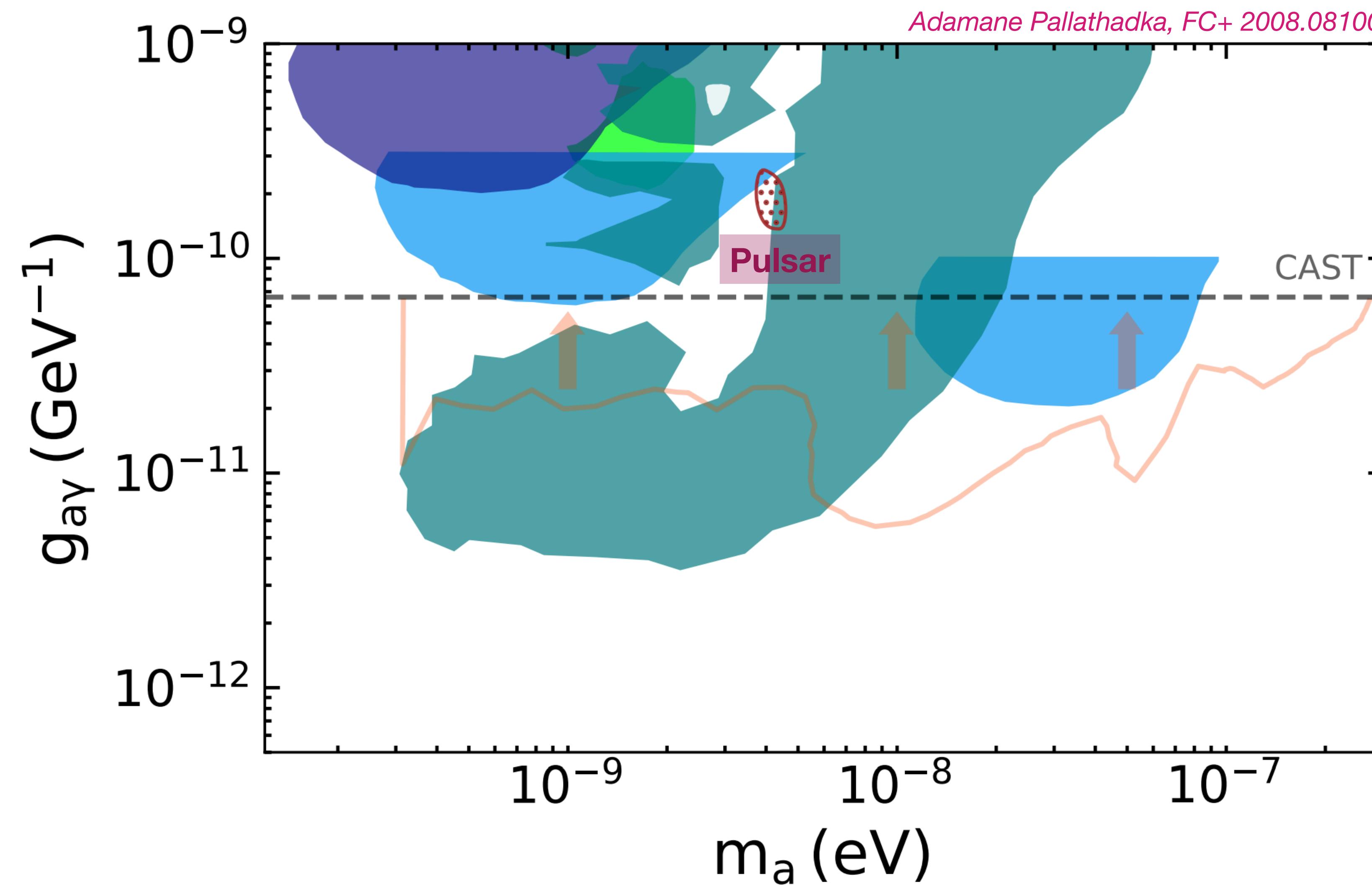
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



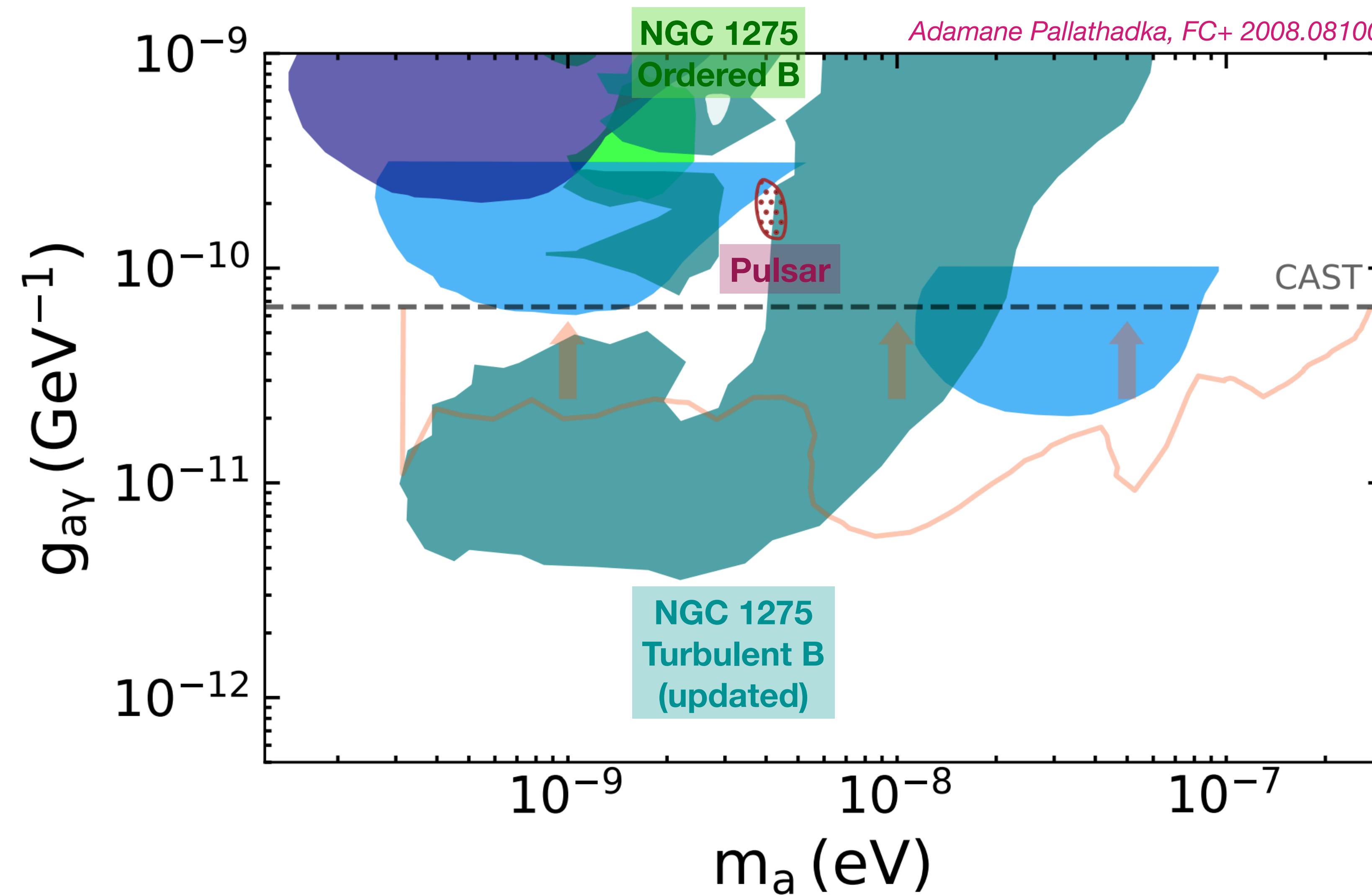
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



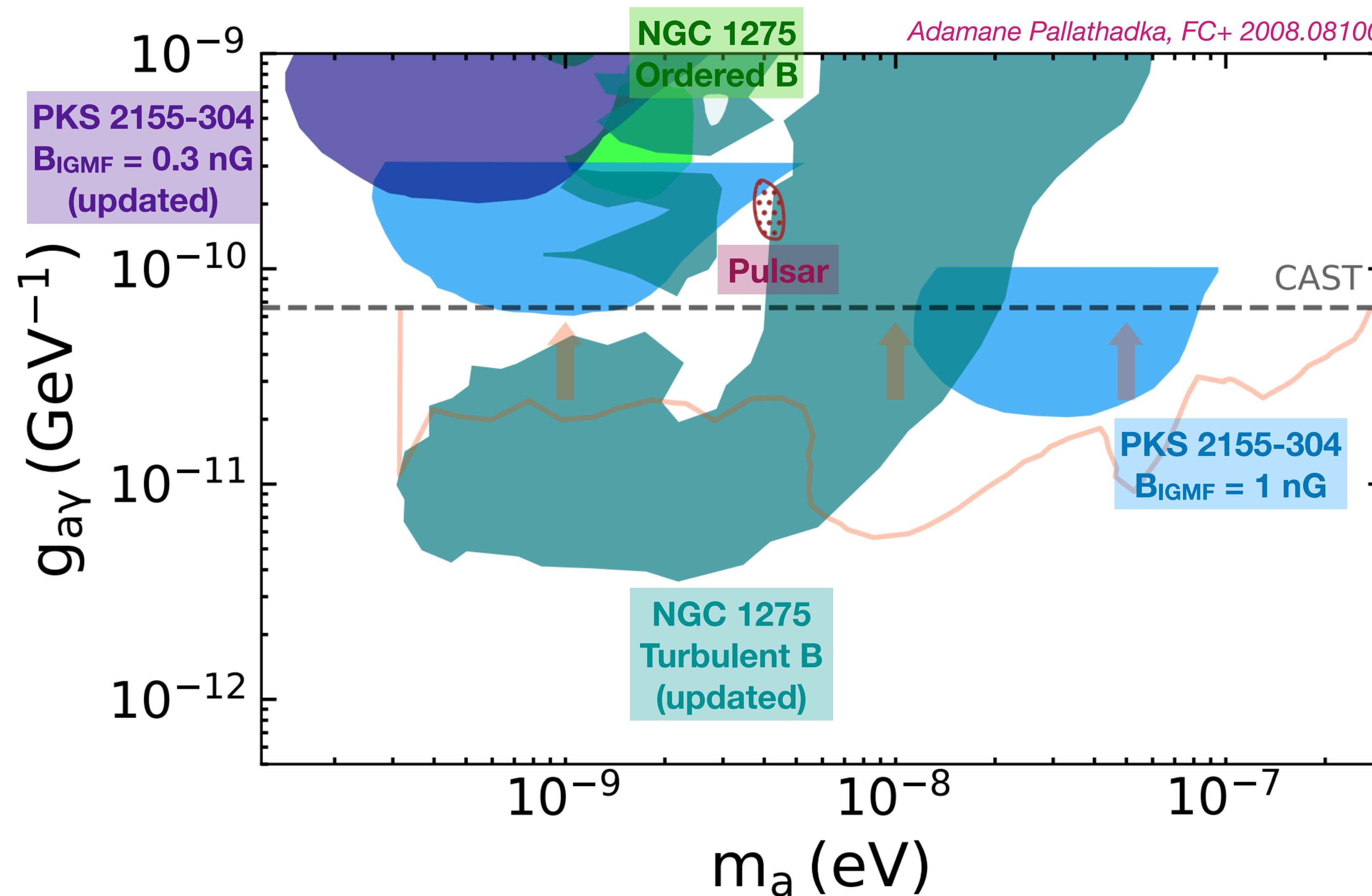
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



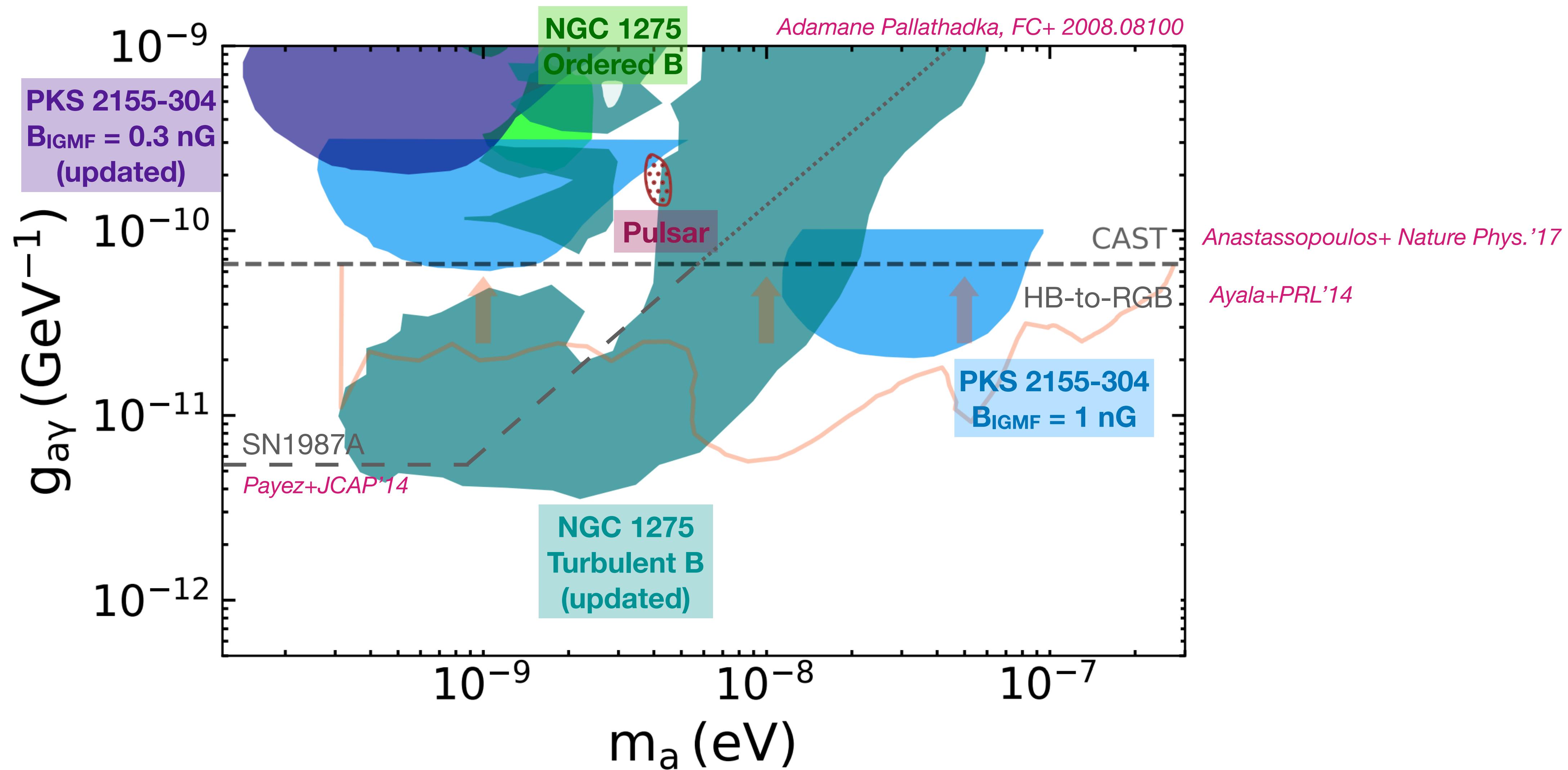
ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



ALP-photon mixing w/ HE gamma rays

Summary of hints and constraints



Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100

CAST limits from null detection of ALP-photon mixing in the direction of the Sun

Production of ALPs in the Sun mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

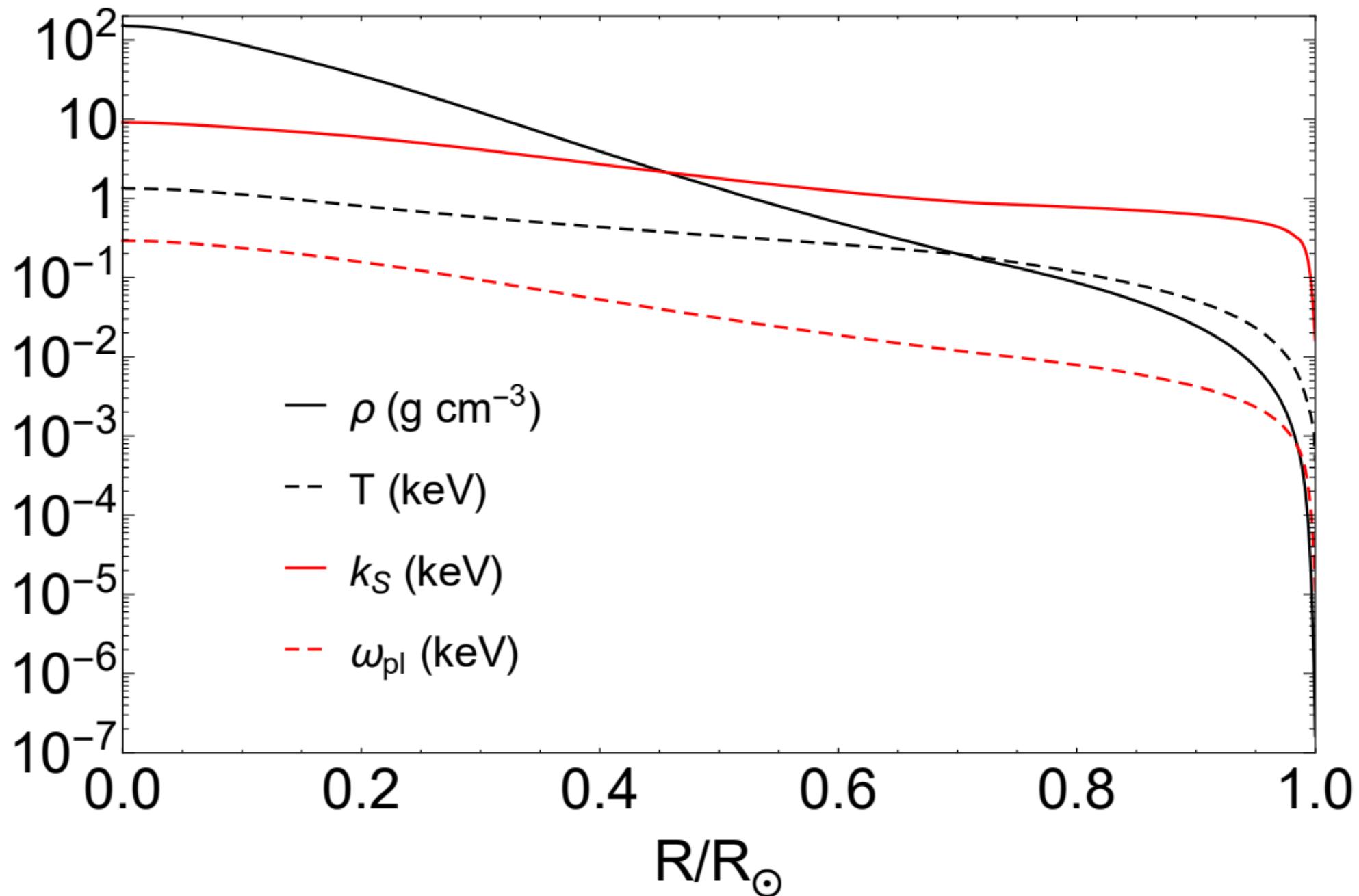
Hp: **ALP-photon coupling is an environment-dependent quantity**

Jaeckel+ PRD'07

$$g_{a\gamma} \rightarrow g_{a\gamma}(\eta)$$

$$\eta = \omega_{pl}, T, \kappa_s^2, \rho, q^2, \dots$$

$$g_{a\gamma}(r, r_c) = g_{\text{PSR}} \theta(r - r_c)$$



Radial profile of environmental parameters in the Sun

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100

CAST limits from null detection of ALP-photon mixing in the direction of the Sun

Production of ALPs in the Sun mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

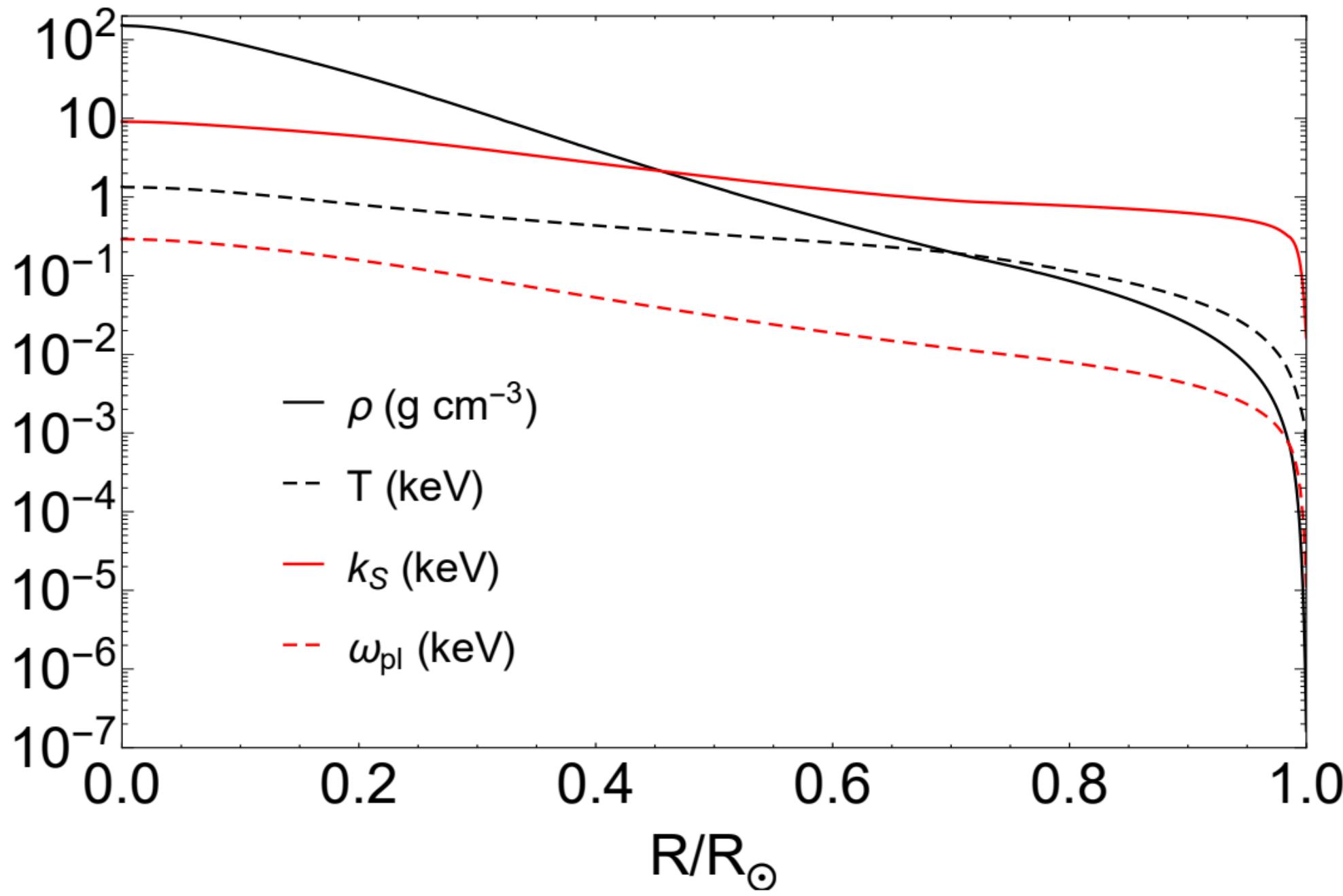
Hp: **ALP-photon coupling is an environment-dependent quantity**

Jaeckel+ PRD'07

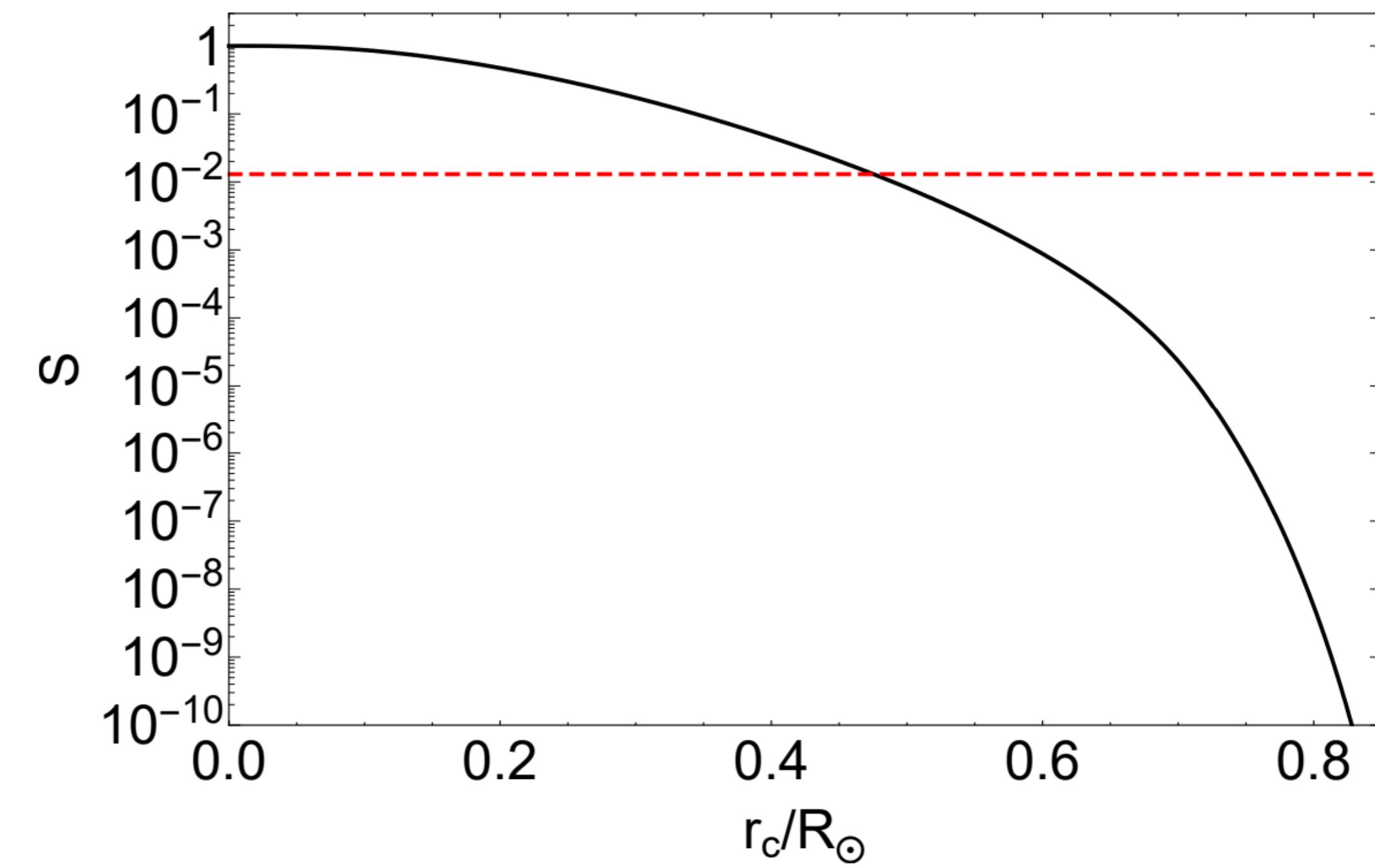
$$g_{a\gamma} \rightarrow g_{a\gamma}(\eta)$$

$$\eta = \omega_{pl}, T, \kappa_s^2, \rho, q^2, \dots$$

$$g_{a\gamma}(r, r_c) = g_{\text{PSR}} \theta(r - r_c)$$



Radial profile of environmental parameters in the Sun



Radial profile of production flux suppression factor

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100

CAST limits from null detection of ALP-photon mixing in the direction of the Sun

Production of ALPs in the Sun mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

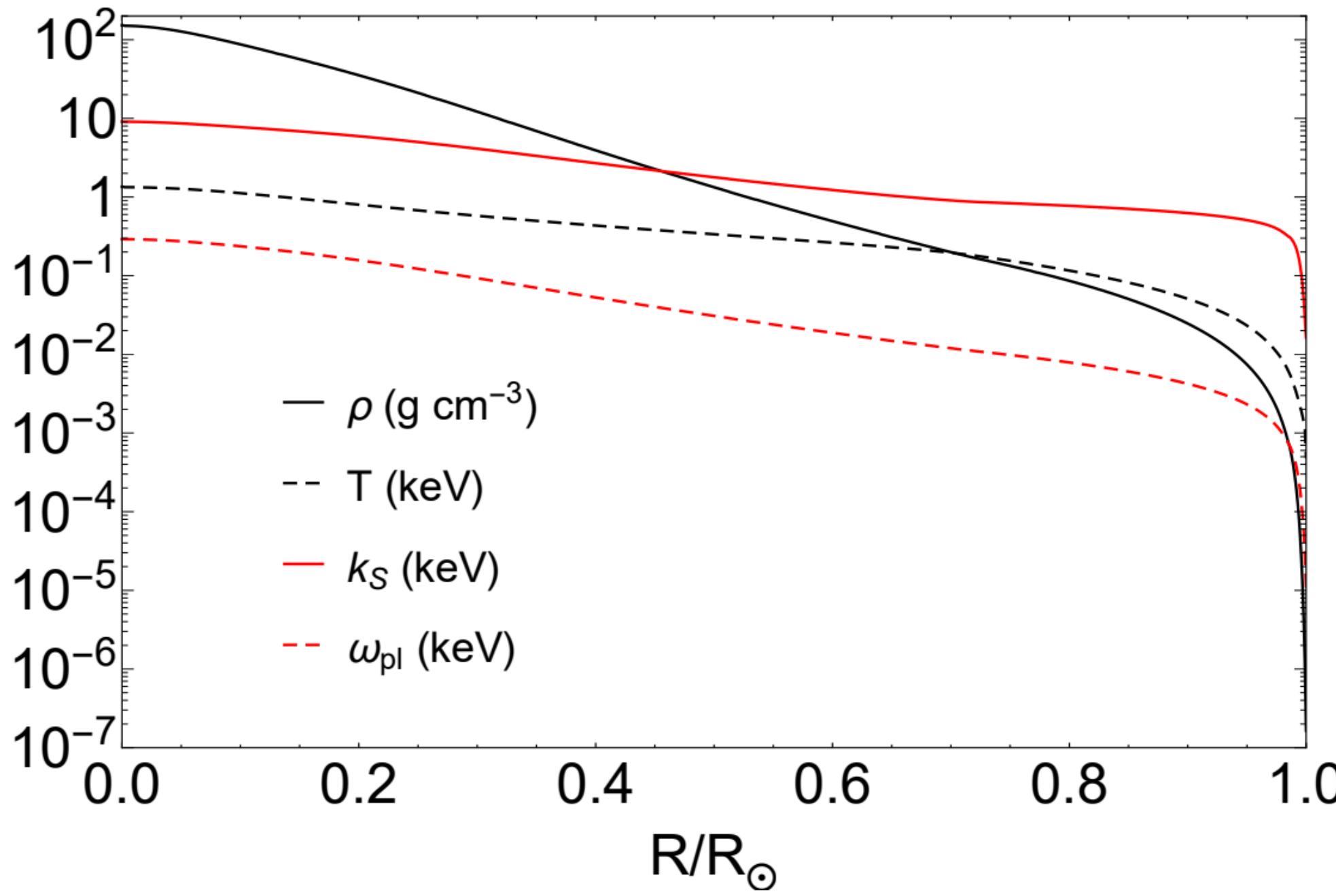
H_p: **ALP-photon coupling is an environment-dependent quantity**

Jaeckel+ PRD'07

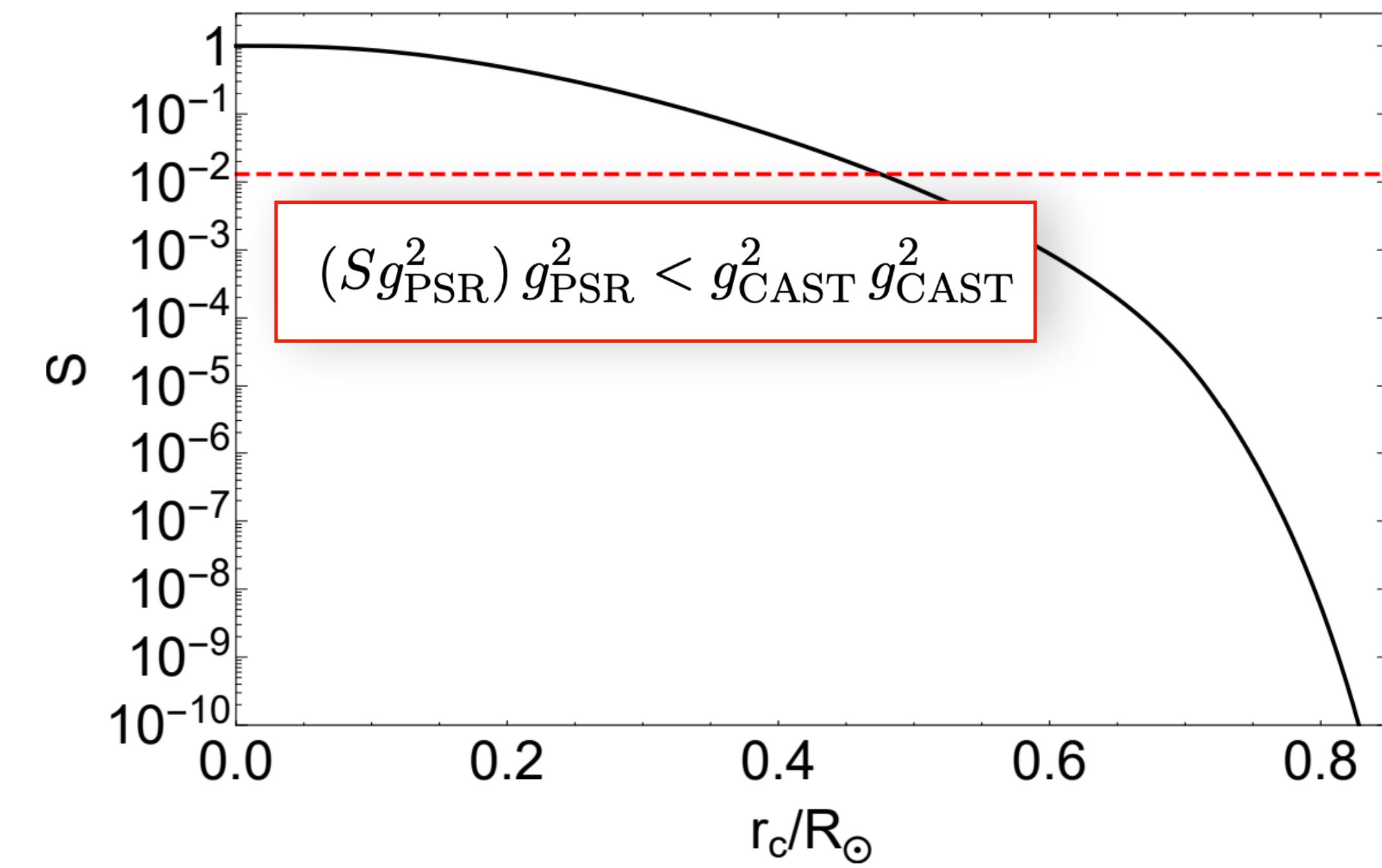
$$g_{a\gamma} \rightarrow g_{a\gamma}(\eta)$$

$$\eta = \omega_{pl}, T, \kappa_s^2, \rho, q^2, \dots$$

$$g_{a\gamma}(r, r_c) = g_{\text{PSR}} \theta(r - r_c)$$



Radial profile of environmental parameters in the Sun



Radial profile of production flux suppression factor

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100

CAST limits from null detection of ALP-photon mixing in the direction of the Sun

Production of ALPs in the Sun mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

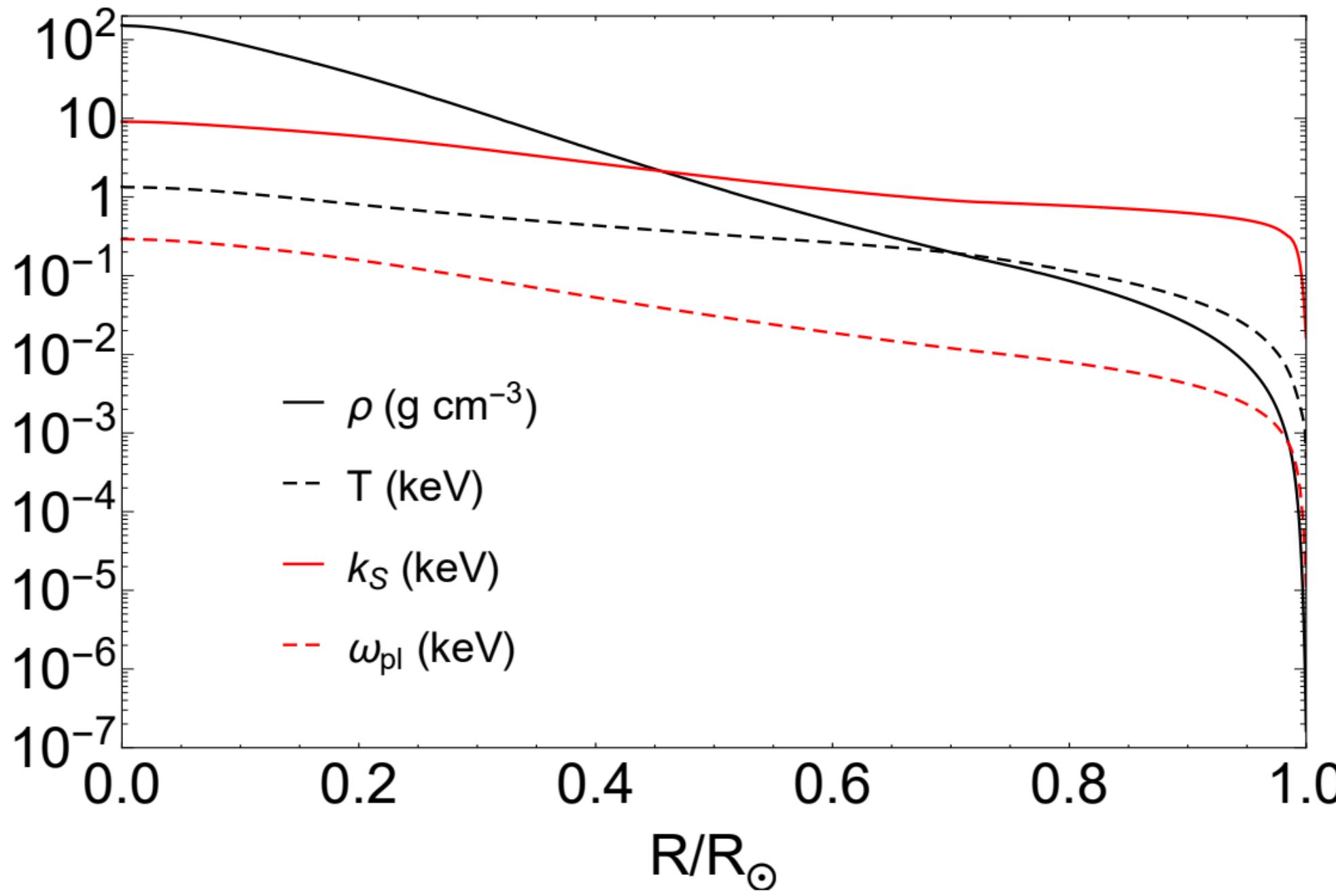
H_p: **ALP-photon coupling is an environment-dependent quantity**

Jaeckel+ PRD'07

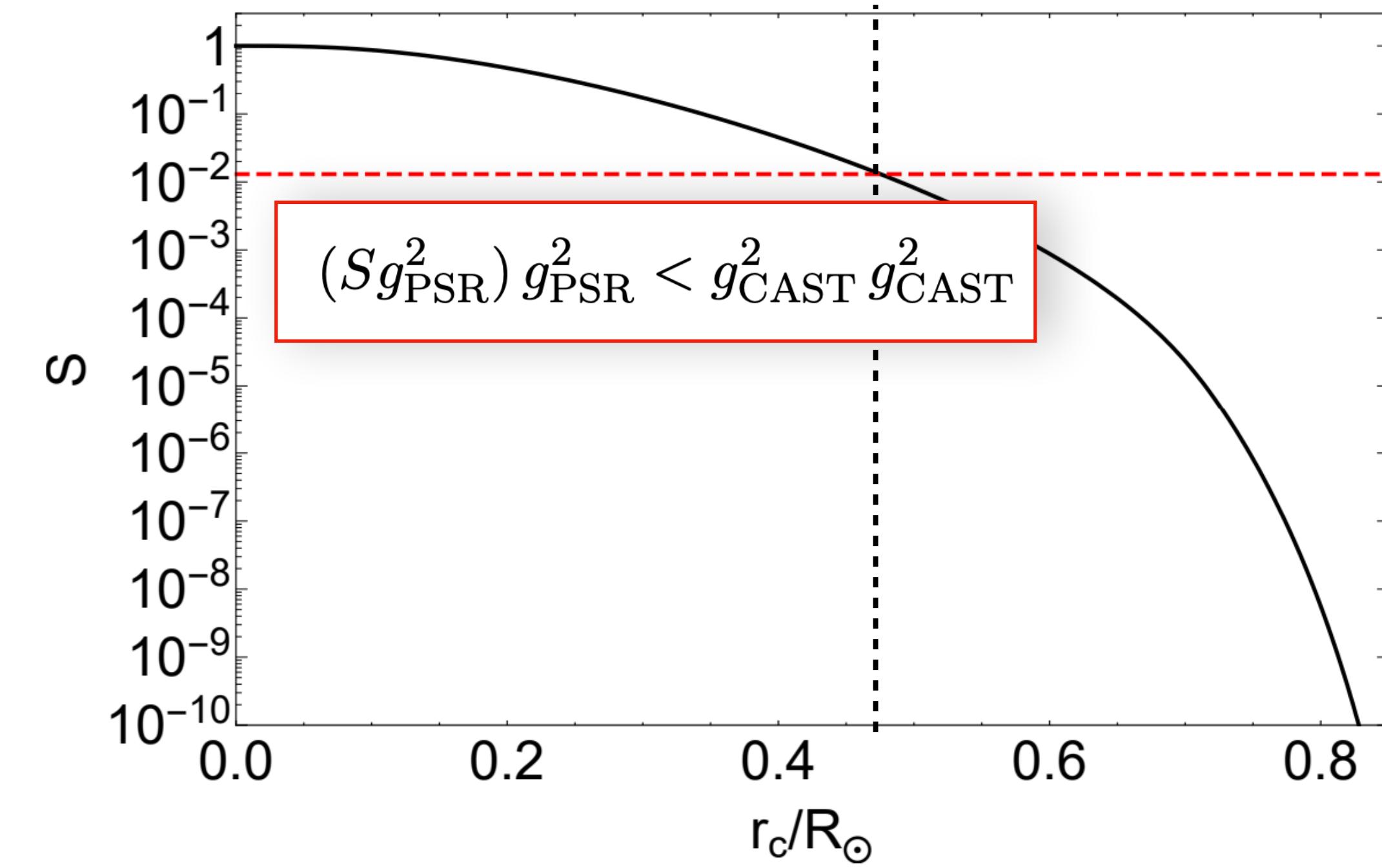
$$g_{a\gamma} \rightarrow g_{a\gamma}(\eta)$$

$$\eta = \omega_{pl}, T, \kappa_s^2, \rho, q^2, \dots$$

$$g_{a\gamma}(r, r_c) = g_{\text{PSR}} \theta(r - r_c)$$



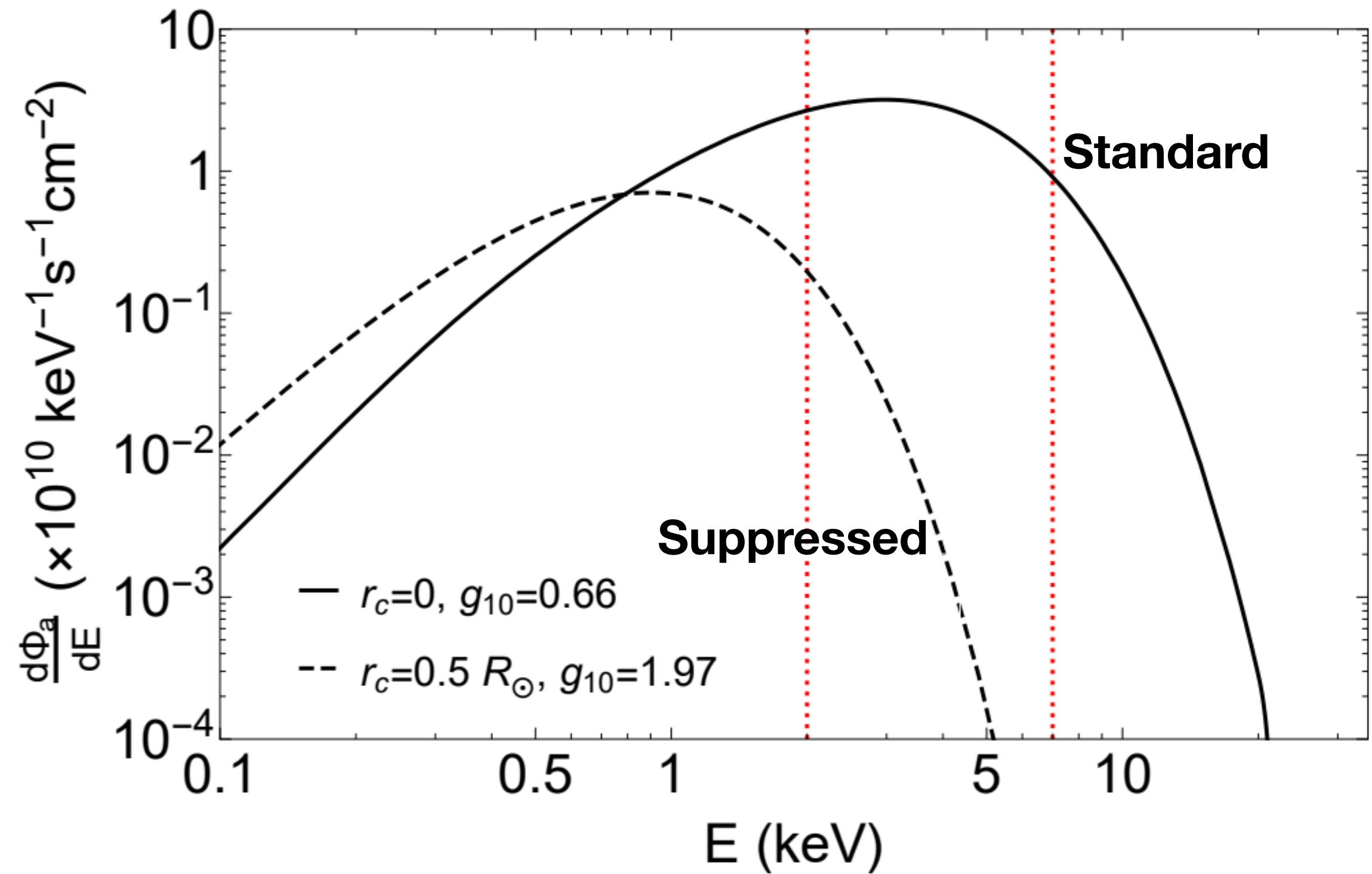
Radial profile of environmental parameters in the Sun



Radial profile of production flux suppression factor

Evading solar and stellar constraints

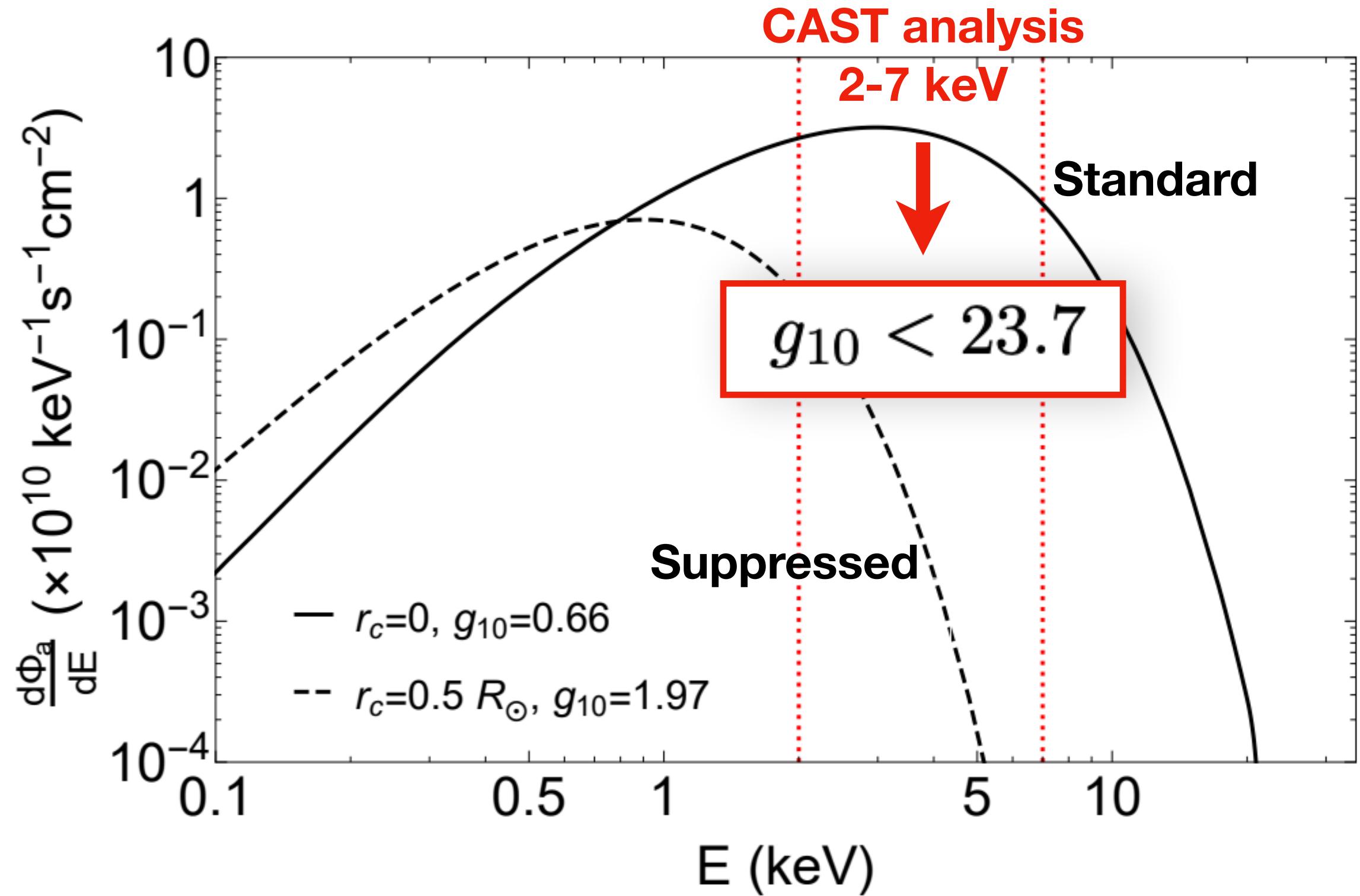
Adamane Pallathadka, FC+ 2008.08100



The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case

Evading solar and stellar constraints

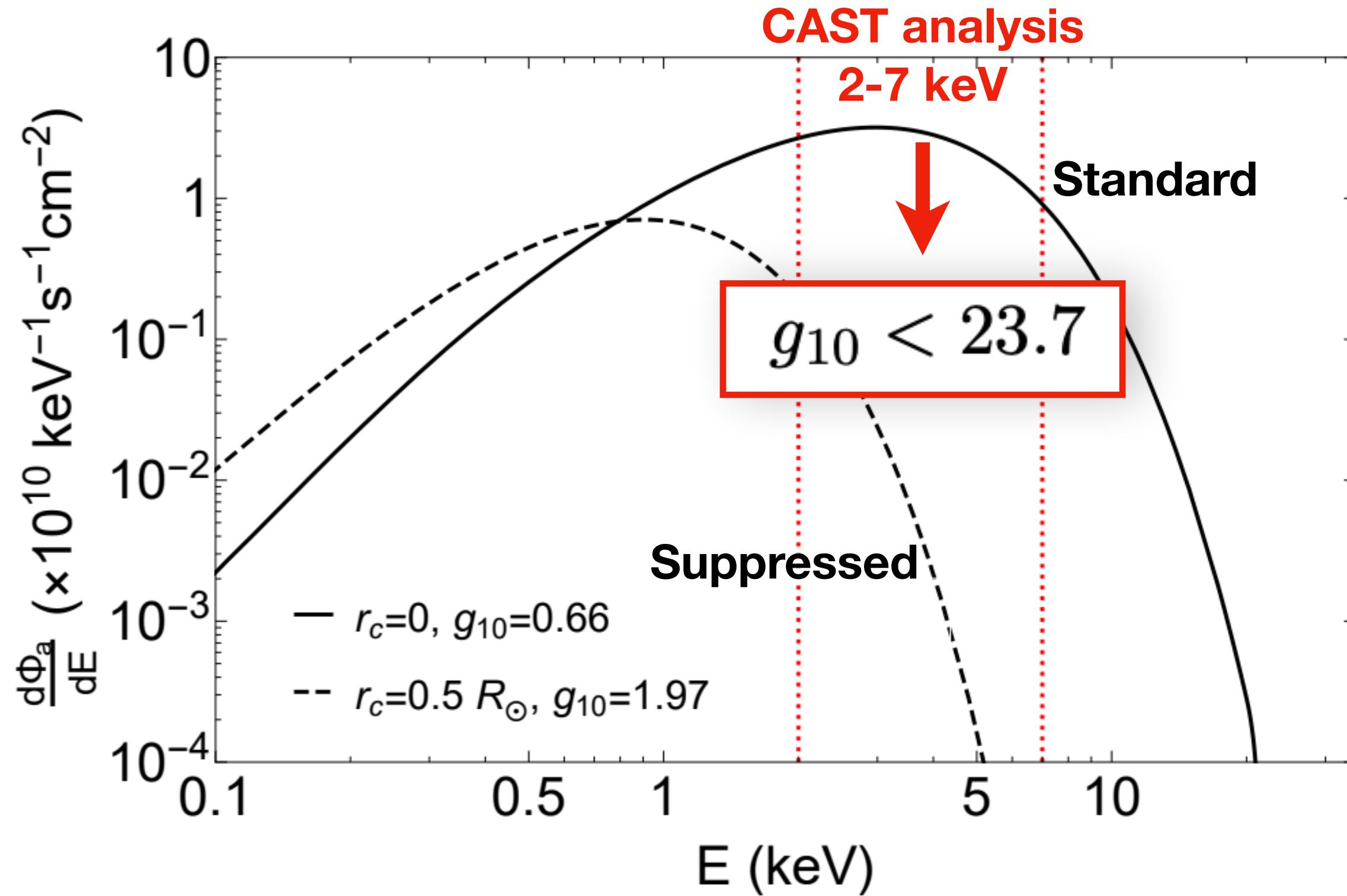
Adamane Pallathadka, FC+ 2008.08100



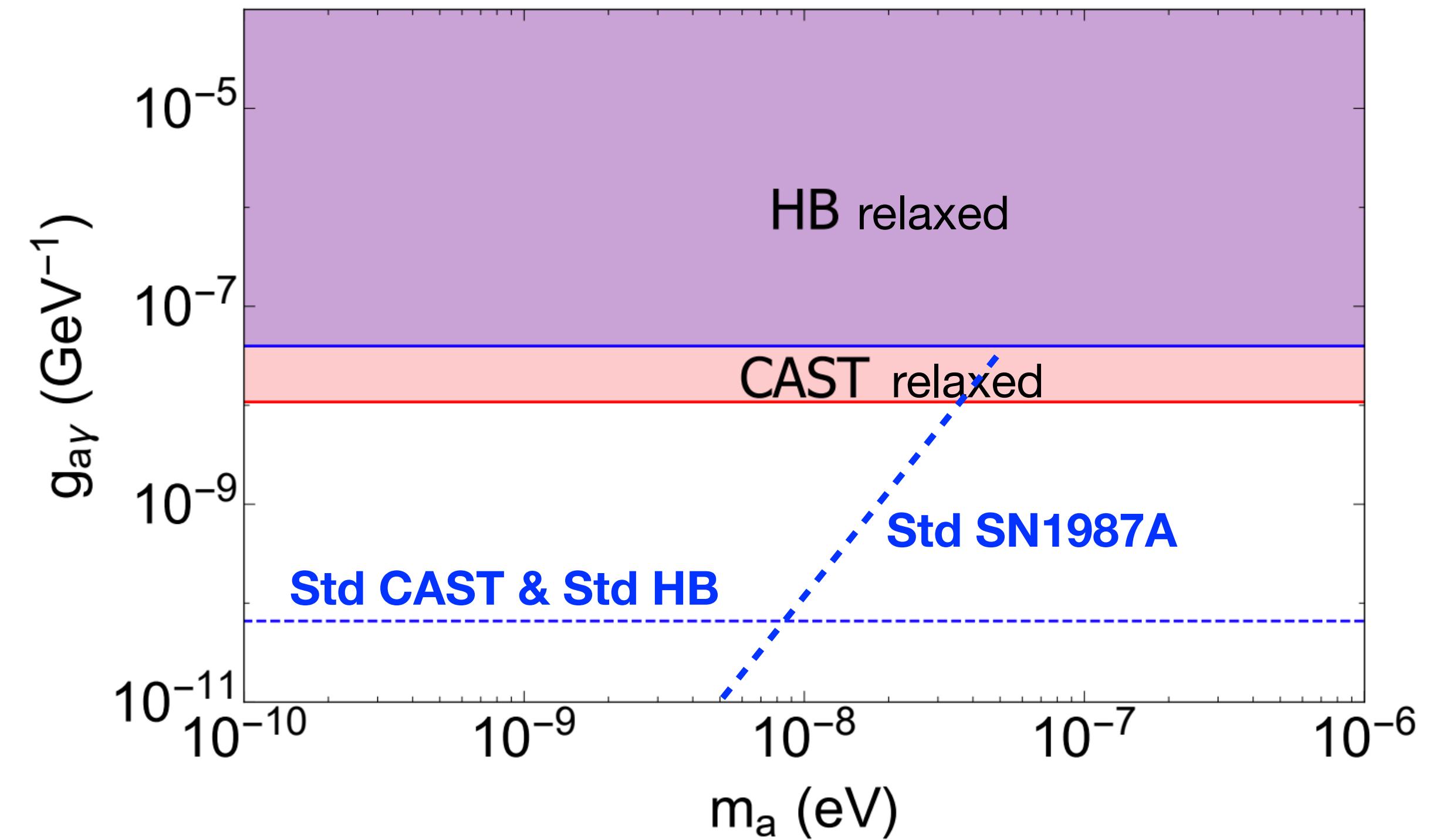
The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case

Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100



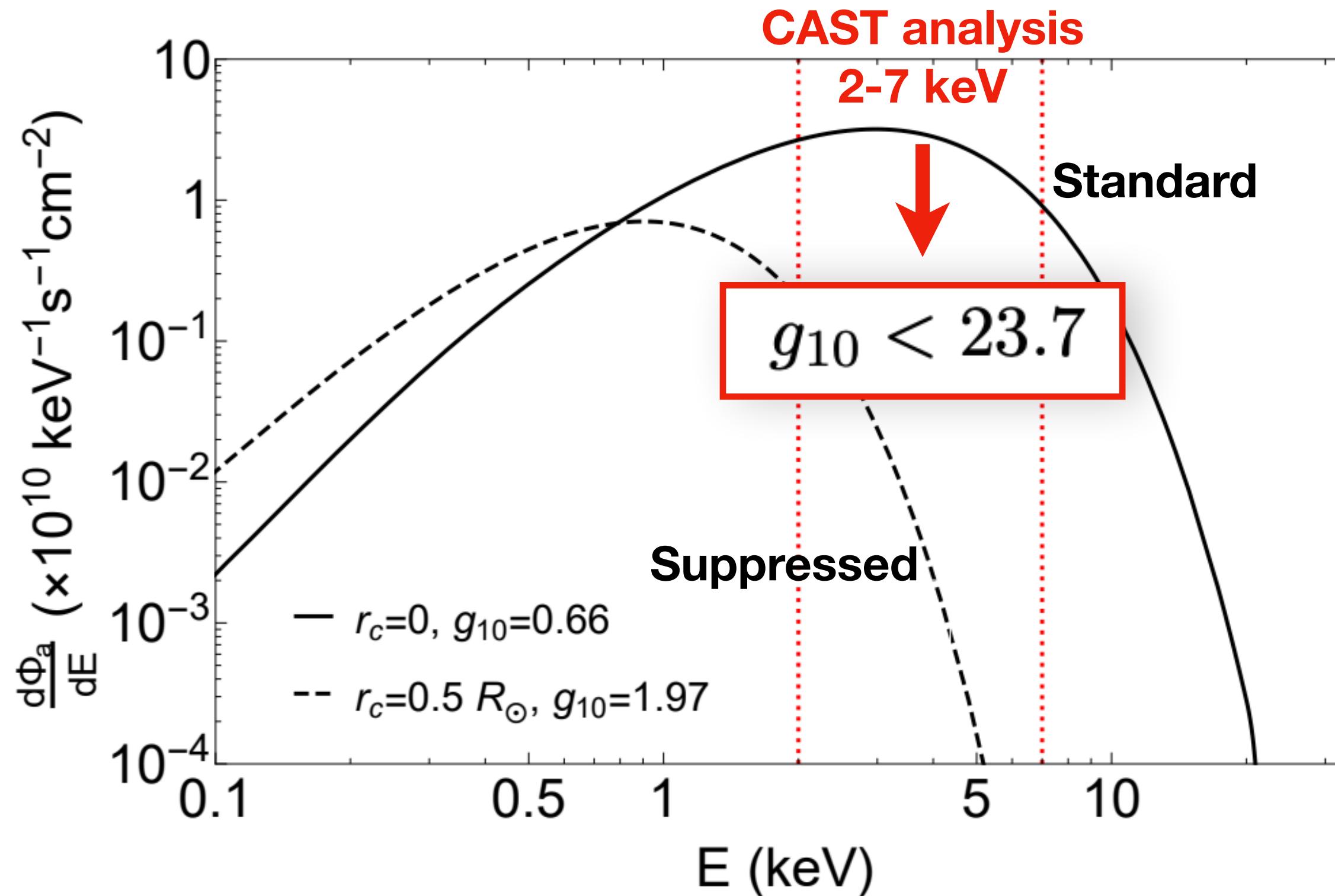
The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case



Same argument can be applied to bounds from HB-to-RGB stars and SN1987A

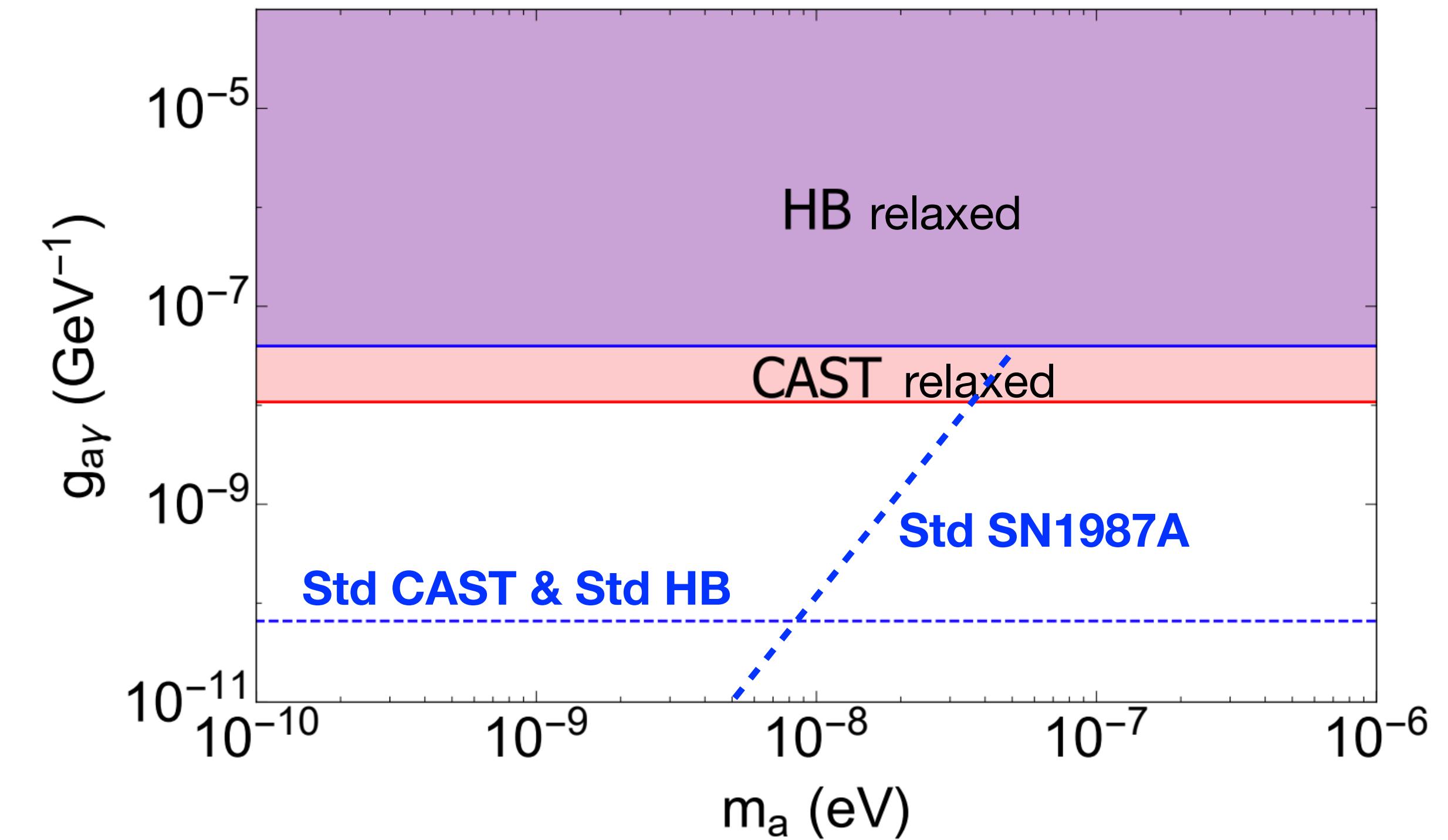
Evading solar and stellar constraints

Adamane Pallathadka, FC+ 2008.08100



The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case

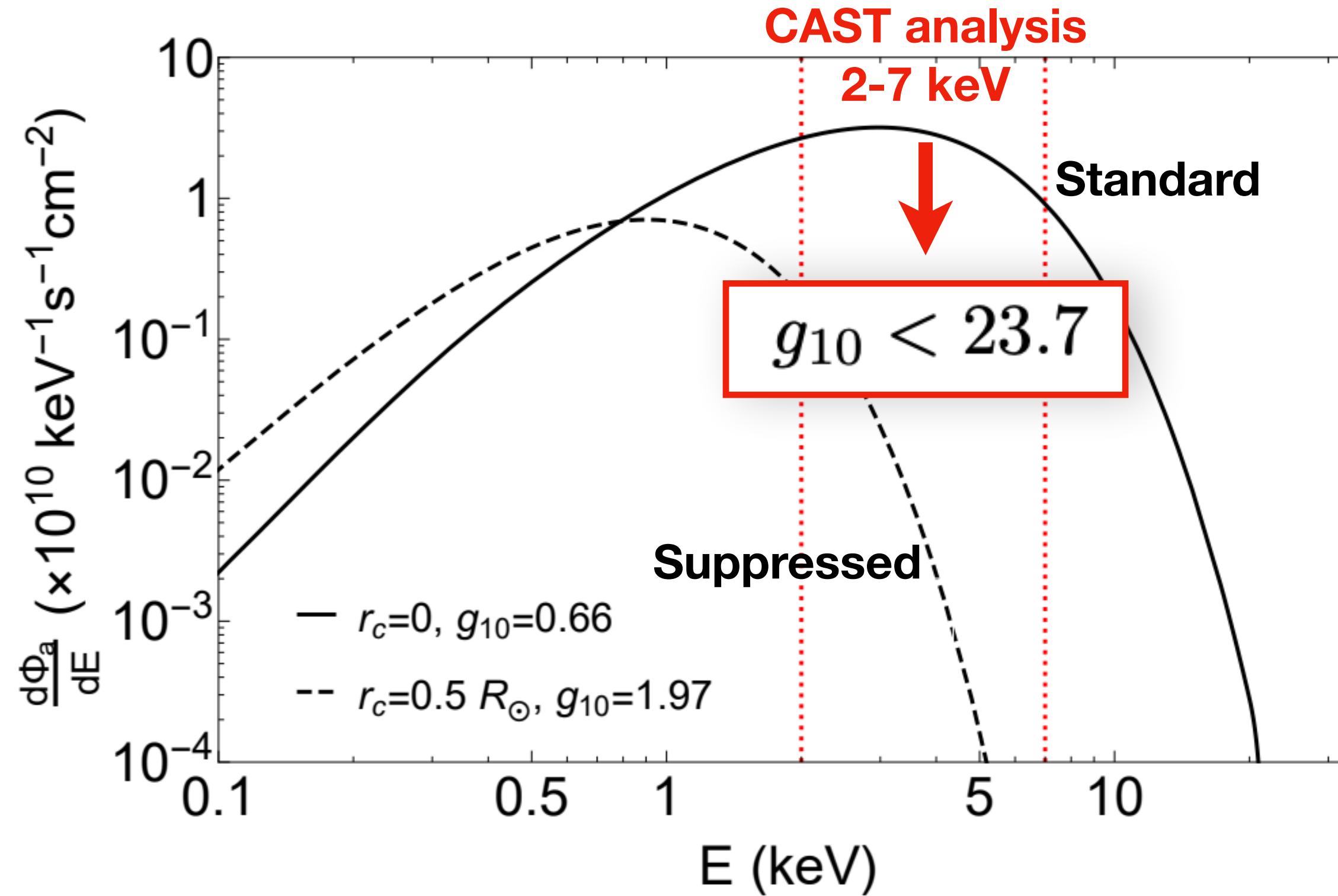
Spectacular signal rate in the pure laboratory experiment ALPS II



Same argument can be applied to bounds from HB-to-RGB stars and SN1987A

Evading solar and stellar constraints

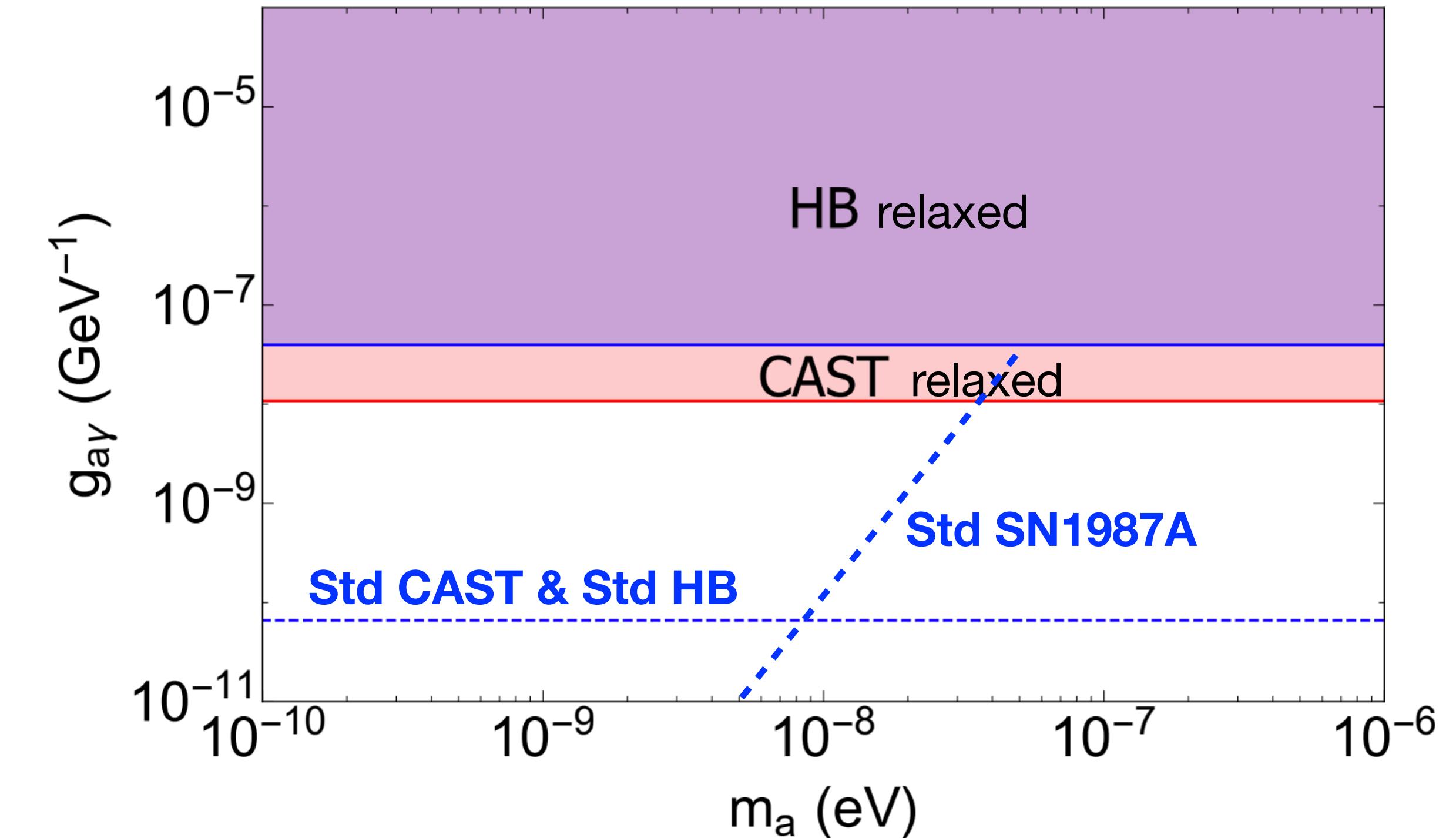
Adamane Pallathadka, FC+ 2008.08100



The ALP flux with an environmental dependent coupling is strongly suppressed with respect to the standard case

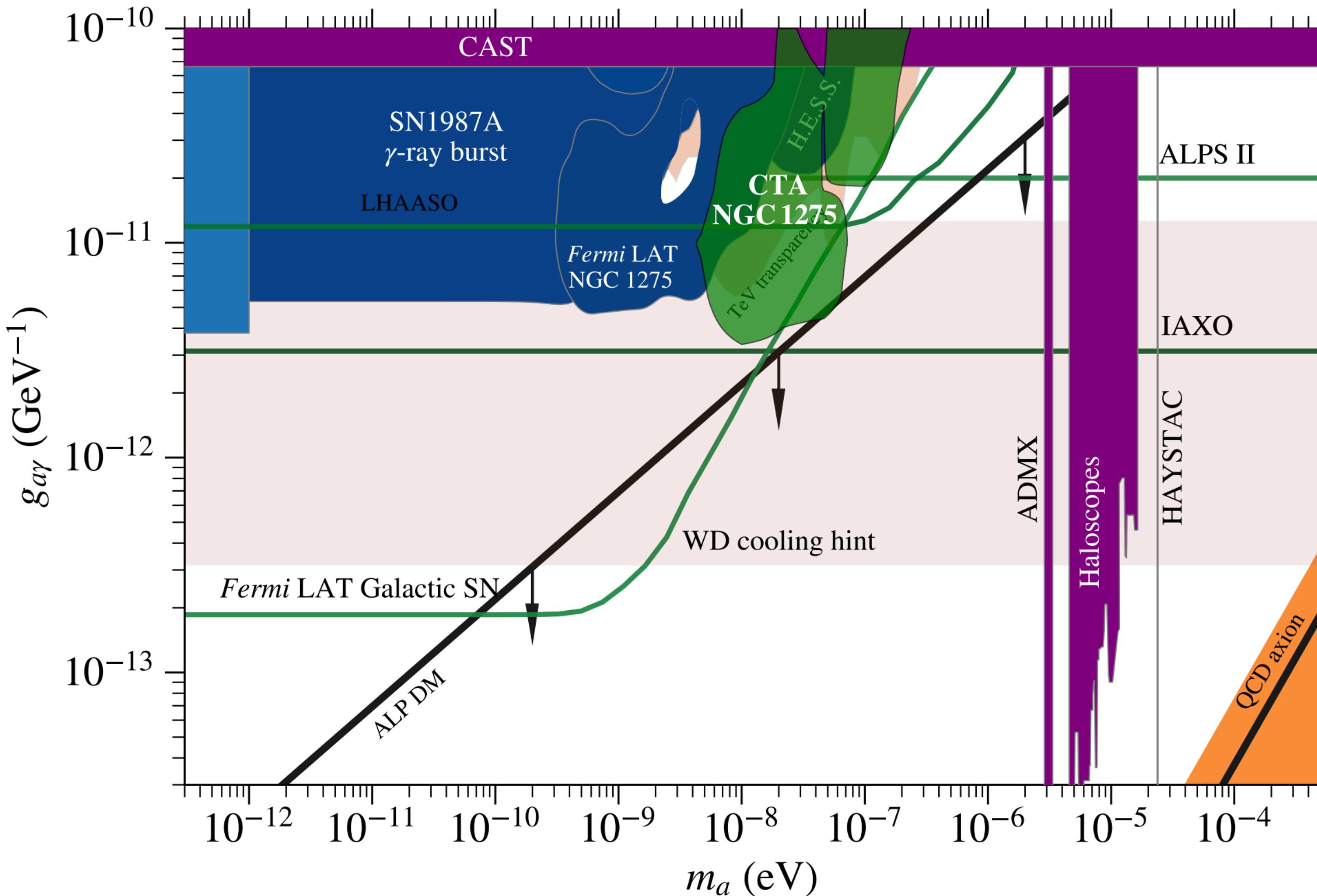
Spectacular signal rate in the pure laboratory experiment ALPS II

[Axion mediated dark-photon mixing can also explain oscillations and the re-casted limits do not exclude the best-fit region]



Same argument can be applied to bounds from HB-to-RGB stars and SN1987A

What future for gamma-ray searches?



- DSNALB, SNe and pulsars constraints would benefit by **future MeV missions**, able to **better resolve the diffuse gamma-ray background** and provide **accurate spectra in the MeV energy range**
FC+ 2008.11741
- Galaxy clusters (e.g. NGC1275) limits would be improved by **CTA** touching ALP DM region
CTA Consortium 2010.01349
- Search for SNe bursts opens exciting complementarity with **optical transient facilities (LSST)**.
Meyer+ PRL'17
Meyer & Petrushevska PRL'20

DarkMachines

About Dark Machines

Dark Machines is a research collective of physicists and data scientists. We are curious about the universe and want to answer cutting edge questions about Dark Matter with the most advanced techniques that data science provides us with.

Visit our indico page



Dark Machines
@dark_machines

The next darkmachines general meeting :

Tuesday 4 September 2018 1400 CERN time.darkmachines.org to register and join event via video link.

(we plan to have monthly meetings, first Tuesday of the month)



Jul 27, 2018



Dark Machines Retweeted



Juan Rojo
@JuanRojOC

Machine Learning, uncertainties, and neural networks! Three of my favourite topics nicely

- Collective effort aimed to explore, and to encourage, the application of state-of-the-art machine learning algorithms to dark matter searches
- Projects, datasets and challenges dedicated to dark matter indirect detection
- New and open research community: anyone can participate!!

<http://darkmachines.org/>

Conclusions and Outlook

- ✓ Searches for dark matter with **astroparticle experiments successfully test different dark matter models** (not only WIMPs! [see ALPs and PBH searches])
- ✓ Nowadays from indirect detection we can get **strong constraints but assessing their robustness is crucial especially when cross-checking signal hints**
- ✓ The **origin of some longstanding excesses is still unclear** and the dark matter interpretation tantalised by astrophysical alternatives
- ✓ We need a **fully multi-messenger approach** to improve our understanding of these anomalous signals through a **continuous refinement of our astrophysical background models**
- ✓ Great experimental progress at multiple wavelengths (LOFAR, SKA, Athena, CTA, etc) will provide us **access to yet uncharted portions of the DM parameter space and new windows of opportunity for DM detection!**