Dark Matter searches... ...In 25 mins :)

Gabrijela Zaharijas

Centre for Astrophysics and Cosmology, University of Nova Gorica

LHC Days 2022, Split, Croatia

Dark Matter searches… with astrophysical probes!
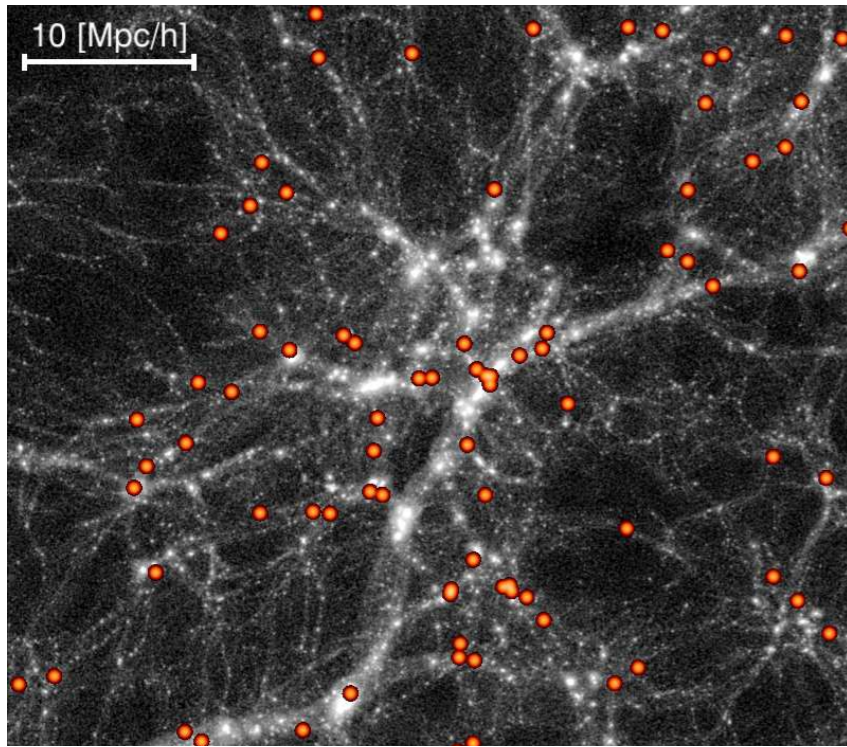
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LHC Days 2022, Split, Croatia
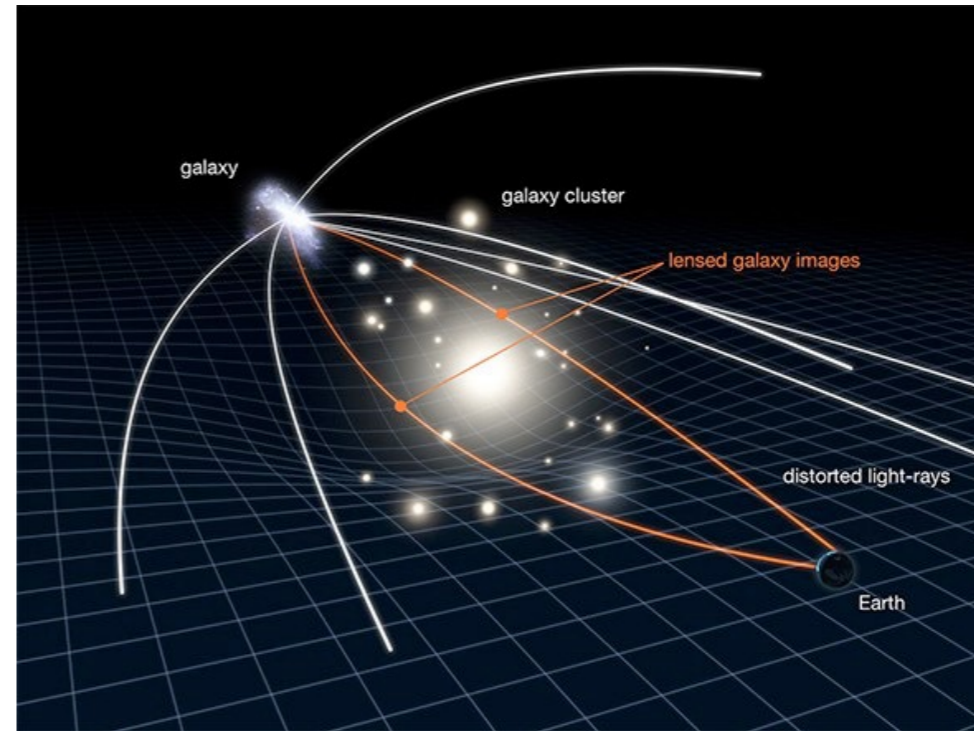
Dark matter

an essential building block of the Standard Model of Cosmology
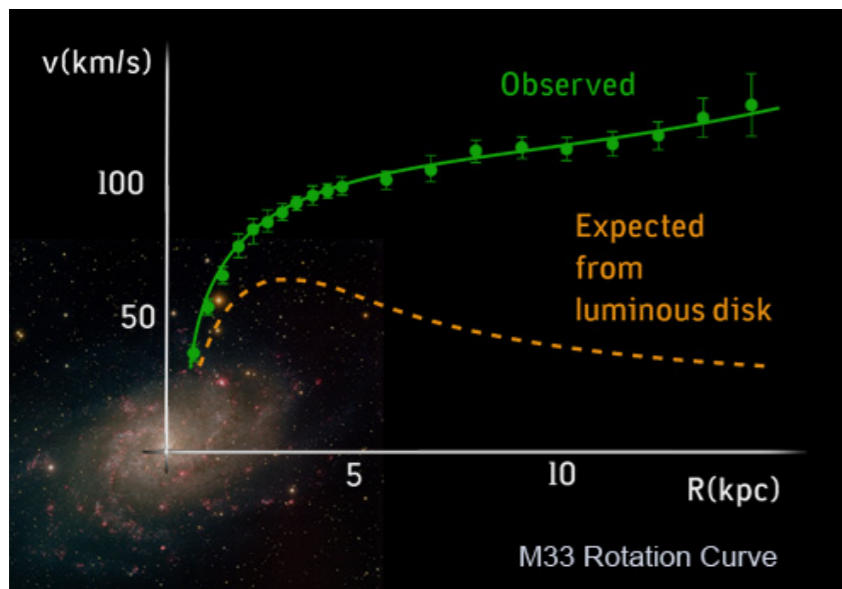
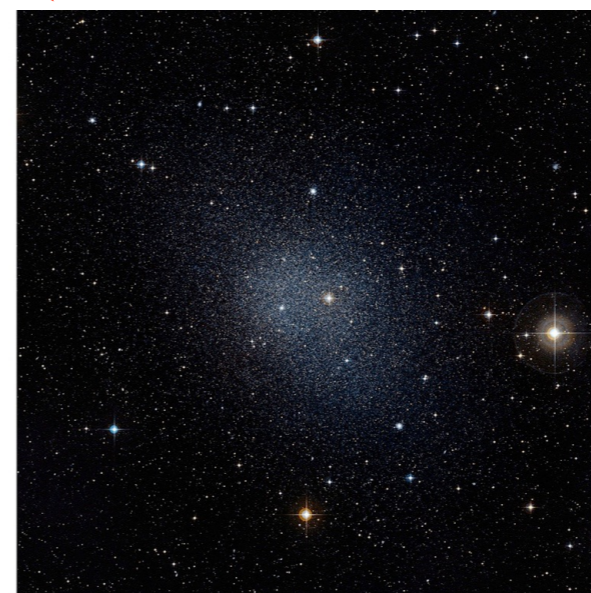large scale structures

100s Mpc

clusters of galaxies

Mpc

Milky Way-size galaxies

100s kpc

dwarf galaxies

<~ kpc

3

Dark matter

an essential building block of the Standard Model of Cosmology

large scale structures

100s Mpc

clusters of galaxies

Mpc

Milky

100s kpc

dwarf galaxies

<~ kpc

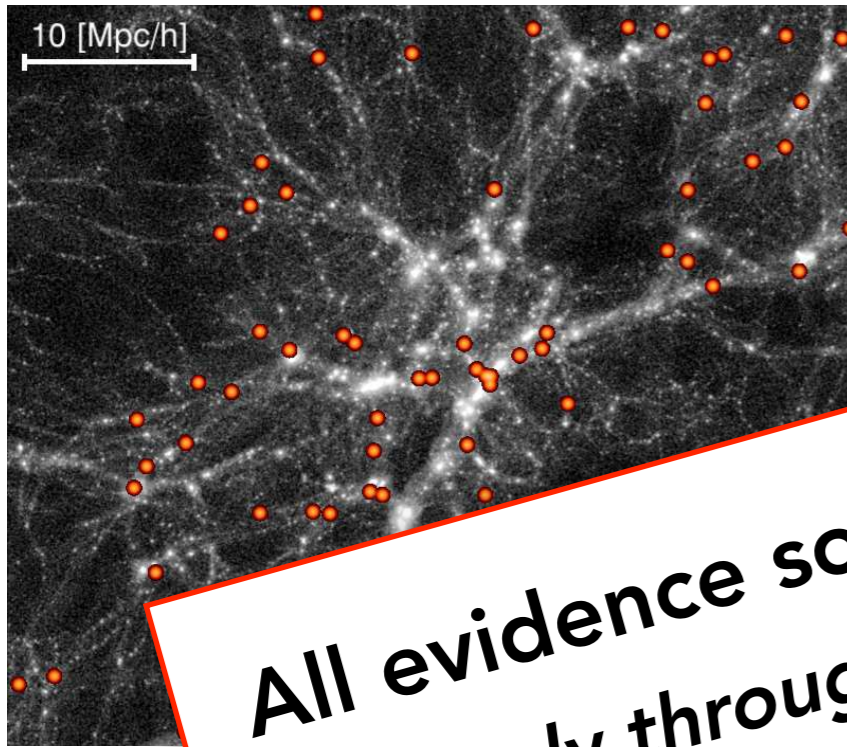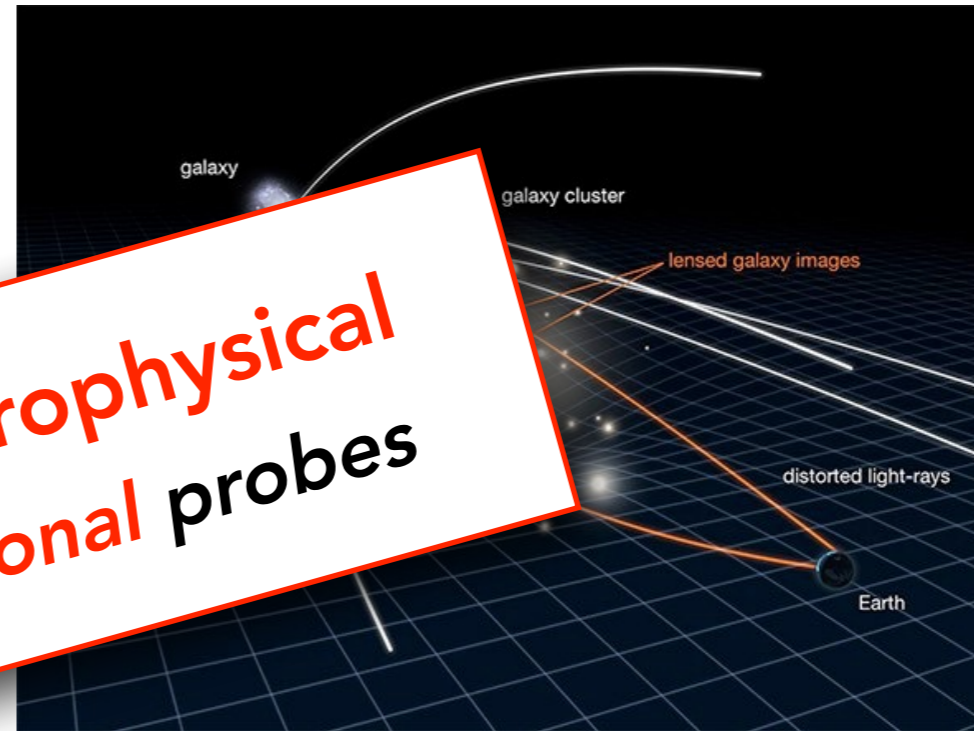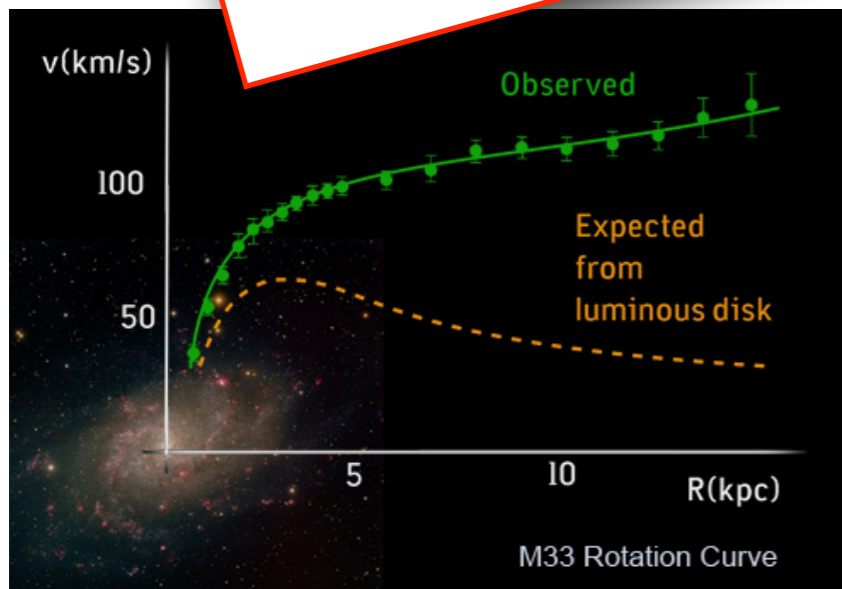All evidence so far is astrophysical
And only through gravitational probes

What are the options?

X & γ rays

Radio lines

X rays

X-ray lines

γ, cosmic rays & ν

Radio, X & γ rays

Structure formation

Structure formation

$$10^{-19}\,\mathrm{eV} \qquad \mu\mathrm{eV} \qquad 0.1\,\mathrm{eV} \qquad \mathrm{keV} \qquad \mathrm{MeV} \qquad \mathrm{GeV} \qquad 10^2\,\mathrm{TeV} \qquad 10^{-16}\,M_\odot \qquad 10\,M_\odot \qquad 10^3\,M_\odot$$

Fuzzy DM   QCD axion/ALPs   Sterile ν WIMPs & WIMPzillas   PBH

Wave vs particle

Particle 'zoo'

Macro objects

[EuCAPT white paper, arXiv: 2110.10074]

Quick conversion :)

Planck scale

10^{-10} 1 kg

10^{30} eV

5

What are the options?

X rays γ, cosmic rays & ν Radio, X & γ rays

Radio lines   X-ray lines

Structure formation   Structure formation

$10^{-19}\,\mathrm{eV}$ $\mu\mathrm{eV}$ $0.1\,\mathrm{eV}$ keV   MeV   GeV $10^2\,\mathrm{TeV}$ $10^{-16}\,M_\odot$ $10\,M_\odot$ $10^3\,M_\odot$

Fuzzy DM   QCD axion/ALPs   Sterile ν WIMPs & WIMPzillas   PBH

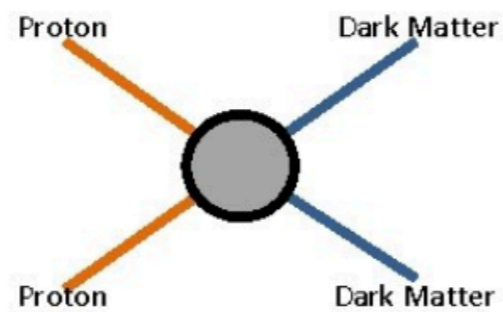*Wave vs particle*   *Particle 'zoo'*   *Macro objects*
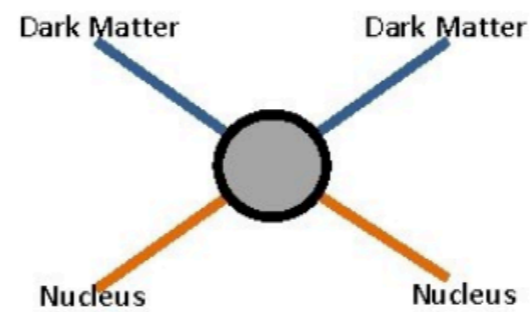

Search under 'theory' lamppost

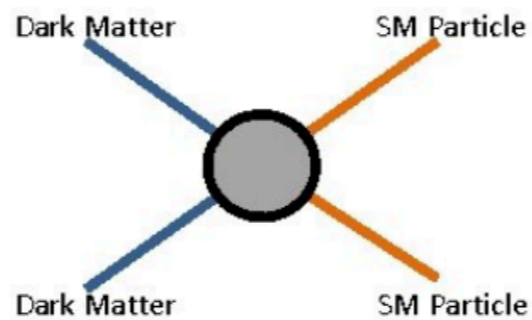# What are the strategies? (…for probes of **'other than' gravitational** interactions)

Ways to Detect Dark Matter – *Make, Shake and Break*

Make – collider production

Shake – direct detection scattering

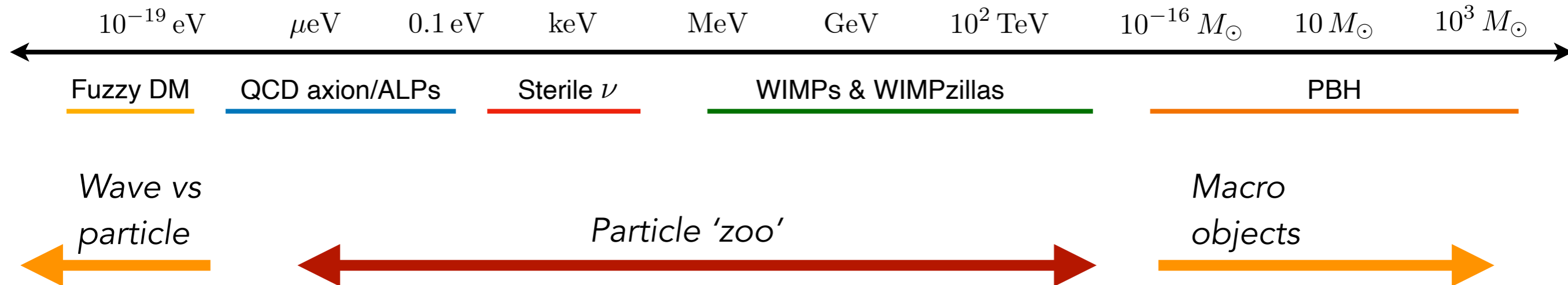**Break** – indirect detection of annihilation

Direct detection:
— elastic scattering
— conversion in Axion experiments
— …

Astrophysical searches:
— DM self annihilation or decay
— PBH evaporation
— …

Astrophysical probes

X & γ rays   X rays   γ, cosmic rays & ν

Radio lines   X-ray lines

Structure formation

| $10^{-19}\,\mathrm{eV}$ | $\mu\mathrm{eV}$ | $0.1\,\mathrm{eV}$ | keV | MeV | GeV | $10^2\,\mathrm{TeV}$ | $10^{-16}\,M_\odot$ | $10\,M_\odot$ | $10^3\,M_\odot$ |

Fuzzy DM   QCD axion/ALPs   Sterile ν WIMPs & WIMPzillas   PBH

Wave vs particle   *Particle 'zoo'*   *Macro objects*
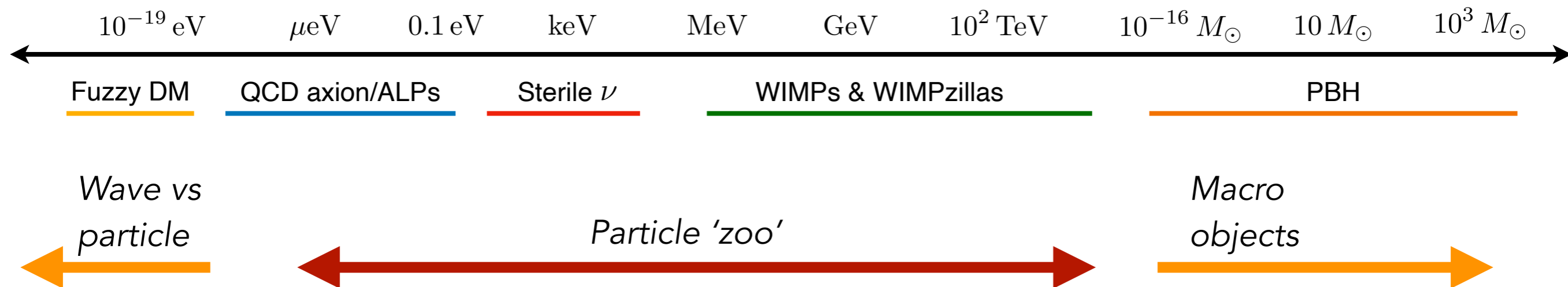
Astrophysical probes of the nature of DM

PROs

— remotely, in places where we have evidence for DM presence

— plenty of astro data available ('*golden age*')

CONs

— learning backgrounds (astrophysics!) and searching for new signals *at the same time*
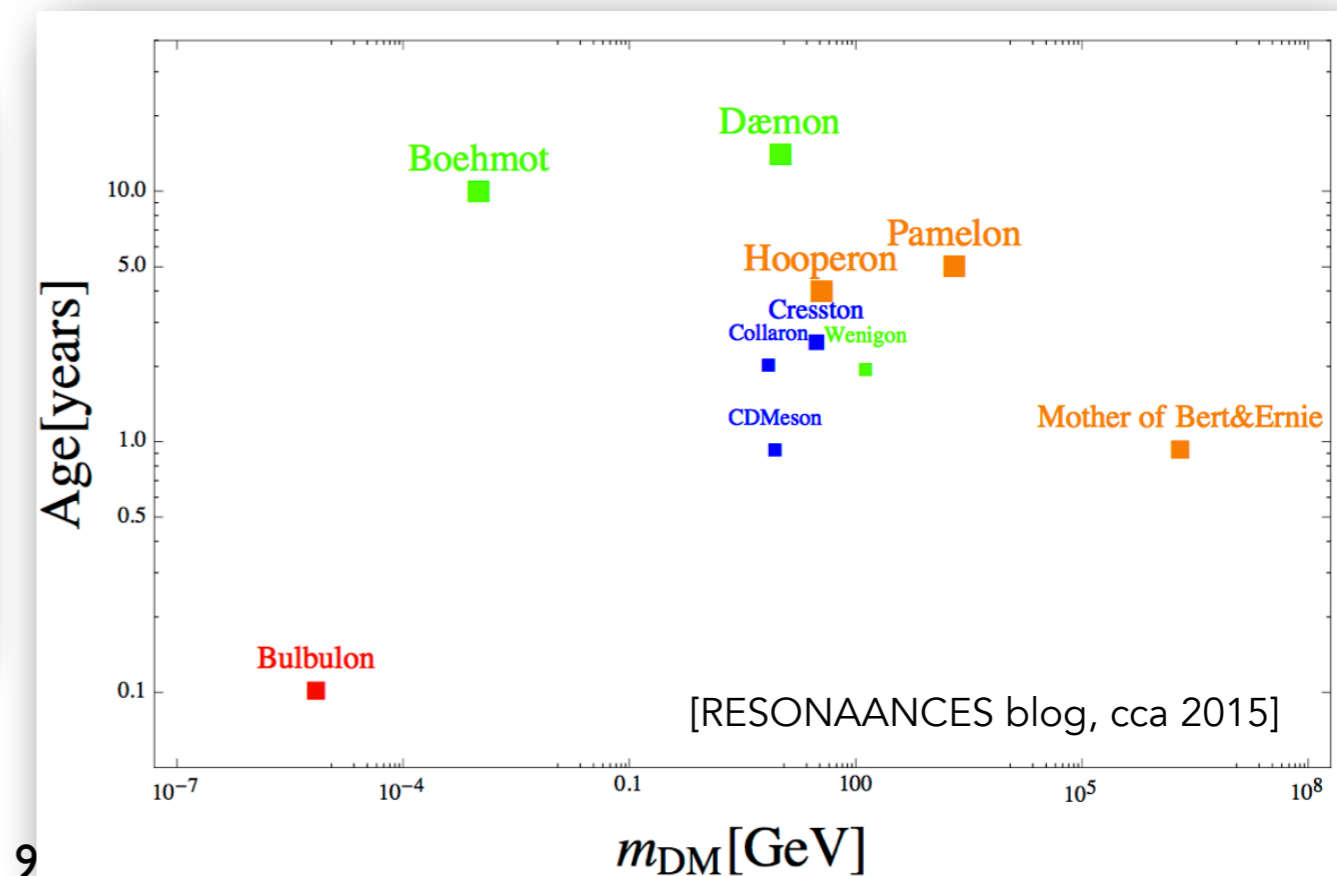
— *all searches model dependent*

What are the options?

X & γ rays   X rays γ, cosmic rays & ν Radio, X & γ rays

Radio lines   X-ray lines

Structure formation   Structure formation

$10^{-19}\,\mathrm{eV}$ $\mu\mathrm{eV}$ $0.1\,\mathrm{eV}$ keV MeV GeV $10^2\,\mathrm{TeV}$ $10^{-16}\,M_\odot$ $10\,M_\odot$ $10^3\,M_\odot$

Fuzzy DM   QCD axion/ALPs   Sterile ν WIMPs & WIMPzillas   PBH

Wave vs particle   *Particle 'zoo'*   *Macro objects*

Astrophysical probes of the nature of DM

Warning!

Given the complexity of astrophysical phenomena and experimental challenges it happens to stumble upon curious signal hints.
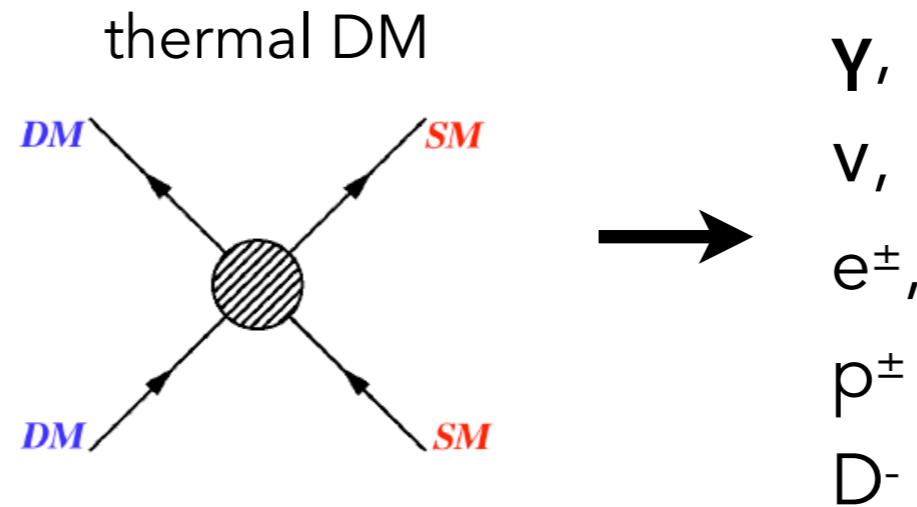

[RESONAANCES blog, cca 2015]

9

thermal particles

ν_s

Planck scale

10^{-10} 1 10^{10} 10^{20} 10^{30} 10^{40} kg

10^{10} 10^{20} 10^{30} eV

weak scale

Primordial black hole   Solar mass

ta *(DM's 'natural habitat')*

- In DM DM interactions

thermal DM

ly' 90 orders of magnitu

γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

γ, ν, $e^{\pm}$, $p^{\pm}$, D^{-}

- In DM conversions/decays
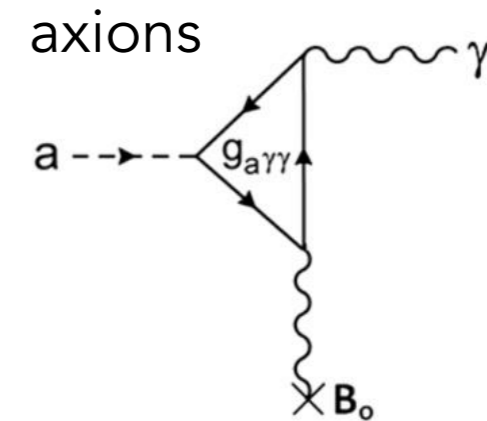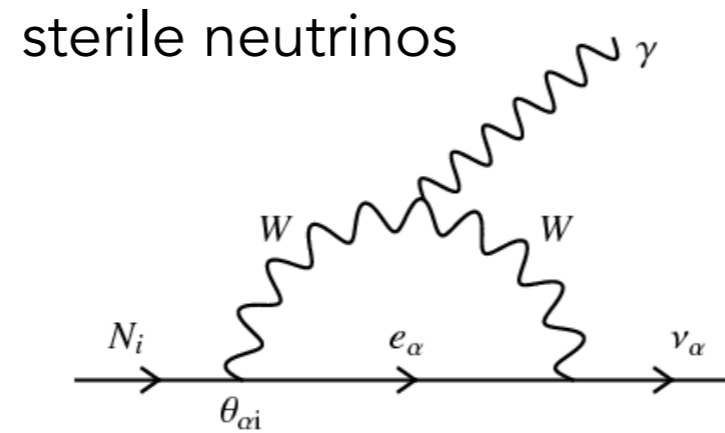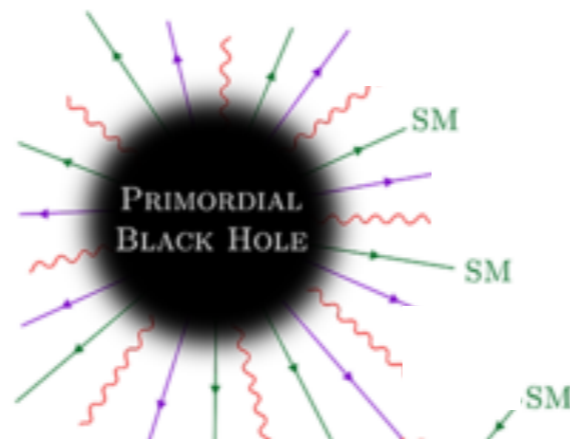
sterile neutrinos

axions

- PBH evaporation…

PRIMORDIAL BLACK HOLE

Searches in astrophysical/cosmological data *(DM's 'natural habitat')*

What are the signatures?

2. Altering of behaviour of astrophysical systems

[credit: Leane, R.]

Dark Matter

Long-lived particle
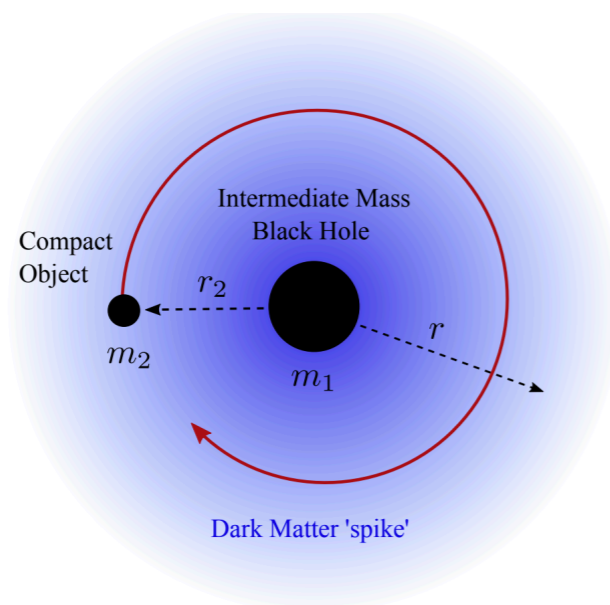
Gamma Rays
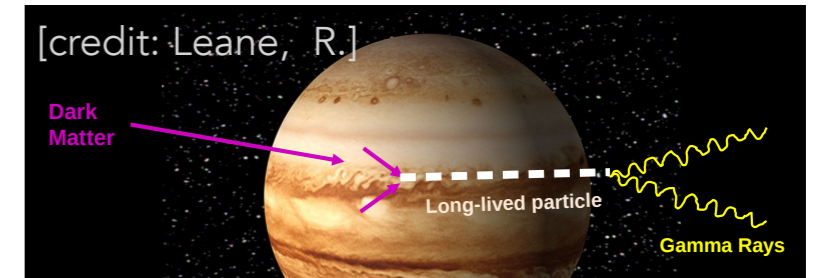
- capture by stars (altering stellar evolution) or planets (altering internal heat production)
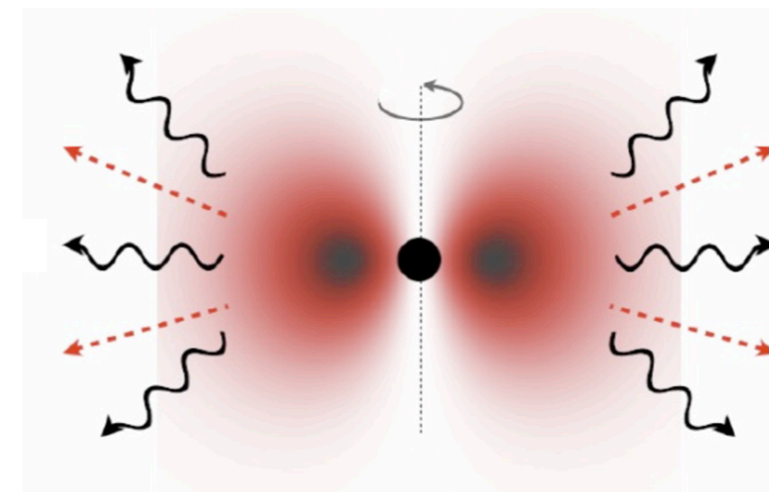
SM

DM

- cooling of stars via DM channel

SM

SM

- affecting GW emission …

DM

SM

Asymmetric DM

Axions…

Compact Object

Intermediate Mass Black Hole

r_2

r

m_2

m_1

Dark Matter 'spike'
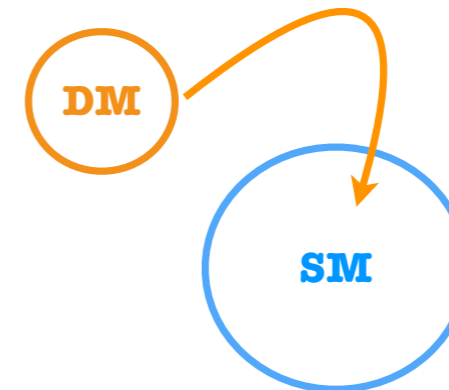
Ultra-ligt bosons

Cold DM "dress" around (P)BHs => de-phasing of GW-form

Gondolo&Silk PRD'99; Zhao&Silk PRD'05; Kavanagh+ PRD'18; Coogan+ arXiv:2108.04154

Light boson fields around BHs => Super-radiance

Brito+ Lect. Notes Phys.'15

Searches in astrophysical/cosmological data *(DM's 'natural habitat')*
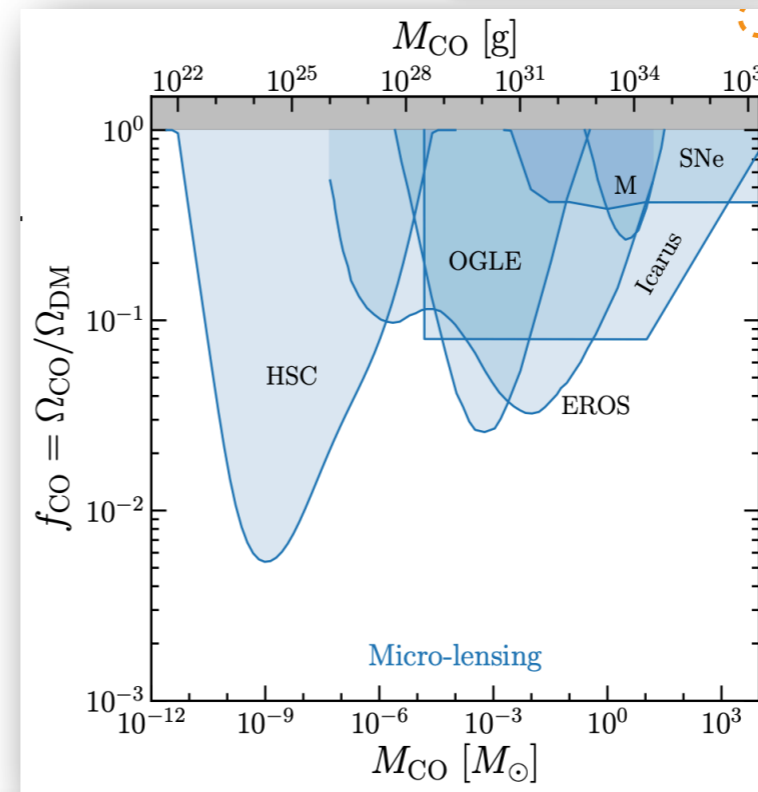
What are the signatures?

PROs: worked so far…

CONs: does not give a handle on other/new forces

3. Purely gravitational interactions with visible matter
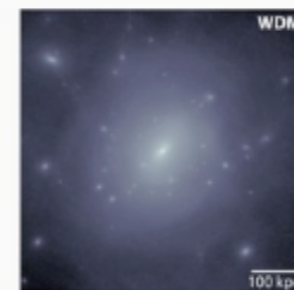
- gravitational lensing

Micro lensing (asteroid to solar masses)
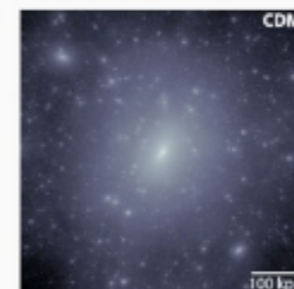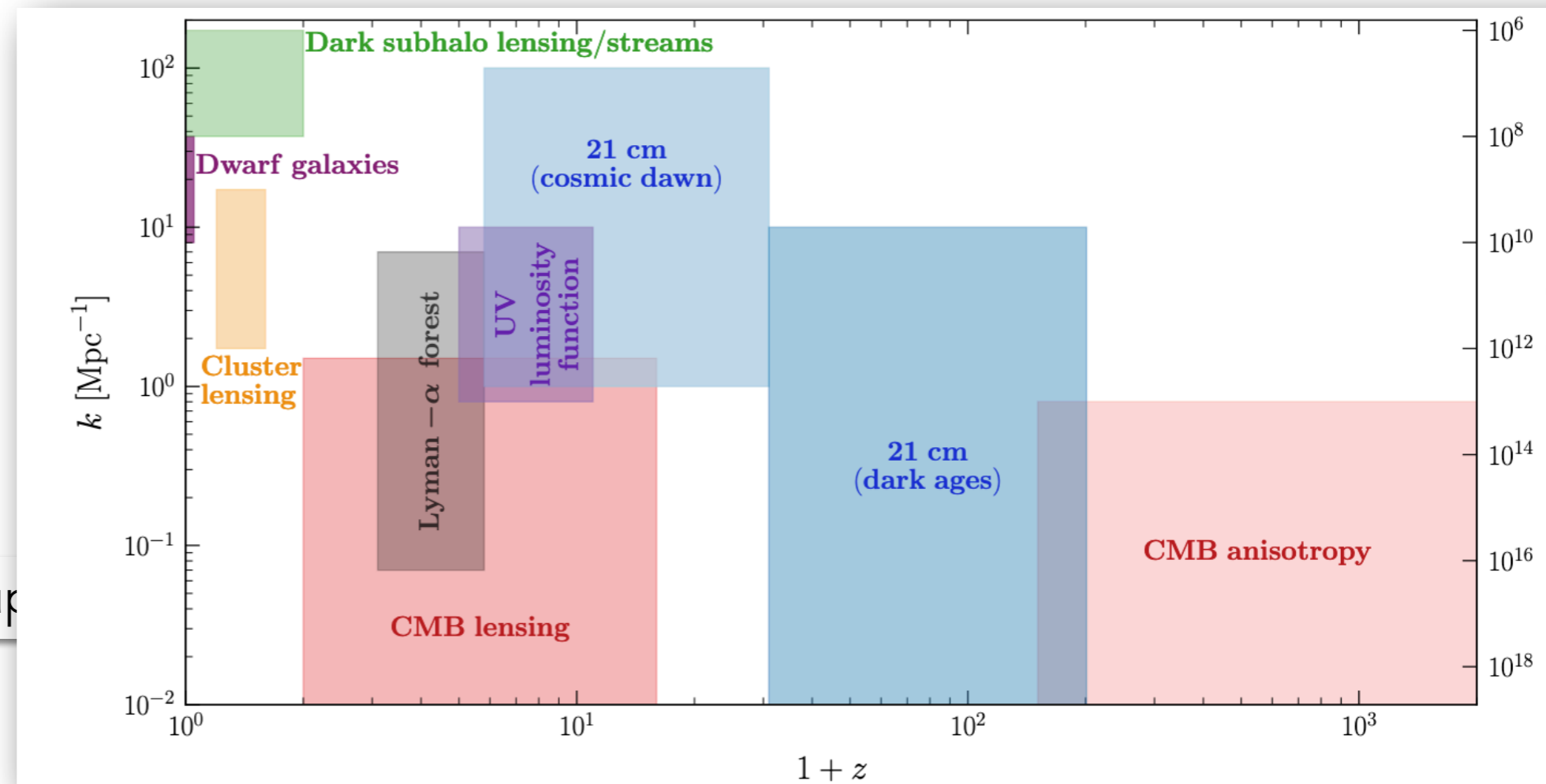
Galaxy-galaxy lensing

- stellar tidal stream disruptions

- stellar wakes…

Stellar stream in a smooth galaxy

Stellar stream in a clumpy galaxy

Bonaca et al. (2014)

Searches in astrophysical/cosmological data *(DM's 'natural habitat')*

What are the signatures?

3. Purely gravitational interactions with visible matter

PROs: worked so far…

CONs: does not give a handle on other/new forces

- gravitational lensing

Micro lensing (asteroid to solar masses)

Galaxy-galaxy lensing

- stellar tidal stream disrup
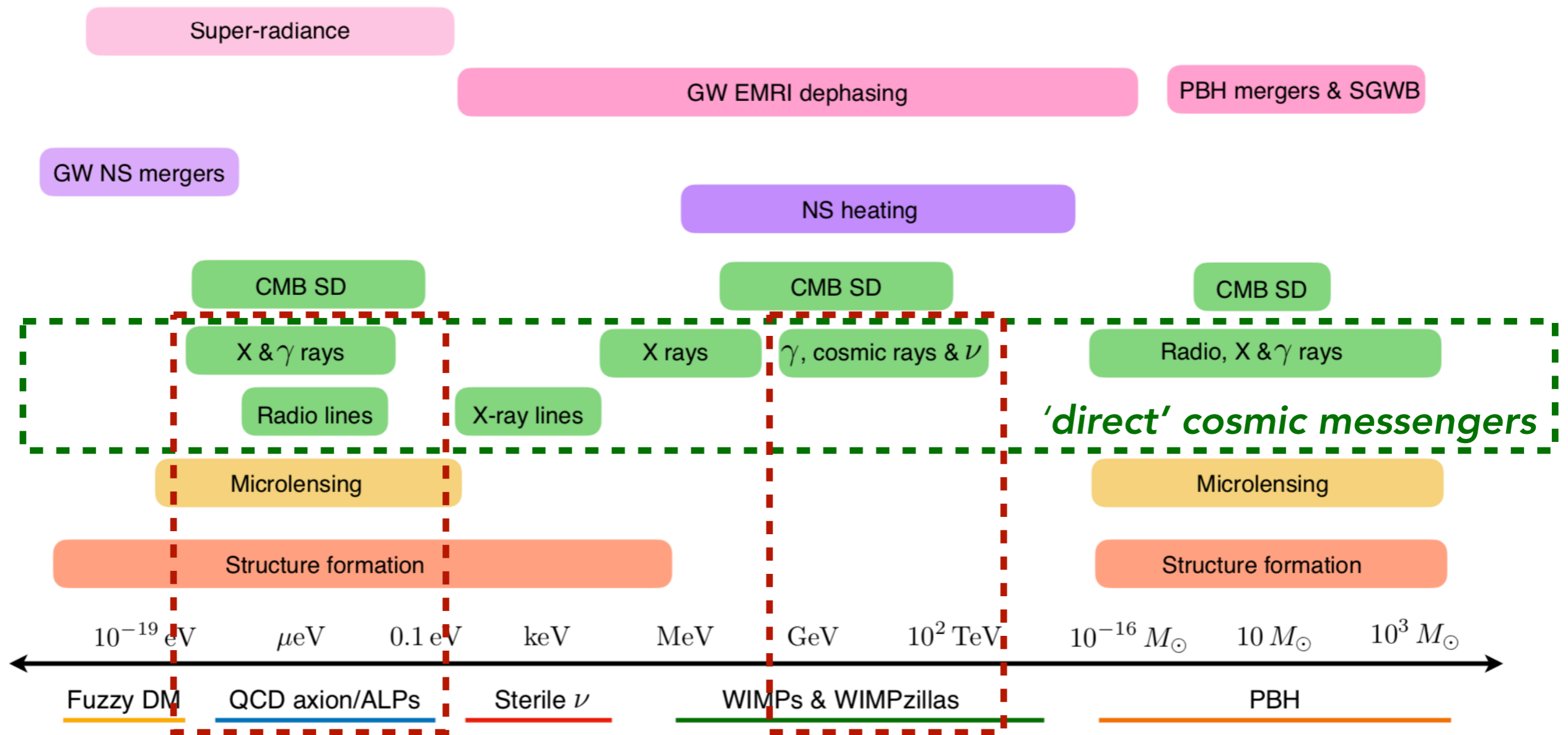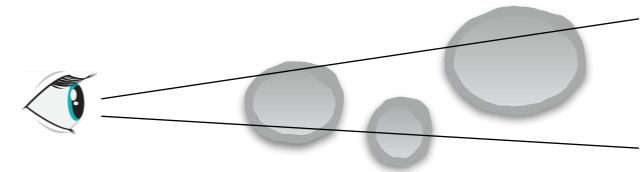
- stellar wakes…

In terms of detection strategies:
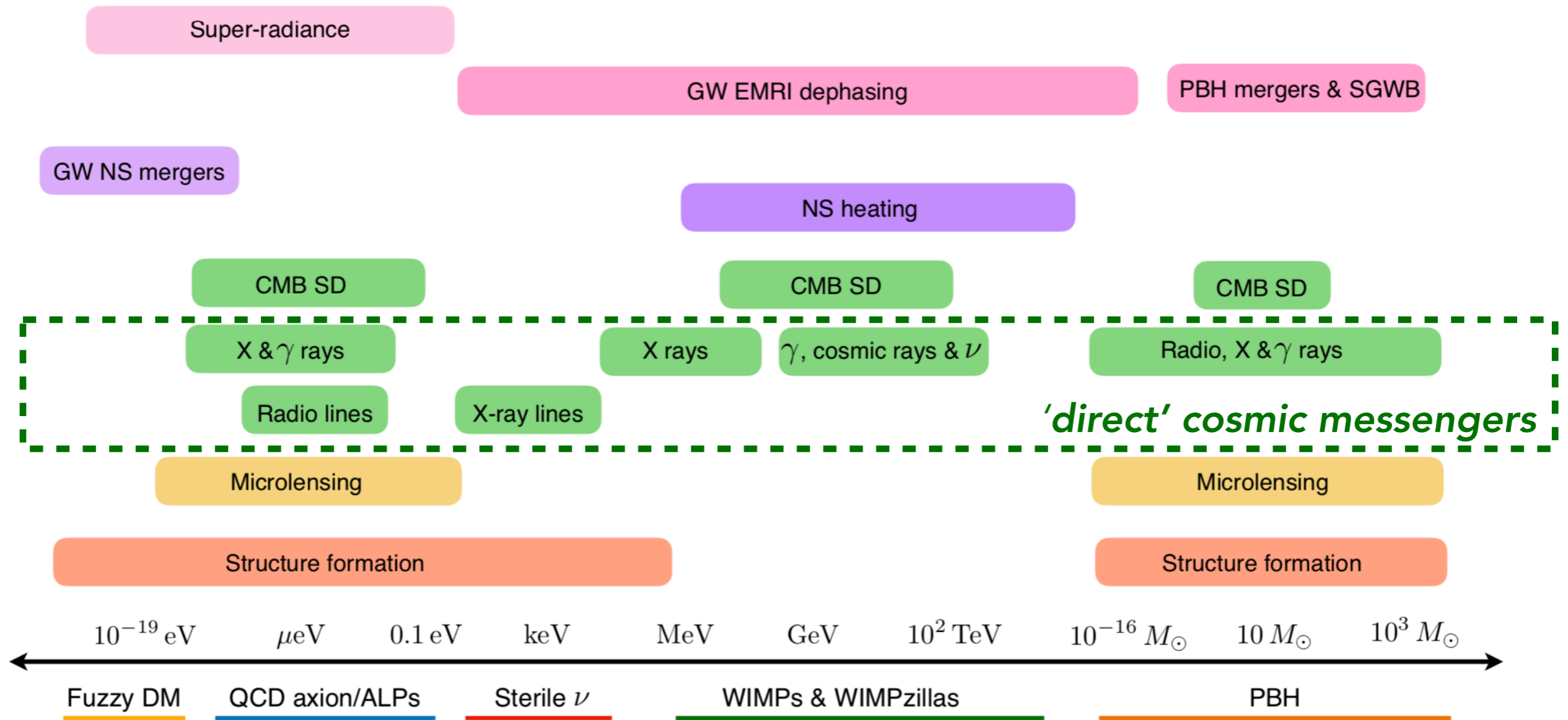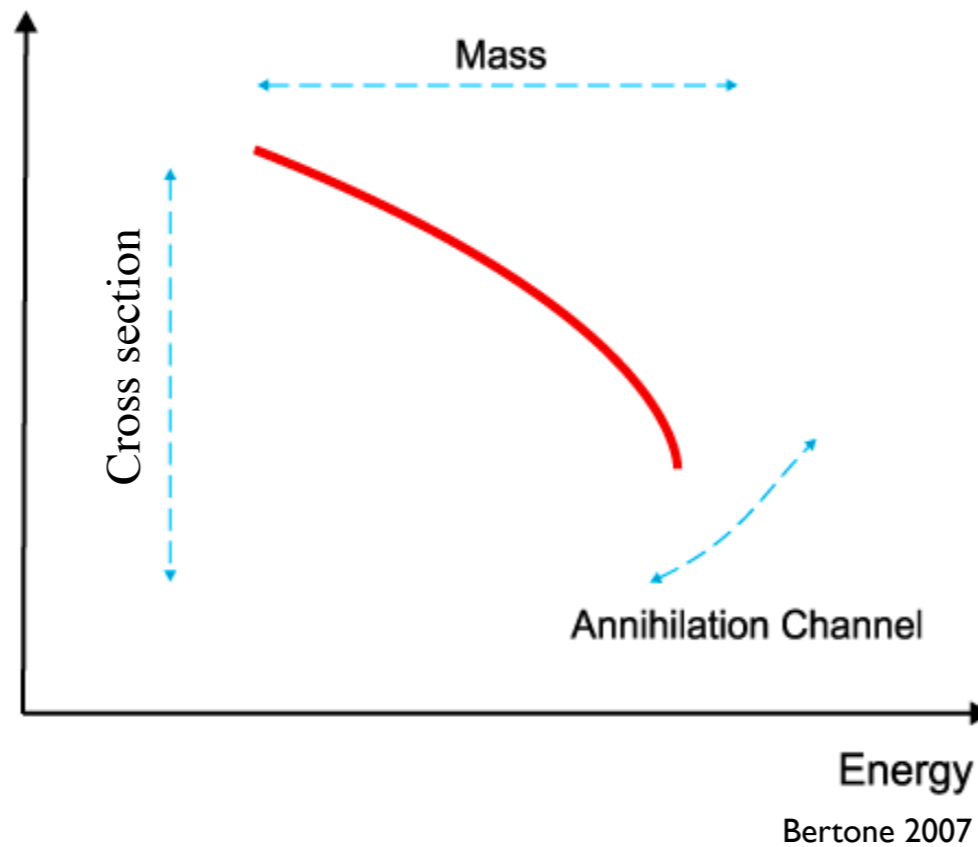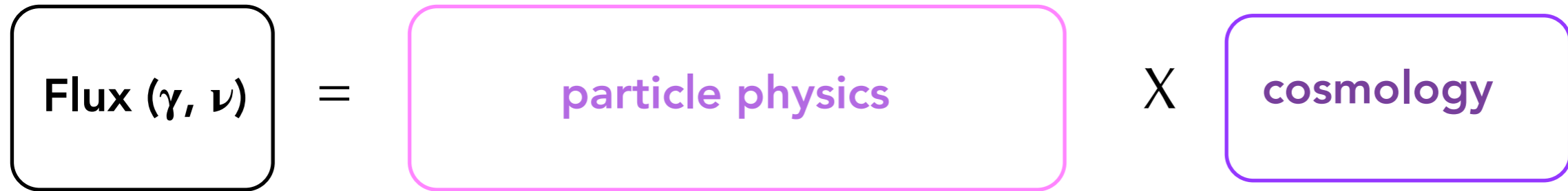
In terms of detection strategies:

EuCAPT white paper,
arXiv: 2110.10074

What is the expected DM signal? - γ's and ν's travel in straight lines!

Indirect dark matter signals

$\text{Flux}(E, \psi) =$ | particle physics | X | **cosmology**

on or decay of dark
an produce a variety of
y detectable Standard
rticles

of annihilation (or decay)
encodes info about
particle properties

in the intensity of the
ng different lines of sight is
ed exclusively by the
on of dark matter
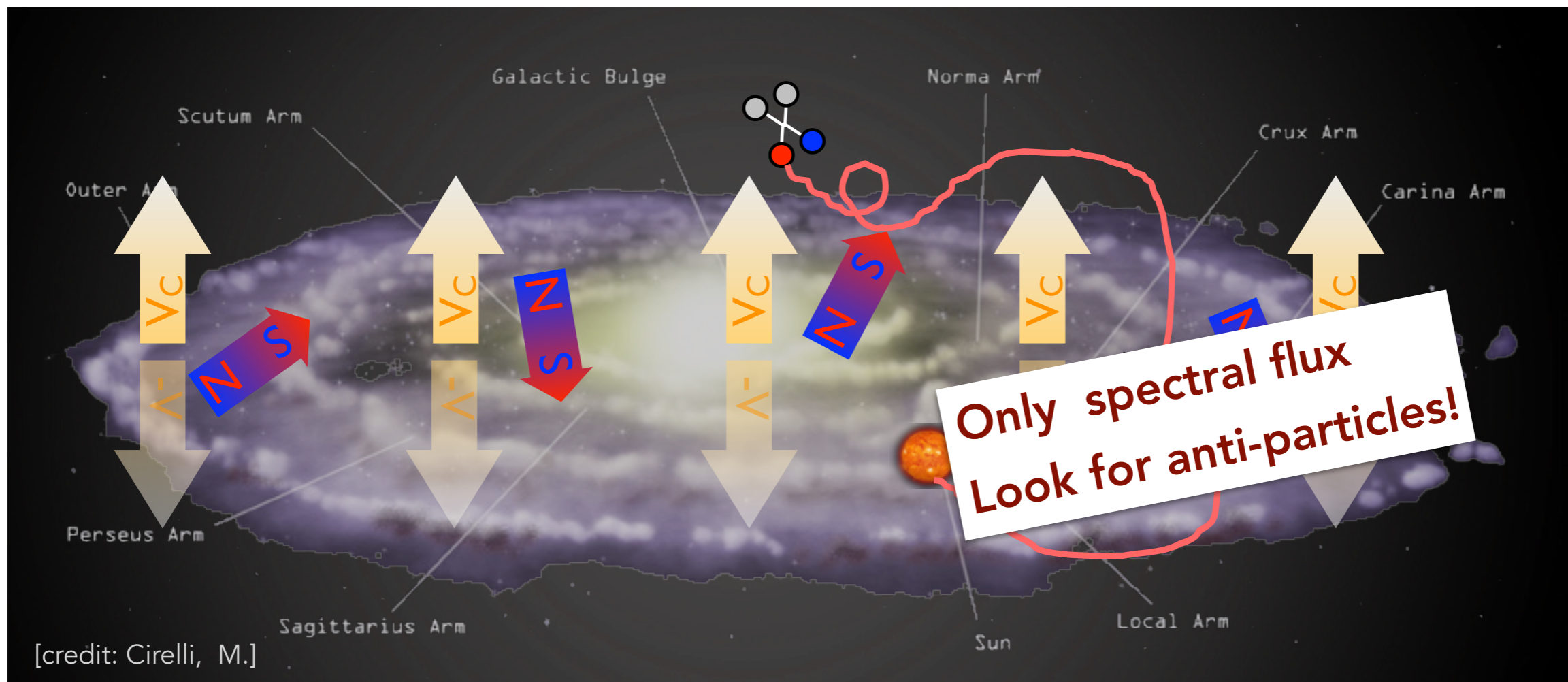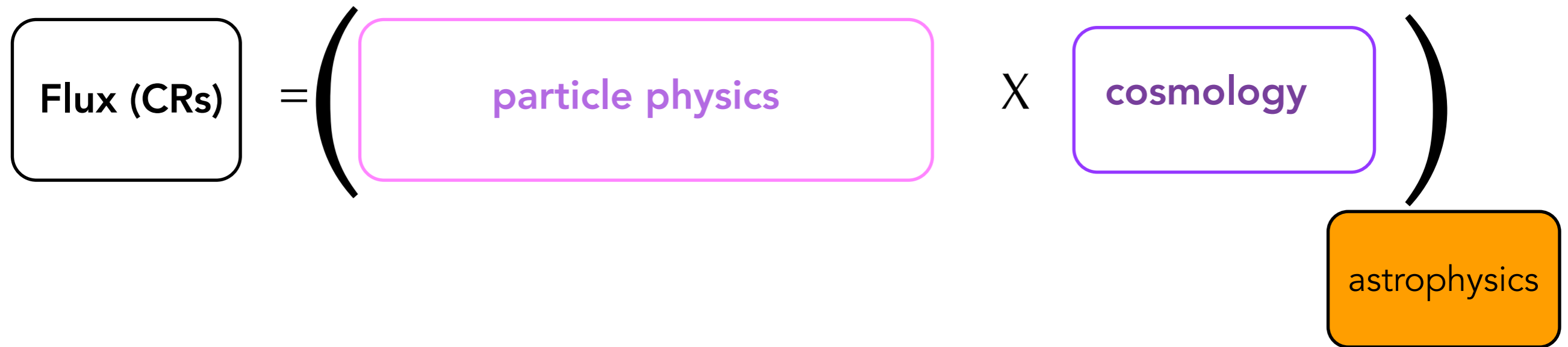

Mass

Cross section

Annihilation Channel

Energy

Bertone 2007

How is DM distributed

WIMP example

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{K}{4\pi} \int_{los} \mathrm{d}s\, \rho^2(s, \psi) \qquad = \qquad \frac{1}{4\pi} \frac{\langle\sigma_{\mathrm{ann}}v\rangle}{2\,m_\chi^2} X^\chi \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma} \qquad X \qquad \int_{\Delta\Omega} d\Omega \int_{los} \mathrm{d}s\, \rho^2(s, \Omega)$$

$$K = \frac{N_\gamma \langle\sigma v\rangle}{2m_\chi^2}$$

What is the expected DM signal? - charged particles

$$\boxed{\text{Flux (CRs)}} = \left(\boxed{\textbf{particle physics}} \quad \text{X} \quad \boxed{\textbf{cosmology}} \right)$$
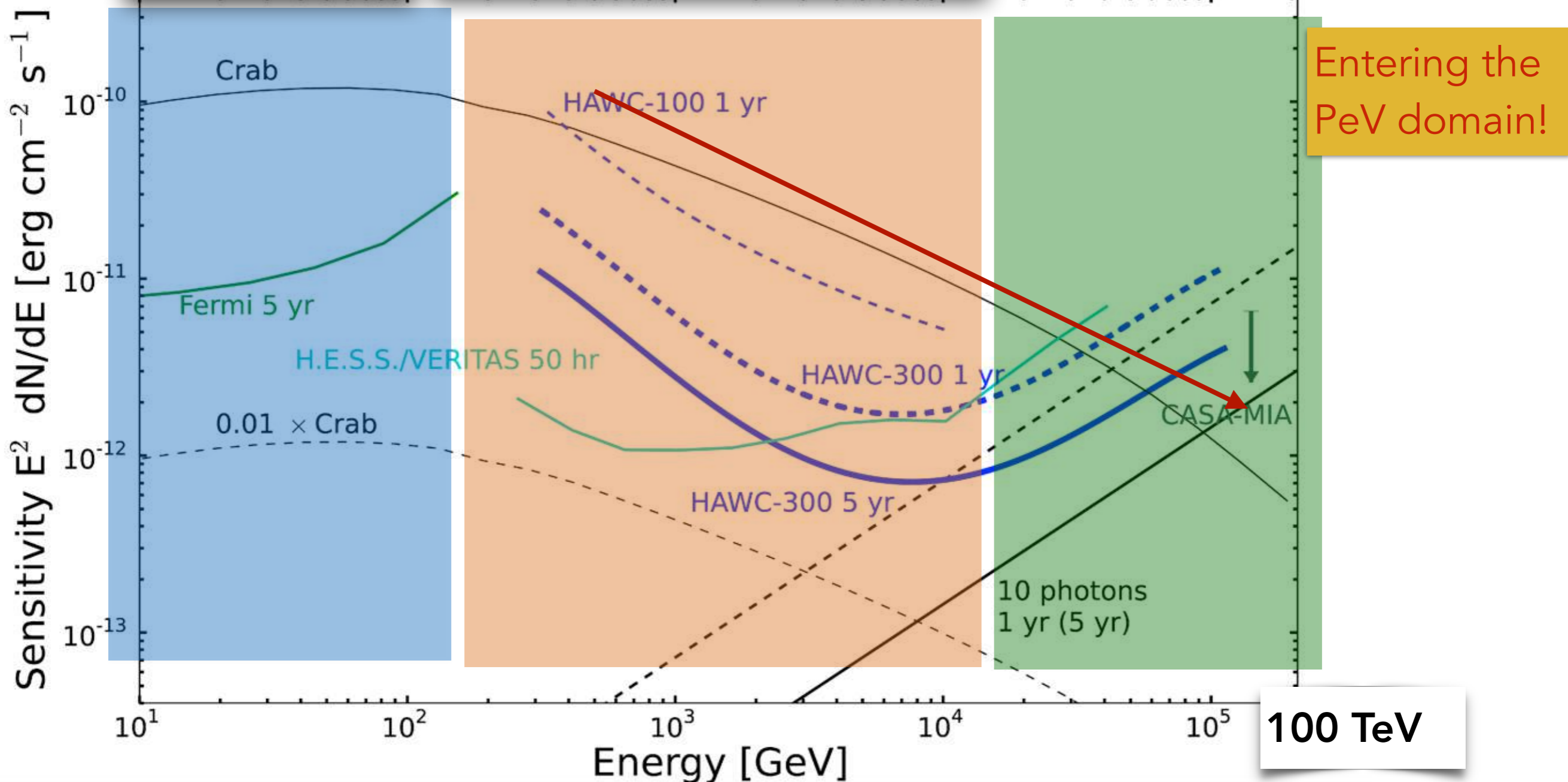
astrophysics

$\bar{p}$ e^+

Only spectral flux
Look for anti-particles!

[credit: Cirelli, M.]

Focus on γ rays
Where to look?

Cumulative signal

500 Mpc/h

Nearby galaxies

Galaxy Clusters

30 kpc

dSph Galaxies

Galactic Centre

Dark sub halos

[Aquarius Simulation]

What tools?

Fermi LAT, AGILE

IACTs (H.E.S.S., MAGIC, VERITAS)

HAWC

Tibet ASγ, LHAASO

Entering the PeV domain!

Crab

HAWC-100 1 yr

Fermi 5 yr

H.E.S.S./VERITAS 50 hr

0.01 × Crab

HAWC-300 1 yr

CASA-MIA

HAWC-300 5 yr

10 photons 1 yr (5 yr)

Sensitivity E^2 dN/dE [erg cm^{-2} s^{-1}]

Energy [GeV]

100 TeV

GeV vs TeV

>300 MeV

LAT sky

>10 GeV

>~100 GeV

HESS, Galactic center Ridge

~5k sources

~1.5k sources

~200 sources
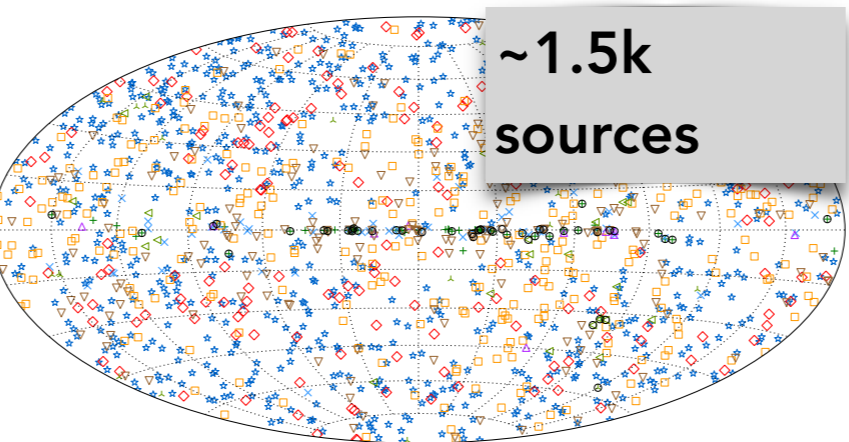
LAT source catalogue, >300 MeV (4FGL)

LAT source catalogue, **>10 GeV** (3FHL)

TeVCat,

+12 sources >0.1 PeV (LHAASO) & HAWC, Tibet AS candidates

What strategies (WIMPs)?

signal strength

GC

dark subhalos

GC halo
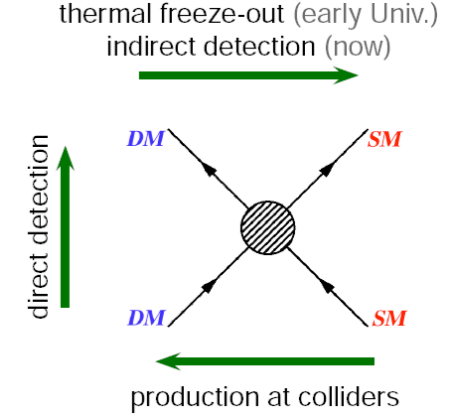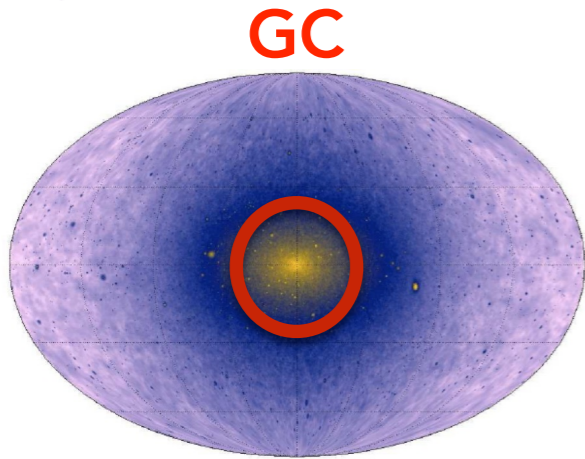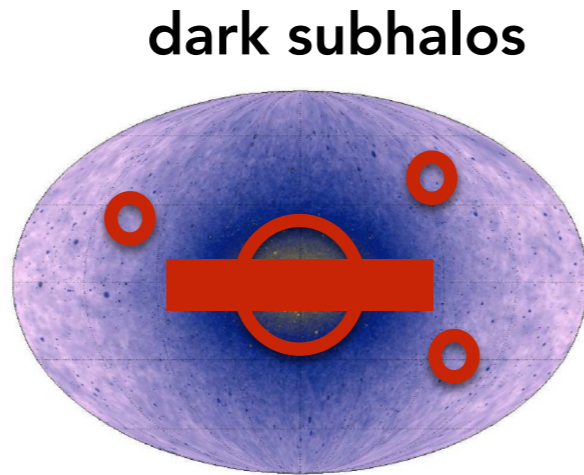
Extragalactic sources

- clusters of galaxies
- other galaxies (M31, M33, LMC, SMC)
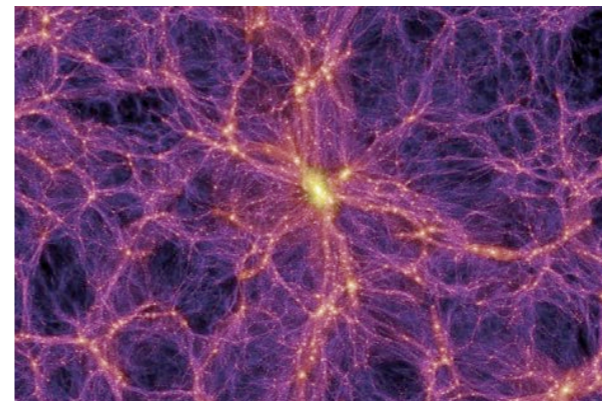
dwarf satellites
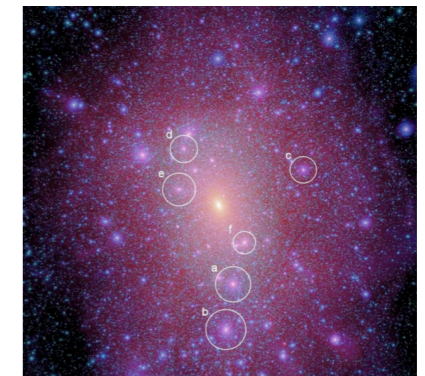
spectral line

- Auto-correlations
- Cross-correlations w G catalogs and cosmic sf

robustness

[Acharyya et al. JCAP 2020.]

[adapted from: H.-S. Zechlin]

Reg4 (SOURCE), $E_\gamma = 129.8$ GeV
Signal counts: 57.0 (4.63σ)   80.5 - 210.1 GeV
p-value=0.46, $\chi^2_{red} = 22.1/22$

Counts

State-of-the-art
cca 2016

Legend:
- LAT dSphs: (proj. 15 yrs 60 dSphs)
- CTA GC Halo 500h: Lefranc+ (2015)
- CTA MW Halo 500h: Carr+ (2015)
- HESS, MW Halo: Lefranc+ (2015)
- Planck: Ade+ (2015)

HESS

H.E.S.S.

HESS GC

Fermi LAT

Thermal Relic Cross Section (Steigman+ 2012)

— Abazajian+ (2015)
— Gordon & Macias (2013)
— Daylan+ (2014)
— Calore+ (2014)

Fermi LAT dSphs

$b\bar{b}$

$\langle\sigma v\rangle$ [cm^3 s^{-1}]

m_χ [GeV]

[Charles, E.+, JCAP, 2016]

State-of-the-art

Note that dSPh limits could be weaker due to DM density distribution uncertainties

[Ando, S.+, 2020]

Bayesian 95% upper limits (cond. on m)

11 years of Pass 8 (R3) data

31 dSphs, $b\bar{b}$ channel

Fermi LAT dSphs

Priors

$- -$ log-uniform + GS15 cut

$-\cdot\cdot$ $V_{\text{peak}}^{\text{th}} = 6\,\text{km s}^{-1}$

$-$ $V_{50} = 10.5\,\text{km s}^{-1}$

$-\cdot\cdot$ $V_{50} = 18\,\text{km s}^{-1}$

$-$ Thermal relic cross section (Steigman+ '12)

Cross section $\langle \sigma v \rangle$ [cm^3 s^{-1}]
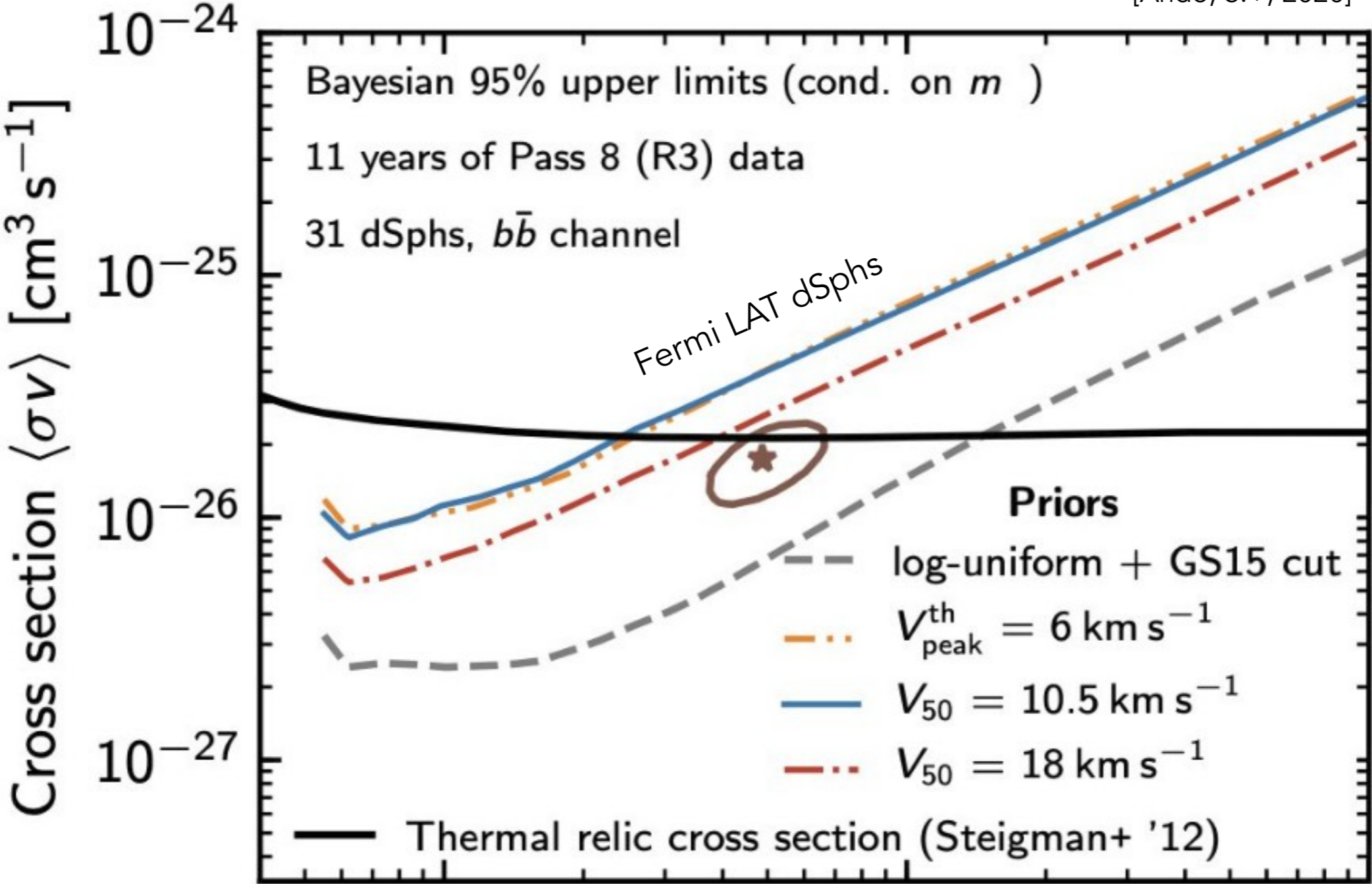
State-of-the-art

★ Stack likelihood functions of 20 dwarf satellite galaxies by 5 gamma-ray telescopes (Fermi-LAT, MAGIC, H.E.S.S., VERITAS, HAWC)

Table 2: Summary of the relevant properties of the dSphs used in the present work. Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance and Galactic coordinates, respectively. Columns 4 and 5 report the J-factors of each source given from the $\mathcal{GS}$ and $\mathcal{B}$ independent studies and their estimated $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ ($\mathcal{GS}$ set) correspond to the mean J-factor values for a source extension truncated at the outermost observed star. The values $\log_{10} J$ ($\mathcal{B}$ set) are provided for a source extension at the tidal radius of each dSph.

Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}$	$17.70^{+1.08}$

$\chi\chi \to b\bar{b}$ — Preliminary (Combination)

$\chi\chi \to \tau^+\tau^-$ — Preliminary

Legend:
- Combination
- H_0 median
- H_0 68% containment
- H_0 95% containment
- Thermal relic (σv)
- Fermi-LAT
- HAWC
- H.E.S.S.
- MAGIC
- VERITAS

$$\mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}|\mathcal{D}_\gamma) = \prod_{i=1}^{N_{E'}}\prod_{j=1}^{N_{\hat{p}'}} P\left(s_{ij}(\alpha\bar{J};\boldsymbol{\mu}) + b_{ij}(\boldsymbol{\mu})|N_{ij}\right) \cdot \mathcal{L}_\mu(\boldsymbol{\mu}|\mathcal{D}_\mu)$$

More data +
excellent collaboration between experiments!

[Armand, C.+, 2108.13646]

State-of-the-art

1-3 GeV residual

Galactic Center Excess
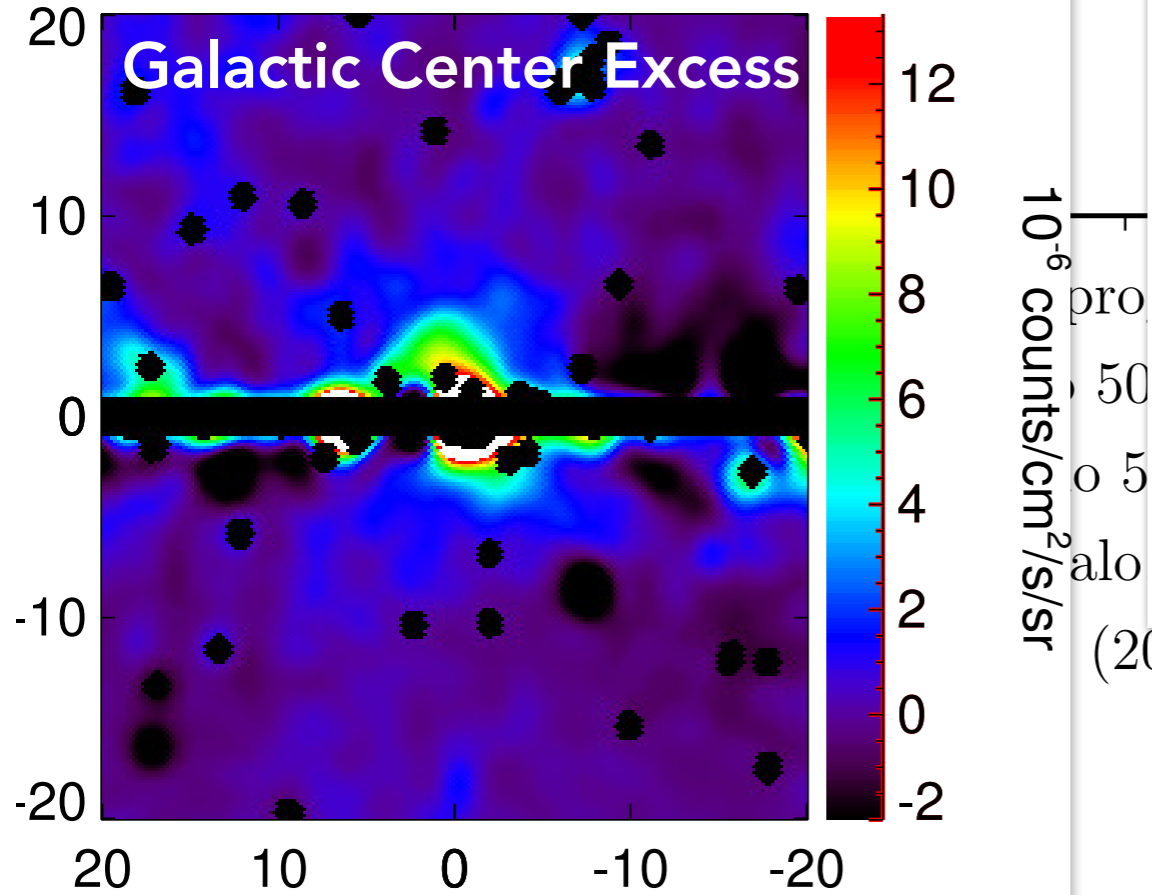
~thermal cross section

~100 GeV
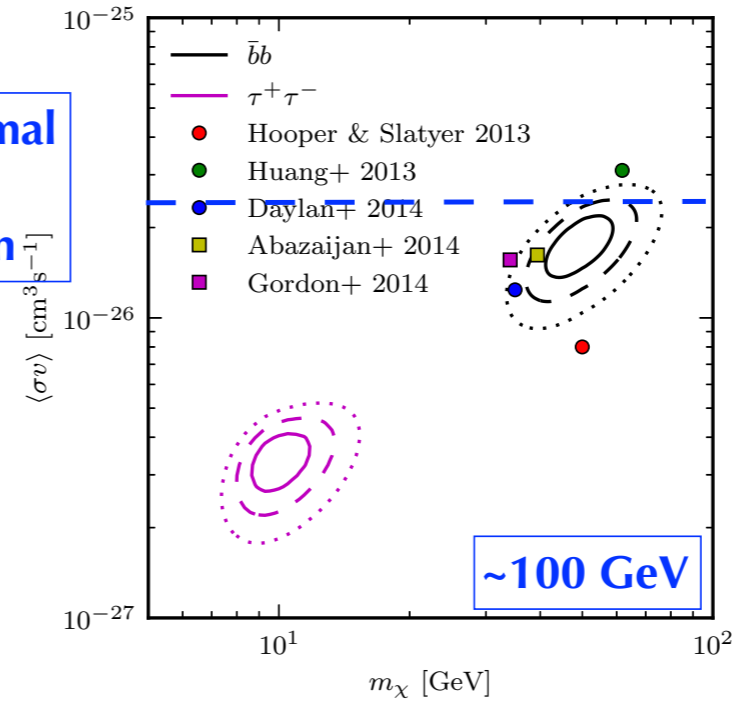
## Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)

Baltz et a (2007)
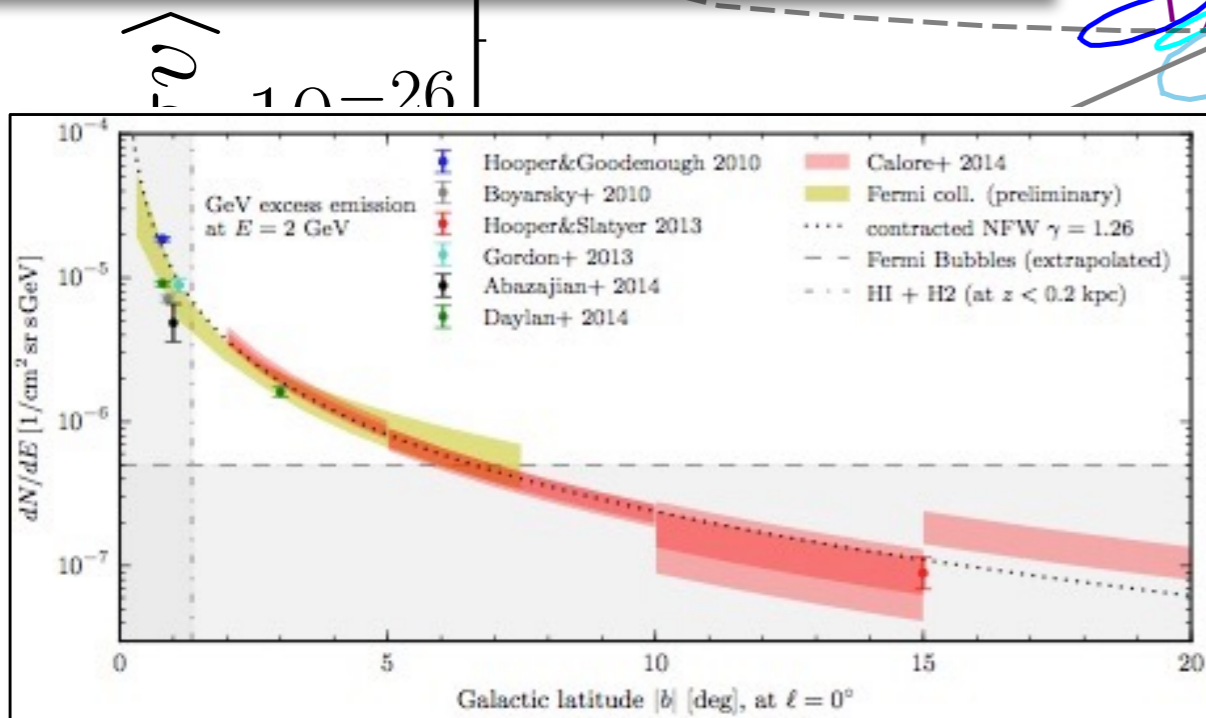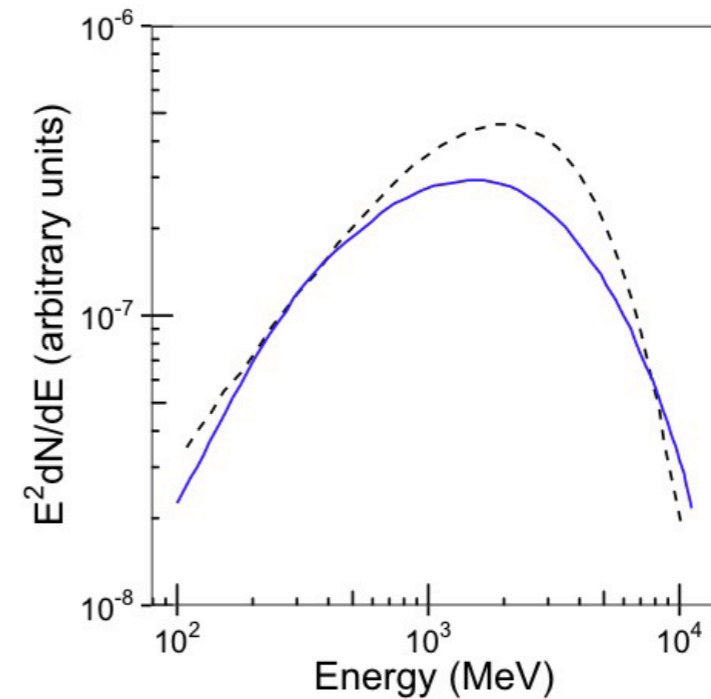
State-of-the-art

Pulsars are spectral twins of DM + about 300 pulsars discovered in the LAT data (none in the inner GC region)
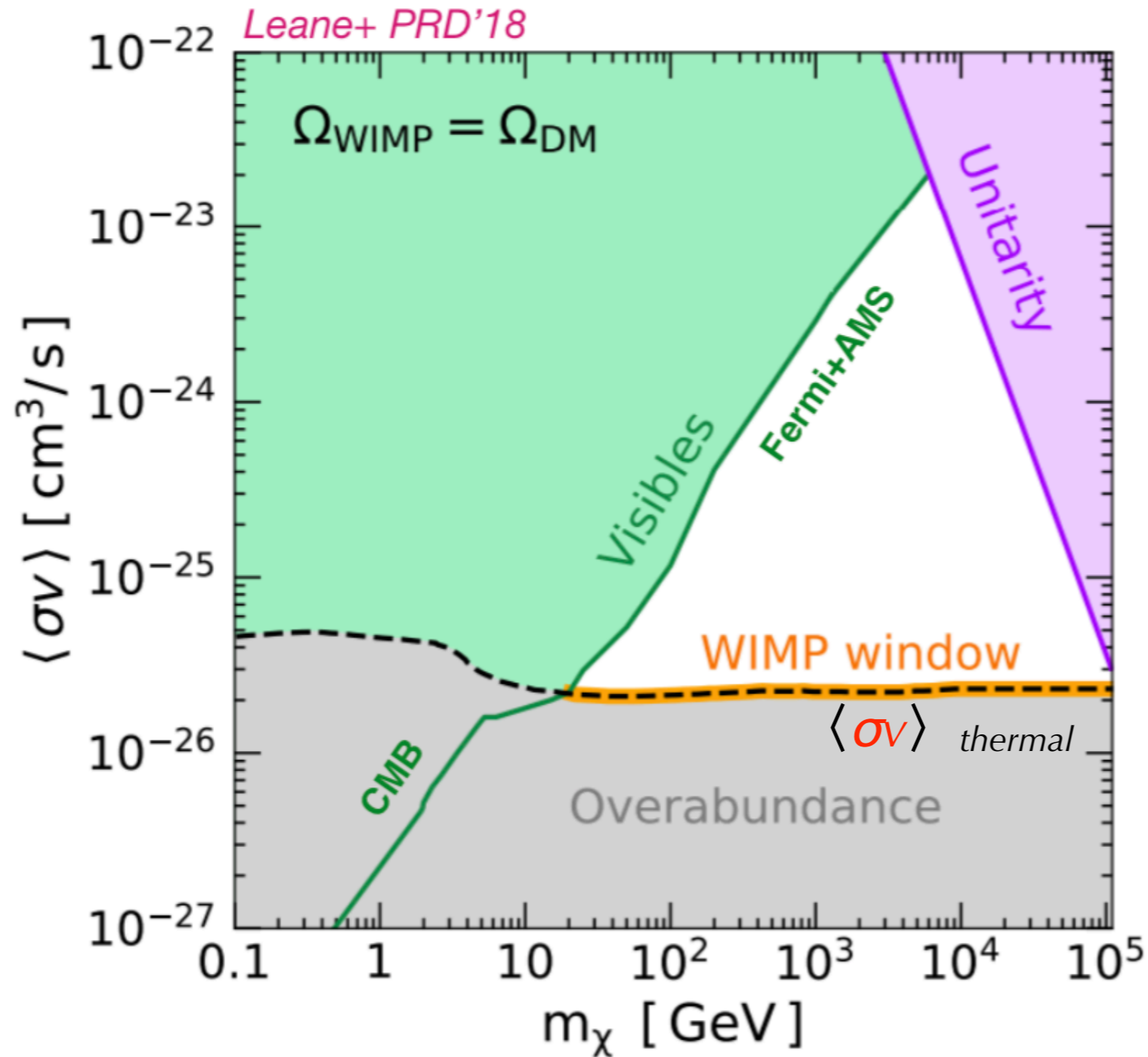
Fierce debate ongoing!

- 1D-PDF analysis: 'DM strikes back at the GC', Leane&Slatyer, 1904.08430
- Wavelet analysis: after accounting for 4FGL sources results changed, Zhong+, 1911.12369
- Detection of a Bulge/Bar-Like morphology questioned, Cholis +, 21...

Mind the (reality) gap!

Using **Deep ensambles of Convolutional Neural Networks**

[Caron, S.+ (wGZ), in prep.]
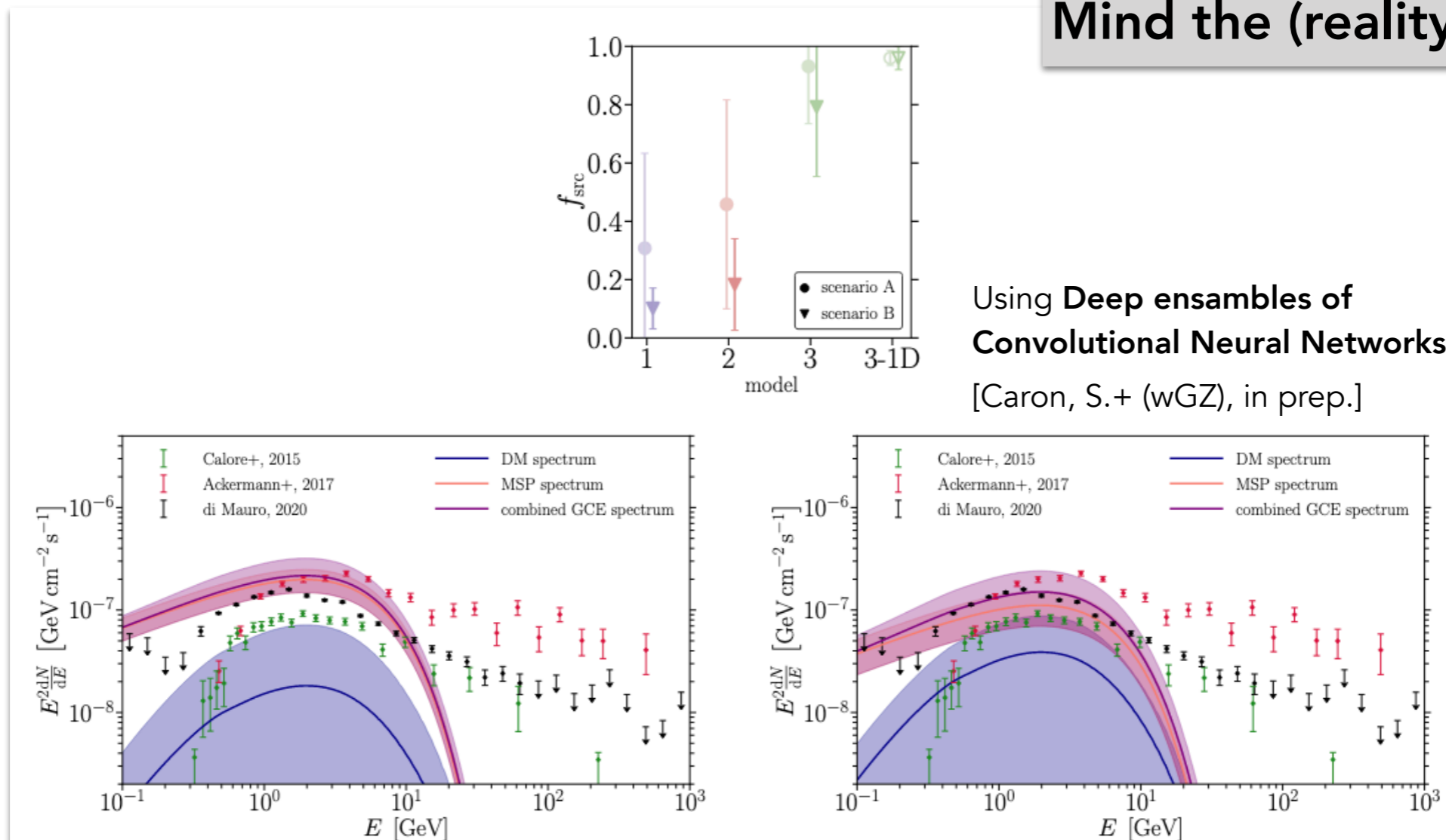
State-of-the-art
'cornering the WIMP'

The 'TeV window' still remains to be explored

The future: CTA

Dedicated observational strategy: **sky surveys**

- **Unbiased view** of the sky
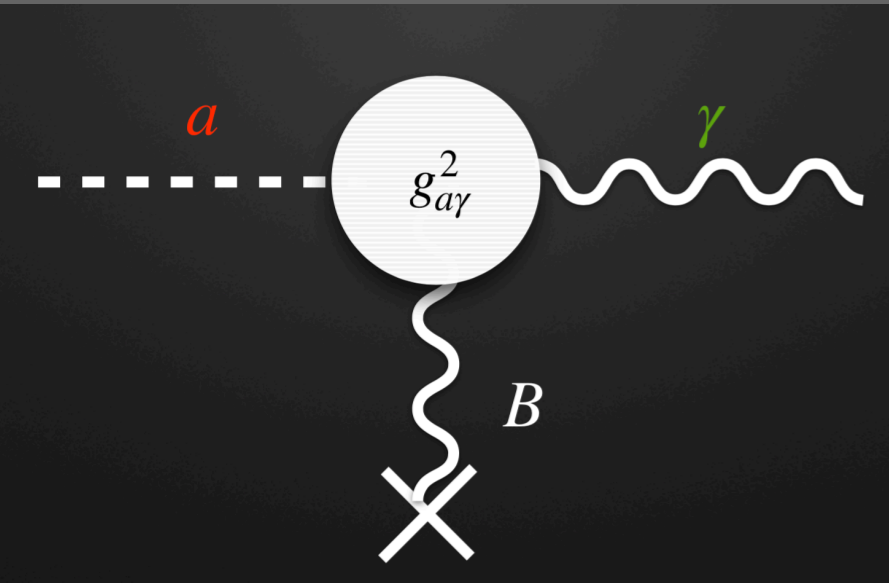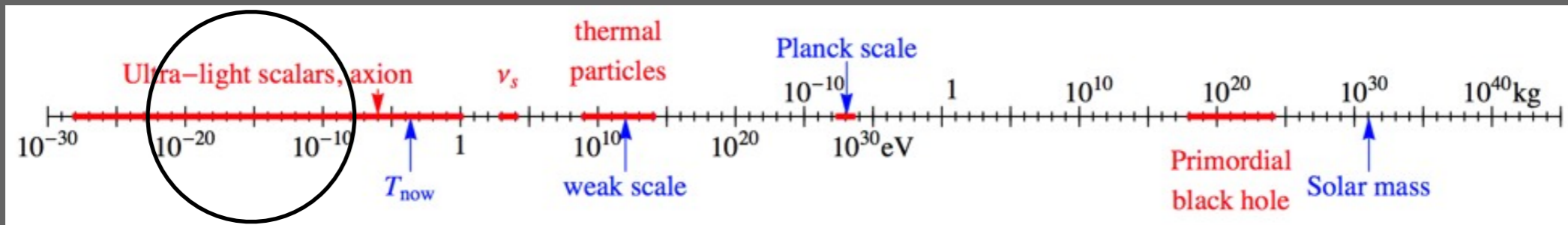- Bridging the differences with **satellite data**
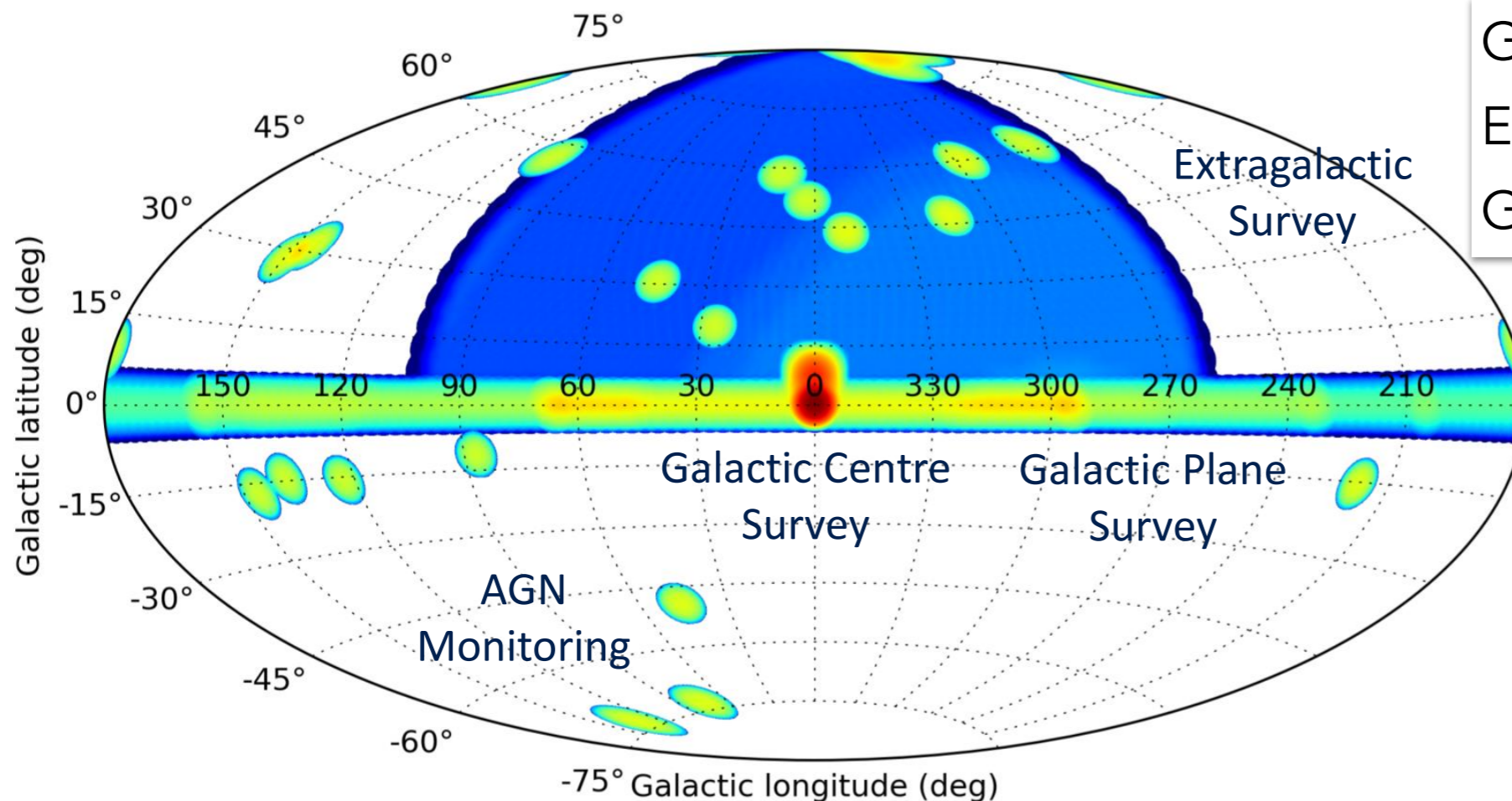
Galactic Plane survey
Extragalactic survey
Galactic center survey

CTA: WIMPs@ GC

DM sensitivity in a range of targets being explored

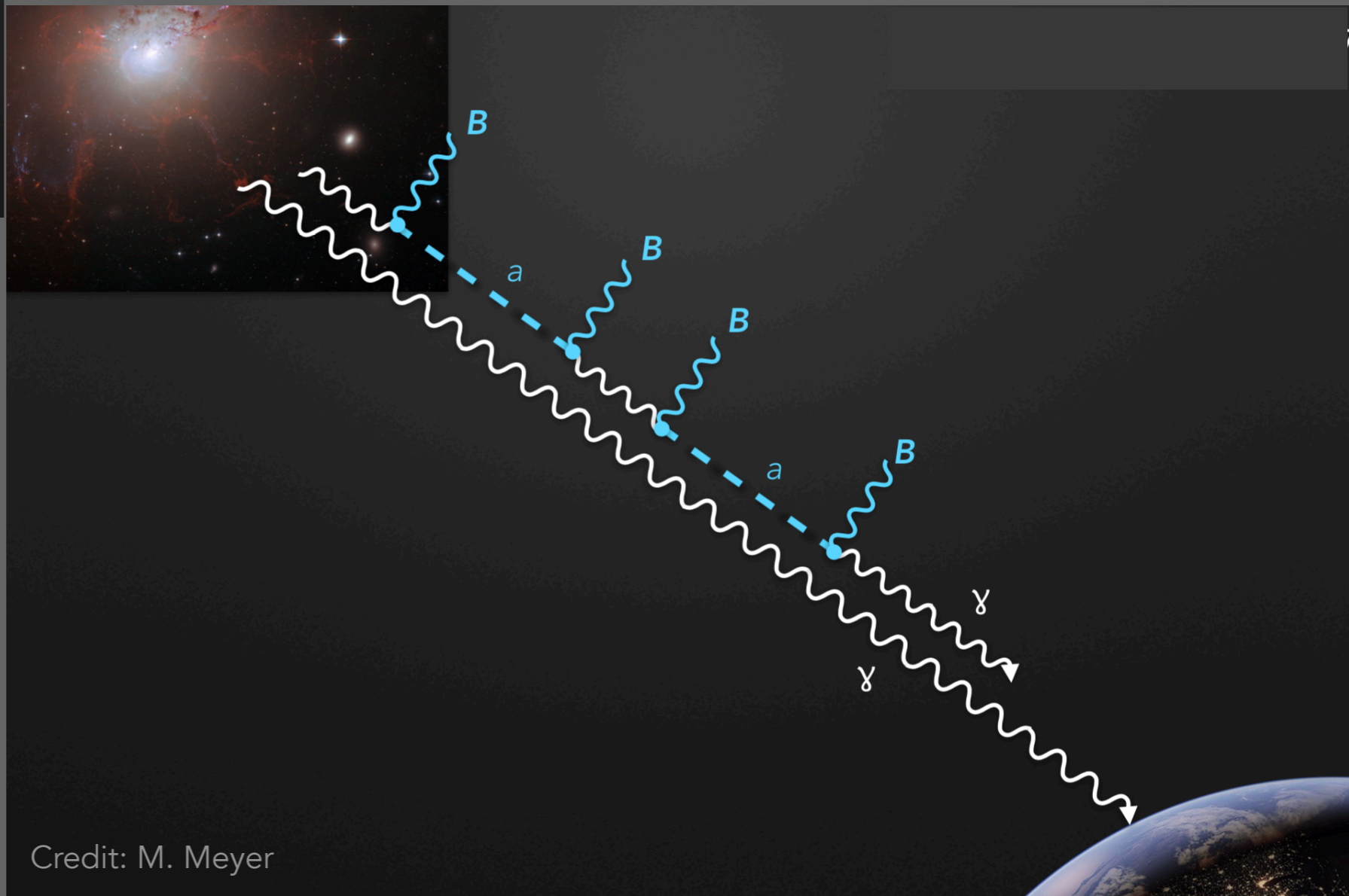The observation of the GC has the potential to close the WIMP TeV window

[Archaryya et al. JCAP (2020)]

signal: Einasto
background: CR + IEM (Gamma)
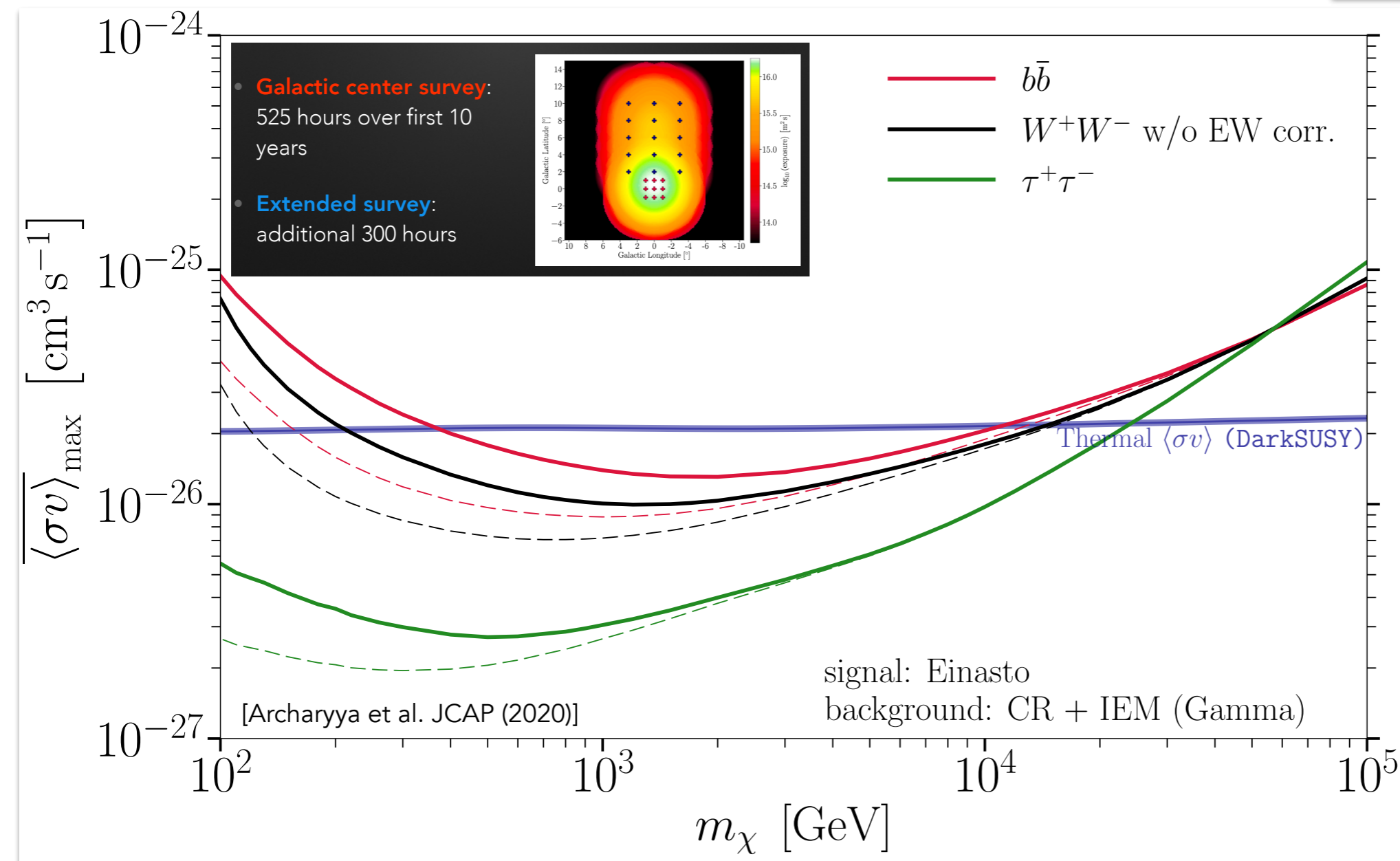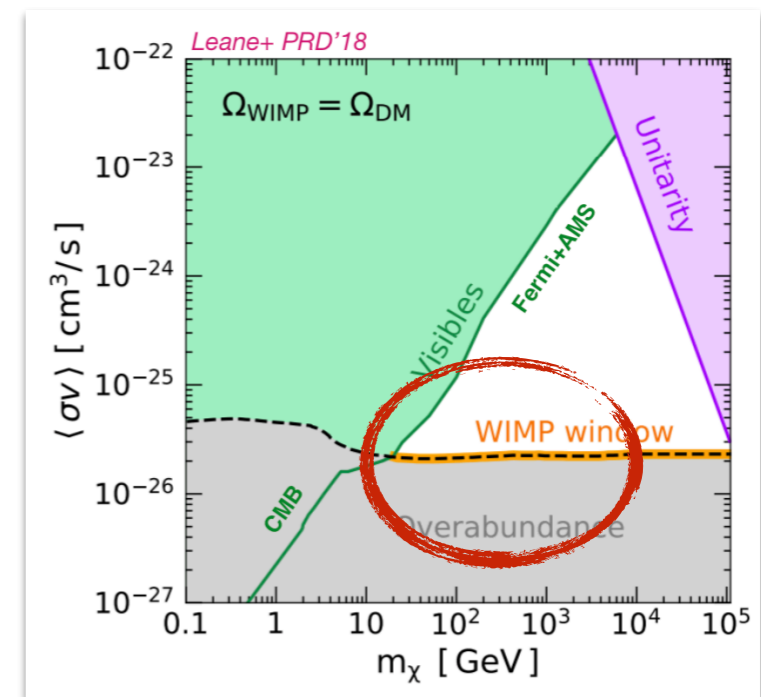
What strategies - **ALPs**?

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

a $g_{a\gamma}^2$ γ

B

Where to look?

- **strong magnetic fields** over
- **large distance scales**
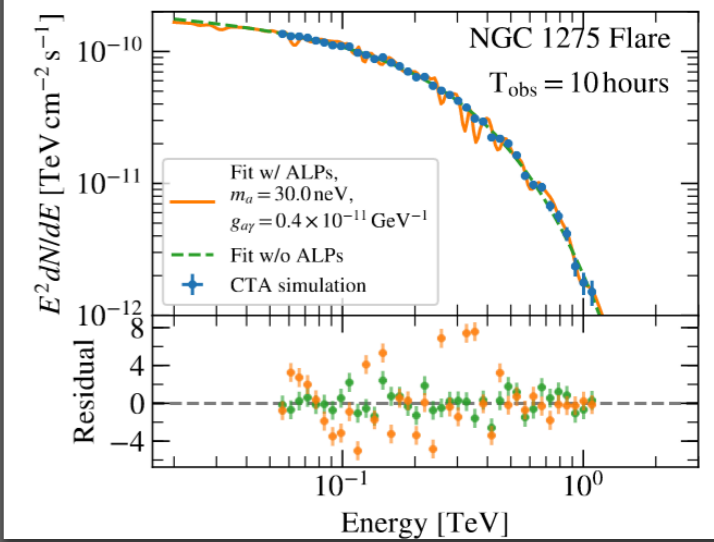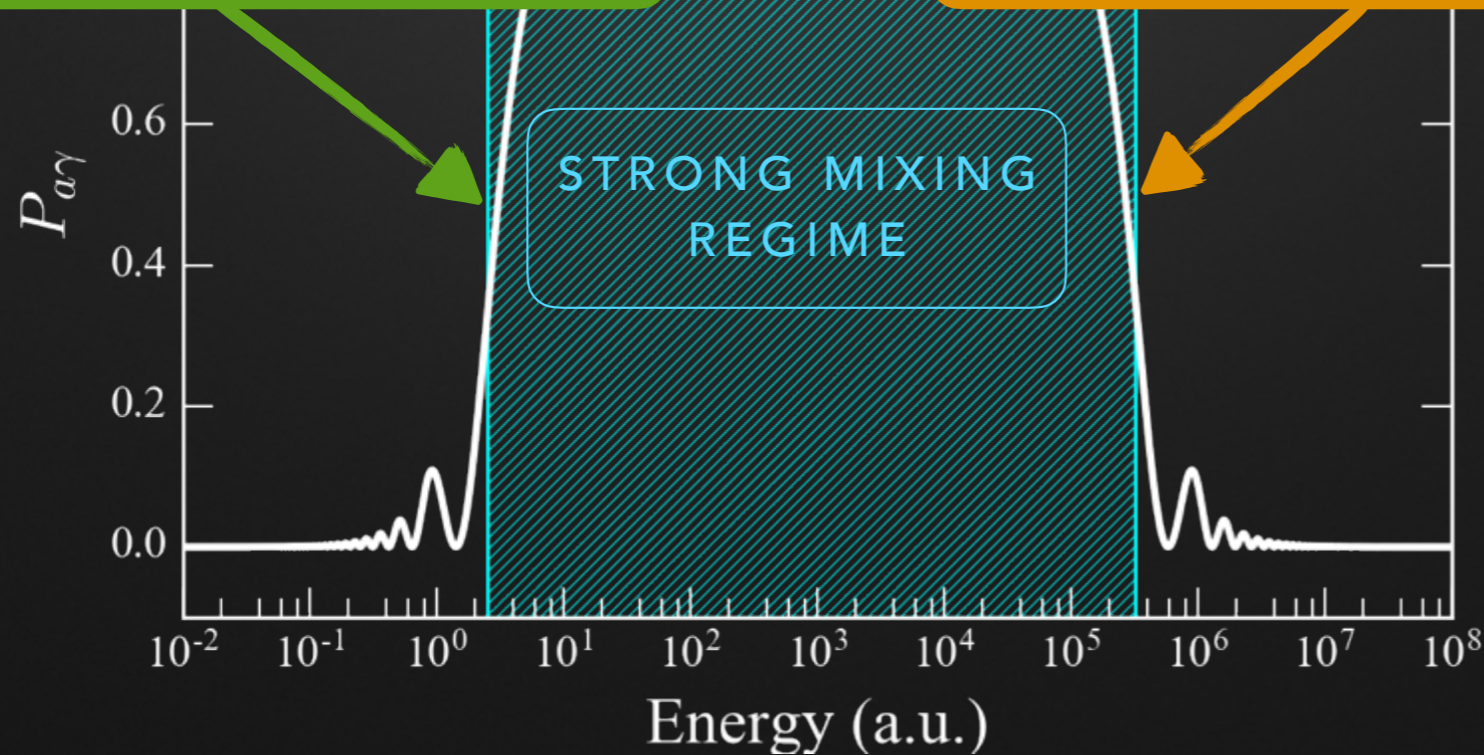
→ e.g. **galaxy clusters**

Credit: M. Meyer

CRITICAL ENERGY

$$E_{\text{crit}} \sim 2.5 \, \text{GeV} \, \frac{|m^2_{a,\text{neV}} - \omega^2_{\text{pl, neV}}|}{g_{11}B_{\mu\text{G}}}$$
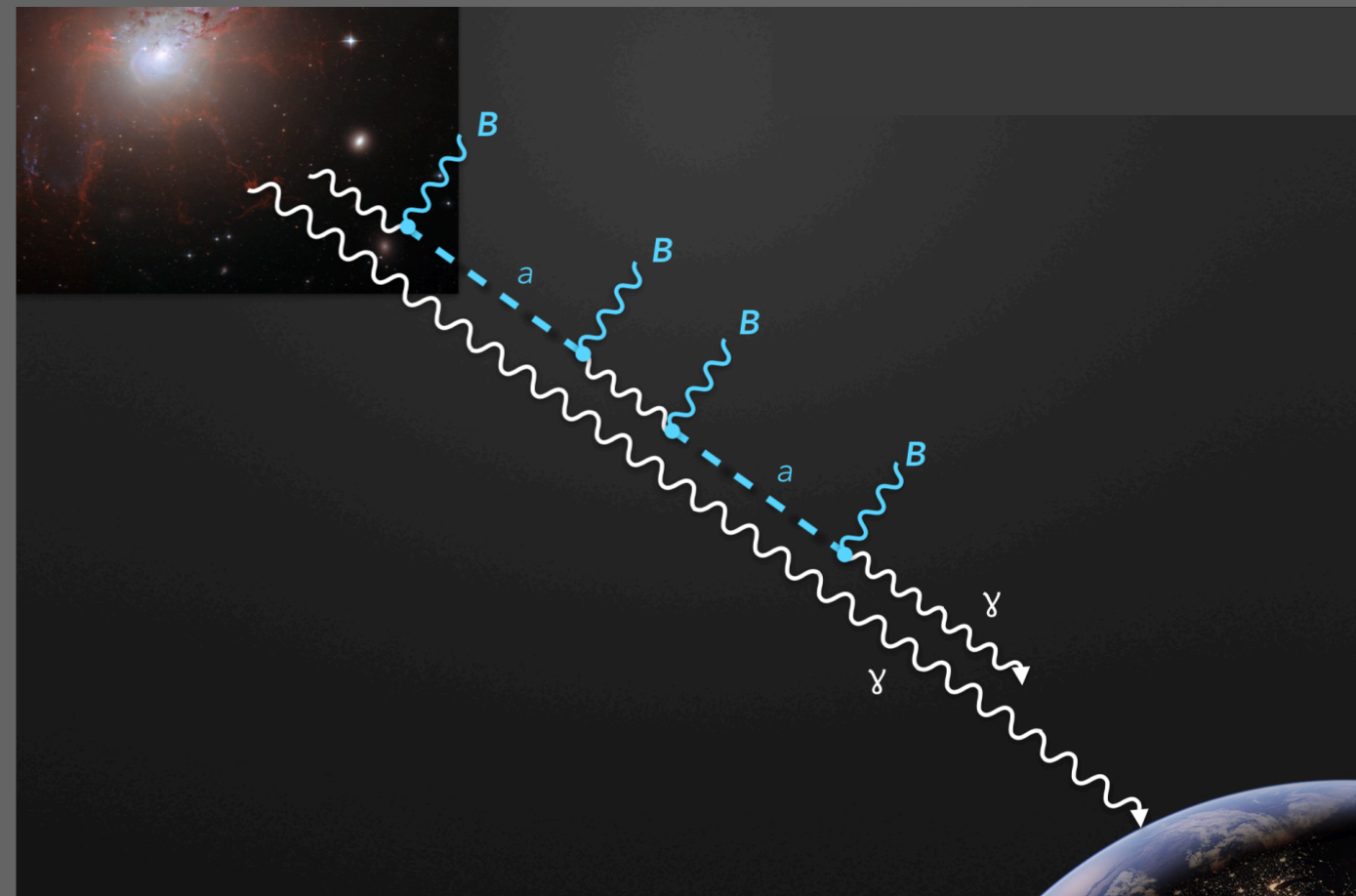
MAXIMUM ENERGY

$$E_{\text{max}} \sim 2.12 \times 10^6 \, \text{GeV} \, g_{11}B^{-1}_{\mu\text{G}}$$

STRONG MIXING REGIME

**Strategy 1**: examine the γ spectra of astro sources and use it to constrain the probability of ALP-γ conversion

— affects gamma ray '**opacity**'

— causes **spectral irregularities around E_crit**
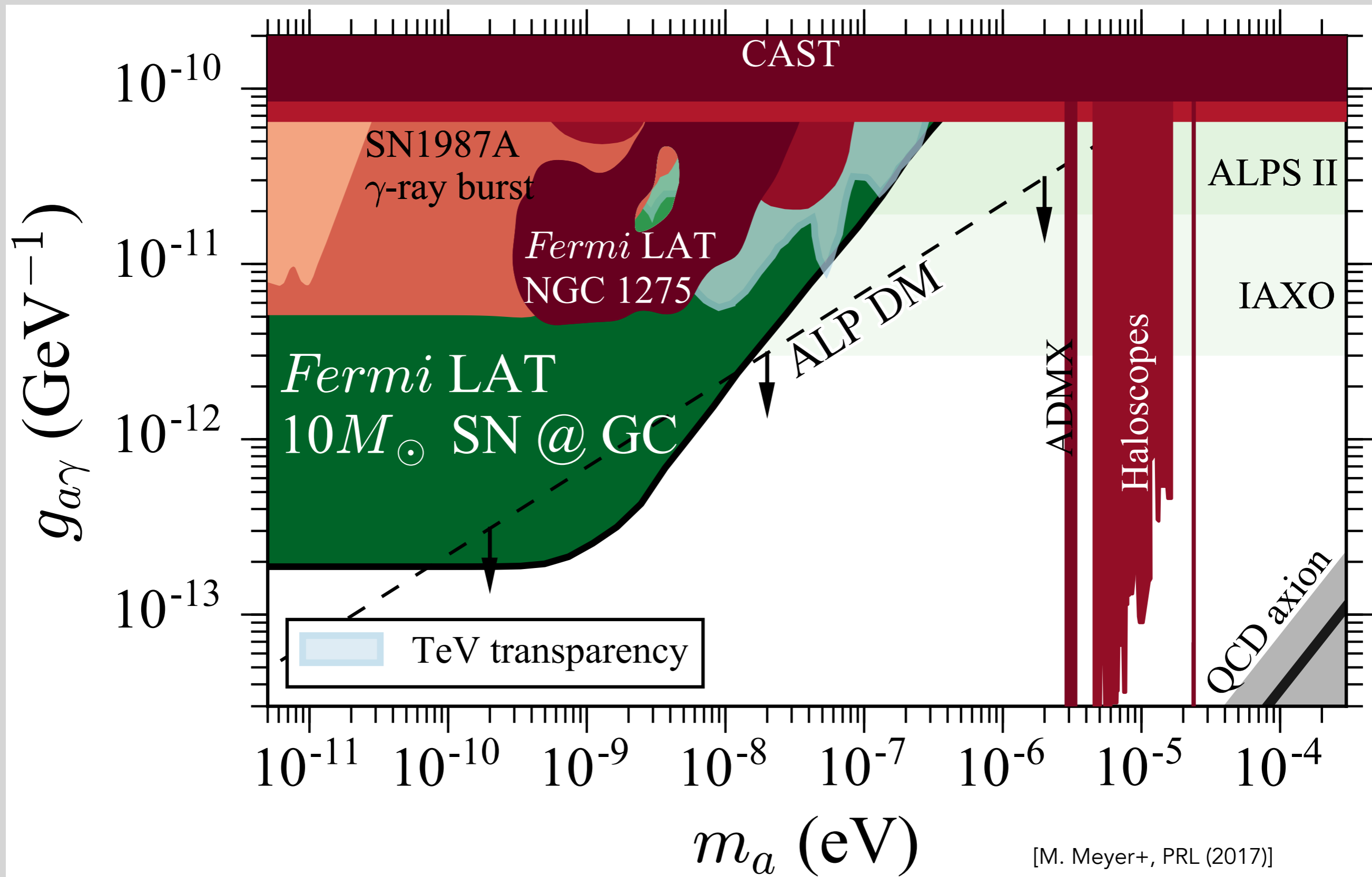
Credit: M. Meyer

What strategies (**ALPs**)?

Strategy 2: ALPs would be produced in a core-collapse SN explosion via Primakoff process

Smoking gun! Gamma rays would arrive contemporary with neutrinos.

Credit: M. Meyer

State-of-the-art

[M. Meyer+, PRL (2017)]
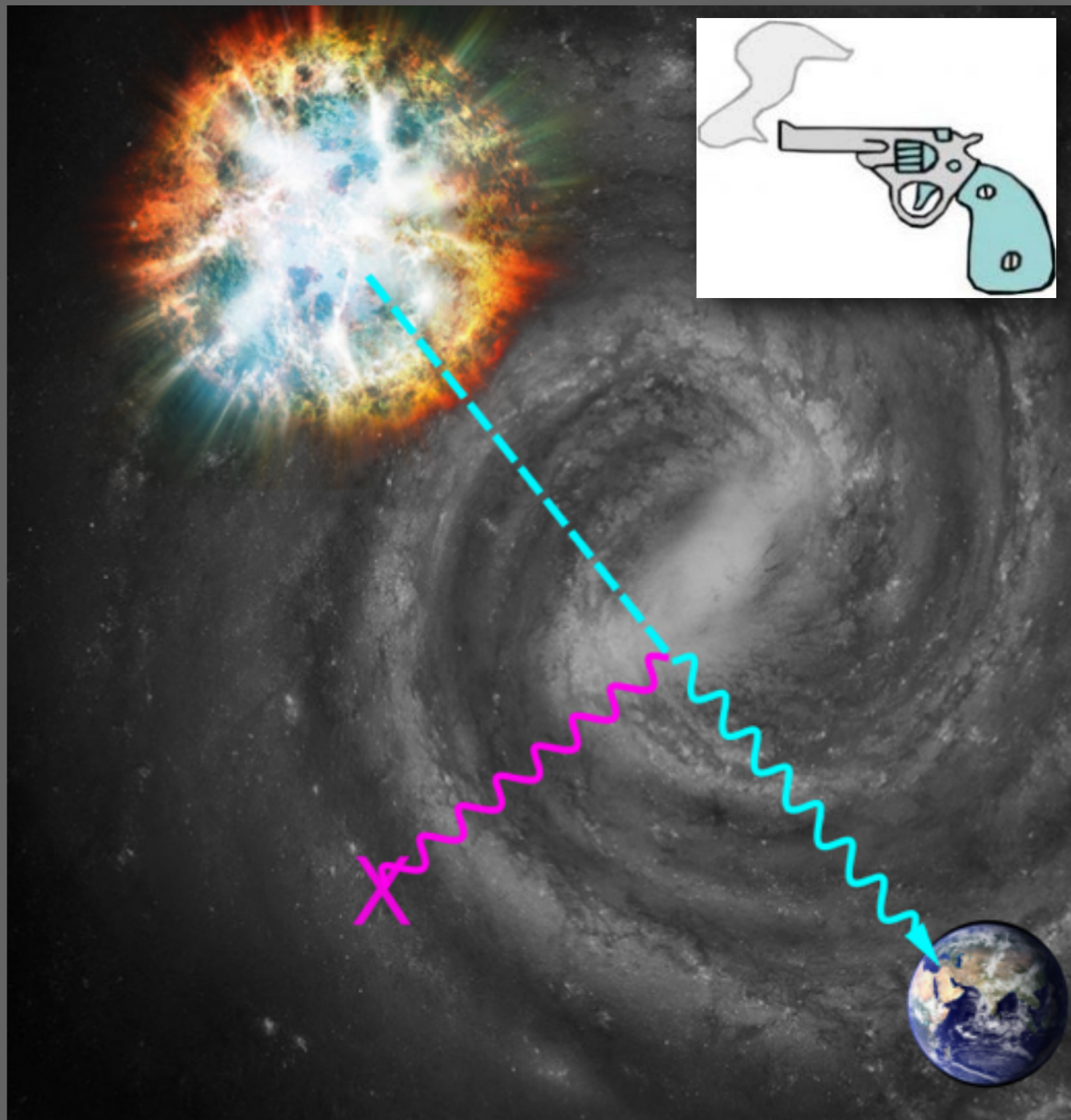
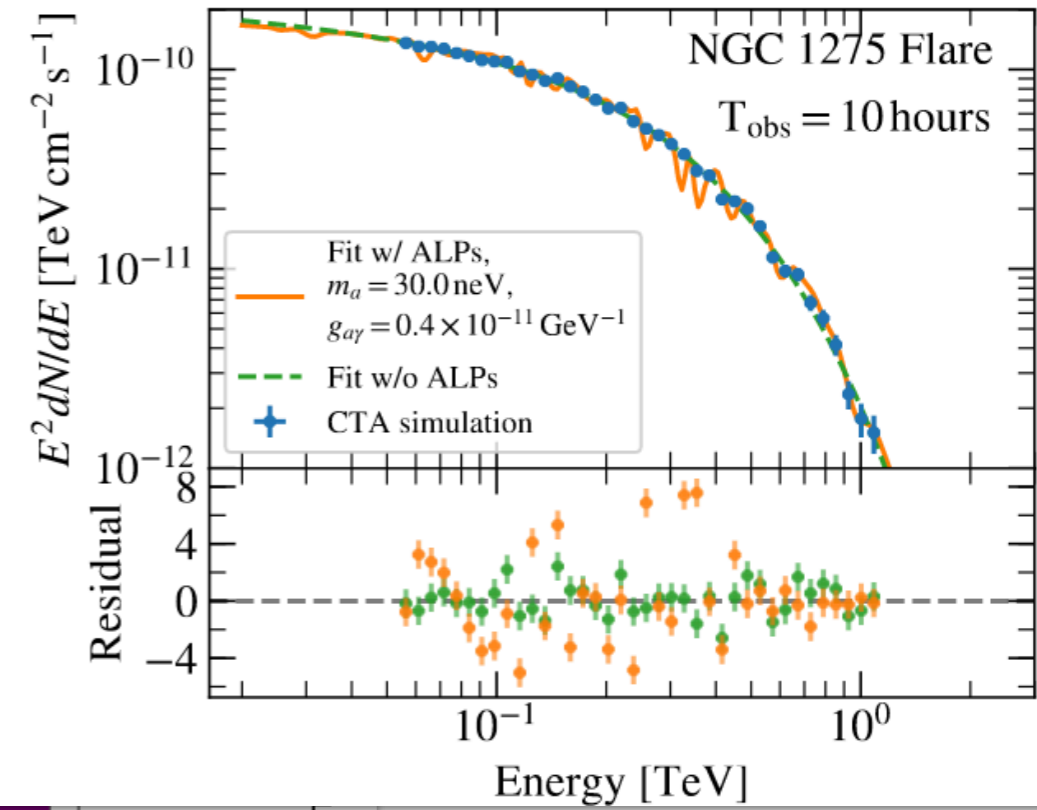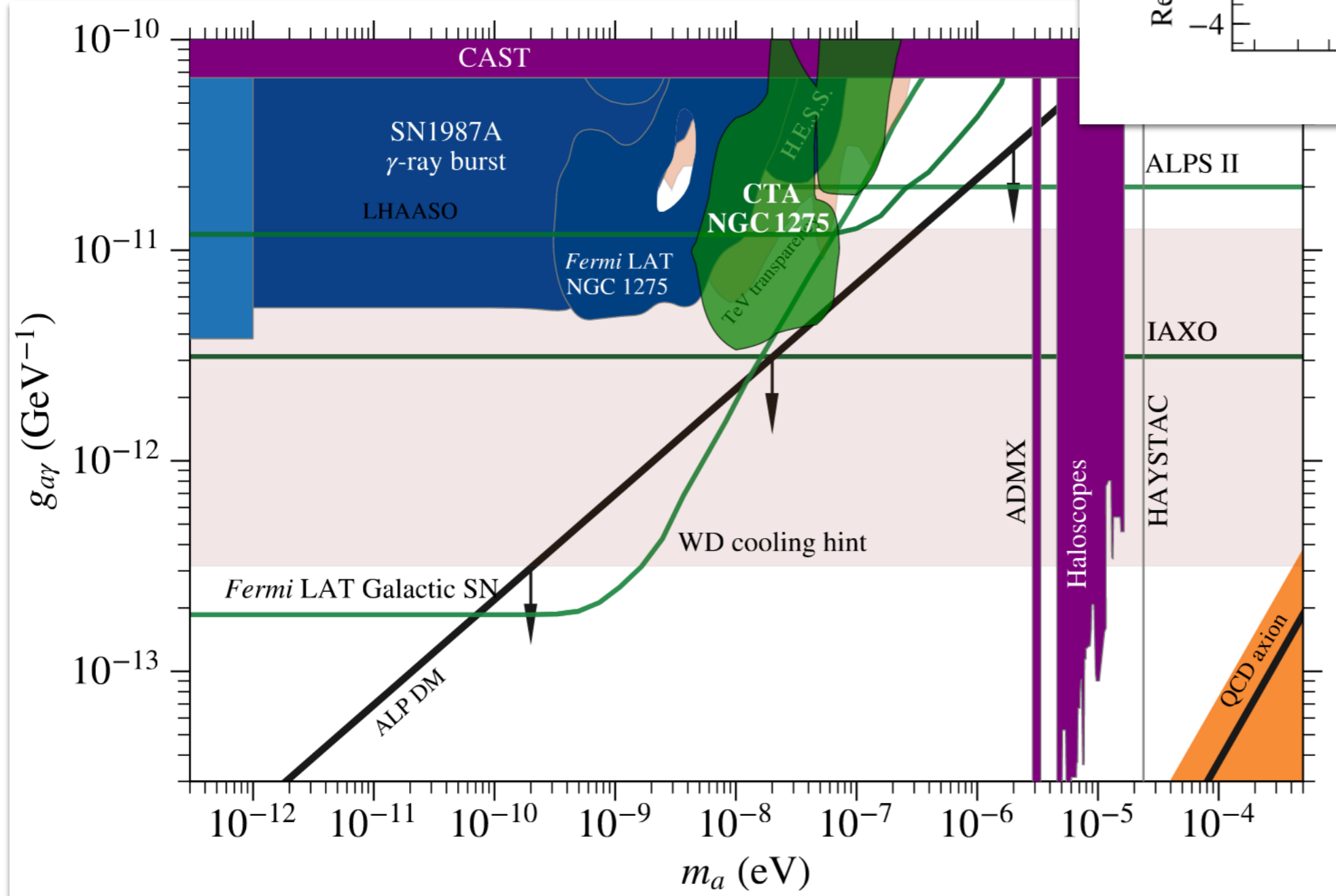# The future:CTA ALPs@ NGC1275

NGC 1275 is the central galaxy of the Perseus cluster, at a distance of ~ 75 Mpc.
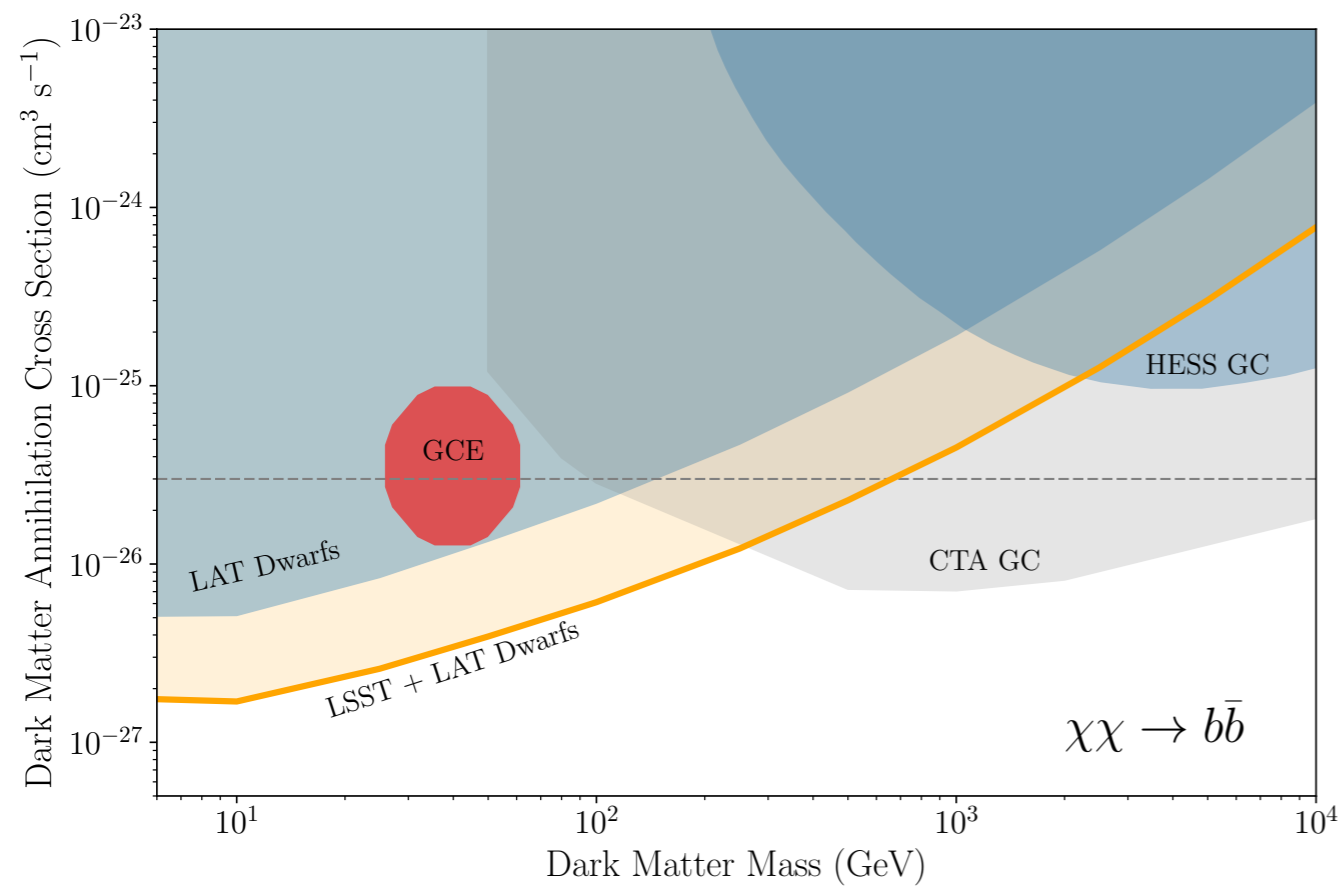
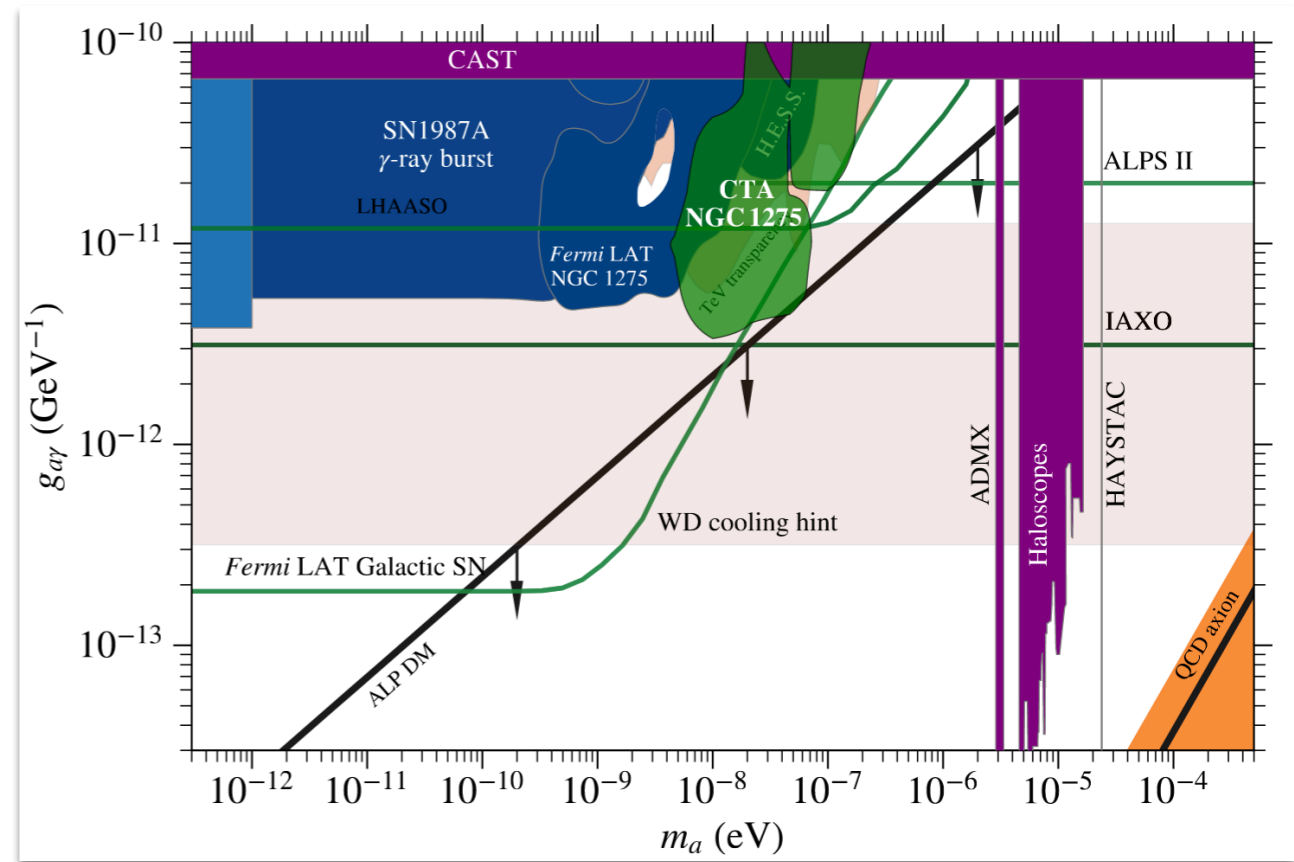Perseus cluster harbors a strong magnetic field, ~25 μG.

Gamma-ray DM search summary

The 'vanilla' WIMP parameter space already largely constrained and the remaining TeV window will be probed by the CTA

Fermi LAT and CTA data (will be) able to constrain chunks of the ALP DM parameter space

[Drlica-Wagner+, 2019]

[Archaryya et al. JCAP 2021]
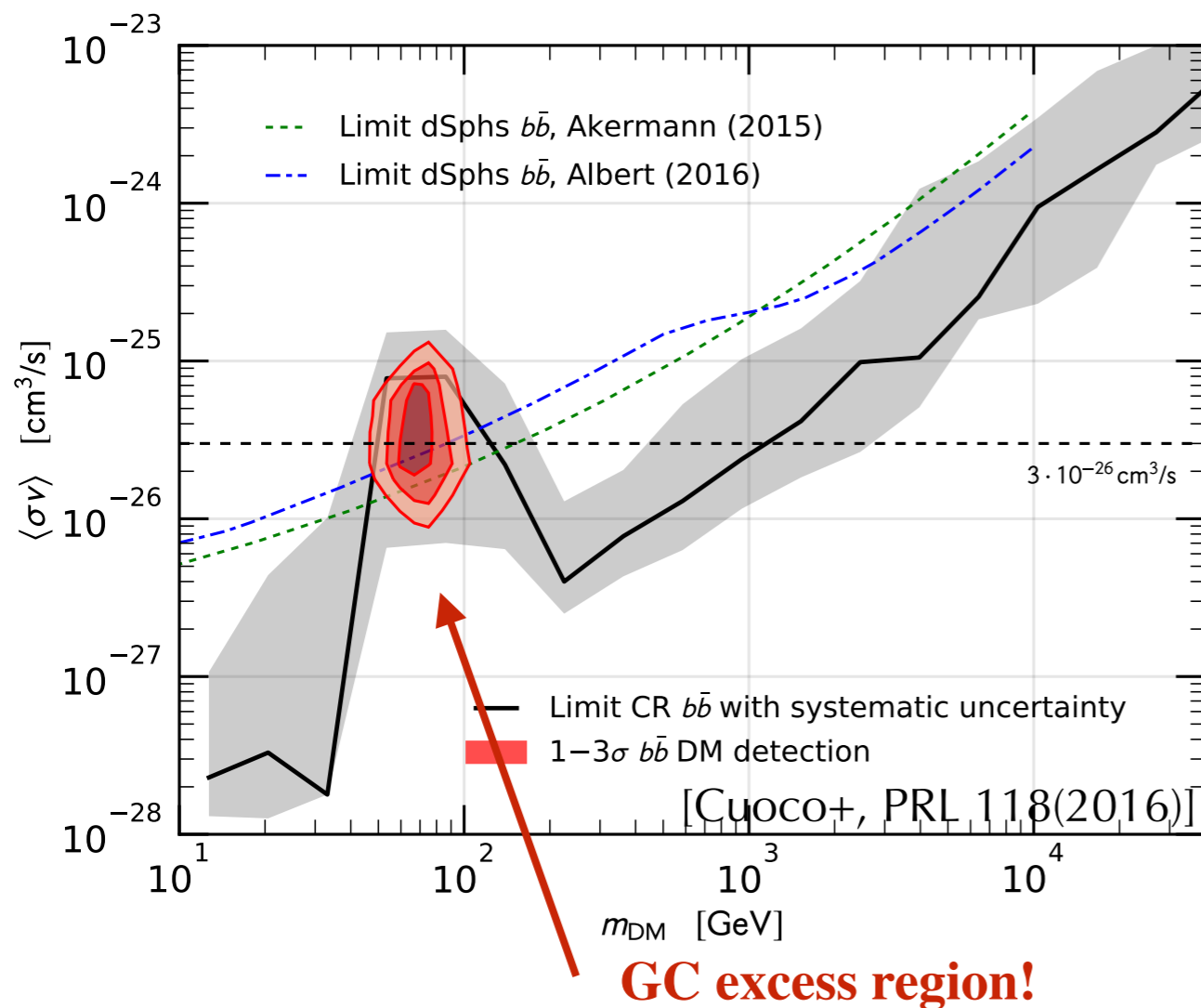
DM search with charged CRs

DM limits:

Antiprotons - one of the most sensitive probes of new physics

— p spectra measured exquisitely well

— anti-p produced as secondaries, with the proton spectra as the source term

Simultaneous fit to p and He spectra (constrain propagation parameters) + DM component

Note strong limits at high masses

However, uncertainty in solar modulation, pp x-section, …

Figure legend:
- Limit dSphs $b\bar{b}$, Akermann (2015)
- Limit dSphs $b\bar{b}$, Albert (2016)
- $3 \cdot 10^{-26}\,cm^3/s$
- Limit CR $b\bar{b}$ with systematic uncertainty
- $1-3\sigma$ $b\bar{b}$ DM detection

[Cuoco+, PRL 118(2016)]

Axis labels: $\langle \sigma v \rangle$ [cm^3/s], m_{DM} [GeV]

GC excess region!

Charged cosmic rays - the precision era

DM limits: Antiprotons

New results that take systematics uncertainties (via covariance matrices) into account
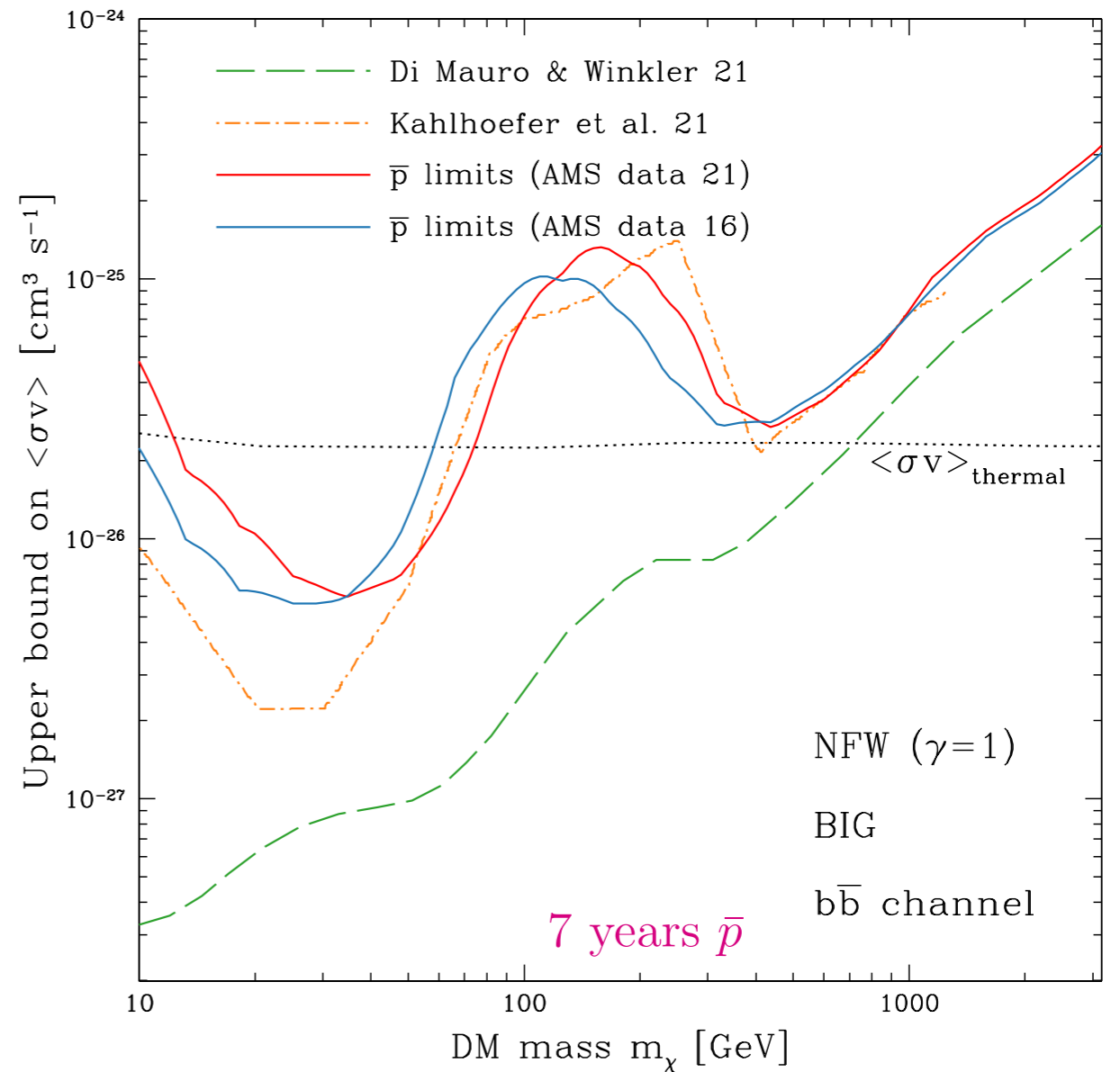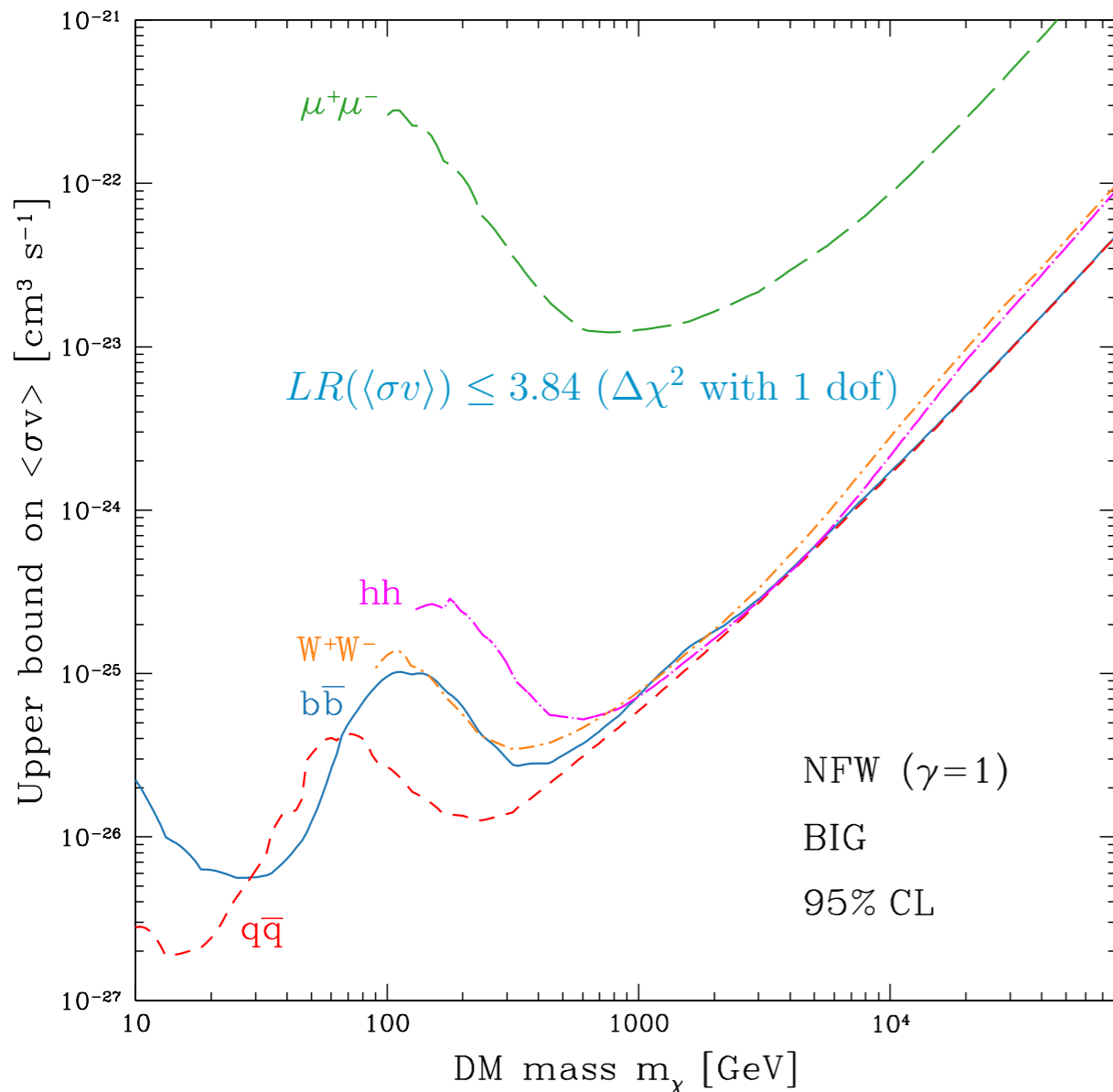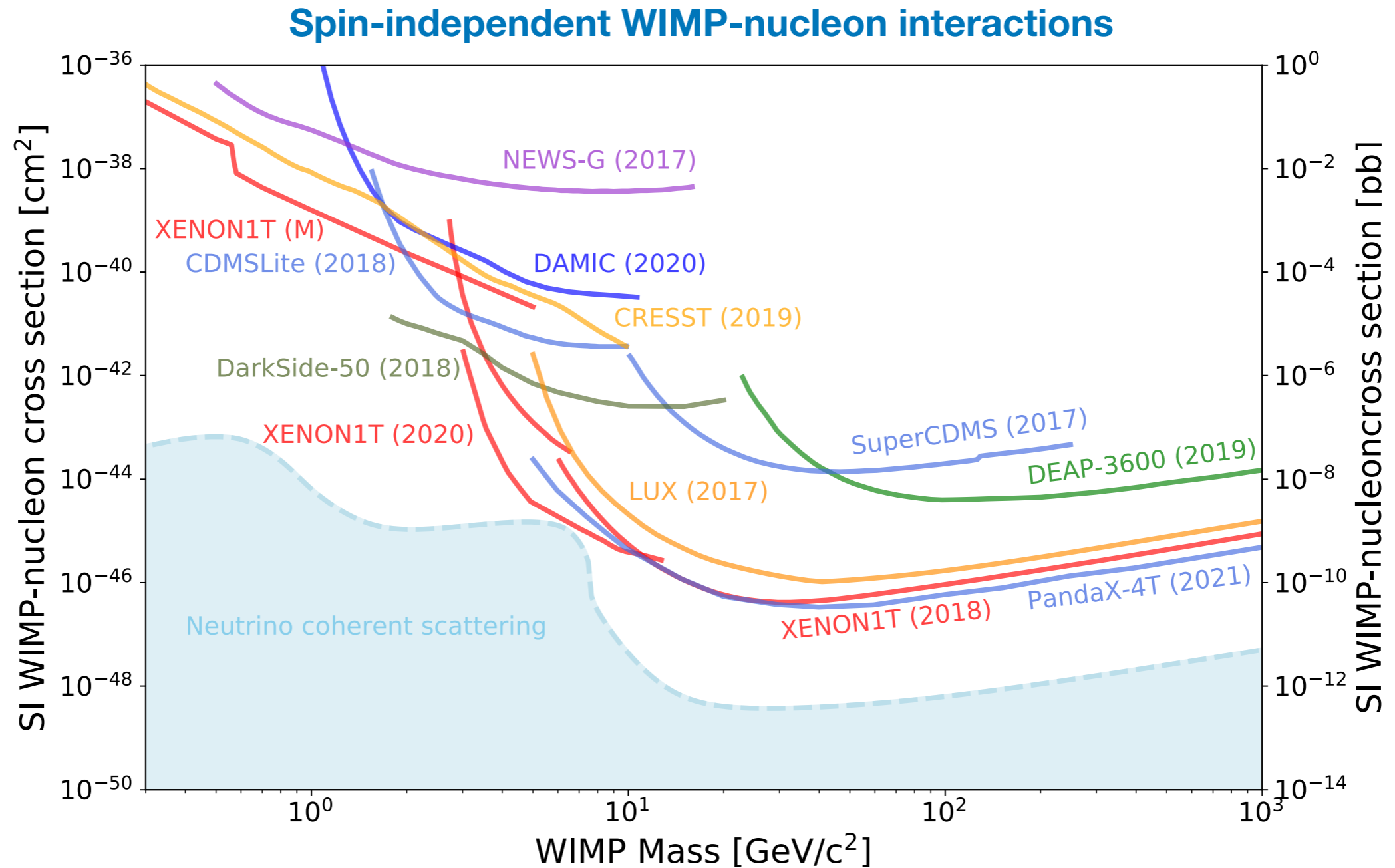
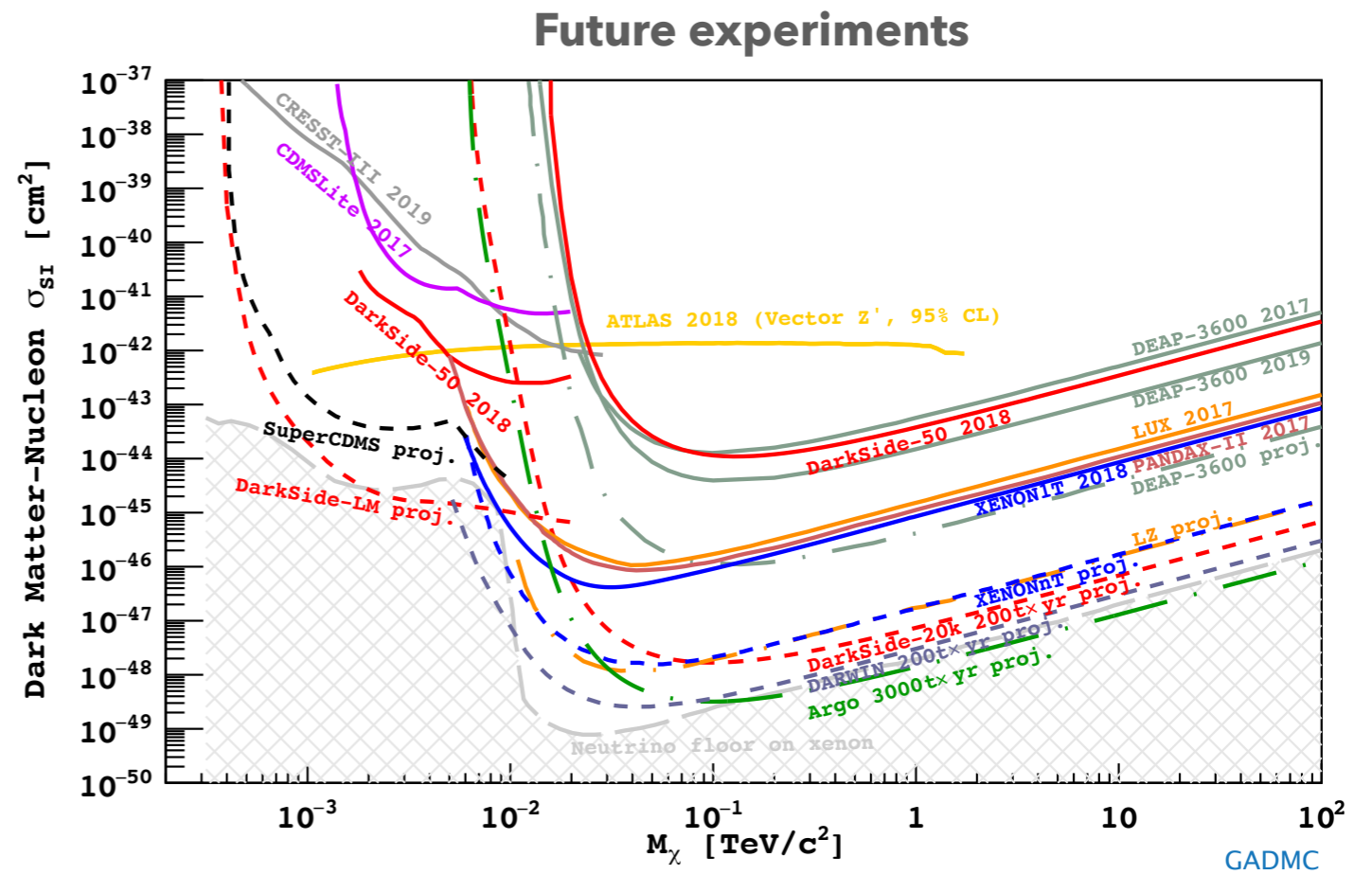# 'Direct' WIMP searches

status cca 2020

Spin-independent WIMP-nucleon interactions

Figure adapted from P.A. Zyla et al. (Particle Data Group) (2020)

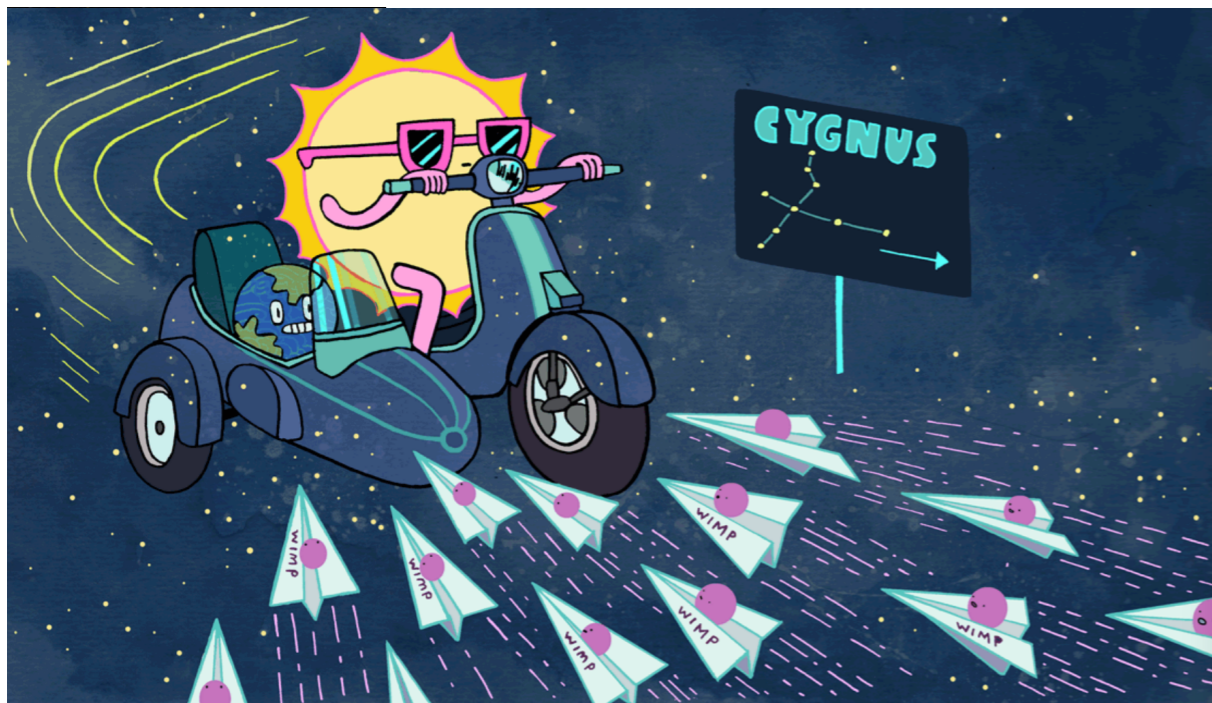# 'Direct' WIMP searches

Future?

Future experiments

GADMC
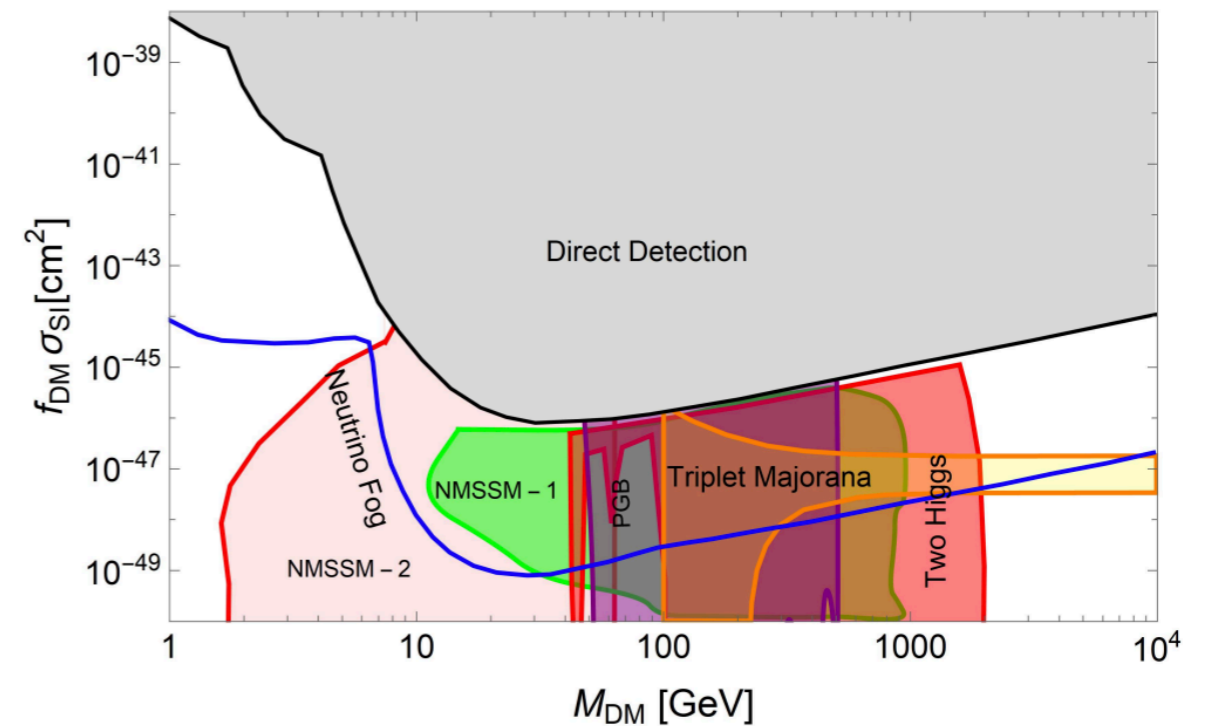
DarkSide-20K
DarkSide-LM
Argo
factor 10⁴

PandaX-30T (not shown)
DARWIN/G3
factor 10

projected sensitivity improvement in next ~10 years

Baracchini
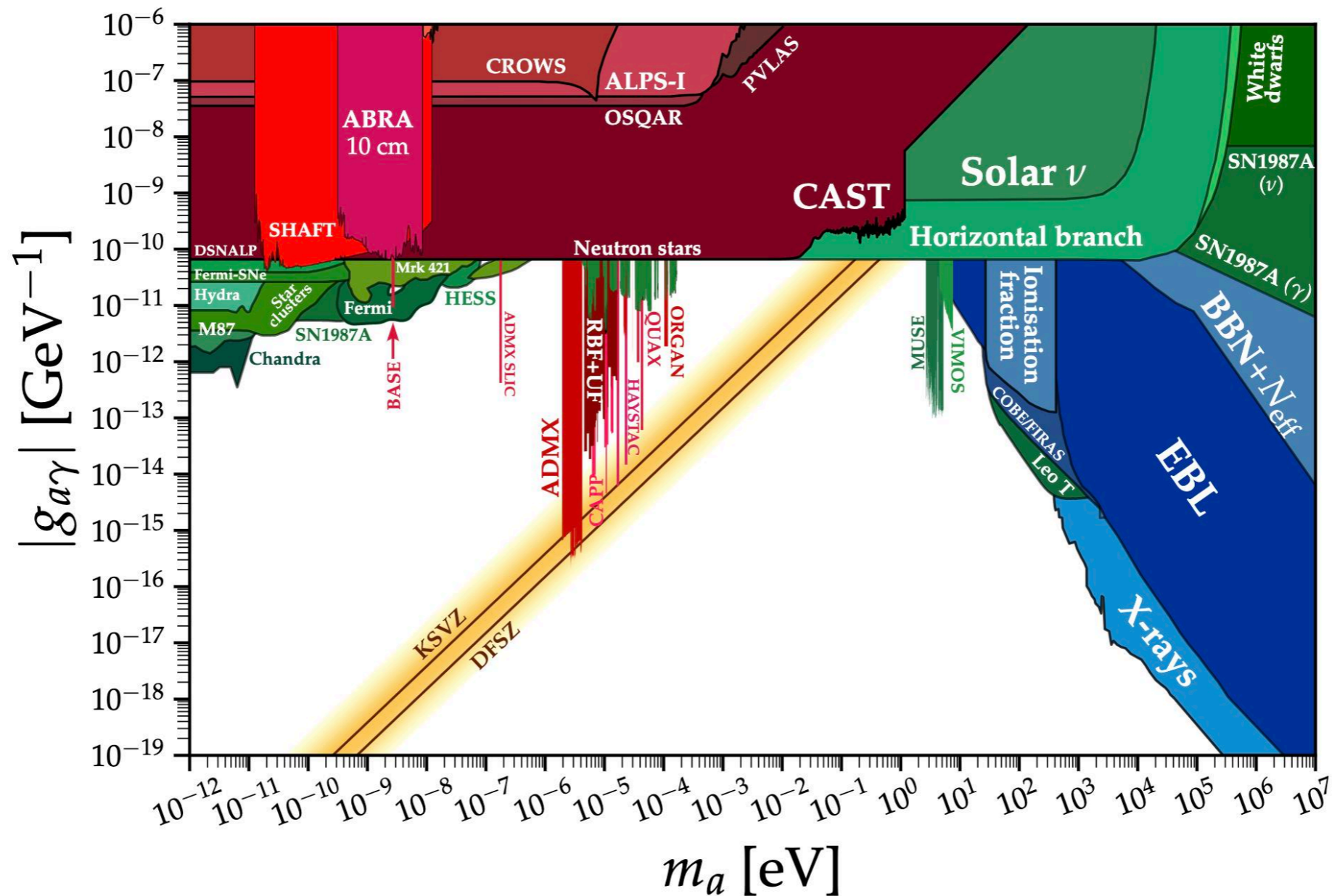
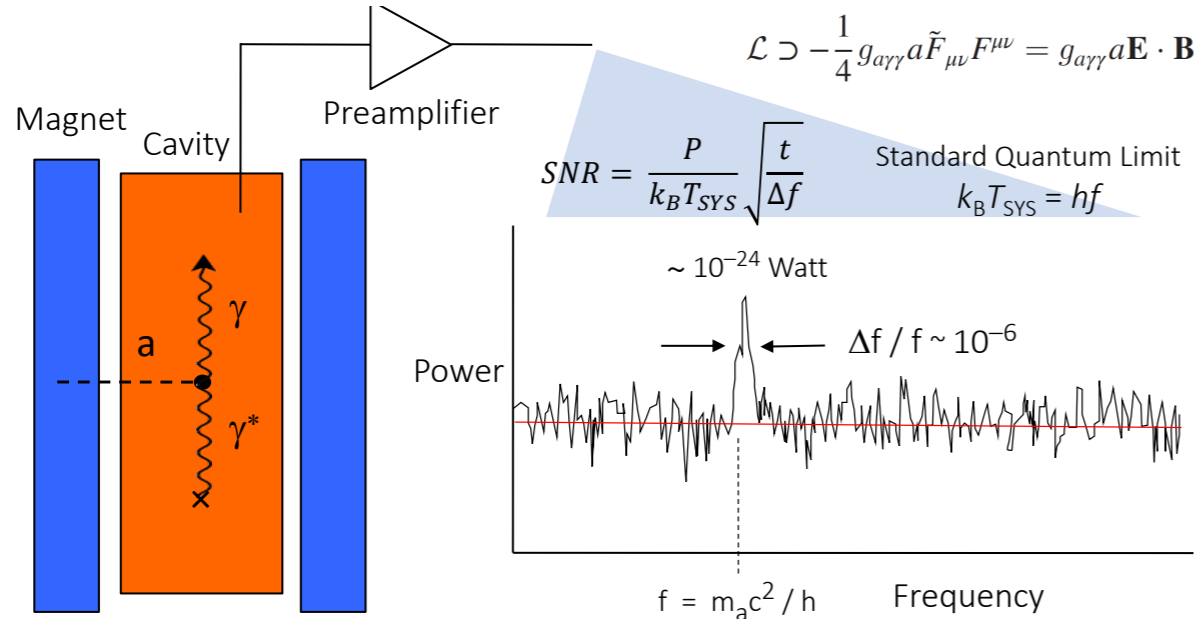*Visible sector models SI*

'Direct' axion and ALP searches

'Direct' axion and ALP searches

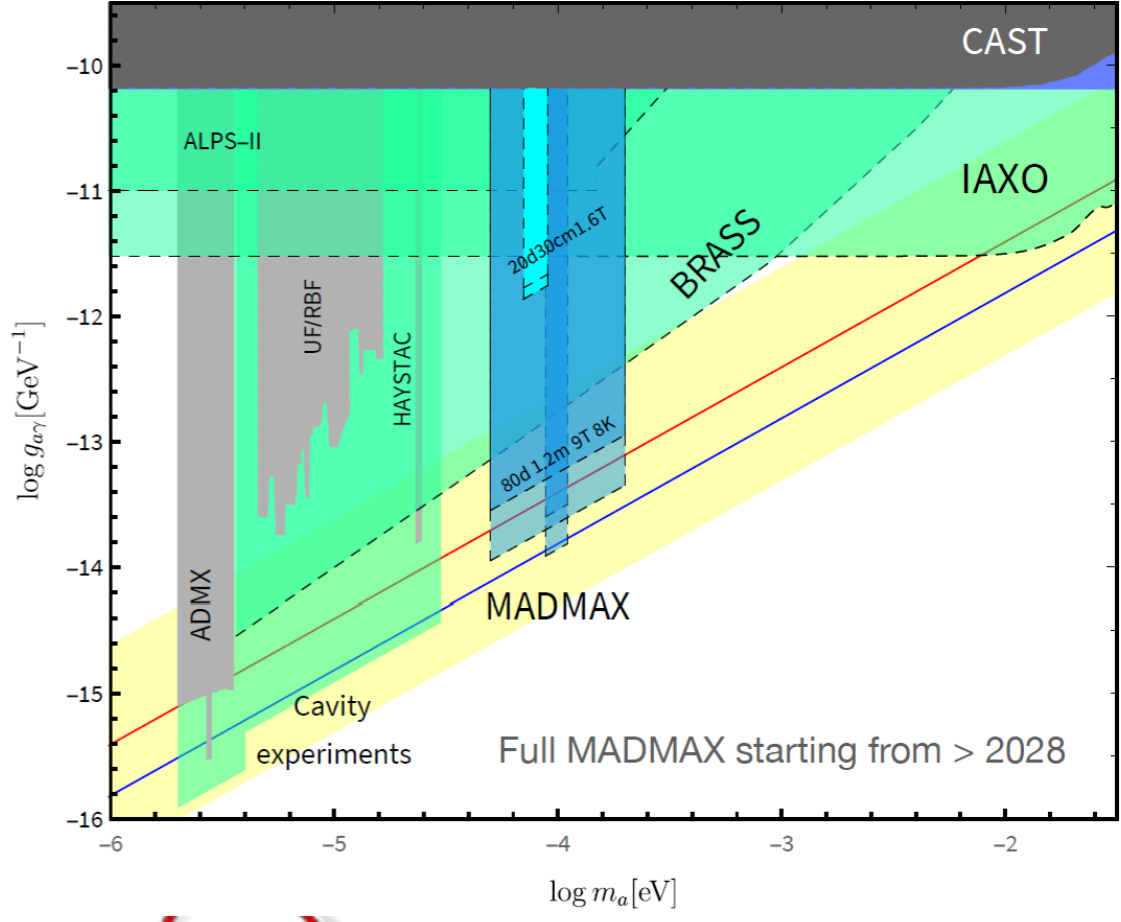## Dark matter axion searches (a.k.a. haloscopes)

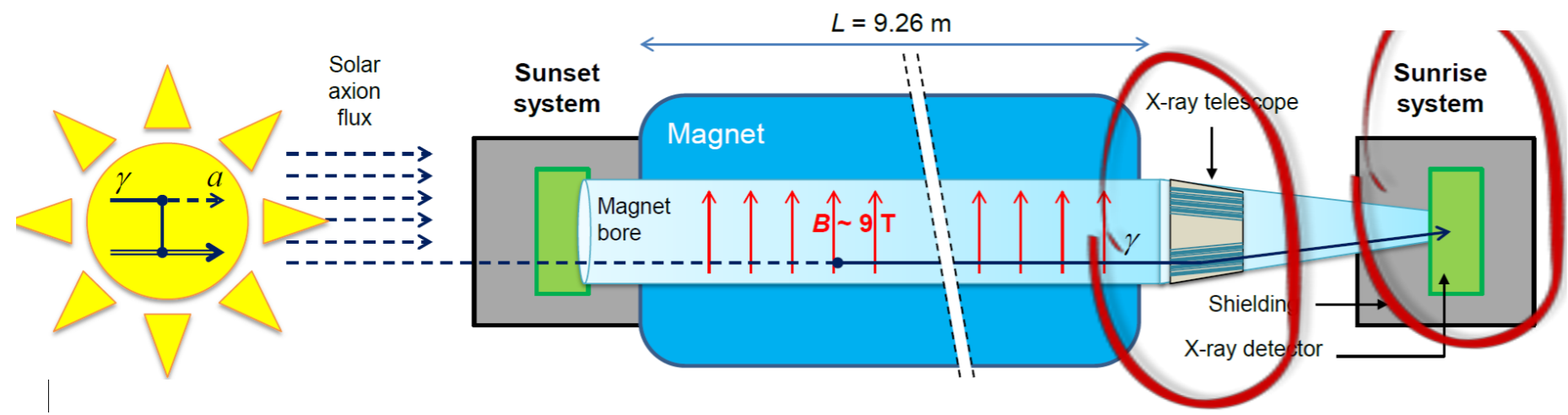$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B} \quad , \quad _{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{I}$$

Receiver

Magnet
Cavity
Preamplifier

$$\left(\frac{B_e}{0\ T}\right)^2 C_{a\gamma}^2$$

$$SNR = \frac{P}{k_B T_{SYS}} \sqrt{\frac{t}{\Delta f}} \quad \text{Standard Quantum Limit} \quad k_B T_{SYS} = hf$$

~ 10^{-24} Watt

Horn antenna
+Receiver system

Lots of ongoing R&D!

Morpurgo 2022 projected sensitivity

room temperature, T_{sys} 200 K, SNR=5

4 disks, 11K, 1.6 T

ADMX... +

Preliminary

CAST

KSVZ

DFSZ

QCD axion

CAST... +

Axion mass [μeV]: 77.0, 77.5, 78.0, 78.5, 79.0, 79.5, 80.0

CAST, ALPS–II, IAXO, BRASS, UF/RBF, HAYSTAC, ADMX, MADMAX, Cavity experiments

20d 30cm 1.6T, 80d 1.2m 9T 8K

$\log g_{a\gamma}$ [GeV^{-1}]

$\log m_a$ [eV]

Full MADMAX starting from > 2028

Solar axion flux

Sunset system

Magnet

Magnet bore

$B \sim 9\,T$

X-ray telescope

Sunrise system

Shielding

X-ray detector

9.26 m

γ a

γ

IAXO: International Axion Observatory

Future? New experiments

More data are coming! (CTA, Vera Rubin, SKA, XENONnT…)

Sheer amounts of (upcoming) data plus the complexity of physics and multiwave/messenger connections are making it increasingly challenging to analyse the data in a comprehensive way via traditional techniques
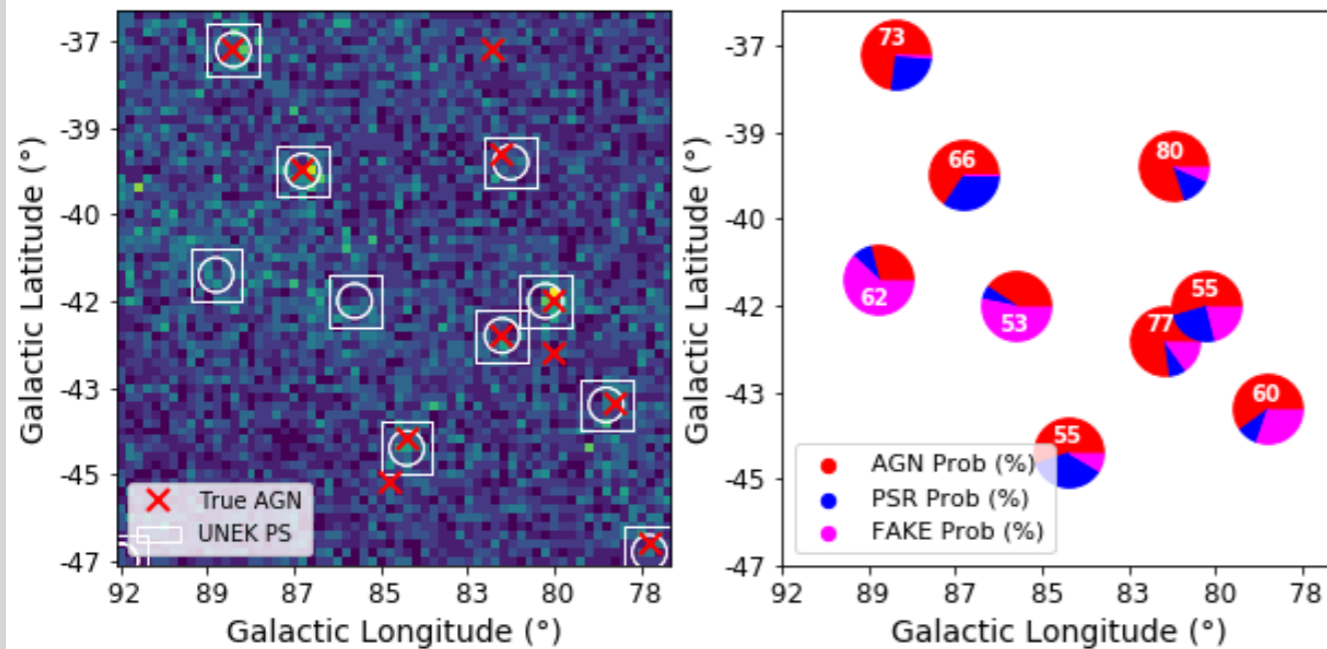

[EuCAPT white paper, arXiv: 2110.10074]
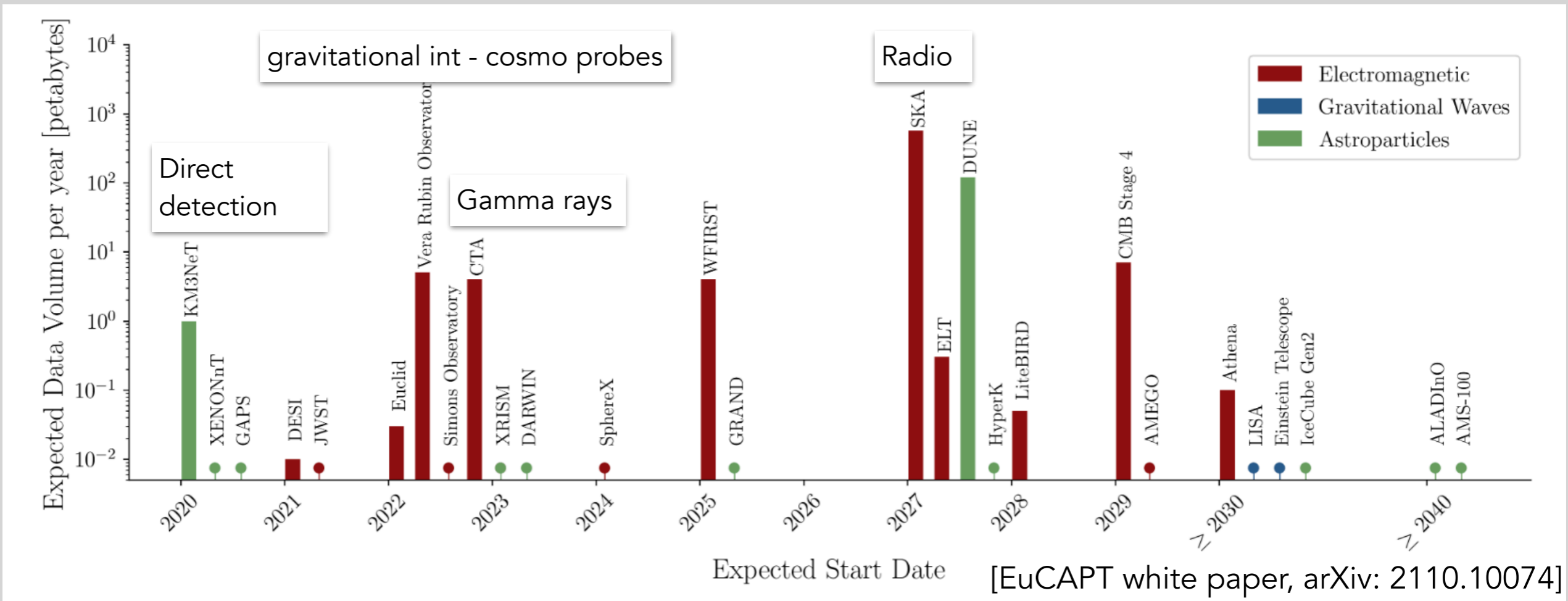
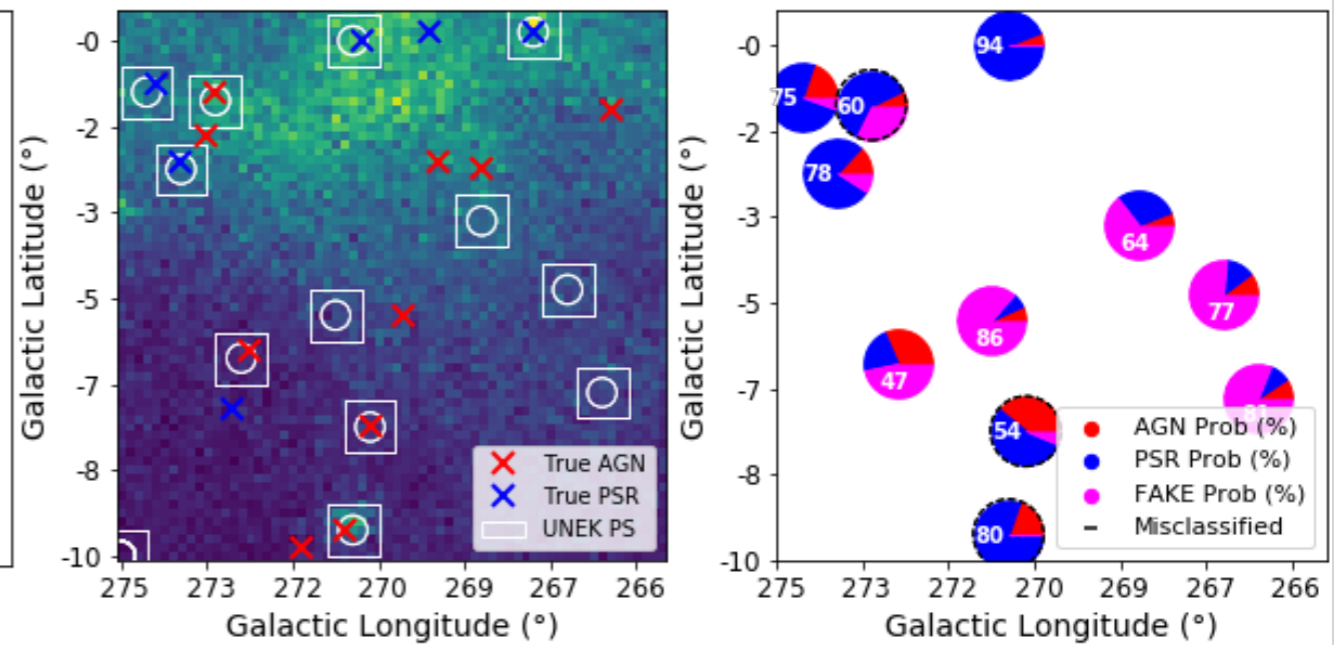# Future - Machine learning?

Starting slowly in this field

An example, automatic source detection and classification from raw LAT images (AutoSourceID):

— faster, more robust to background model

— extension to multi-wavelength ~natural

Results for High Latitude: $|b| > 20°$

Results for Low Latitude: $|b| < 20°$

Low background emission. Higher accuracy in localization.

Better classification.
(www.autosourceid.org, A&A, 2103.11068)

Regions closer to galactic plane. Background emission dominates.

Algorithm performance deteriorates.

Outlook

Exciting multi-disciplinary field & lots of data to play with !

Significant progress on probing WIMP and ALP models and more to come soon

The search is widening - ***It always seems impossible until it's done*** :)

Curious to find out more?

http://www.idmeu.org — *a go-to place for all things dark matter*

A hub for News/Events/Experiments/Models/Tools….