THE UNIVERSITY OF SYDNEY

Centre fo… Matter
Pa… ysics

coming soon

Dark Matter Detection

Ciaran O'Hare
University of Sydney

7 Nov 2019

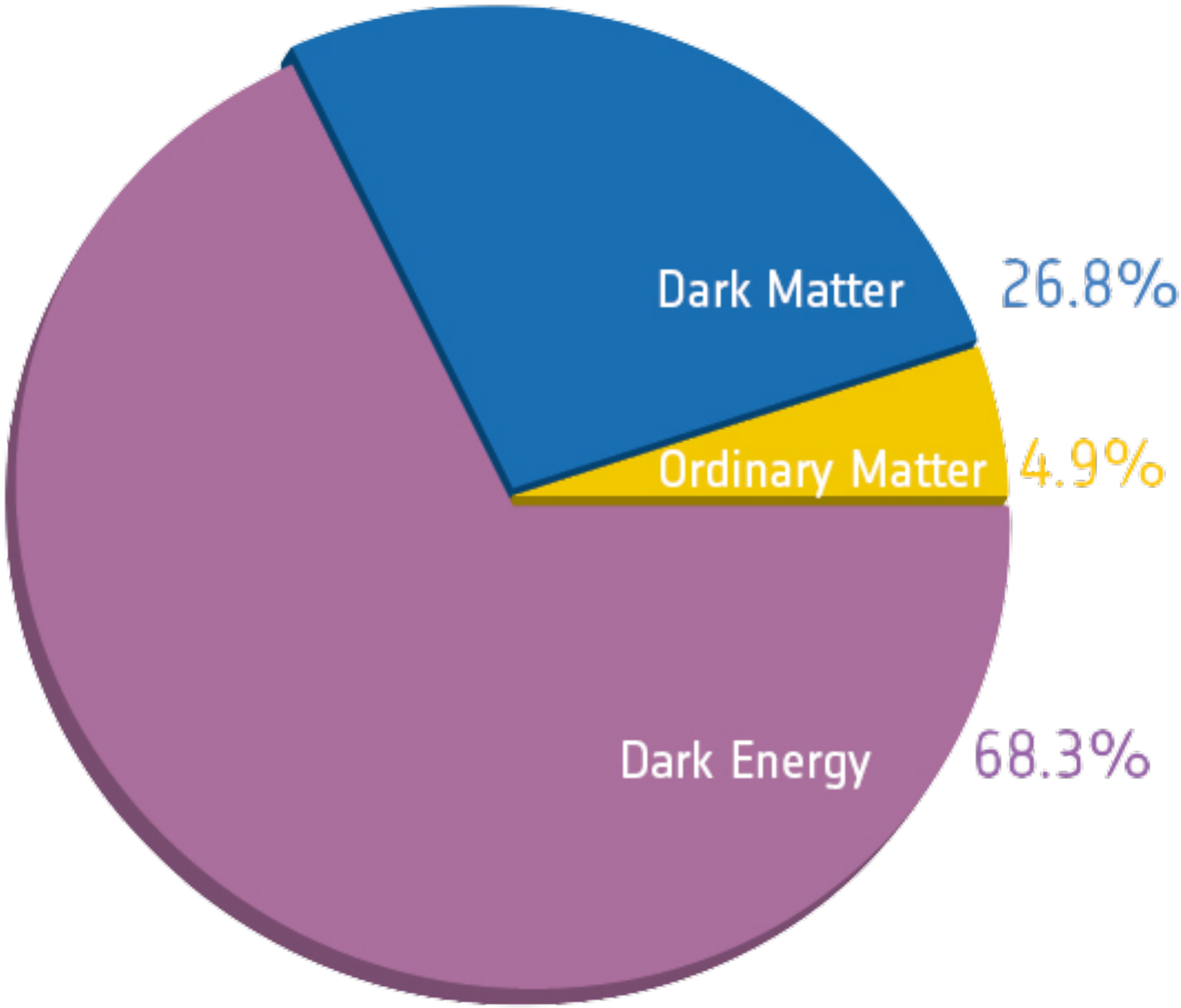
Dark matter

WIMP and axion searches

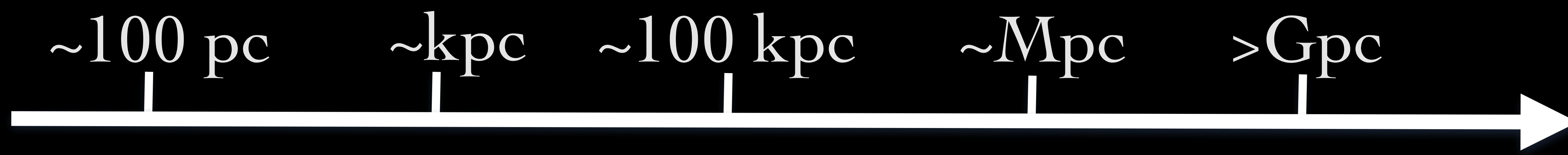
Selected topics from my work:

- Dark matter+neutrinos
- Dark matter experiments+*Gaia*
- Directional dark matter detection

The dreaded pie chart…



We have evidence for dark matter's existence on length scales spanning ~10 orders of magnitude…



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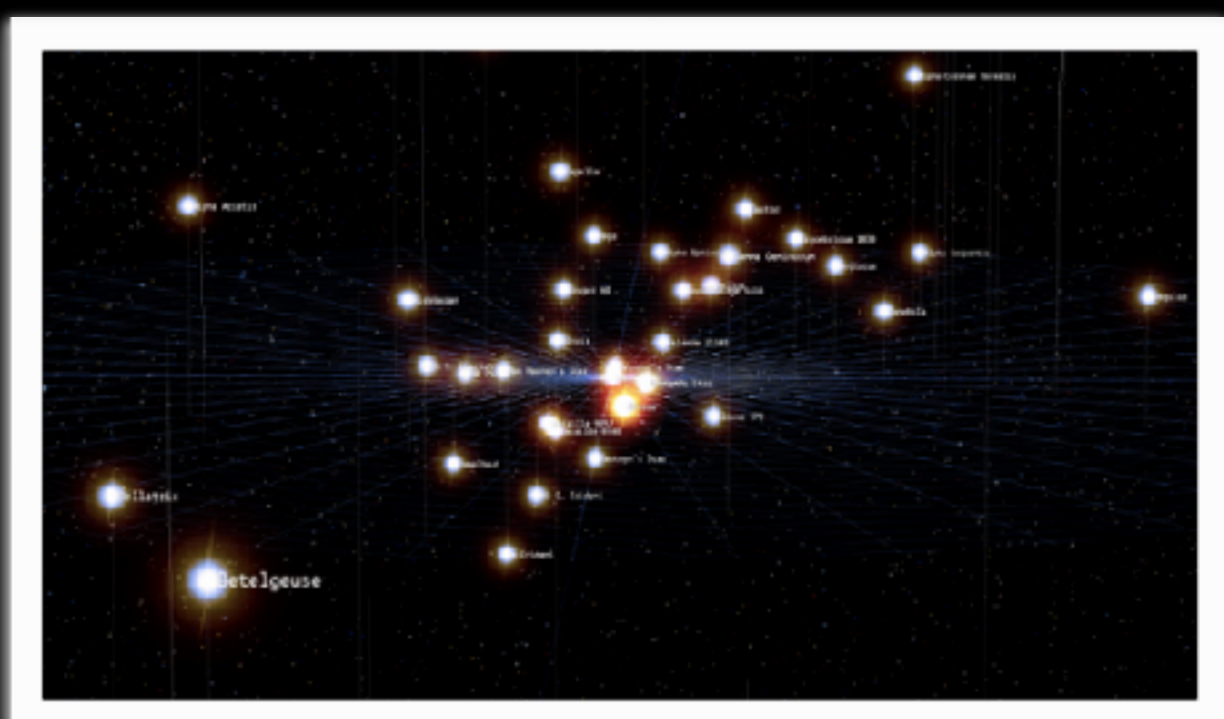
~100 pc — ~kpc — ~100 kpc — ~Mpc — >Gpc

Affects nearby stars



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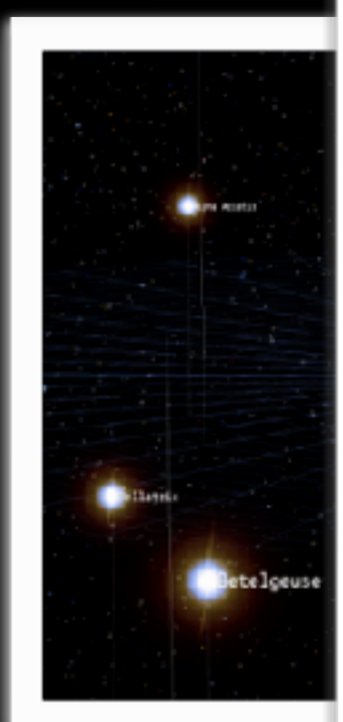
Affects nearby stars

Dominates dwarf galaxies



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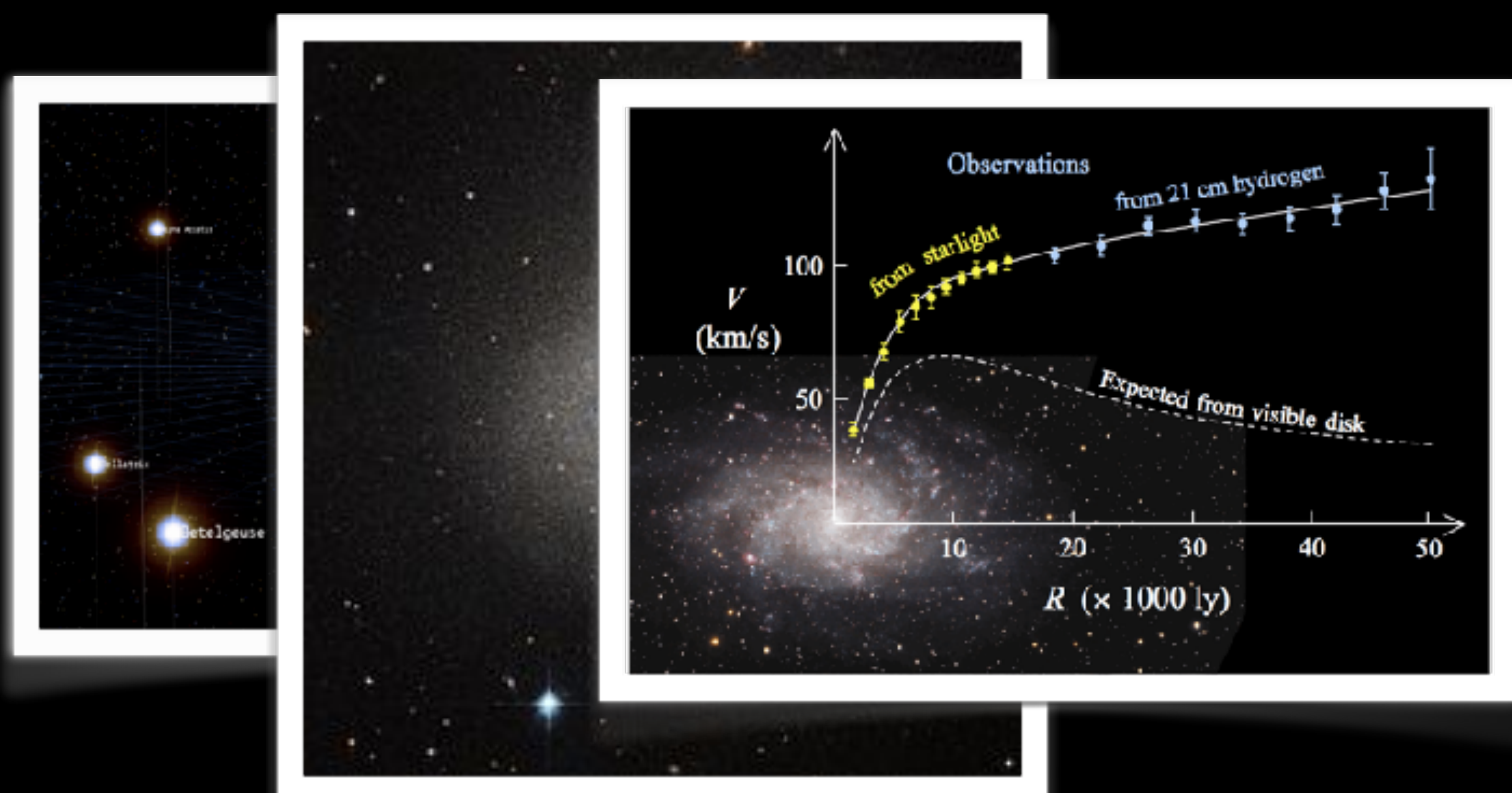
~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation		



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We have evidence for dark matter's existence on length scales spanning ~10 orders of magnitude…

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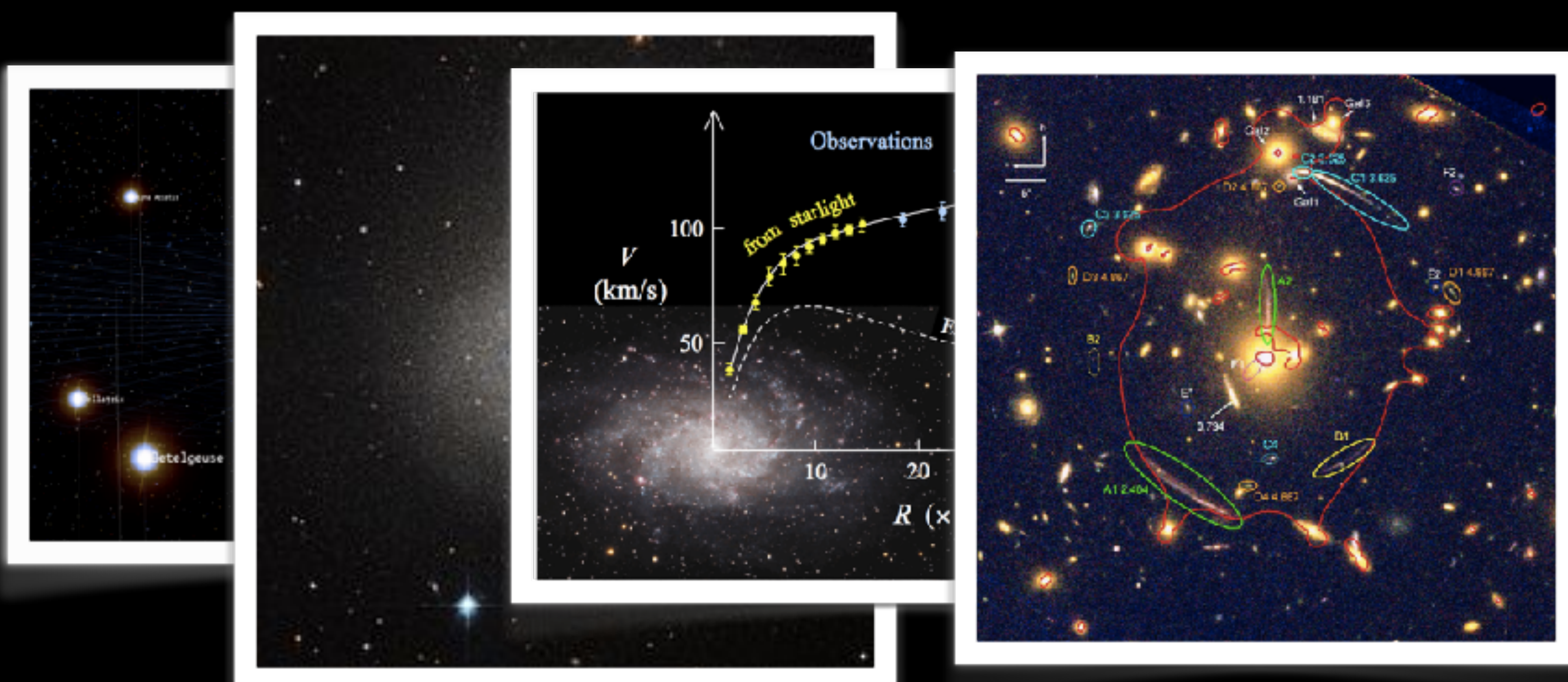

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We have evidence for dark matter's existence on length scales spanning ~10 orders of magnitude…

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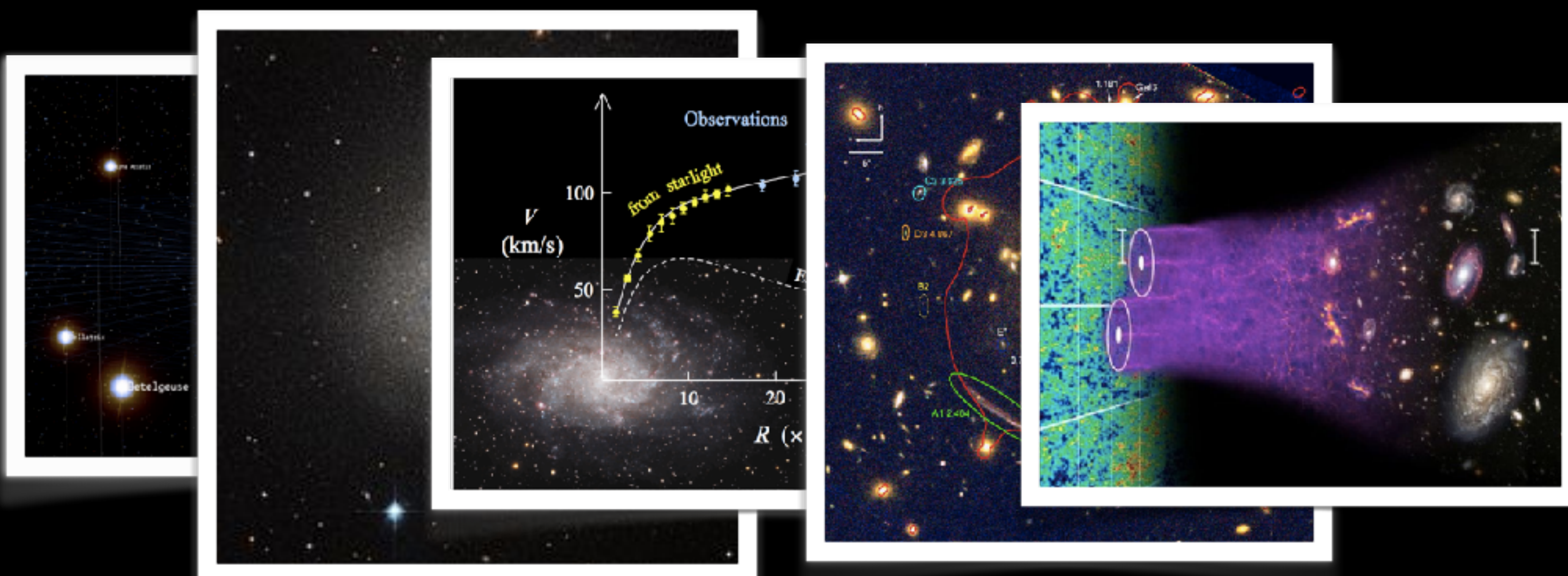
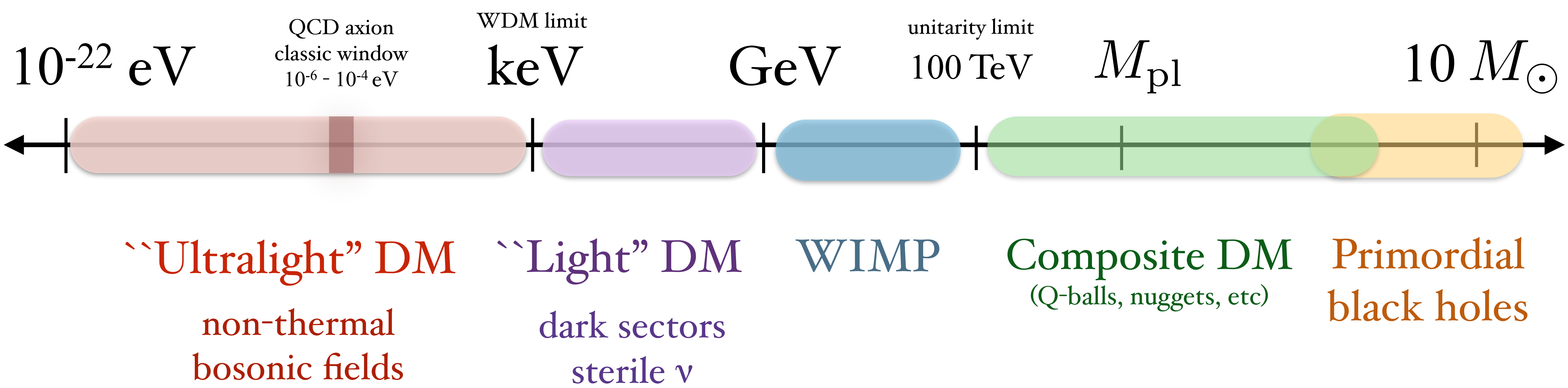
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	CMB+ Large scale structure



[1904.07915]

Mass scale of dark matter

(not to scale)



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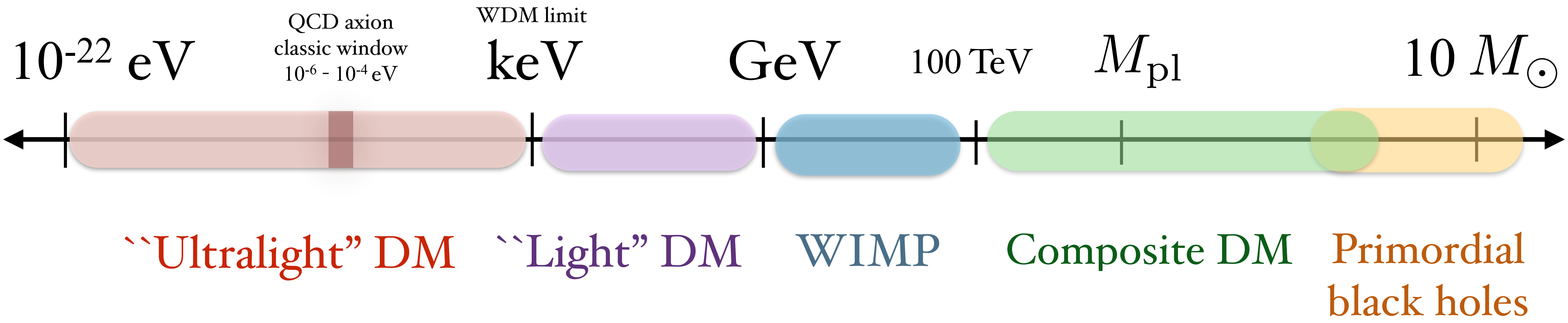


Important to remember

- All candidates basically work as dark matter in a broad sense (i.e. have mass+don’t interact much)
- But not all are “vanilla CDM”. Some forms of DM make structures in the Universe look a bit different (e.g. self-interacting DM, fuzzy DM, warm DM)
- They are generally speaking **not** mutually exclusive, in terms of existence, or as dark matter…
- Complementary probes exist, collider searches, fifth force experiments, light-shining through walls, helioscopes

WIMPs

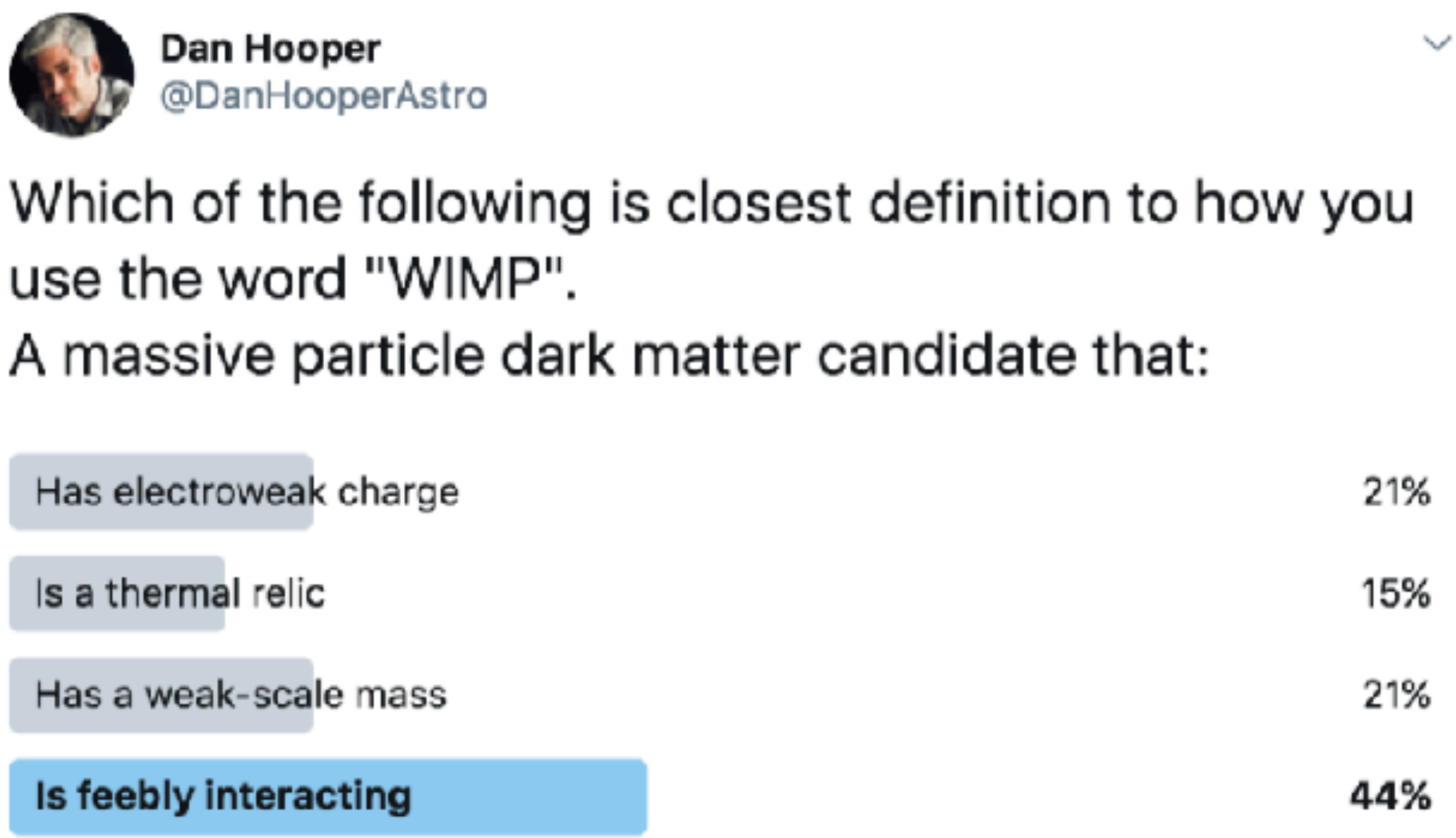
Weakly **I**nteracting **M**assive **P**articles

What does that actually mean?

WIMPs

Weakly Interacting Massive Particles

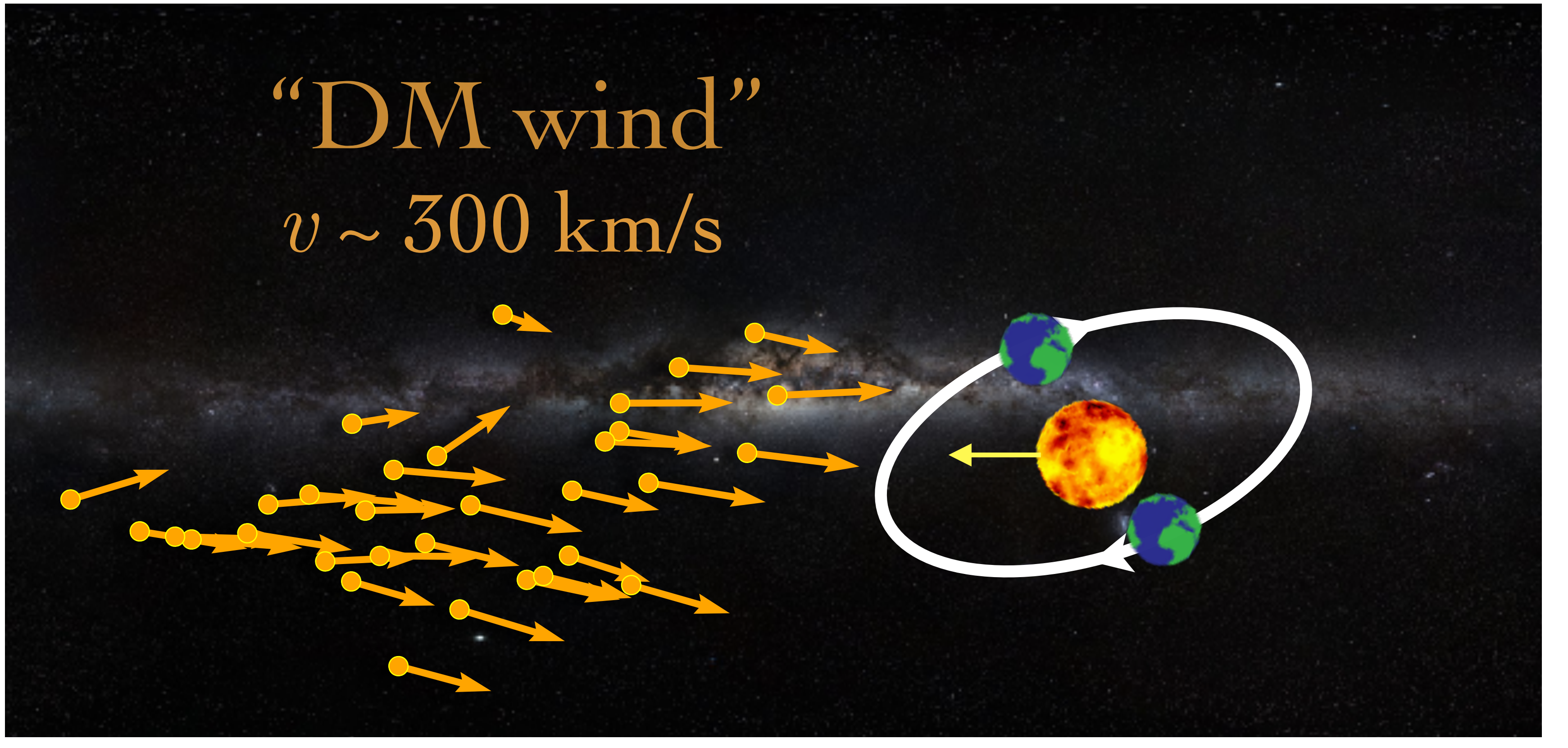
What does that actually mean?



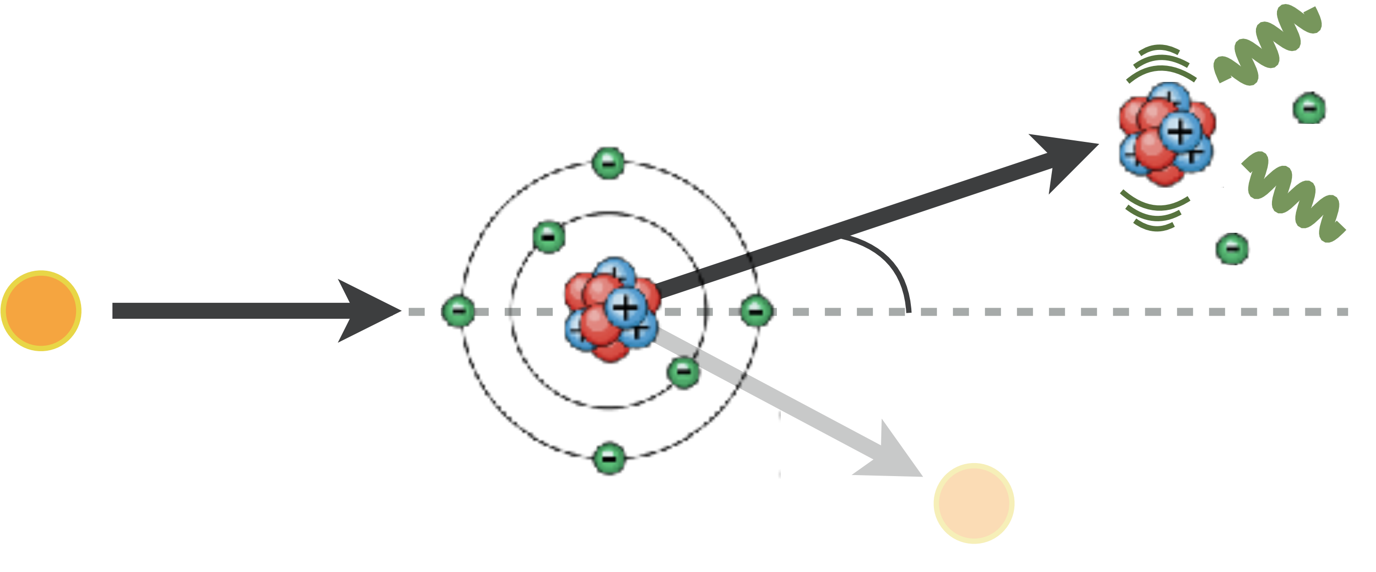
Direct searches for WIMPs

Relies on two things:

1. There are WIMPs from the galaxy passing through the Earth right now



2. They will interact with atoms



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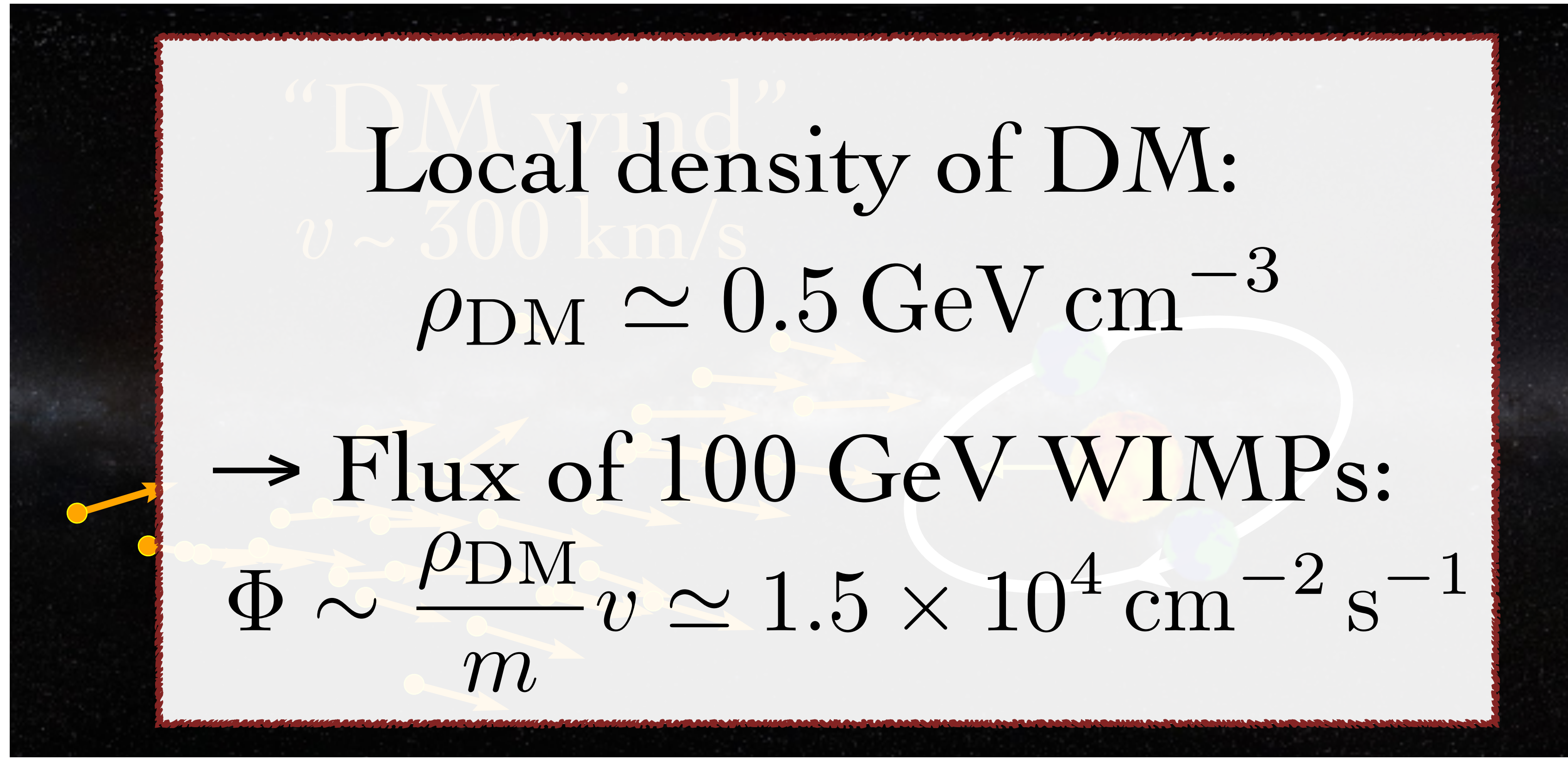

Local density of DM:

$$\rho_{\rm DM} \simeq 0.5\,{\rm GeV\,cm^{-3}}$$

$\rightarrow$ Flux of 100 GeV WIMPs:

$$\Phi \sim \frac{\rho_{\rm DM}}{m} v \simeq 1.5 \times 10^4\,{\rm cm^{-2}\,s^{-1}}$$

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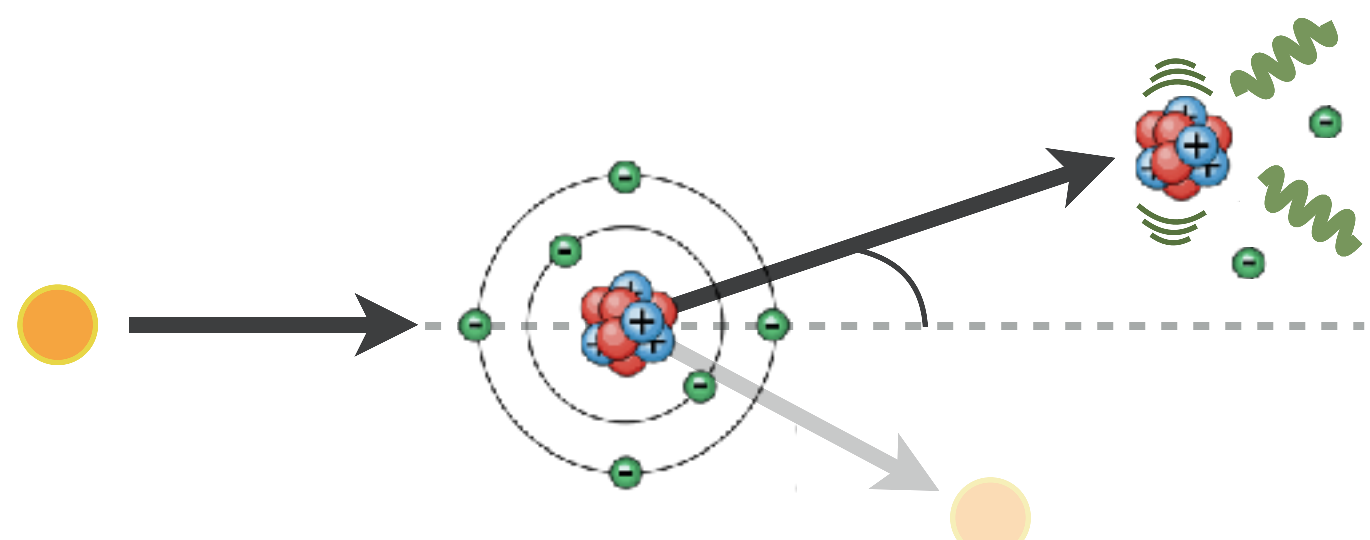

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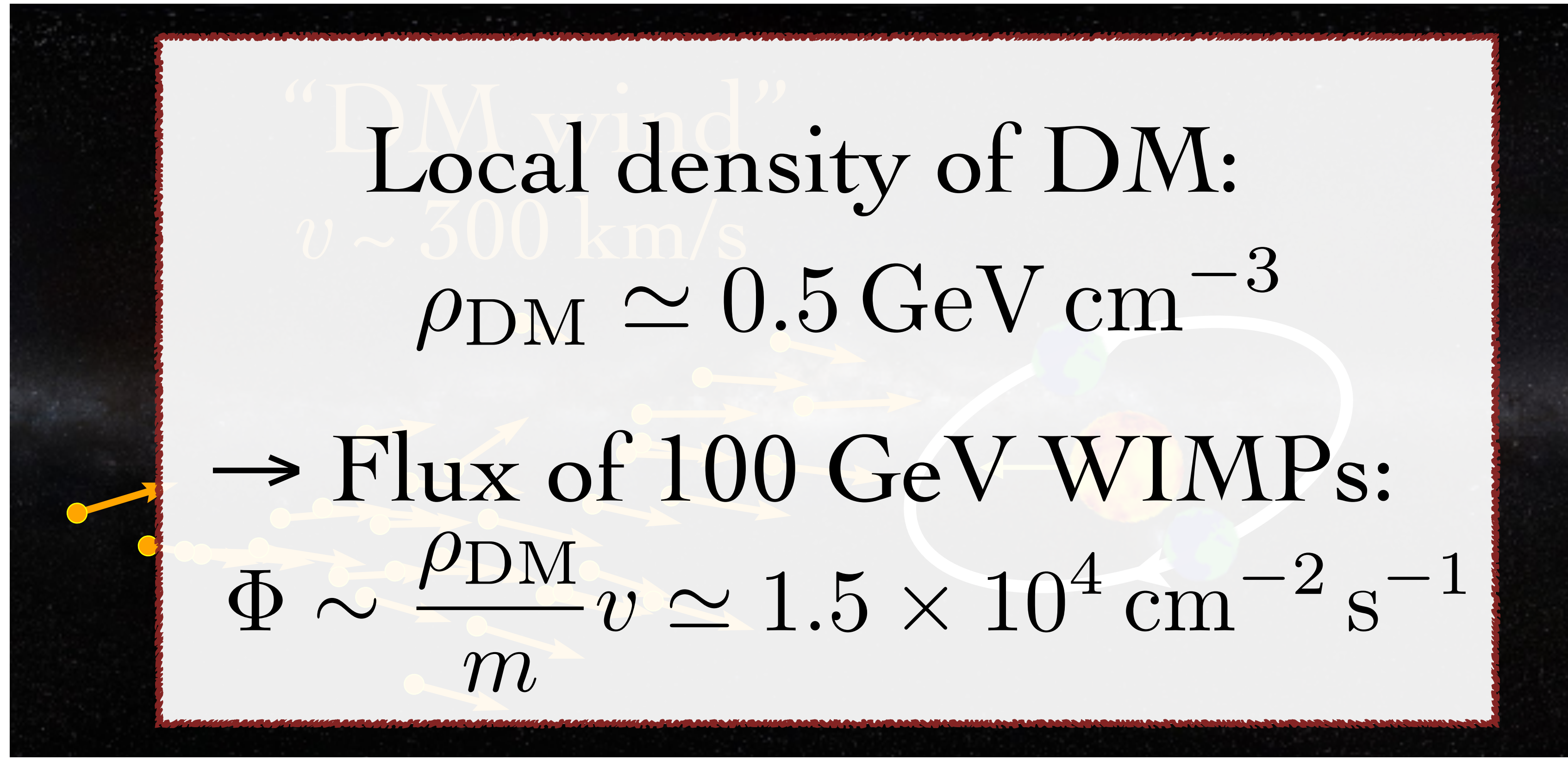

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If cross section w/ nucleus (e.g. Xe)

$$\sigma \sim 10^{-41}\,{\rm cm}^2$$

$\rightarrow$ number of events per unit detector mass

$$R \simeq \Phi\sigma/m_N \sim 0.5\,{\rm events\,ton^{-1}\,year^{-1}}$$

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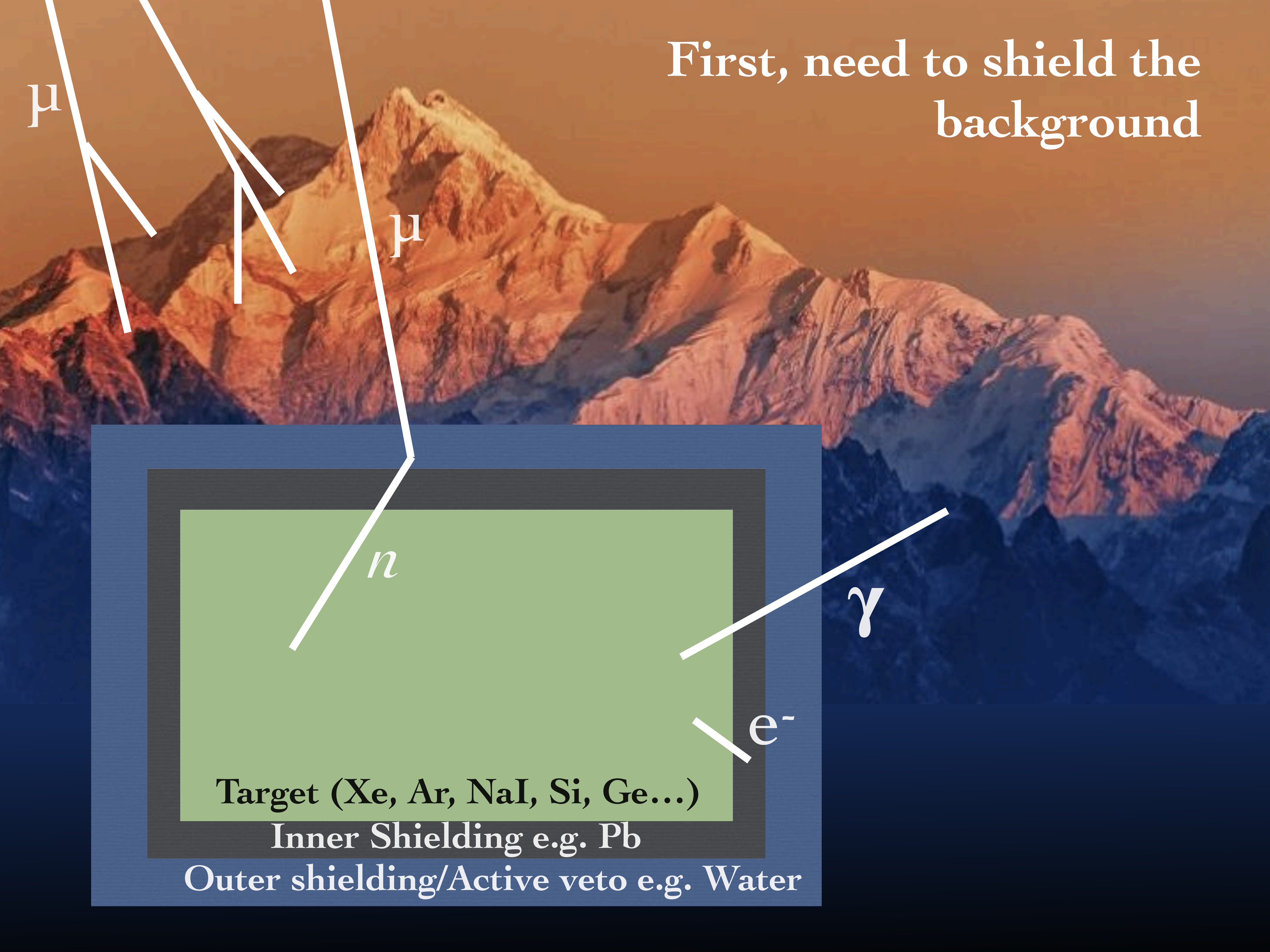
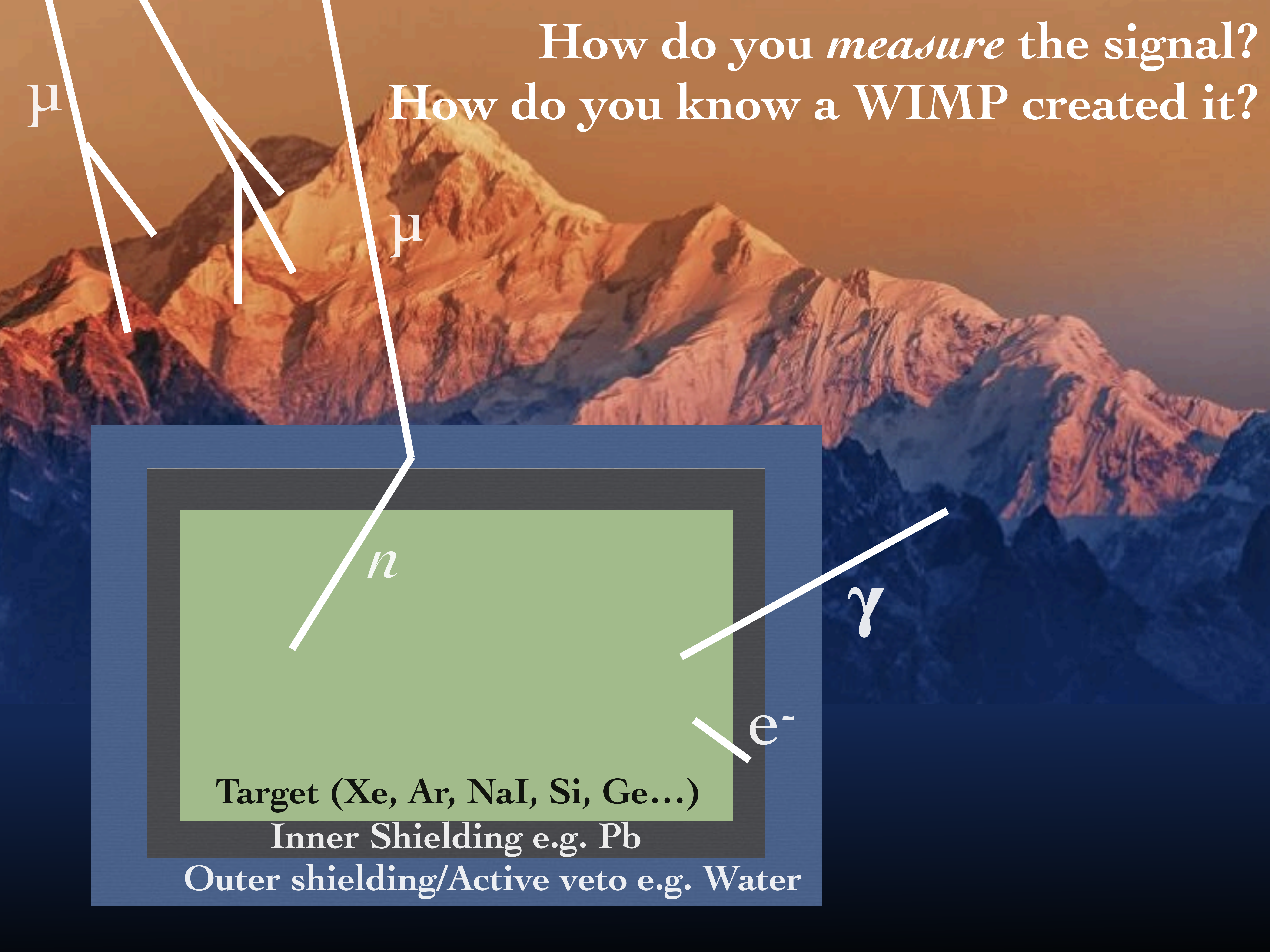
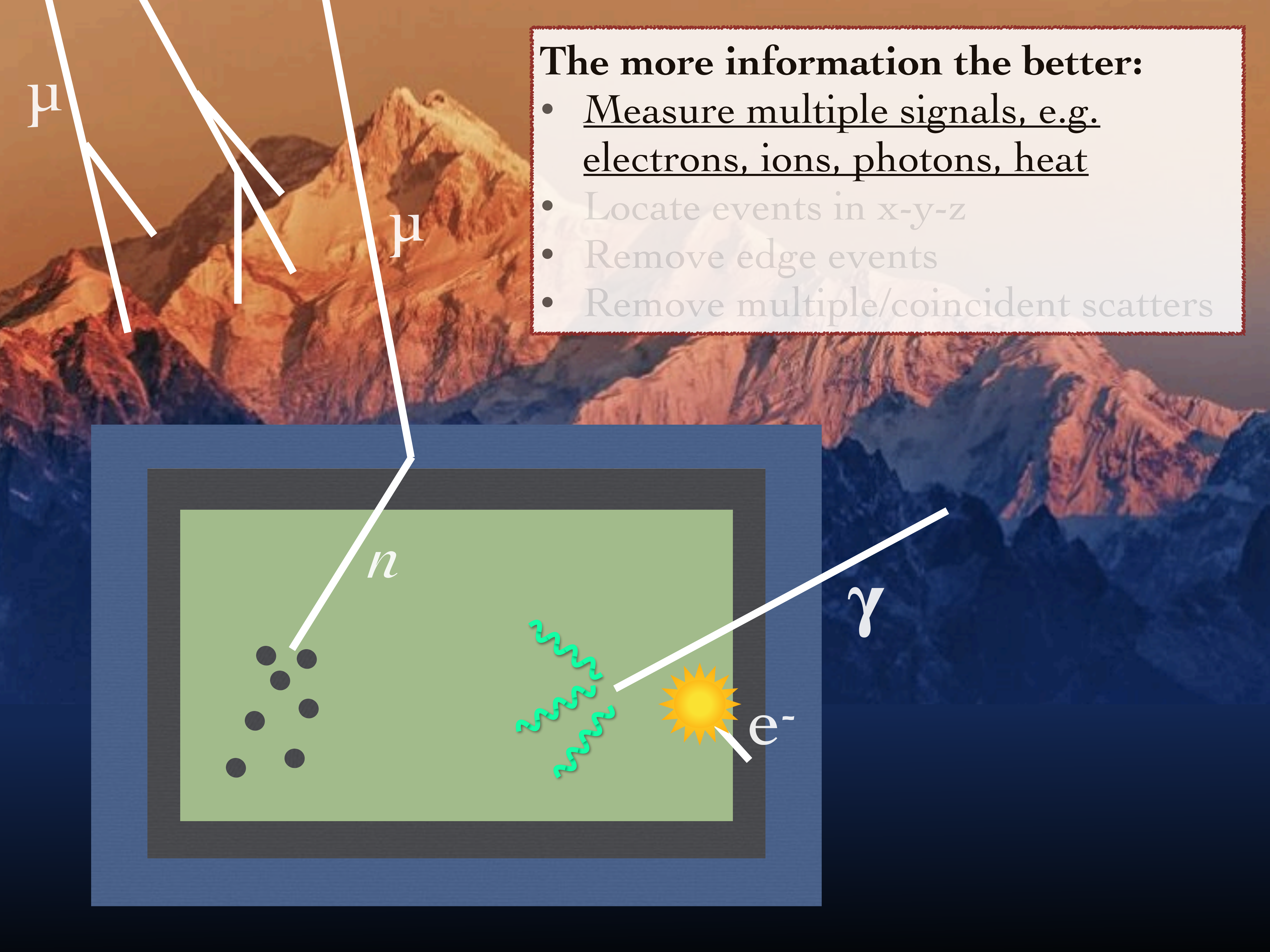

First, need to shield the background
μ
μ
n
γ
e-
Target (Xe, Ar, NaI, Si, Ge…)
Inner Shielding e.g. Pb
Outer shielding/Active veto e.g. Water


How do you *measure* the signal?
How do you know a WIMP created it?
μ
μ
n
γ
e⁻
Target (Xe, Ar, NaI, Si, Ge…)
Inner Shielding e.g. Pb
Outer shielding/Active veto e.g. Water

The more information the better:

- <u>Measure multiple signals, e.g. electrons, ions, photons, heat</u>
- Locate events in x-y-z
- Remove edge events
- Remove multiple/coincident scatters



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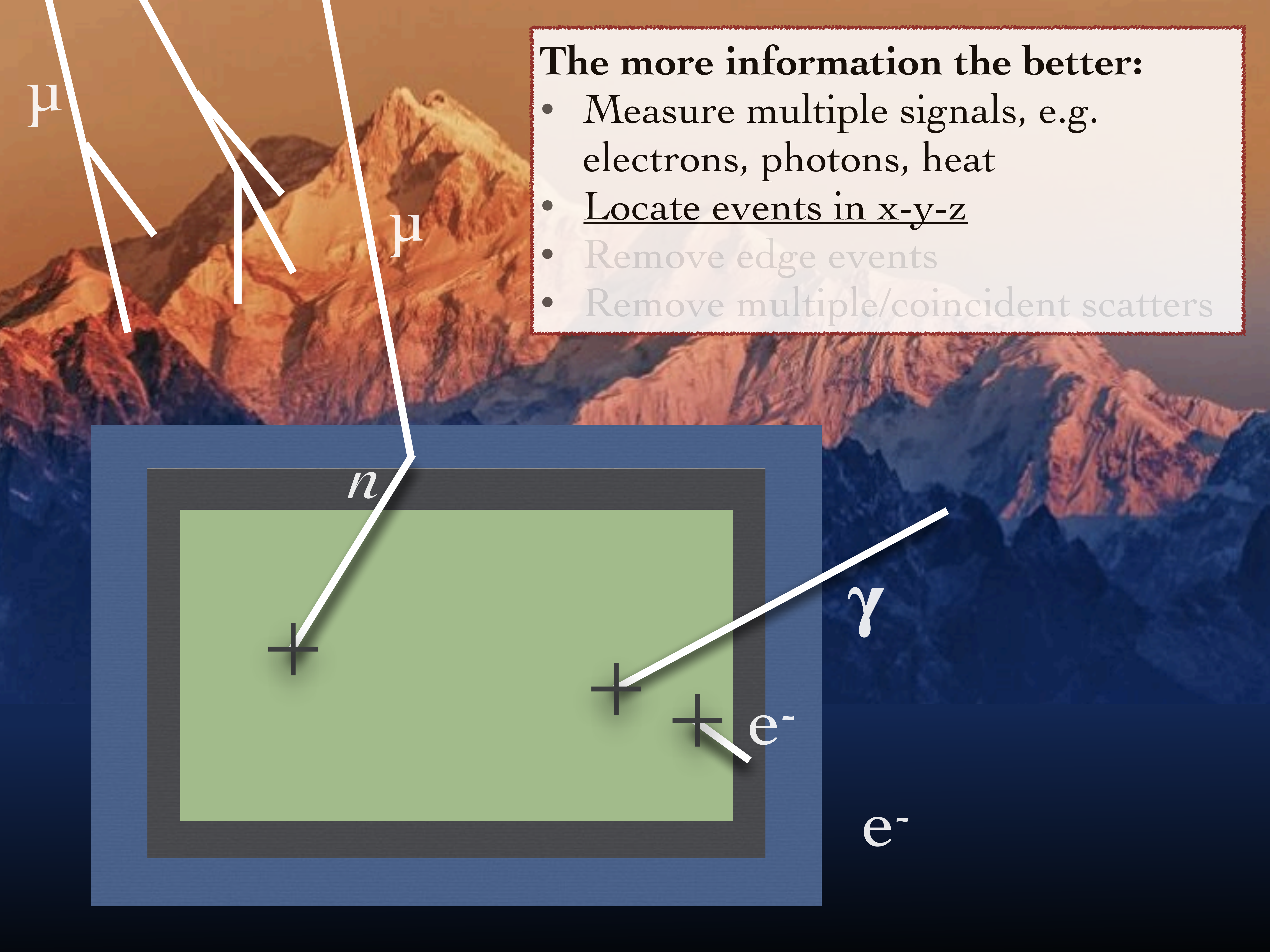

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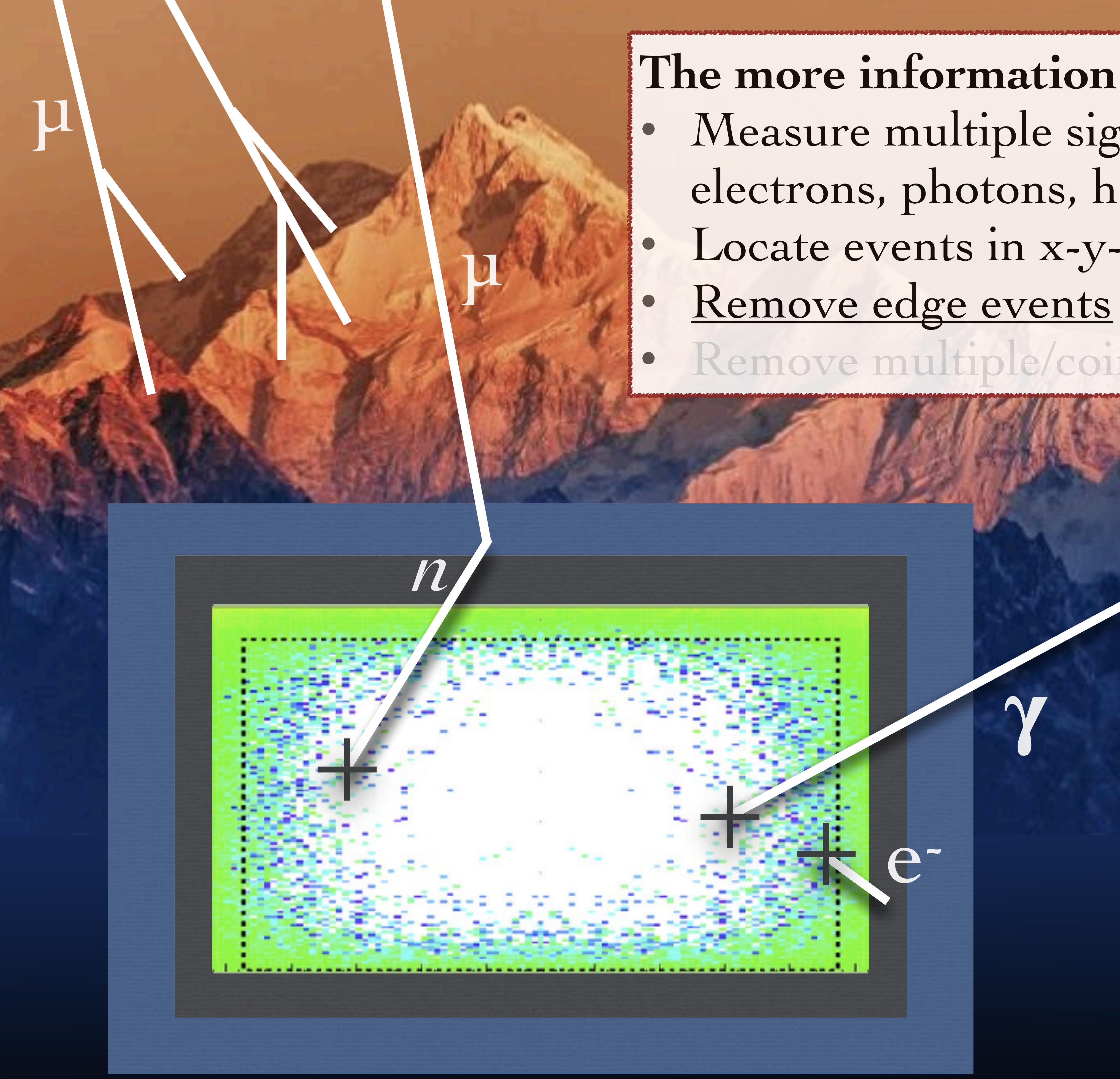

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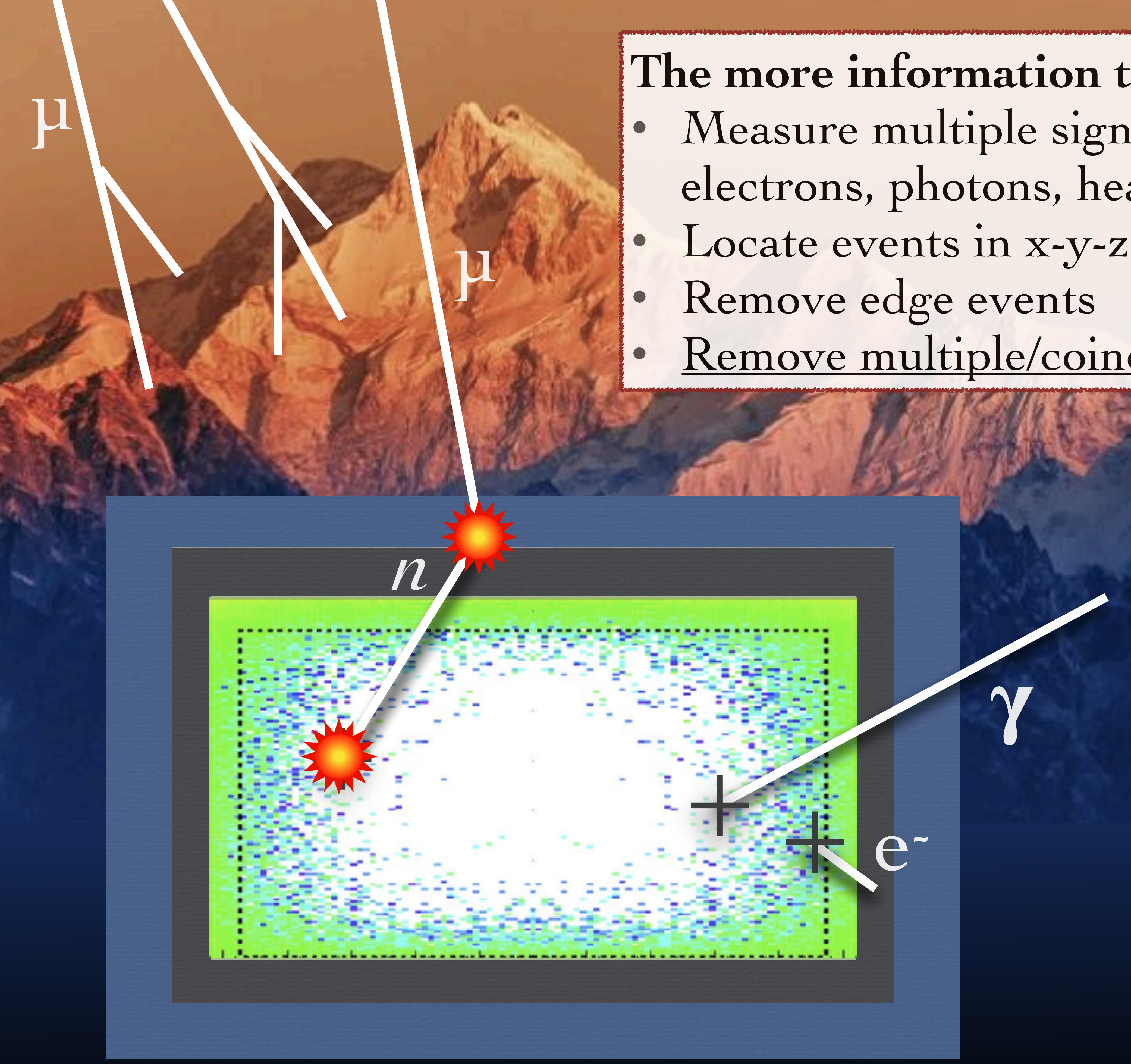
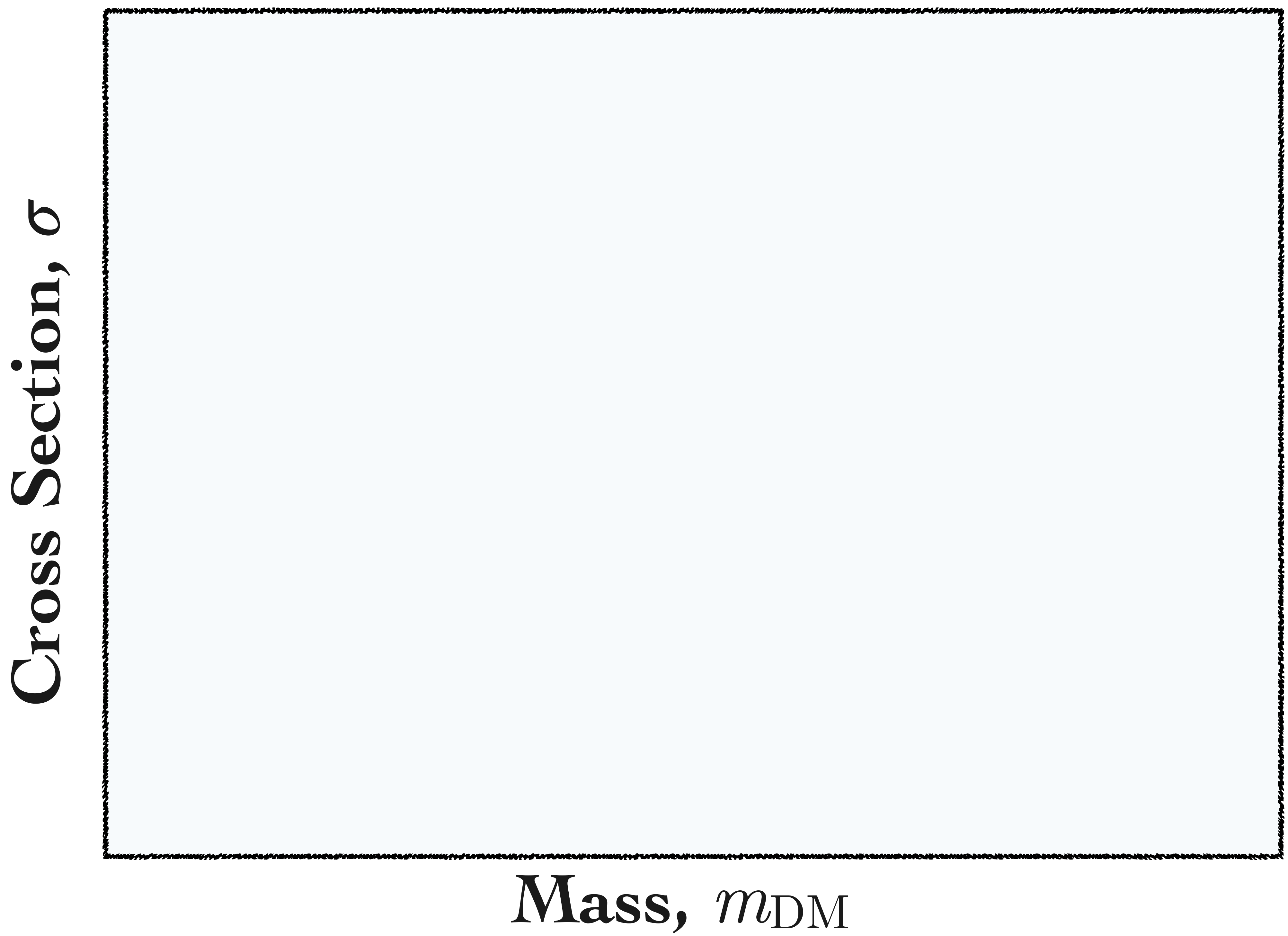


How to set a WIMP limit when you have run an experiment and seen nothing:



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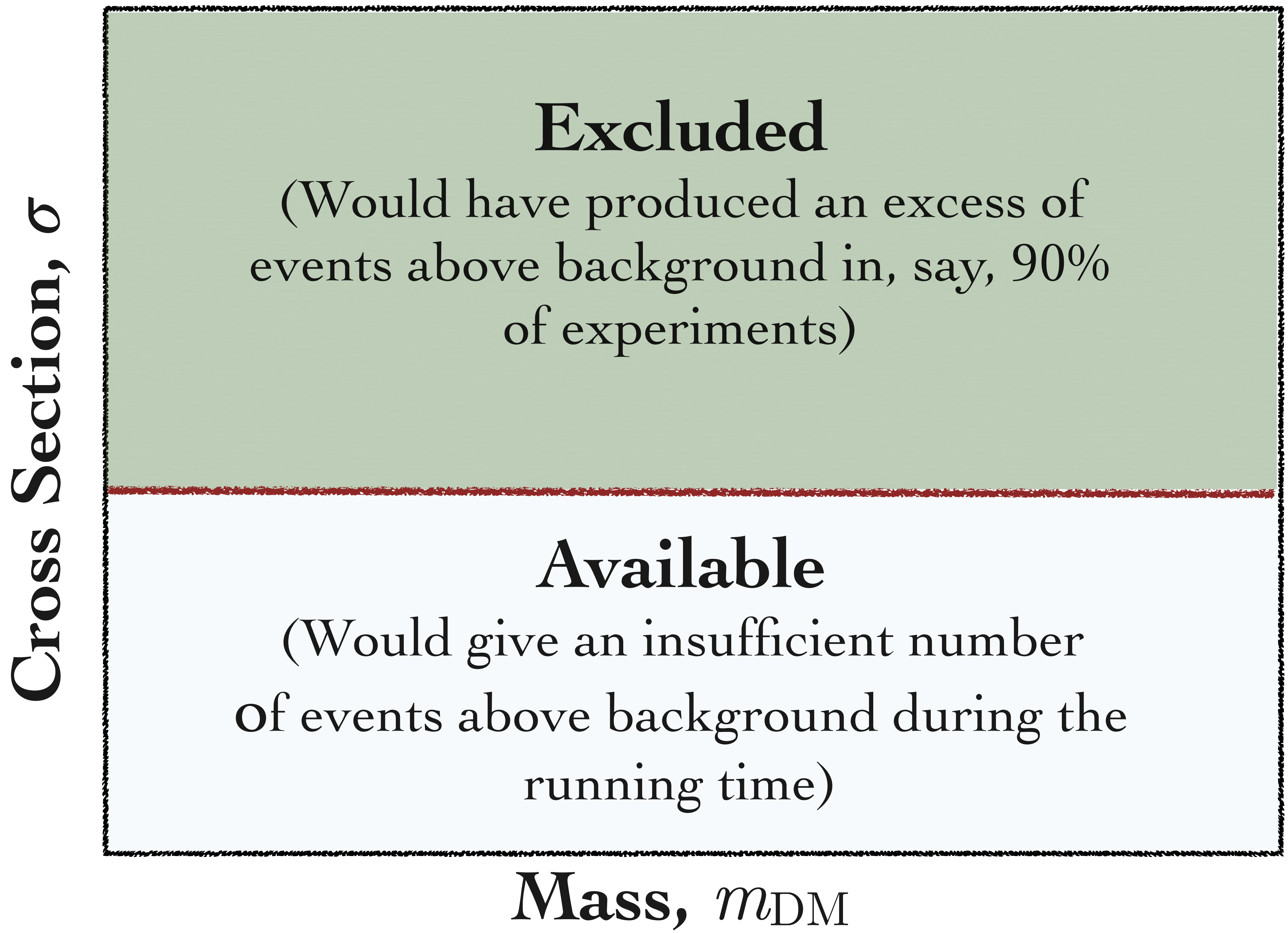

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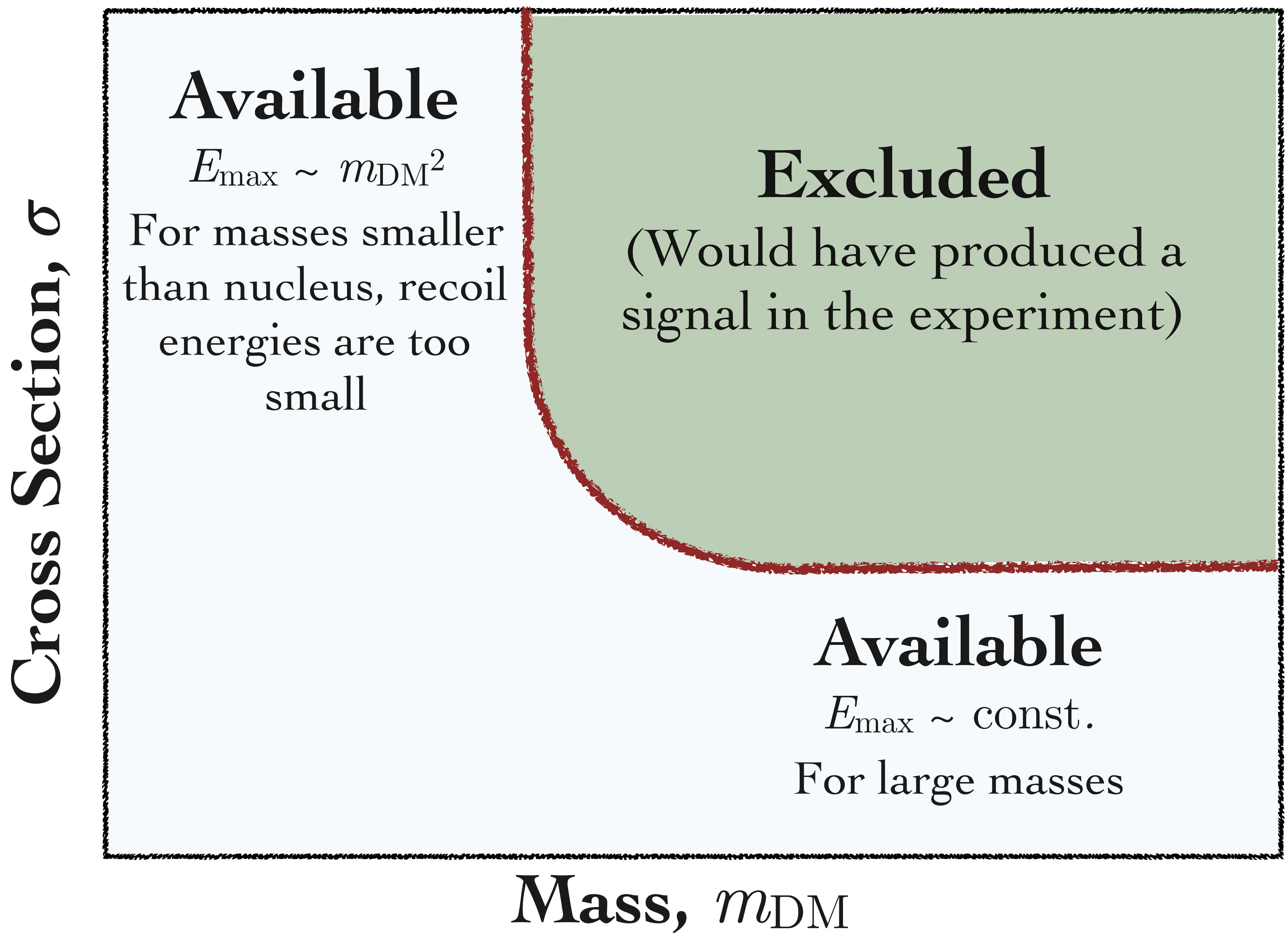
Effect of recoil energy sensitivity:

$$E_{\rm max} = \frac{2 m_N m_{\rm DM}^2}{(m_N + m_{\rm DM})^2} v_{\rm max}^2$$

~800 km/s



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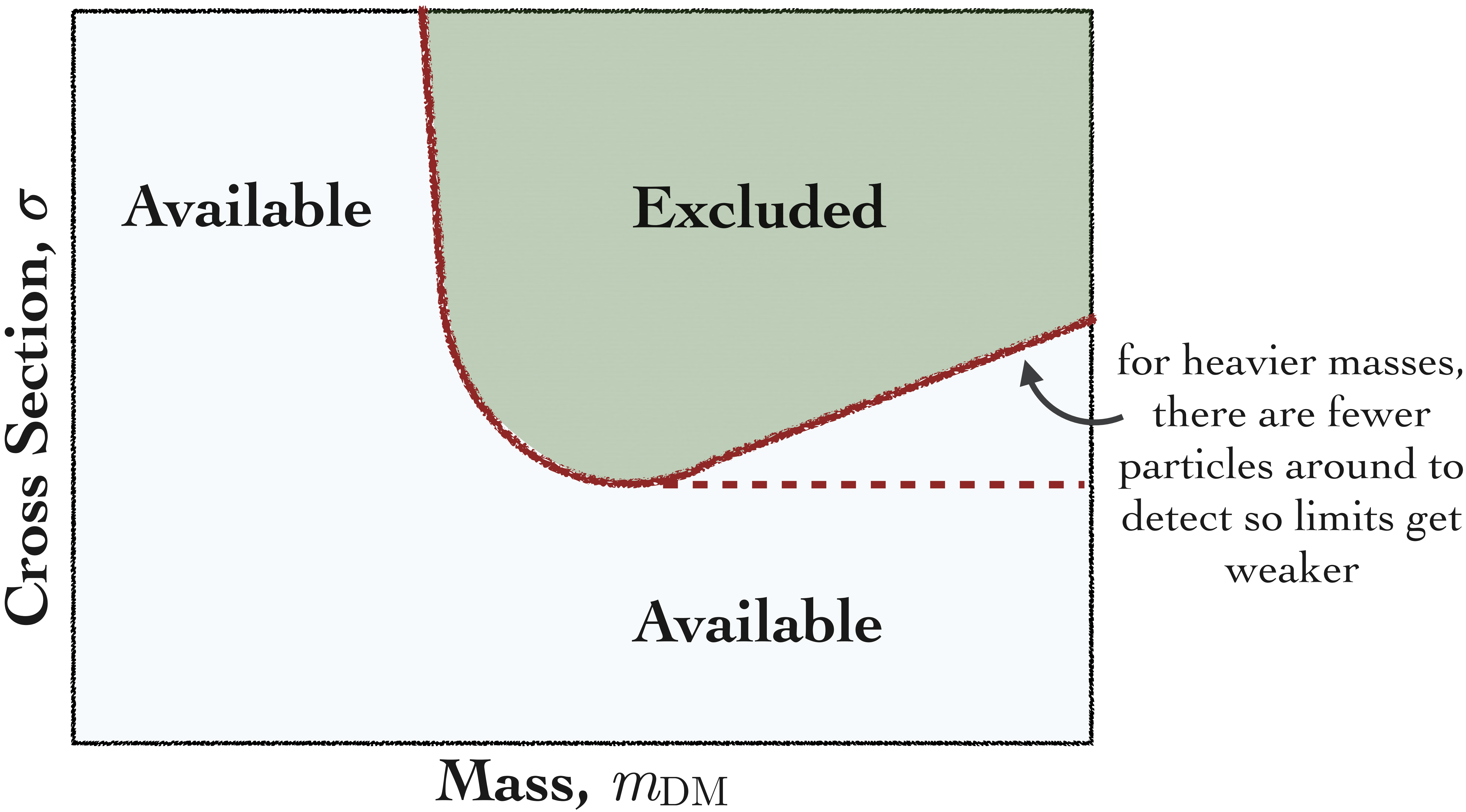
Event rate proportional to DM **number** density

$$R \propto \frac{\sigma \rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}$$



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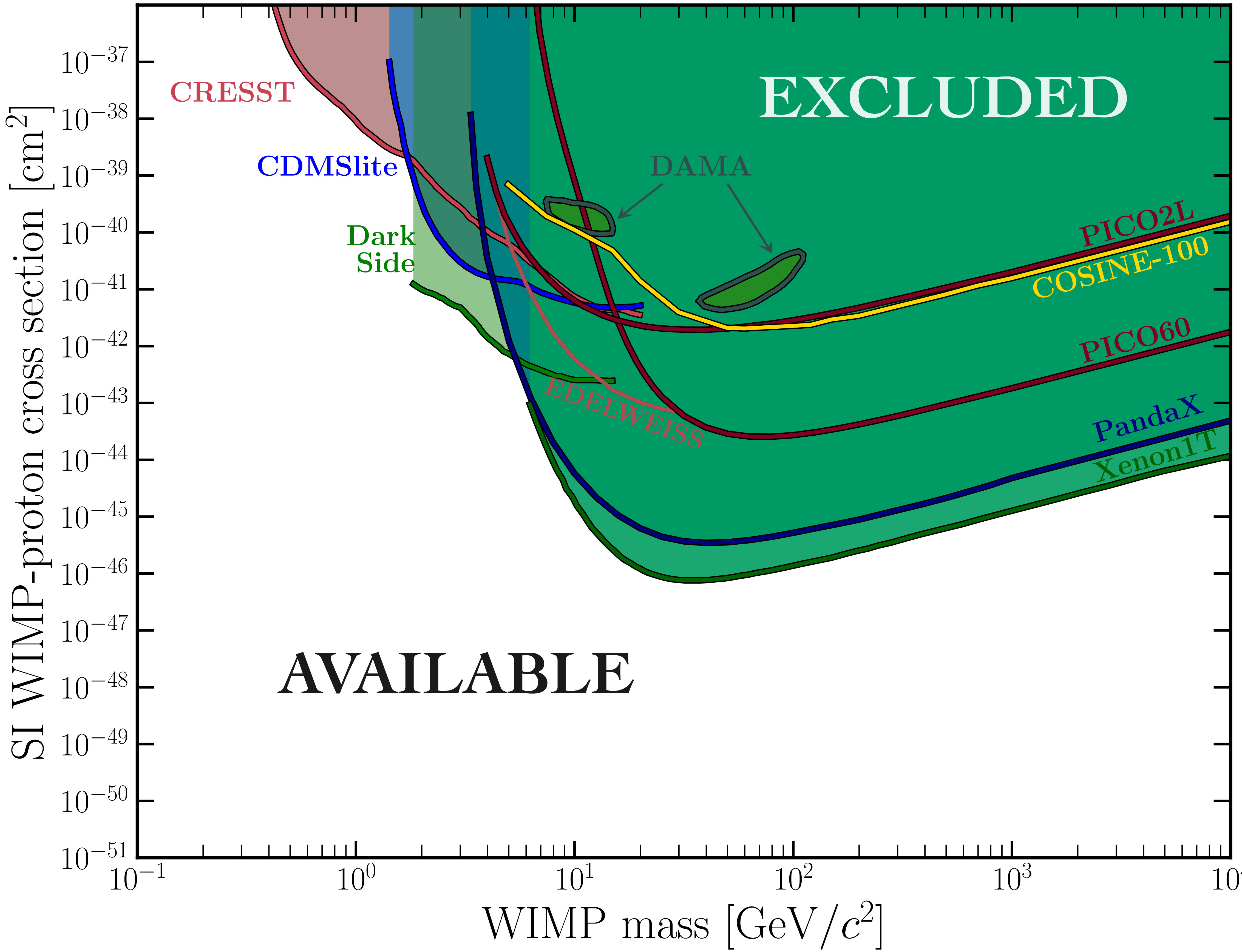
Current status on the spin independent WIMP-proton cross section



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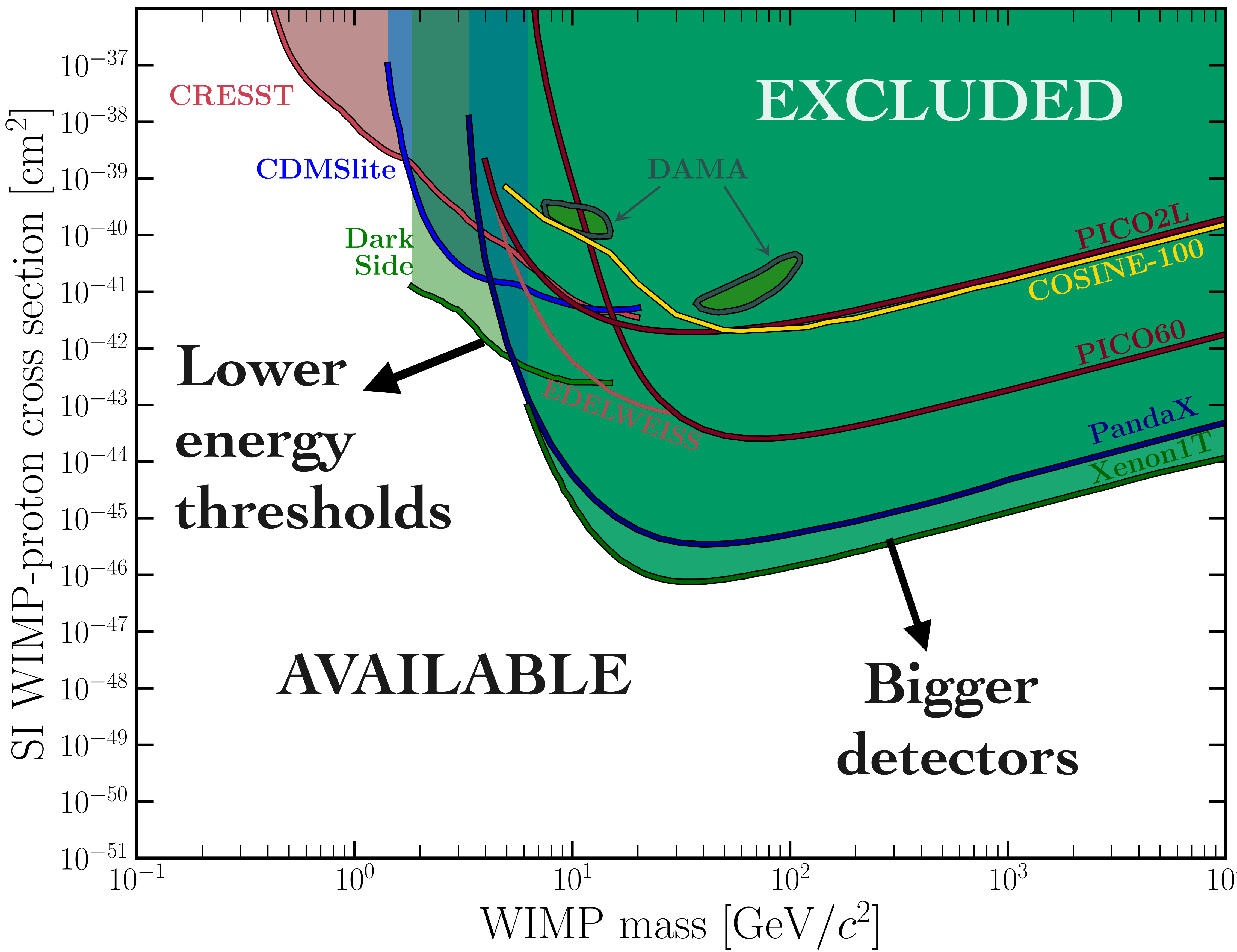

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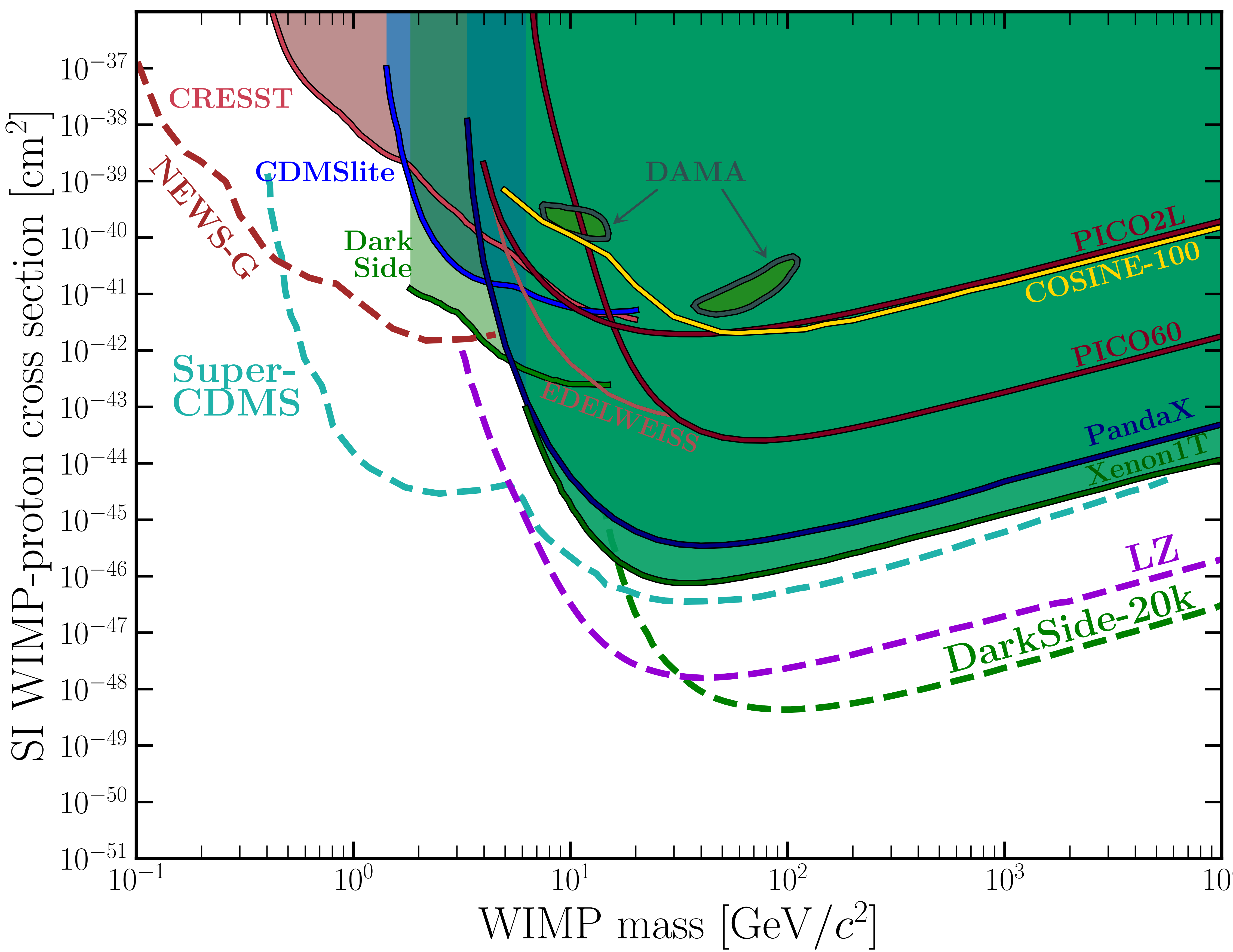
Future status



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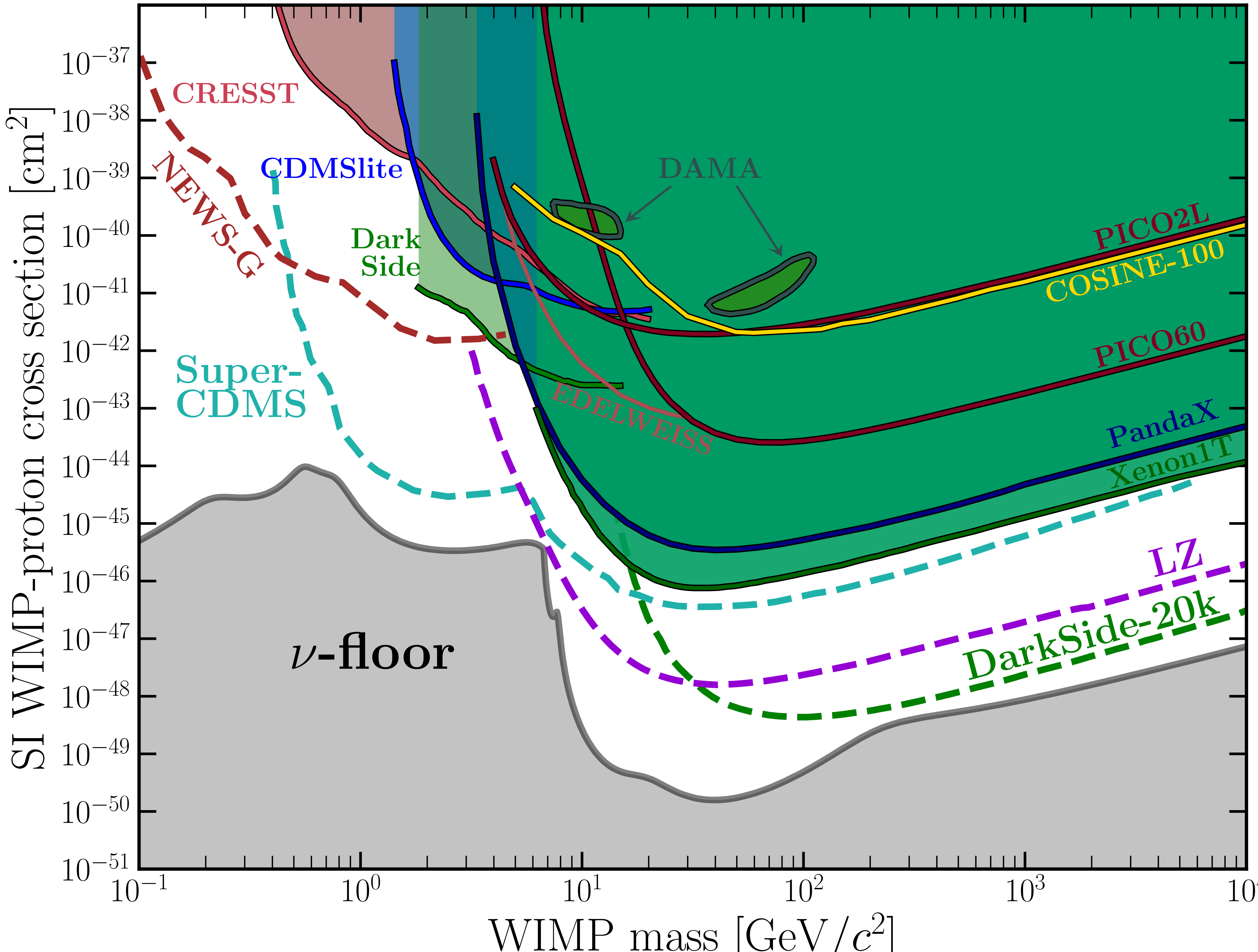

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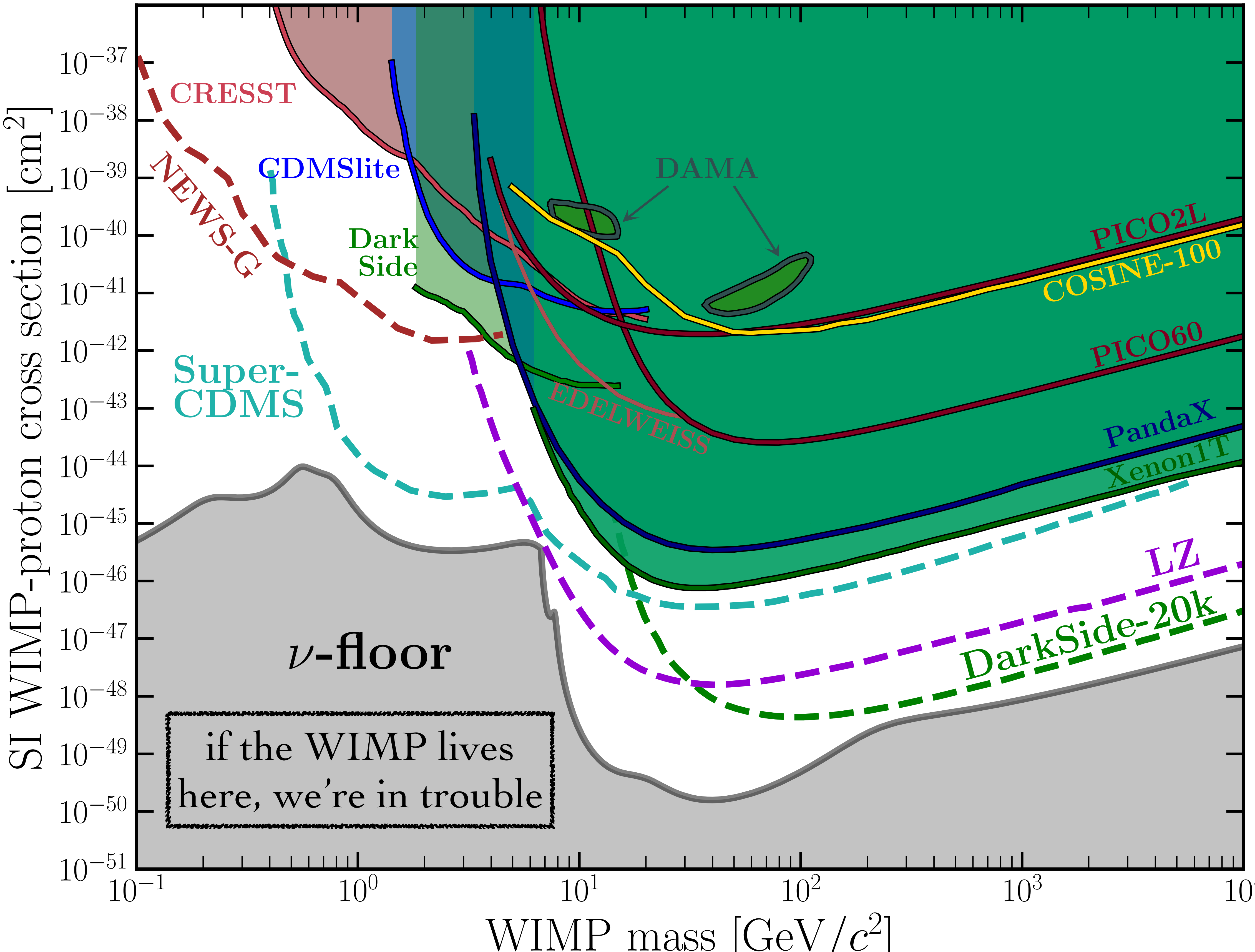

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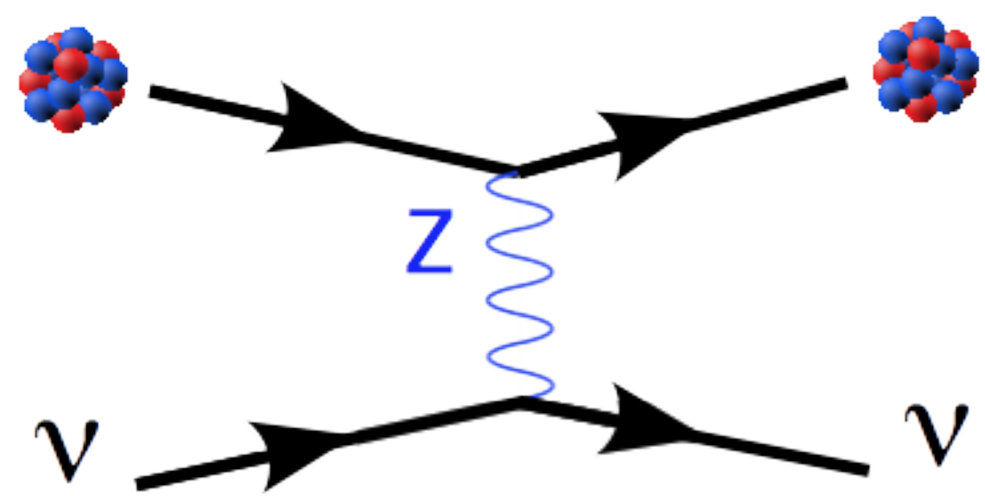
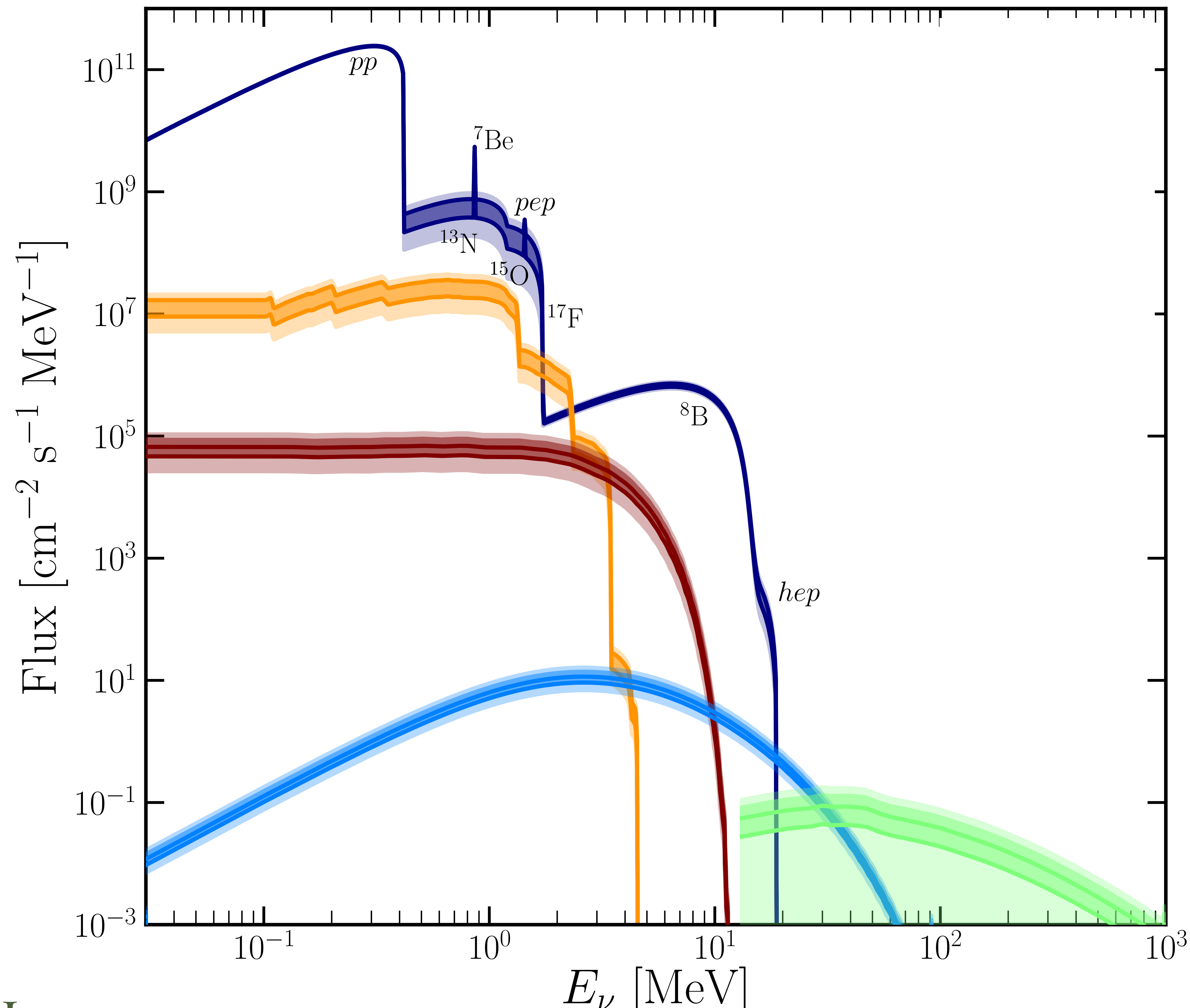
The neutrino floor

Spectrum of coherent neutrino-nucleus scattering looks just like WIMPs.



But neutrinos are impossible to shield

Sources of neutrino



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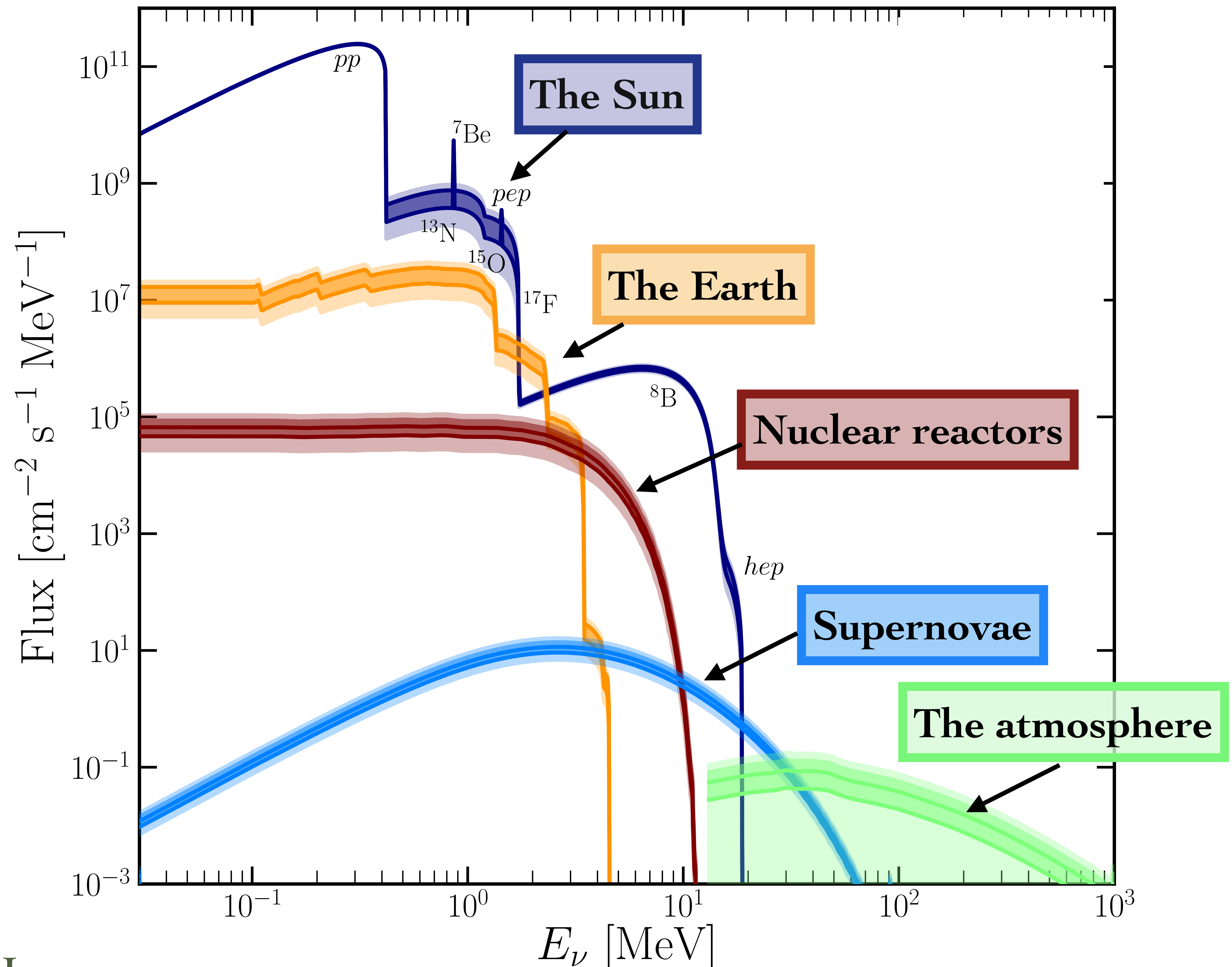
Sources of neutrino



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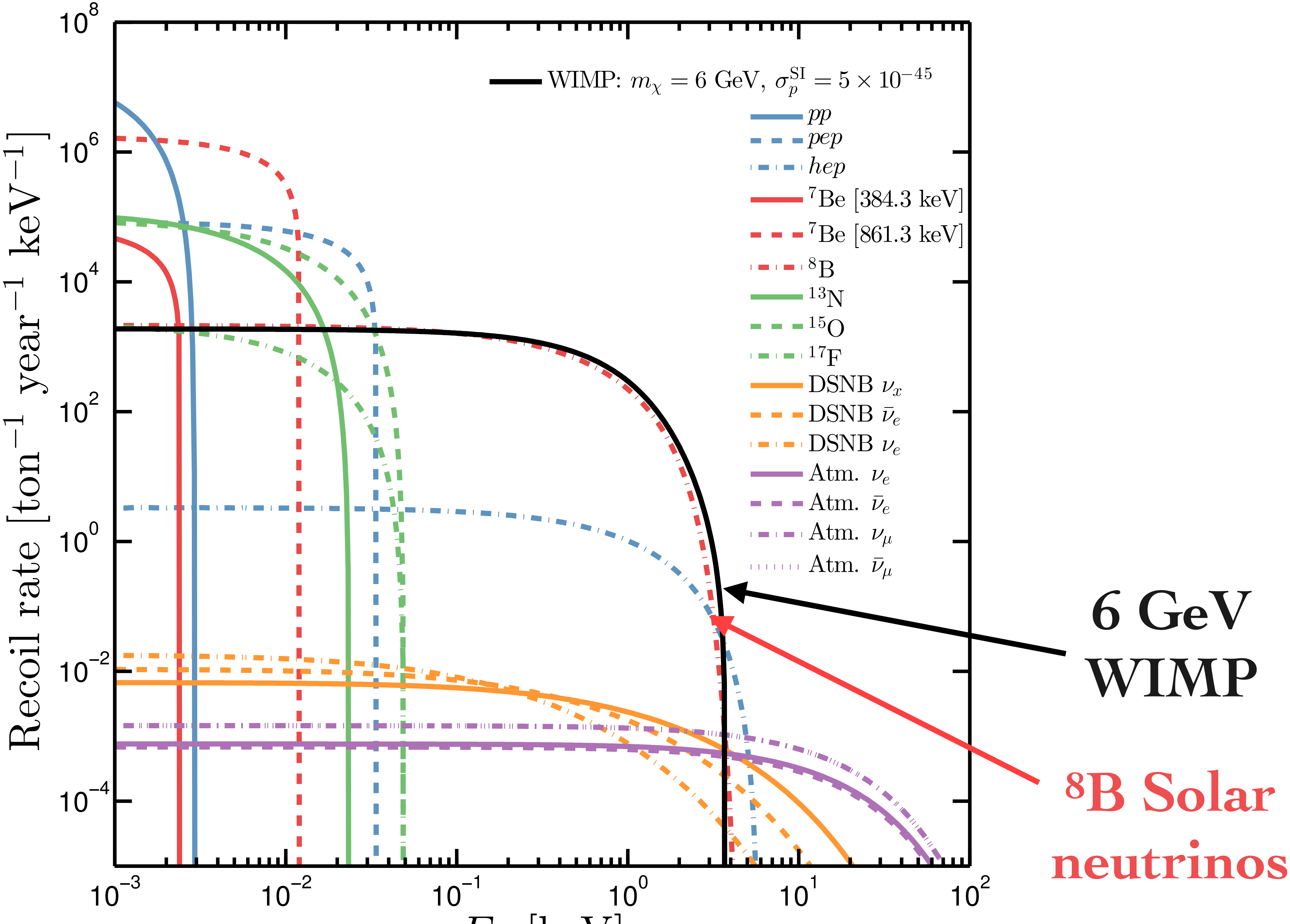
Comparing WIMP and neutrino event rates (in Xenon)



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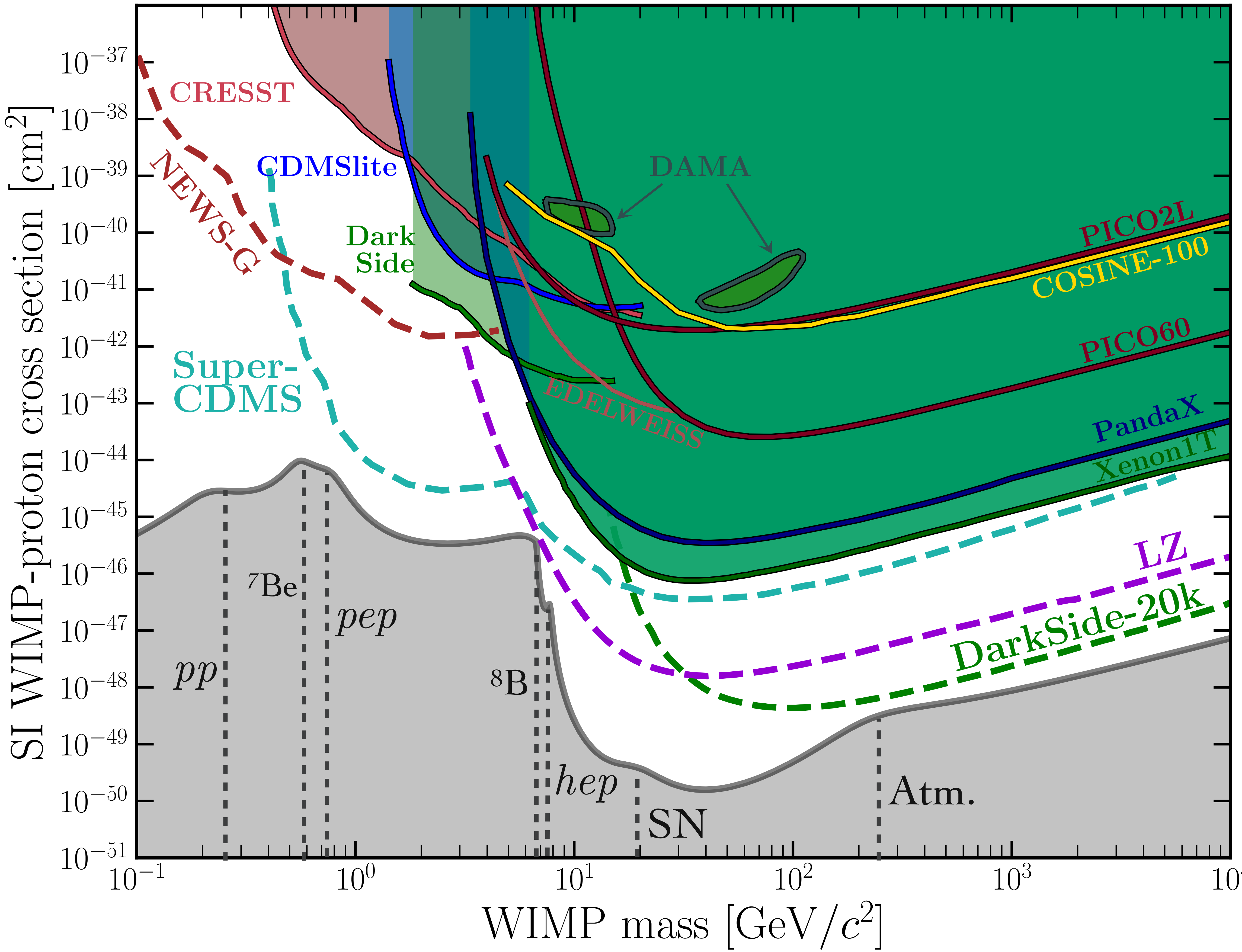

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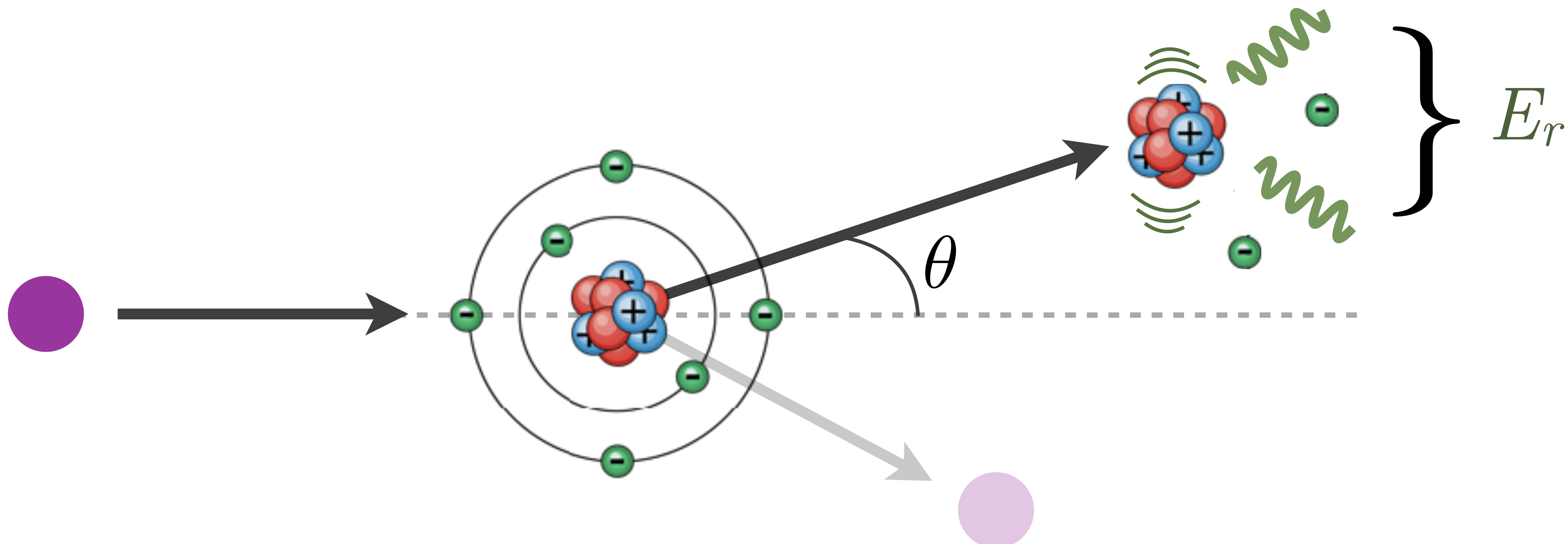
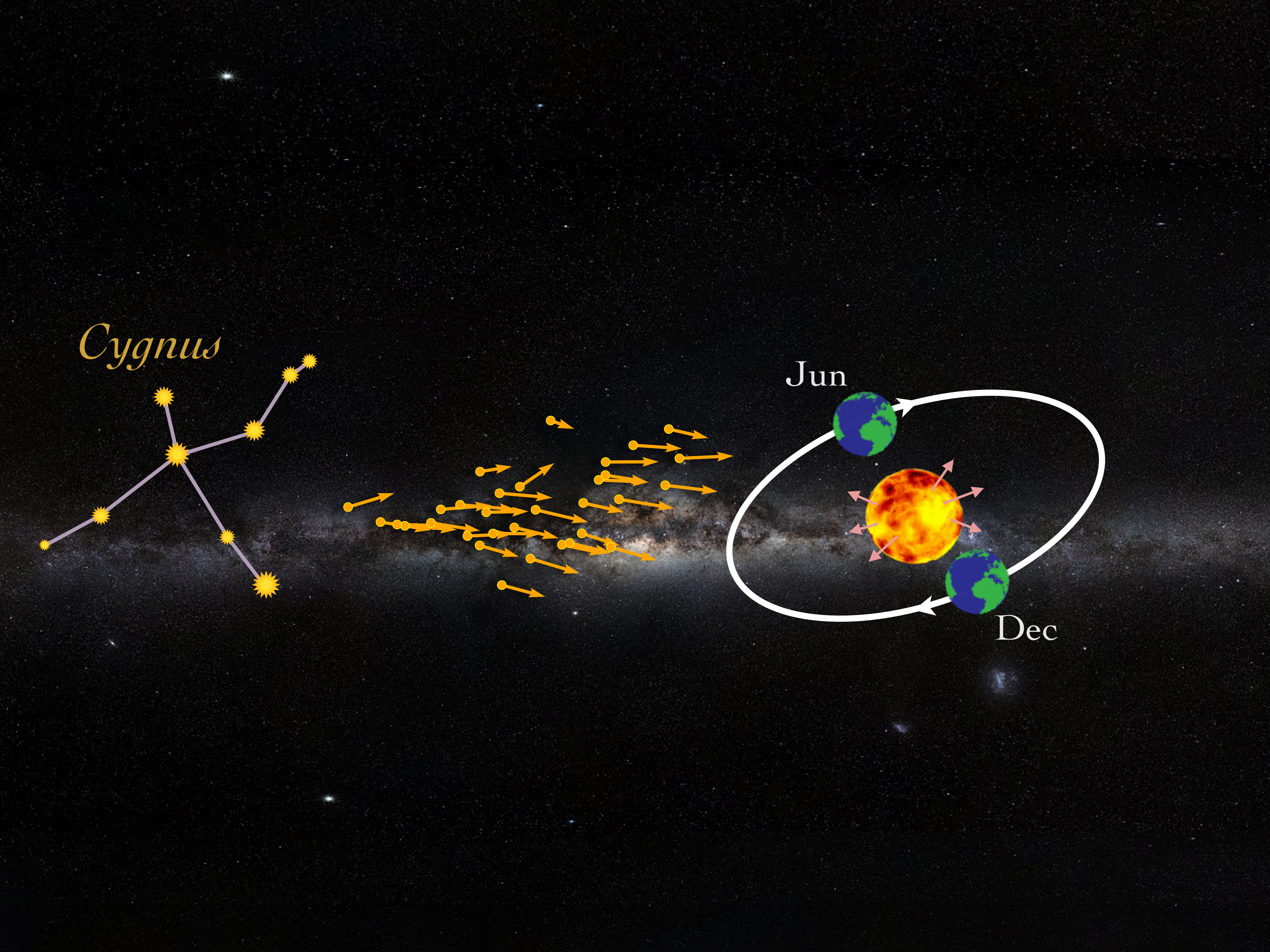
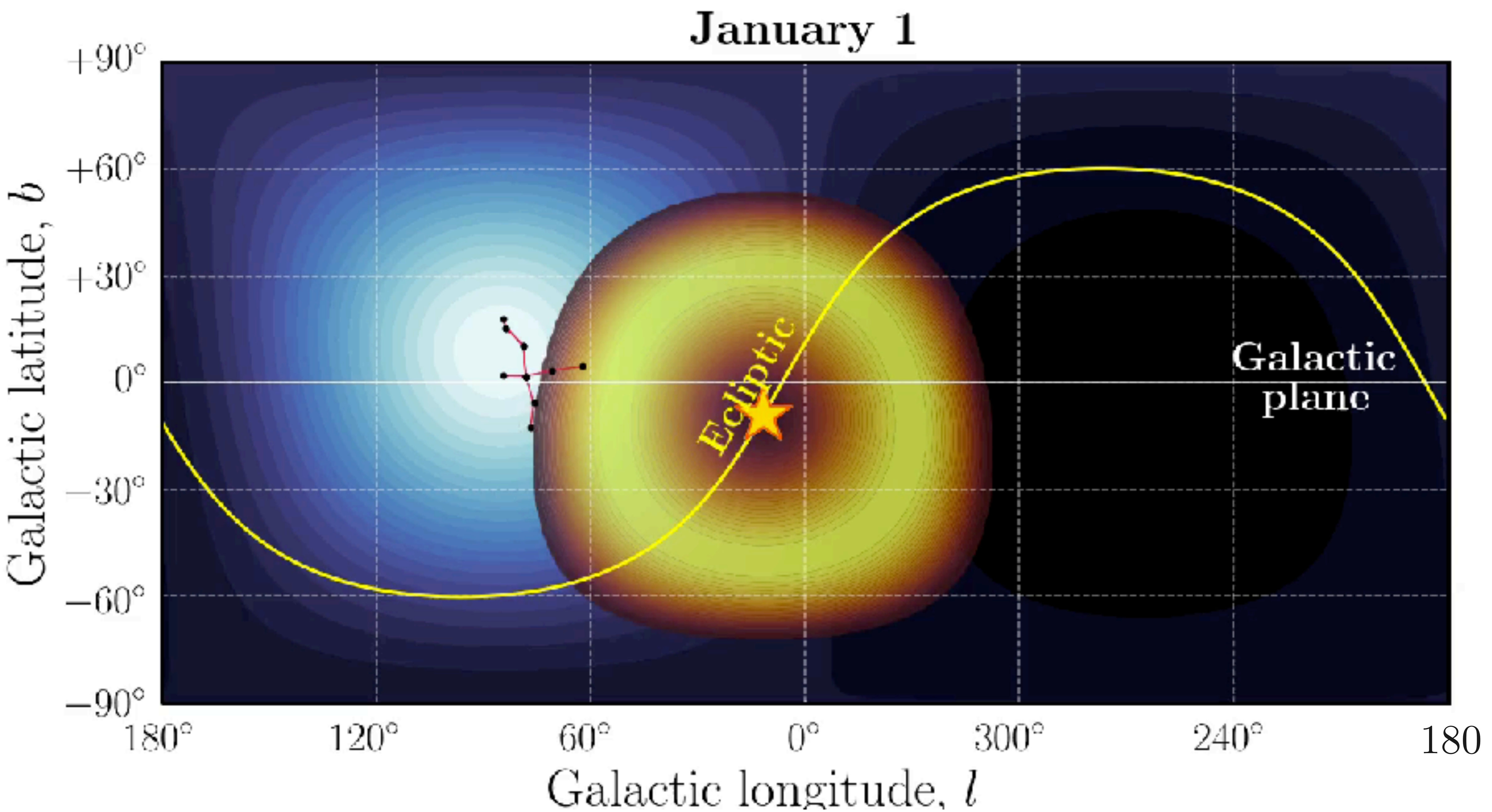


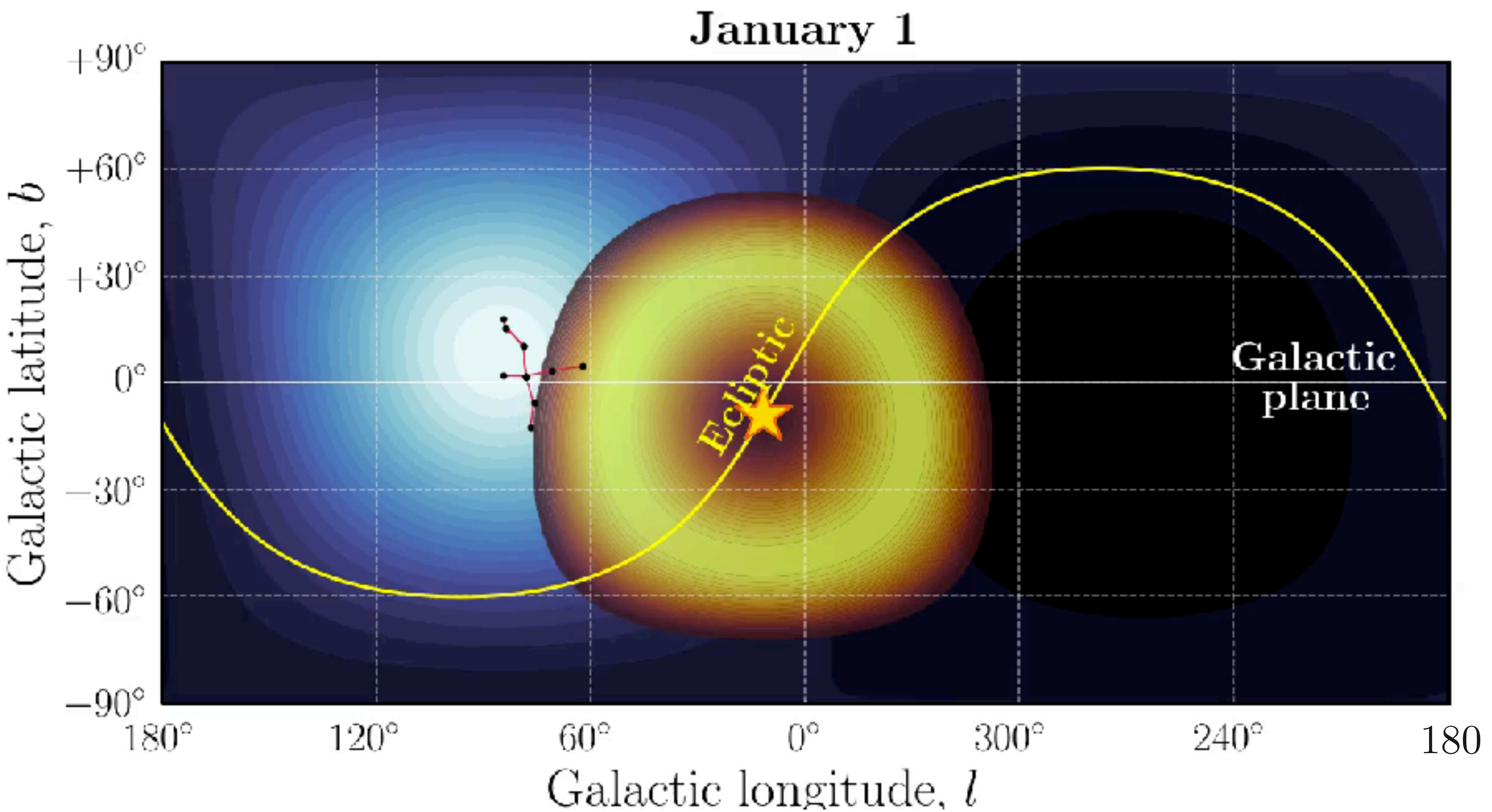
For neutrinos and WIMPs, the recoil energies are the same, but the **directions** are not


Cygnus
Jun
Dec

WIMP recoils **Solar neutrino recoils**



WIMP recoils **Solar neutrino recoils**

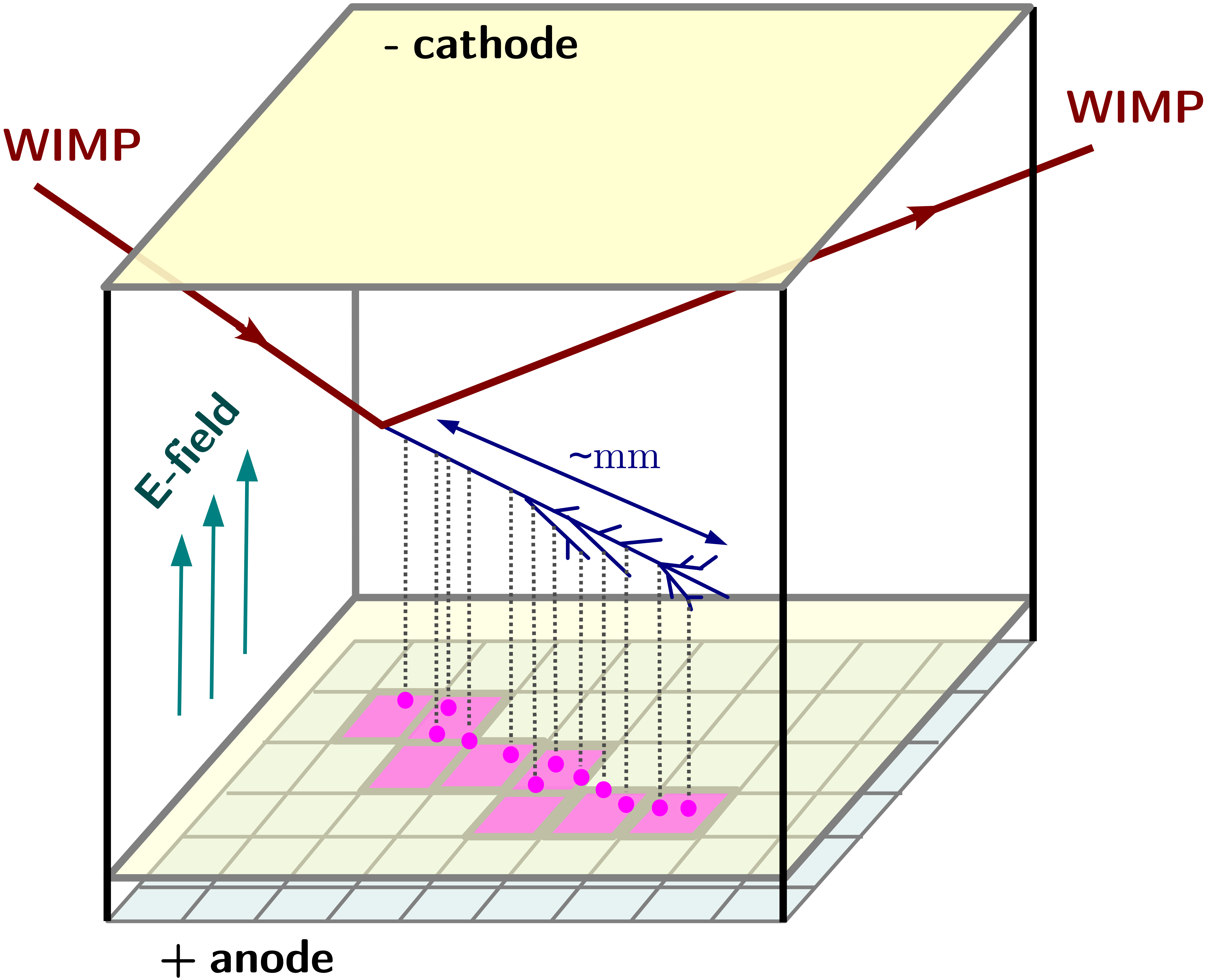


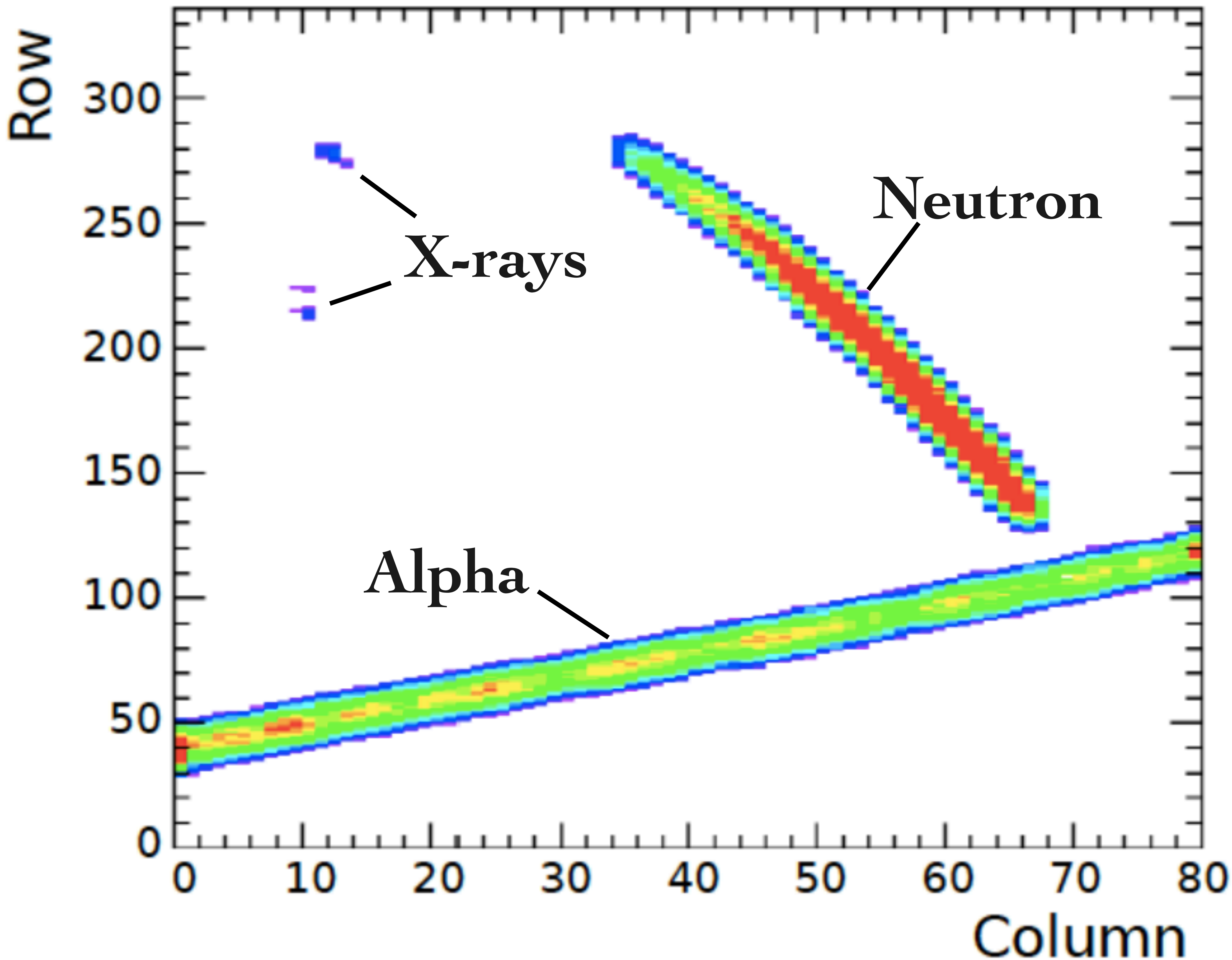
CYGNUS

- Collaboration of ~50 signed members from the directional detection community
- Members from USA, UK, Japan, Spain, Australia, Italy
- Towards a ton-scale directional WIMP search below the neutrino floor
- Investigating gas-based time projection chamber (TPC) with various readout technologies

CYGNUS: Feasibility of a Nuclear Recoil Observatory with Directional Sensitivity to Dark Matter and Neutrinos

E. Baracchini,[1,2,3] P. Barbeau,[4] J. B. R. Battat,[5] B. Crow,[6] C. Deaconu,[7] C. Eldridge,[8] A. C. Ezeribe,[8] D. Loomba,[9] W. A. Lynch,[8] K. J. Mack,[10] K. Miuchi,[11] N. S. Phan,[12] C. A. J. O'Hare,[13,14] K. Scholberg,[4] N. J. C. Spooner,[8] T. N. Thorpe,[6] and S. E. Vahsen[6]


- cathode
WIMP
WIMP
E-field
~mm
+ anode



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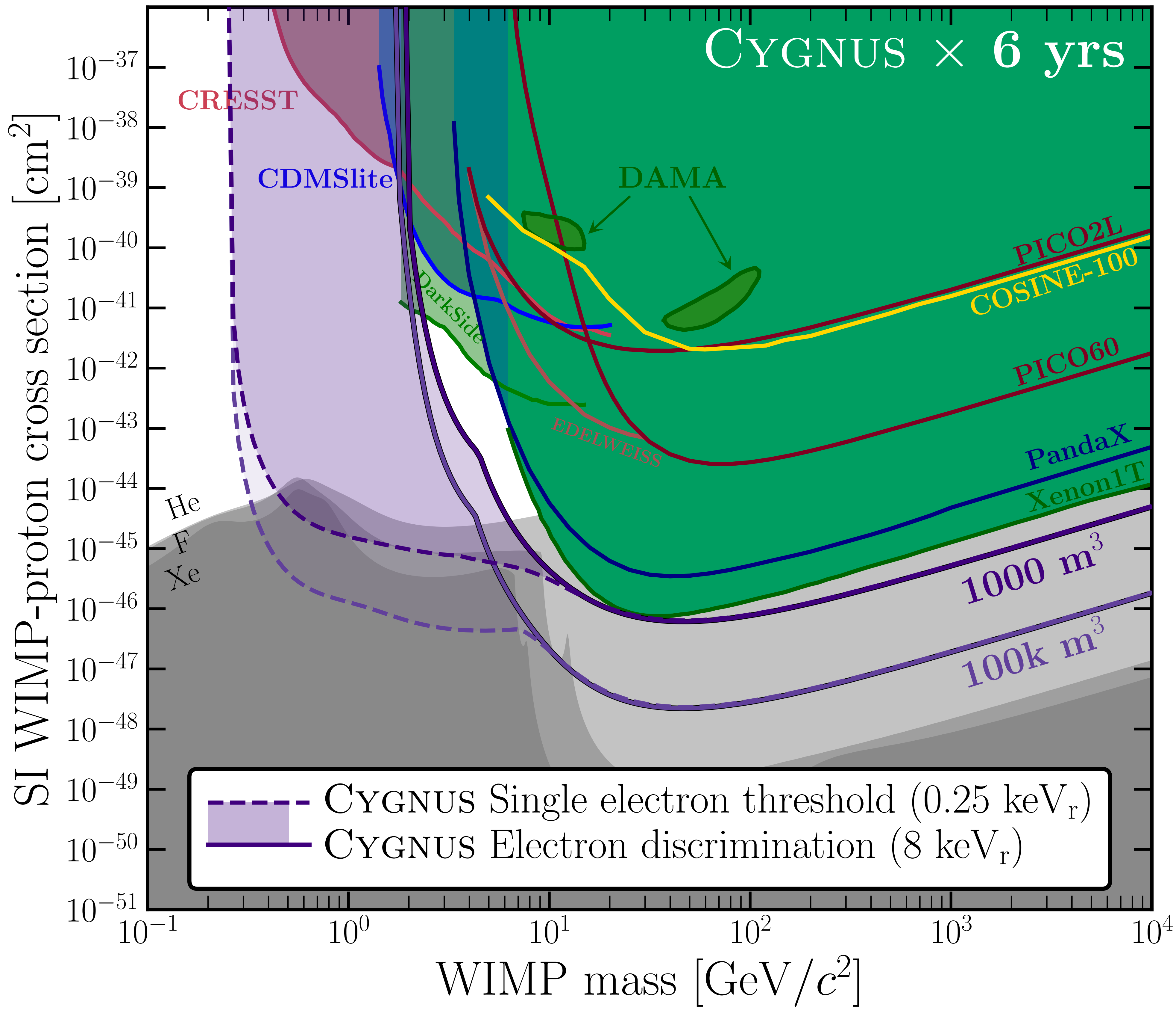
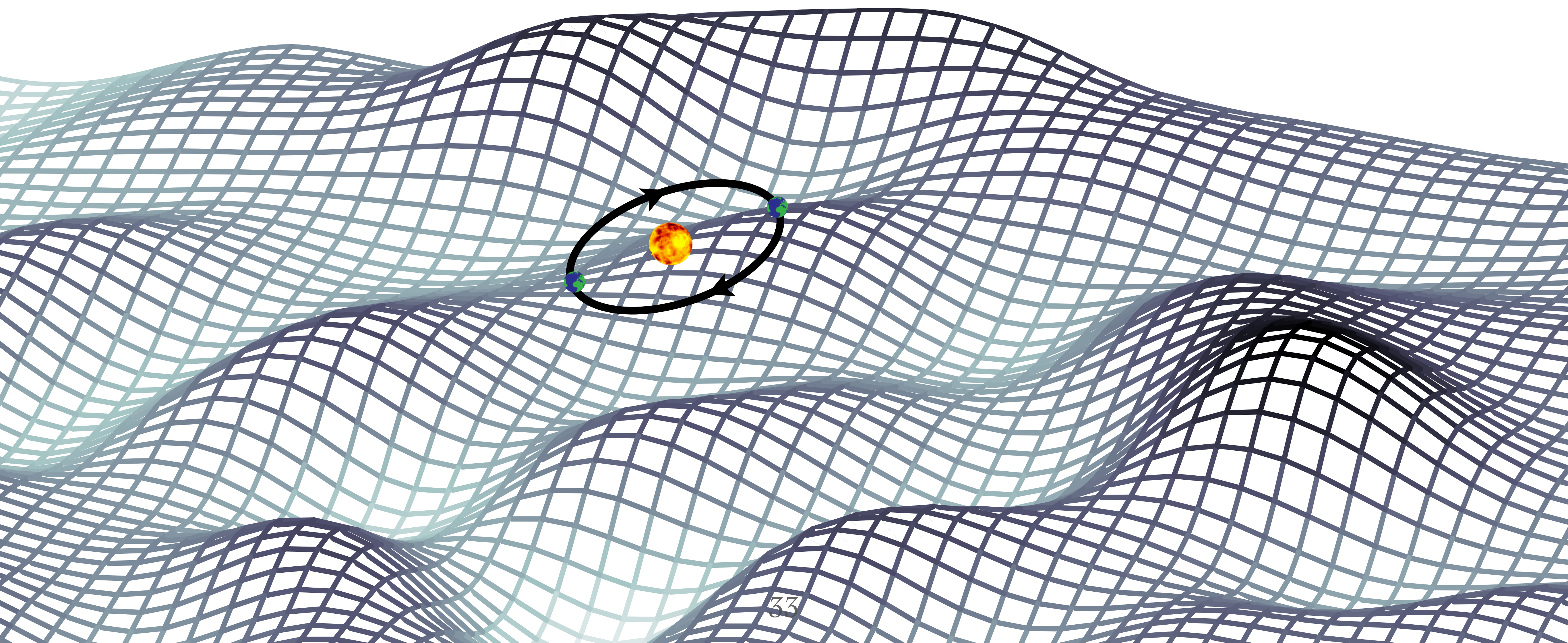


Preliminary, to appear…

The axion

Extremely light bosonic DM: 10^{-6} —10^{-4} eV (classic QCD axion)

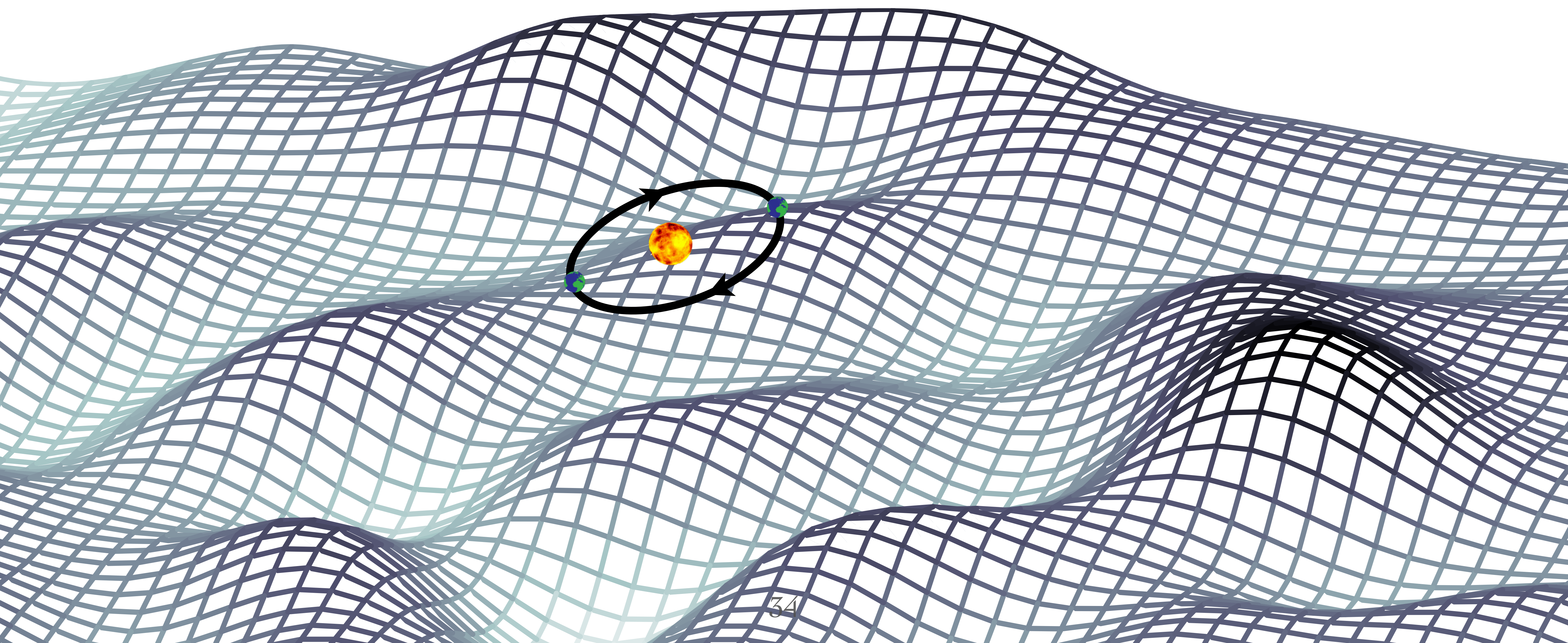
→ macroscopic occupation numbers needed to make up dark matter ~ 0.5 GeV cm^{-3}



DM axion field: $a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos\left(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha\right)$

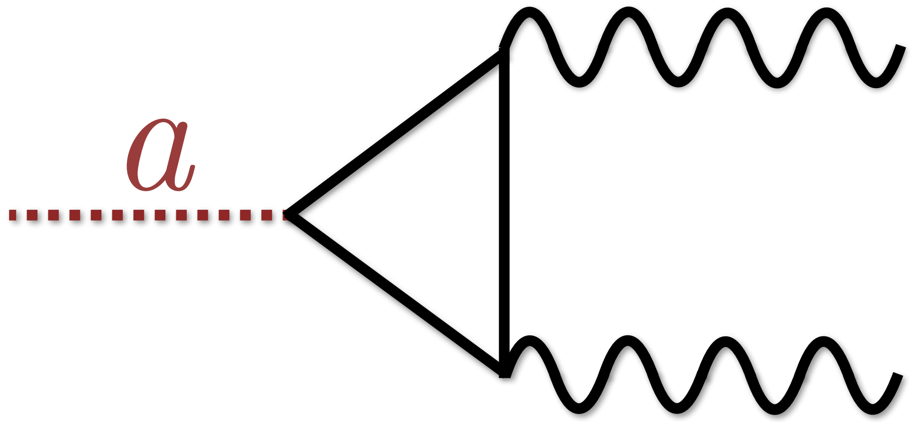
$\omega \approx m_a$

Oscillating at the axion mass



Axion-photon coupling: $g_{a\gamma}$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$



For QCD axion: $g_{a\gamma} \propto m_a$

$$\nabla \cdot \mathbf{E} = \rho_q$$

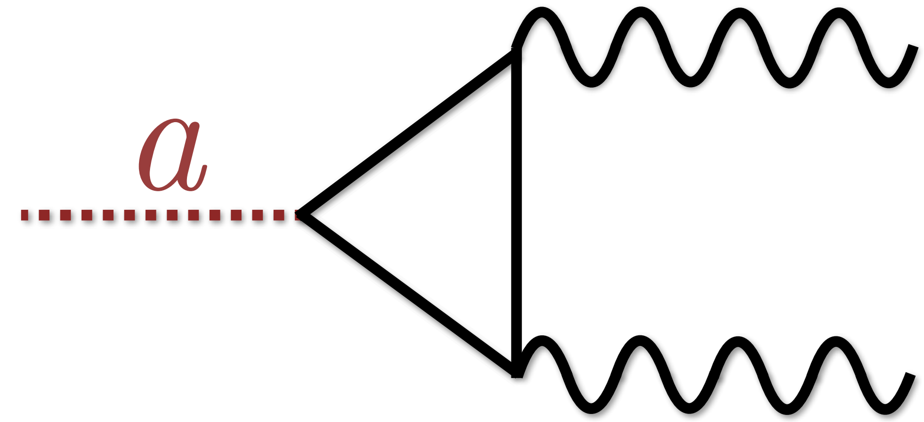
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

Axion-photon coupling: $g_{a\gamma}$

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$



For QCD axion: $g_{a\gamma} \propto m_a$

$$\nabla \cdot \mathbf{E} = \rho_q - g_{a\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma} (\mathbf{B}\, \dot{a} - \mathbf{E} \times \nabla a)$$

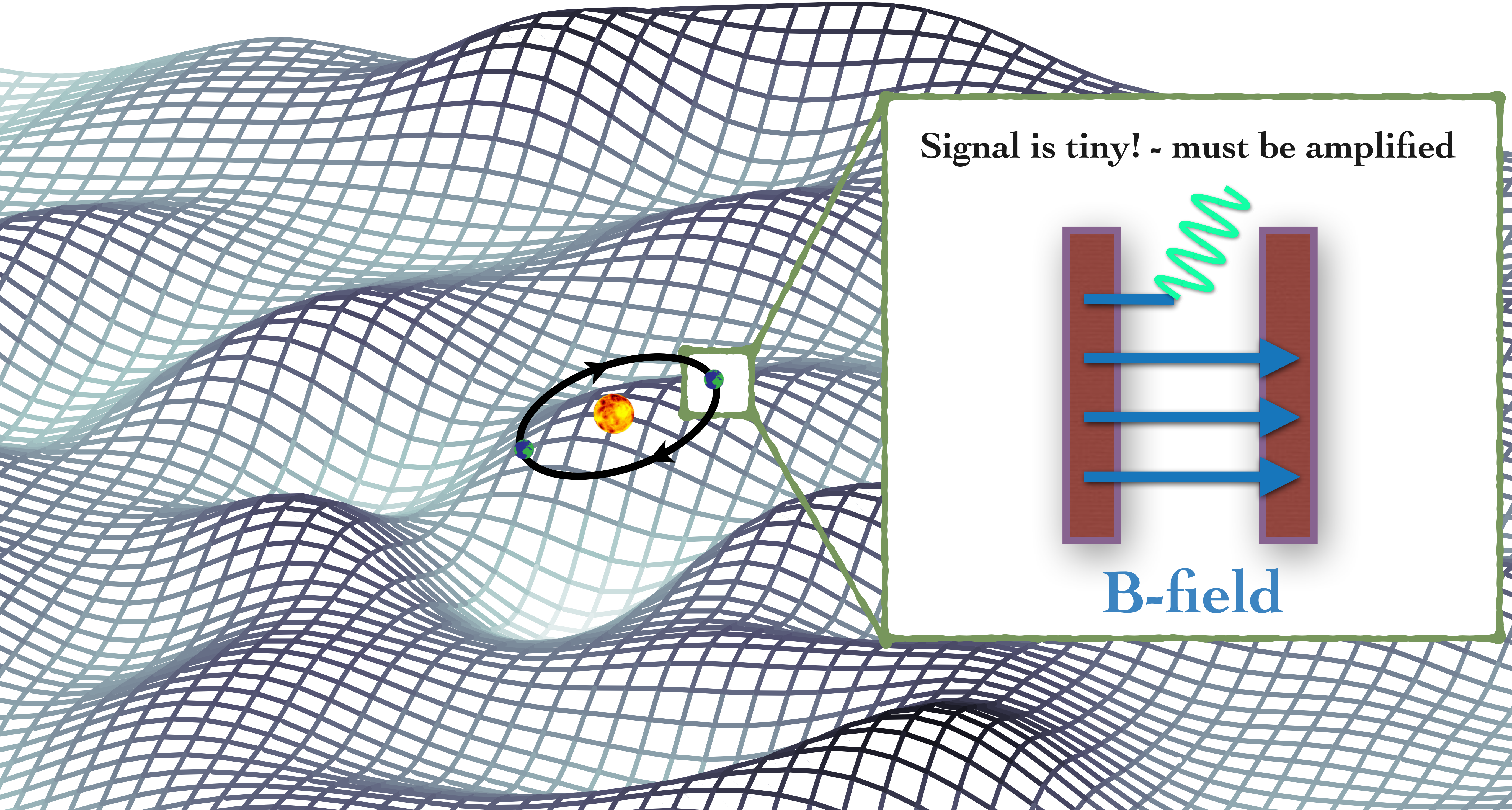
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

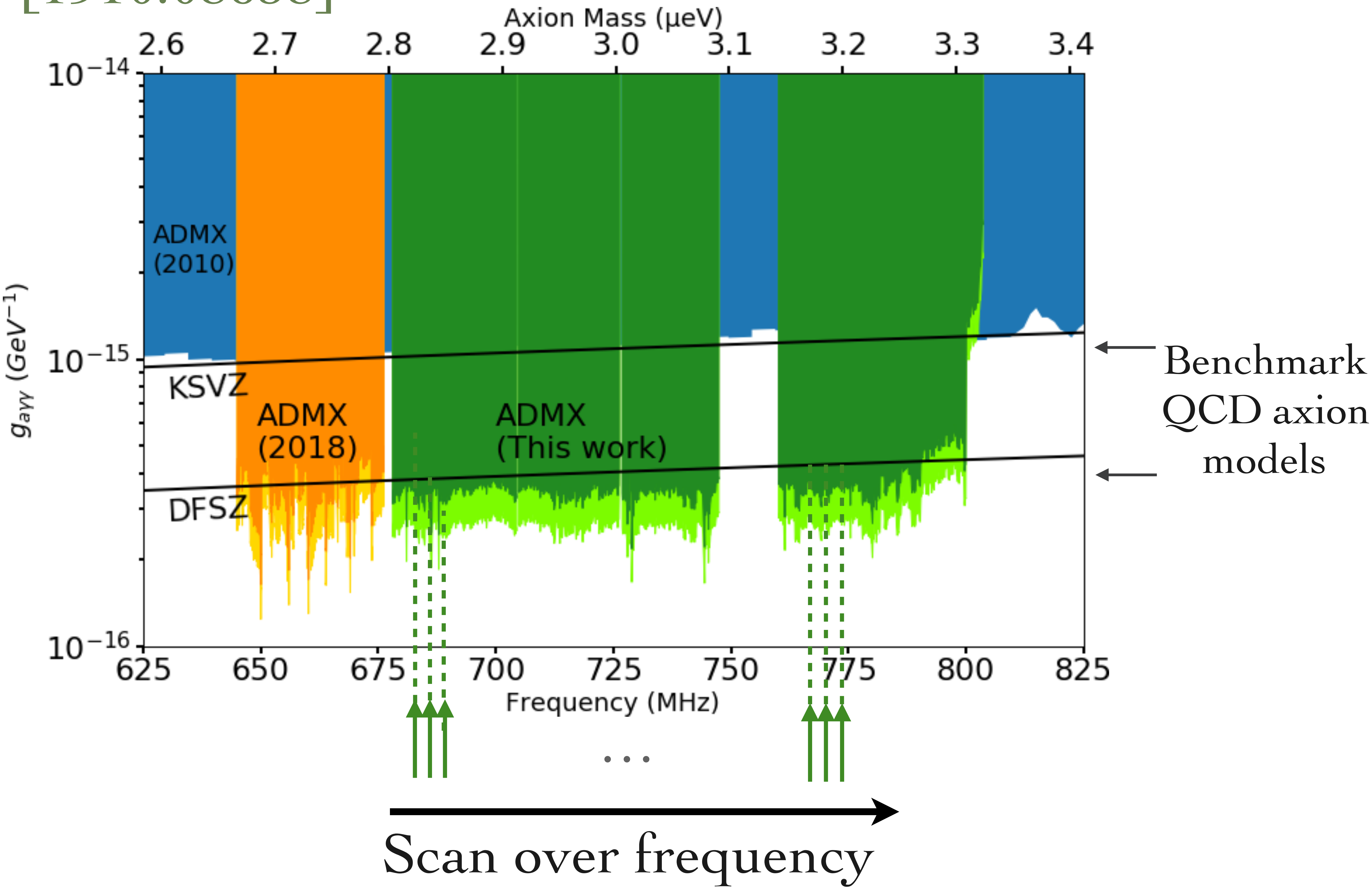
$$(\Box + m_a^2) a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}$$

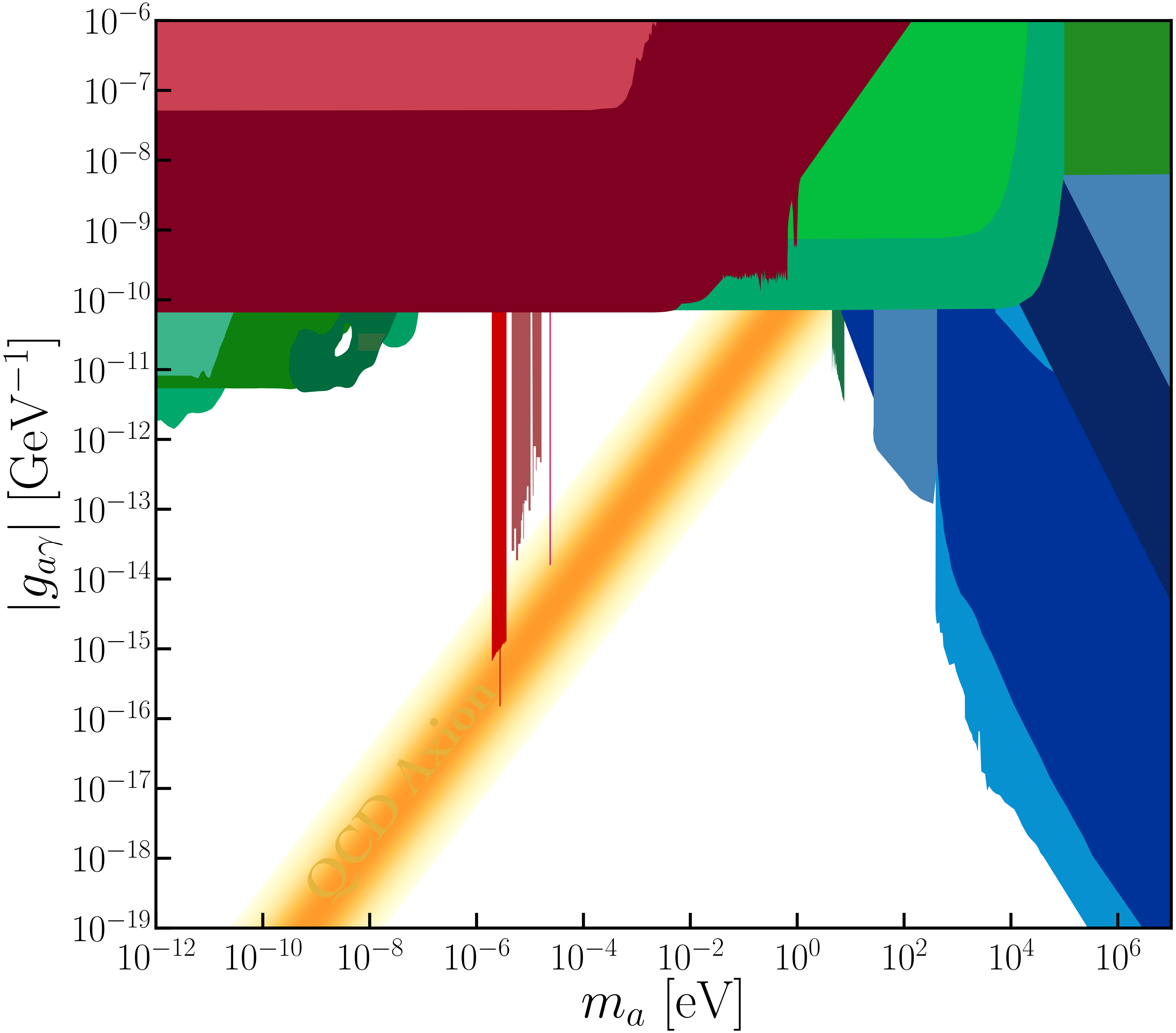
$$\omega \approx m_a$$

Searching for DM axions
→ "tune in" to EM signal oscillating at $\sim m_a$



[1910.08638]


Axion Mass (μeV)
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
3.4
10^{-14}
10^{-15}
10^{-16}
$g_{a\gamma\gamma}$ (GeV^{-1})
ADMX (2010)
KSVZ
DFSZ
ADMX (2018)
ADMX (This work)
625
650
675
700
725
750
775
800
825
Frequency (MHz)
...
Benchmark QCD axion models
Scan over frequency



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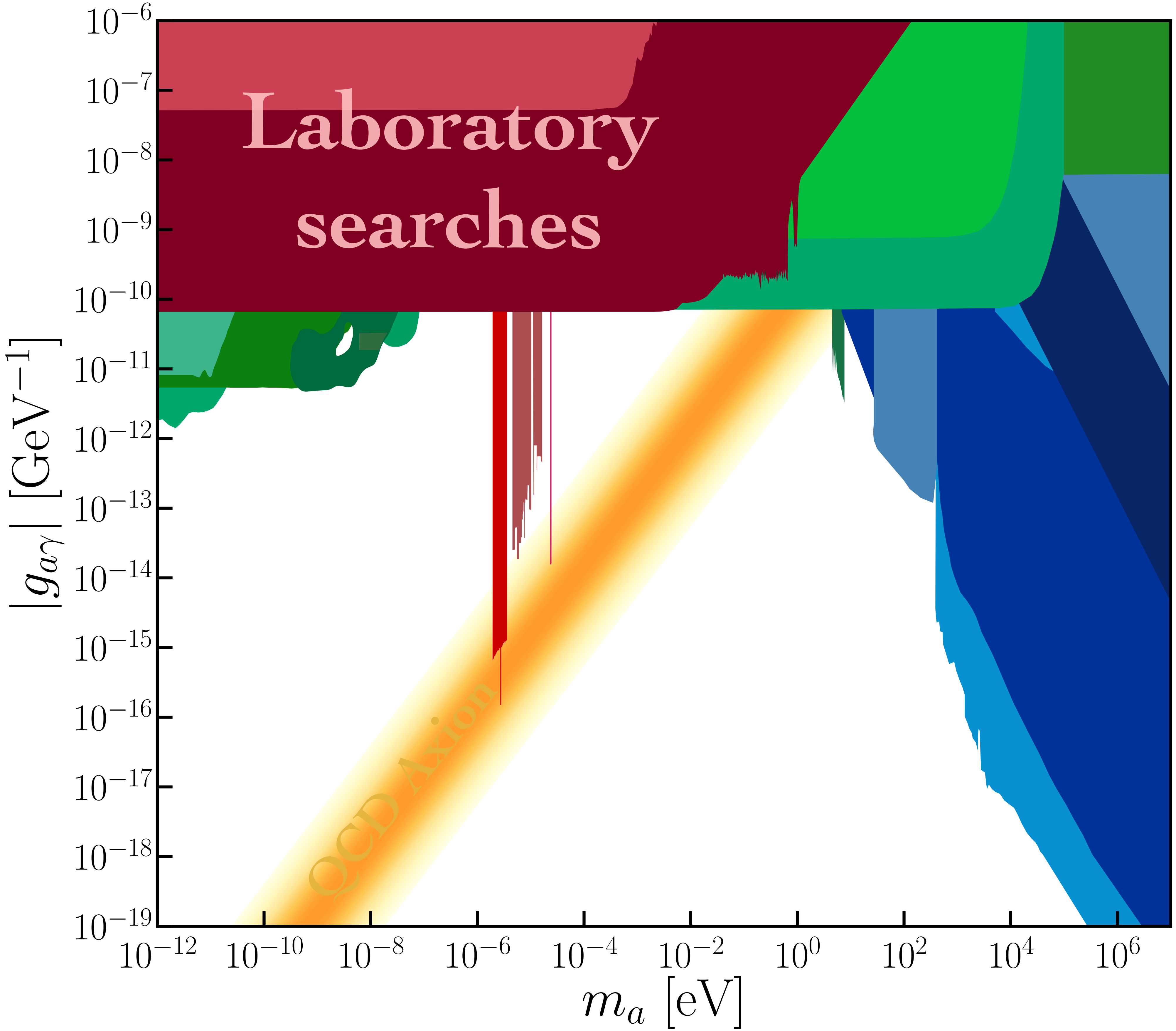

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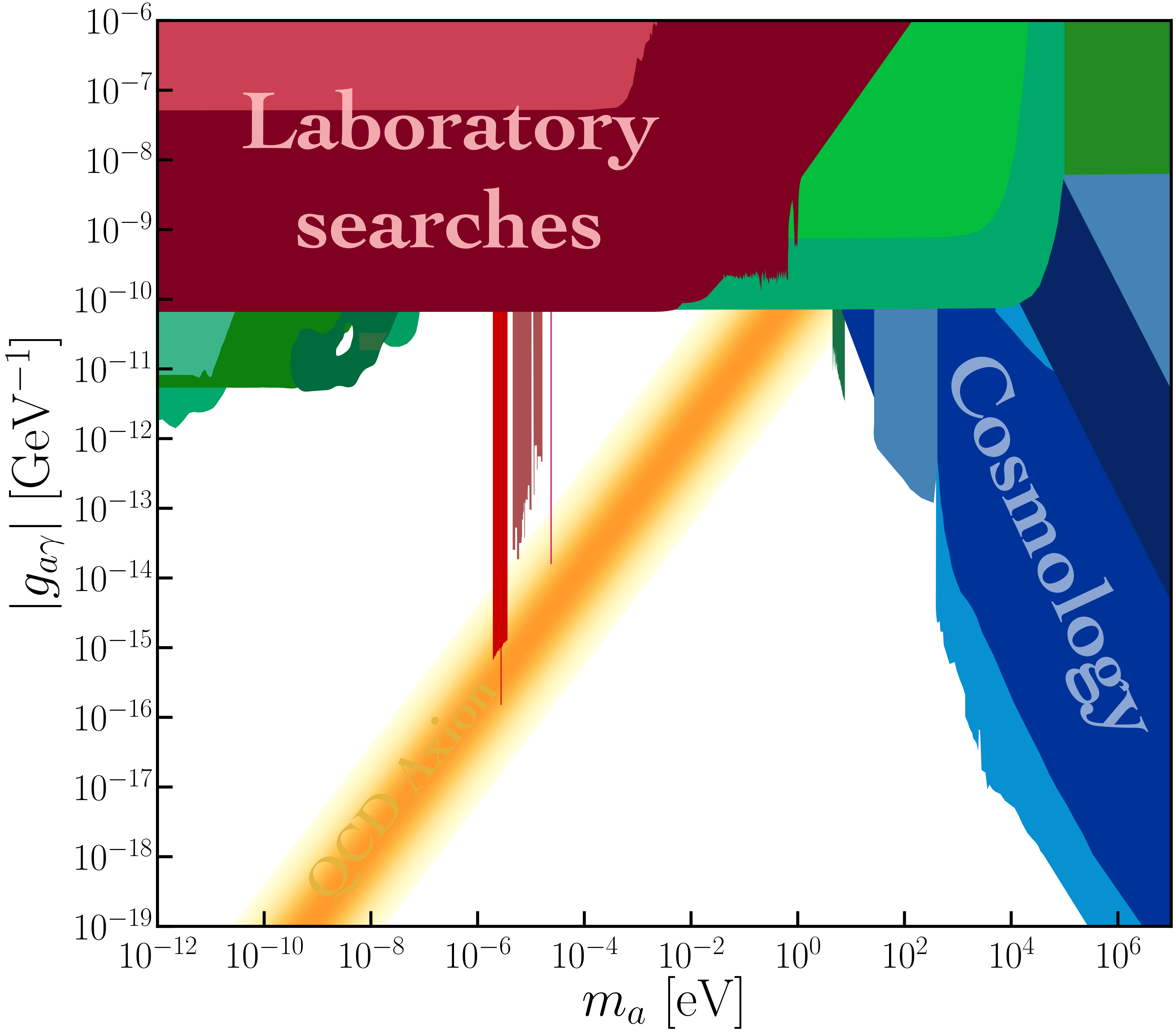

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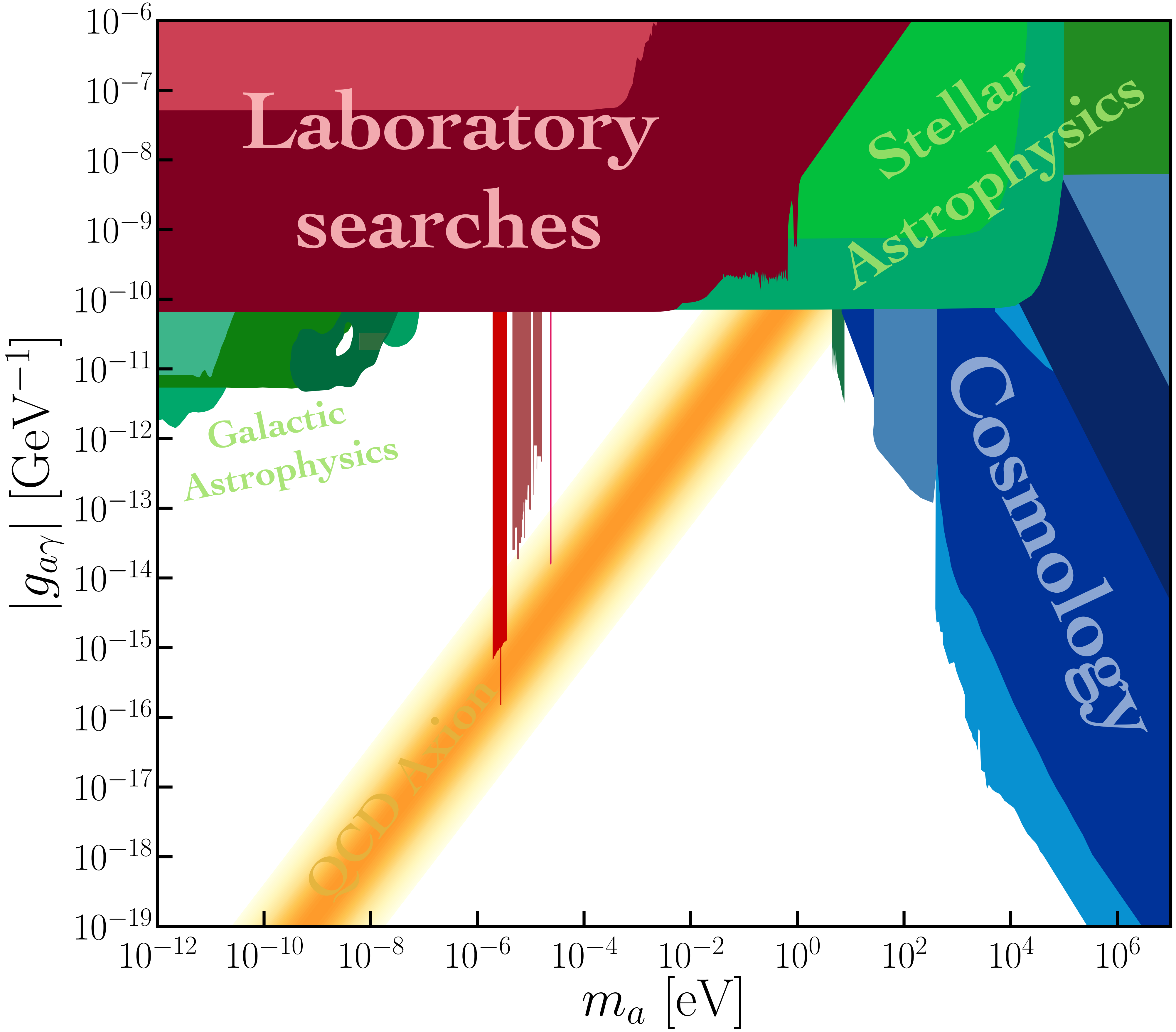

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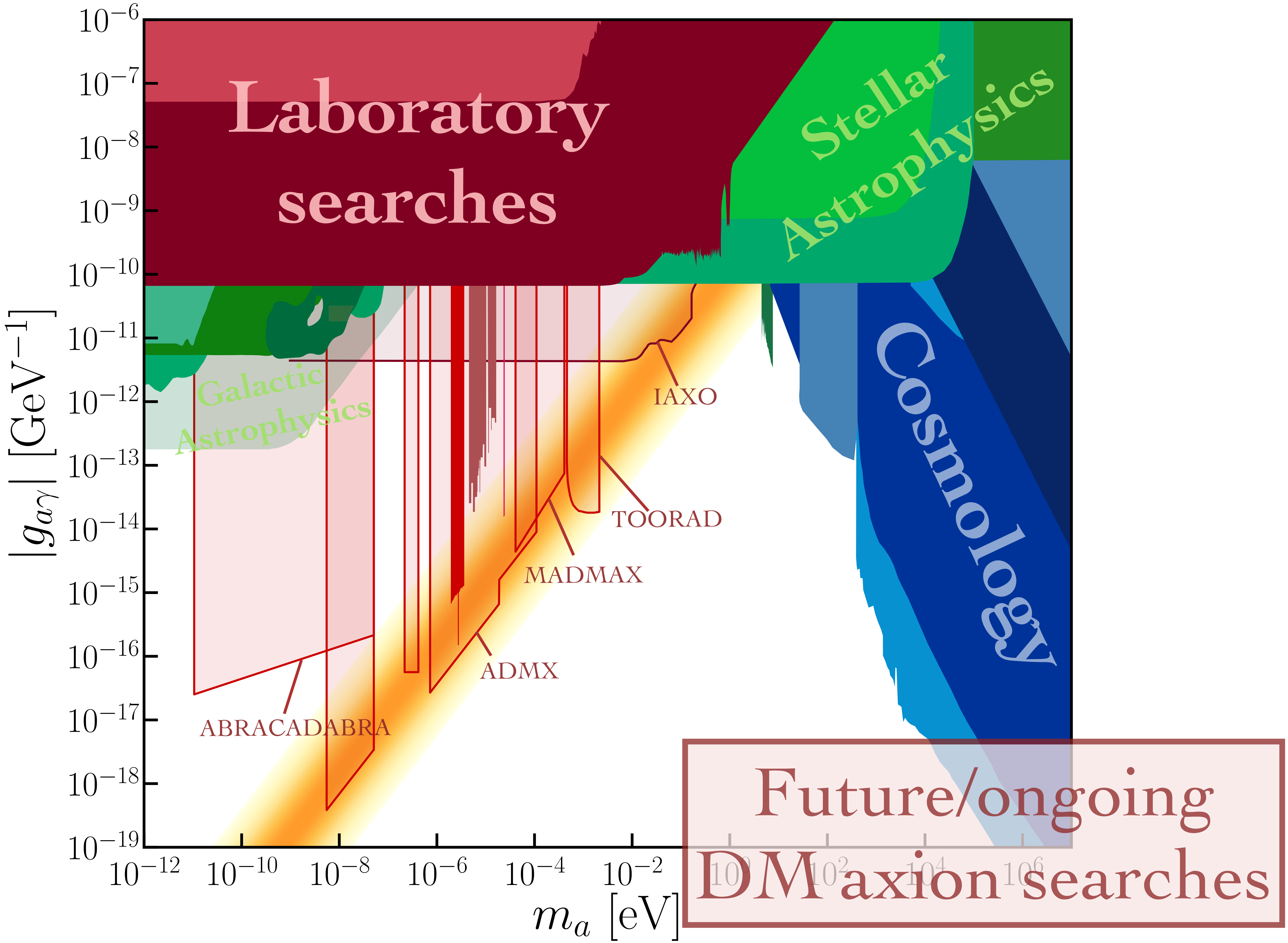

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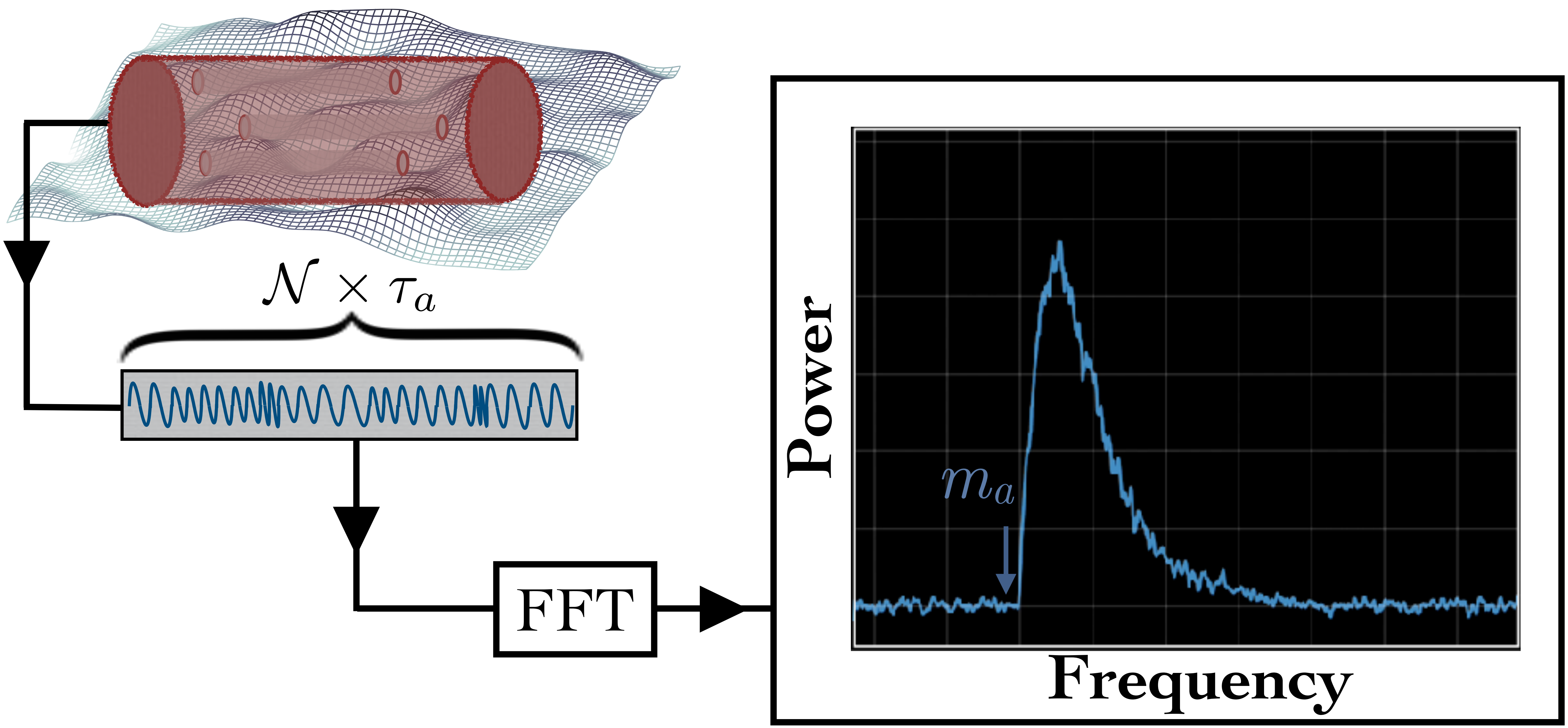
Measuring the axion distribution

Sampling axion field over many, N, coherence times:

→ Power spectrum ~ DM speed distribution $f(v)$



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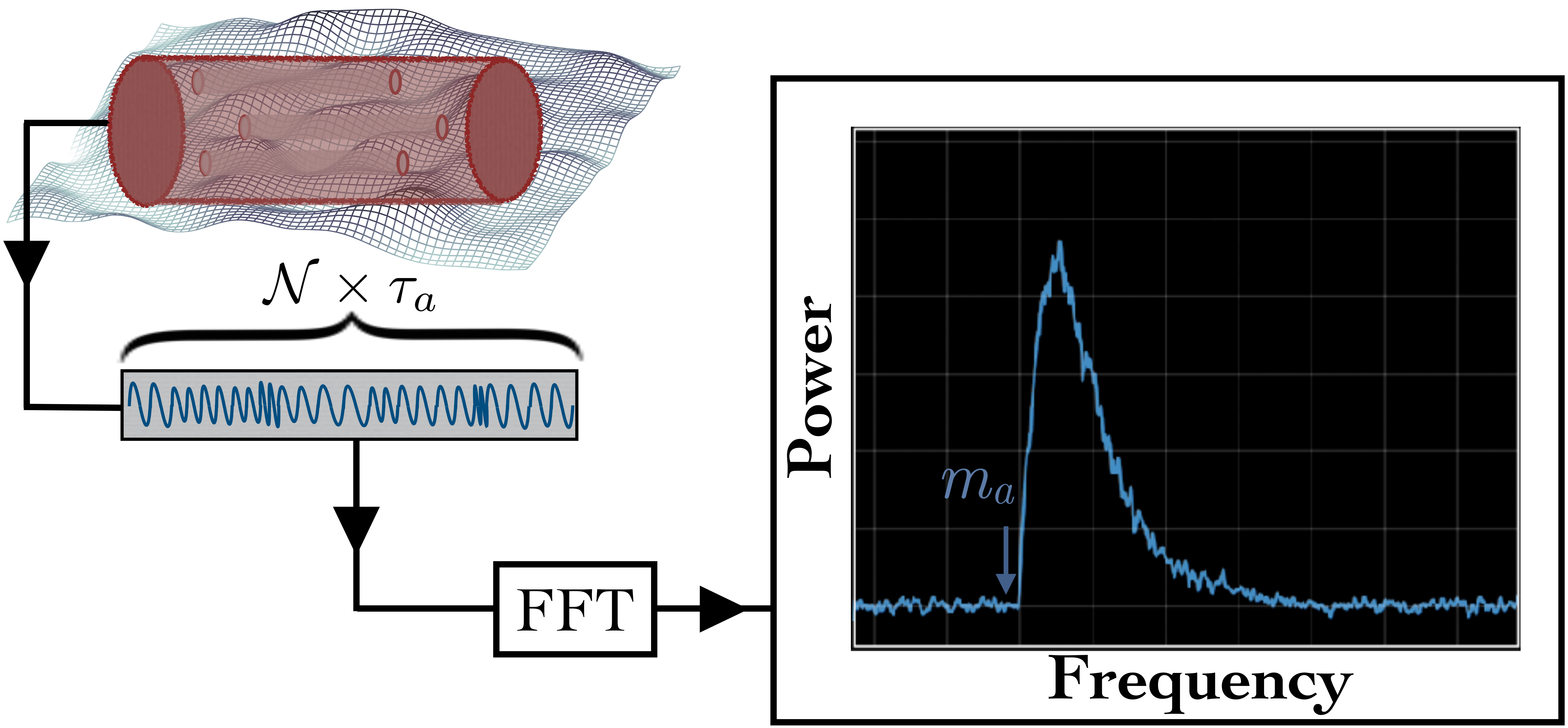

The dark matter velocity distribution

Rate of WIMP recoils:

$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{\rho_0}{m_N m_\chi} \int_{v>v_{\mathrm{min}}}^{\infty} v f_{\mathrm{lab}}(\mathbf{v}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \mathrm{d}^3\mathbf{v}$$

Axion-photon power spectrum

$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} f(v)$$

The dark matter velocity distribution

Rate of WIMP recoils:

$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{\rho_0}{m_N m_\chi} \int_{v>v_{\rm min}}^{\infty} \boxed{v f_{\rm lab}(\mathbf{v})} \frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \mathrm{d}^3\mathbf{v}$$

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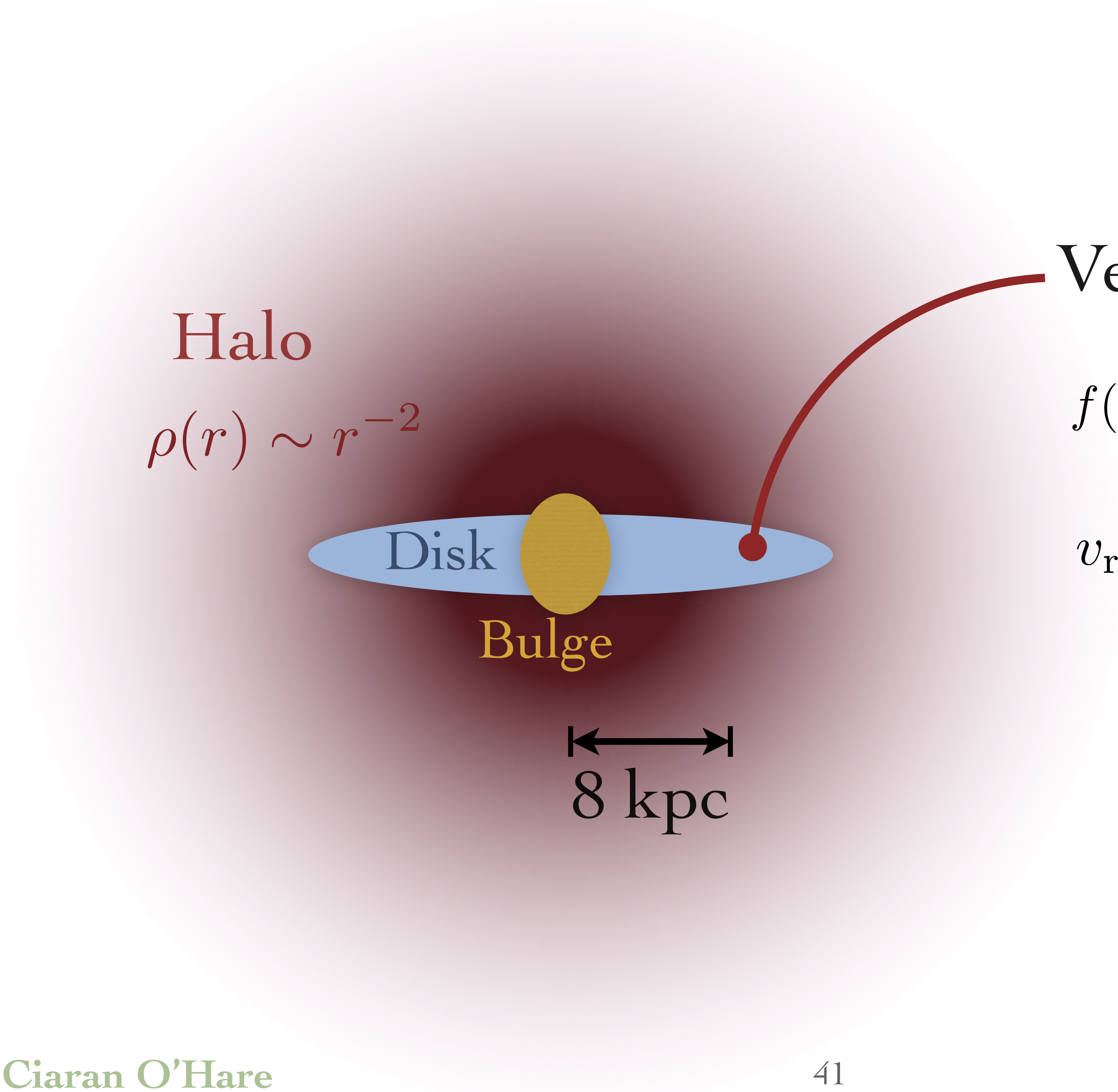
Axion-photon power spectrum

$$\frac{\mathrm{d}P_s}{\mathrm{d}\omega} \propto \frac{\rho_a g_{a\gamma}^2}{m_a^2} \boxed{f(v)}$$

Fundamentally astrophysical, relies on a model for the galaxy

Ciaran O'Hare

The Standard Halo Model

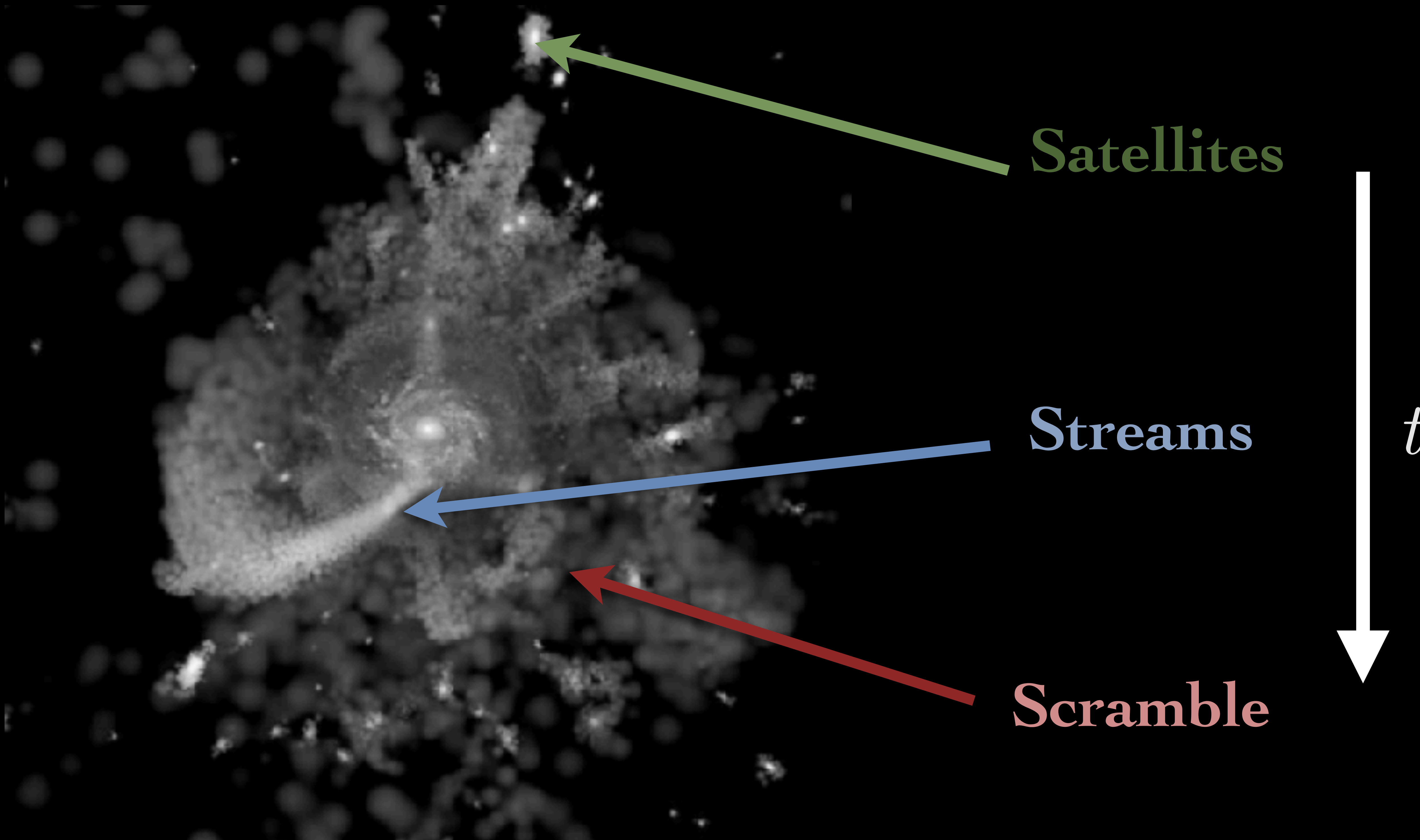


Velocity dist. locally:

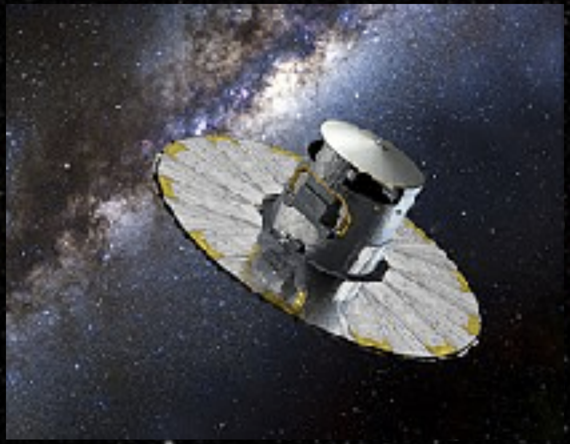
$$f(\mathbf{v}) \sim \exp\left(-\frac{|\mathbf{v}|^2}{v_{\rm rot}^2}\right)$$

$$v_{\rm rot} = 220\,{\rm km\,s^{-1}}$$

A dark matter halo (really)



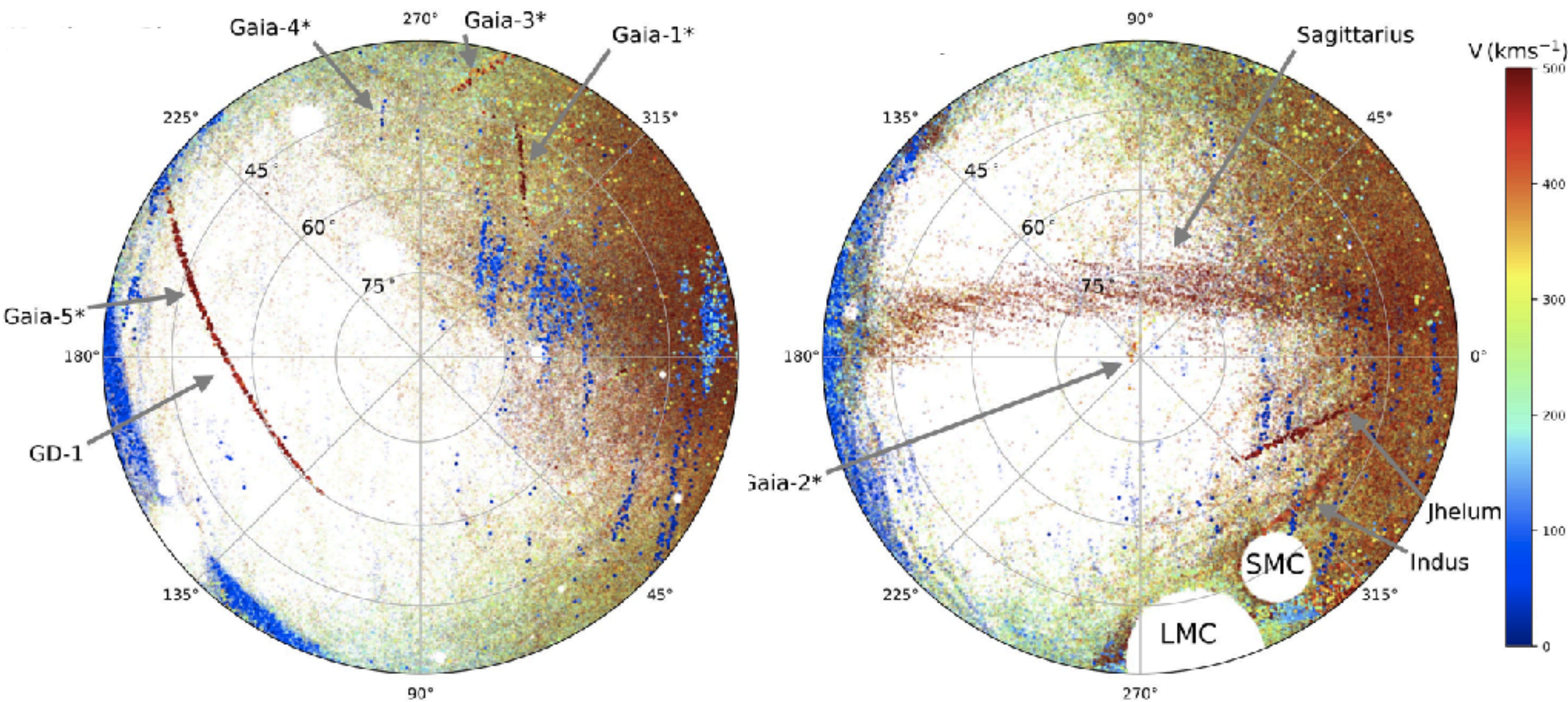
Gaia



- Launched in 2013
- Will operate until ~2022
- 1.7 billion stars (1% of MW)
- Parallax+proper motion on 1.3 billion
- 20 million stars with distance precise to 1%
- 40 million stars with tangential velocity precise to < 0.5 km/s
- 7 million stars with full 6D solution (x, y, z, v_x, v_y, v_z)

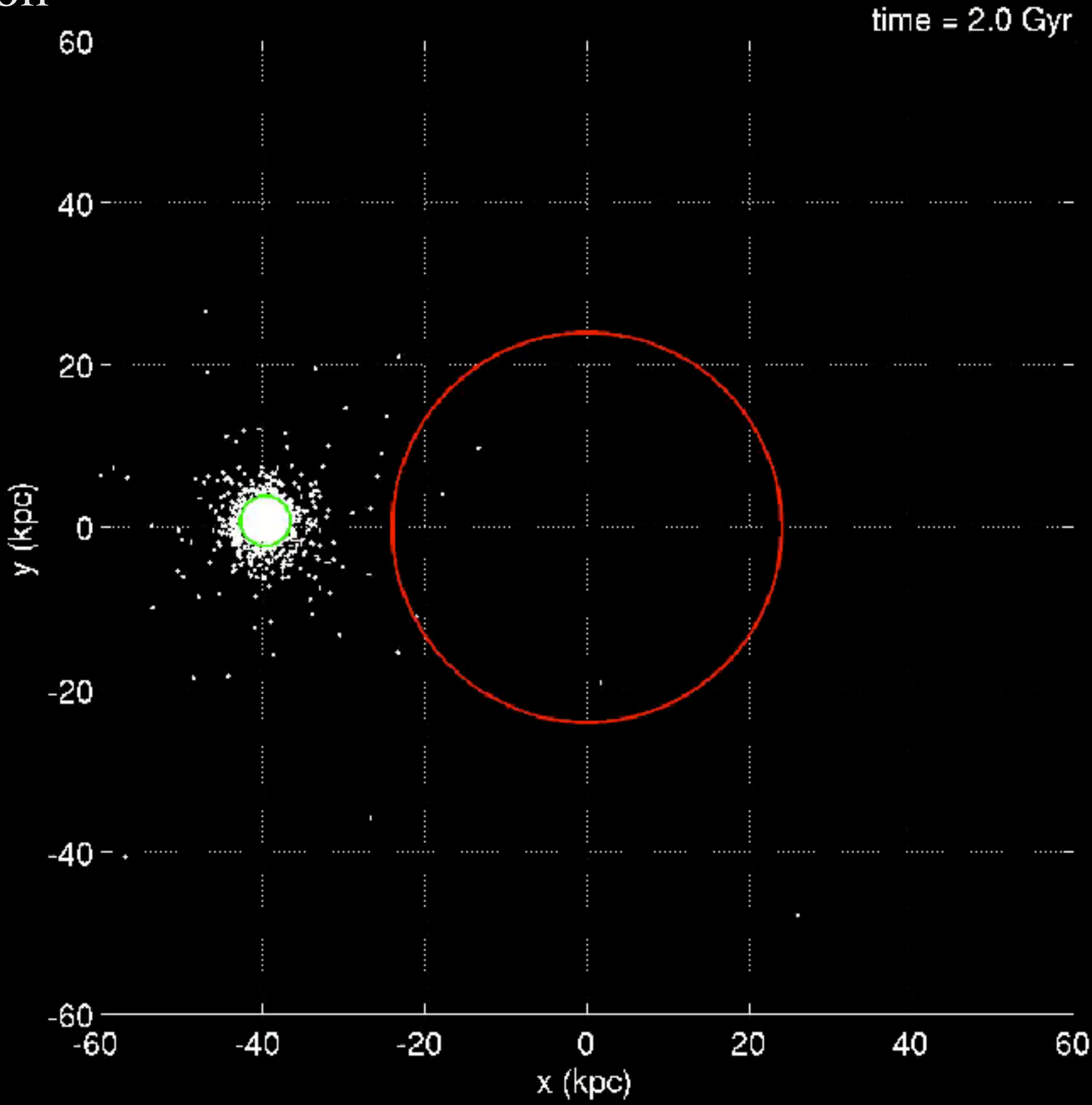
Compared to predecessor, Gaia has 10,000 times more stars, over a volume 100,000 times larger, with 1000 times better accuracy

Northern sky   Southern sky

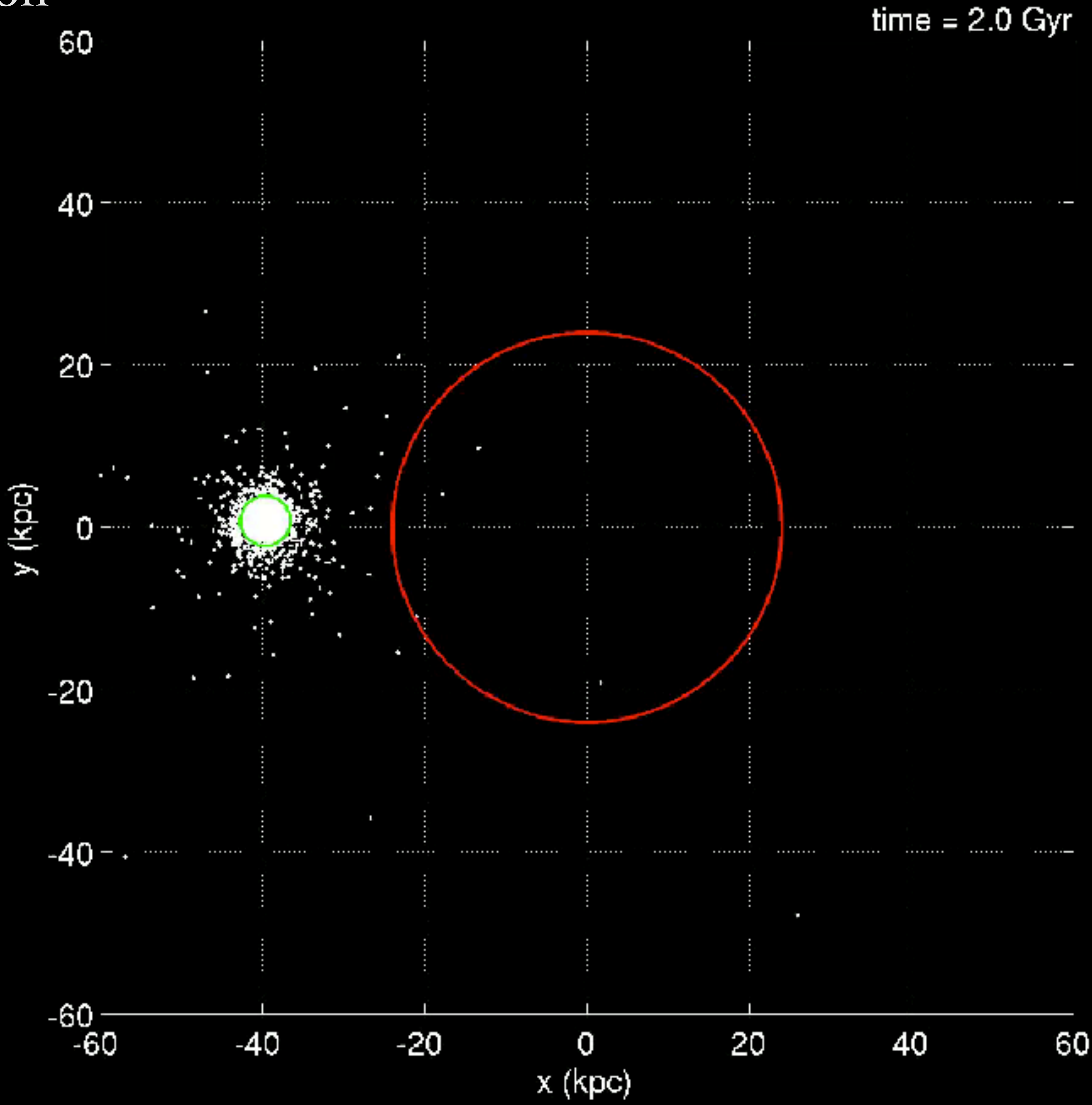


ESA

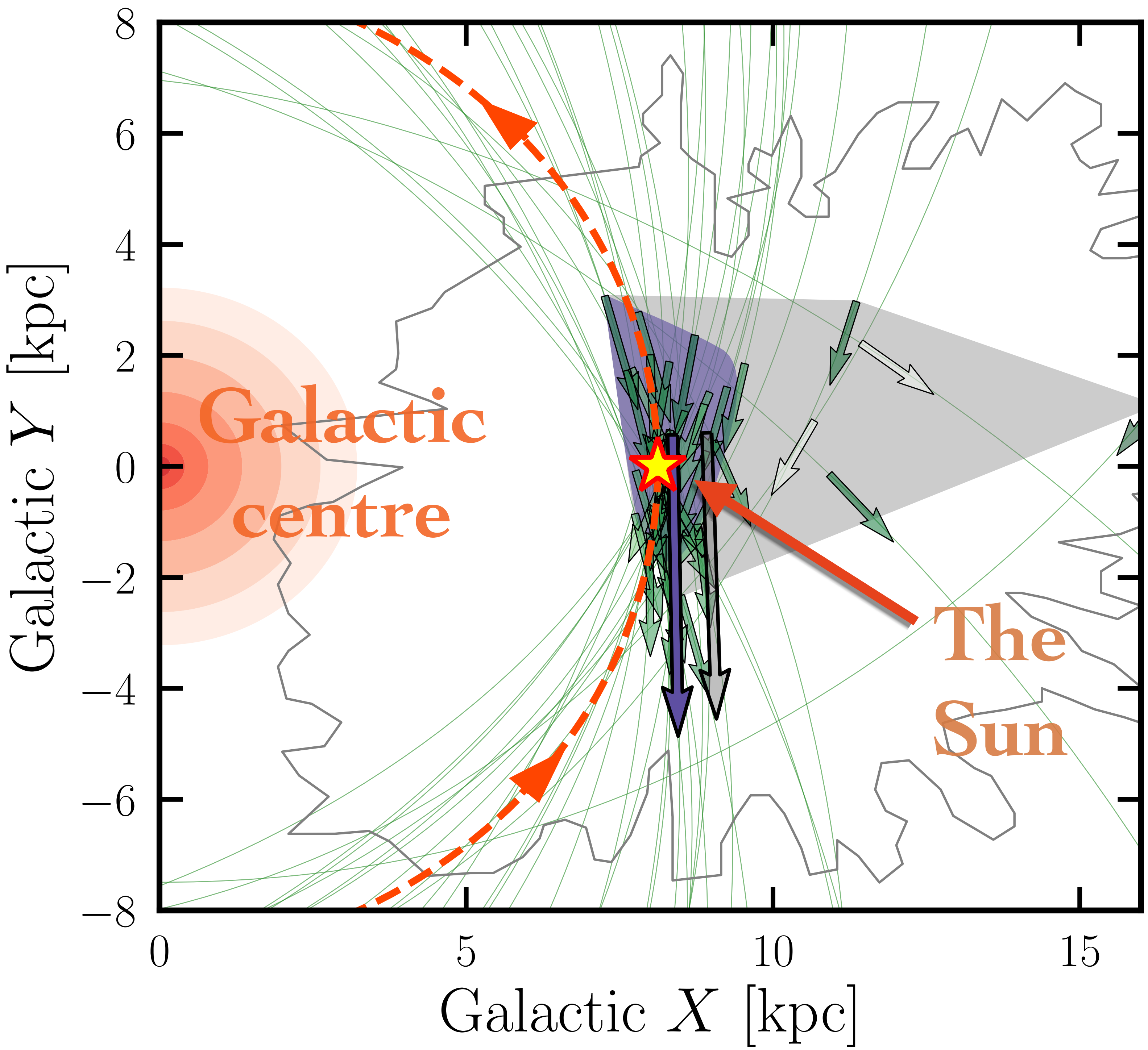
R. Sanderson



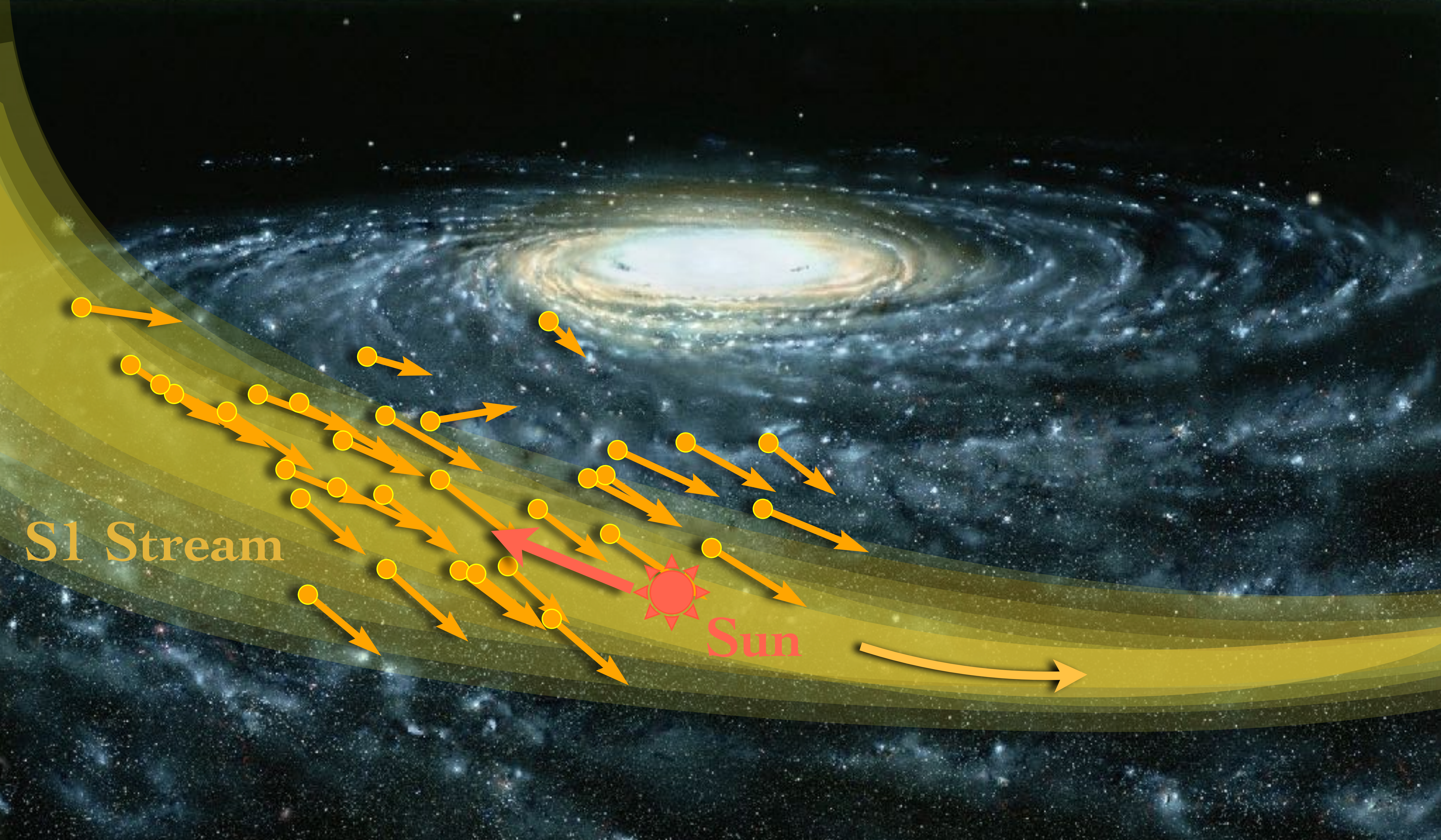
R. Sanderson



The S1 stream



- Most prominent Gaia substructure encompassing the Solar System
- Likely the remnant of a large (Fornax-sized) dwarf spheroidal accreted around 8-10 billion years ago
- S1 and other retrograde stars possibly linked to a larger "Sequoia" event. Also responsible for several anomalous retrograde globular clusters (see 1904.03185)



S1 is on a retrograde infall, so impacts the solar system at high speeds

Dark matter wind → A dark matter hurricane?

O'Hare et al. [1807.09004]

KCL-PH-TH-2018-38

A Dark Matter Hurricane: Measuring the S1 Stream with Dark Matter Detectors

Ciaran A. J. O'Hare,[1,*] Christopher McCabe,[2,†] N. Wyn Evans,[3,‡] GyuChul Myeong,[3] and Vasily Belokurov[3]

[1]*Departamento de Física Teórica, Universidad de Zaragoza, Pedro Cerbuna 12, E-50009, Zaragoza, España*
[2]*Department of Physics, King's College London, Strand, London, WC2R 2LS, United Kingdom*
[3]*Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, United Kingdom*
(Dated: November 8, 2018)

The recently discovered S1 stream passes through the Solar neighbourhood on a low inclination, counter-rotating orbit. The progenitor of S1 is a dwarf galaxy with a total mass comparable to the present-day Fornax dwarf spheroidal, so the stream is expected to have a significant DM component. We compute the effects of the S1 stream on WIMP and axion detectors as a function of the density

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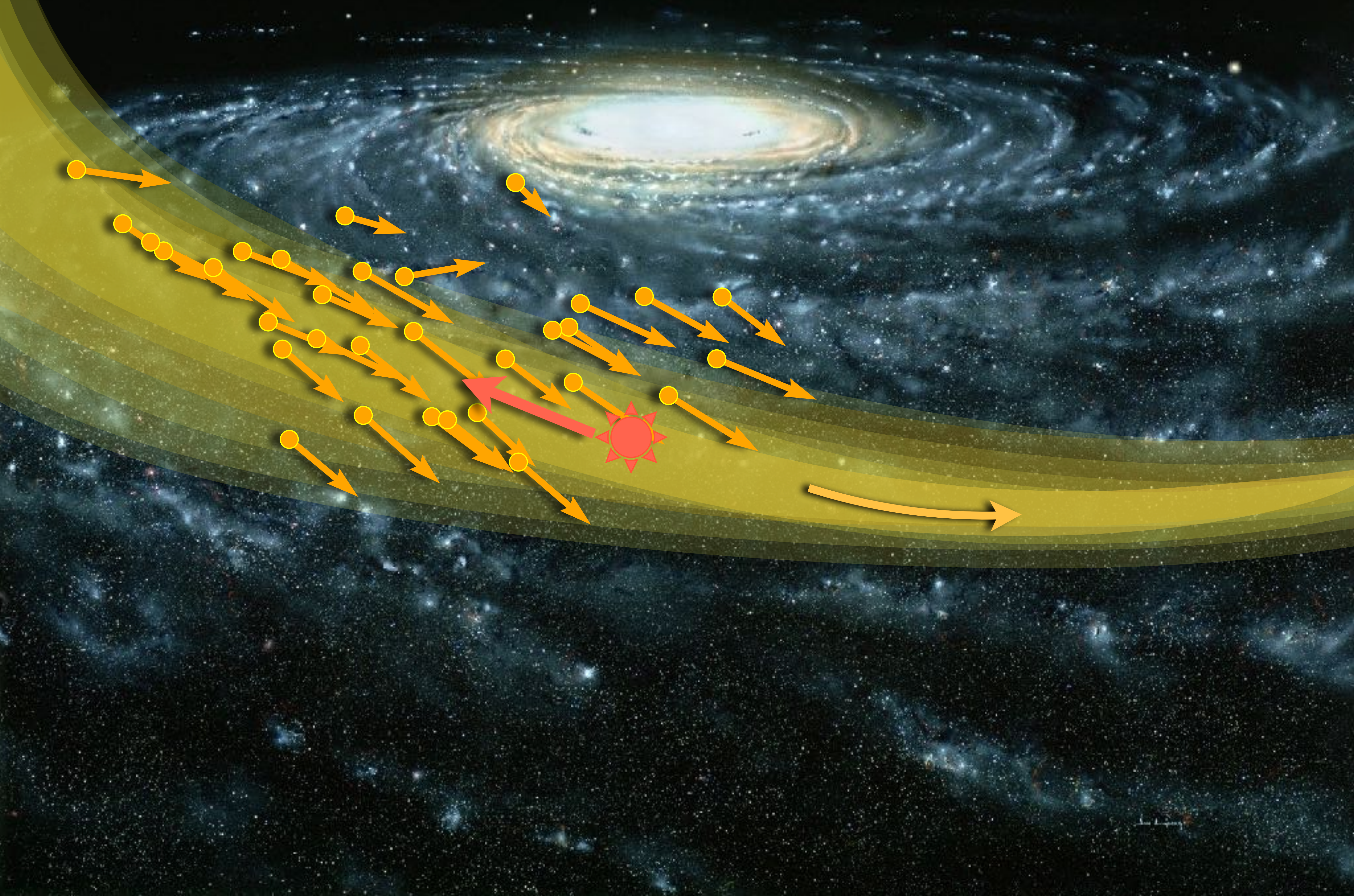
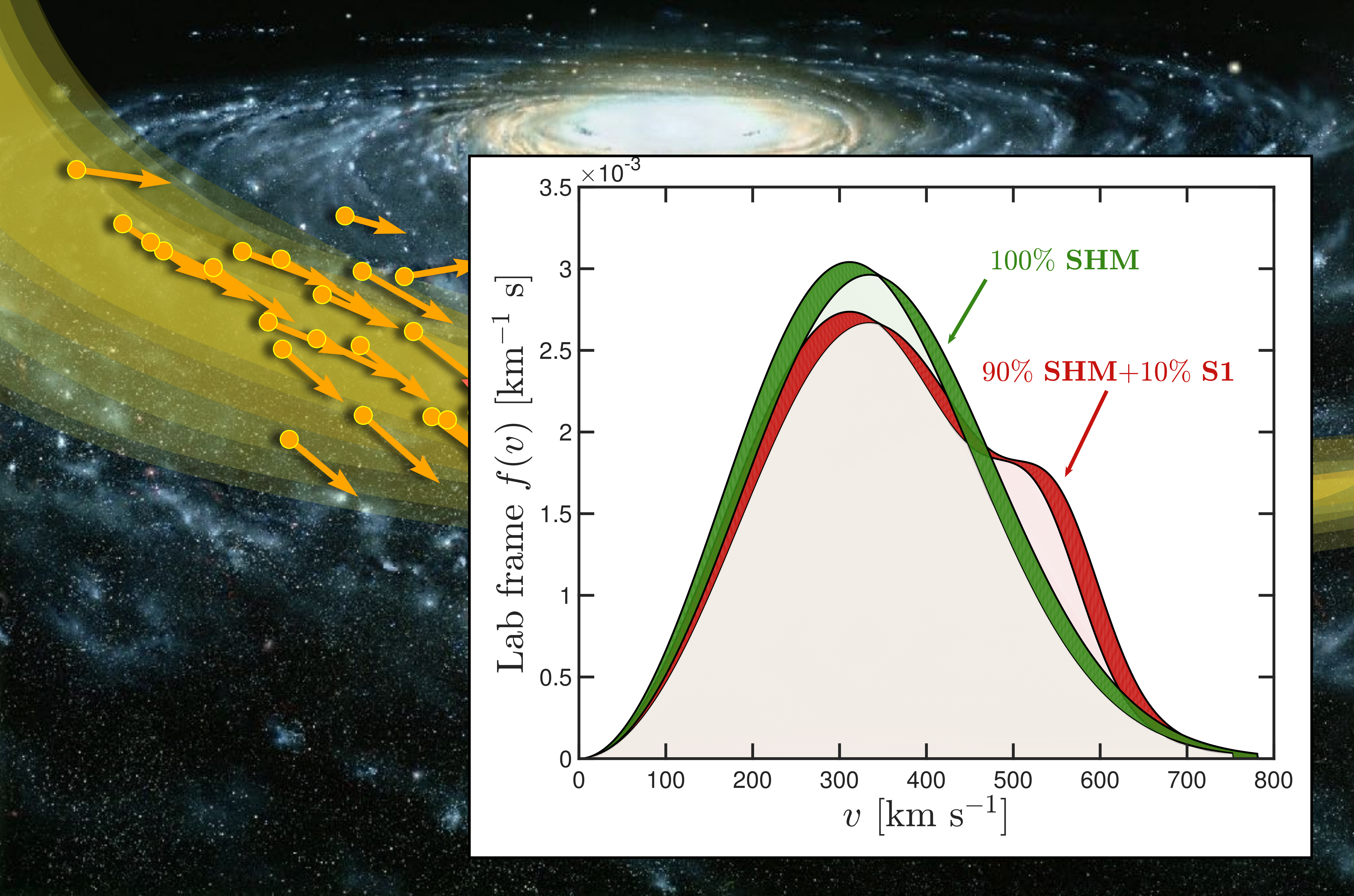
Modelling S1



Modelling S1



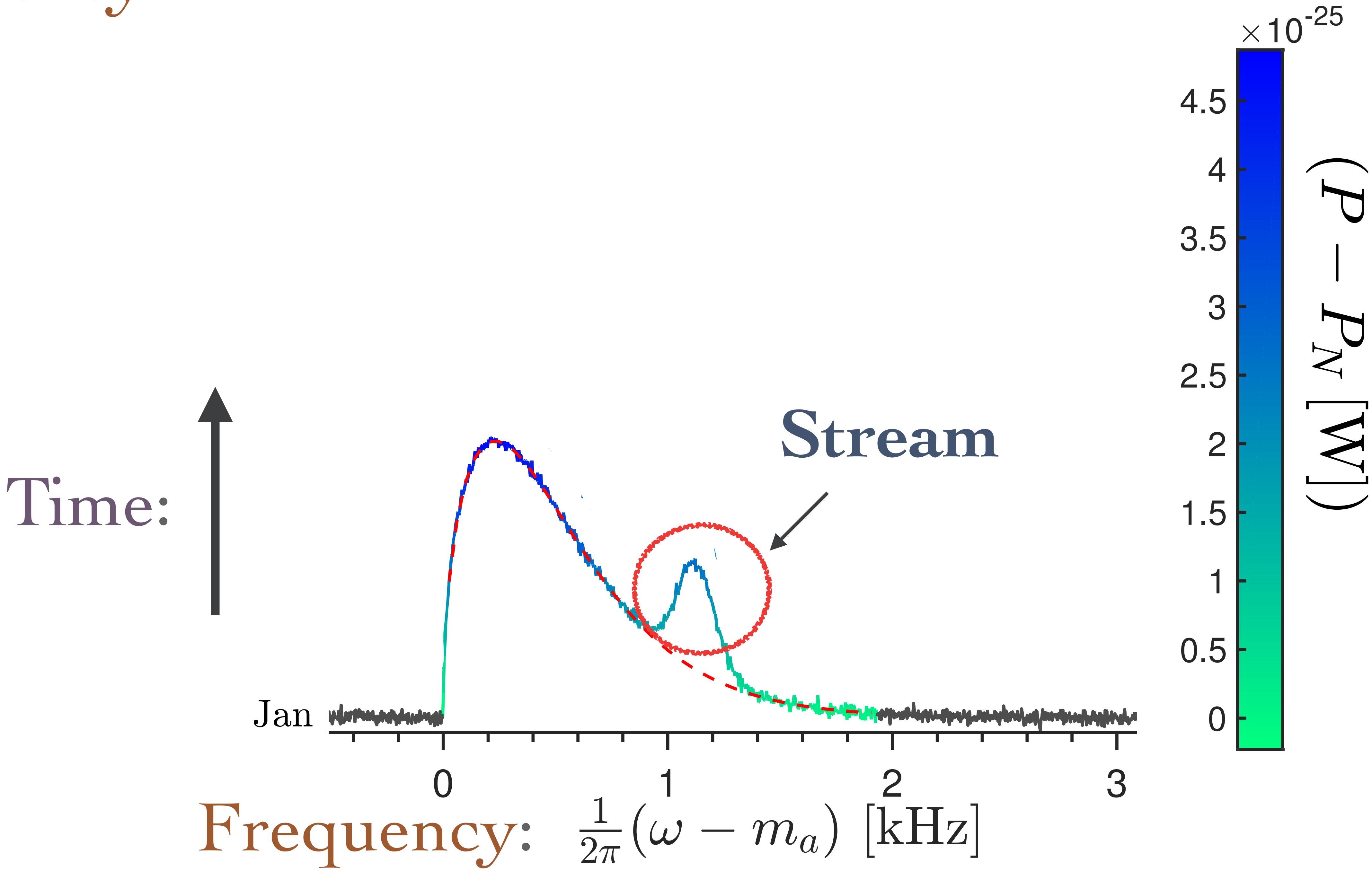
Axion haloscope:

Signal power

vs time

vs frequency

O'Hare et al. [1807.09004]



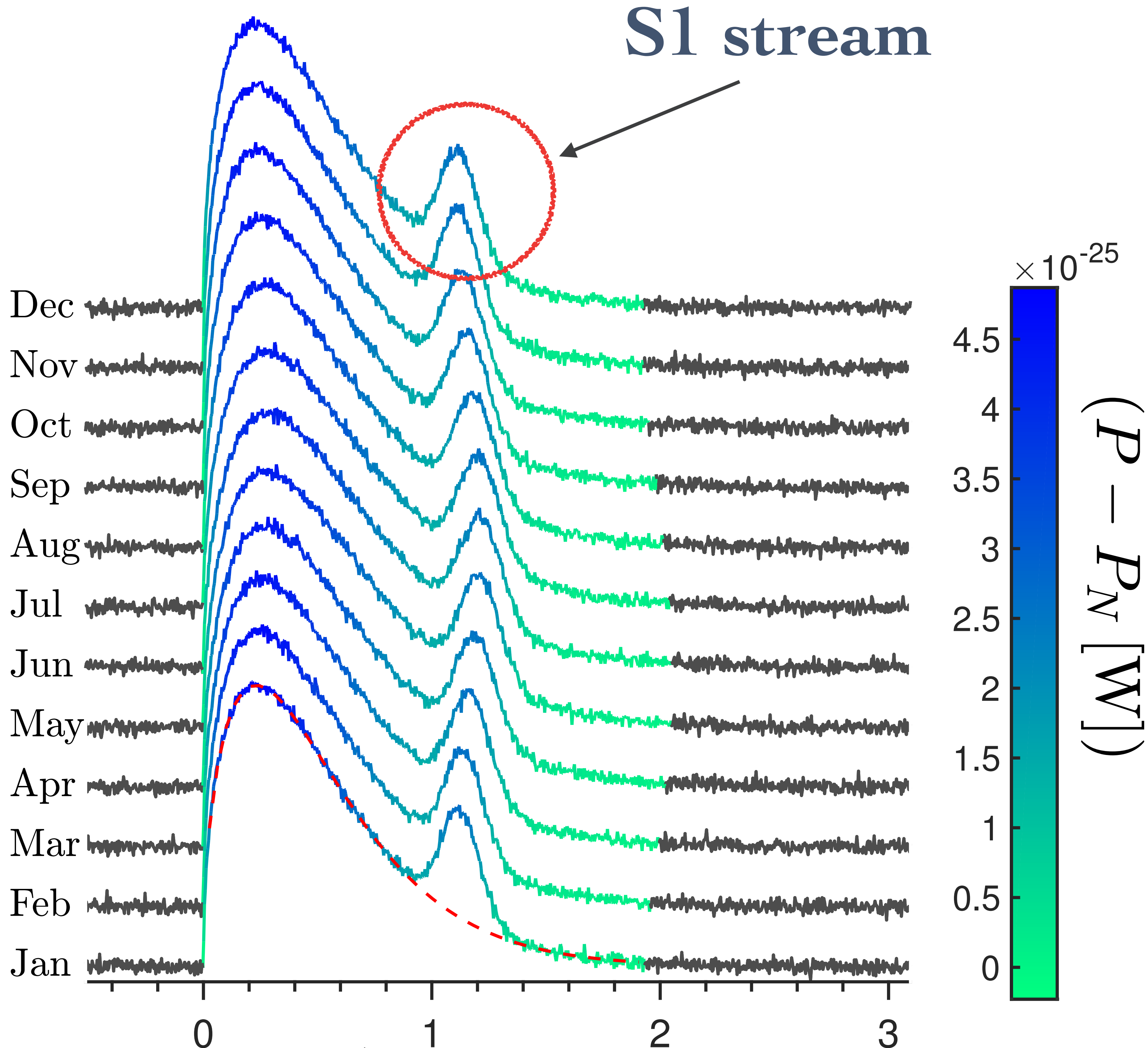
Axion haloscope:

Signal power
vs time
vs frequency

O'Hare et al. [1807.09004]

Wobble in frequency
due to Earth's motion

Time:



Frequency: $\frac{1}{2\pi}(\omega - m_a)$ [kHz]

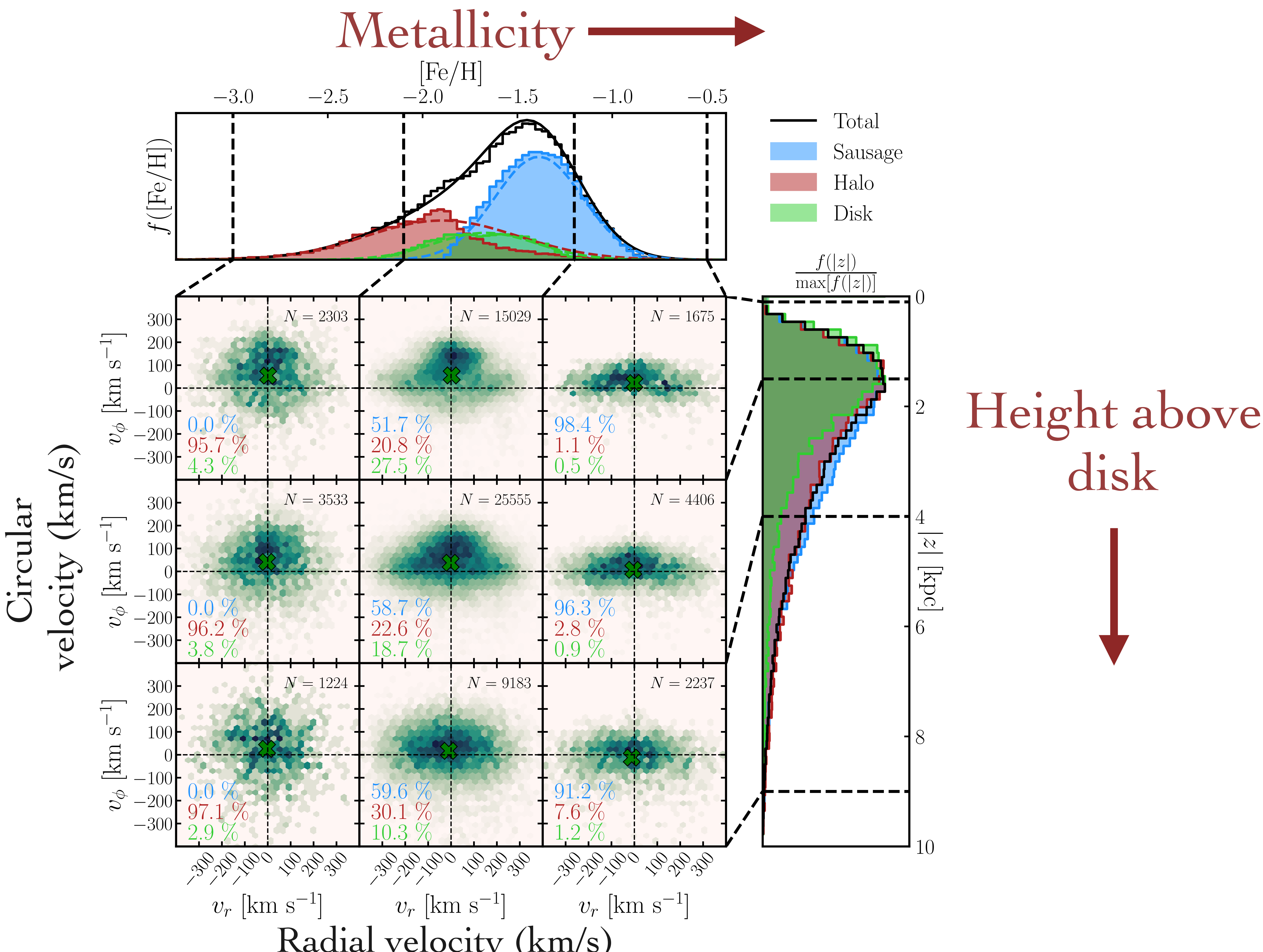
Summary

Summary

I like dark matter

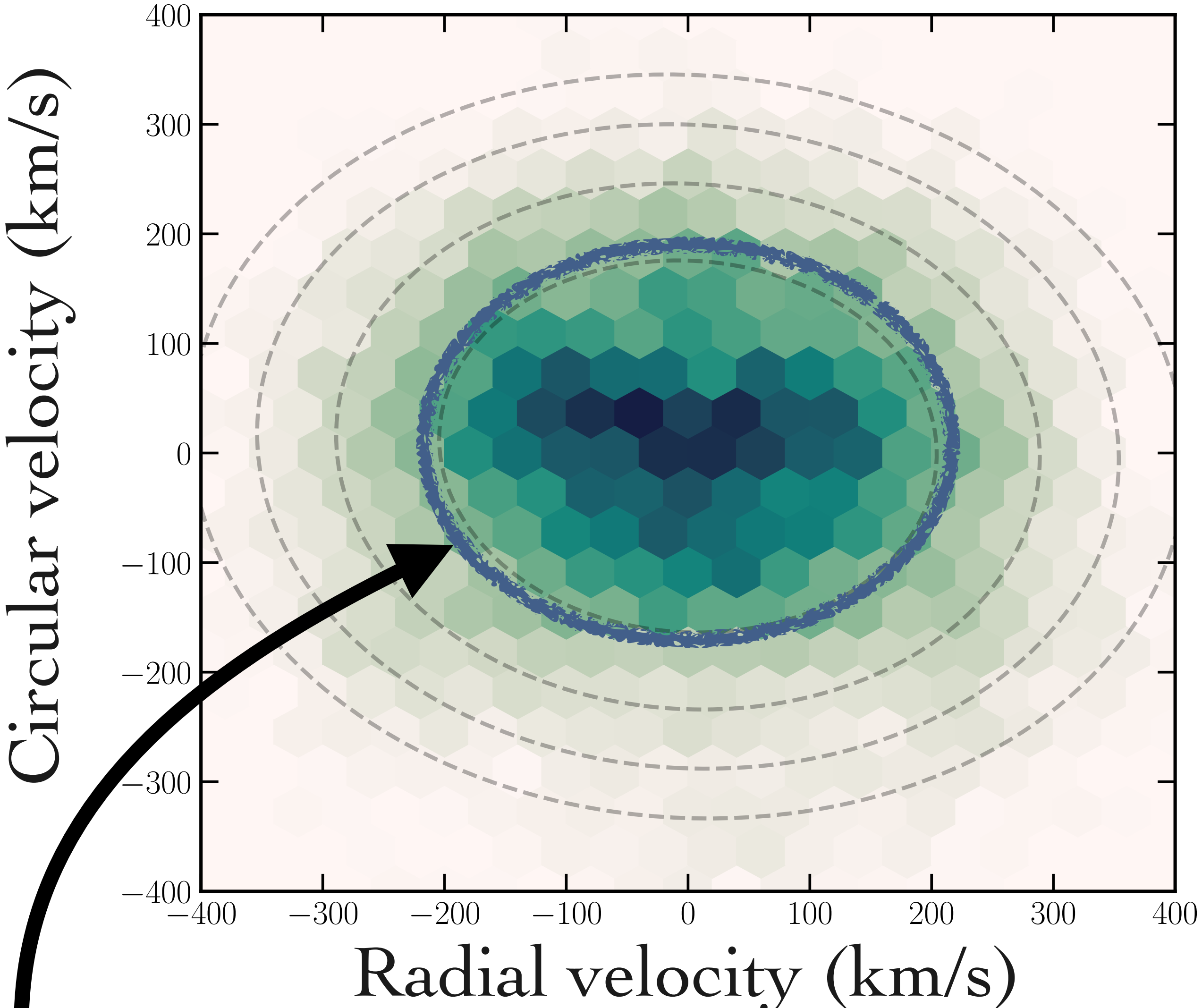
Extras

The Sausage

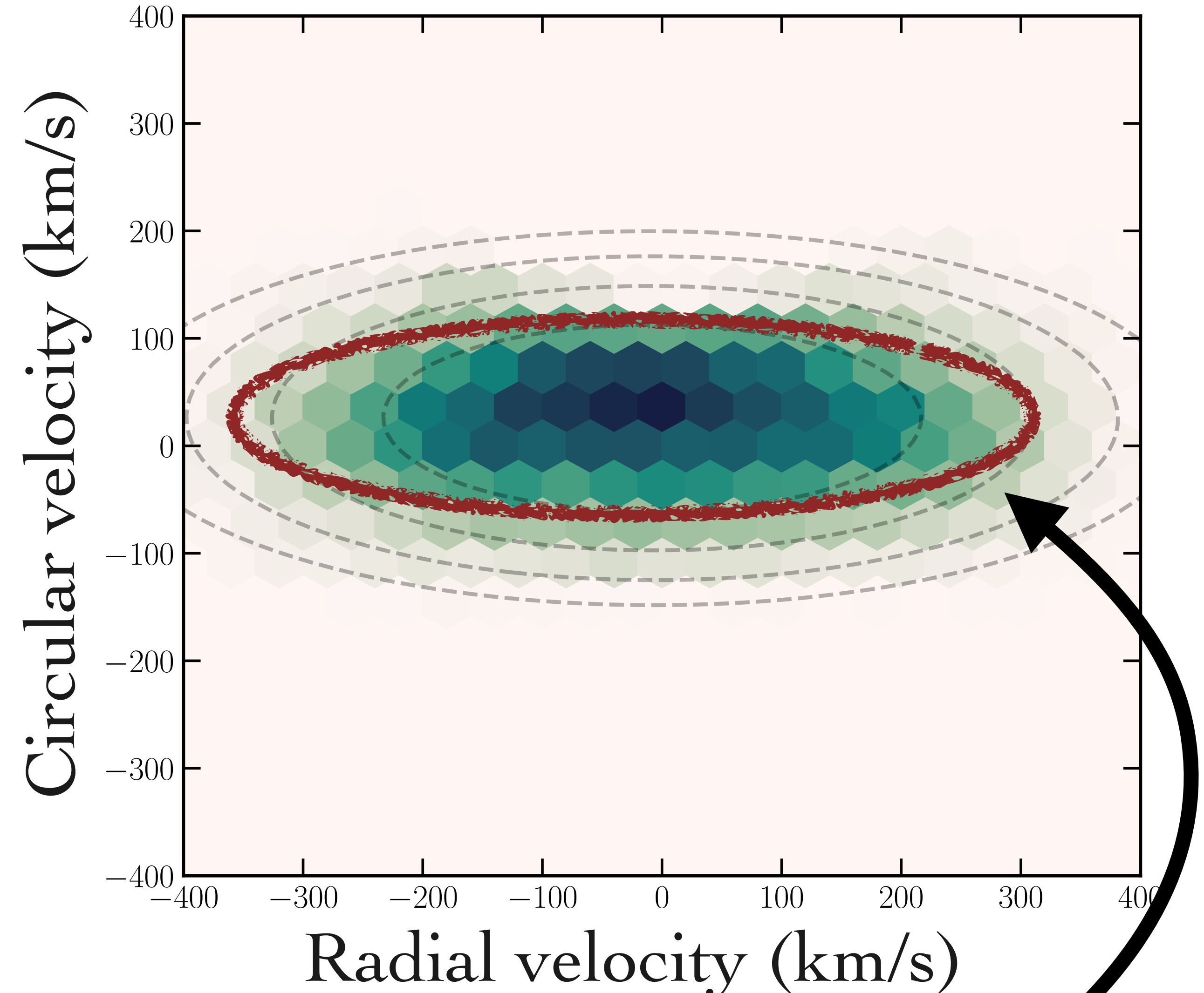


Metallicity
[Fe/H]
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
f([Fe/H])
Total
Sausage
Halo
Disk
f(|z|) / max[f(|z|)]
N = 2303
N = 15029
N = 1675
N = 3533
N = 25555
N = 4406
N = 1224
N = 9183
N = 2237
0.0 %
95.7 %
4.3 %
51.7 %
20.8 %
27.5 %
98.4 %
1.1 %
0.5 %
0.0 %
96.2 %
3.8 %
58.7 %
22.6 %
18.7 %
96.3 %
2.8 %
0.9 %
0.0 %
97.1 %
2.9 %
59.6 %
30.1 %
10.3 %
91.2 %
7.6 %
1.2 %
v_ϕ [km s^{-1}]
v_r [km s^{-1}]
|z| [kpc]
Circular velocity (km/s)
Radial velocity (km/s)
Height above disk

Metal-poor halo [Fe/H]<-1.5



Metal-rich halo [Fe/H]>-1.5



The "Halo"

- Round velocity ellipsoid
- ~30% of main sequence halo sample
- More metal-poor on average

The "Sausage"

- Highly eccentric radial orbits
- Dominant contribution ~50%
- Characteristic metallicity [Fe/H] = -1.4

Gaia Sausage

From Wikipedia, the free encyclopedia

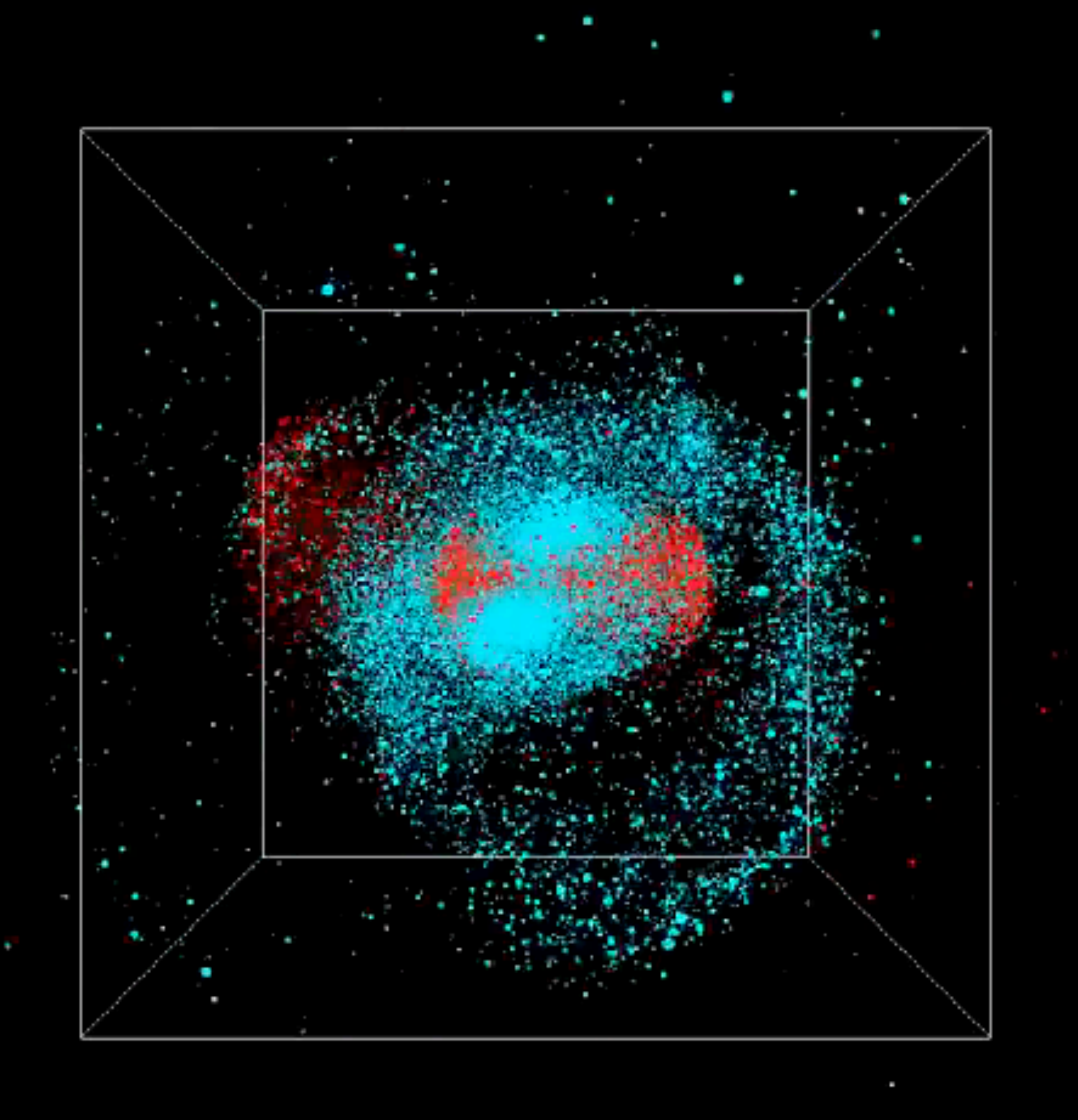
The **Gaia Sausage** is the remains of a dwarf galaxy, the "Sausage Galaxy" or **Gaia-Enceladus-Sausage** or just **Gaia-Enceladus**, that merged with the Milky Way about 8 - 11 billion years ago. At least eight globular clusters were added to the Milky Way along with 50 billion solar masses of stars, gas and dark matter.[1] The "Gaia Sausage" is so-called because of the characteristic sausage shape of the population in velocity space, the appearance on a plot of radial versus azimuthal and vertical velocities of stars measured in the Gaia Mission.[1] The stars that have merged with the Milky Way have orbits that are highly radial. The outermost points of their orbits are around 20 kiloparsecs from the galactic centre at what is called the halo break.[2]

Contents [hide]

Components [edit]

The Sausage globular clusters are NGC 1851, NGC 1904, NGC 2298, NGC 2808 (possibly the old galactic core), NGC 5286, NGC 6864, NGC 6779, and NGC 7089.[1]

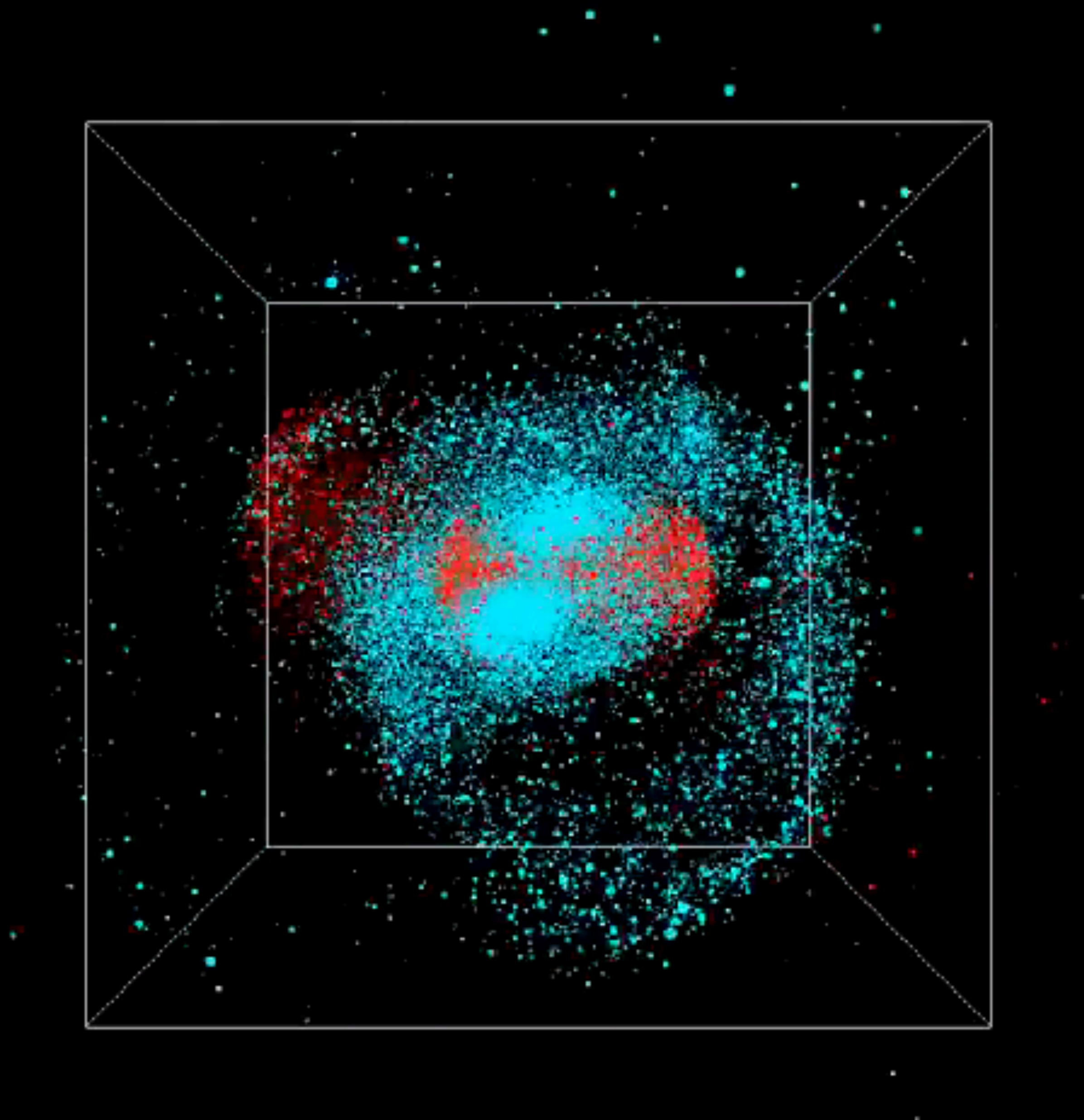
Distinct chemodynamical signature implies that the **Gaia sausage** formed after a large merger with a 10^{11} $M_\odot$ dwarf galaxy, 8-10 billion years ago



- Highly radial orbits $\beta \sim 0.9$ suggest head-on collision with small impact parameter
- Interpretation consistent with the break in stellar density at 20 kpc $\rightarrow$ pileup of stars at apocentre
- Associated with 8 known globular clusters

Helmi et al. 1806.06038

Distinct chemodynamical signature implies that the **Gaia sausage** formed after a large merger with a $10^{11}\ M_{\odot}$ dwarf galaxy, 8-10 billion years ago



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Helmi et al. 1806.06038

New understanding of Milky Way halo
→ New signal model for dark matter experiments

arXiv:[1810.11468]

KCL-PH-TH-2018-49

SHM^{++}: A Refinement of the Standard Halo Model for Dark Matter Searches

N. Wyn Evans,[1,*] Ciaran A. J. O'Hare,[2,†] and Christopher McCabe[3,‡]

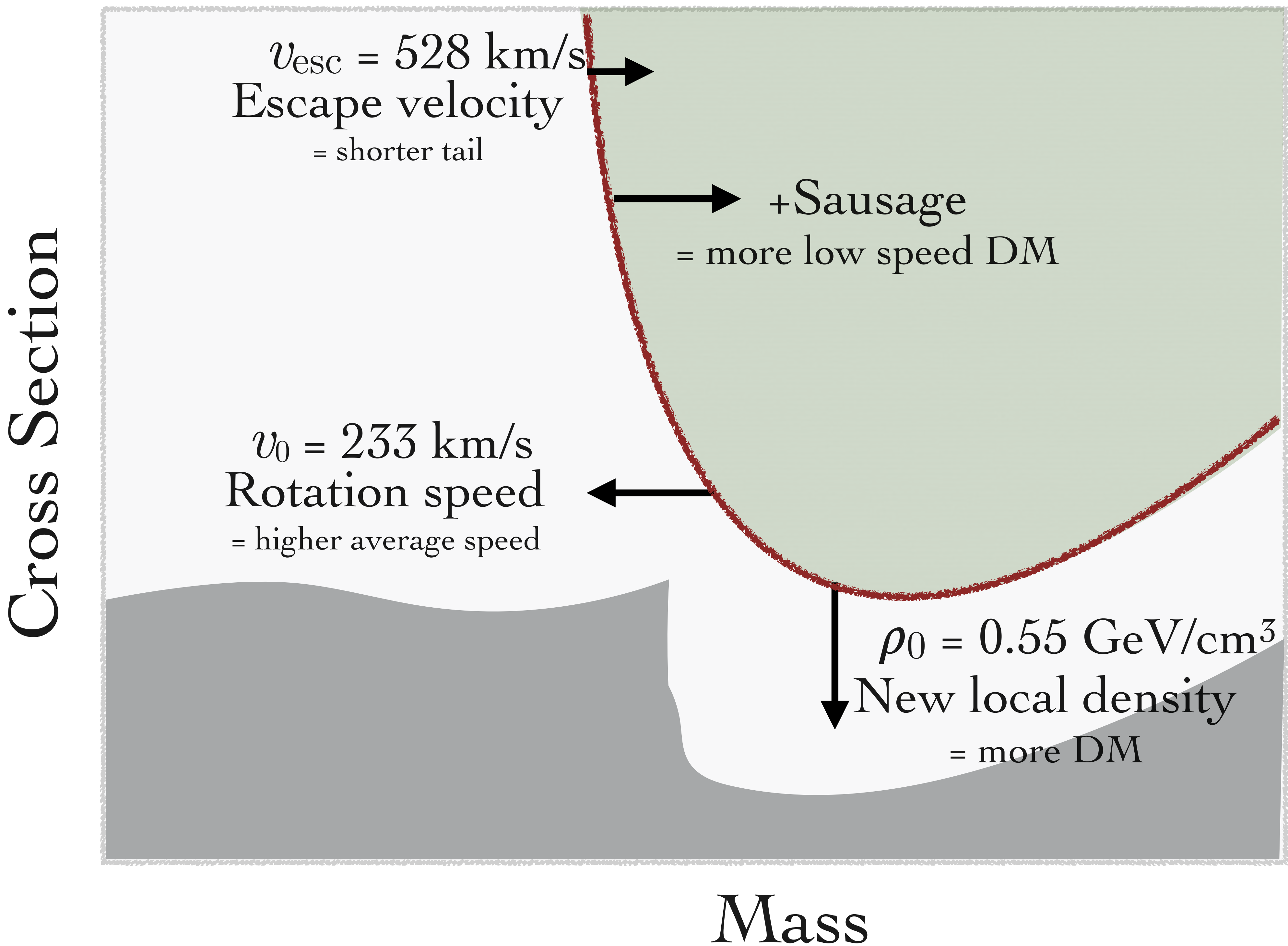
[1] *Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, United Kingdom*
[2] *Departamento de Física Teórica, Universidad de Zaragoza, Pedro Cerbuna 12, E-50009, Zaragoza, España*
[3] *Department of Physics, King's College London, Strand, London, WC2R 2LS, United Kingdom*

(Dated: October 30, 2018)

Predicting signals in experiments to directly detect dark matter (DM) requires a form for the local DM velocity distribution. Hitherto, the standard halo model (SHM), in which velocities are isotropic and follow a truncated Gaussian law, has performed this job. New data, however, suggest that a substantial fraction of our stellar halo lies in a strongly radially anisotropic population, the '*Gaia* Sausage'. Inspired by this recent discovery, we introduce an updated DM halo model, the

Impact of new model on WIMPs

Summary of the updates included in the **SHM^{++}**



Ciaran O'Hare

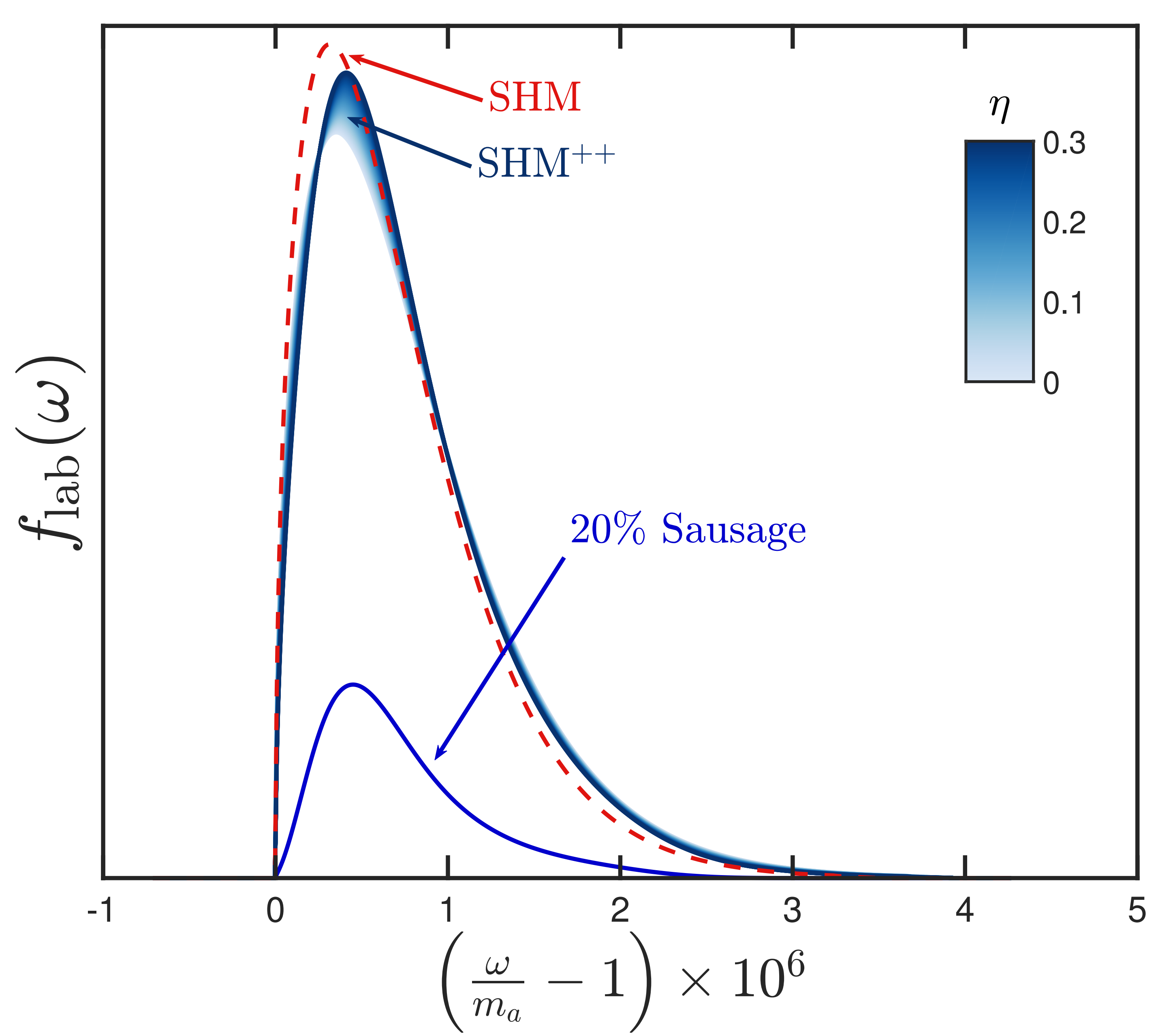
For axions…

- Increase in axion linewidth → weaker limits
- Increase in local density → stronger limits
- Overall, SHM++ limits only about 8% stronger

SHM still ok for axions,

However…

→ Presence of the Sausage means the lineshape is much wider along the Galactic radial direction. Potentially important for axion wind and modulation-based experiments



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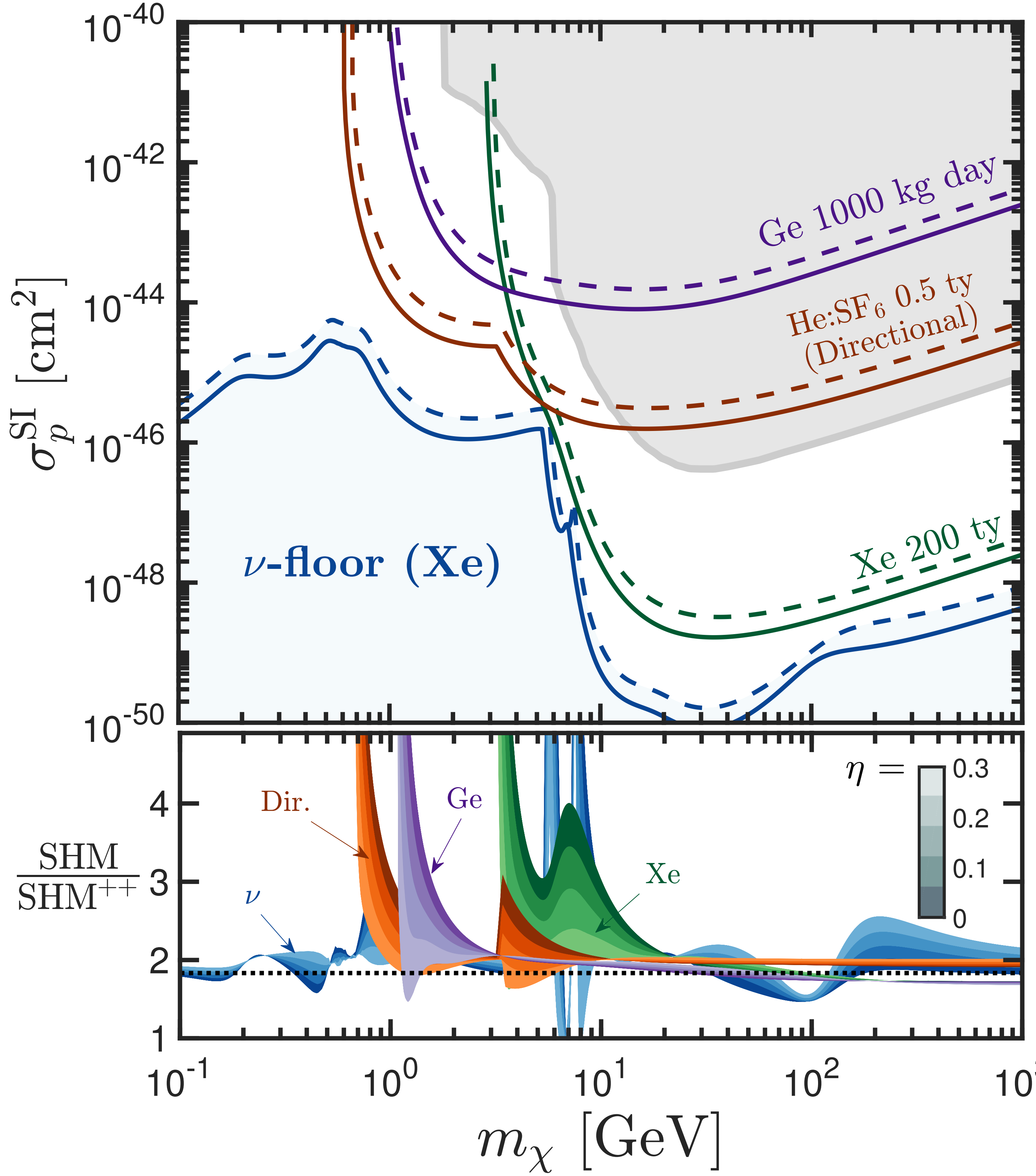
→ Multiple competing effects mean that the differences between the two models are smaller than expected

- - **SHM**

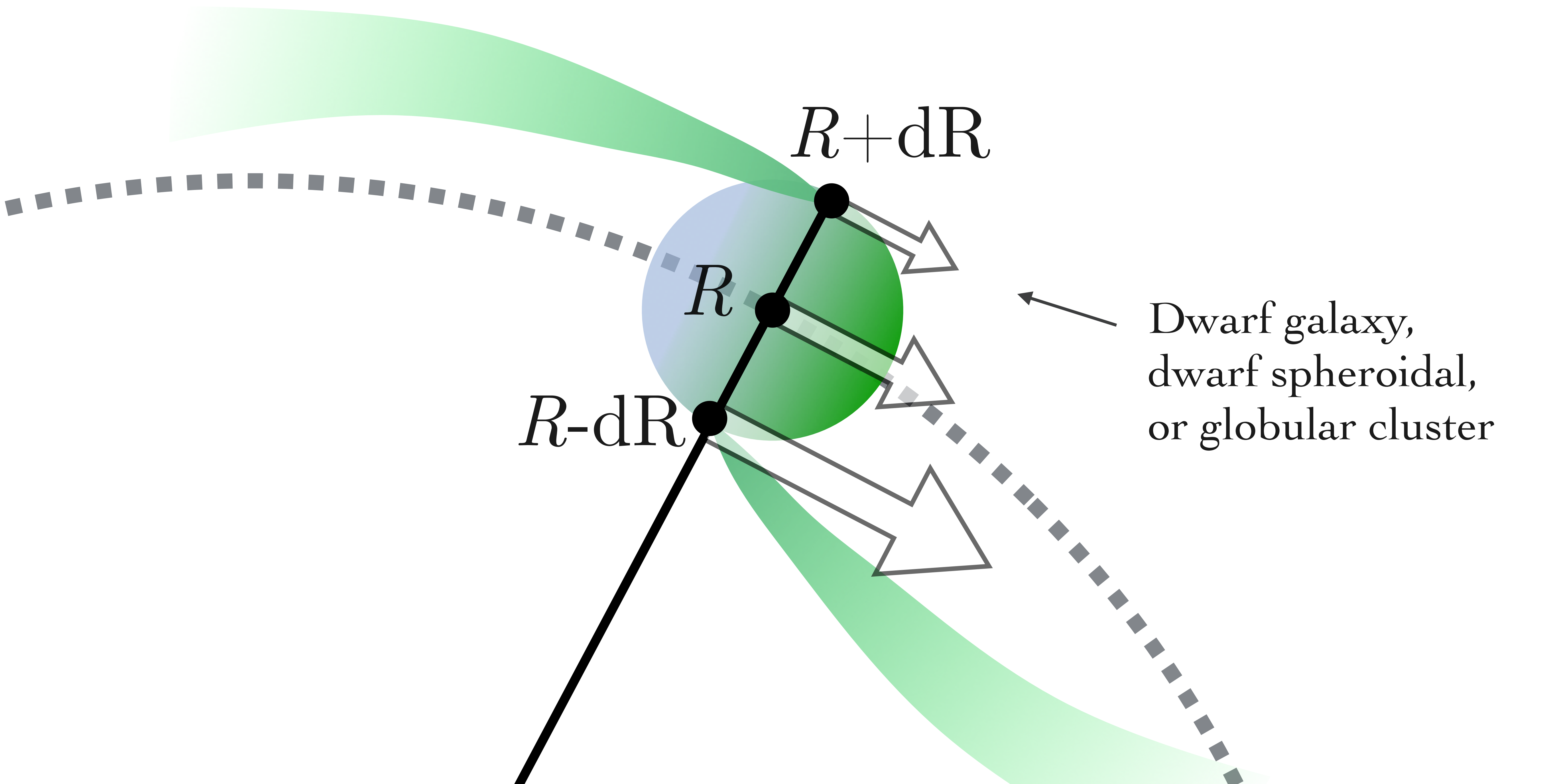
— **SHM++**



The S1 stream

Forming tidal streams

Satellite is pulled apart when the tidal force across it overcomes its own self-gravity



Importance for DM

Satellites → Distinguishing warm/cold DM
→ Targets for DM annihilation or decay

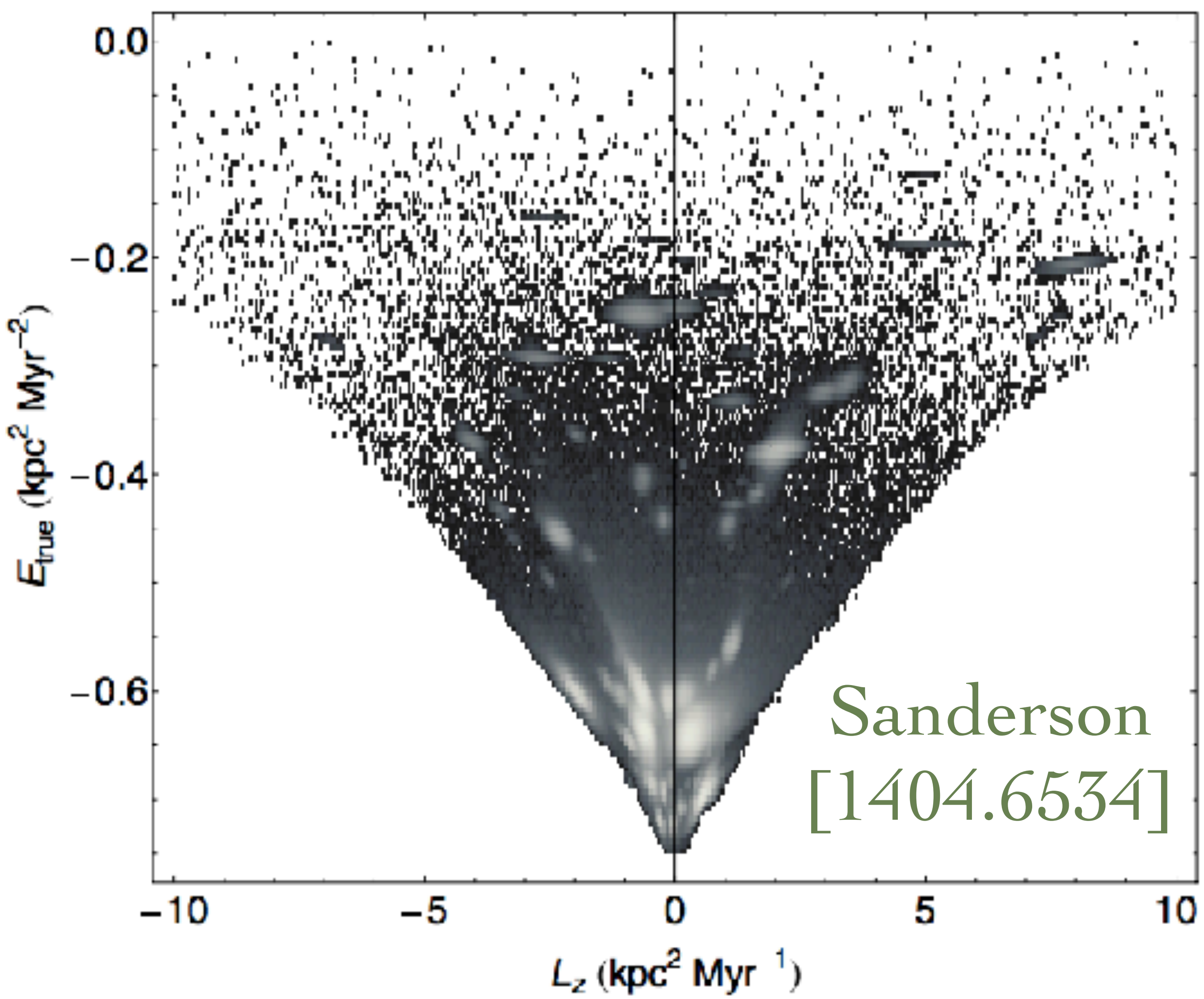
Streams → Informs about the granularity of DM halo
→ Traces the shape of MW potential
→ Can be used to constrain fuzzy DM

Scramble → Clumpiness of the dark matter halo
→ Crucial input for all direct DM searches

Finding streams kinematically

"**Angle-Actions**" - map orbital parameters into variables that are conserved for orbits in slowly varying potentials
→ hence streams remain clustered in "<u>action space</u>" long after they have ceased to be visible in star counts

Computing these variables for stars requires full orbital information
→ **Need complete 6D kinematic data to find streams this way…**



Sanderson [1404.6534]

S1 stream: what we know so far

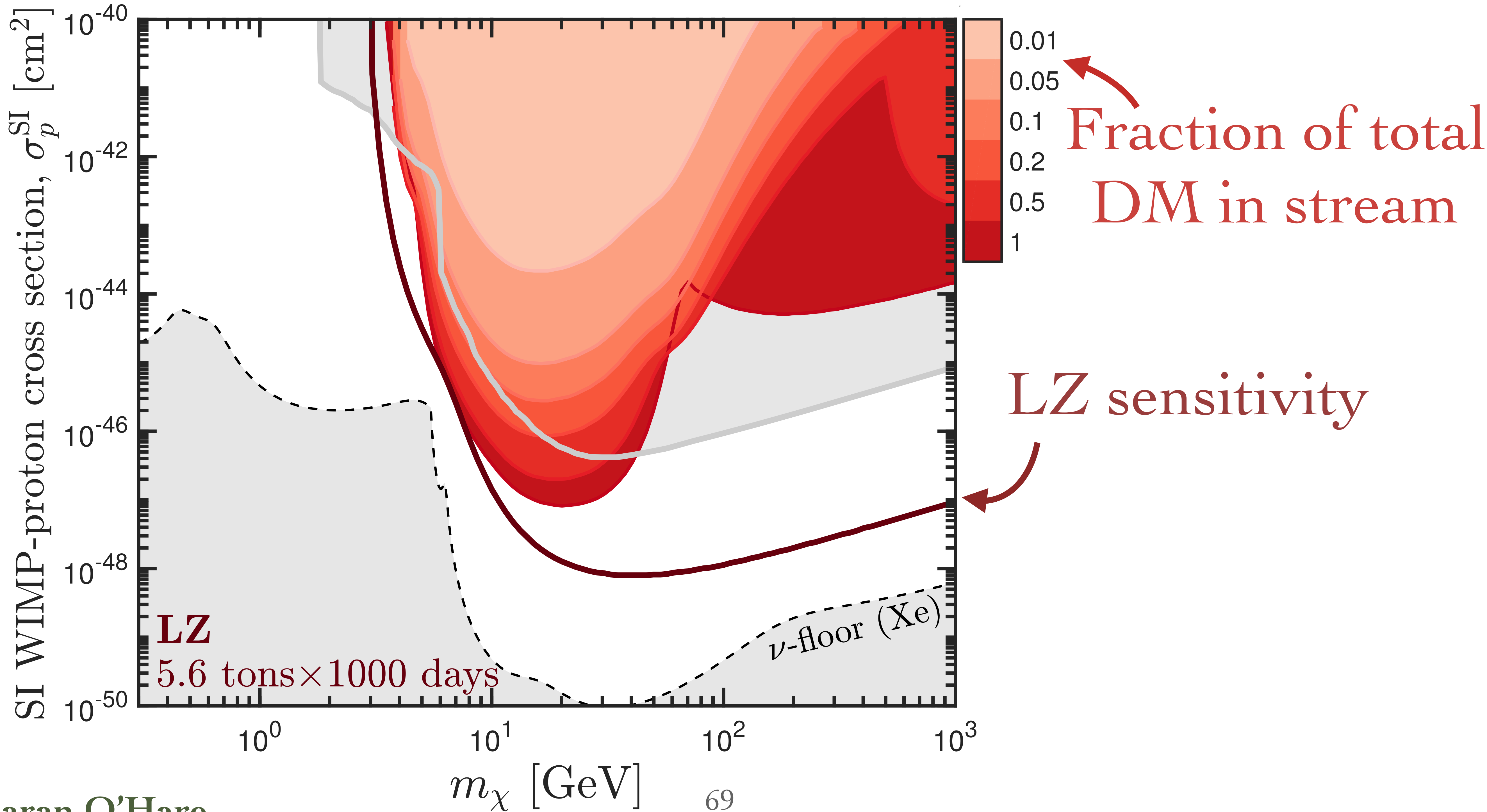
Galactic velocity: $\mathbf{v}_{\rm str} = (8.6,\ -286.7,\ -67.9)\ \mathrm{km\,s^{-1}}$
→ Stream on a strongly retrograde orbit, so DM impacts us at high velocity ~ 500 km/s

Velocity dispersion: $\sigma_{\rm str} = 46\,\mathrm{km\,s^{-1}}$
→ Suggests a dwarf spheroidal origin, around the mass of the present day Fornax satellite galaxy accreted over 8-10 billion years

Dark matter content: $0 + \epsilon < \rho_{\rm str} < 0.55\,\mathrm{GeV\,cm^{-3}}$
→ Upper bound: is probably the local DM density probed over length scales smaller than the stream
→ Lower bound: Progenitor very likely had dark matter but other than that we cannot say, must remain agnostic

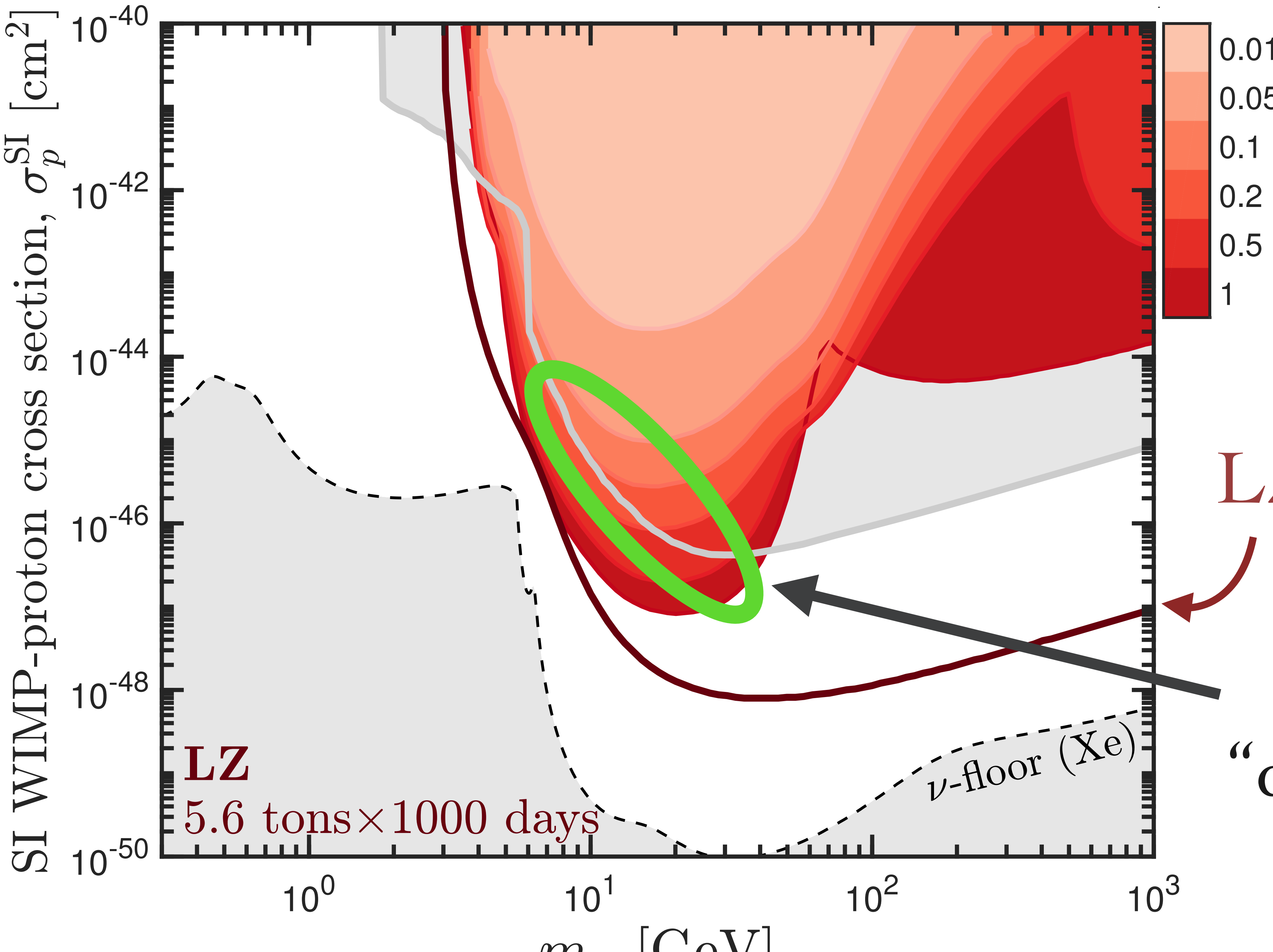
S1 in LZ

Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma



S1 in LZ

Red regions: range of WIMP models for which the stream can be distinguished from the halo in LZ at 3 sigma



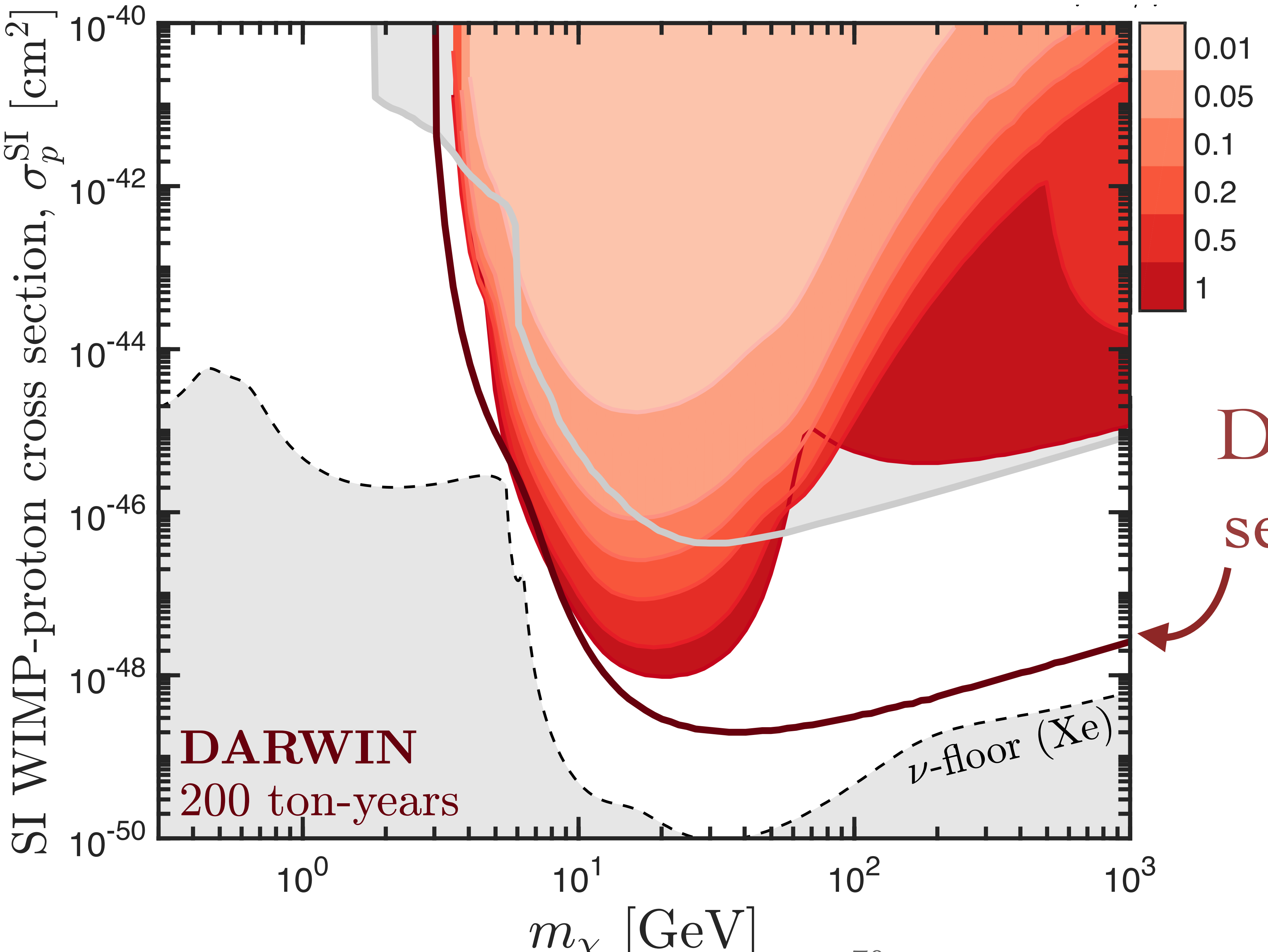
Fraction of total DM in stream

LZ sensitivity

Stream only "detectable" here

S1 in DARWIN

Red regions: range of WIMP models for which the stream can be distinguished from the halo in DARWIN at 3 sigma

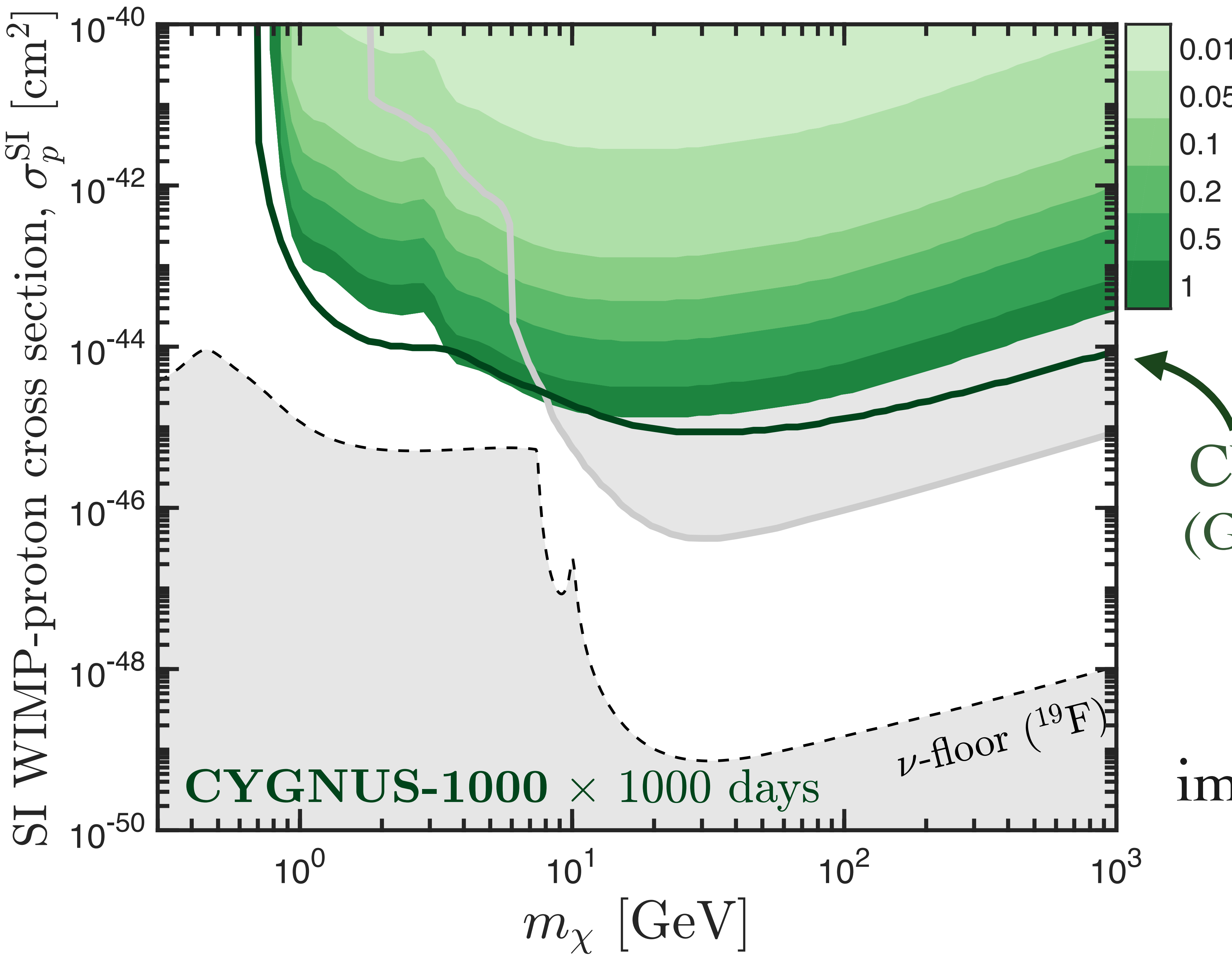


Fraction of total DM in stream

DARWIN sensitivity

S1 in a directional detector

Green regions: range of WIMP models for which the stream can be distinguished from the halo in CYGNUS at 3 sigma

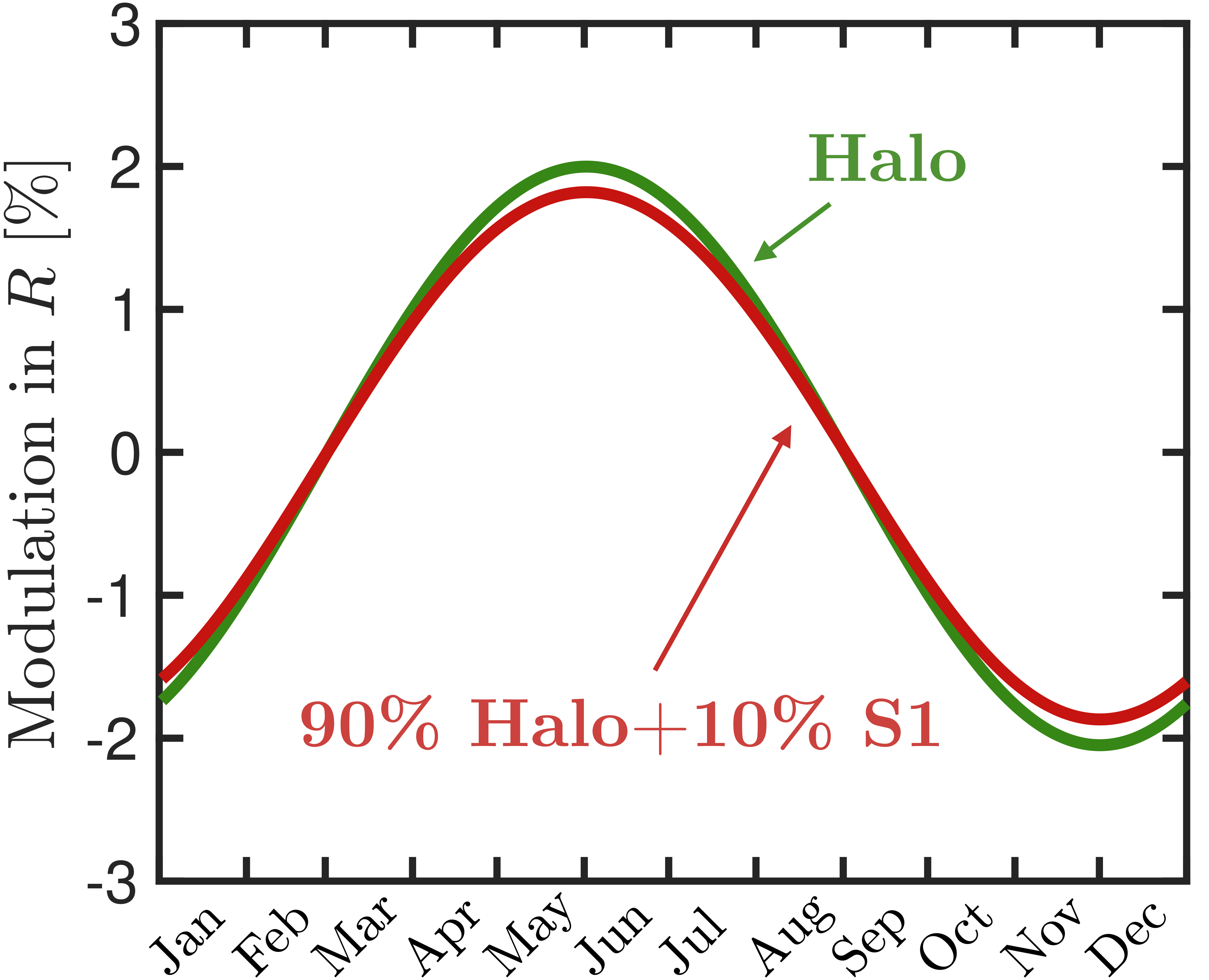


Fraction of DM in stream

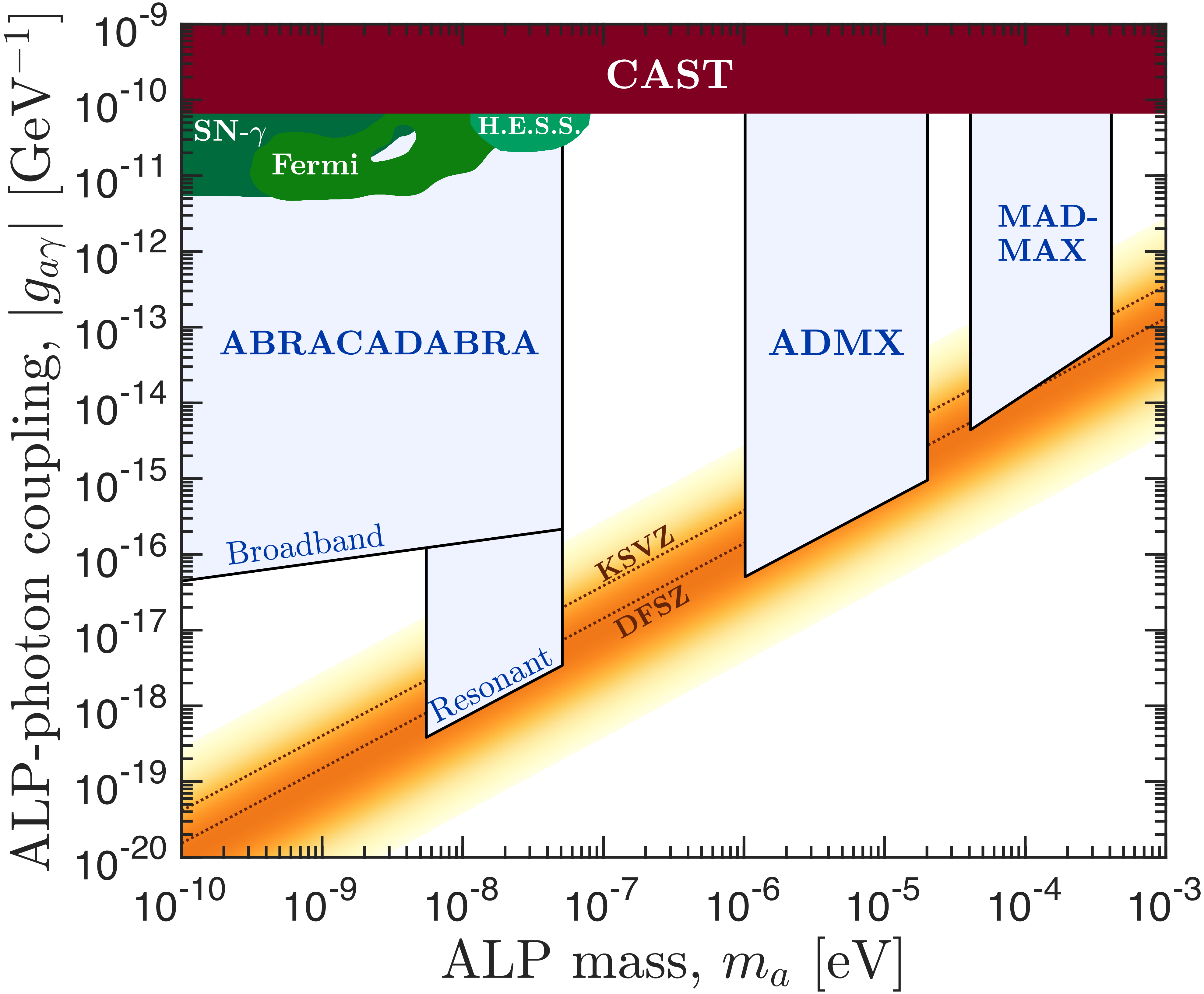
CYGNUS sensitivity (Gas TPC with He+SF_6)

Directionality improves sensitivity to stream

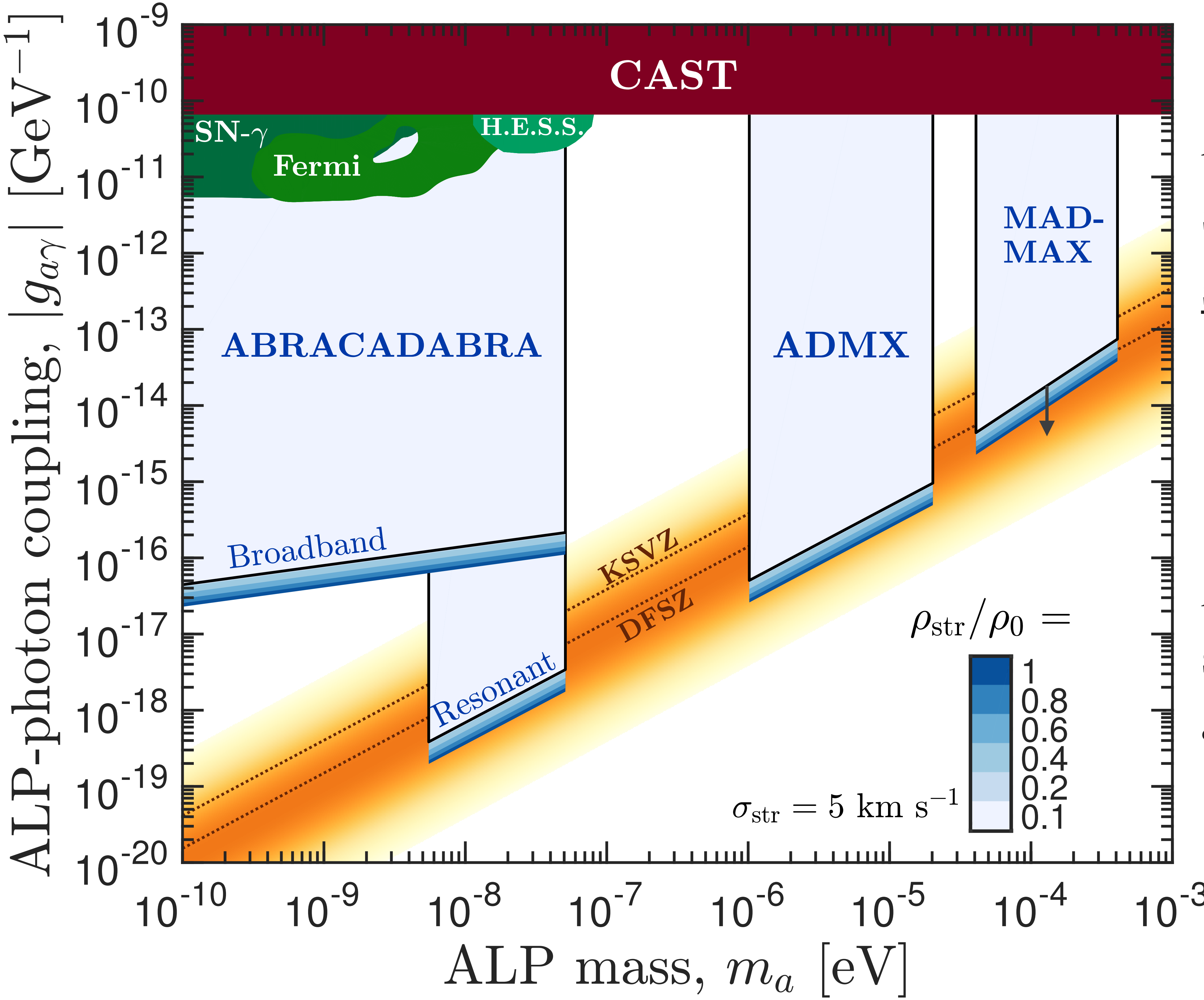
Annual modulation



Axion experimental projections



Impact of streams on axion searches:



Axion searches like <u>sharp</u> signals

↓

A cold S1 stream <u>improves</u> axion sensitivity