# Direct dark matter detection

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# Direct dark matter detection

Today

Dark matter in the Solar System
Direct detection of *particle-like* dark matter

Tomorrow

Direct detection of *wave-like* dark matter

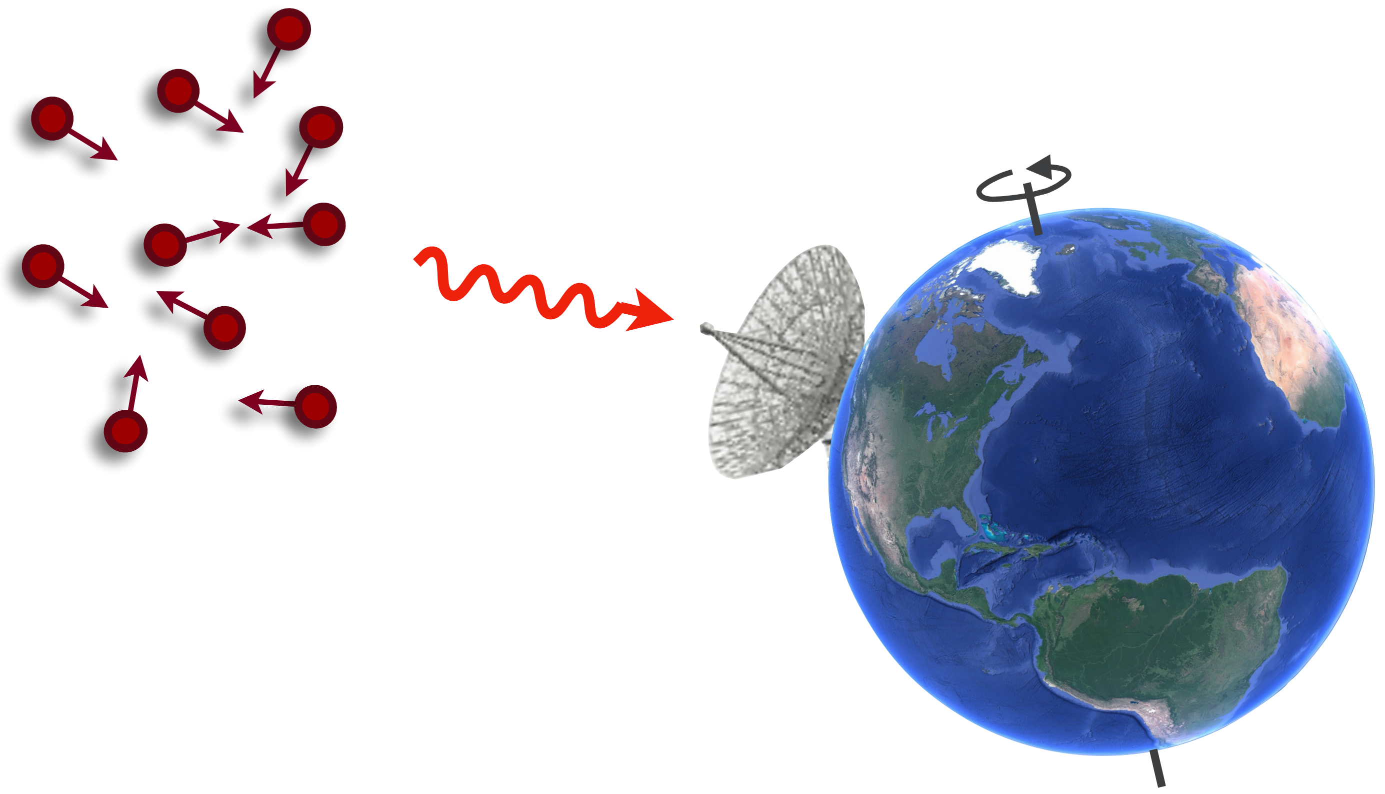
# What is "direct detection"?

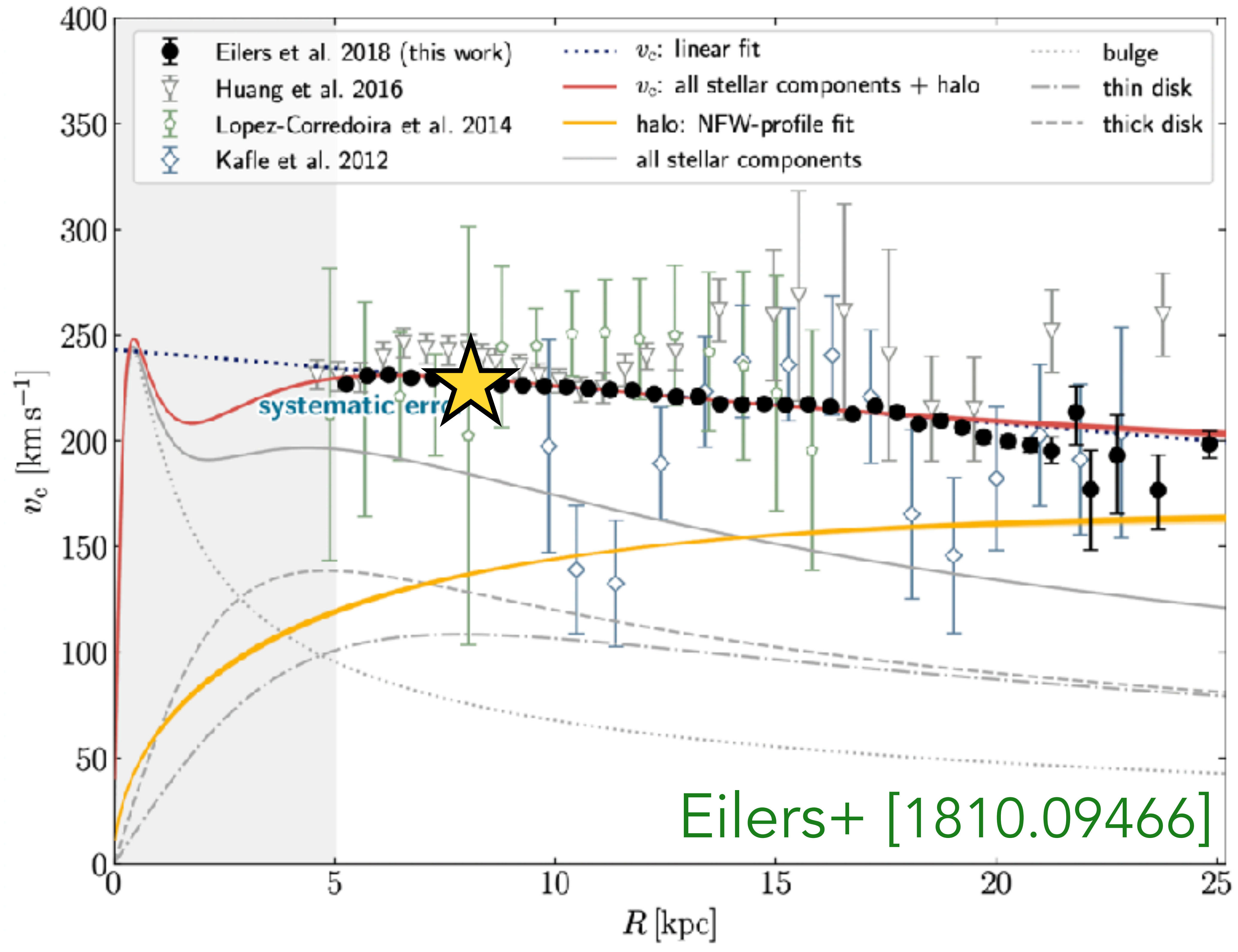
## *Direct* detection

Dark matter comes in from galaxy, interacts inside laboratory experiment

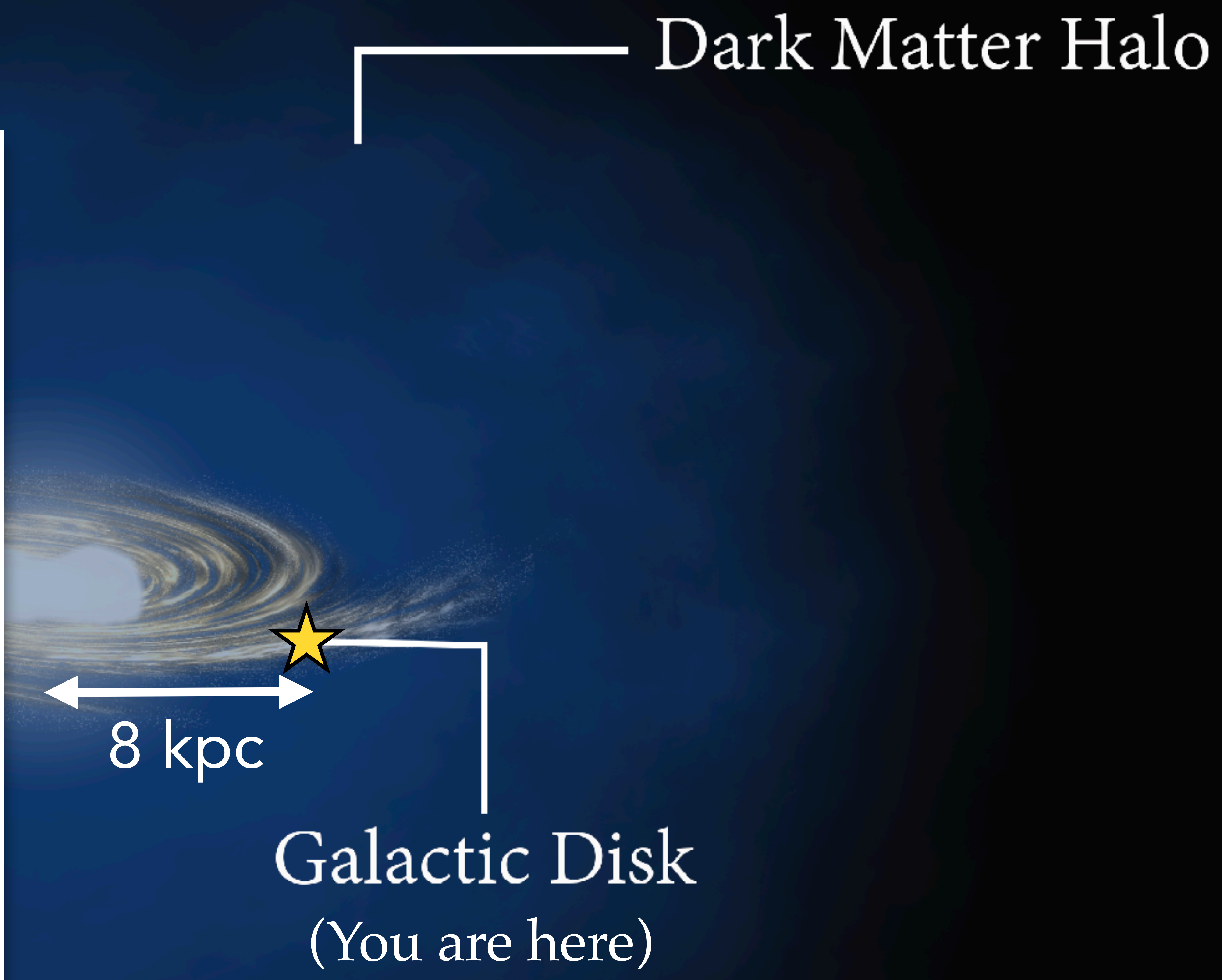
## *Indirect* detection

Dark matter interacts with itself or with other stuff in space producing signals we detect in telescopes






$$\rho(R = 8\,\mathrm{kpc}) = 0.3 \pm 0.03\ \mathrm{GeV/cm^3}$$



# Dark matter in the Solar System

We can measure the dark matter locally because stellar motions trace the gravitational potential

Model

$$\Phi = \Phi_{\text{stars}} + \Phi_{\text{gas}} + \Phi_{\text{DM}}$$

↓

(collisionless) Boltzmann eq.

Distribution function → Grav. potential

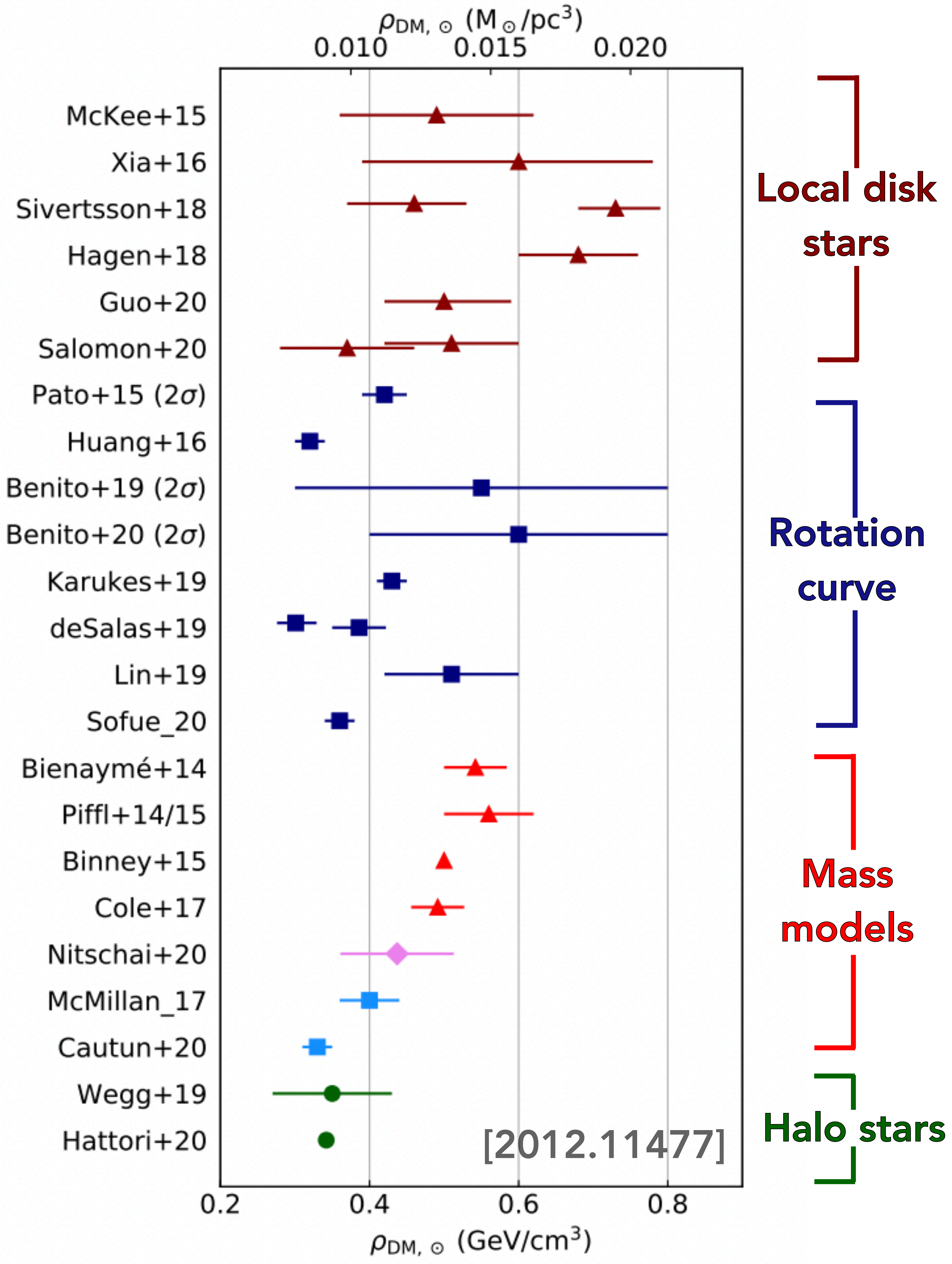
$$\frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0$$

↓

Poission eq.

Grav. potential → matter density

$$\nabla_x^2 \Phi = 4\pi G \rho$$




# Long history of this

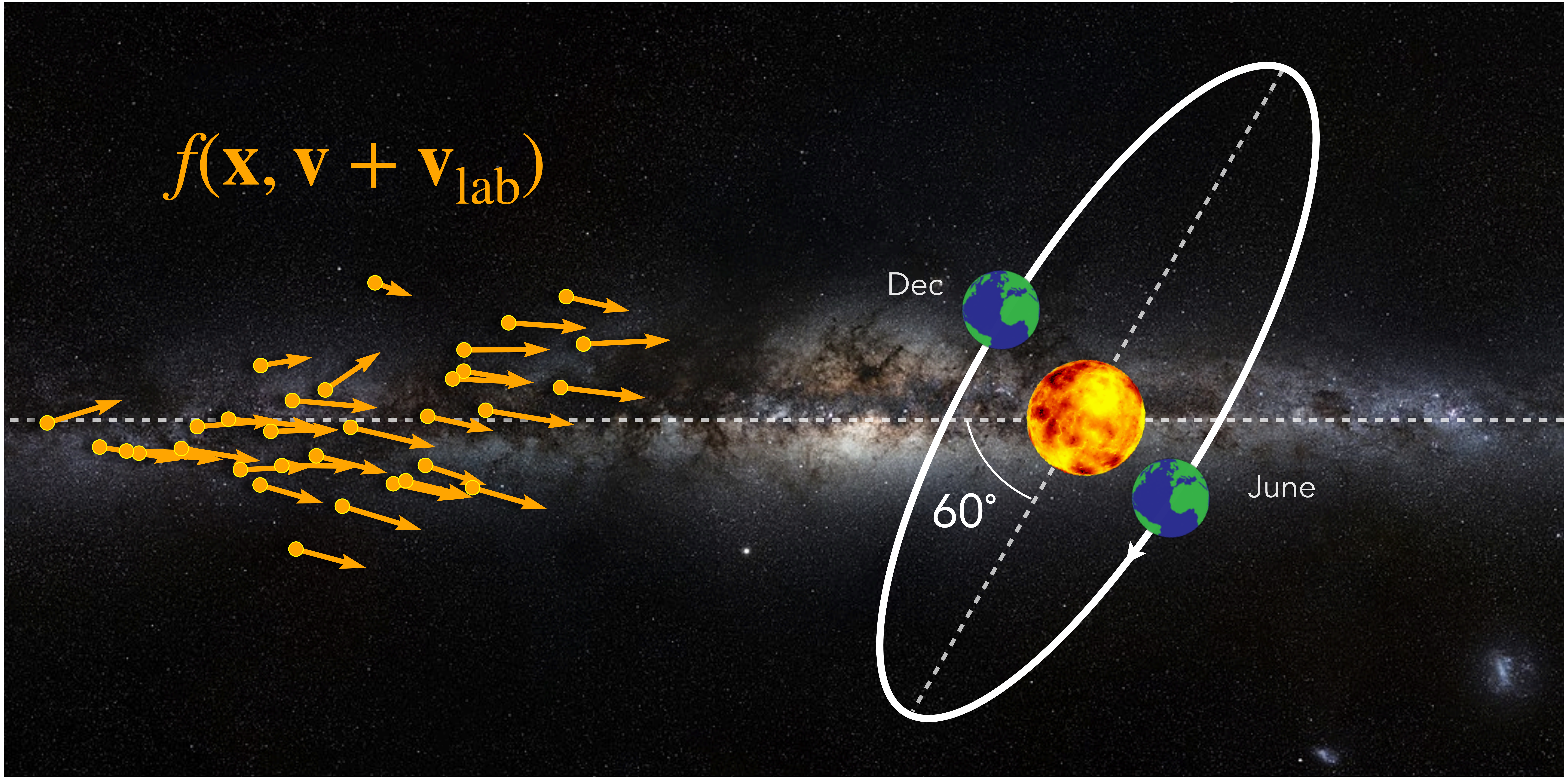
*(Kapteyn 1922, Oort 1932)*

Current estimates span the range 0.3—0.7 GeV cm$^{-3}$ depending on the method and dataset used

$\rho_{\mathrm{DM}} = 0$ excluded at many $\sigma$

→ Post-*Gaia* there is no lack of data. Fundamental problem is modelling, disequilibrium, and uncertainty in baryon density in the disk

# Distribution function for dark matter in the Solar System



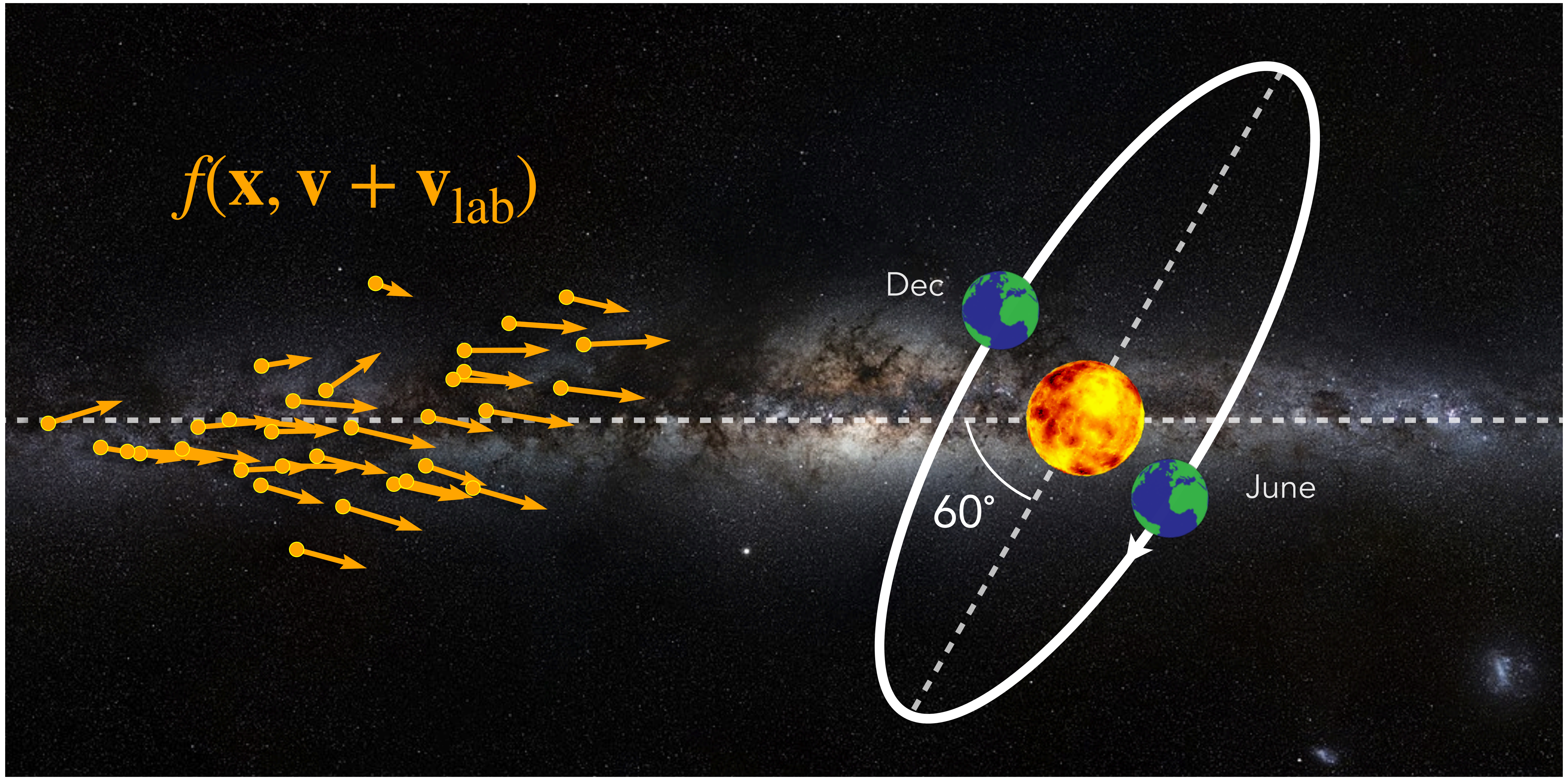

Assuming the dark matter does not co-rotate with the disk, most effects come about from our laboratory's motion **through** the dark matter: $v_{\rm lab} \sim 300$ km/s

Typical DM speed $v \sim 300$ km/s

DM density $\rho_{\rm DM} \approx 0.4$ GeV/cc

→ Flux: $$\Phi = n_{\rm DM} v = \frac{\rho_{\rm DM}}{m_{\rm DM}} v$$

Assuming O(m)-scale experiments, and O(year) running times, direct detection is reasonable to think about for DM masses up to the Planck-scale




**Relative Sun/Earth motion can lead to some interesting signals that are independent of DM particle model**

→ Annual modulation
→ Gravitational focusing by Sun
→ Direction-dependence

$$\mathbf{v}_{\rm lab} = \underbrace{\mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec}}_{\text{Sun: 260 km/s}} + \underbrace{\mathbf{v}_{\oplus,\,\rm rev.}(t)}_{\text{Earth: } \pm 15 \text{ km/s (left-right)}, \pm 20 \text{ km/s (up-down)}}$$

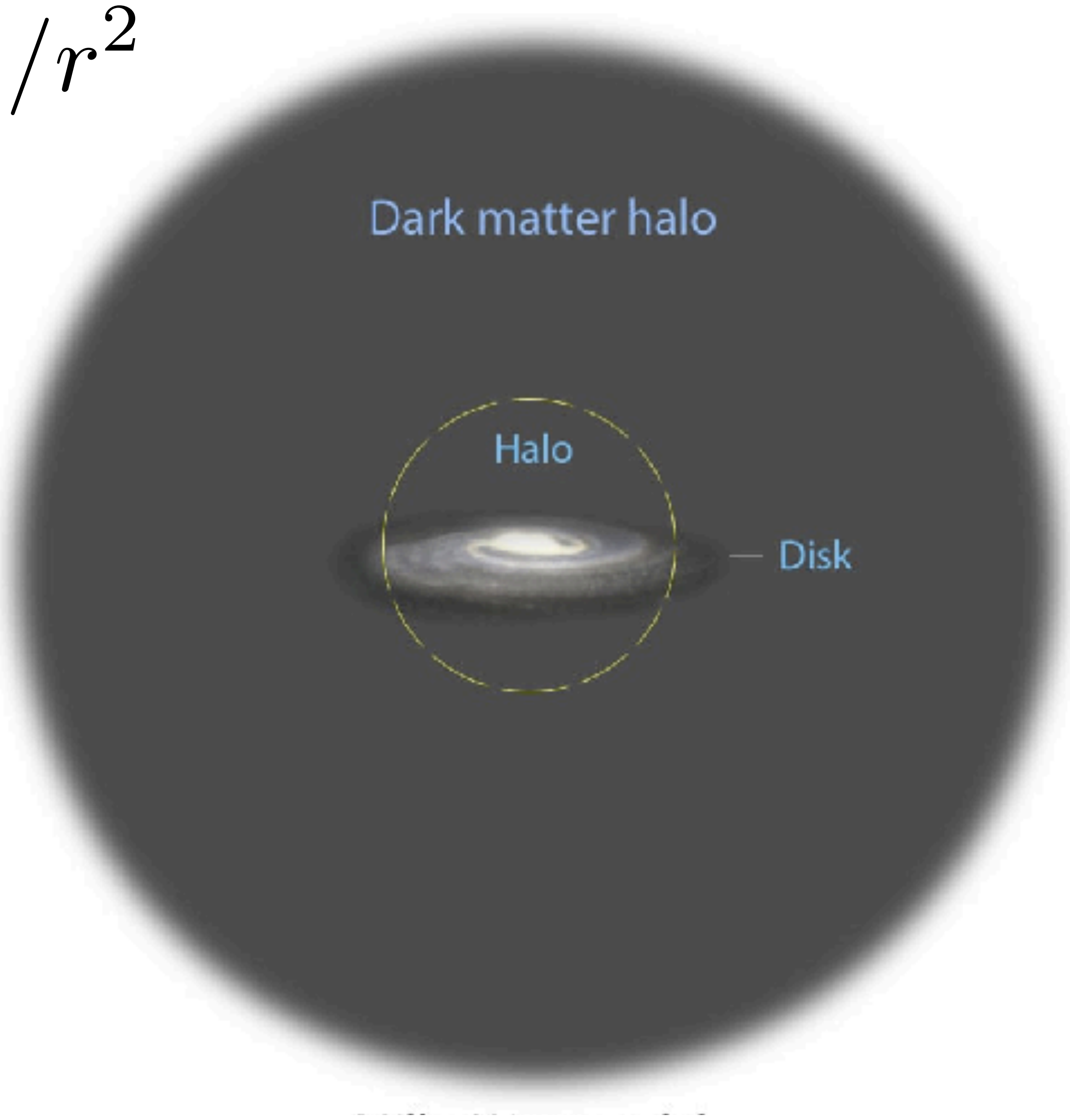
Sun:
260 km/s

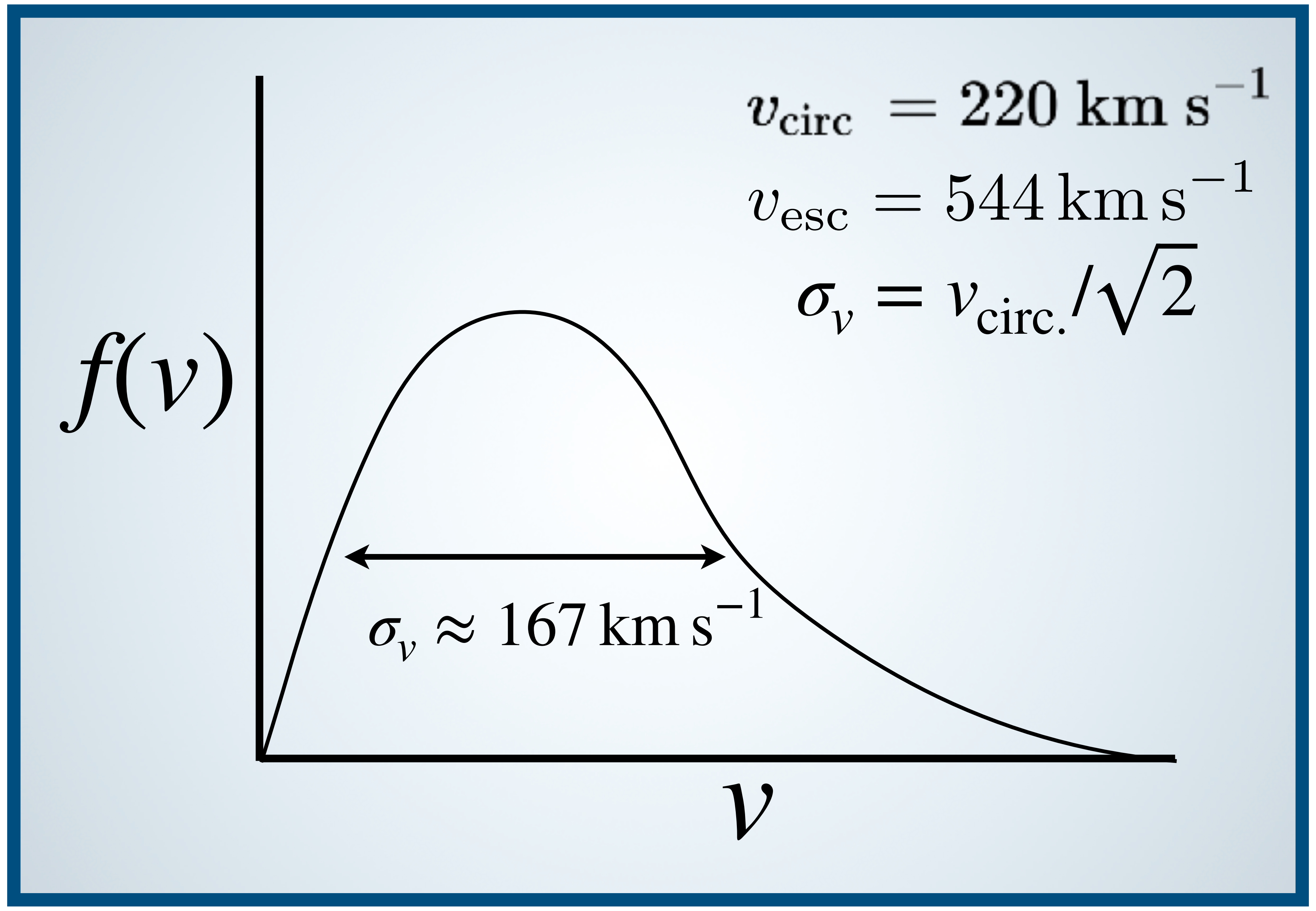
Earth:
$\pm 15$ km/s (left-right)
$\pm 20$ km/s (up-down)

# The usual assumption for $f(\mathbf{x}, \mathbf{v})$: the Standard Halo Model (SHM)

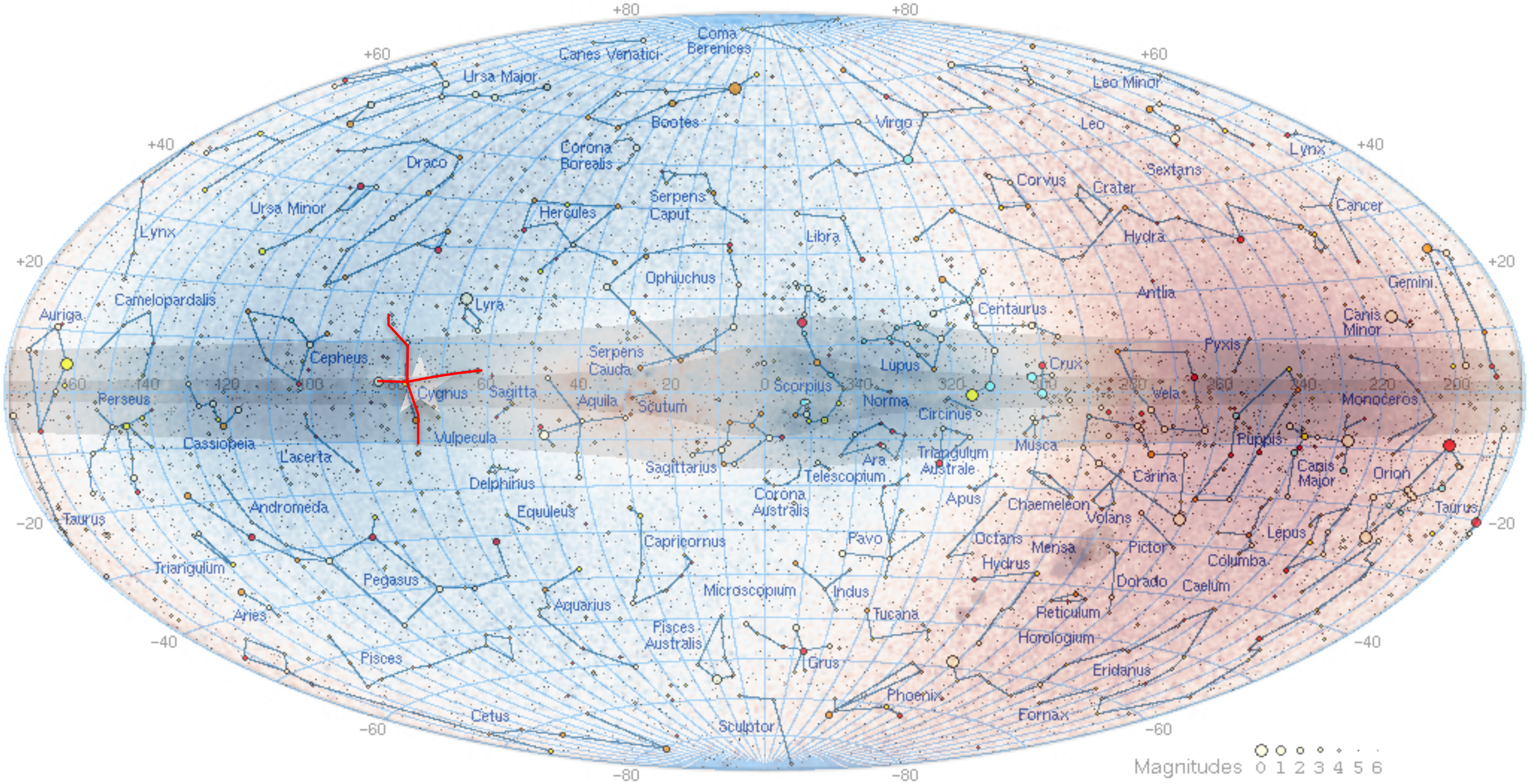
- Infinite isothermal sphere → Simplest halo model that gives a flat asymptotic rotation curve
- Truncate at $v > v_{esc}$ so as to not include unbound particles

$\rho \sim 1/r^2$



# Directionality

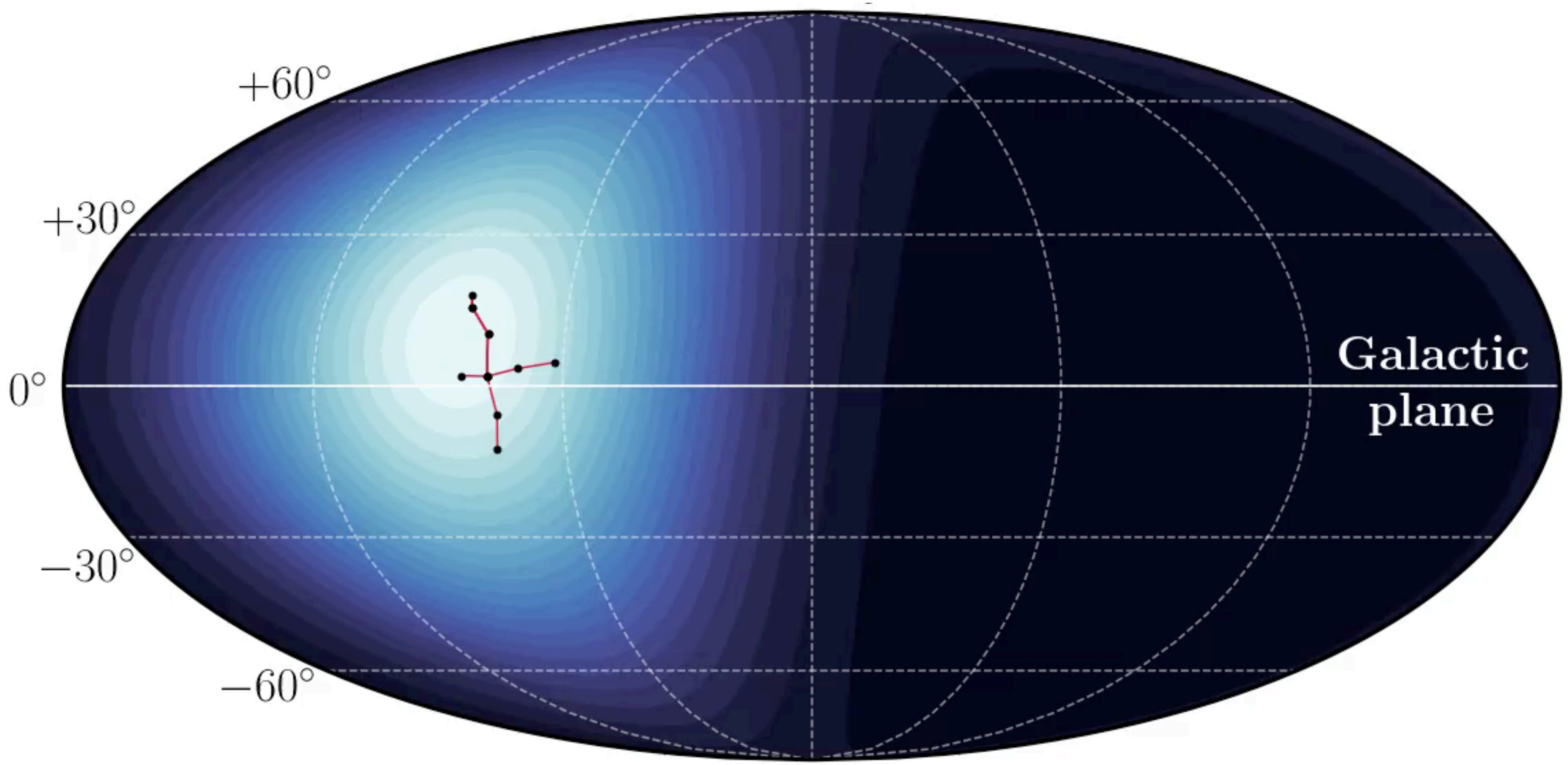



*Gaia* RVS galactic coordinates skymap of stellar line-of-sight velocities

Blue = moving towards us

Red = moving away from us

# Directionality




The dark matter flux on Earth is highly anisotropic towards constellation of Cygnus

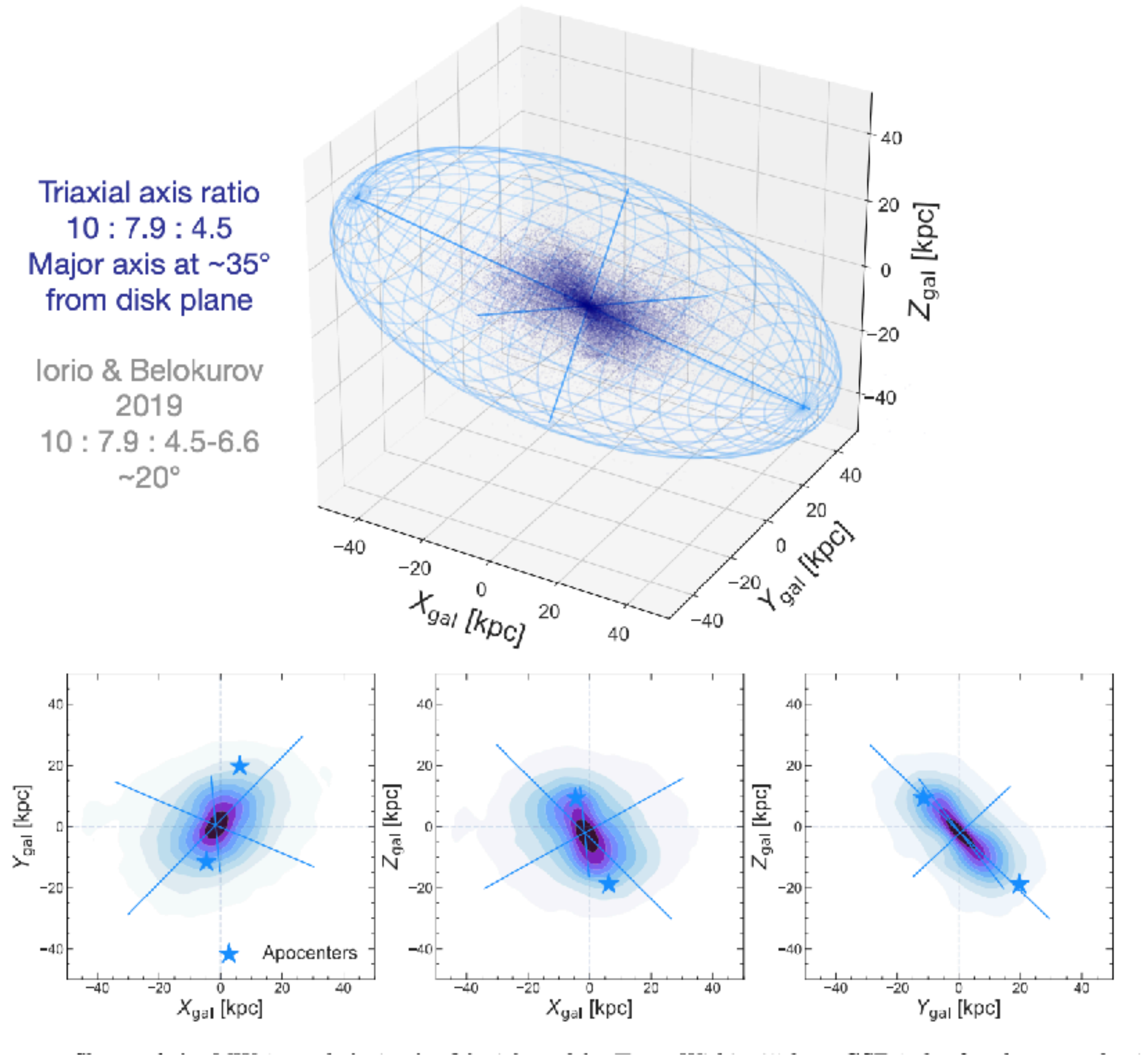
$$\Phi_{\text{forward}}/\Phi_{\text{backward}} \sim O(10)$$

I am claiming this is a generic/model-independent expectation for a DM signals in the Solar System

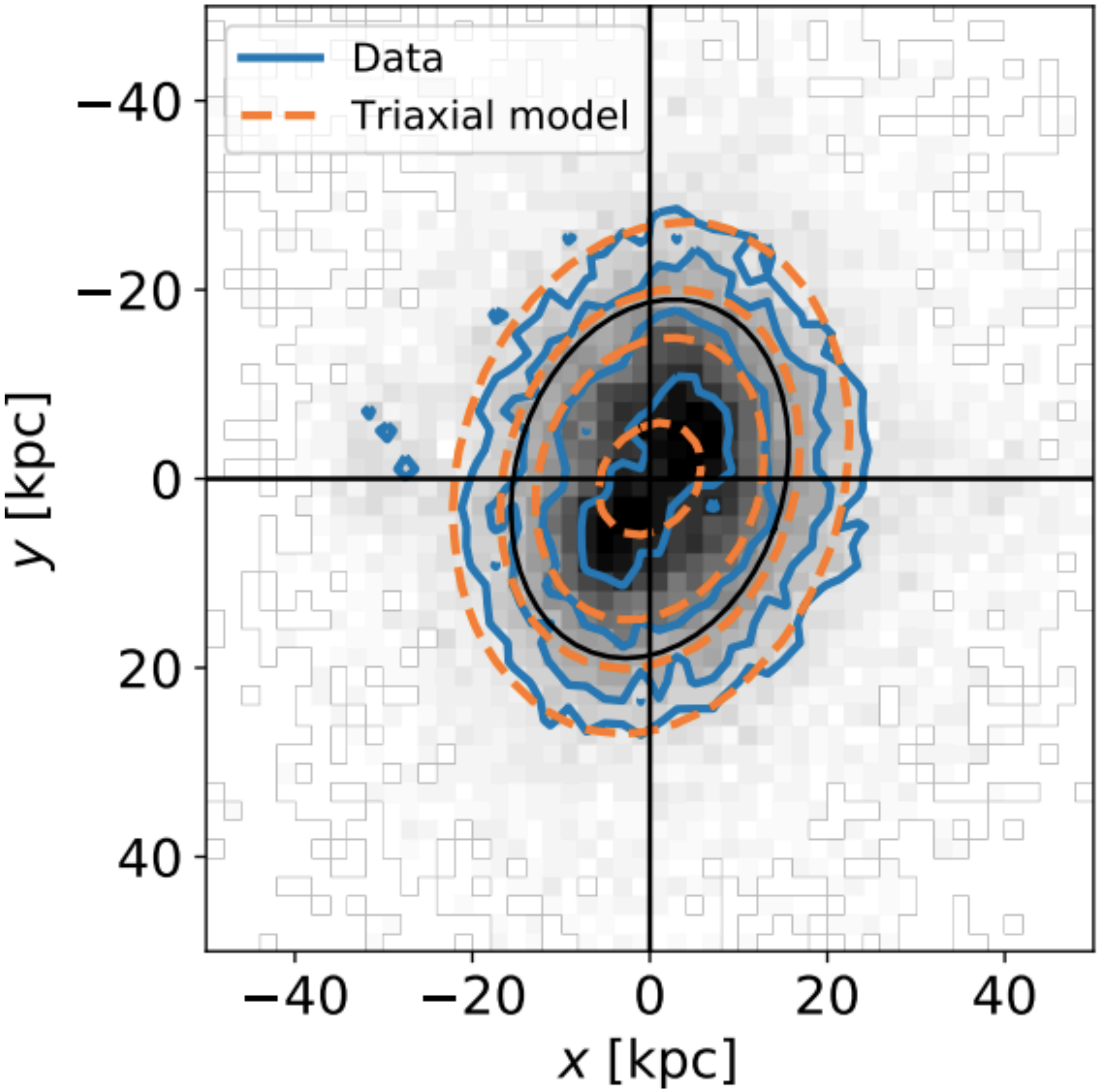
**But how much do we trust our assumptions?**

| | | |
|---|---|---|
| Is the DM halo spherical? | → | No |
| Is the DM speed distribution Maxwellian? | → | Probably not |
| Is the DM halo stationary? | → | Probably not |

## Han+ [2208.04327]
## Naidu+[2103.03251]
## (H3 survey)




## Iorio & Belokurov
## [1804.11347] (RR Lyraes)



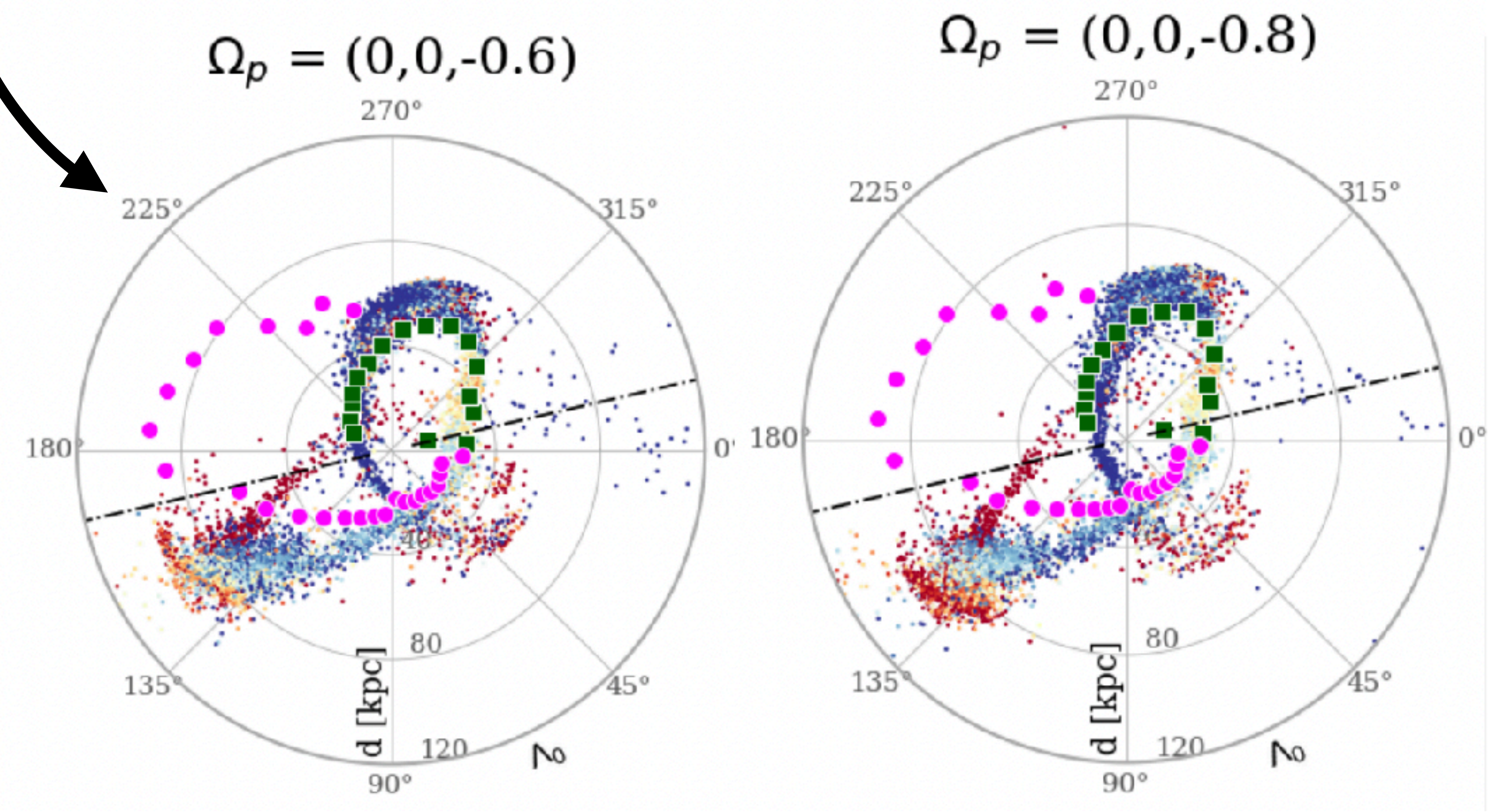
# Figure rotation/tumbling of DM halo

Simulations find typical pattern speeds for triaxial halos in the range

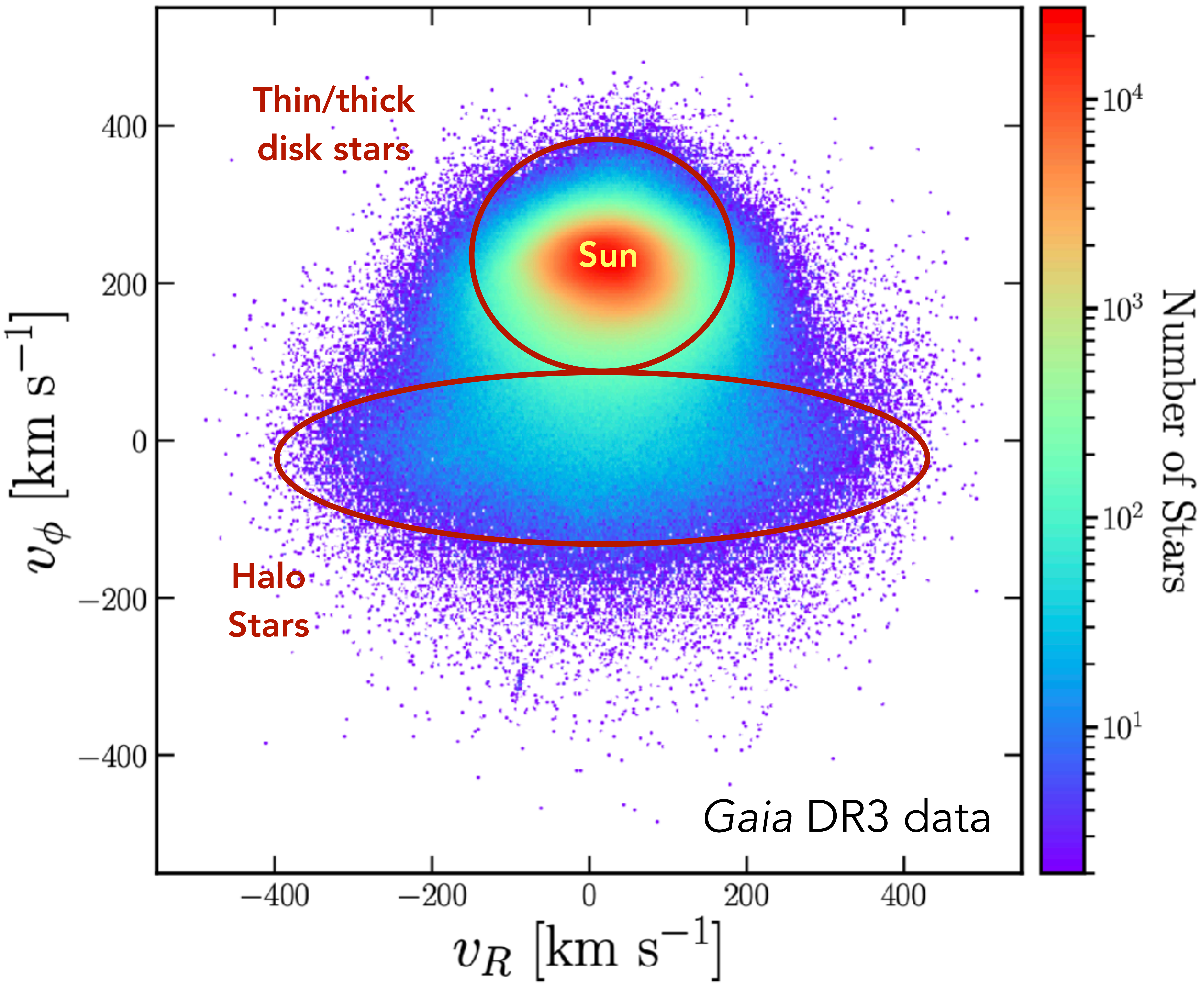
$$\Omega_p \sim 0.15 - 0.6 \text{ km s}^{-1}\text{kpc}^{-1} \sim 9^\circ - 35^\circ \text{Gyr}^{-1}$$

→ MW spin cannot be anomalously large or the Sagittarius stream would look measurably different from the way it does (Valluri et al. 2009.09004)

**Even extreme figure rotation would not reduce anisotropy of DM flux in Solar System**

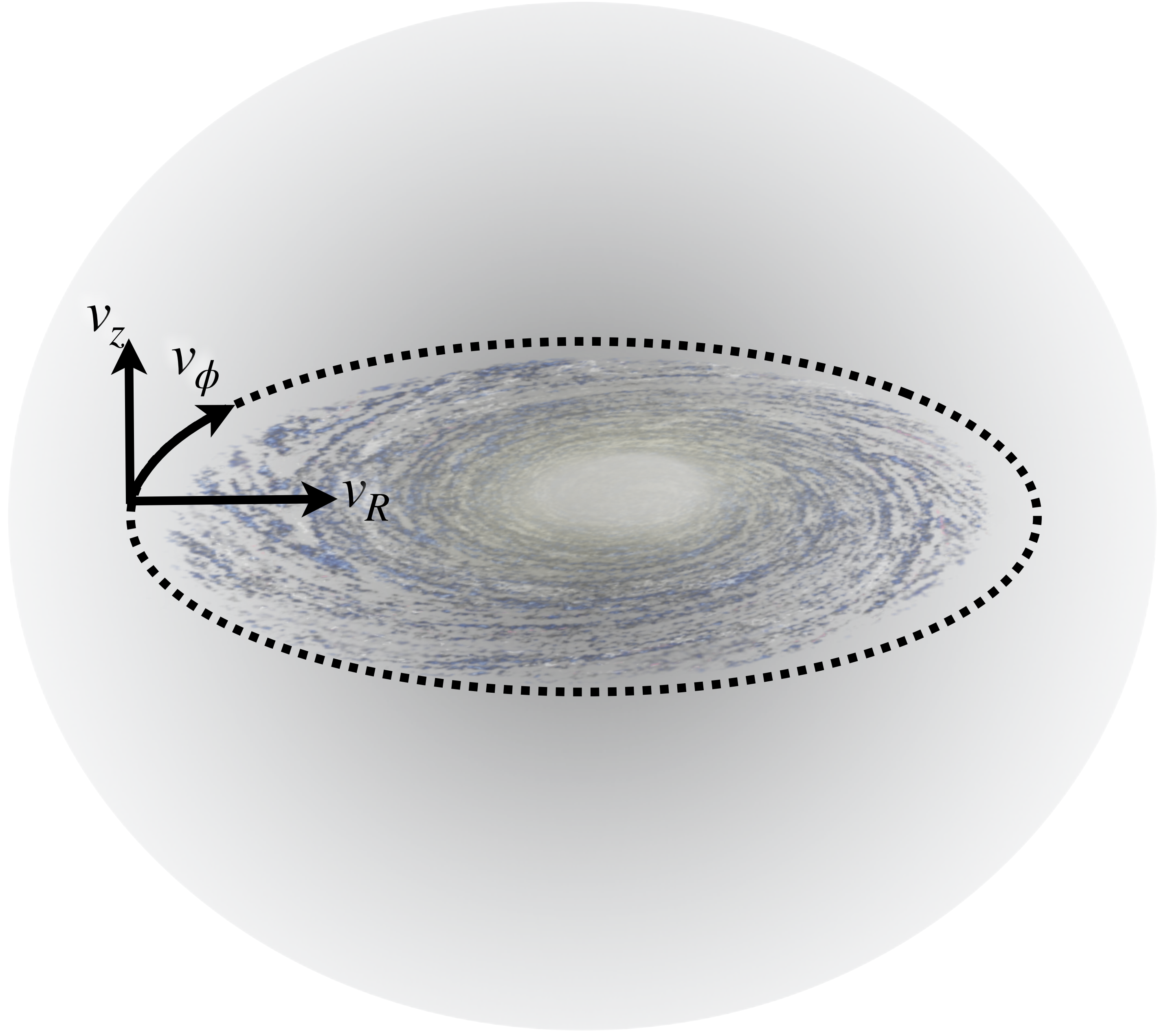


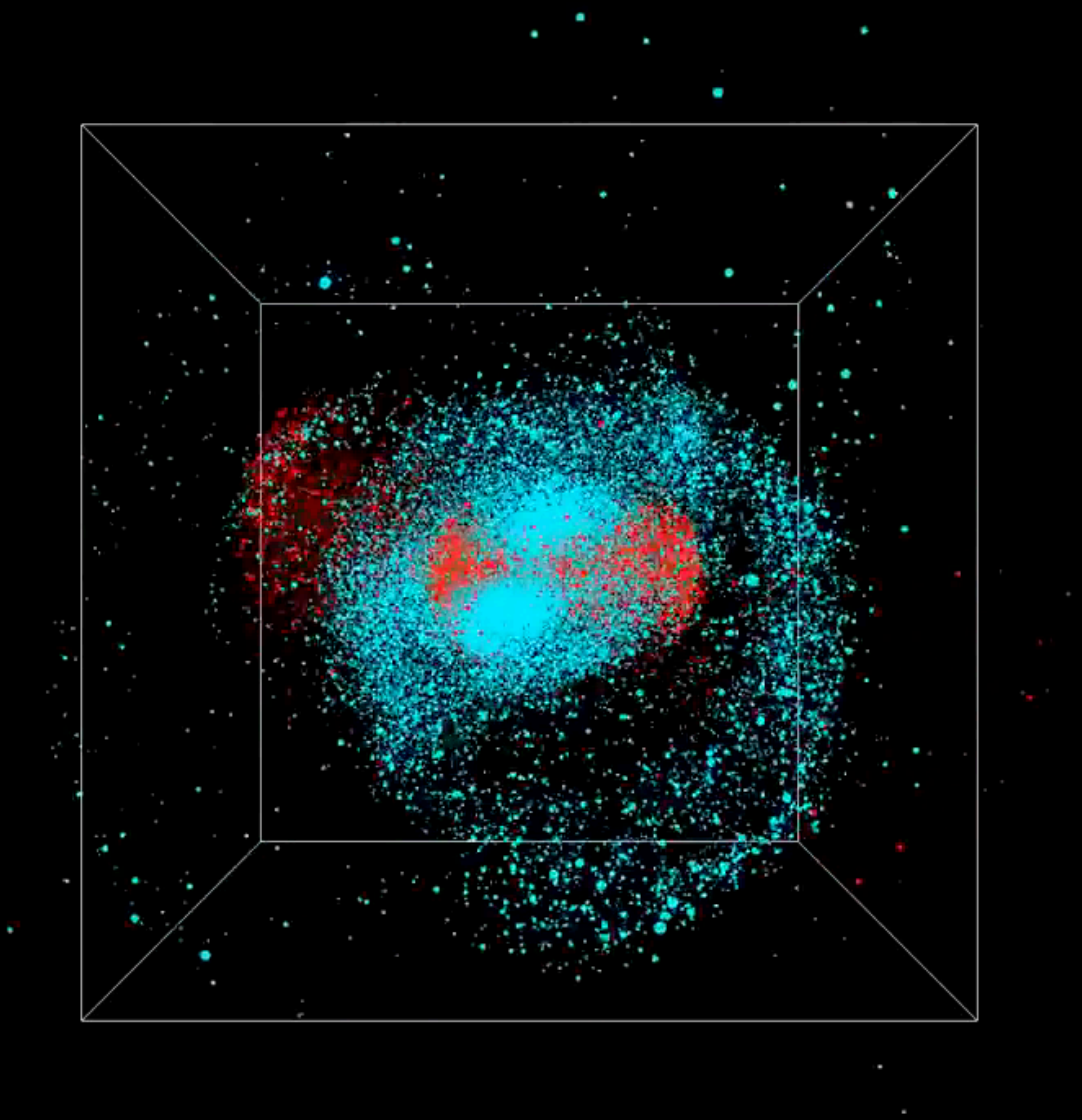
# Velocity distribution of the MW halo




Substantial evidence for recent merger event with a dwarf galaxy filling much of the inner halo

→ **The Gaia-Sausage-Enceladus (GSE)**





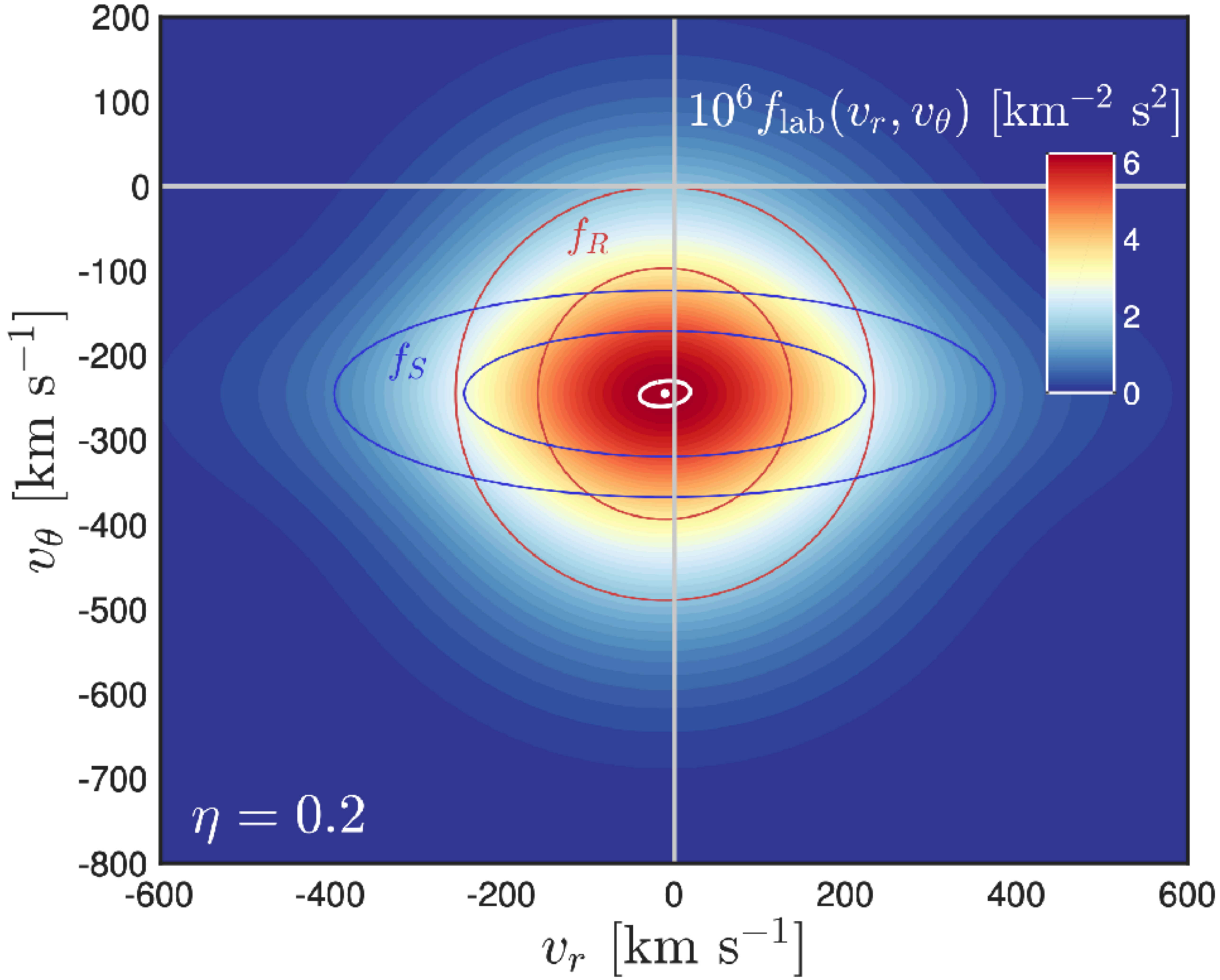
**The GSE Merger:**
Stars+DM brought in on **highly radial orbits** by a merger with a $10^{9\text{-}10}\ M_\odot$ stellar mass galaxy, 8-10 billion years ago

Helmi et al. [1806.06038]

**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,‡]

1810.11468




Simple model for the DM halo velocity distribution composed of a round part ($f_R$), and the radially anisotropic GSE ($f_S$)

With GSE making up ~ 10-20% of DM

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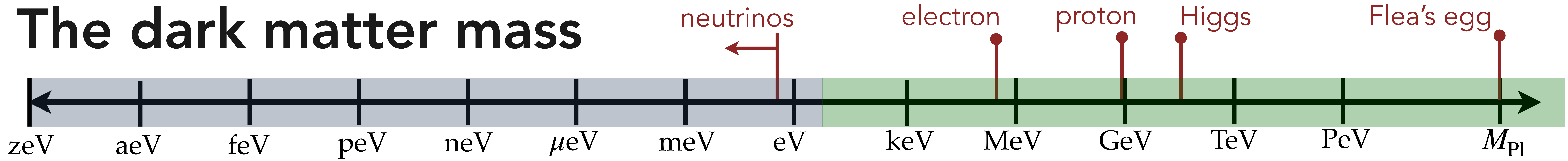
1810.11468

| | | | |
|---|---|---|---|
| **SHM** | Local DM density | $\rho_0$ | $0.3\,\mathrm{GeV\,cm^{-3}}$ |
| | Circular rotation speed | $v_0$ | $220$ km s$^{-1}$ |
| | Escape speed | $v_{\rm esc}$ | $544$ km s$^{-1}$ |
| | Velocity distribution | $f_{\rm R}(\mathbf{v})$ | Eq. (1) |
| **SHM$^{++}$** | Local DM density | $\rho_0$ | $0.55 \pm 0.17$ GeV cm$^{-3}$ |
| | Circular rotation speed | $v_0$ | $233 \pm 3$ km s$^{-1}$ |
| | Escape speed | $v_{\rm esc}$ | $528^{+24}_{-25}$ km s$^{-1}$ |
| | Sausage anisotropy | $\beta$ | $0.9 \pm 0.05$ |
| | Sausage fraction | $\eta$ | $0.2 \pm 0.1$ |
| | Velocity distribution | $f(\mathbf{v})$ | Eq. (3) |

# Direct detection

# The dark matter mass



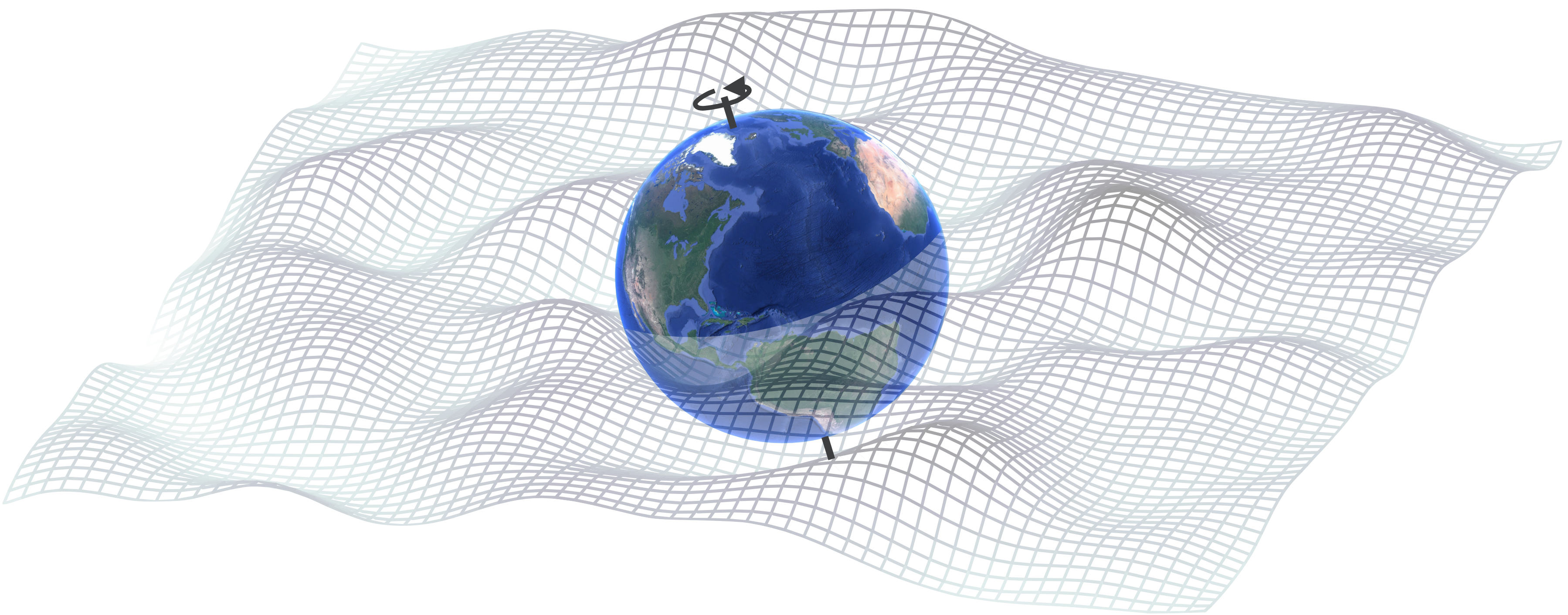

We know the local mass density of DM ( $\rho_{\rm DM} \approx 0.4$ GeV/cc ), but not the *number* density

Number of particles per de Broglie volume: $\mathcal{N} \approx (\rho_{\rm DM}/m) \times \lambda_{\rm dB}^3$

$\mathcal{N} \gg 1 \longleftarrow$ | $\longrightarrow \mathcal{N} \ll 1$

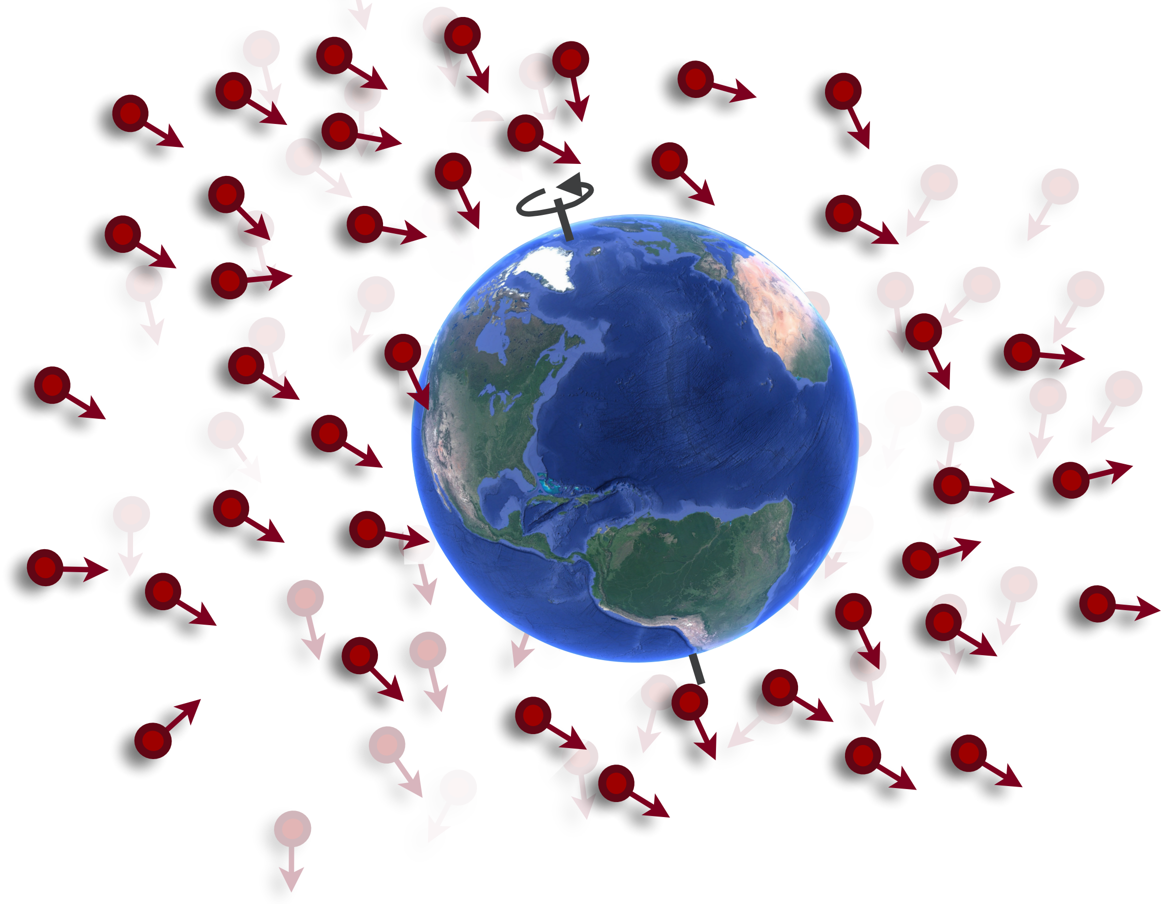
## Wave-like dark matter

(Must be a boson due to Pauli exclusion principle)



## Particle-like dark matter

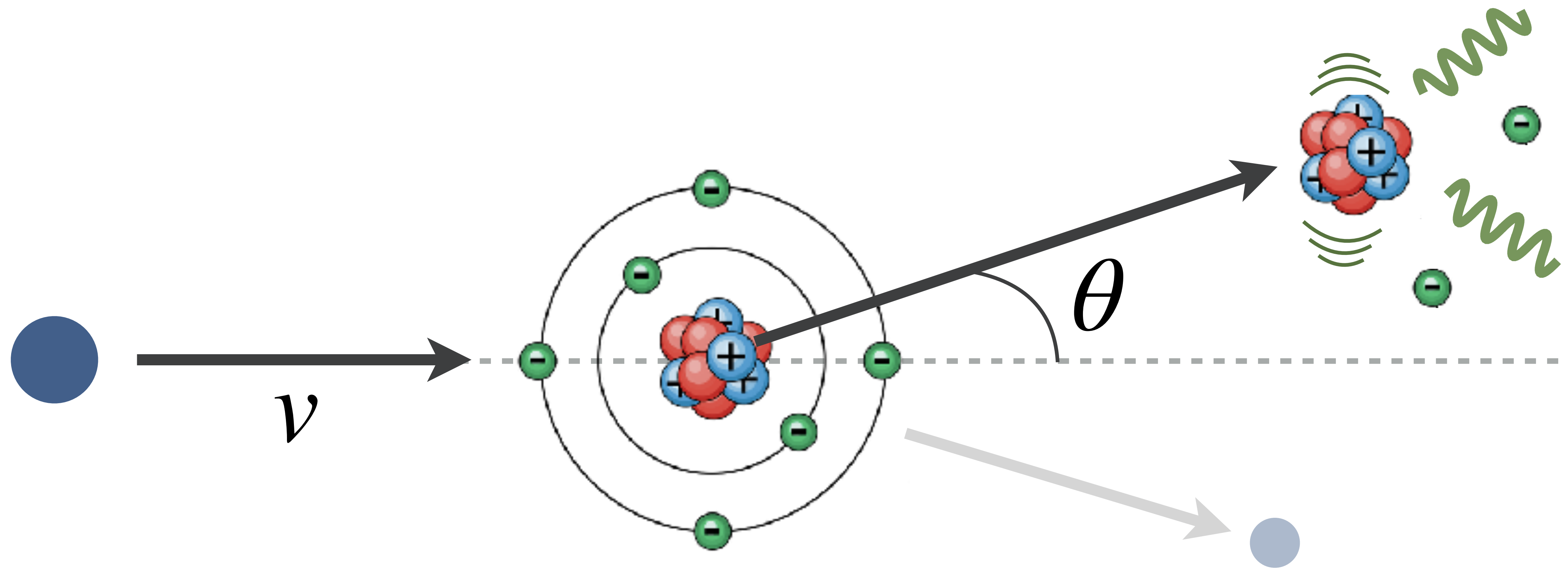
(Can be fermions, bosons or even composite particles like dark nuclei)



# Direct detection of particle-like dark matter

Main signals are non-relativistic scattering events producing **recoils**

→ could be electrons or nuclei

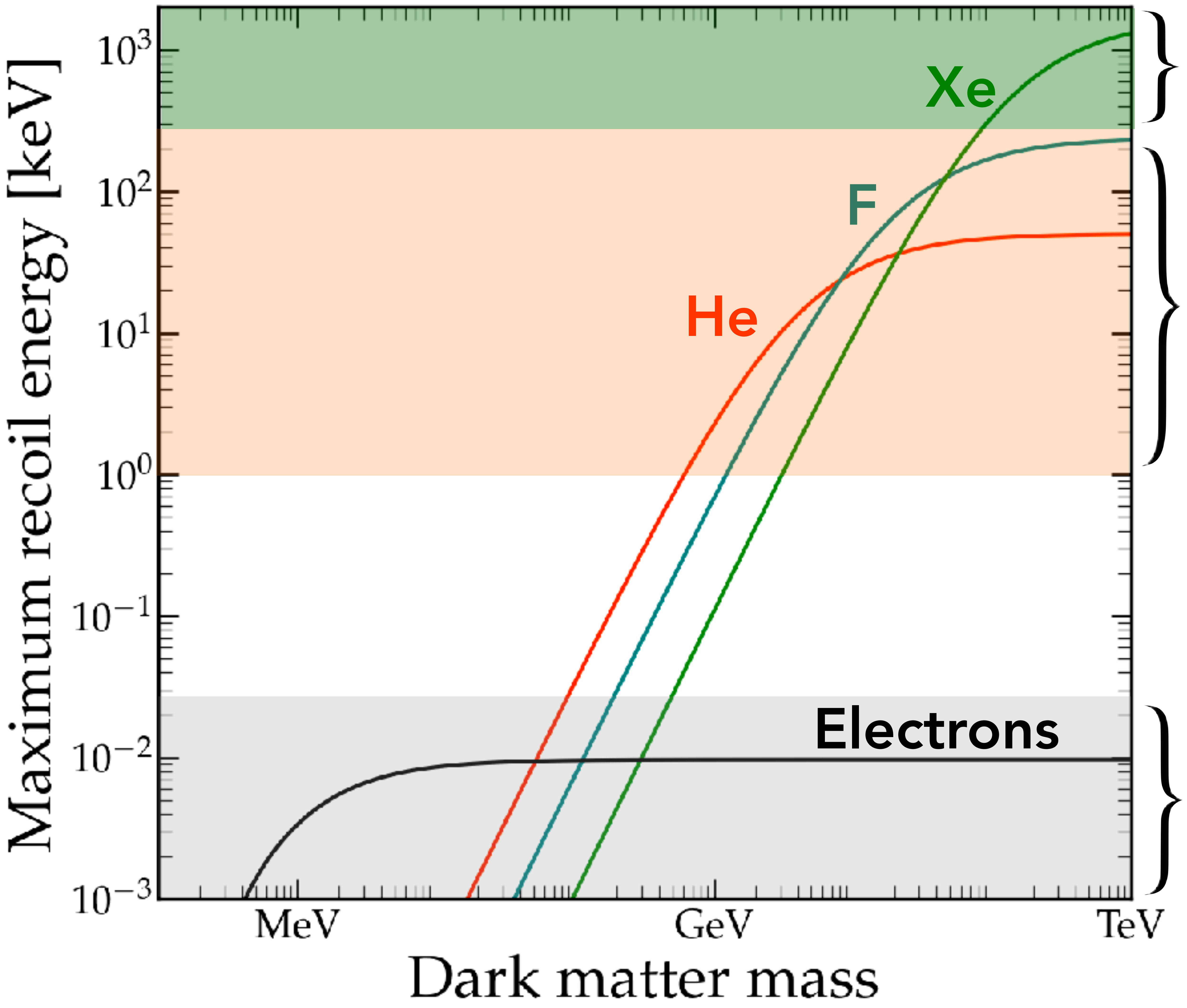



DM-target reduced mass:

$$\mu = \frac{m_T m_\chi}{m_T + m_\chi}$$

$$E_r = \frac{2\mu^2 v^2}{m_T}\cos^2\theta$$

# Recoil energies




$$\lambda_{dB} = \frac{2\pi}{q} = \frac{2\pi}{\sqrt{2m_N E}} < 10^{-14}\,\mathrm{m}$$

Interaction resolves nuclear structure, i.e. cannot assume coherent scattering

**Nuclear recoils**

$E_r$ ~ 1—200 keV

→ TPCs, scintillators etc.

**Electron recoils** (assuming $v_e \approx \alpha$)

$E_r$ ~ 1—10 eV

→ bandgap of semiconductors

**Event rate** for some interaction cross section with nuclei, $\sigma$, given the DM flux, $\Phi$

$$R = N_T \, \Phi \, \sigma = \frac{M}{m_N} \Phi \sigma$$
$$\approx 1 \text{ year}^{-1} \left( \frac{10 \, \text{GeV}}{m_\chi} \right) \left( \frac{M}{1 \text{ ton}} \right) \left( \frac{m_{\text{Xe}}}{m_N} \right) \left( \frac{\sigma}{10^{-43} \text{ cm}^2} \right)$$

Given the fact that the DM flux is a function of velocity $\Phi(\mathbf{v})$ and the cross-section may also depend on velocity, we usually prefer to express this as a *differential* rate as a function of recoil energy $E_r$

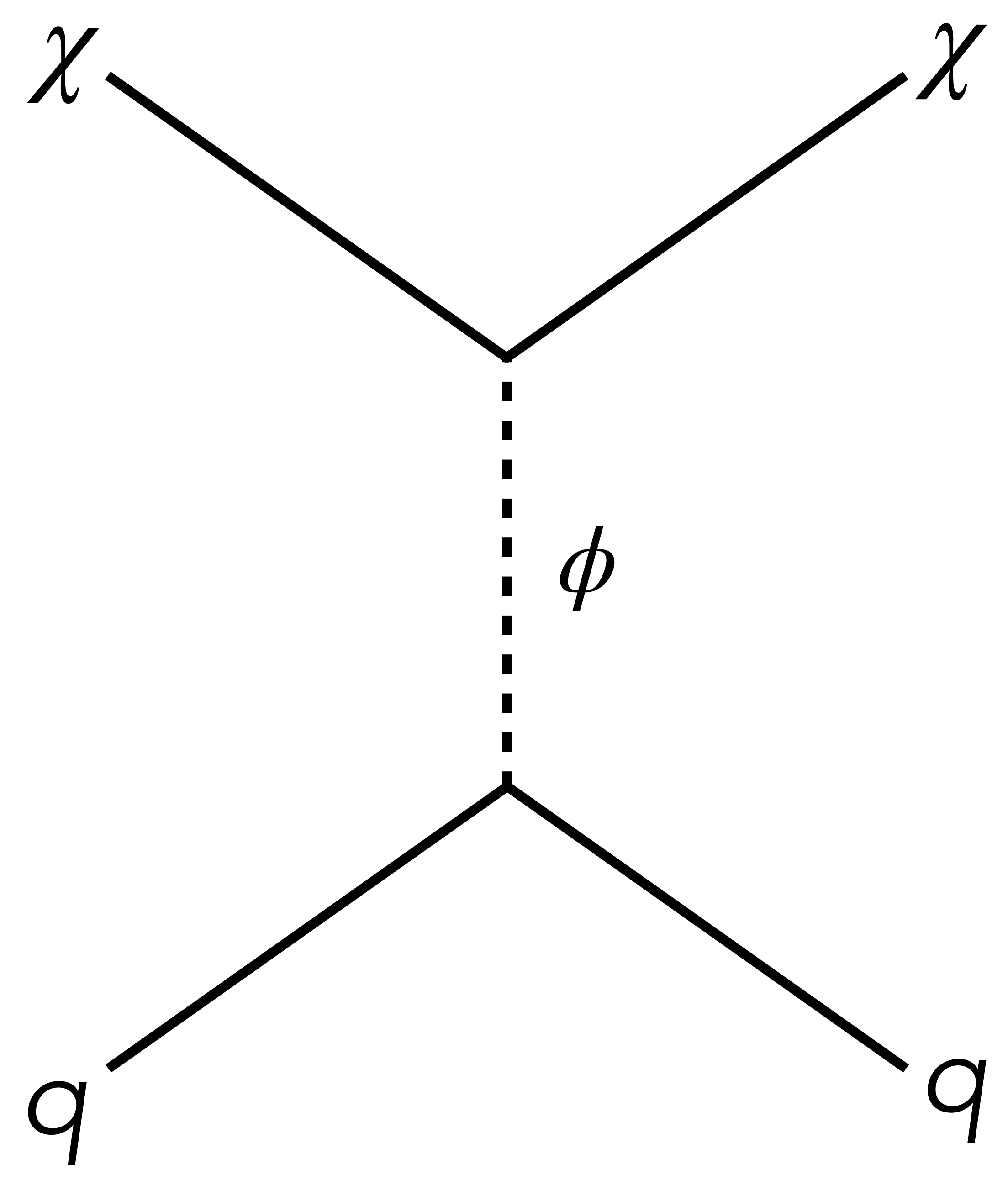
$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{M \rho_{\text{DM}}}{m_N m_\chi} \int_{v > v_{\text{min}}}^{\infty} \Phi(\mathbf{v}) \frac{\mathrm{d}\sigma(v)}{\mathrm{d}E_r} \, \mathrm{d}^3\mathbf{v}$$

**Event rate** for some interaction cross section with nuclei, $\sigma$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{1}{32\pi m_N m_\chi^2 v^2} |\mathcal{M}|^2$$

$$\mathcal{L} \sim g_q \, \bar{\chi}\chi\bar{q}\,q$$

Take the simplest case of the exchange of a scalar




$$\mathcal{M} = \langle \psi'_\chi | \bar{\chi}\chi | \psi_\chi \rangle \left( \langle \psi'_N | \sum_{\text{proton}} g_q \, \bar{q} q + \sum_{\text{neutron}} g_q \, \bar{q} q | \psi_N \rangle \right)$$

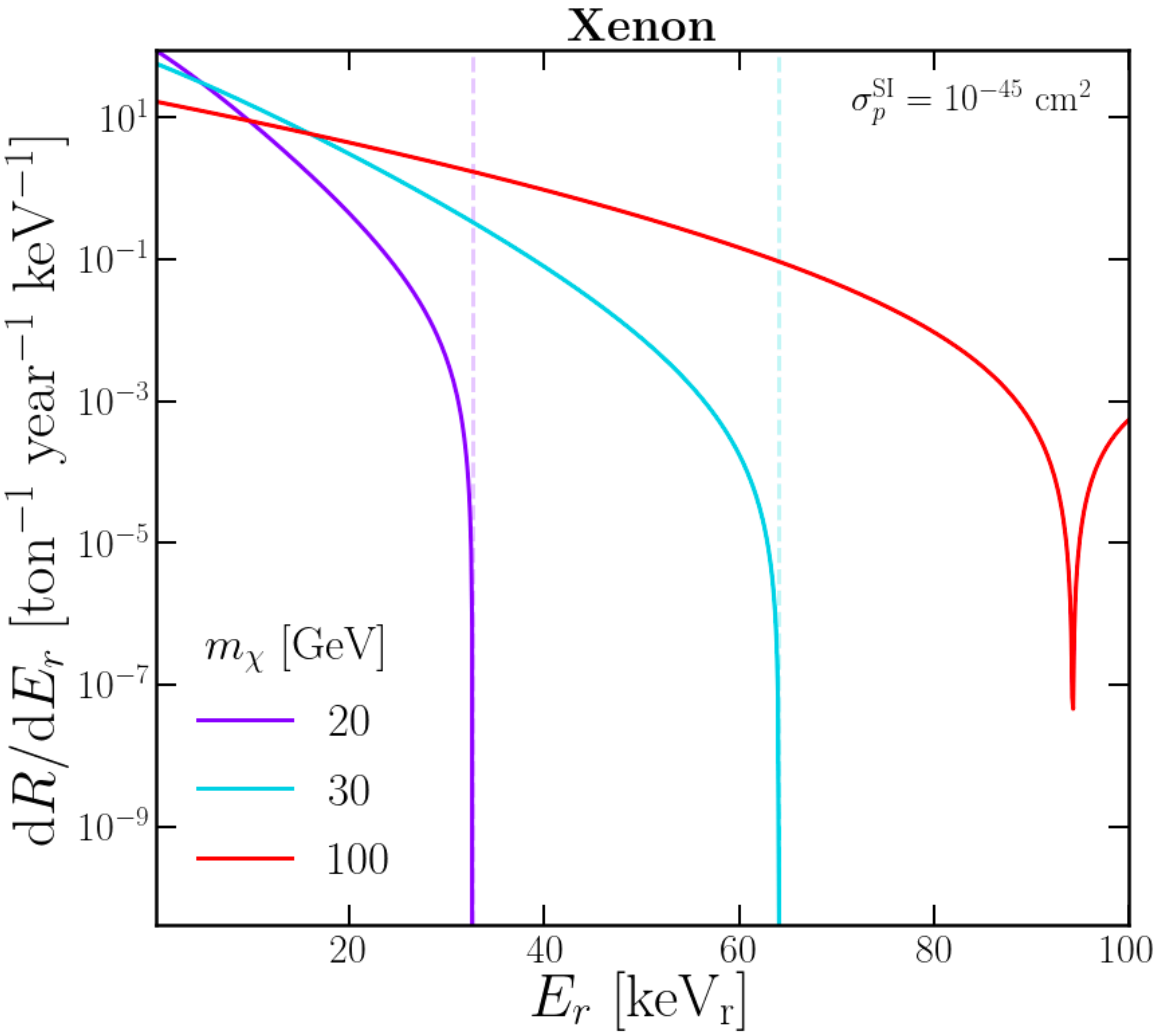
$$= \underbrace{4 m_\chi m_N (f_p N_{\text{protons}} + f_n N_{\text{neutrons}})}_{\text{Coherent scattering limit}} \underbrace{F(E_r)}_{\text{Nuclear structure}}$$

# Nuclear recoils

e.g. assuming spin-independent scattering

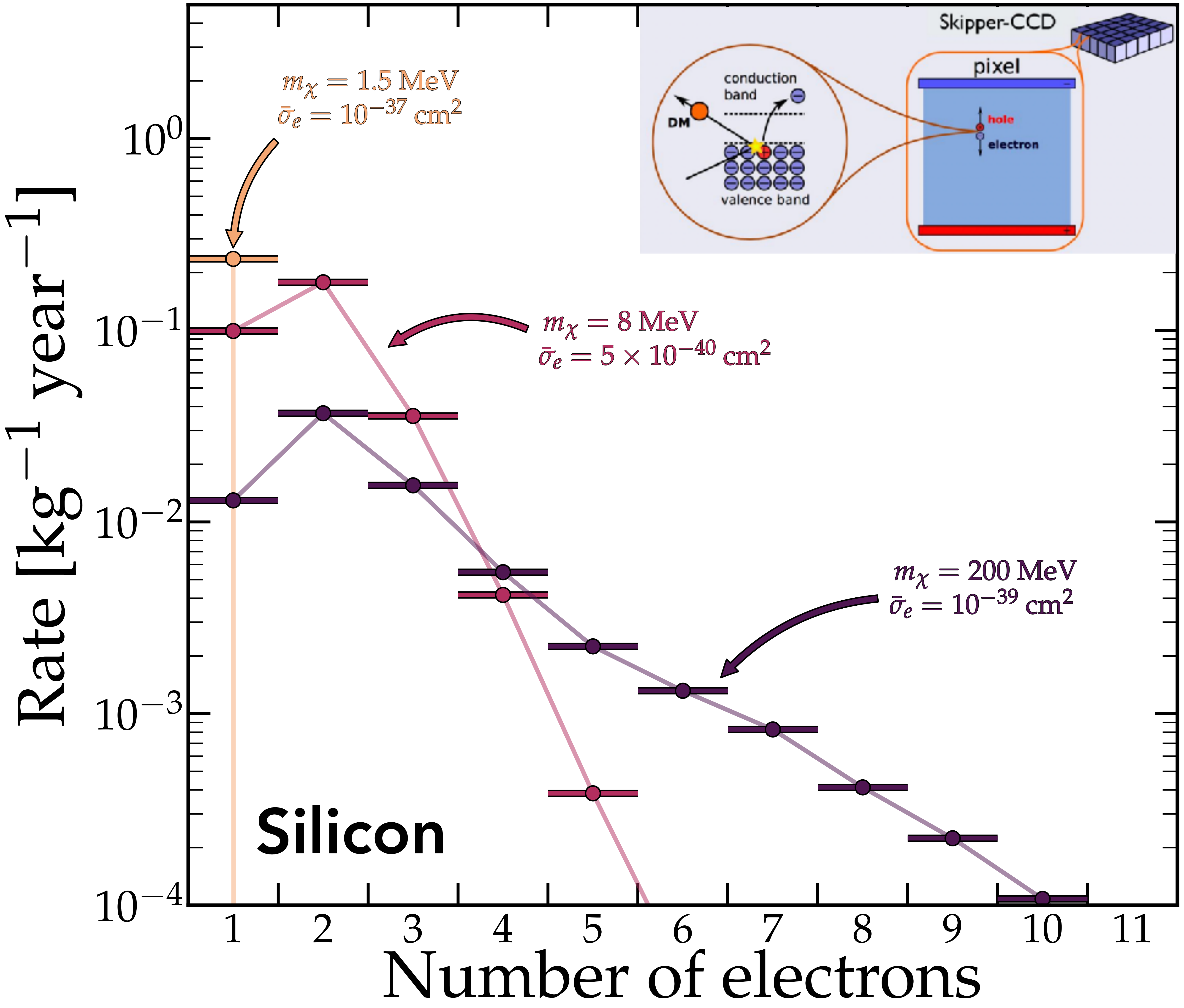
Exponentially falling with sharp cutoff at maximum energy set by escape speed

Interference features appear at high momentum-transfer when nuclear structure is resolved



# Electron recoils

Need to fold in atomic structure




Some reference cross section for a free-electron scattering with momentum transfer $q = \alpha m_e$

Related to $f(v)$

$$\frac{\mathrm{d}R}{\mathrm{d}E_e} = \frac{\bar{\sigma}_e\, \rho_{\rm DM}}{8\mu_e^2 E_e m_N m_\chi} \sum_{\rm orbitals} \int_{q_-}^{q_+} q dq \left| f_{\rm ion}^{i\to f} \right|^2 g(v_{\rm min})$$

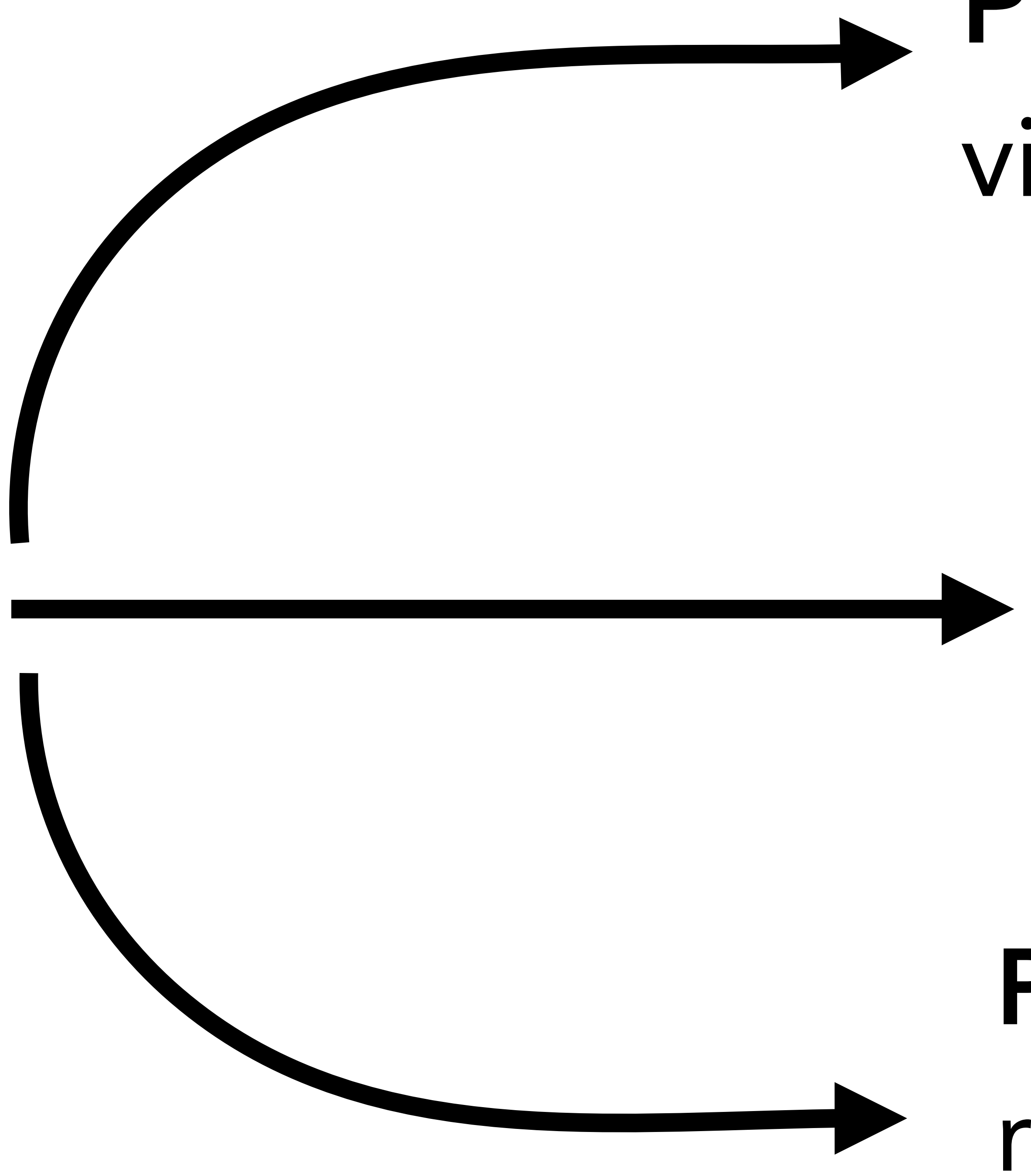
## "Ionisation form factor"

$$\left| f_{\rm ion}^{i\to f} \right|^2 = \left\langle \int \mathrm{d}\Omega_{k_e} \frac{2k_e^3}{8\pi^3} \left| \int \mathrm{d}^3x\, \psi_f^*(\mathbf{x}, \mathbf{k_e}) e^{i\mathbf{q}\cdot\mathbf{x}} \psi_i(\mathbf{x}) \right|^2 \right\rangle$$

Related to transition probability for a bound state $\psi_i$ to go to some unbound state $\psi_f$ after gaining momentum $\mathbf{q}$

# Detection of a recoil energy deposited in a medium

**Recoil energy**



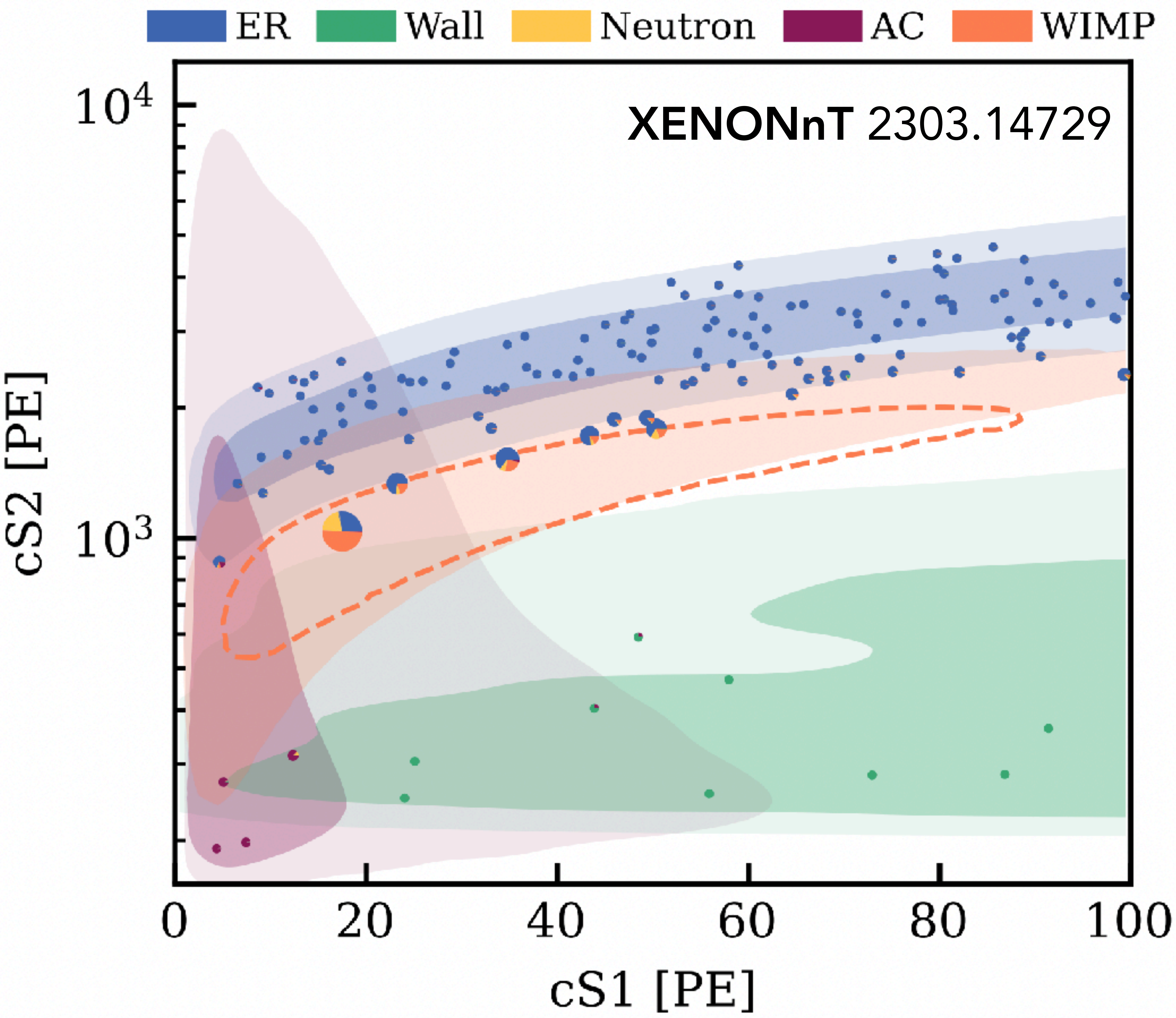
**Phonons:** lattice vibrations, heat

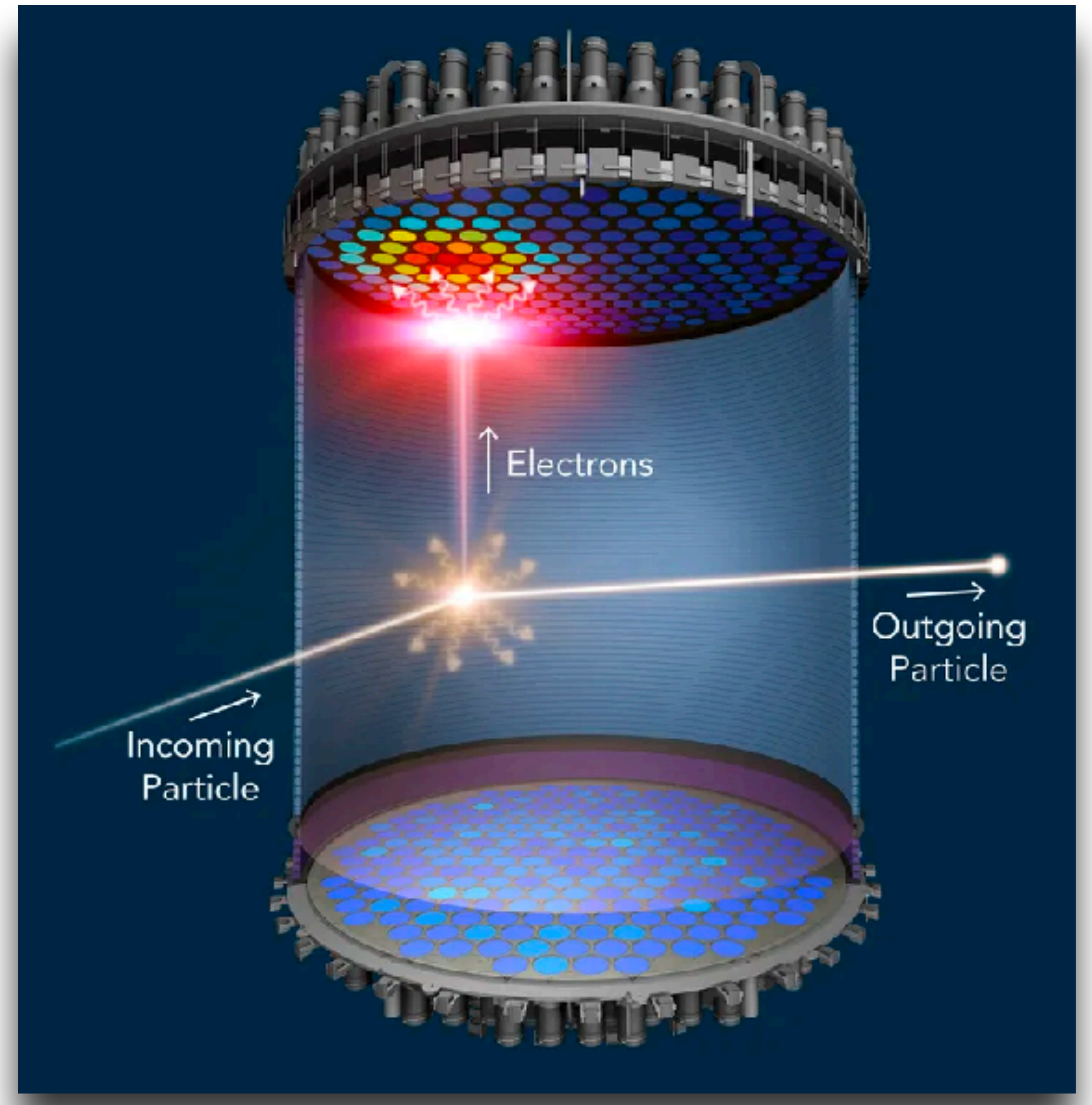
**Ionisation**: electrons, positive/negative ions

**Photons**: scintillation, recombination, de-excitation etc.

Ratios of deposit going into each channel depends on energy and particle type
→ ideal experiment measures each event via multiple channels

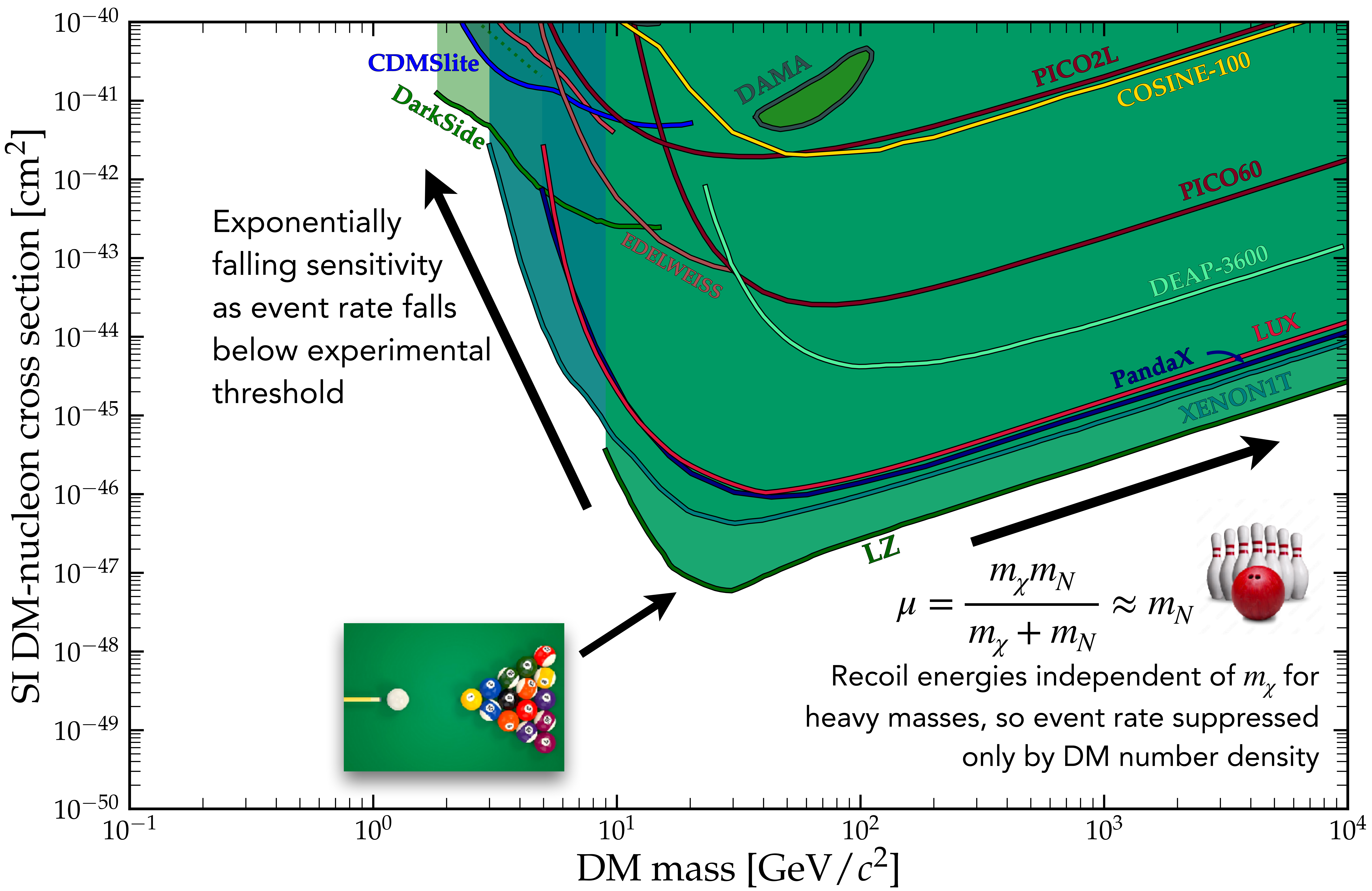
# Example: LXe time-projection chamber



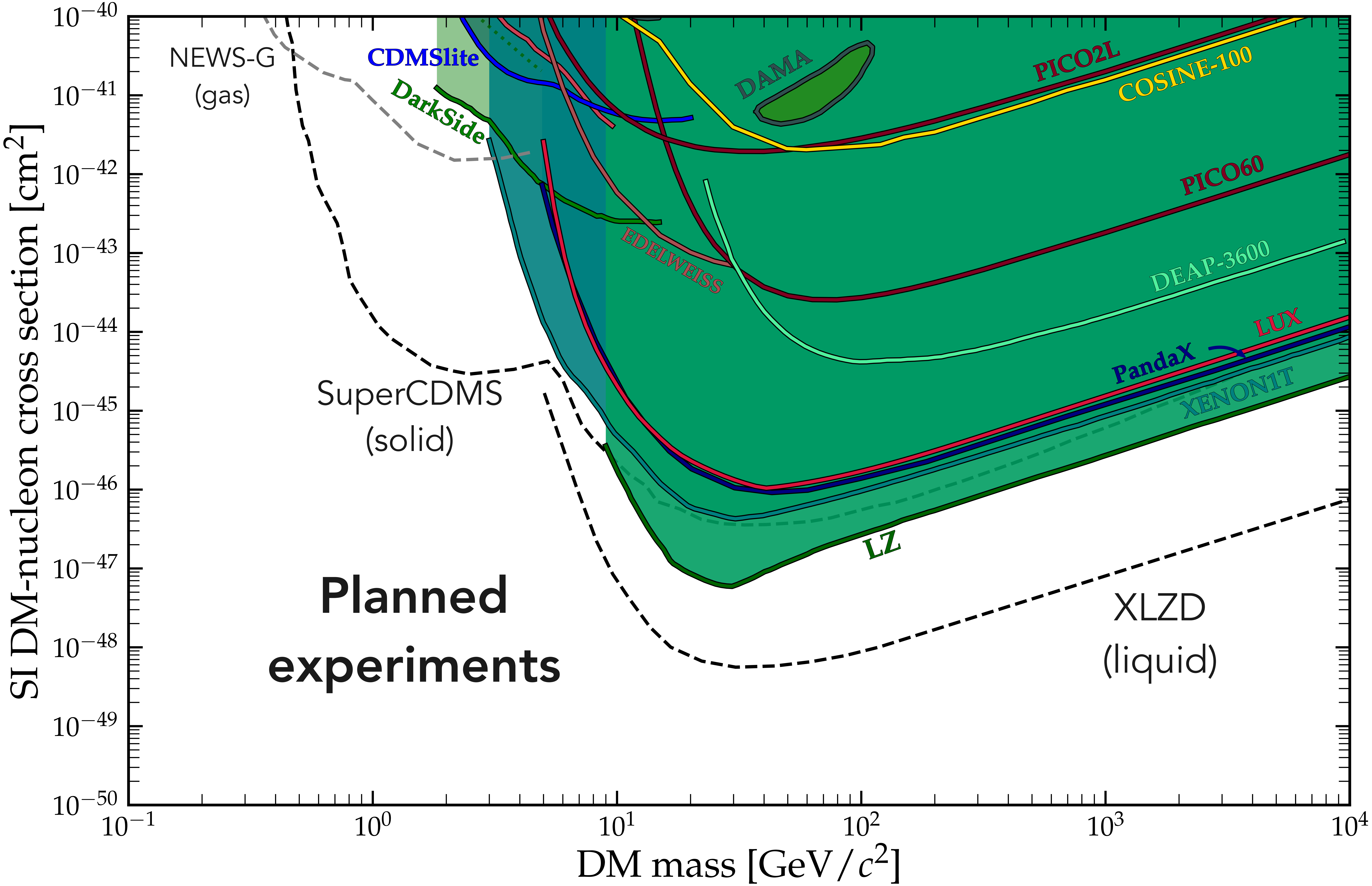




**S1:** prompt scintillation light from recoil event

**S2:** secondary scintillation from drifted ionisation arriving at gas phase



SI DM-nucleon cross section [cm$^2$]
DM mass [GeV/$c^2$]
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
$10^{-49}$
$10^{-50}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
LZ
Exponentially falling sensitivity as event rate falls below experimental threshold
$$\mu = \frac{m_\chi m_N}{m_\chi + m_N} \approx m_N$$
Recoil energies independent of $m_\chi$ for heavy masses, so event rate suppressed only by DM number density


NEWS-G
(gas)
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
LZ
SuperCDMS
(solid)
Planned
experiments
XLZD
(liquid)
SI DM-nucleon cross section [cm$^2$]
DM mass [GeV / $c^2$]
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
$10^{-49}$
$10^{-50}$
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$10^{0}$
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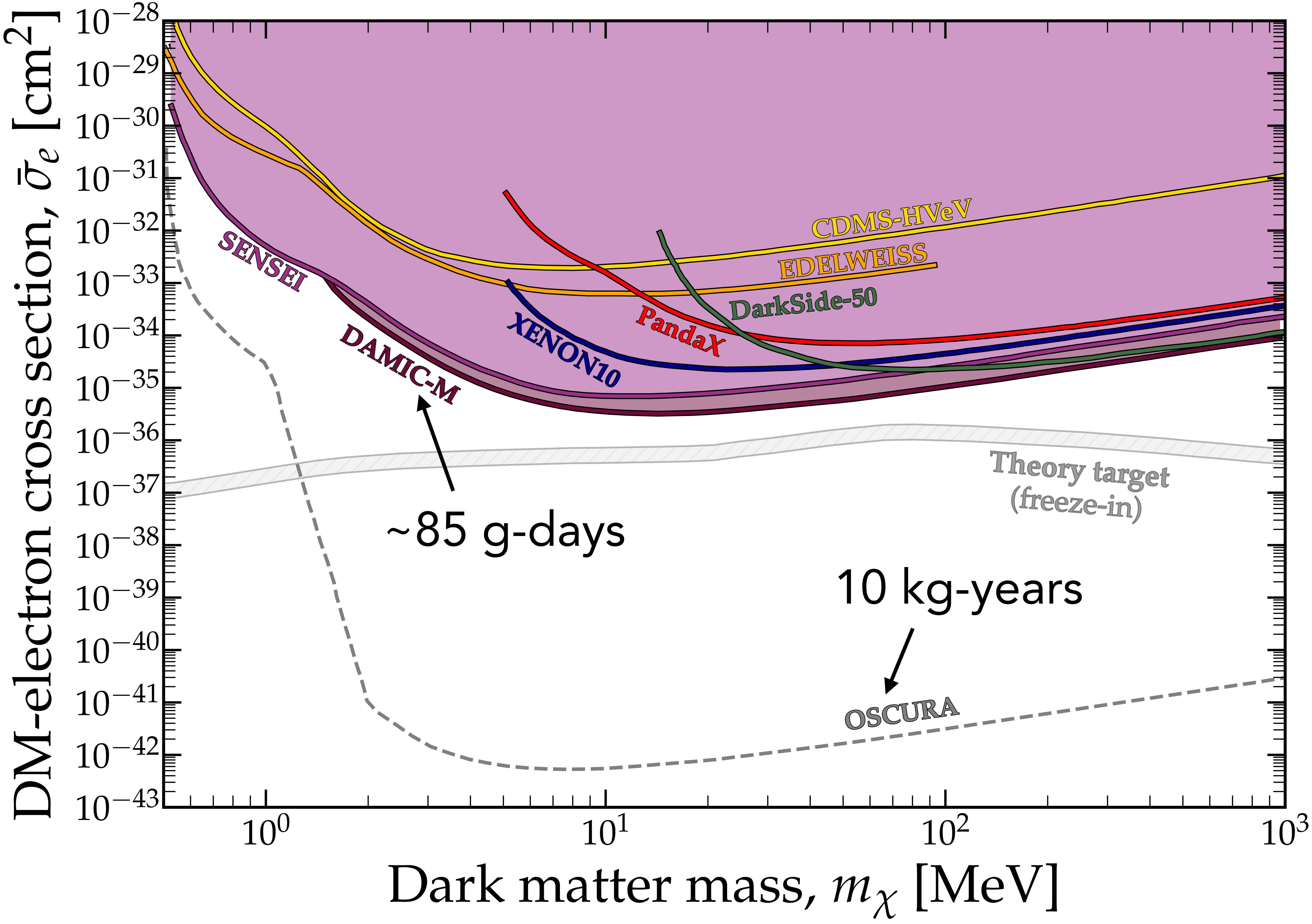
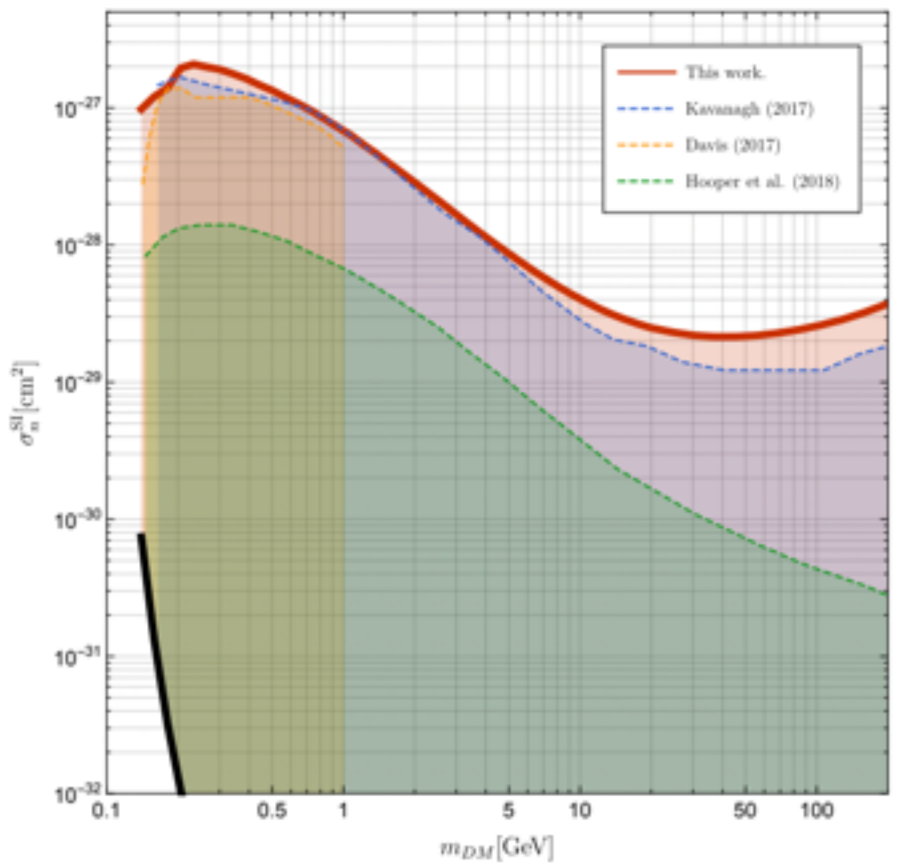
$10^{3}$
$10^{4}$



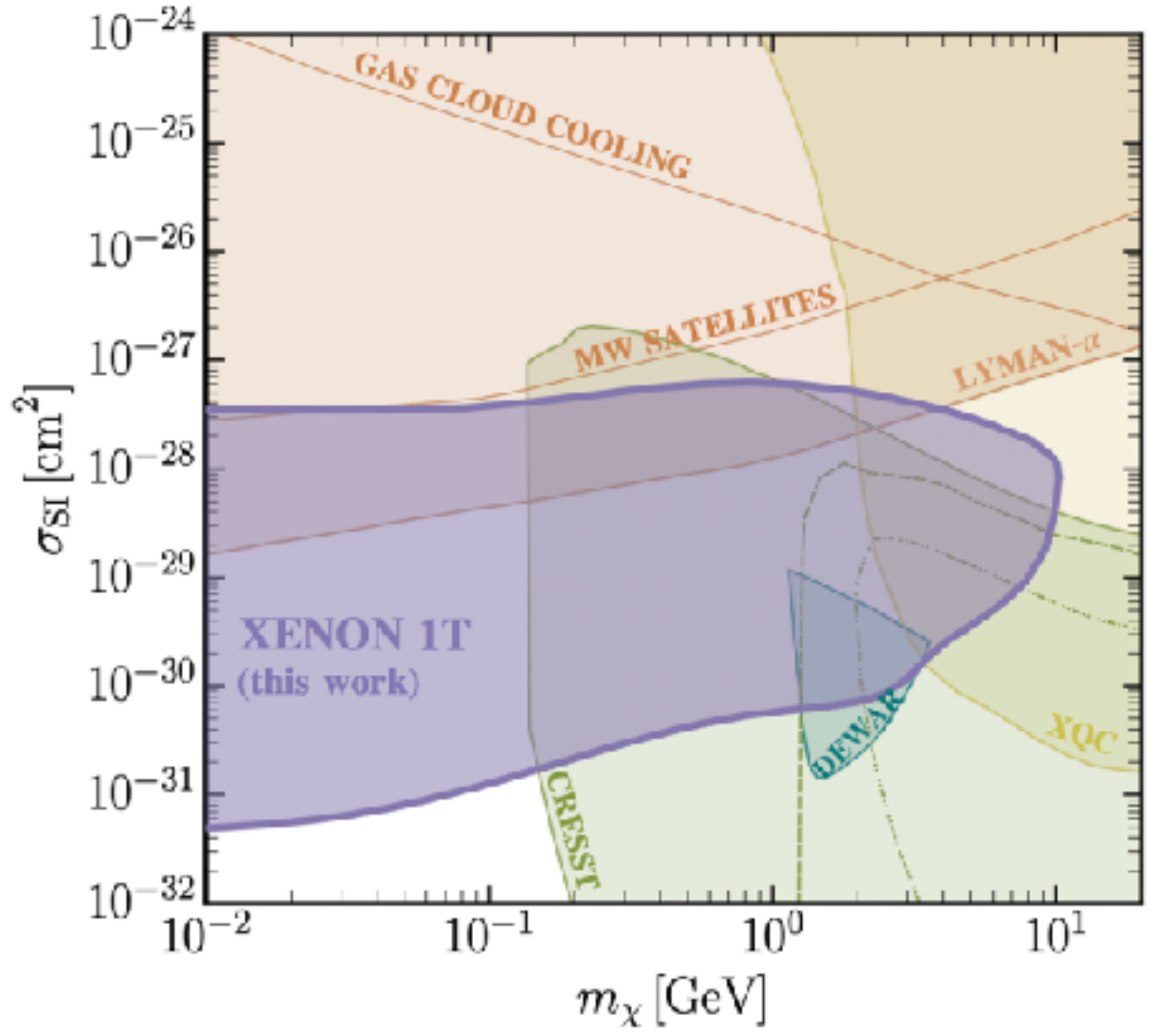
DM-electron cross section, $\bar{\sigma}_e$ [cm$^2$]
$10^{-28}$
$10^{-29}$
$10^{-30}$
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^{-36}$
$10^{-37}$
$10^{-38}$
$10^{-39}$
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
Dark matter mass, $m_\chi$ [MeV]
CDMS-HVeV
EDELWEISS
DarkSide-50
PandaX
XENON10
SENSEI
DAMIC-M
~85 g-days
Theory target
(freeze-in)
10 kg-years
OSCURA

Towards higher cross sections DM blocked by experimental overburden, use shallow/ surface experiments

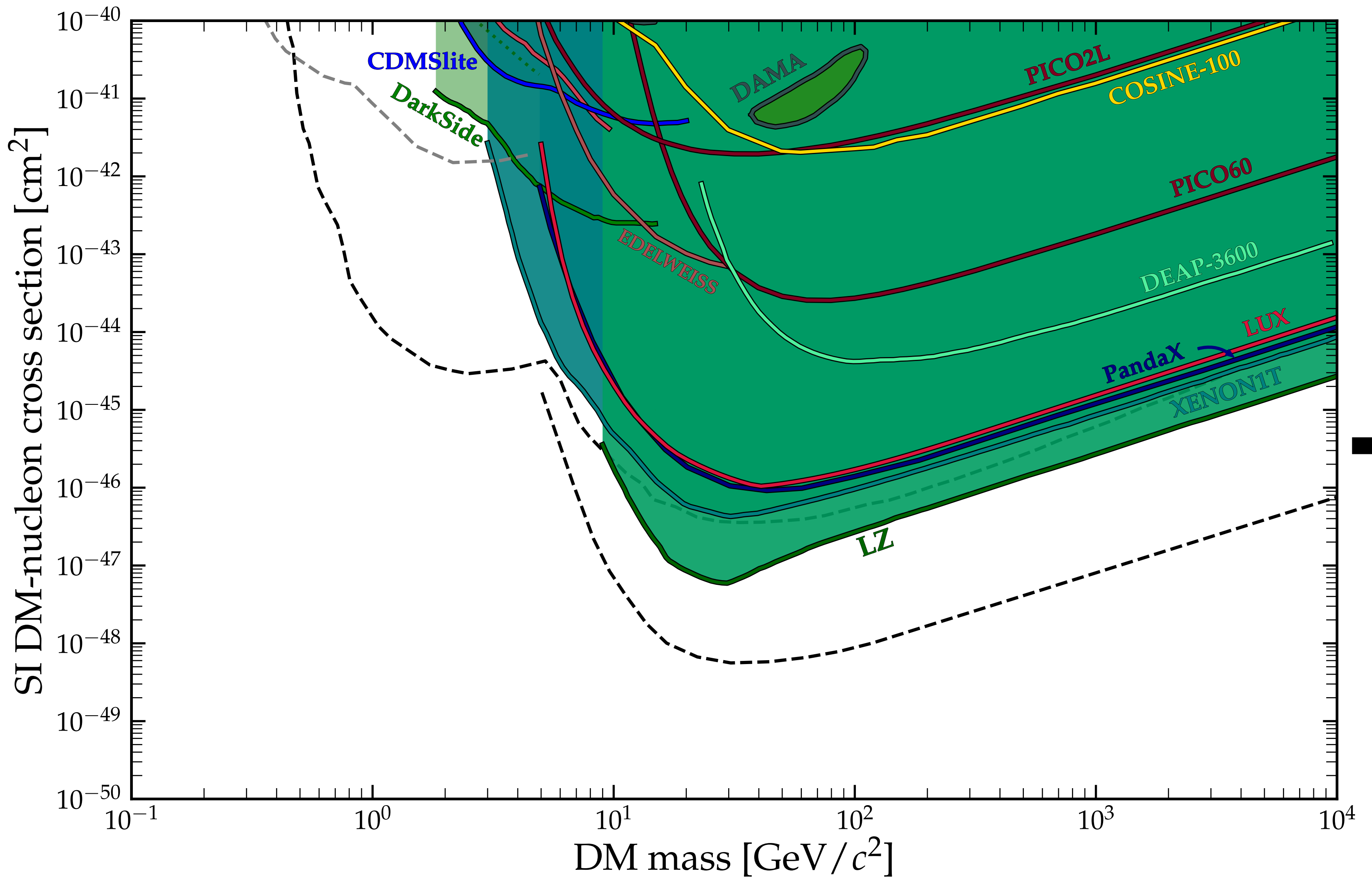



e.g. 1802.04764

DM has too low kinetic energy to see in detectors, Instead detect a boosted sub-population of DM by e.g. cosmic rays, the sun

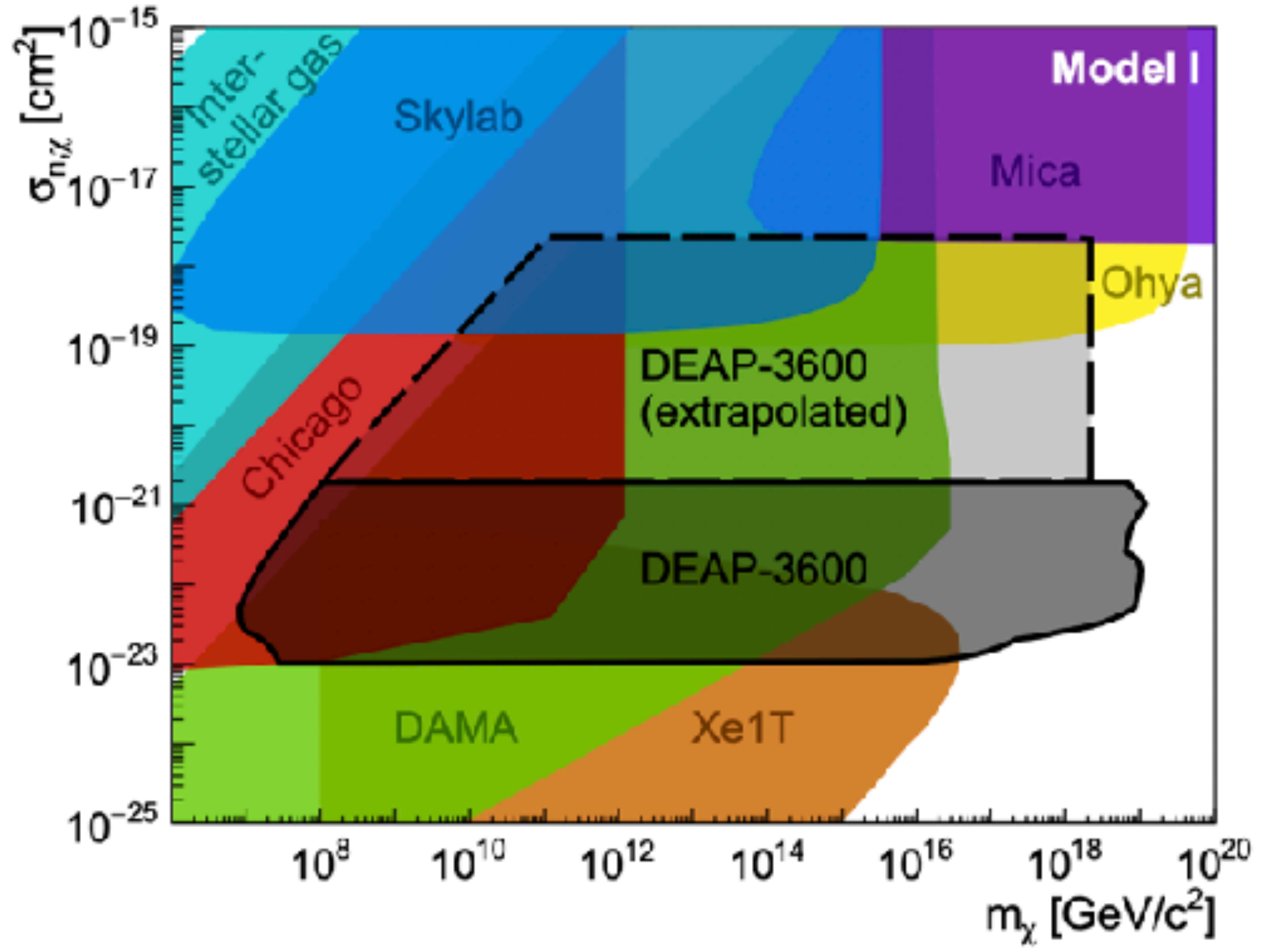



e.g. 2209.03360




DM hidden beneath neutrino backgrounds → the “neutrino fog”

Ultraheavy-DM loses very little momentum in scatters, and can create tracks in detectors if it interacts strongly enough




e.g. 2108.09405

# Non-relativistic effective field theory

- Attempt to capture a fully general set of DM-nucleon operators that satisfy basic non-relativistic requirements & symmetries, e.g. Galilean and rotational invariance, Hermitian

- Expressed in basis of momentum, transverse velocity and DM/nuclear spins:

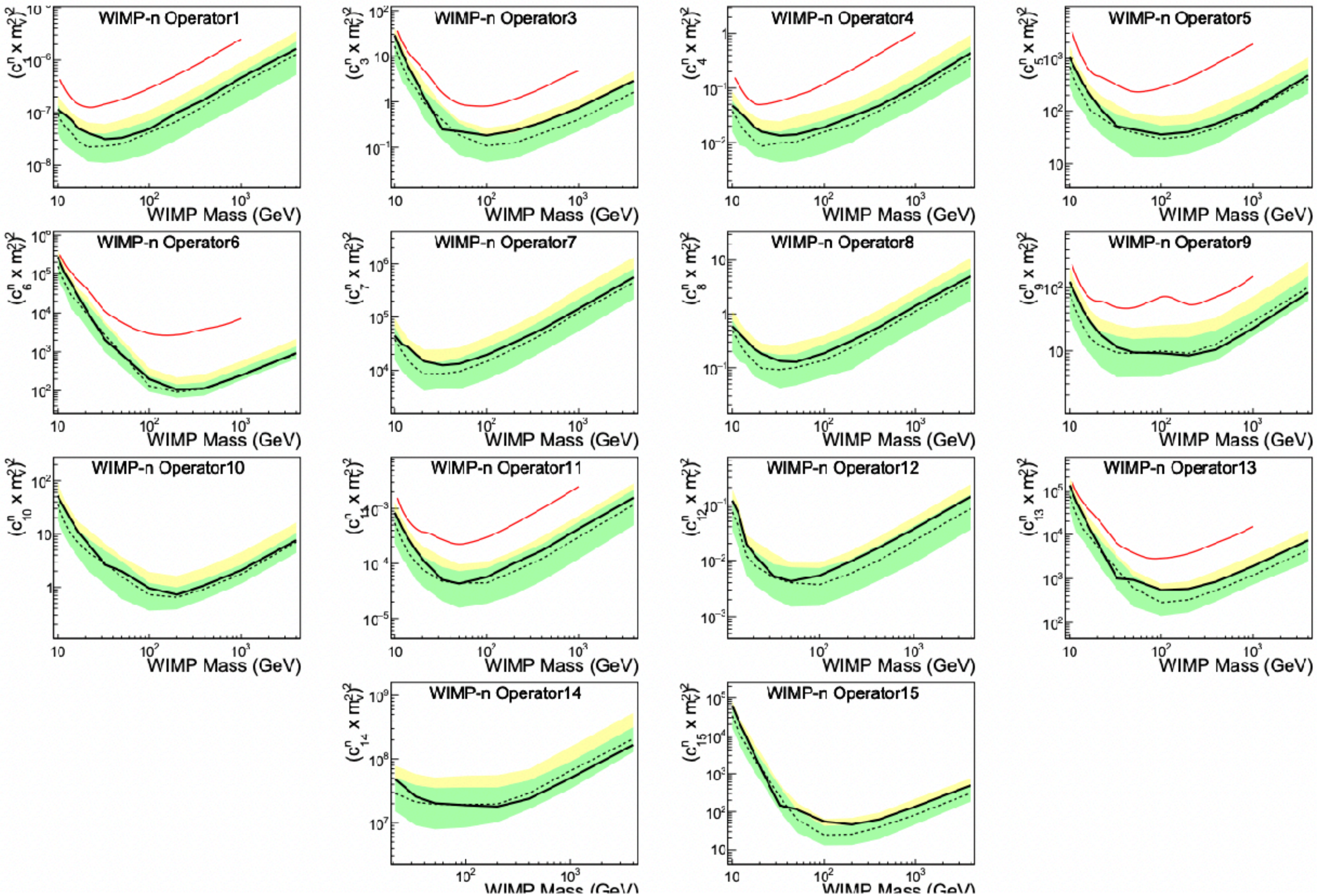
$$i\frac{\vec{q}}{m_N}, \quad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu}, \quad \vec{S}_\chi, \quad \vec{S}_N$$

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^{\perp}\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^{\perp}$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^{\perp}\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^{\perp}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^{\perp}\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^{\perp}\right) \cdot \frac{\vec{q}}{m_N}\right]$$

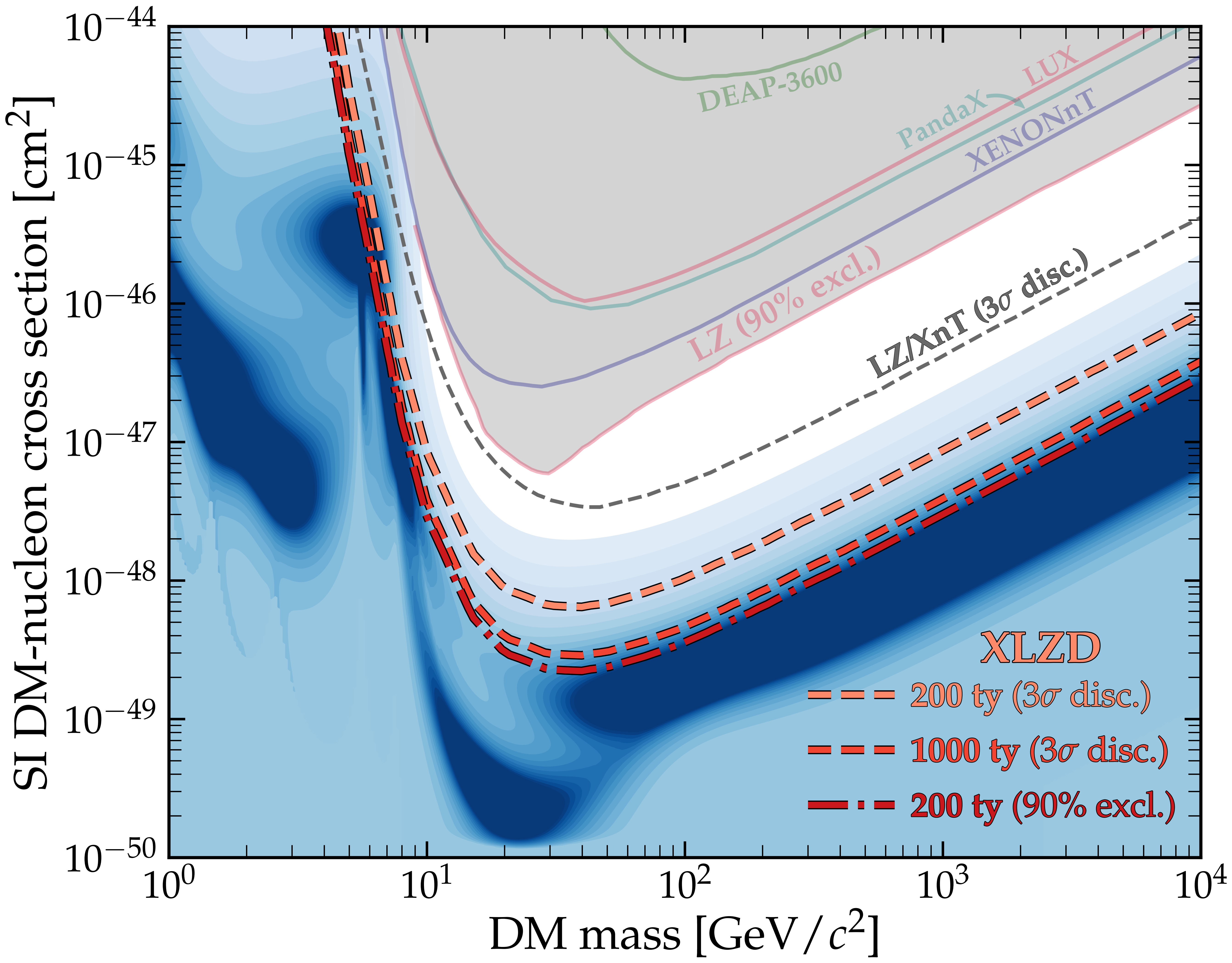
# Non-relativistic effective field theory

- Common to see papers doing scans over all possible coupling constants.

e.g. LUX [2102.06998]



# The Ultimate liquid xenon detector: XLZD



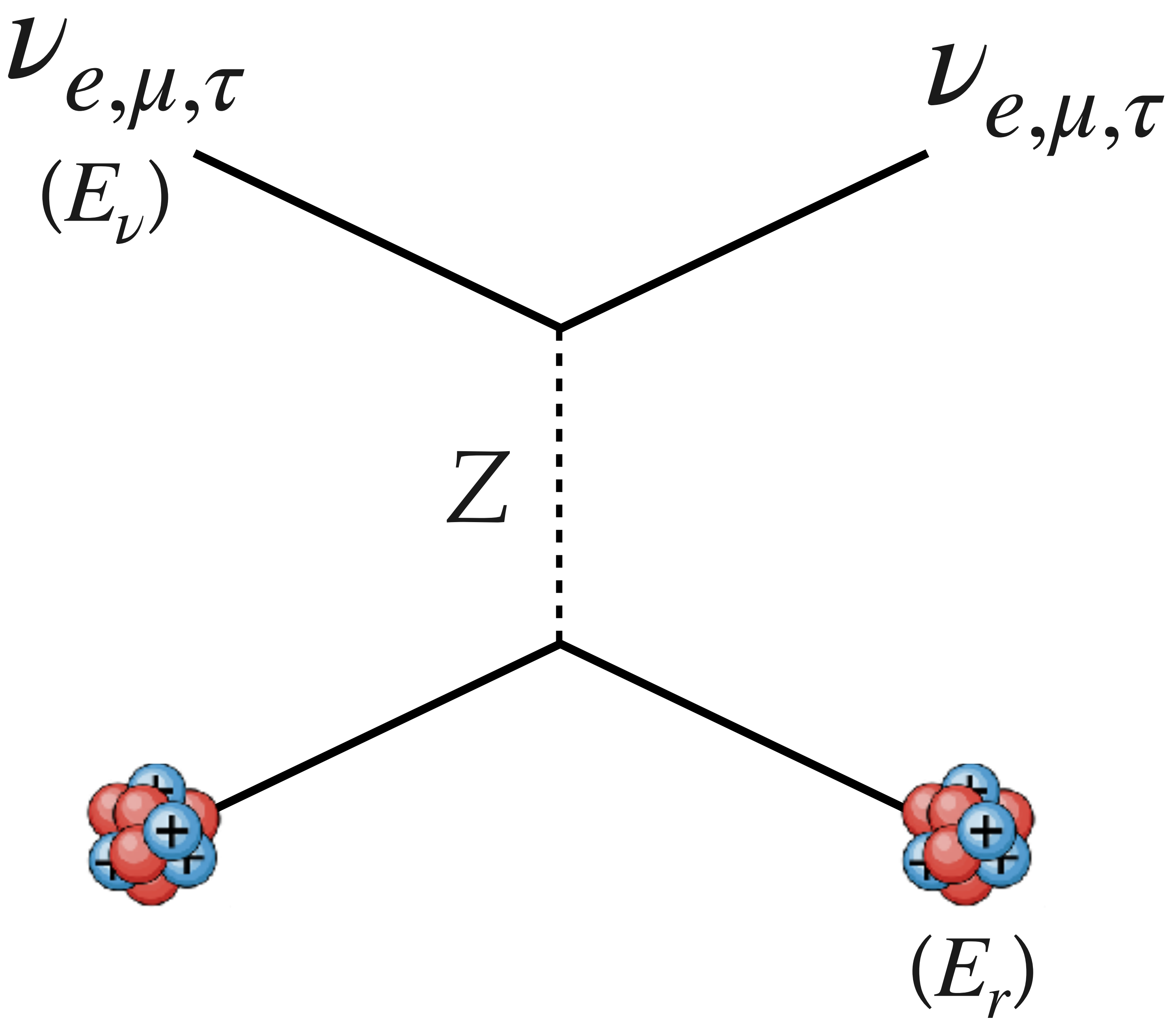

Aims for final exposure approaching ~1000 ton-year scale. In an ideal world, ultimately limited by neutrino backgrounds

Feasibility of such an experiment still under discussions

See Xenon white paper: Aalbers et al. [2203.02309]

# Coherent elastic neutrino-nucleus scattering (CEvNS)

Freedman (1974), detected by COHERENT [2003.10630]



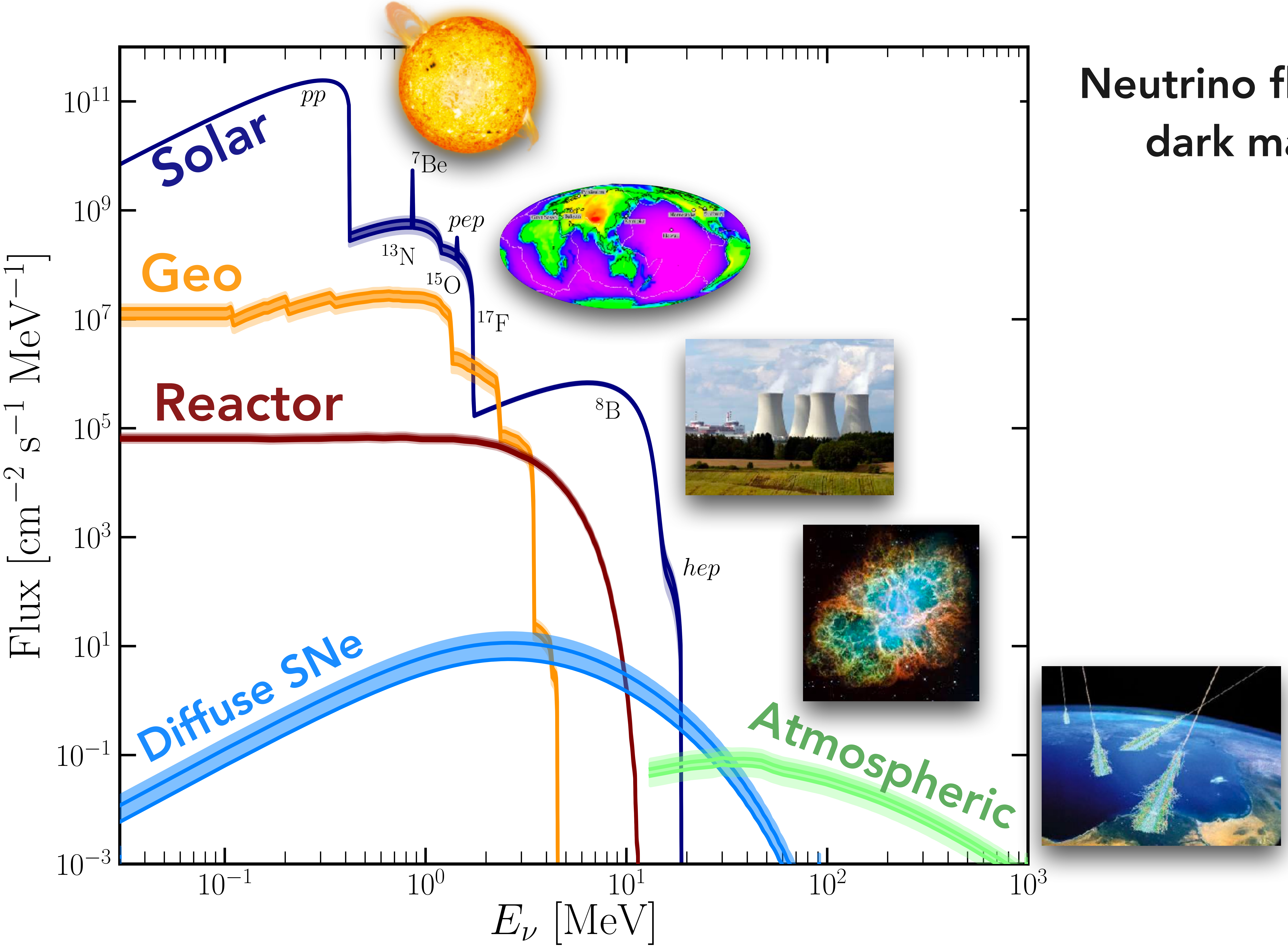

Neutral current
→ flavour blind

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} = \frac{G_F^2}{4\pi} \underbrace{Q_W^2}_{\text{Weak nuclear hypercharge}} m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

$$E_r \approx \mathcal{O}(10\,\mathrm{keV}) \Rightarrow E_\nu \lesssim \sqrt{\frac{m_N E_r}{2}} \approx 10\,\mathrm{MeV}$$

⇒ >10 MeV neutrinos will give a nuclear recoil background in a similar energy range to $m_\chi \gtrsim$ GeV dark matter

# Neutrino fluxes relevant for dark matter searches

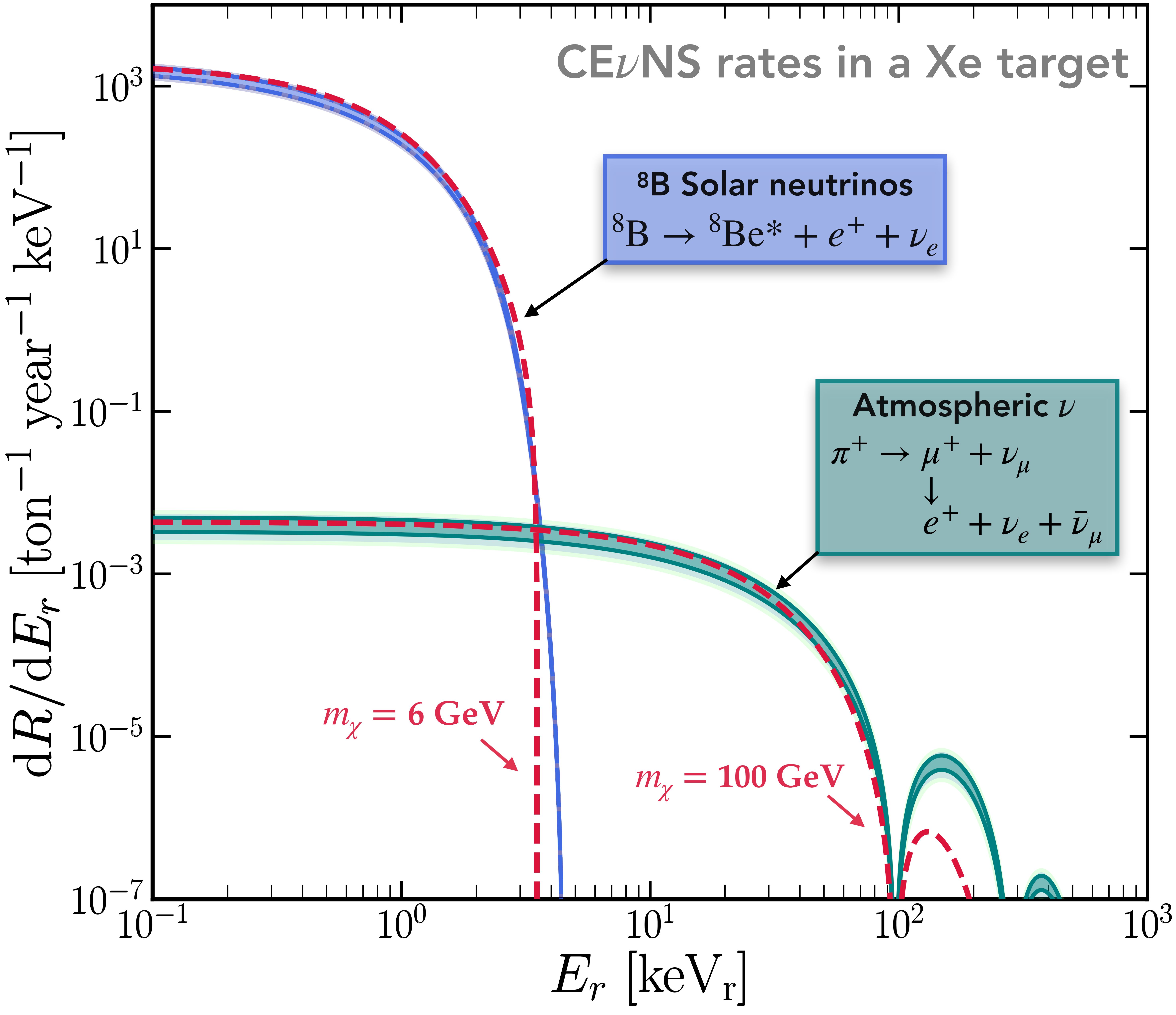


# Two major neutrino backgrounds for DM searches

**High-energy flux:** Atmospheric neutrinos from cosmic-ray-induced pions

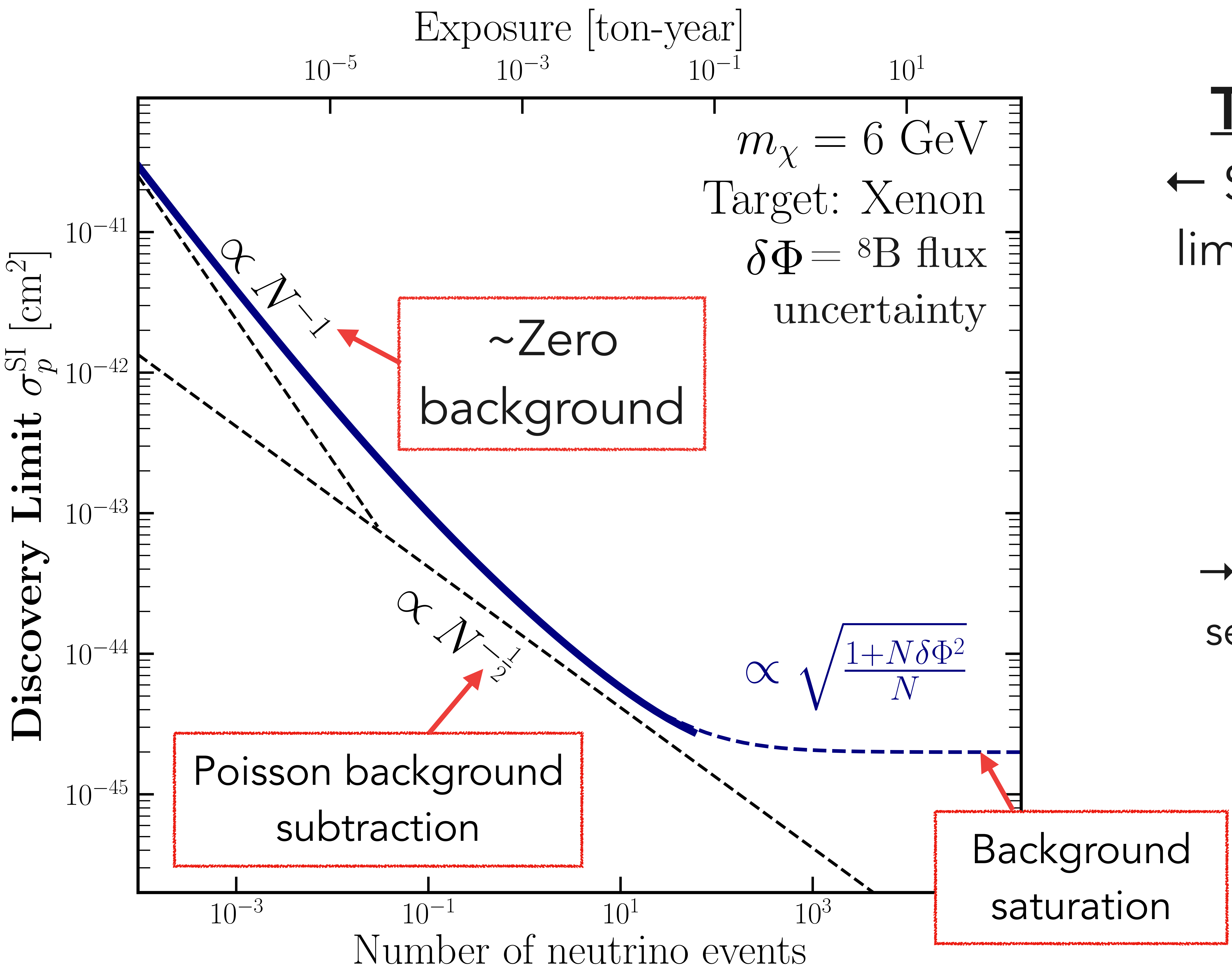
**Low-energy flux:** $^{8}$B and other solar neutrinos

→ CE$\nu$NS event rates & energy spectrum look just like low mass (~GeV) and high mass (~100 GeV) **DM signals** respectively



# The neutrino "floor" as it's usually presented

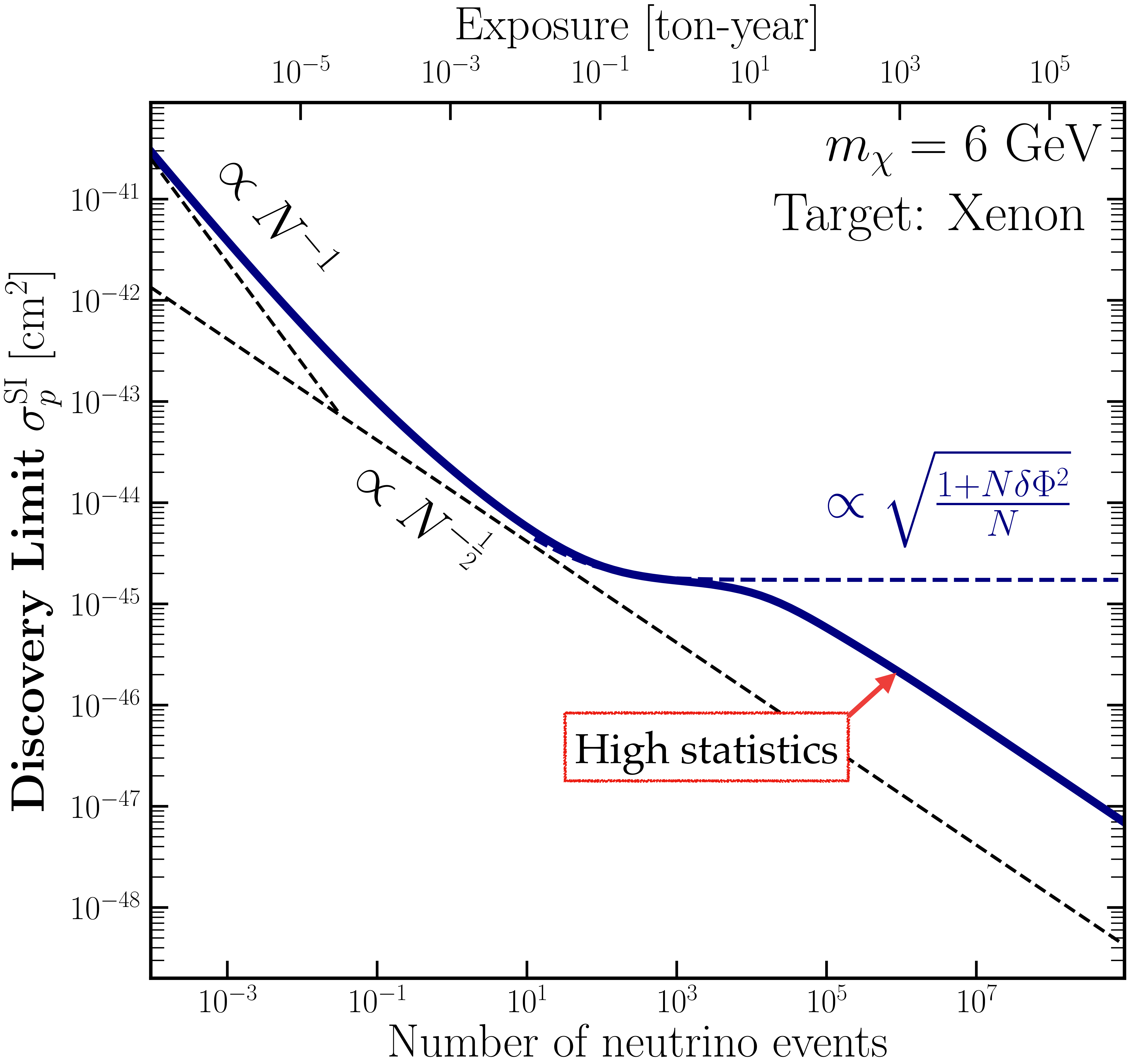
e.g. for LXe TPCs




# The neutrino "floor"

← Scaling of a DM discovery limit for increasing exposure

→ Experiment can't probe cross sections smaller than those that generate an excess in events below the level of expected background fluctuations

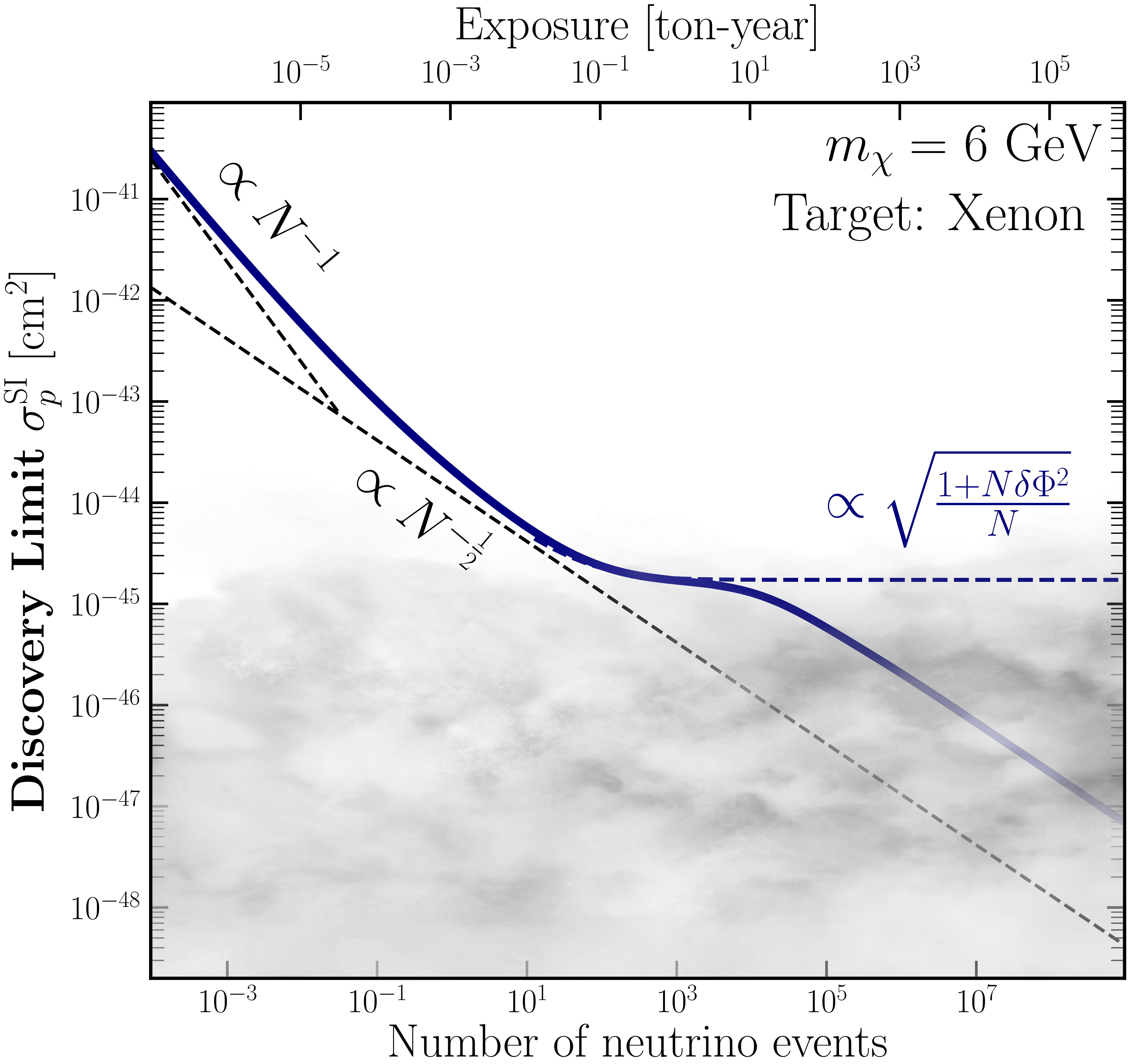



# The full story:

**There is no neutrino "floor"**

DM/CEvNS signals not **identical**
→ with high statistics, an experiment can bootstrap itself through the background uncertainty using spectral information

**→ Required exposures are large, but there can never be a hard sensitivity floor unless the signal and background are *identical***

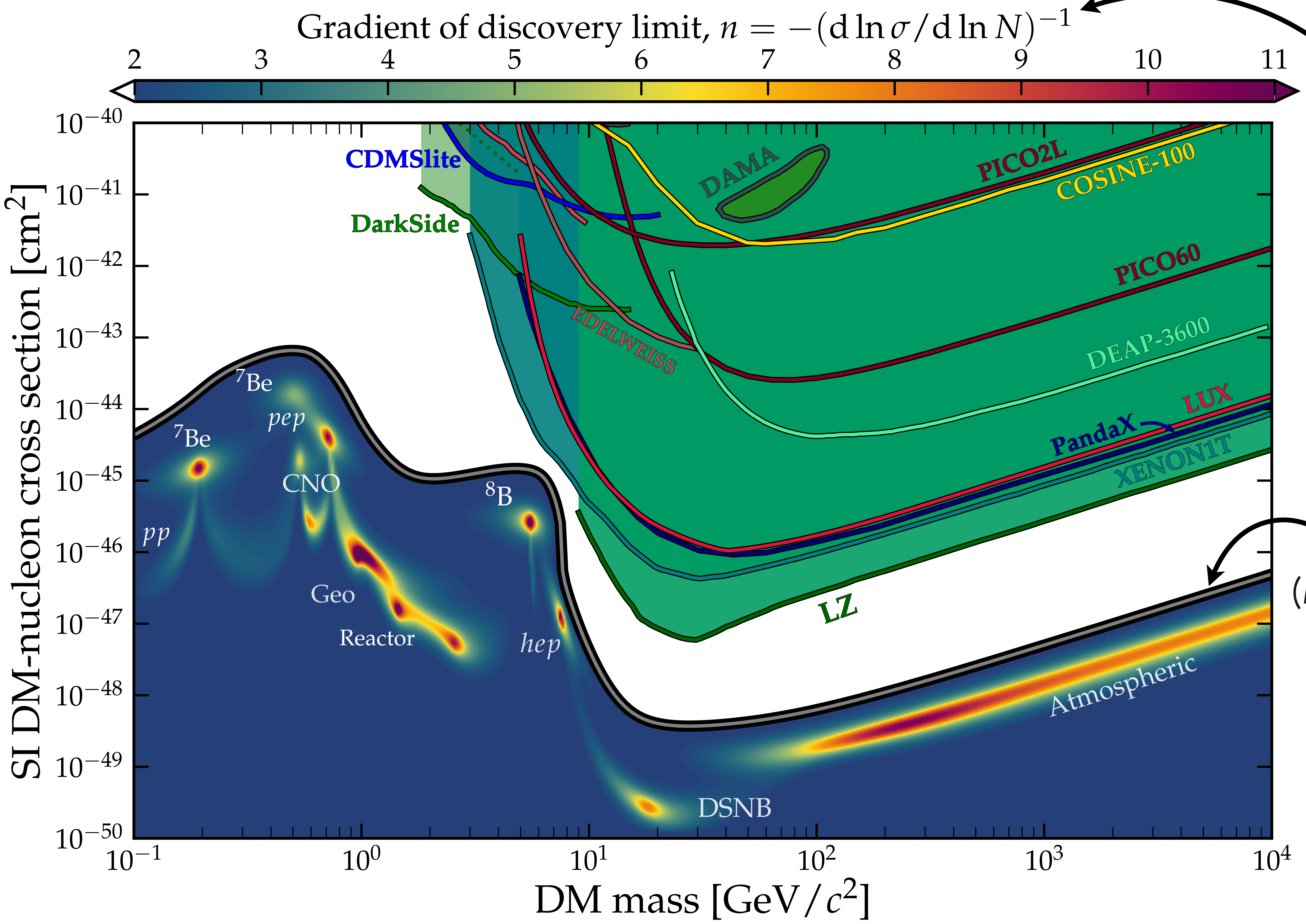



There is no "floor", but we can quantify the neutrino "fog" by looking at the scaling

**Define:**

$$n = -(\mathrm{d}\ln\sigma/\mathrm{d}\ln N)^{-1}$$

So $n = 2$ for Poissonian background subtraction and $n > 2$ for worse than Poissonian

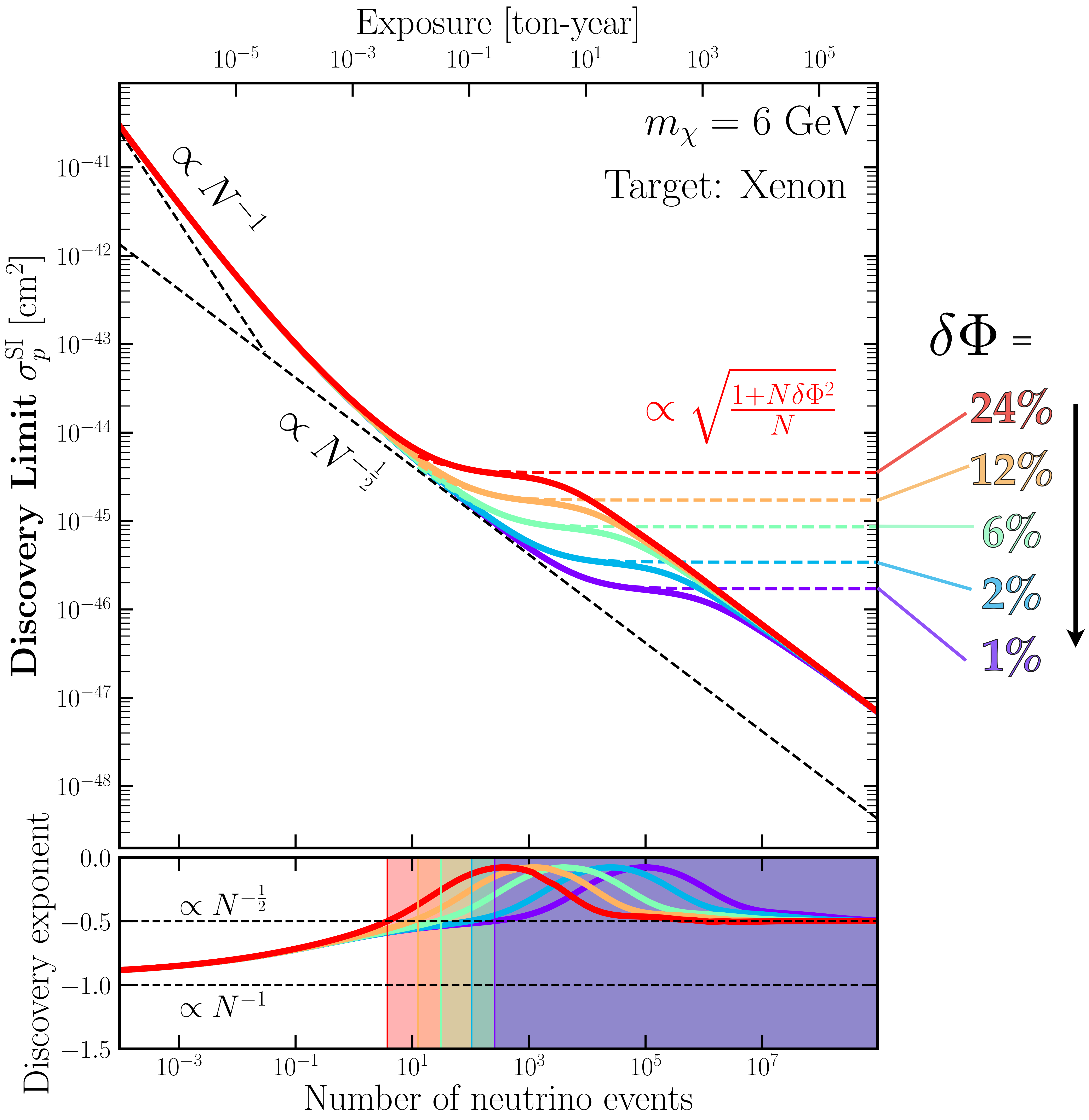



*n* parameterises the "fogginess" of the neutrino fog
→ note that it's not uniformly foggy everywhere

The "edge" of the fog (*n*>2), once you get past it, you can never do better than Poissonian again.

O'Hare
[2109.03116]

# Flux uncertainties



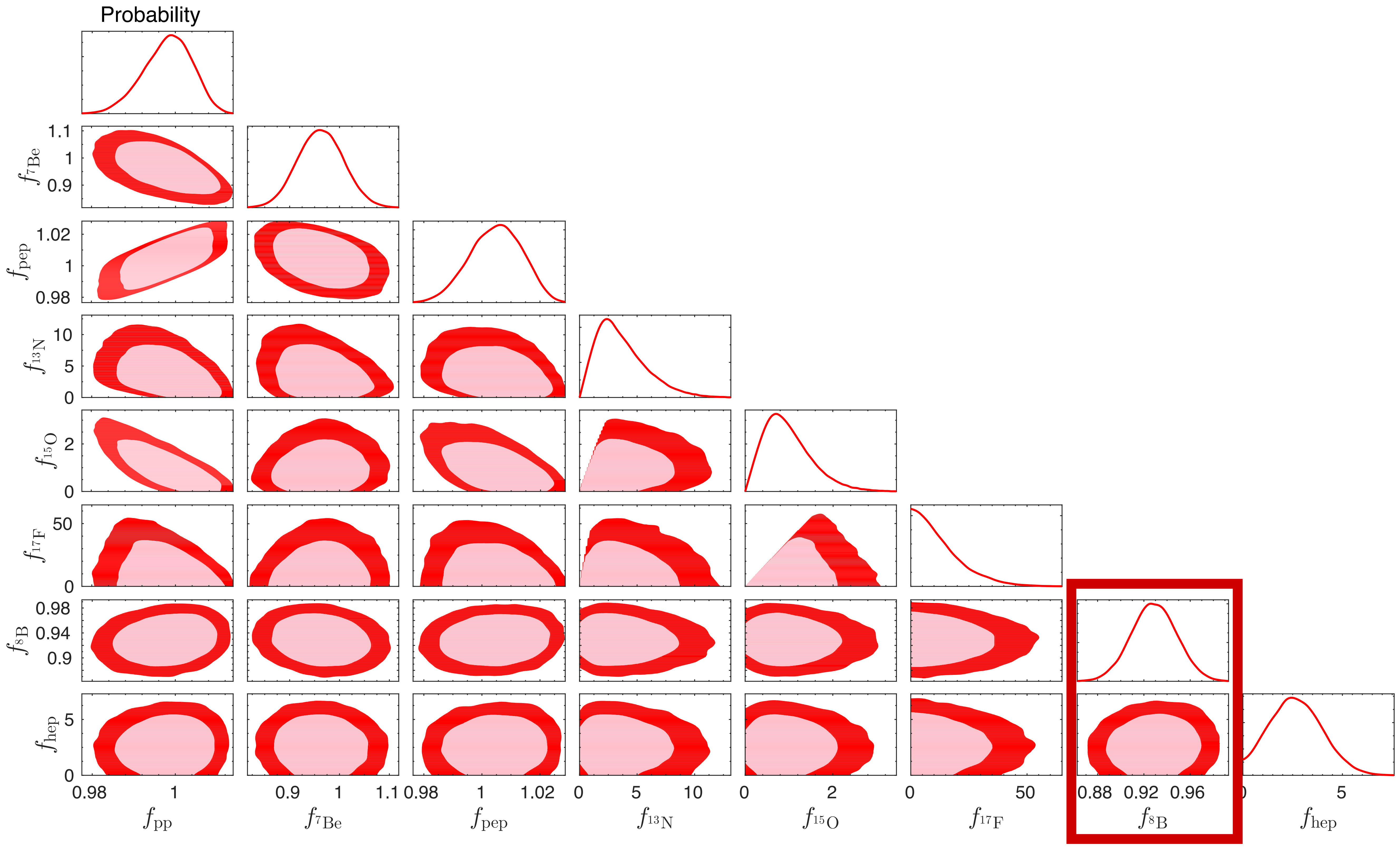

**With a smaller neutrino flux uncertainty, the onset of the neutrino fog is pushed to lower cross sections**

i.e. if you go in with a better prior knowledge of the background, you can tolerate more of it before it starts to impact sensitivity

# Flux uncertainties

| $\nu$ type | | $\Phi(1 \pm \delta\Phi/\Phi)$ $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$ | $\times 10^n$ |
|---|---|---|---|
| Solar | $pp$ | $5.98\,(1 \pm 0.006)$ | $10^{10}$ |
| | $pep$ | $1.44\,(1 \pm 0.01)$ | $10^{8}$ |
| | $hep$ | $7.98\,(1 \pm 0.30)$ | $10^{3}$ |
| | $^{7}\mathrm{Be}$ | $4.93\,(1 \pm 0.06)$ | $10^{8}$ |
| | $^{7}\mathrm{Be}$ | $4.50\,(1 \pm 0.06)$ | $10^{9}$ |
| | $^{8}\mathrm{B}$ | $5.16\,(1 \pm 0.02)$ | $10^{6}$ |
| | $^{13}\mathrm{N}$ | $2.78\,(1 \pm 0.15)$ | $10^{8}$ |
| | $^{15}\mathrm{O}$ | $2.05\,(1 \pm 0.17)$ | $10^{8}$ |
| | $^{17}\mathrm{F}$ | $5.29\,(1 \pm 0.20)$ | $10^{6}$ |
| Geo. | U | $4.34(1 \pm 0.20)$ | $10^{6}$ |
| | Th | $4.23(1 \pm 0.25)$ | $10^{6}$ |
| | K | $2.05(1 \pm 0.17)$ | $10^{7}$ |
| Reactor | | $3.06(1 \pm 0.08)$ | $10^{6}$ |
| DSNB | | $8.57(1 \pm 0.50)$ | $10^{1}$ |
| Atmospheric | | $1.07(1 \pm 0.25)$ | $10^{1}$ |

**$^{8}$B flux** at ~2% (from global fit 1601.00972), so already well-measured. Could improve further with experiments like DUNE, JUNO, Hyper-K



# Flux uncertainties

| $\nu$ **type** | | $\Phi(1 \pm \delta\Phi/\Phi)$ $[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$ | $\times 10^n$ |
|---|---|---|---|
| **Solar** | *pp* | $5.98\,(1 \pm 0.006)$ | $10^{10}$ |
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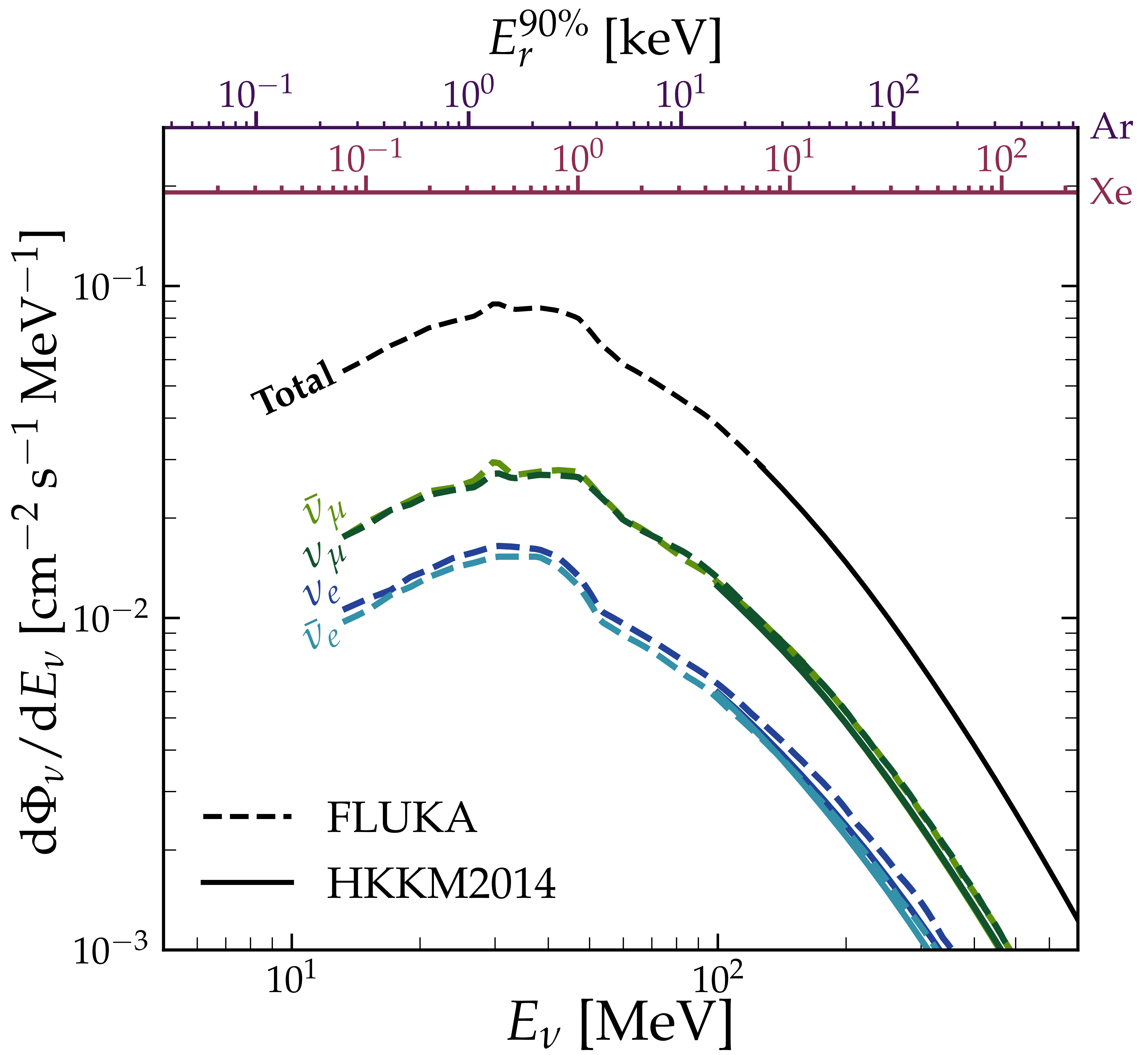
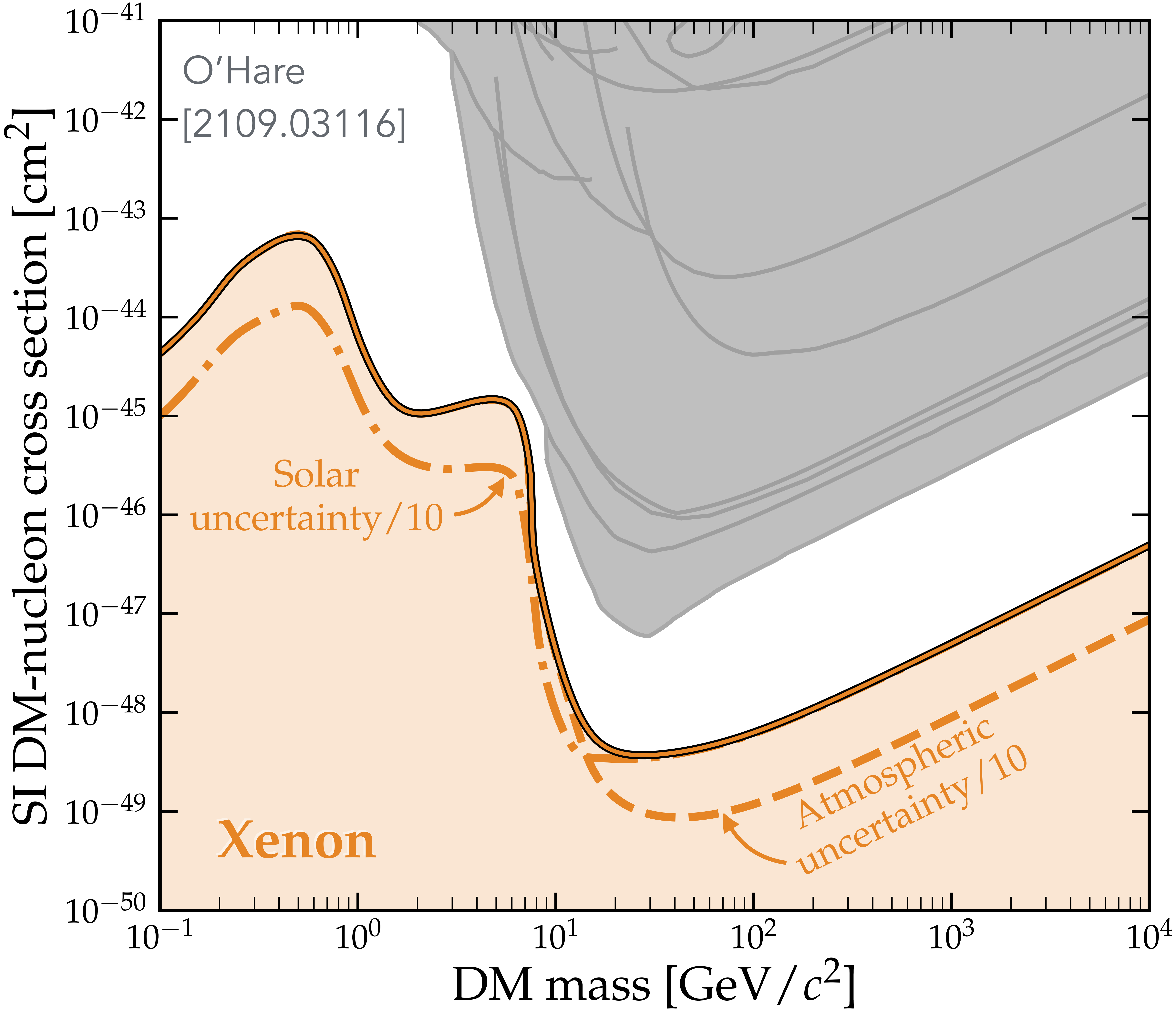
| **DSNB** | | $8.57(1 \pm 0.50)$ | $10^{1}$ |
| **Atmospheric** | | $1.07(1 \pm 0.25)$ | $10^{1}$ |

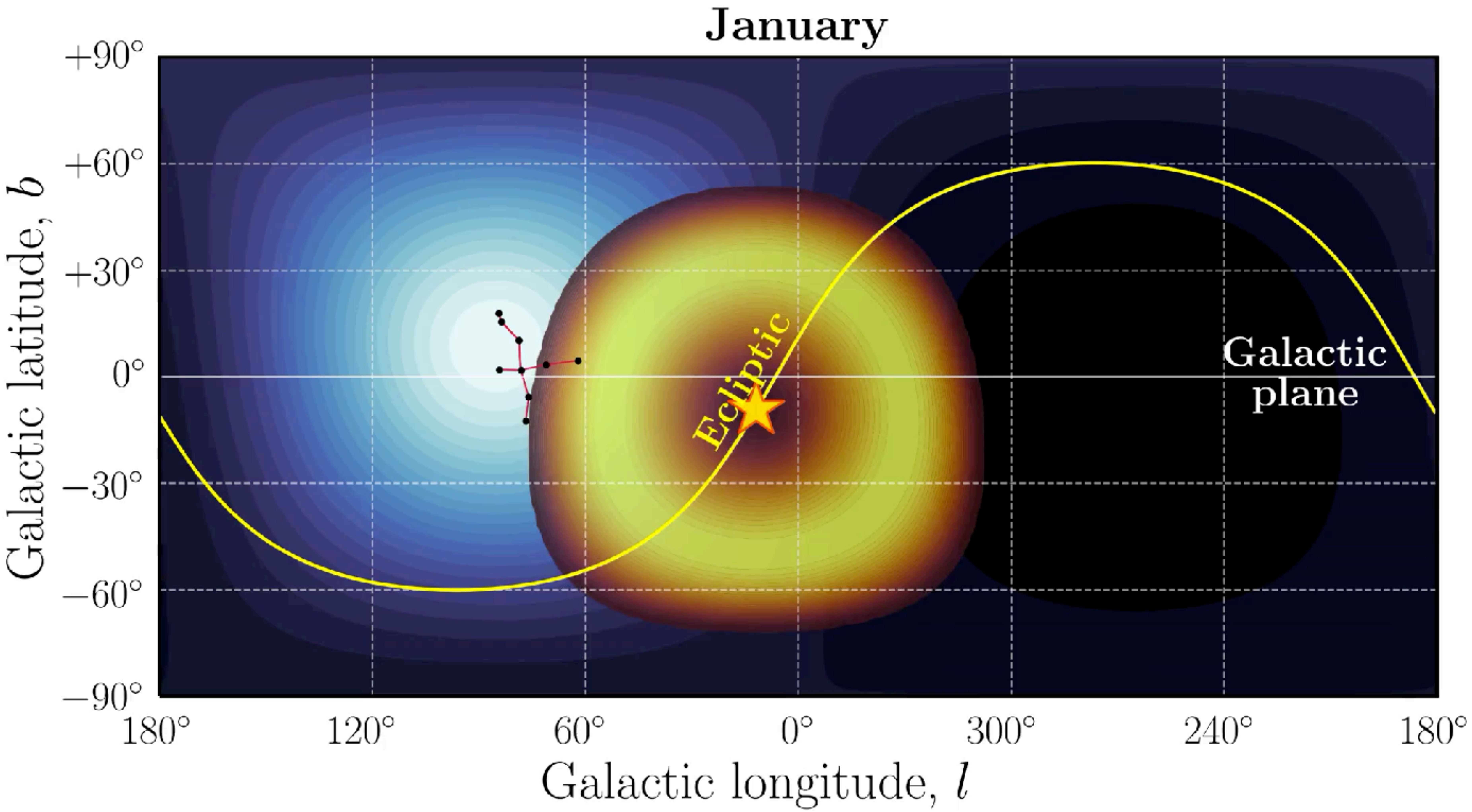
Low-E tail of **atmospheric flux** not yet measured at the relevant energies—25% uncertainty is pessimistic



# Effect of reducing flux uncertainties on the neutrino fog



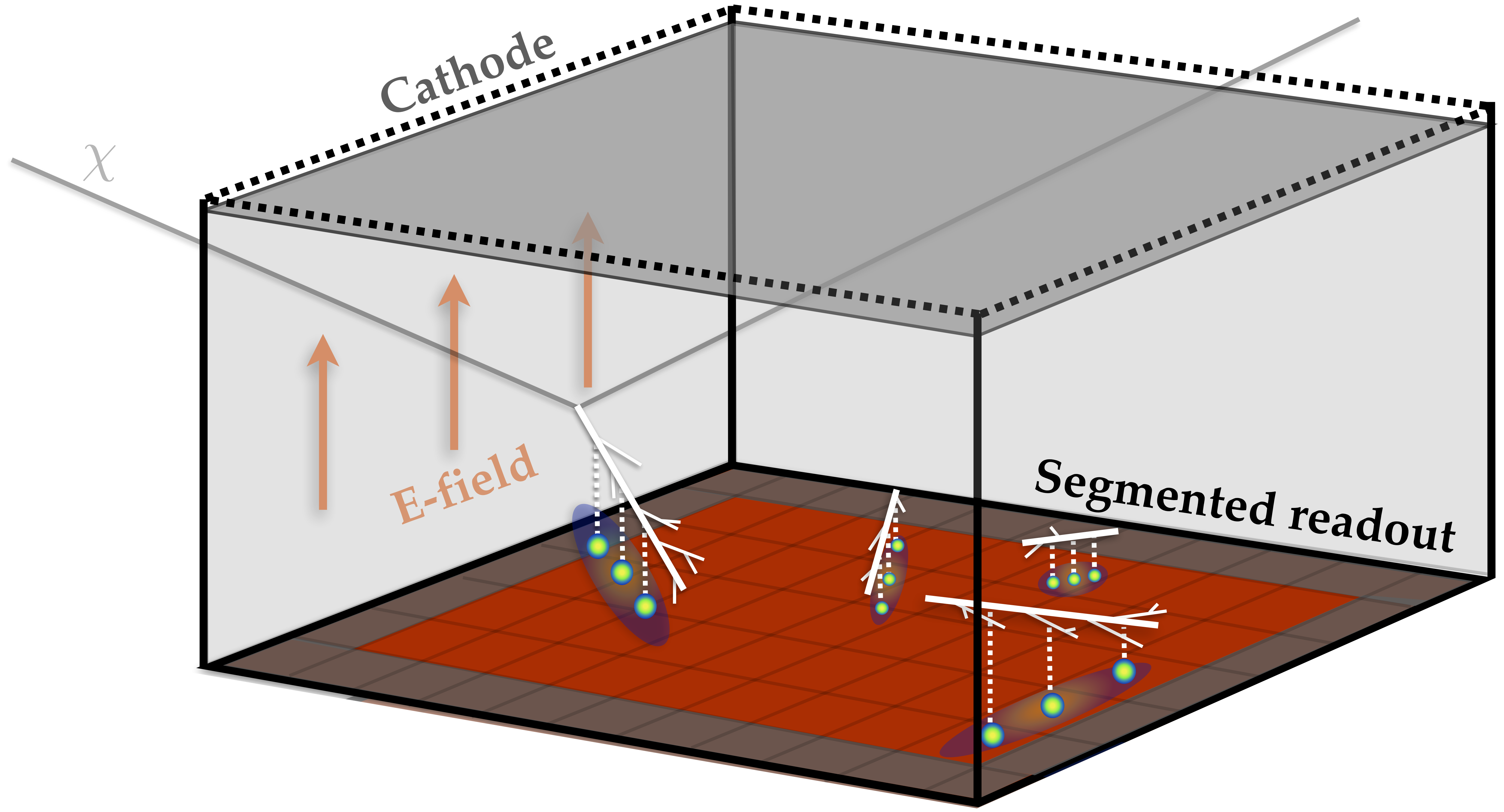
## Nothing should mimic dark matter's directional signal, including neutrinos




A directional detector should be able to "see through" the neutrino fog, O'Hare et al. [1505.08061]

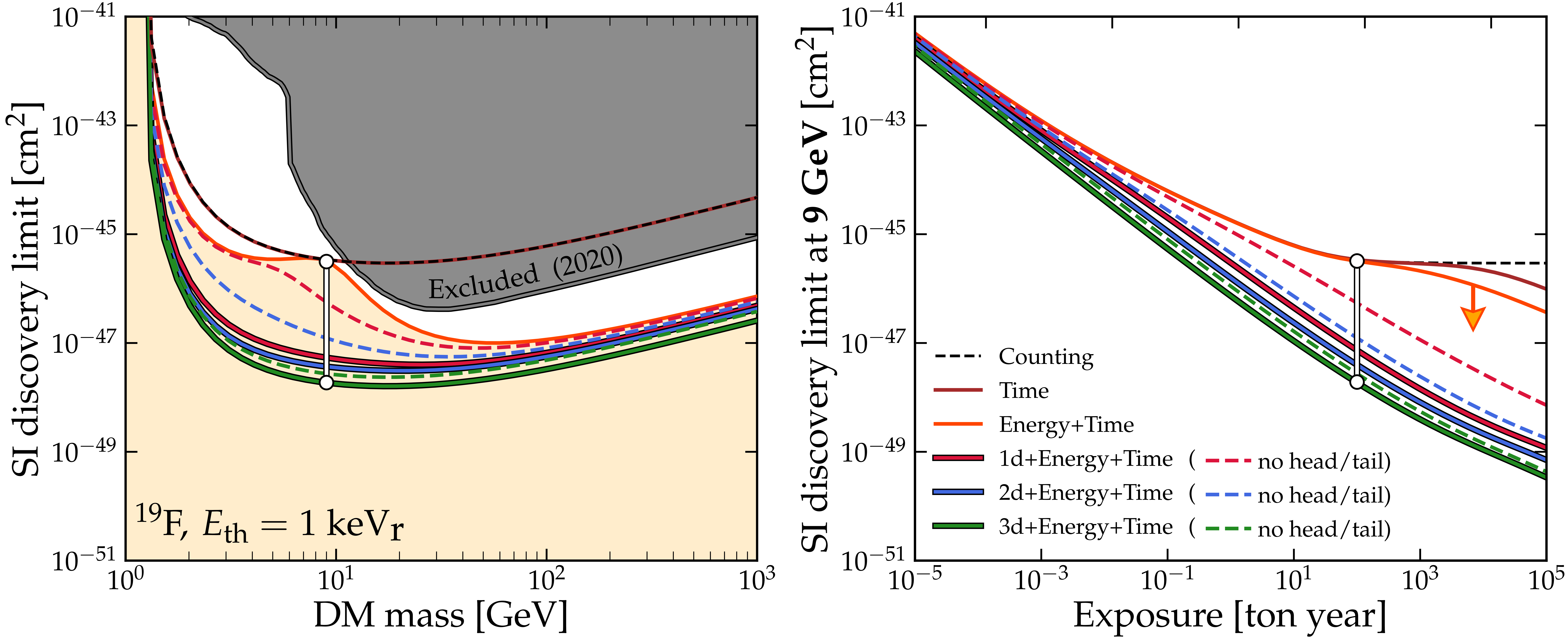
# How would a *directional* detector work?

e.g. gas time projection chamber



# Subtracting the neutrino background with directionality

In an idealised case a directional experiment doesn't see the background at all—its sensitivity scales almost as $\sigma \propto (MT)^{-1}$



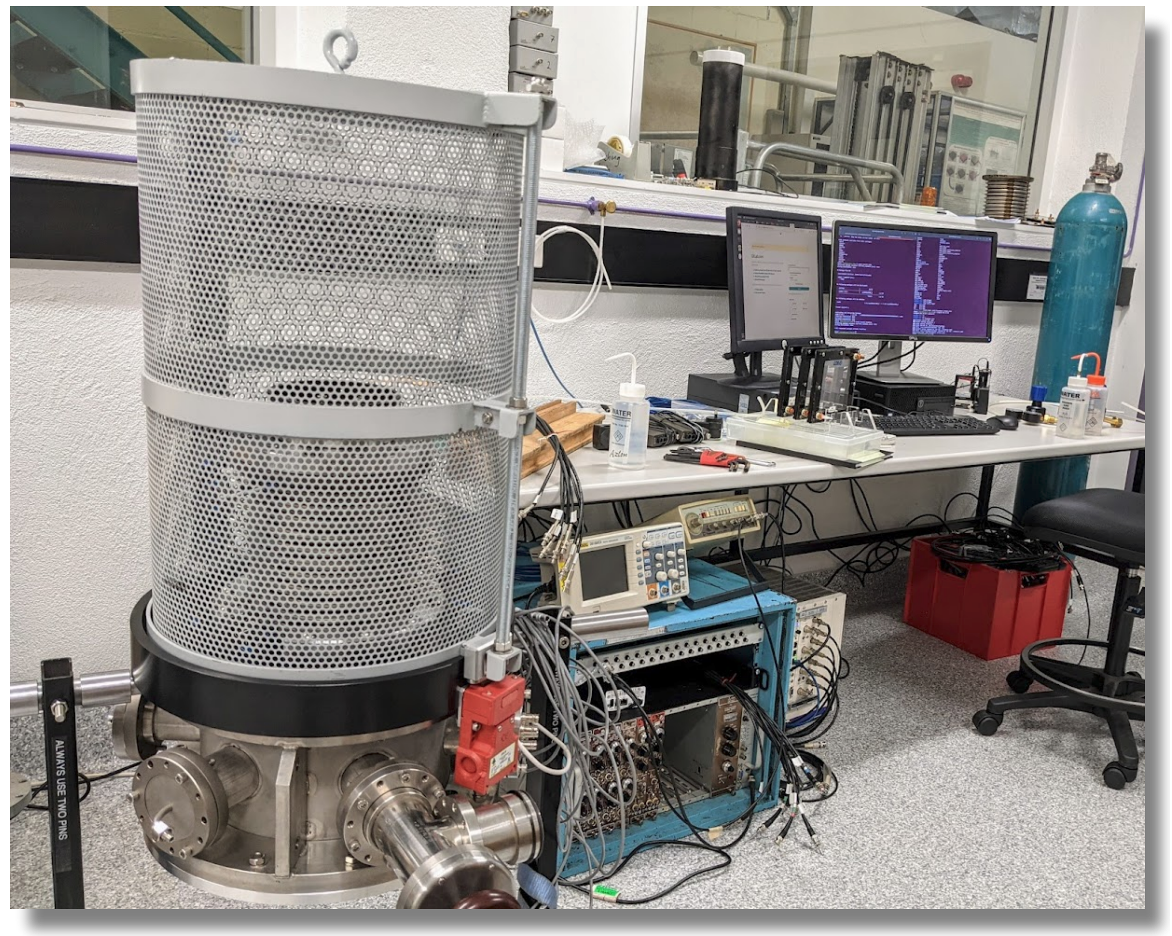

Vahsen, O'Hare, Loomba [2102.04596]

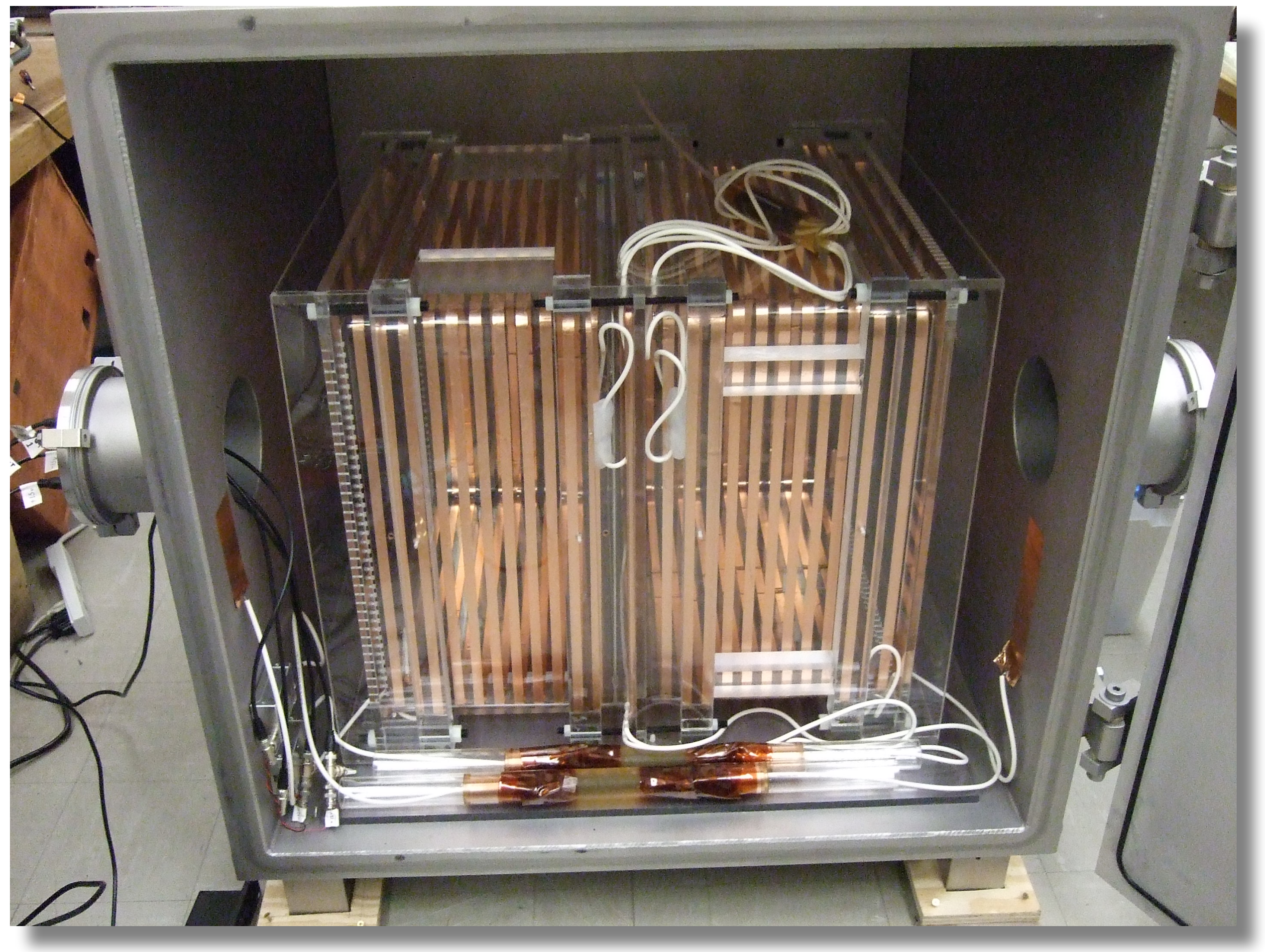
**CYGNUS collaboration** is working towards a HD "recoil imaging" time projection chamber. See O'Hare et al. [2203.05914] for details

CYGNO (Italy)

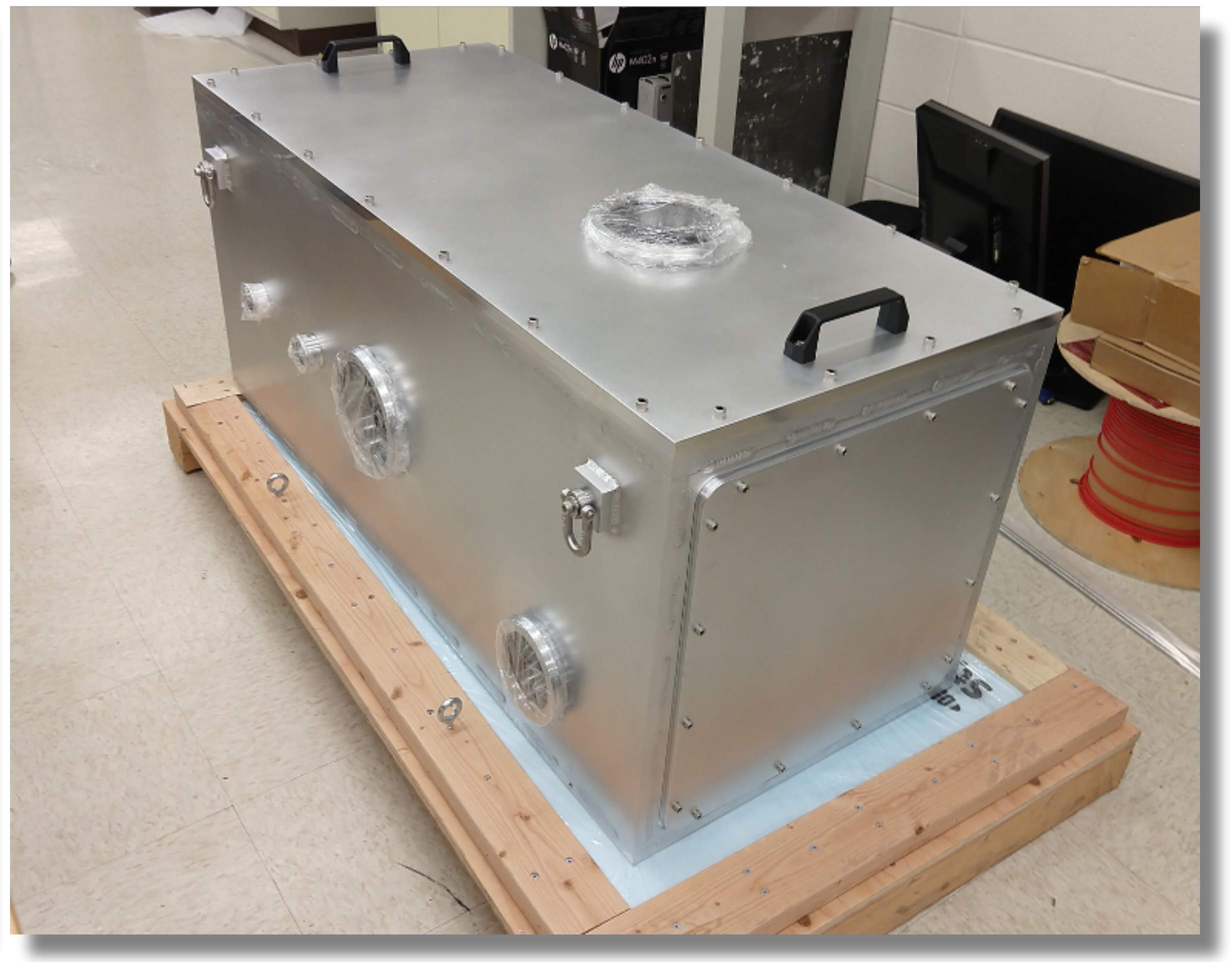
CYGNUS/DRIFT (UK)


CYGNUS-Oz (Australia)

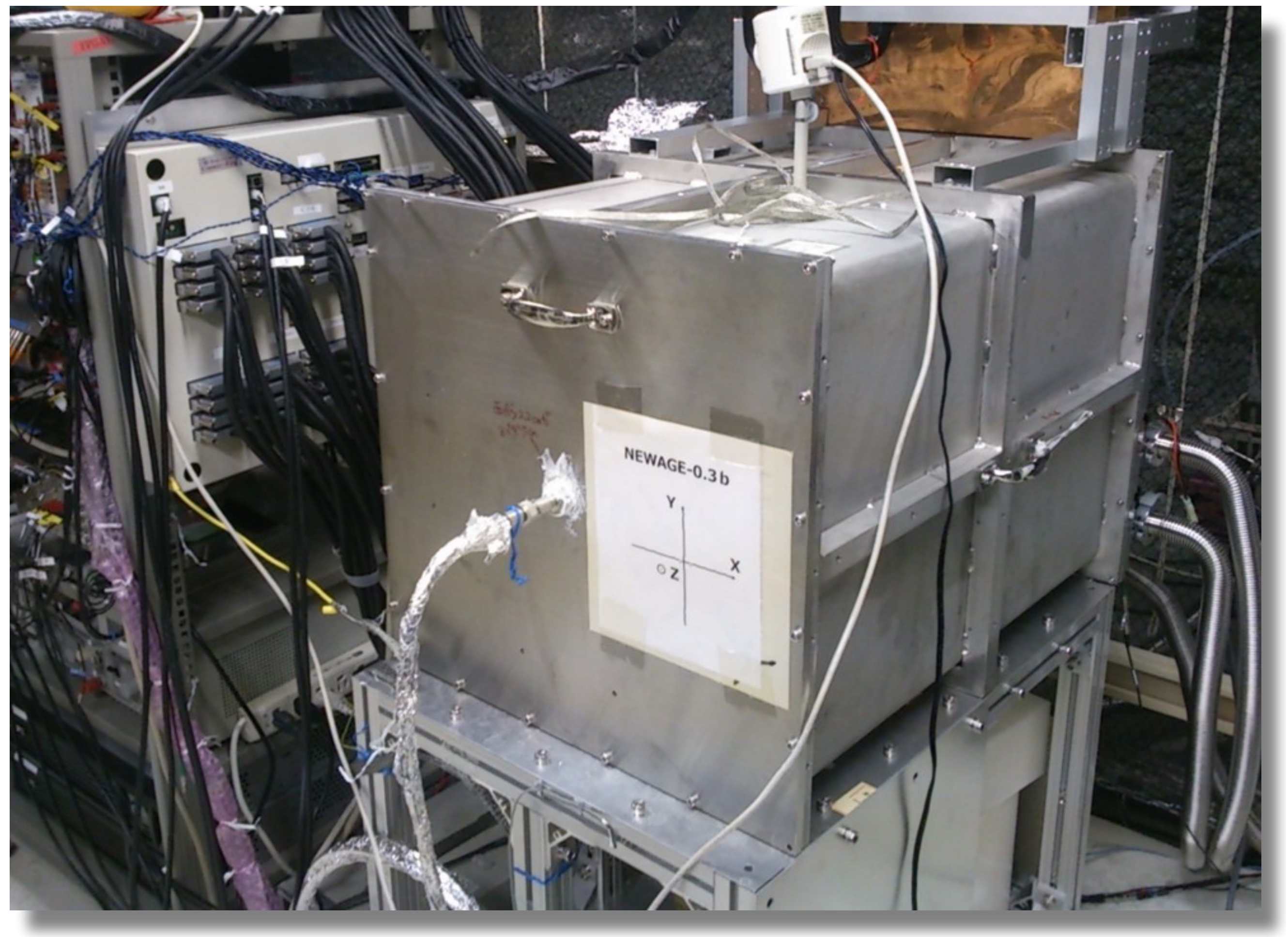




CYGNUS/UNM (USA)

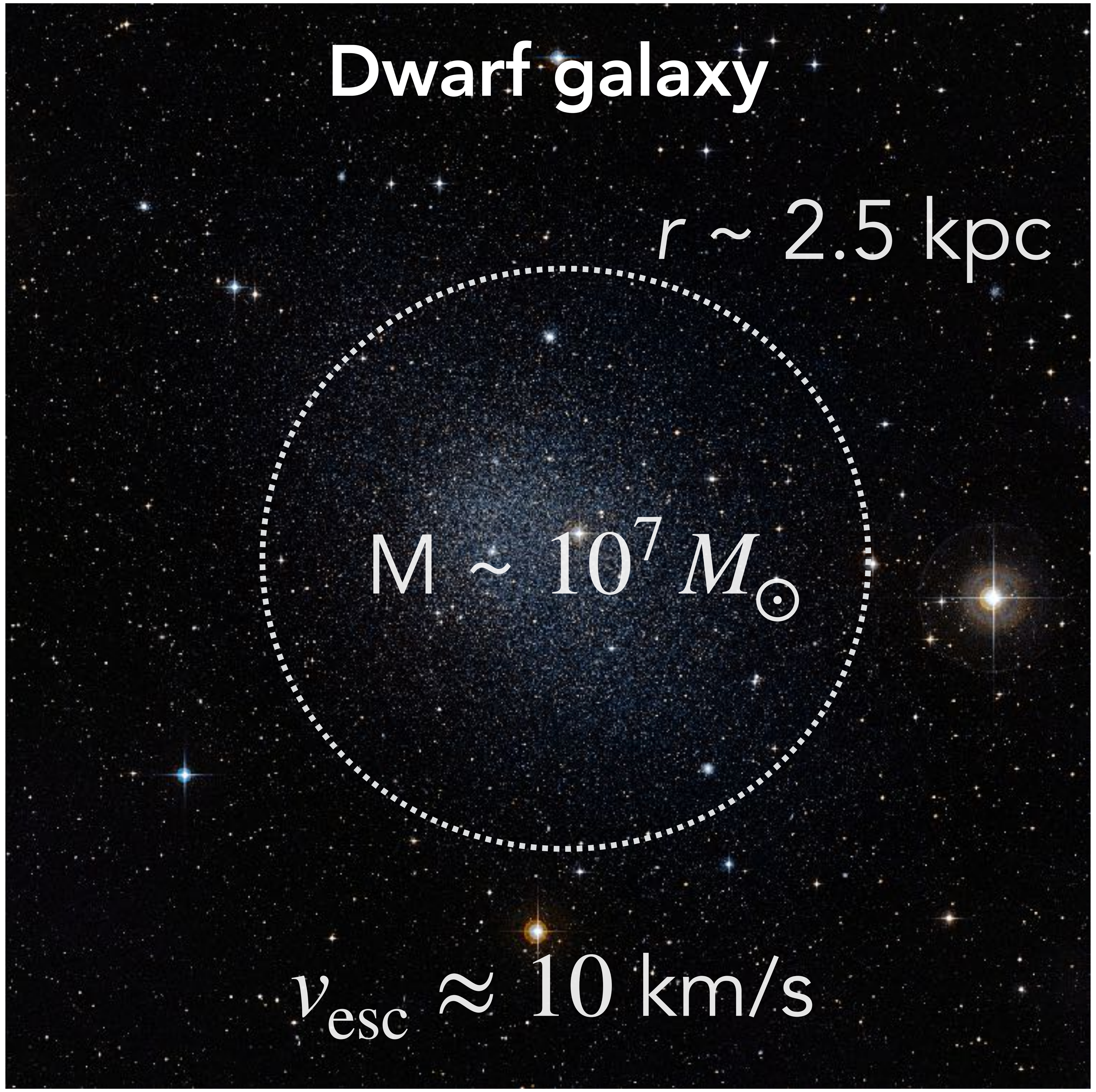


CYGNUS-HD 40 L (USA)

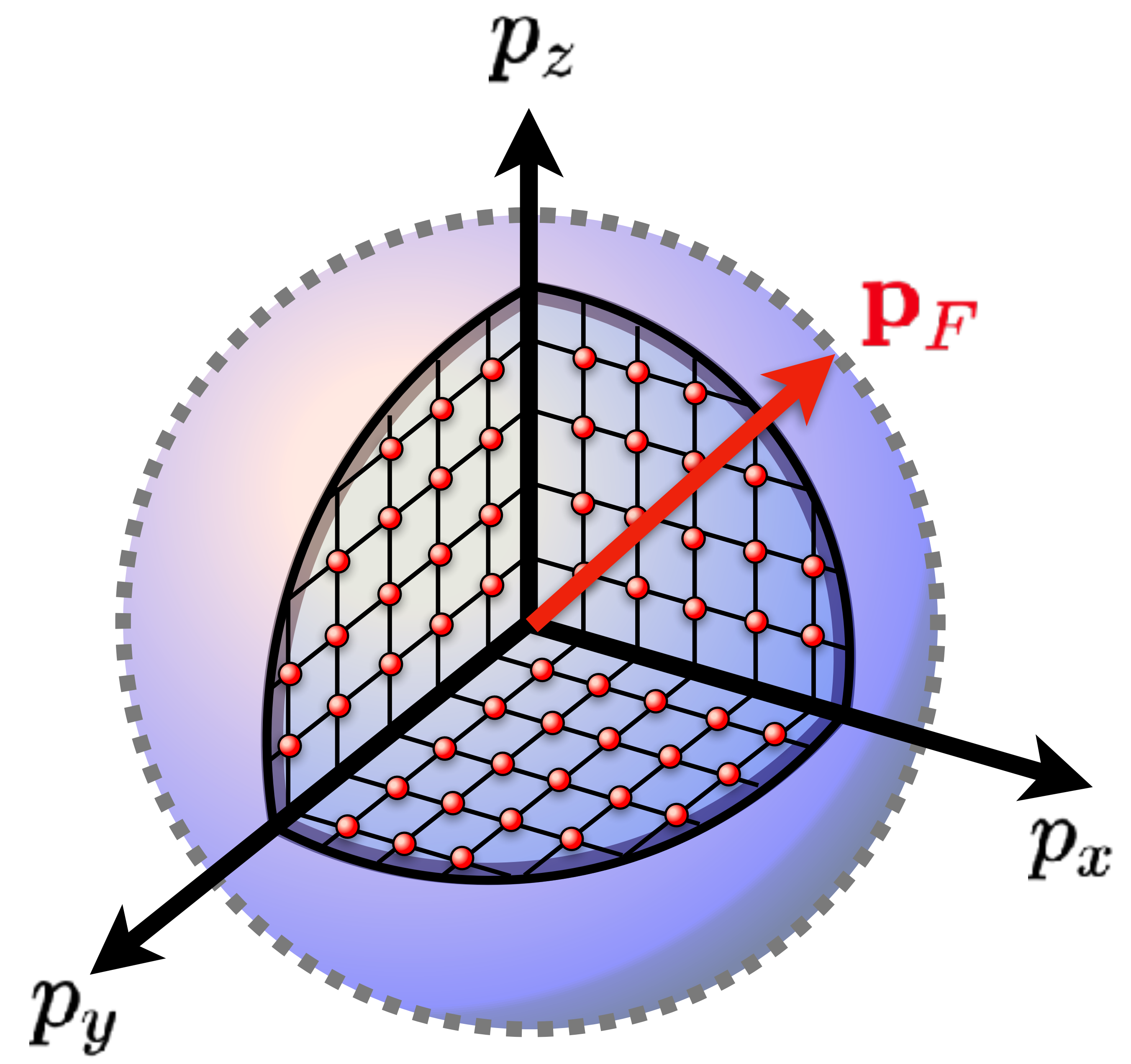



CYGNUS/NEWAGE (Japan)

# How light can dark matter be if it is made of fermions?




**Sphere of degenerate fermions**

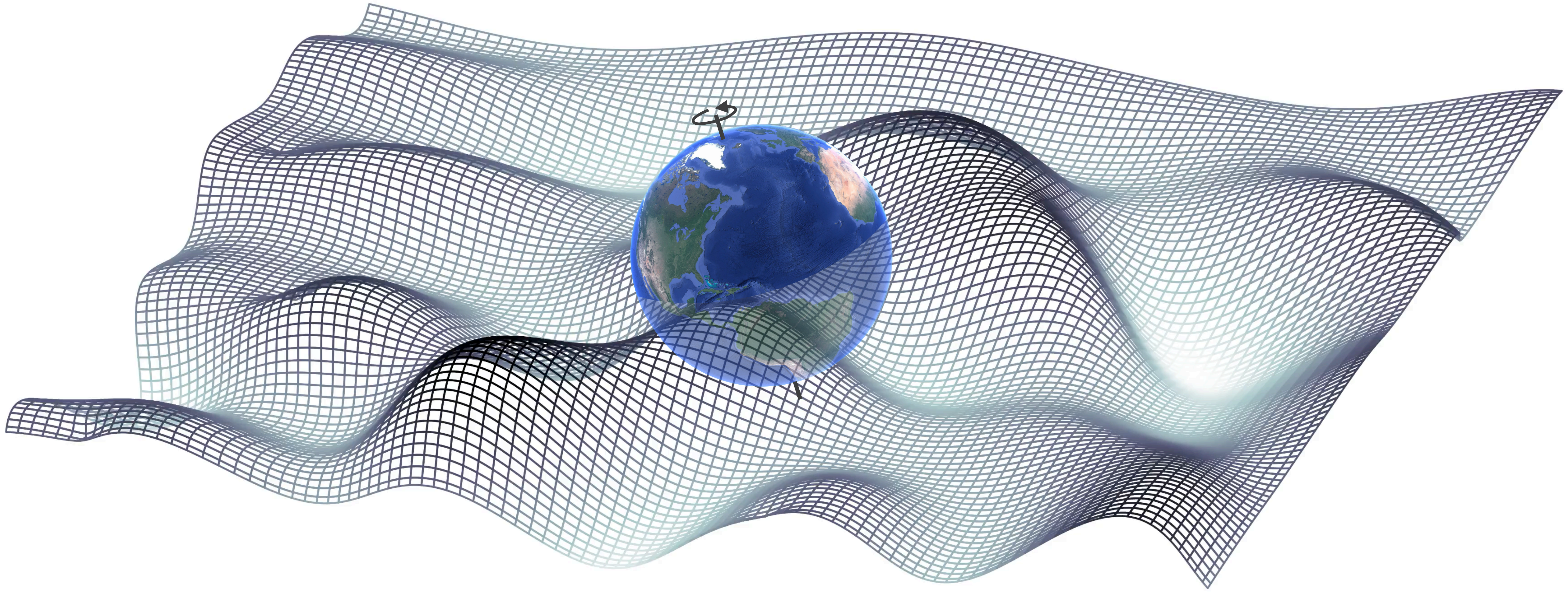



$$v_F < v_{\mathrm{esc}}$$
$$\Rightarrow m_\chi \gtrsim 100 \text{ eV}$$

**"Tremaine-Gunn bound"**: Pauli exclusion principle prevents you from cramming fermions lighter than ~100 eV into dwarf galaxies

# Wave-like dark matter

DM in the regime of *macroscopic* occupancy numbers → classical field description



$$\phi(t) \approx A \cos \omega t$$

**Amplitude:** $A = \frac{\sqrt{2\rho_{\rm DM}}}{m}$

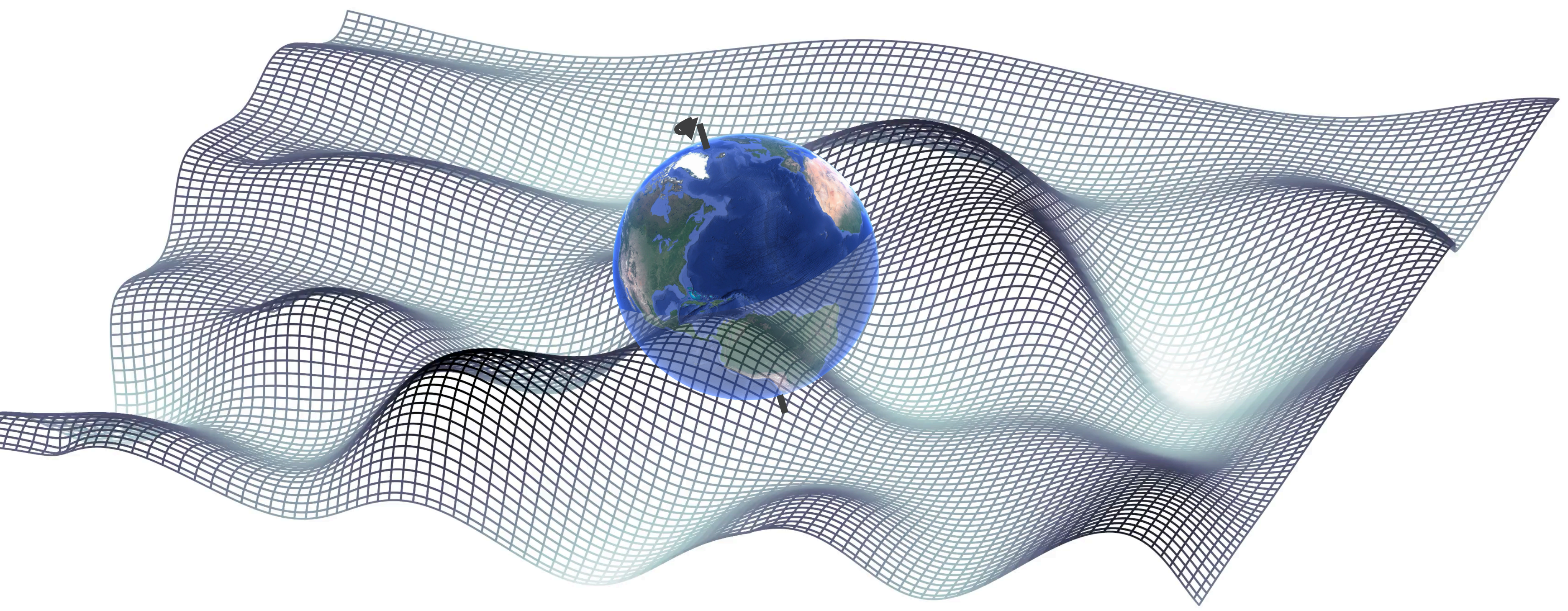
**Frequency:** $\omega = m + \frac{1}{2}mv^2$

$$\approx \underbrace{m(1 + 10^{-6})}$$

*Oscillation remains coherent for $10^6$ cycles*

No discrete particle-scattering events, instead we imagine coupling to the field in some way and extracting energy from it via these characteristic oscillations

# Wave-like dark matter, properly



Superposition of plane waves in some box of volume, *V*

$$\phi(t,\mathbf{x}) = \sqrt{V}\int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3}\phi(\mathbf{p})e^{-i(\omega t - \mathbf{p}\cdot\mathbf{x}+\beta(\mathbf{p}))}$$

Only when we measure over some **short enough** time/length scale do we have:

$$\phi = \phi_0 \cos(\omega t - \mathbf{p}\cdot\mathbf{x} + \beta)$$

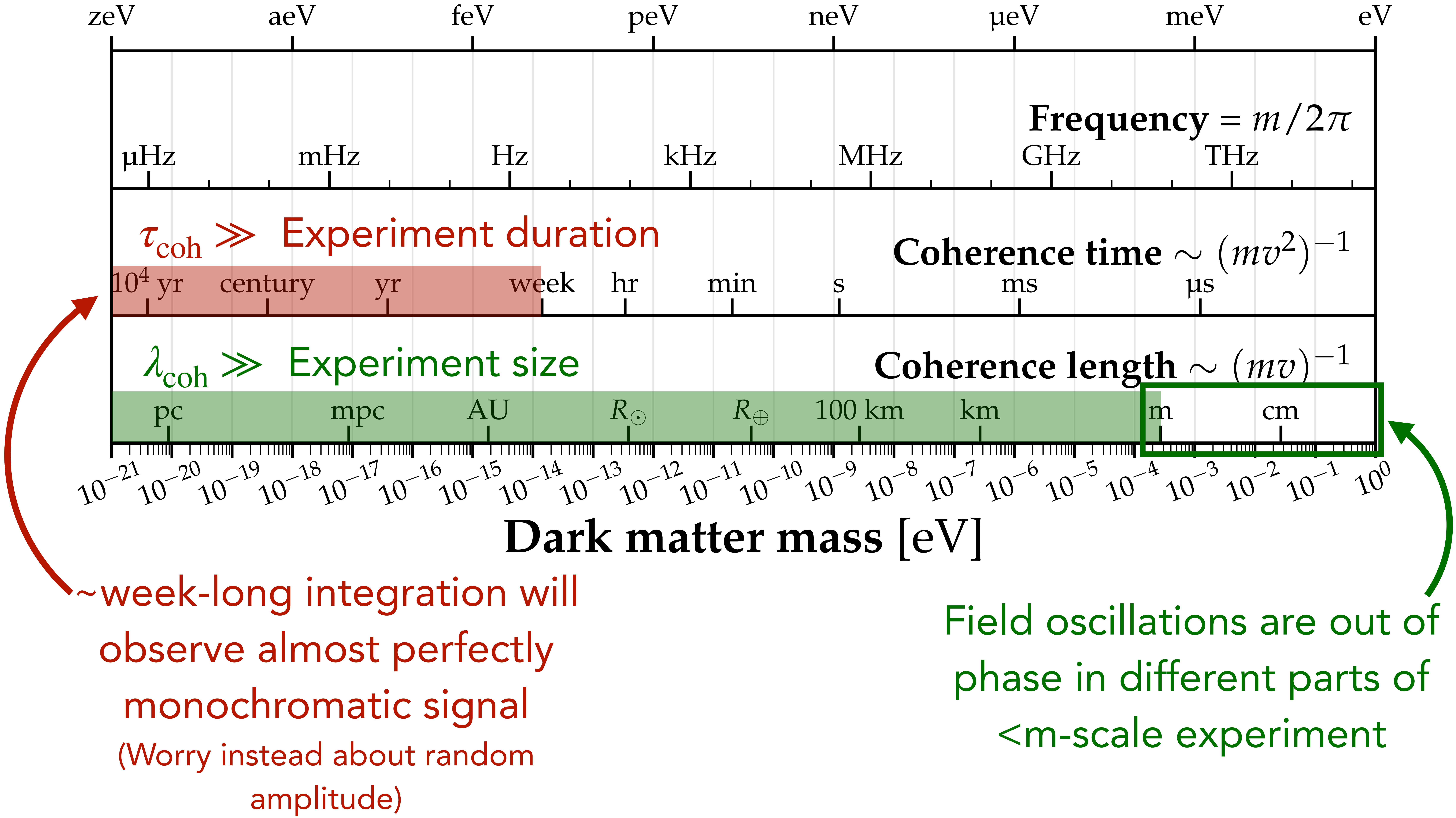
- $\phi_0$: Random amplitude
- $\omega$, $\mathbf{p}$: Random draw from the velocity distribution
- $\beta$: Arbitrary phase

**What is considered short?**

< Coherence length and coherence time

→ The length/timescale over which field will be out of phase with itself

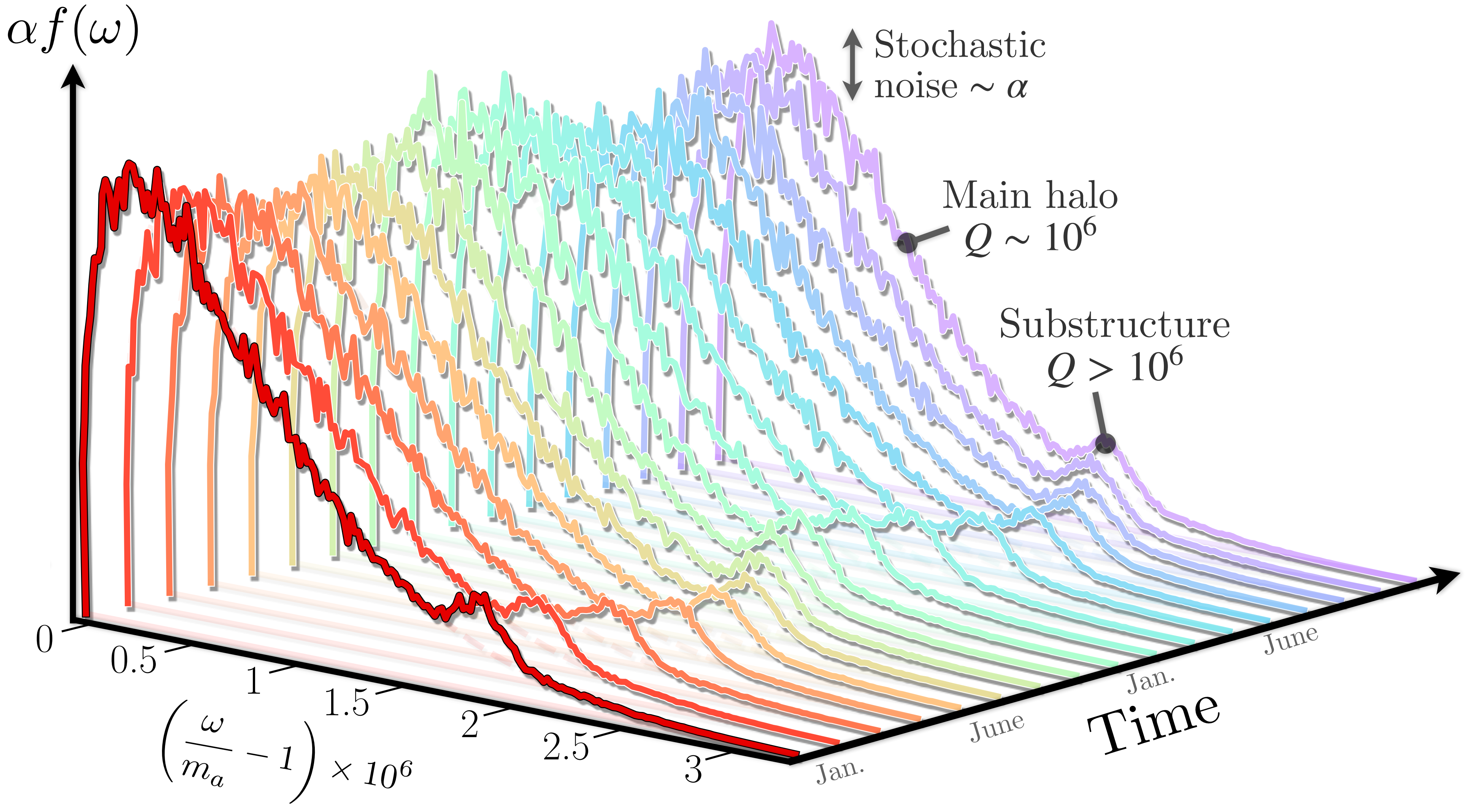
$$\lambda_{\rm coh} \sim \frac{2\pi}{mv} \qquad \tau_{\rm coh} \sim \frac{2\pi}{mv^2}$$



zeV
aeV
feV
peV
neV
μeV
meV
eV
Frequency = $m/2\pi$
μHz
mHz
Hz
kHz
MHz
GHz
THz
$\tau_{coh} \gg$ Experiment duration
Coherence time $\sim (mv^2)^{-1}$
$10^4$ yr
century
yr
week
hr
min
s
ms
μs
$\lambda_{coh} \gg$ Experiment size
Coherence length $\sim (mv)^{-1}$
pc
mpc
AU
$R_\odot$
$R_\oplus$
100 km
km
m
cm
$10^{-21}$ $10^{-20}$ $10^{-19}$ $10^{-18}$ $10^{-17}$ $10^{-16}$ $10^{-15}$ $10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$
Dark matter mass [eV]
~week-long integration will observe almost perfectly monochromatic signal
(Worry instead about random amplitude)
Field oscillations are out of phase in different parts of <m-scale experiment

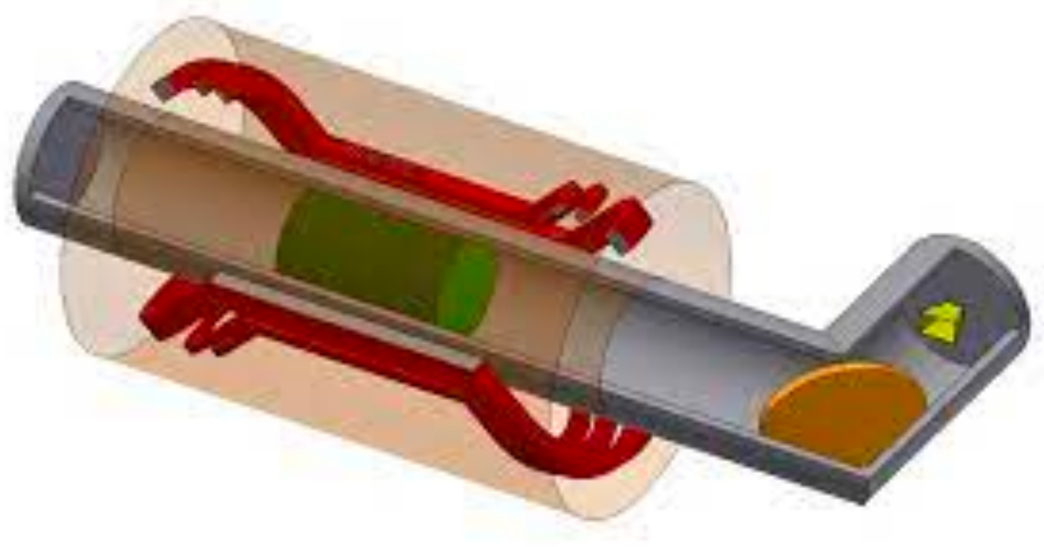
# Wave-like dark matter

How do the speed distribution, annual modulation, directionality manifest in the wave-like case?

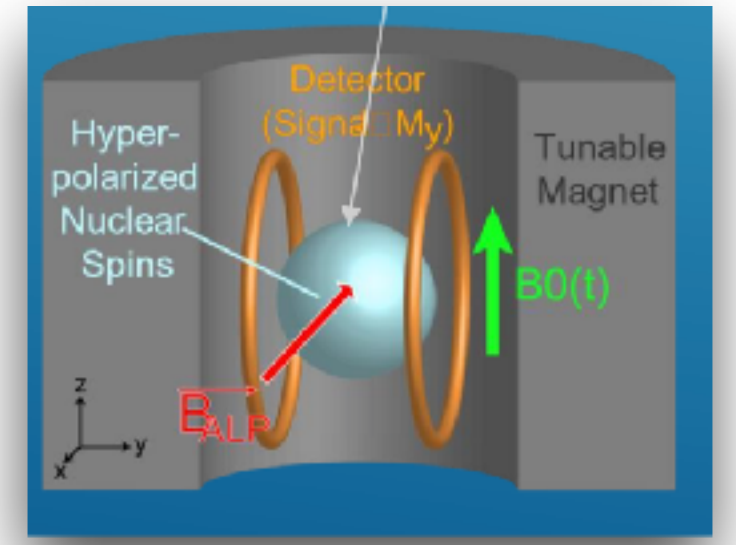



→ Speed distribution leads to a distinctive "lineshape" in frequency that will modulate over the year

$$f(\omega, t) = f(v, t)\frac{\mathrm{d}v}{\mathrm{d}\omega}$$



MADMAX




CASPEr-Gradient

→ Directionality could appear in two forms:

- → Experiments that are larger than coherence length
- → Experiments that measure the field-gradient:

$$\nabla \phi = \sqrt{2\rho}\, \mathbf{v} \sin(\omega t - m_a \mathbf{v} \cdot \mathbf{x} + \beta)$$

# Specific model: the axion

**Minimal working definition:** New light pseudoscalar, with coupling to photons and/or derivative couplings to fermions

Axion-gluon (QCD axion only) | Axion-Photon | Axion-Fermion

$$\mathcal{L}_{\text{axion}} \supset \frac{\alpha}{8\pi}\frac{a}{f_a}G\widetilde{G} + \frac{1}{4}g_{a\gamma}aF\widetilde{F} + \partial_\mu a \sum_\psi g_{a\psi}\bar{\psi}\gamma^\mu\gamma^5\psi$$

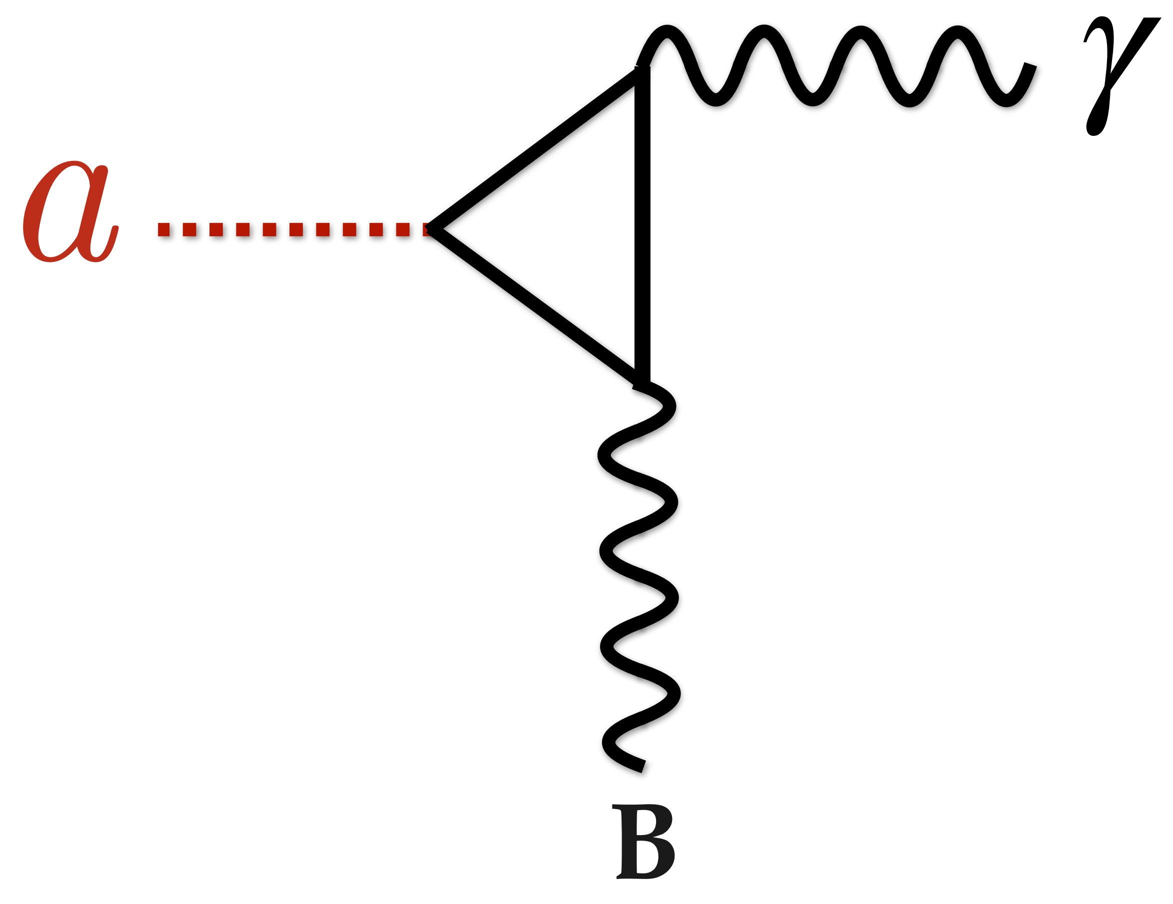
+ a few model-dependent assumptions

→ Usually pseudo-Goldstone boson of spontaneously broken U(1)
→ Could solve strong CP problem (= **QCD axion**)
→ Could be DM

# Axion-photon interaction

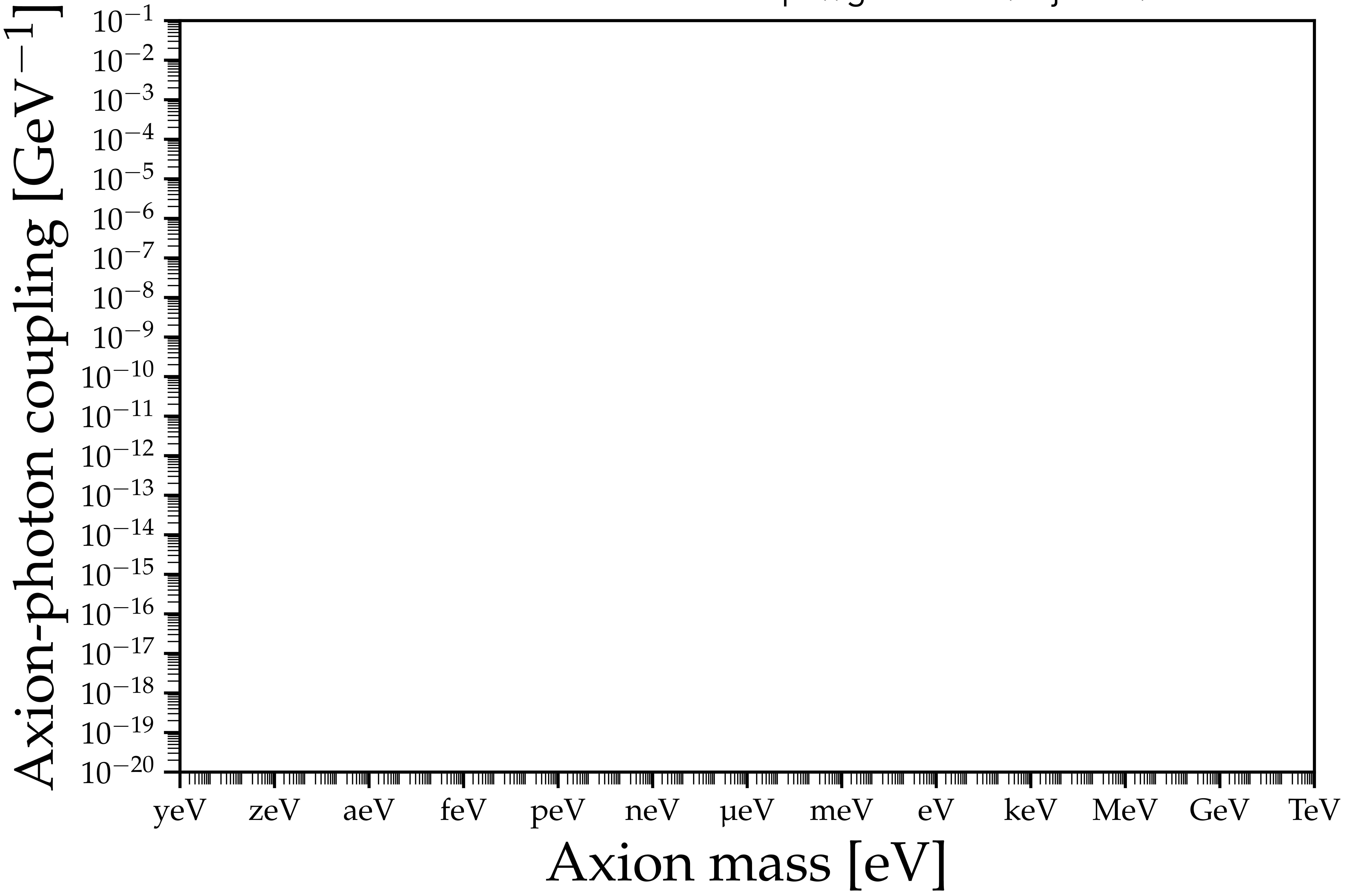
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a(\mathbf{x},t) F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma} a(\mathbf{x},t)\mathbf{E}\cdot\mathbf{B}$$

**DM axion** → Photon

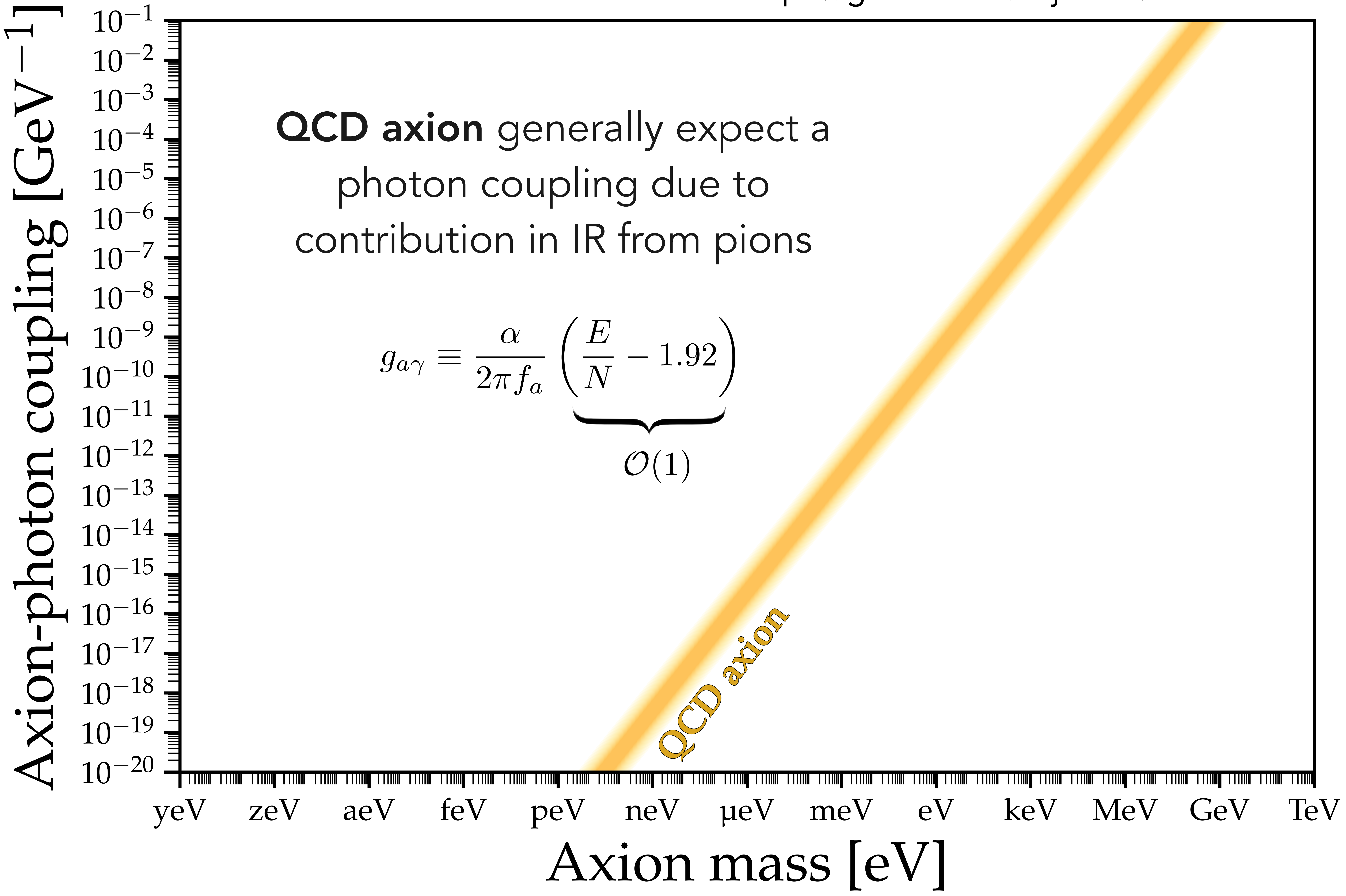



- DM axions source photons with energy $\approx m_a$ in the presence of an EM-field
- Could use E-field or B-field to supply EM-background, but in practice only B-fields are used
- Axion mixes only with component of photon parallel to an B-field, can lead to some interesting polarisation signals like birefringence

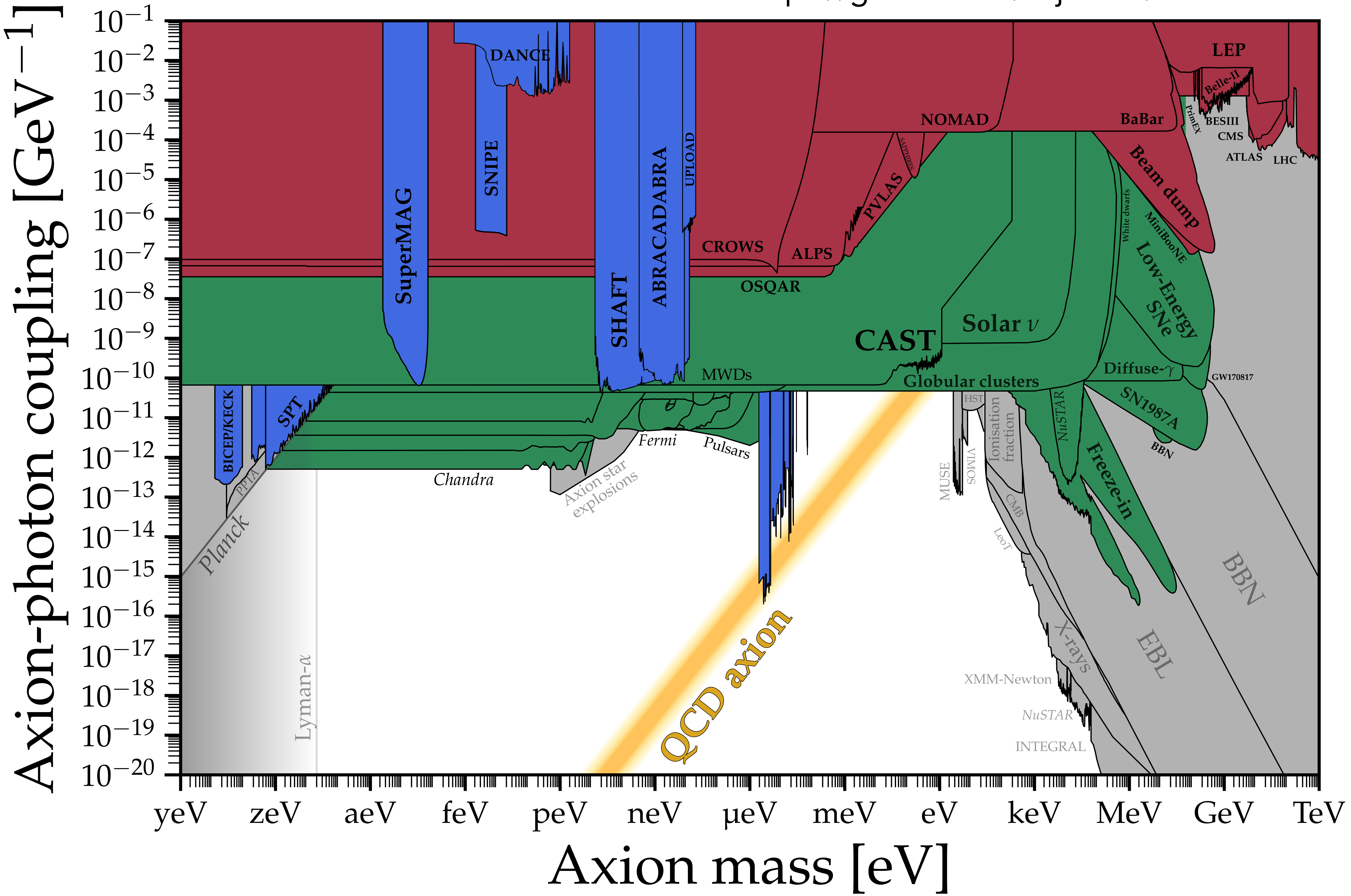
https://github.com/cajohare/AxionLimits

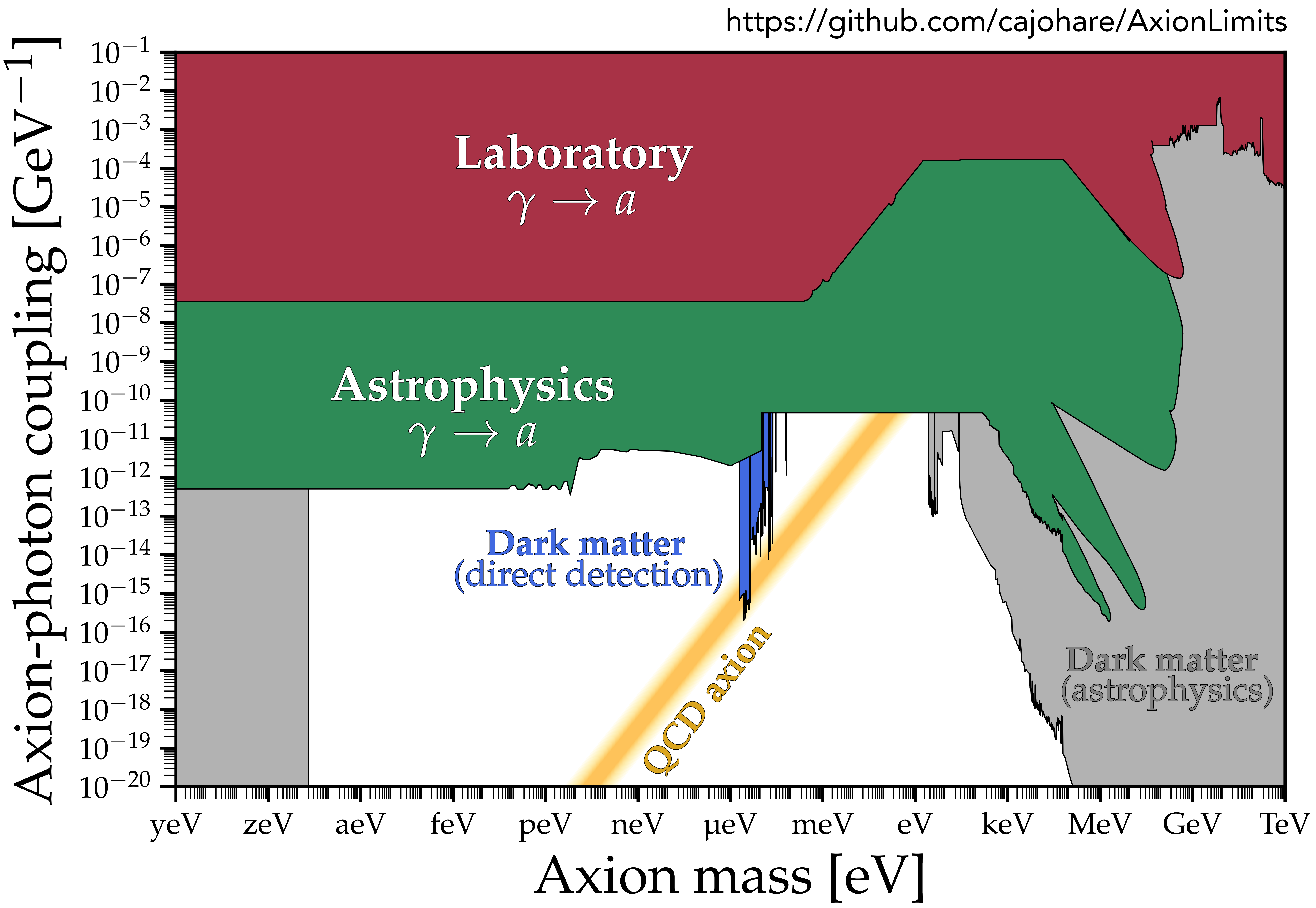


https://github.com/cajohare/AxionLimits



https://github.com/cajohare/AxionLimits




https://github.com/cajohare/AxionLimits
Laboratory
$\gamma \to a$
Astrophysics
$\gamma \to a$
Dark matter
(direct detection)
QCD axion
Dark matter
(astrophysics)
Axion-photon coupling [GeV$^{-1}$]
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$10^{-17}$
$10^{-18}$
$10^{-19}$
$10^{-20}$
yeV
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
Axion mass [eV]

# Axion electrodynamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

- We can interpret axion as the source of an effective current:

$$\partial_\nu F^{\mu\nu} = J^\mu \underbrace{- g_{a\gamma}\widetilde{F}^{\mu\nu}\partial_\nu a}$$

$$J_a^\mu = g_{a\gamma}(-\mathbf{B}\cdot\nabla a, -\mathbf{E}\times\nabla a + \partial_t a\mathbf{B})$$

- Rewrite Maxwell's equations with $J \to J + J_a$:

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

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

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \mathbf{J}$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \cancel{\mathbf{J}} - g_{a\gamma} \left( \cancel{\mathbf{E} \times \nabla a} - \frac{\partial a}{\partial t} \mathbf{B} \right)$$

↓

Usually not important unless experiment larger than

$$\lambda_{\text{coh}} \sim (\nabla a)^{-1} \sim (m_a \mathbf{v})^{-1} \sim 10^3 \lambda_{\text{Compton}}$$

(Most experiments are actually around $\lambda_{\text{Compton}} \sim 1/m_a$ )

**Combine Ampere & Faraday** ⟶ $$\ddot{\mathbf{E}} - \nabla^2 \mathbf{E} = -g_{a\gamma} \mathbf{B} \ddot{a}(t)$$

Driven harmonic oscillator

# Cavity haloscope (1D example)

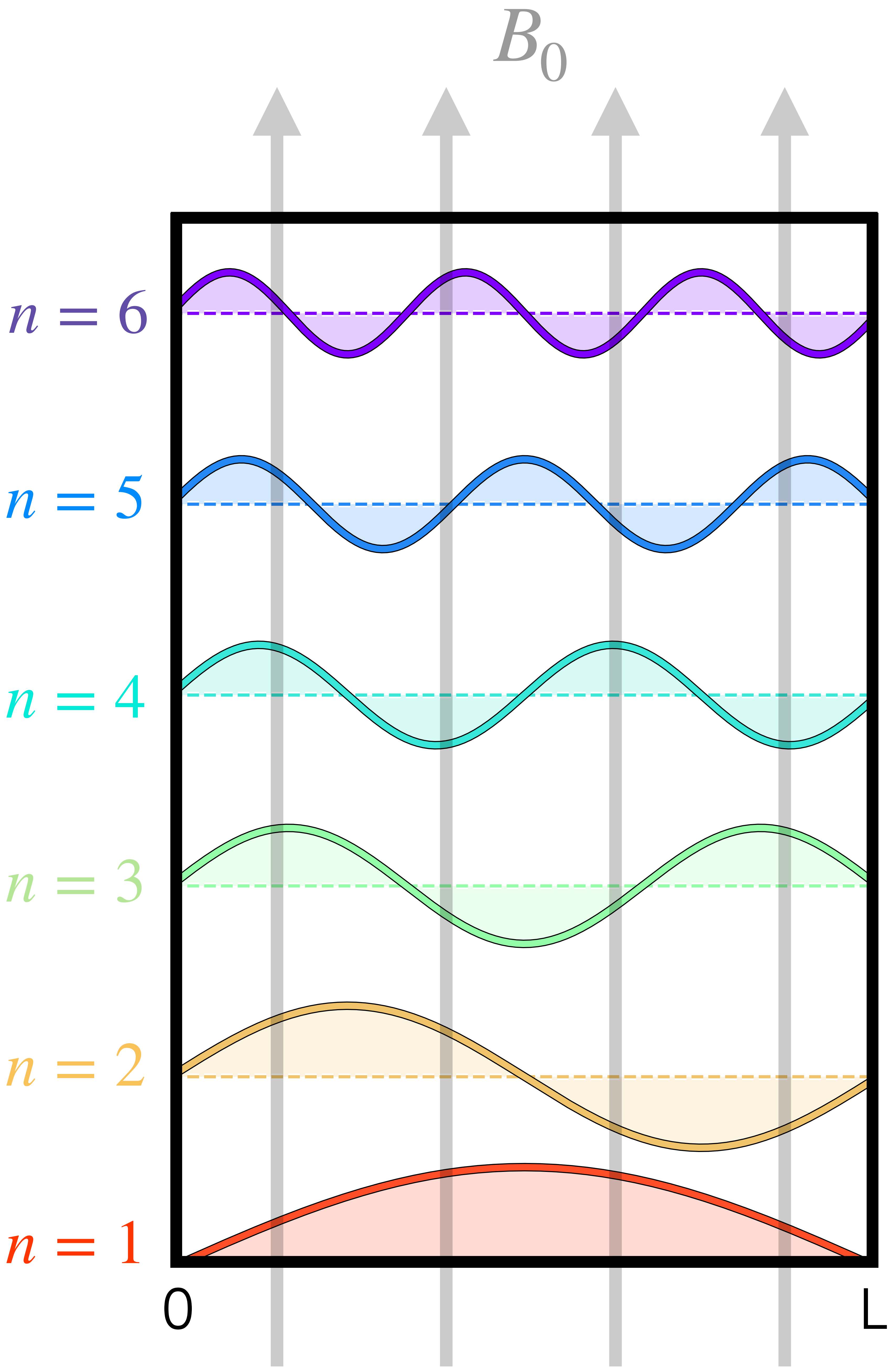
$$E_n(x,t) = E(t)\sin\left(\frac{n\pi x}{L}\right)$$

$$\ddot{\mathbf{E}} - \nabla^2\mathbf{E} = -g_{a\gamma}\mathbf{B}\ddot{a}(t)$$

$a(t) \sim \cos(m_a t)$

Axion excites mode and drives resonance at

$$m_a = \frac{n\pi}{L}$$



# Cavity haloscope

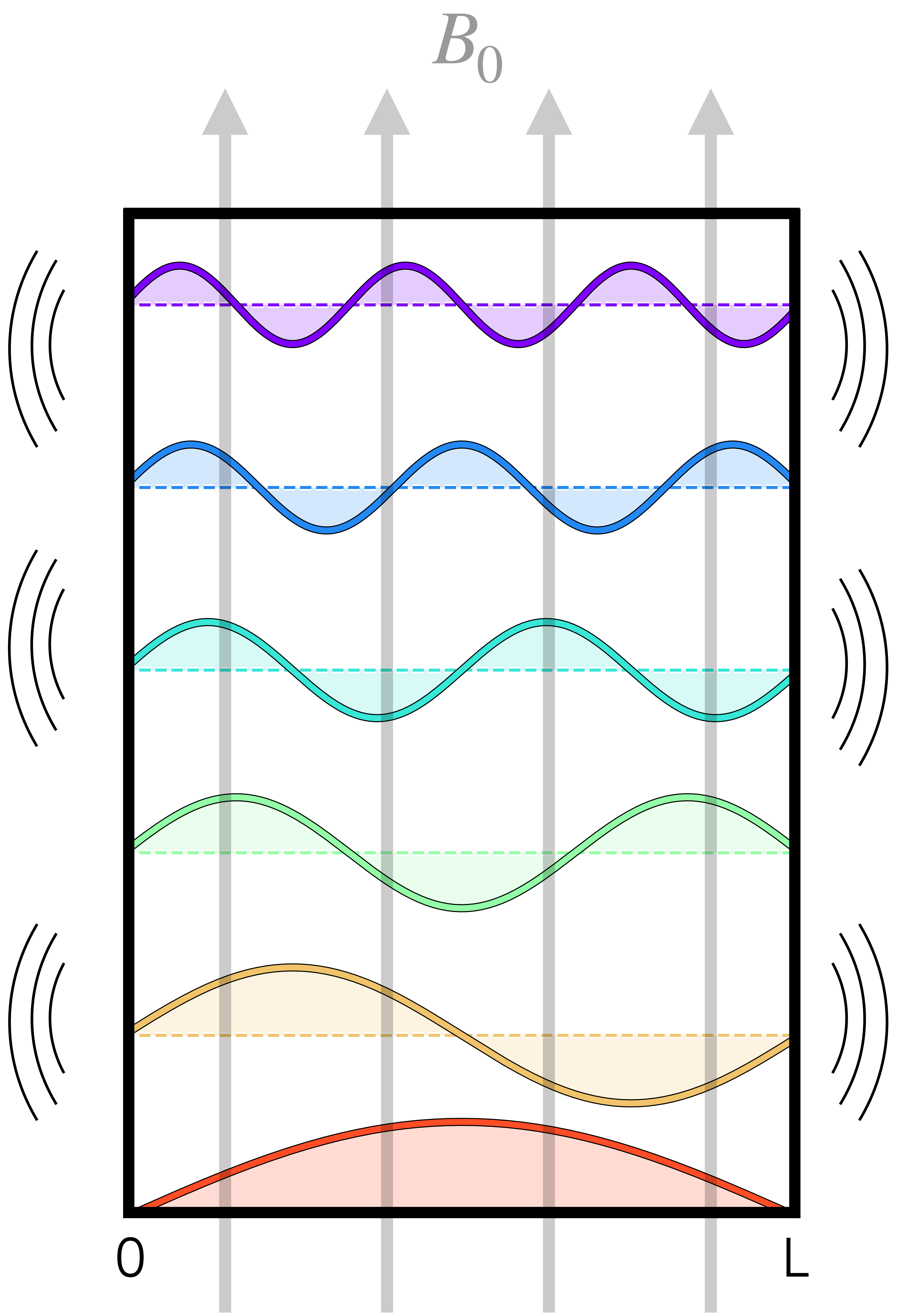
Power lost from the cavity quantified in terms of the "quality factor"

Q = energy stored/energy lost per oscillation period

$$P = \frac{\omega_n}{Q} U_{\text{stored}} = \frac{\omega_n}{Q} \times \frac{1}{2} |E|^2 V$$

When on-resonance ($\omega_n = m_a$):

$$|E| = Q(g_{a\gamma} B) \frac{\sqrt{2\rho}}{m_a}$$



# Cavity haloscope

More detailed calculation for a cylindrical cavity:

Axion coupling | Volume | B-field | Geometric factor | DM density | Axion mass | Quality factor

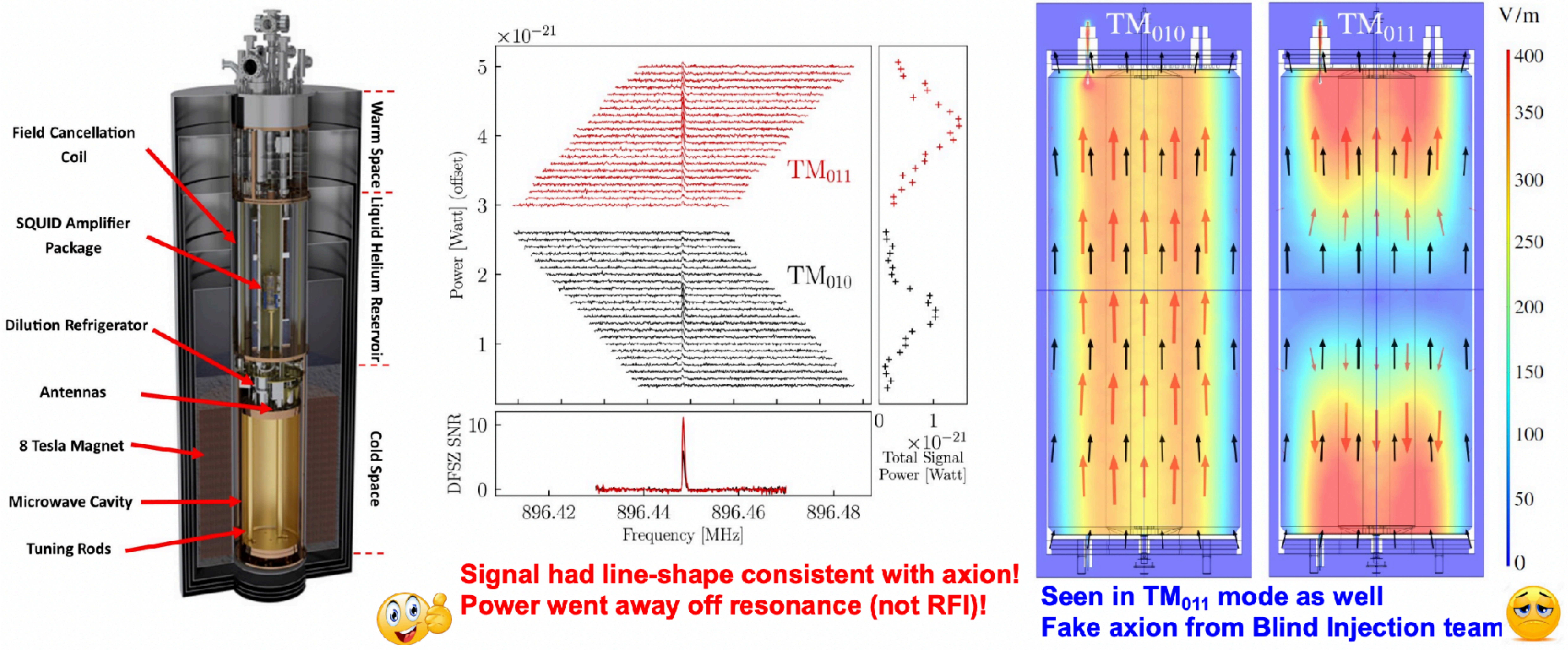
$$P_a = 6.3 \times 10^{-22}\ \mathrm{W} \left(\frac{g_{a\gamma\gamma}}{10^{-15}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{V}{220\ \mathrm{l}}\right) \left(\frac{B}{8\ \mathrm{T}}\right)^2 \left(\frac{C_{nlm}}{0.69}\right) \left(\frac{\rho_a}{0.3\ \mathrm{GeV\ cm}^{-3}}\right) \left(\frac{3\ \mu\mathrm{eV}}{m_a}\right) \left(\frac{Q}{7 \times 10^4}\right)$$

Volume fixed by resonant frequency

Search @ higher masses? → Forced to use smaller V → Power suppressed $\propto V$

Search @ lower masses? → Forced to use larger V → Impractical while maintaining large B

Achieve sensitivity across a band of axion masses by tuning resonance
→ achieved in ADMX by making small adjustments to the internal geometry




**Signal had line-shape consistent with axion!**
**Power went away off resonance (not RFI)!**

**Seen in $TM_{011}$ mode as well**
**Fake axion from Blind Injection team**

**ADMX**, Slide from Gianpaolo Carosi

# Frequency scan rate

→ Signal-to-Noise:
(Dicke Radiometer Eq.)

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_{\mathrm{sig}}}{k_B T} \cdot \sqrt{\frac{t_{\mathrm{int}}}{\Delta\nu}}$$

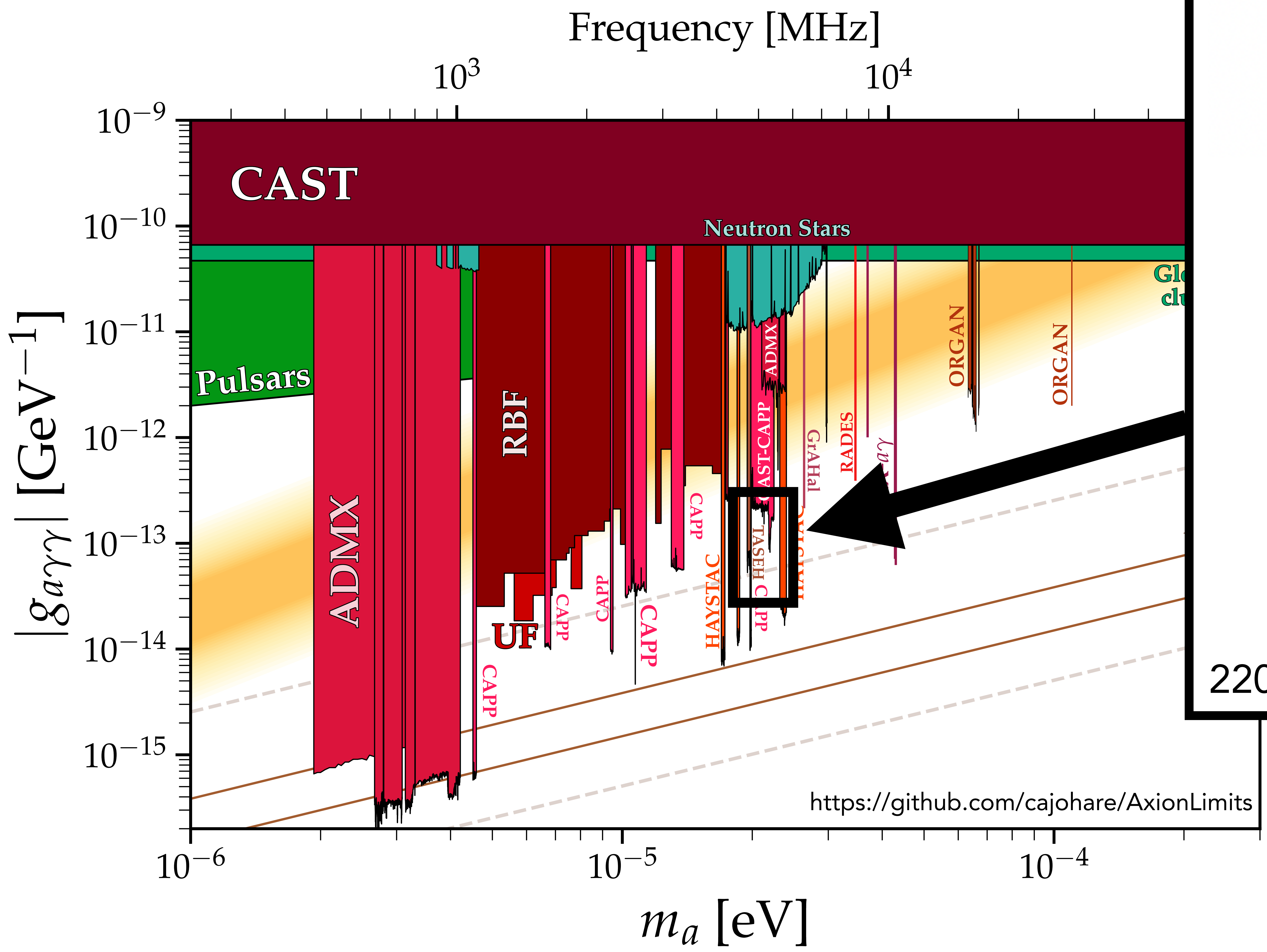
T = Noise temp.
$t_{\mathrm{int}}$ = integration time
$\Delta\nu$ = bandwidth

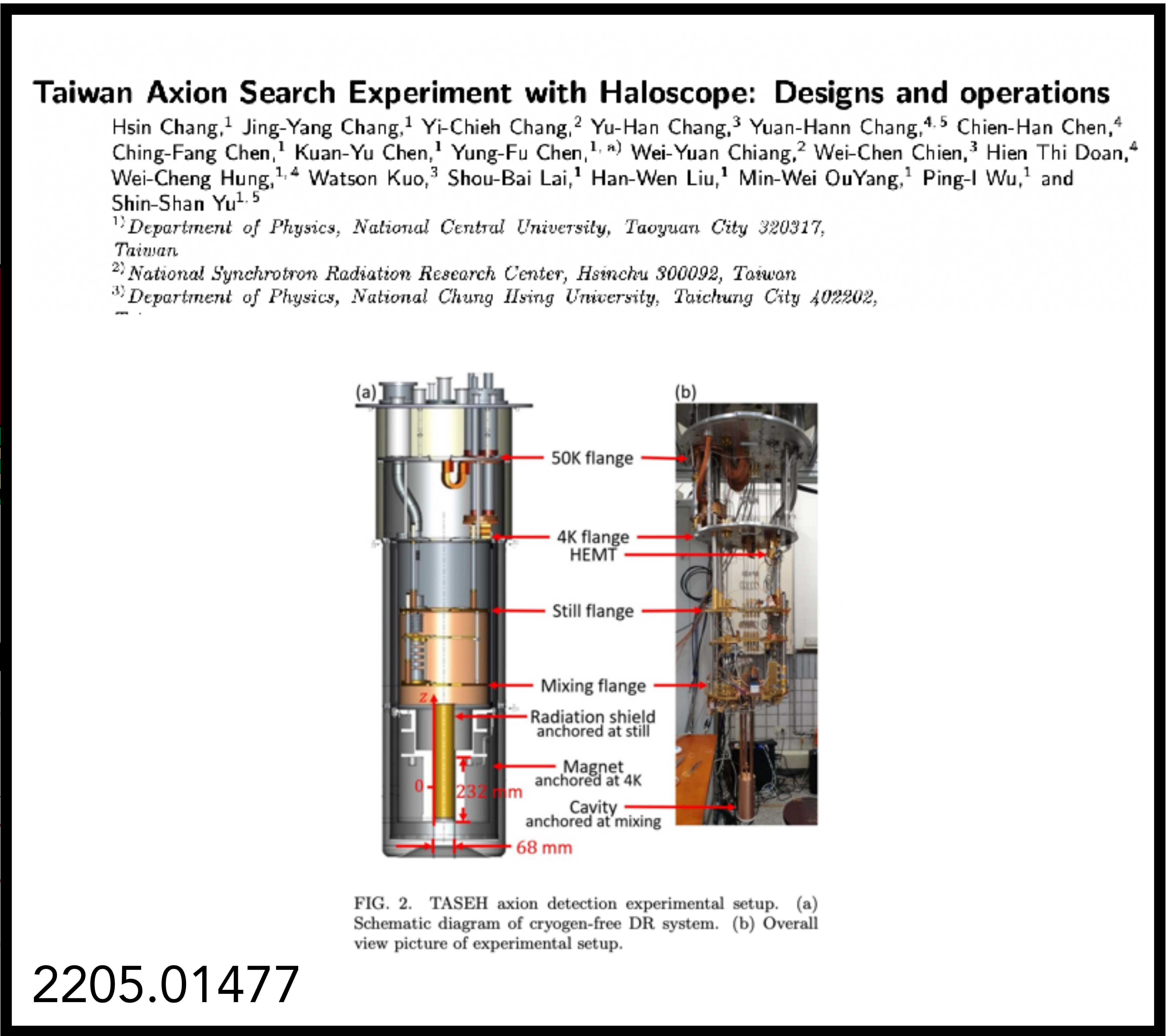
→ **figure of merit** given by how fast the experiment must scan in order to rule out a section of the QCD band (i.e. fixed value of $C_{a\gamma}$)

$$\frac{\mathrm{d}m}{\mathrm{d}t} \propto C_{a\gamma}^4 \cdot m_a^2 \cdot \rho^2 \cdot \left(\frac{S}{N}\right)^2 \cdot B^4 \cdot V^2 \cdot Q \cdot C_{nlm}^2 \cdot T_{\mathrm{sys}}^{-2}$$

e.g. $C_{a\gamma} = 1.92$ for KSVZ axion

Actually $m_a^{-6}$



**Taiwan Axion Search Experiment with Haloscope: Designs and operations**

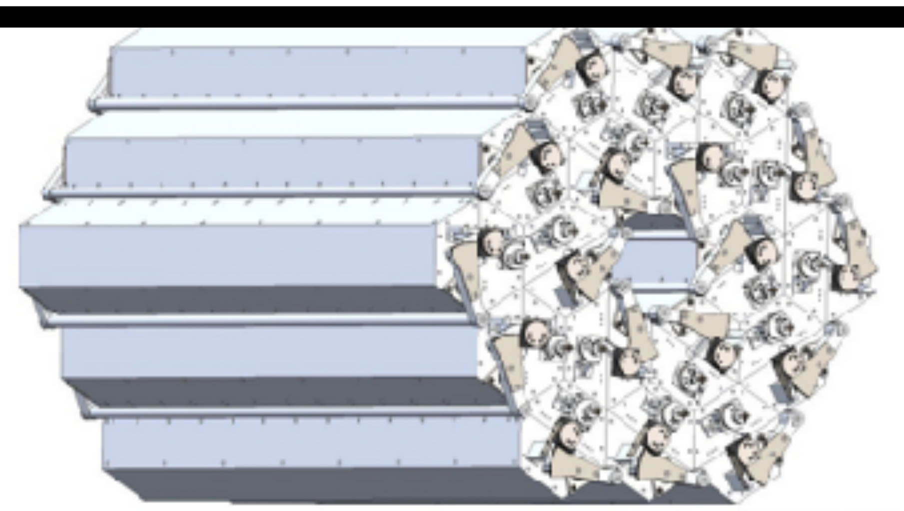

Hsin Chang,[1] Jing-Yang Chang,[1] Yi-Chieh Chang,[2] Yu-Han Chang,[3] Yuan-Hann Chang,[4,5] Chien-Han Chen,[4] Ching-Fang Chen,[1] Kuan-Yu Chen,[1] Yung-Fu Chen,[1, a)] Wei-Yuan Chiang,[2] Wei-Chen Chien,[3] Hien Thi Doan,[4] Wei-Cheng Hung,[1,4] Watson Kuo,[3] Shou-Bai Lai,[1] Han-Wen Liu,[1] Min-Wei OuYang,[1] Ping-I Wu,[1] and Shin-Shan Yu[1,5]

[1)] Department of Physics, National Central University, Taoyuan City 320317, Taiwan
[2)] National Synchrotron Radiation Research Center, Hsinchu 300092, Taiwan
[3)] Department of Physics, National Chung Hsing University, Taichung City 402202,

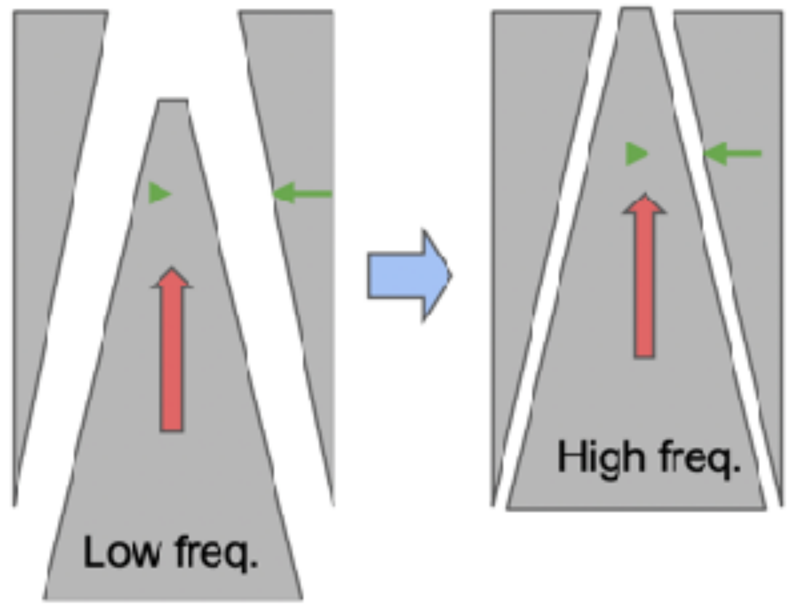



FIG. 2. TASEH axion detection experimental setup. (a) Schematic diagram of cryogen-free DR system. (b) Overall view picture of experimental setup.

2205.01477



ADMX EFR




ADMX Wedge design

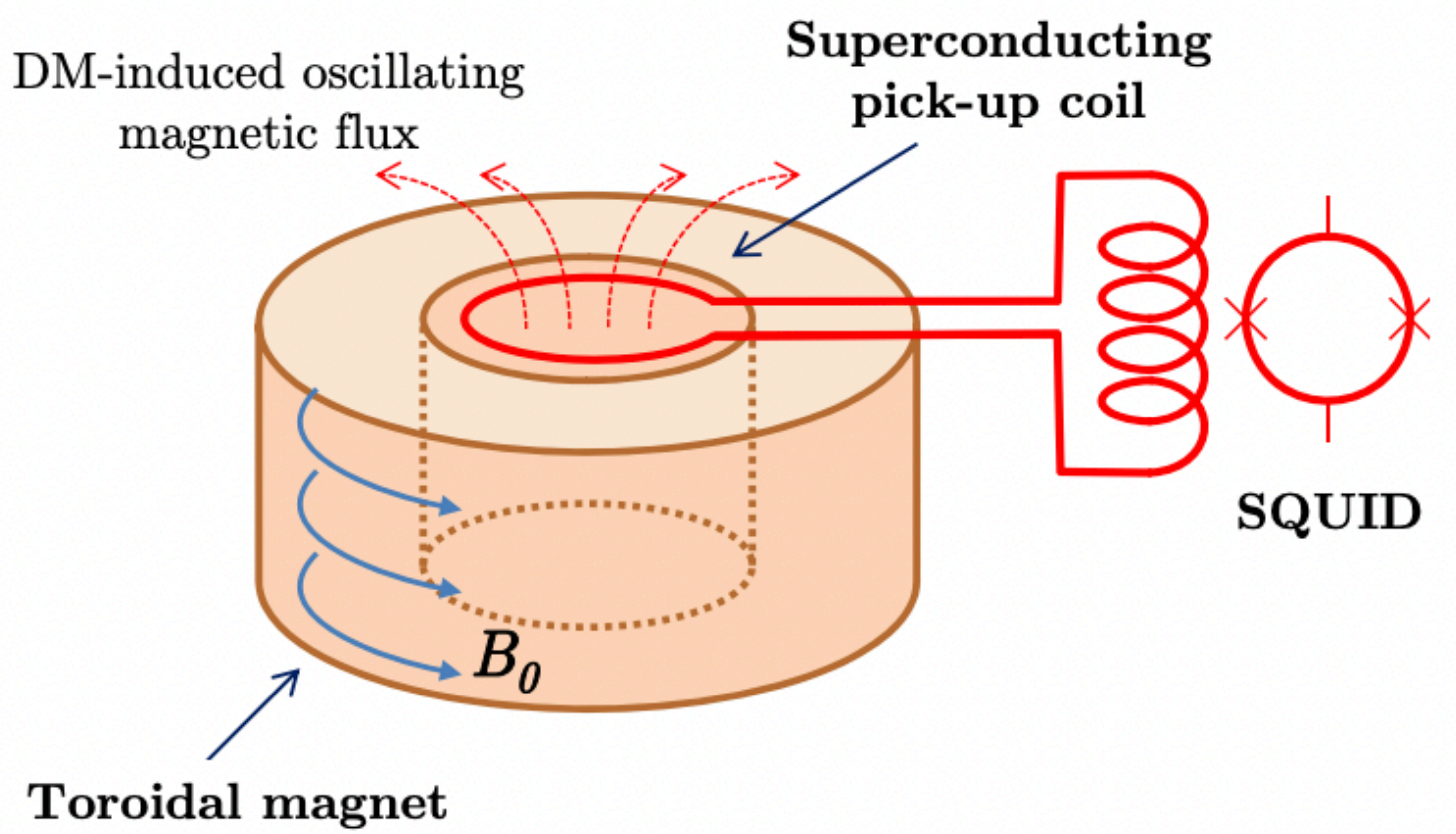
## Low-mass approach — "Lumped element detectors"

### e.g. SHAFT, ABRACADABRA, DMRadio, WISPLC

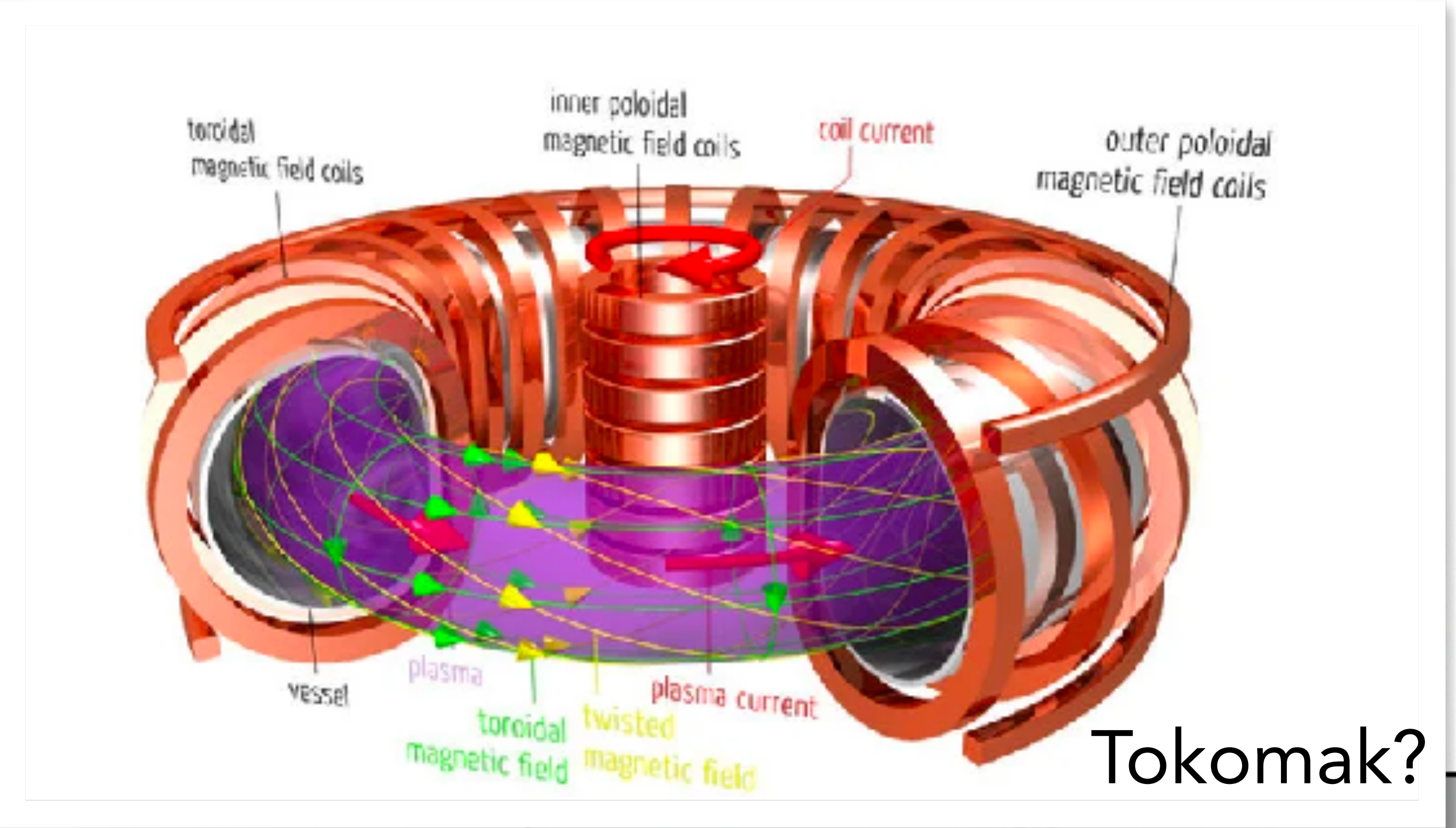
- Need to decouple the experiment size (V) from the Compton wavelength ($1/m_a$)
- Don't couple to axion effective current directly, instead look for secondary B-field induced by axion current
- **Measured B-field** can be enhanced geometrically by size of instrument

$$B_a \sim g_{a\gamma} B_0 (\partial_t a) \times R$$

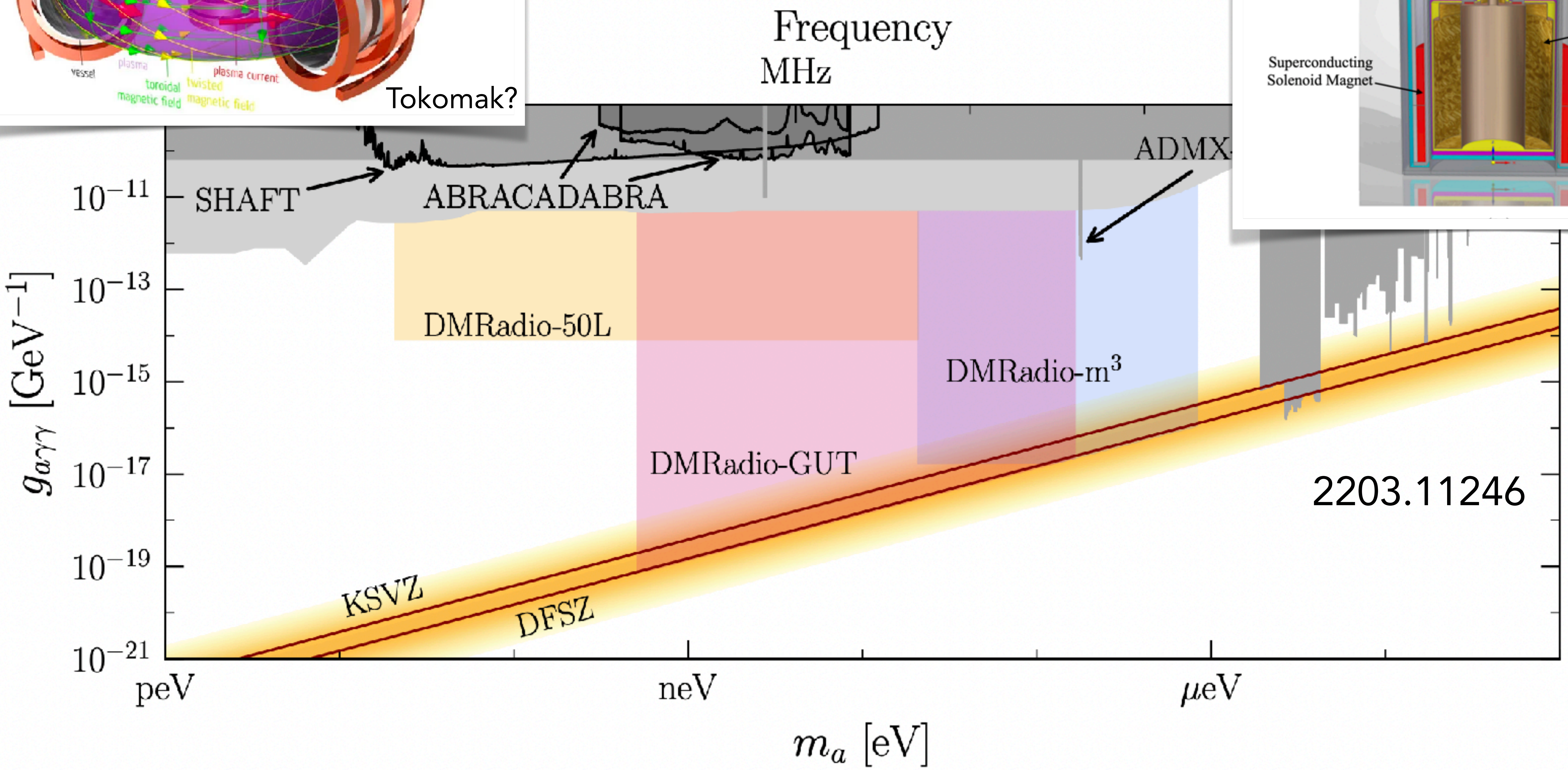
$$\sim 10^{-15}\,\mathrm{T} \left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}^{-1}}\right)\left(\frac{R}{1\,\mathrm{m}}\right)\left(\frac{B_0}{10\,\mathrm{T}}\right)$$



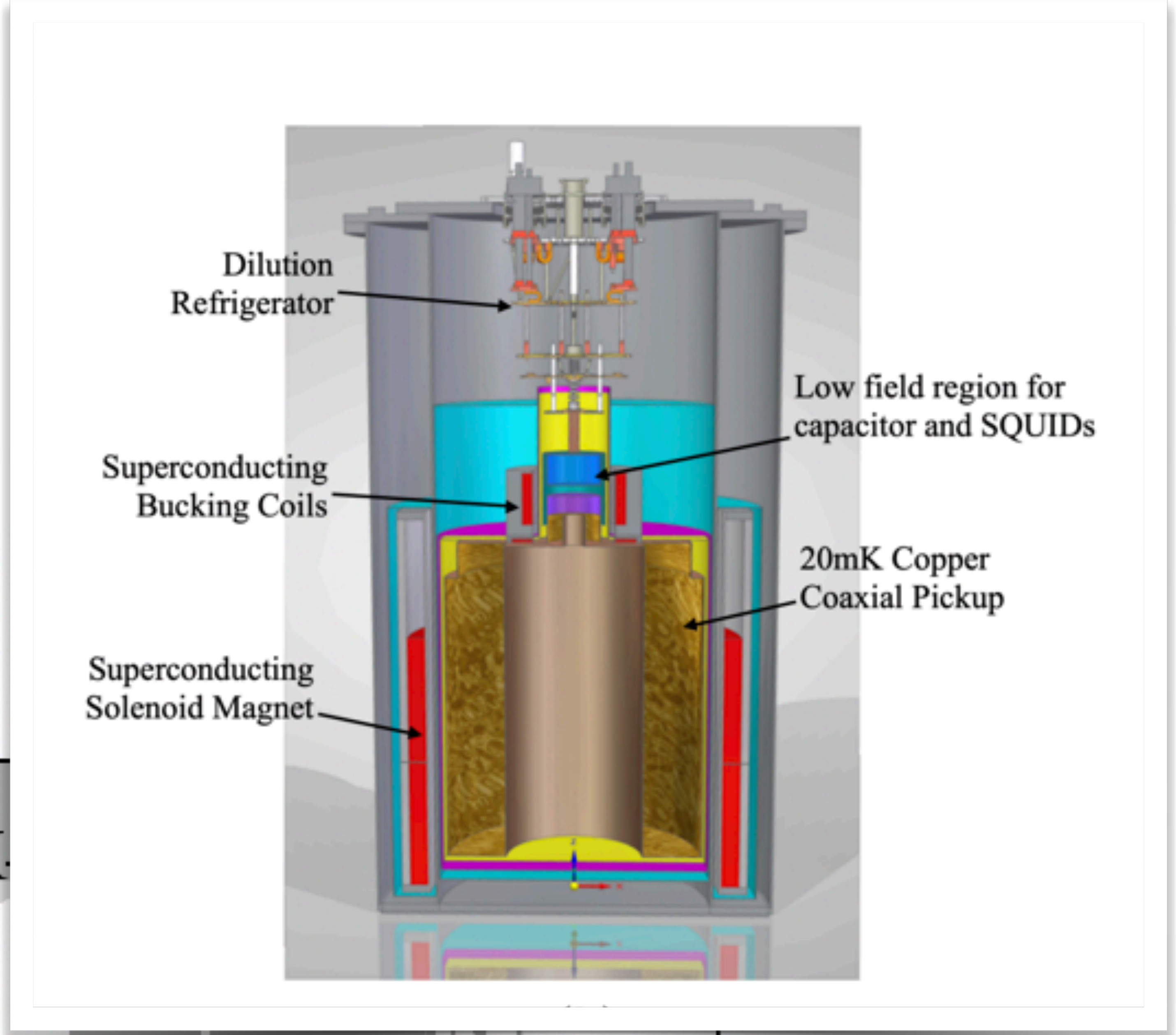
# DMRadio



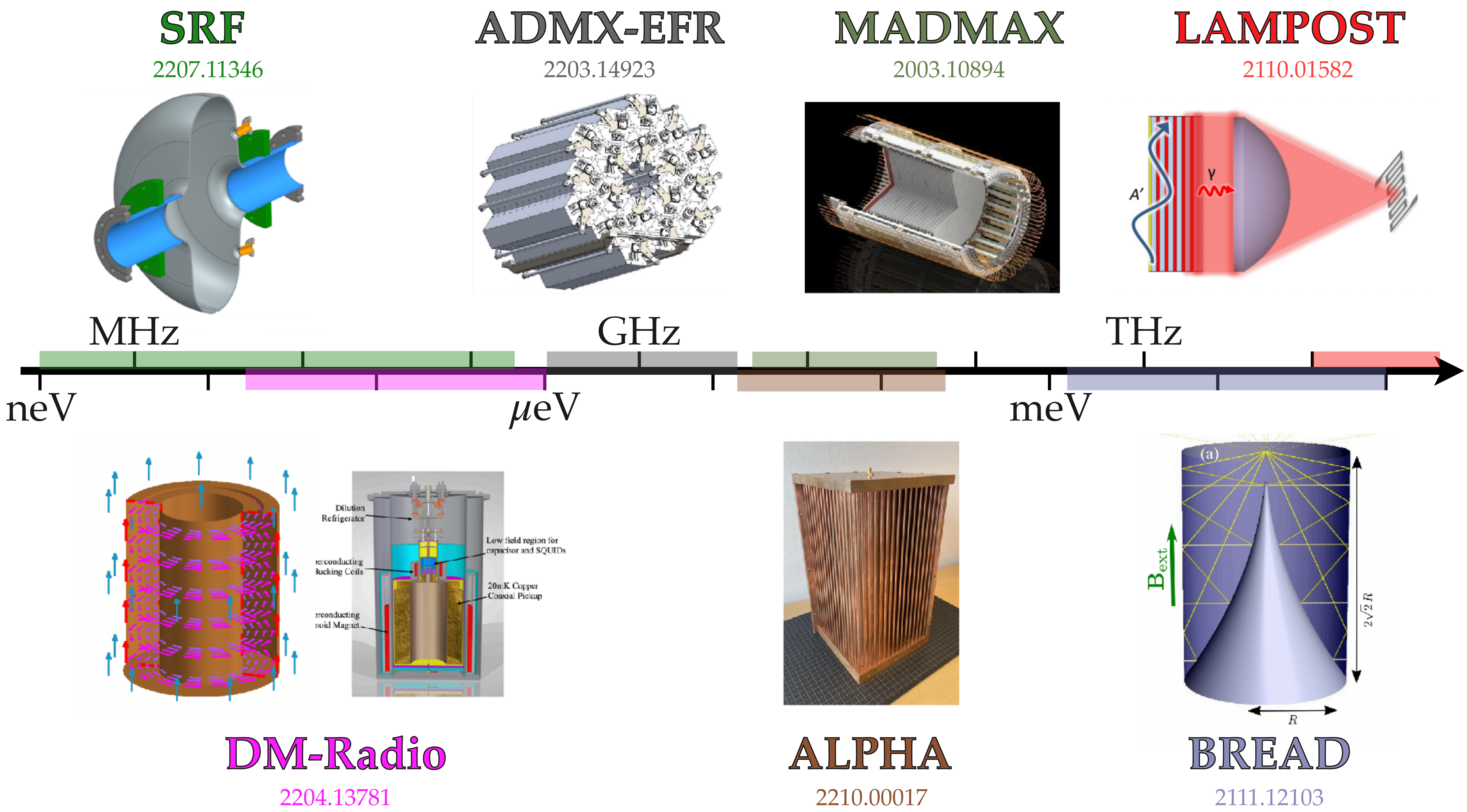
toroidal magnetic field coils
inner poloidal magnetic field coils
coil current
outer poloidal magnetic field coils
vessel
plasma
toroidal magnetic field
twisted magnetic field
plasma current
Tokomak?

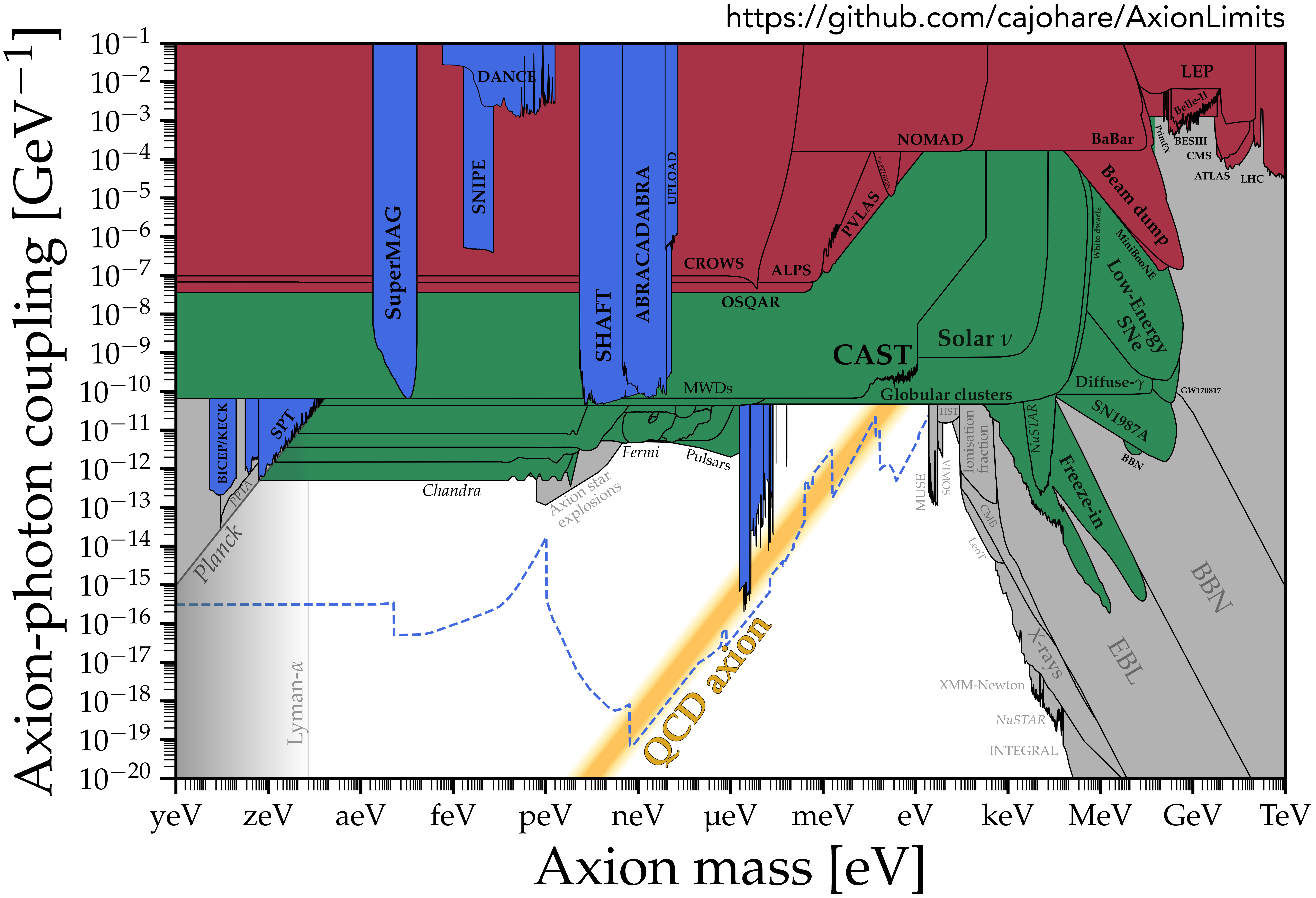



Frequency
MHz
SHAFT
ABRACADABRA
ADMX
DMRadio-50L
DMRadio-m$^3$
DMRadio-GUT
KSVZ
DFSZ
2203.11246
$10^{-11}$
$10^{-13}$
$10^{-15}$
$10^{-17}$
$10^{-19}$
$10^{-21}$
$g_{a\gamma\gamma}$ [GeV$^{-1}$]
peV
neV
$\mu$eV
$m_a$ [eV]

Dilution Refrigerator
Low field region for capacitor and SQUIDs
Superconducting Bucking Coils
20mK Copper Coaxial Pickup
Superconducting Solenoid Magnet


SRF
2207.11346
ADMX-EFR
2203.14923
MADMAX
2003.10894
LAMPOST
2110.01582
A′
γ
MHz
GHz
THz
neV
μeV
meV
Dilution Refrigerator
Low field region for capacitor and SQUIDs
20mK Copper Coaxial Pickup
(a)
B_ext
2√2 R
R
DM-Radio
2204.13781
ALPHA
2210.00017
BREAD
2111.12103



https://github.com/cajohare/AxionLimits
Axion-photon coupling [GeV$^{-1}$]
Axion mass [eV]
yeV
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
DANCE
SNIPE
SuperMAG
SHAFT
ABRACADABRA
UPLOAD
CROWS
OSQAR
ALPS
PVLAS
NOMAD
BaBar
LEP
Belle-II
PrimEx
BESIII
CMS
ATLAS
LHC
Beam dump
White dwarfs
MiniBooNE
Low-Energy SNe
CAST
Solar ν
MWDs
Globular clusters
Diffuse-γ
GW170817
SN1987A
BBN
BICEP/KECK
SPT
PPTA
Planck
Chandra
Fermi
Pulsars
Axion star explosions
HST
MUSE
VIMOS
Ionisation fraction
NuSTAR
Freeze-in
CMB
LeoT
X-rays
EBL
BBN
XMM-Newton
NuSTAR
INTEGRAL
Lyman-α
QCD axion

# Axion-nucleon coupling

$$\mathcal{L} = -\frac{g_{an}}{2m_n}\partial_\mu a\,\bar{n}\gamma^5\gamma^\mu n$$

---

**Hamiltonian for axion-nucleus interaction**

$$H \supset \frac{g_{an}}{2m_n}\nabla a \cdot \mathbf{S}_N$$

Axion field gradient $\propto \sqrt{\rho}\mathbf{v}$

Nuclear spin

**Hamiltonian for a nucleus in a B-field**

$$H \supset \gamma\mathbf{B} \cdot \mathbf{S}_N$$

"Gyromagnetic ratio"

The axion acts on nuclear spins as if it were a magnetic field of strength:

$$\mathbf{B}_a = \frac{g_{an}\sqrt{2\rho}}{2m_n\gamma}\mathbf{v}\sin(m_a t)$$

$$\approx 2 \times 10^{-17}\ \mathrm{T}\left(\frac{g_{an}}{10^{-9}}\right)\left(\frac{\gamma(^{129}\mathrm{Xe})}{\gamma}\right)$$

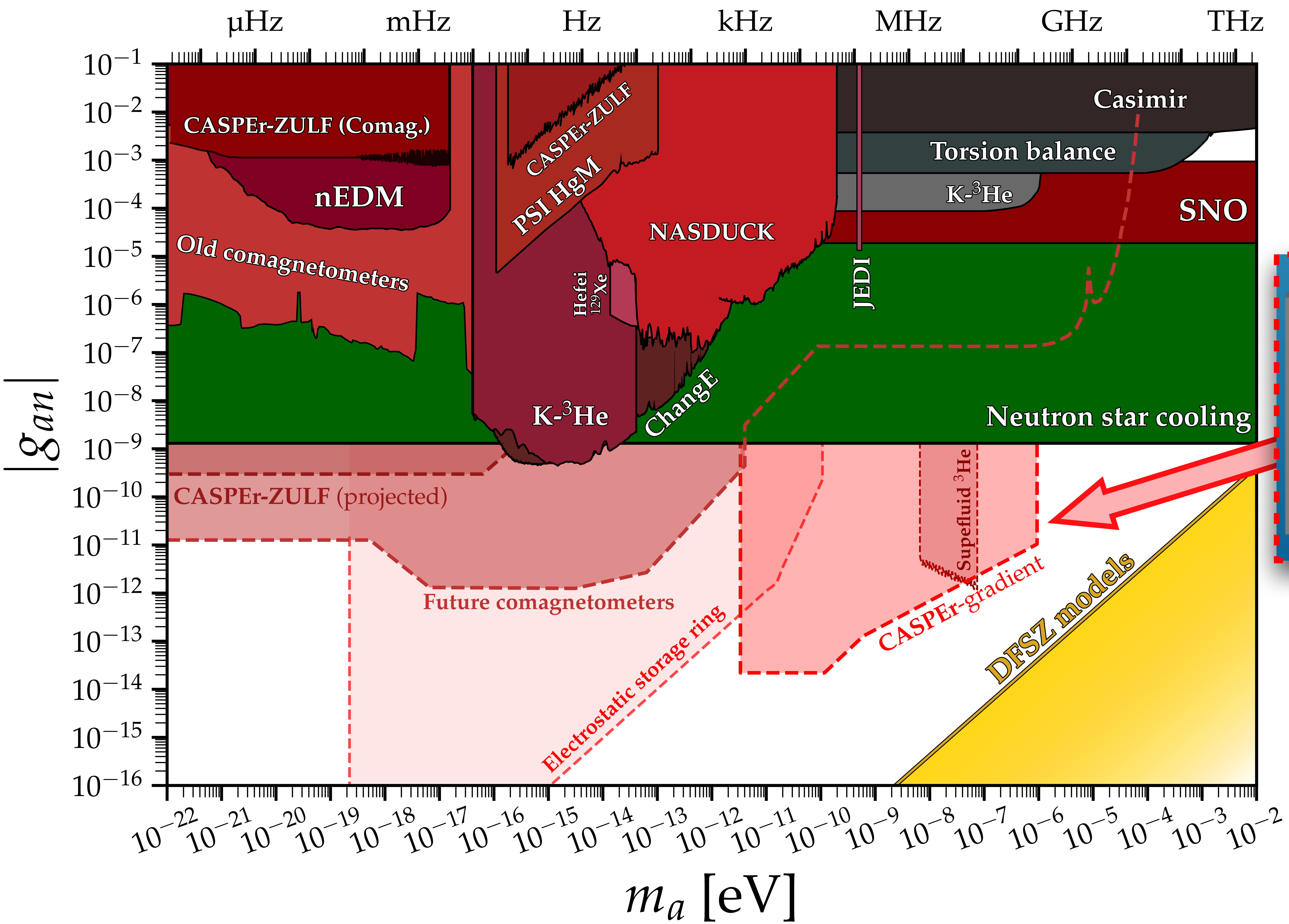
→ For sensitivity competitive with astrophysical bounds

How to measure tiny magnetic fields acting on nuclei?

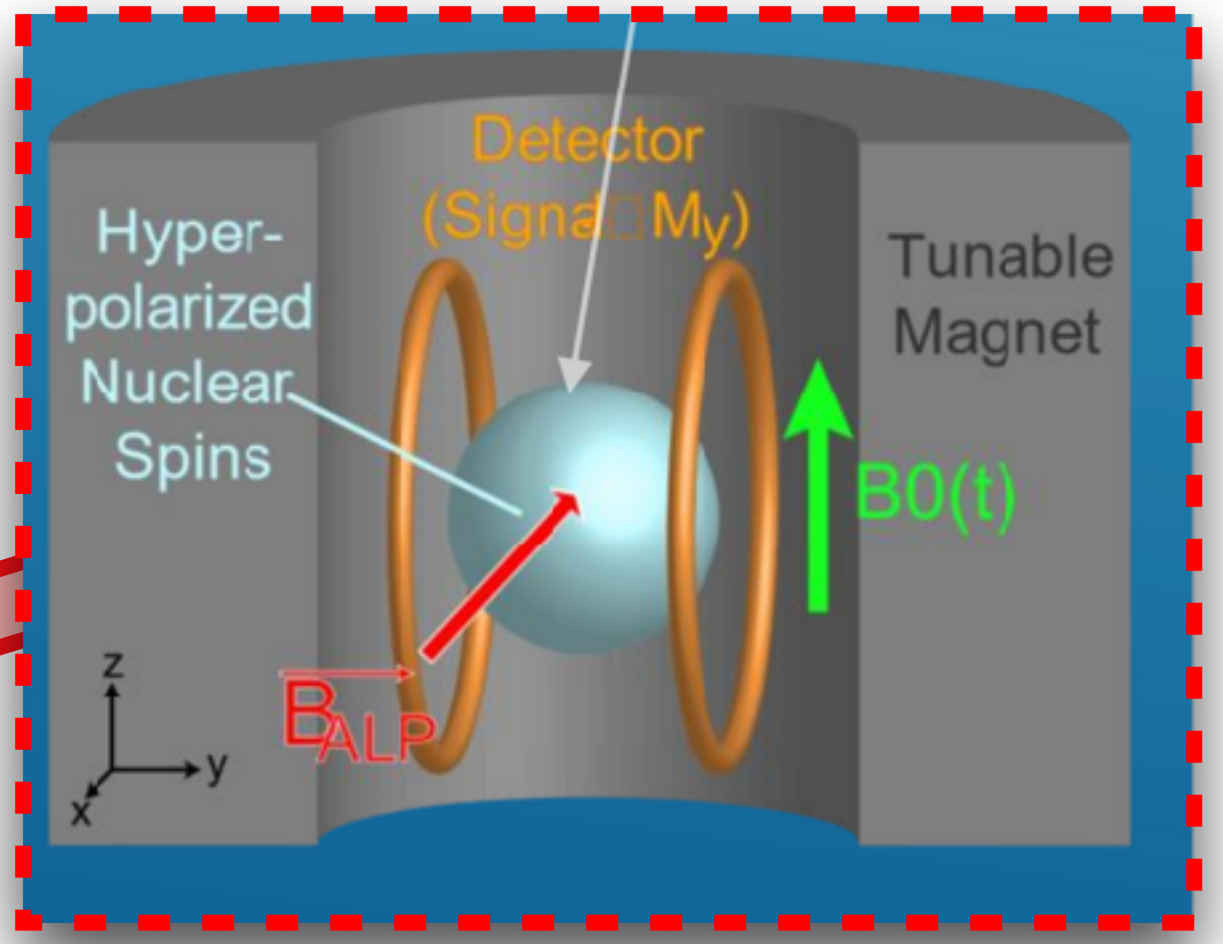
→ Comagnetometers

→ Nuclear magnetic resonance

https://github.com/cajohare/AxionLimits

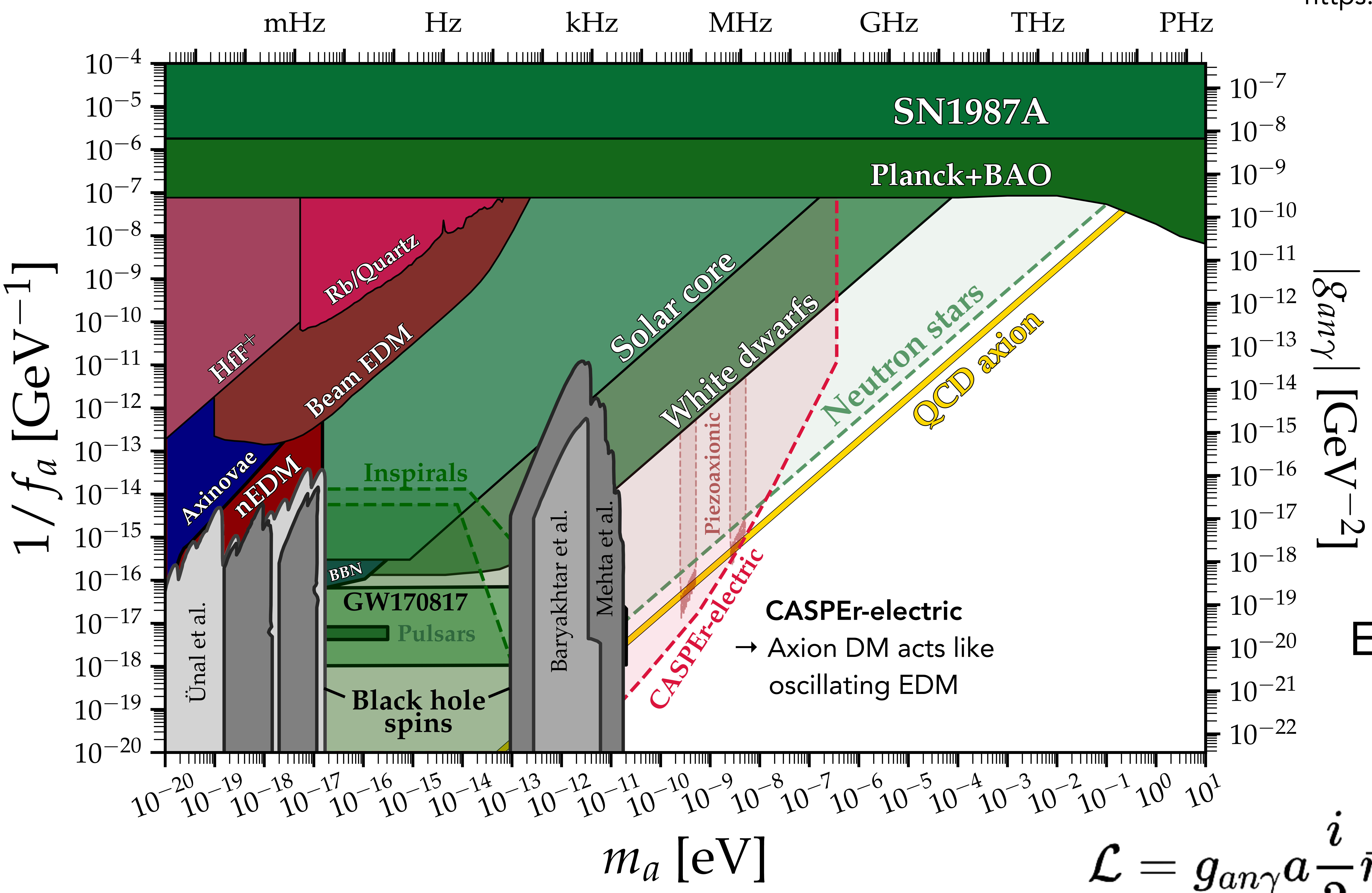



# CASPEr




$$\omega_L = \gamma B \to m_a$$

Larmor freq. tuned to scan across axion mass https://github.com/cajohare/AxionLimits/




Effectively an axion-EDM coupling

$$\mathcal{L} = g_{an\gamma} a \frac{i}{2} \bar{n} \sigma^{\mu\nu} \gamma^5 n F_{\mu\nu}$$

# Vector wave-dark matter:
## Dark photons

Extend SM gauge group: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$

with some gauge boson $X^\mu$

Below EW → $\mathcal{L} \supset -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$

"Kinetic mixing" with SM photon $\chi \ll 1$

Need a mass-generation mechanism, but that's it, very minimal model

Various bases one can choose to remove the kinetic mixing, e.g the "**interaction basis**", i.e. where A is the only thing that interacts with charges

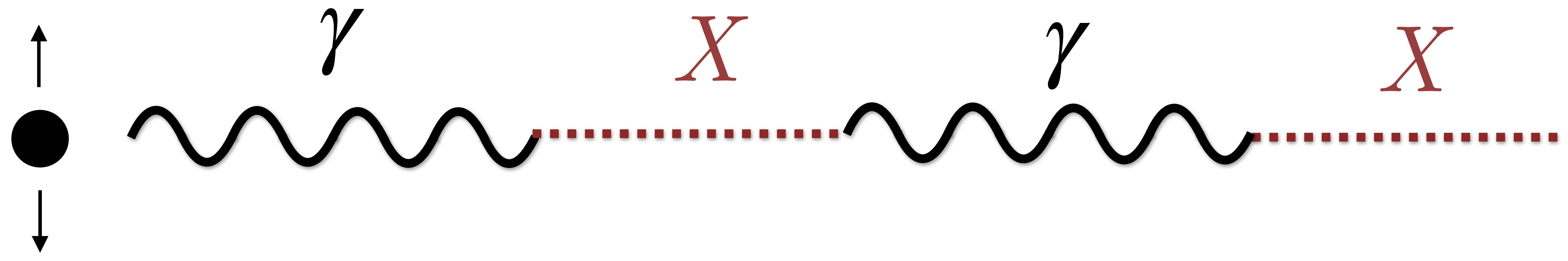
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu - \chi m_X^2 A_\mu X^\mu + J^\mu A_\mu$$

However a field redefinition can give you a form with a diagonal mass matrix, the "**propagation basis**", which reveals the states that actually propagate in vacuum

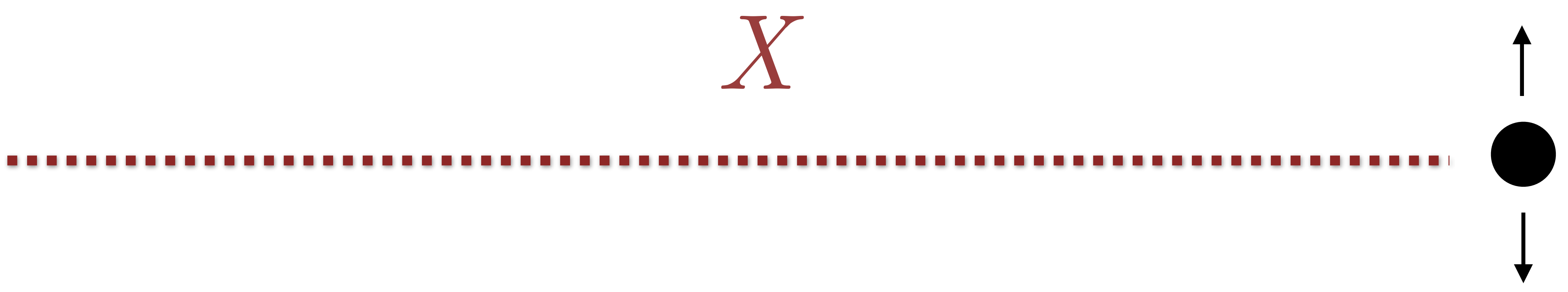
$$\mathcal{L} = -\frac{1}{4}\,\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \frac{1}{4}\mathbf{X}_{\mu\nu}\mathbf{X}^{\mu\nu} + \frac{1}{2}m_X^2\mathbf{X}_\mu\mathbf{X}^\mu - J^\mu[\mathbf{A}_\mu + \chi\mathbf{X}_\mu]$$

However the thing that interacts with electric charges is now $A + \chi X$

The resolution to these two pictures is this: when you move electric charges you produce the “active” interaction state (the SM photon), however this active state is superposition of the two propagation states with different masses, and so they will start to oscillate

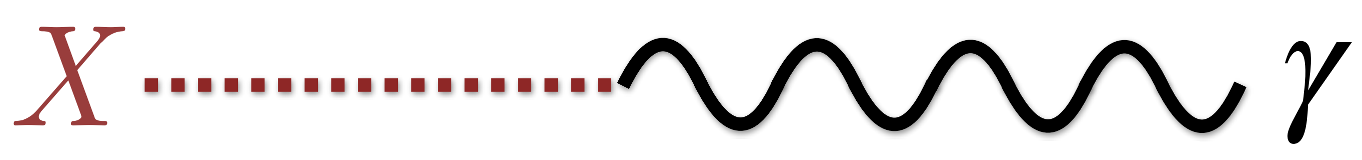


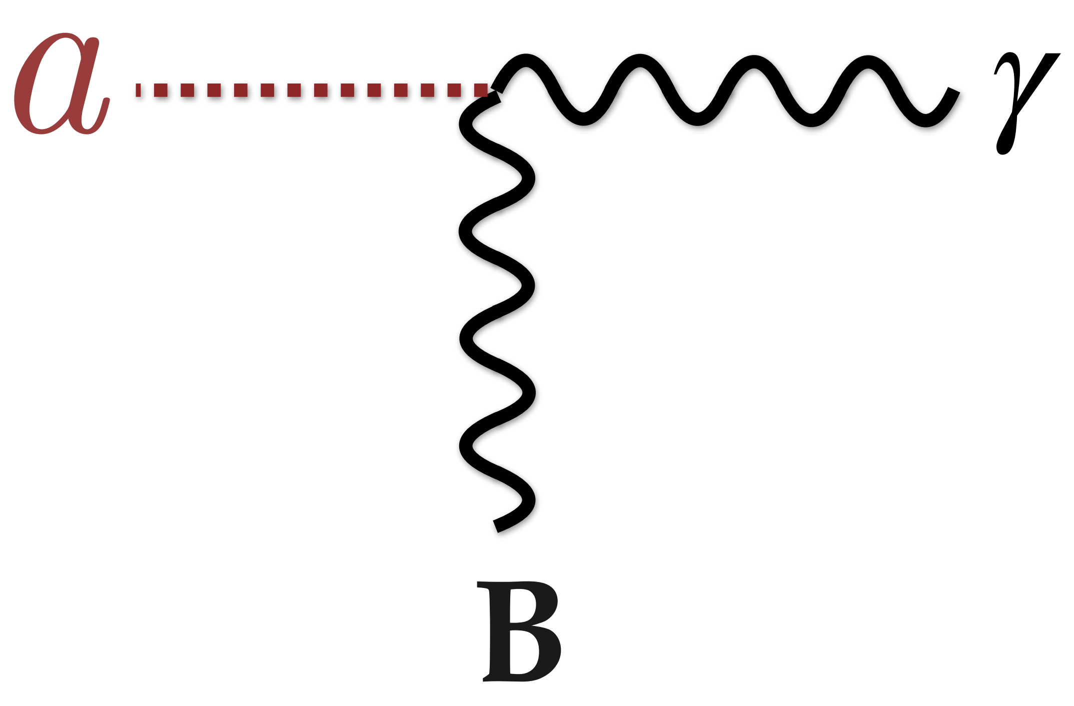

In the case of dark matter we imagine a condensate in the massive propagation state, however this state couples to $J_\mu$ so **it can move electric charges.**



# Dark photon electrodynamics

DPs act in a similar way to the axion, only they do not require a B-field for the coupling to E&M to be switched on. (Easiest to see by writing down the effective current in each case)



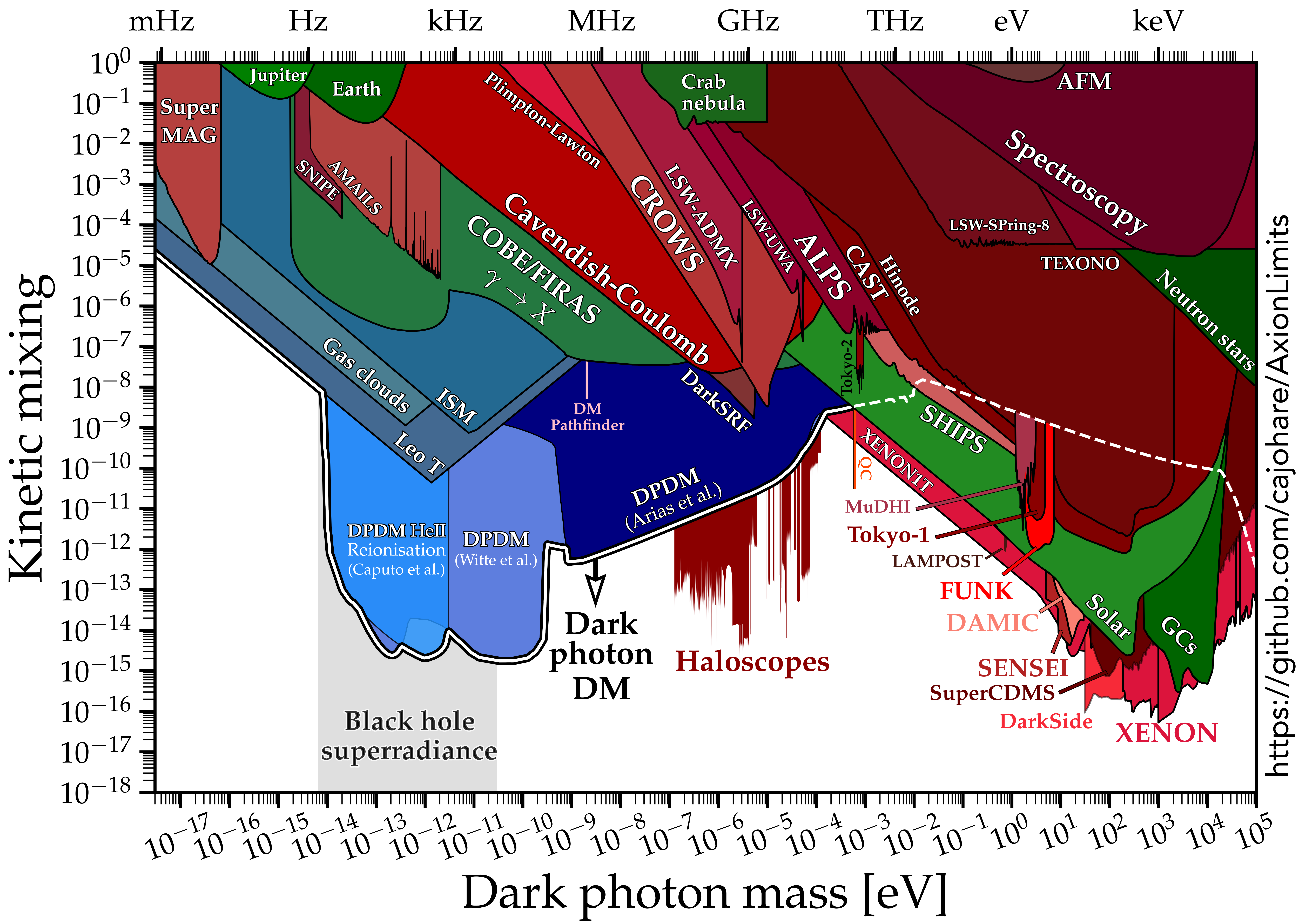




Can translate between the two

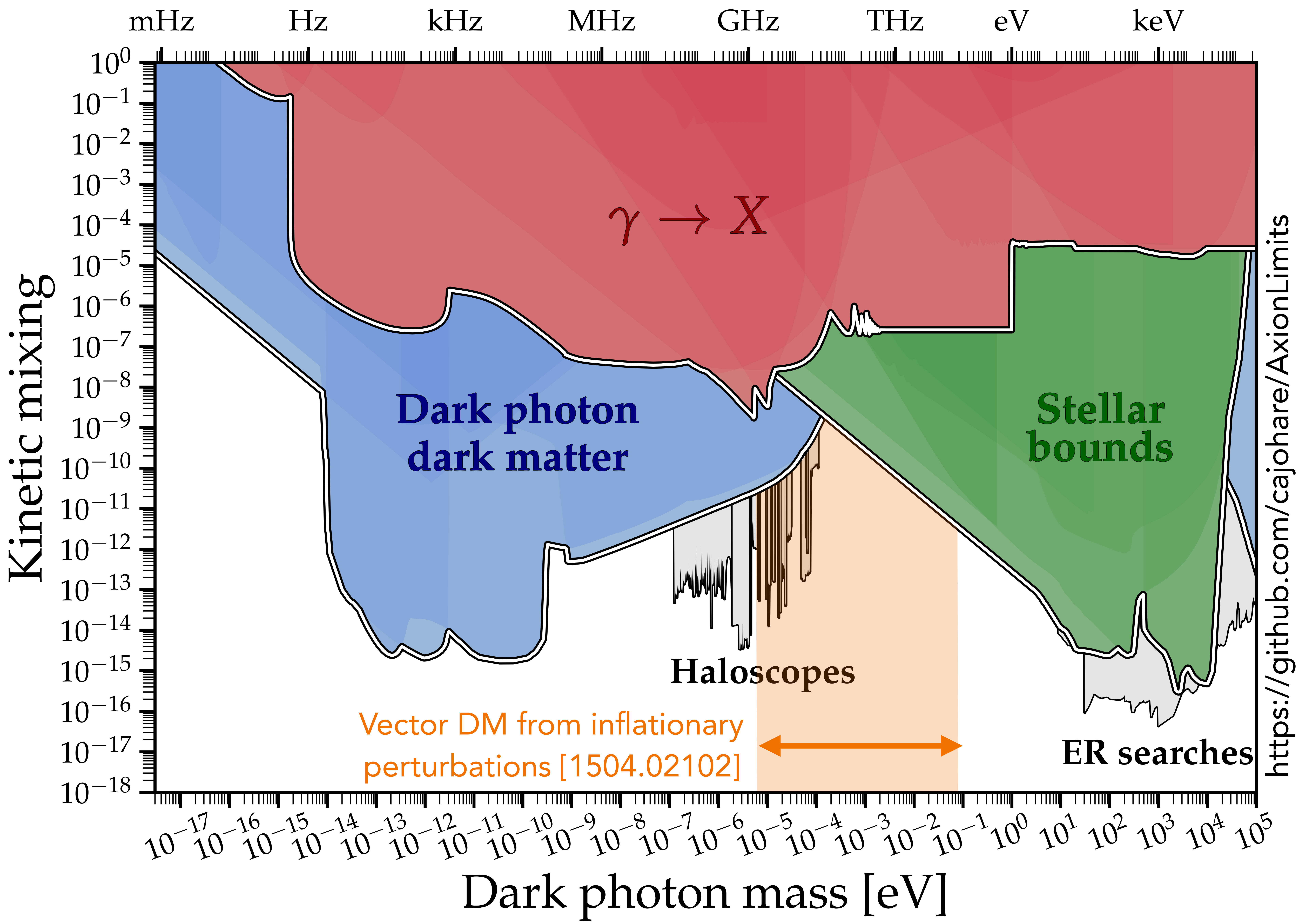
**Dark photons**

$$\chi m_X \leftrightarrow g_{a\gamma} B$$

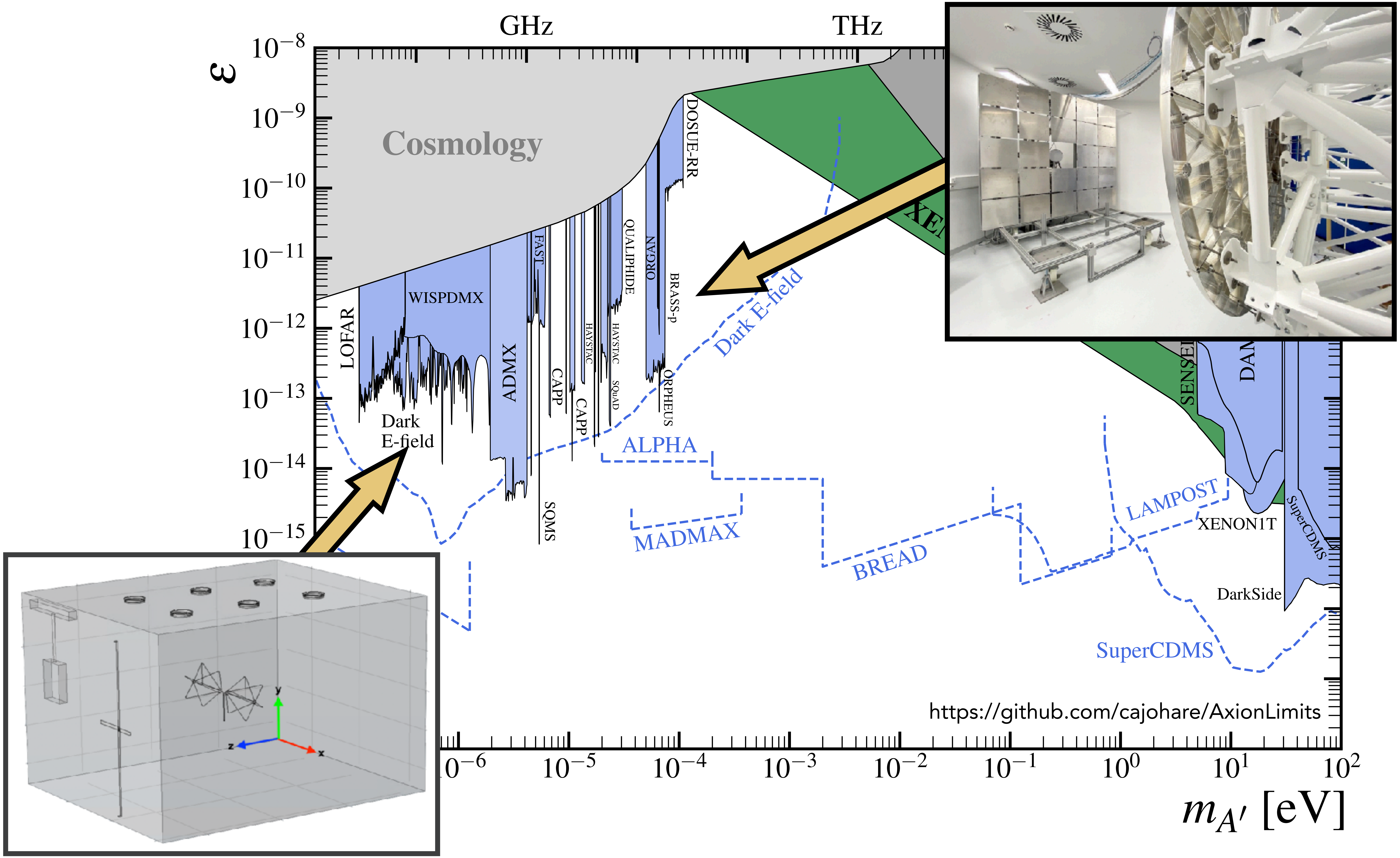
**Axions**



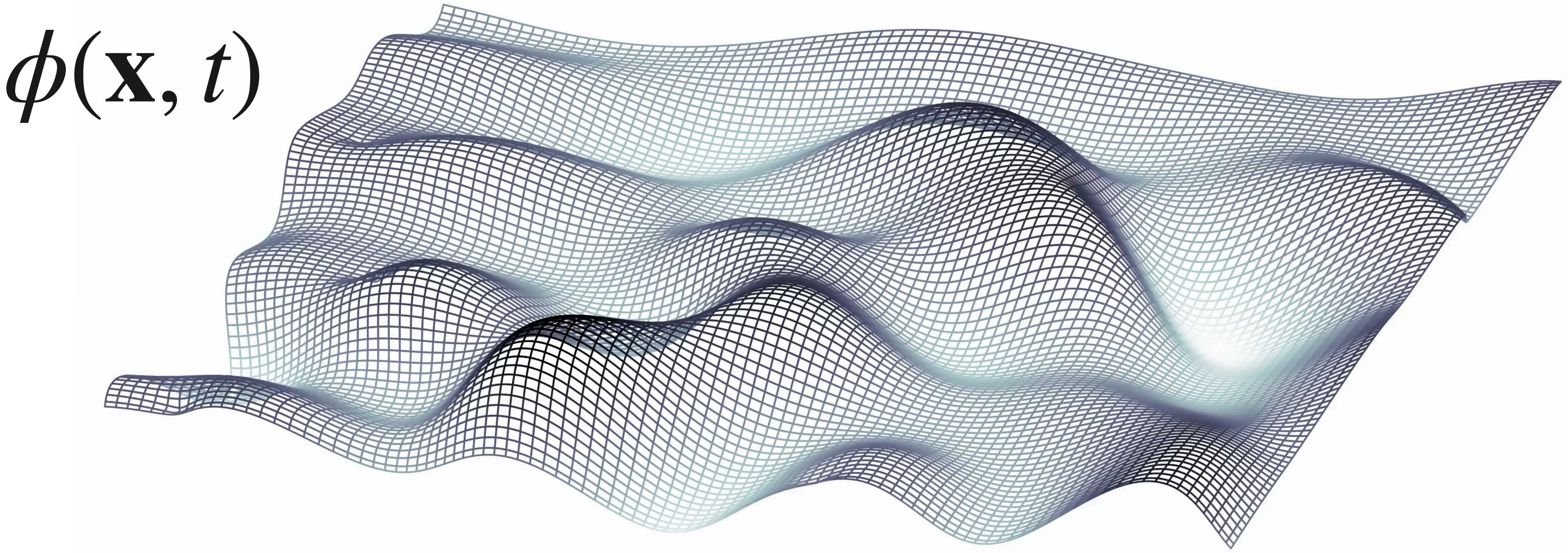
mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
https://github.com/cajohare/AxionLimits
Super MAG
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
SNIPE
AMAILS
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Hinode
LSW-SPring-8
TEXONO
Neutron stars
Cavendish-Coulomb
COBE/FIRAS
$\gamma \to X$
Gas clouds
ISM
Leo T
DM Pathfinder
DarkSRF
Tokyo-2
SHIPS
XENON1T
QC
DPDM (Arias et al.)
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs
Black hole superradiance



mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
$\gamma \to X$
Dark photon dark matter
Stellar bounds
Haloscopes
ER searches
Vector DM from inflationary perturbations [1504.02102]
https://github.com/cajohare/AxionLimits


GHz
THz
$\varepsilon$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
Cosmology
DOSUE-RR
WISPDMX
LOFAR
ADMX
FAST
CAPP
HAYSTAC
QUALIPHIDE
ORGAN
BRASS-p
SQuAD
ORPHEUS
SQMS
Dark E-field
ALPHA
MADMAX
BREAD
LAMPOST
SENSEI
XENON1T
SuperCDMS
DarkSide
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$m_{A'}$ [eV]
https://github.com/cajohare/AxionLimits

# Scalar dark matter



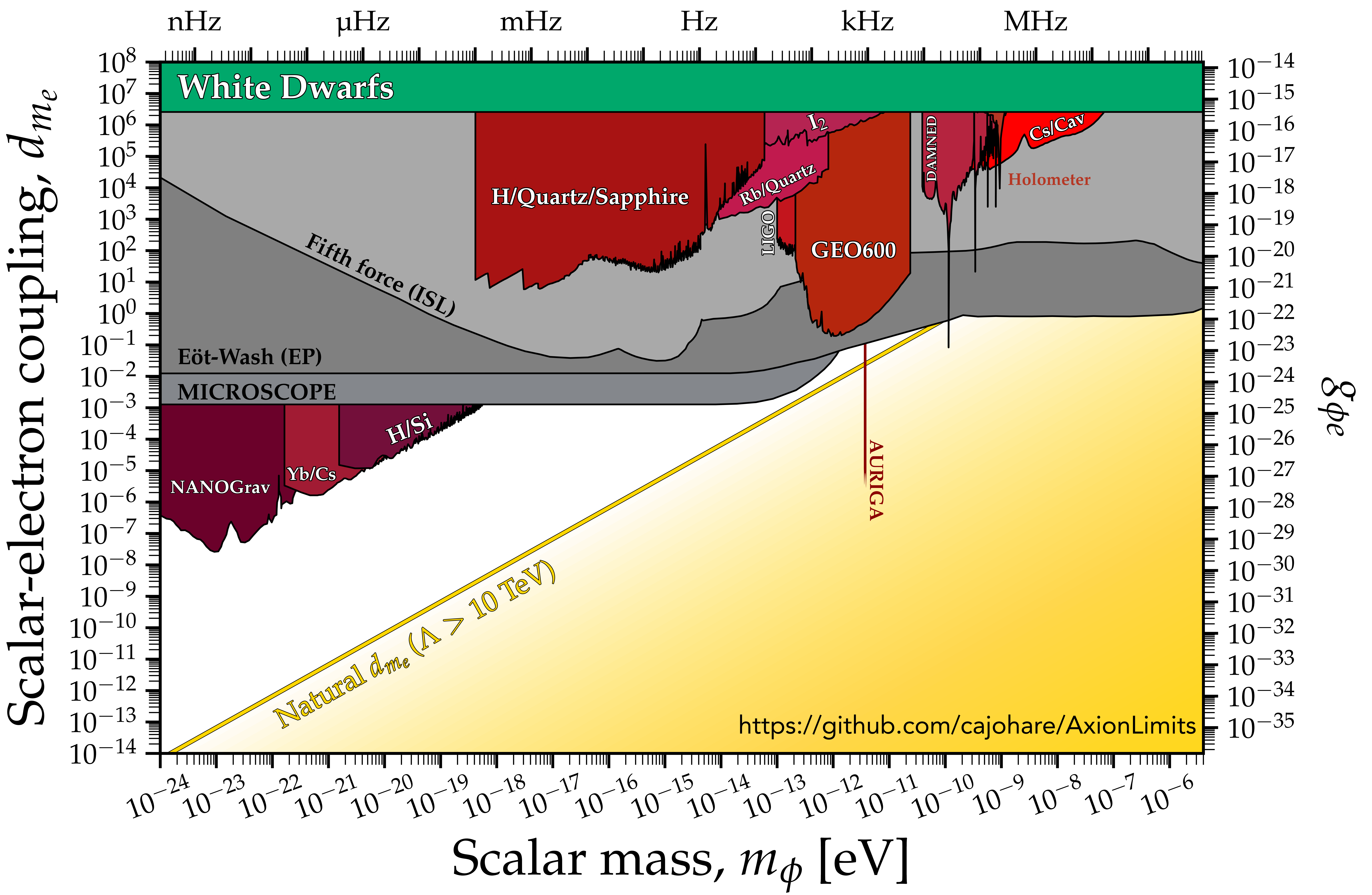

$$\mathcal{L} = \cdots + \frac{1}{4} g_\gamma \phi(\mathbf{x}, t) F_{\mu\nu} F^{\mu\nu} - g_\psi \phi(\mathbf{x}, t) \bar{\psi} \psi$$

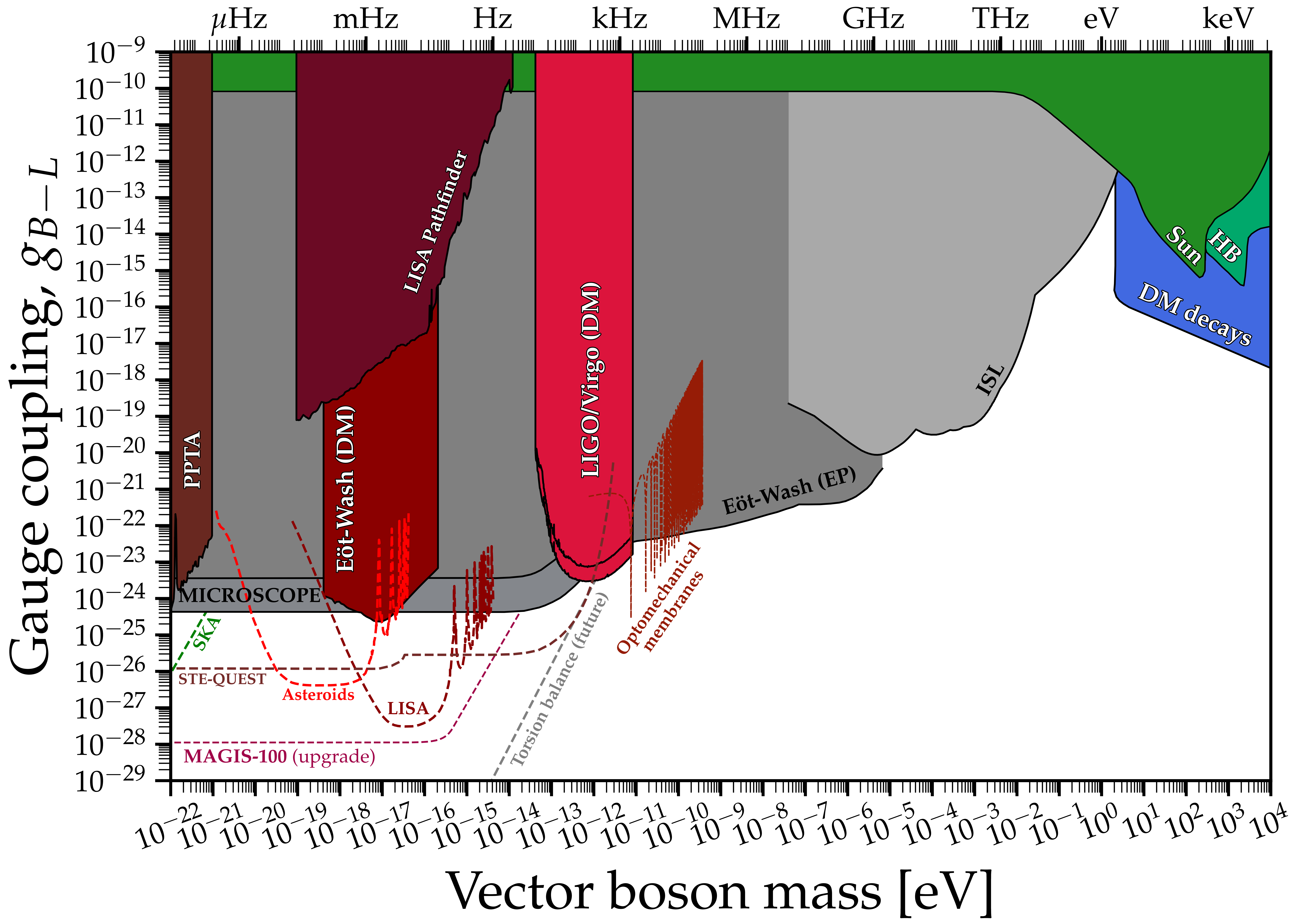
**Interaction looks like a mass term**

→ i.e. time-varying electron mass

$$m_e(\mathbf{x}, t) = m_e\big(1 + g_e \phi(\mathbf{x}, t)\big)$$

# Scalar dark matter coupled to electron





μHz
mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Gauge coupling, $g_{B-L}$
Vector boson mass [eV]
PPTA
LISA Pathfinder
Eöt-Wash (DM)
LIGO/Virgo (DM)
ISL
Sun
HB
DM decays
Eöt-Wash (EP)
MICROSCOPE
SKA
STE-QUEST
Asteroids
LISA
MAGIS-100 (upgrade)
Torsion balance (future)
Optomechanical membranes