Introduction to dark matter direct detection

sample text

Kiaron O'Hair

Introduction to 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

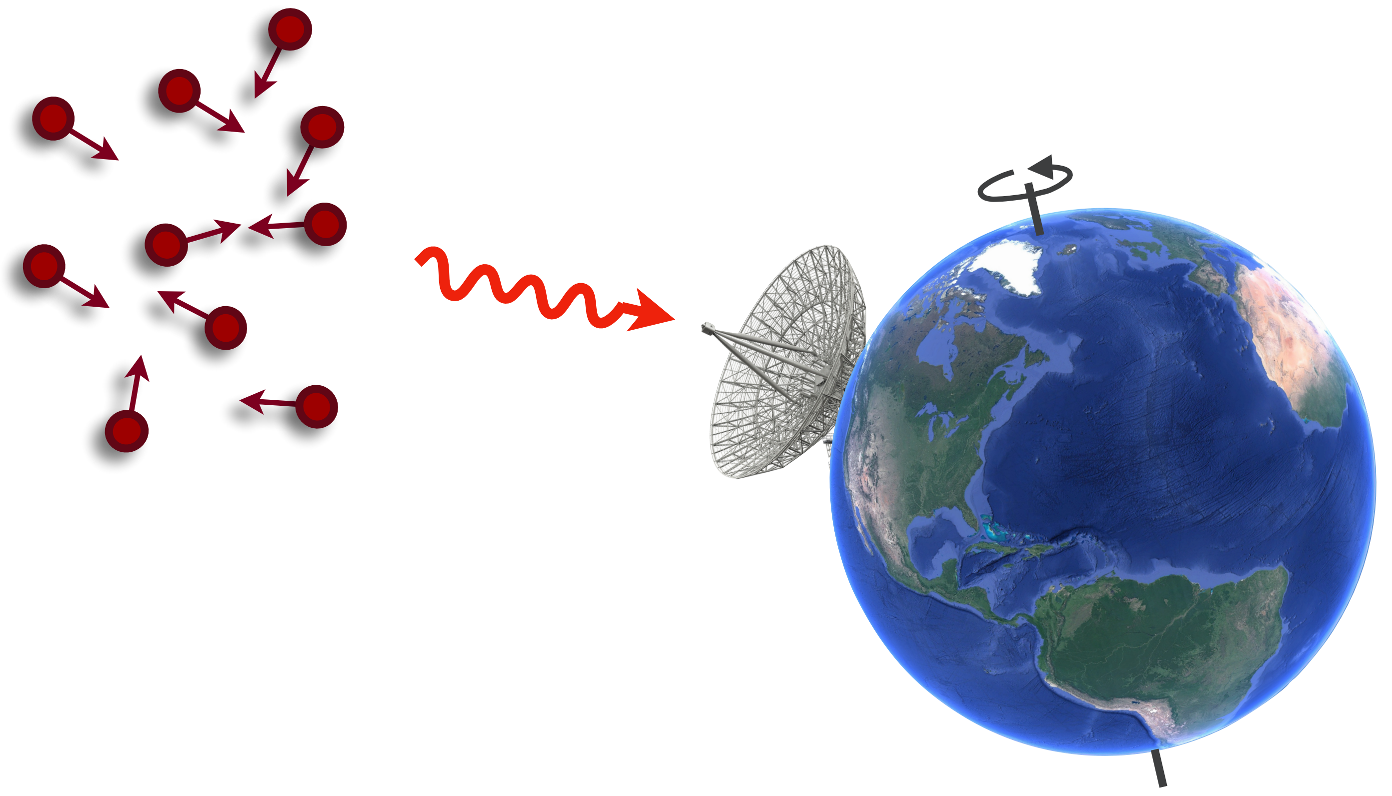
What is "direct detection"?

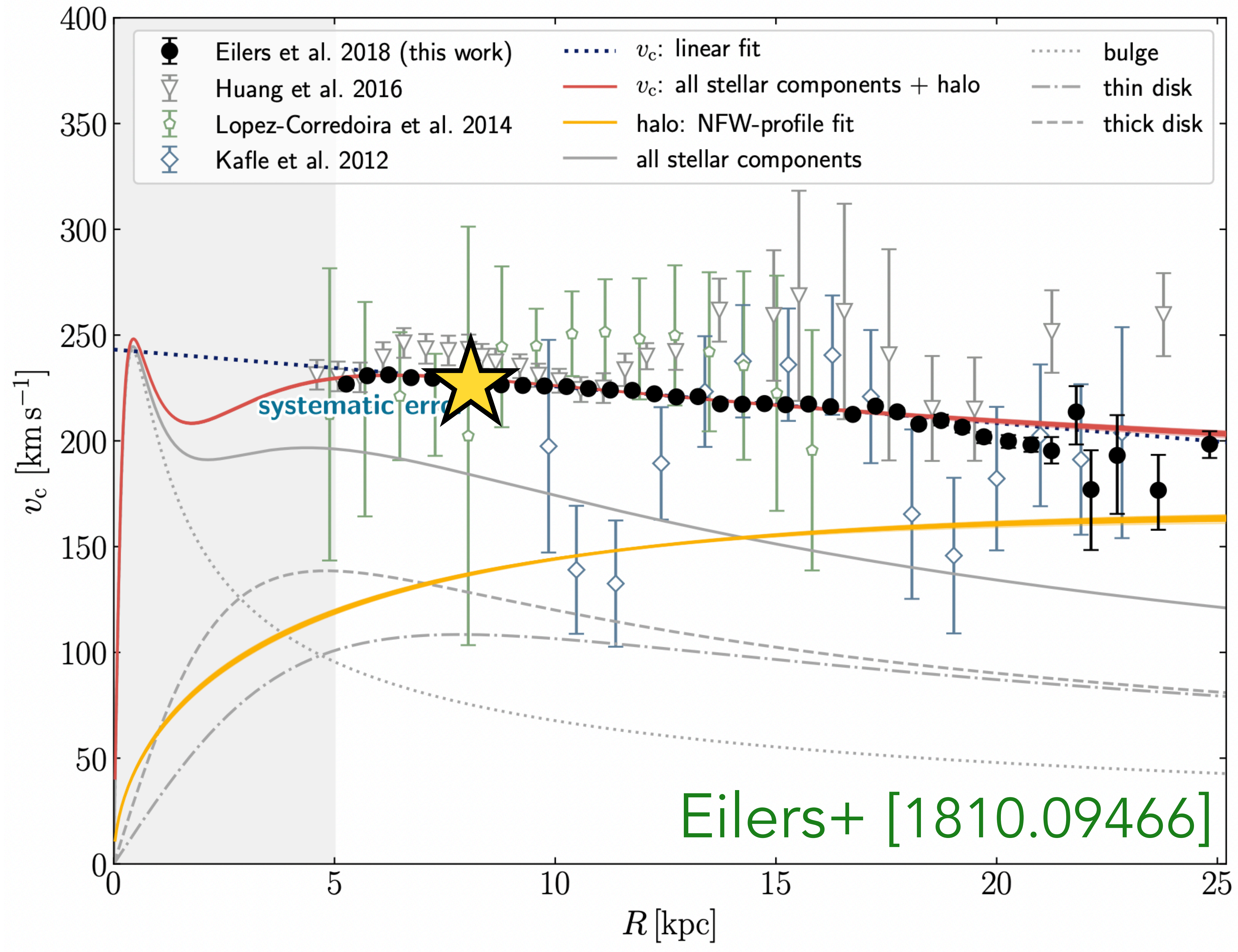
Direct detection

Dark matter comes in from galaxy, interacts inside laboratory experiment

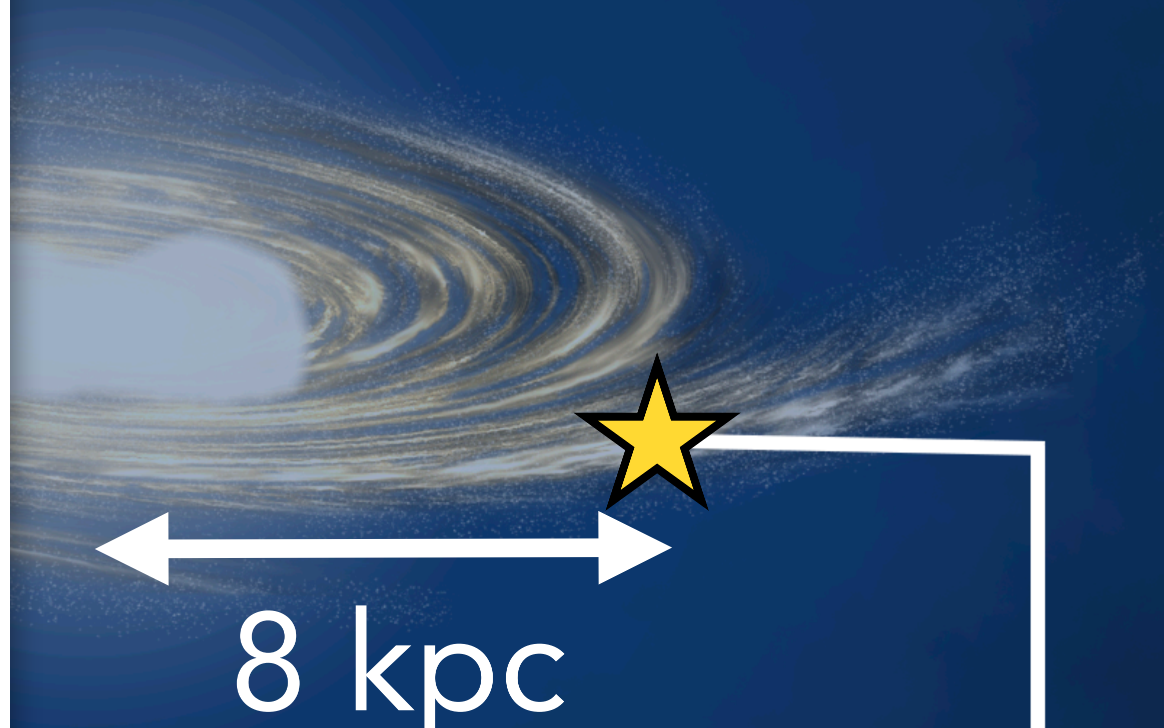
Indirect detection

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



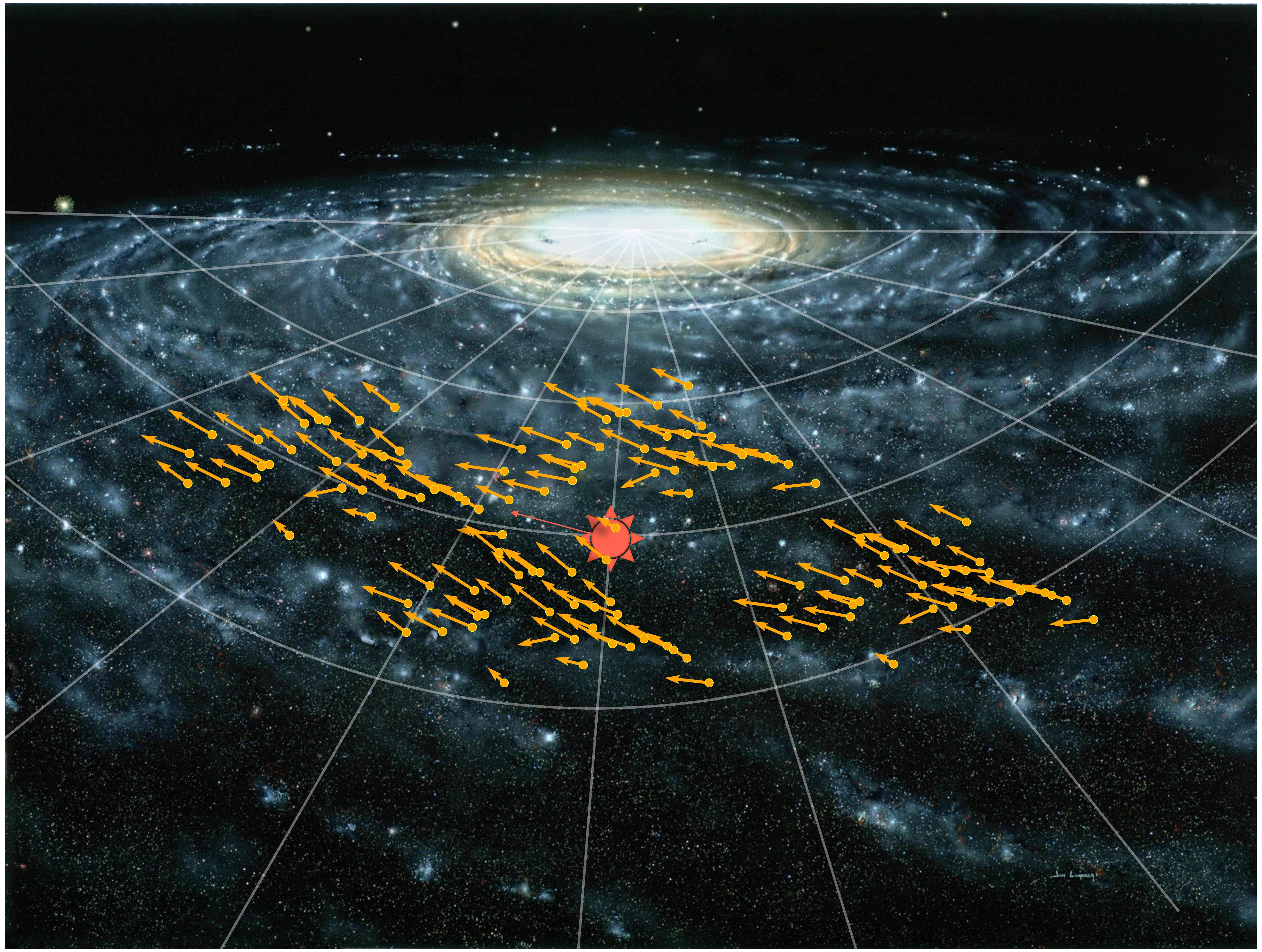


$\rho(R = 8\,\mathrm{kpc}) = 0.3 \pm 0.03\ \mathrm{GeV/cm^3}$



Dark matter in the Solar System

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



Model

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

(collisionless) Boltzmann eq.

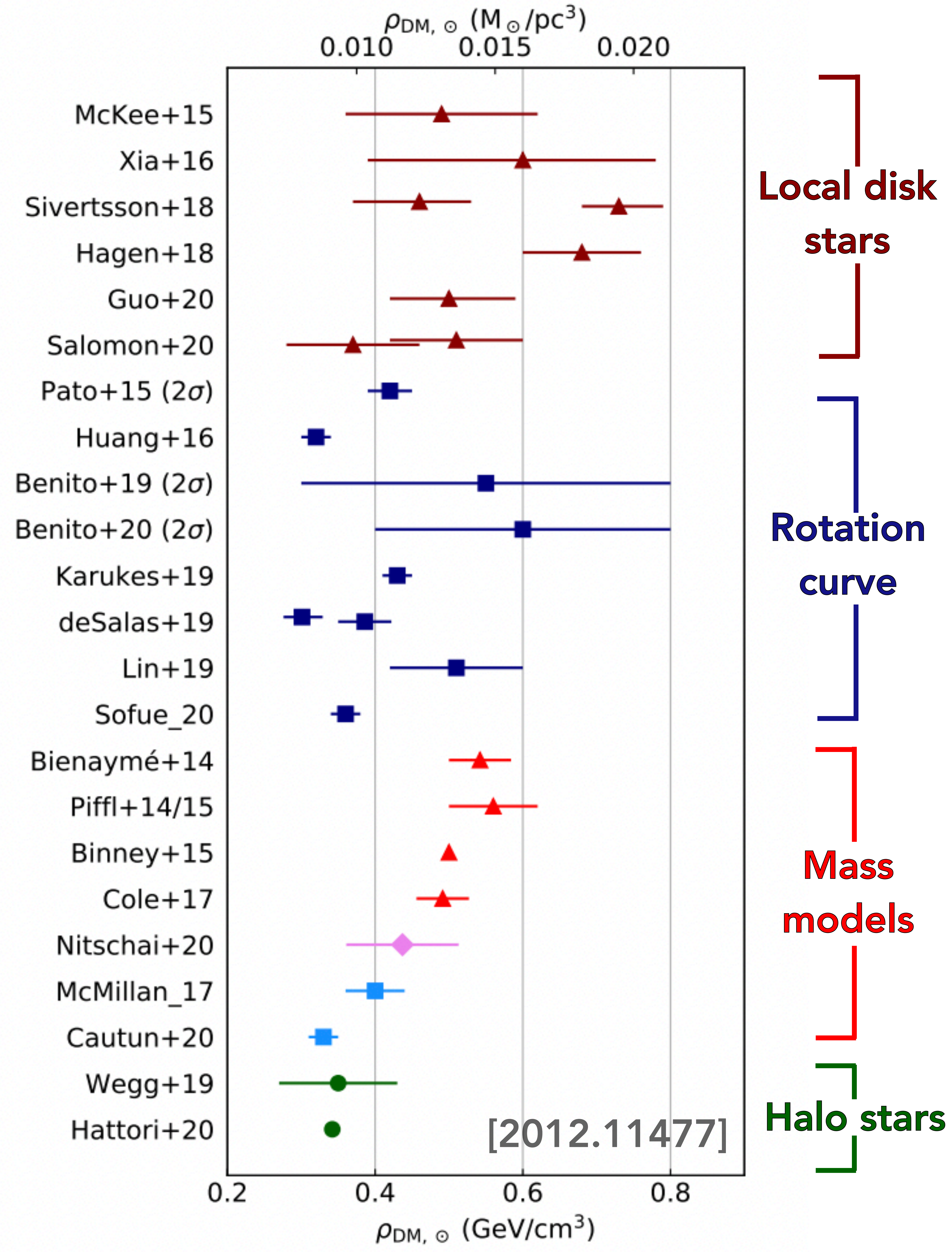
Distribution function → Grav. potential

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

Poission eq.

Grav. potential → matter density

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



Long history of this

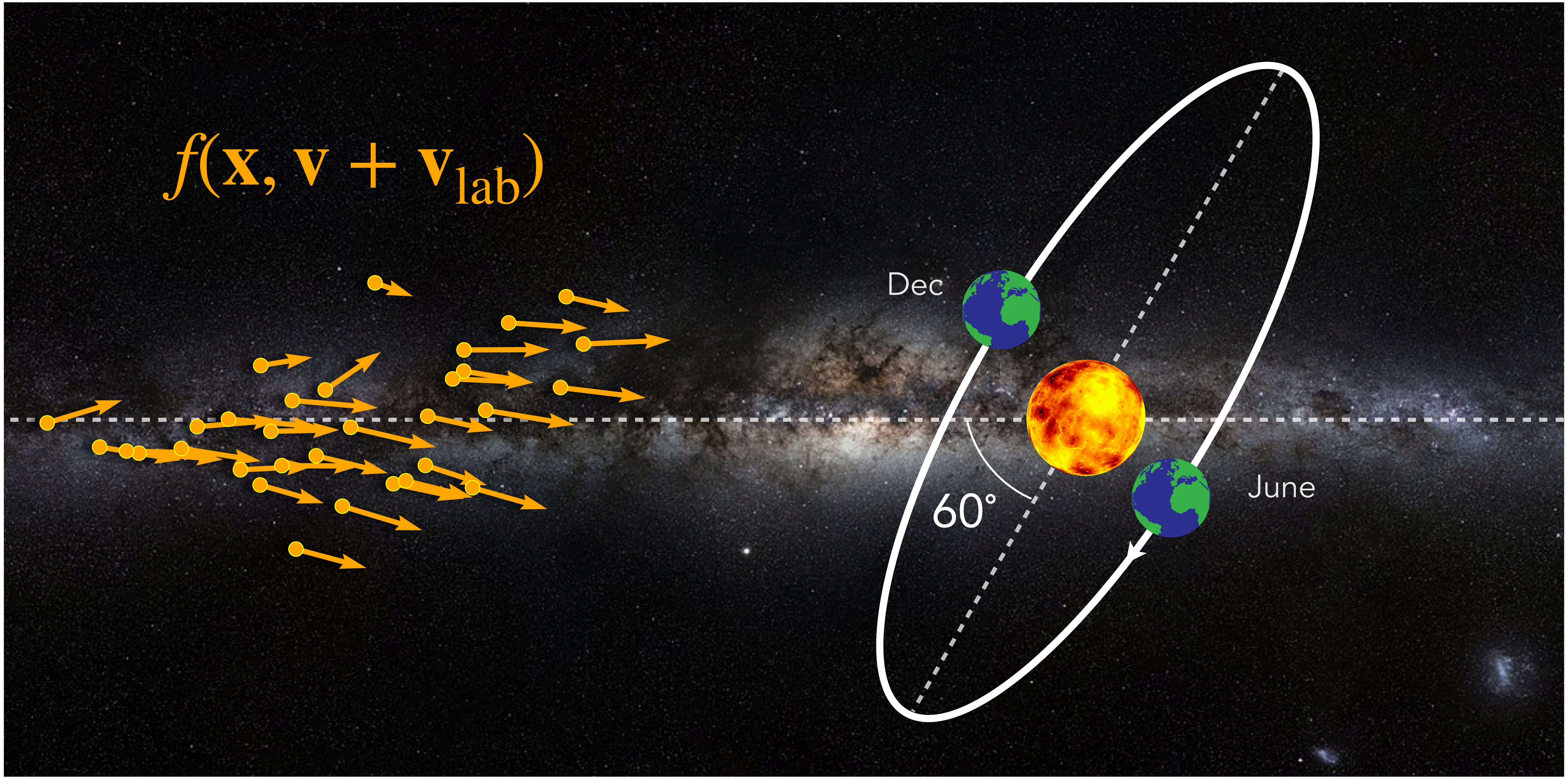
(Kapteyn 1922, Oort 1932)

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

$\rho_{\rm DM} = 0$ excluded at many σ

→ 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



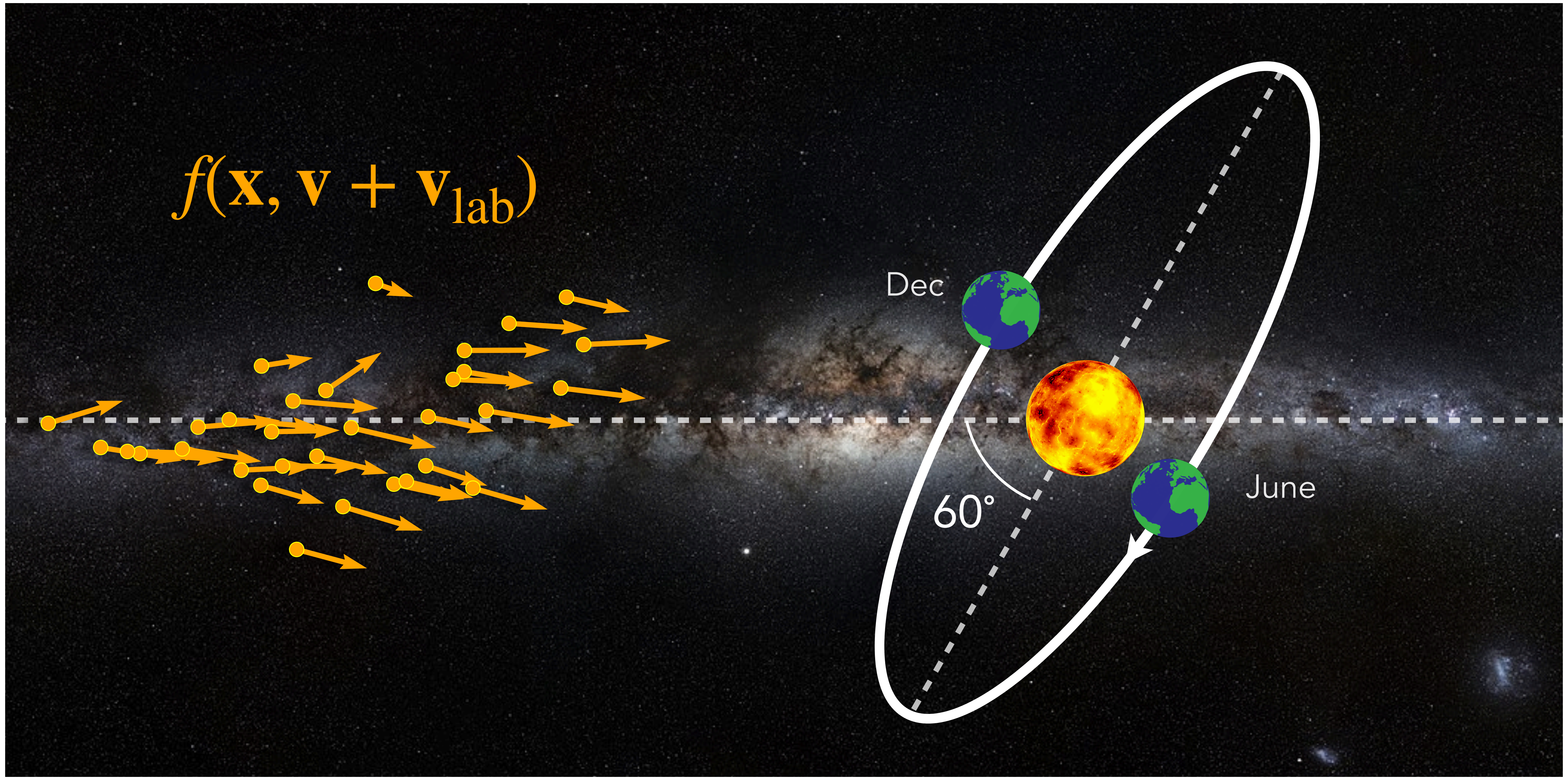
Assuming the dark matter does not co-rotate with the disk, most effects come about from our laboratory's motion **through** the dark matter: $v_{\rm lab} \sim 300$ km/s

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

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

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

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

$$\mathbf{v}_{\rm lab} = \underbrace{\mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec}}_{\text{Sun: 260 km/s}} + \underbrace{\mathbf{v}_{\oplus,\,\rm rev.}(t)}_{\text{Earth}}$$

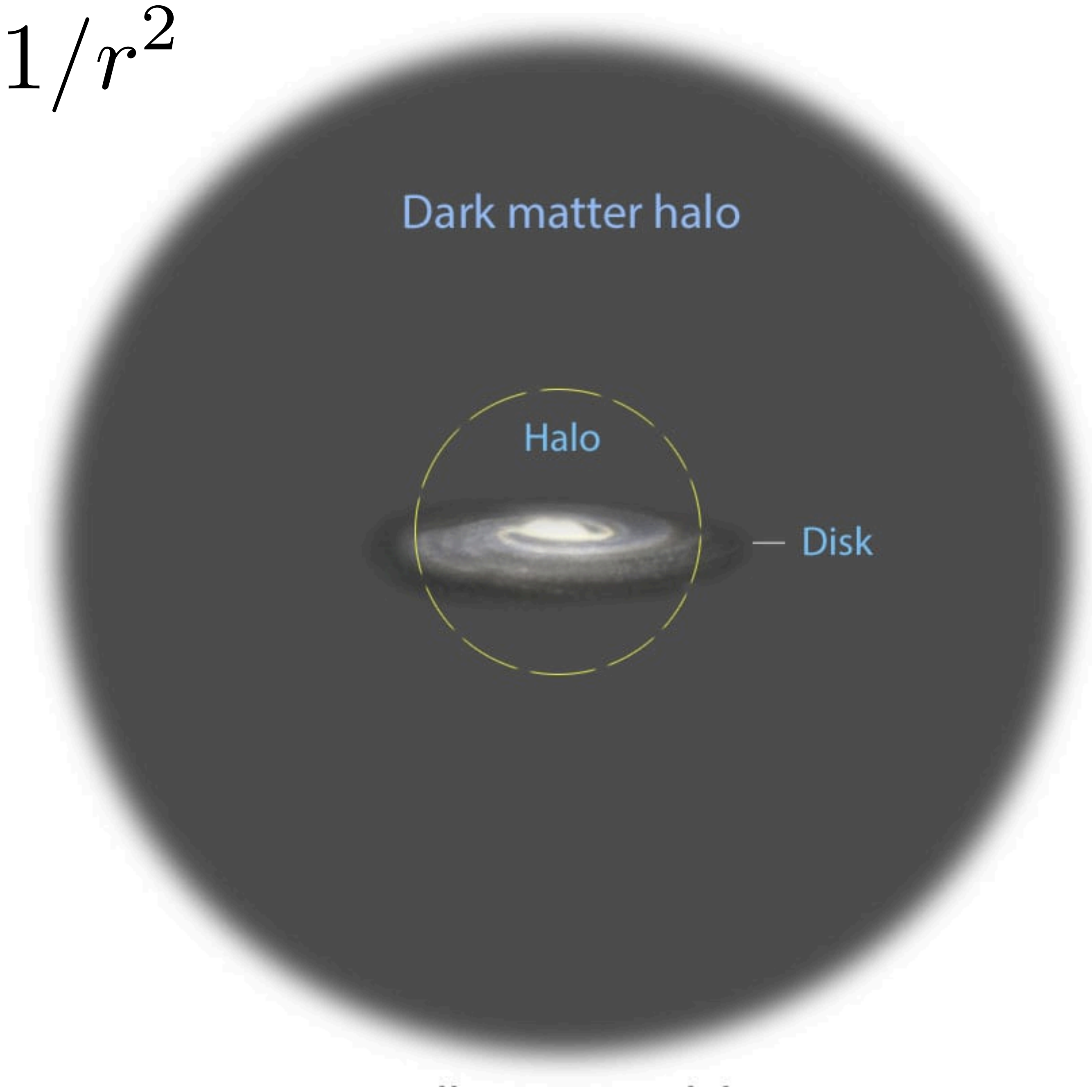
Sun:
260 km/s

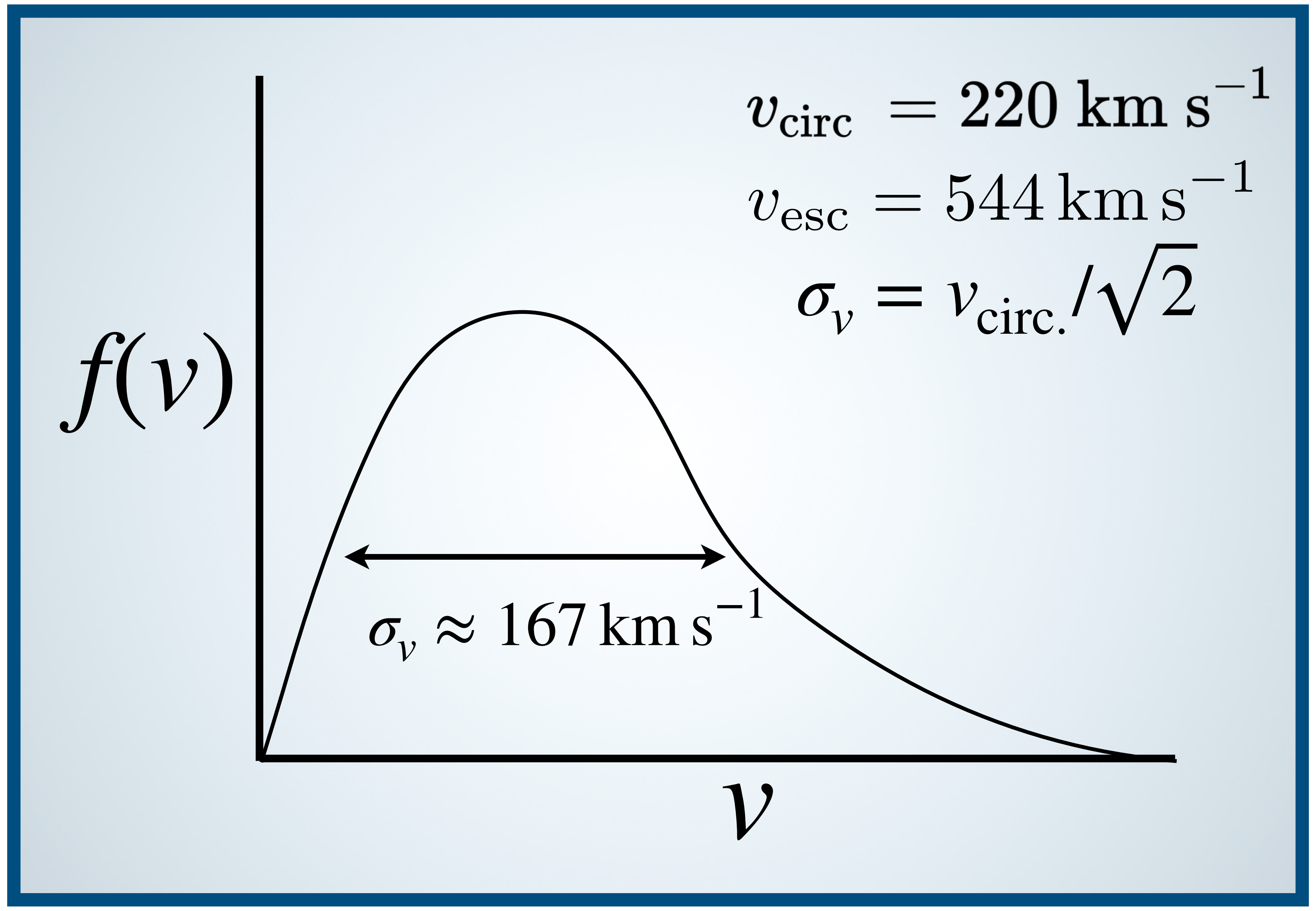
Earth:
± 15 km/s (left-right)
± 20 km/s (up-down)

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

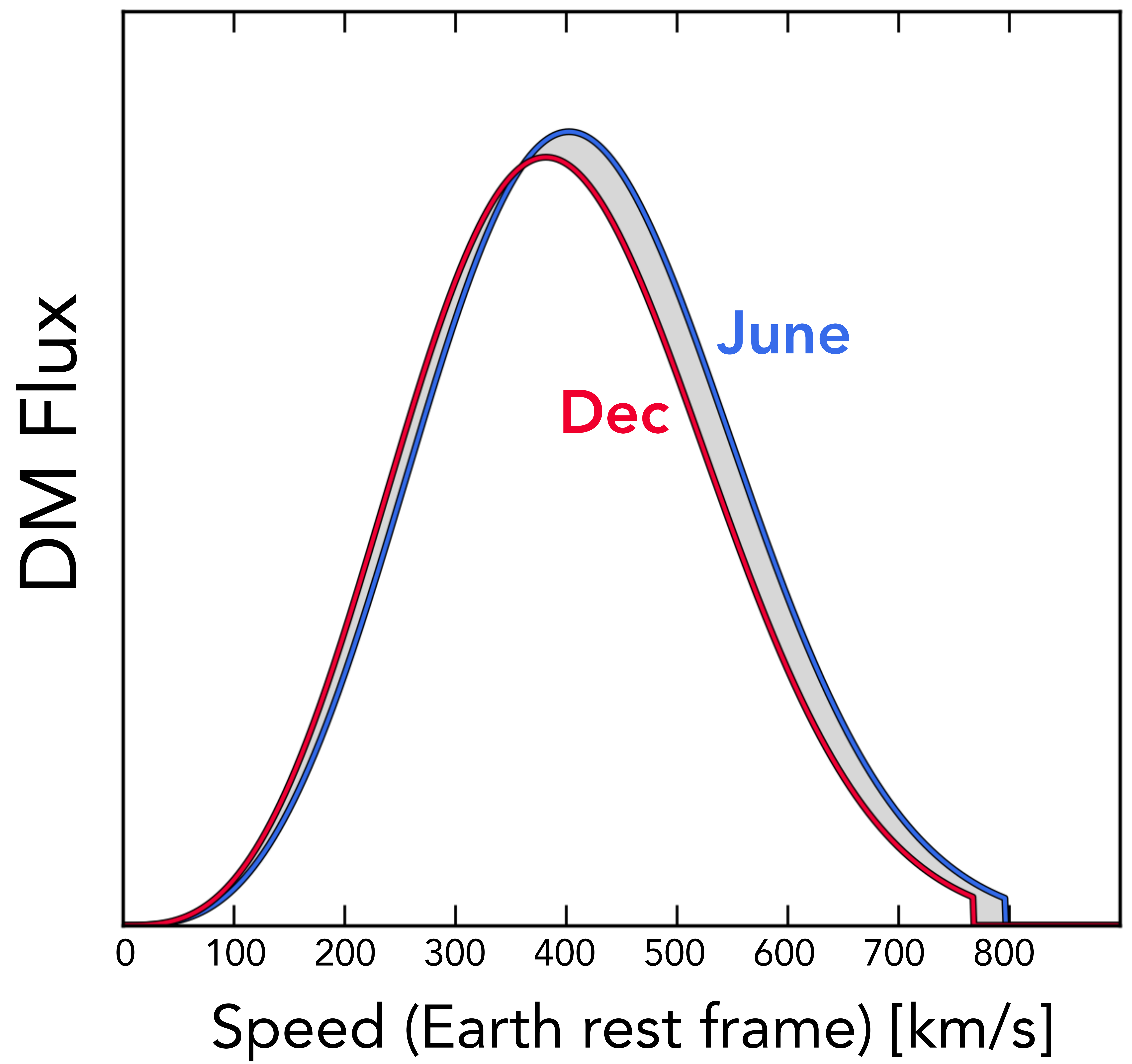
- Infinite isothermal sphere → Simplest halo model that gives a flat asymptotic rotation curve
- Truncate at $v > v_{esc}$ so as to not include unbound particles

$\rho \sim 1/r^2$





1. Annual modulation

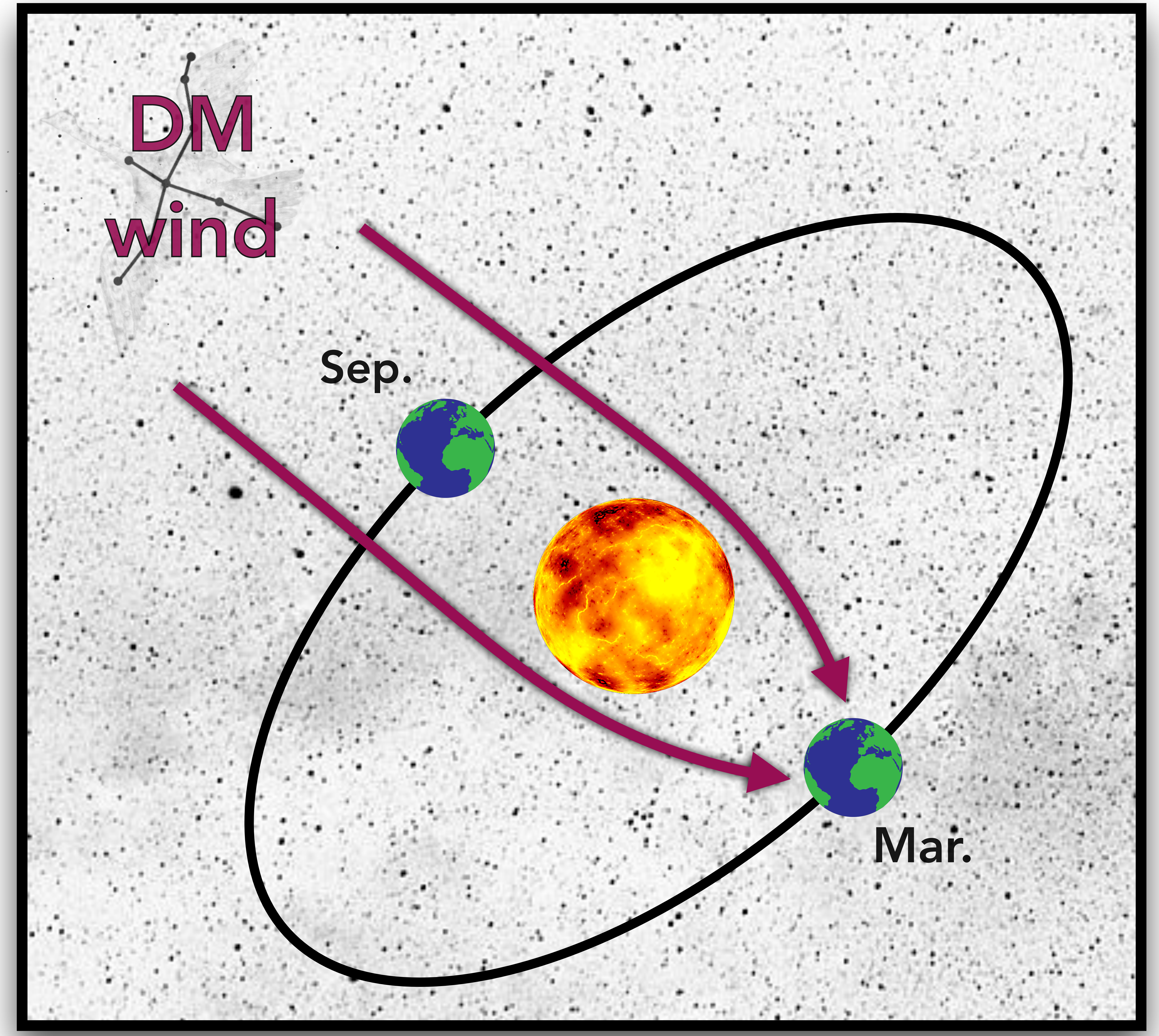


$$\mathbf{v}_{\rm lab} = \mathbf{v}_{\rm LSR} + \mathbf{v}_{\rm pec} + \mathbf{v}_{\oplus,\,{\rm rev.}}(t)$$

$$\text{DM Flux} \propto v\, f(\mathbf{v} + \mathbf{v}_{\rm lab})$$

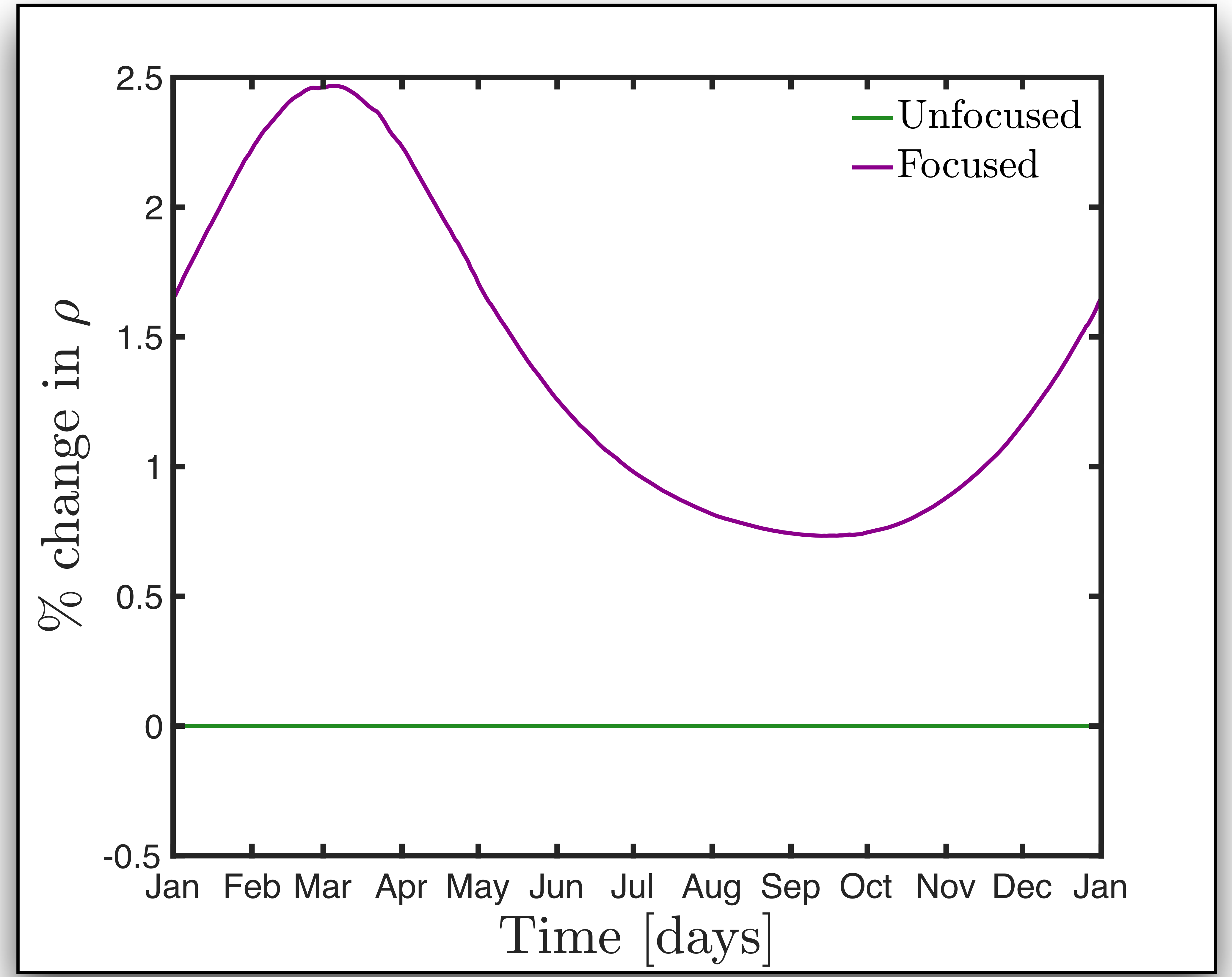
- Integrated flux is maximum during June and minimum in December (few % modulation)
- If sampling over distribution at lower-speeds only, phase is flipped (maximum in Dec.)

2. Gravitational focusing

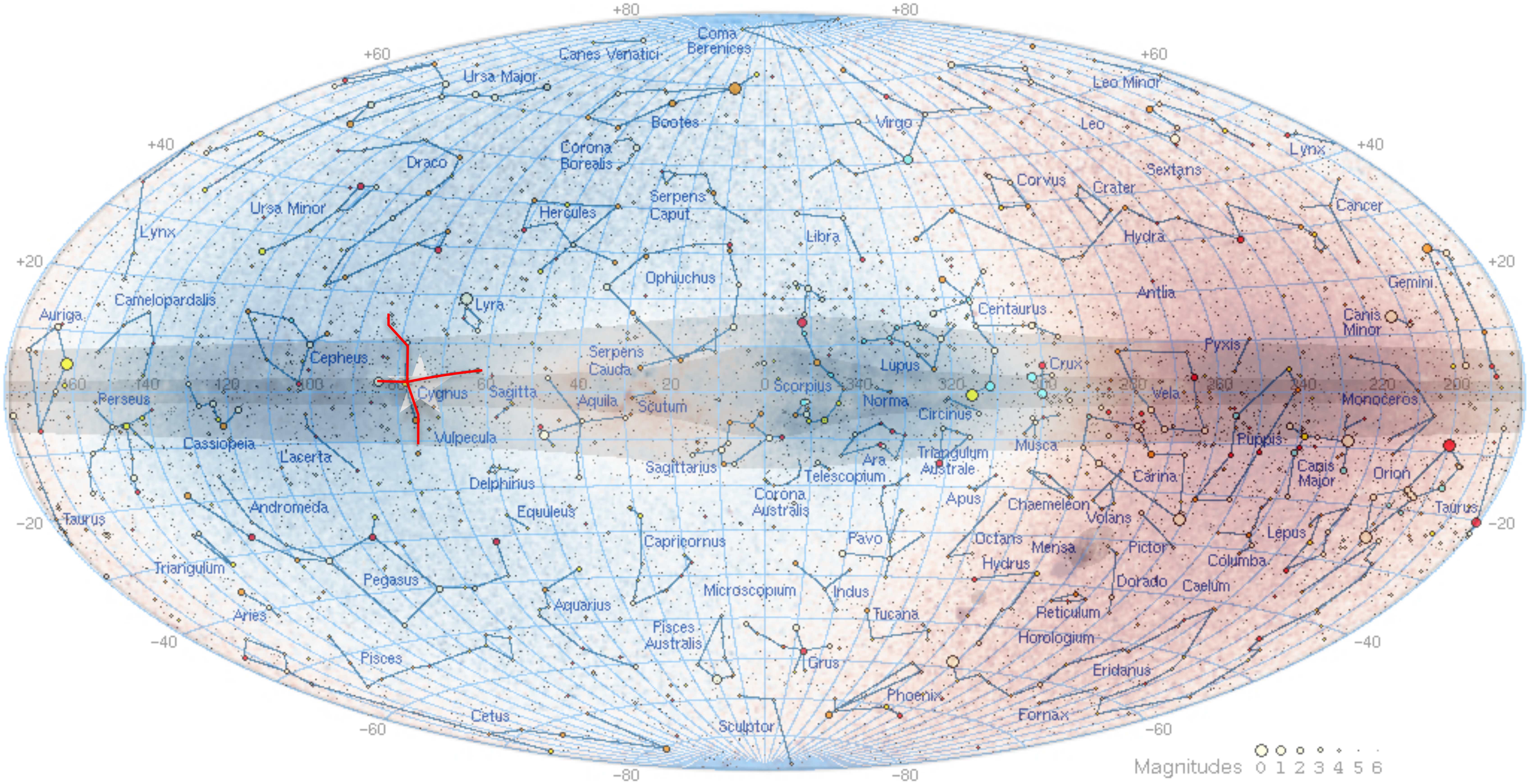


- Additional ~2% modulation in DM **density**
- Distortion to $f(v)$ at small speeds:

$$v < v_{\rm esc} = \sqrt{2GM_\odot/r} \approx 40\,{\rm km/s}$$



3. Directionality

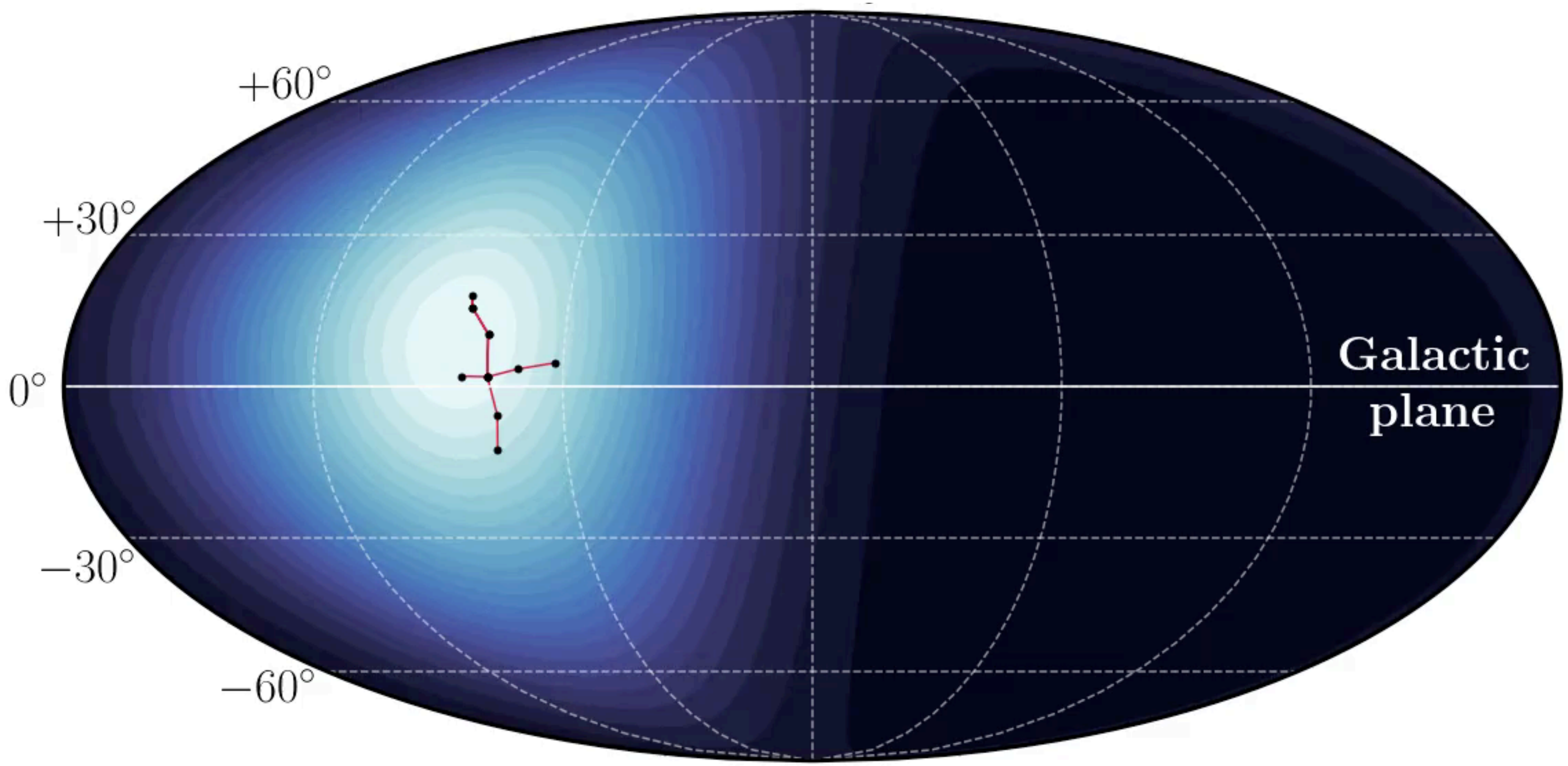


Gaia RVS galactic coordinates skymap of stellar line-of-sight velocities

Blue = moving towards us

Red = moving away from us

3. Directionality



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

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

These are supposedly generic model-independent expectations for signals in the Solar System

How much do we trust them?

Is the DM halo spherical? → No

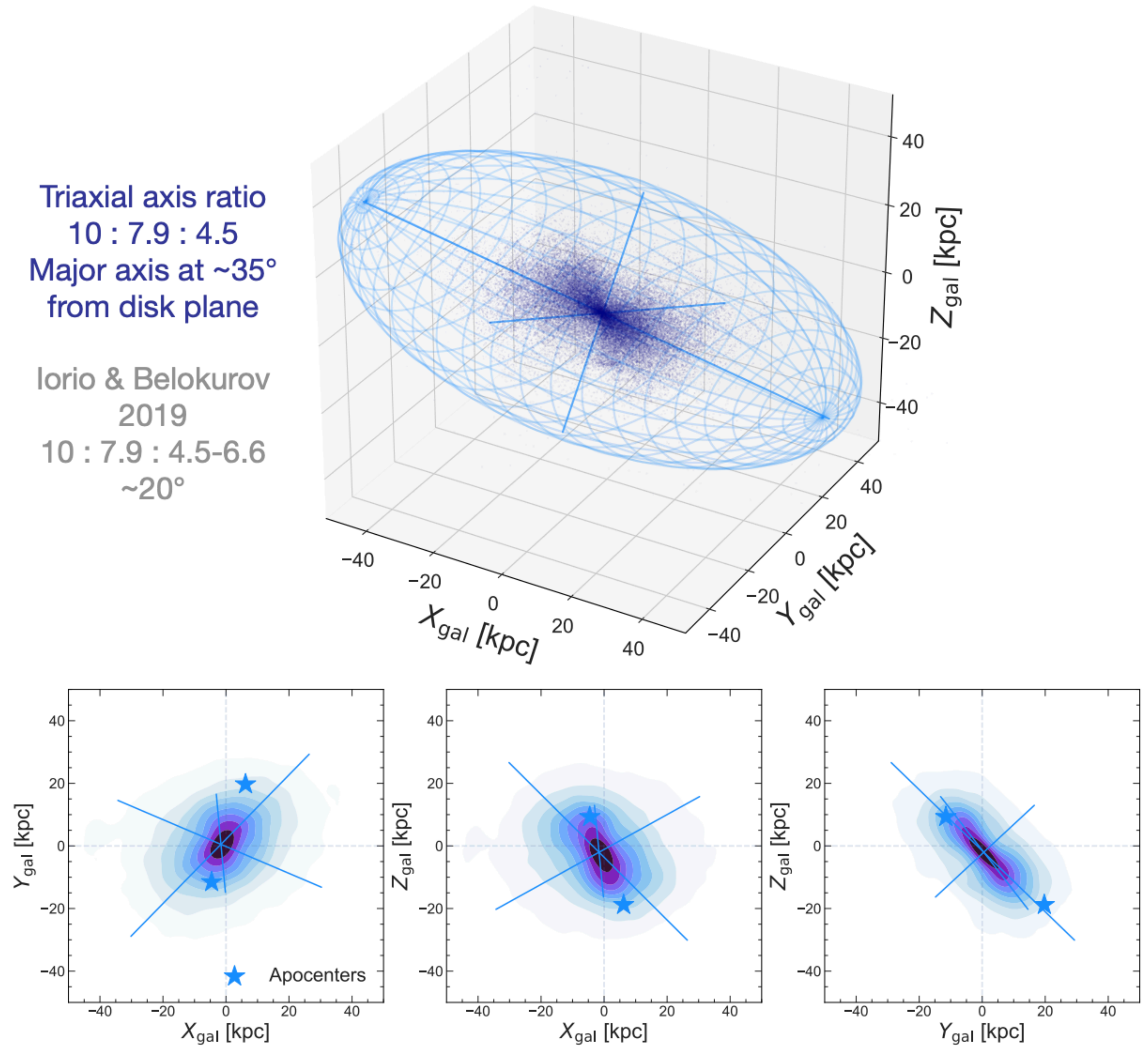
Is the DM speed distribution Maxwellian? → Probably not

Is the DM halo rotating? → A bit probably, not much

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

Triaxial axis ratio
10 : 7.9 : 4.5
Major axis at ~35° from disk plane

Iorio & Belokurov
2019
10 : 7.9 : 4.5-6.6
~20°



Iorio & Belokurov
[1804.11347] (RR Lyraes)

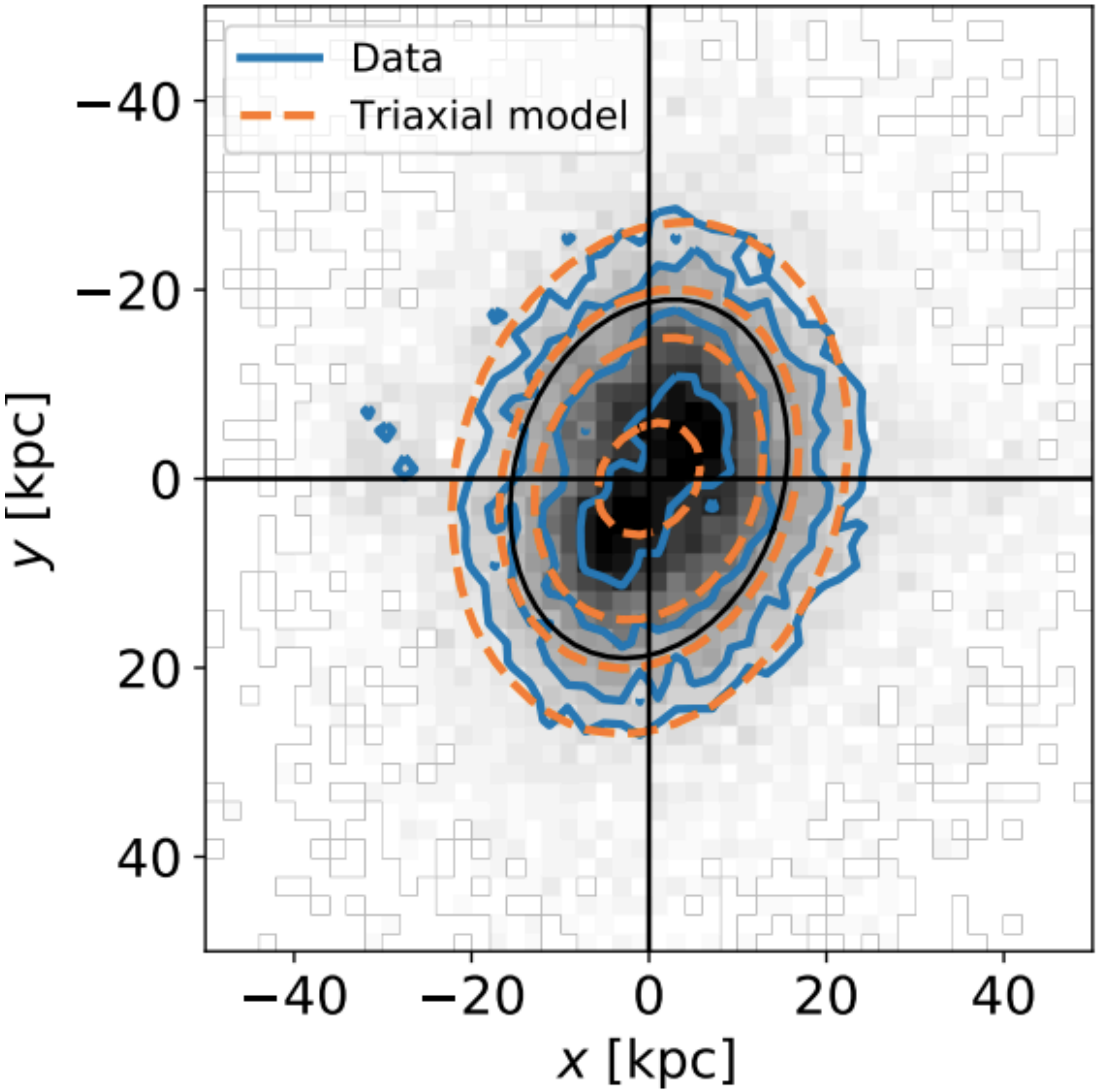


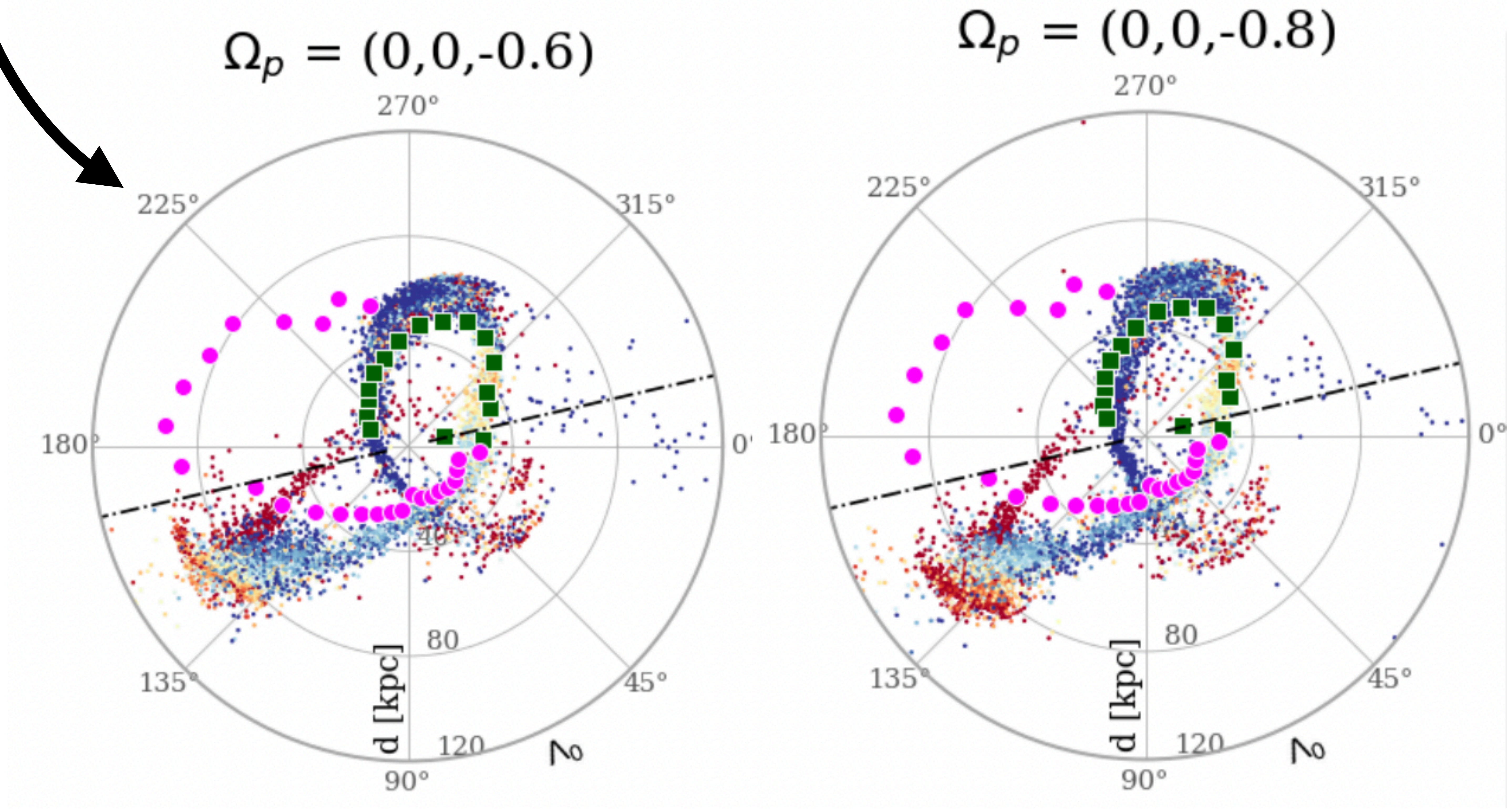
Figure rotation of DM halo

Simulations find typical pattern speeds for triaxial halos in the range

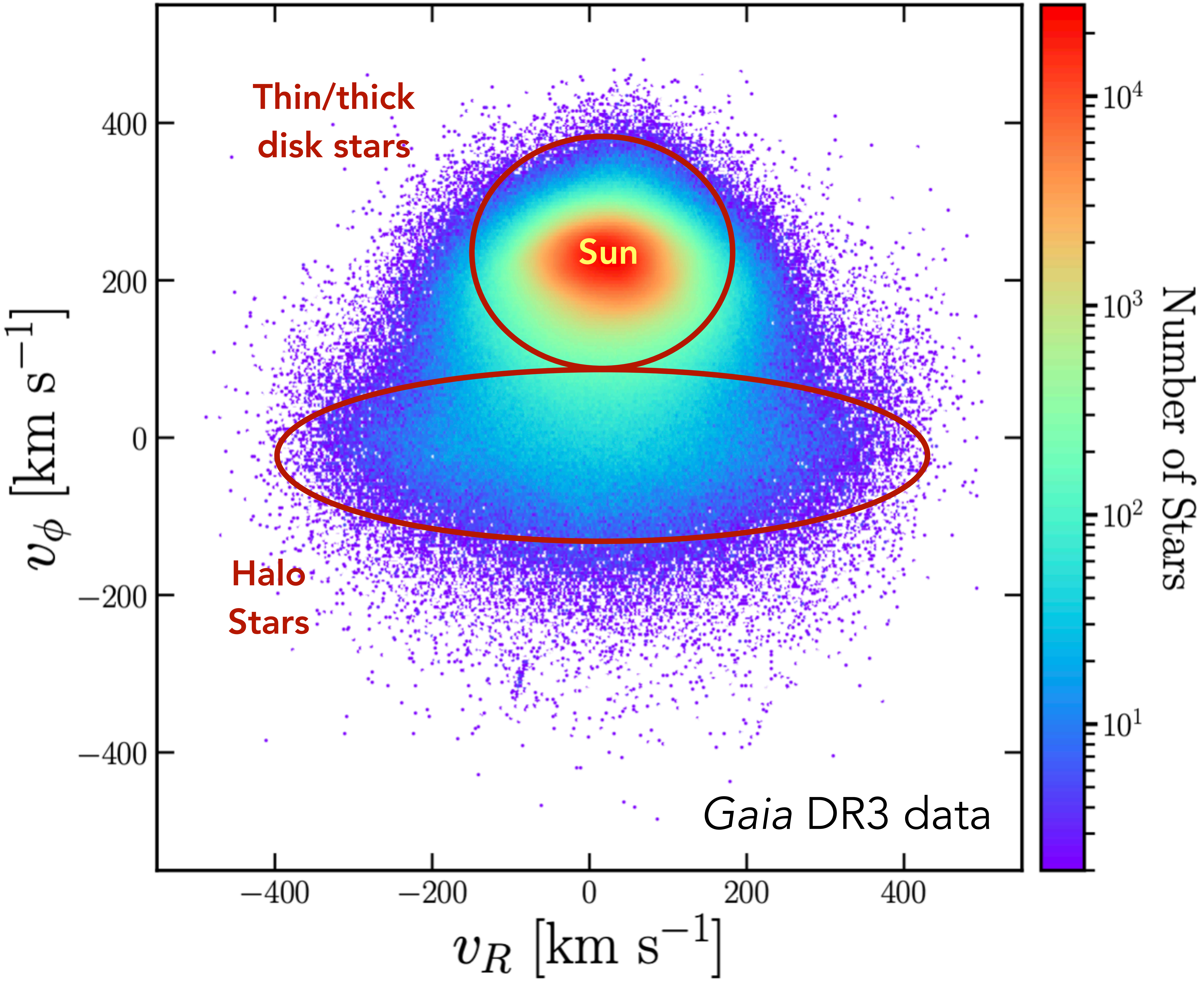
$$\Omega_p \sim 0.15 - 0.6\ \mathrm{km\ s^{-1} kpc^{-1}} \sim 9^\circ - 35^\circ \mathrm{Gyr}^{-1}$$

→ 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

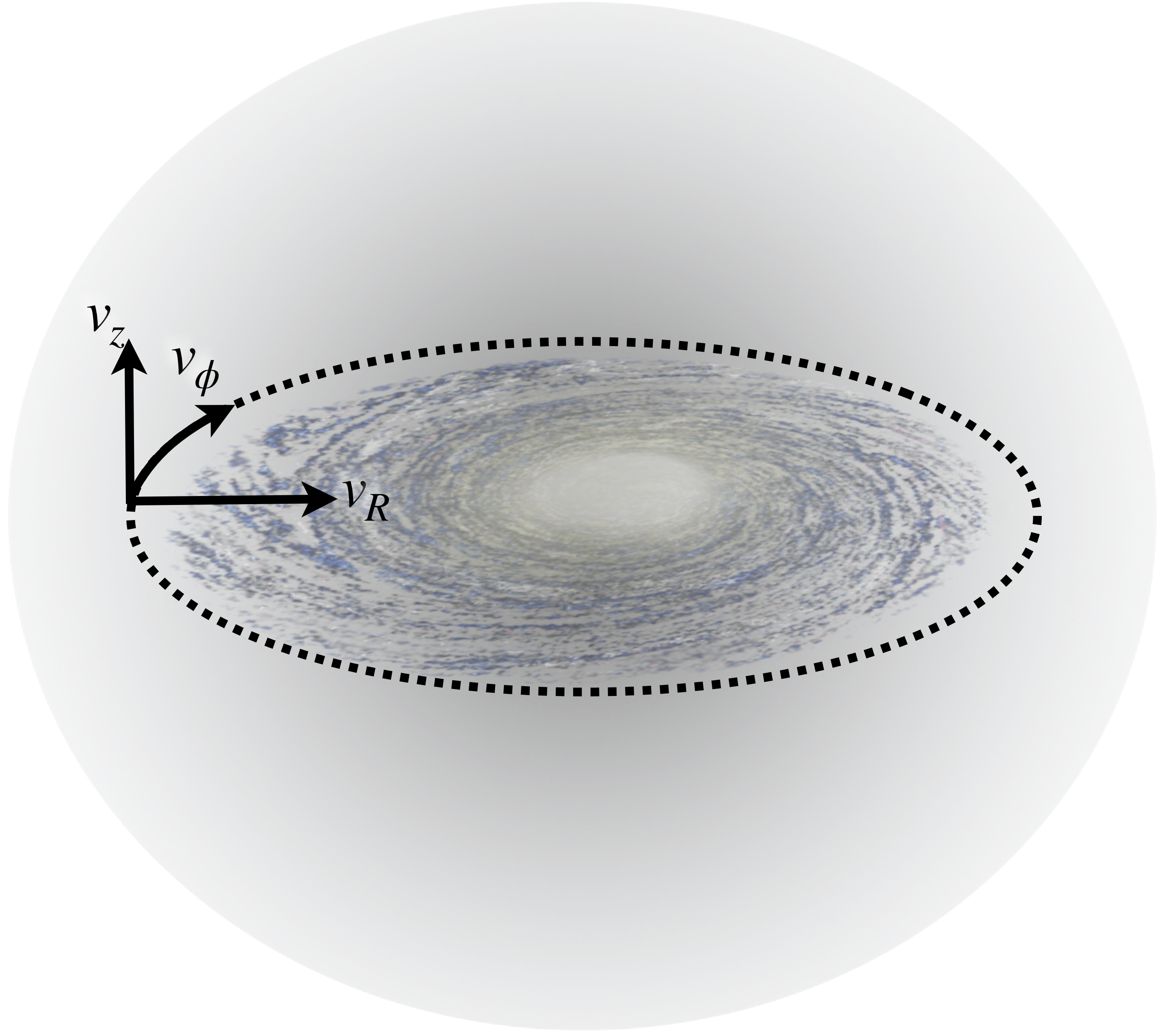


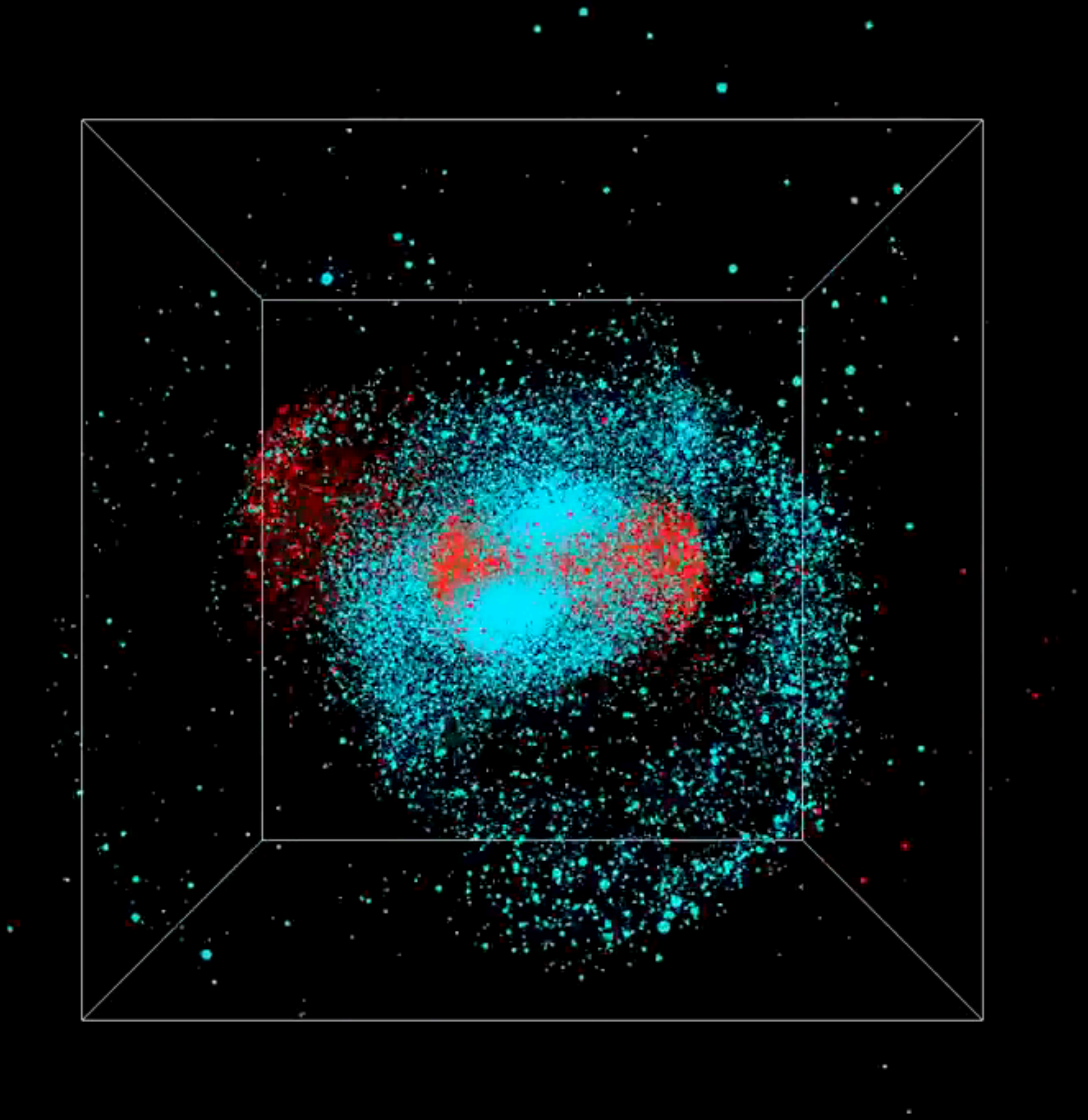
Velocity distribution of the MW halo



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

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



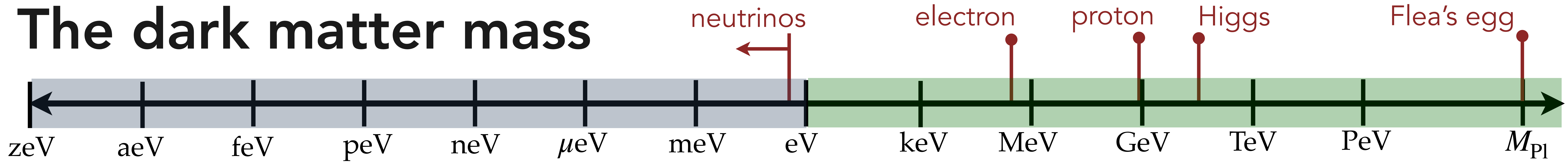


The GSE Merger:
Stars+DM brought in on **highly radial orbits** by a merger with a $10^{9\text{-}10}\ M_\odot$ stellar mass galaxy, 8-10 billion years ago

Helmi et al. [1806.06038]

Direct detection

The dark matter mass



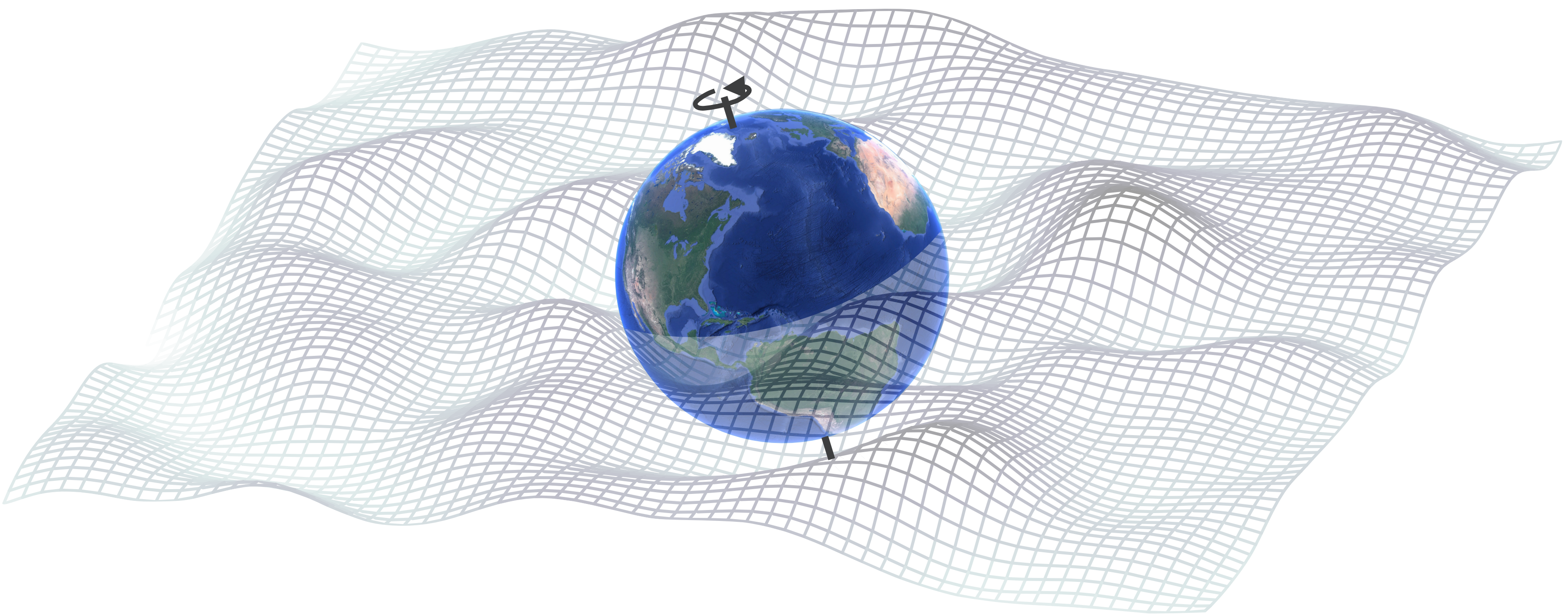
We know the local mass density of DM ($\rho_{\rm DM} \approx 0.4$ GeV/cc), but not the *number* density

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

$\mathcal{N} \gg 1$ ⟵ ⟶ $\mathcal{N} \ll 1$

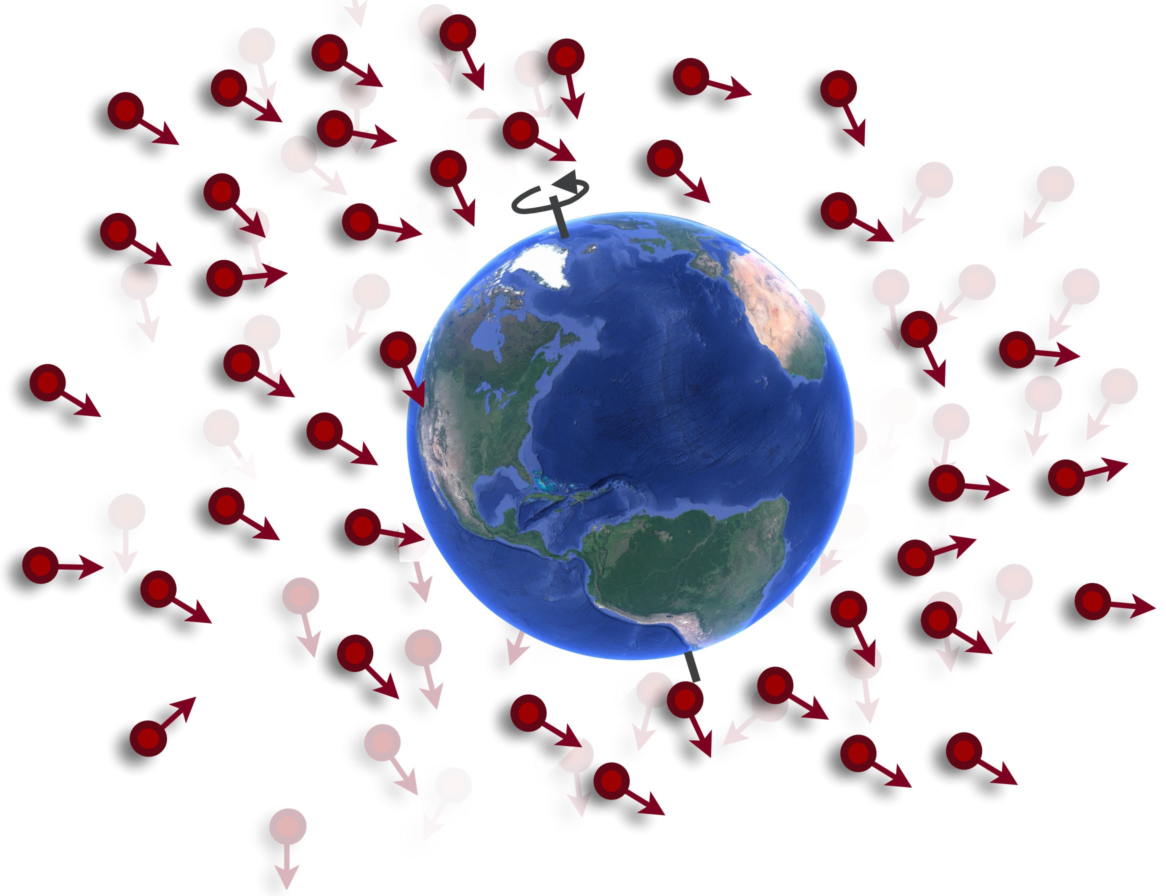
Wave-like dark matter

(Must be a boson due to Pauli exclusion principle)



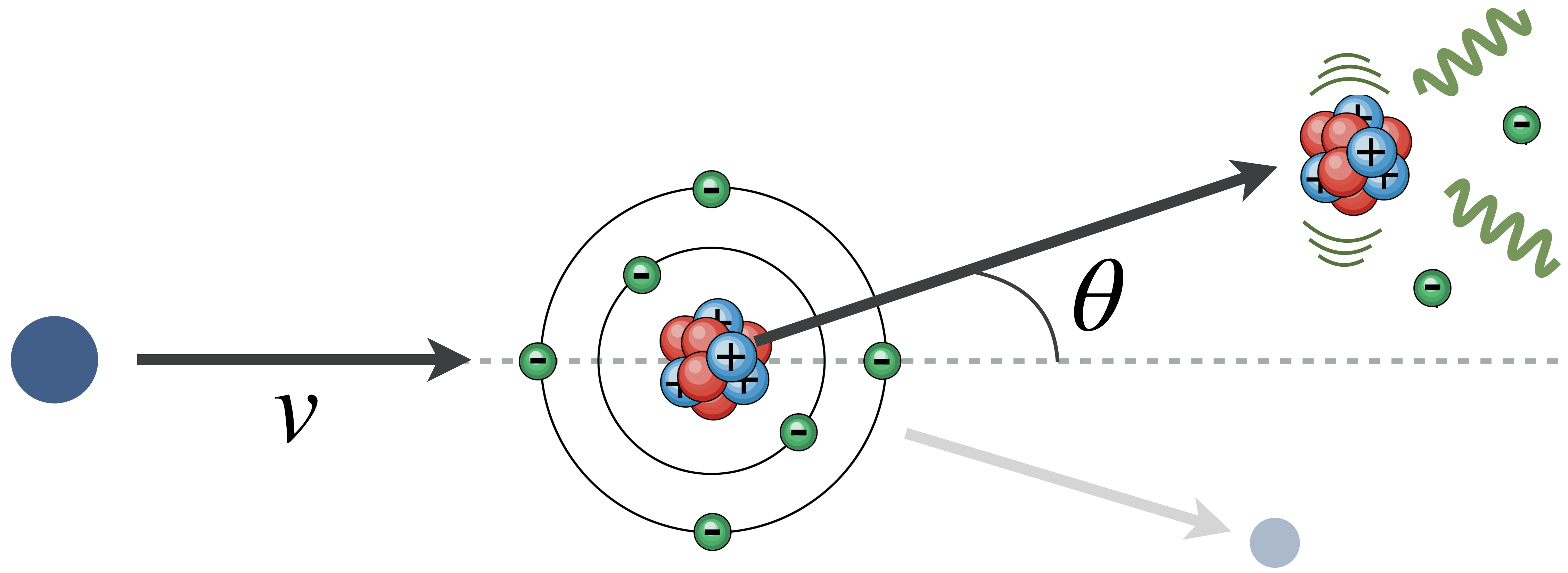
Particle-like dark matter

(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

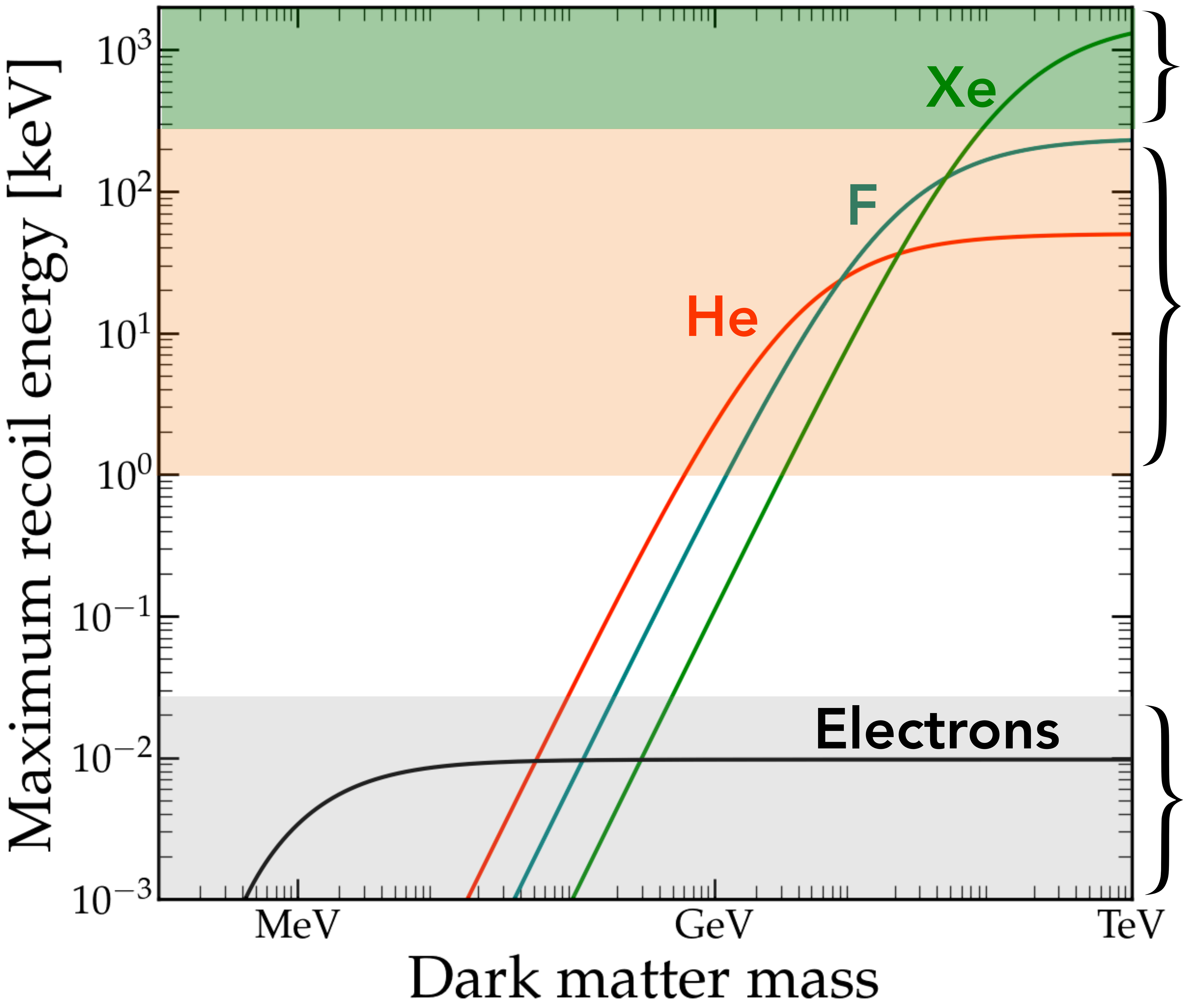


DM-target reduced mass:

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

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

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, σ, given the DM flux, Φ

$$R = N_T \, \Phi \, \sigma = \frac{M}{m_N} \Phi \sigma$$

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

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

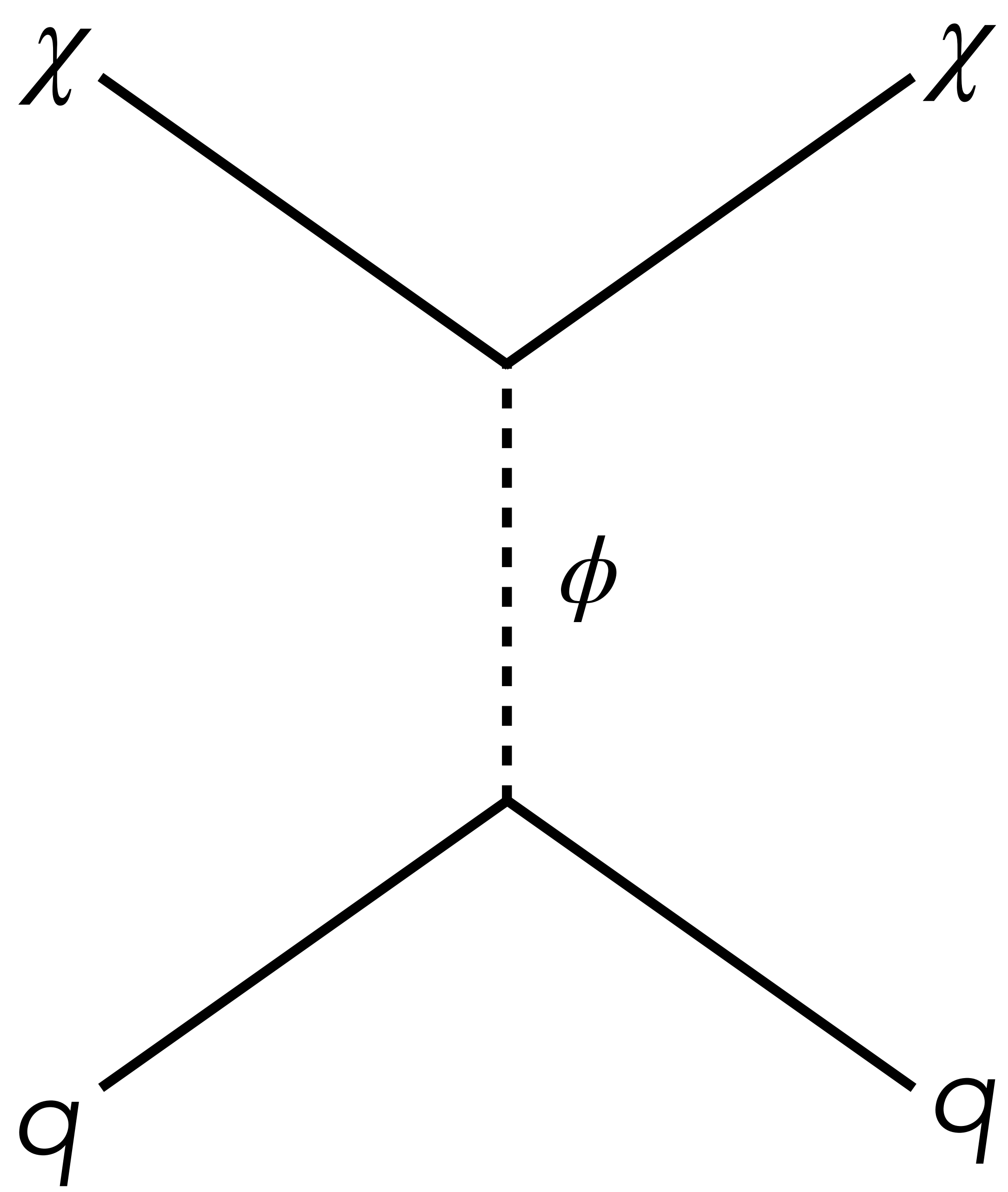
$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{M \rho_{\text{DM}}}{m_N m_\chi} \int_{v > v_{\min}}^{\infty} \Phi(\mathbf{v}) \frac{\mathrm{d}\sigma(v)}{\mathrm{d}E_r} \, \mathrm{d}^3\mathbf{v}$$

Event rate for some interaction cross section with nuclei, σ

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

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

Take the simplest case of the exchange of a scalar



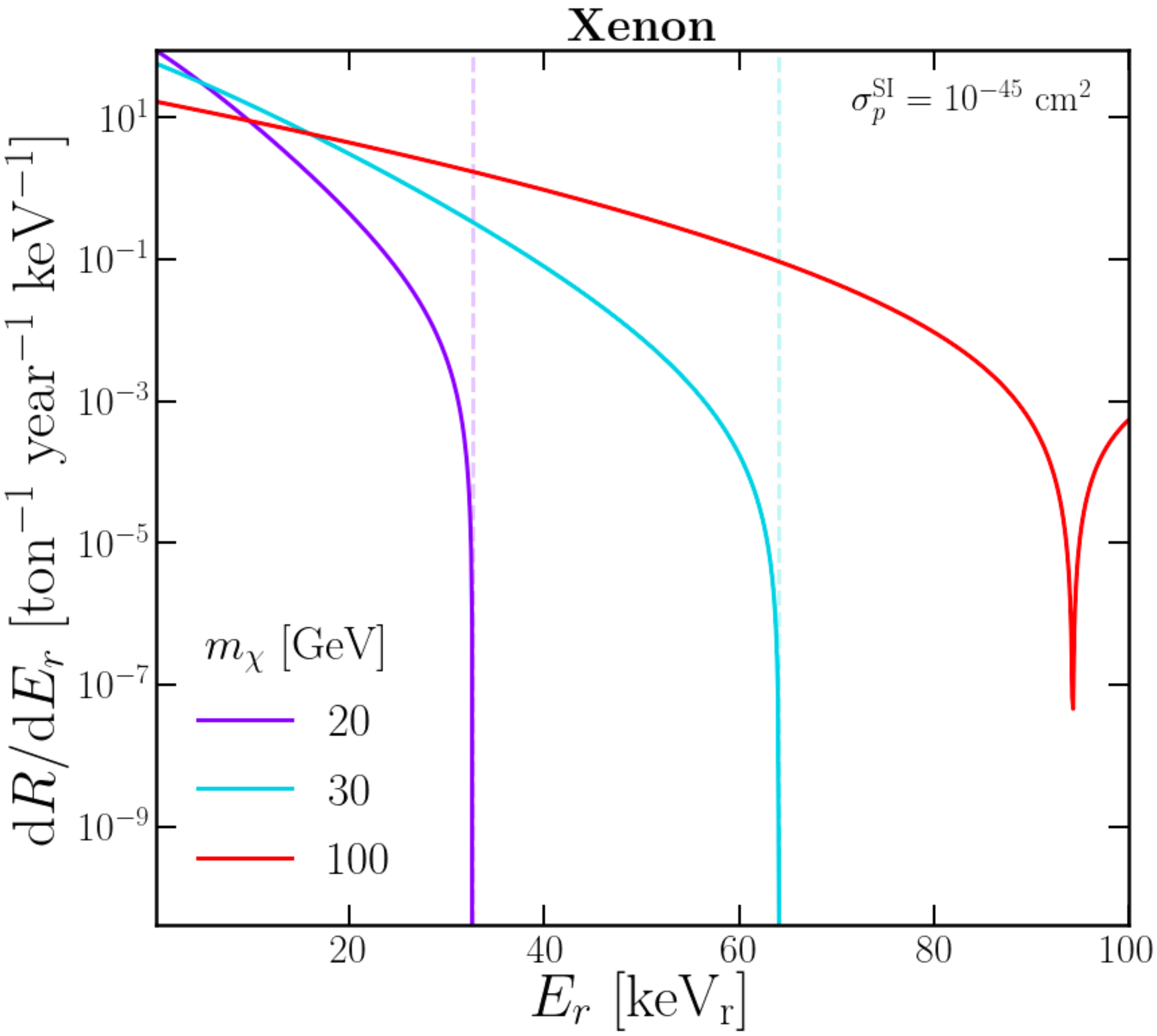
$$\mathcal{M} = \langle \psi'_\chi | \bar{\chi}\chi | \psi_\chi \rangle \left(\langle \psi'_N | \sum_{\text{proton}} g_q\, \bar{q}\,q + \sum_{\text{neutron}} g_q\, \bar{q}\,q | \psi_N \rangle \right)$$

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

Nuclear recoils

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

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



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:

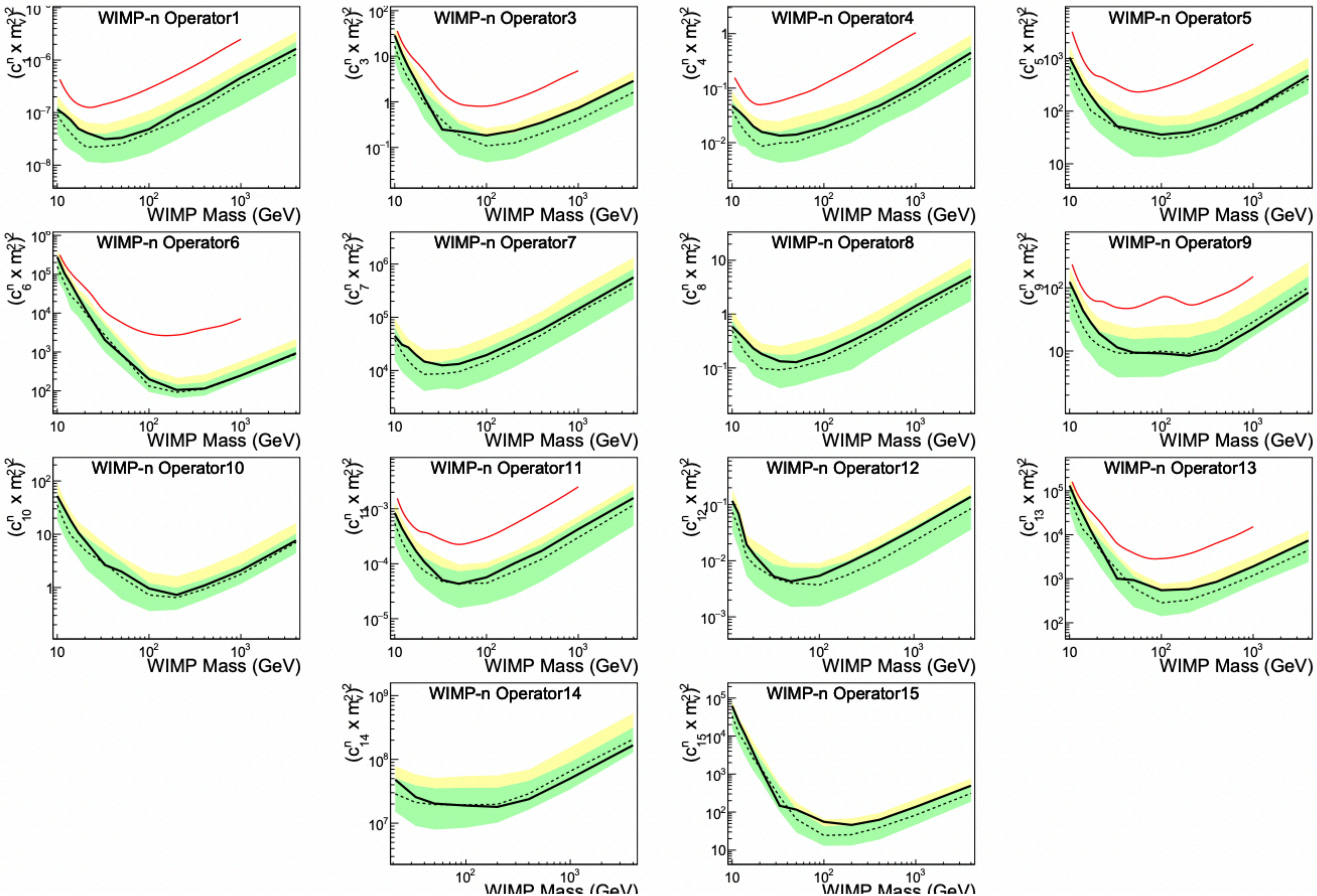
$$i\frac{\vec{q}}{m_N}, \quad \vec{v}^{\perp} \equiv \vec{v} + \frac{\vec{q}}{2\mu}, \quad \vec{S}_\chi, \quad \vec{S}_N$$

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

Non-relativistic effective field theory

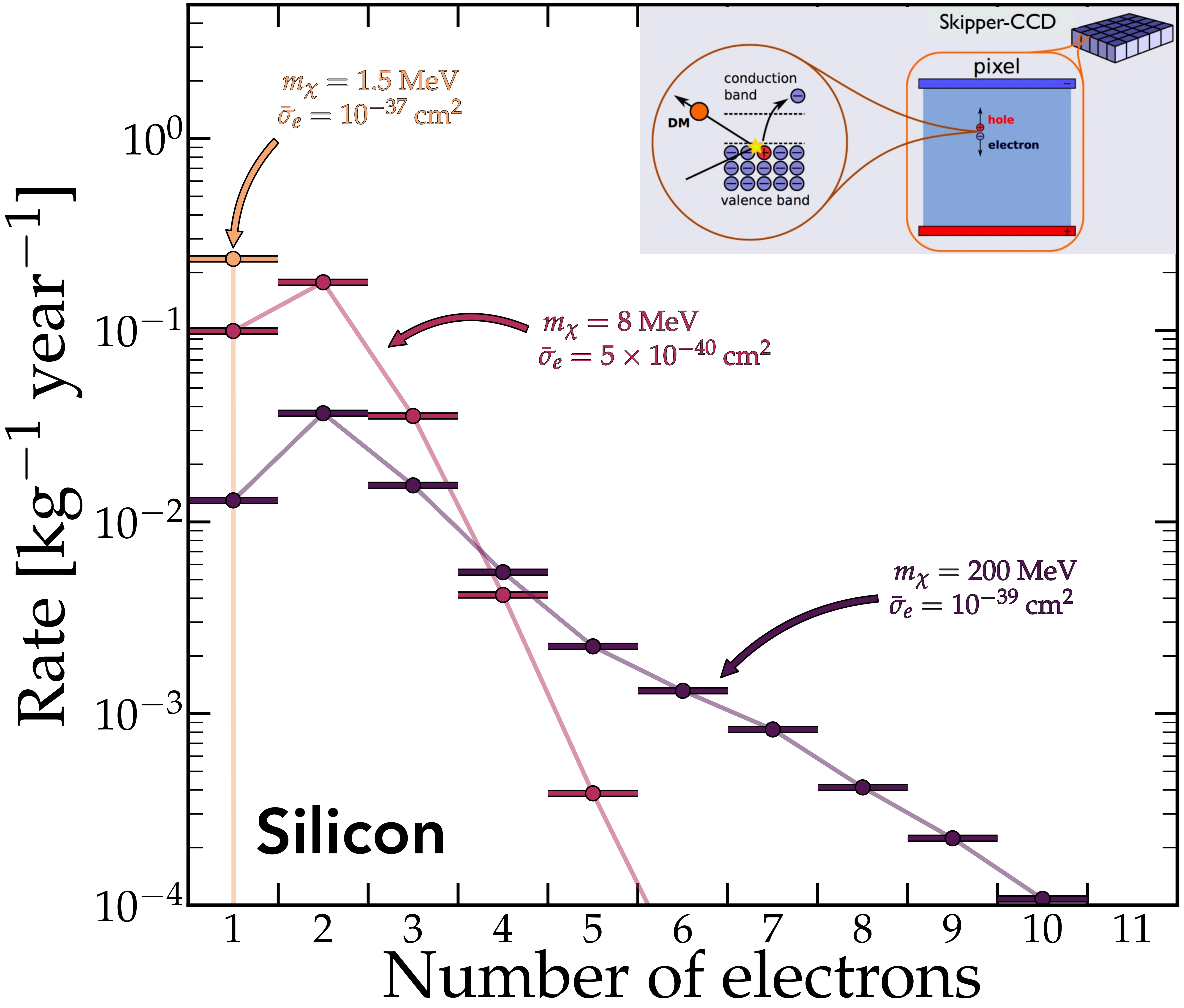
- Common to see papers doing scans over all possible coupling constants.

e.g. LUX [2102.06998]



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 $f(v)$

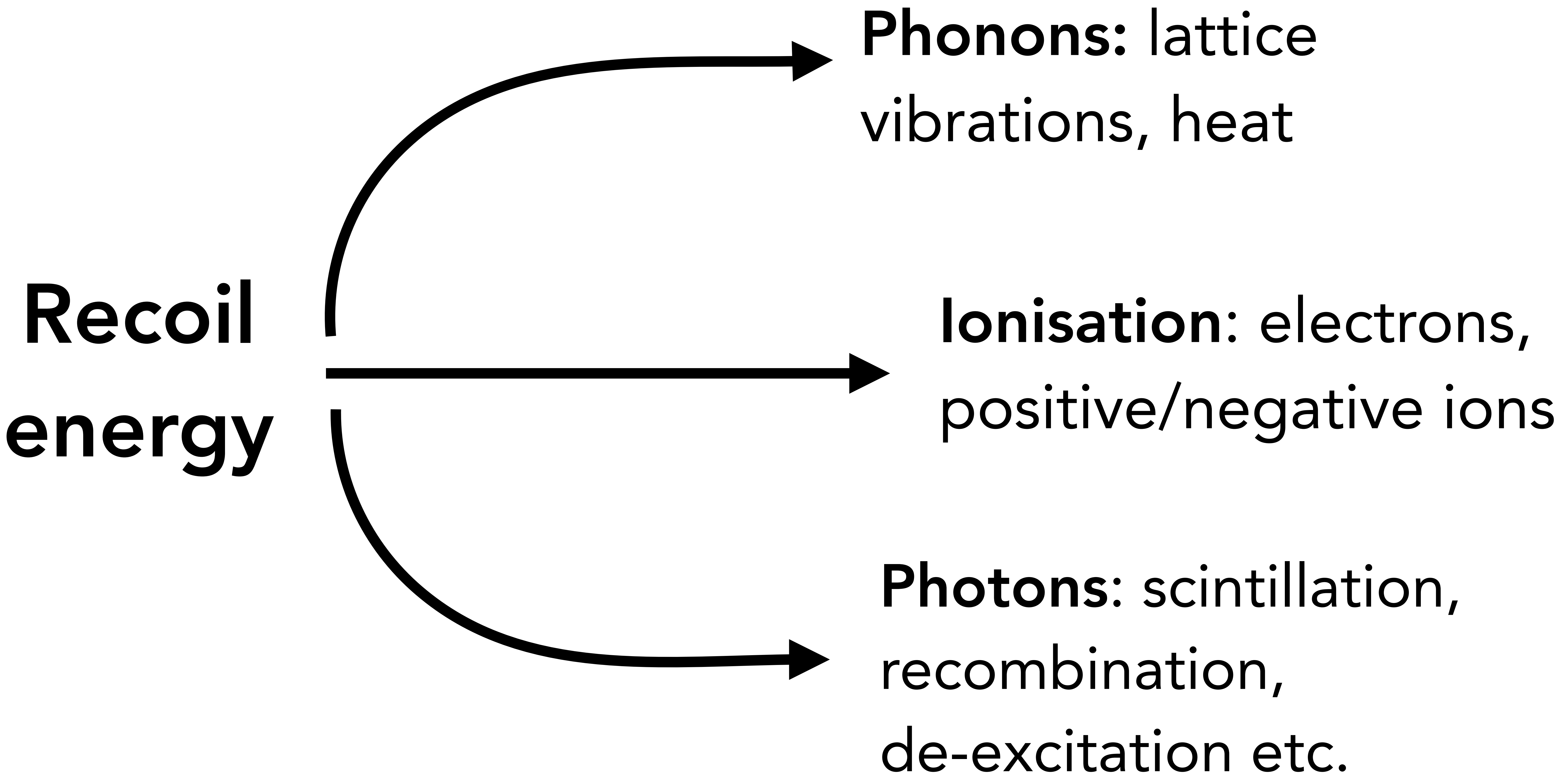
$$\frac{\mathrm{d}R}{\mathrm{d}E_e} = \frac{\bar{\sigma}_e \, \rho_{\rm DM}}{8\mu_e^2 E_e m_N m_\chi} \sum_{\rm orbitals} \int_{q_-}^{q_+} q dq \left| f_{\rm ion}^{i\to f} \right|^2 g(v_{\rm min})$$

"Ionisation form factor"

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

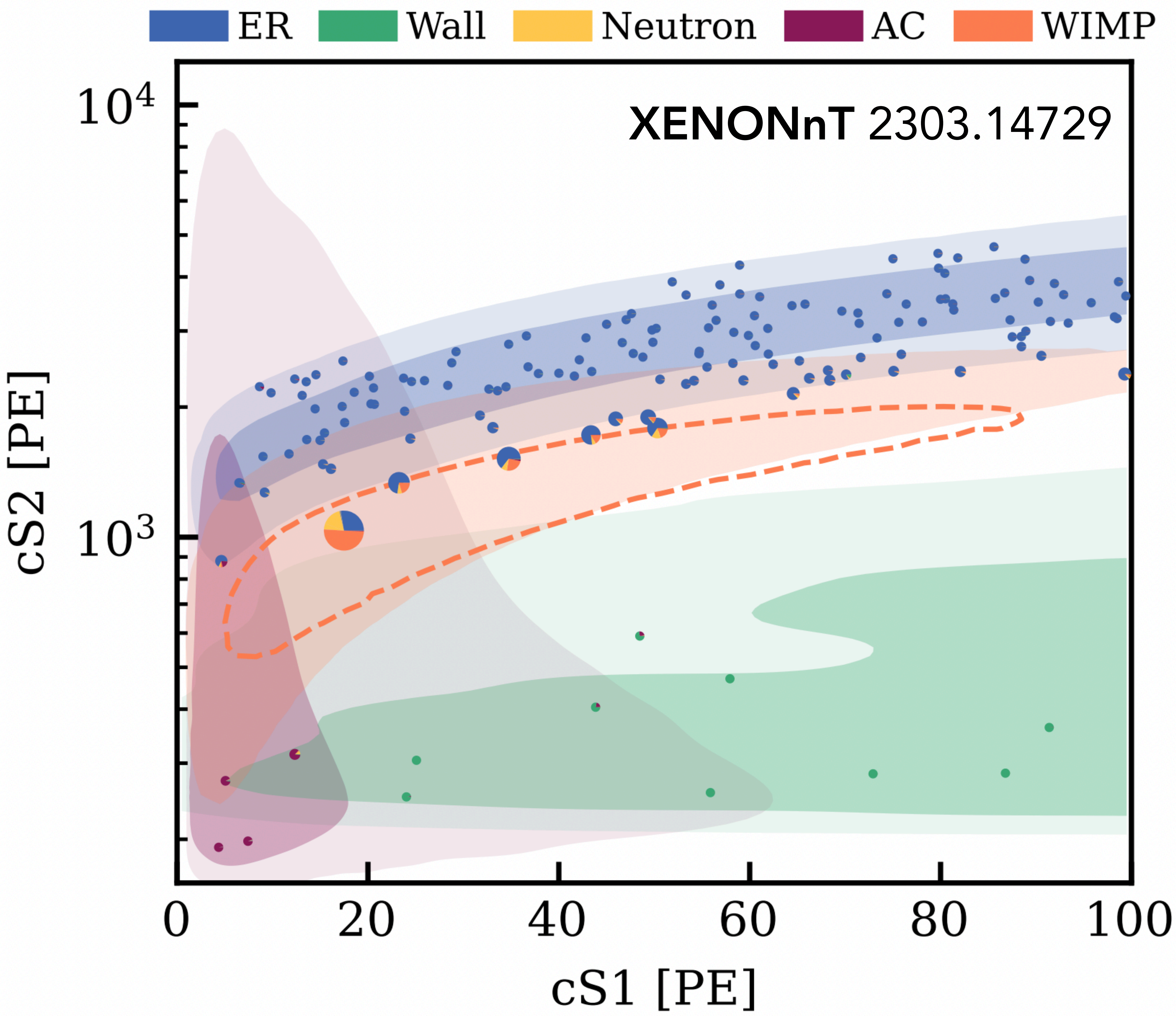
Related to transition probability for a bound state ψ_i to go to some unbound state ψ_f after gaining momentum $\mathbf{q}$

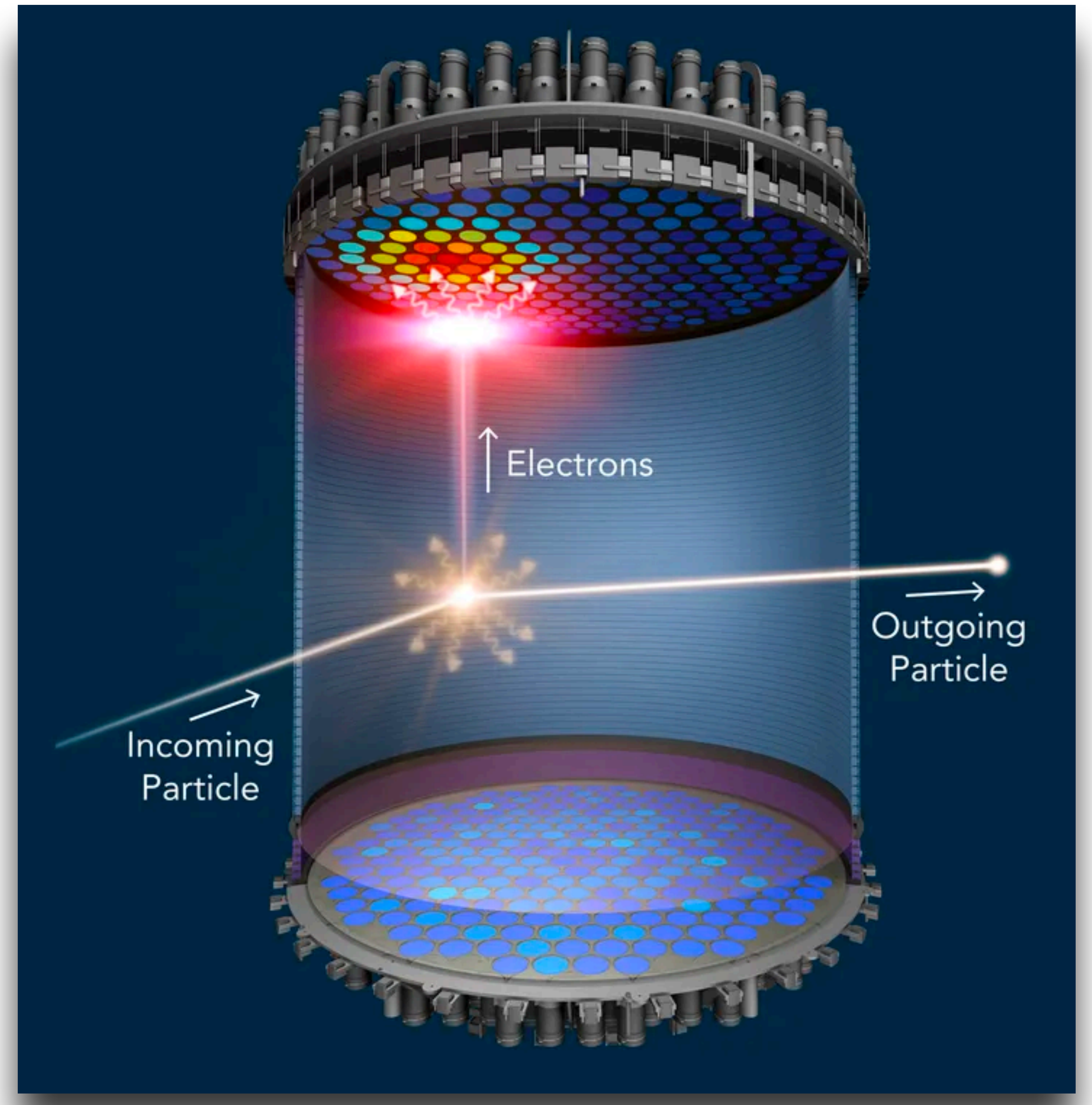
Detection of a recoil energy deposited in a medium



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

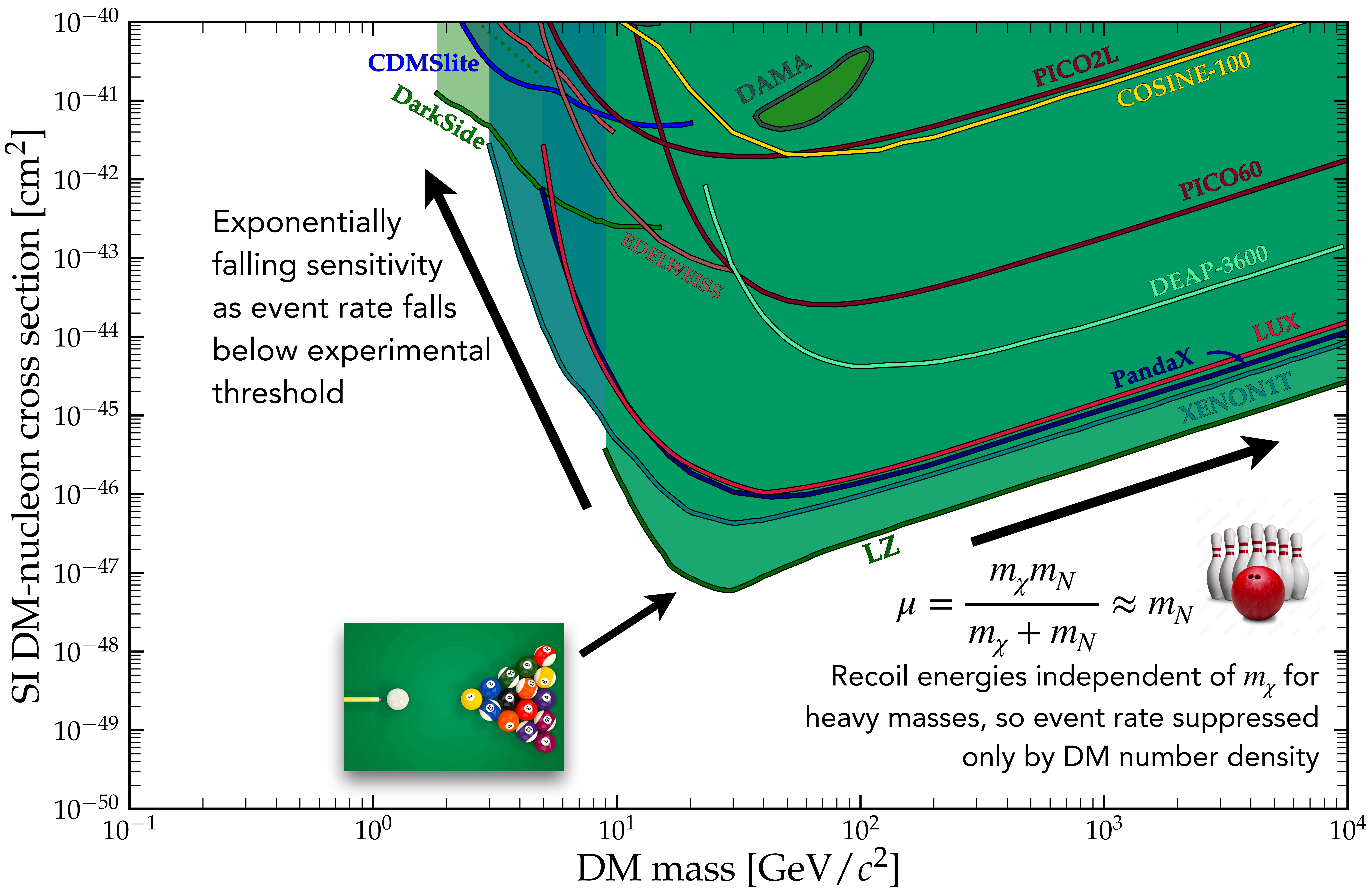
Example: LXe time-projection chamber

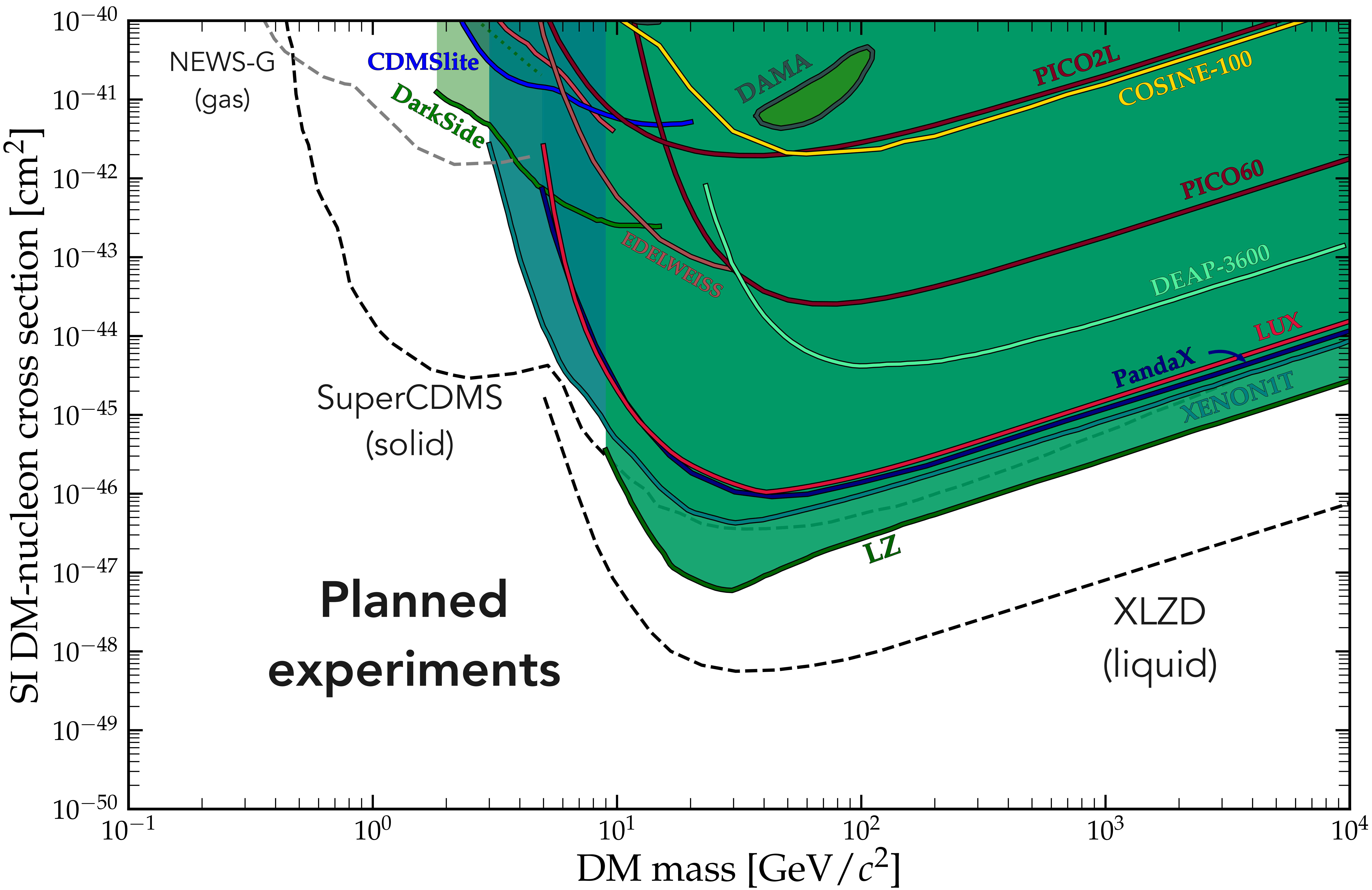




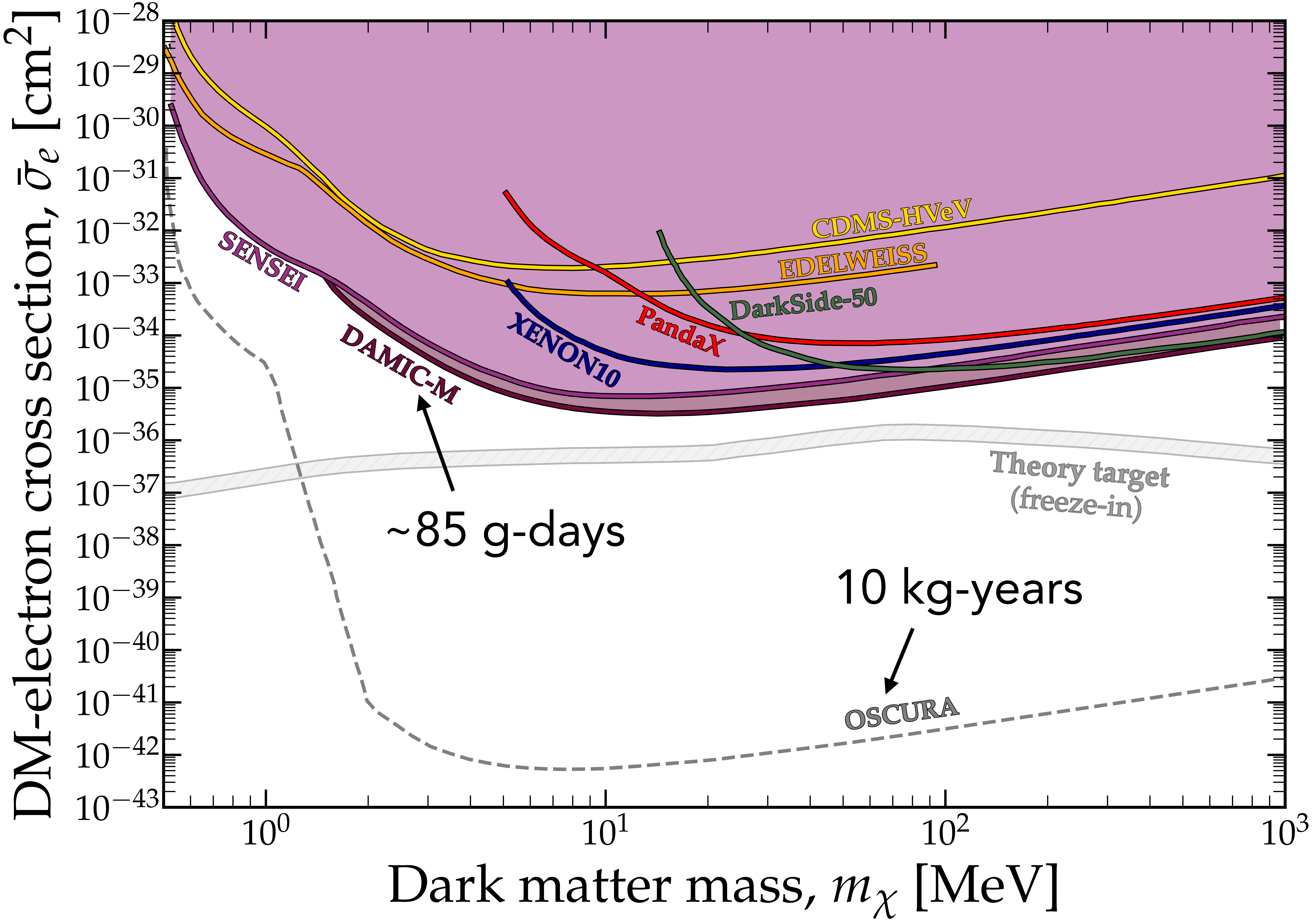
S1: prompt scintillation light from recoil event

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_χ for heavy masses, so event rate suppressed only by DM number density

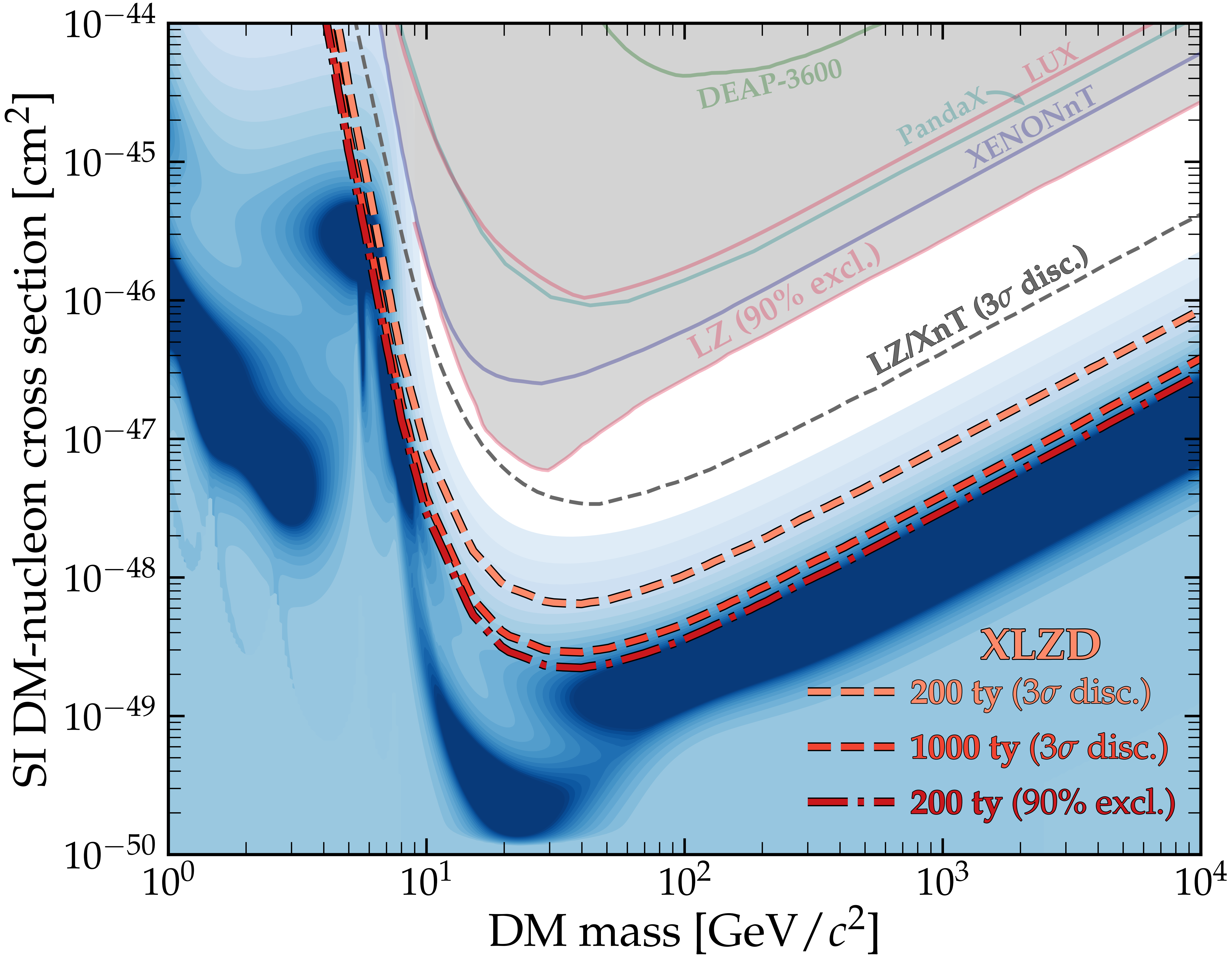


NEWS-G
(gas)
CDMSlite
DarkSide
DAMA
PICO2L
COSINE-100
PICO60
EDELWEISS
DEAP-3600
LUX
PandaX
XENON1T
LZ
SuperCDMS
(solid)
Planned
experiments
XLZD
(liquid)
SI DM-nucleon cross section [cm²]
DM mass [GeV/c²]



DM-electron cross section, $\bar{\sigma}_e$ [cm^2]
Dark matter mass, m_χ [MeV]
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
CDMS-HVeV
EDELWEISS
DarkSide-50
SENSEI
PandaX
XENON10
DAMIC-M
~85 g-days
Theory target
(freeze-in)
10 kg-years
OSCURA

The Ultimate liquid xenon detector: XLZD



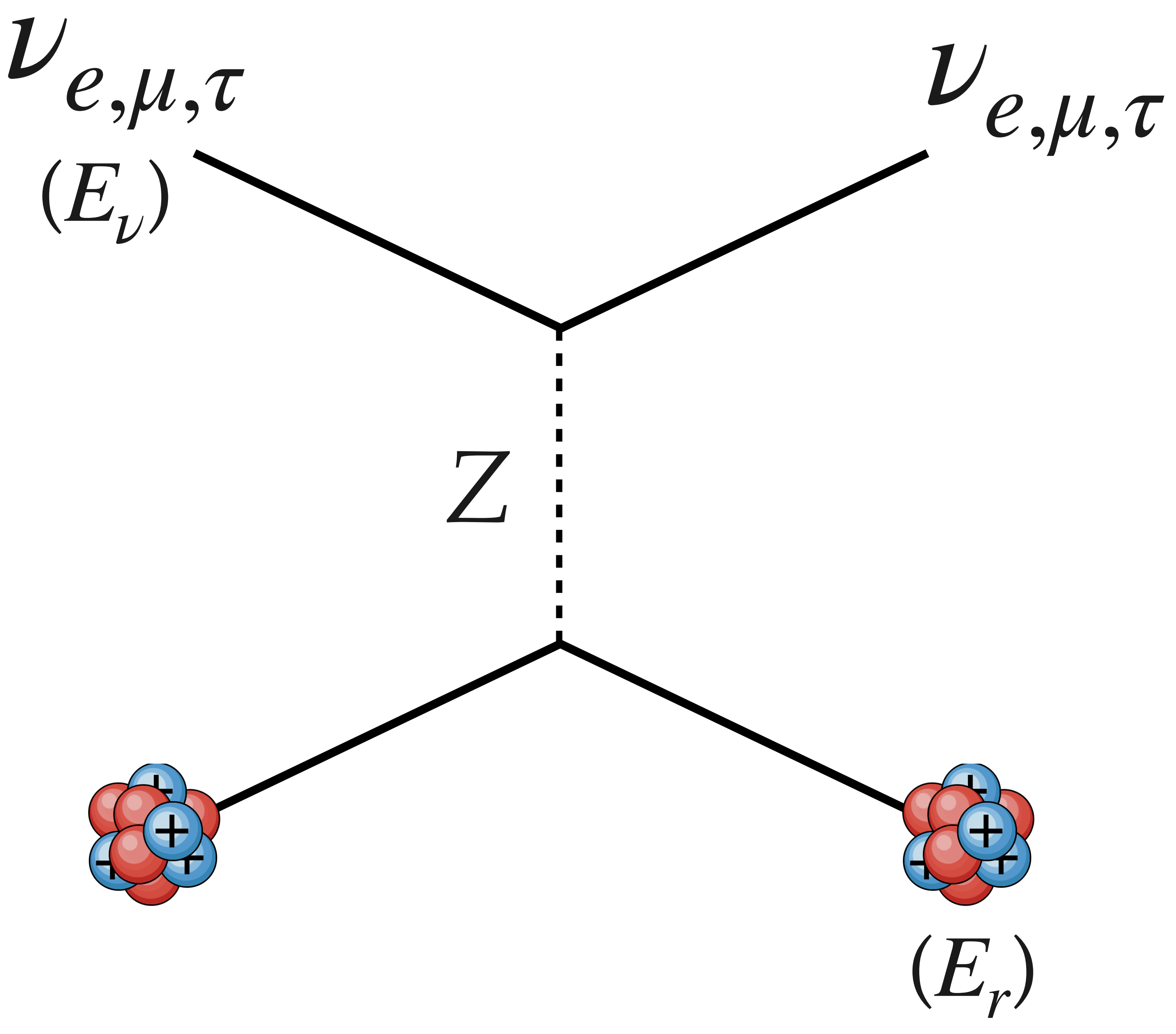
Aims for final exposure approaching ~1000 ton-year scale. In an ideal world, ultimately limited by neutrino backgrounds

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]



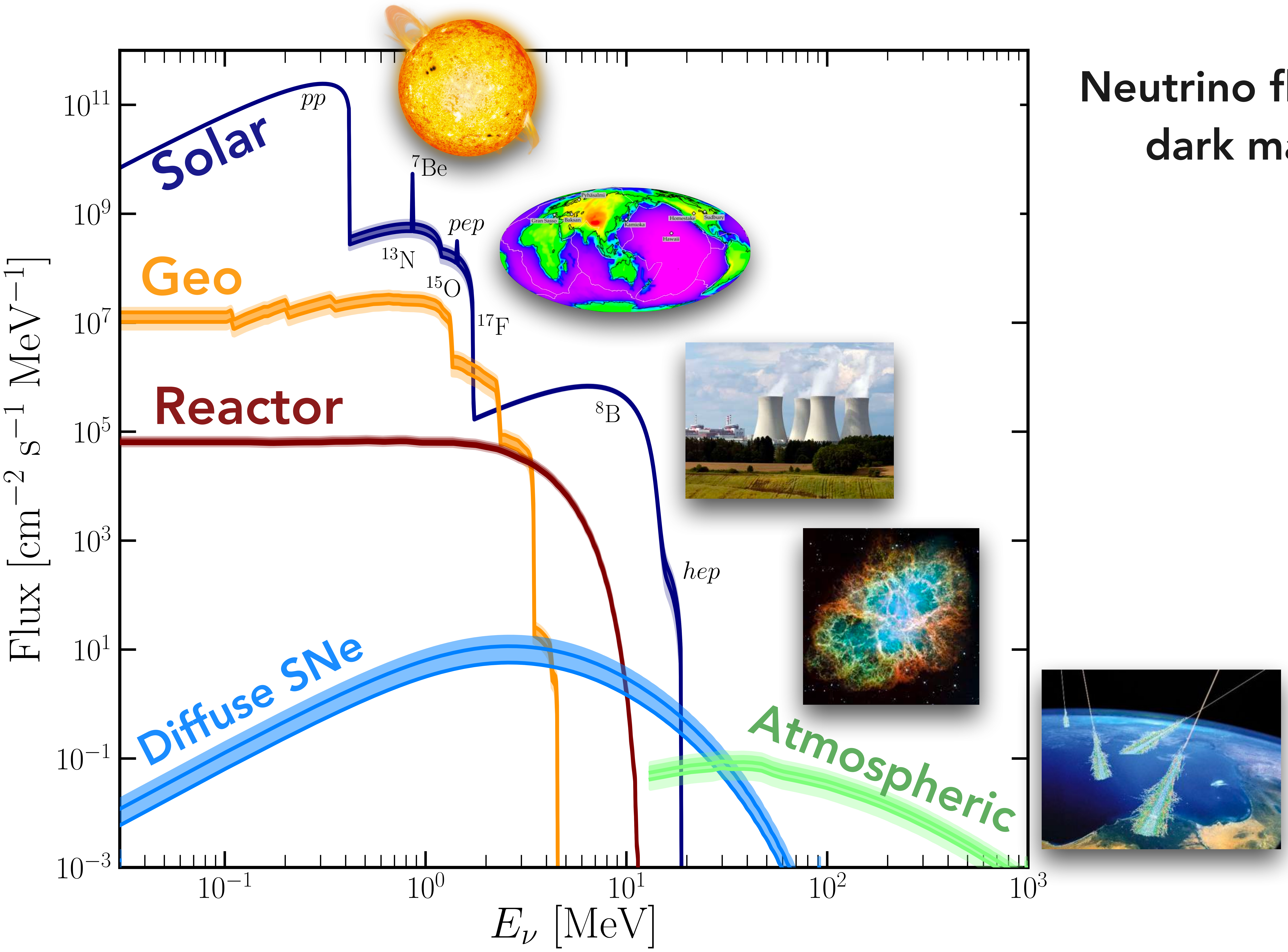
Neutral current
→ flavour blind

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

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

$\Rightarrow$ >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

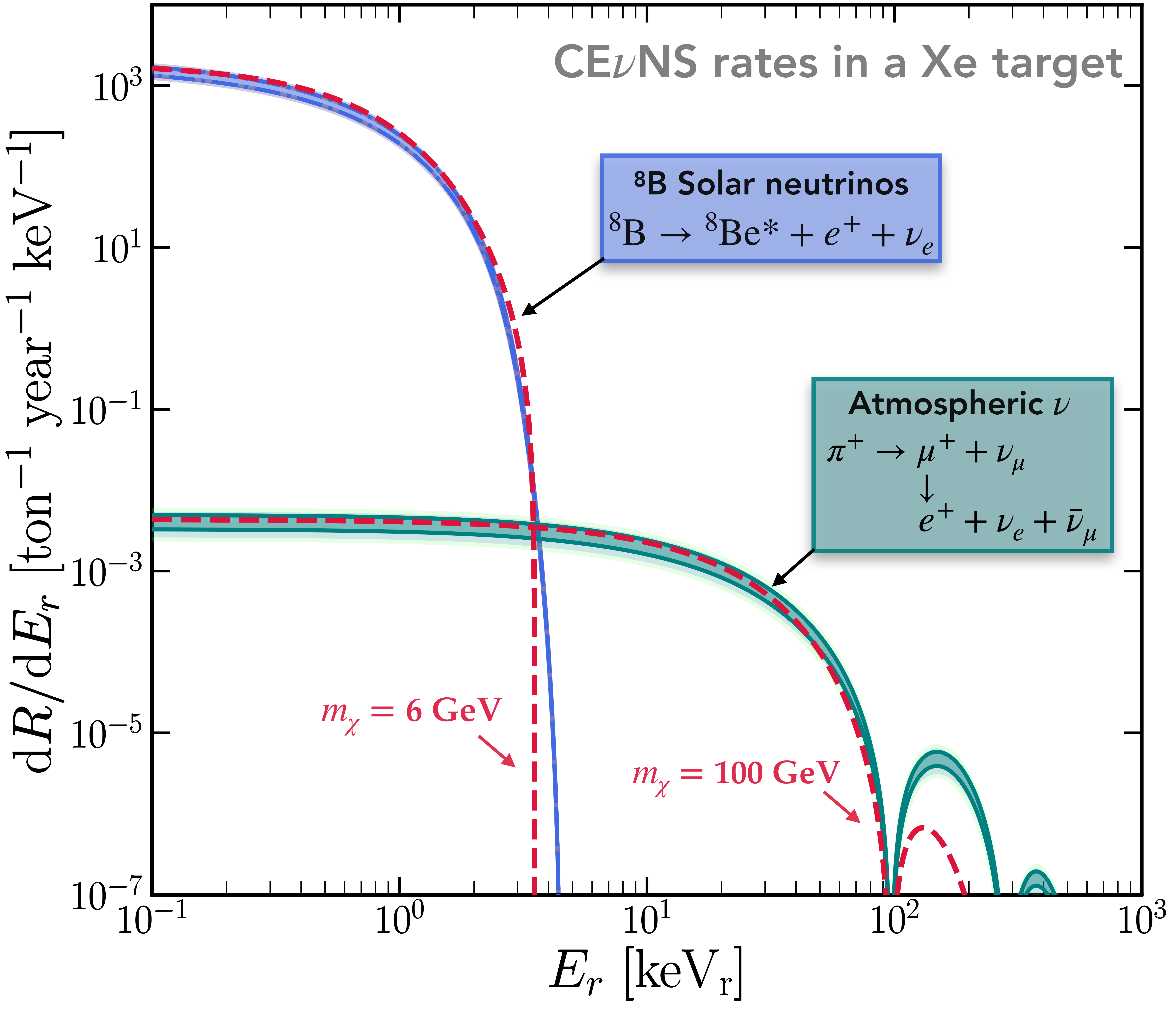


Two major neutrino backgrounds for DM searches

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

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

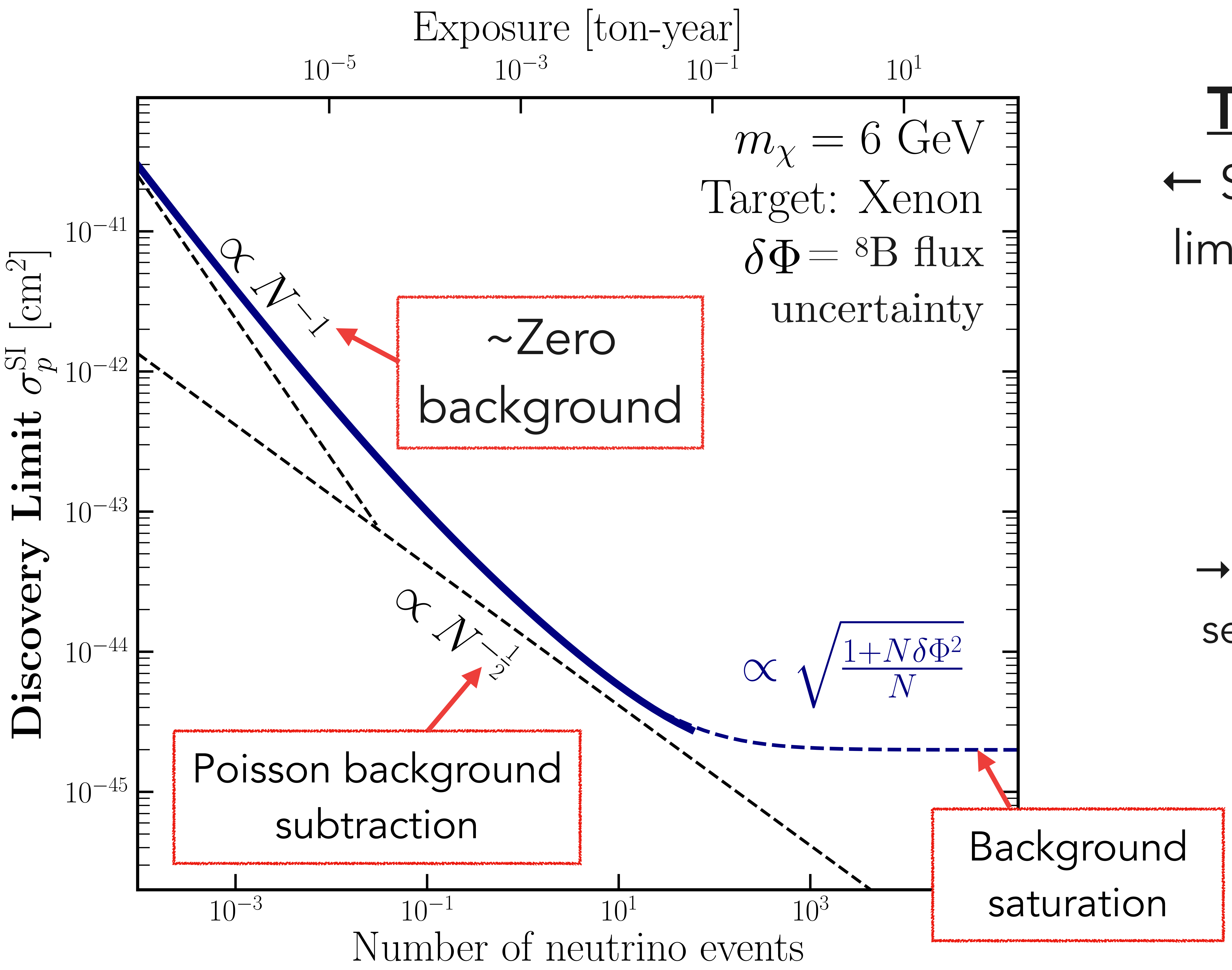
→ CEνNS event rates & energy spectrum look just like low mass (~GeV) and high mass (~100 GeV) **DM signals** respectively



The neutrino "floor" as it's usually presented

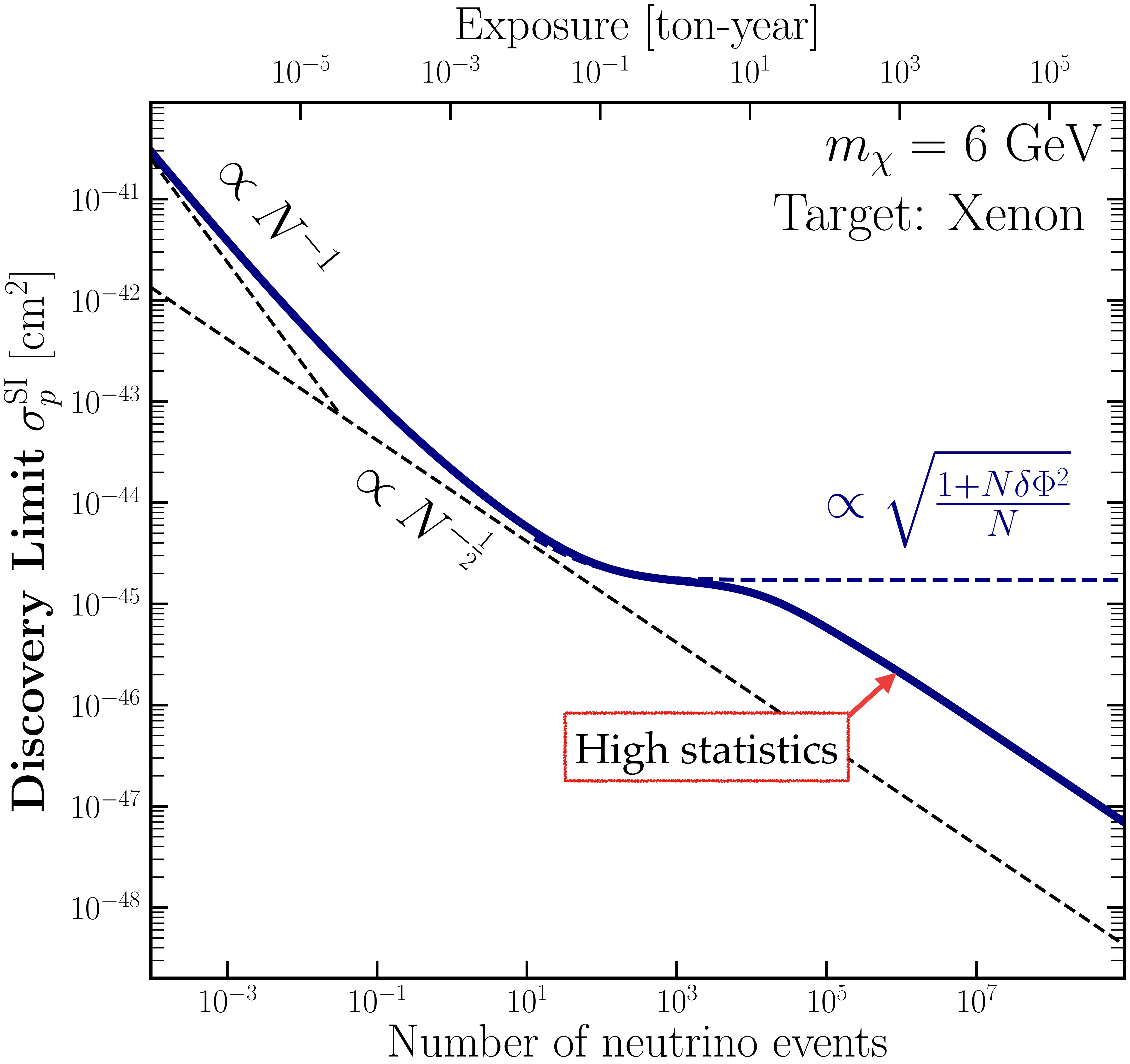
e.g. for LXe TPCs

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



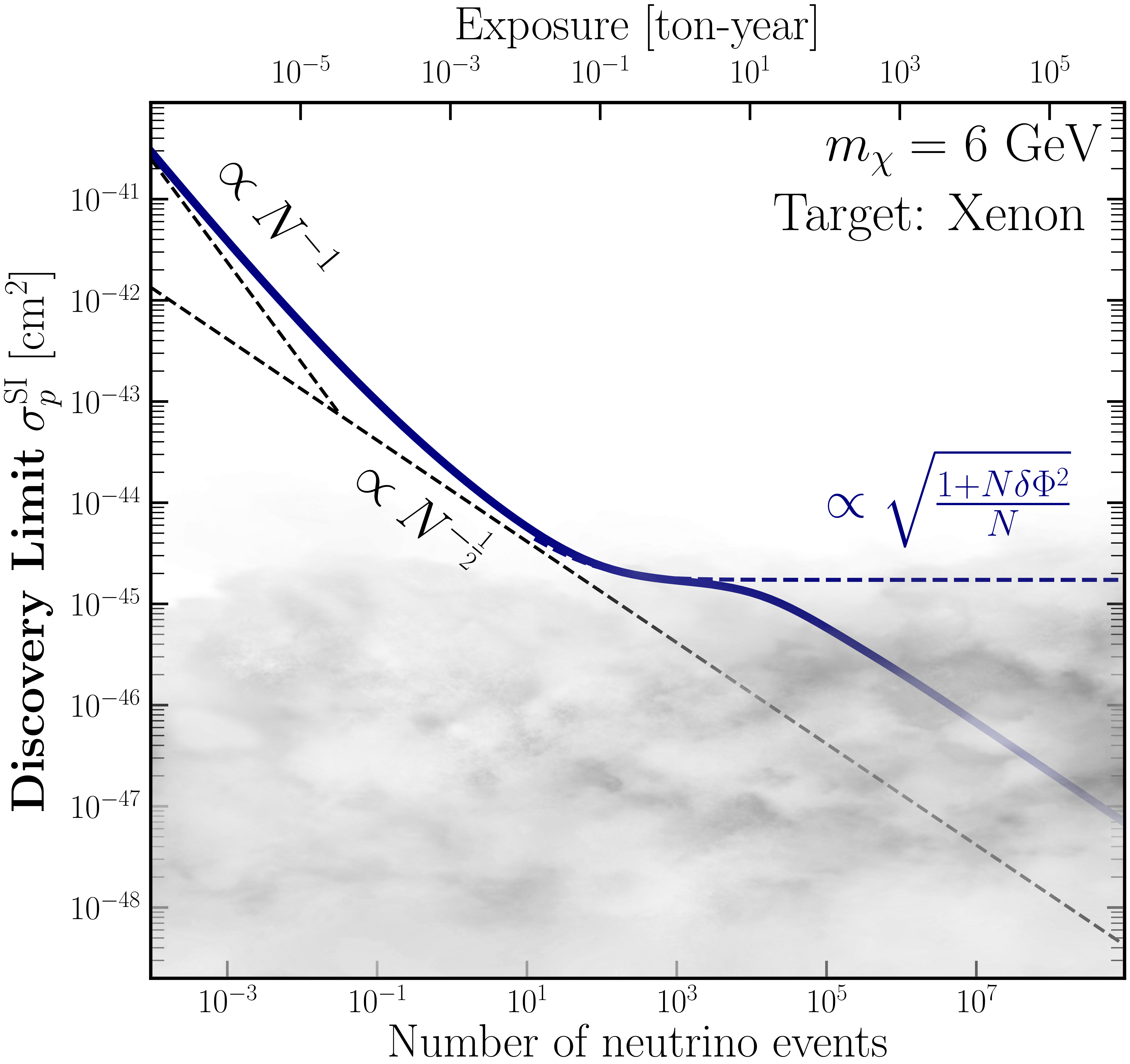
The full story:

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*

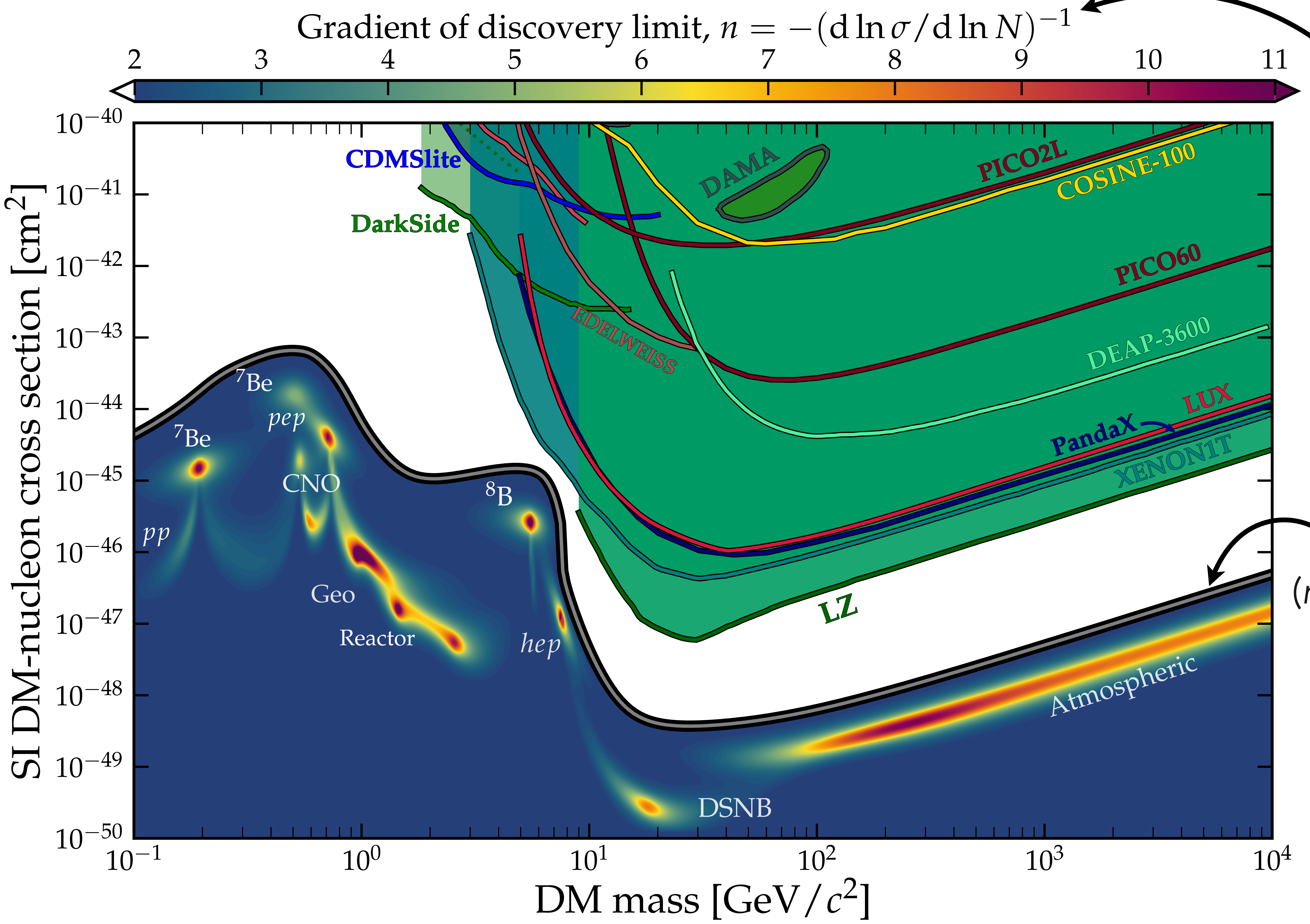


There is no "floor", but we can quantify the neutrino "fog" by looking at the scaling

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

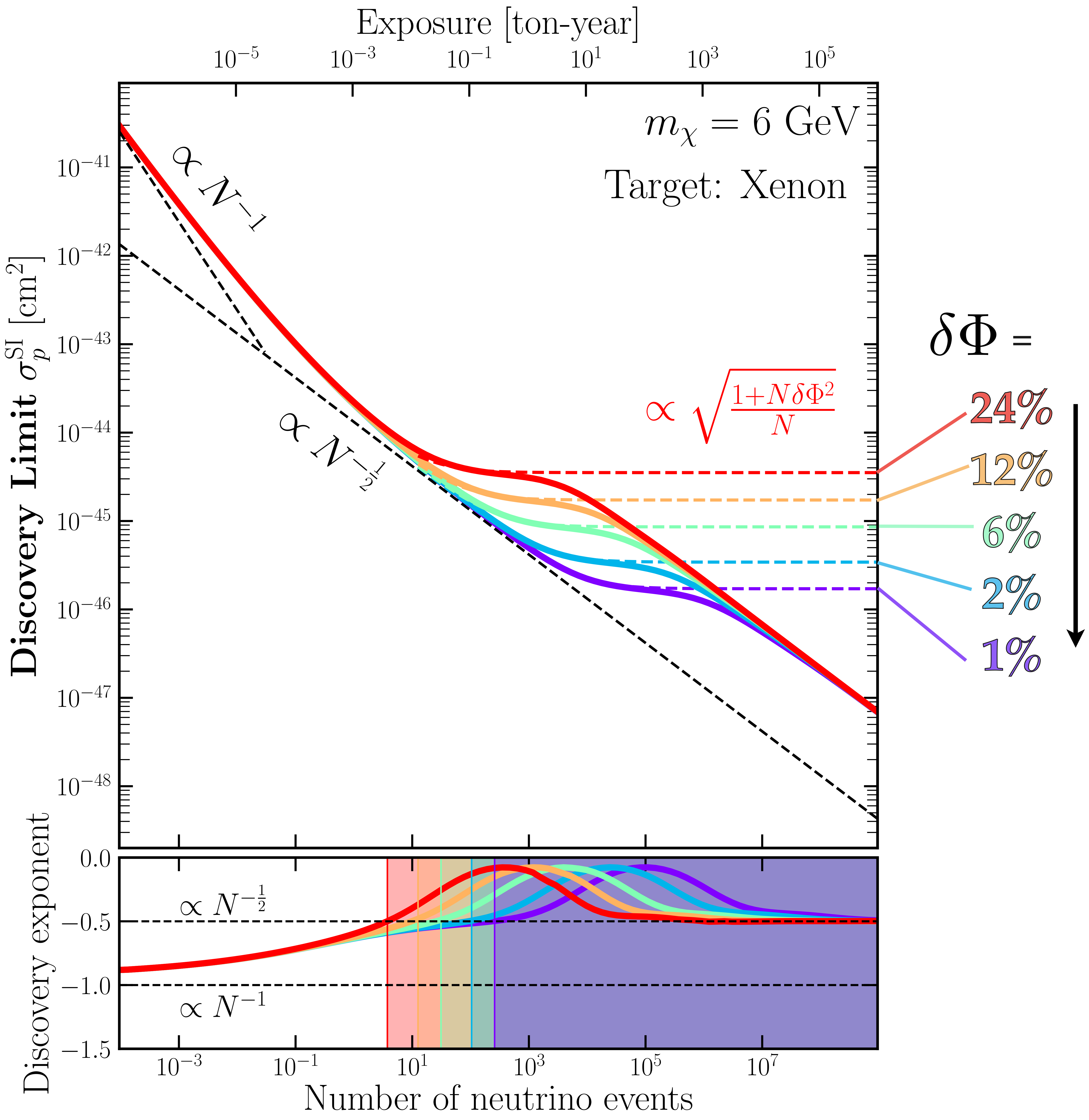


n parameterises the "fogginess" of the neutrino fog
→ note that it's not uniformly foggy everywhere

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



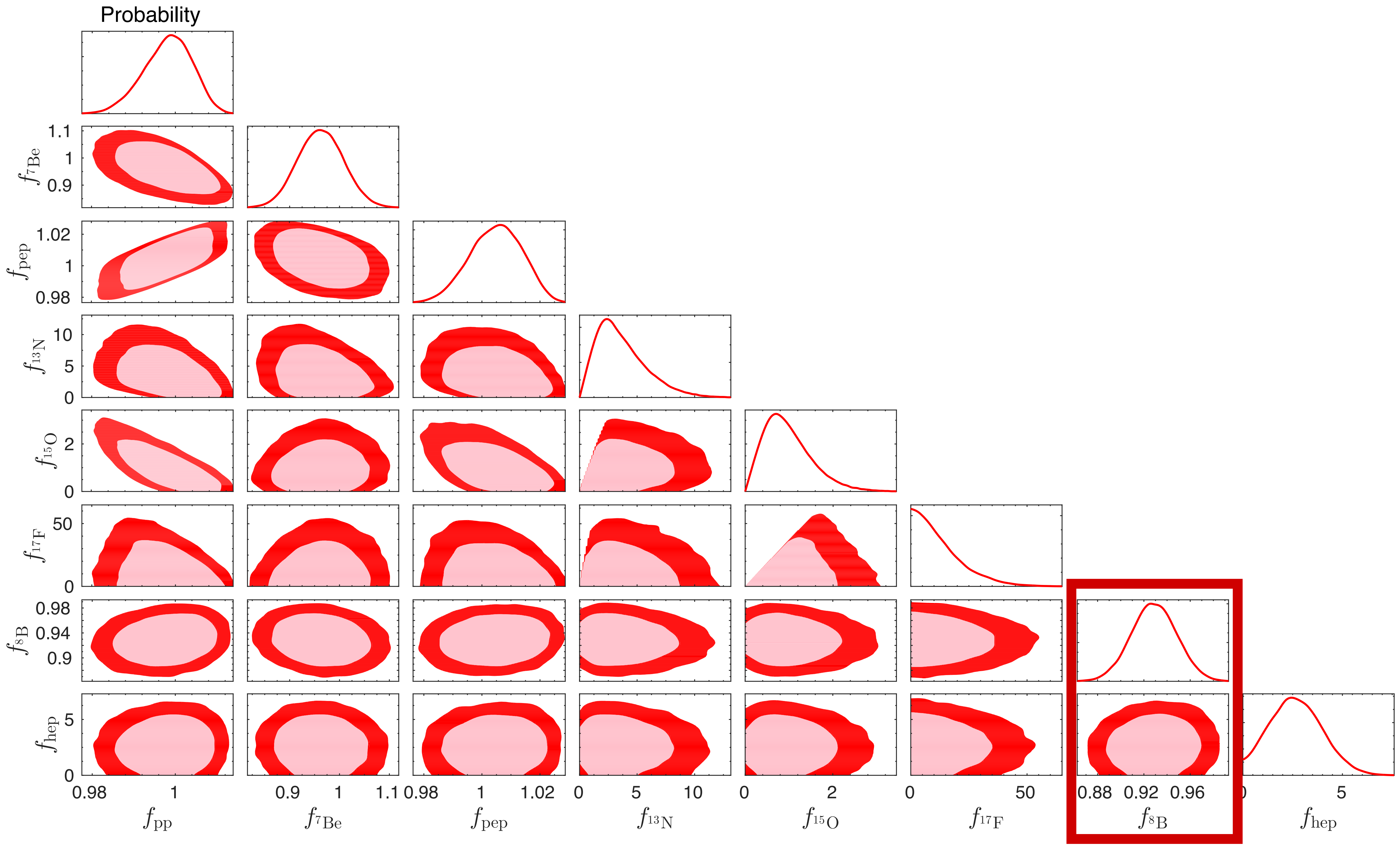
With a smaller neutrino flux uncertainty, the onset of the neutrino fog is pushed to lower cross sections

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

ν **type**		$\Phi(1 \pm \delta\Phi/\Phi)$ $[\text{cm}^{-2}\ \text{s}^{-1}]$	$\times 10^n$
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}Be	$4.93\,(1 \pm 0.06)$	10^{8}
	^{7}Be	$4.50\,(1 \pm 0.06)$	10^{9}
	^{8}B	$5.16\,(1 \pm 0.02)$	10^{6}
	^{13}N	$2.78\,(1 \pm 0.15)$	10^{8}
	^{15}O	$2.05\,(1 \pm 0.17)$	10^{8}
	^{17}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



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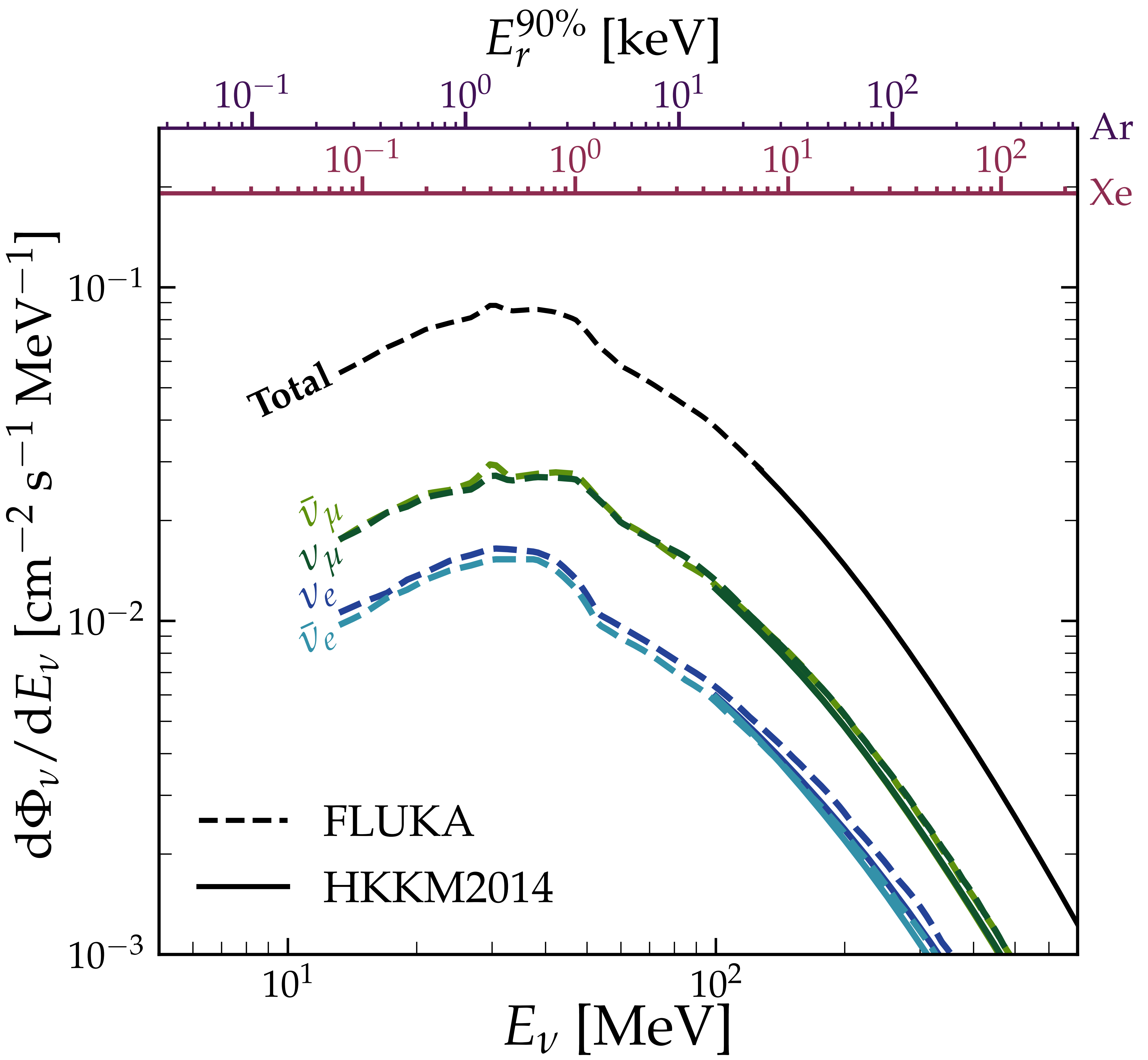
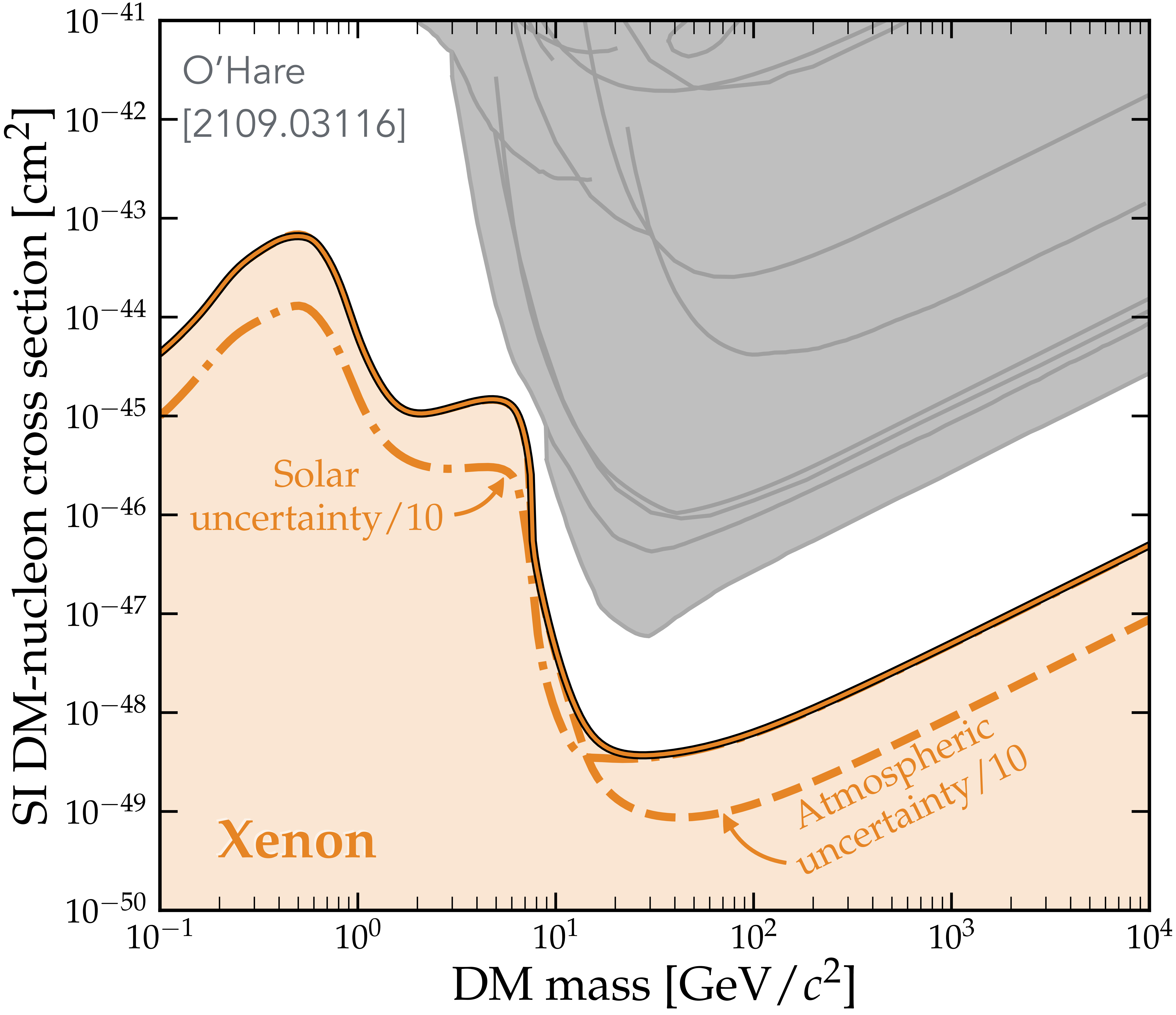
Low-E tail of **atmospheric flux** not yet measured at the relevant energies—25% uncertainty is pessimistic



Effect of reducing flux uncertainties on the neutrino fog




x14 038248
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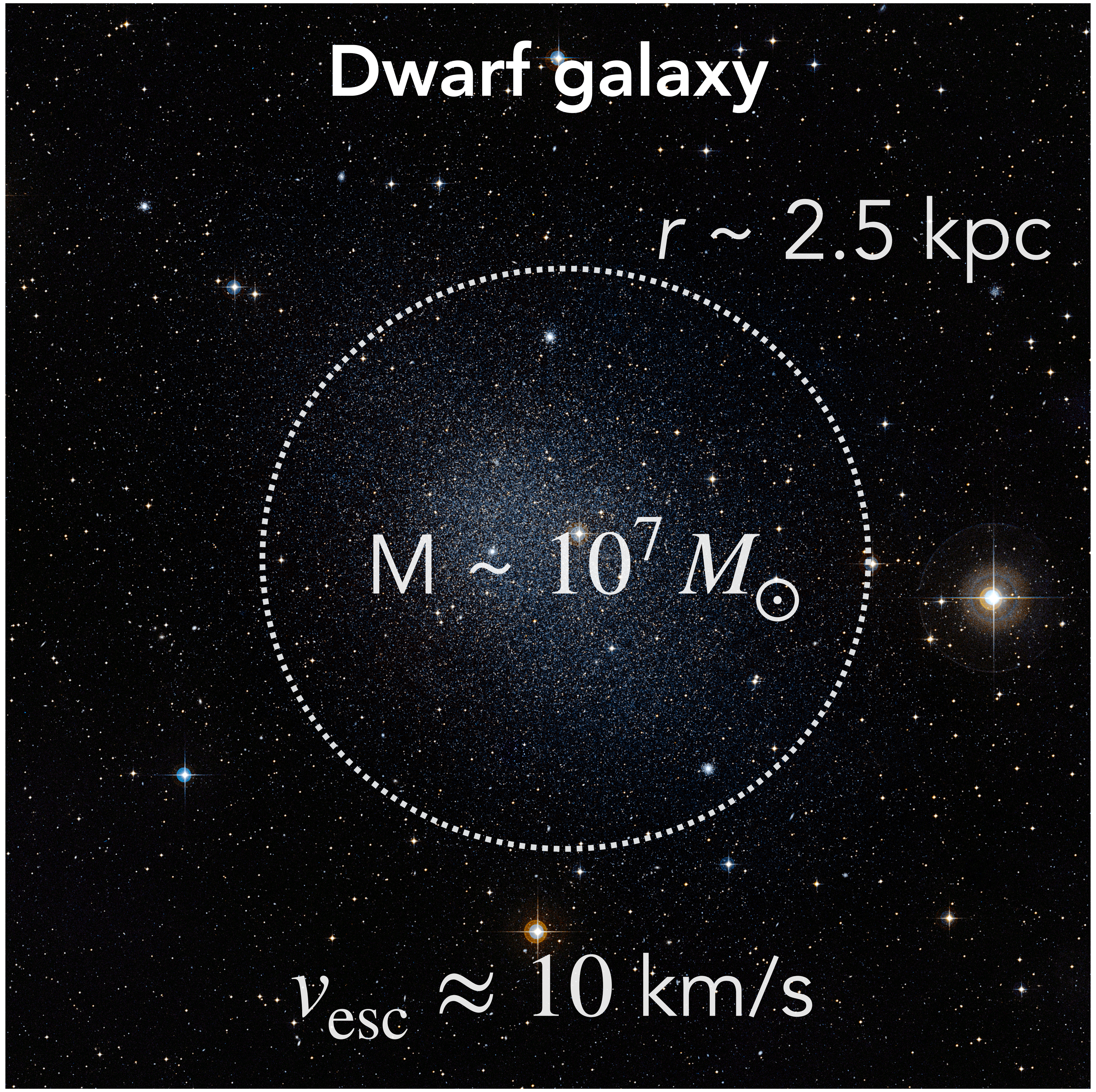
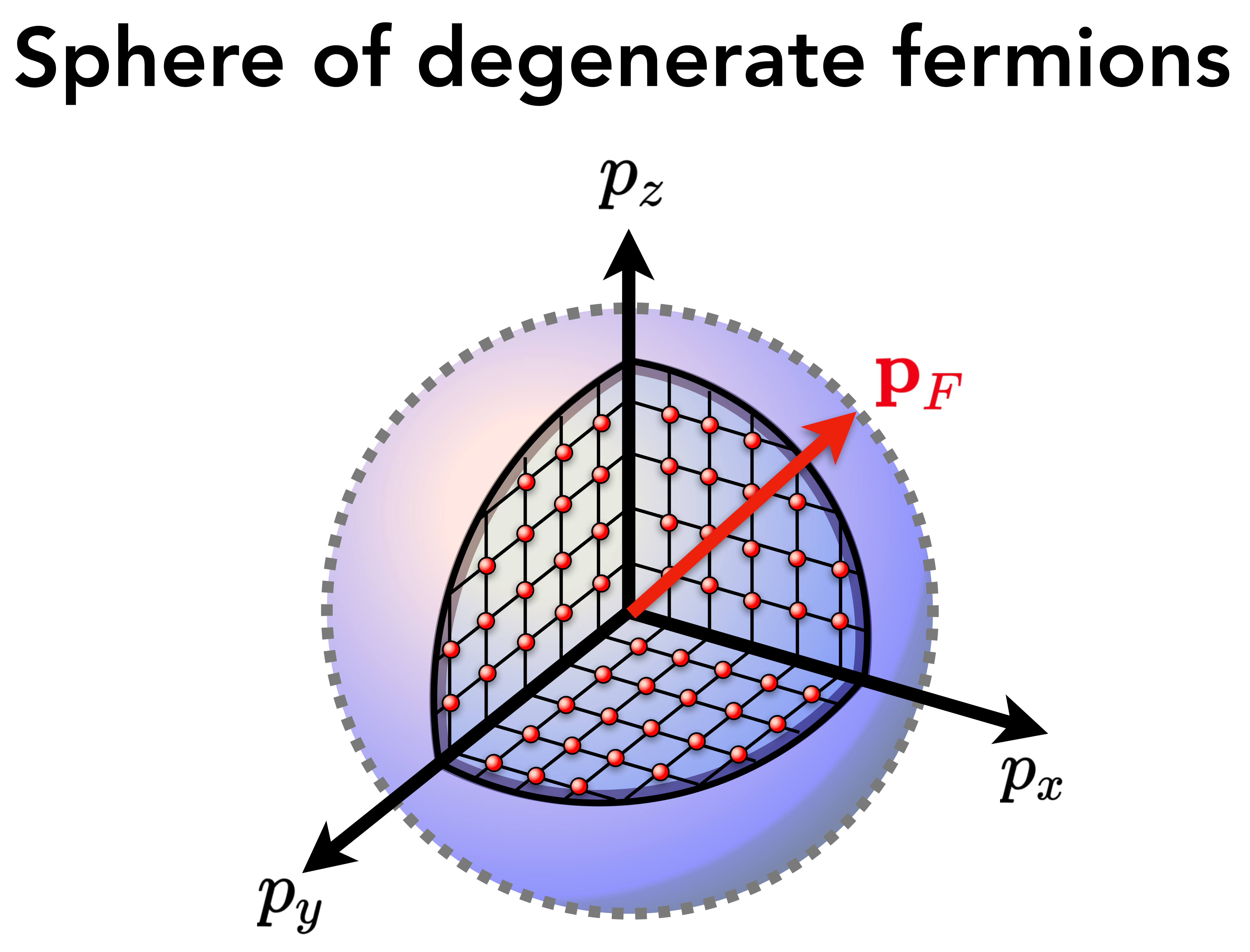
TIKTOKER


快手
CSM
Relaxing
CSM
Relaxing

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





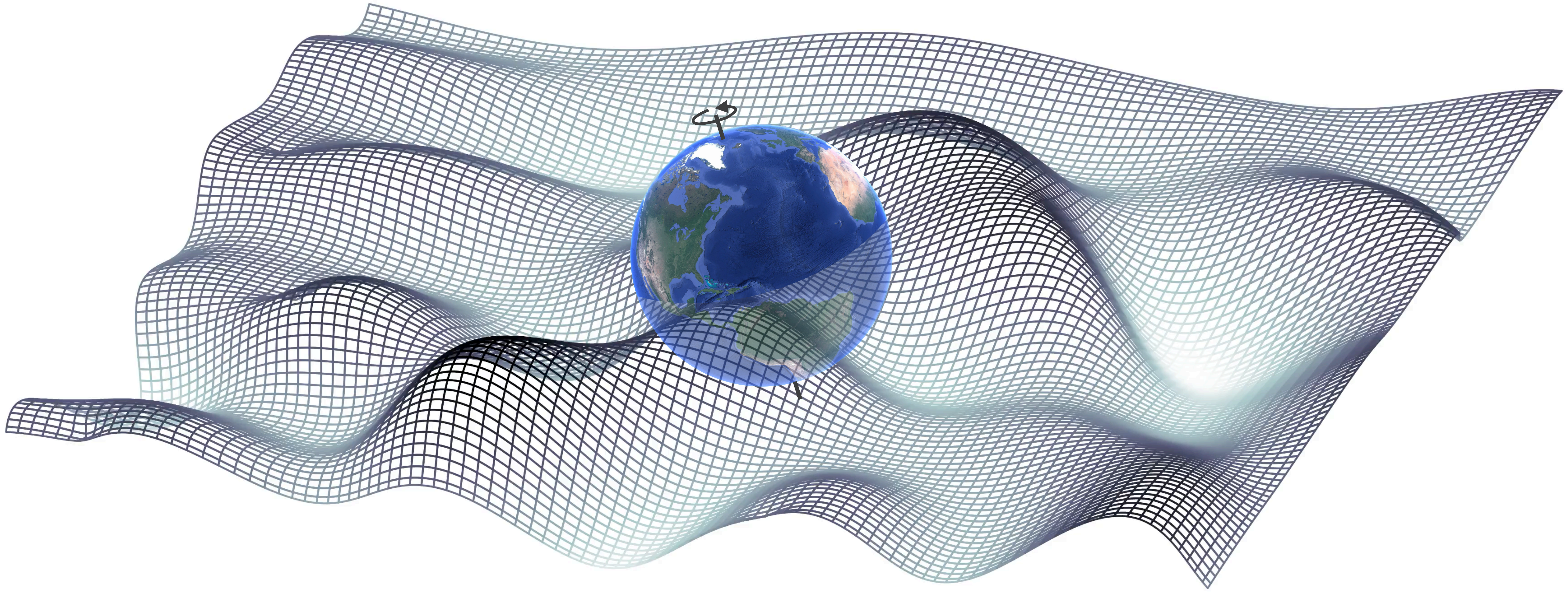
$$v_F < v_{esc}$$

$$\Rightarrow m_\chi \gtrsim 100 \text{ eV}$$

"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: $A = \dfrac{\sqrt{2\rho_{\rm DM}}}{m}$

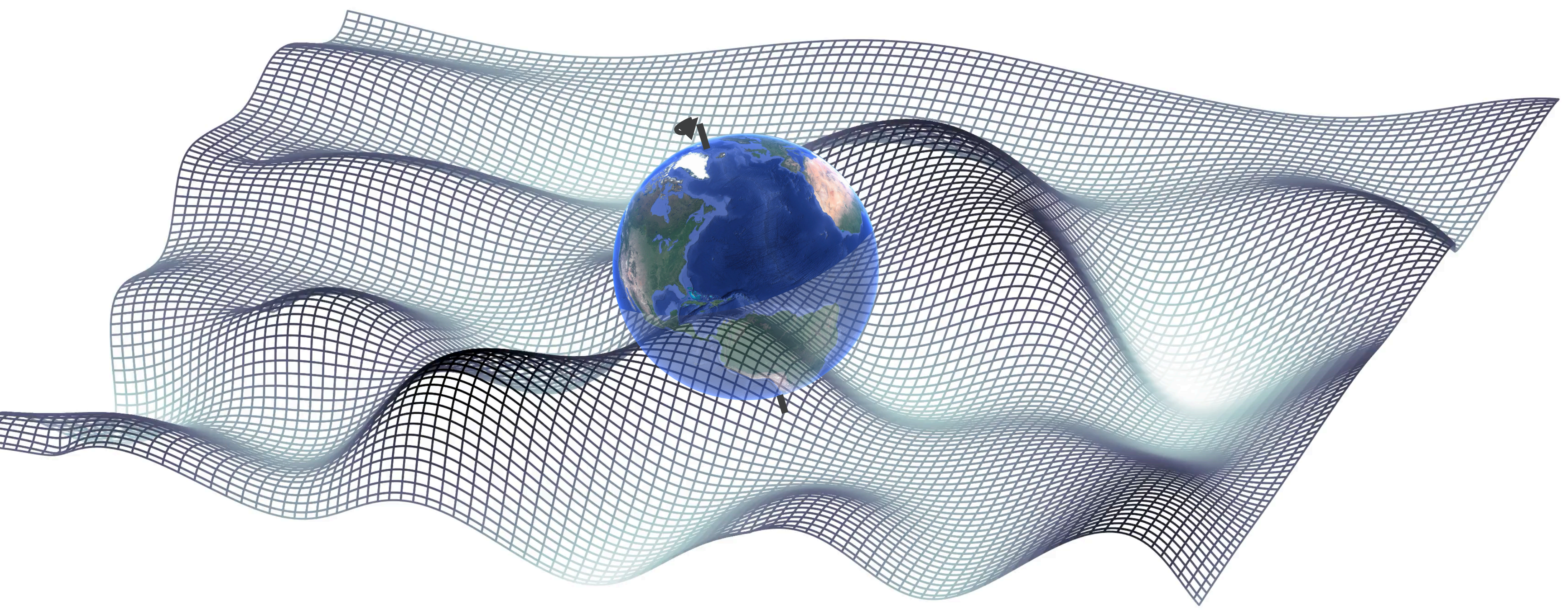
Frequency: $\omega = m + \dfrac{1}{2}mv^2$

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

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:

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

Arbitrary phase

Random amplitude

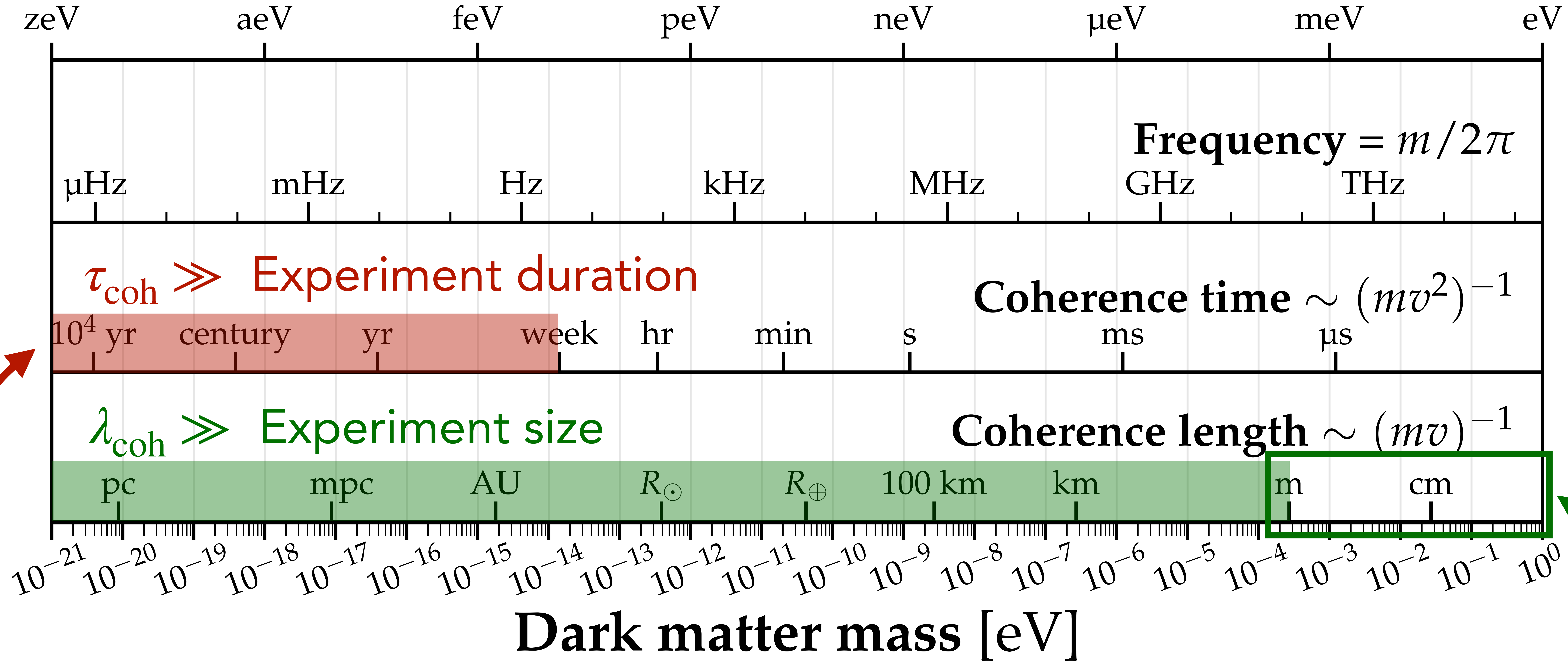
Random draw from the velocity distribution

What is considered short?

< Coherence length and coherence time

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

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



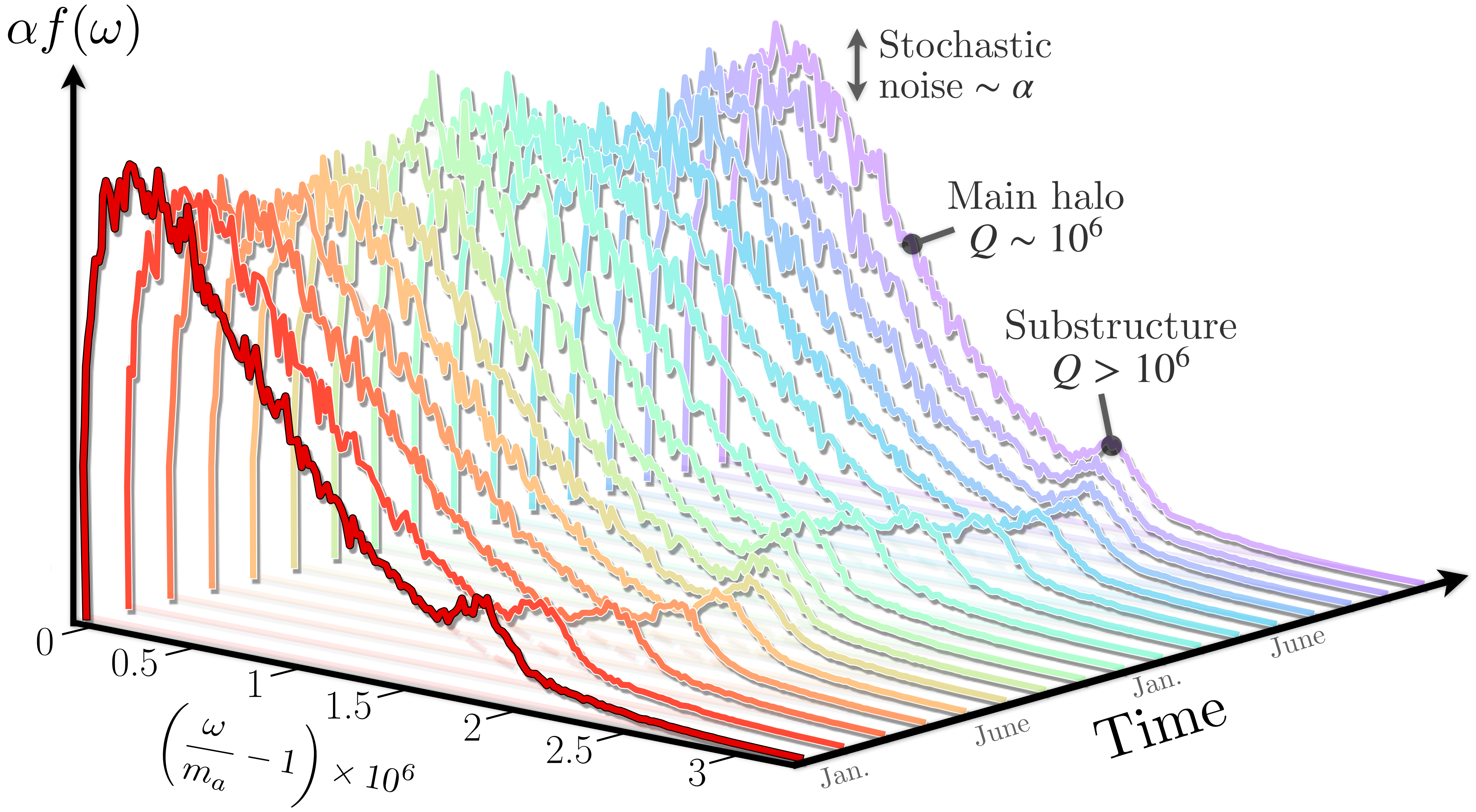
~week-long integration will observe almost perfectly monochromatic signal

(Worry instead about random amplitude)

Field oscillations are out of phase in different parts of <m-scale experiment

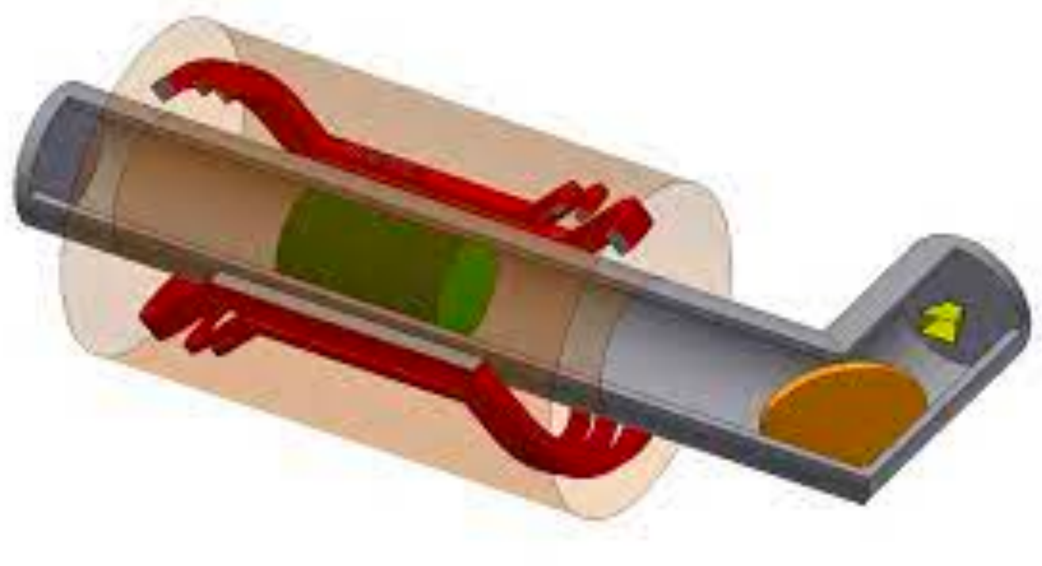
Wave-like dark matter

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

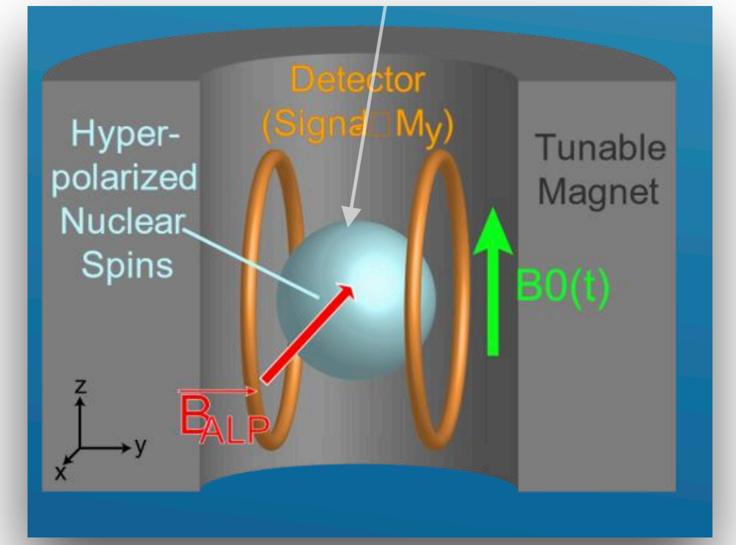


→ Speed distribution leads to a distinctive "lineshape" in frequency that will modulate over the year

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



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

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

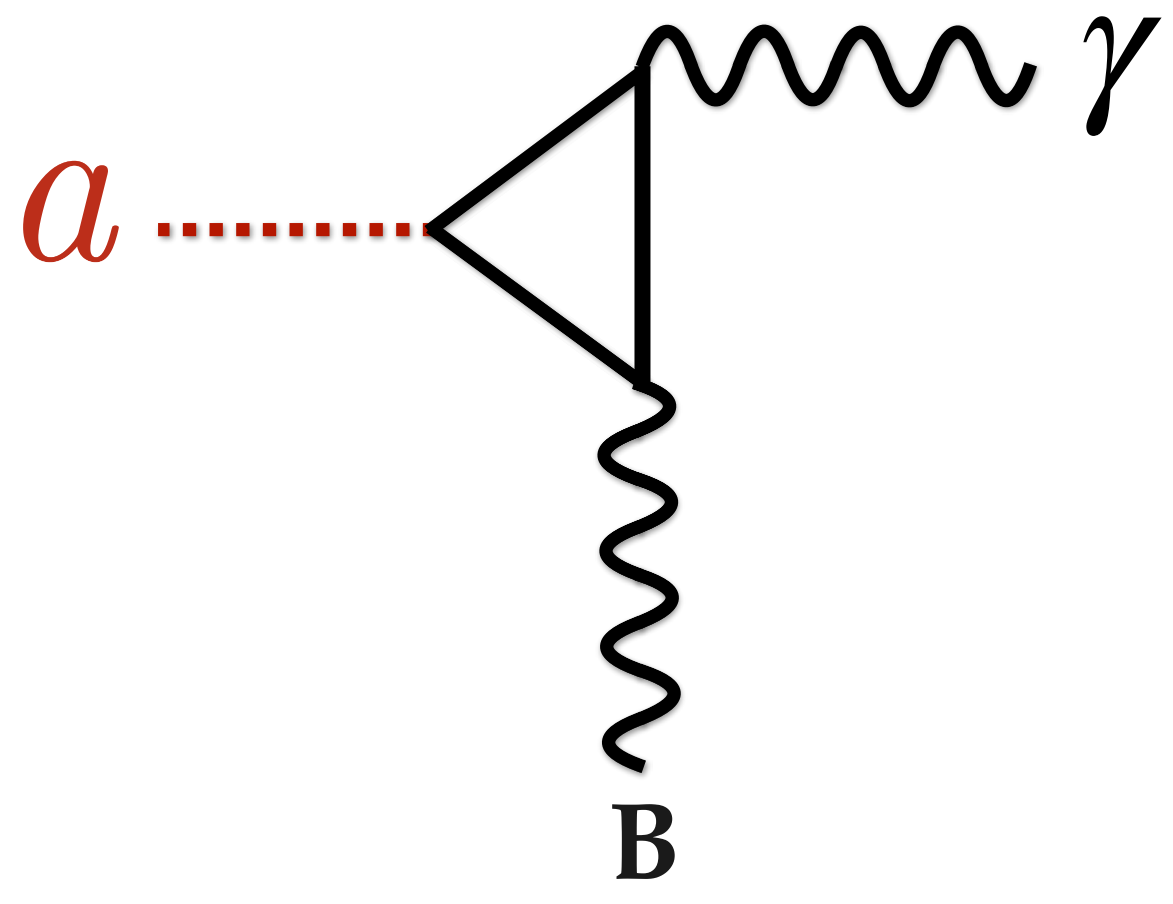
+ a few model-dependent assumptions

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

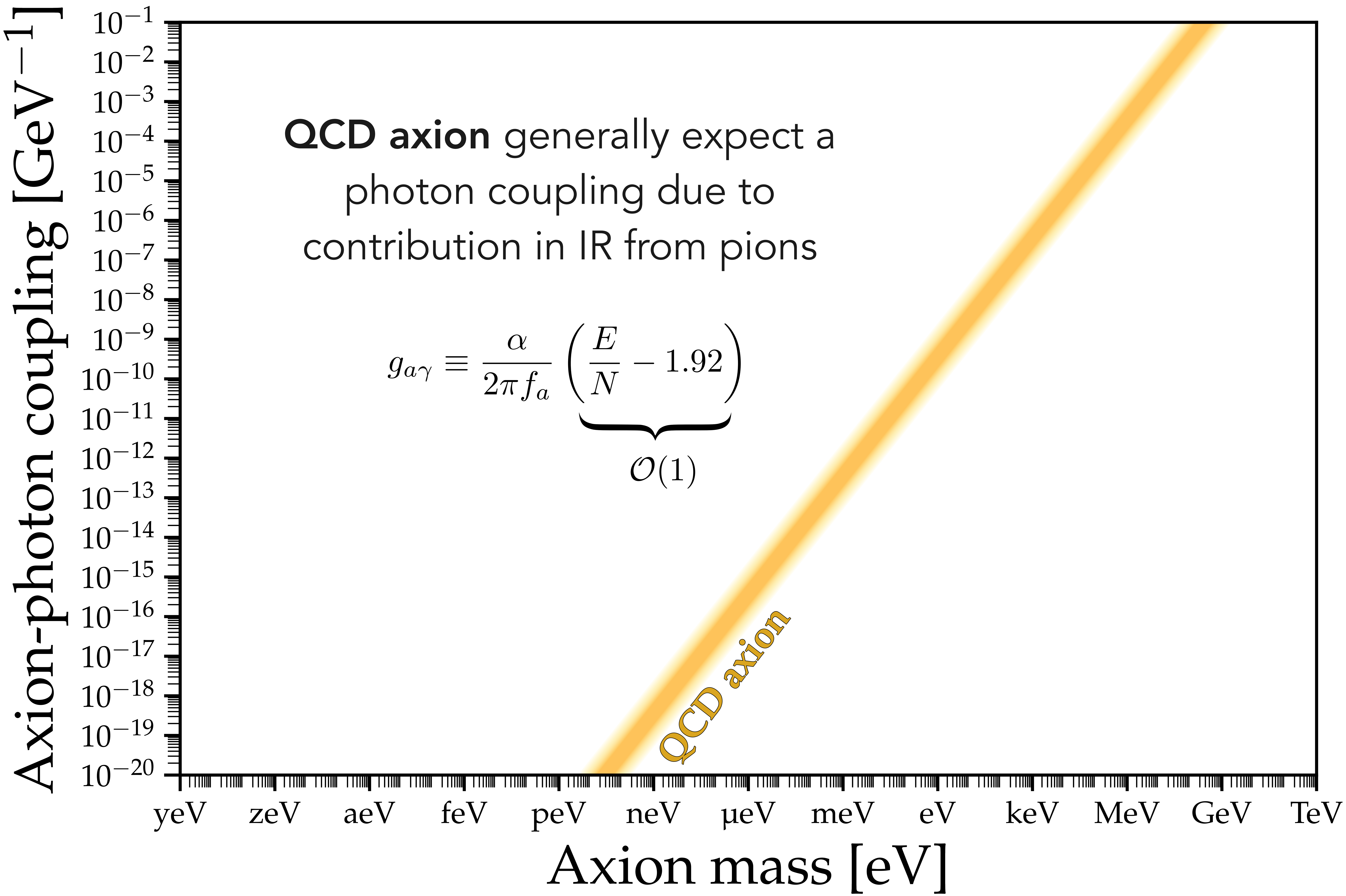
Axion-photon interaction

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

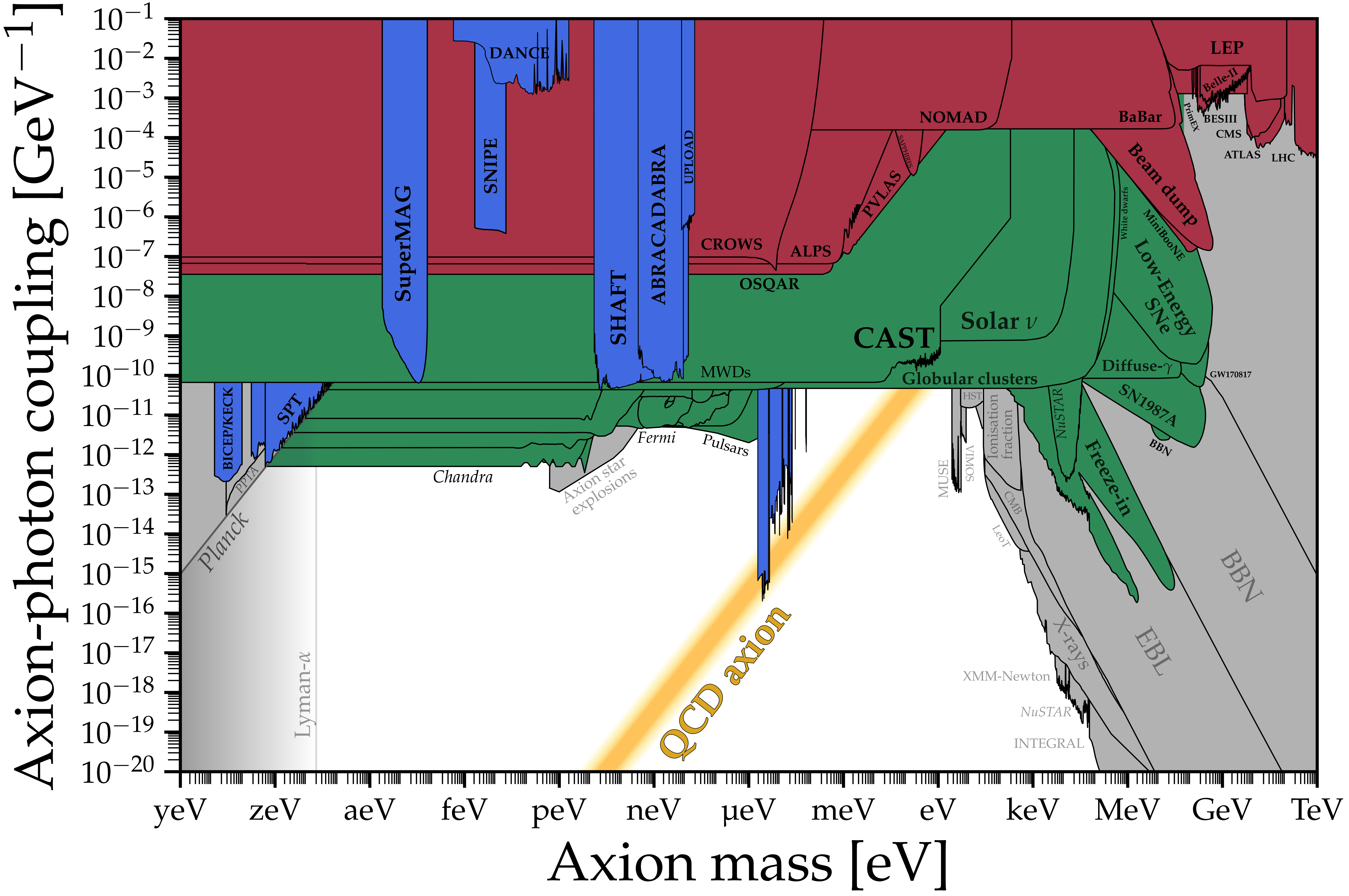
DM axion → Photon



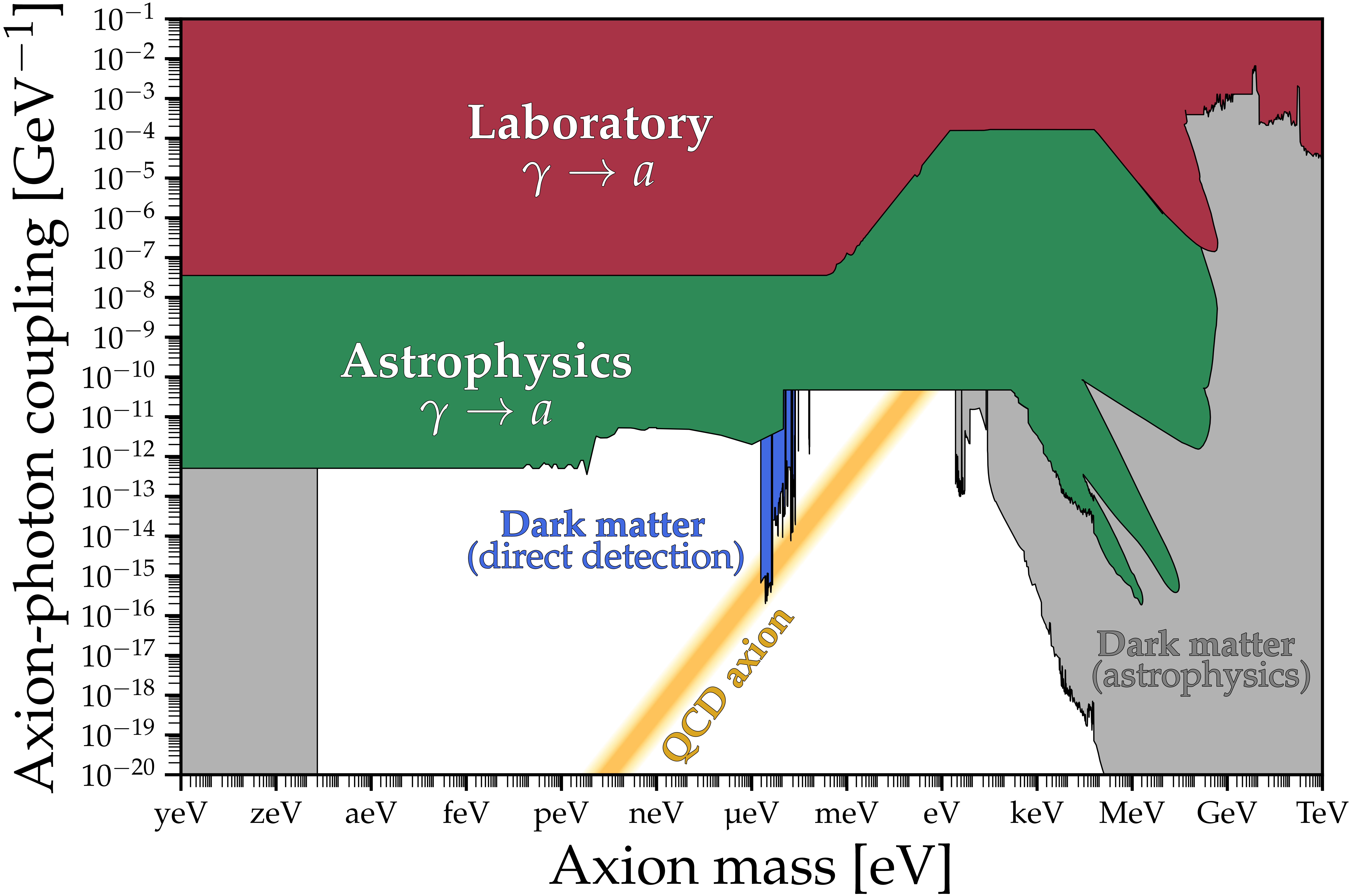
- DM axions source photons with energy = m_a in the presence of an EM-field
- Could use E-field or B-field to supply EM-background, but in practice only B-fields are used
- Axion mixes only with component of photon parallel to an B-field, can lead to some interesting polarisation signals like birefringence



QCD axion generally expect a
photon coupling due to
contribution in IR from pions
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} \underbrace{\left(\frac{E}{N} - 1.92\right)}_{\mathcal{O}(1)}$$
QCD axion
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-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
ALPS
OSQAR
PVLAS
NOMAD
BaBar
LEP
Belle-II
PrimEx
BESIII
CMS
ATLAS
LHC
Beam dump
MiniBooNE
White dwarfs
Low-Energy SNe
CAST
Solar ν
MWDs
Globular clusters
Diffuse-γ
GW170817
SN1987A
BBN
NuSTAR
Freeze-in
BICEP/KECK
SPT
PPTA
Planck
Chandra
Fermi
Pulsars
Axion star explosions
HST
Ionisation fraction
MUSE
VIMOS
CMB
LeoT
X-rays
EBL
BBN
XMM-Newton
NuSTAR
INTEGRAL
Lyman-α
QCD axion



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]

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$
$$\mathbf{E} = -\nabla A_0 - \dot{\mathbf{A}}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axion electrodynamics

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

- E-L equation for A_μ shows 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

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

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

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)

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

↓

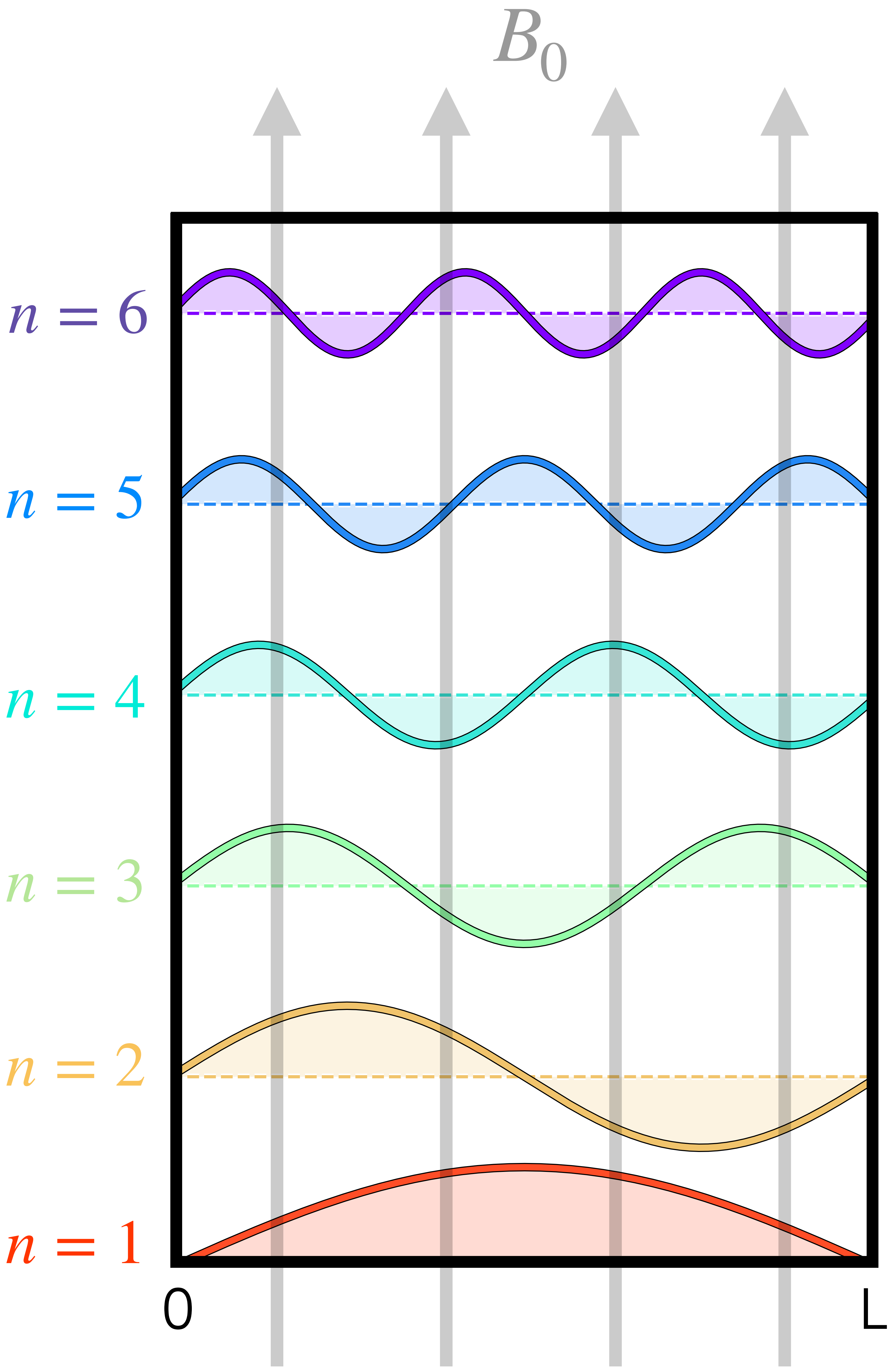
$$a(t) \sim \cos(m_a t)$$

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

↓

Axion excites mode and drives resonance at

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



Cavity haloscope

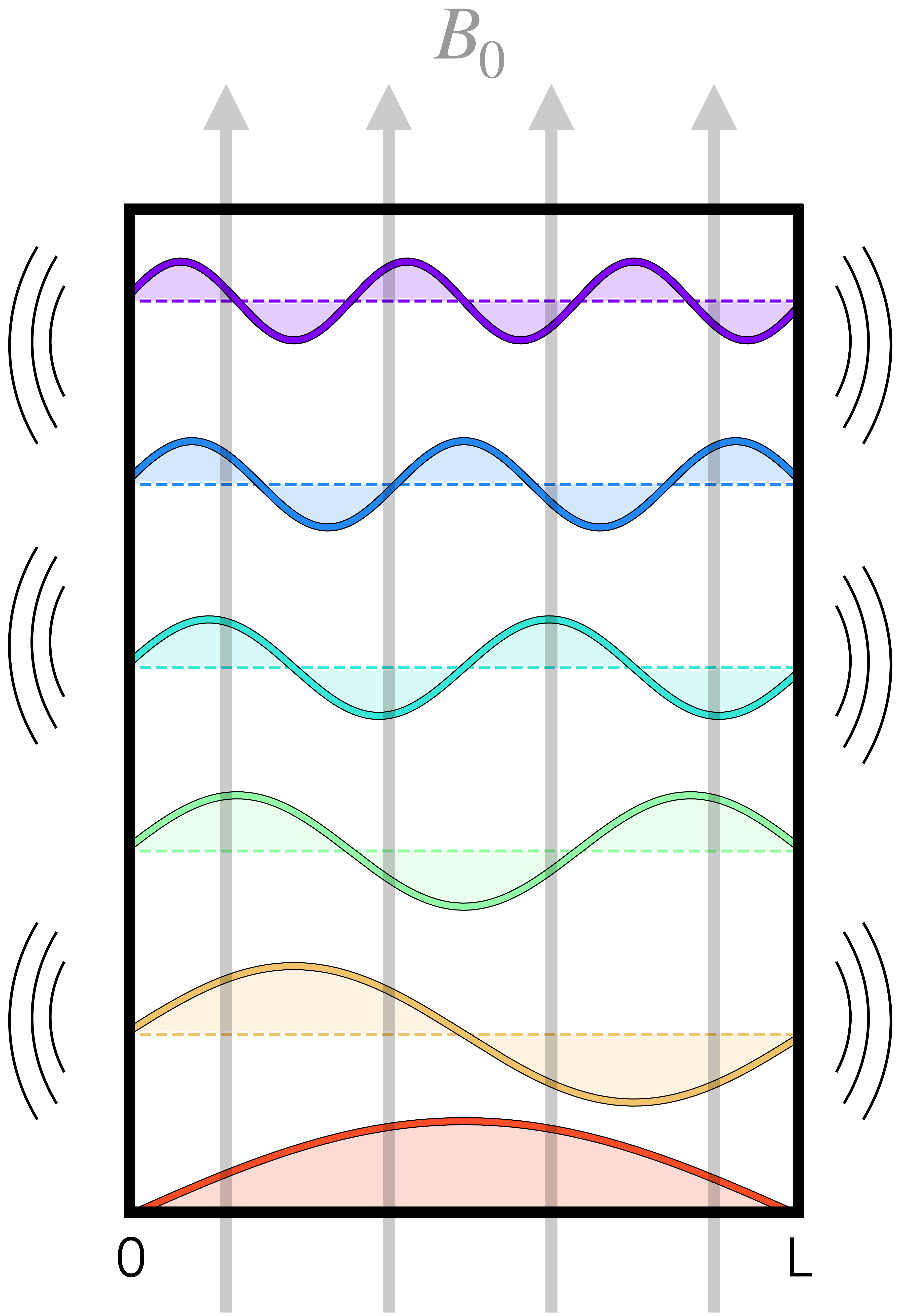
Power lost from the cavity quantified in terms of the "quality factor"

Q = energy stored/energy lost per oscillation period

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

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

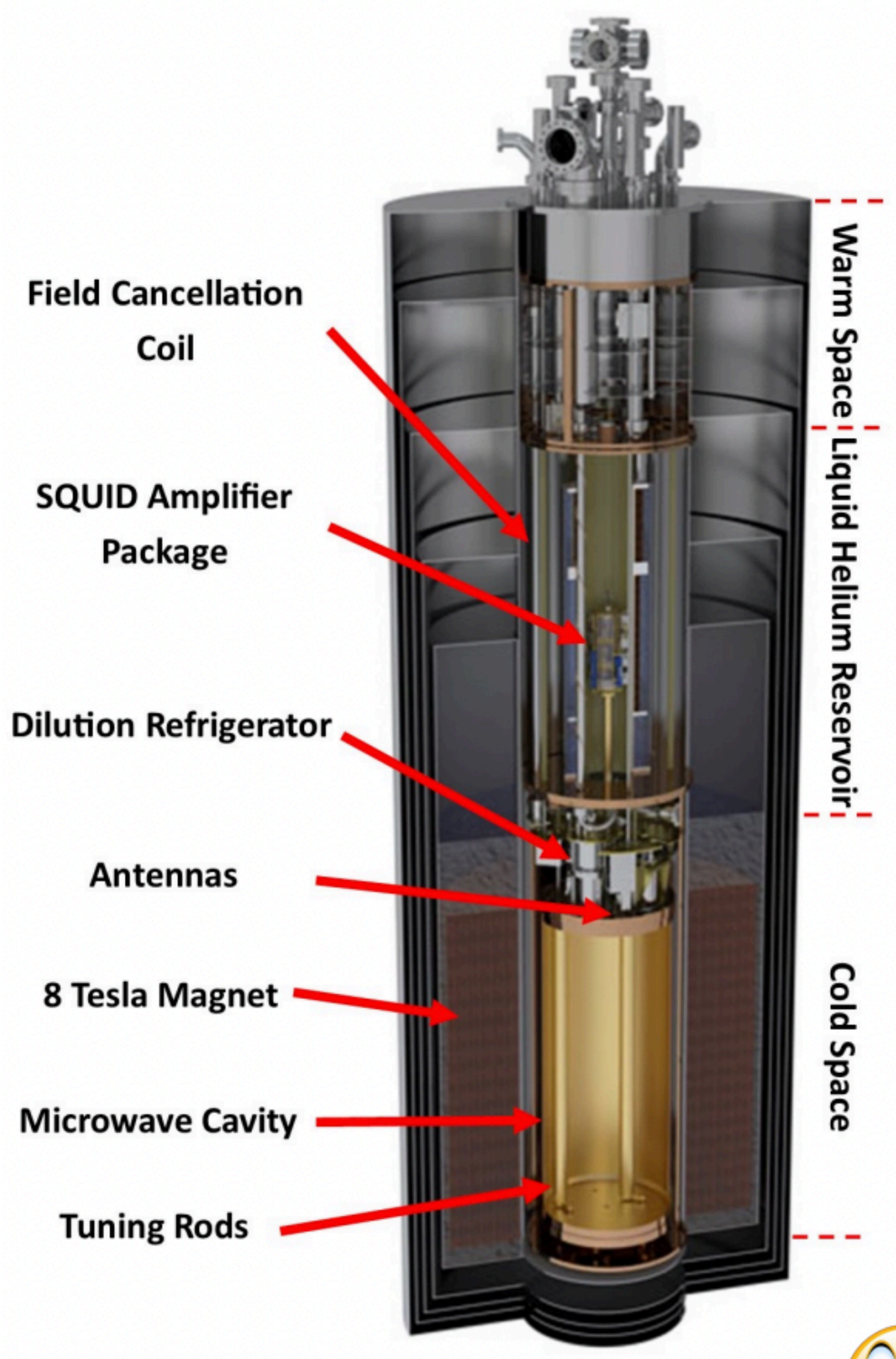
$$P_a = 6.3 \times 10^{-22}\ \mathrm{W} \cancel{\left(\frac{g_{a\gamma\gamma}}{10^{-15}\,\mathrm{GeV}^{-1}}\right)^2} \cancel{\left(\frac{V}{220\,\mathrm{l}}\right)} \left(\frac{B}{8\ \mathrm{T}}\right)^2 \left(\frac{C_{nlm}}{0.69}\right) \cancel{\left(\frac{\rho_a}{0.3\,\mathrm{GeV\,cm^{-3}}}\right)}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

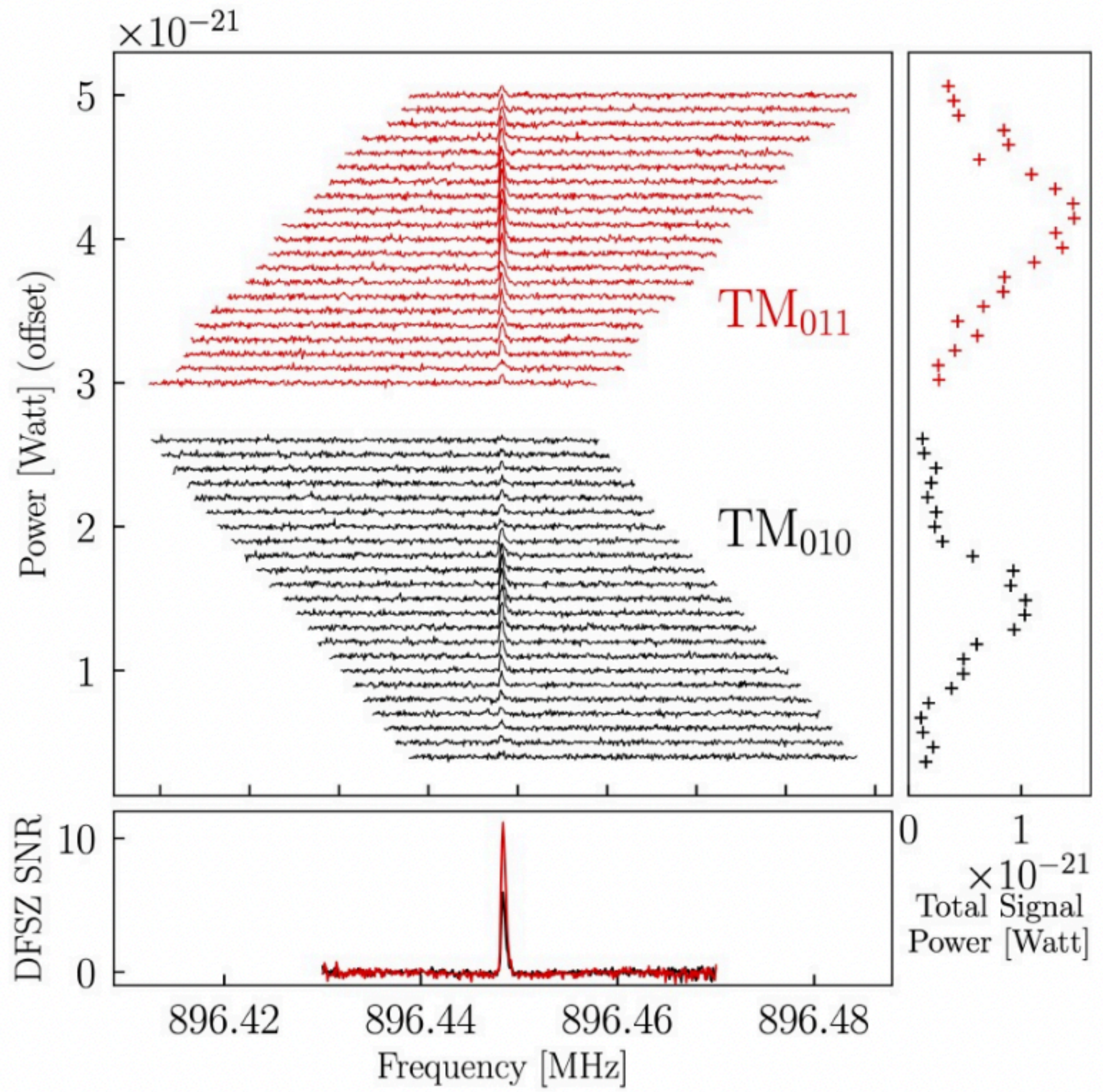
Volume fixed by resonant frequency

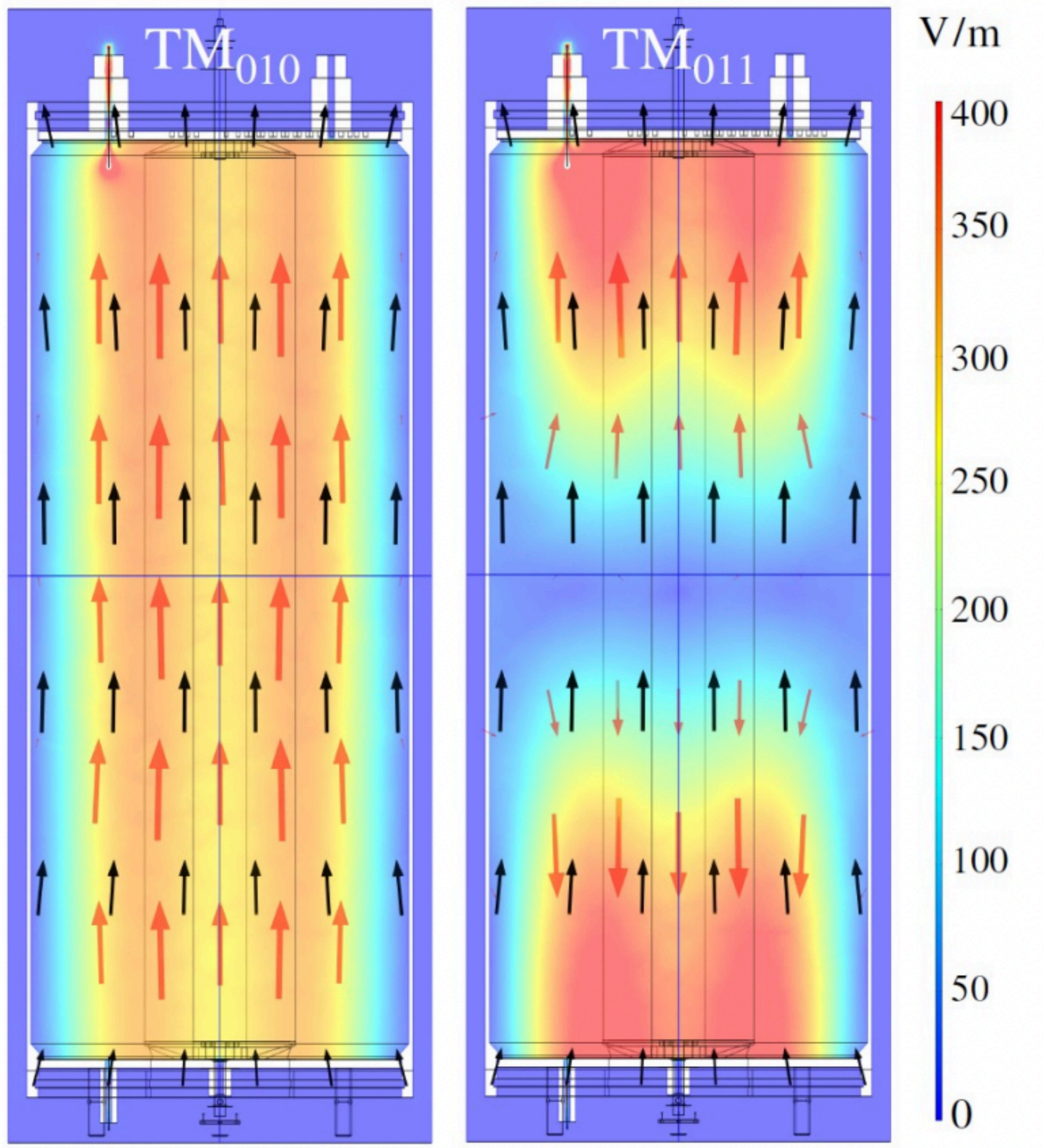
Search @ higher masses? → Forced to use smaller V → Power suppressed ∝ V

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

Achieve sensitivity across a band of axion masses by tuning resonance 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.)

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

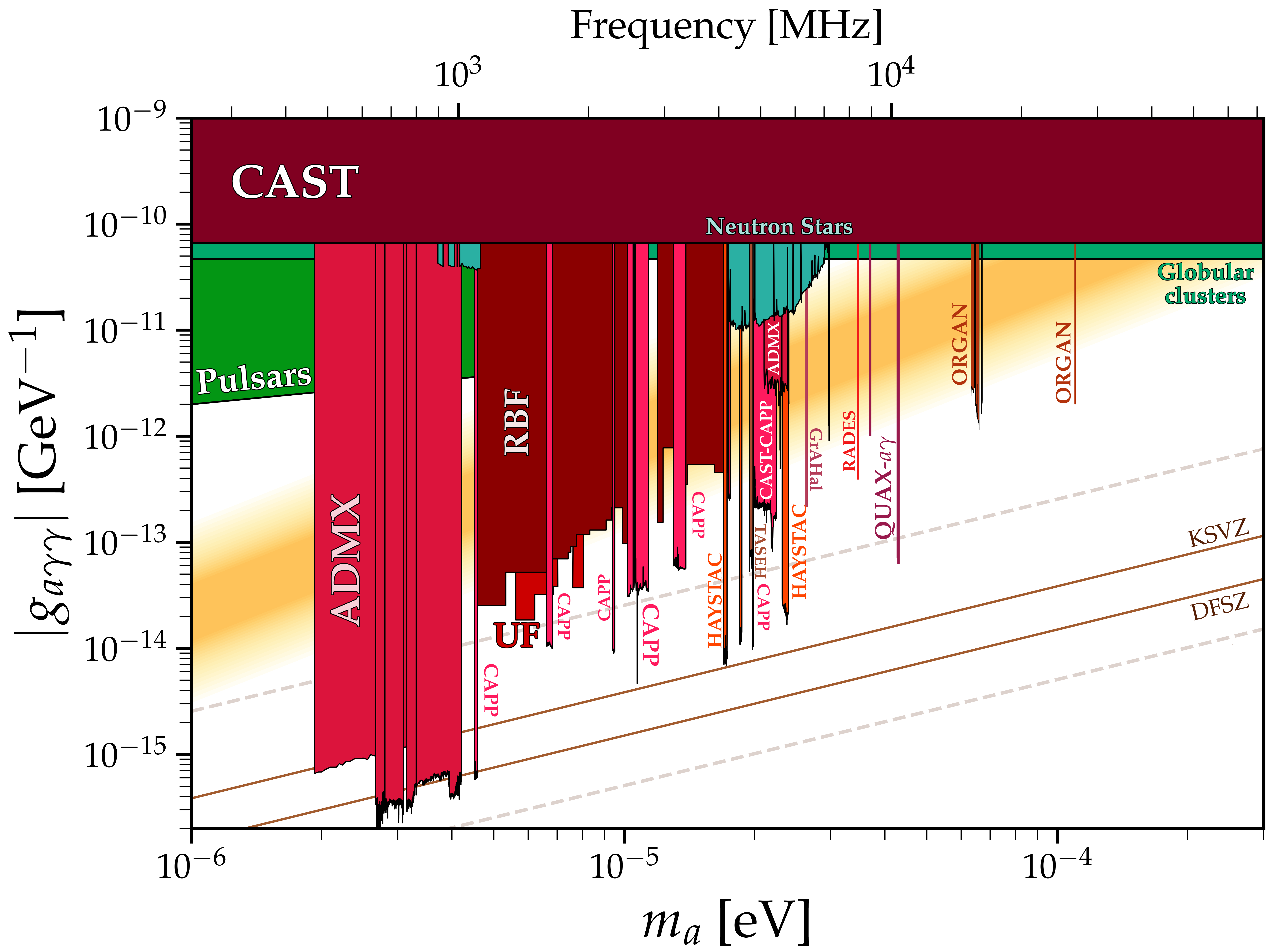
T = Noise temp.
t_{int} = integration time
$\Delta\nu$ = bandwidth

→ **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 $C_{a\gamma}$)

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

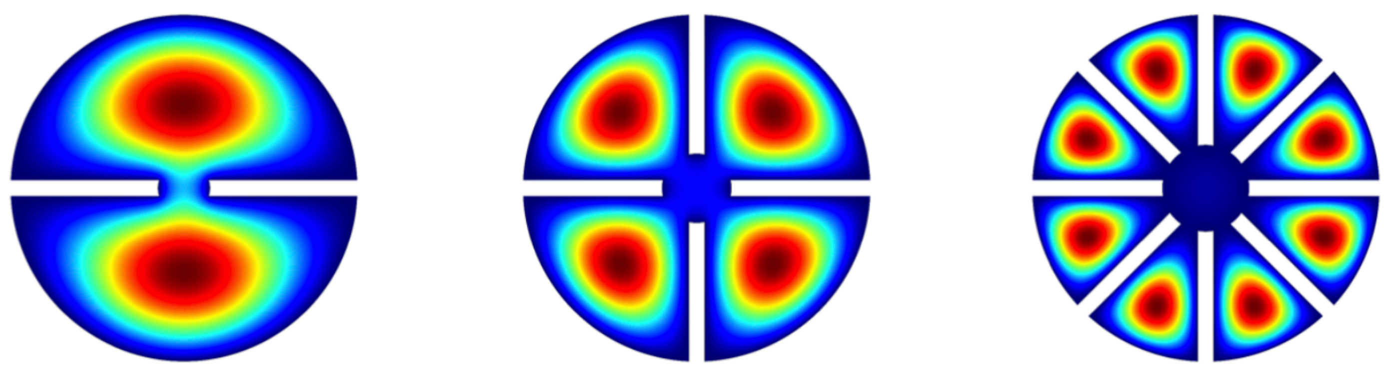
e.g. $C_{a\gamma} = 1.92$ for KSVZ axion

Actually m_a^{-6}

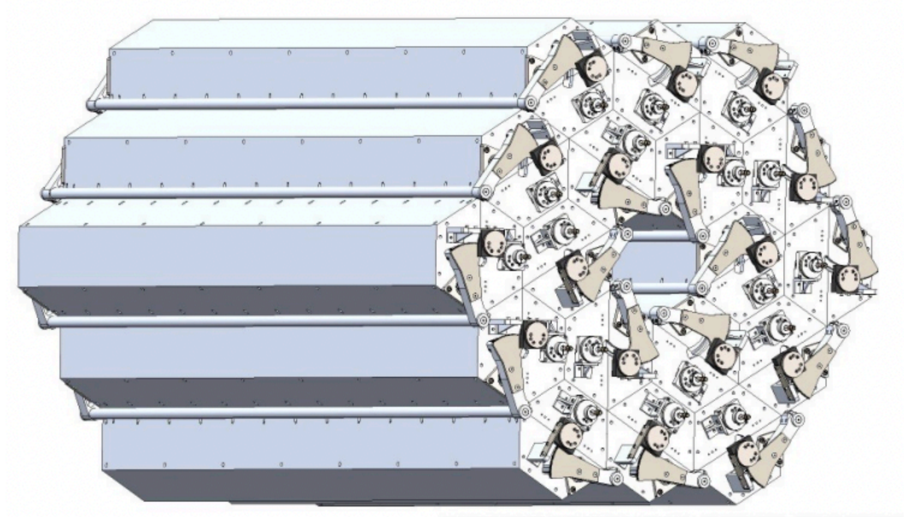


How to advance in sensitivity:

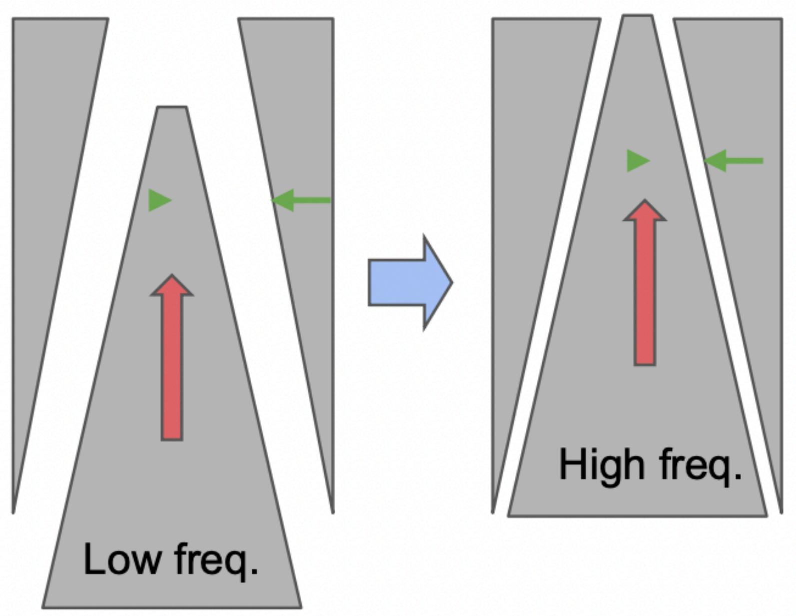
- Decouple V and $1/m_a$ (complicate the geometry)
- Lower noise (including sub-quantum-limit noise)



CAPP "Pizza cavity"



ADMX EFR



ADMX Wedge design

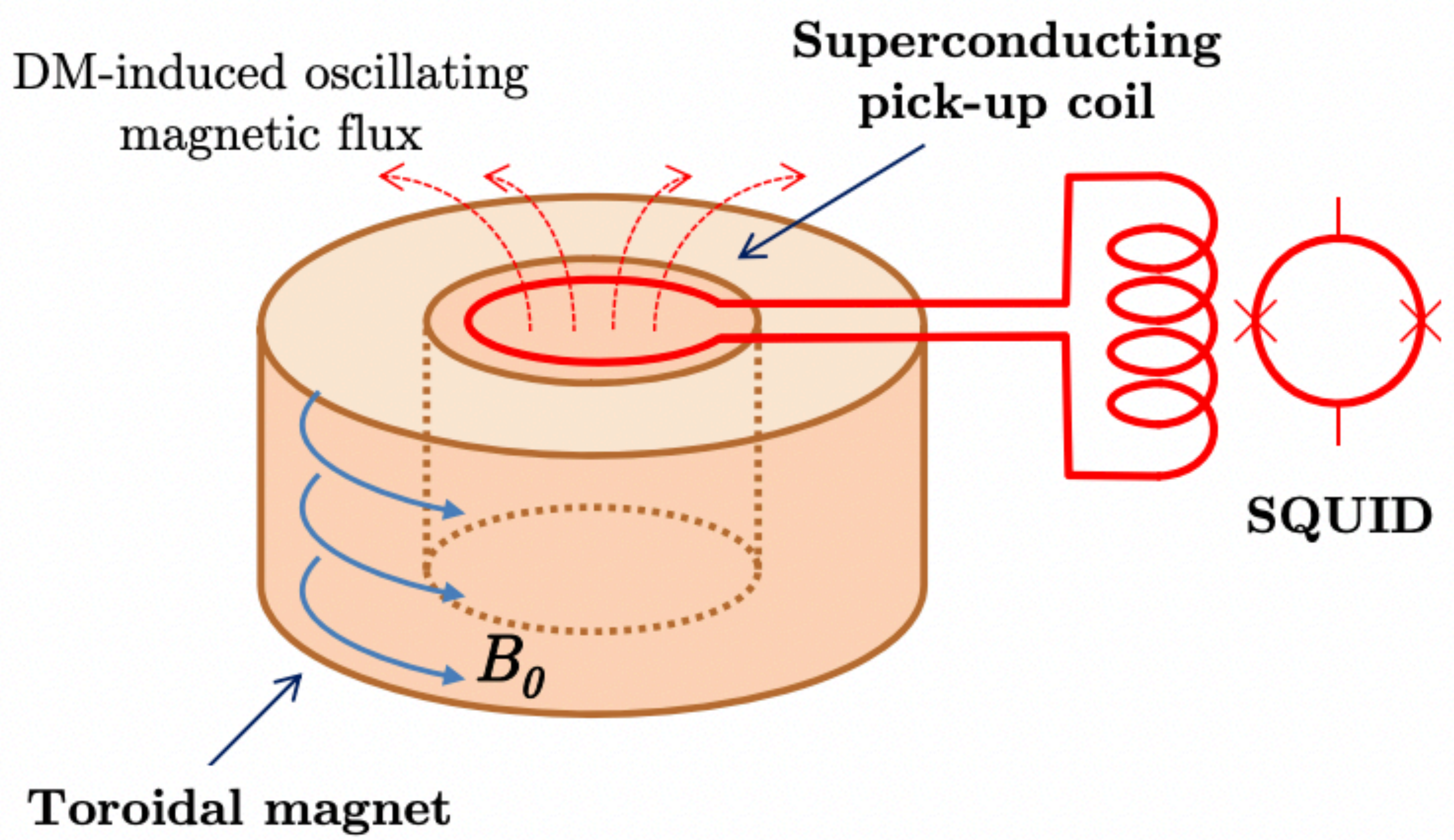
Low-mass approach — "Lumped element detectors"

e.g. SHAFT, ABRACADABRA, DMRadio, WISPLC

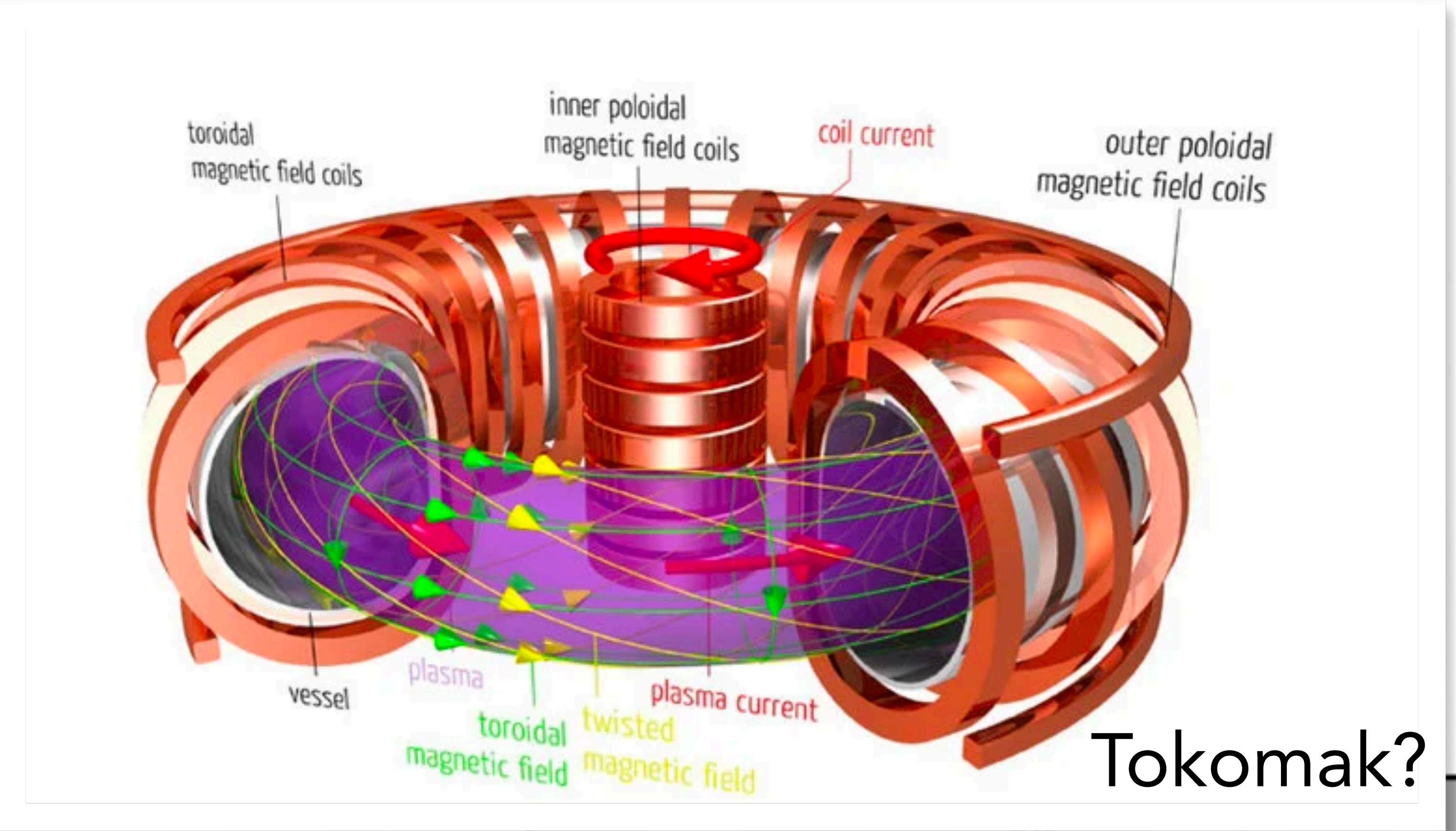
- Need to decouple the experiment size (V) from the Compton wavelength ($1/m_a$)
- Don't couple to axion effective current directly, instead look for secondary B-field induced by axion current
- **Measured B-field** can be enhanced geometrically by size of instrument

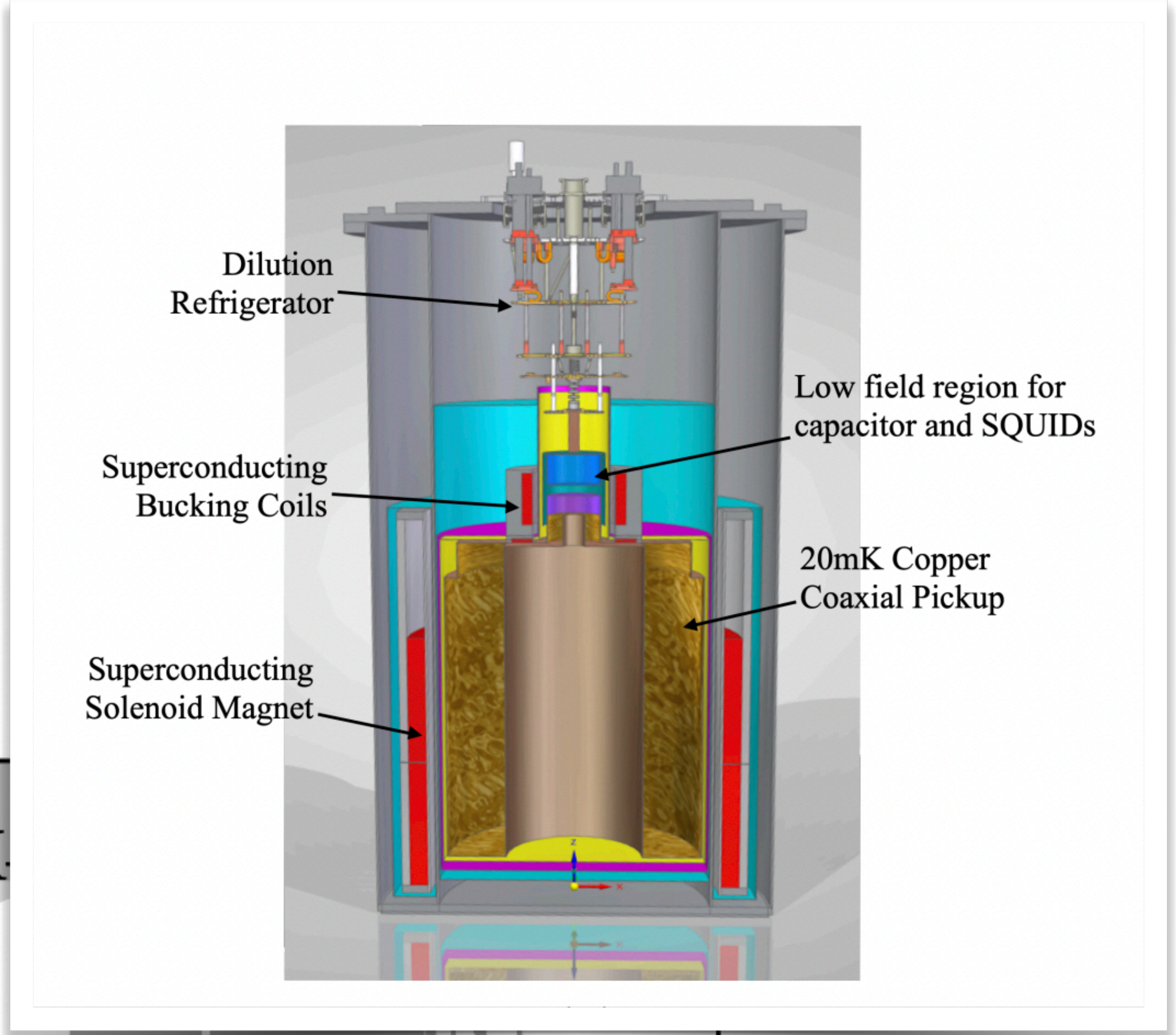
$$B_a \sim g_{a\gamma} B_0 (\partial_t a) \times R$$

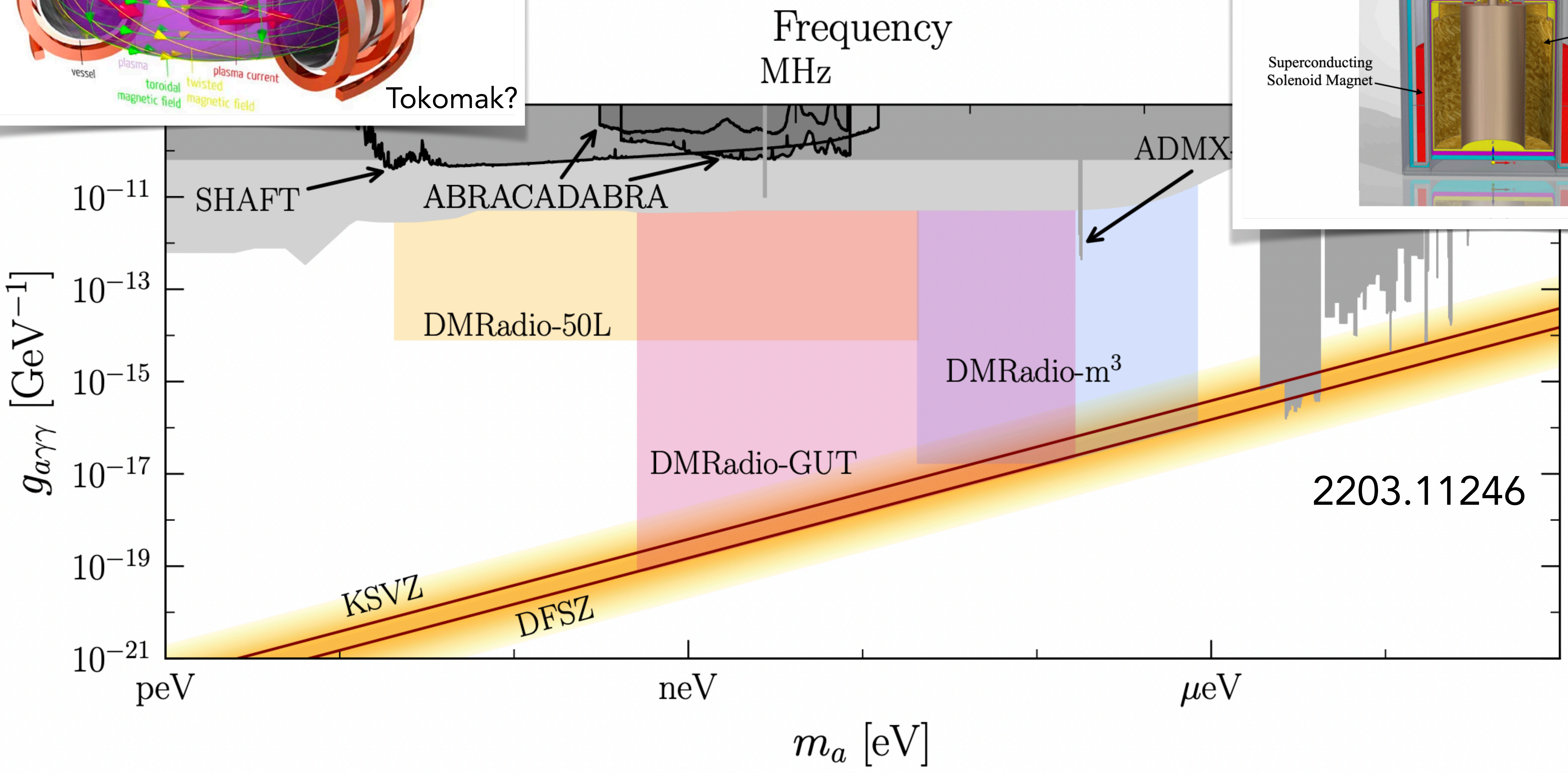
$$\sim 10^{-15}\,\mathrm{T} \left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}^{-1}}\right)\left(\frac{R}{1\,\mathrm{m}}\right)\left(\frac{B_0}{10\,\mathrm{T}}\right)$$

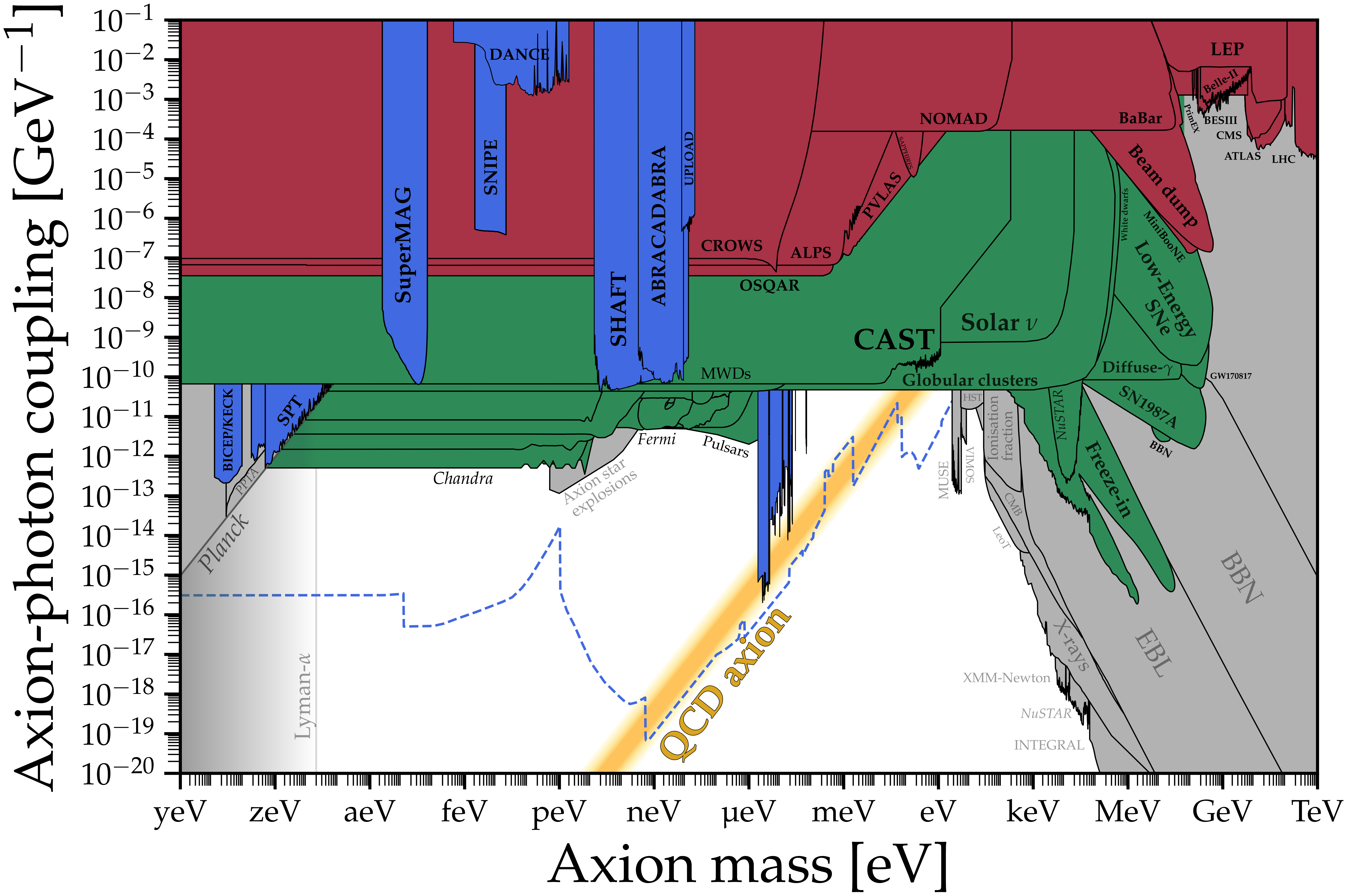


DMRadio


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?


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


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



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

Axion-nucleon coupling

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

Non-relativistic 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:

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

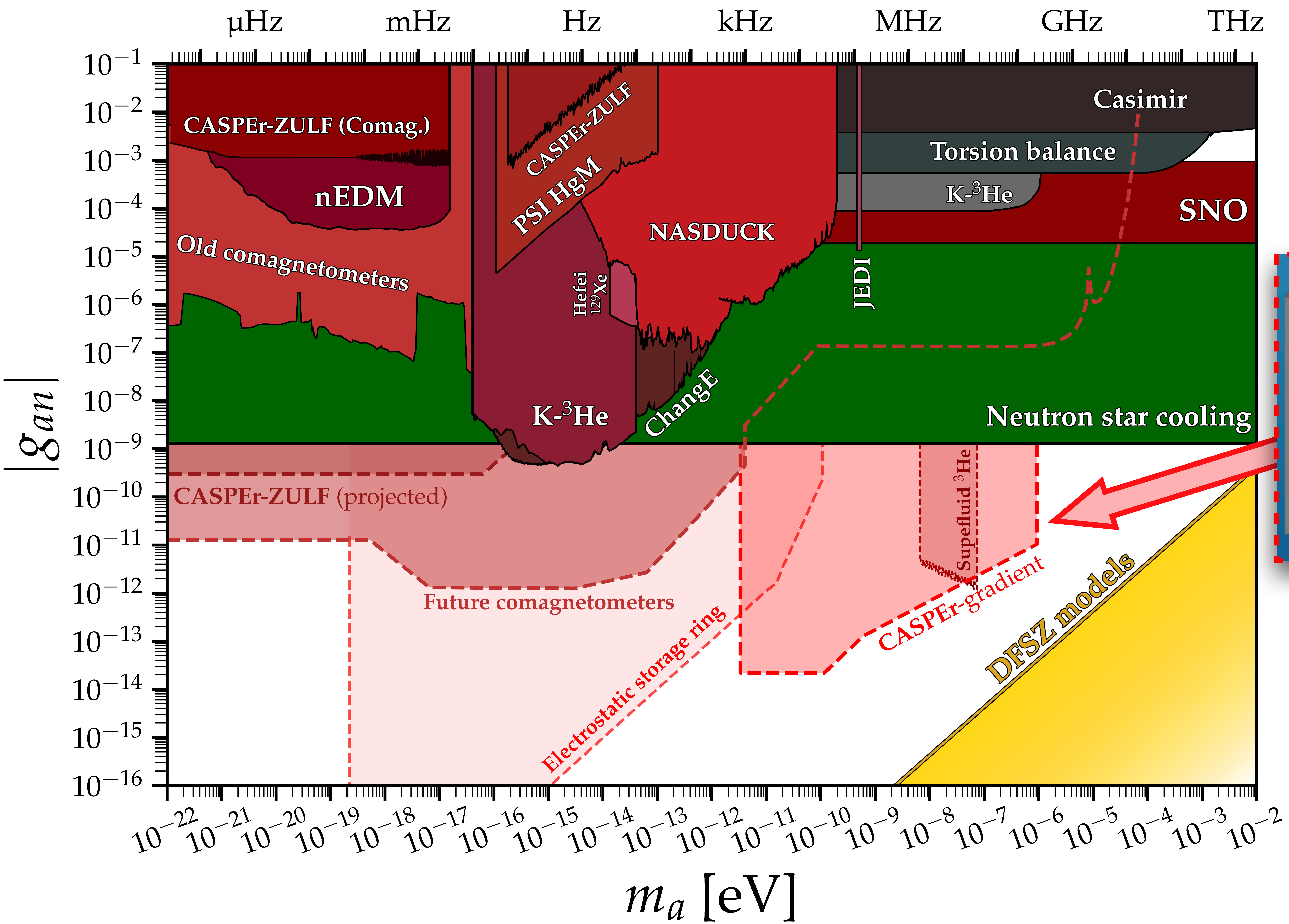
$$\approx 2 \times 10^{-17}\ \mathrm{T}\left(\frac{g_{an}}{10^{-9}}\right)\left(\frac{\gamma(^{129}\mathrm{Xe})}{\gamma}\right)$$

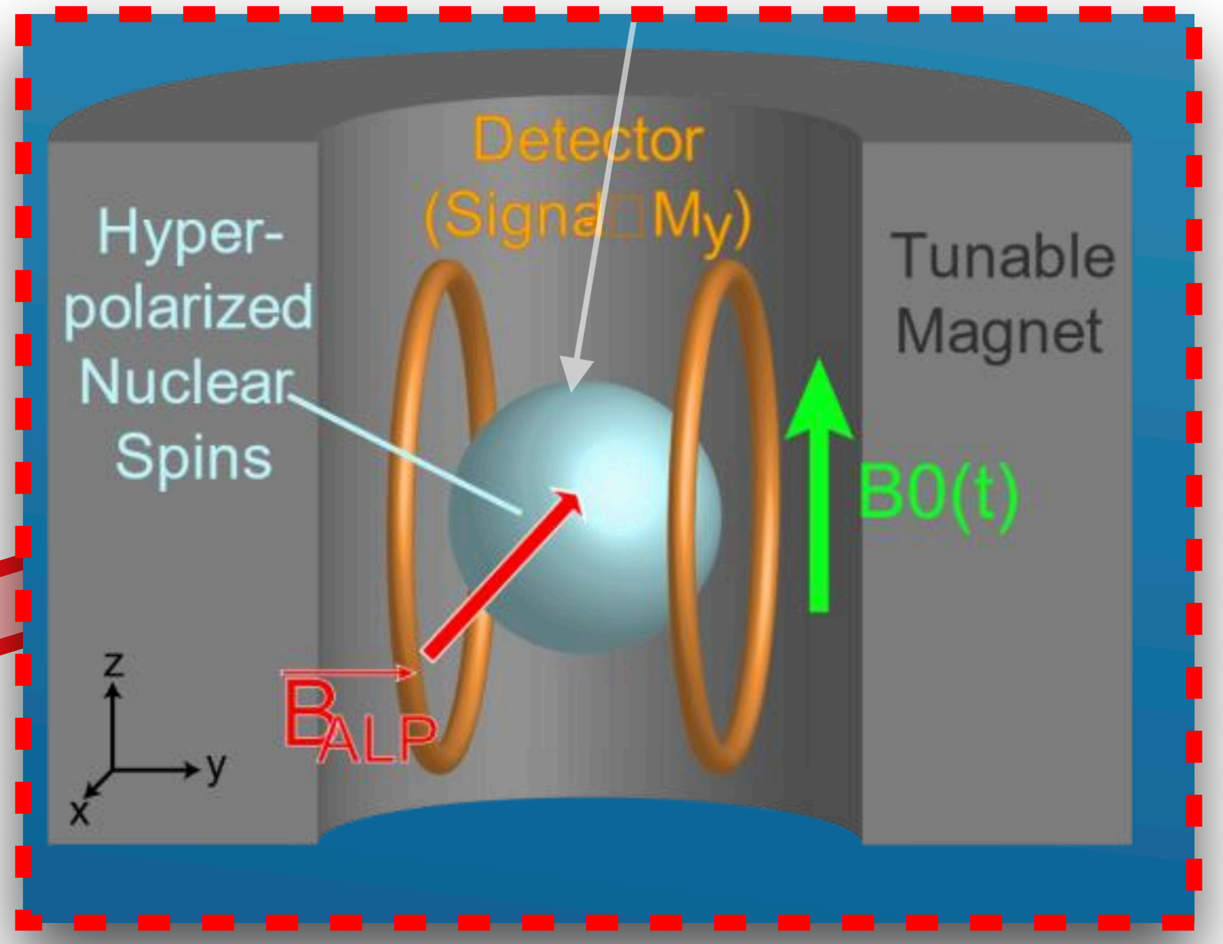
→ For sensitivity competitive against astrophysical bounds

How to measure tiny magnetic fields with nuclei?

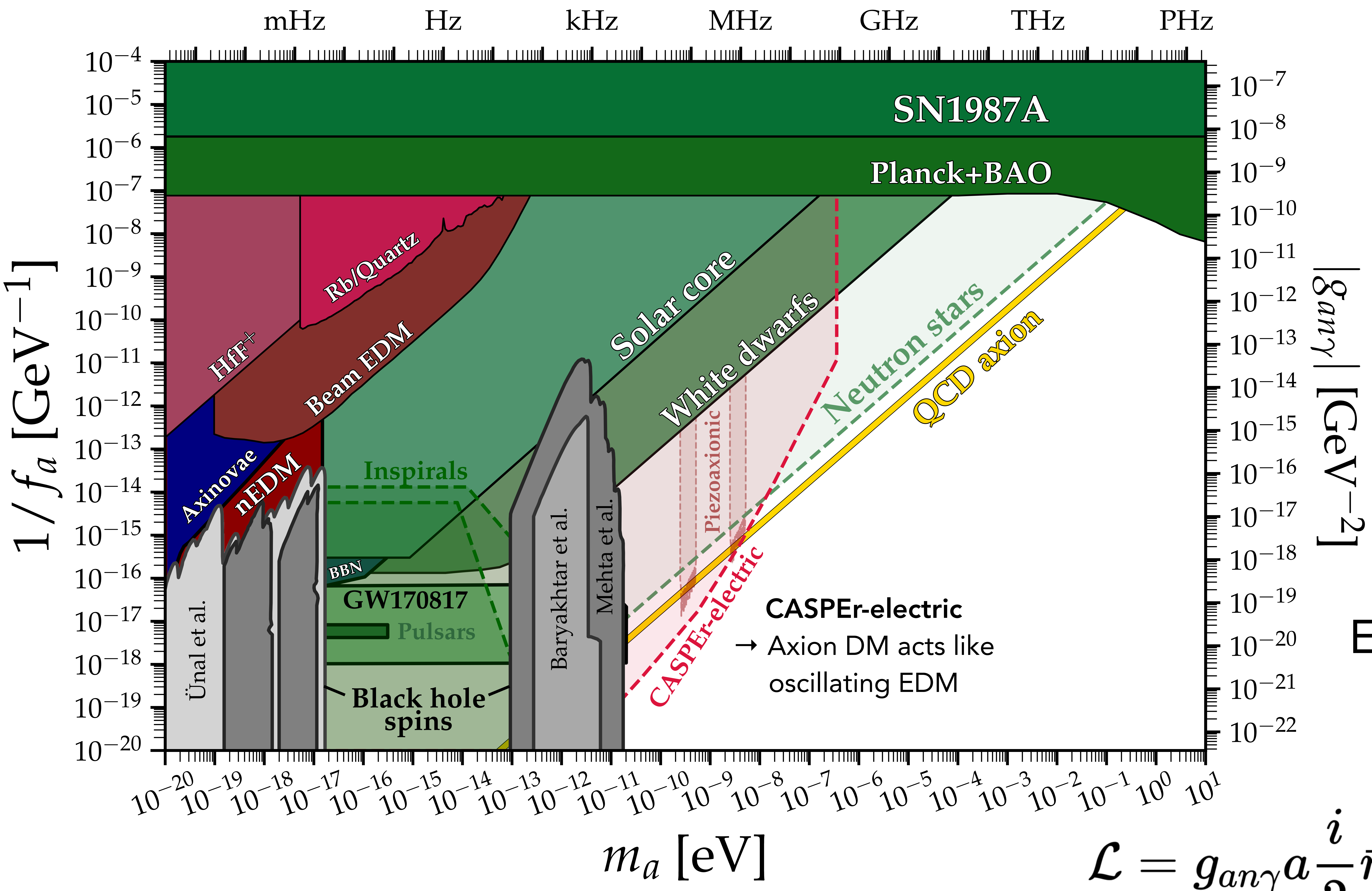
→ Comagnetometers

→ Nuclear magnetic resonance





Larmor freq. tuned to scan across axion mass



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^μ

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

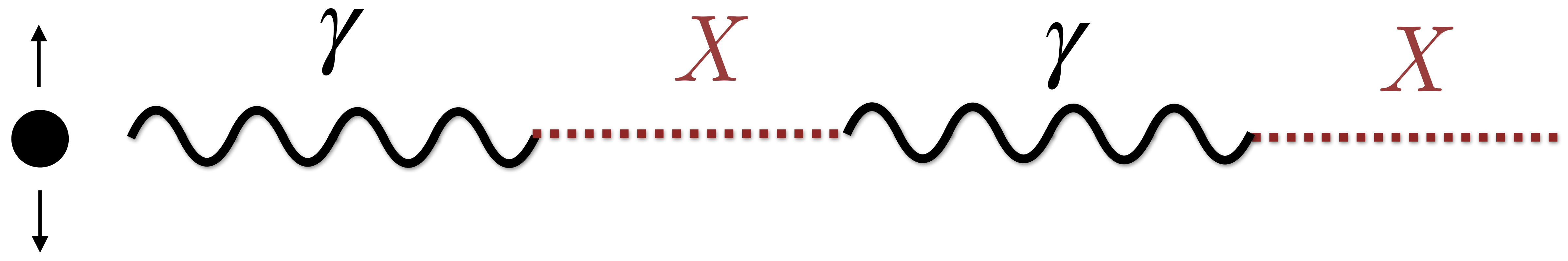
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu - \chi m_X^2 A_\mu X^\mu + J^\mu A_\mu$$

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

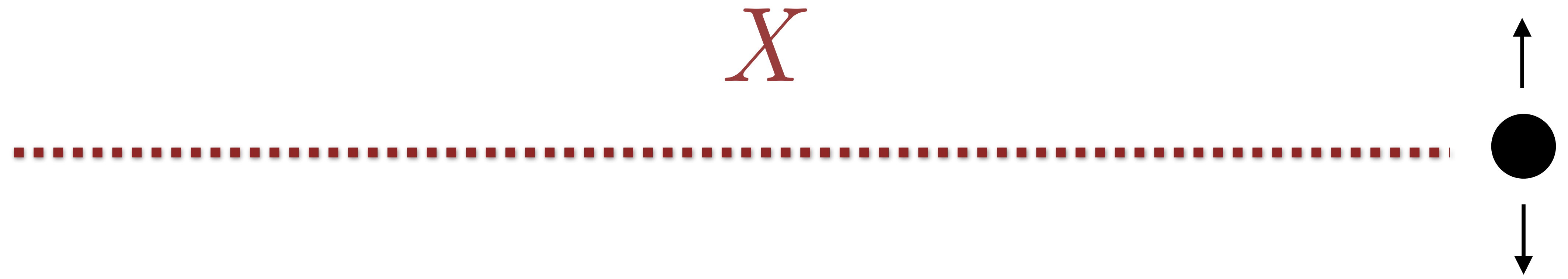
$$\mathcal{L} = -\frac{1}{4}\,\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \frac{1}{4}\mathbf{X}_{\mu\nu}\mathbf{X}^{\mu\nu} + \frac{1}{2}m_X^2\mathbf{X}_\mu\mathbf{X}^\mu - J^\mu[\mathbf{A}_\mu + \chi\mathbf{X}_\mu]$$

However the thing that interacts with electric charges is now A + χX

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

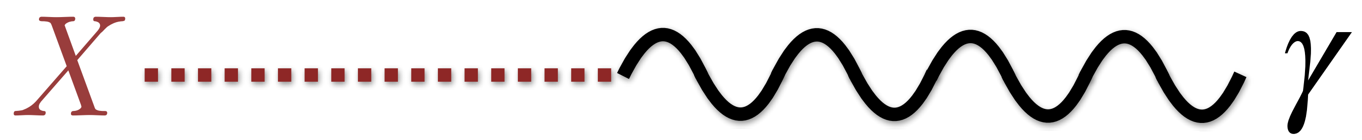


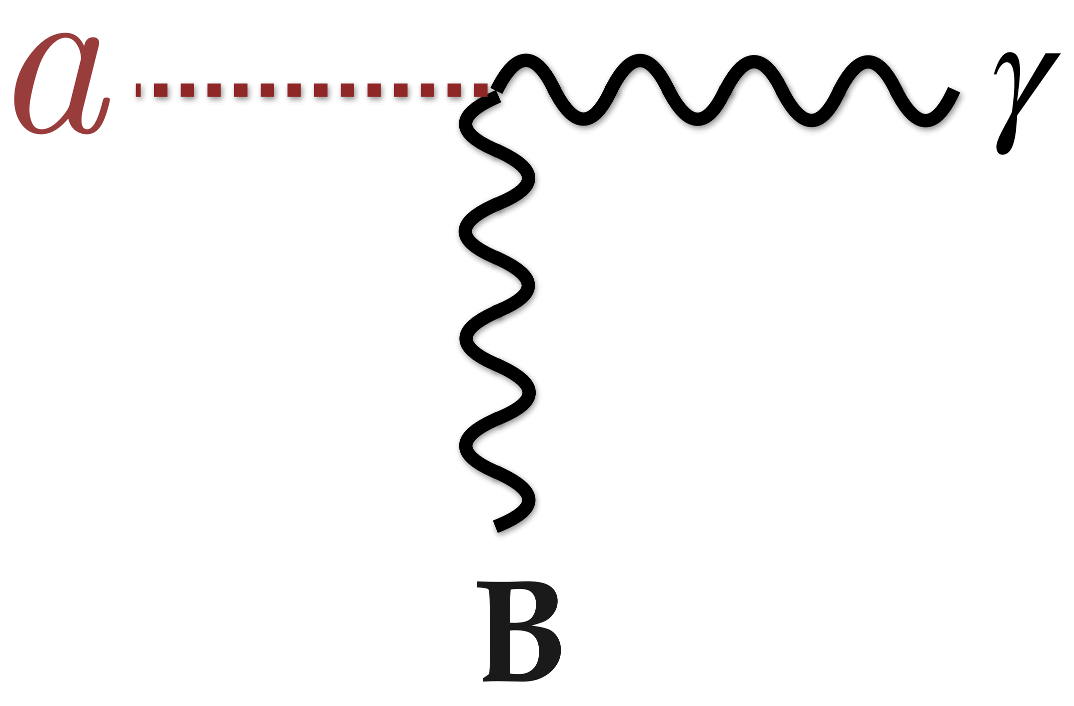
In the case of dark matter we imagine a condensate in the massive propagation state, however this state couples to J_μ so **it can move electric charges.**



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)

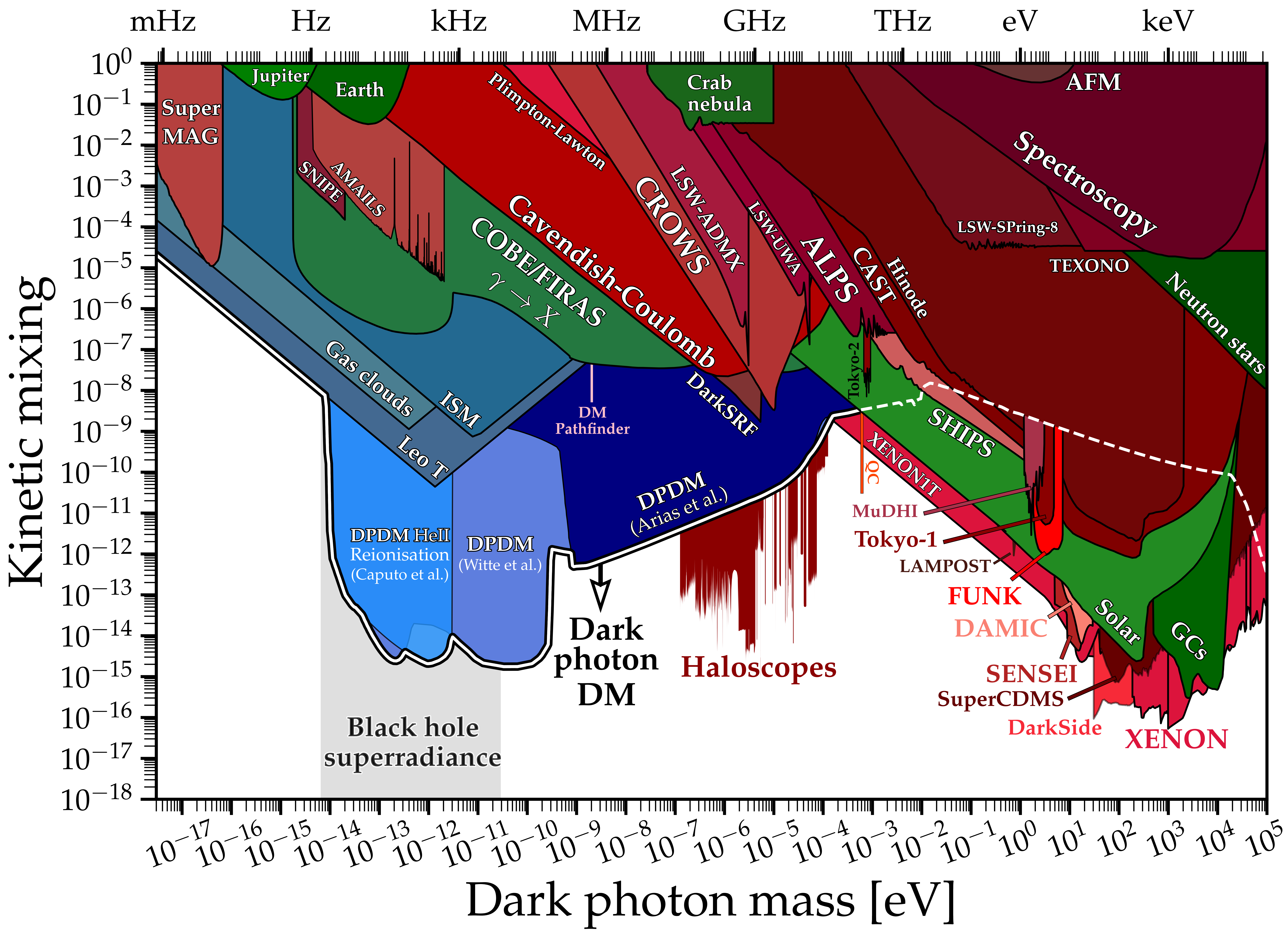


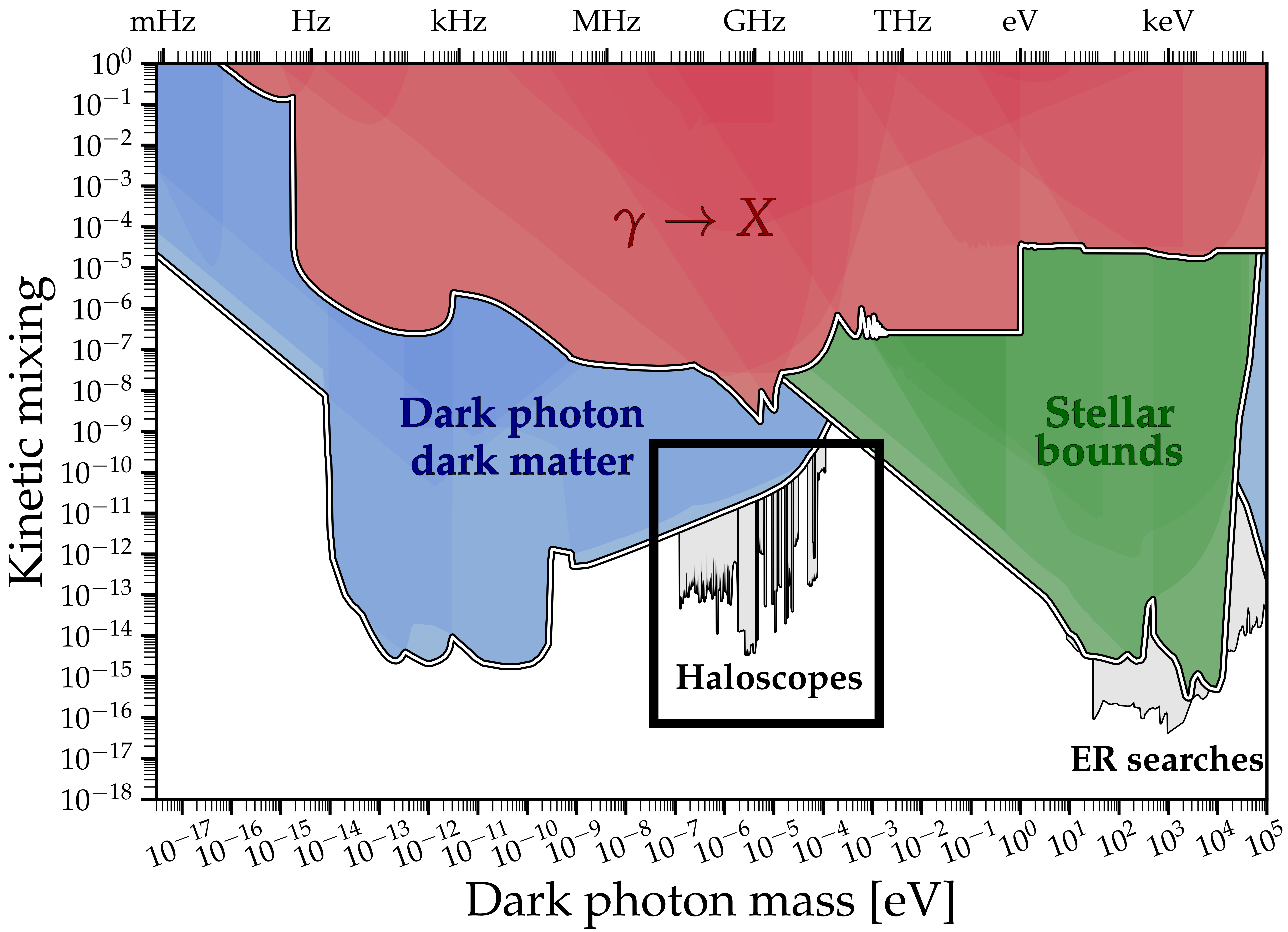


Dark photons

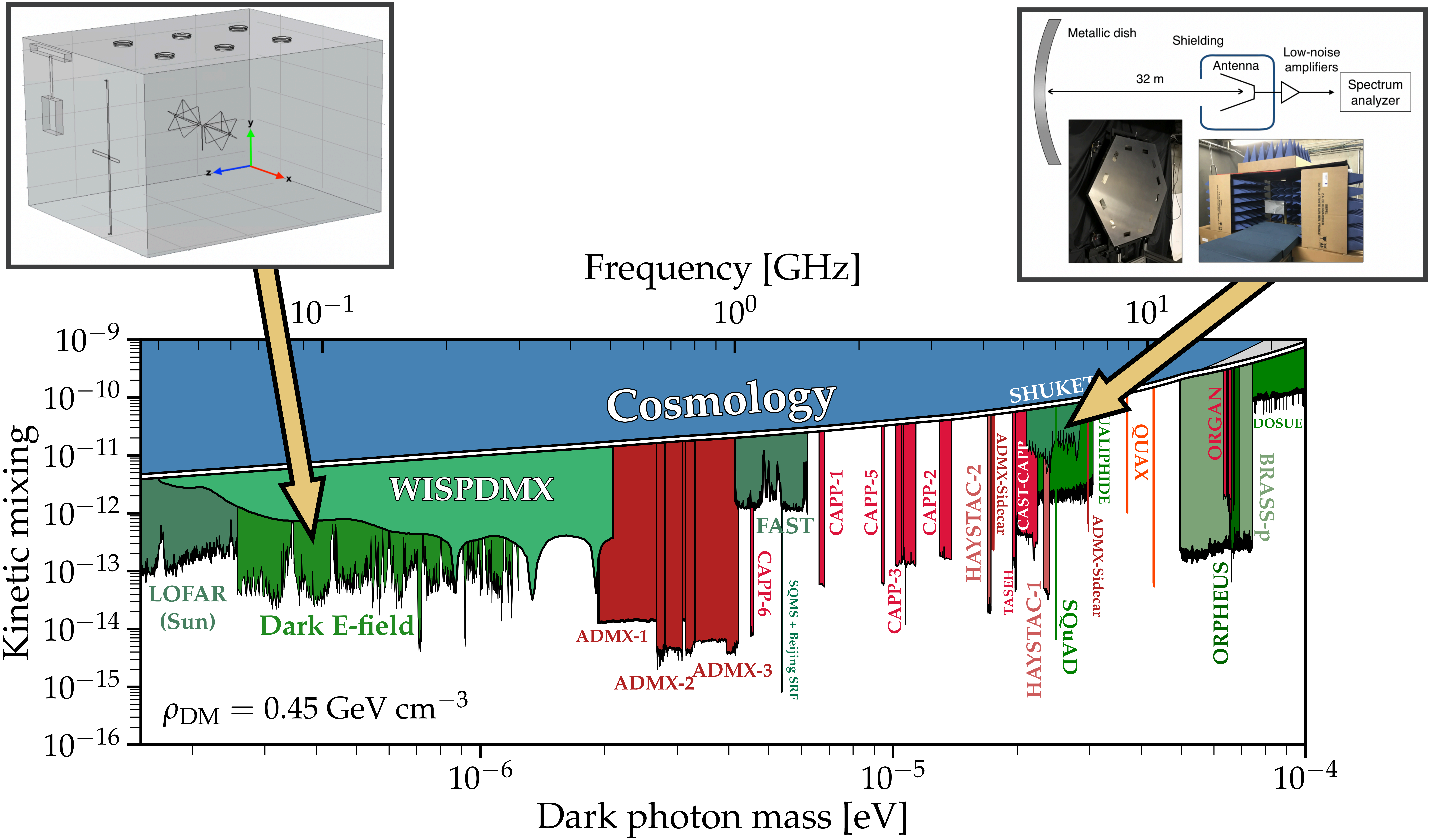
$$\chi m_X \leftrightarrow g_{a\gamma} B$$

Axions


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
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
DarkSRF
DM Pathfinder
Tokyo-2
SHIPS
XENON1T
QC
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs
DPDM (Arias et al.)
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
Black hole superradiance

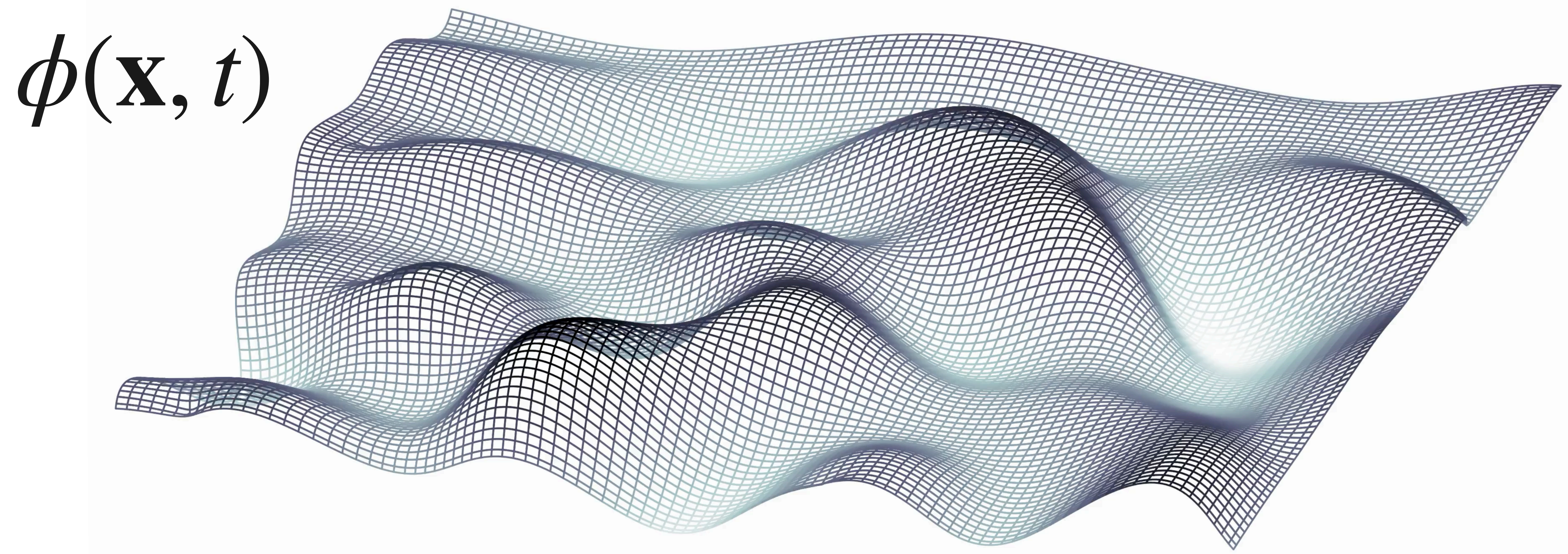


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
$\gamma \to X$
Dark photon dark matter
Stellar bounds
Haloscopes
ER searches
Dark photon mass [eV]



Metallic dish
Shielding
Low-noise amplifiers
Antenna
32 m
Spectrum analyzer
Frequency [GHz]
10^{-1}
10^{0}
10^{1}
Kinetic mixing
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Cosmology
SHUKET
WISPDMX
LOFAR (Sun)
Dark E-field
ADMX-1
ADMX-2
ADMX-3
FAST
CAPP-6
SQMS + Beijing SRF
CAPP-1
CAPP-5
CAPP-3
CAPP-2
HAYSTAC-2
ADMX-Sidecar
TASEH
CAST-CAPP
HAYSTAC-1
SQuAD
QUALIPHIDE
ADMX-Sidecar
QUAX
ORGAN
ORPHEUS
DOSUE
BRASS-p
$\rho_{\rm DM} = 0.45$ GeV cm^{-3}
10^{-6}
10^{-5}
10^{-4}
Dark photon mass [eV]

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

→ e.g. time-varying electron mass

Scalar dark matter coupled to electron