Welcome to Microsoft's Homepage - Microsoft Internet Explorer - Da...

10 crazy ways to detect dark mater that physcists DON'T want you to know about (*shocking*!) 😳😂👌

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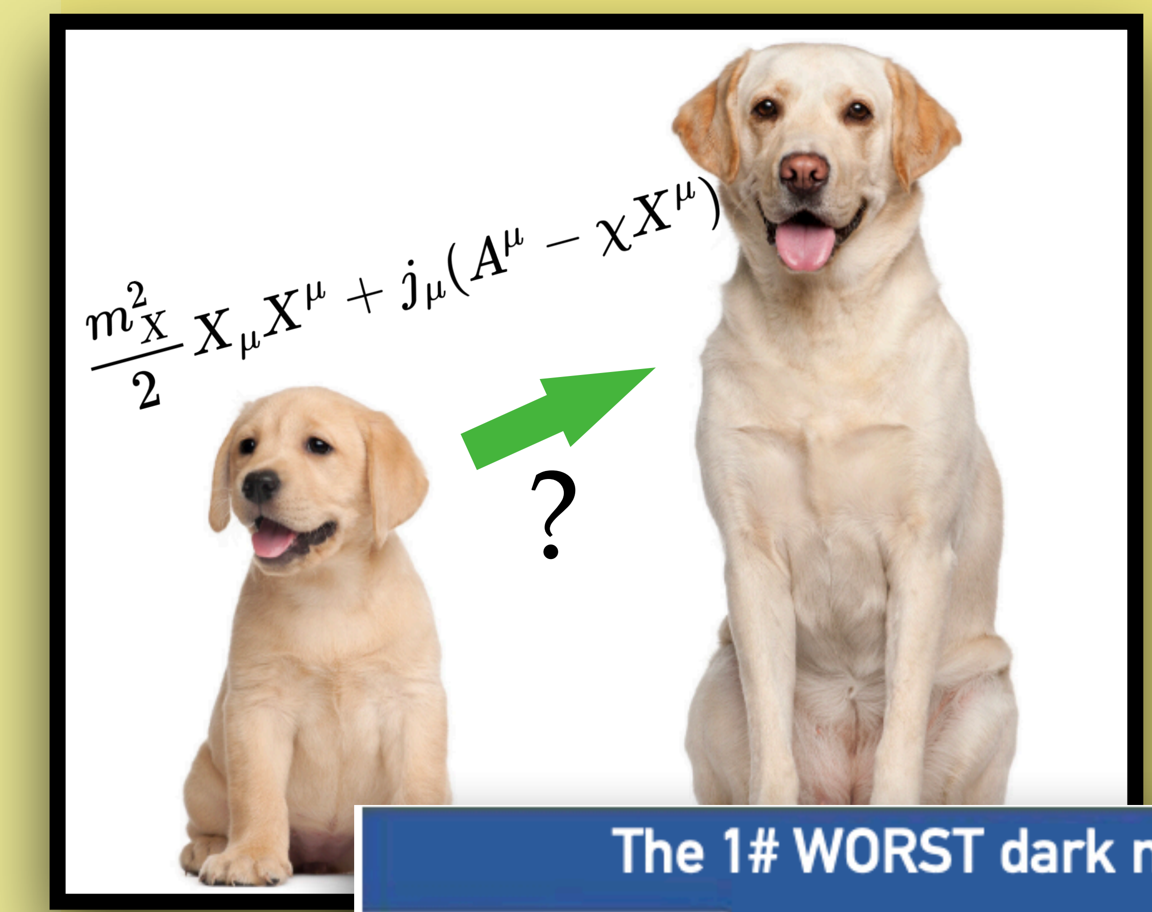
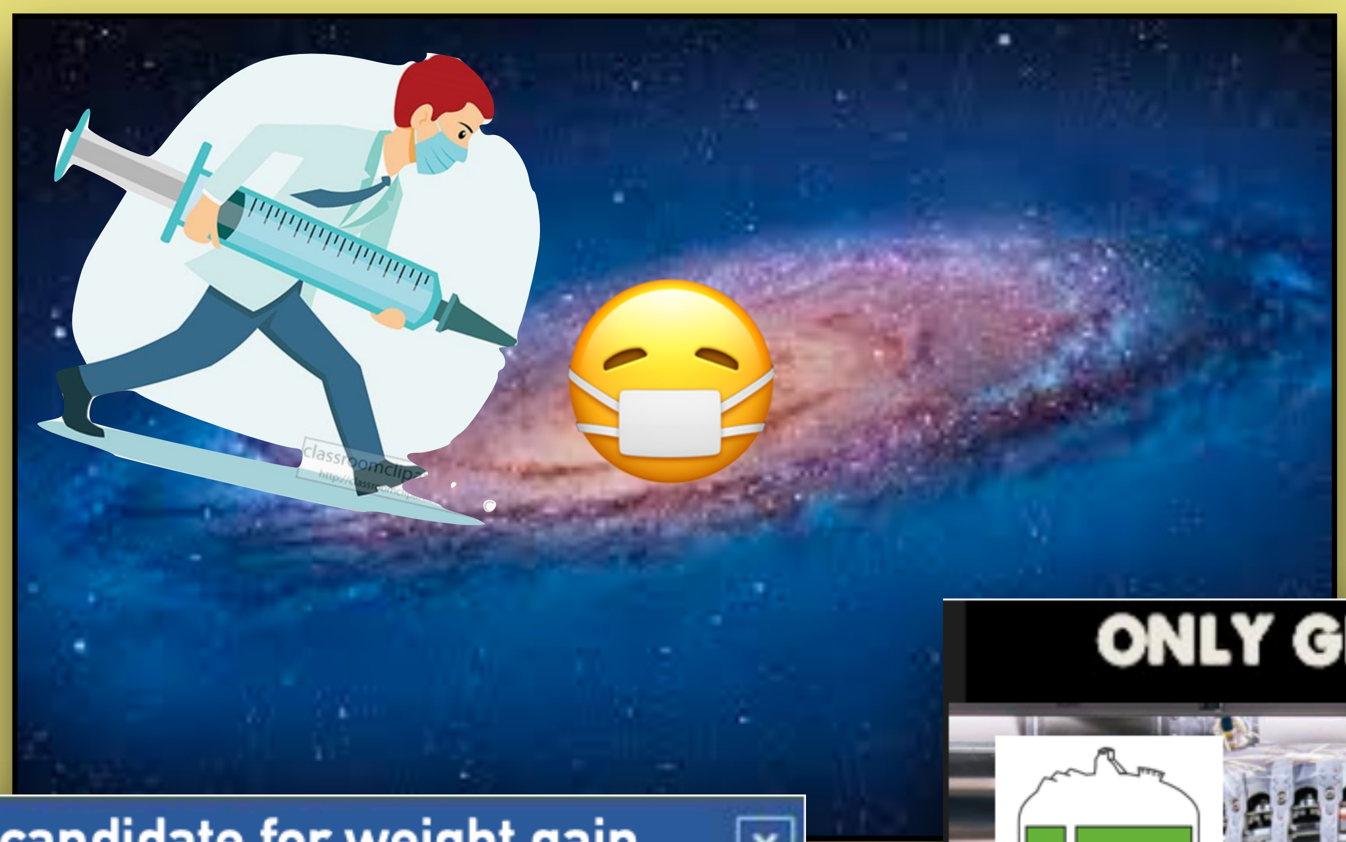
Recommended for you

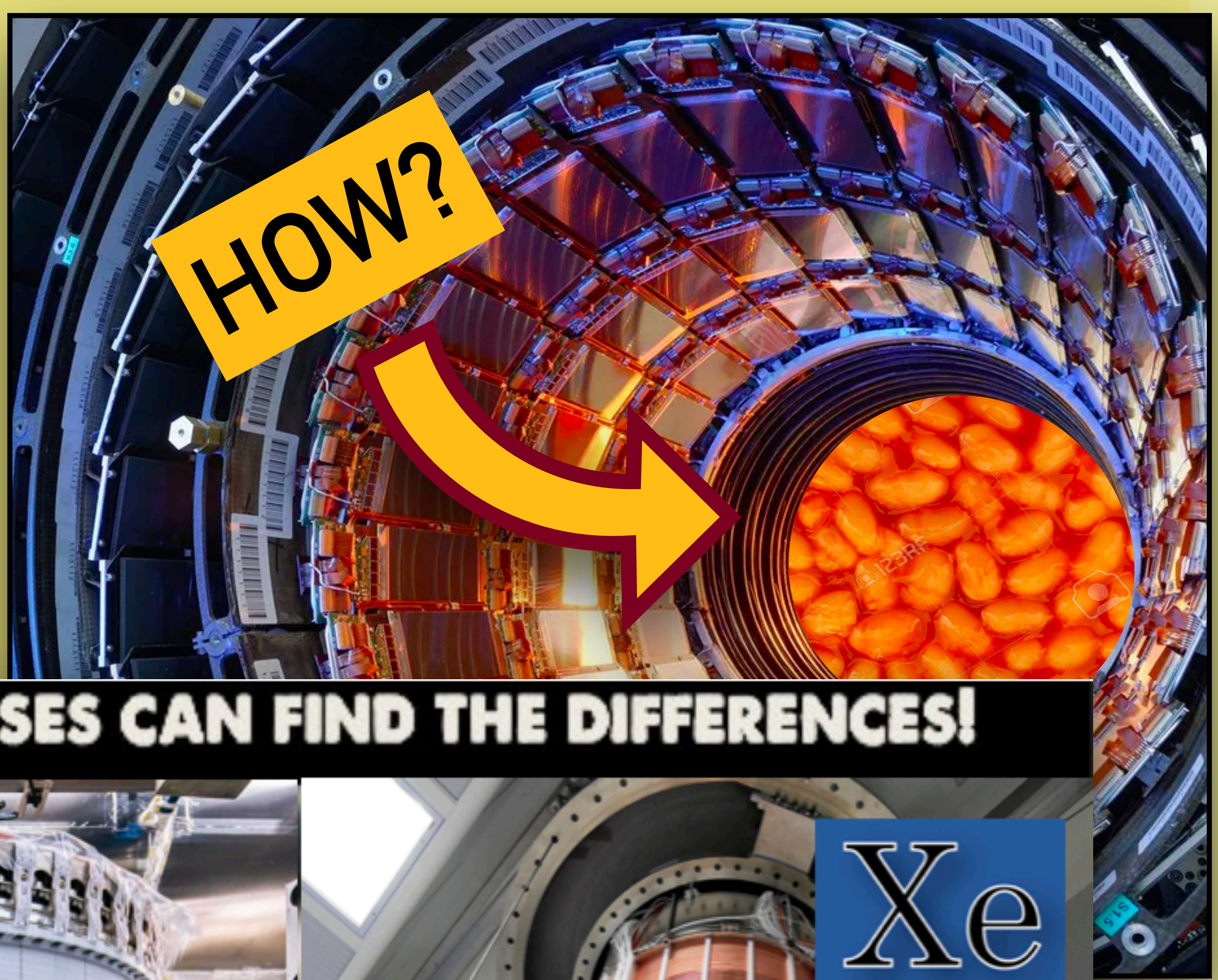
What did she know about dark matter?

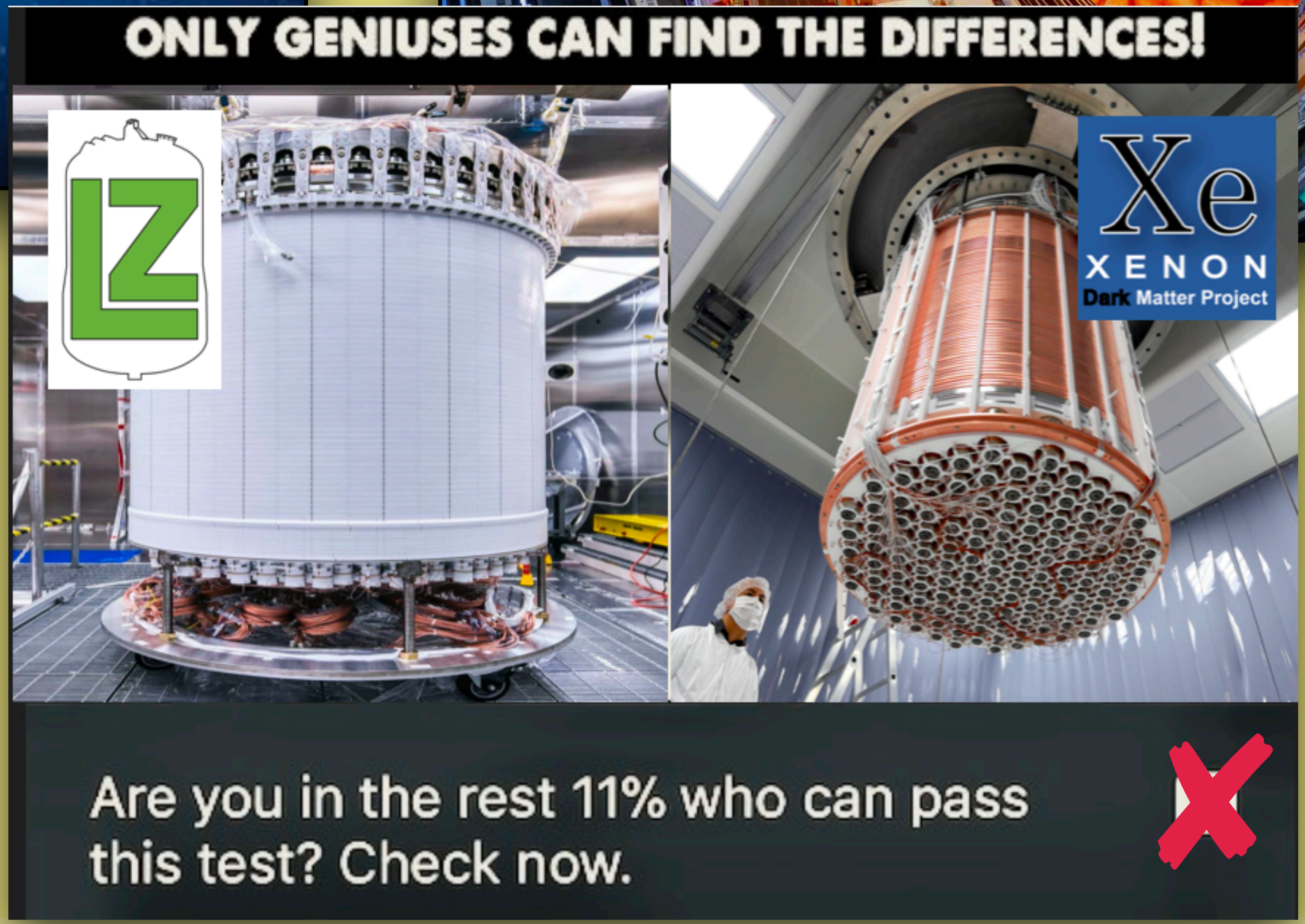
The dark matter SECRET hidden within Fortnite

WIMPs (10 years in prison) For what!?



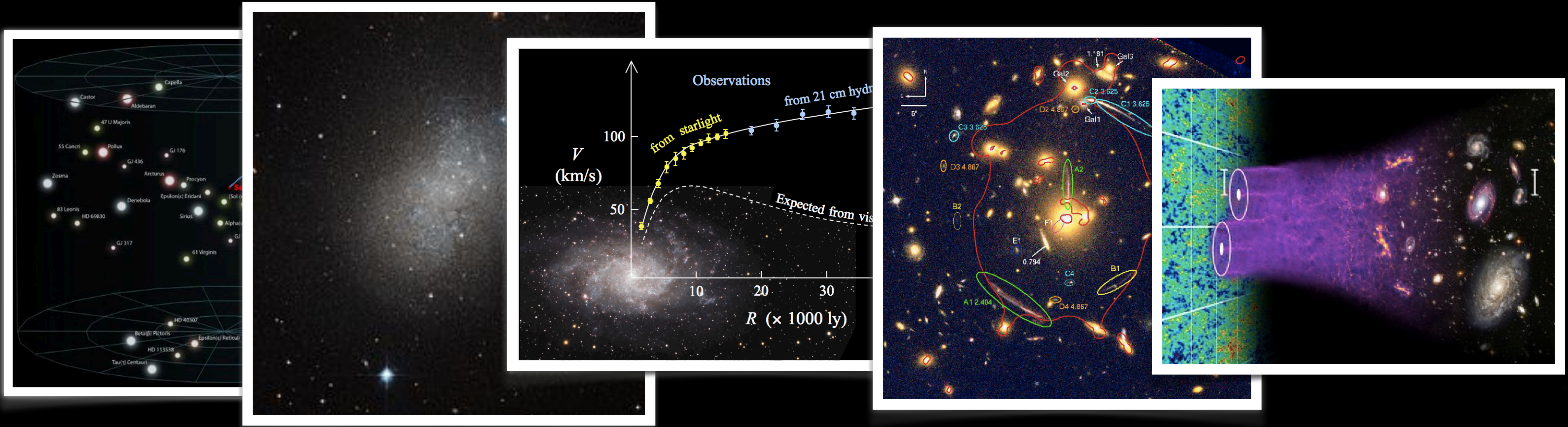






Evidence for dark matter

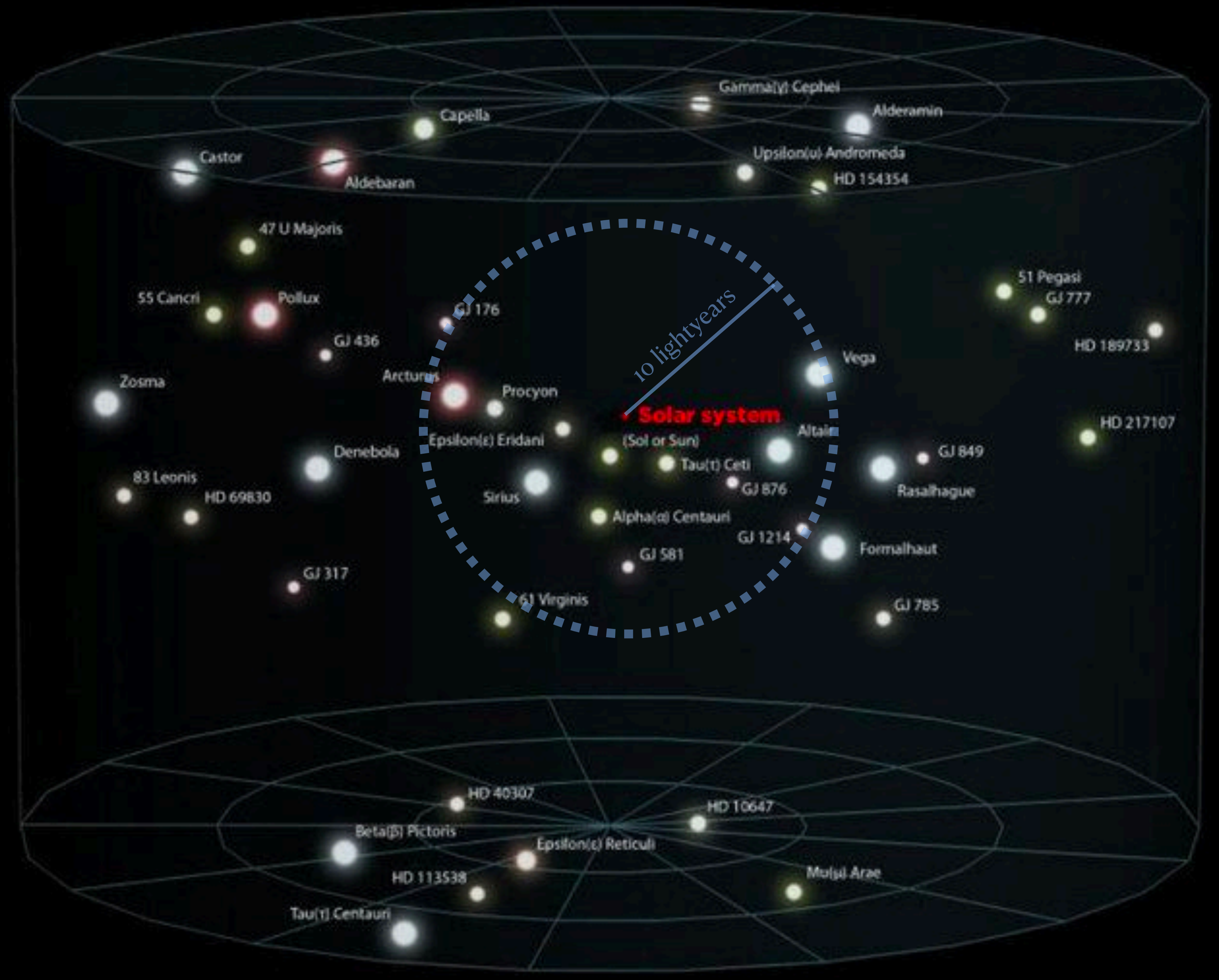
~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	Seeds large scale structure



Evidence for dark matter

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

Affects nearby stars → infer **local** density of dark matter



How do we infer the local dark matter density?

Distribution function of stars → *Boltzmann eq.* $\frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0$ → Gravitational potential → *Poisson eq.* $\nabla_x^2 \Phi = 4\pi G \rho$ → Matter density

Local measure

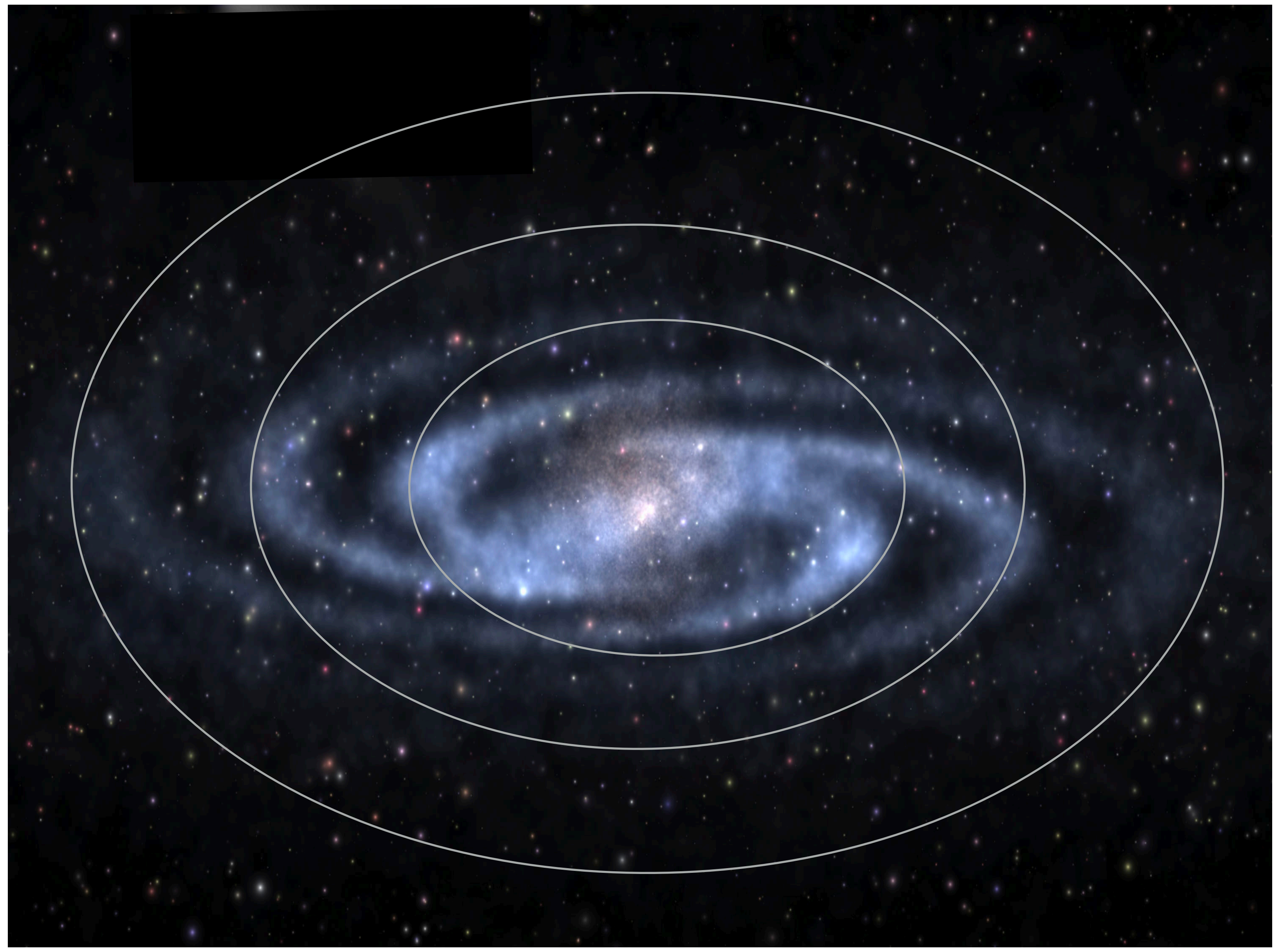
(kinematics of nearby stars)

Pro: density that we are interested in

Con: sensitive to baryonic density model

Global measure

(build mass model for MW)



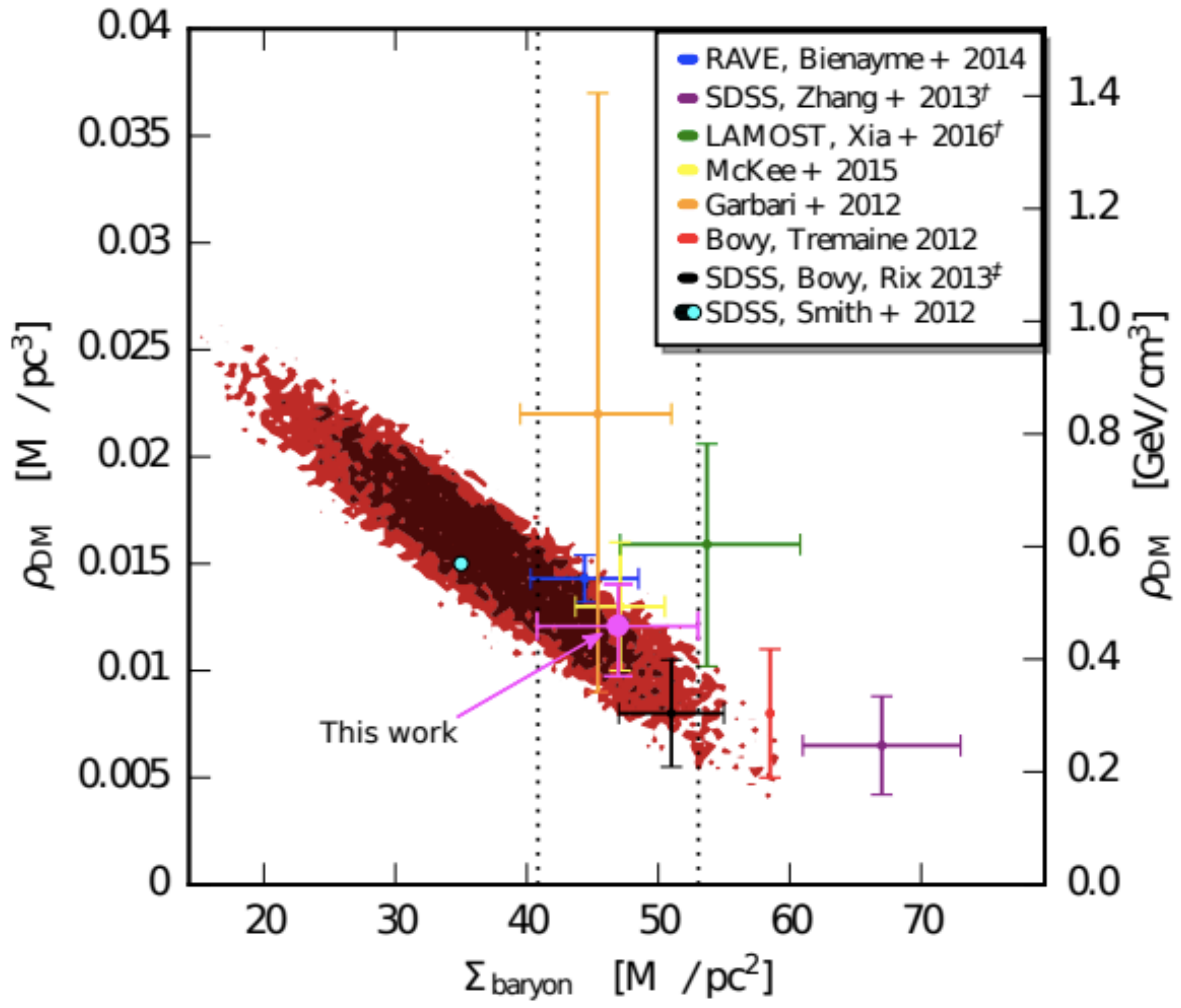
Pro: Average over a lot of halo/disk

Con: less direct measure of local density

Local measures

e.g. Sivertsson+ [1708.07836]

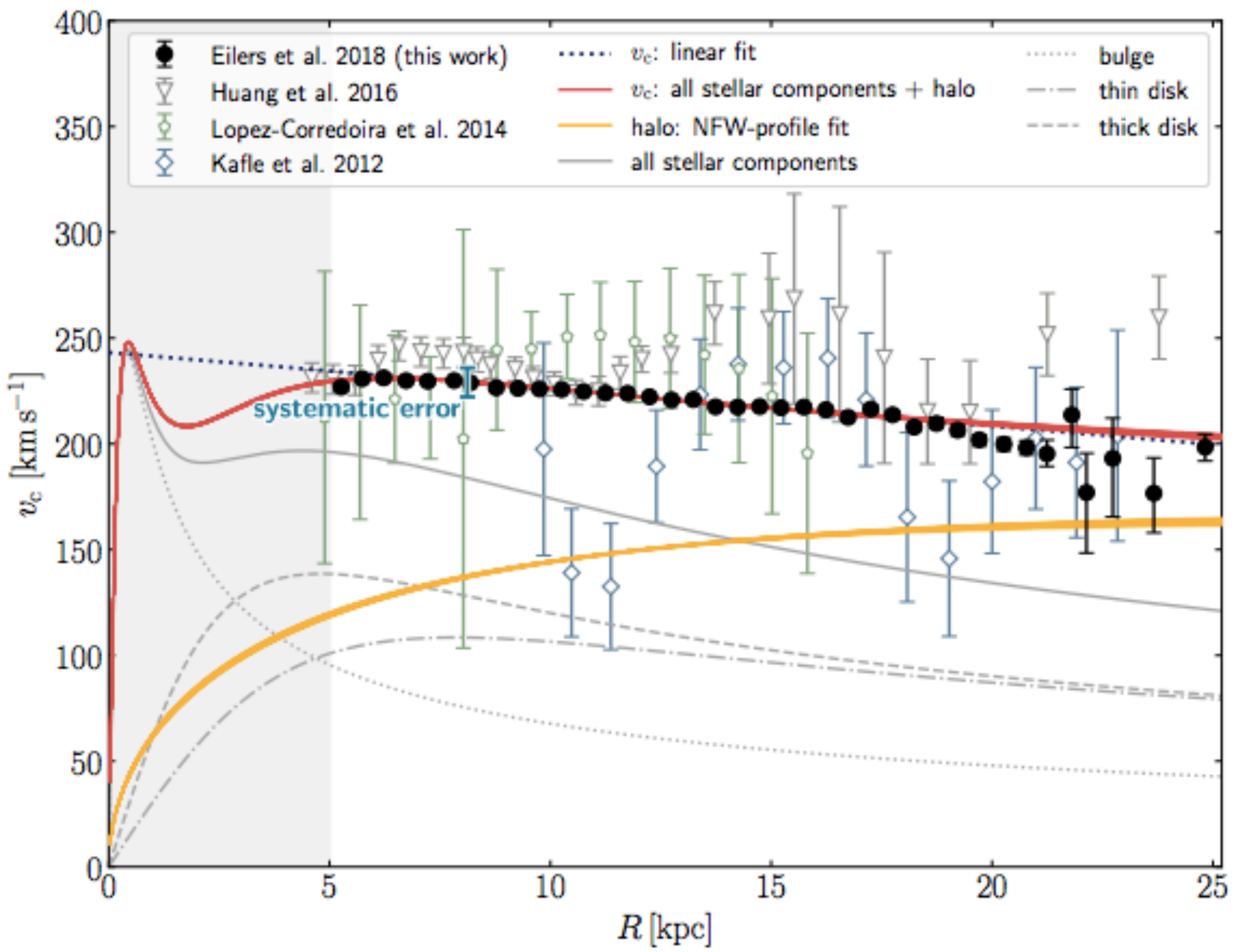
$0.46 \pm \sim 0.1$ GeV / cm^3



Global measures

e.g. Eilers+ [1810.09466]

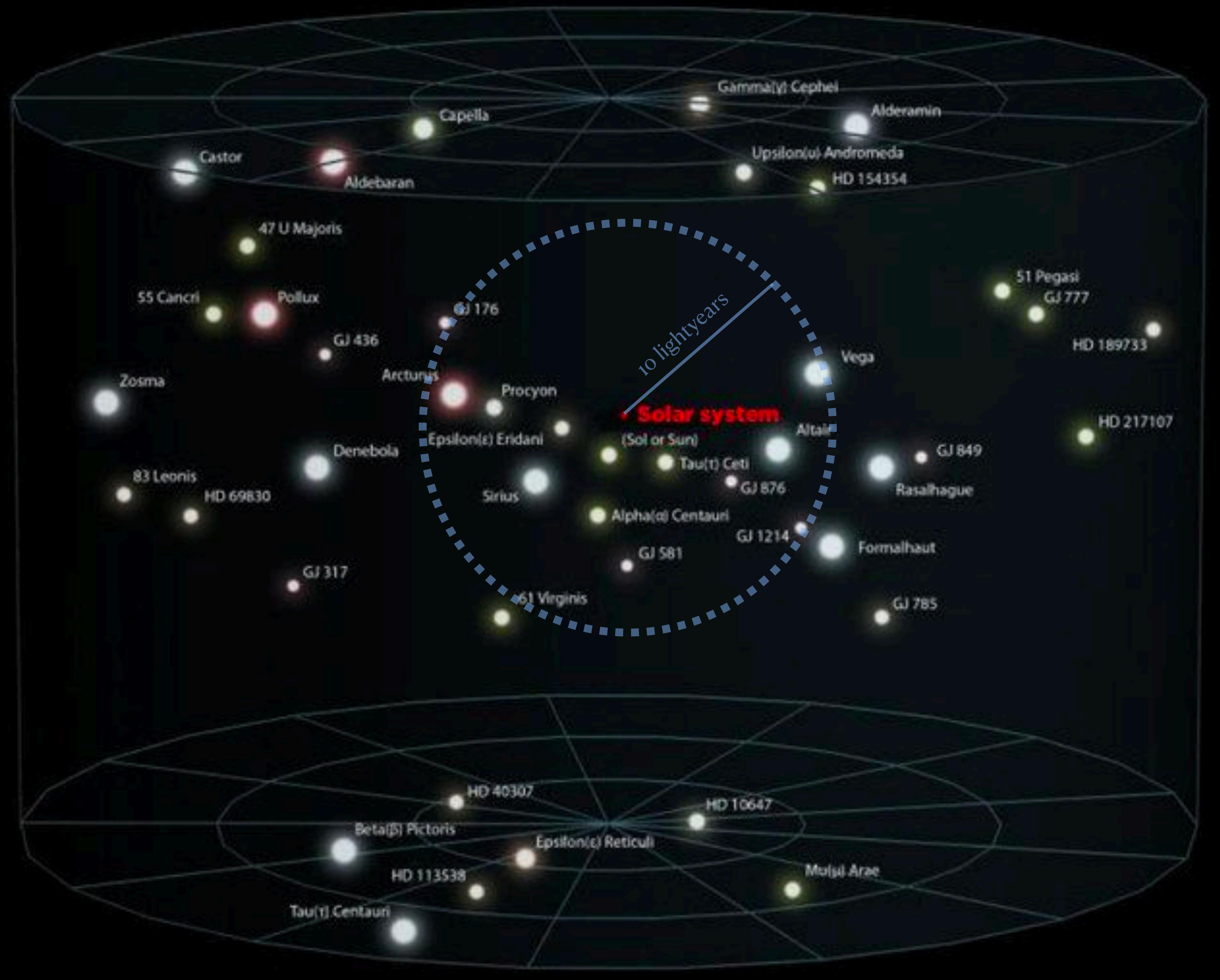
0.3 ± 0.03 GeV / cm^3



- Global measure has tiny statistical errors, but inferred over large scales
- Local measures give the more relevant density but are still systematics dominated
- Two techniques broadly in agreement → **nonzero dark matter density in Solar System**

Evidence for dark matter

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



<u>Local density of dark matter</u>

$$
\begin{aligned}
\rho_{\rm dm} &\approx 0.4\,{\rm GeV/cm^3} \\
&\approx 0.01\,{\rm M_\odot/pc^3} \\
&\approx 2\,\text{protons/teaspoon} \\
&\approx 1\,\text{sand grain/Sydney harbour} \\
&\approx 1\,\text{cockatoo/Earth} \\
&\approx 1\,\text{asteroid/Solar System}
\end{aligned}
$$

Ingredients for direct dark matter detection

1. The dark matter halo of the Milky Way

2. The dark matter particle

3. Dark matter-Standard Model interaction

Ingredients for direct dark matter detection

1. The dark matter halo of the Milky Way

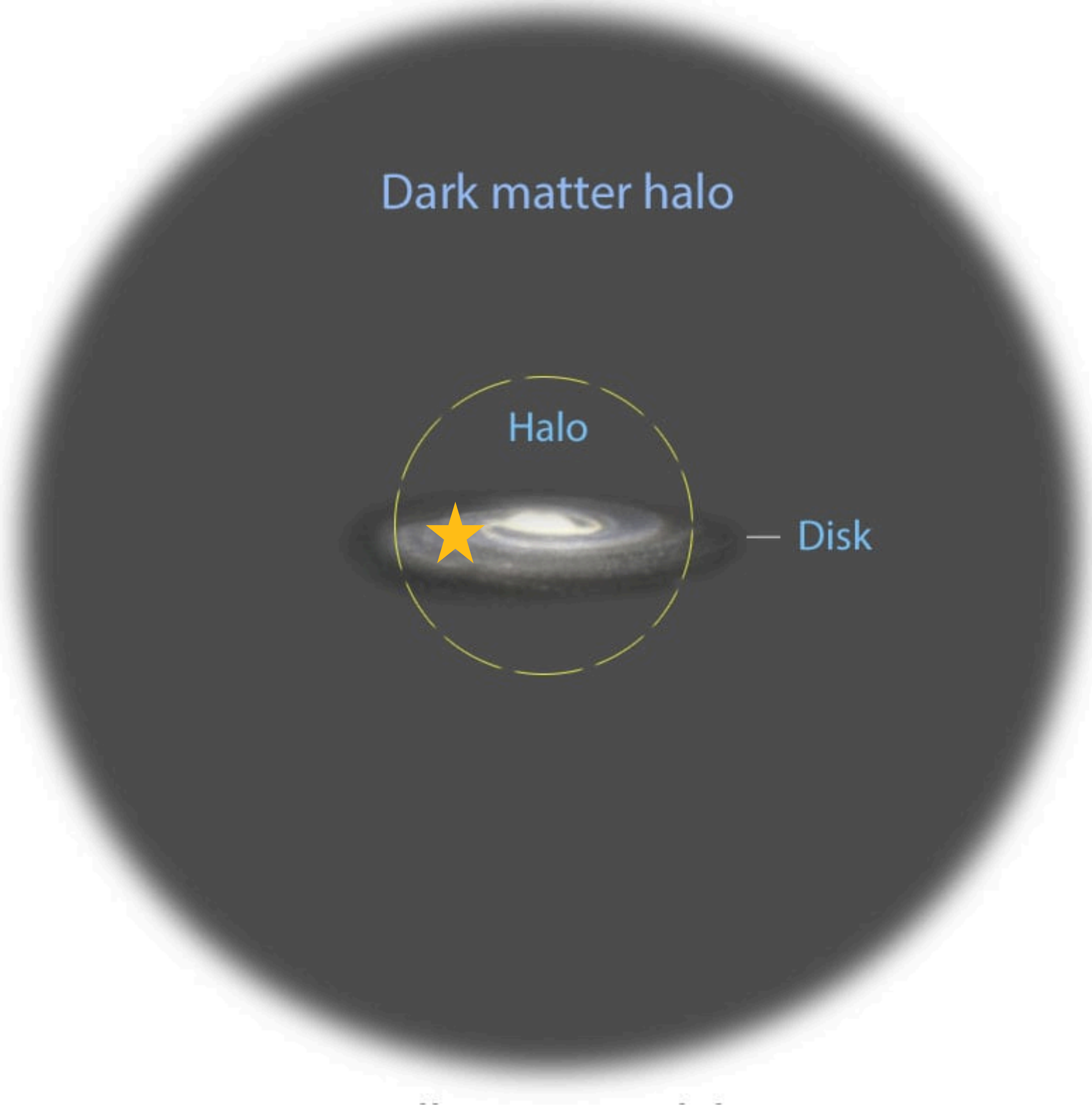
- Density at the solar position → how much dark matter is around us
- Velocity distribution → how fast it's moving

<u>Infinite Isothermal sphere</u> (standard halo model)

$$\rho \sim 1/r^2$$

$$f(\mathbf{v}) \sim \exp(-|\mathbf{v}^2|/v_{\rm circ}^2)$$

→ Local DM density of 0.4 GeV/cm³ sets local circular speed of around $v_{\rm circ,\odot} \sim 220$ km/s, meaning typical Earth-frame DM speed is around $v \sim 10^{-3}\,c$



Ingredients for direct dark matter detection

2. The dark matter particle

→ Mass

→ Statistical properties, i.e. spin, fermonic vs boson

These are cannot be independently chosen, take for example the density of DM in the solar system

de Broglie wavelength: $\lambda_{\mathrm{dB}} = \frac{2\pi}{p} \approx \frac{2\pi}{mv}$

DM density: $\rho_{\mathrm{DM}} \approx 0.4\,\mathrm{GeV\,cm^{-3}}$

$\longrightarrow$

Local occupation number:

$$\mathcal{N} \approx (\rho_{\mathrm{DM}}/m) \times \lambda_{\mathrm{db}}^3$$

$m = 100\ \mathrm{GeV}$	$\longrightarrow$	$\mathcal{N} \approx 10^{-36}$	$\longrightarrow$	Particle
$m = 1\ \mu\mathrm{eV}$	$\longrightarrow$	$\mathcal{N} \approx 10^{32}$	$\longrightarrow$	Classical field

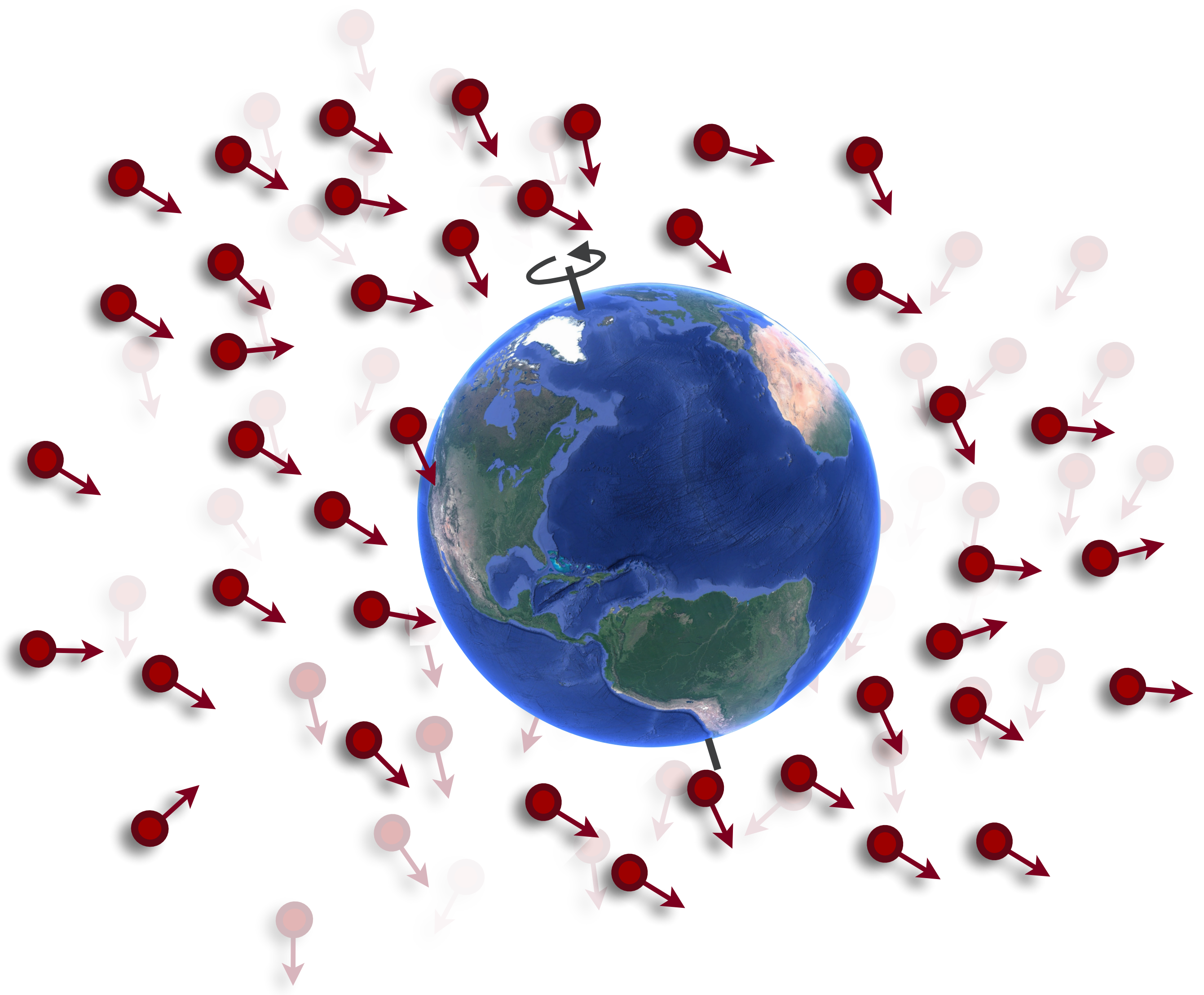
Ingredients for direct dark matter detection

2. The dark matter particle

→ Mass

→ Statistical properties, i.e. spin, fermonic vs boson

Particle/object-like

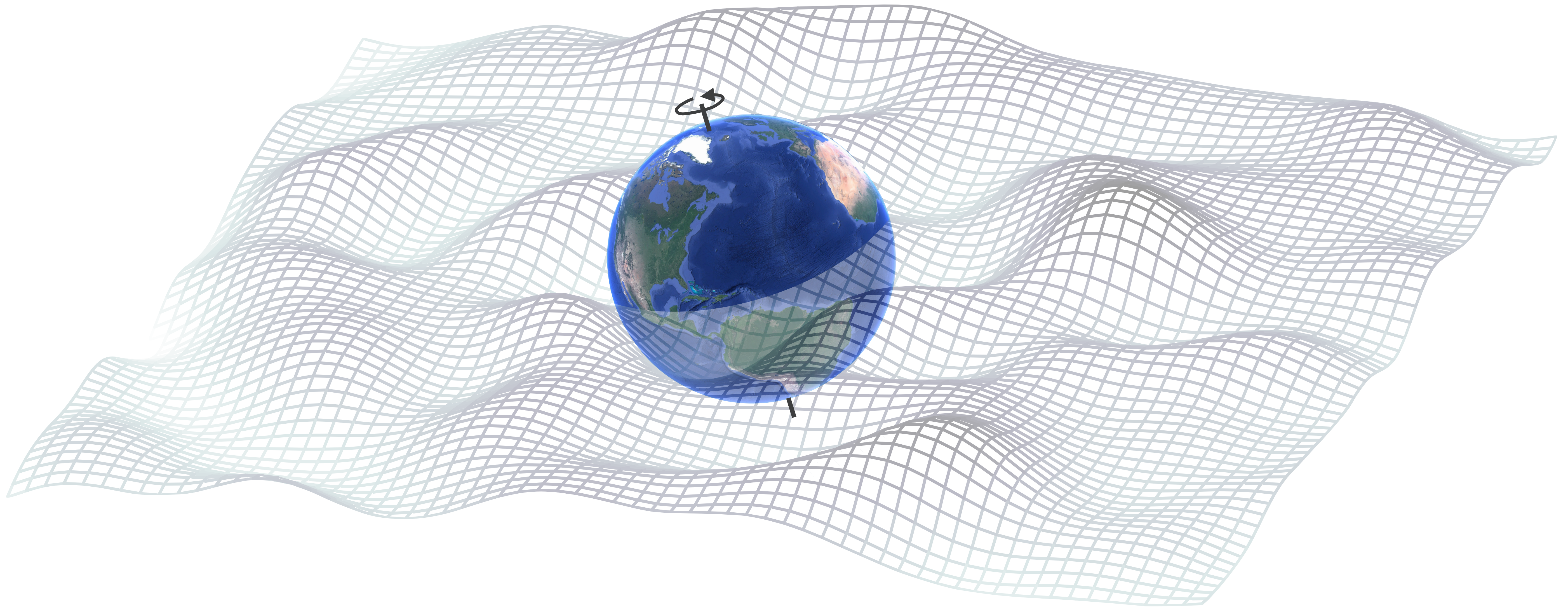


Number density $n_\chi = \rho/m_\chi$

Flux $\Phi = v n_\chi$

Discrete, stochastic interactions

Wave-like



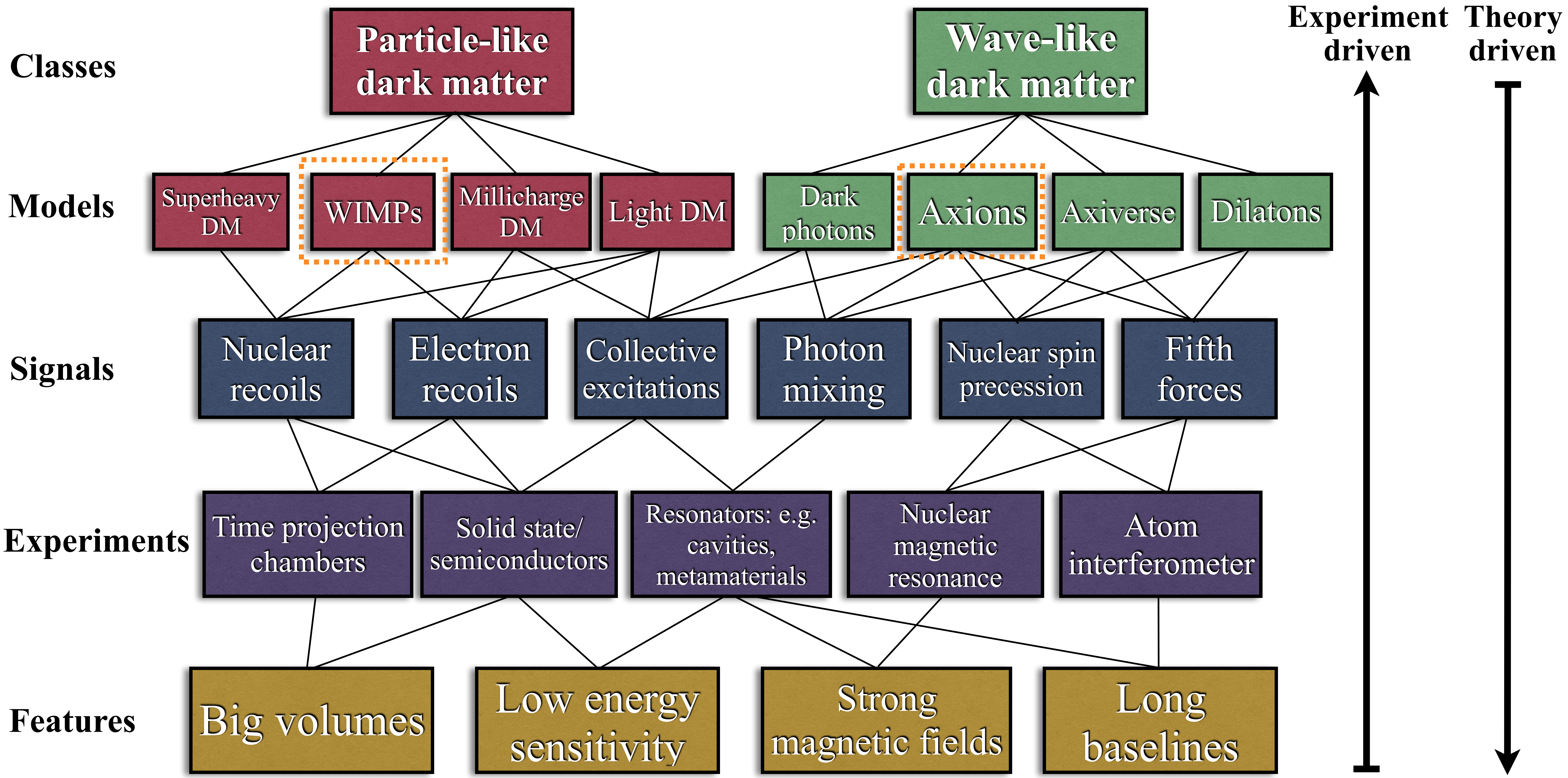
Amplitude $A = \dfrac{\sqrt{2\rho}}{m_\chi}$

Frequency $\omega = m_\chi + \dfrac{1}{2} m_\chi v^2$

Continuous oscillating signals

Ingredients for direct dark matter detection

3. The dark matter-Standard Model interaction



Principles of dark matter detection

1. The dark matter halo of the Milky Way
→ Density at the solar radius
→ Velocity distribution

Sanity check 1: Does this particle form dark matter halos as we see them?

2. The dark matter particle
→ Mass
→ Statistical properties, i.e. spin, fermonic vs boson

Sanity check 2: can you produce it in the right amounts prior to BBN, in a way that is not already ruled out with cosmological data?

3. Dark matter-Standard Model interaction
→ Agnostic/experiment driven: e.g. "I can search for any kind of DM that generates ionisation in my detector"
→ Simplified model: e.g. "I will search for a dirac fermion DM that couples to quarks via a vector mediator"
→ EFT approach: e.g. "I will look for any non-relativistic DM-nucleon interaction preserving basic symmetries"
→ UV complete model → check DM relic abundance and then derive low energy phenomenology


Vanilla dark matter candidates
Axions
WIMPs
Primordial black holes
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
kg
$M_\oplus$
$M_\odot$
$10^6\,M_\odot$
a
χ
χ
SM
SM
Definition: light goldstone boson of spontaneously broken U(1)
Motivation: solves the strong CP problem of QCD
Signatures: mixes with the photon, derivative couplings to fermions
Definition: no rigorous one, but typically a heavy particle that was once in thermal equilibrium with SM
Motivation: Supersymmetry, or just generic thermal relic
Signatures: self-annihilation to SM states, nucleon scattering
Definition: black holes, primordial ones
Motivation: inflation, generic result of collapse of sufficiently large density perturbations
Signatures: gravitational interactions, Hawking radiation

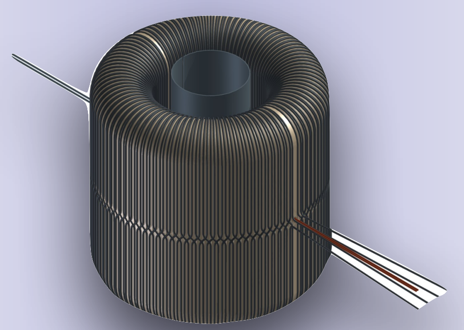
Existing constraints (loosely)

Searches (very incomplete)

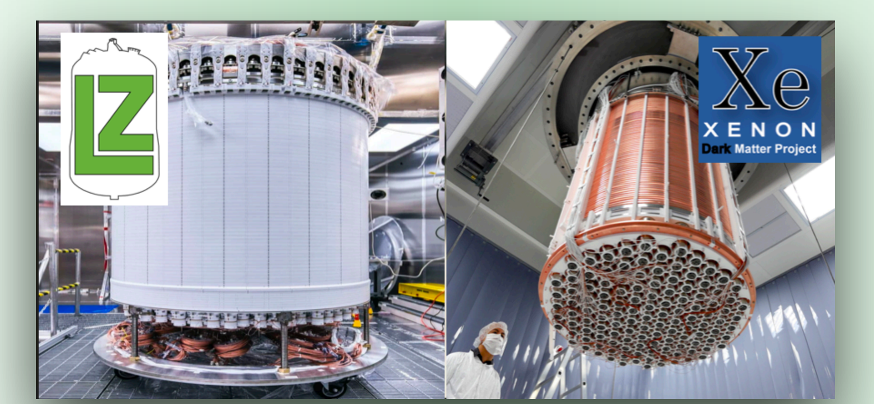
Axions | **WIMPs** | **PBHs**

Direct searches:

"Haloscopes"



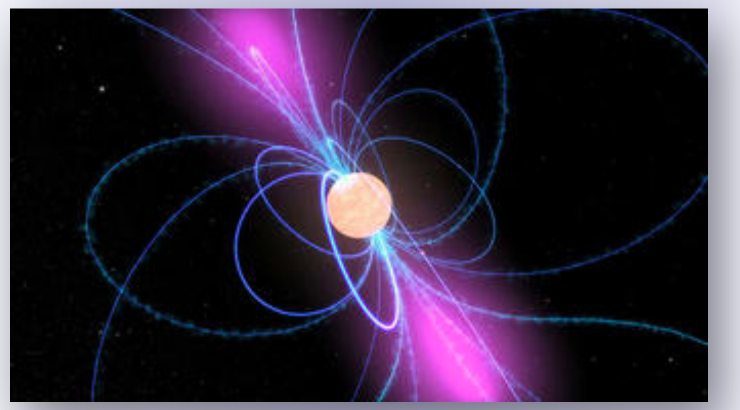
Underground detectors



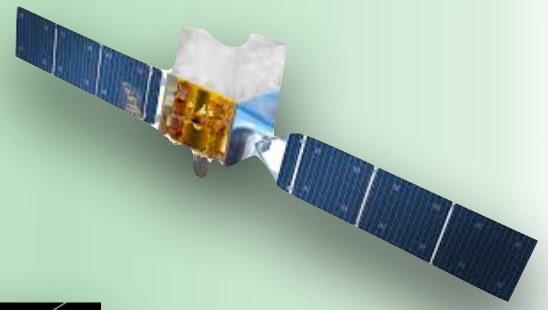
?

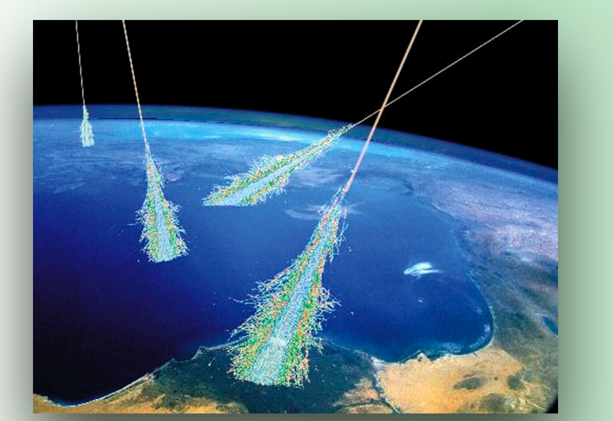
Indirect searches:

Radio signals from neutron stars



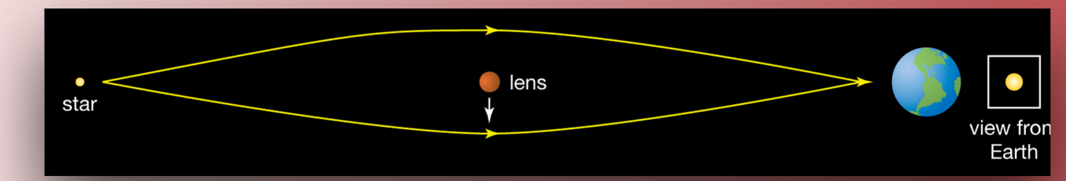
Gamma rays



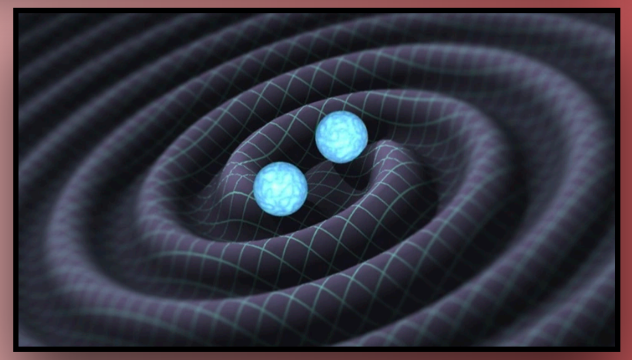


Cosmic rays

Stellar microlensing



Gravitational waves



Moving off the beaten path…

Ultralight (bosonic) dark matter

$$\phi(\mathbf{x}, t) \simeq \sqrt{\frac{2\rho_{\rm DM}}{m_\phi}} \cos(\omega t - \mathbf{k}\cdot\mathbf{x} + \theta)$$

$$\omega \sim m_\phi$$

$$\mathbf{k} \sim m_\phi \mathbf{v}$$

Example of ultralight dark matter: scalar ϕ

Scalar coupled linearly to electrons/1st gen. of quarks

e.g. dilatons, quintessence fields, can also arise via Higgs portal

$$\mathcal{L}_\phi = \phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}\left(d_{m_i} + \gamma_{m_i}d_g\right)m_i\bar{\psi}_i\psi_i\right]$$

Can also describe axion/axion-like particles which can have scalar (CP-violating) nucleon couplings

$$\mathcal{L} \supset -a\sum_\psi \underbrace{g_p^\psi\left(i\bar{\psi}\gamma^5\psi\right)}_{\text{CP}} - a\sum_\psi \underbrace{g_s^\psi(\bar{\psi}\psi)}_{\not{\text{CP}}}$$

QCD axion models: $\left(\frac{10^{-20}}{f_a}\right) \lesssim \frac{\sqrt{4\pi}}{M_{\text{Pl}}}\left(\frac{d_{m_d}m_d + d_{m_u}m_u}{m_d + m_u}\right) \lesssim \left(\frac{10^{-12}}{f_a}\right)$

Example of ultralight dark matter: scalar ϕ

$$\mathcal{L}_\phi = \phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i}+\gamma_{m_i}d_g)\,m_i\bar{\psi}_i\psi_i\right]$$

Time variation of fundamental constants

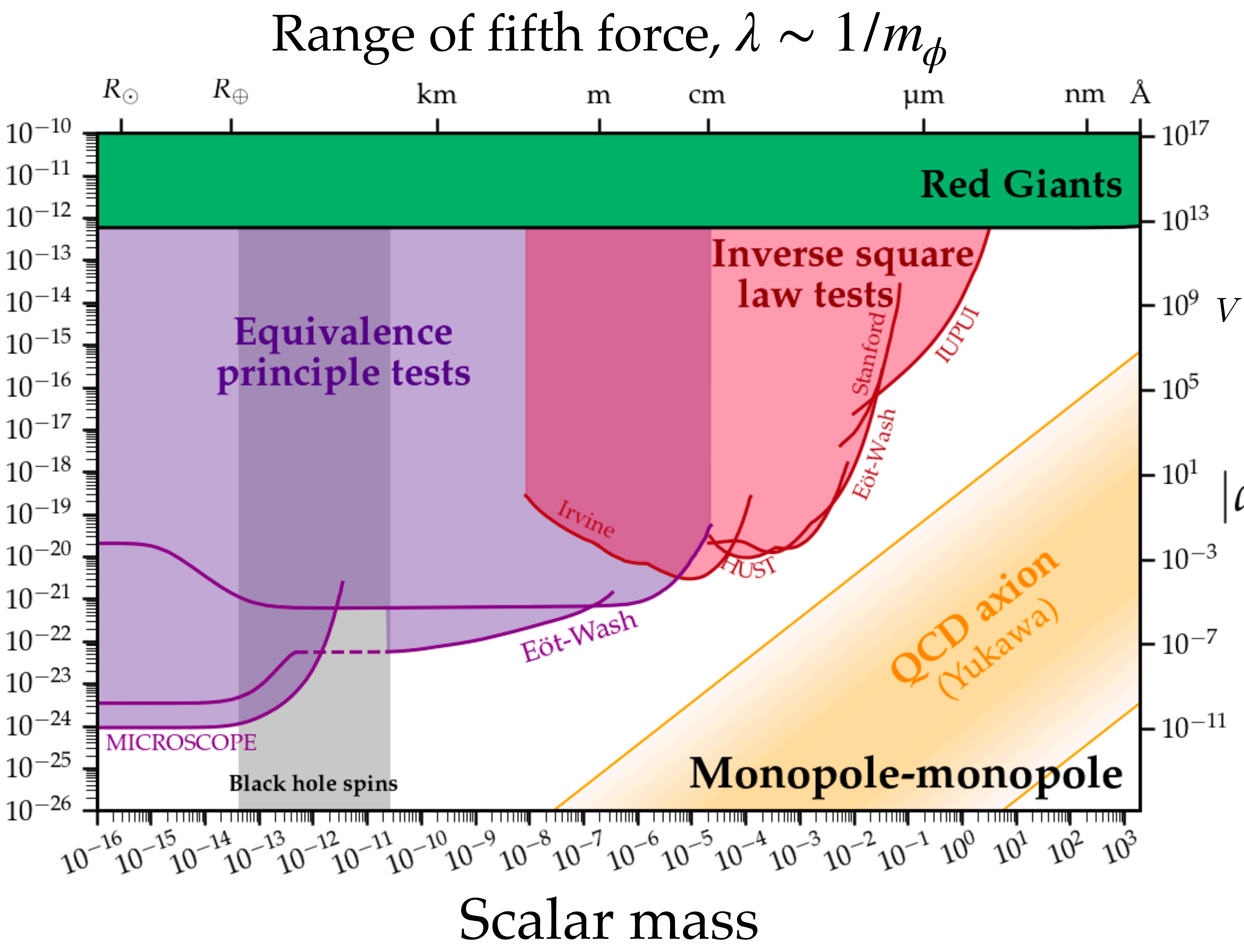
$$m_e(t,\mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha(t,\mathbf{x}) \approx \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

(Parameterised relative to gravity, G_N)

Scalar mediated forces between fermions tightly constrained by gravity tests:

$$a \sum_{\psi} g_s^{\psi} (\bar{\psi}\psi)$$

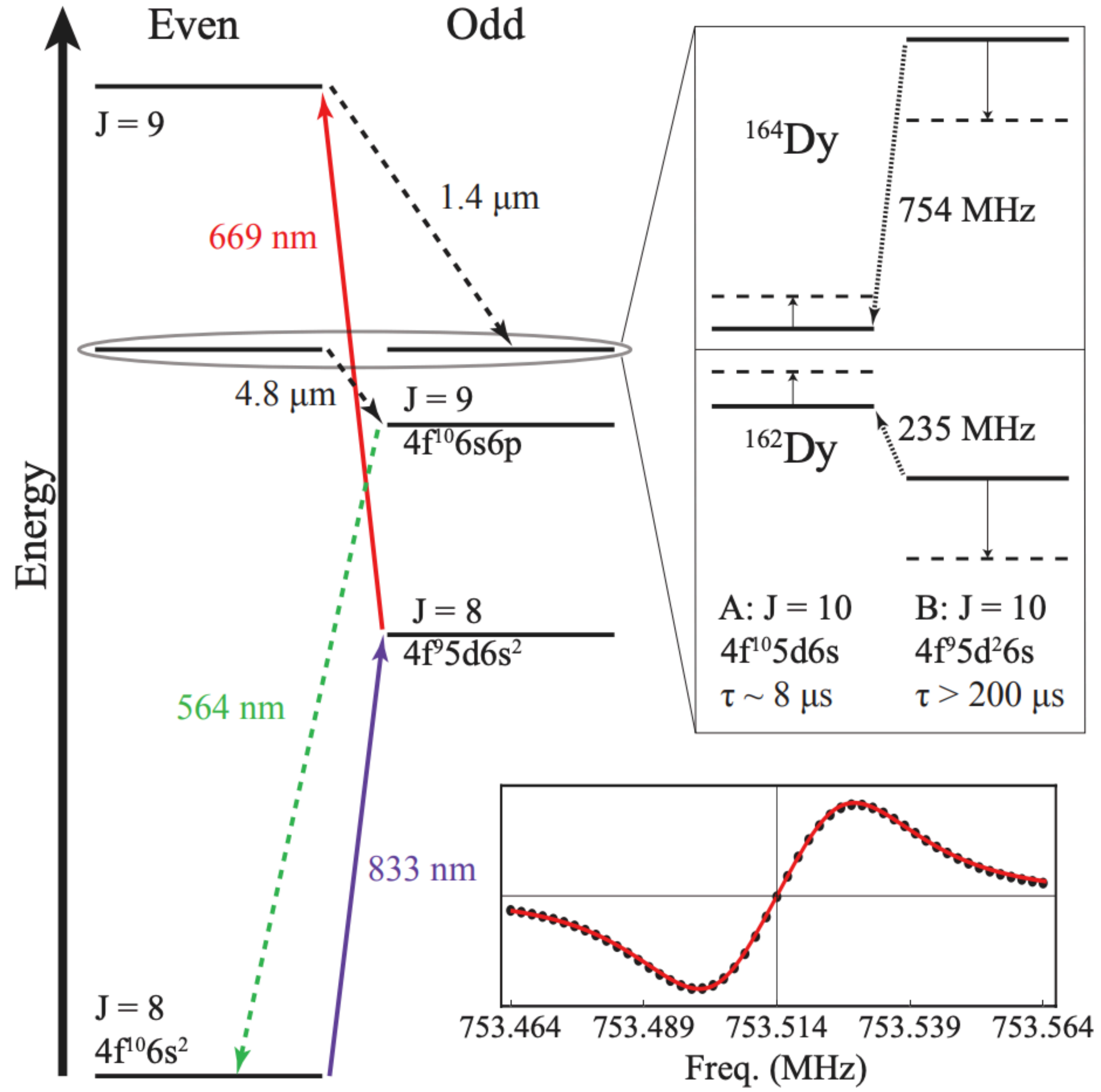


$$V = -\frac{G_N m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

Testing for dilatonic dark matter with linear scalar couplings

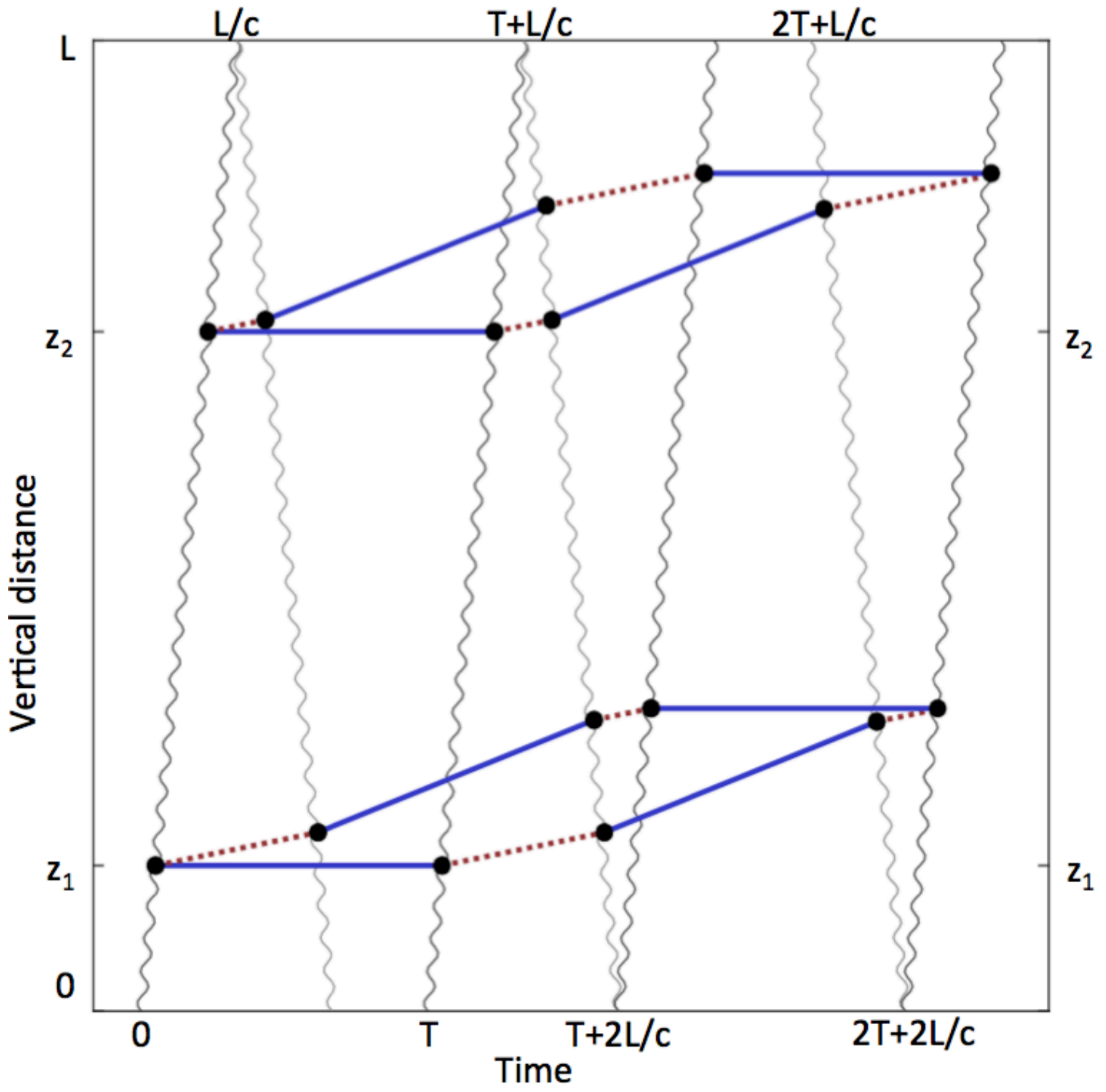
[1405.2925, 1604.08514, 1503.06886, 2008.08773]

Atomic spectroscopy / atomic clocks with energy levels highly sensitive to α



[1911.11755, 1908.00802]

Atom interferometry: interference between cold atomic clouds travelling on different spacetime paths



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[1405.2925, 1604.08514, 1503.06886, 2008.08773]

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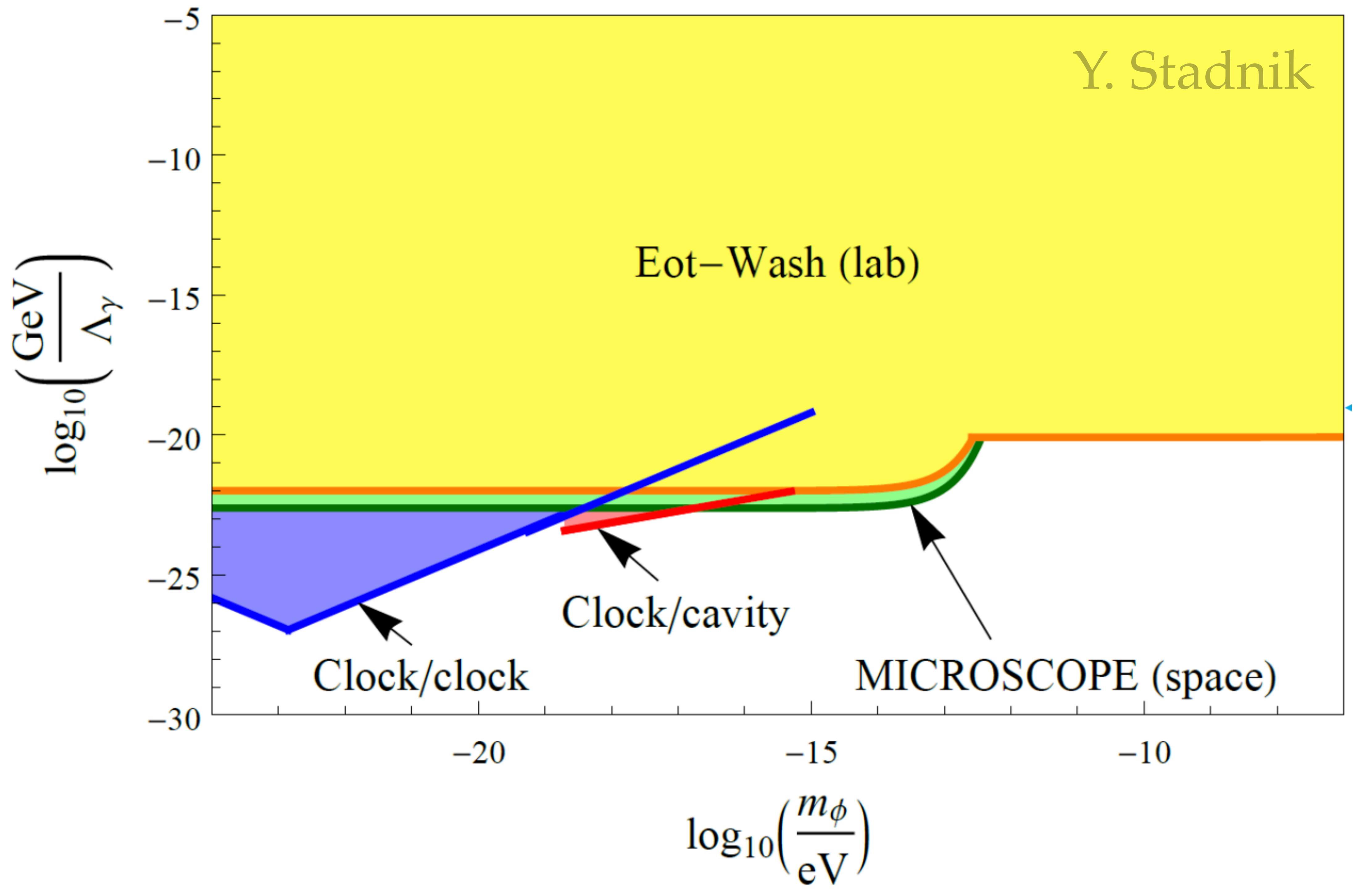
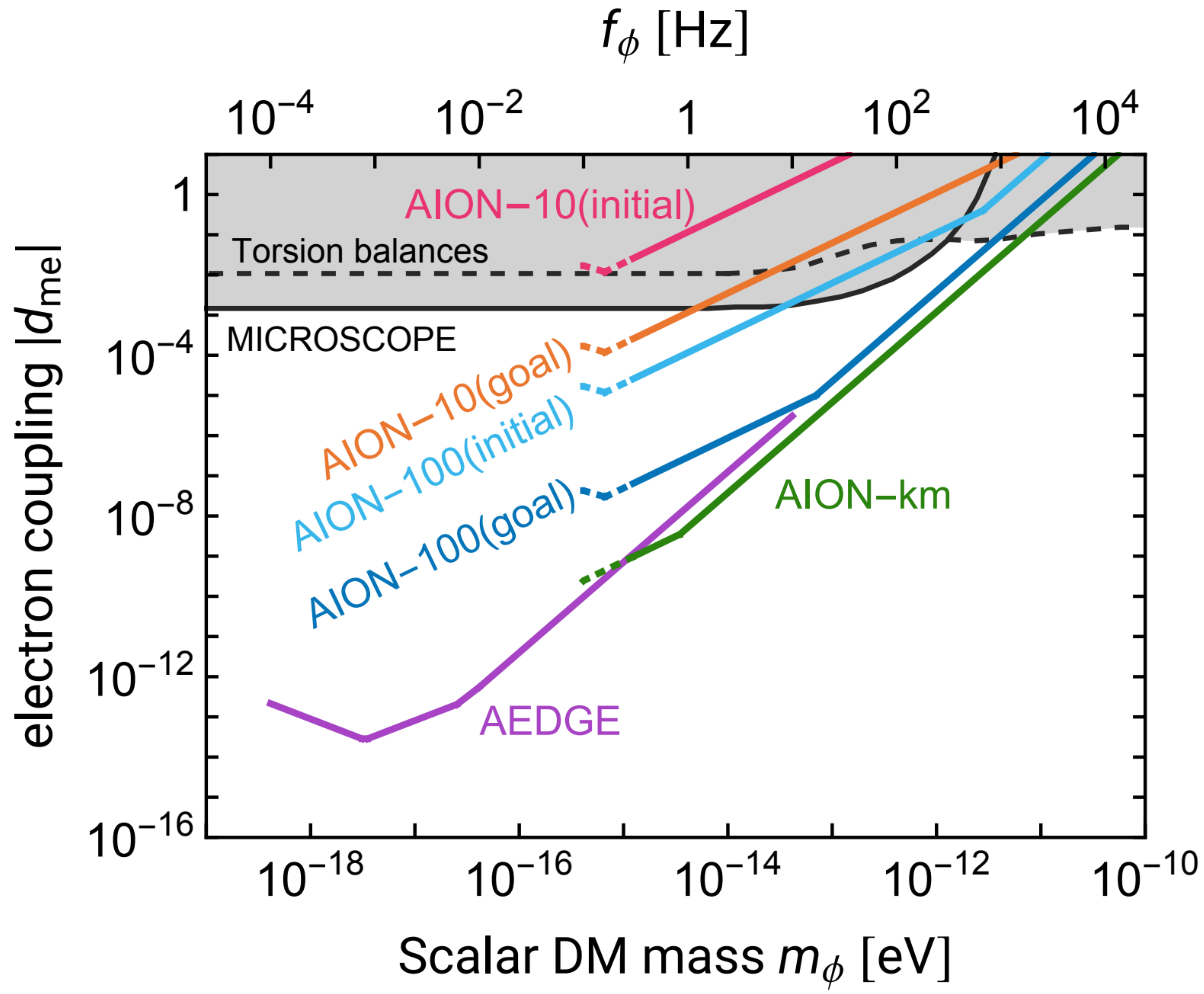


[1911.11755, 1908.00802]

Atom interferometry: interference between cold atomic clouds travelling on slightly different spacetime paths



Example 2: Dark photons

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

with vector X^μ

Below EW → $\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} \boxed{- \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$

"Kinetic mixing"

$A^\mu \to A^\mu - \chi X^\mu$

$$\frac{m_X^2}{2}X_\mu X^\mu + j_\mu(A^\mu - \chi X^\mu)$$

→ X is massive uncharged vector (i.e. Z'),
→ Particles given additional dark millicharge ~ χe
→ Can also be coupled to other dark sector particles to create millicharged DM

$X^\mu \to X^\mu - \chi A^\mu$

$$\frac{m_X^2}{2}(X_\mu X^\mu - 2\chi X_\mu A^\mu + \chi^2 A_\mu A^\mu) + j_\mu A^\mu$$

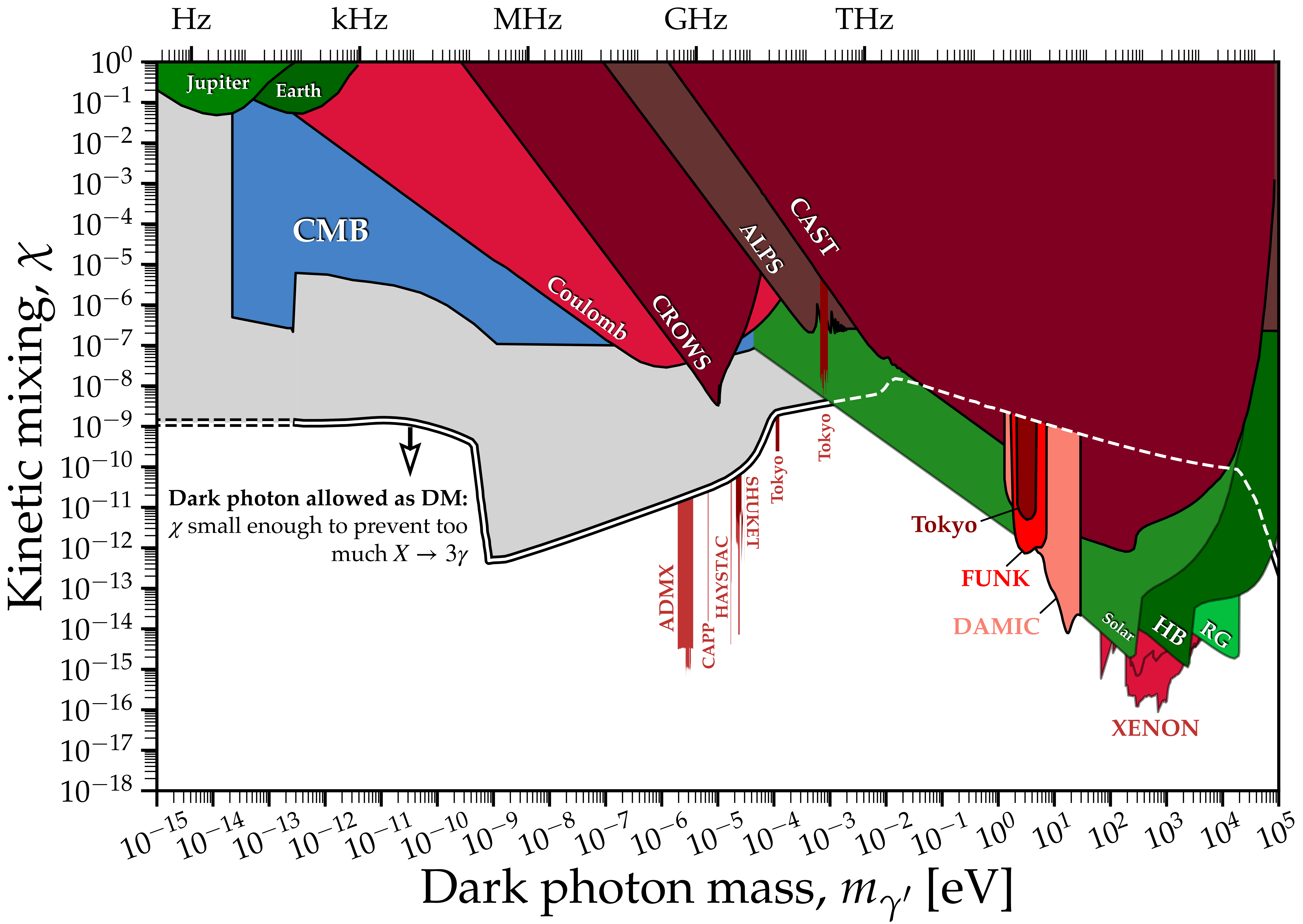
→ Non-diagonal mass term
→ SM photon-Dark photon mixing

Dark photon constraints

Experiments

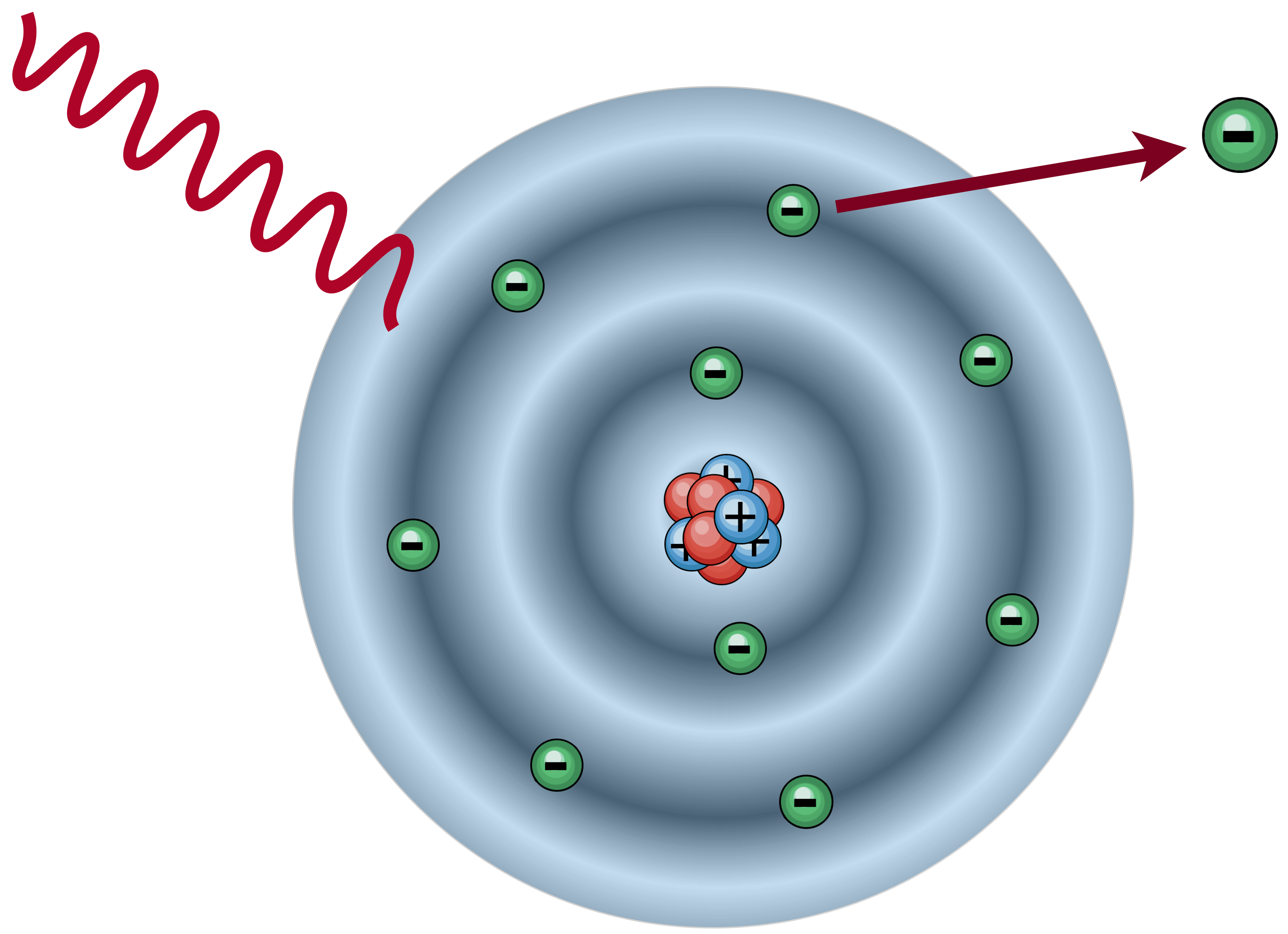
Cosmology

Astrophysical



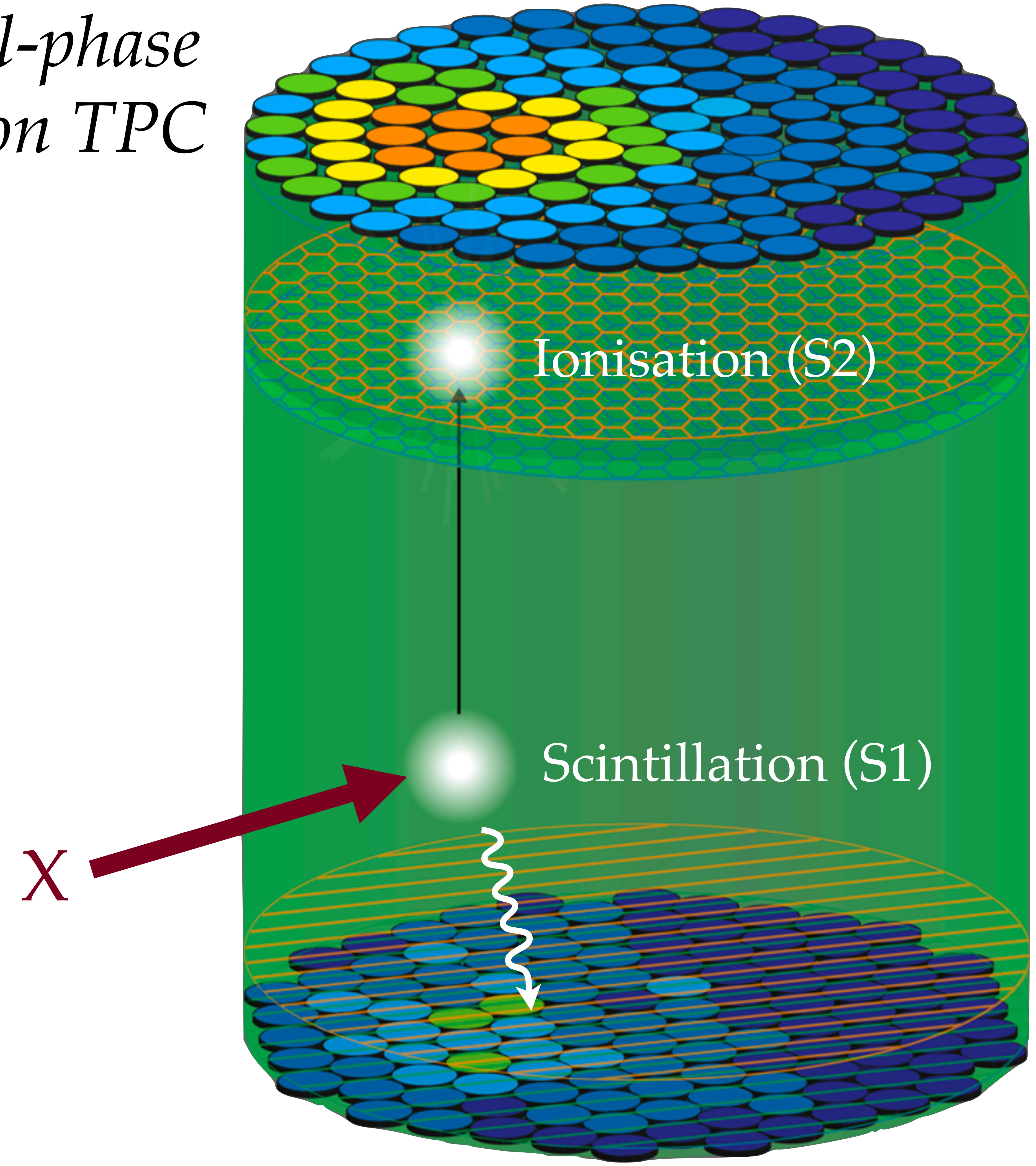
Dark photons: straightforwardly detected in ionisation detectors

dark photon absorption → emission of photoelectron with energy $\approx m_X$

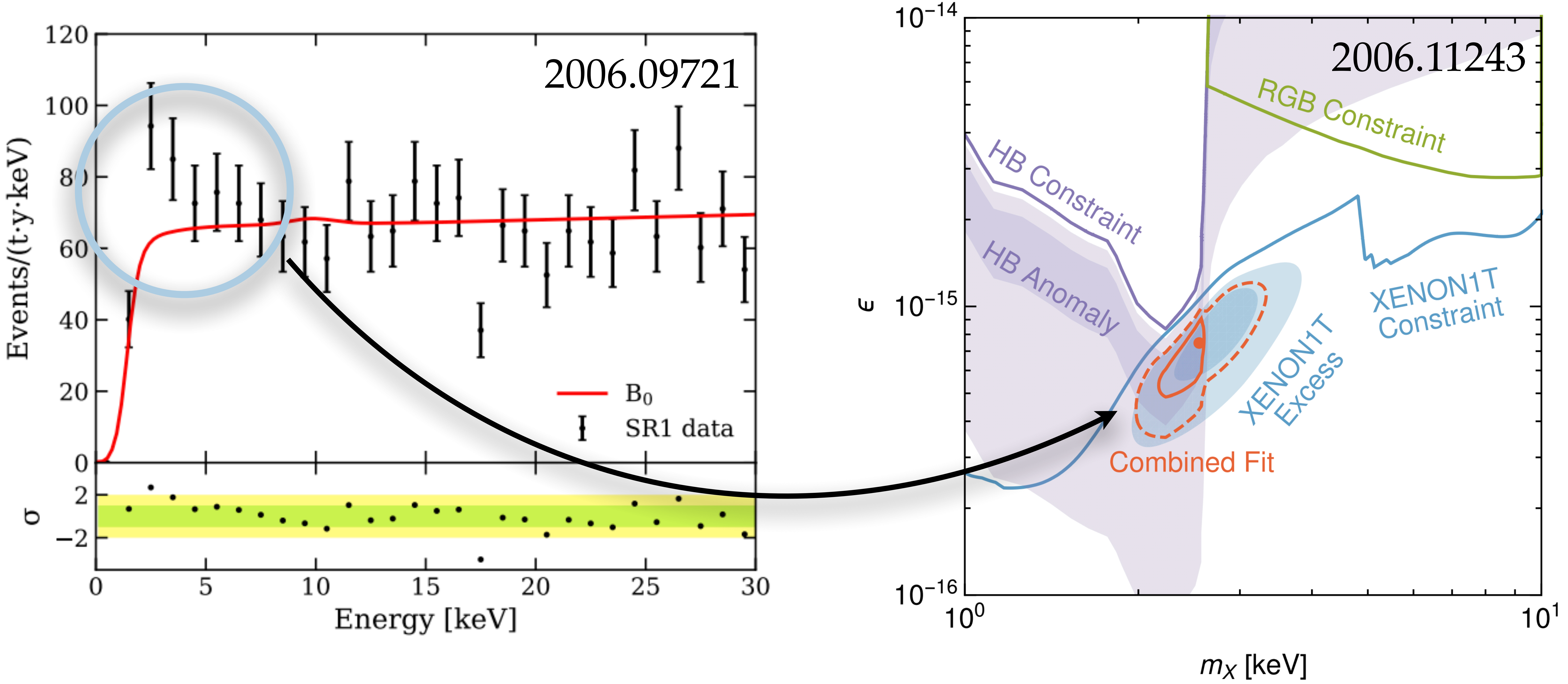


$$\text{Rate} = \chi^2 \frac{\rho_{\rm dm}\sigma_{\rm pe}}{m_X m_N}$$

→ Noble gas TPCs and cryogenic scintillators optimised for ~keV ionisation signals, so primed to detect ~keV mass dark photons



Dark photons: (one of the many) interpretations of the XENON1T's electronic channel excess

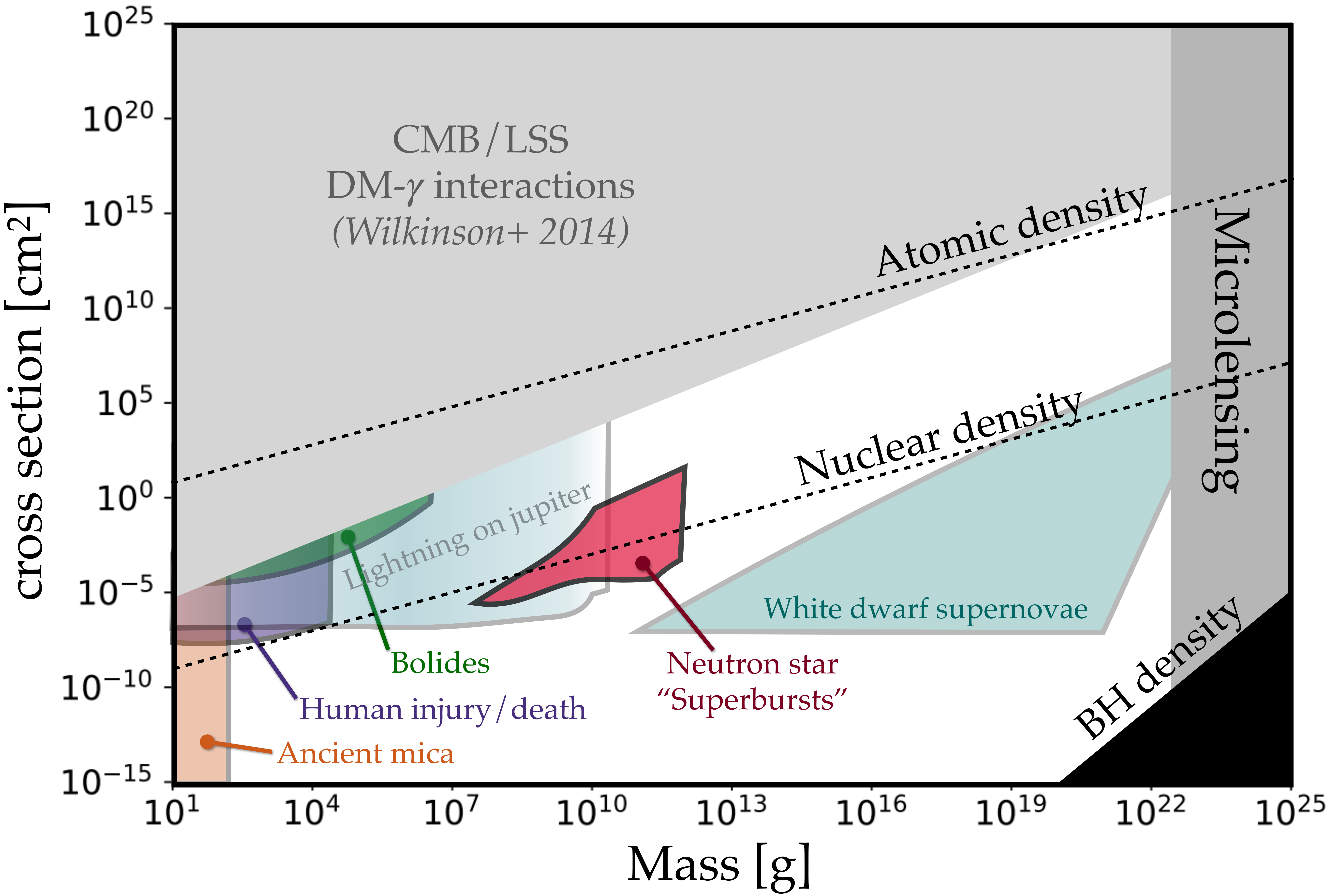


Even further off the beaten path

Macroscopic dark matter

Energy deposition by macro: $\frac{\mathrm{d}E}{\mathrm{d}x} = \sigma_{\mathrm{dm}} \cdot \rho_{\mathrm{target}} \cdot v_{\mathrm{dm}}^2$

- No fixed models
- Some ideas of composite dark matter in the form of bound states of quarks formed during phase transitions dating back to work by Witten
- One can form an agnostic parameter space and look for signatures of anomalous high dE/dx collisions e.g. [2006.16272]
- See also work by Zhitnitsky on "axion quark nuggets"



Given an abundance of ideas, what if we never see anything?

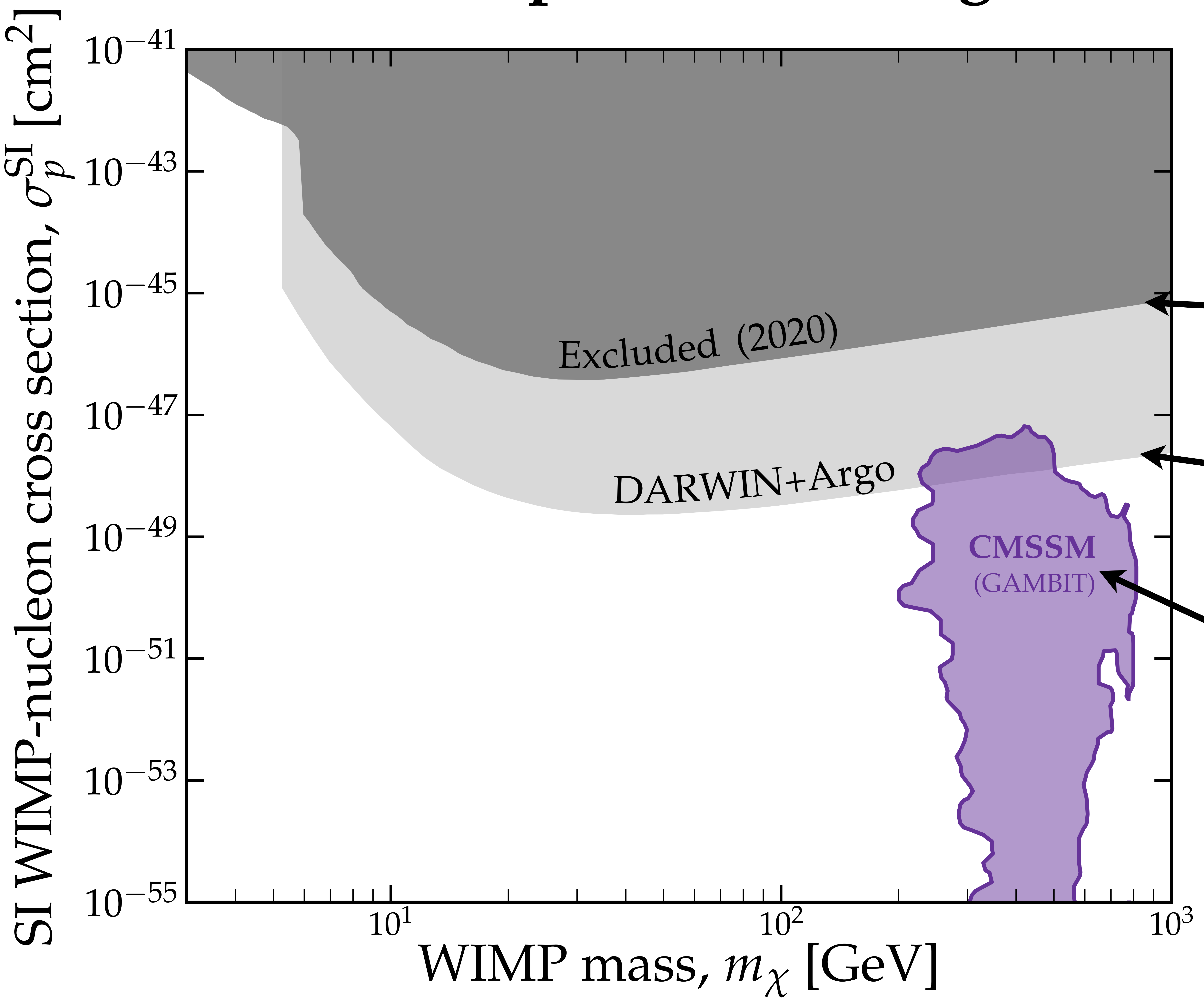
Are direct detection experiments doomed to fail?

Ways in which dark matter experiments might fail

(Even if we guess the right model!)

1. DM couplings are so small that they would require impractically large and/or sensitive experiments to ever measure

Example 1: searching for SUSY WIMPs

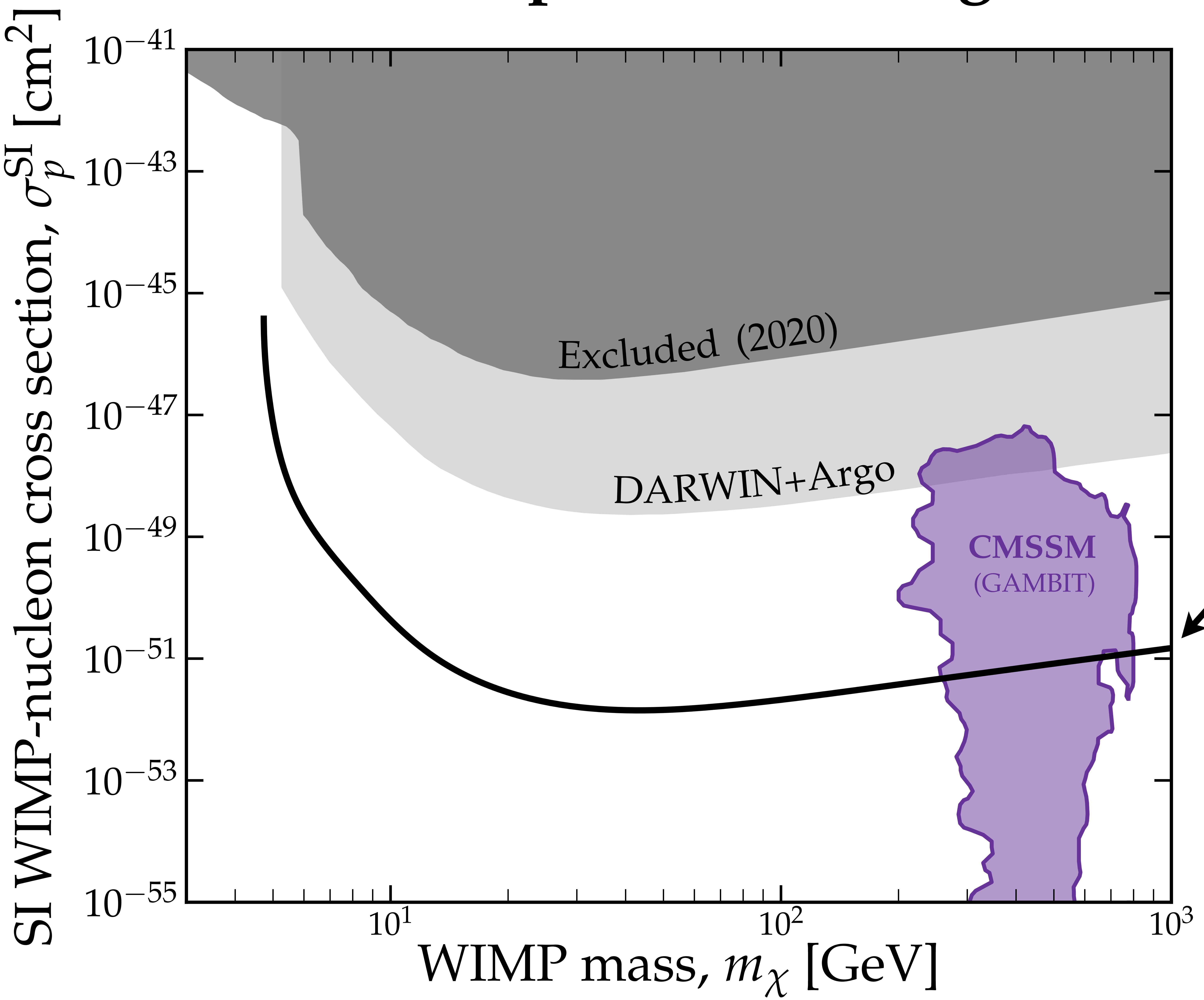


Currently excluded with ~ 1 tons of xenon

Planned experiments with ~ 100 ton-years of xenon

Preferred model: thermal relic supersymmetric WIMP from CMSSM

Example 1: searching for SUSY WIMPs



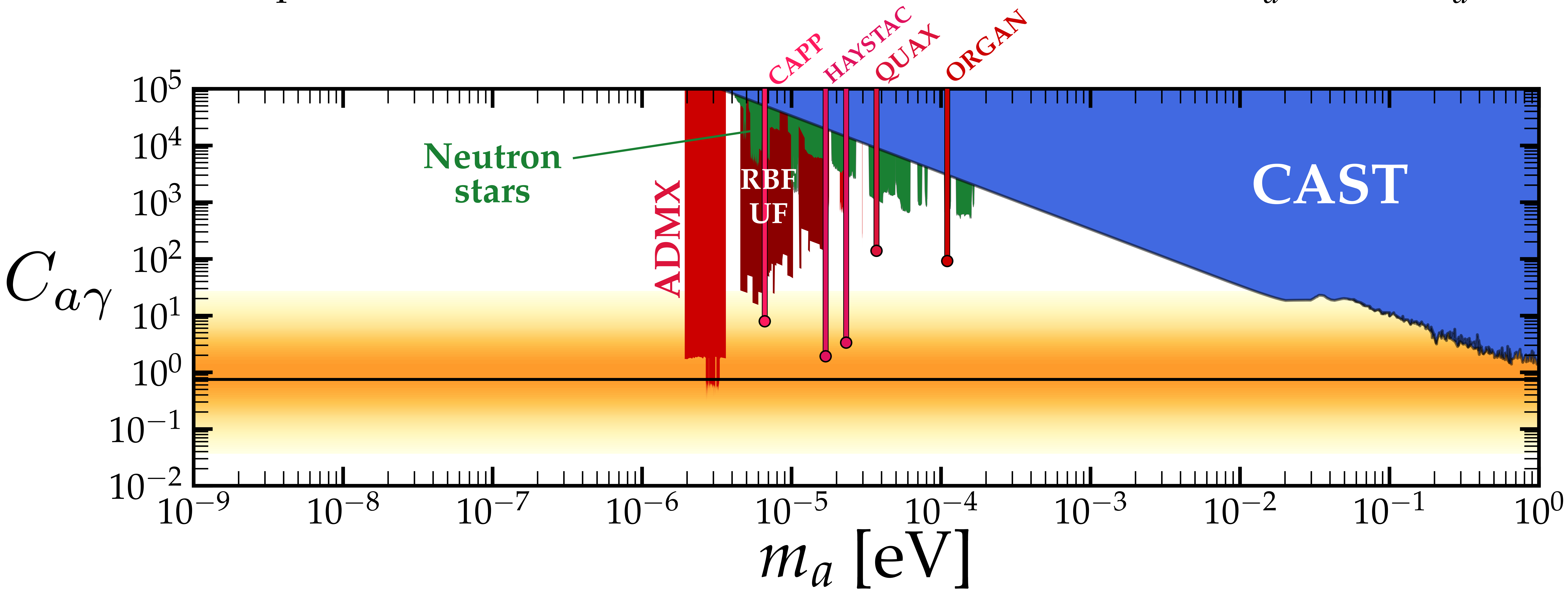
Reaching here would require using all the xenon that exists on Earth

(And would take about 300,000 years to extract at current rates)

Example 2: searching for the QCD axion

Axion-photon coupling: $C_{a\gamma} = \frac{E}{N} - 1.92 \sim \mathcal{O}(1)$

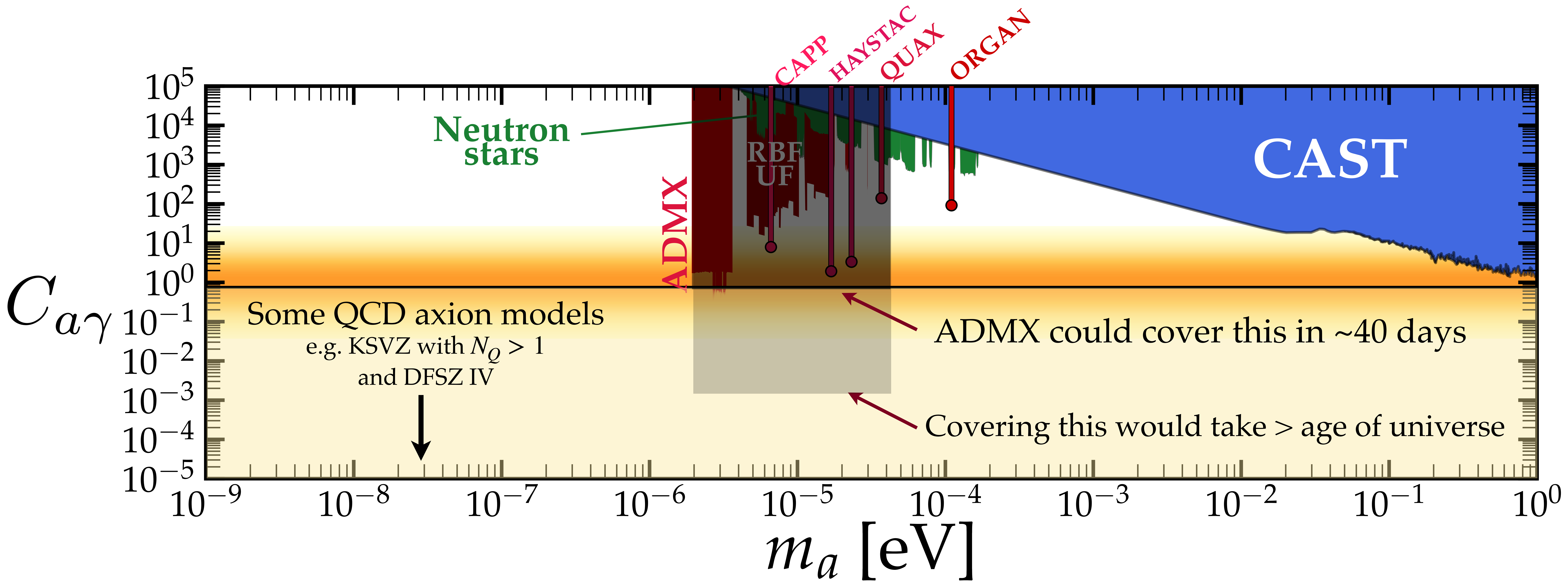
Most experiments can search a small mass window at a time $\delta m_a \sim 10^{-6}\, m_a$



Example 2: searching for the QCD axion

Some UV-completions of the axion, within theoretical uncertainty, allow for close cancellations in couplings i.e. E/N ~ 1.92

But: required scan rate to discover the axion: $dm_a/dt \propto C_{a\gamma}^{-4} \rightarrow$



Ways in which dark matter experiments might fail

(Even if we guess the right model!)

1. DM couplings are so small that they would require impractically large and/or sensitive experiments to ever measure

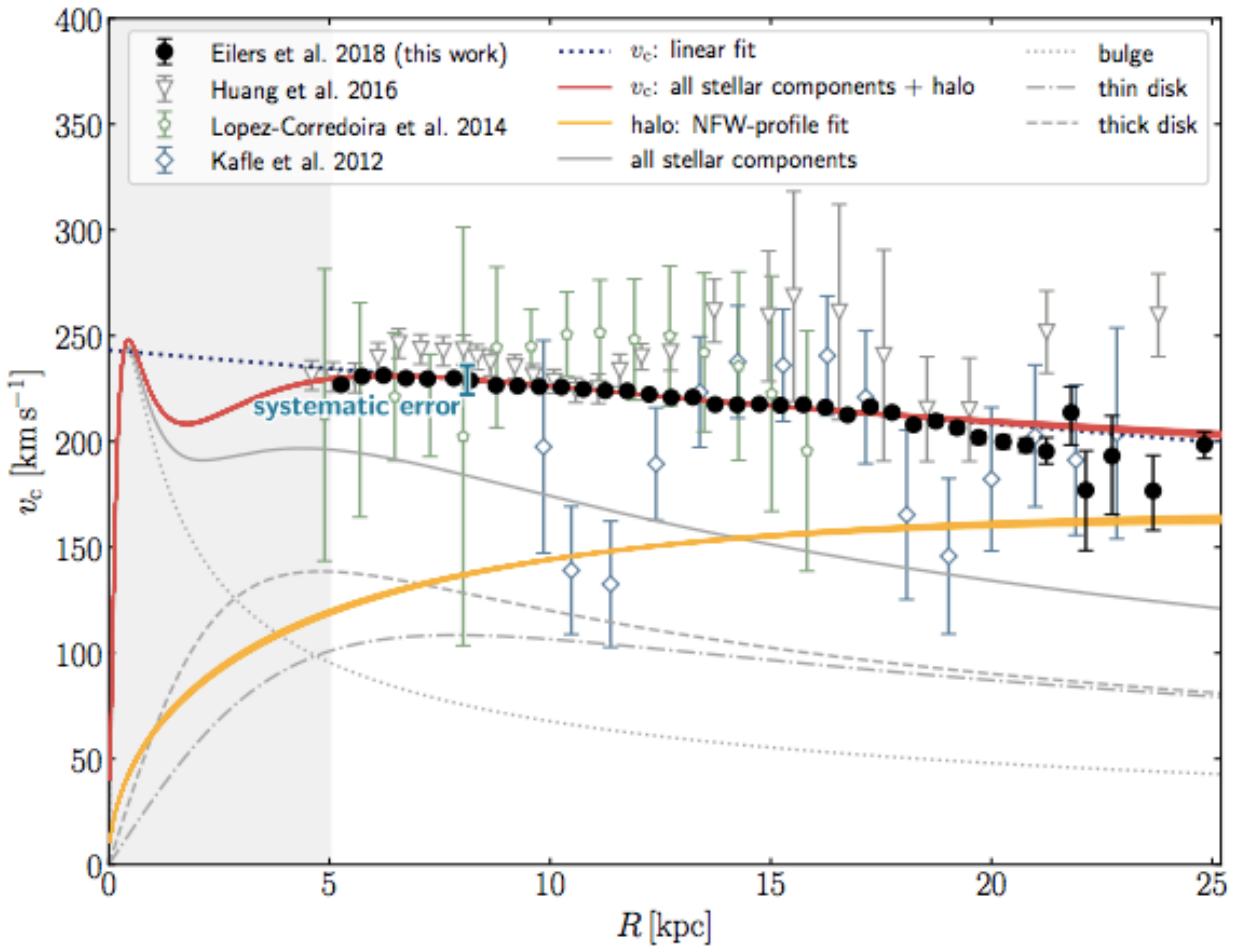
2. There is no dark matter around the Earth to detect

The local dark matter density

We can be confident that $\rho_{\rm dm} \sim 0.4\,{\rm GeV\,cm^{-3}}$ from astronomical observations of the MW

→ However we have no measurements of the density of DM on scales smaller than ~100 pc

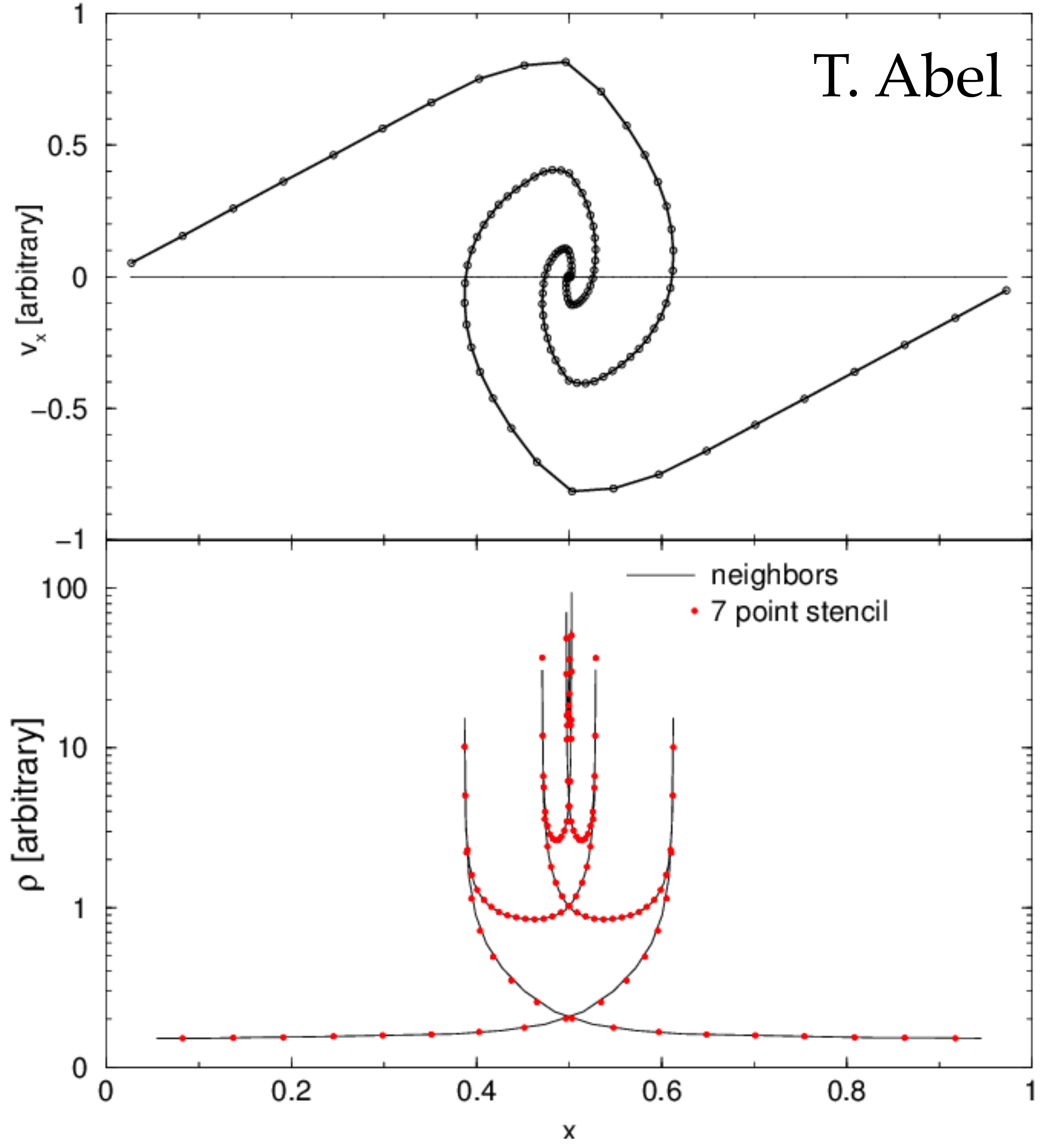
→ Experiments probe on **mpc** scales!



Streams and caustics

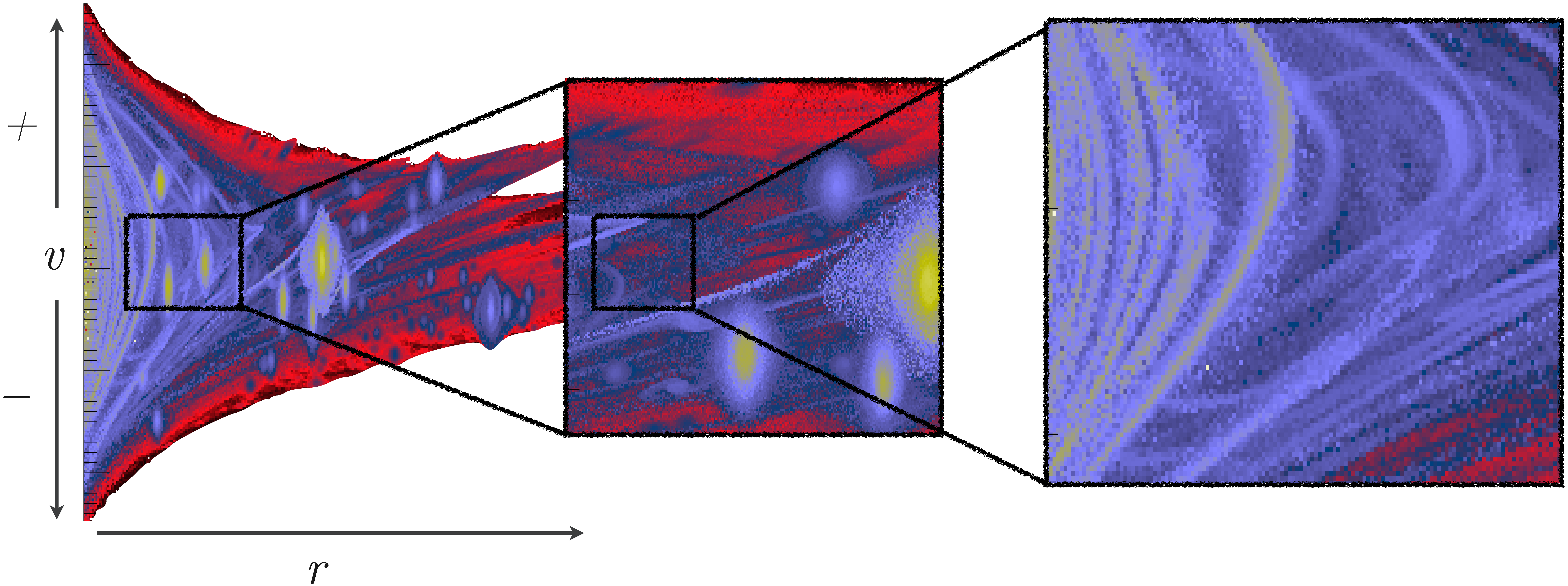
Assuming something close to spherical collapse, DM halos form via the wrapping up of many 3d hypersurfaces in 6d phase space
→ leads to caustics and fine-grained substructure

Even state of the art simulations cannot resolve sub-pc caustics, and likely never will



Fine-grained substructure

- At some level the halo should have ultrafine substructure, even though simulations suggest a slow disruption of this via non-radial perturbations Vogelsberger+ [1002.3162]
- Fortunately, even if this is the case, this implies enhanced indirect detection signals
- Also, sub-grid extrapolation studies suggest mpc distribution is the sum of many millions of overlapping streams



Ways in which dark matter experiments might fail

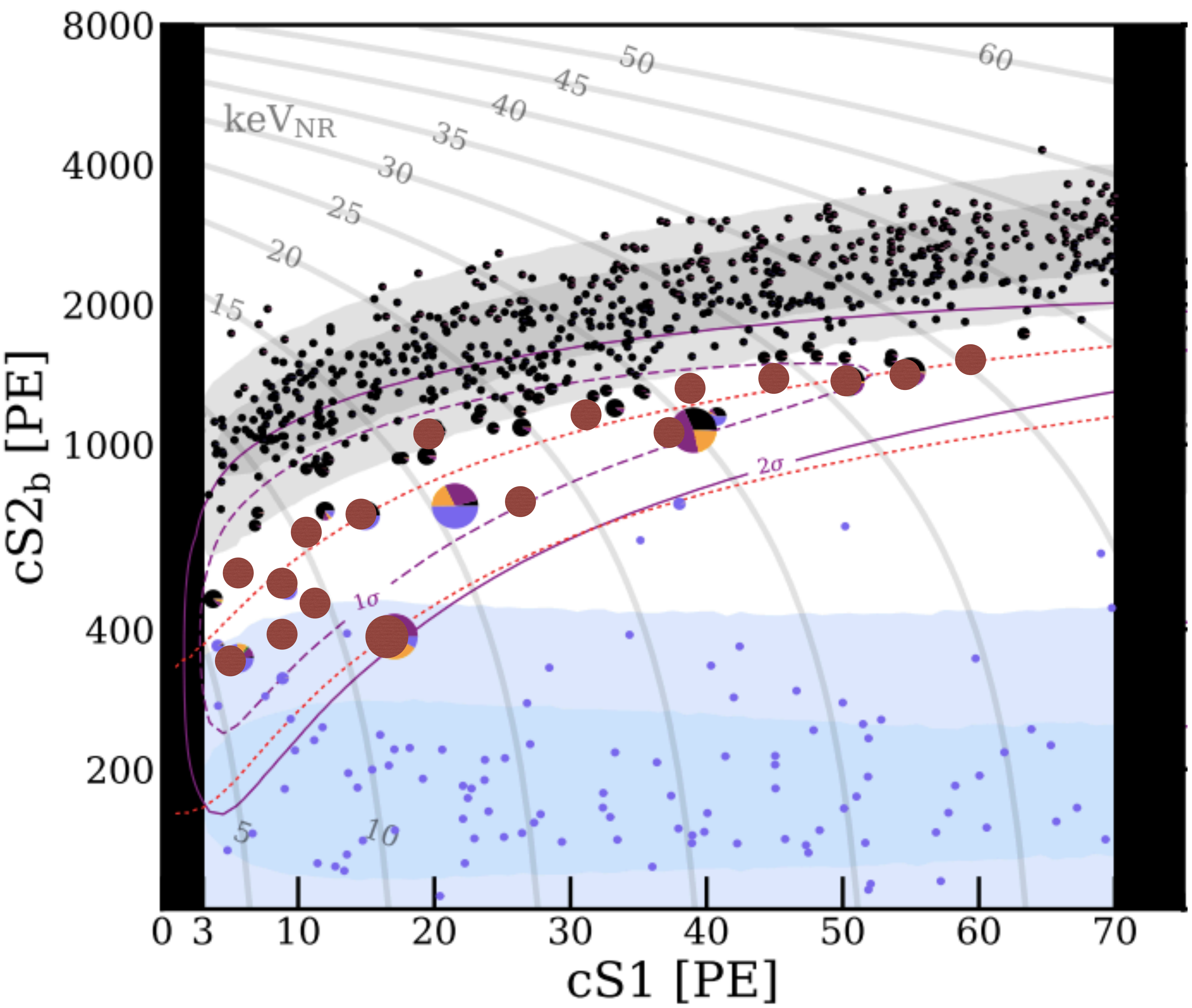
(Even if we guess the right model!)

1. DM couplings are so small that they would require impractically large and/or sensitive experiments to ever measure

2. There is no dark matter around the Earth to detect

3. The experiment cannot "confirm" any signal as dark matter

This is what a “discovery” of dark matter could look like



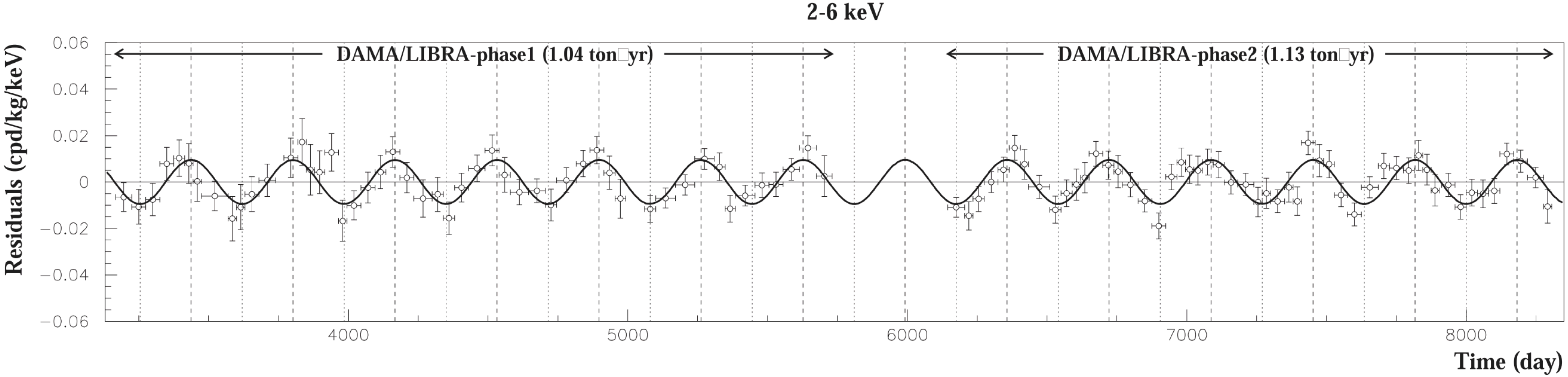
“Smoking gun” signals of dark matter

1. Annual modulation
   → DM flux peaks in June

2. Directionality
   → DM flux peaks towards Cygnus

3. Gravitational focusing by Sun
   → DM focused towards Earth during March

Annual modulation



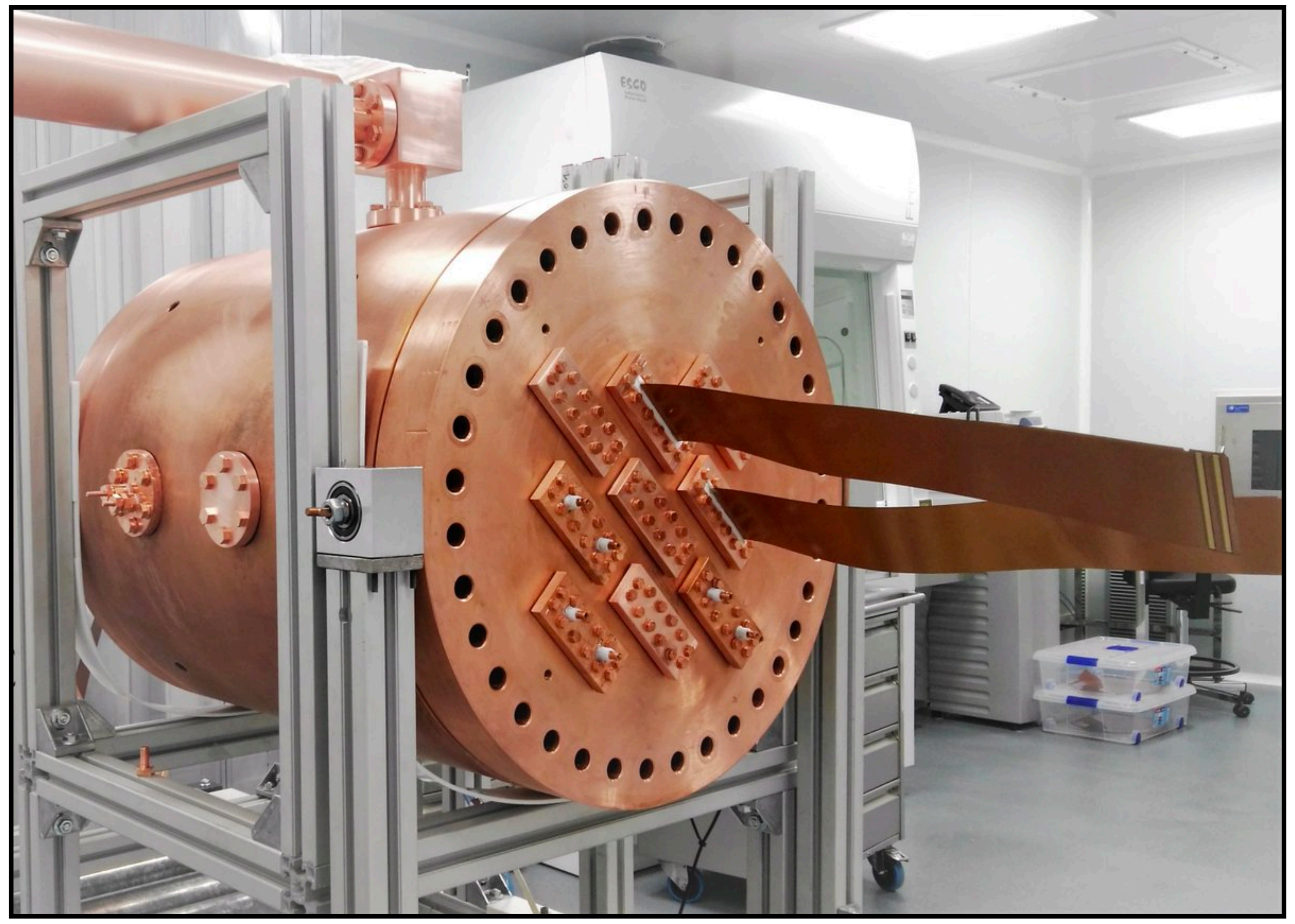
12.9σ observation of modulation by DAMA / LIBRA (NaI scintillator).

Close to impossible to explain this with DM and remain consistent with other null observations

Ruling out DAMA

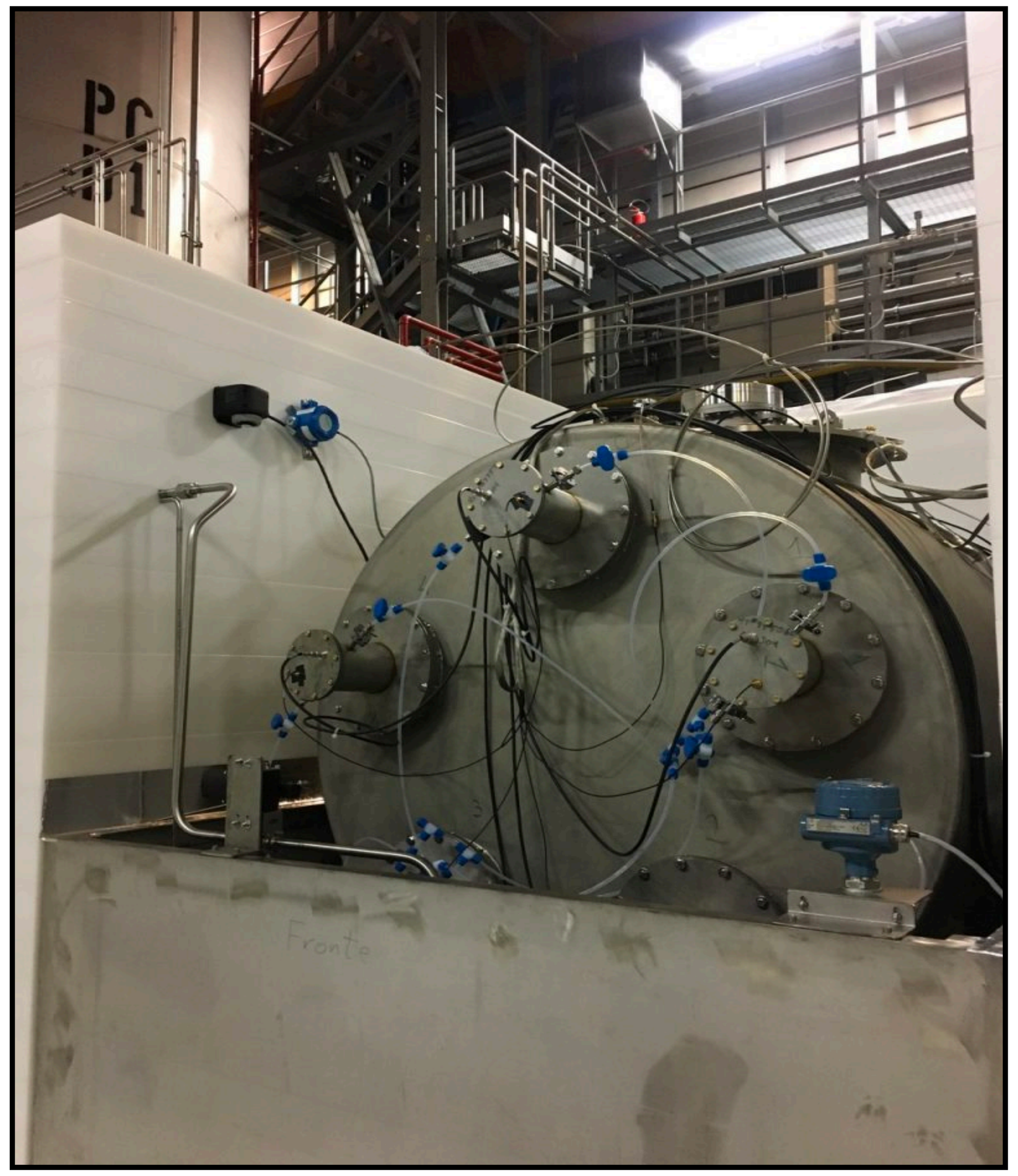
Clearly something is modulating, presumably seasonally. Several identical experiments have been spawned trying to check this.

ANAIS



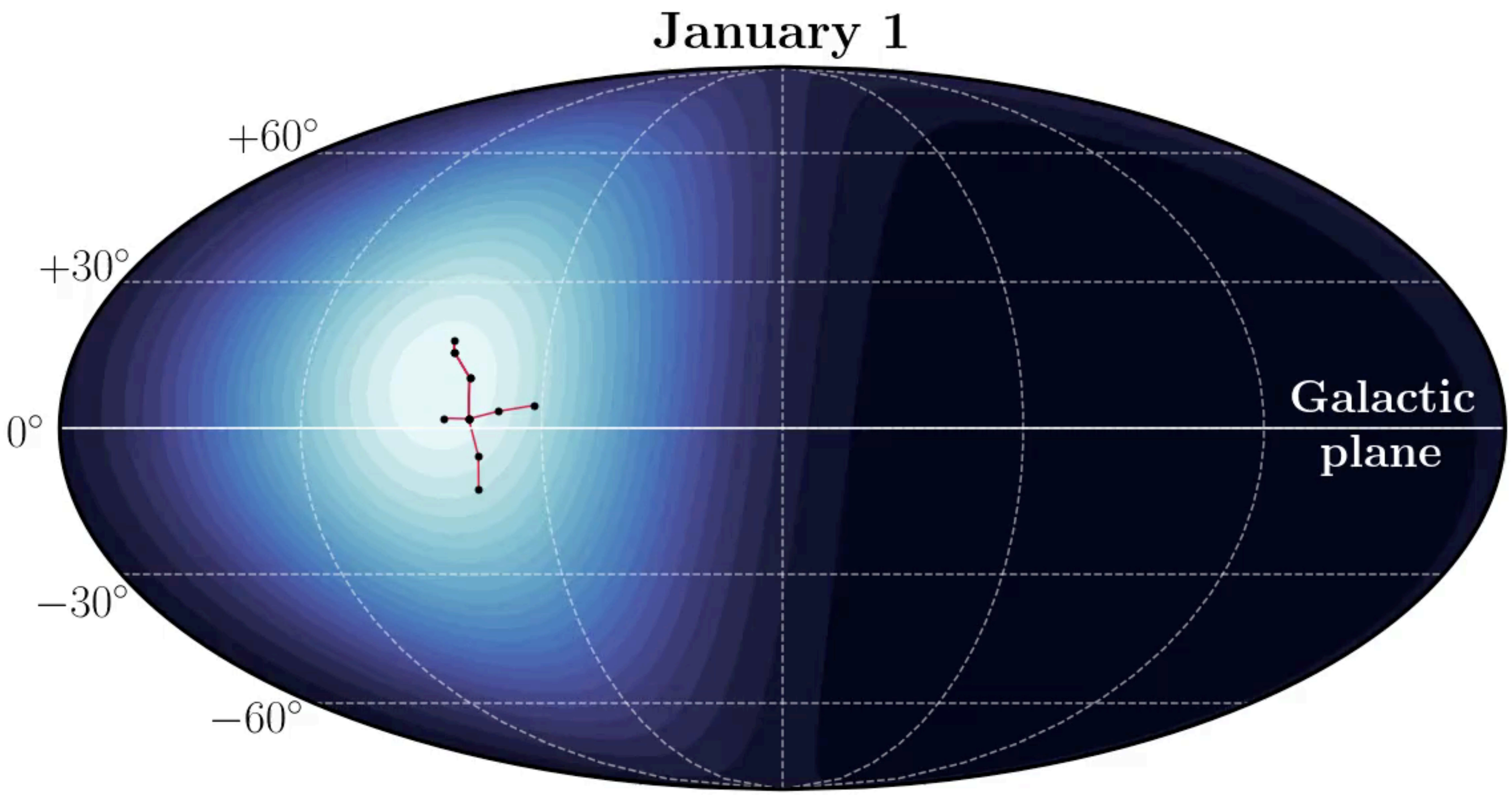
COSINE

SABRE (Italy/Australia)



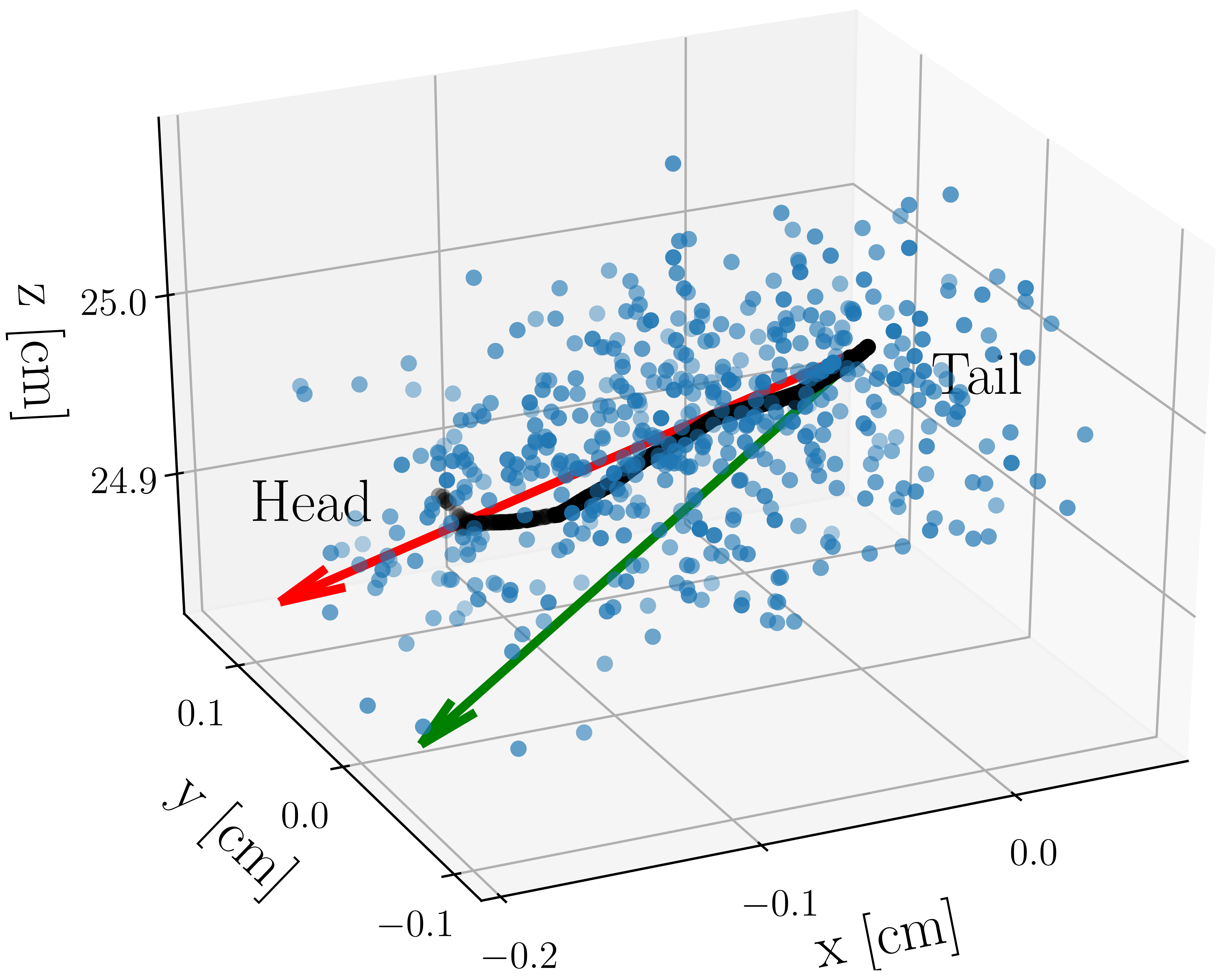
Hopefully one day we can stop talking about this

Directionality: should see a roughly Gaussian dipole in DM interactions peaking towards Cygnus



This signal is strong and robust against particle/astrophysical models, and should not be mimicked by any background or systematic

Directionality for DM-induced recoils



● Initial track

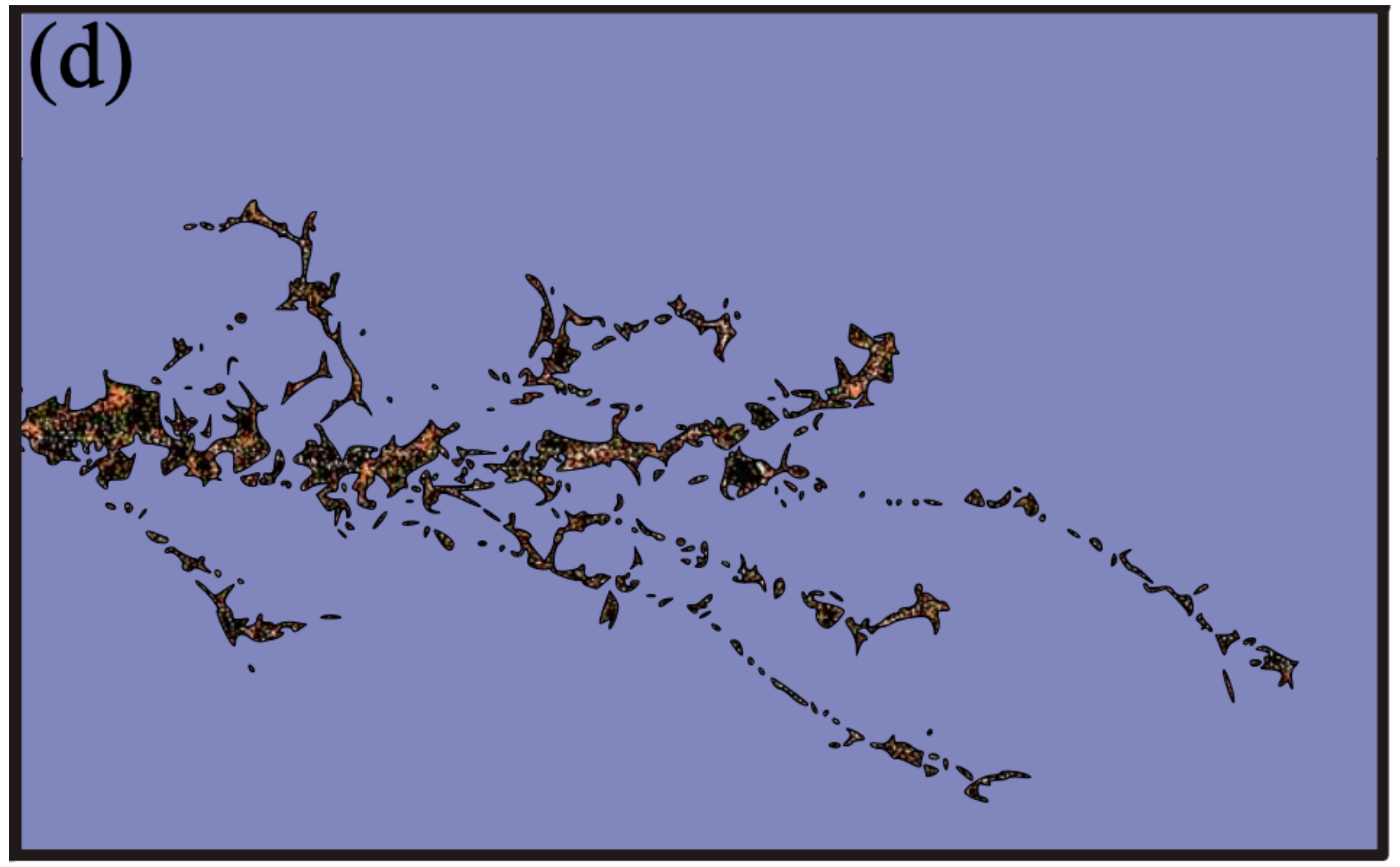
● After diffusion

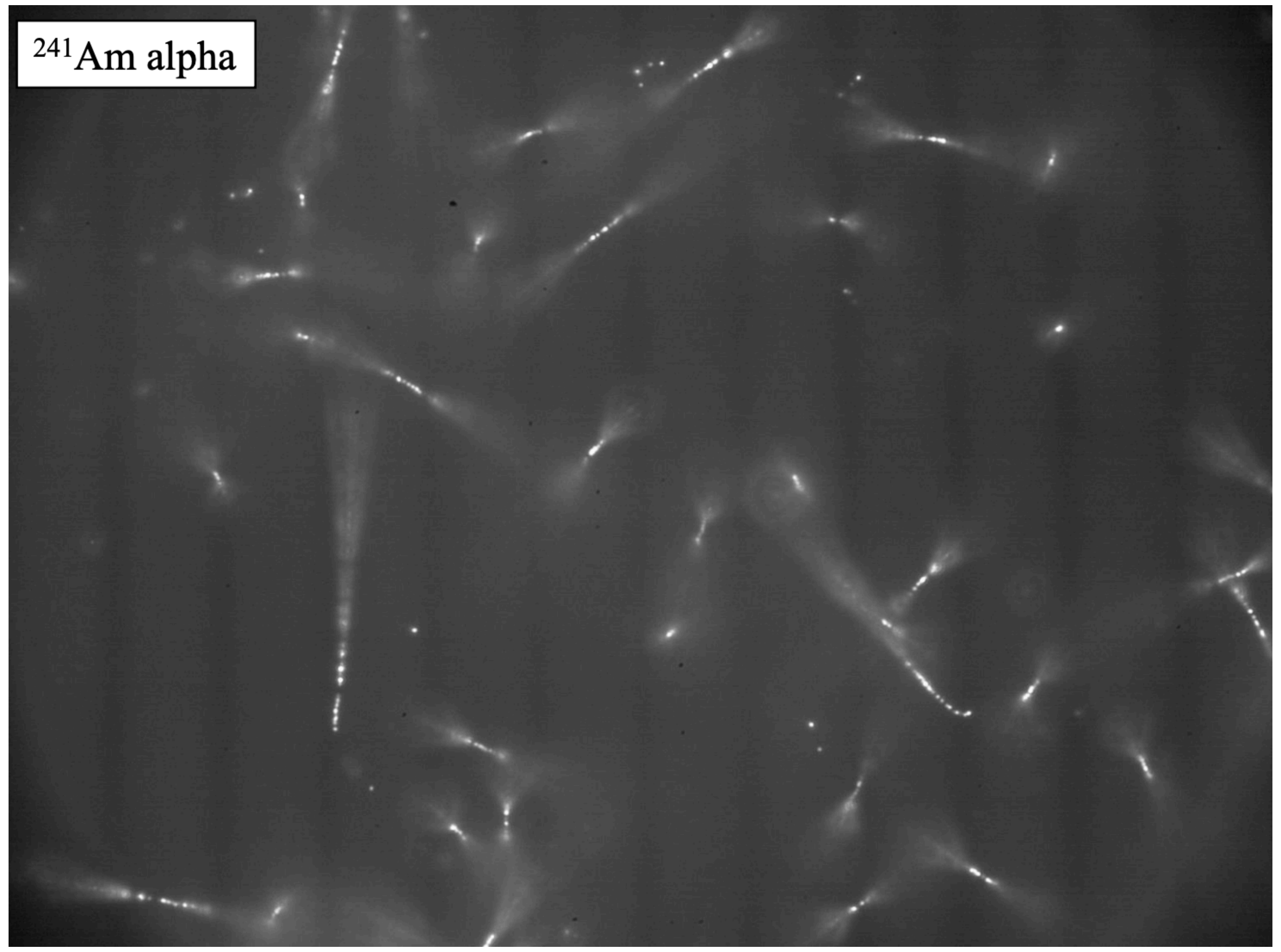
↑ True recoil dir.

↑ Straggled recoil dir.

Challenging to detect low energy recoils in virtually any medium

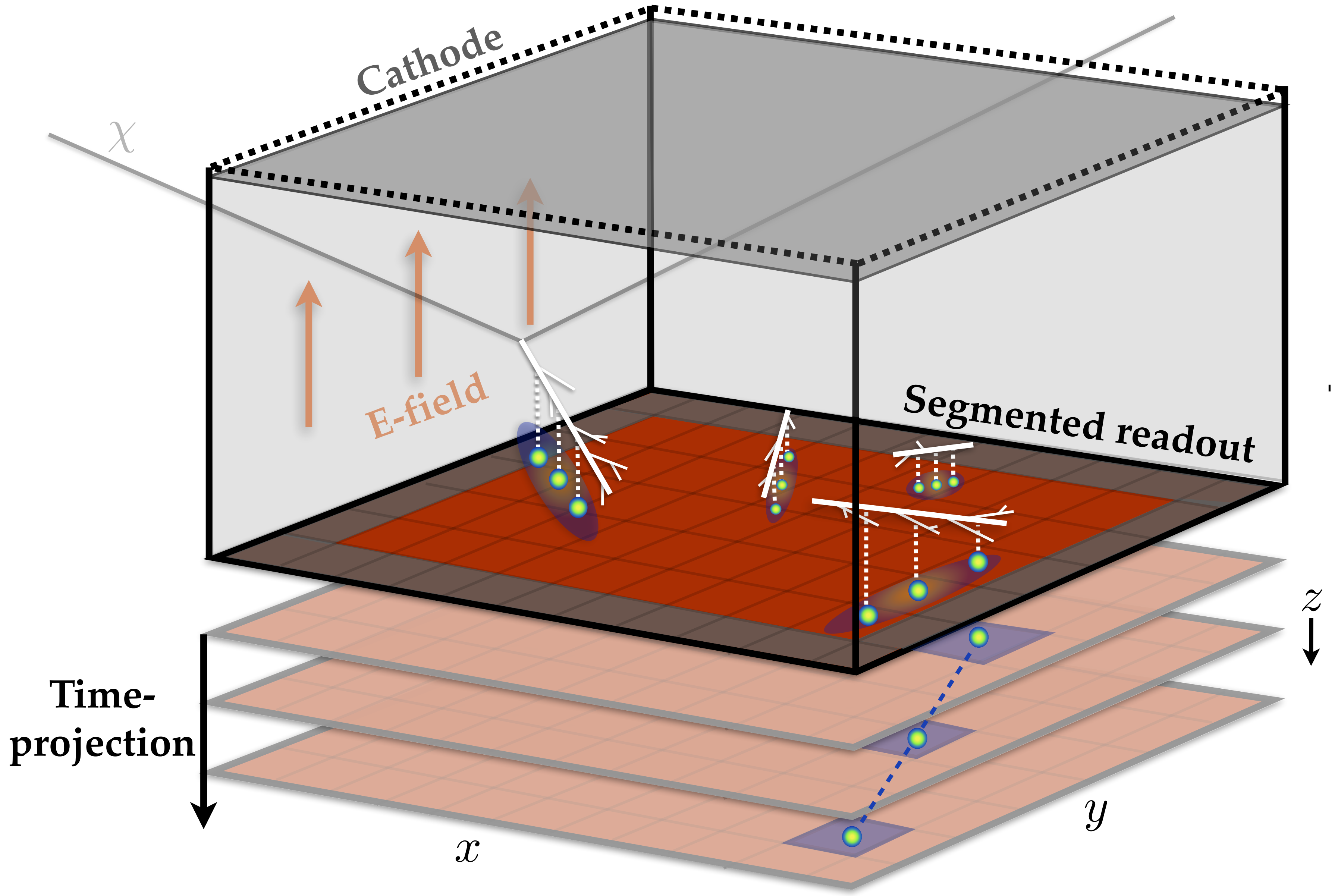
Crystal defect spectroscopy

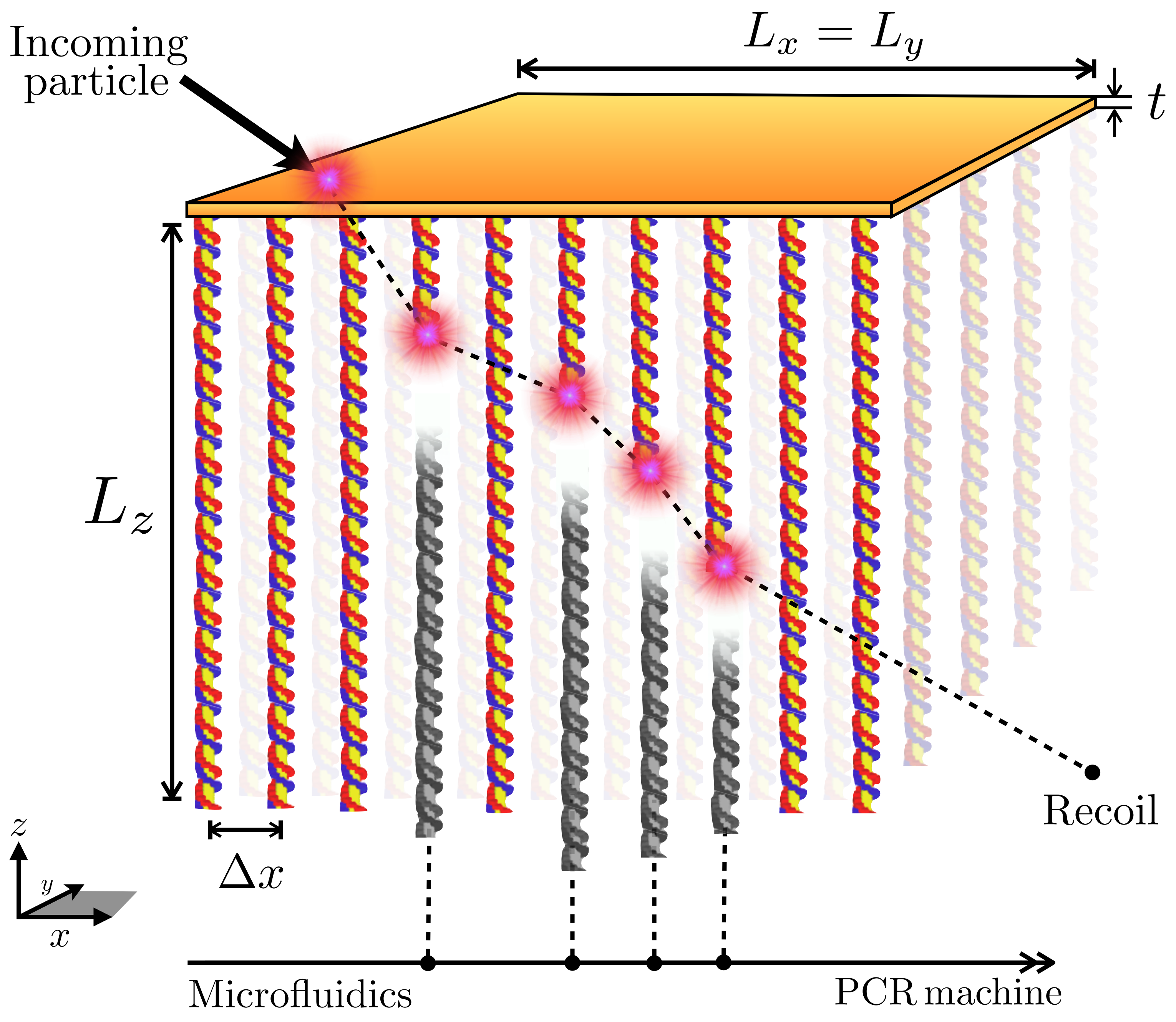




Nuclear Emulsions

Time projection chamber





DNA

2102.04596

Directional Recoil Detection

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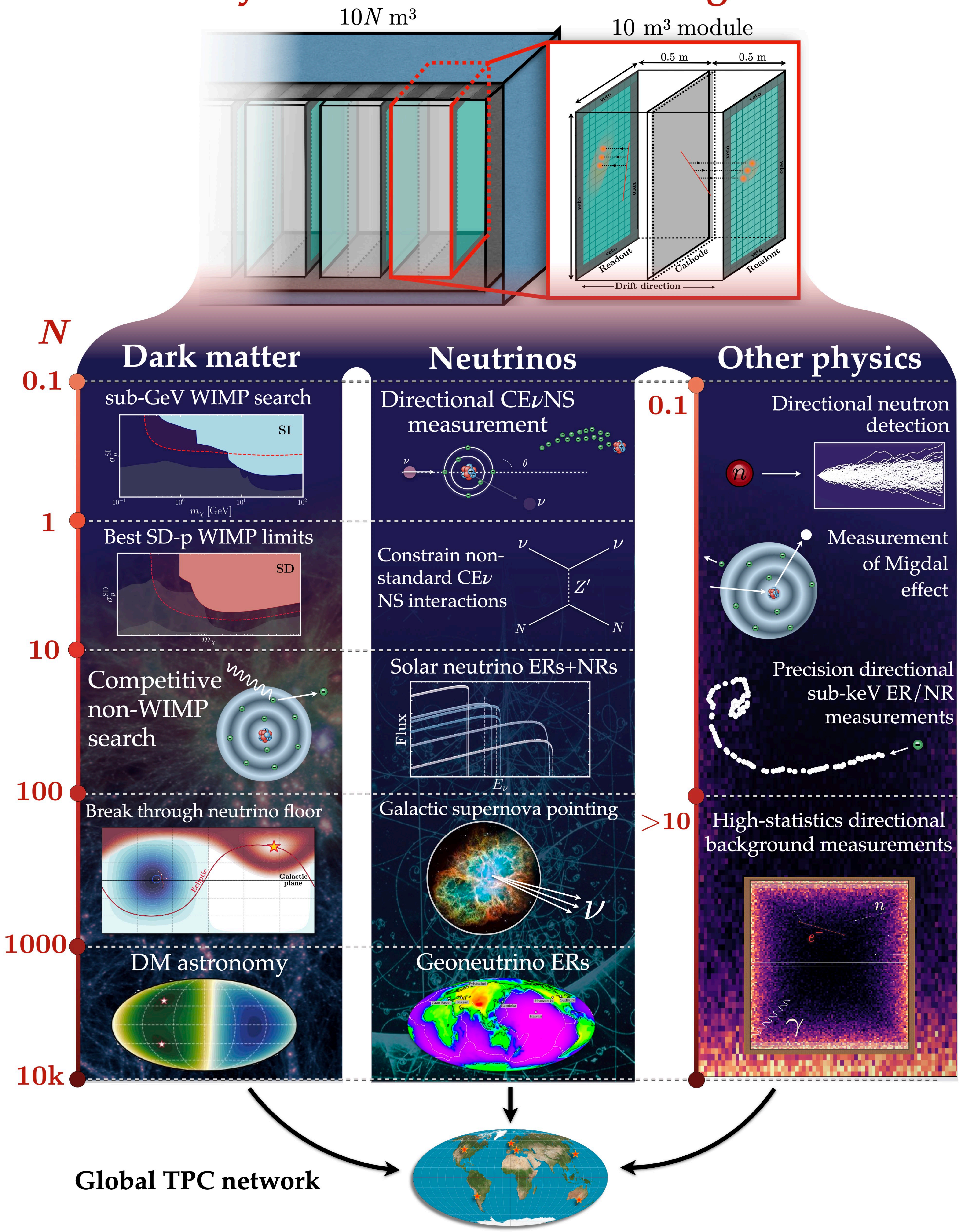
nuclear recoils, electron recoils, dark matter, neutrinos, gas time projection chambers, Migdal effect

Abstract

Searches for dark matter-induced recoils have made impressive advances in the last few years. Yet the field is confronted by several outstanding problems. First, the inevitable background of solar neutrinos will soon inhibit the conclusive identification of many dark matter models. Second, and more fundamentally, current experiments have no practical way of confirming a detected signal's galactic origin. The concept of directional detection addresses both of these issues while offering opportunities to study novel dark matter and neutrino-related physics. The concept remains experimentally challenging, but gas time projection chambers are an increasingly attractive option, and when properly configured, would allow directional measurements of both nuclear and electron recoils. In this review, we reassess the required detector performance and survey relevant technologies. Fortuitously, the highly-segmented detectors required to achieve good directionality also enable several fundamental and applied physics measurements. We comment on near-term challenges and how the field could be advanced.

Physics case for a directional gas TPC



Ways in which dark matter experiments might fail

(Even if we guess the right model!)

1. DM couplings are so small that they would require impractically large and/or sensitive experiments to ever measure

    Solution → 🤷‍♂️

2. There is no dark matter around the Earth to detect

    Solution → Indirect detection?

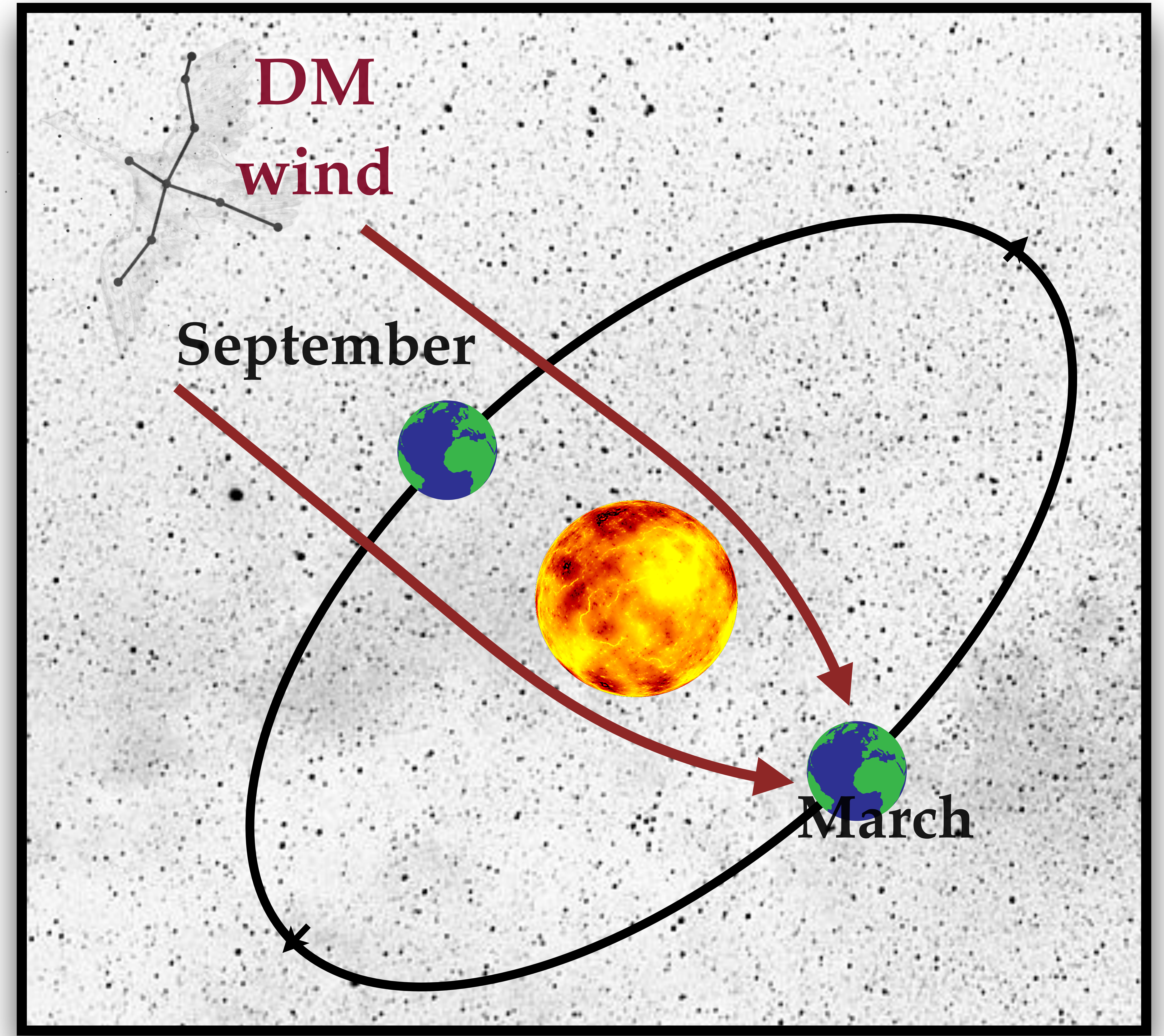
3. The experiment cannot "confirm" any signal as dark matter

    Solution → Directional searches

Summary

1. Dark matter experiments could fail.

Gravitational focusing



~2% modulation in DM density
→ seems to not be practical