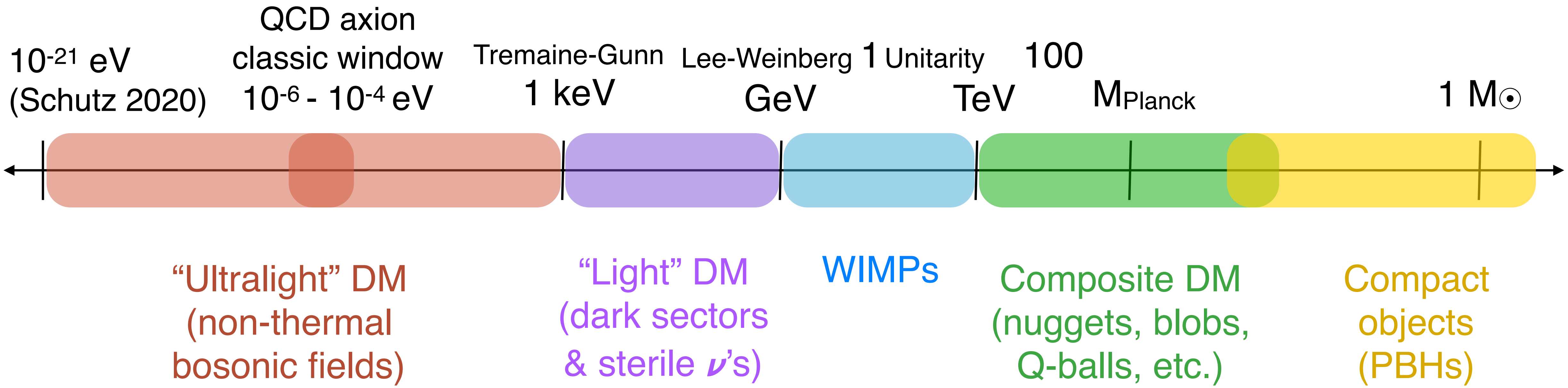
ASTROPHYSICAL HANDLES ON SEARCHES FOR NEW PARTICLES

Katelin Schutz, McGill University
Brookhaven High Energy Theory Seminar
April 7th, 2022

THEORIES OF DARK SECTORS ARE INCREDIBLY DIVERSE

DARK MATTER MASS

(not to scale)



10^{-21} eV
(Schutz 2020)

QCD axion
classic window
10^{-6} - 10^{-4} eV

Tremaine-Gunn
1 keV

Lee-Weinberg 1
GeV

Unitarity
100
TeV

M_{Planck}

1 $M_{\odot}$

"Ultralight" DM
(non-thermal
bosonic fields)

"Light" DM
(dark sectors
& sterile ν's)

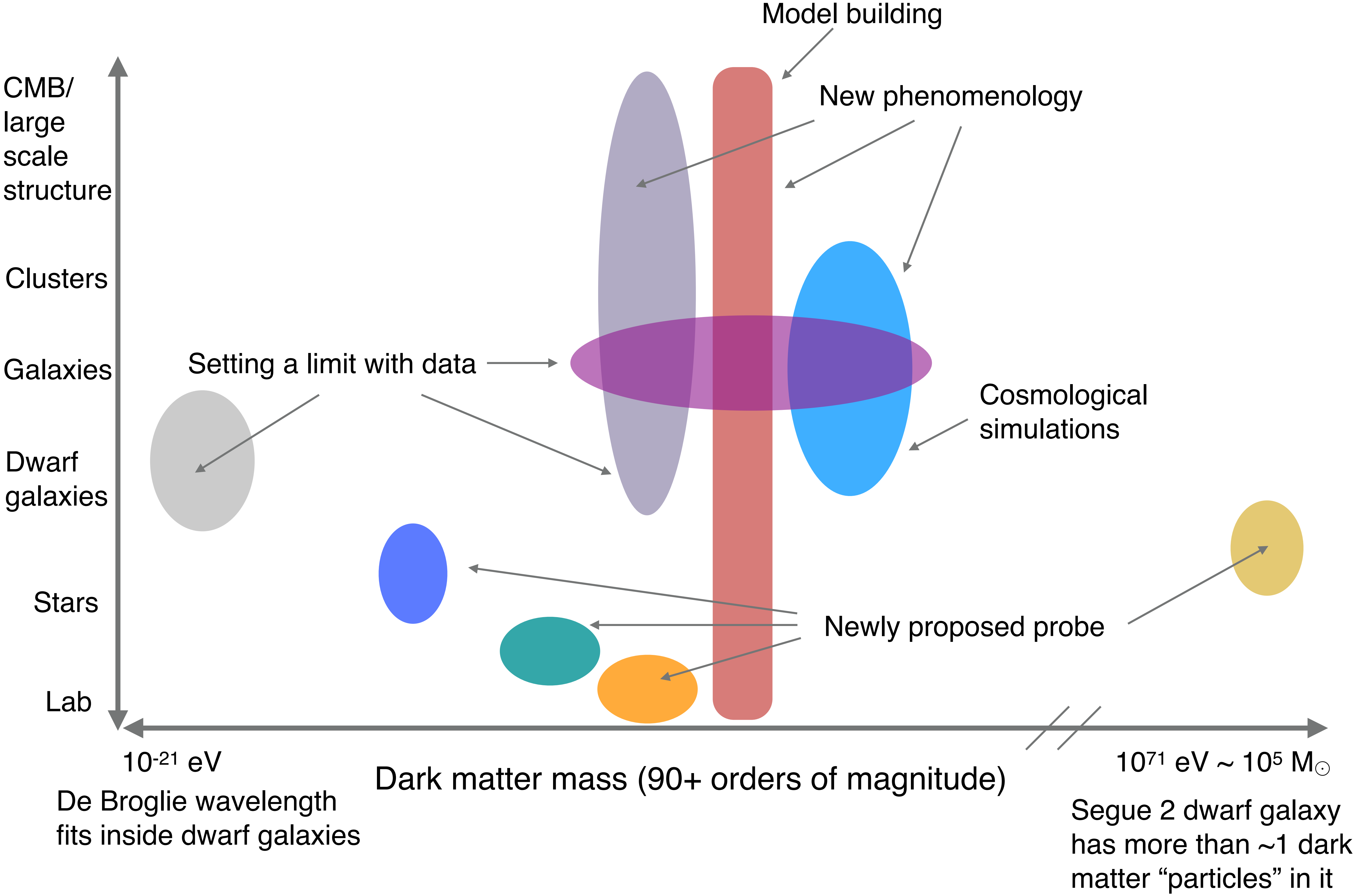
WIMPs

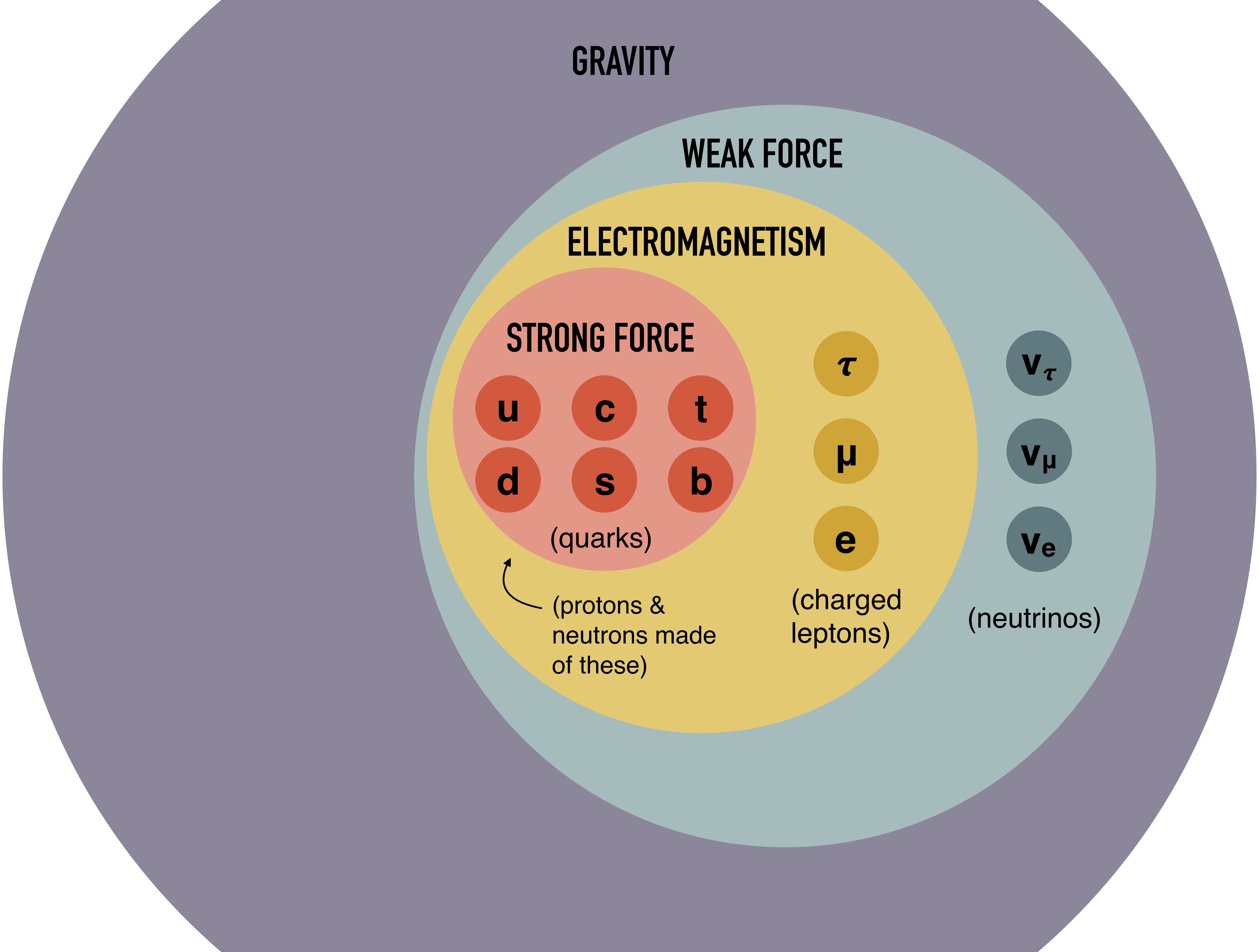
Composite DM
(nuggets, blobs,
Q-balls, etc.)

Compact
objects
(PBHs)

- Many possibilities spanning 90+ orders of magnitude!

Scale where we can test theories

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ELECTROMAGNETISM
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(protons & neutrons made of these)
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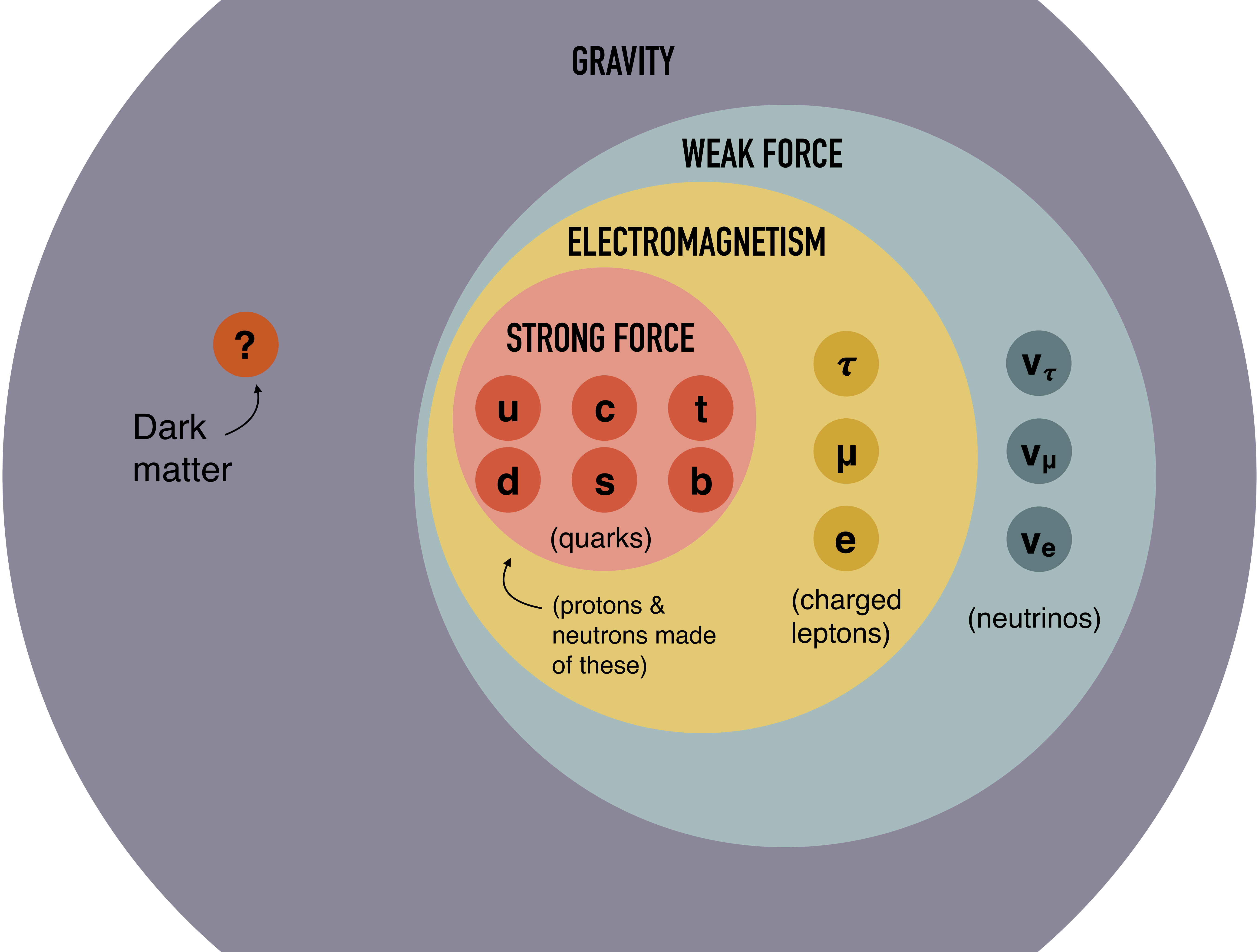
(neutrinos)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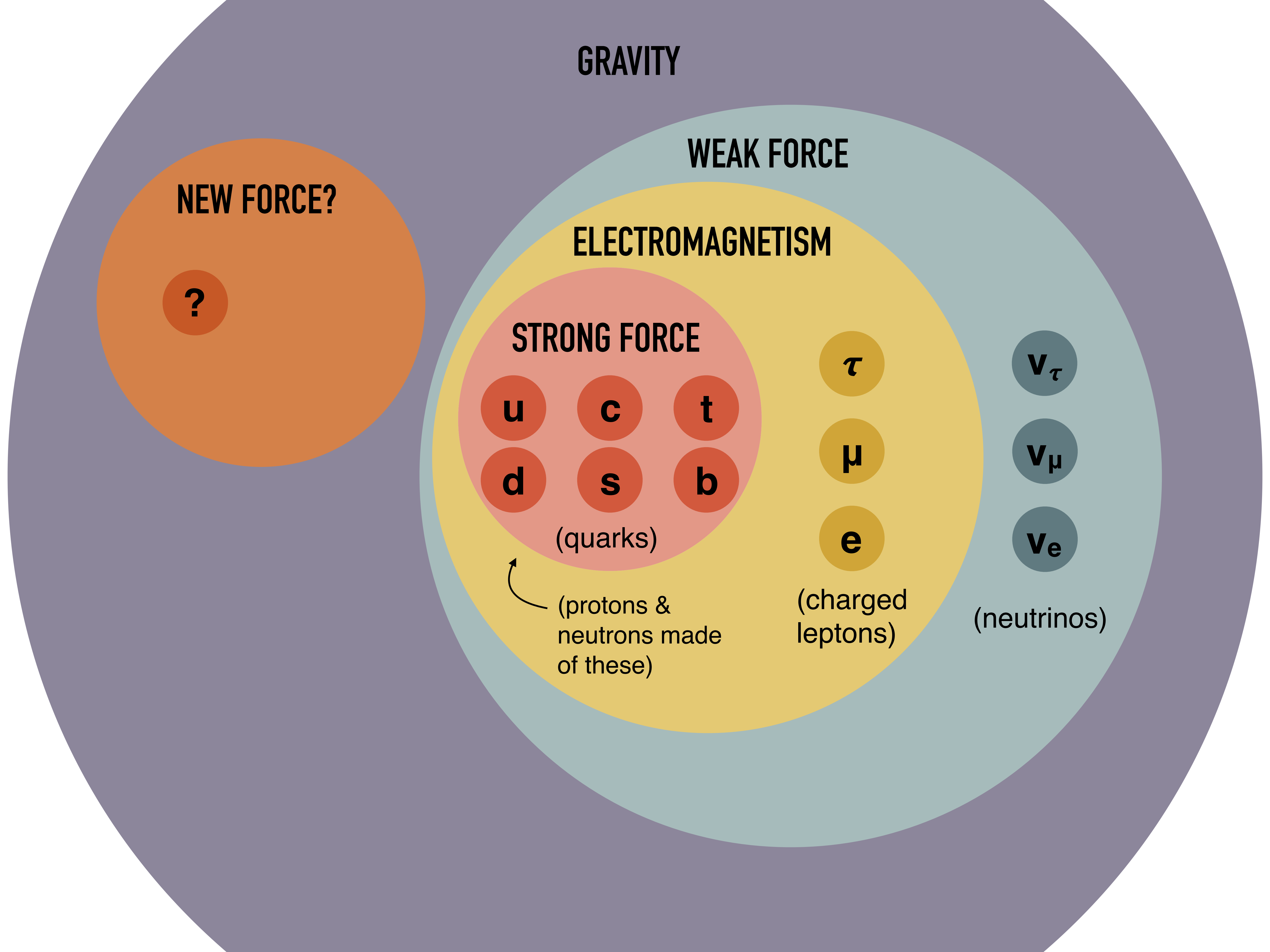
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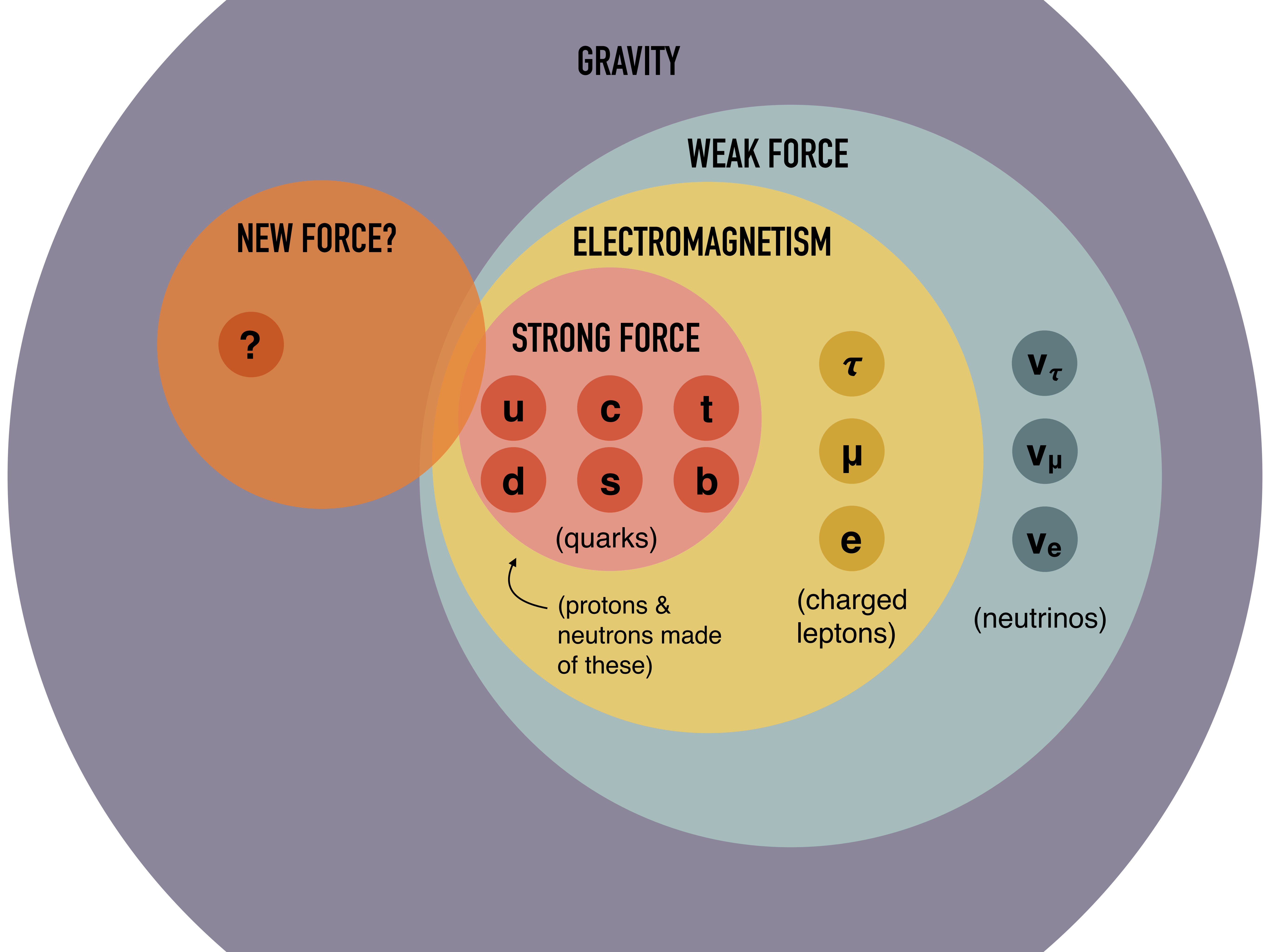
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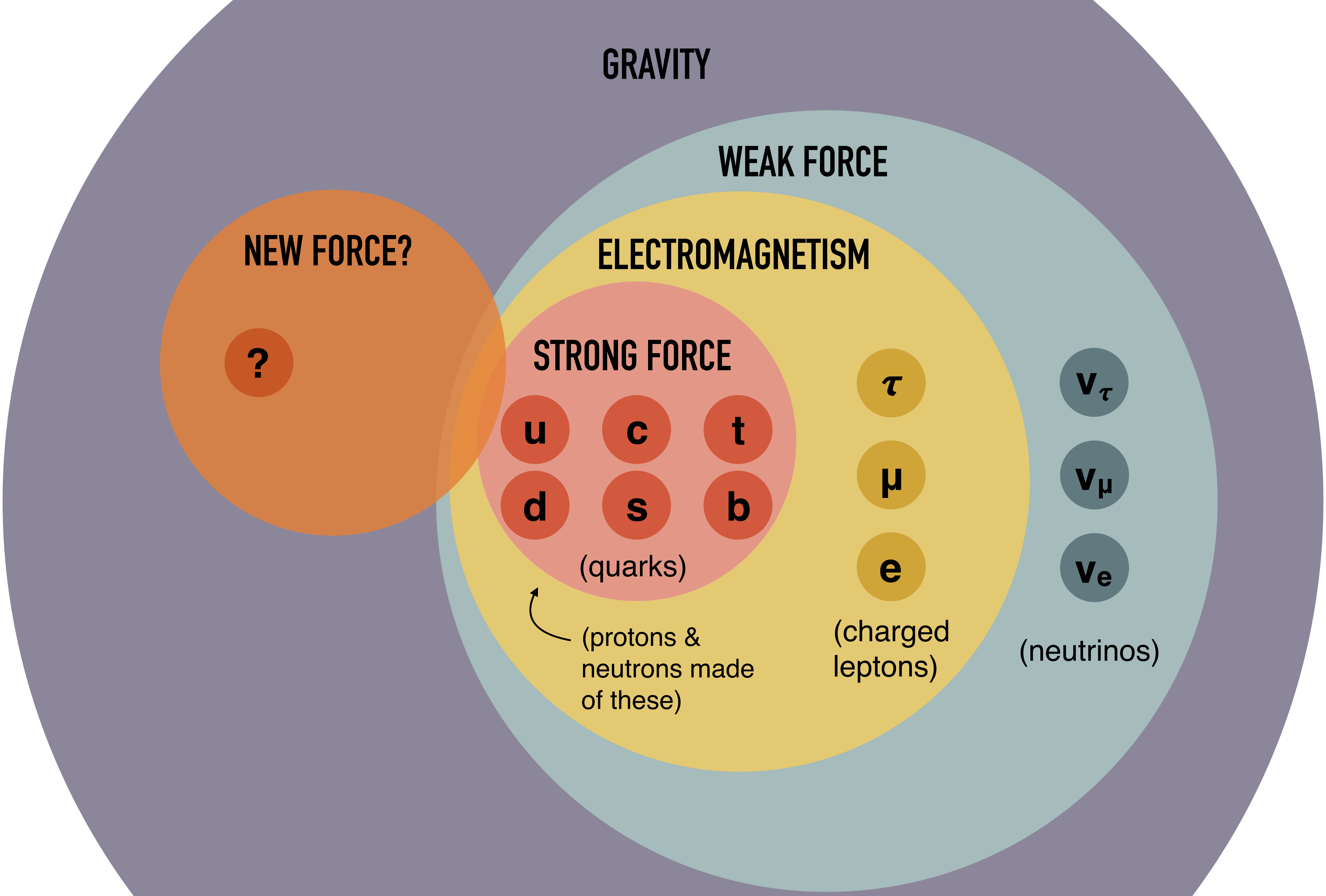
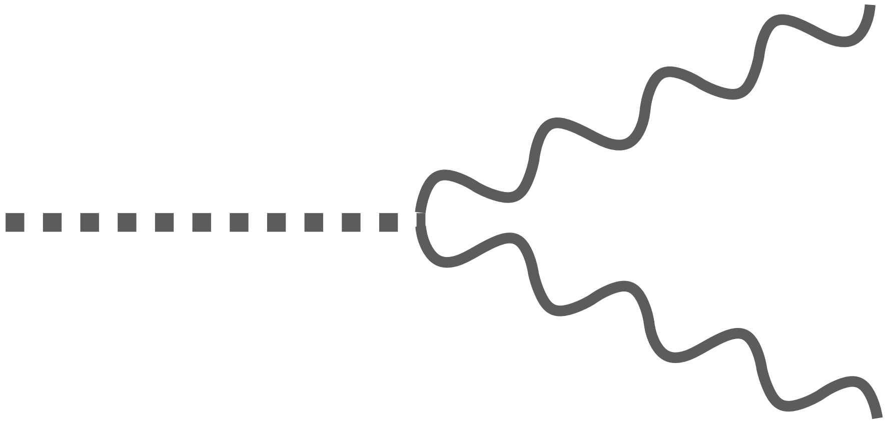


TODAY: TWO EXAMPLES OF DARK–VISIBLE INTERACTIONS IN ASTROPHYSICS

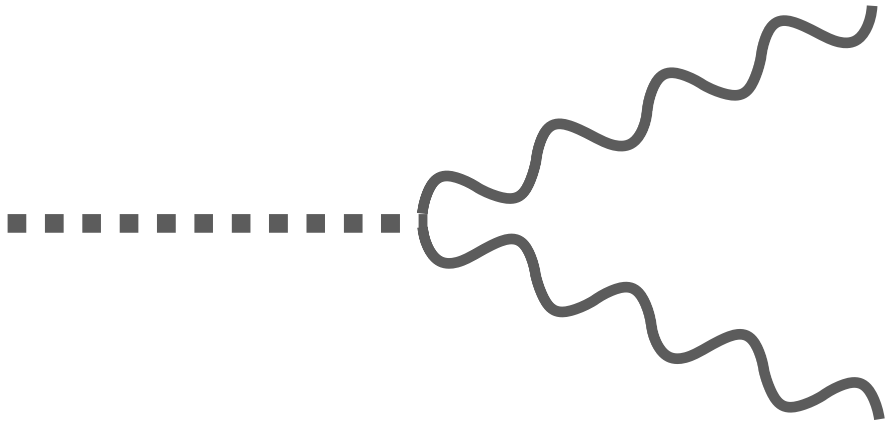
ONE EXAMPLE: AXION DARK MATTER

AXION COUPLING TO PHOTONS



$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\, (\overrightarrow{E} \cdot \overrightarrow{B})$$

AXION COUPLING TO PHOTONS



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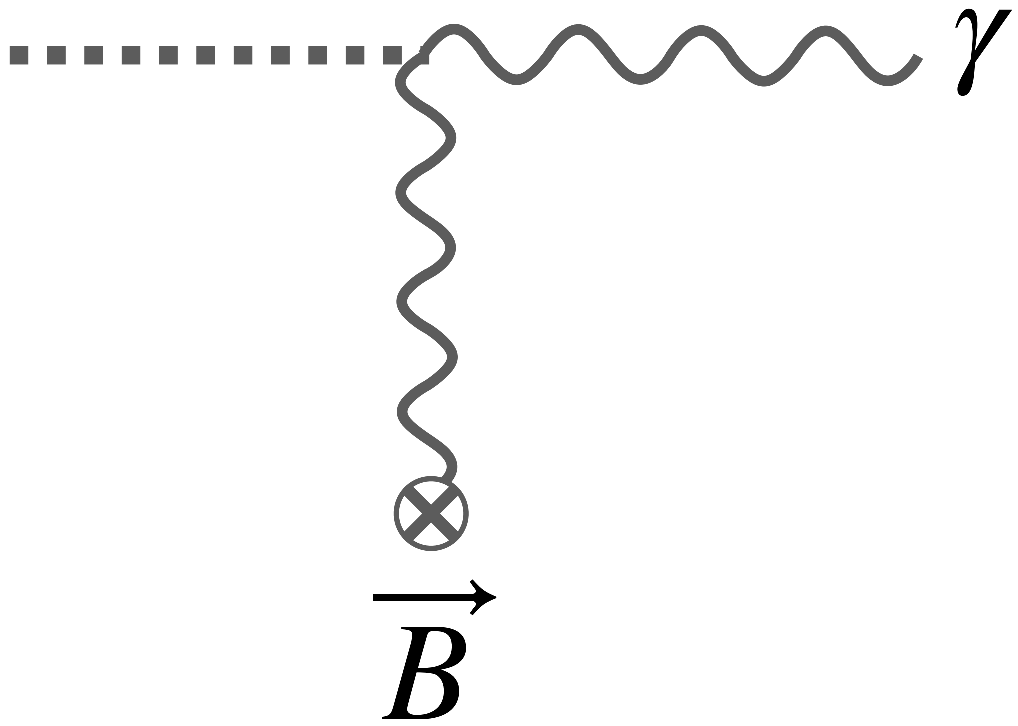
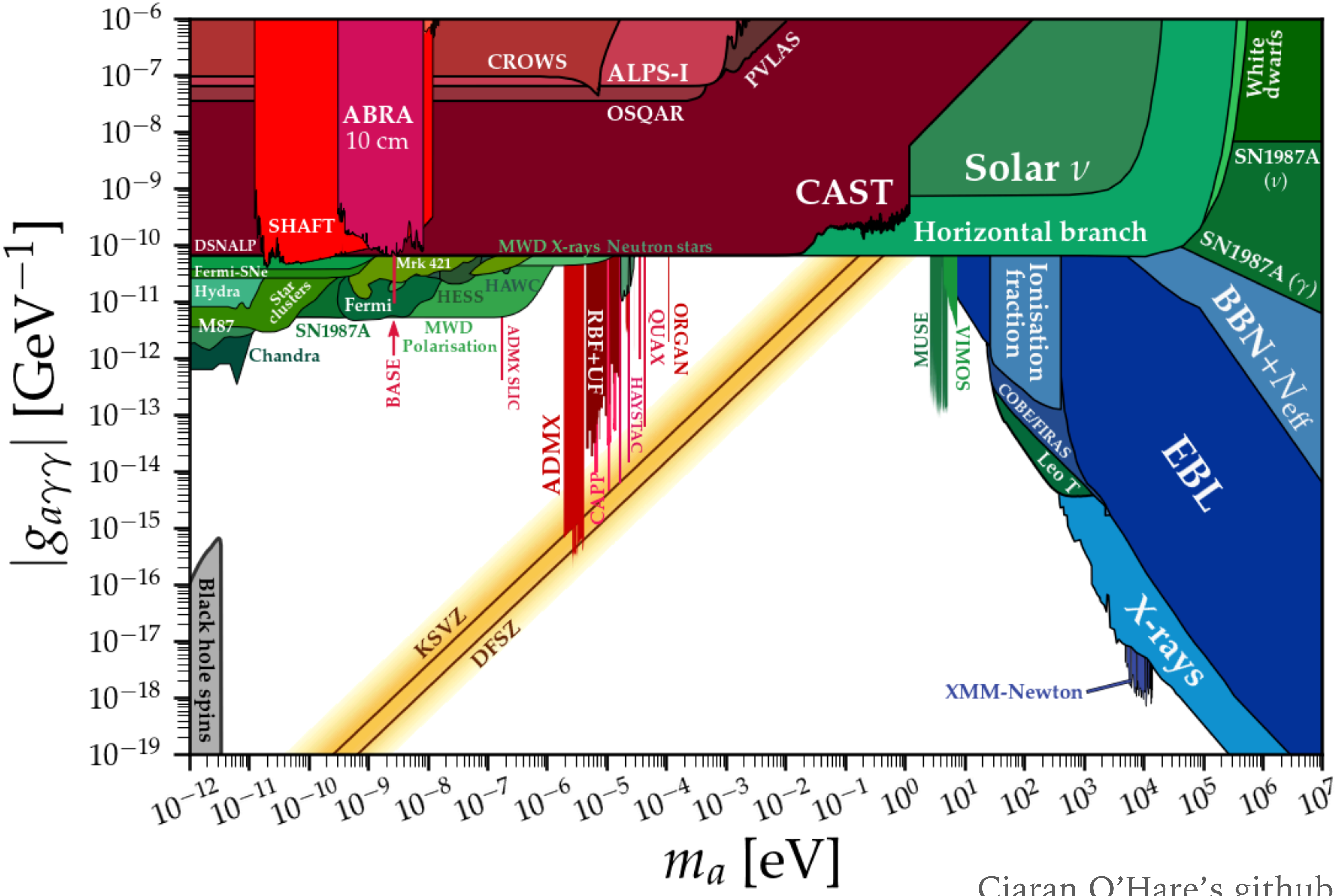


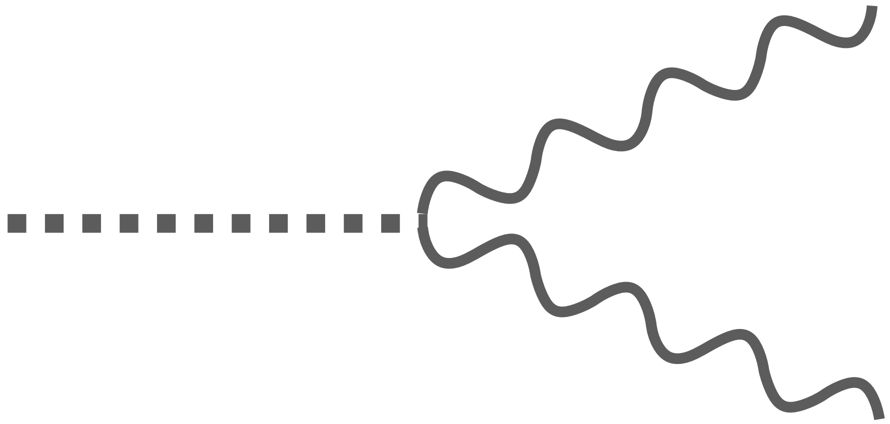
Primakoff process: can be leveraged in terrestrial experiments (e.g. resonant cavities) and astrophysical systems (e.g. neutron star magnetospheres)

AXION COUPLING TO PHOTONS



Ciaran O'Hare's github

AXION SPONTANEOUS DECAY



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Axions can decay to two photons, spontaneously or through stimulated decay

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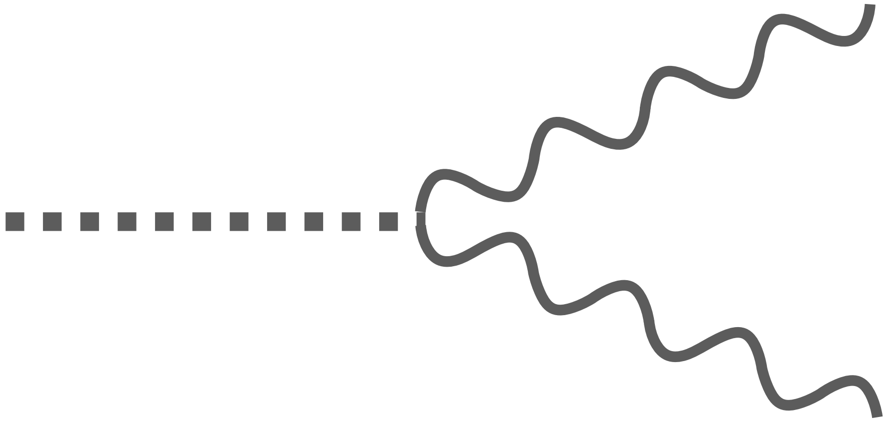

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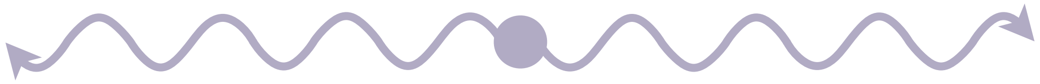
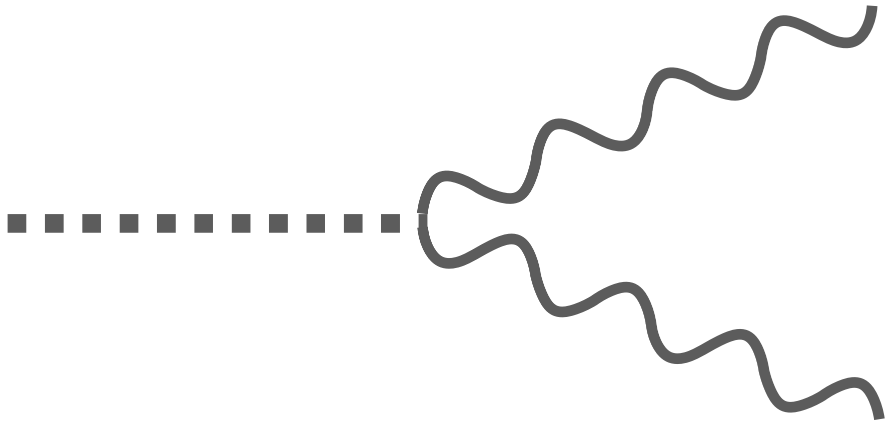


$\omega = m_a/2$ in axion rest frame

$$\tau = \frac{64\pi}{m_a^3\, g_{a\gamma\gamma}^2} \sim 4 \times 10^{35}\,\mathrm{yr}\left(\frac{m_a}{\mu\mathrm{eV}}\right)^{-3}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^{-2}$$

AXION STIMULATED DECAY



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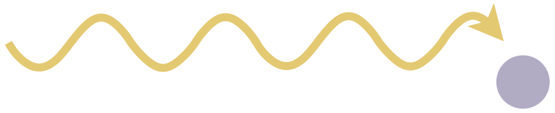
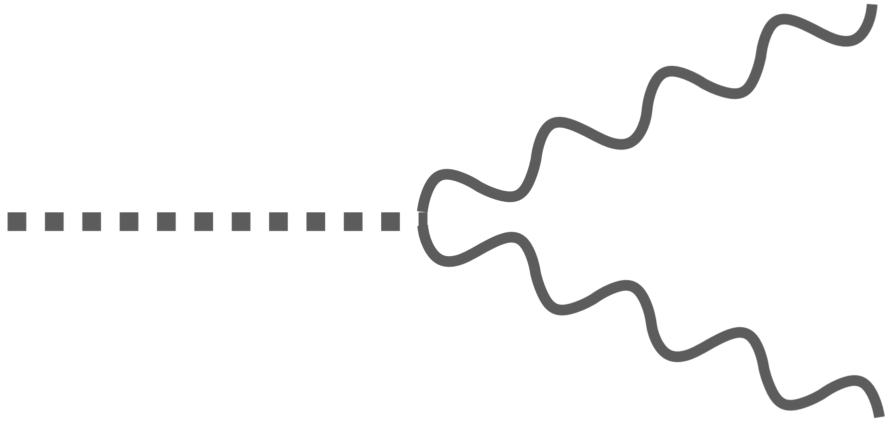


$\omega = m_a/2$ in axion rest frame

e.g. Arza & Sikivie (2019)

AXION STIMULATED DECAY



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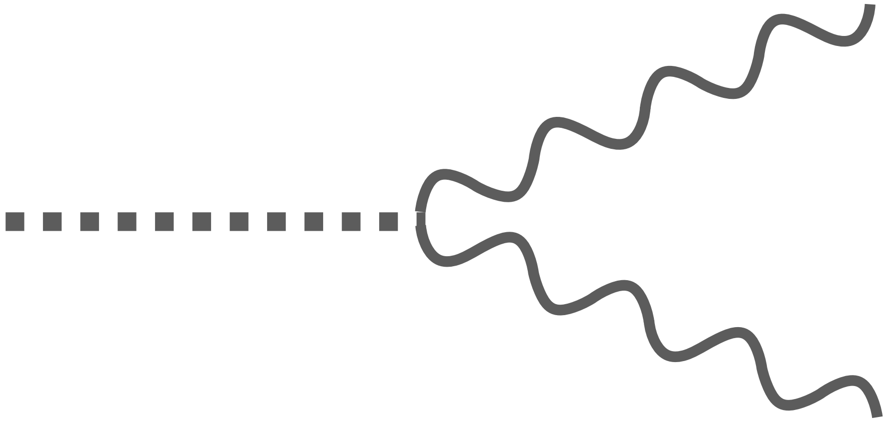

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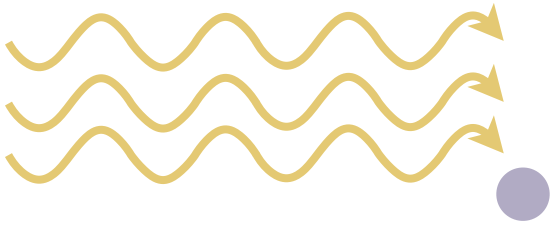
This is Bose enhanced



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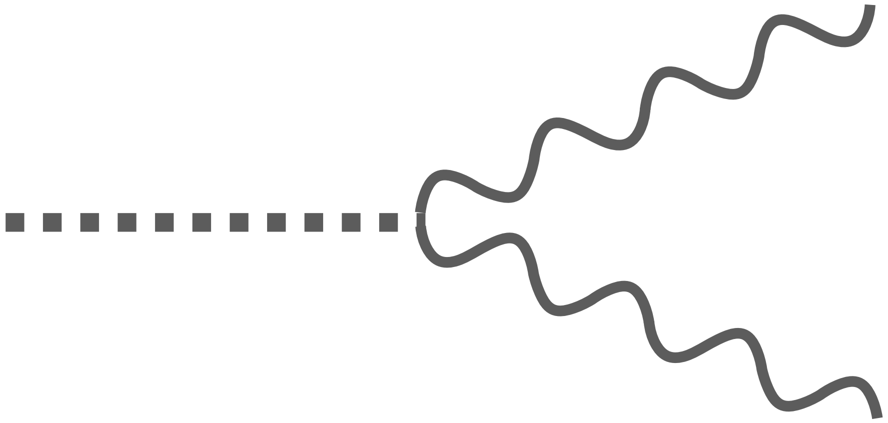

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Axions can decay to two photons, spontaneously or through stimulated decay

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$$S_{\text{out}} \sim \left.\frac{dS_{\text{in}}}{d\omega}\right|_{\omega=m_a/2}$$

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e.g. Arza & Sikivie (2019)

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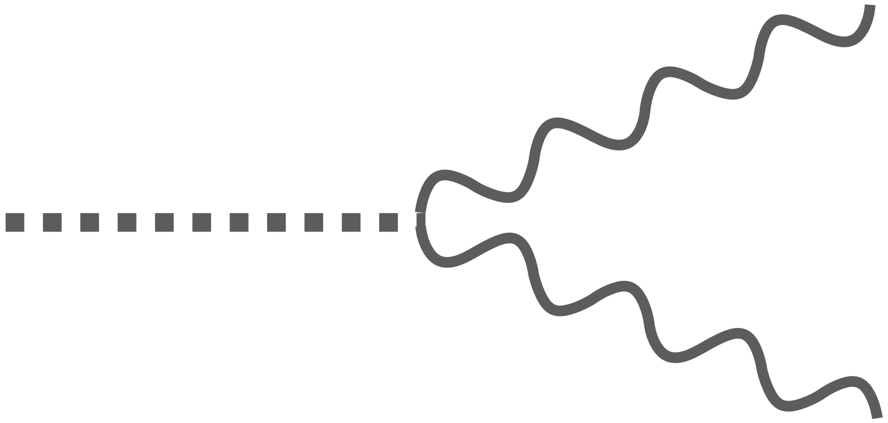

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Along axion column, flux of decay products

$$S_{\text{out}} = \frac{g_{a\gamma\gamma}^2}{16}\left.\frac{dS_{\text{in}}}{d\omega}\right|_{m_a/2}\int \rho_a\,dx$$

e.g. Arza & Sikivie (2019)

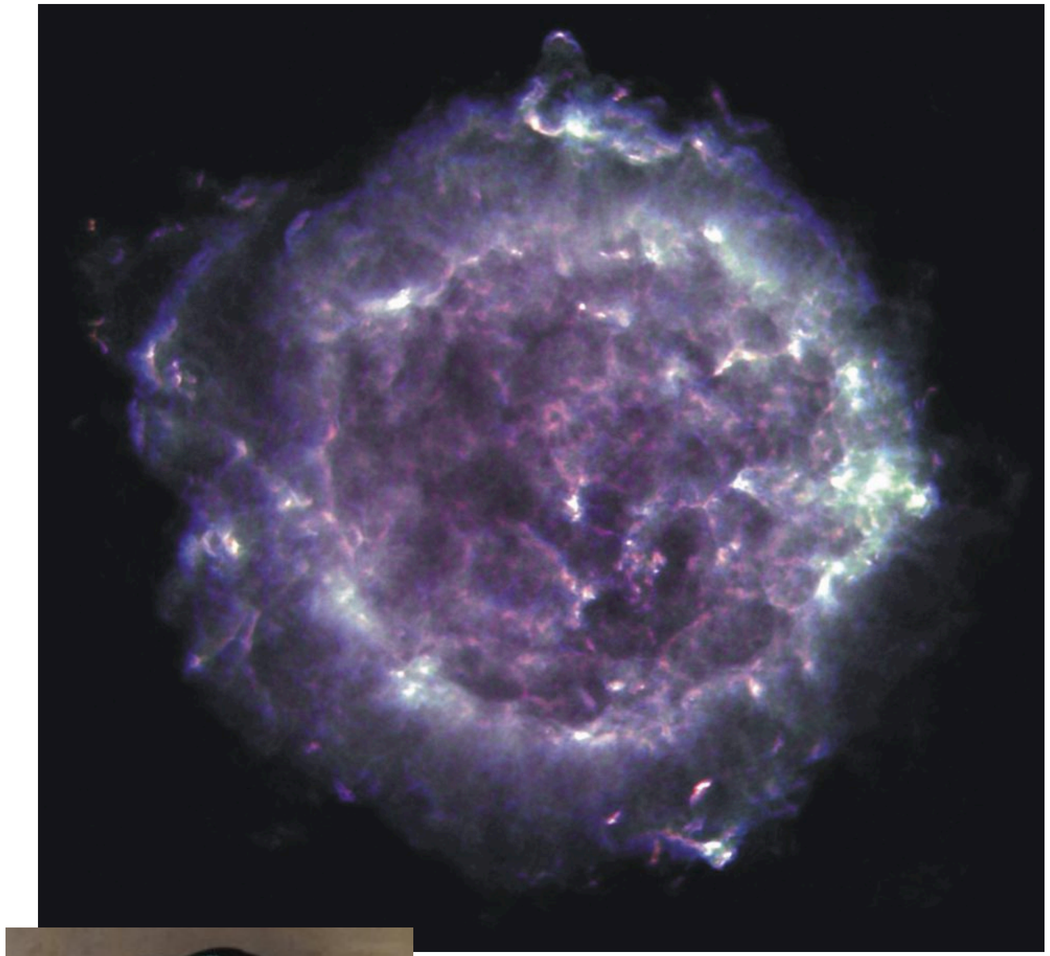
THE UPSHOT:

AXIONS ARE AN IMPERFECT MONOCHROMATIC MIRROR

“AXION GEGENSCHEIN”

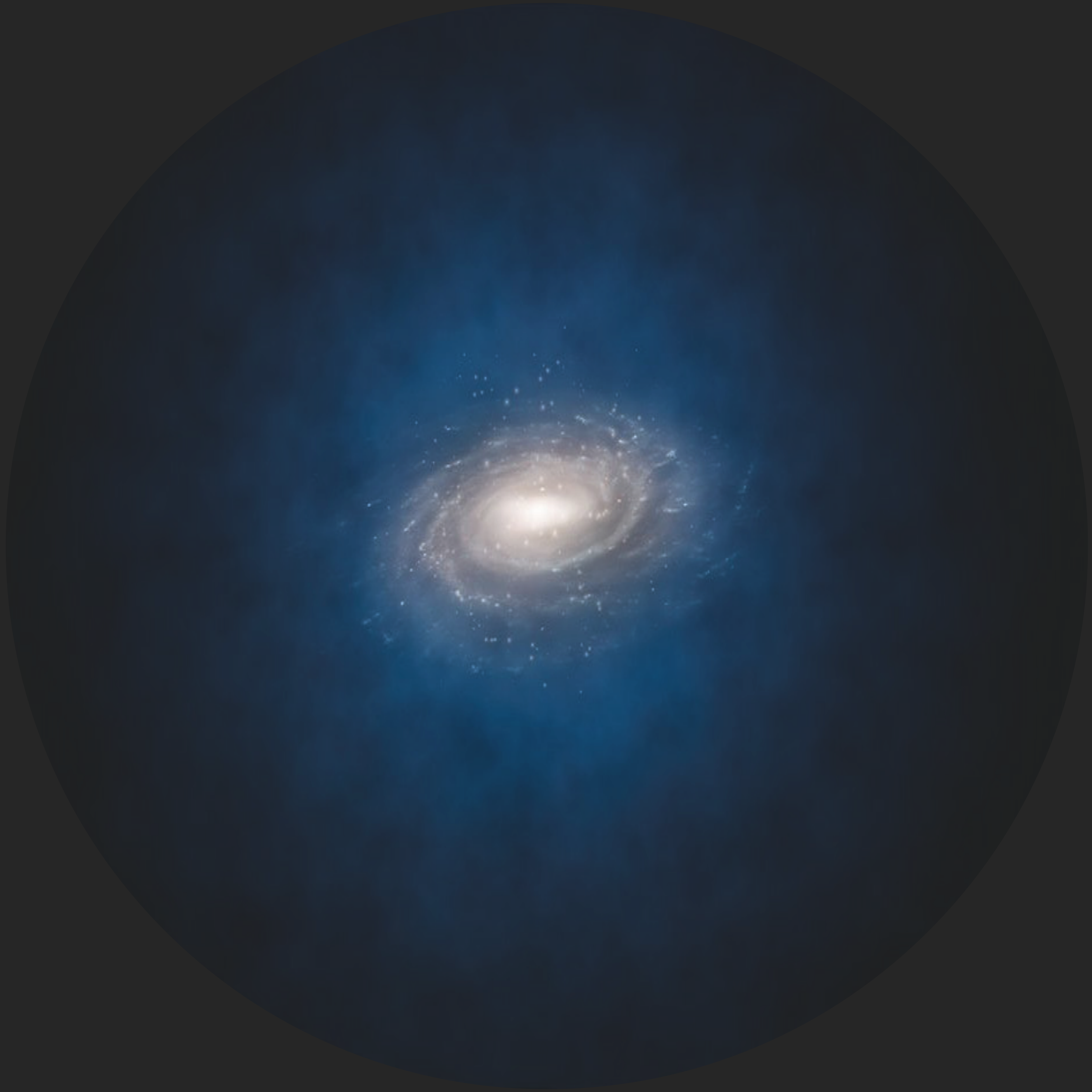
PROGRESS ON AXION GEGENSCHEIN

- You could generate stimulating radiation, e.g. shoot a beam of radiation to space and see if there is an echo (Arza & Sikivie 2019)
- Alternatively, you could use existing radiation from astrophysical sources!
- Previous work by Ghosh et al. considered idealized sources (radio galaxies like Cygnus A) that are in the limit where they are pointlike, infinitely far and have a flux that is constant on light-crossing timescale of Milky Way
- In work led by MIT graduate student Yitian Sun we initially wanted to generalize this to other sources and see where it led us (ultimately, supernova remnants)



Sun, KS, et al. PRD (2022)

Axions as dark matter



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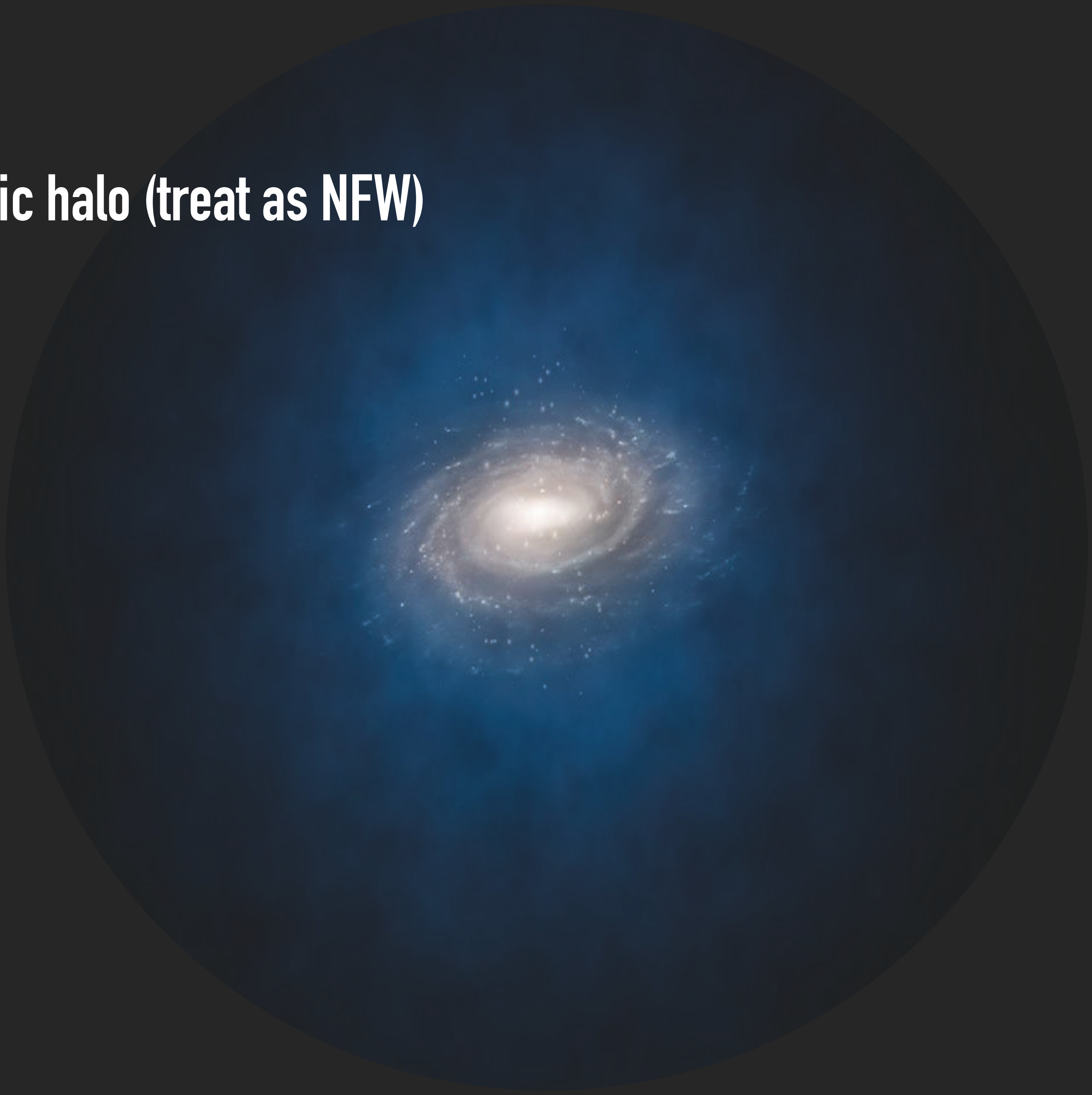
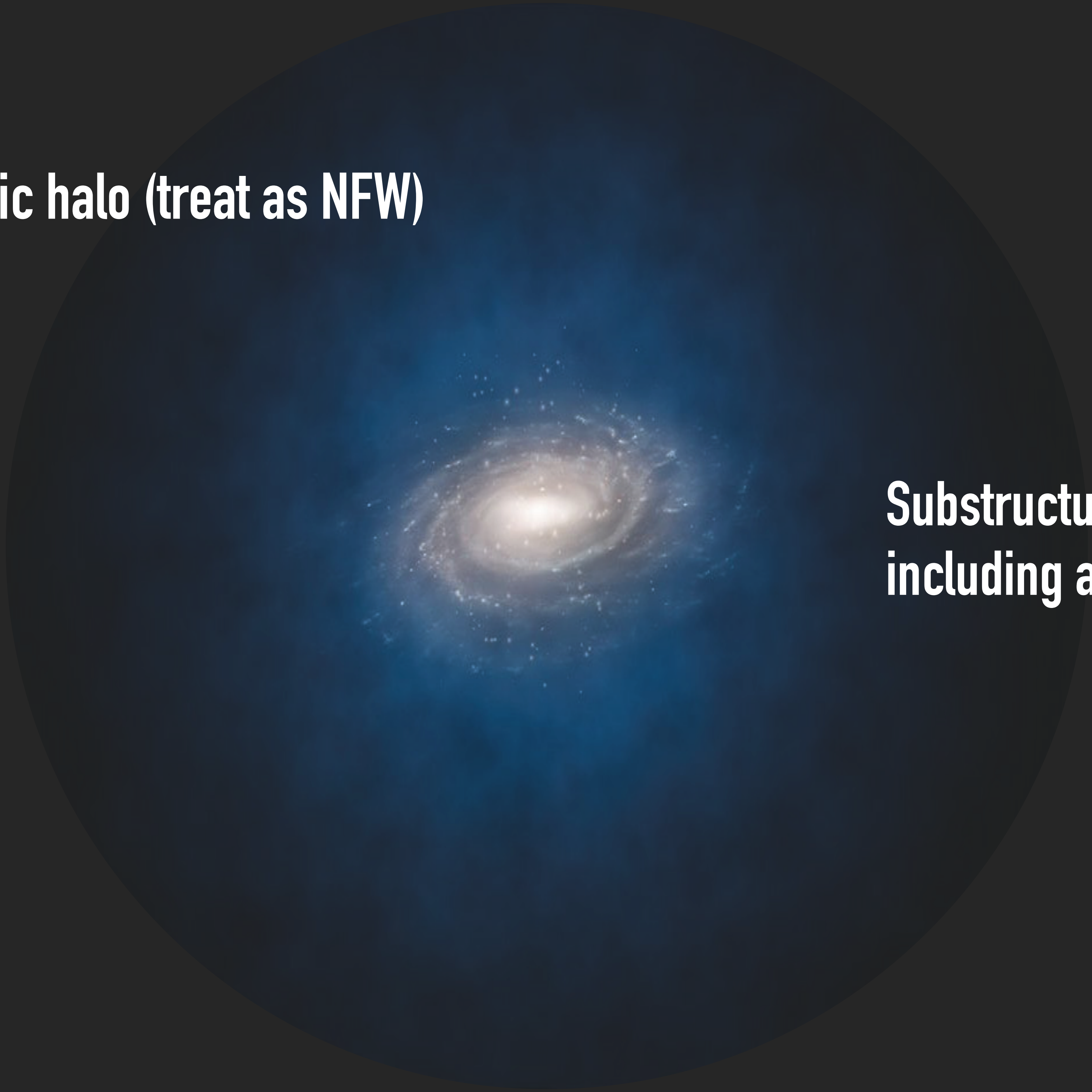


Galactic halo (treat as NFW)

Axions as dark matter



Galactic halo (treat as NFW)

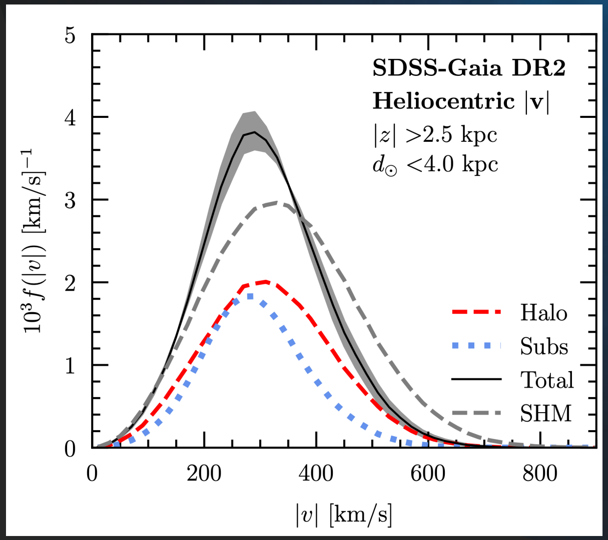
Substructure (possibly including axion mini-halos)

Axions as dark matter

Galactic halo (treat as NFW)

Substructure (possibly including axion mini-halos)

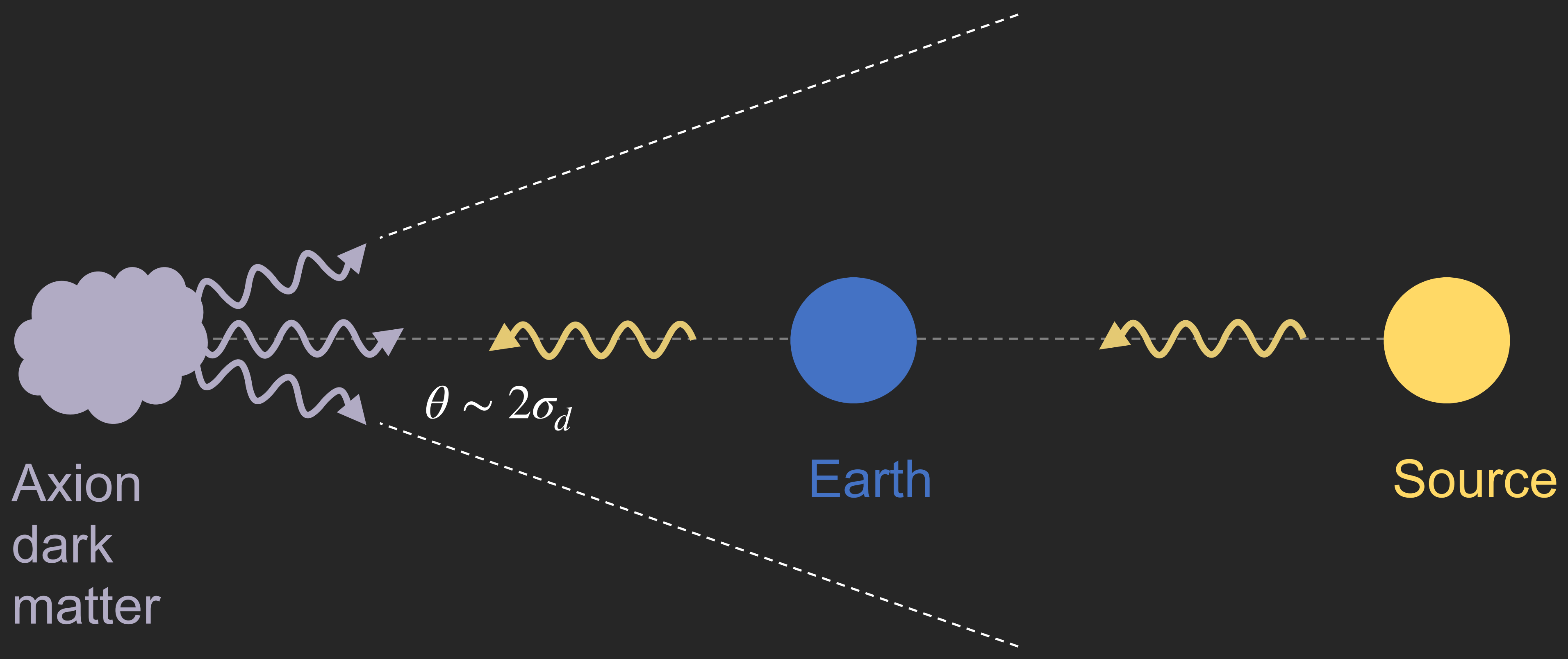
Velocity dispersion ~100 km/s near Earth



e.g. Necib et al. (2018)

Dispersion smears spectrally (Doppler effect) and spatially

Geometry of axion gegenschein



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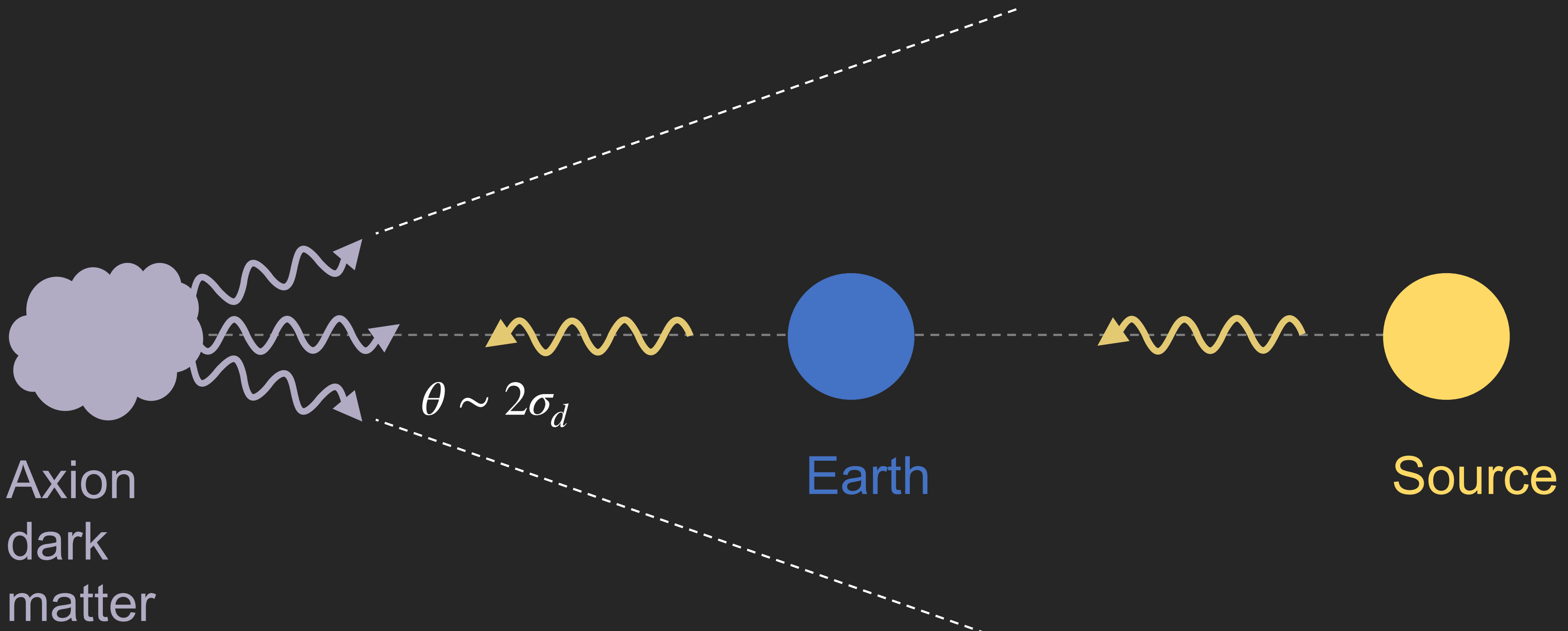
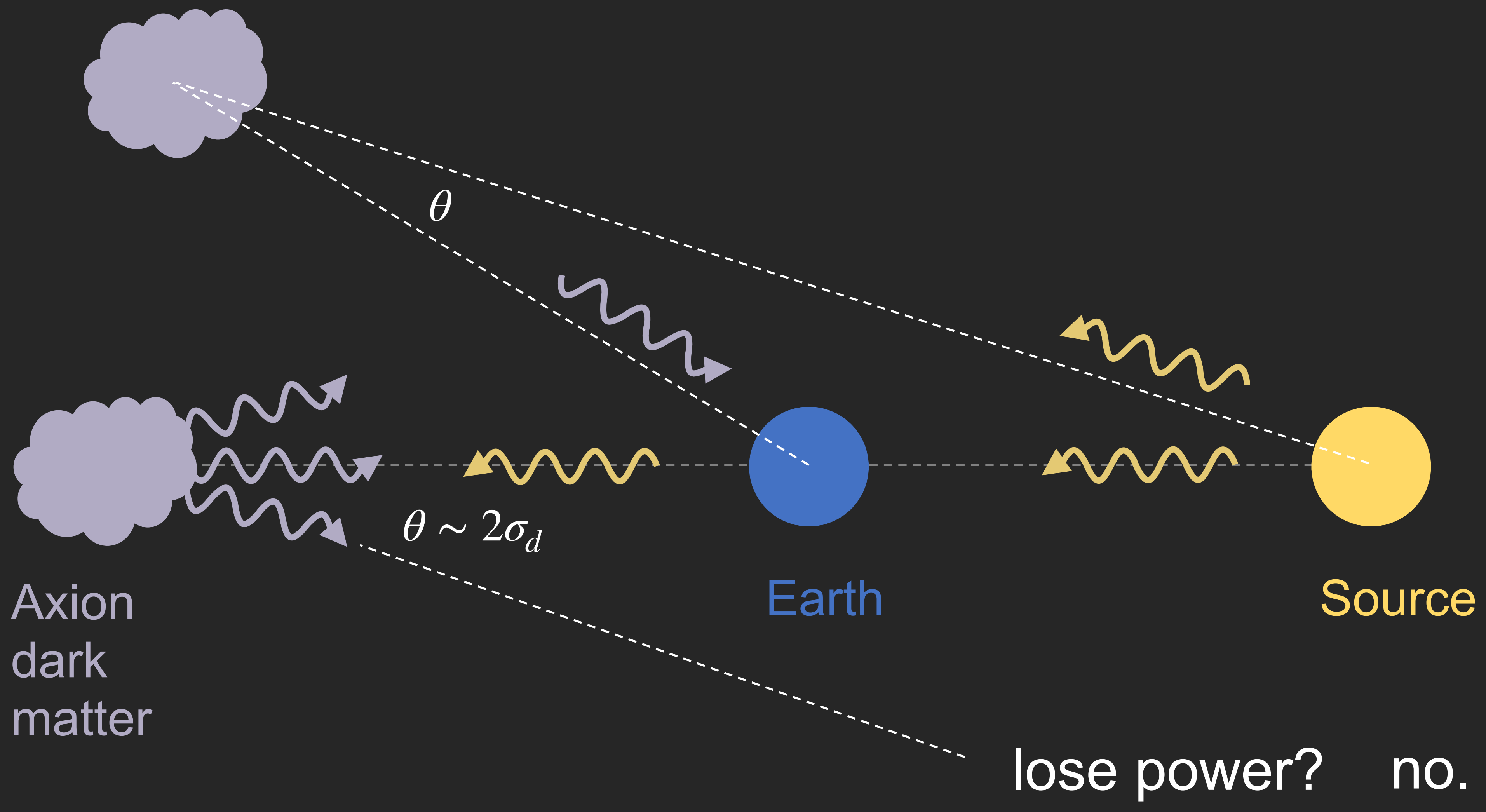


lose power? no.

Geometry of axion gegenschein



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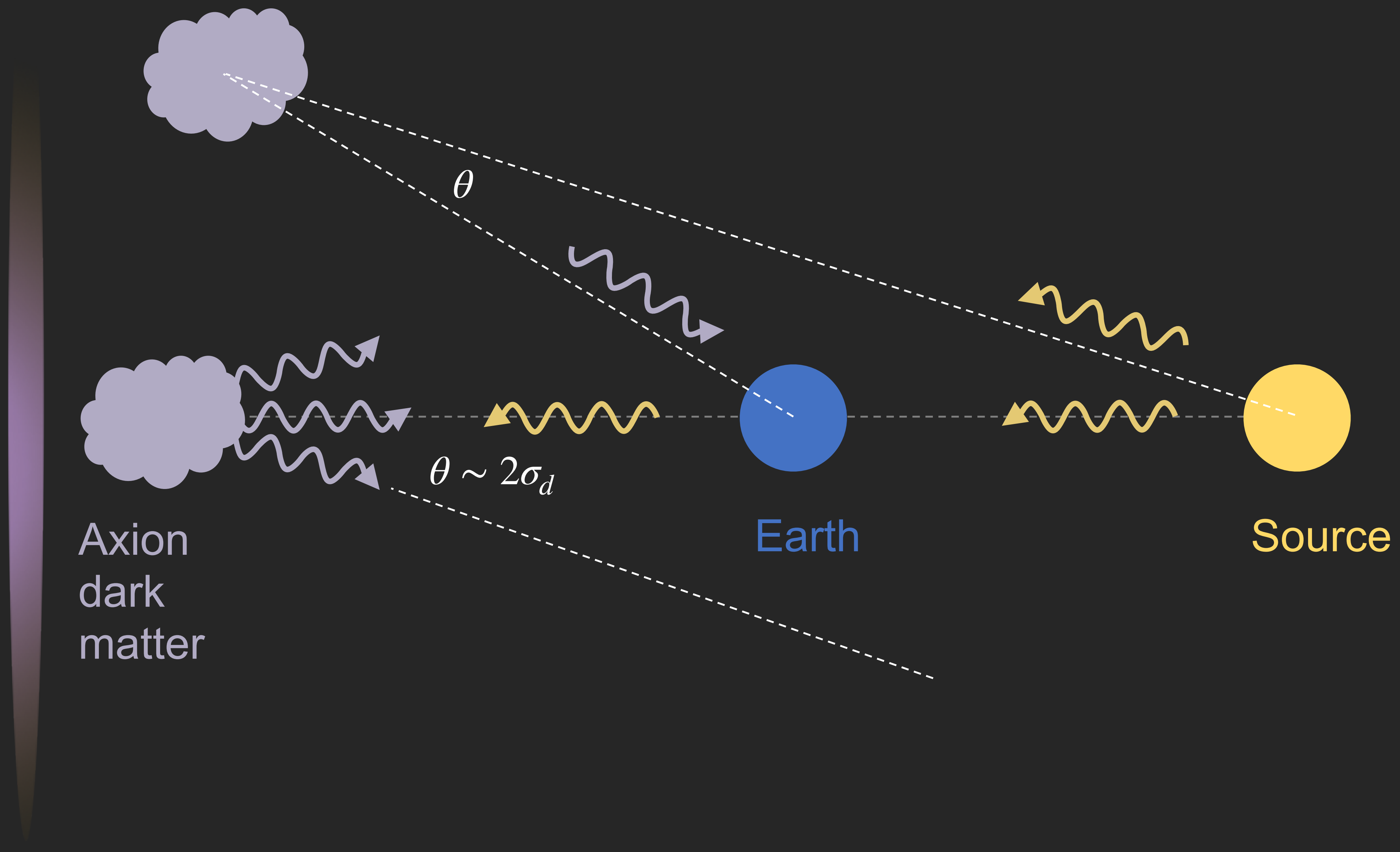
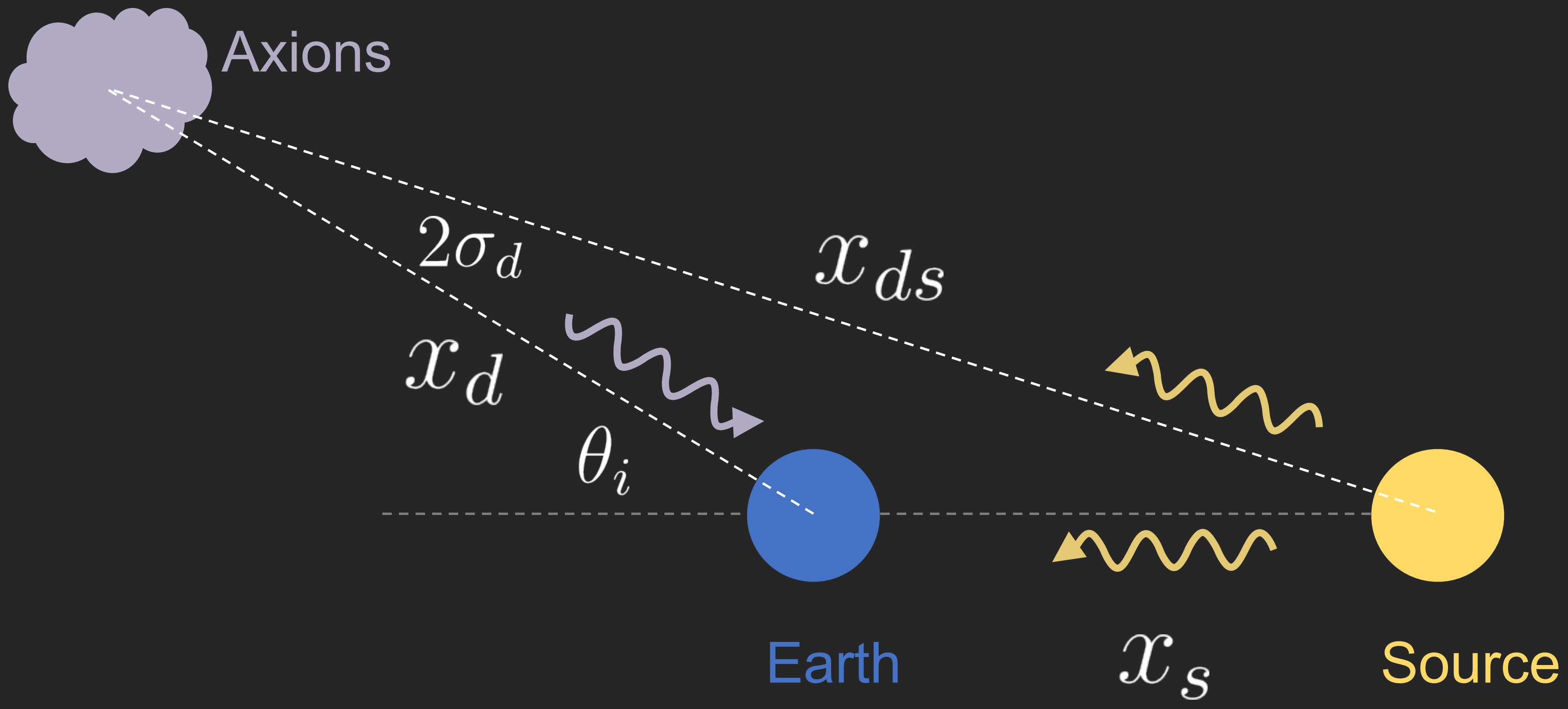
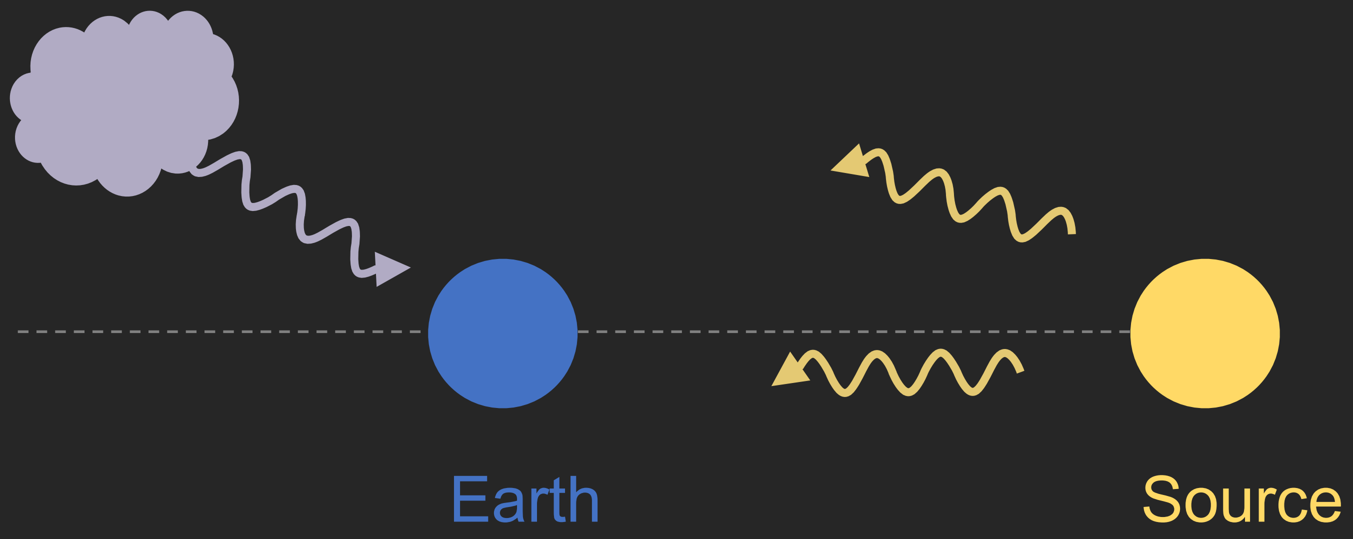




$$\sin\theta_i = \sin 2\sigma_d \, \frac{x_{ds}}{x_s}$$

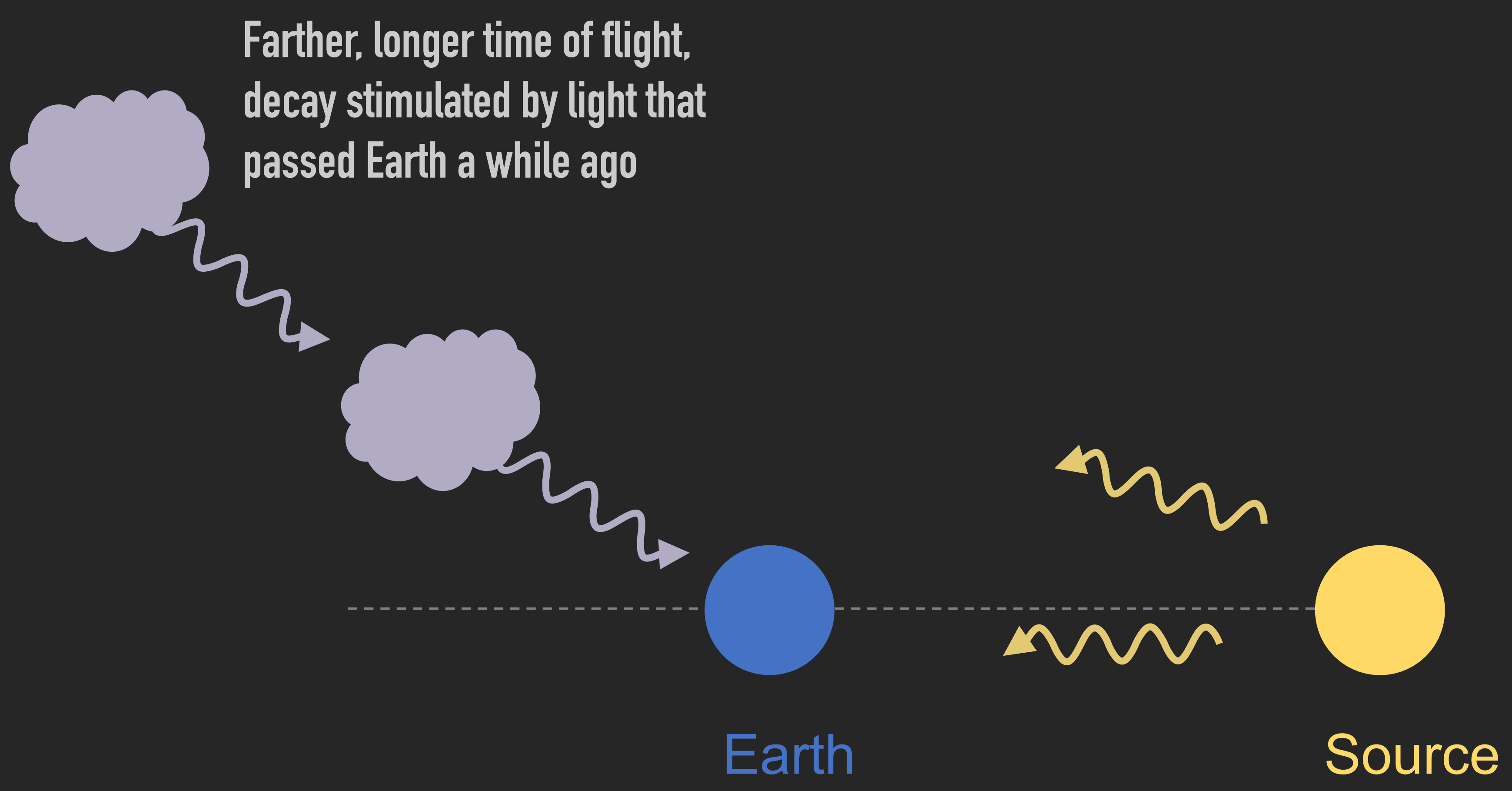
Closer sources imply more angular smearing, but dark matter distance isn't fixed (have to integrate along a column) so deeper in the column we get more smearing

Sun, KS, et al. PRD (2022)

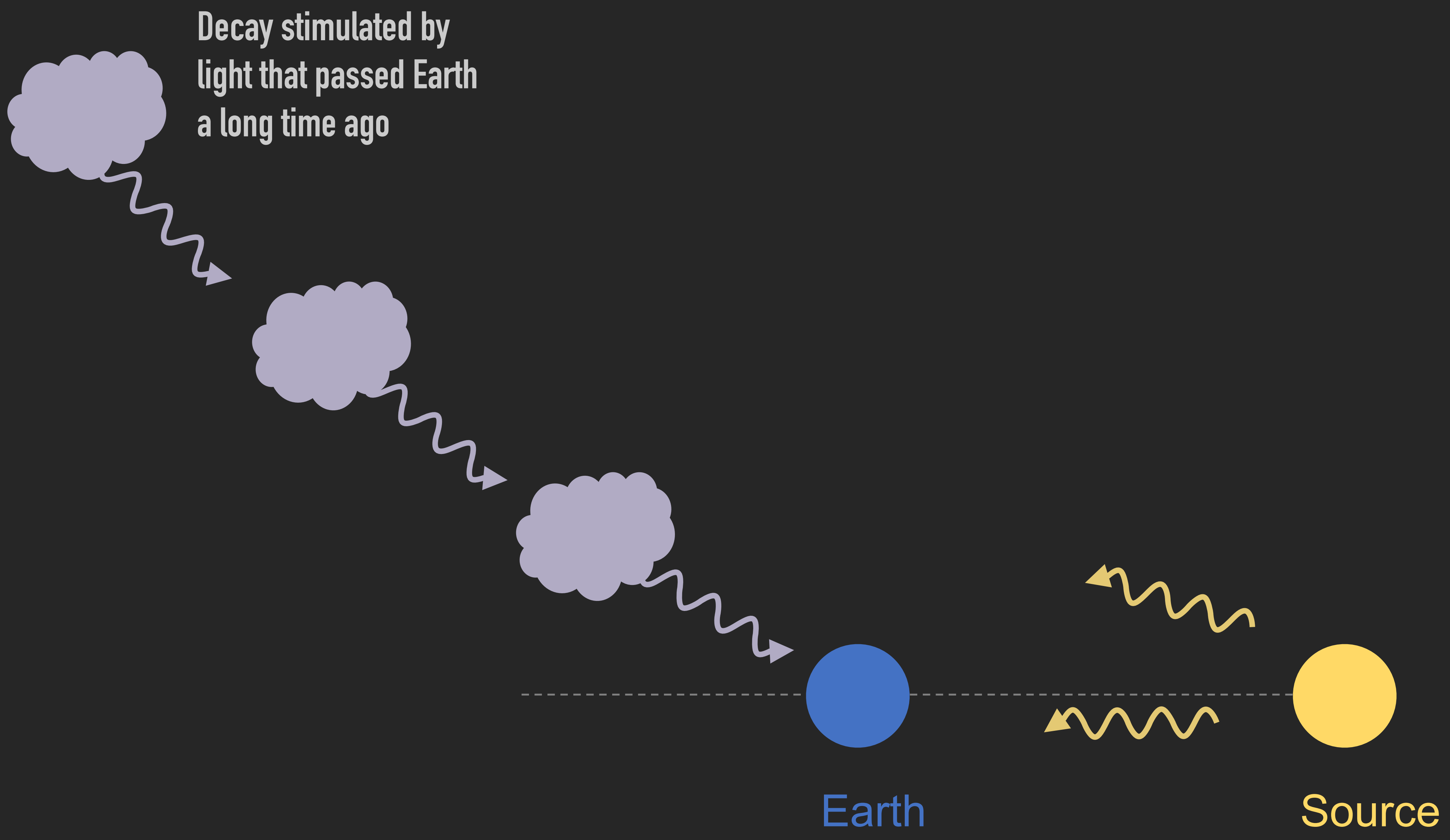


Nearby, short time of flight, decay stimulated by light that recently passed Earth

Sun, KS, et al. PRD (2022)


Farther, longer time of flight, decay stimulated by light that passed Earth a while ago

Sun, KS, et al. PRD (2022)



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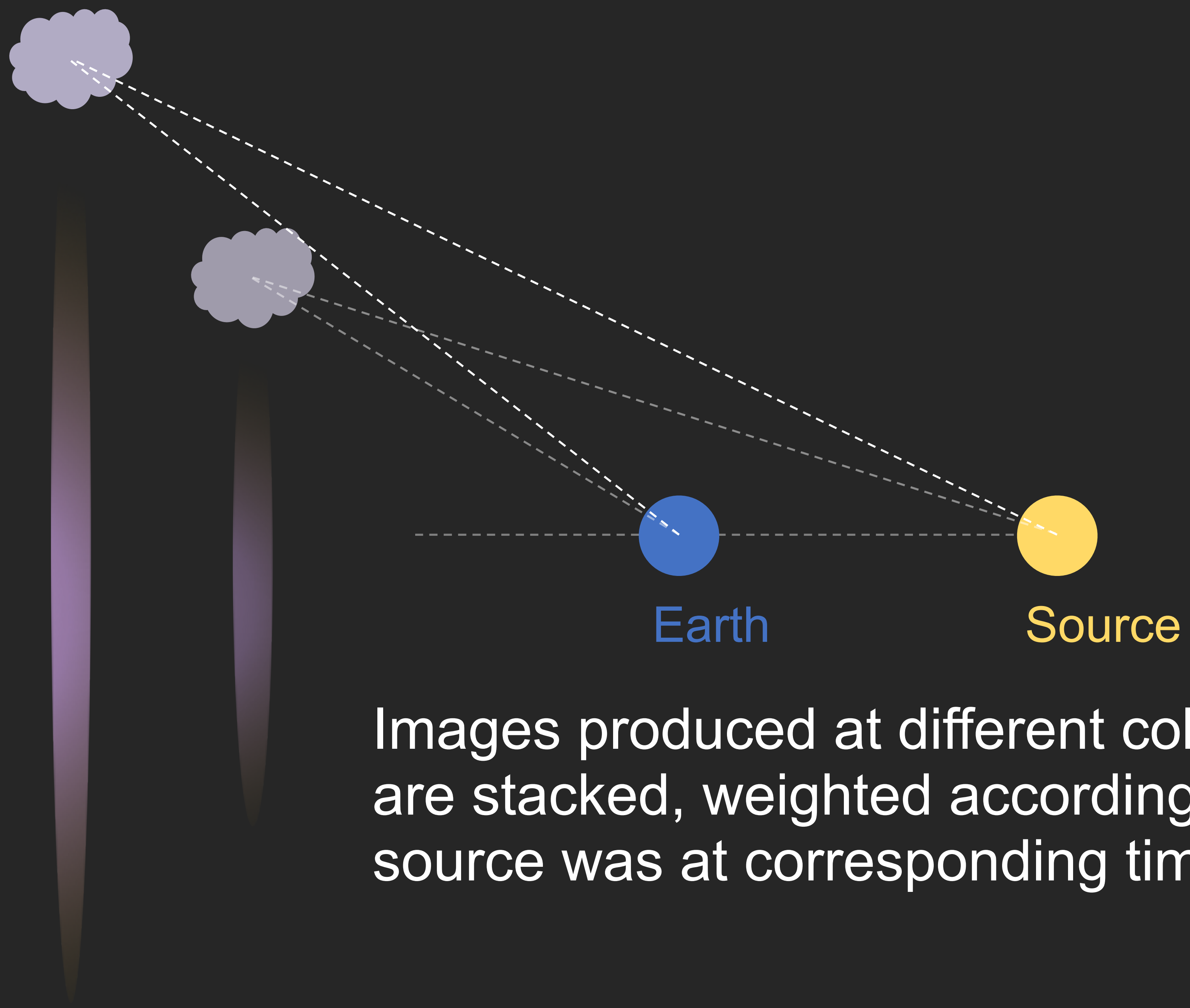


Images produced at different column depths are stacked, weighted according to how bright source was at corresponding time in the past

Sun, KS, et al. PRD (2022)

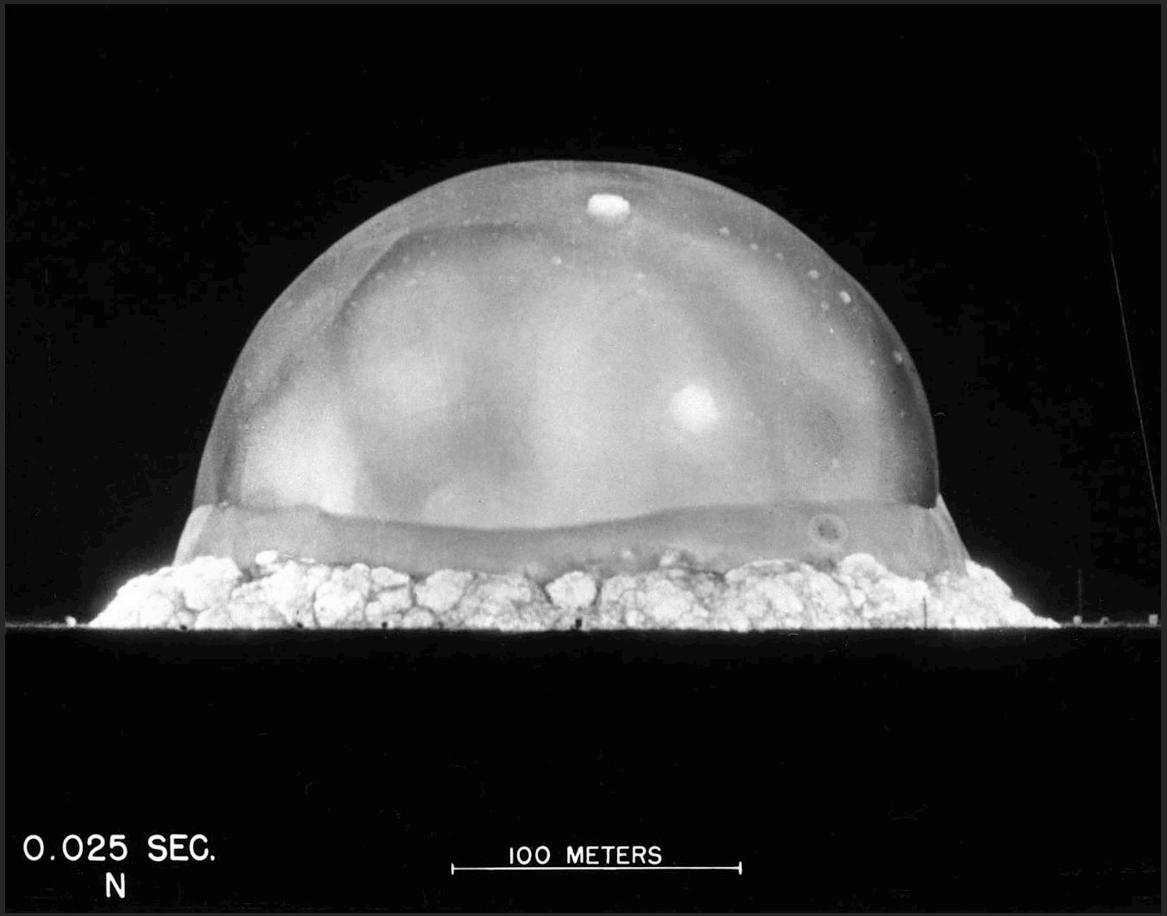
UPSHOT: OPTIMAL SOURCES OF STIMULATING RADIATION ARE BRIGHT AND WERE SIGNIFICANTLY BRIGHTER IN THE PAST

Supernova Remnants (SNRs) as sources

3-color image of the W28 supernova remnant seen in Very Large Array (VLA) and Southern Galactic Plane Survey. NRAO/AUI and Brogan et al. 2006.

- Shock-excited electrons emit synchrotron radiation in radio frequencies
- Brightness decrease steeply --- much brighter in the past
- Age ~10^4 years, similar to light crossing time of local Milky Way DM halo
- Brightness history can be modeled with mix of theory and simulation

Supernova remnant expansion



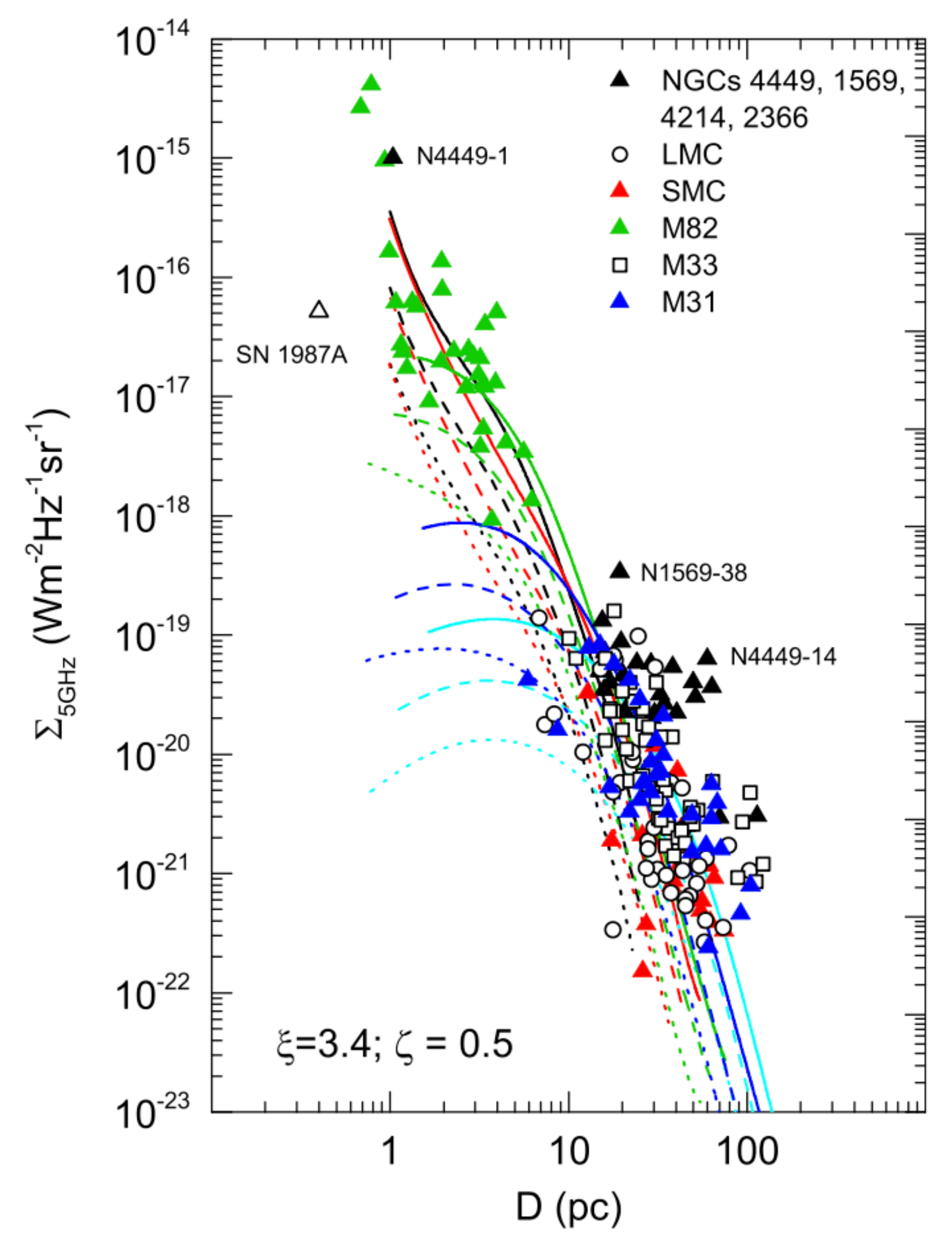
Published photograph of Trinity atomic bomb tests that allowed British physicist G.I. Taylor to estimate explosion energy and deduce that this was a nuclear weapon

- Initial ejecta dominated phase: constant shock velocity due to high velocity ejecta ~ 300 yr
- Sedov-Taylor phase: shock front slowed down in interstellar medium while conserving energy ~ 10^4 yr
- Radiative phase: radiative cooling, energy in shock wave no longer conserved ~ 10^5 yr
- Terminal phase

Sedov-Taylor solution from dimensional analysis

$$R = \xi_{\text{front}} \left(\frac{E}{\rho_{\text{ISM}}} \right)^{1/5} t^{2/5}$$

SNR Brightness evolution



Measured radio surface brightness to diameter relation for SNRs and simulations.
Pavlović, Urošević, Arbutina 2018.

- Synchrotron radiation flux (isotropic):

$$S_{\rm syn} \sim V K_e B^{\frac{p+1}{2}} \nu^{-\frac{p-1}{2}}$$

for an electron distribution:

$$\frac{\Delta n}{\Delta E} \sim K_e E^{-p}$$

- Electron distribution index can be measured from radio spectra
- Total electron energy and magnetic field evolution must be modeled

SNR modelling: electrons

- Electron spectral index p :
  - Uncertainty can arise from a nonlinear synchrotron spectrum, or different portions of the SNR having slightly different spectra
  - e.g. for our best candidate SNR W50 (SNR G039.7-02.0):

$$p = 2.4 \pm 0.2$$

- Electron energy evolution:
  - Classical model [1]: electrons produced (ionized) at the shock front but lose energy in the expanding nebula:

$$VK_e \sim R^{1-p}$$

  - Alternative toy model: total electron energy is conserved:

$$VK_e \sim \text{const.}$$

[1] Shklovskii 1960

SNR modelling: Magnetic field

- Magnetic field evolution:
  - Classical model: compression of interstellar magnetic field, flux is conserved:

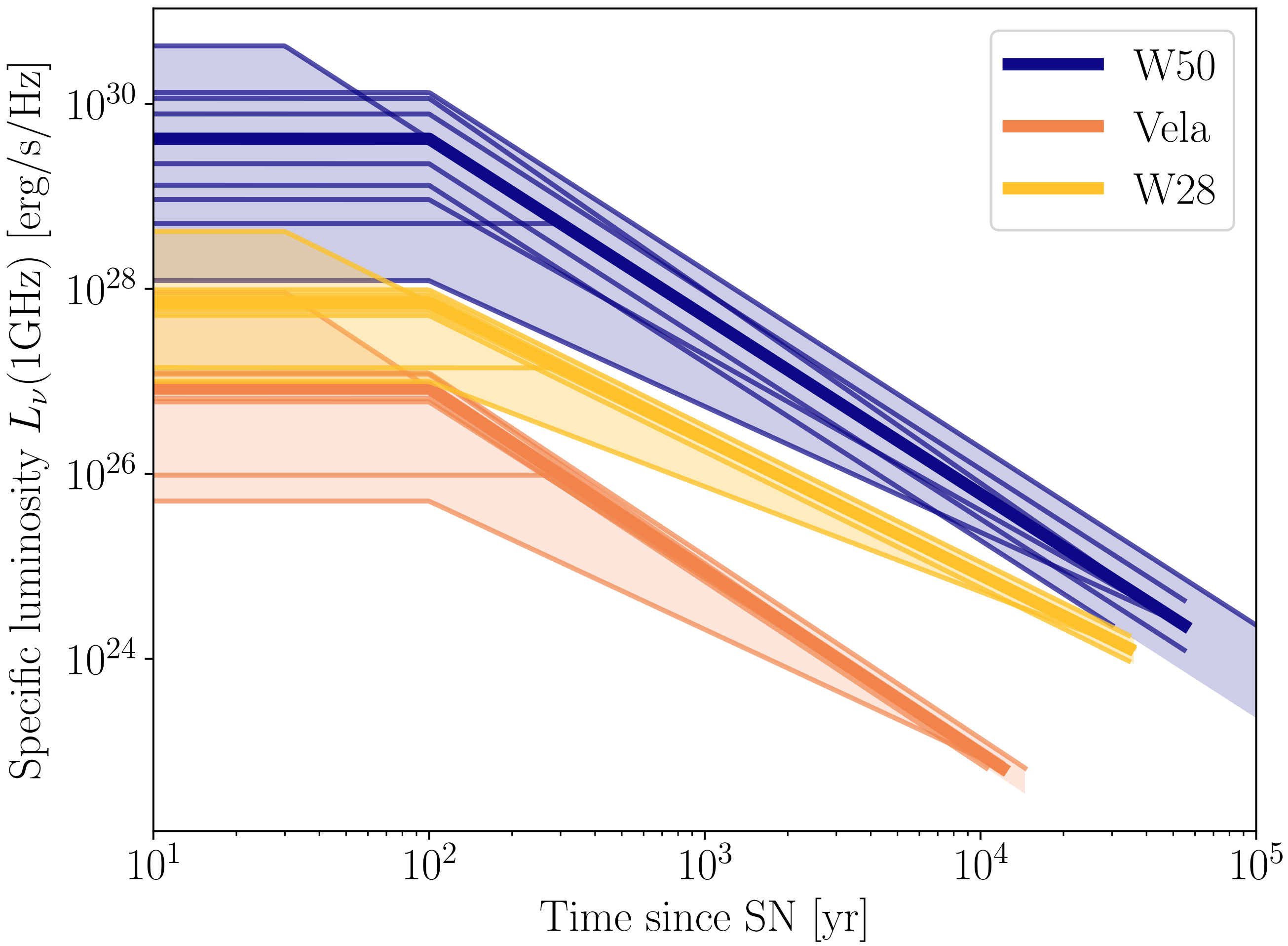
$$B \sim R^{-2}$$

  - Magnetic field amplification (MFA) simulations:

$$B \sim v_{\mathrm{sh}}^{2\sim3} \sim R^{-1.5\sim2.25}$$

- Magnetic field amplification onset time:
  - Core-collapse supernovae have dense circumstellar medium, which interacts with shock front very early on
  - Simulations suggest onset of B field around ~100 years

MODELING OUR BEST SOURCES

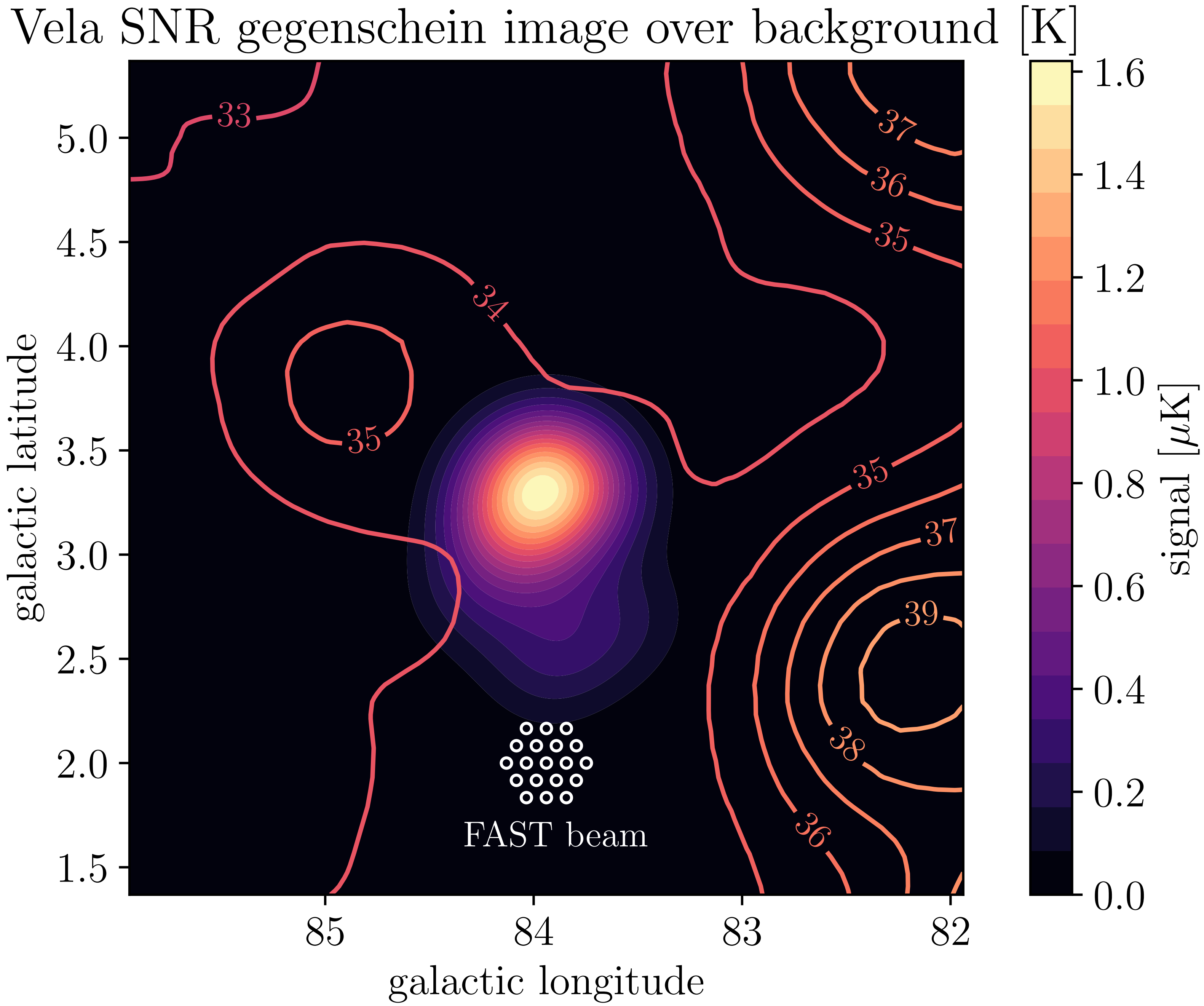


- Data obtained from SNRcat and Green's SNR catalog
- We vary the B field amplification time, electron model, spectral index, age, distance, etc.
- We conservatively assume no growth of the luminosity prior to the magnetic field amplification (observed light curves of young SNe suggest these should be even brighter than we are assuming at early times)

Sun, KS, et al. PRD (2022)

UPSHOT: SUPERNOVA REMNANT BRIGHTNESS EVOLUTION CAN BE MODELED UP TO SOME THEORY UNCERTAINTY, CAN MAKE CONSERVATIVE ASSUMPTIONS

So how does axion gegenschein of supernova remnants look in the sky?

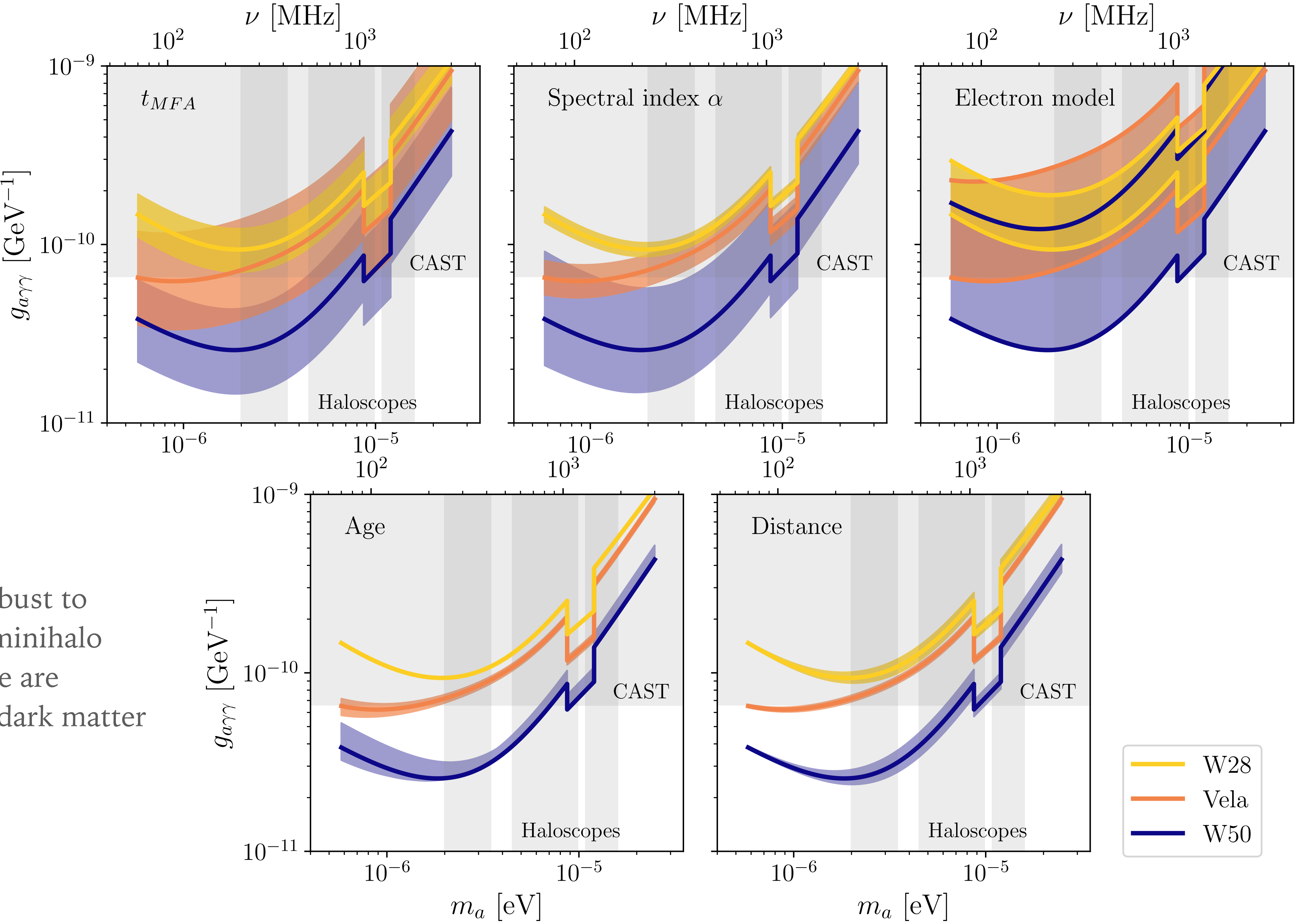


Sun, KS, et al. PRD (2022)

Five-hundred-meter Aperture Spherical Telescope (FAST)

We have already obtained 30 hours of observing time and have obtained 20 hours worth of data (led by Xuelei Chen's group at National Astronomical Observatories)

FAST projected sensitivity



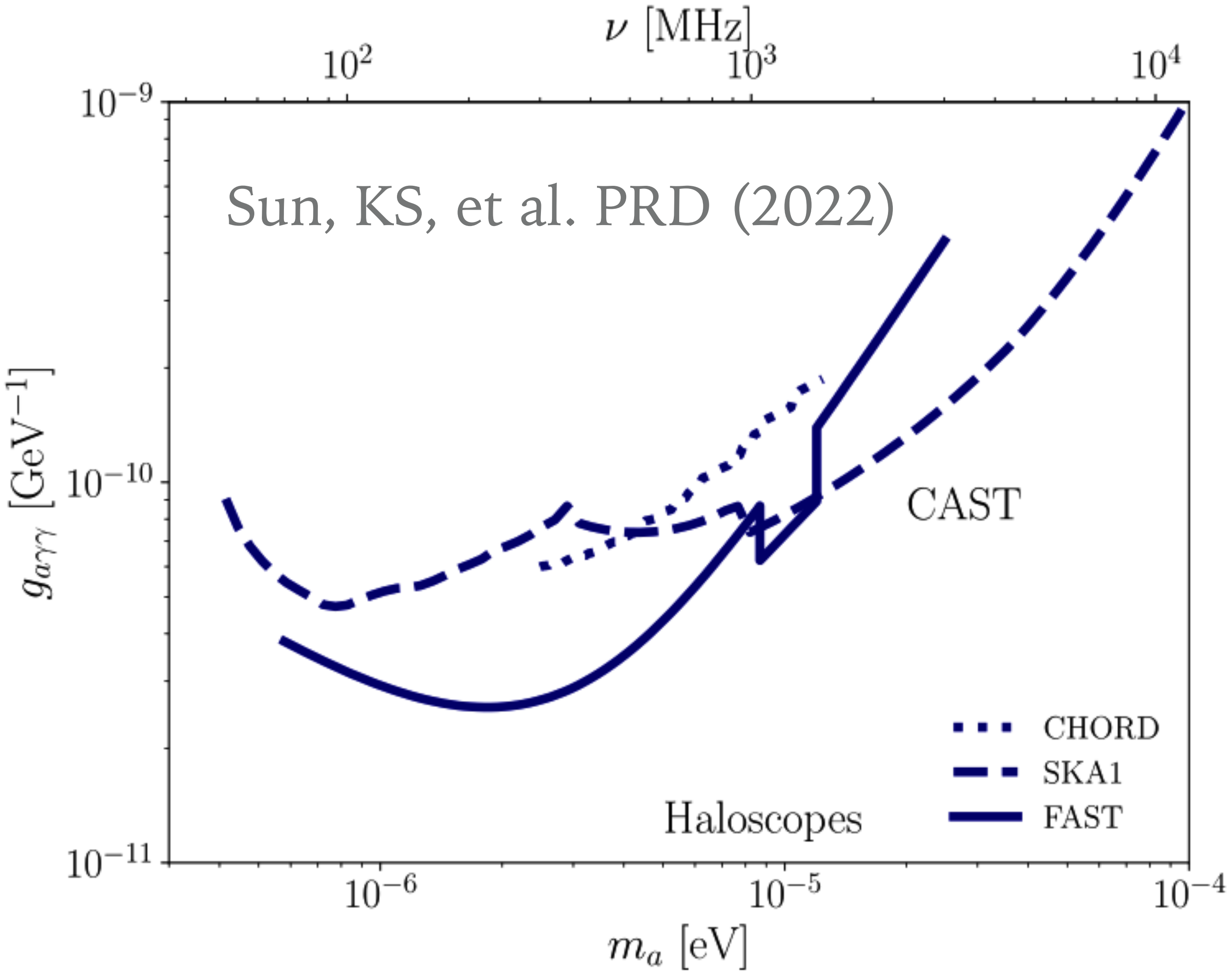
Note this is robust to substructure/minihalo effects since we are probing ~kpc dark matter column!

- Even with astrophysical modeling uncertainties on evolution, FAST radio telescope in China could explore new axion parameter space. Observations are underway!

Sun, KS, et al. PRD (2022)

What about other telescopes?

- ➤ Imaging interferometer like SKA “resolves out” the extended gegenschein image, rendering it invisible
- ➤ Can still observe with individual interferometer elements and add incoherently
- ➤ Survey interferometers (made for 21 cm) do better because they have shorter baselines, are optimized to look at extended structures



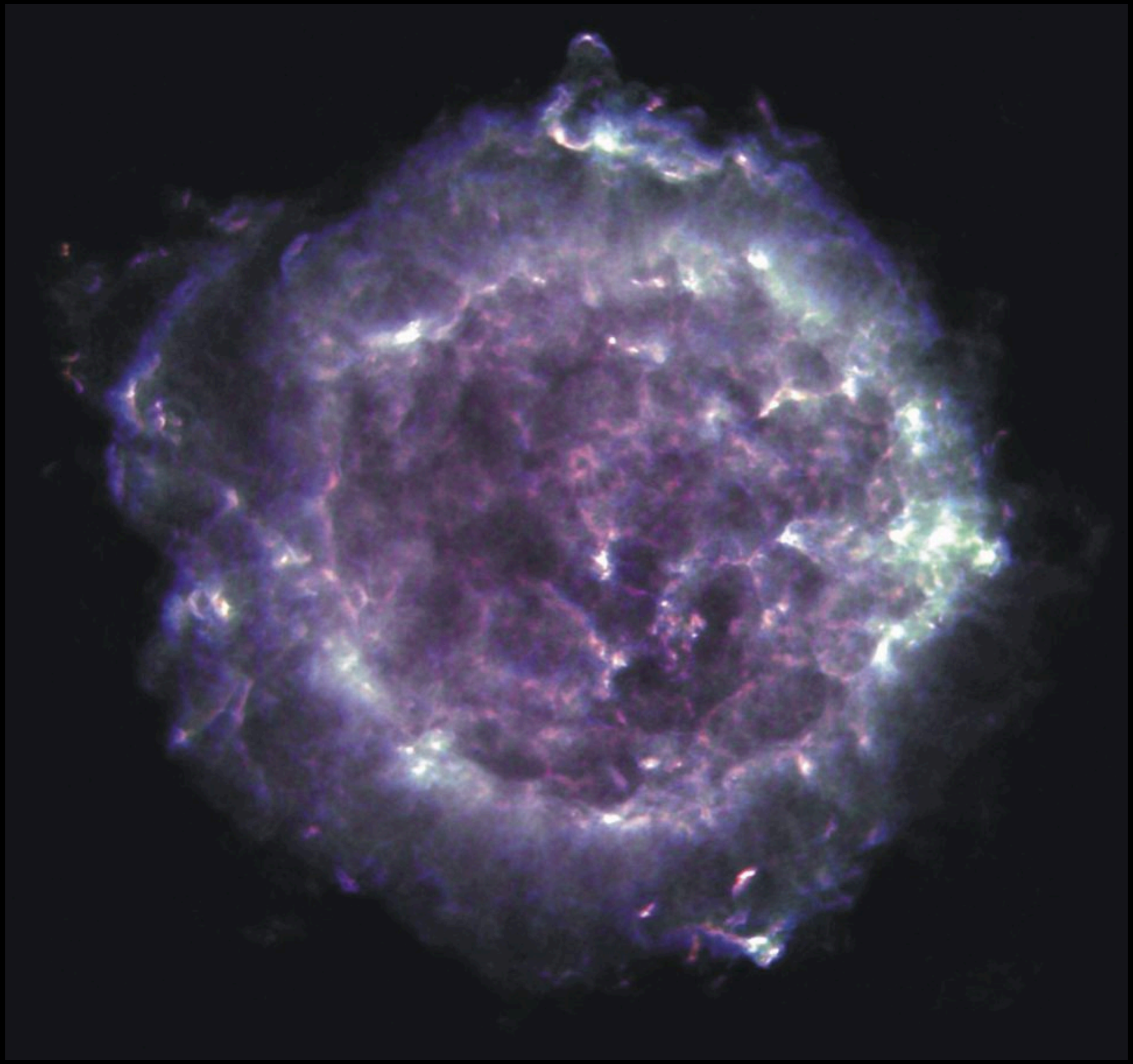
Sun, KS, et al. PRD (2022)

Fiducial sensitivity for W50 SNR

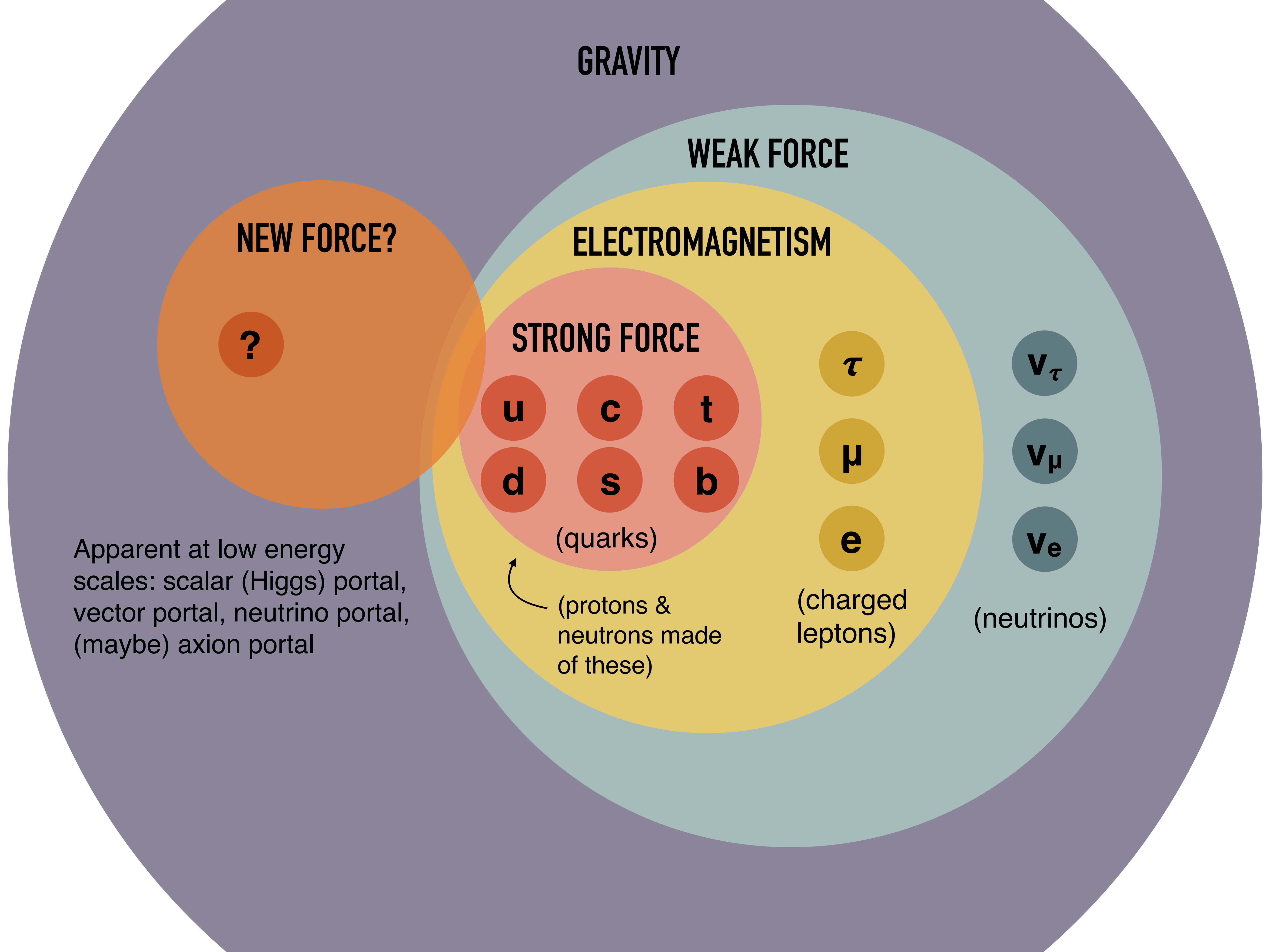
- ➤ Biggest improvements are likely to come from better modeling of remnant (lower theory uncertainty and including brighter/earlier times than what we included) and more observing time

MINI-SUMMARY

- Axion dark matter behaves like a blurry, monochromatic mirror
- Taking into account geometry and time of flight, supernova remnants are an ideal source of stimulating radiation
- With existing telescopes like FAST, we may have immediate sensitivity to new axion parameter space despite conservative modeling choices



OTHER DARK–VISIBLE INTERACTIONS



GRAVITY

WEAK FORCE

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

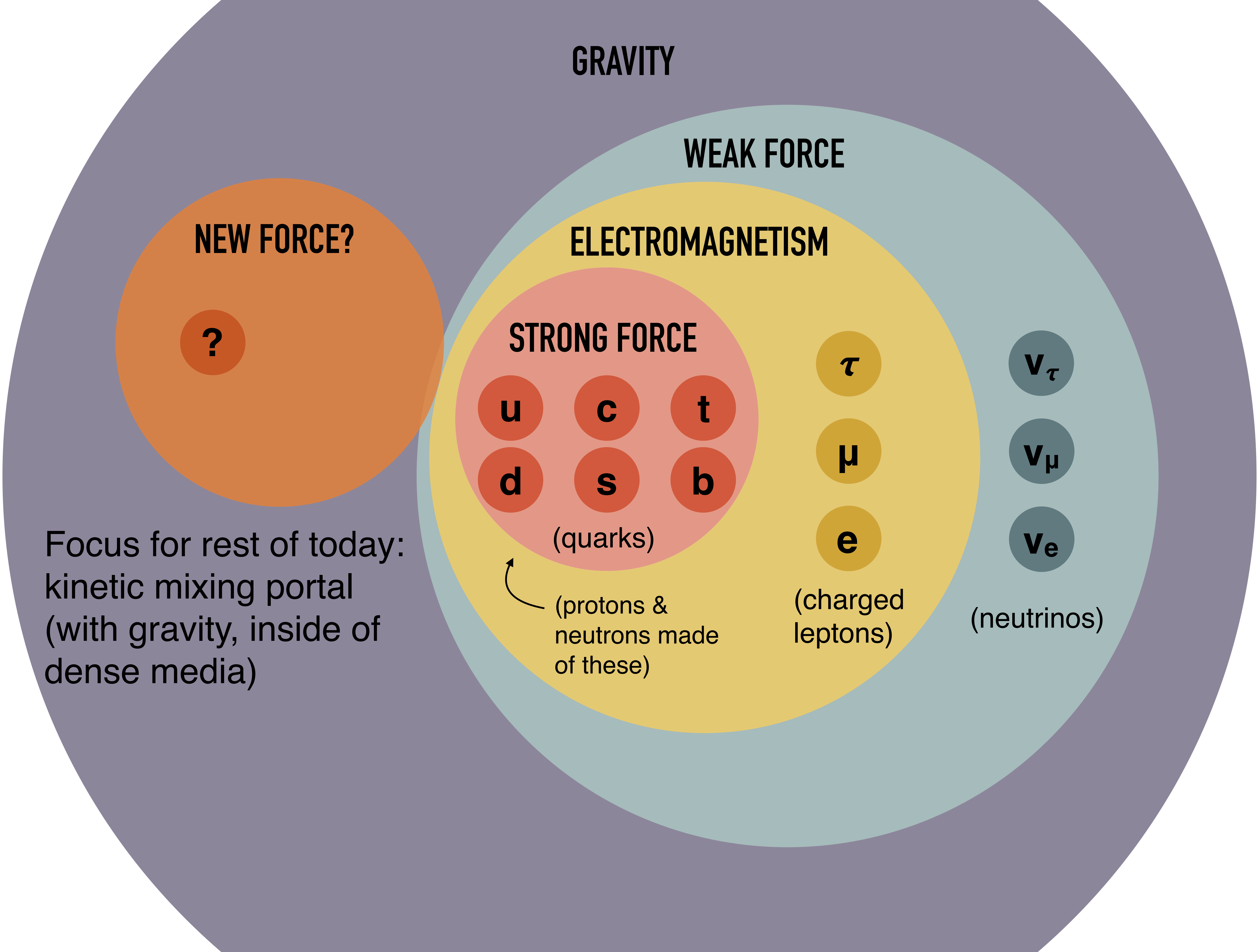
ν_e

(neutrinos)

NEW FORCE?

?

Apparent at low energy scales: scalar (Higgs) portal, vector portal, neutrino portal, (maybe) axion portal



GRAVITY

WEAK FORCE

ELECTROMAGNETISM

NEW FORCE?

?

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

Focus for rest of today: kinetic mixing portal (with gravity, inside of dense media)

ULTRALIGHT, ABELIAN KINETIC MIXING PORTAL

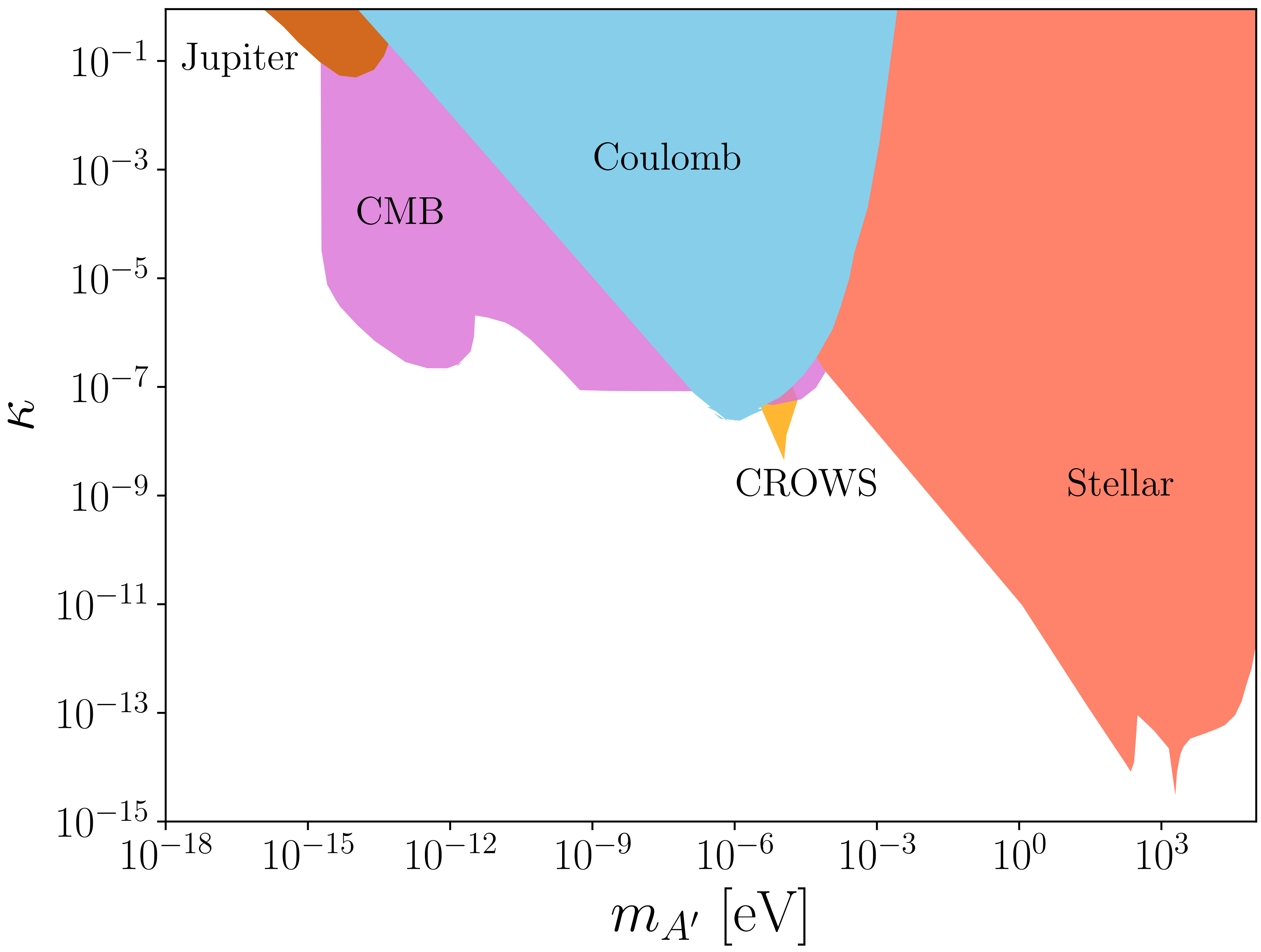
$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^{\mu} + g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu$$

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

Dirac fermion charged under U(1)’

ULTRALIGHT DARK PHOTON PARAMETER SPACE



ULTRALIGHT, ABELIAN KINETIC MIXING PORTAL

$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu$$

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

Dirac fermion charged under U(1)’

In a medium, rotating away mixing term

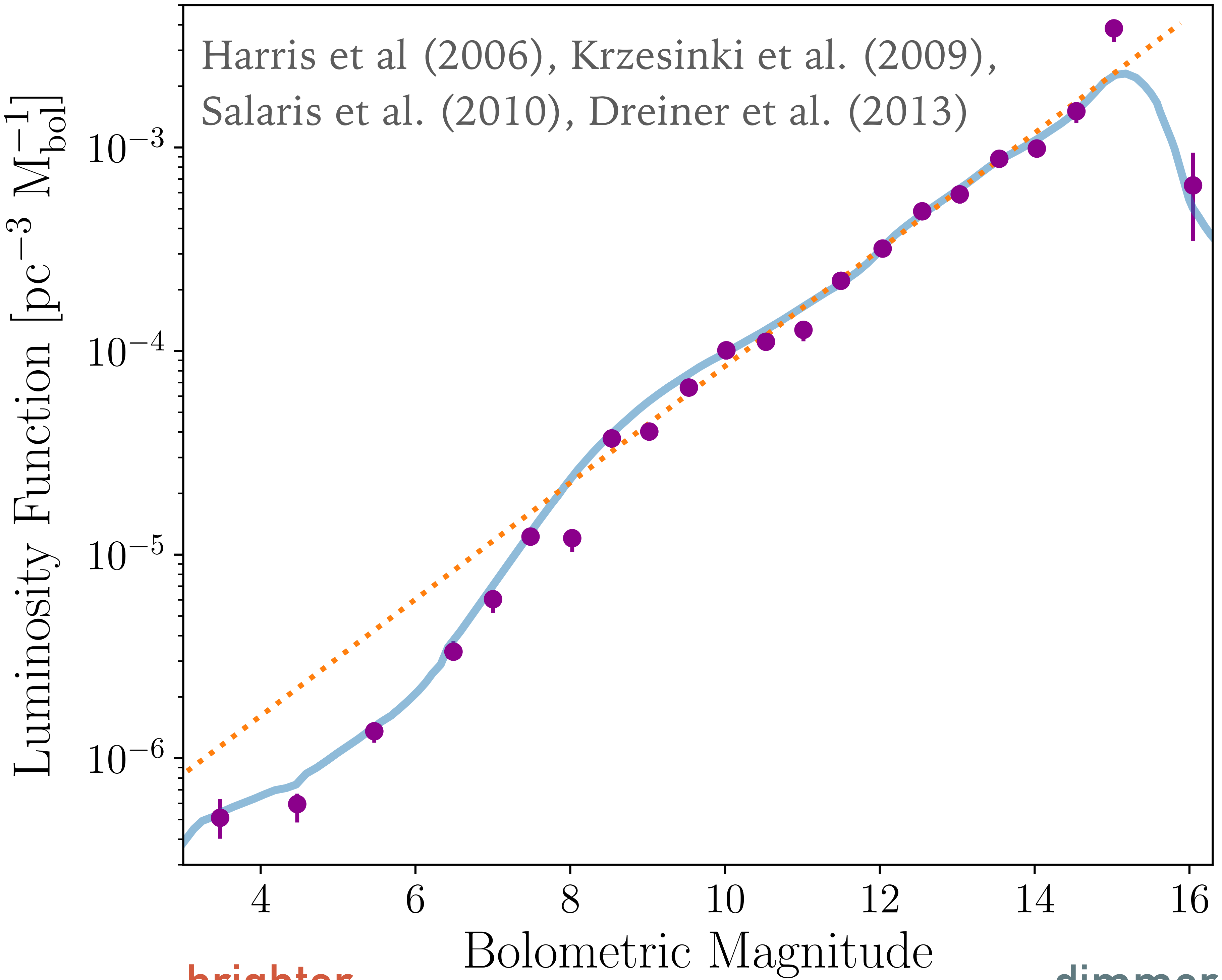
$$\mathscr{L} \supset J^\mu_{EM}\left(eA_\mu\right) + g_\chi \bar{\chi} \gamma^\mu \chi \left(A'_\mu + \kappa A_\mu\right) + \textit{higher order in } \frac{m_{A'}}{m_A}$$

Particle charged under dark U(1) appears to be “millicharged” under E&M, $Q = g_\chi \kappa / e$

Depends on kinematics, medium properties

KEY PROCESS: PLASMON DECAY

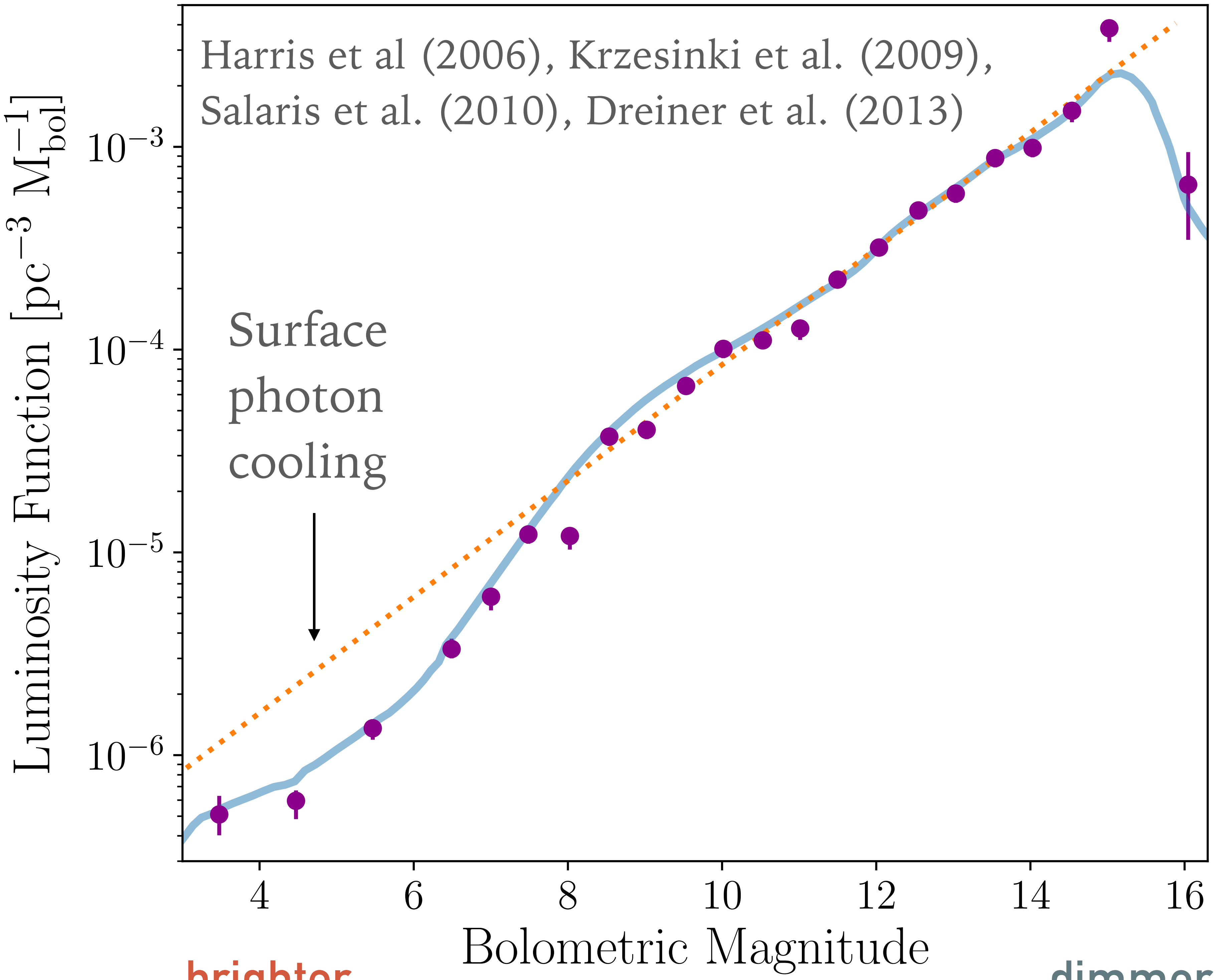
WHITE DWARF COOLING AND POPULATION



← **brighter**
hotter

dimmer →
cooler

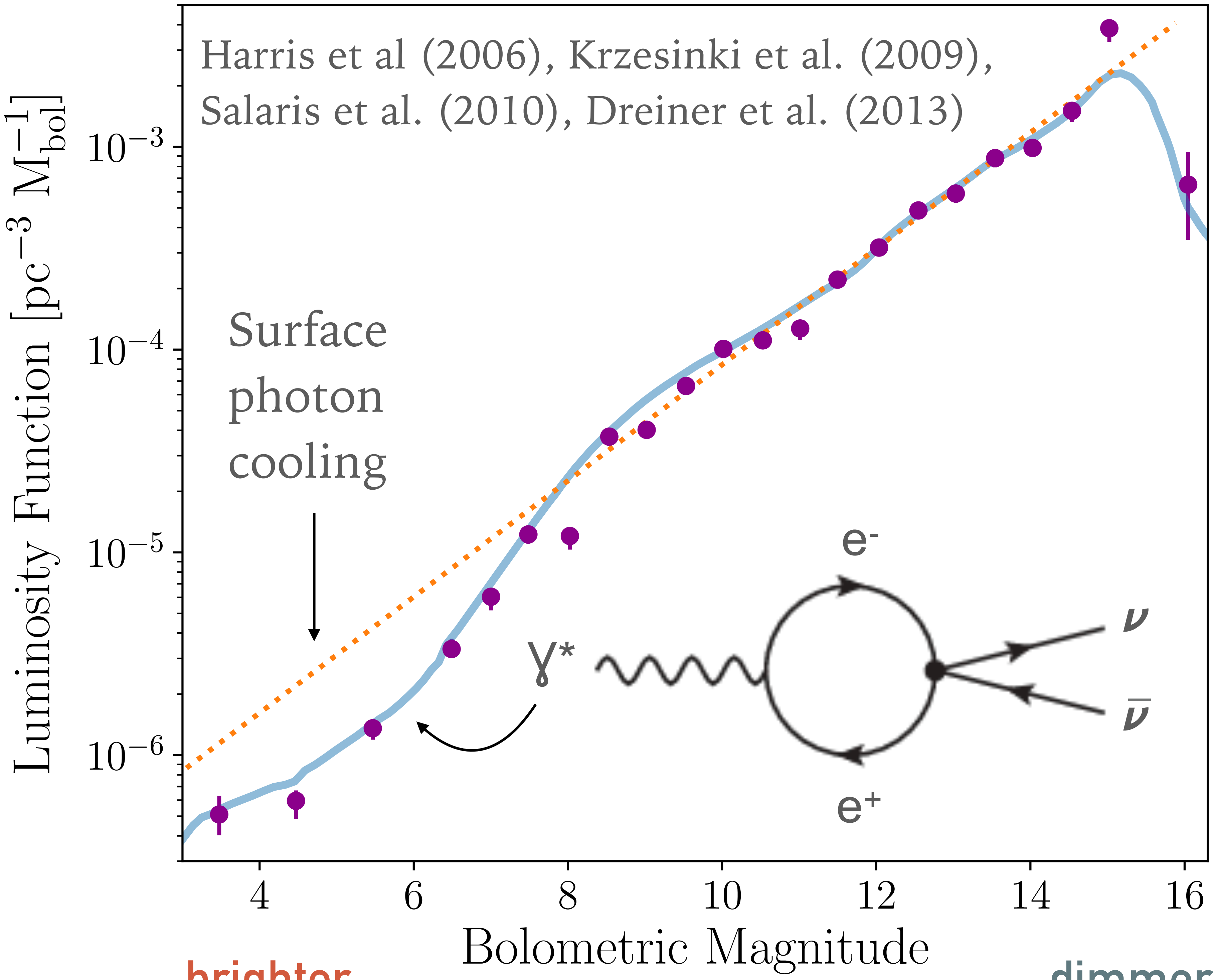
WHITE DWARF COOLING AND POPULATION



← **brighter**
hotter

dimmer →
cooler

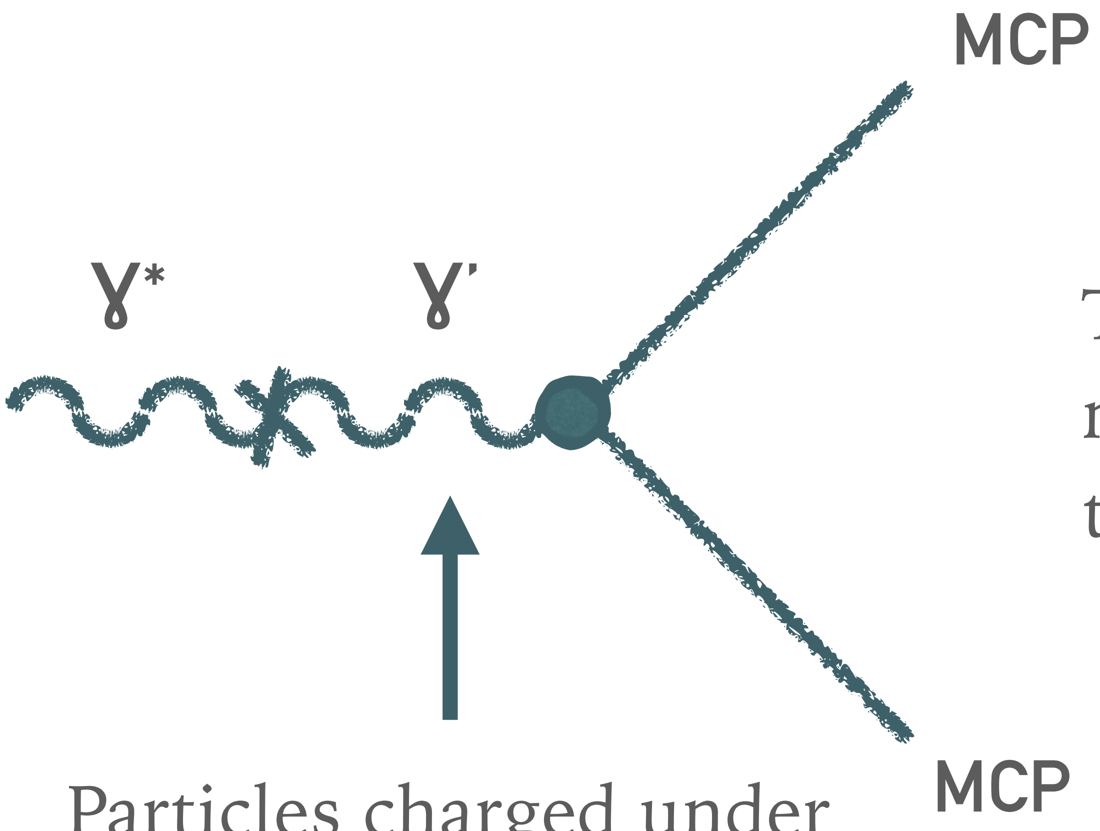
WHITE DWARF COOLING AND POPULATION



← brighter hotter

dimmer cooler →

PLASMON PRODUCTION OF PARTICLES CHARGED UNDER HIDDEN U(1)



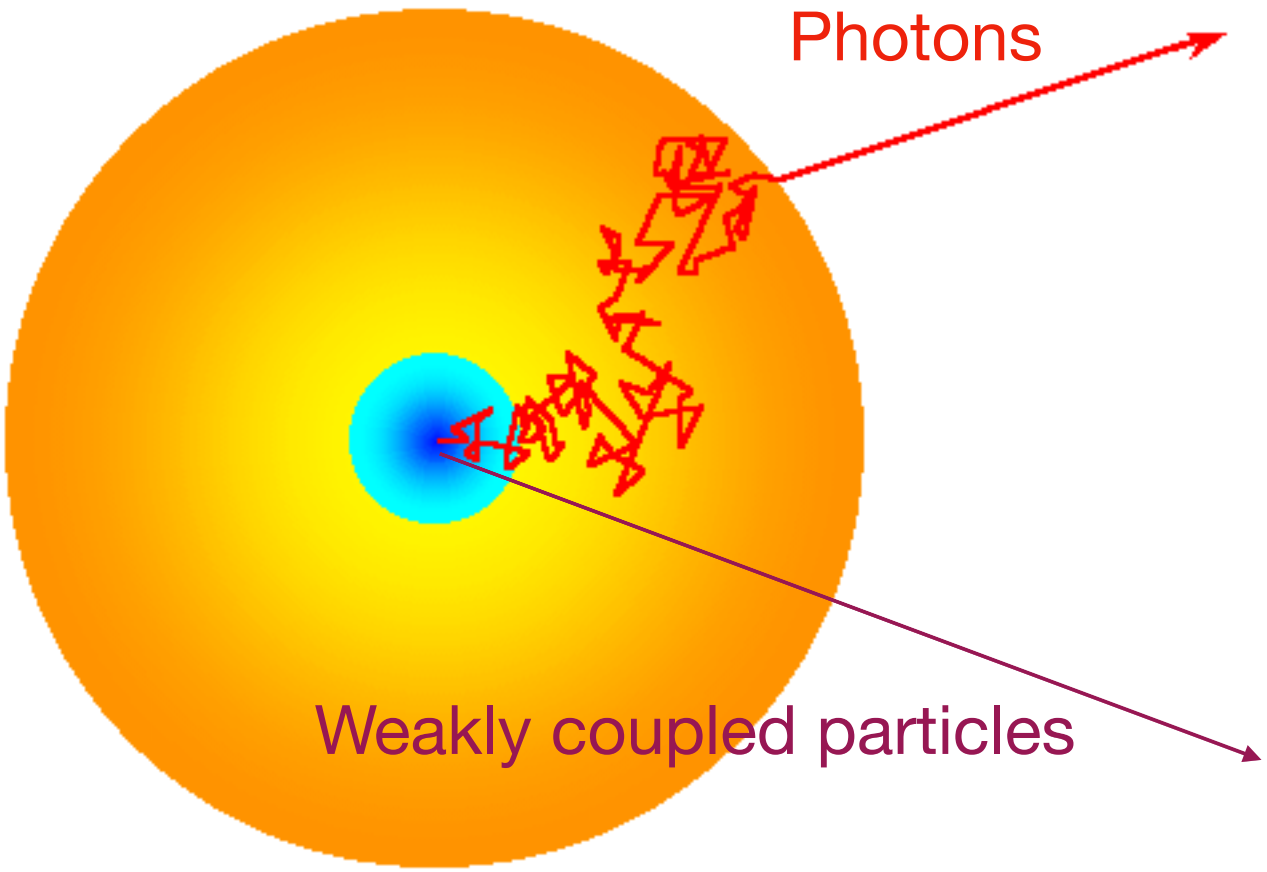
Particles charged under
dark version of E&M
with a “dark photon”

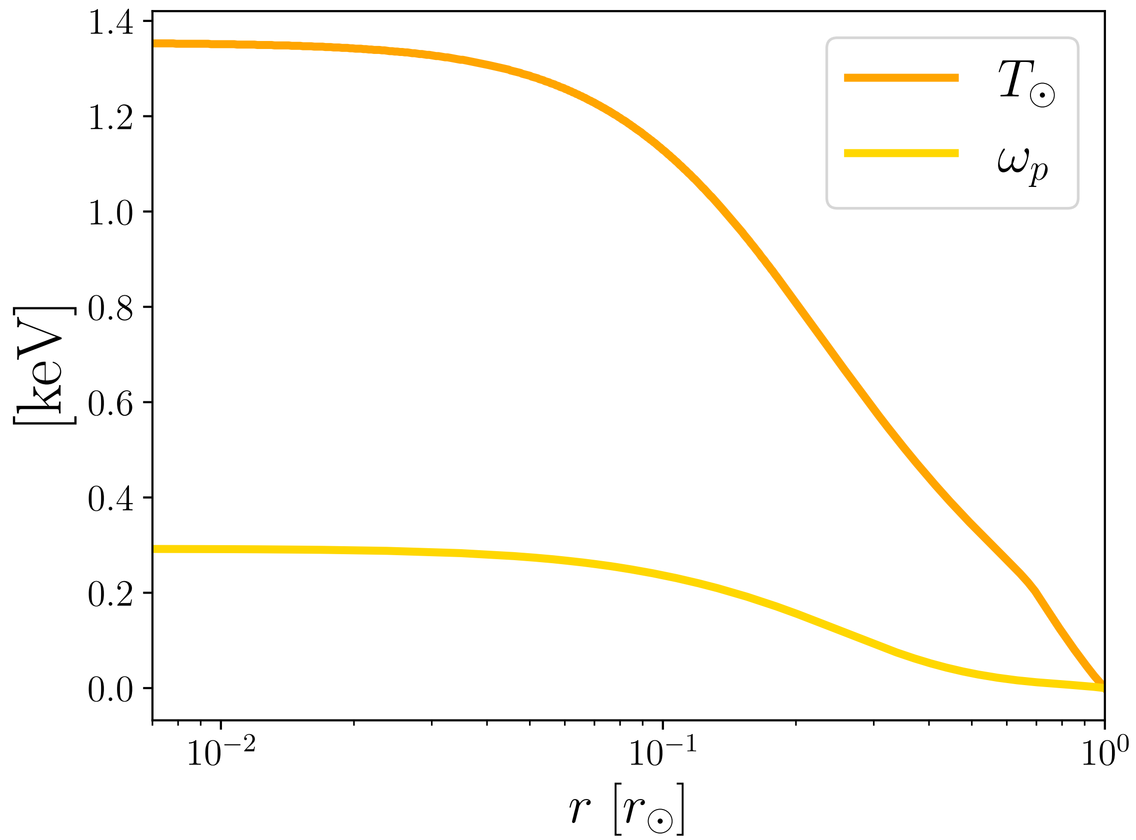
This process efficiently makes millicharged particles (MCP) lighter than half the plasma frequency

A HELIOSCOPE FOR GRAVITATIONALLY BOUND MILLICHARGED PARTICLES

Berlin & **KS** 2111.01796

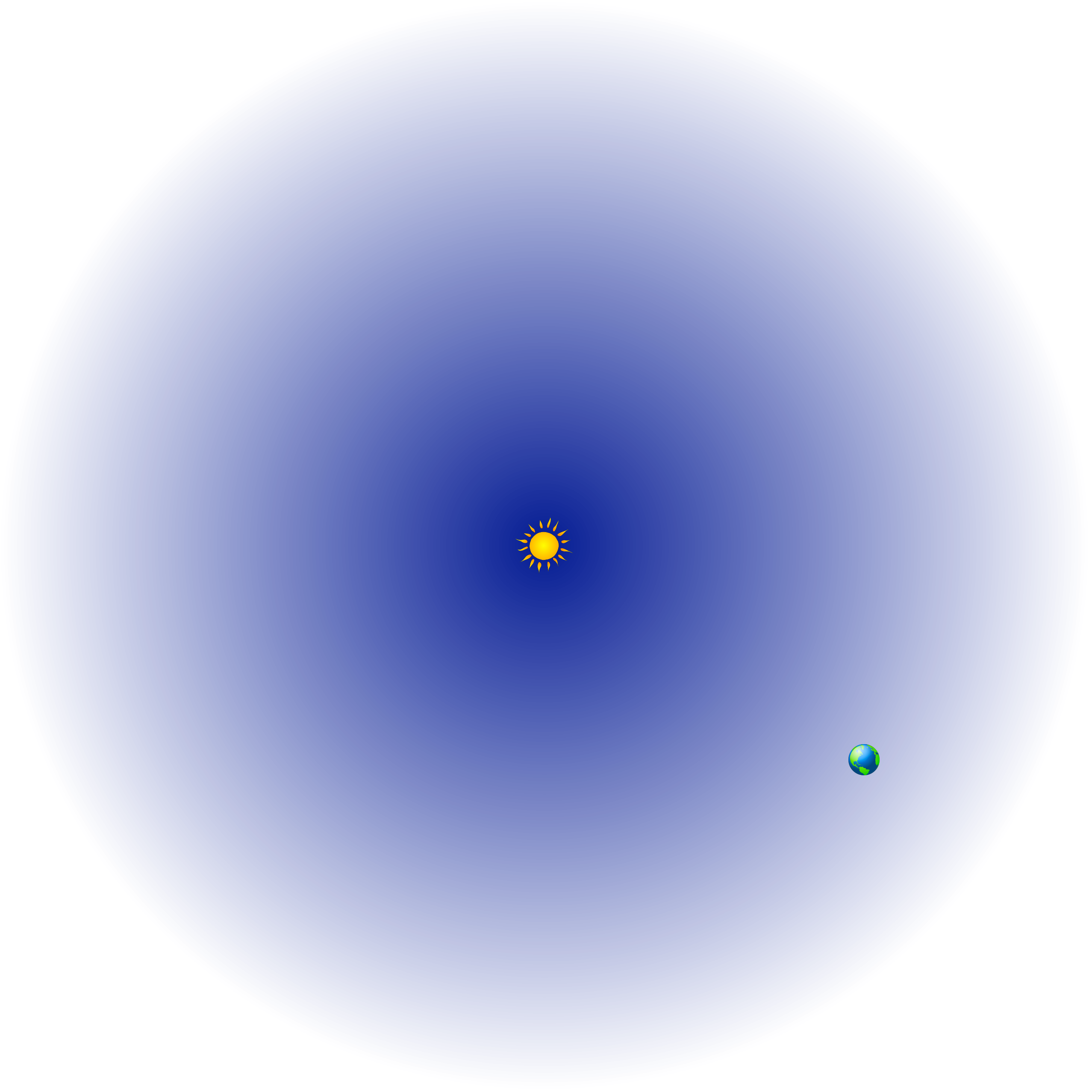
SOLAR PRODUCTION OF MCP





- MCP lighter than ~100 eV can be produced in the sun and escape if Q≪1, lots of volume to compensate for rareness of plasmon decay process

A SOLAR BASIN OF MCP DUE TO GRAVITY



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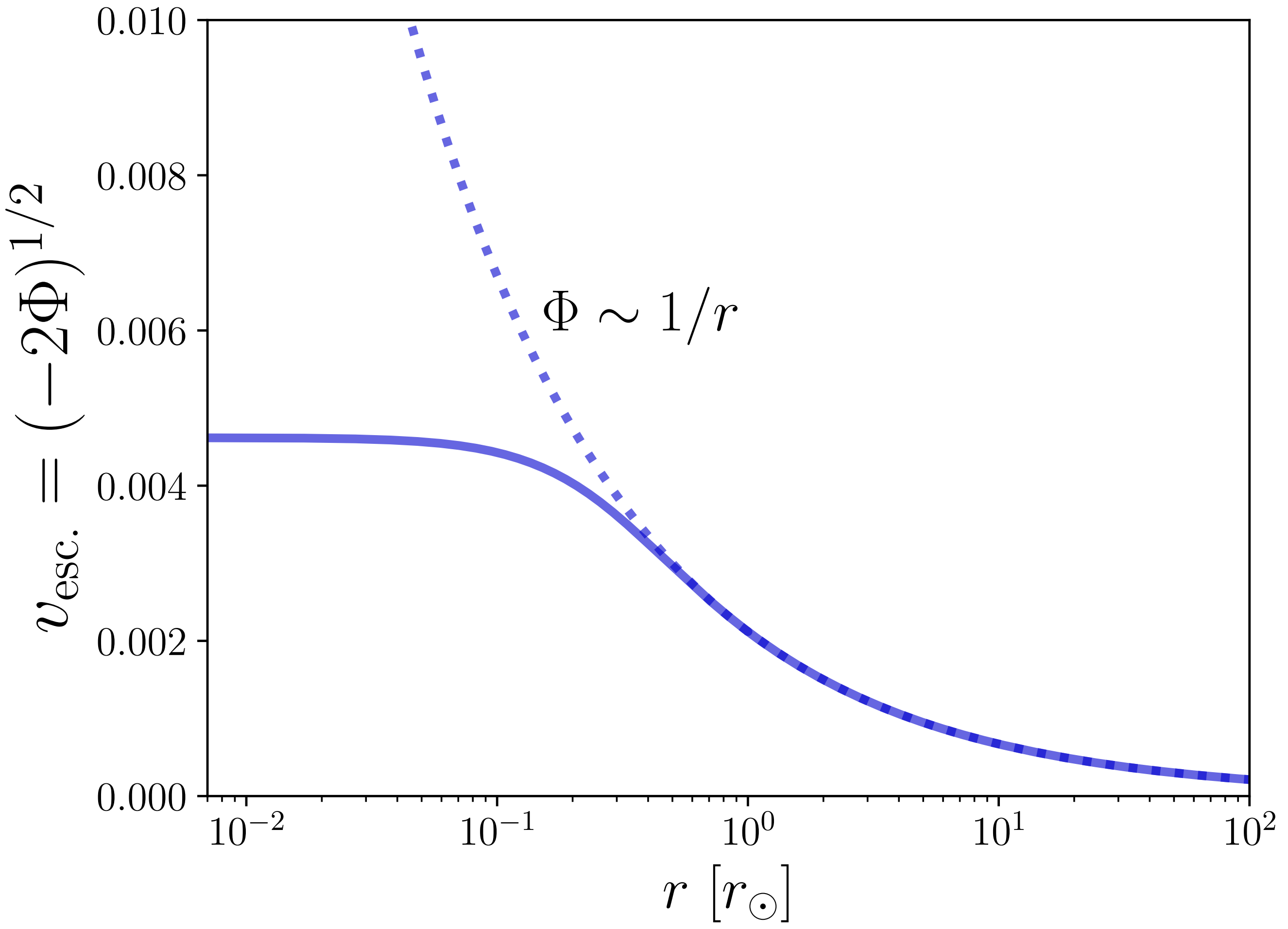
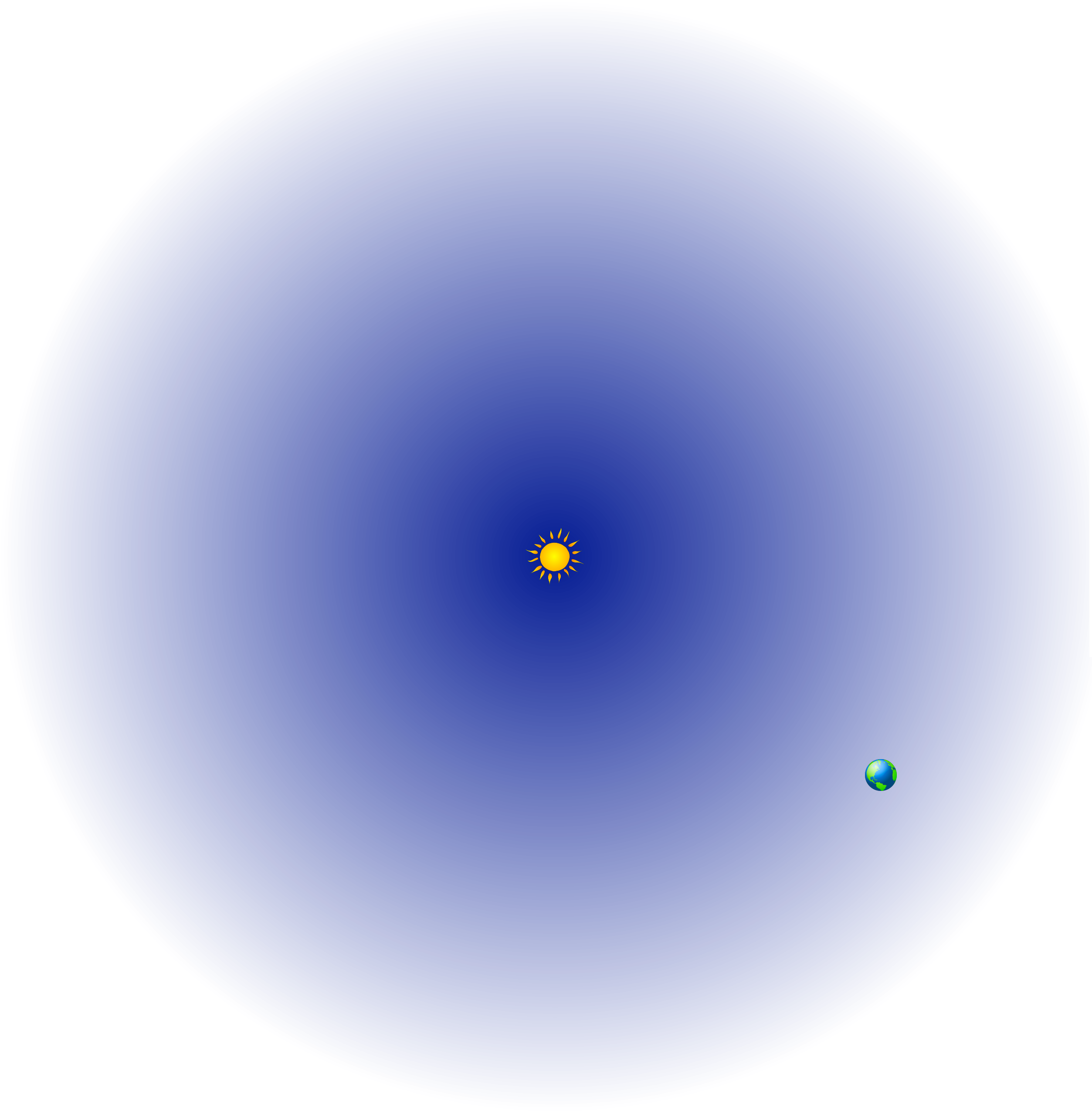


- MCP produced going slower than ~0.005c will be gravitationally bound, accumulate over time
(Van Tilburg 2020)

A SOLAR BASIN OF MCP DUE TO GRAVITY



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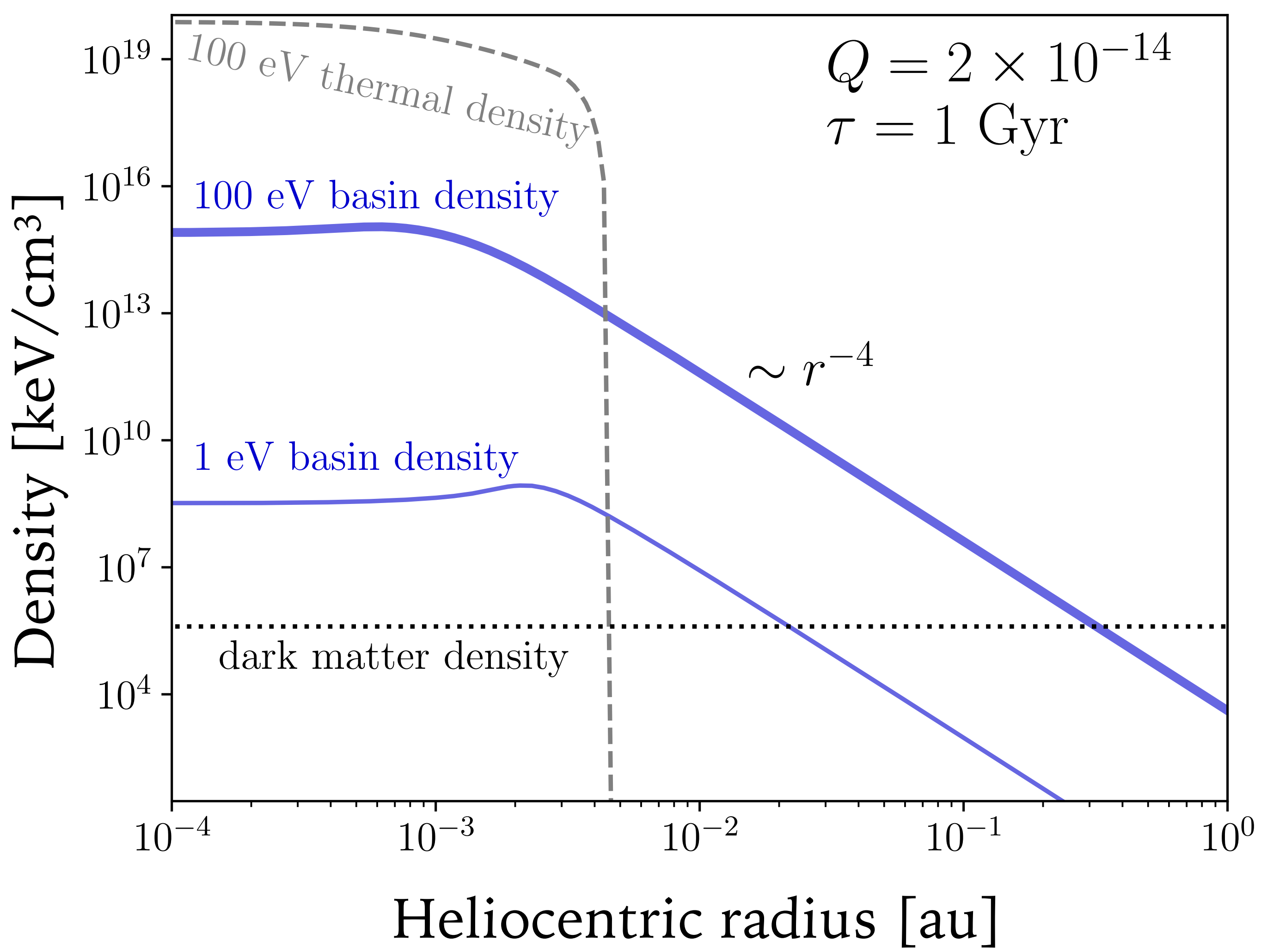

- Density falls precipitously but can be non-negligible at Earth

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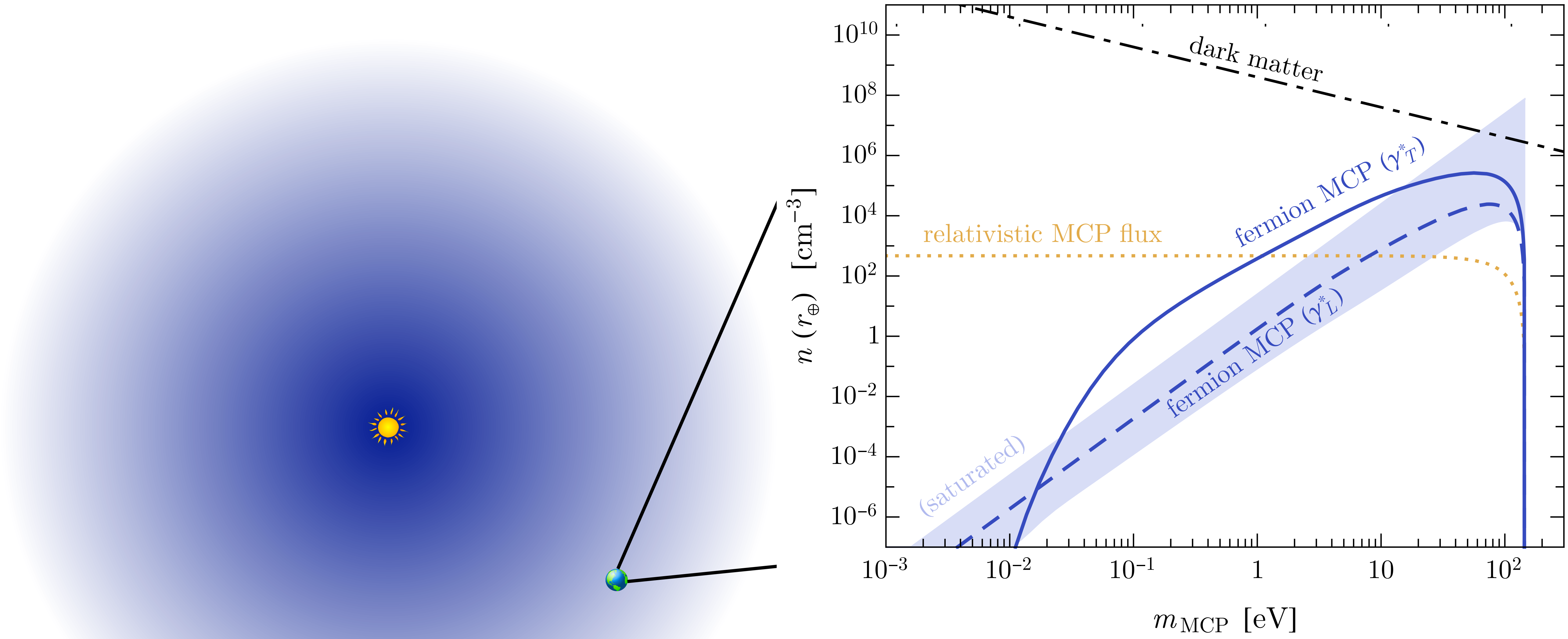
LIST OF CAVEATS/REQUIREMENTS

- ☑ MCP can’t be trapped by scattering in the Sun or the Sun’s ~Gauss magnetic field
- ☑ Annihilation can’t efficiently deplete the abundance
- ☑ Scattering can’t efficiently transport orbital energy and distort the density profile and phase space
- ☑ MCP needs to be able to reach experiment at sea level in spite of Earth atmospheric voltage

Claim: these can be satisfied with massive dark photon and small charge in wide portions of parameter space

DENSITY AT EARTH



(not to scale)

- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

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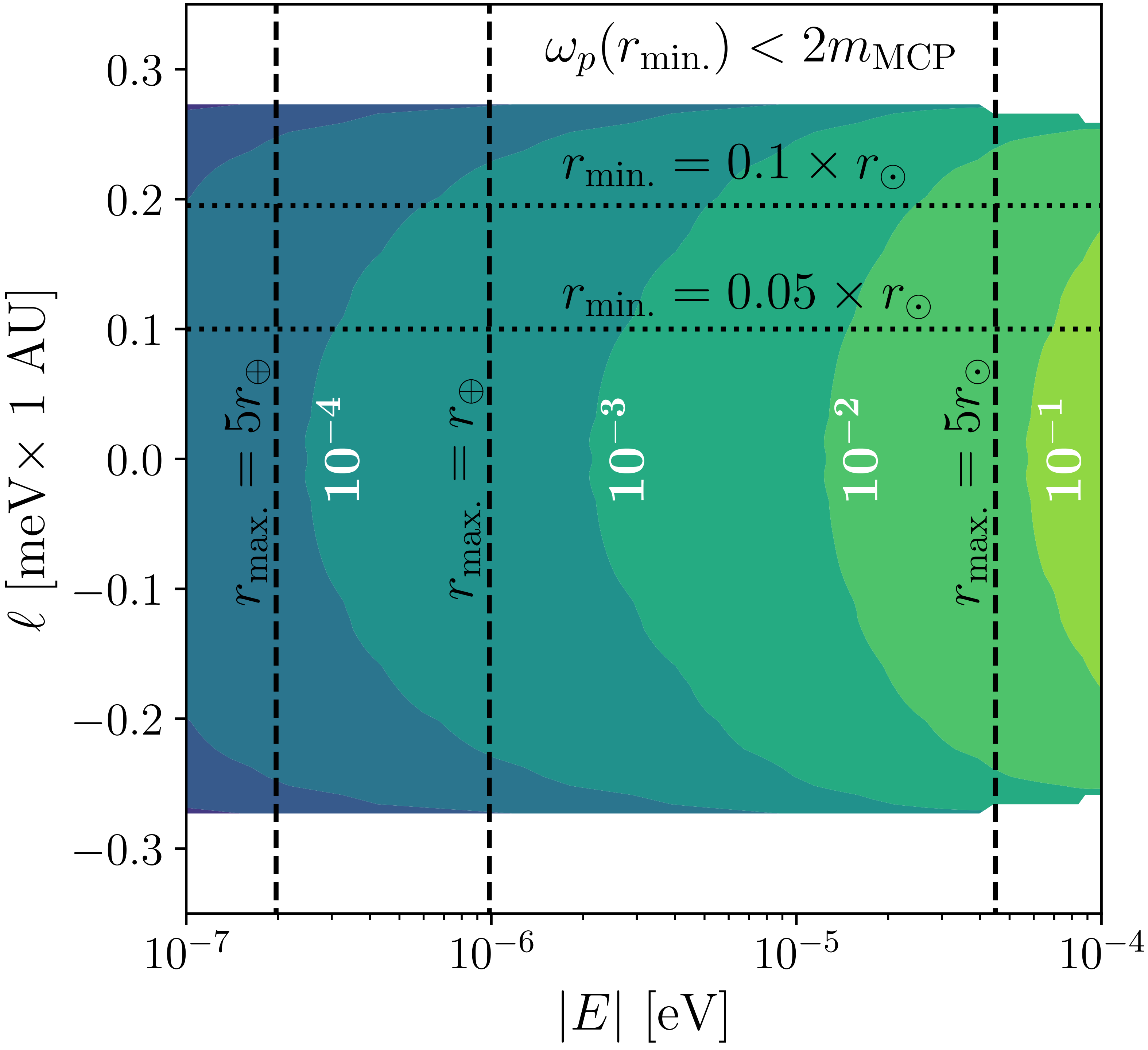
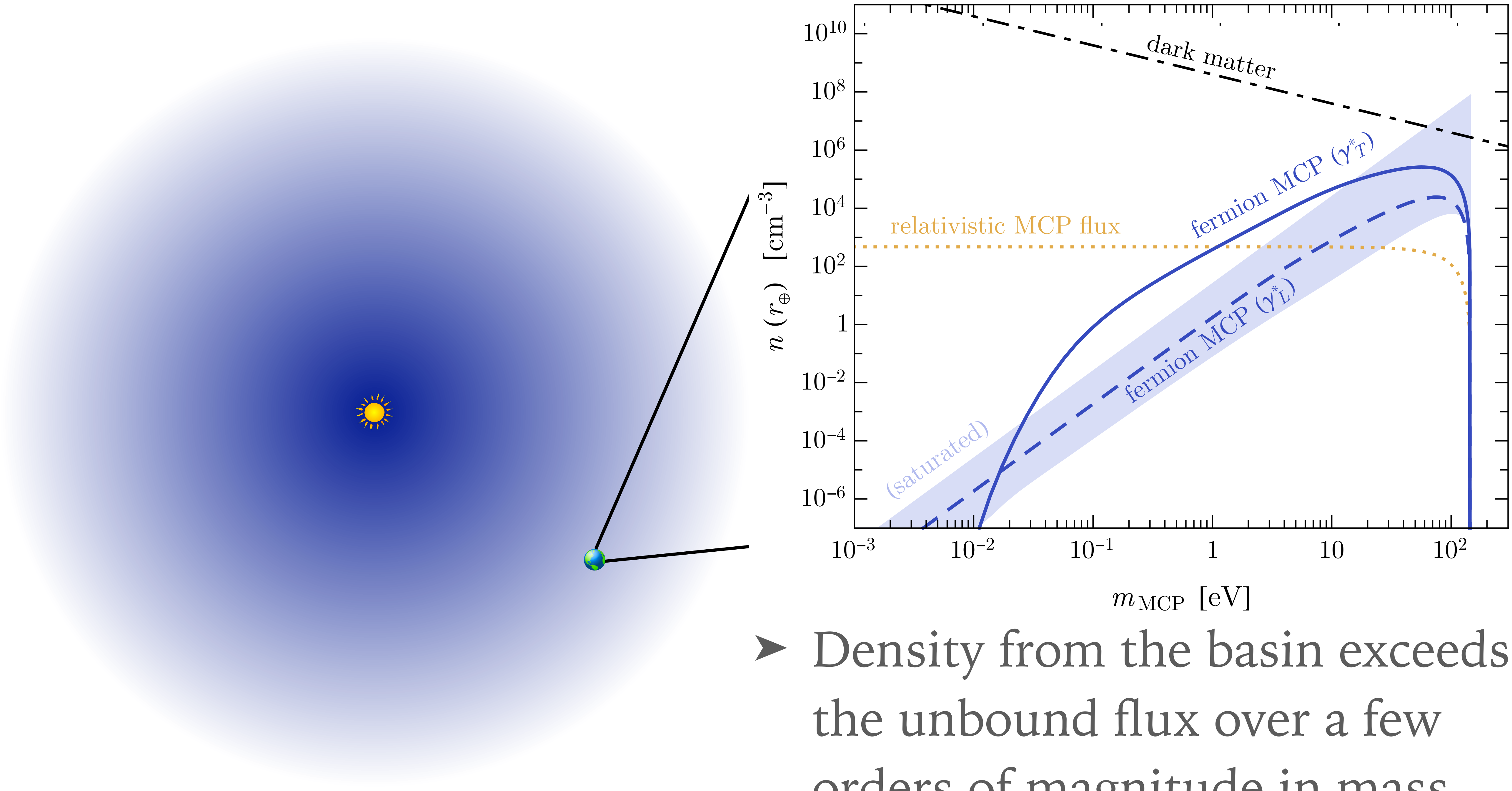
PHASE SPACE AT EARTH FROM PRODUCTION AND ORBITAL MOTION

- Motion of particles coming from is radially collimated (low angular momentum/ high orbital eccentricity)
- Occupation numbers can be very high, even Pauli blocked in some parts of phase space that saturate
- Gravitational encounters with planets can scramble phase space, "isotropize" orbits on long timescales



DENSITY AT EARTH



(not to scale)

- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

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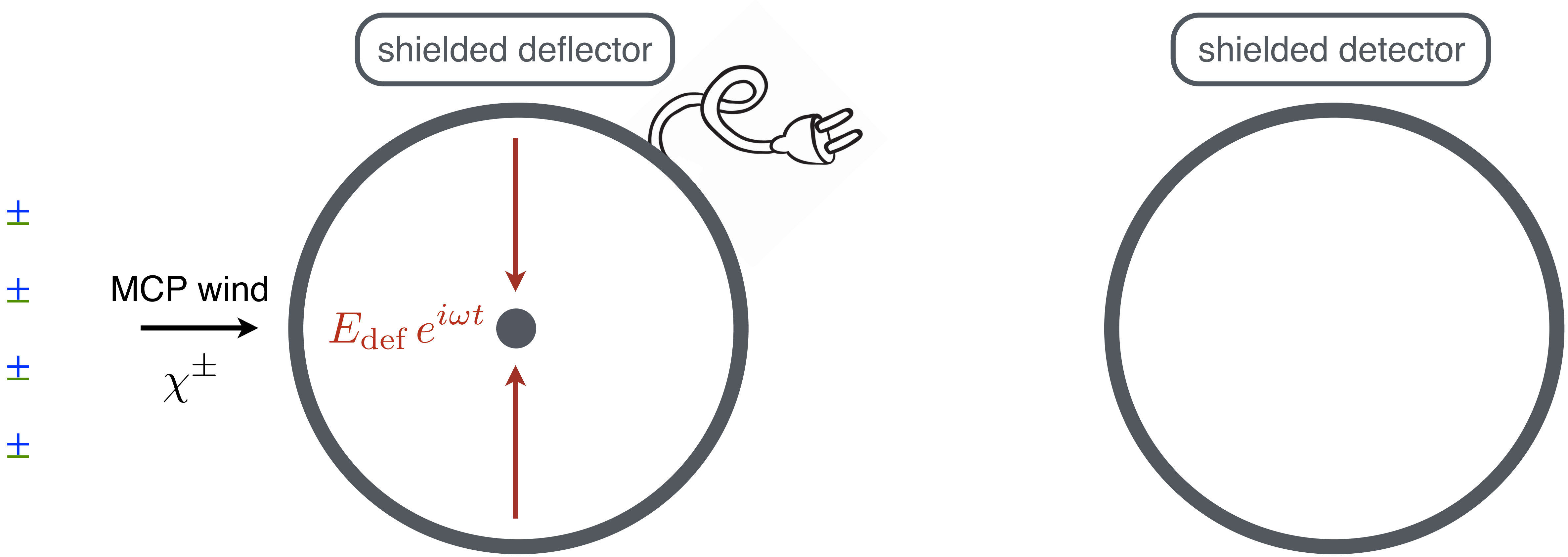
TRADITIONAL METHODS OF DETECTION WILL BE CHALLENGING

- Particles with conserved charge can only scatter elastically
- Unlike previous stellar basins (axions and dark photons considered by van Tilburg, Lasenby) particle absorption is not a viable detection strategy
- Typical particle speed in basin is 10^{-4} c, so sub-keV particles will have at most μeV kinetic energy, not enough to be above experimental energy threshold
- Need to exploit collective effects that are not penalized for low particle speed in order to observe something

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



shielded deflector

shielded detector

MCP wind

$\chi^{\pm}$

$E_{\text{def}}\, e^{i\omega t}$

$\pm$

$\pm$

$\pm$

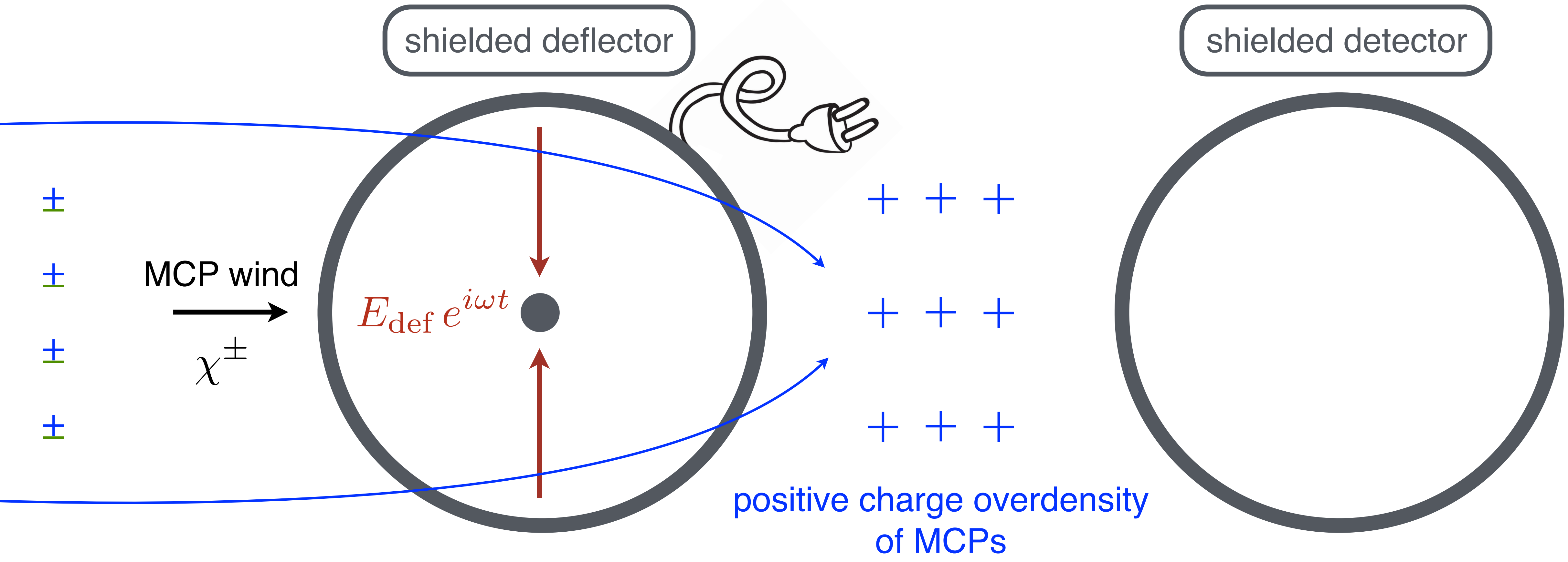
$\pm$

wind-blowing

(similar to “~~light-shining~~-through-wall” experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



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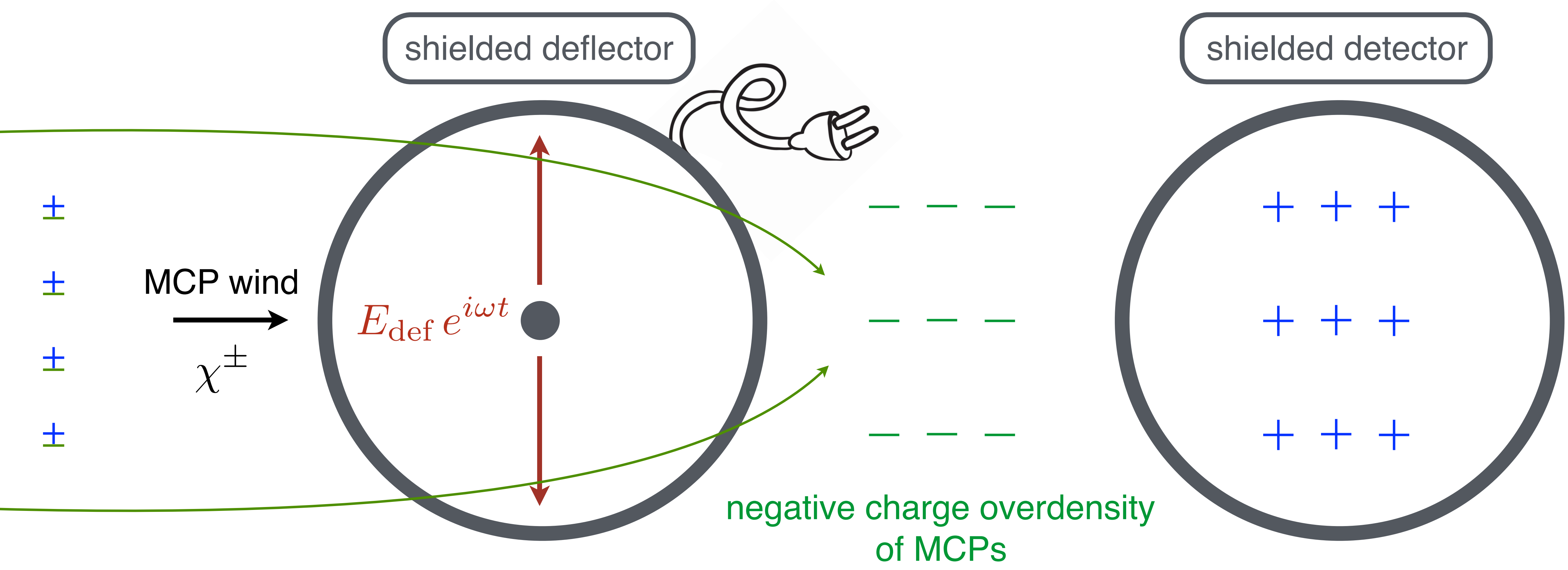
DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



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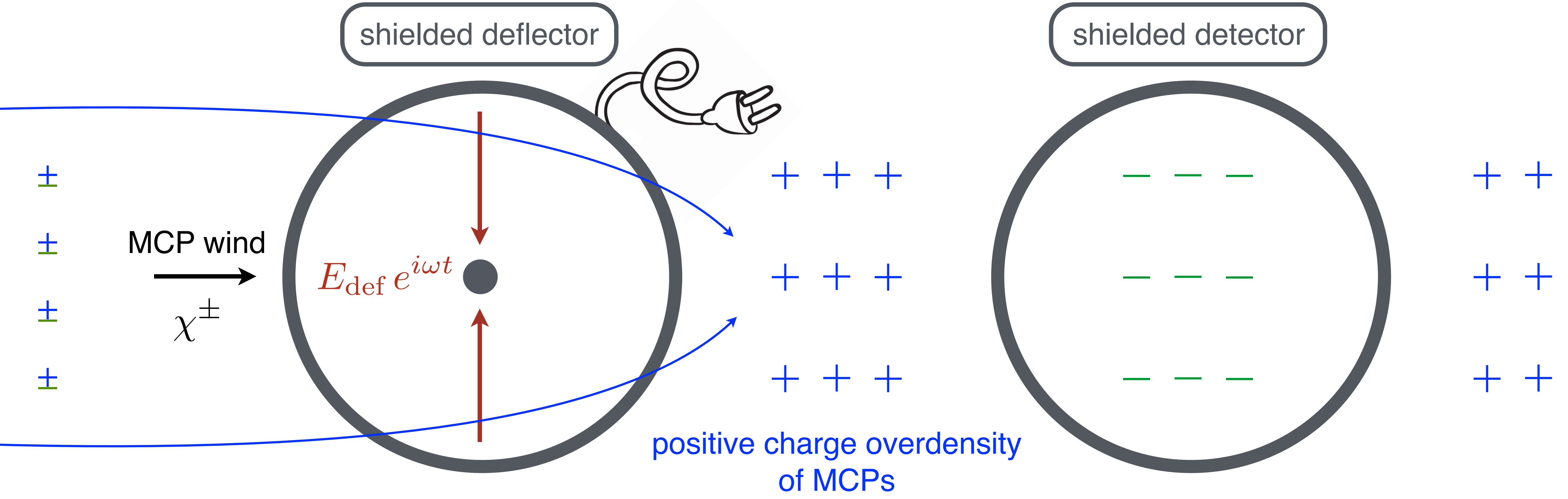

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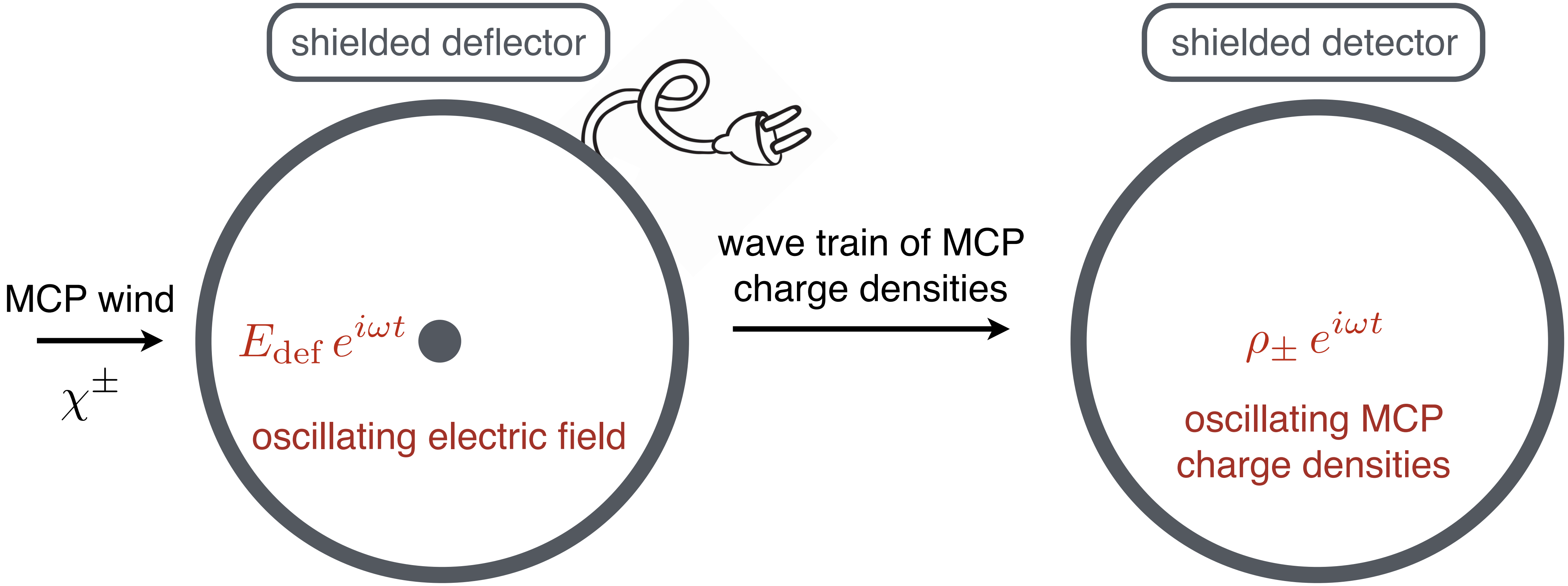

shielded deflector

shielded detector

MCP wind

$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

oscillating electric field

wave train of MCP charge densities

$\rho_{\pm}\, e^{i\omega t}$

oscillating MCP charge densities

wind-blowing

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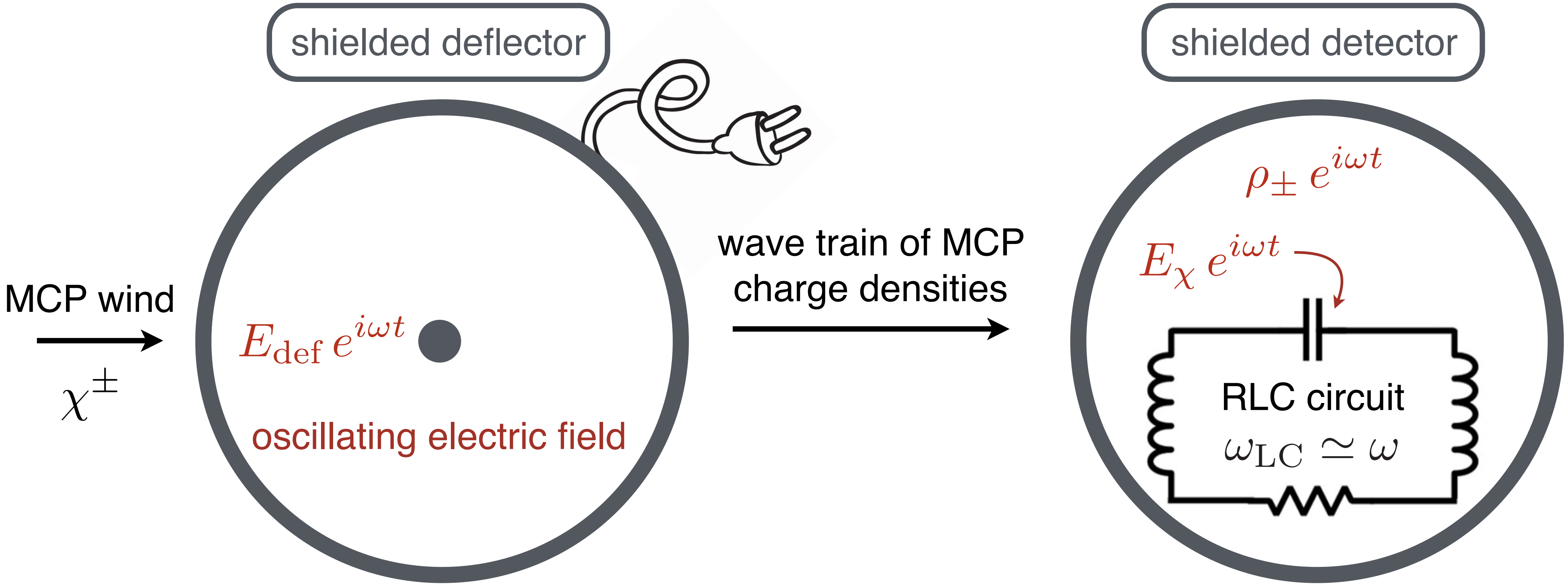
DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



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$\chi^{\pm}$

$E_{\rm def}\, e^{i\omega t}$

oscillating electric field

wave train of MCP charge densities

$\rho_{\pm}\, e^{i\omega t}$

$E_{\chi}\, e^{i\omega t}$

RLC circuit

$\omega_{\rm LC} \simeq \omega$

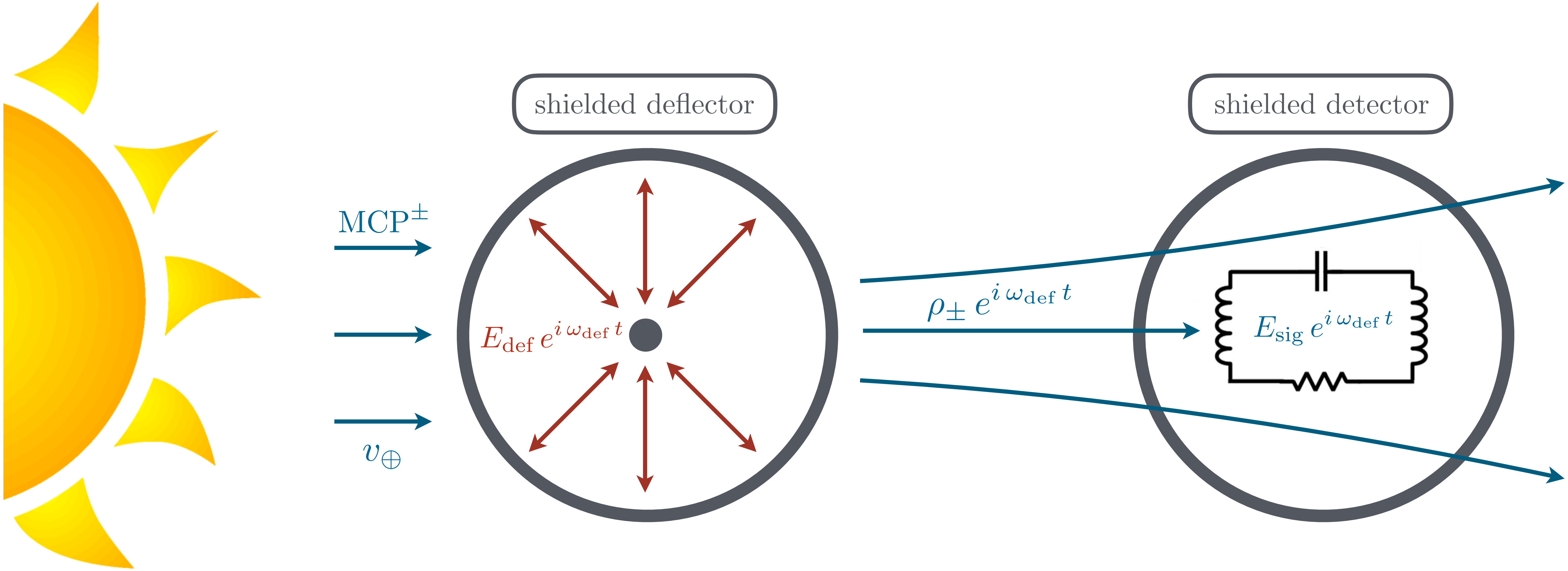
wind-blowing

(similar to “~~light-shining~~-through-wall” experiments)

inducing and detecting collective disturbances $\Longrightarrow$ no kinematic barrier

Slide credit: Asher Berlin

DEFLECTION OF MCPS FROM THE SUN



- MCP velocity distribution determines how easy particles are to deflect and size of resulting charge overdensity

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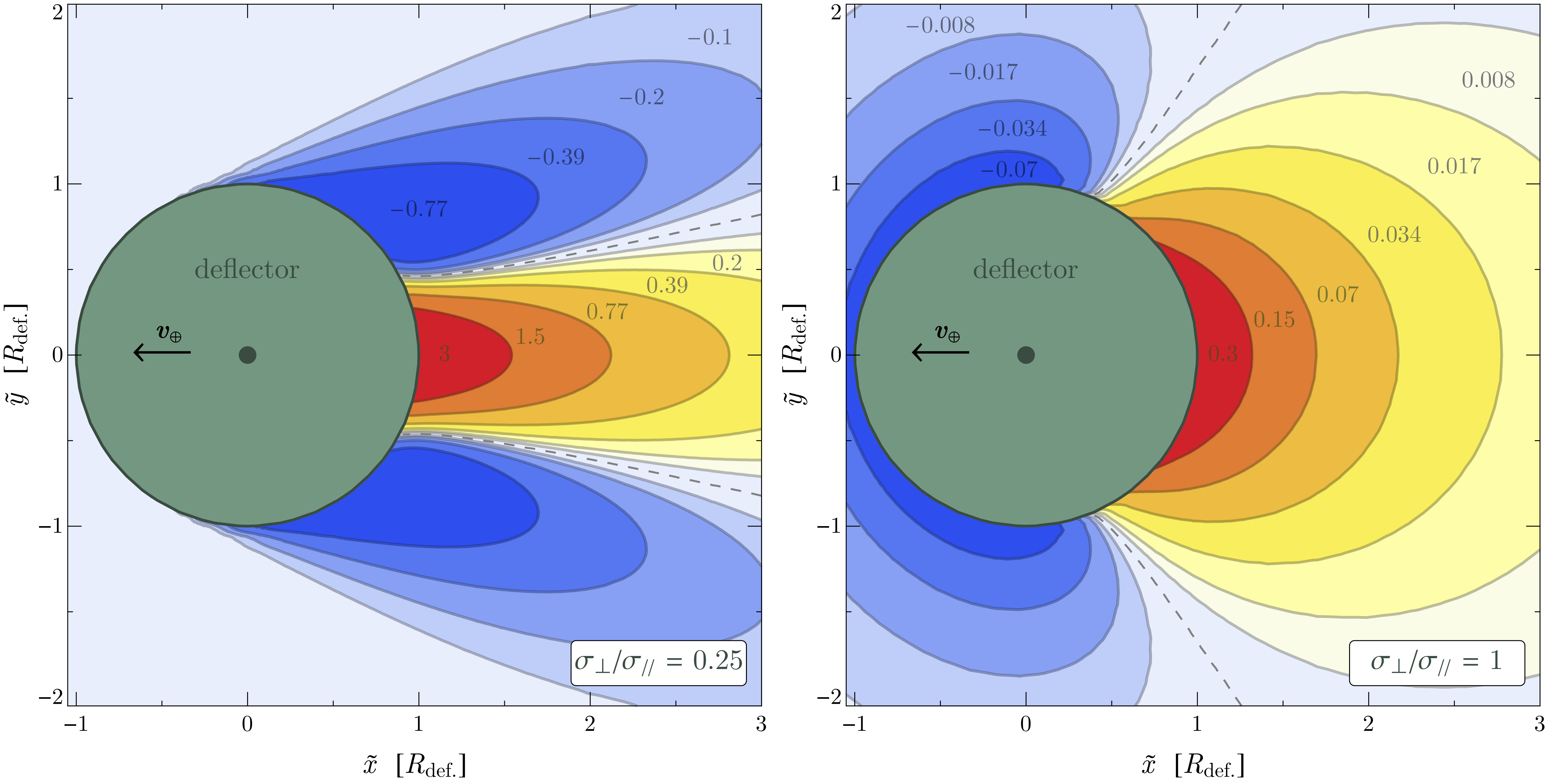
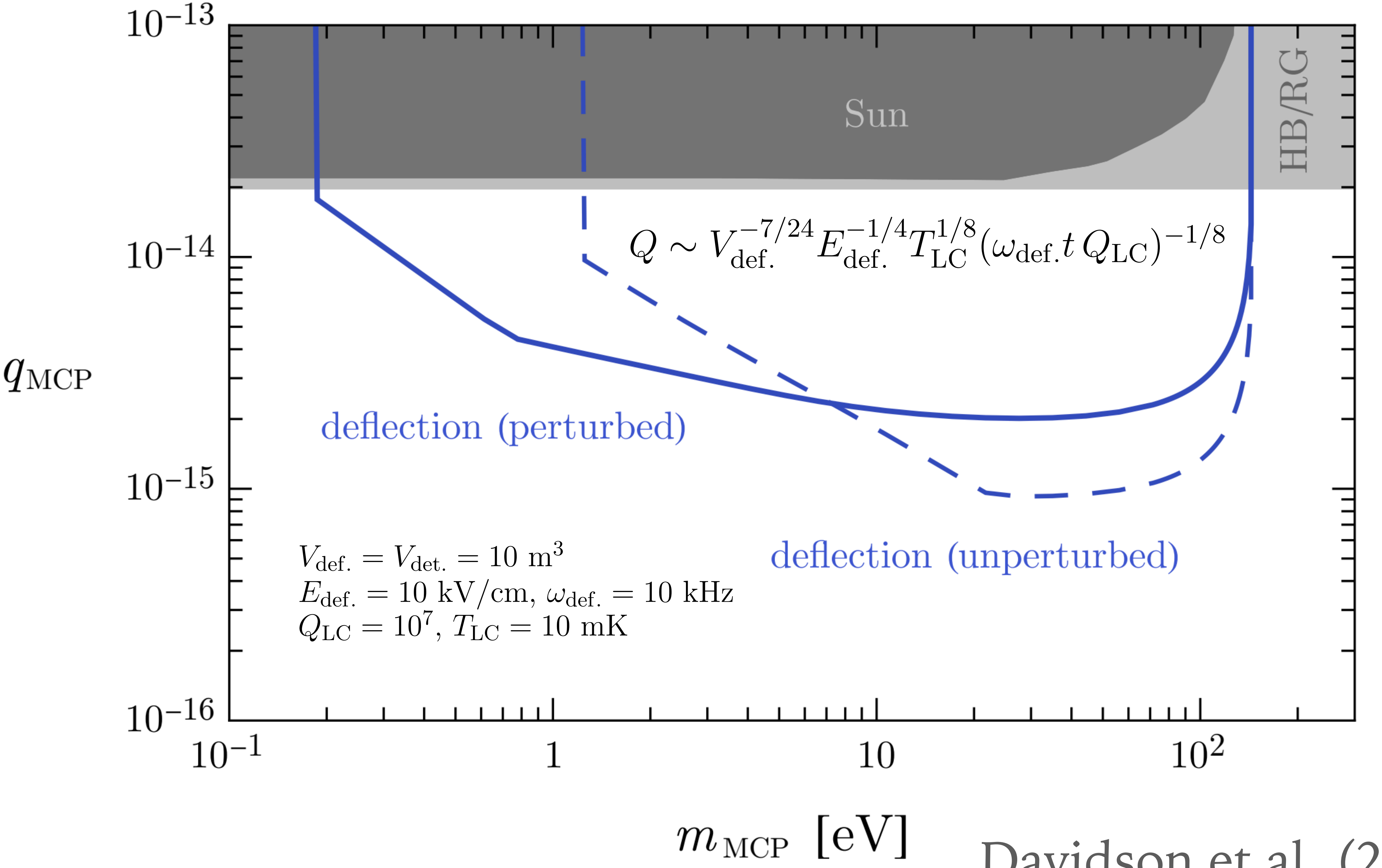
DEFLECTION DEPENDENCE ON PHASE SPACE



- More coherent velocity phase space leads to an enhanced charge density in the wake Berlin & **KS** (2111.01796)

PREDICTED REACH



Davidson et al. (2000)

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SUMMARY

- Particles in dark sector can be created and destroyed in astrophysical environments, can search for decay products or particles themselves
- Axions and/or MCPs may be observable/constrained in near future through a mix of lab and astrophysical probes
- It's a big Universe… lots more room for creativity in repurposing astrophysical systems!