AN AXION DARK MATTER-INDUCED ECHO OF SUPERNOVA REMNANTS

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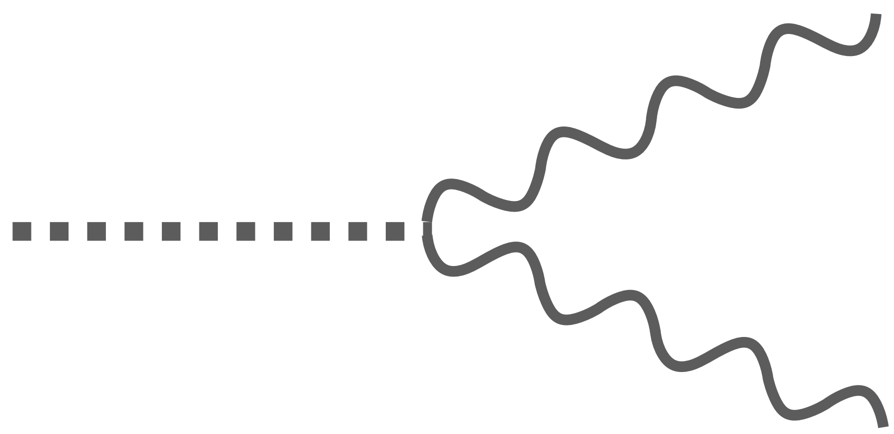
Aspen Center for Physics
New Methods and Ideas at the Frontiers of Particle Physics
3/24/2022

based on work with Yitian Sun, Anjali Nambrath, Calvin Leung, and Kiyo Masui

AXION COUPLING TO PHOTONS



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

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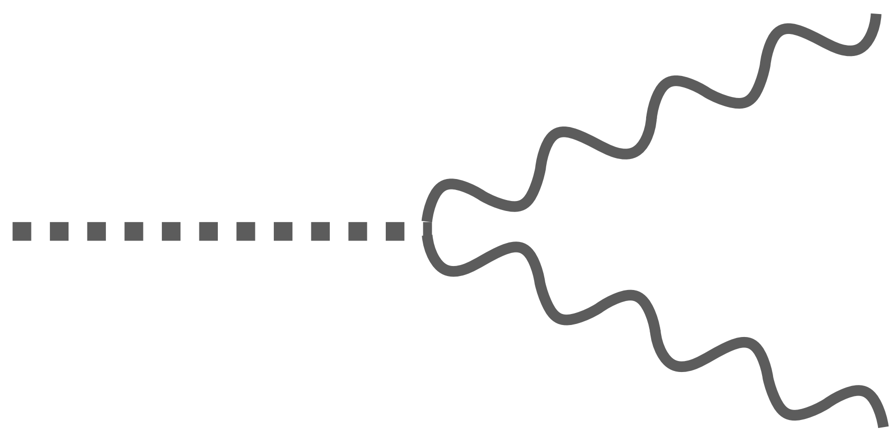

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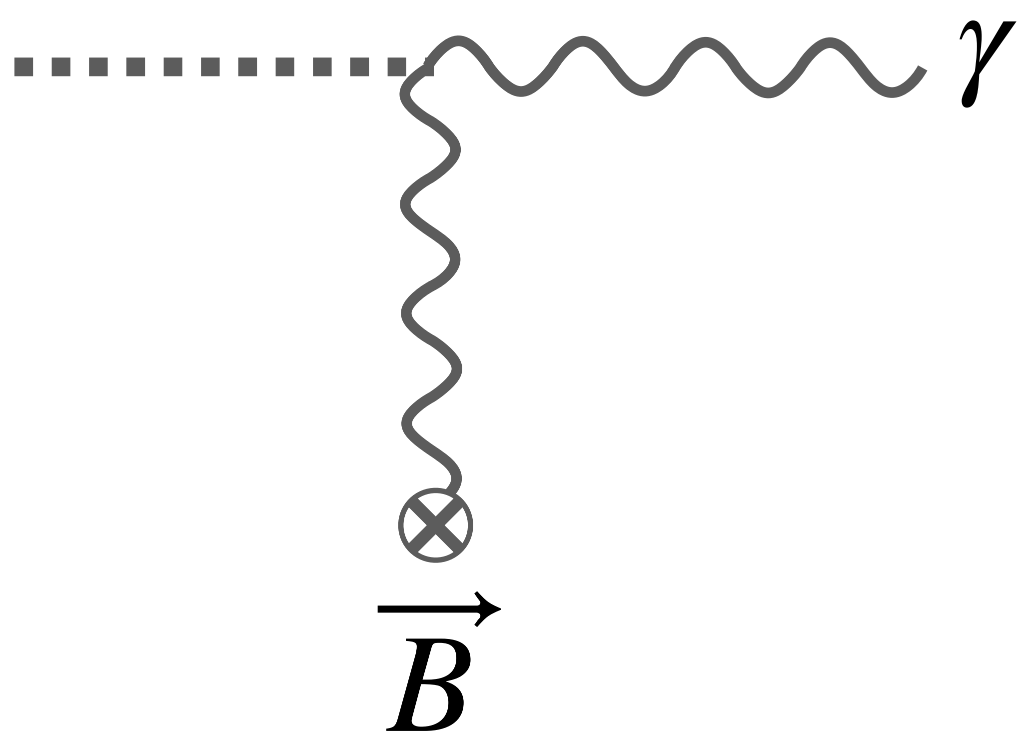
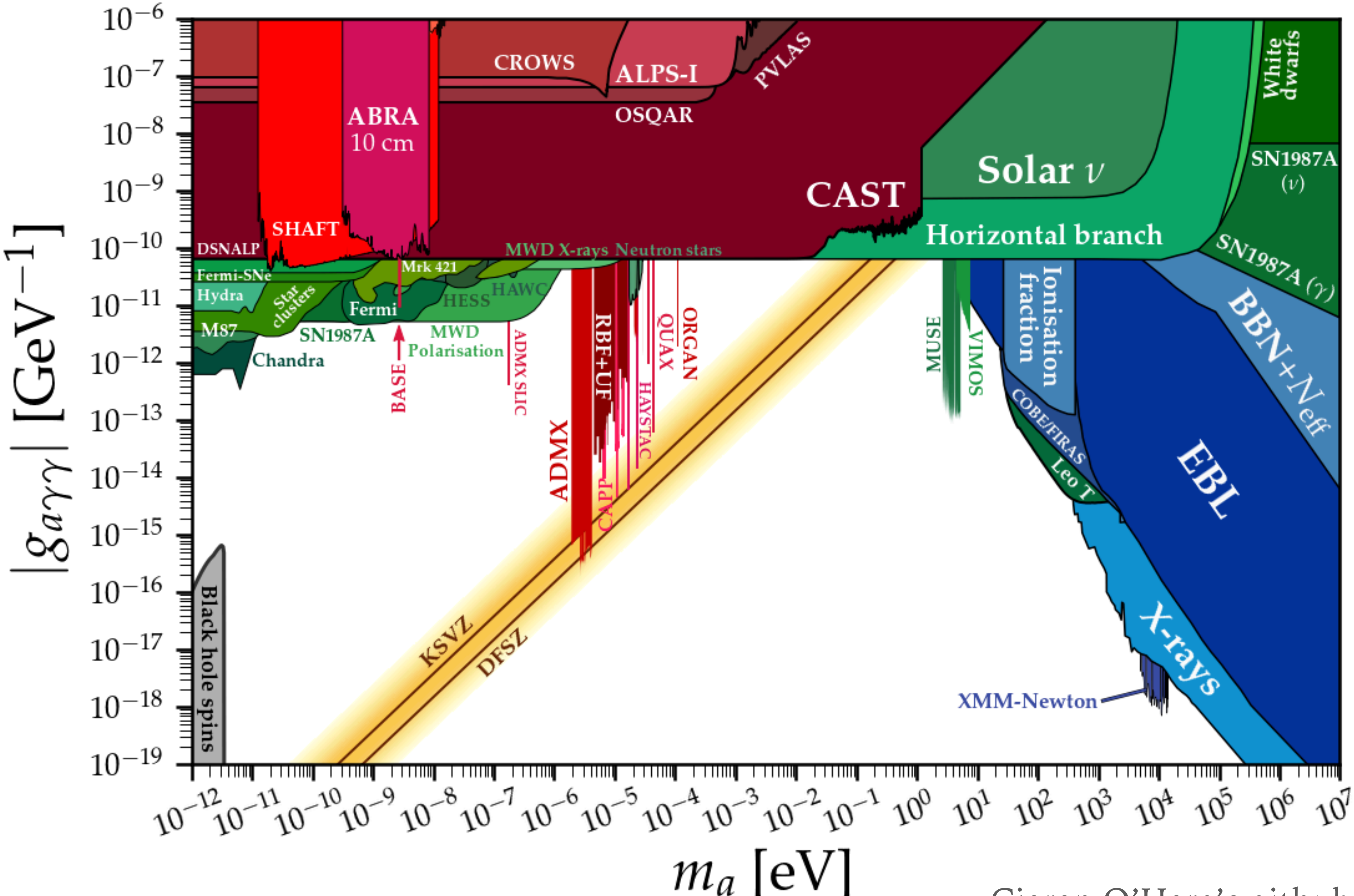


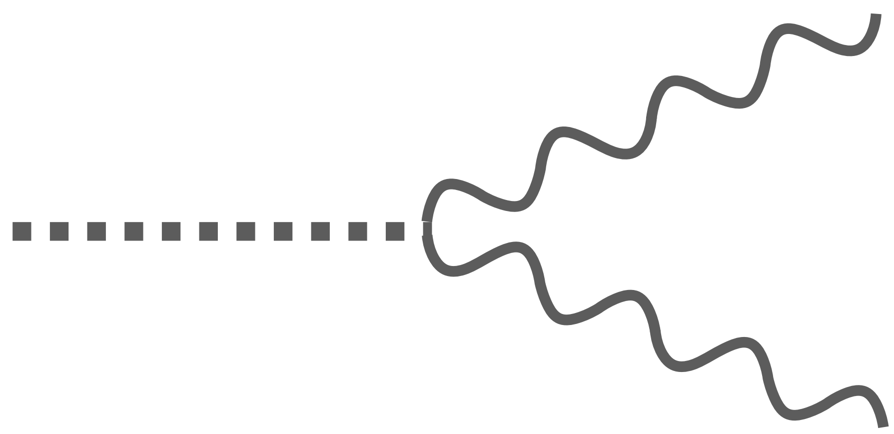
Primakoff process: can be leveraged in terrestrial experiments (e.g. resonant cavities) and astrophysical systems (e.g. neutron star magnetospheres)

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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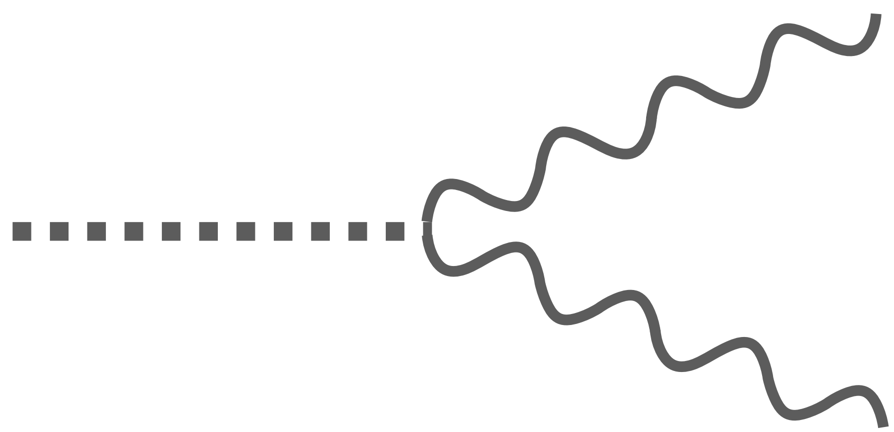

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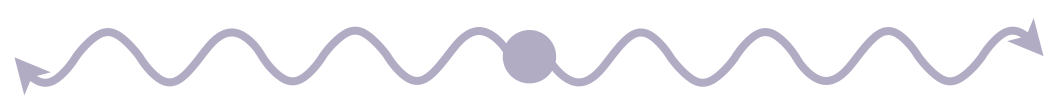
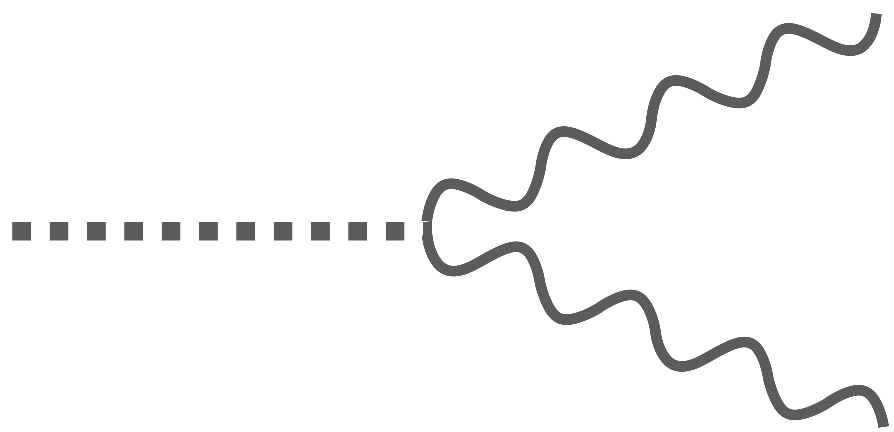


$\omega = m_a/2$ in axion rest frame

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

AXION STIMULATED DECAY



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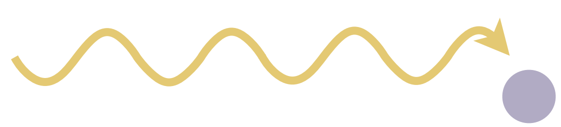

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e.g. Arza & Sikivie (2019)

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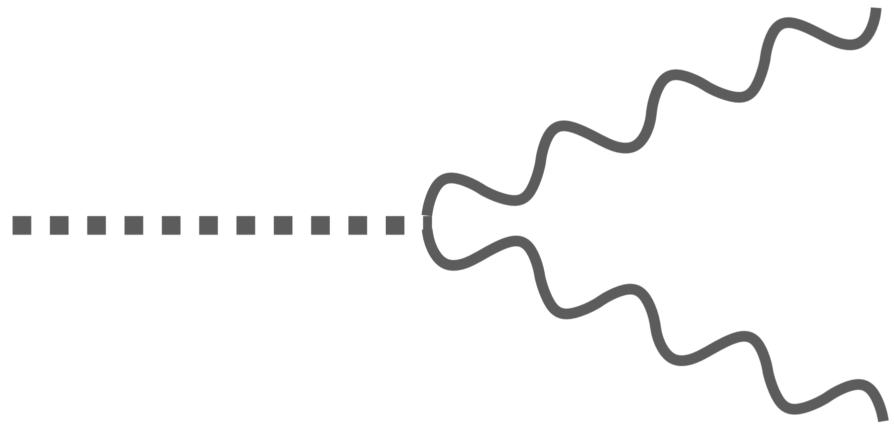

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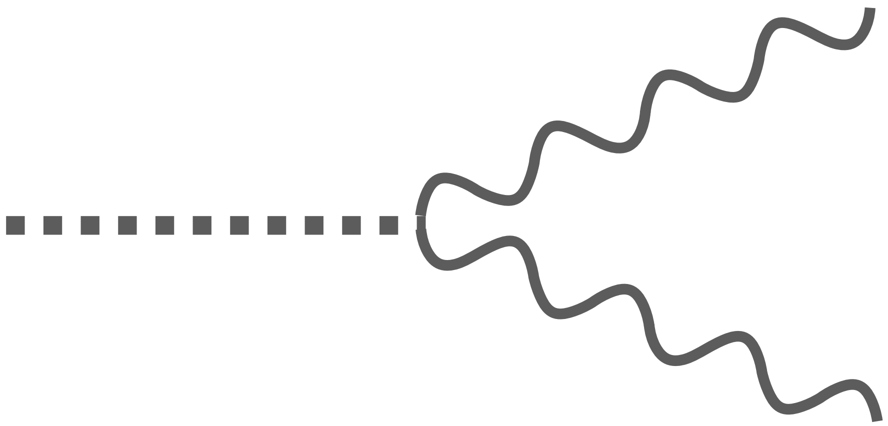

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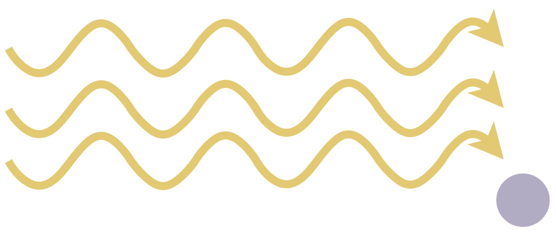
This is Bose enhanced



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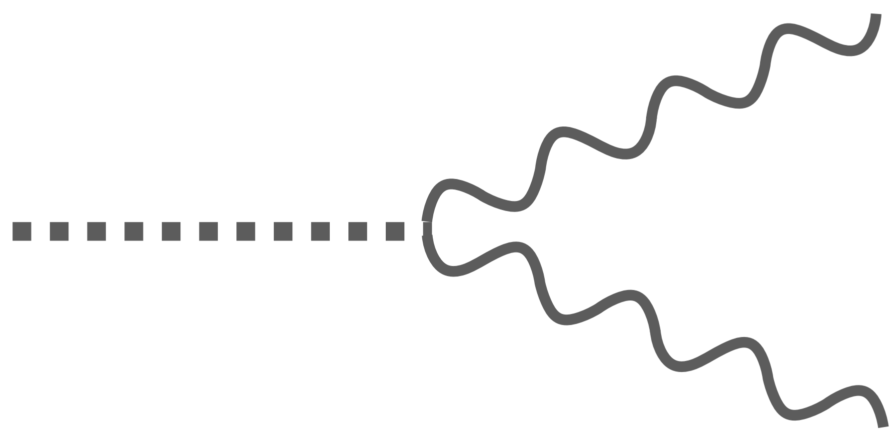

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$$S_{\mathrm{out}} \sim \left.\frac{dS_{\mathrm{in}}}{d\omega}\right|_{\omega=m_a/2}$$

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e.g. Arza & Sikivie (2019)

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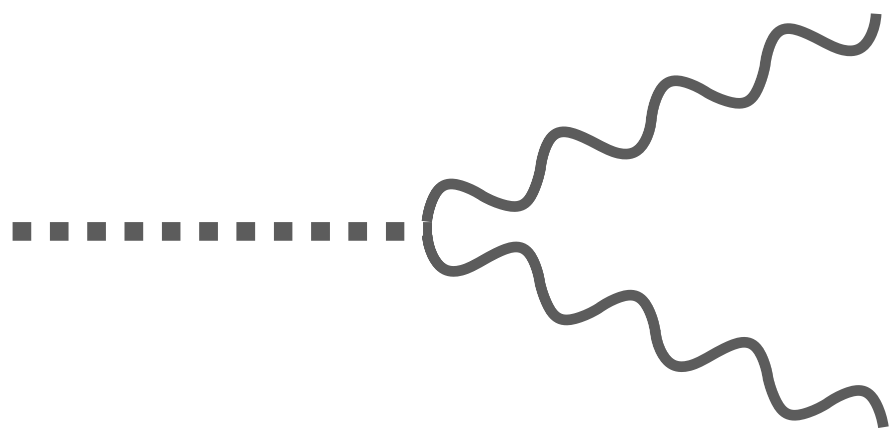

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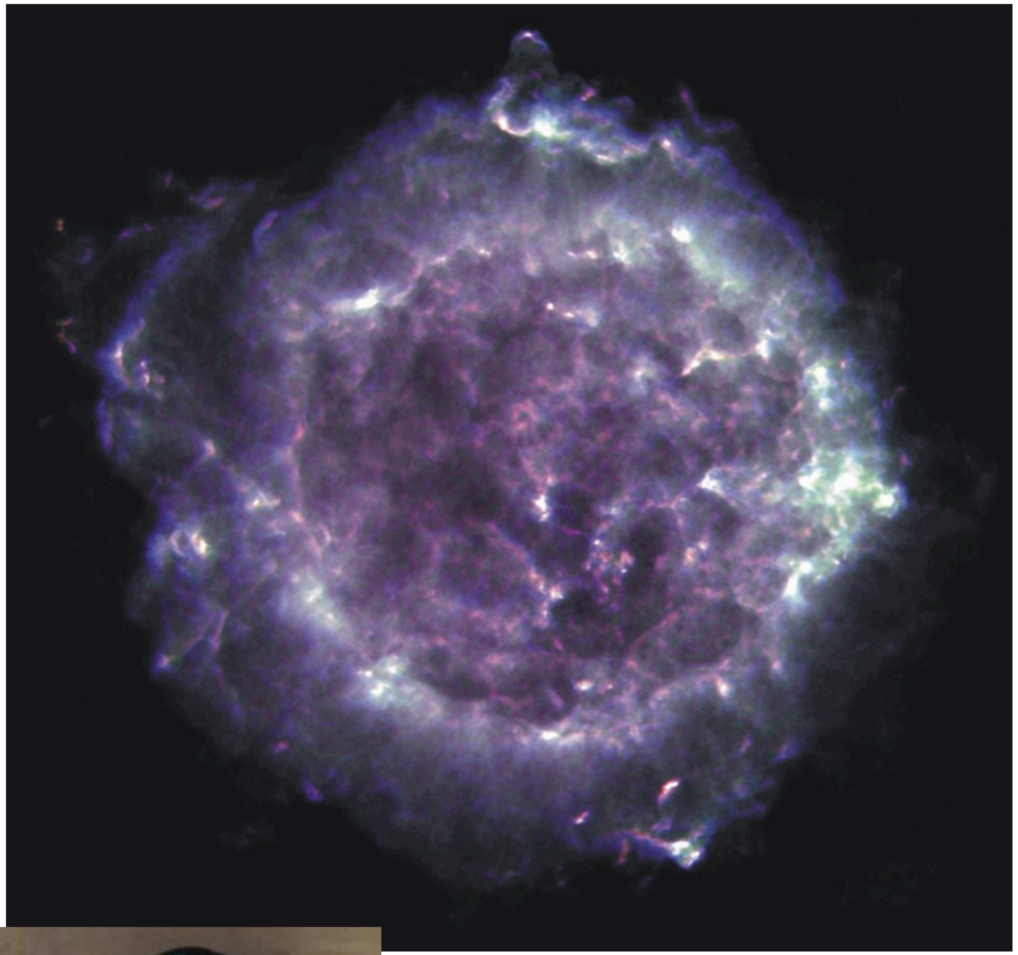
Along axion column, flux of decay products $$S_{\text{out}} = \frac{g_{a\gamma\gamma}^2}{16}\left.\frac{dS_{\text{in}}}{d\omega}\right|_{m_a/2}\int \rho_a\, dx$$

e.g. Arza & Sikivie (2019)

THE UPSHOT:
AXIONS ARE AN IMPERFECT MONOCHROMATIC MIRROR
“AXION GEGENSCHEIN”

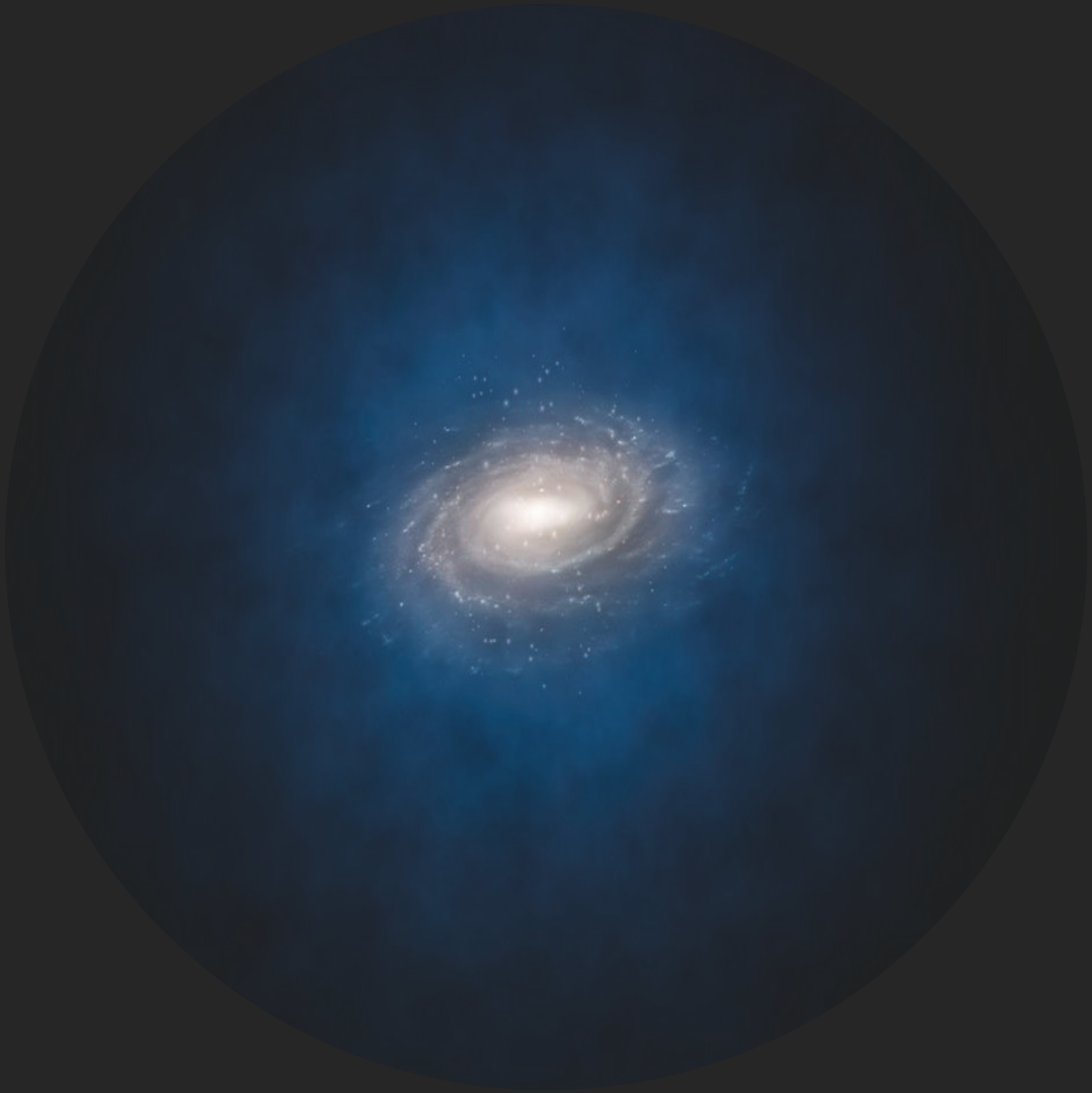
PROGRESS ON AXION GEGENSCHEIN

- 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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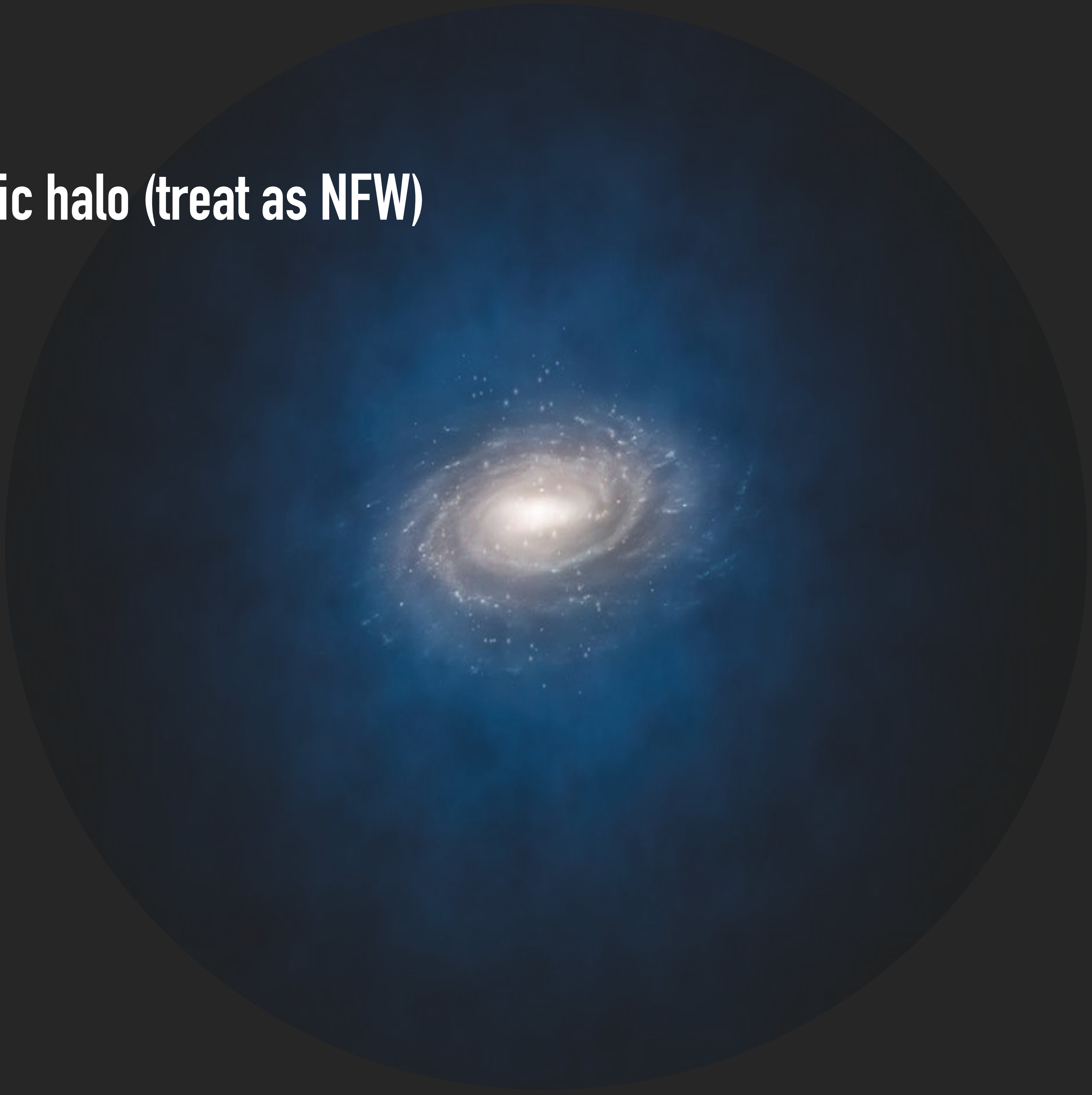

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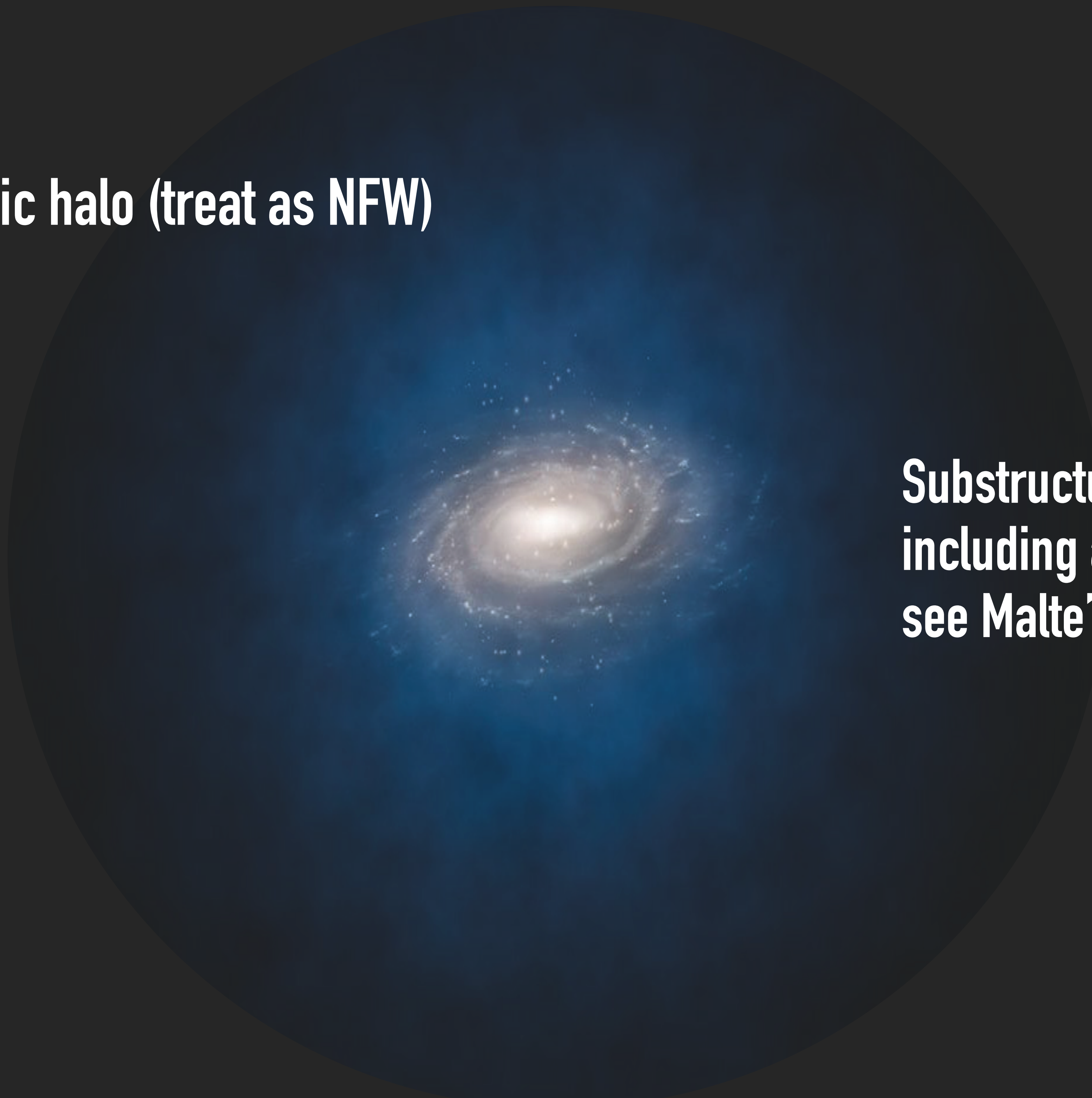
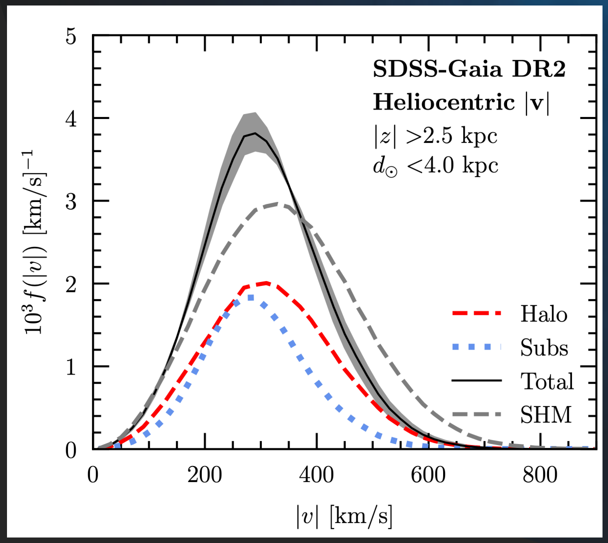


Axions as dark matter

Galactic halo (treat as NFW)

Substructure (possibly including axion mini-halos, see Malte's talk!)

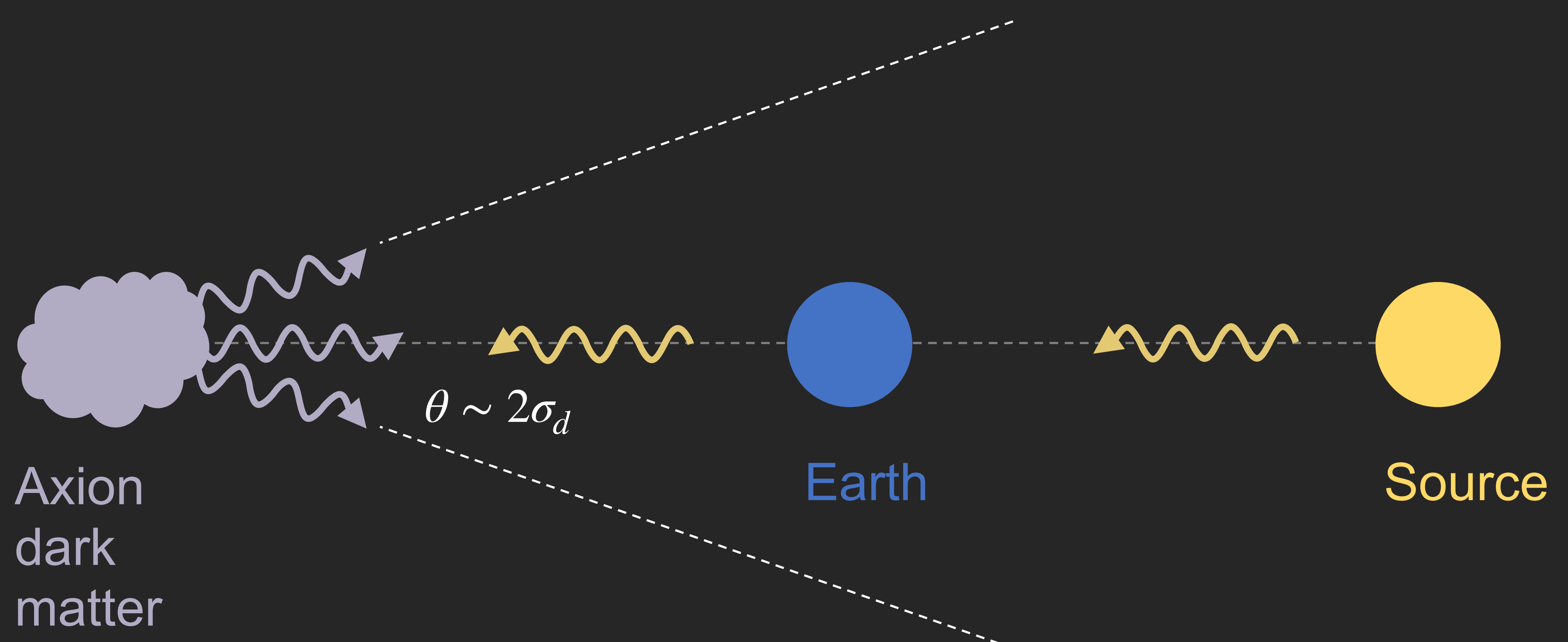
Velocity dispersion ~100 km/s near Earth



e.g. Necib et al. (2018)

Dispersion smears spectrally (Doppler effect) and spatially

Geometry of axion gegenschein



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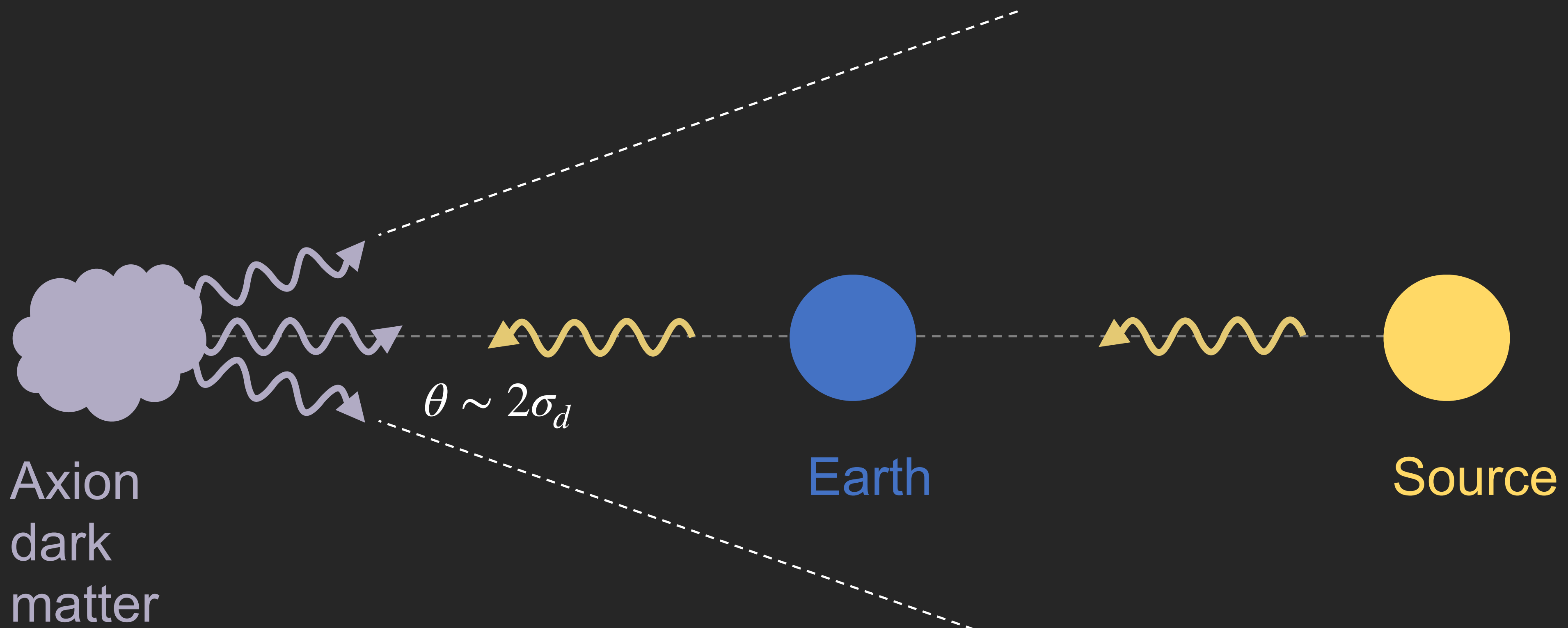

lose power? no.

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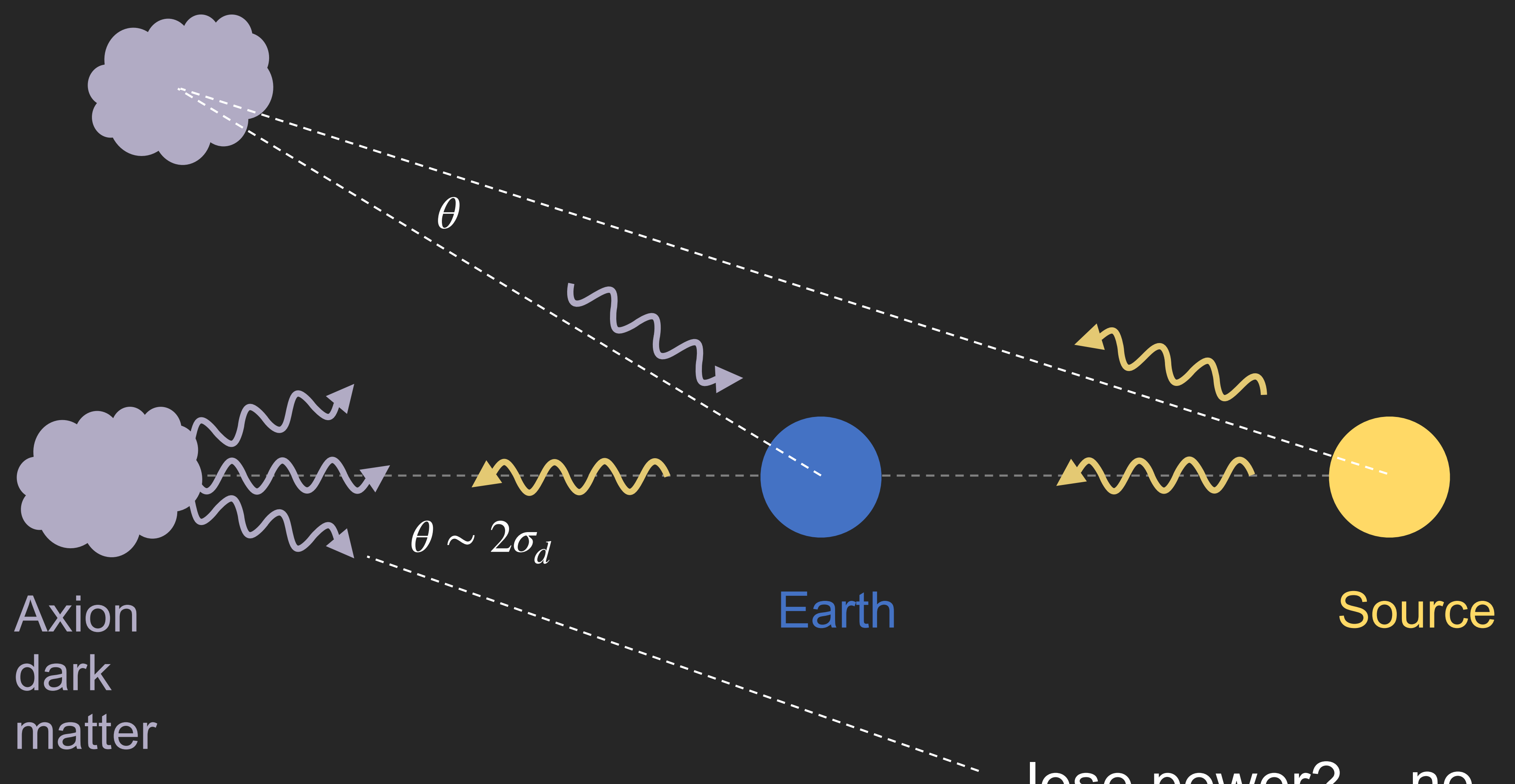

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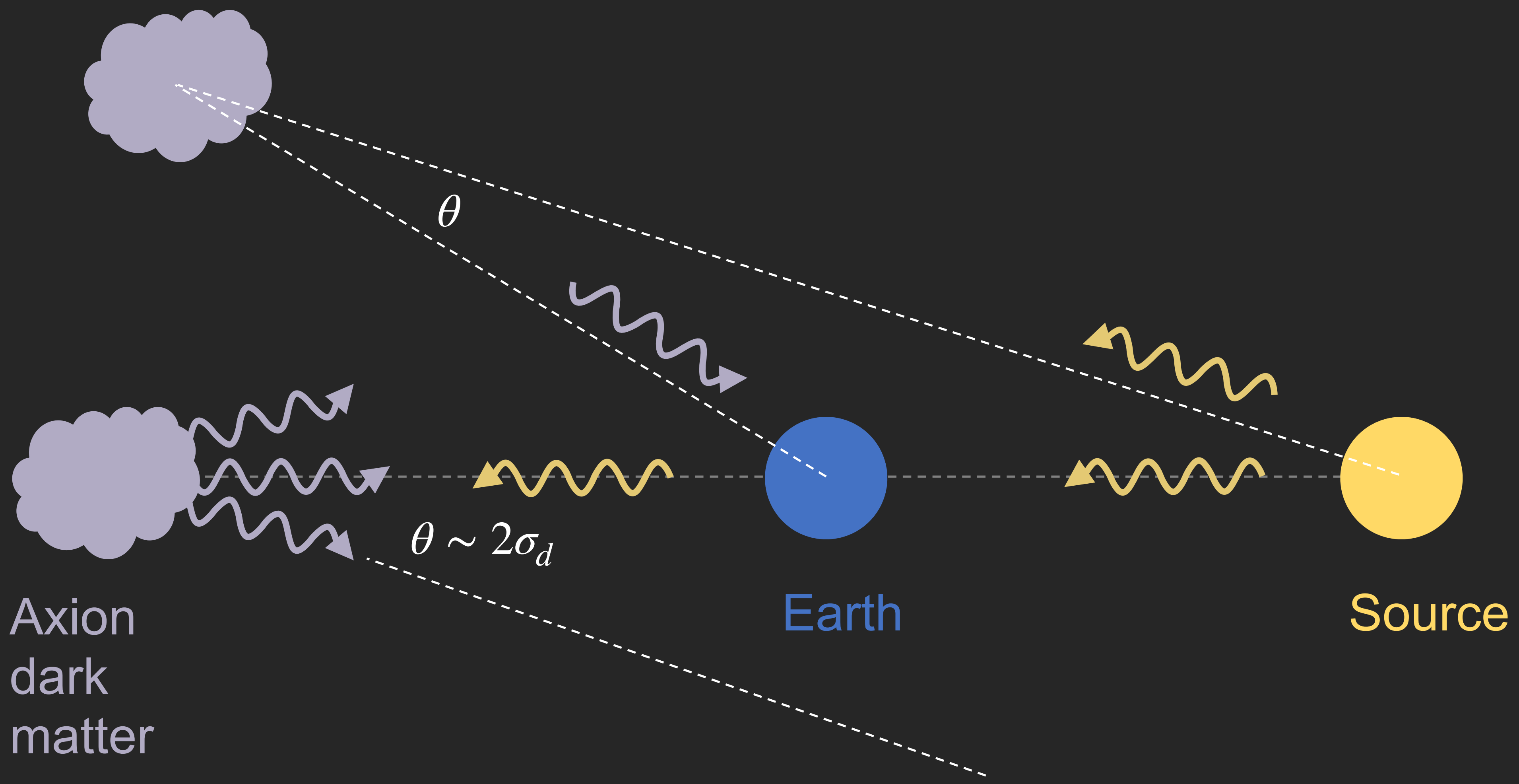

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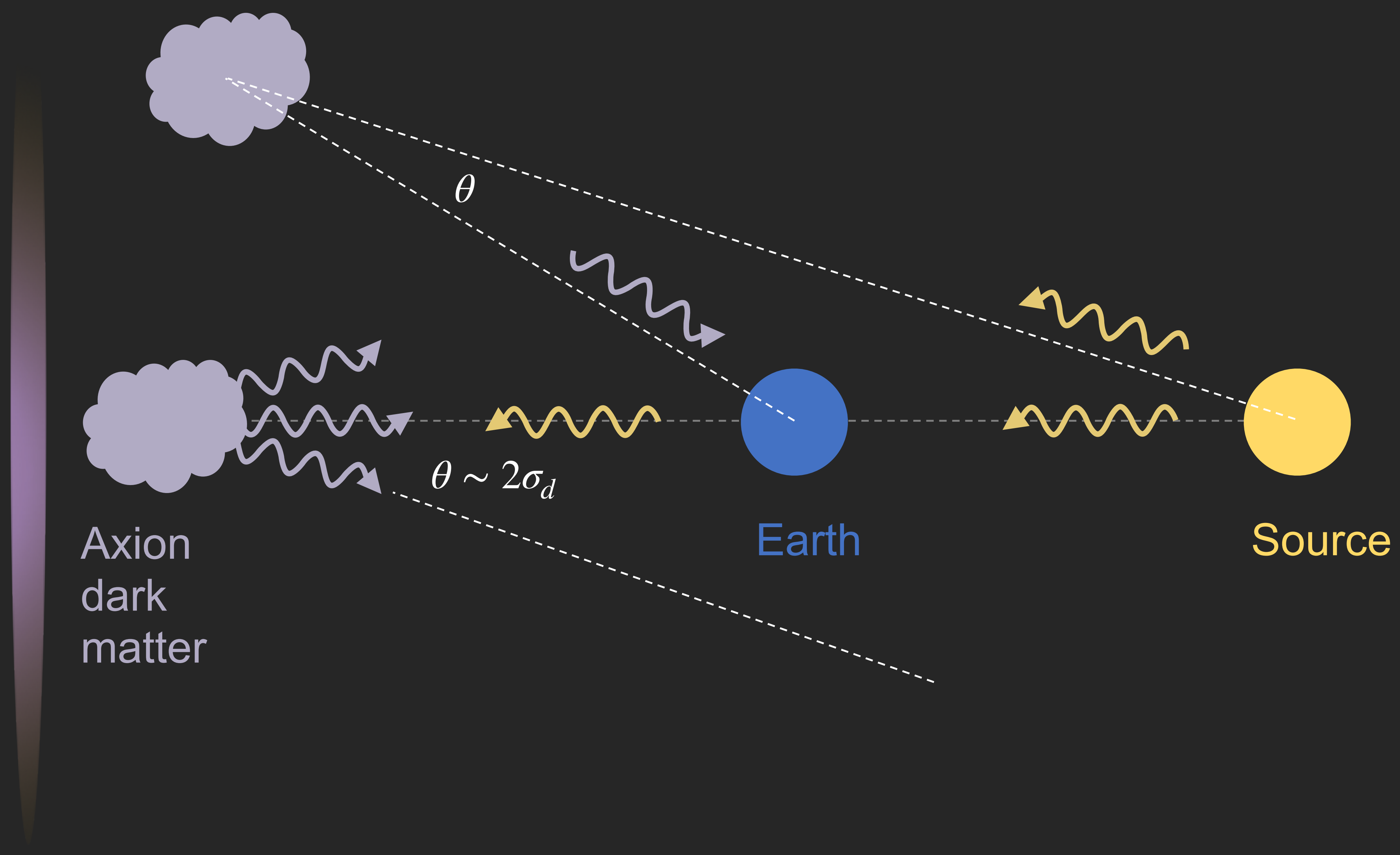
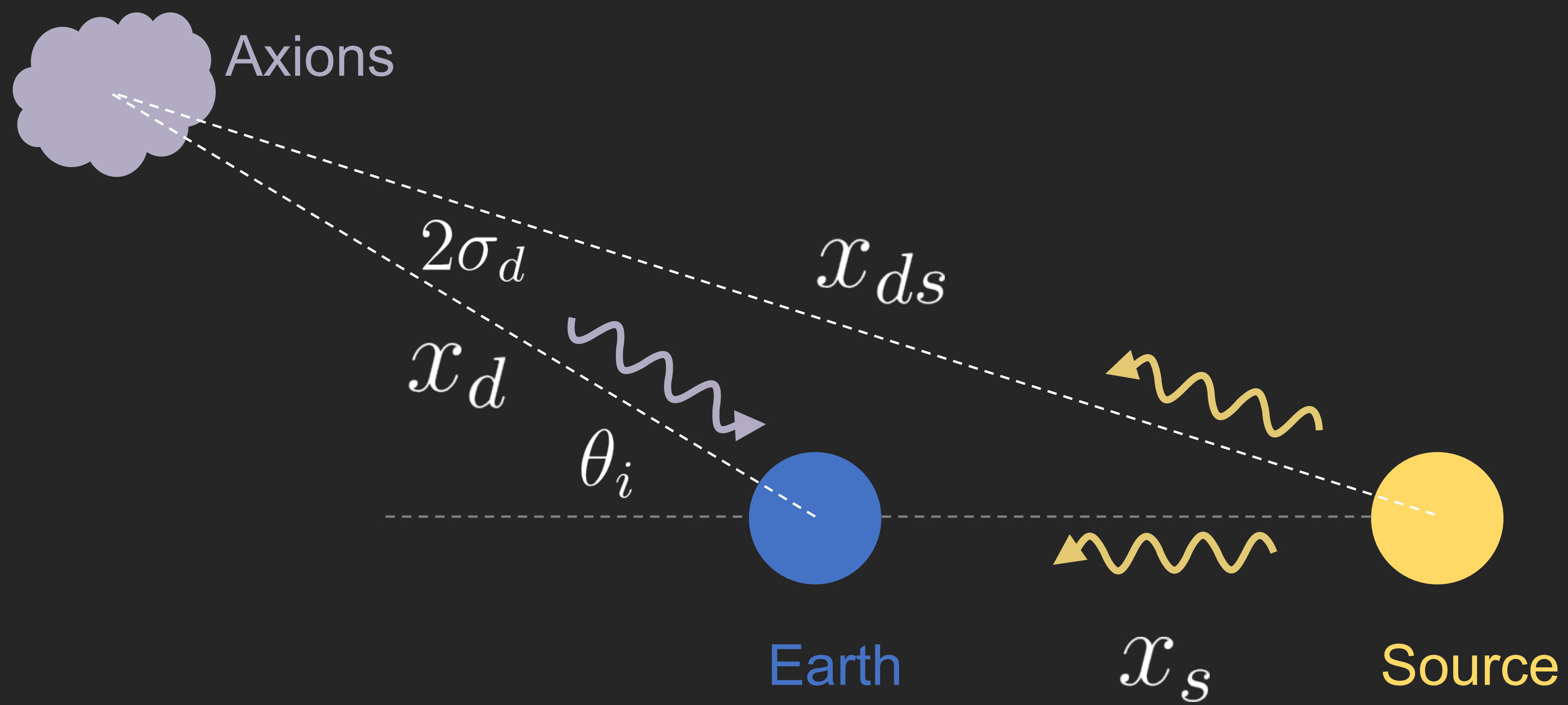


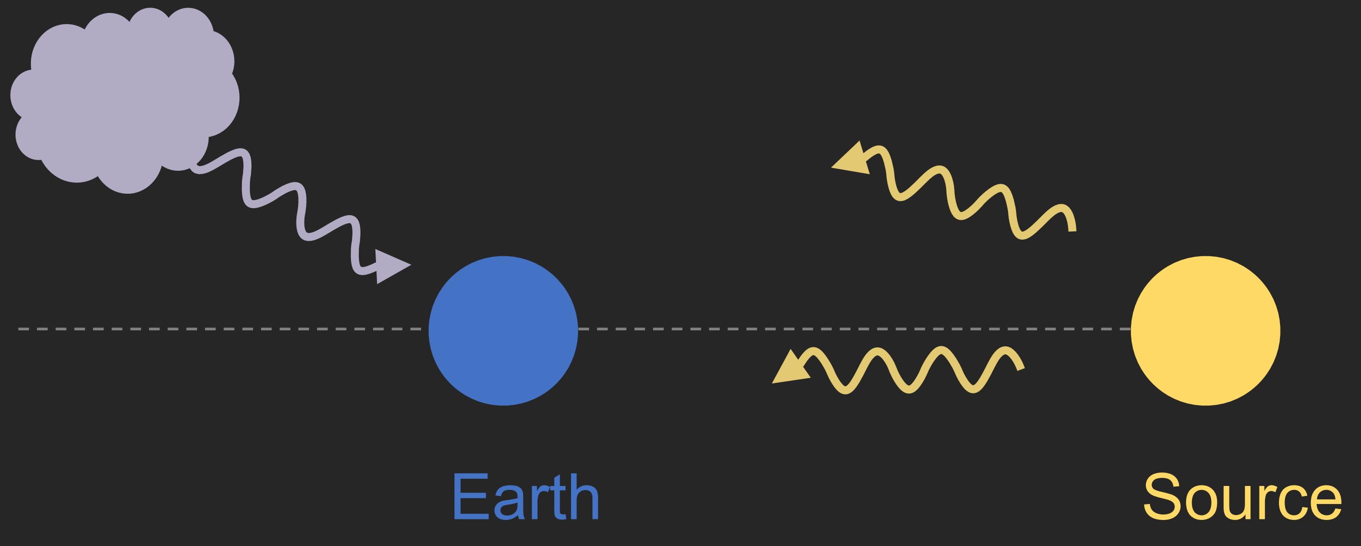


$$\sin\theta_i = \sin 2\sigma_d \, \frac{x_{ds}}{x_s}$$

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



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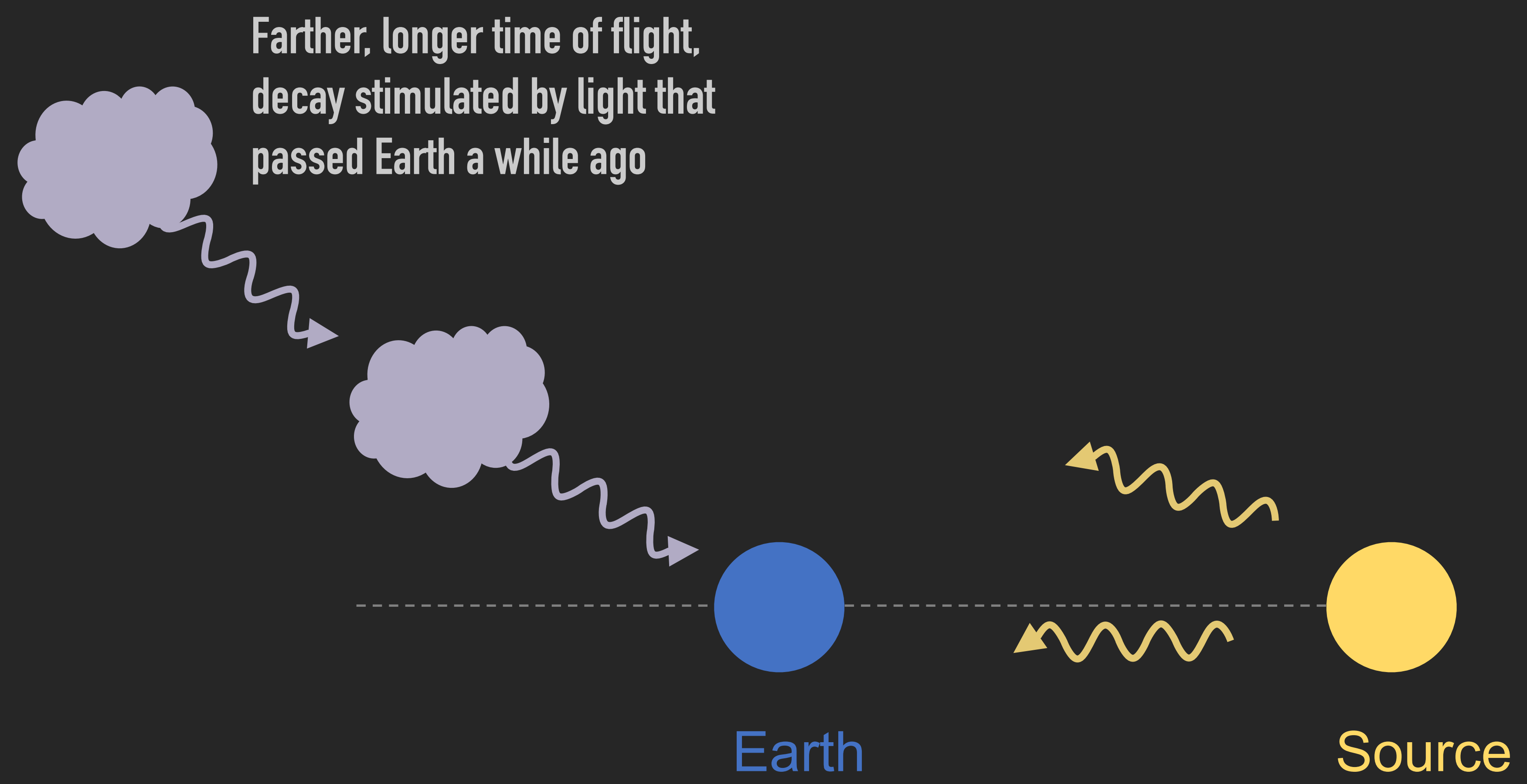

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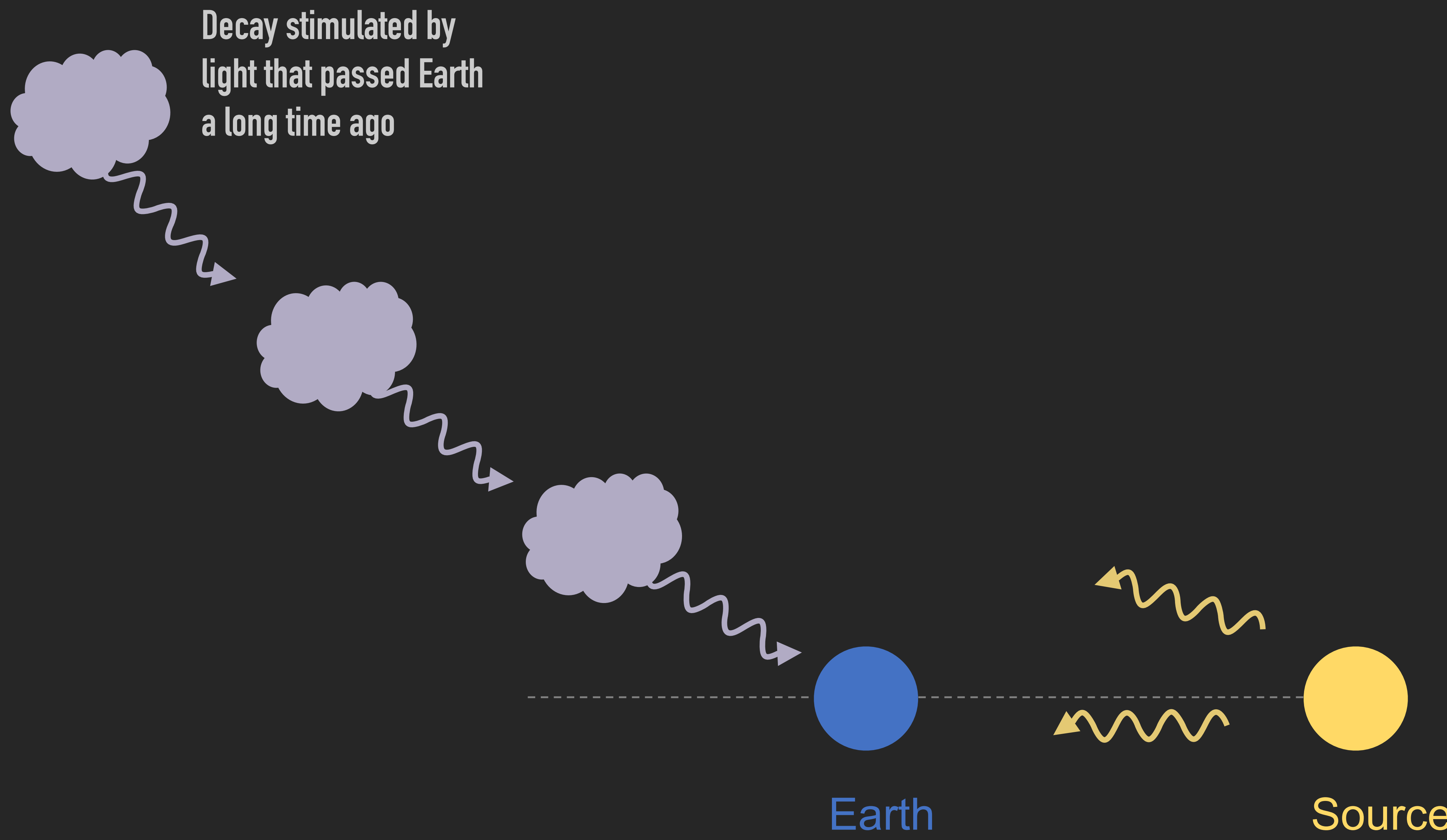

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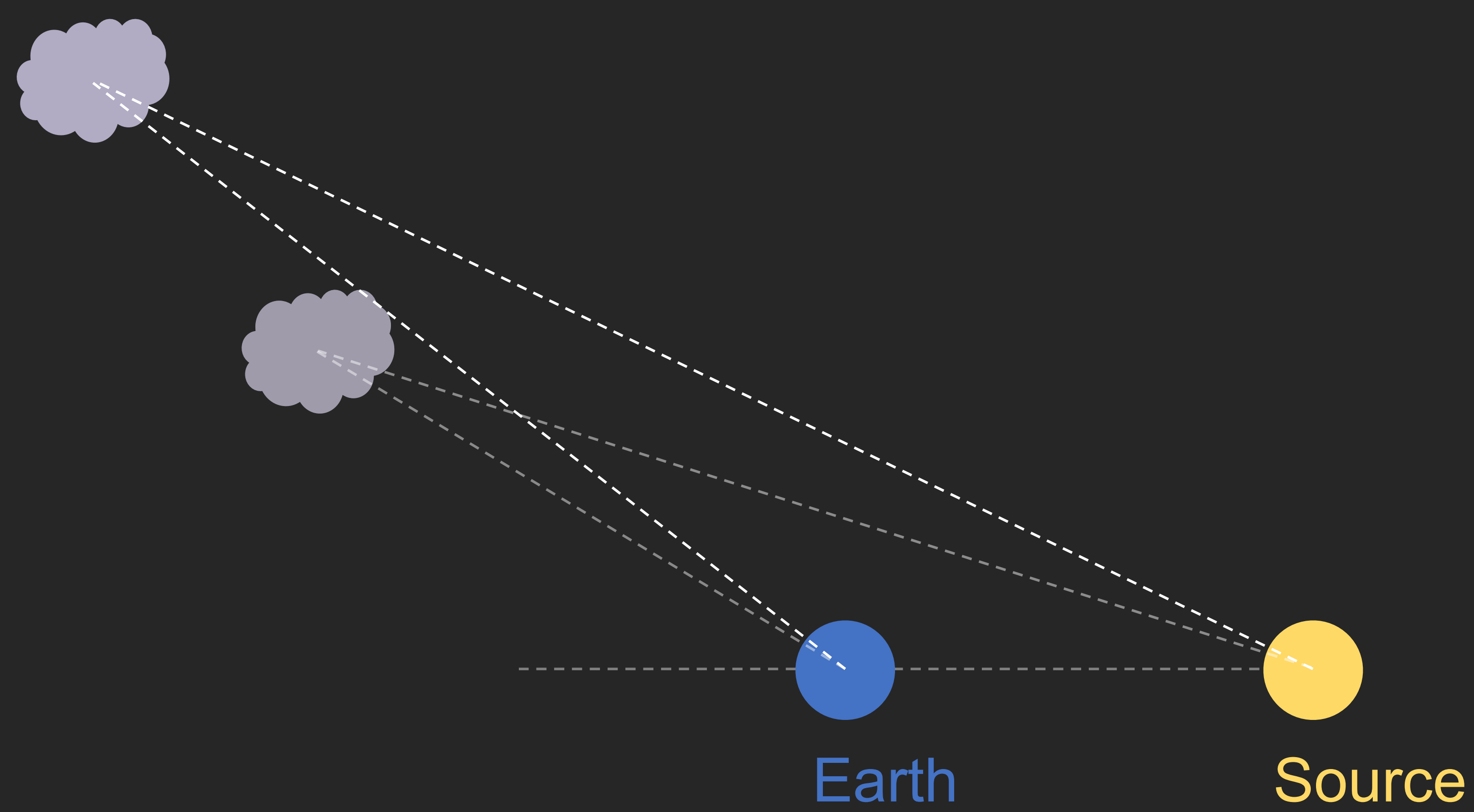
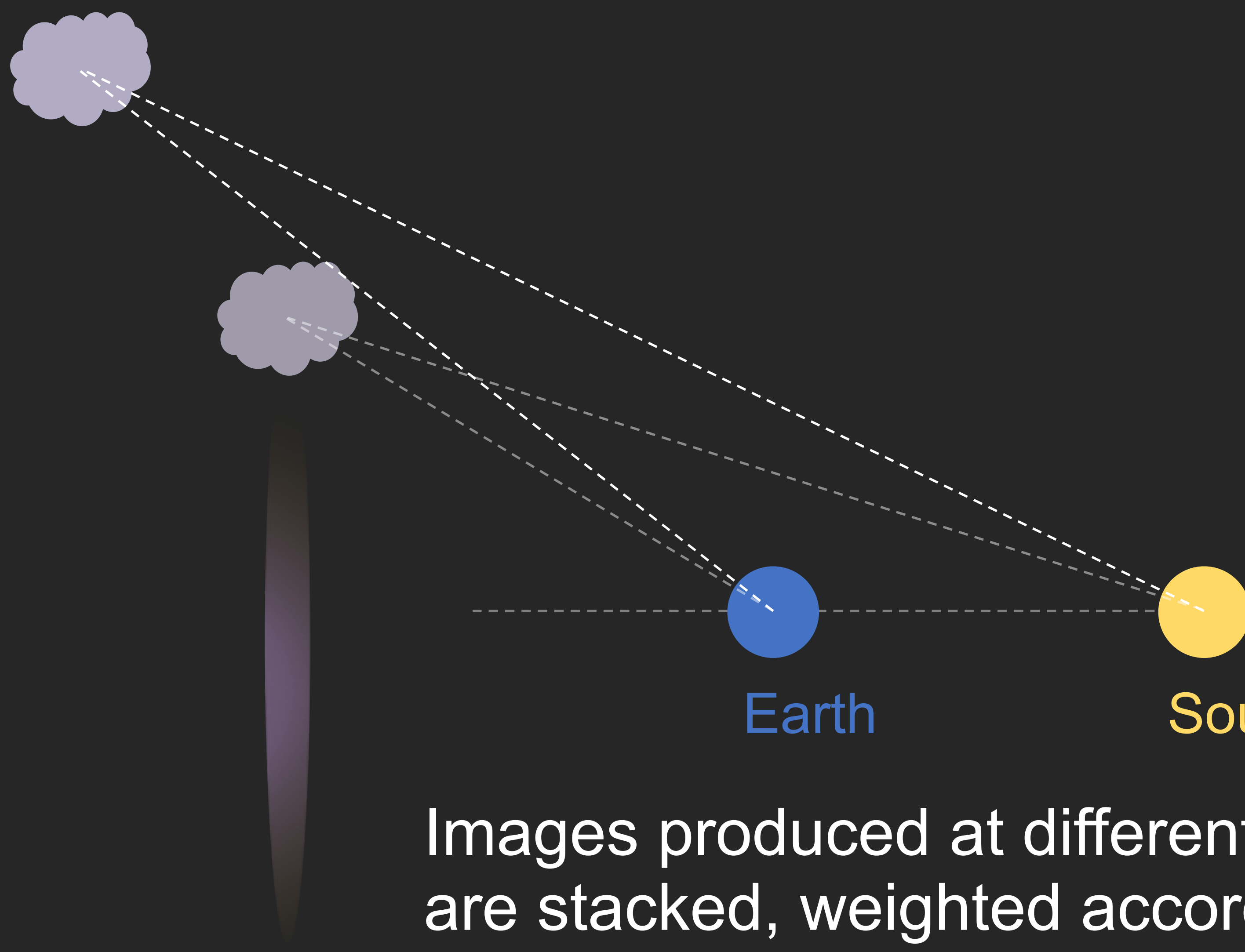


Images produced at different column depths are stacked, weighted according to how bright source was at corresponding time in the past

Sun, KS, et al. PRD (2022)



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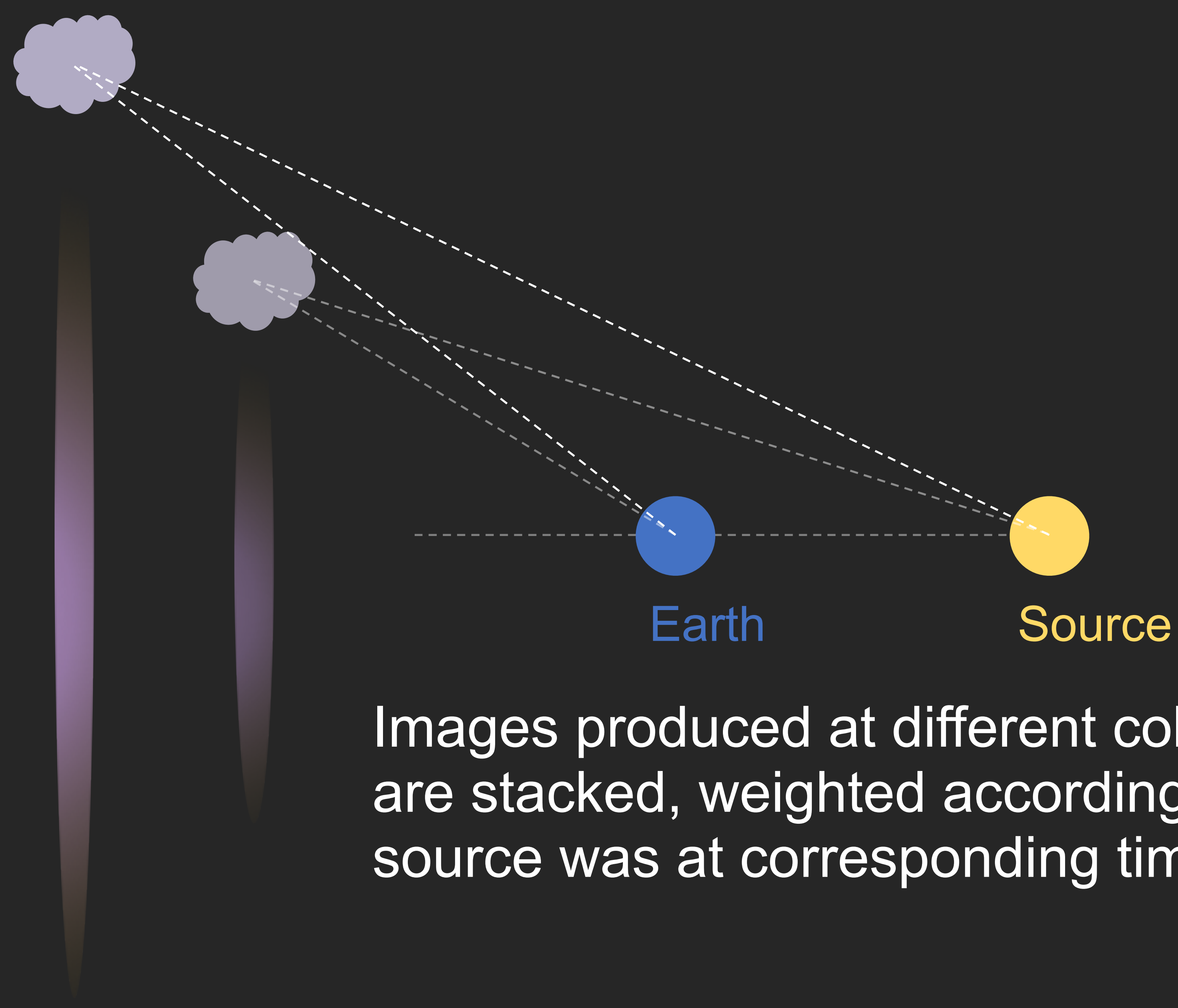

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Sun, KS, et al. PRD (2022)

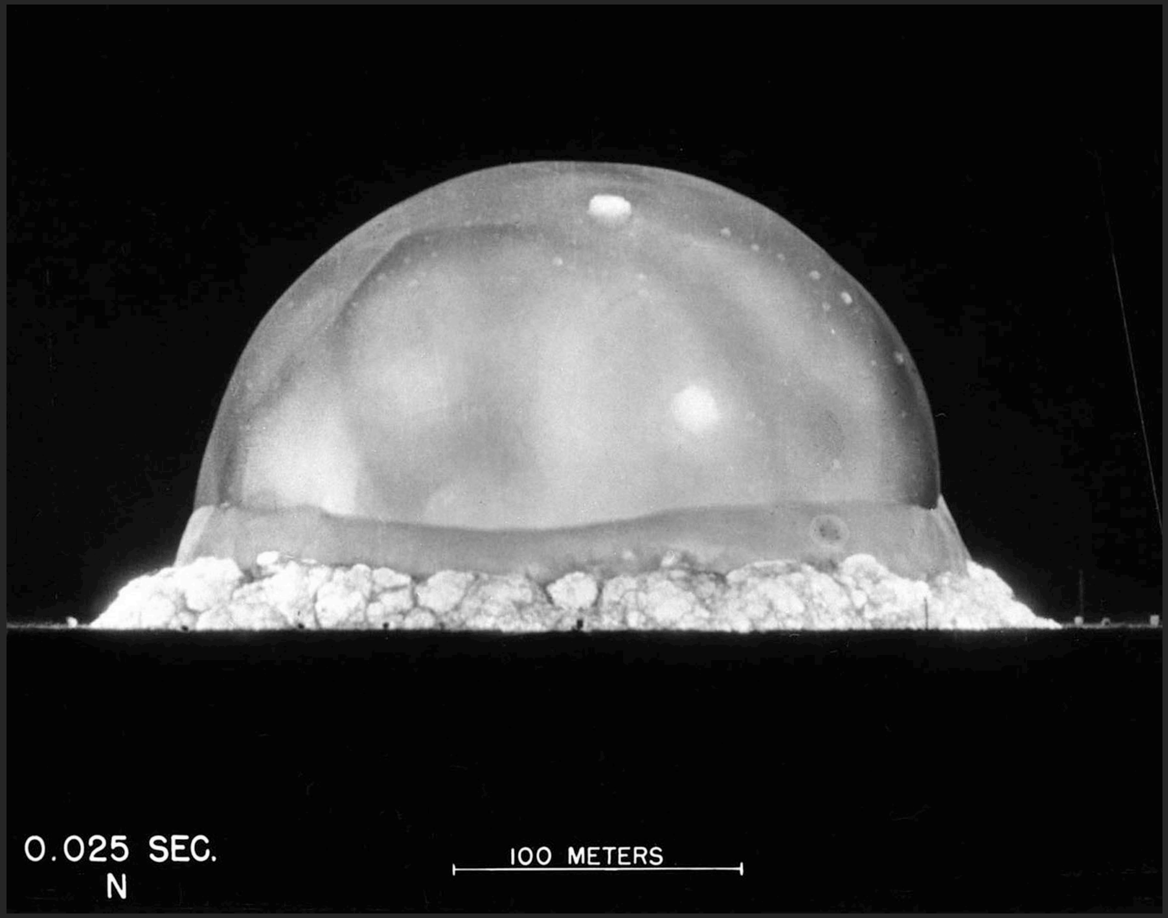
UPSHOT: OPTIMAL SOURCES OF STIMULATING RADIATION ARE BRIGHT AND WERE SIGNIFICANTLY BRIGHTER IN THE PAST

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



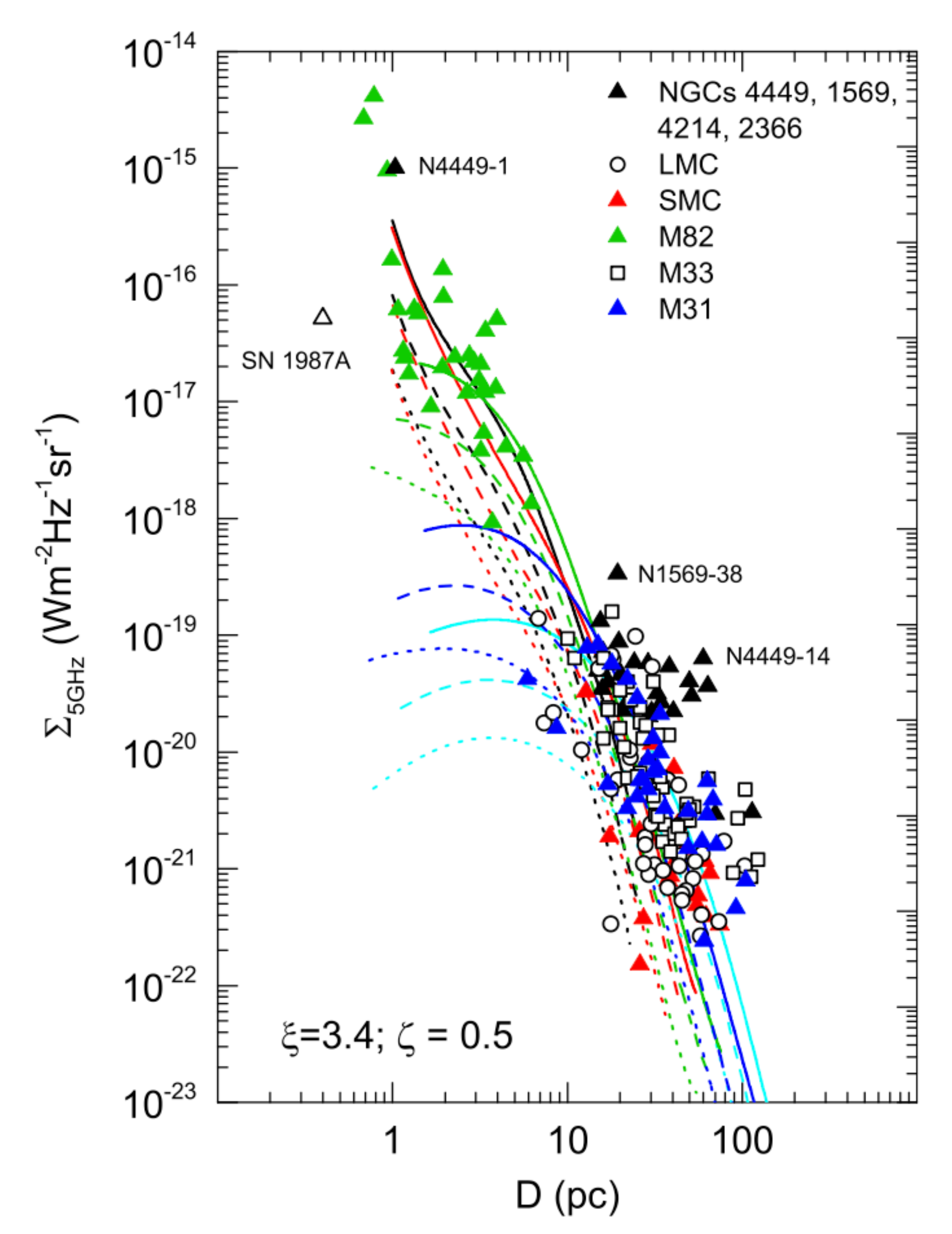
3-color image of the W28 supernova remnant seen in Very Large Array (VLA) and Southern Galactic Plane Survey. NRAO/AUI and Brogan et al. 2006.

- 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

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

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):

$$p = 2.4 \pm 0.2$$

[1] Shklovskii 1960

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- 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:

$$B \sim v_{\mathrm{sh}}^{2\sim 3} \sim R^{-1.5\sim 2.25}$$

- Magnetic field amplification onset time:
  - Core-collapse supernovae have dense circumstellar medium, which interacts with shock front very early on

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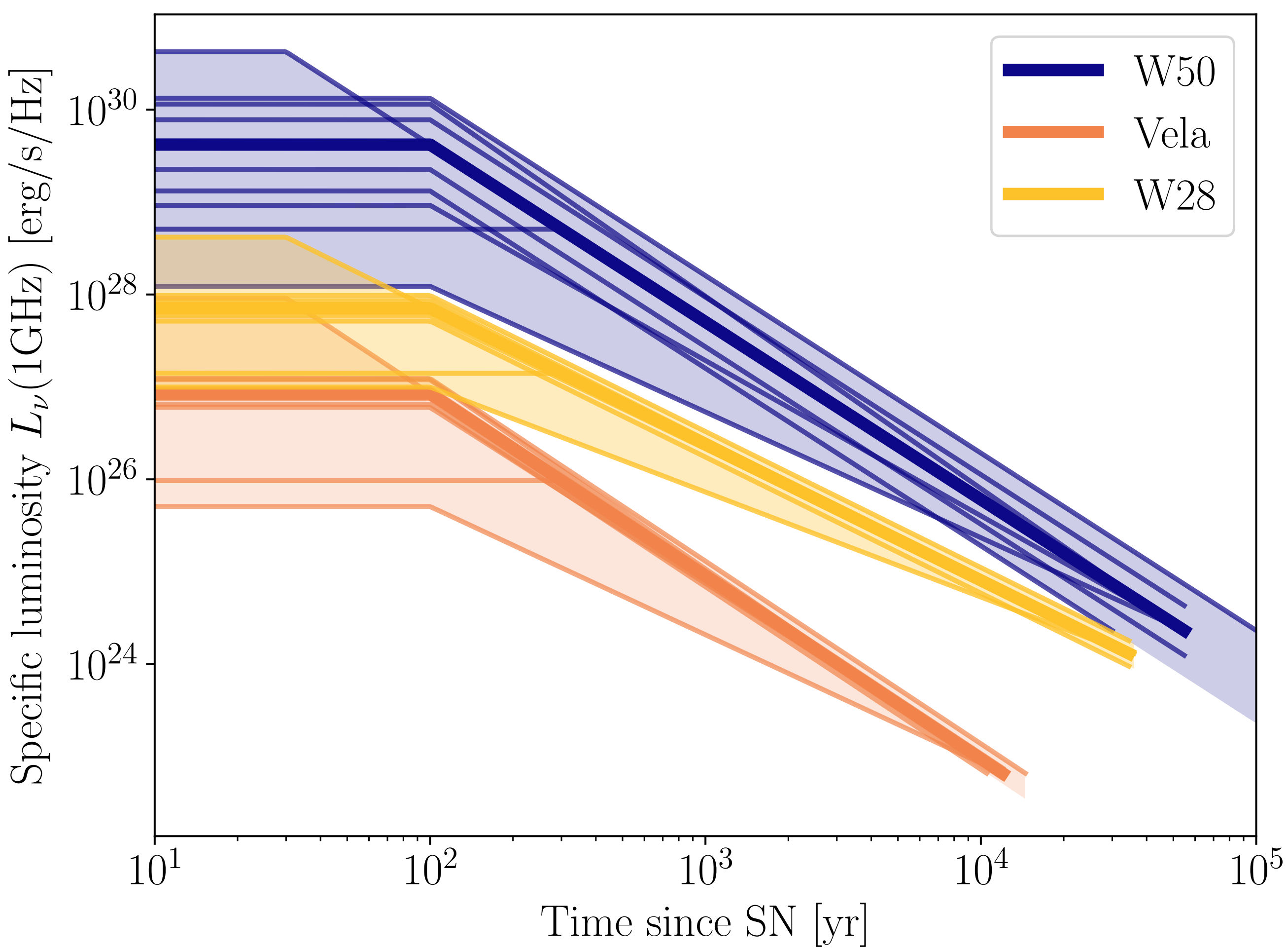
  - Simulations suggest onset of B field around ~100 years

MODELING OUR BEST SOURCES

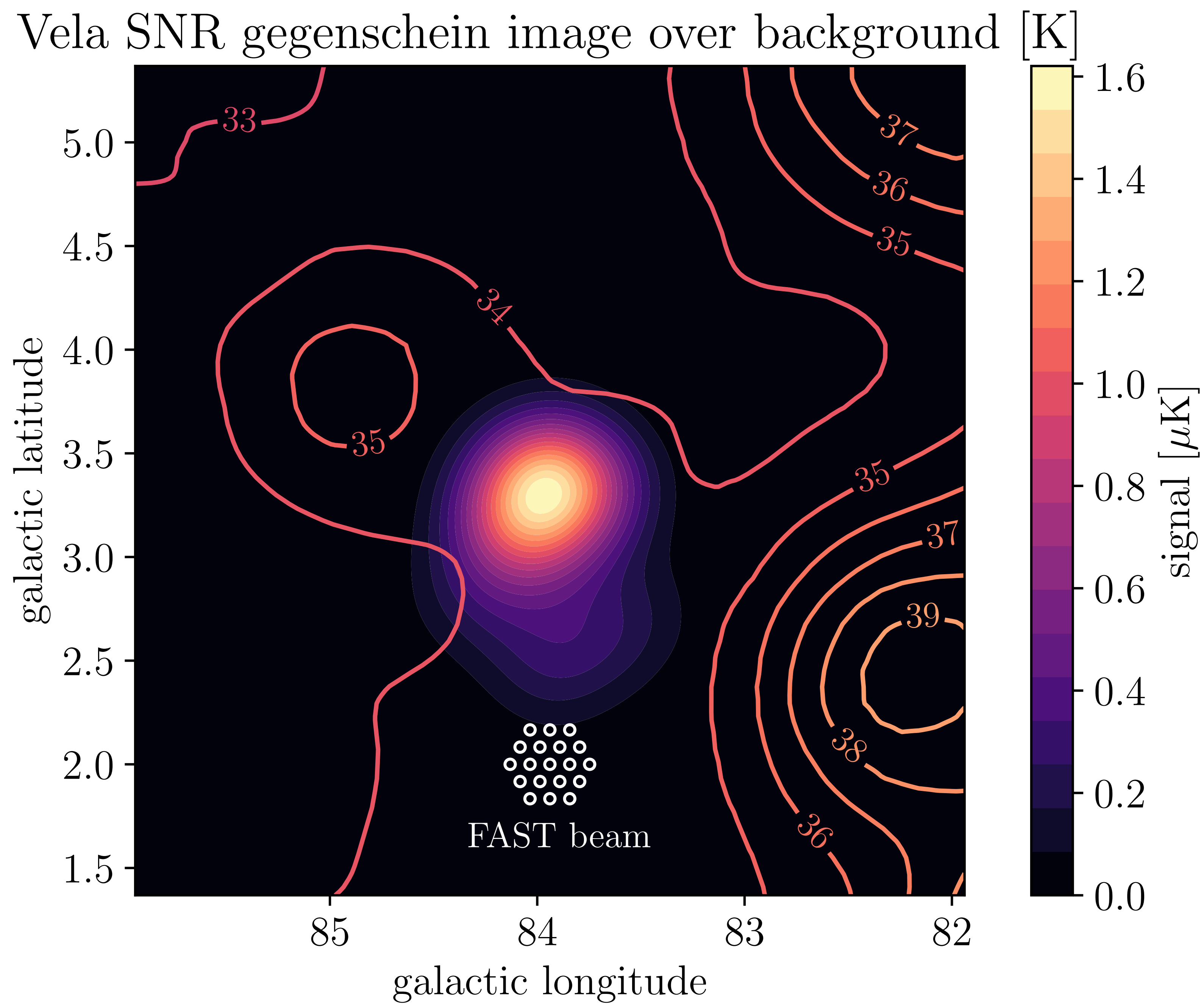


- Data obtained from SNRcat and Green's SNR catalog
- We vary the B field amplification time, electron model, spectral index, age, distance, etc.
- We conservatively assume no growth of the luminosity prior to the magnetic field amplification (observed light curves of young SNe suggest these should be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



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)

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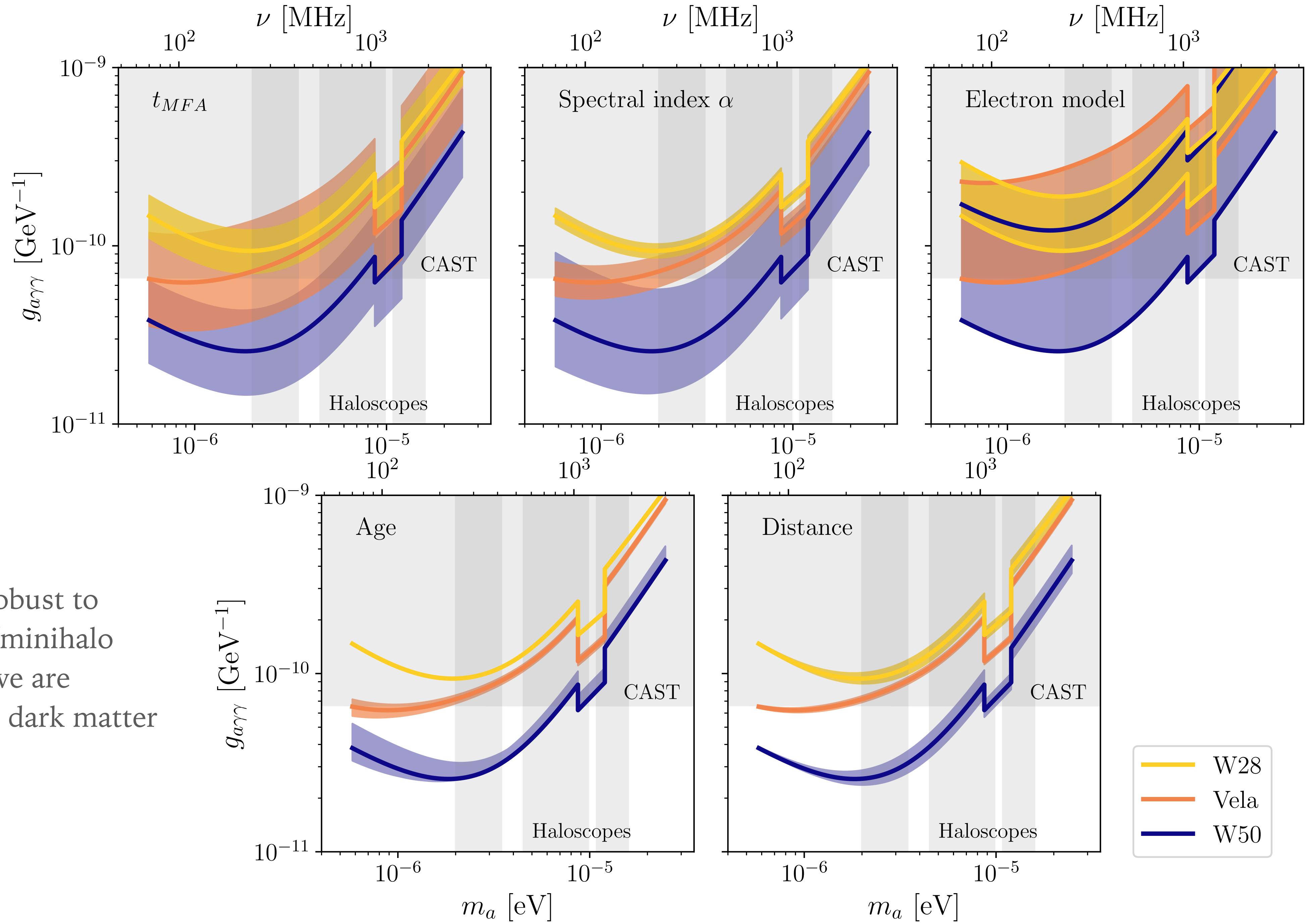
FAST projected sensitivity



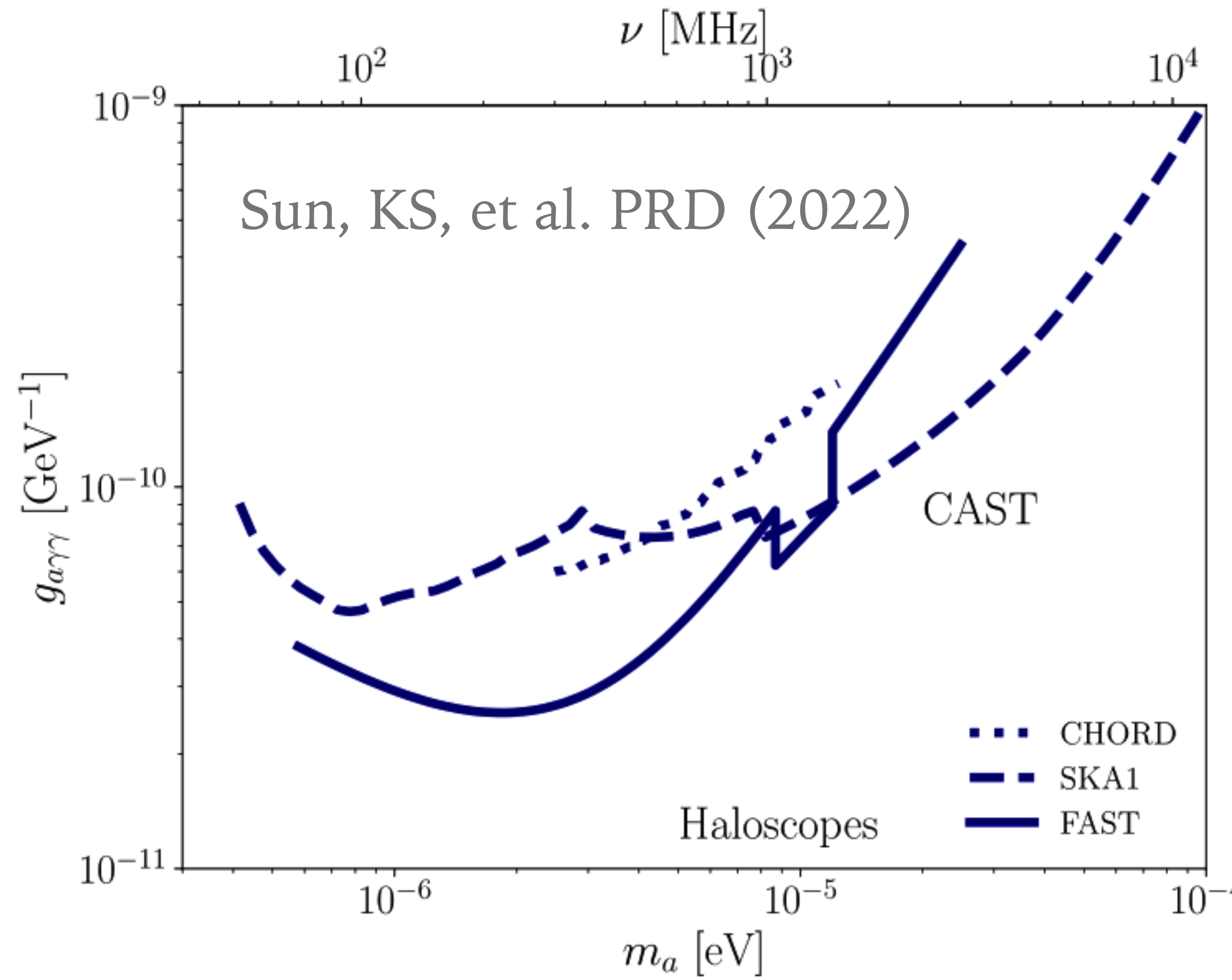
Note this is robust to substructure/minihalo effects since we are probing ~kpc dark matter column!

- 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

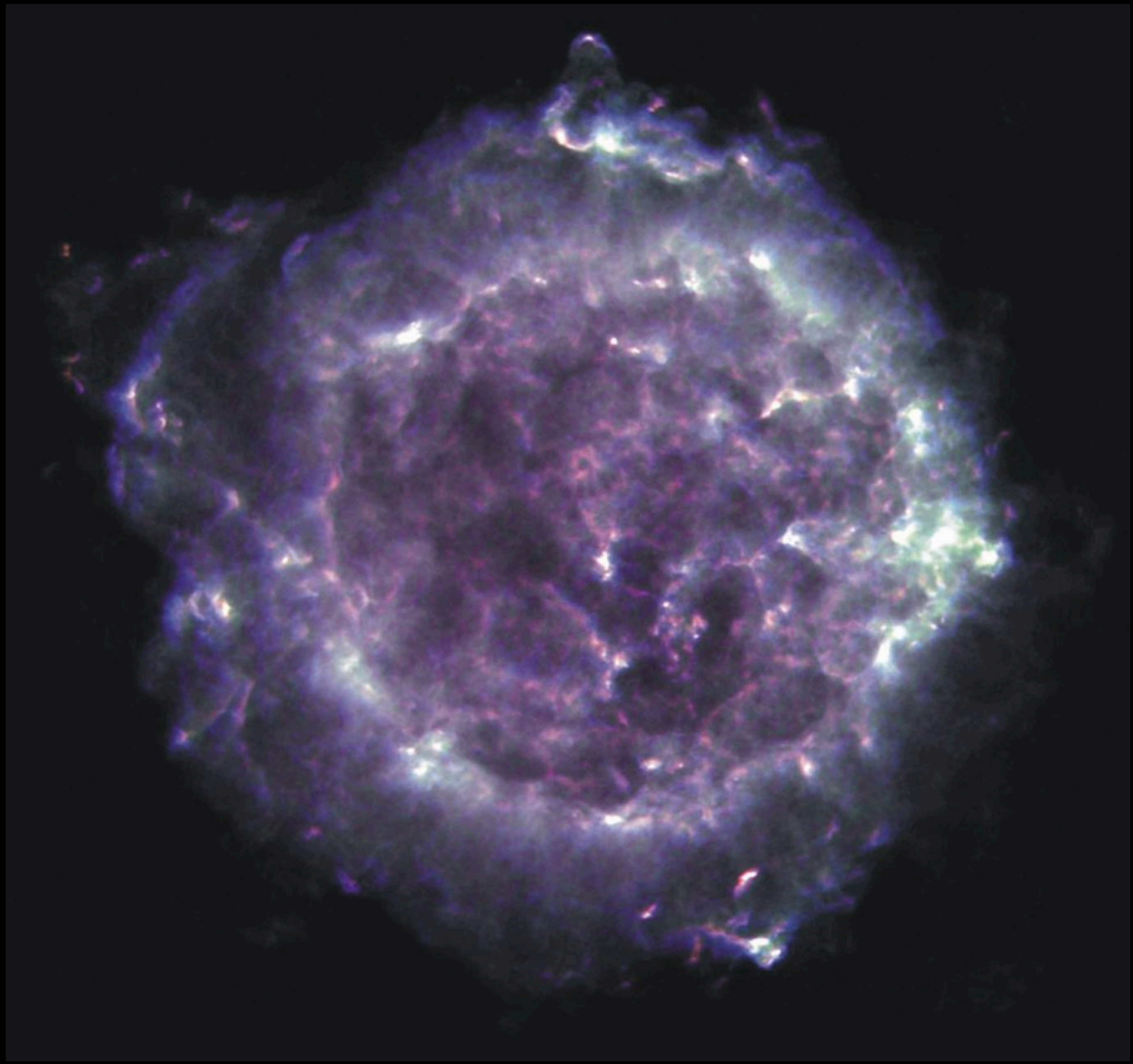


Fiducial sensitivity for W50 SNR

- ➤ 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

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



THANK YOU!