AN AXION DARK MATTER INDUCED ECHO OF SUPERNOVA REMNANTS

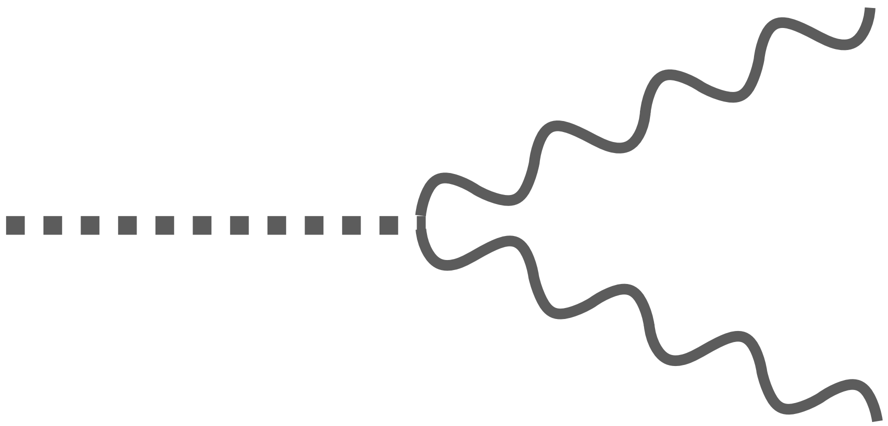
Katelin Schutz, McGill University

IDM 2022, Vienna

Based on work with Yitian Sun, Anjali Nambrath, Calvin Leung, and Kiyo Masui
Additional ongoing work with Rohan Kulkarni, Harper Sewalls

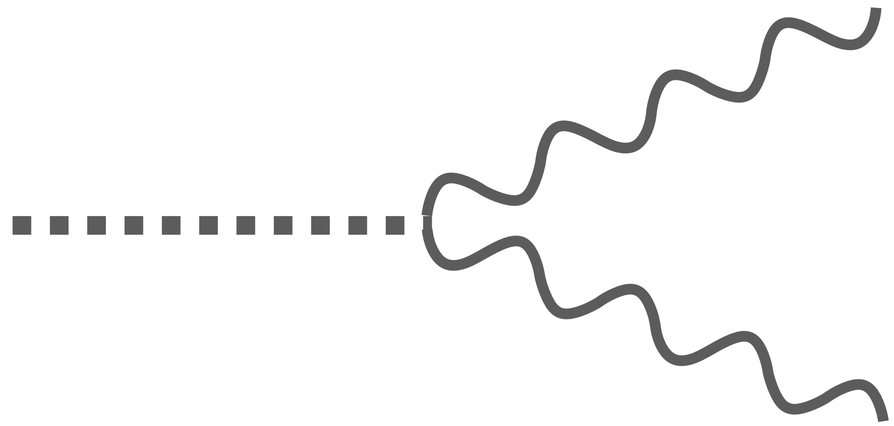
See also related work by Manuel Buen-Abad, JiJi Fan, and Chen Sun

AXION COUPLING TO PHOTONS

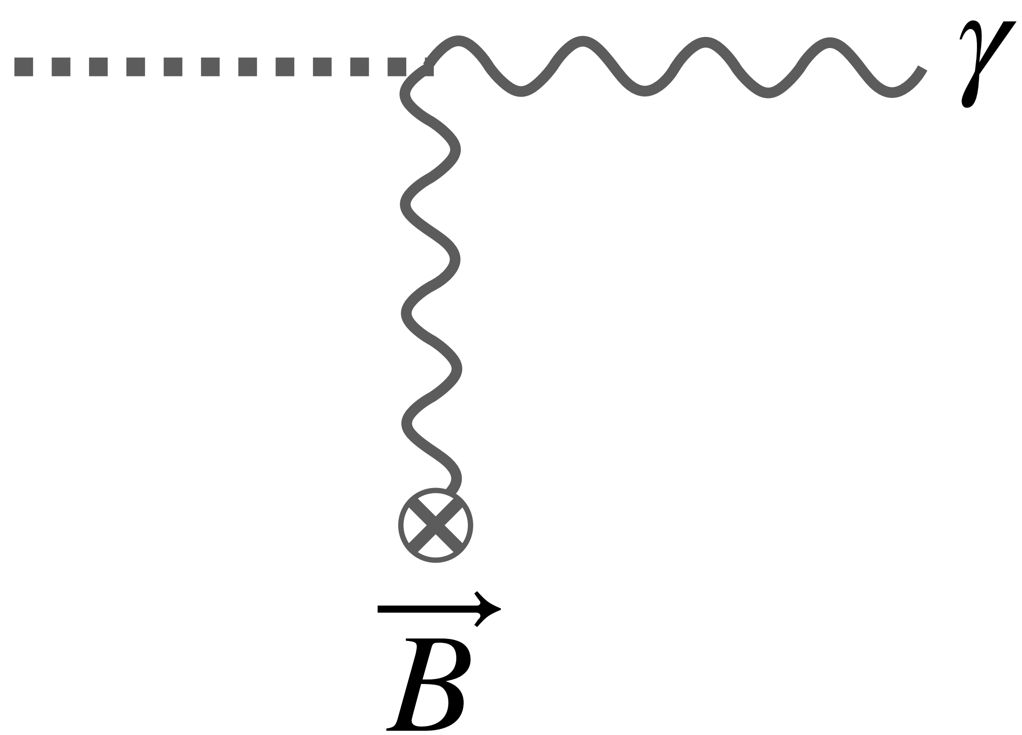


$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\, (\vec{E} \cdot \vec{B})$$

AXION COUPLING TO PHOTONS

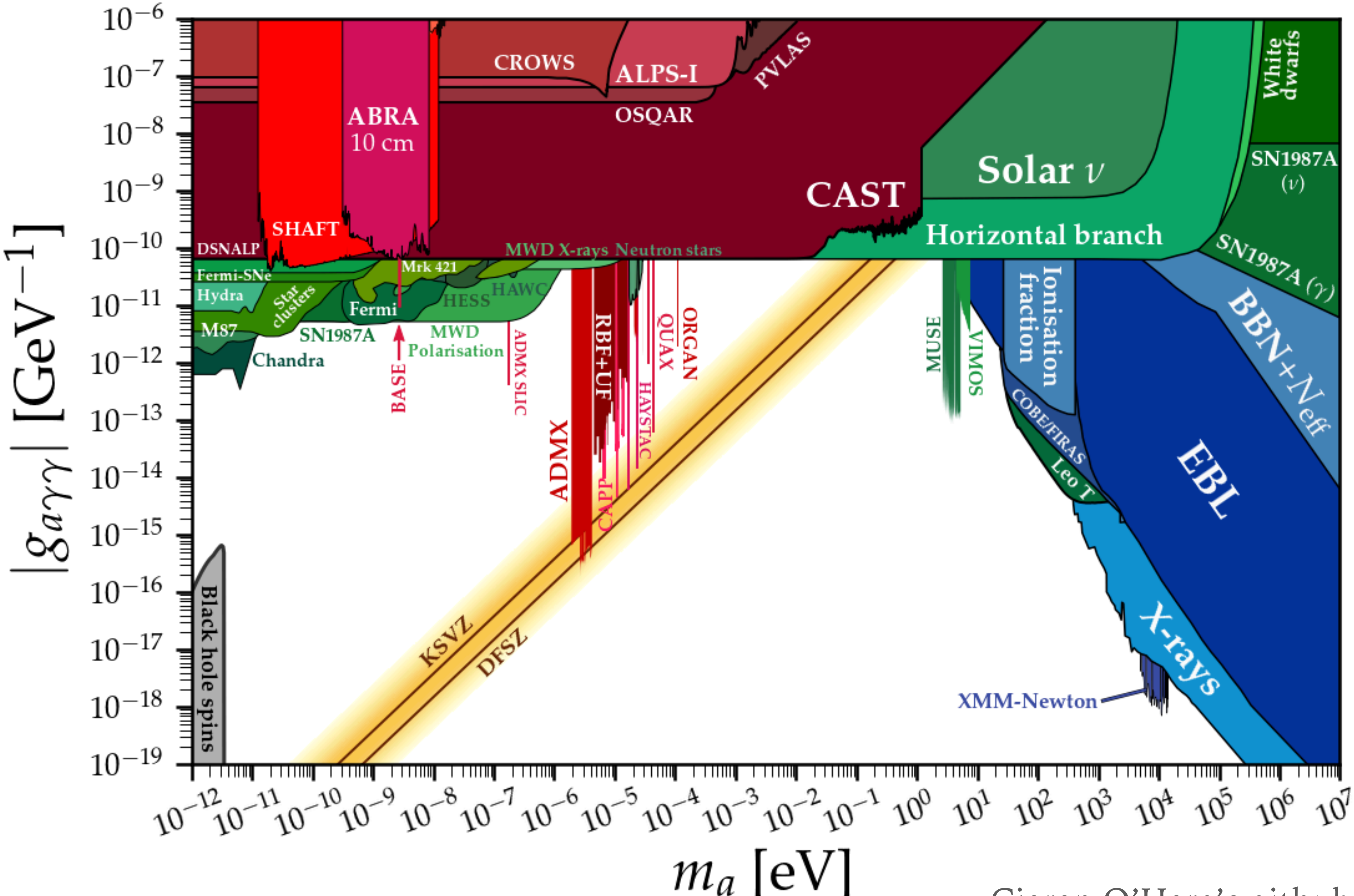


$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\,(\vec{E} \cdot \vec{B})$$



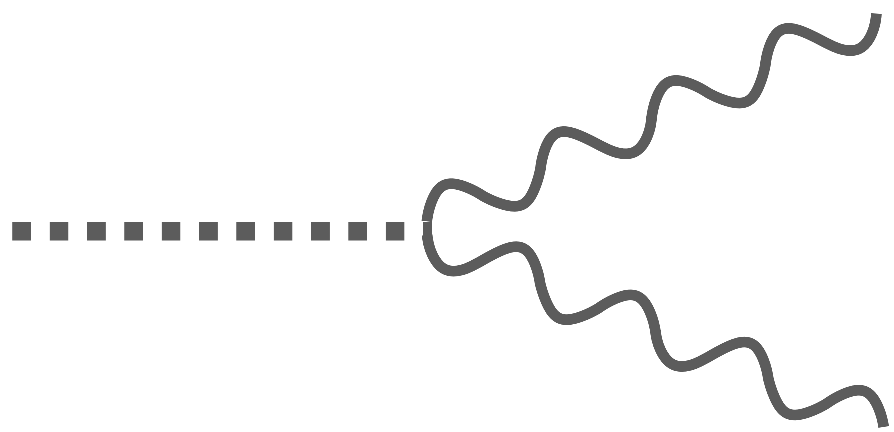
Primakoff process: can be leveraged in terrestrial experiments (e.g. resonant cavities) and astrophysical systems (e.g. neutron star magnetospheres)

AXION COUPLING TO PHOTONS



Ciaran O'Hare's github

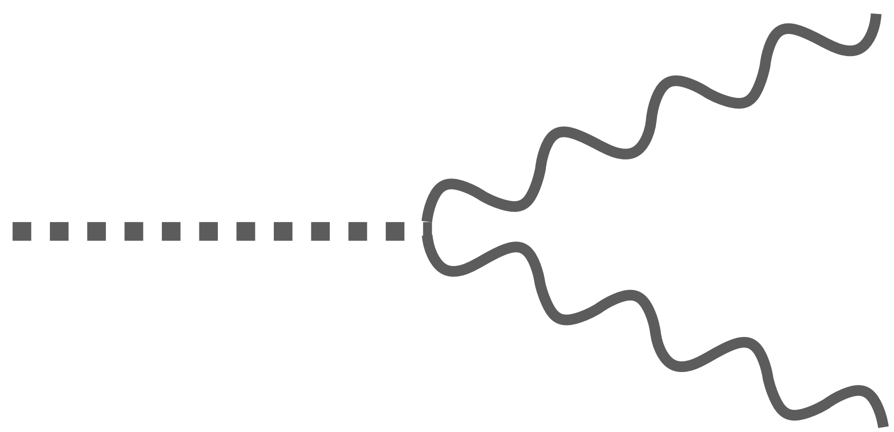
AXION SPONTANEOUS DECAY



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

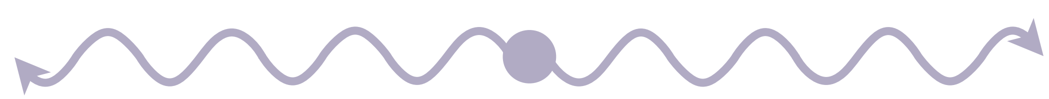
Axions can decay to two photons spontaneously

AXION SPONTANEOUS DECAY



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

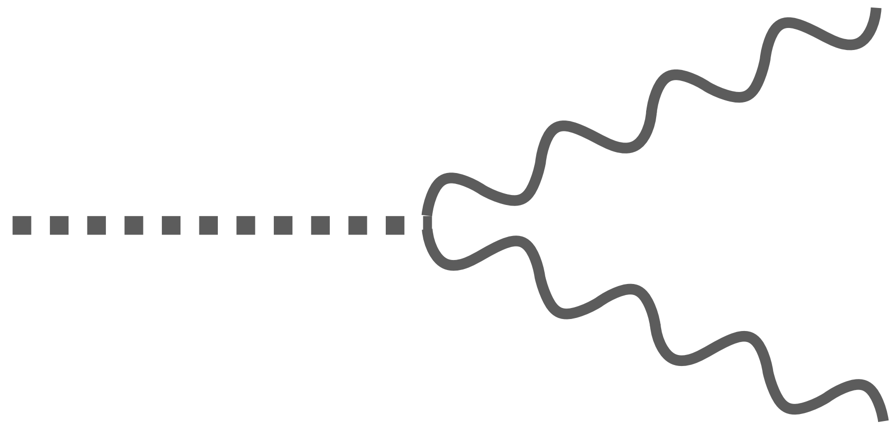
Axions can decay to two photons spontaneously



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

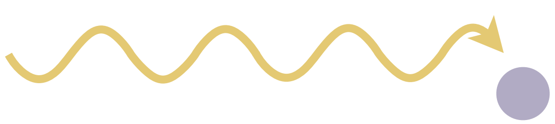
$$\tau = \frac{64\pi}{m_a^3\, g_{a\gamma\gamma}^2} \sim 4 \times 10^{35}\,\mathrm{yr} \left(\frac{m_a}{\mu\mathrm{eV}}\right)^3 \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^{-2}$$

AXION STIMULATED DECAY



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

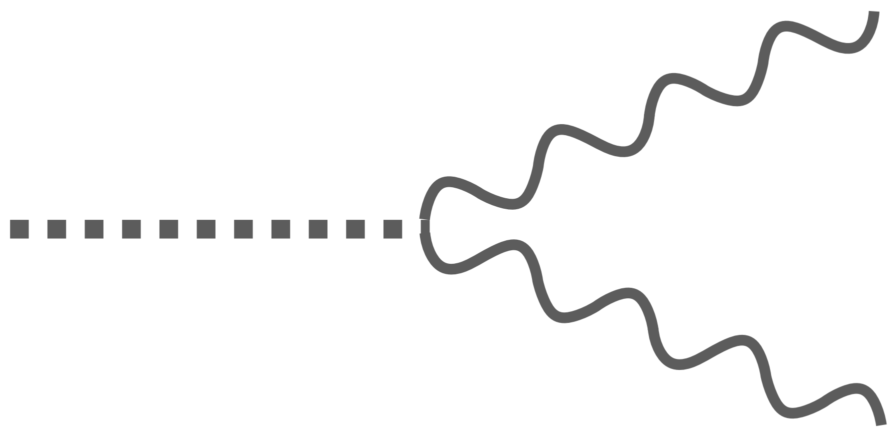
Axions can decay to two photons, spontaneously or through stimulated decay



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

e.g. Arza & Sikivie (2019)

AXION STIMULATED DECAY



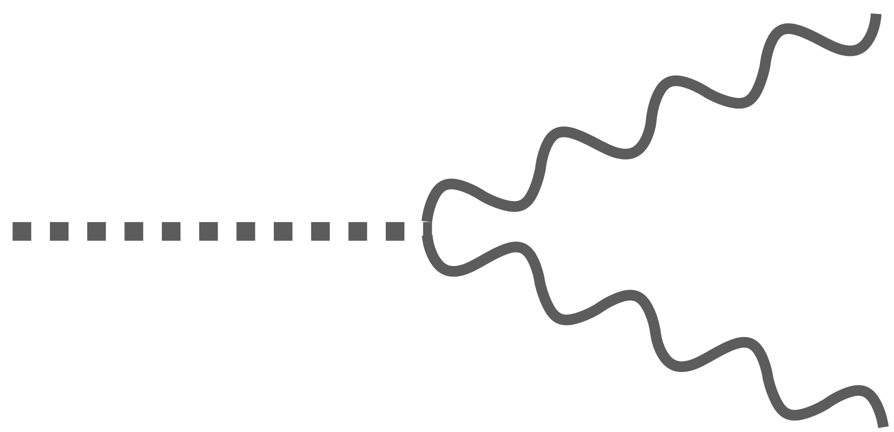
$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\, (\vec{E} \cdot \vec{B})$$

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

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

e.g. Arza & Sikivie (2019)

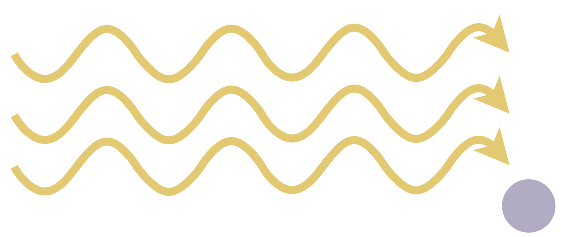
AXION STIMULATED DECAY



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

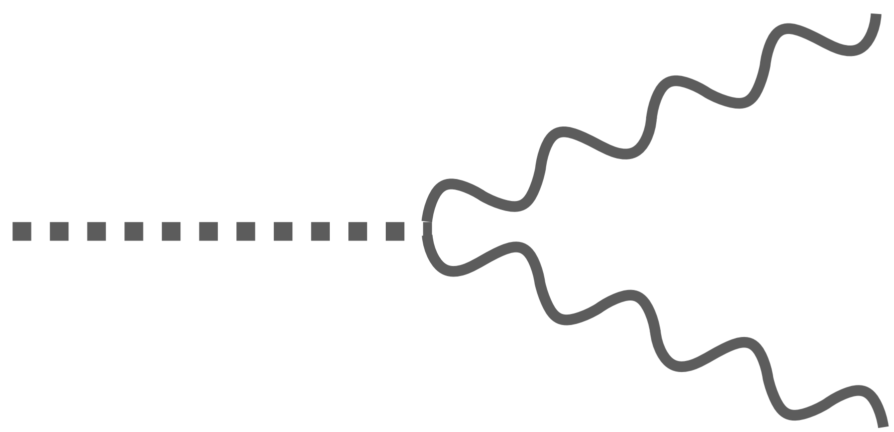
Axions can decay to two photons, spontaneously or through stimulated decay

This is Bose enhanced



e.g. Arza & Sikivie (2019)

AXION STIMULATED DECAY



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

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

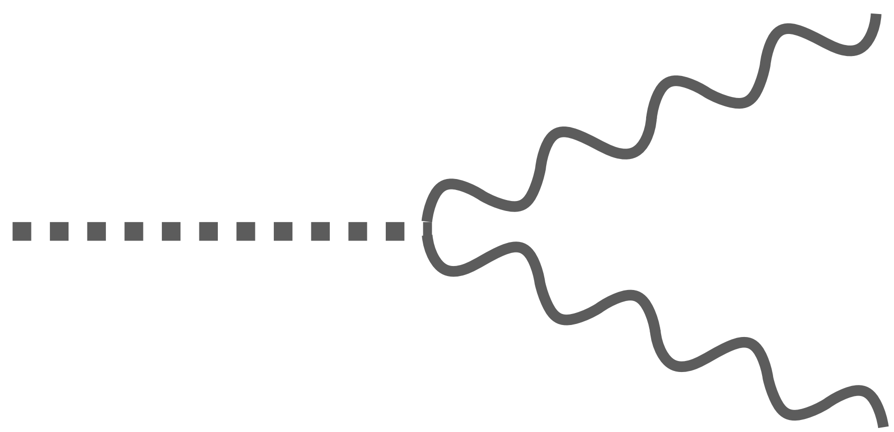
This is Bose enhanced

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

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

e.g. Arza & Sikivie (2019)

AXION STIMULATED DECAY



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

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

This is Bose enhanced

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

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

When you have lots of axions, integrate along line of sight antipodal to the source to see total flux of decay products

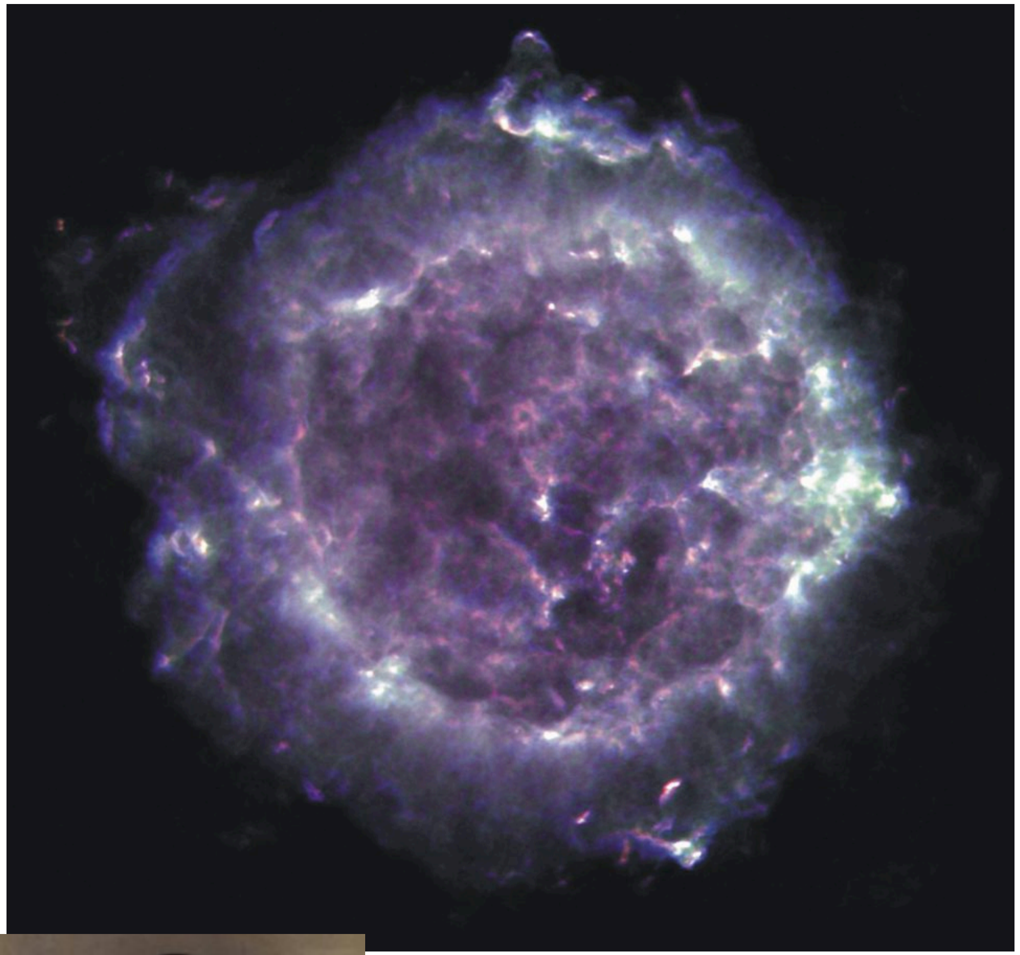
$$S_{\text{out}} = \frac{g_{a\gamma\gamma}^2}{16} \left.\frac{dS_{\text{in}}}{d\omega}\right|_{m_a/2} \int \rho_a\, dx$$

e.g. Arza & Sikivie (2019)

THE UPSHOT:
AXIONS ARE AN IMPERFECT MONOCHROMATIC MIRROR
"AXION GEGENSCHEIN"

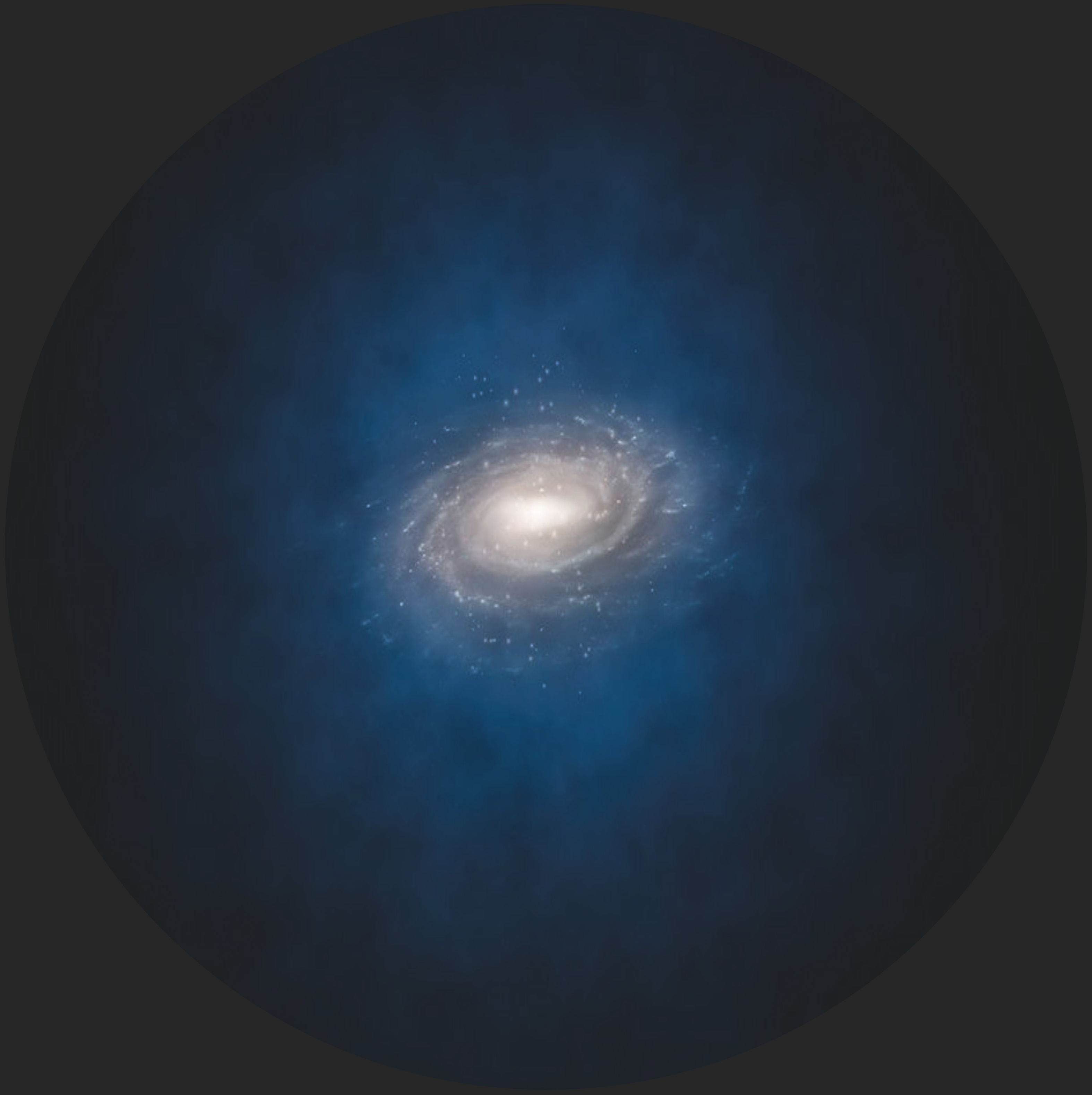
PROGRESS ON AXION GEGENSCHEIN

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

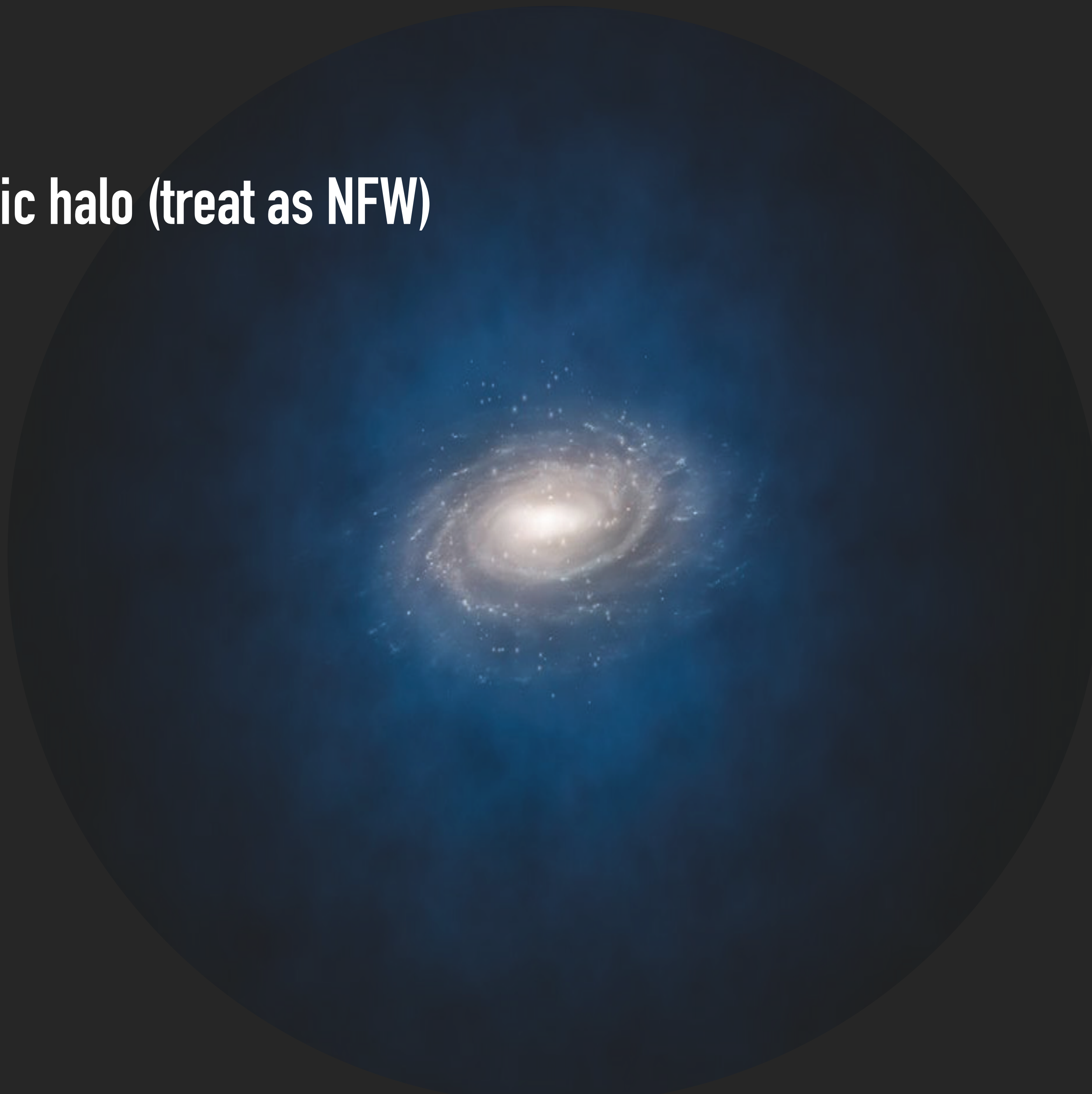


Sun, KS, et al. PRD (2022)

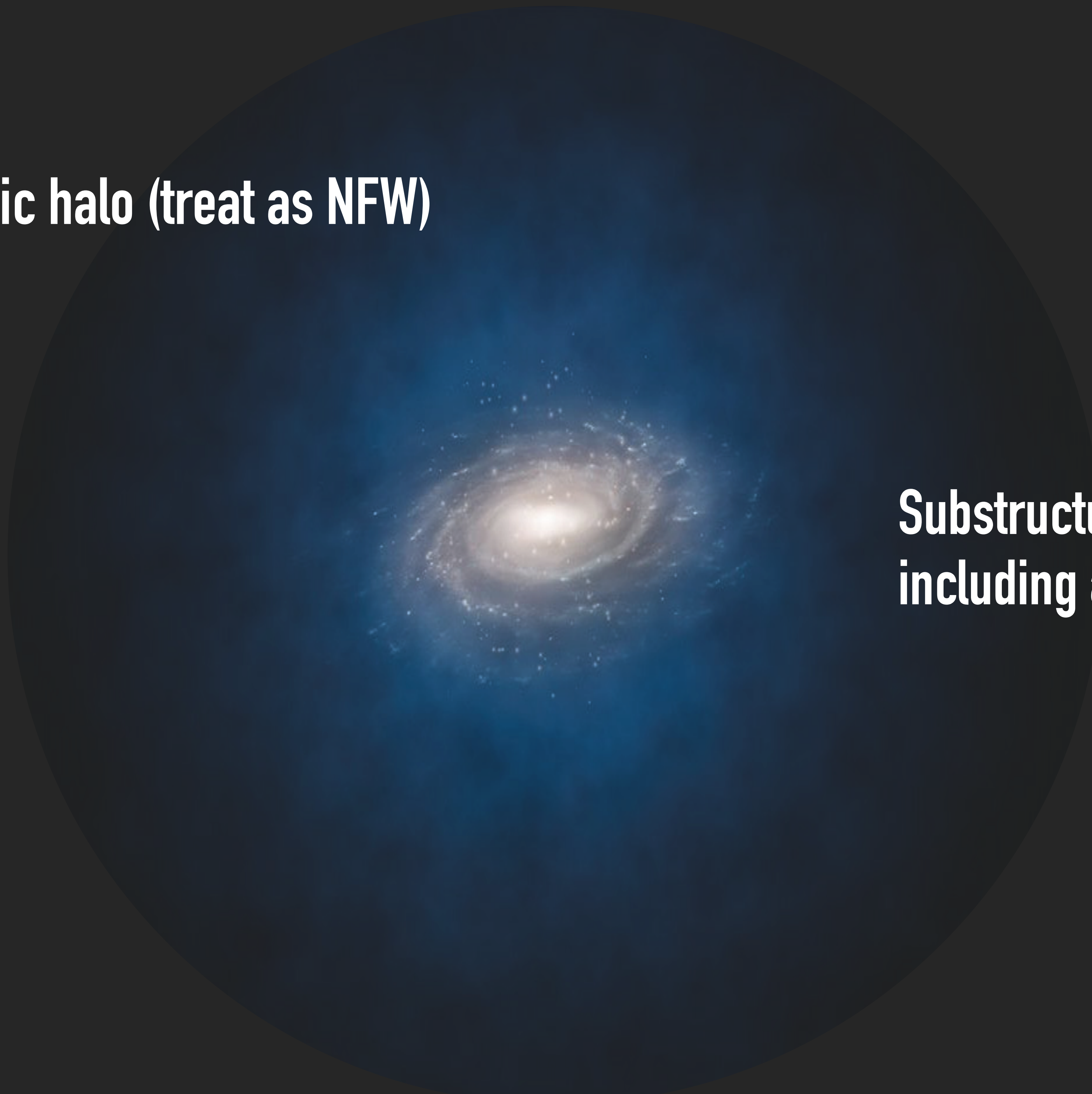
Axions as dark matter



Axions as dark matter



Axions as dark matter

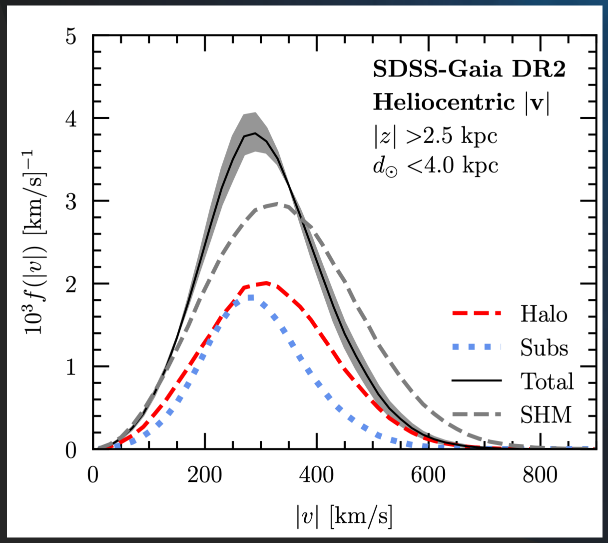


Axions as dark matter

Galactic halo (treat as NFW)

Substructure (possibly including axion mini-halos)

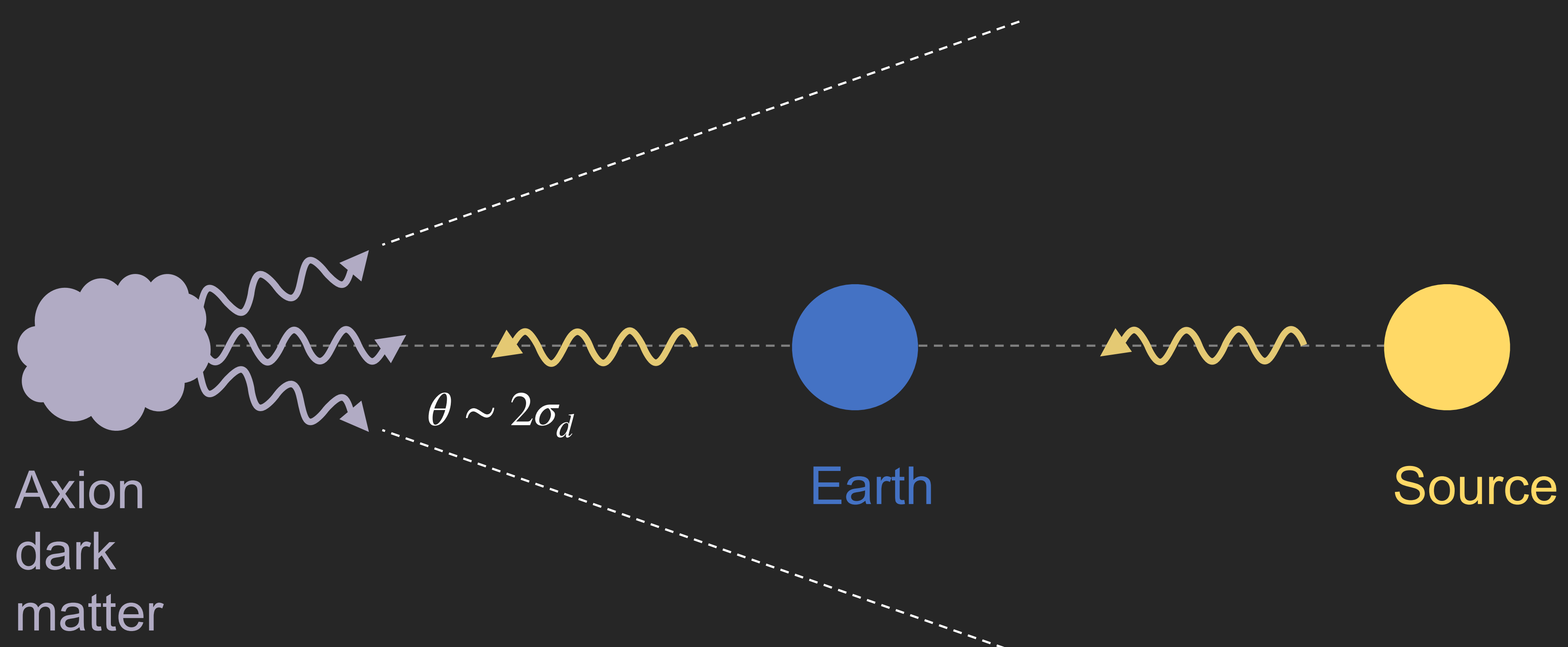
Velocity dispersion ~100 km/s or ~10^{-3} c near Earth



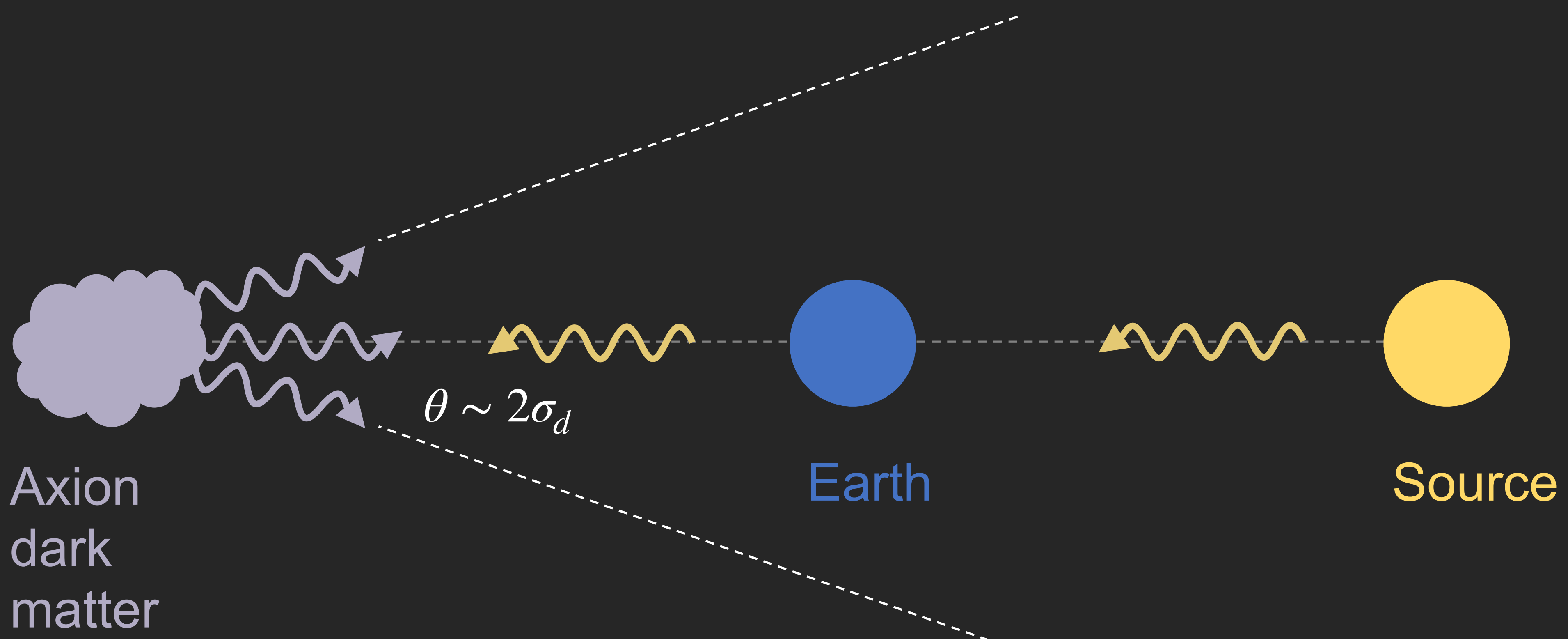
e.g. Necib et al. (2018)

Dispersion smears spectrally (Doppler effect) and spatially

Geometry of axion gegenschein

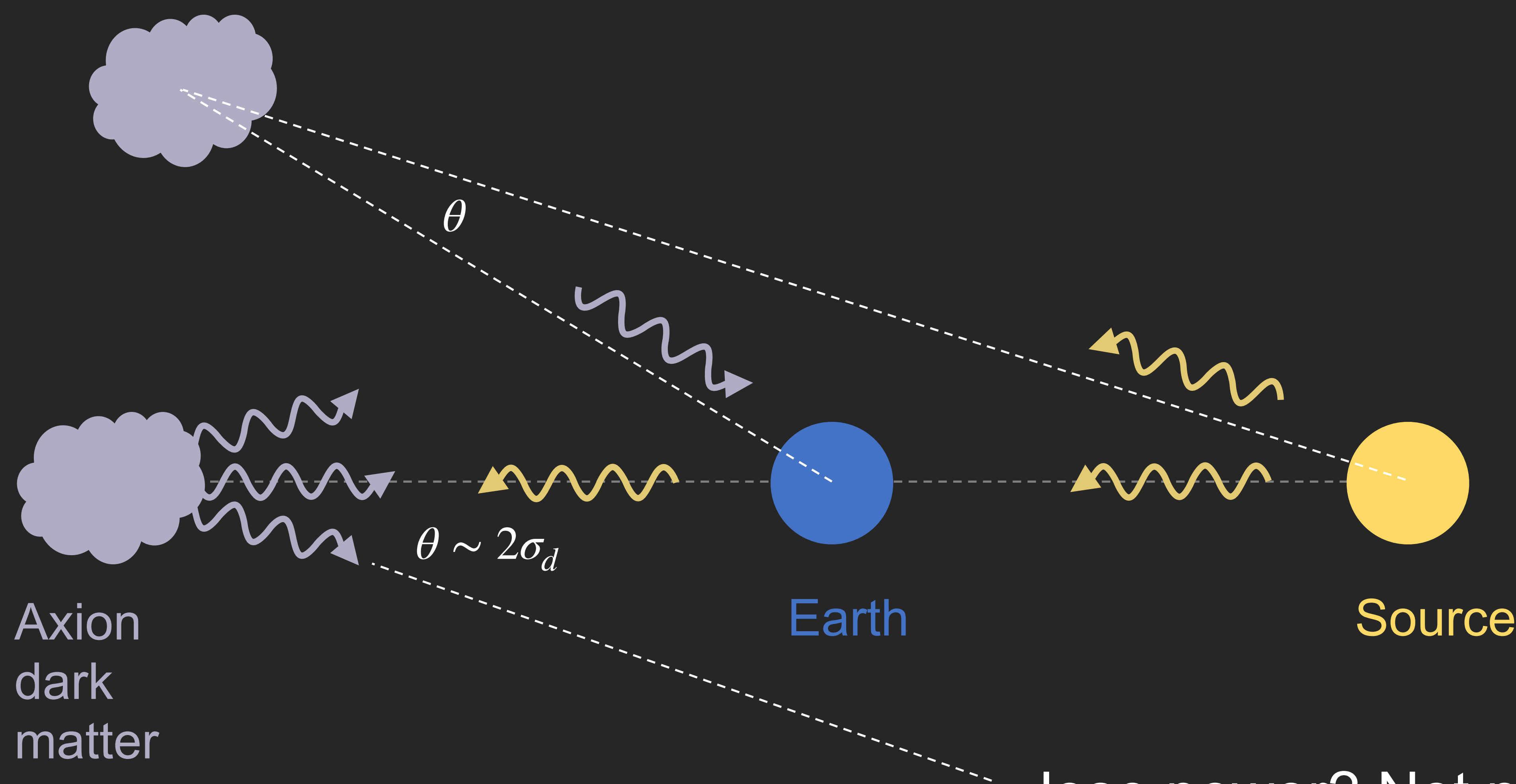


Geometry of axion gegenschein



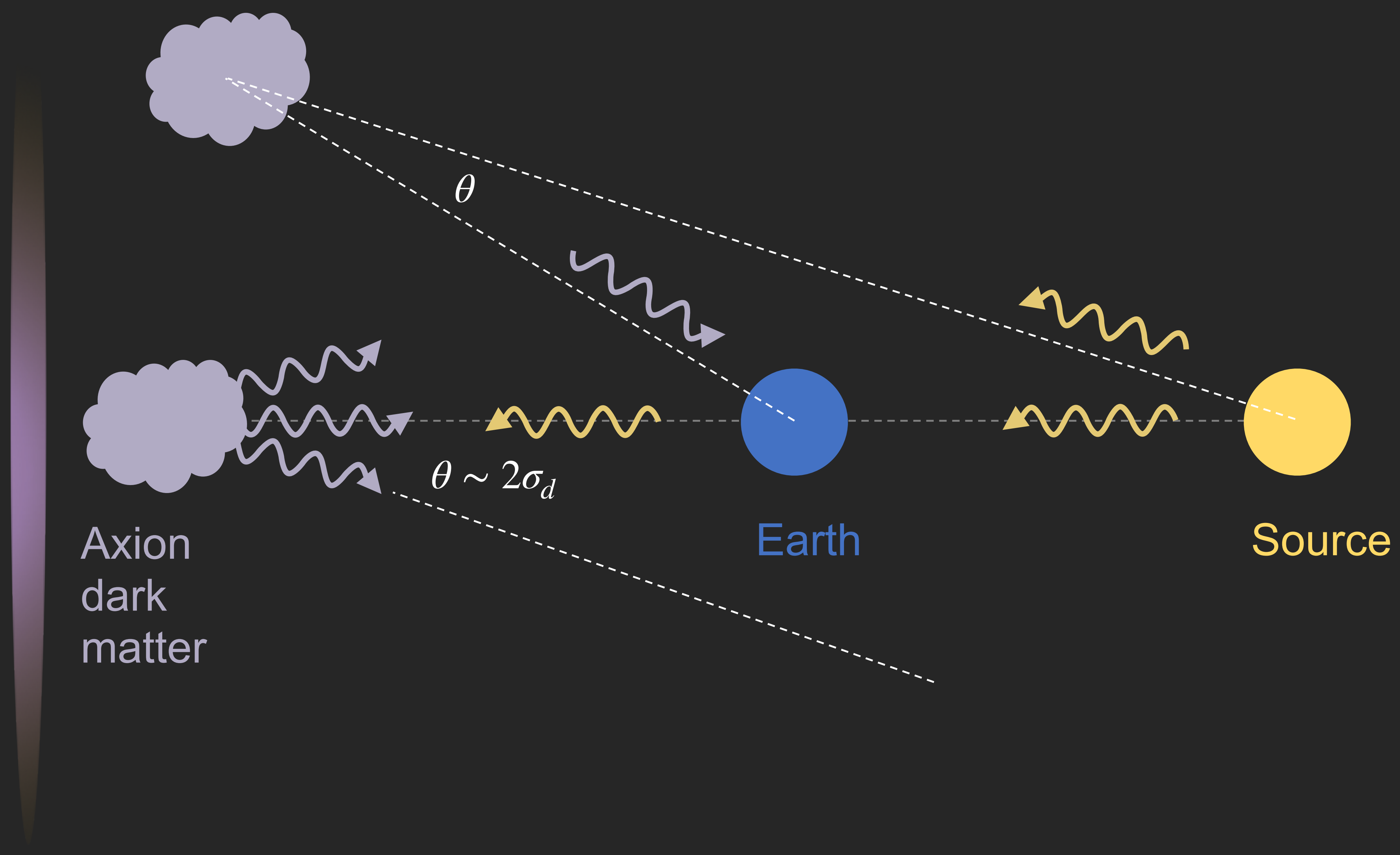
lose power? Not necessarily!

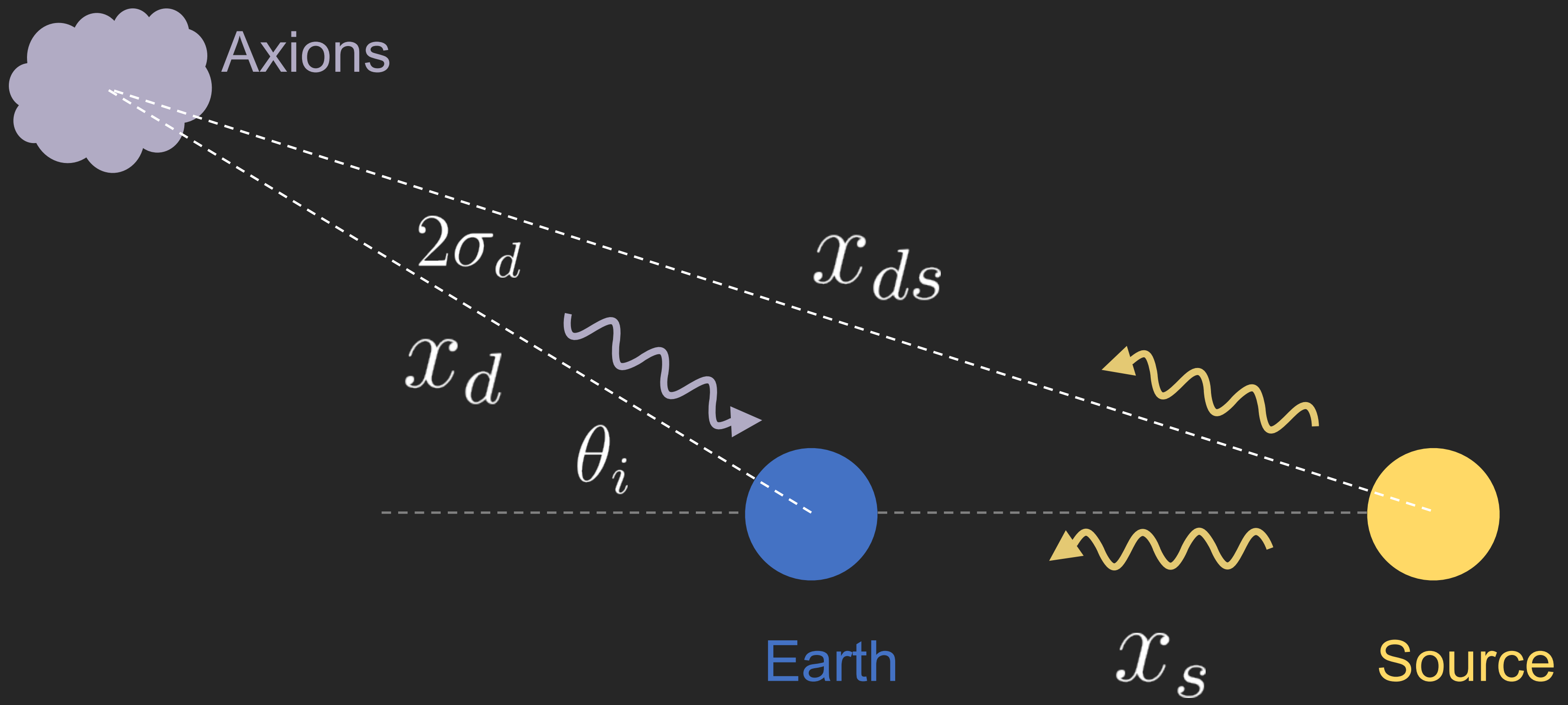
Geometry of axion gegenschein



lose power? Not necessarily!

Geometry of axion gegenschein

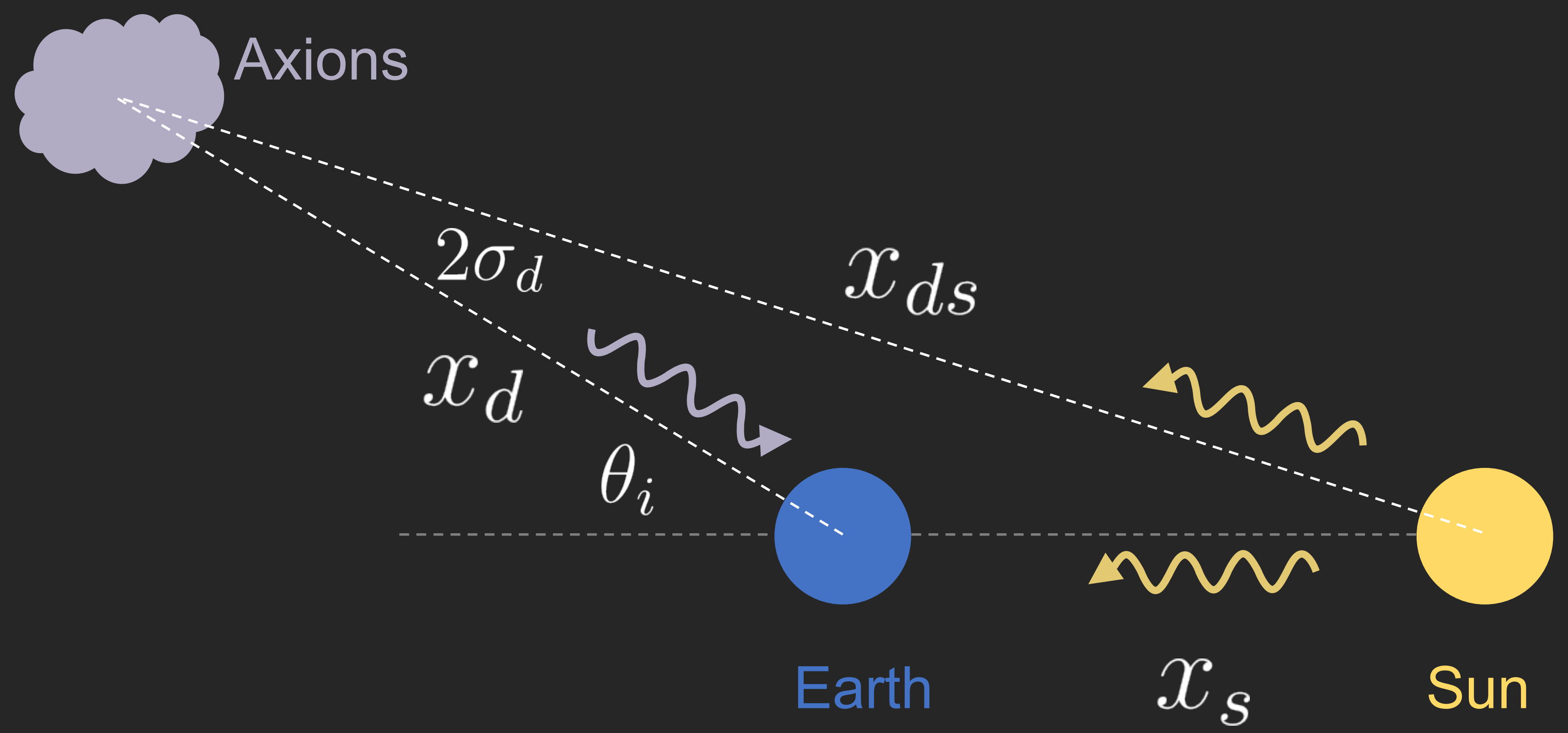




$$\sin\theta_i = \sin 2\sigma_d \,\frac{x_{ds}}{x_s}$$

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)

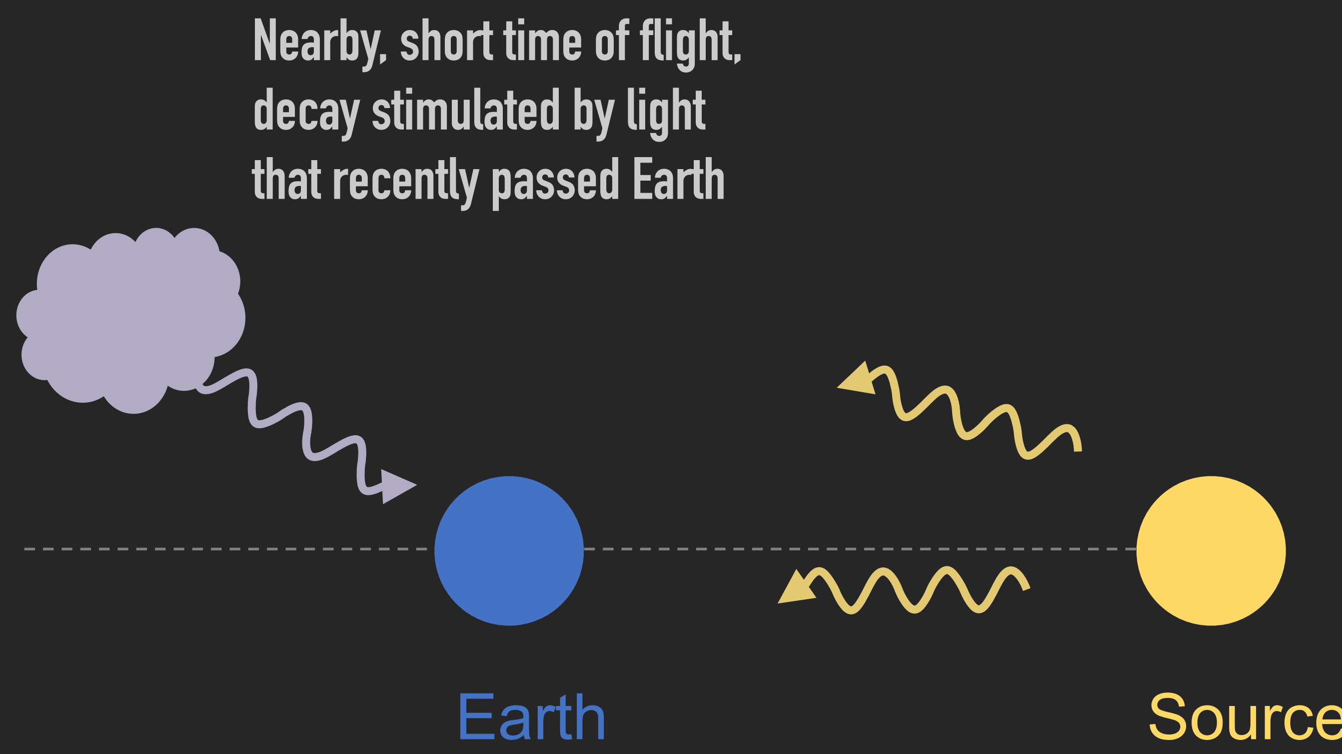


$$\sin\theta_i = \sin 2\sigma_d \,\frac{x_{ds}}{x_s}$$

The Sun is very bright in radio waves but is not a very good source! Given $\sim 10^{-3}$ velocity dispersion, once you get a dark matter column deeper than $\sim 10^{3}$ a.u. the image fills the entire sky… not easy to recover signal and we don't get to benefit much from deeper ~10 kpc dark matter column!

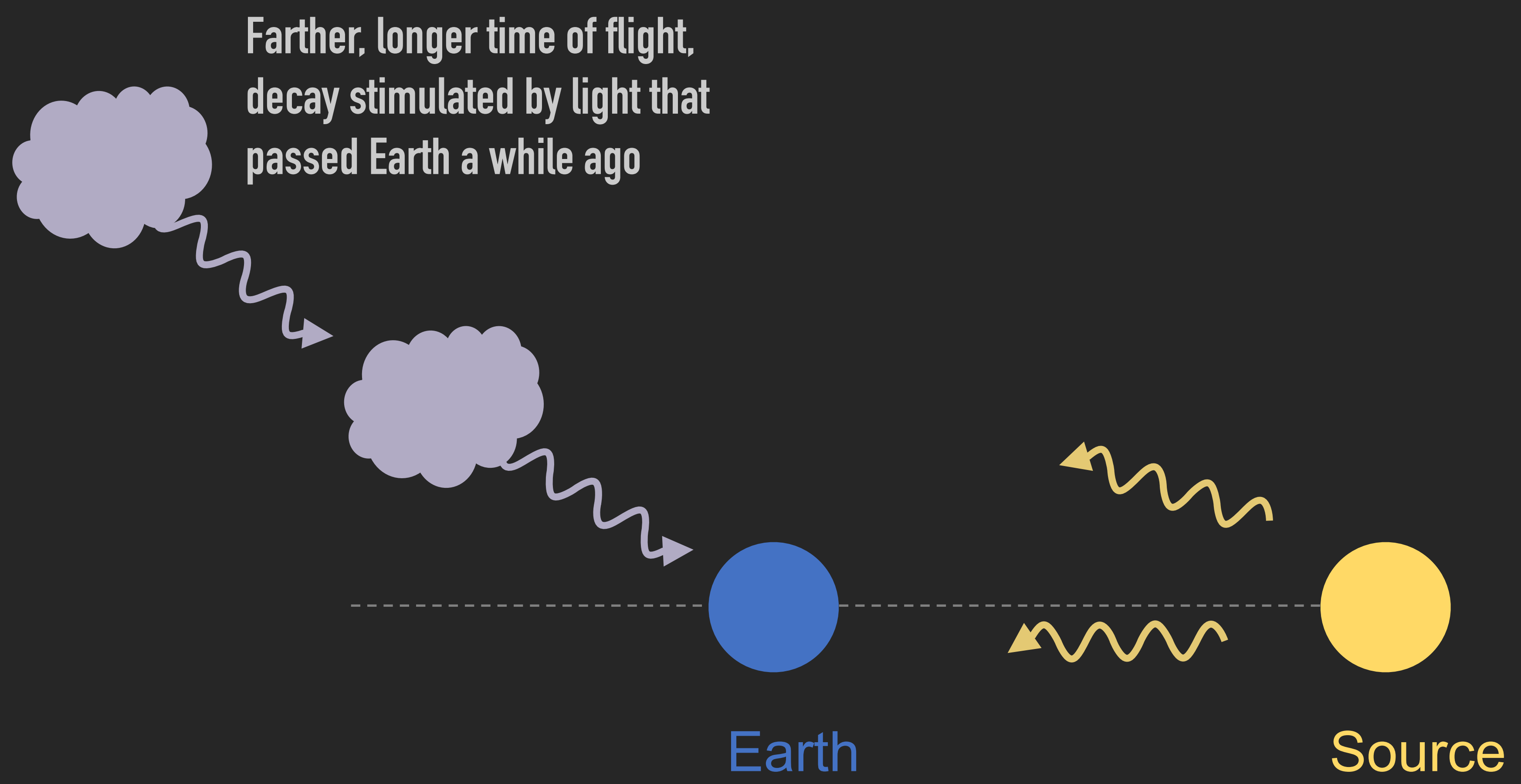
Sun, KS, et al. PRD (2022)

TIME-OF-FLIGHT EFFECTS



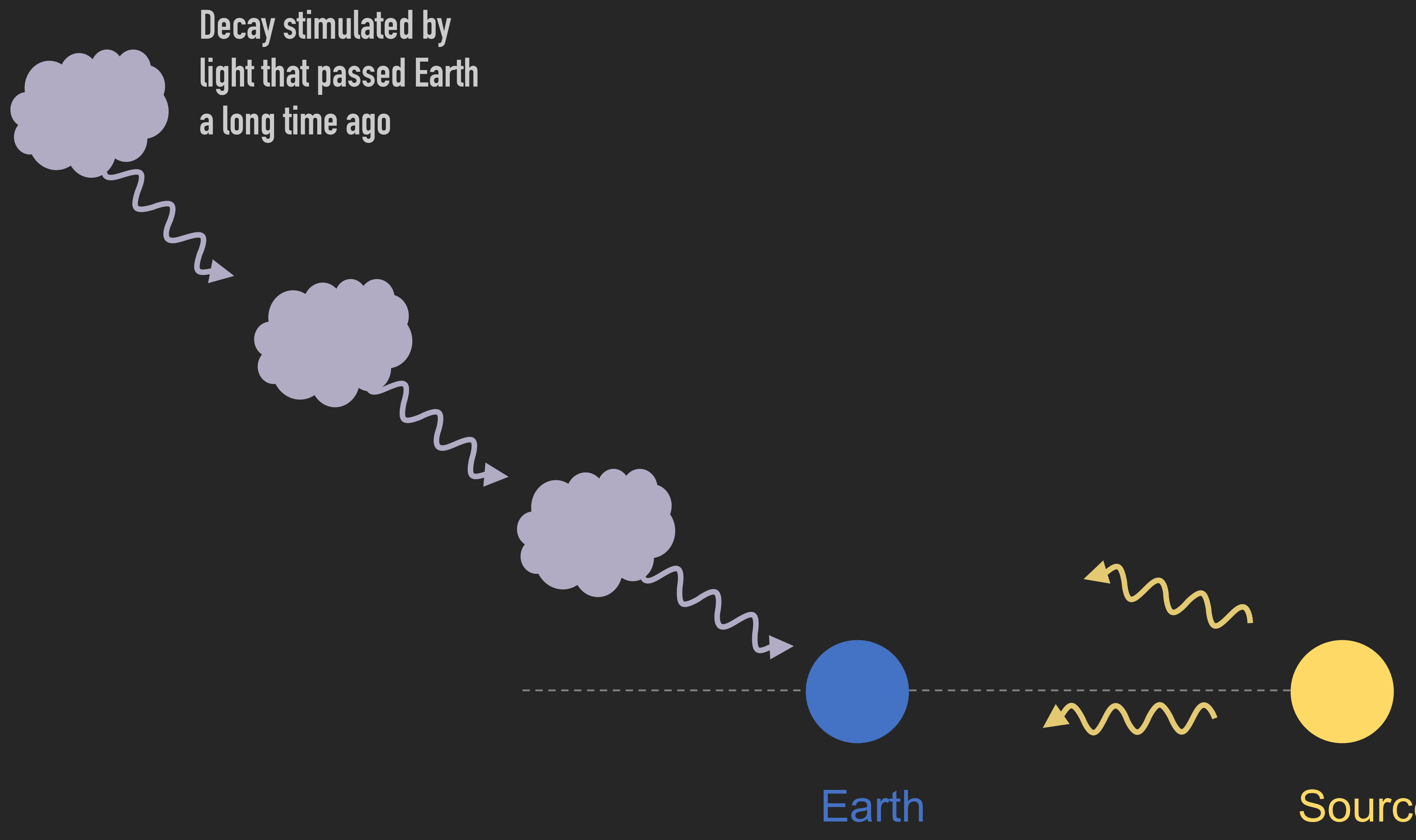
Sun, KS, et al. PRD (2022)

TIME-OF-FLIGHT EFFECTS

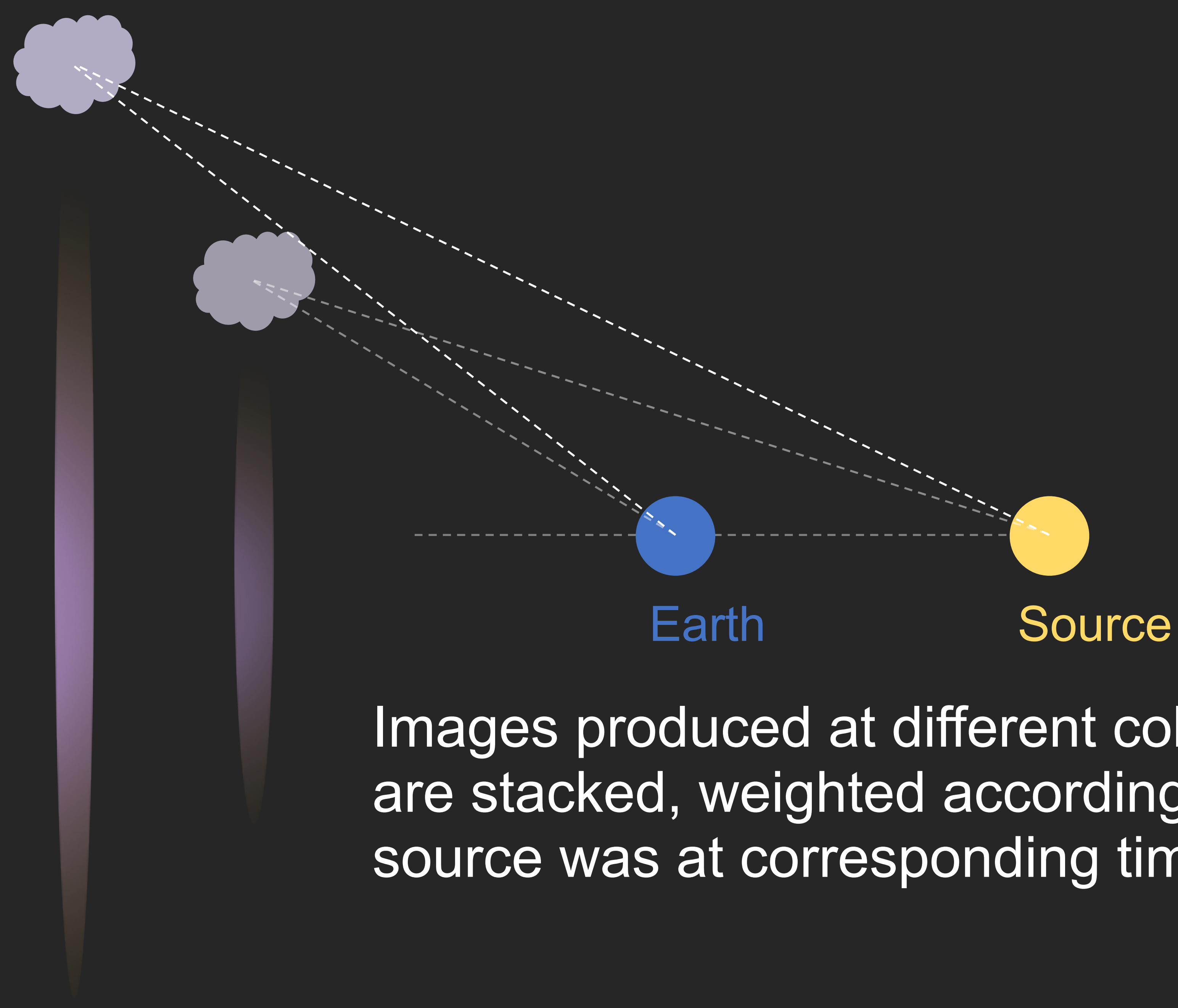


Sun, KS, et al. PRD (2022)

TIME-OF-FLIGHT EFFECTS



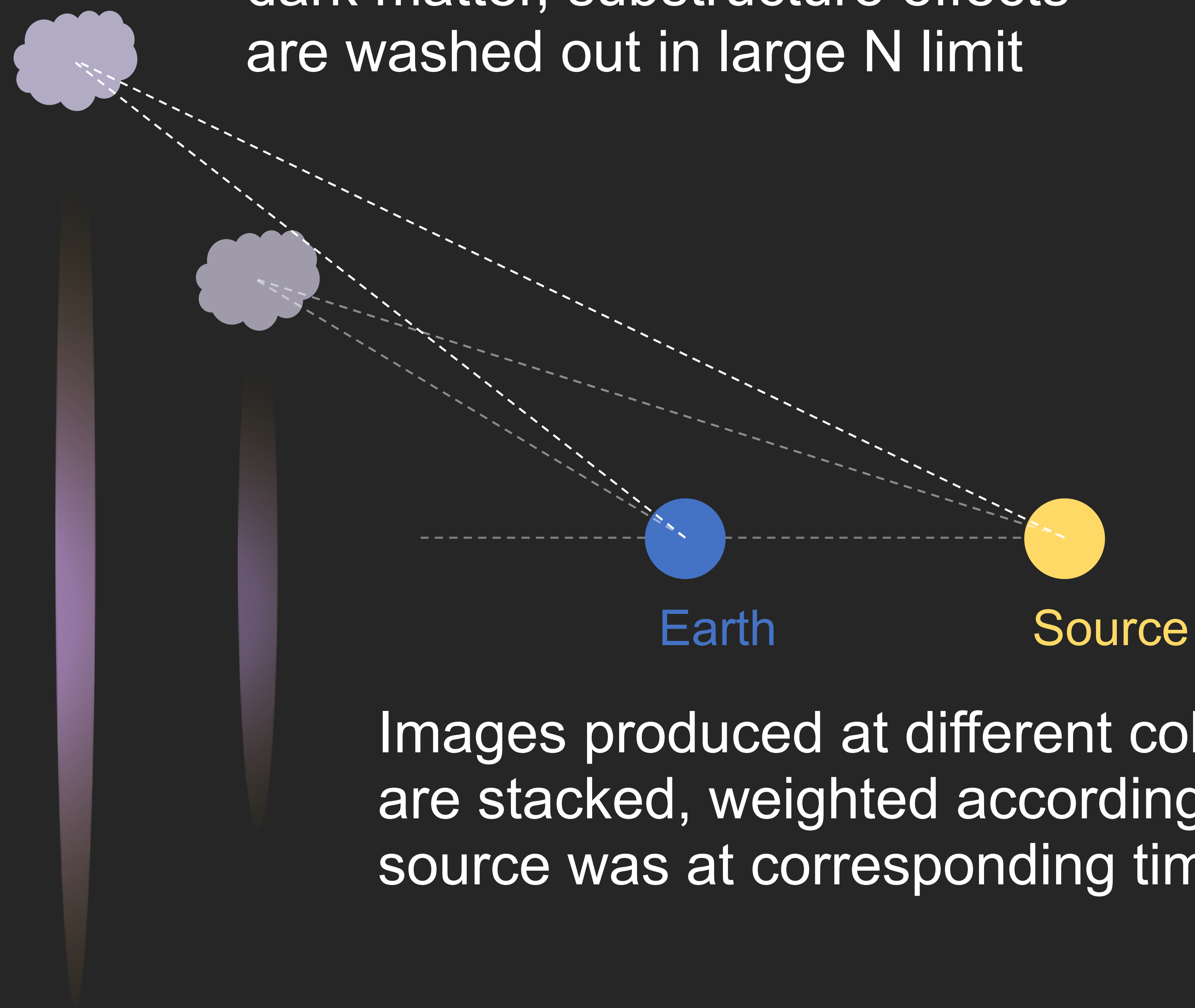
Sun, KS, et al. PRD (2022)



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)

Sensitive to whole column of dark matter, substructure effects are washed out in large N limit



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)

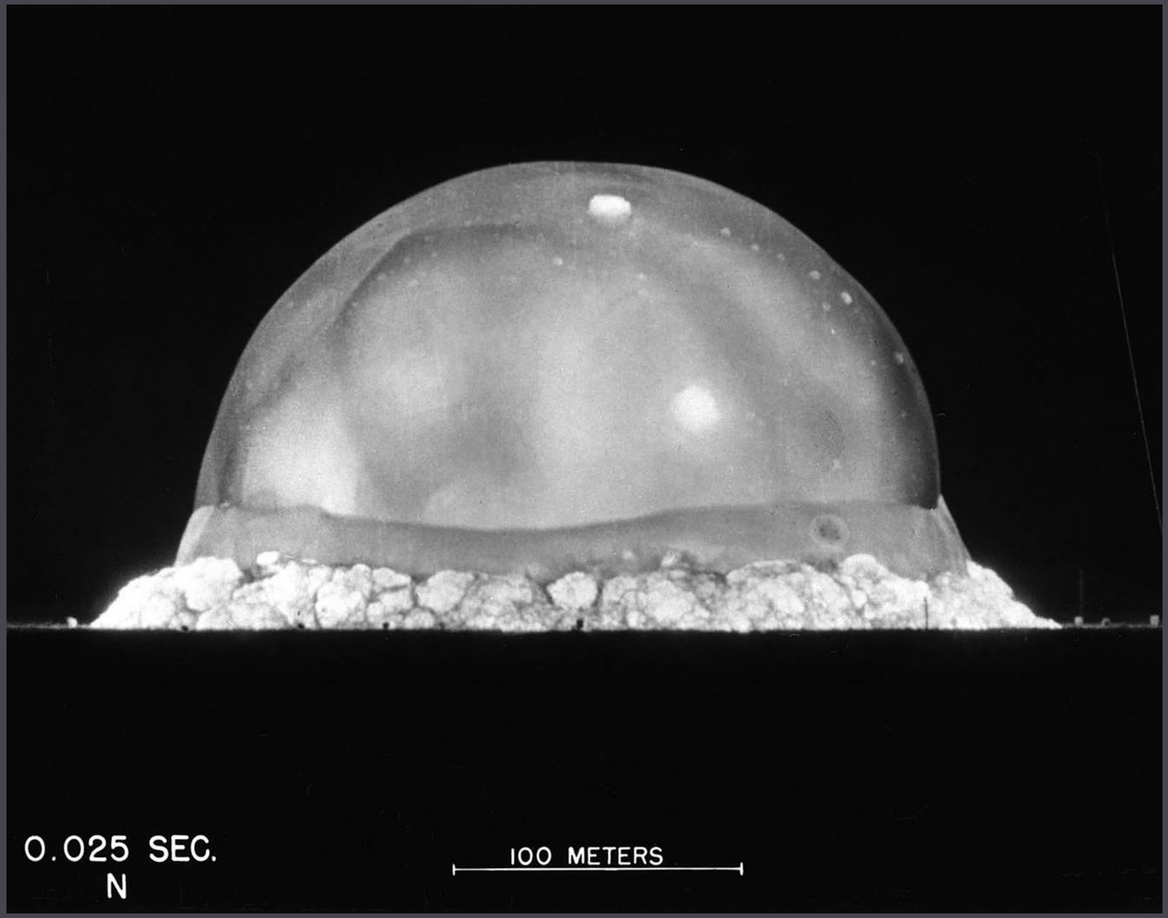
UPSHOT: OPTIMAL SOURCES OF STIMULATING RADIATION WERE THE BRIGHTEST RADIO SOURCE IN SKY AT SOME POINT IN THEIR PAST HISTORY

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 decreases steeply—much brighter in the past
- Age $\sim 10^4$ 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



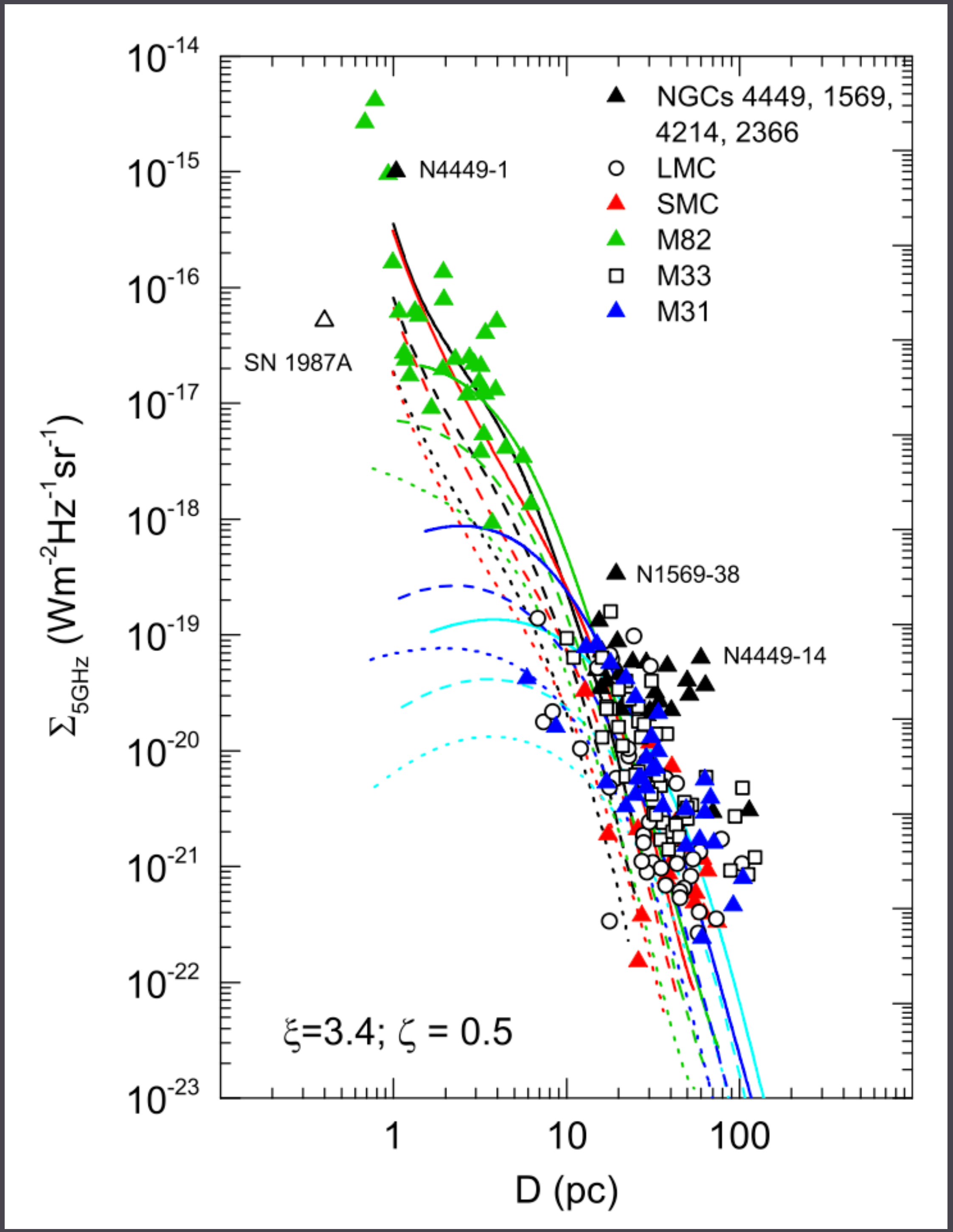
Published photograph of Trinity atomic bomb tests that allowed British physicist G.I. Taylor to estimate explosion energy and deduce that this was a nuclear weapon

- Initial ejecta dominated phase: constant shock velocity ("free expansion") due to high inertia, lasts ~300 years
- Sedov-Taylor phase: shock front slowed down in interstellar medium while conserving energy, lasts $\sim 10^4$ years
- Radiative phase: radiative cooling, energy in shock wave no longer conserved, lasts $\sim 10^5$ years
- Terminal phase

Sedov-Taylor solution from dimensional analysis, true regardless of smooth or cloudy ISM:

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

SNR Brightness evolution



Measured radio surface brightness to diameter relation for SNRs and simulations. Colors are different ISM densities and textures are different explosion energies. Pavlović, Urošević, Arbutina 2018.

- Synchrotron radiation flux:

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

for an electron spectrum:

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

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

MODELING CHOICES

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

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

Electron spectrum:

Electrons enter shock constantly, collide with expanding B field perturbations $V K_e \sim R^{1-p}$

Electrons take up fixed small fraction of explosion energy, $V K_e \sim \text{const.}$

B field evolution:

Compression of interstellar B field, flux through shock front conserved $B \sim R^{-2}$

Full MHD simulations

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

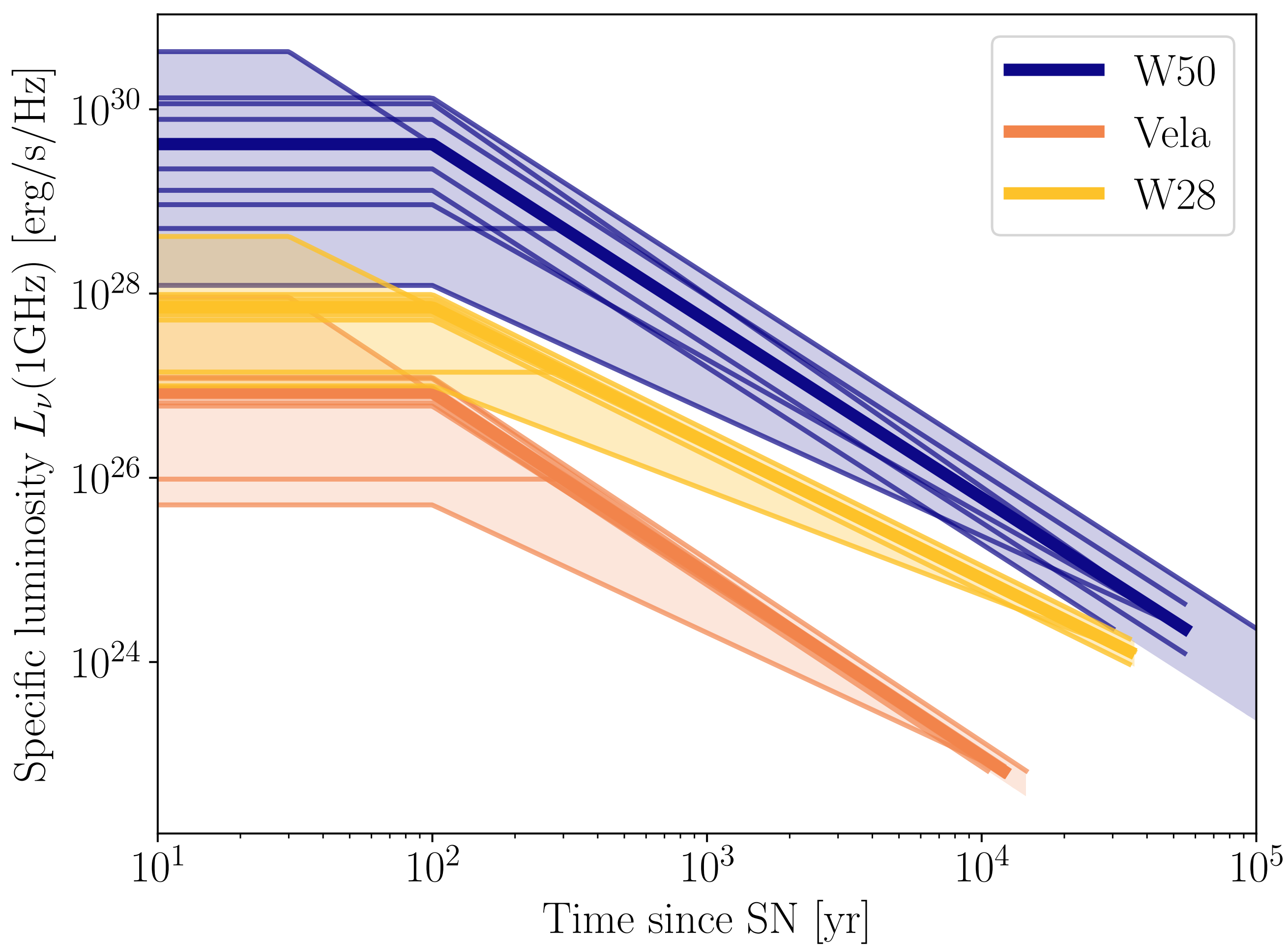
B field onset:

Interactions of shock front with dense circumstellar medium in simulation suggests B field turns on after $\sim$100 years

… but it could be 30 years

… or 300 years

MODELING CHOICE EFFECTS ON OUR BEST SOURCES

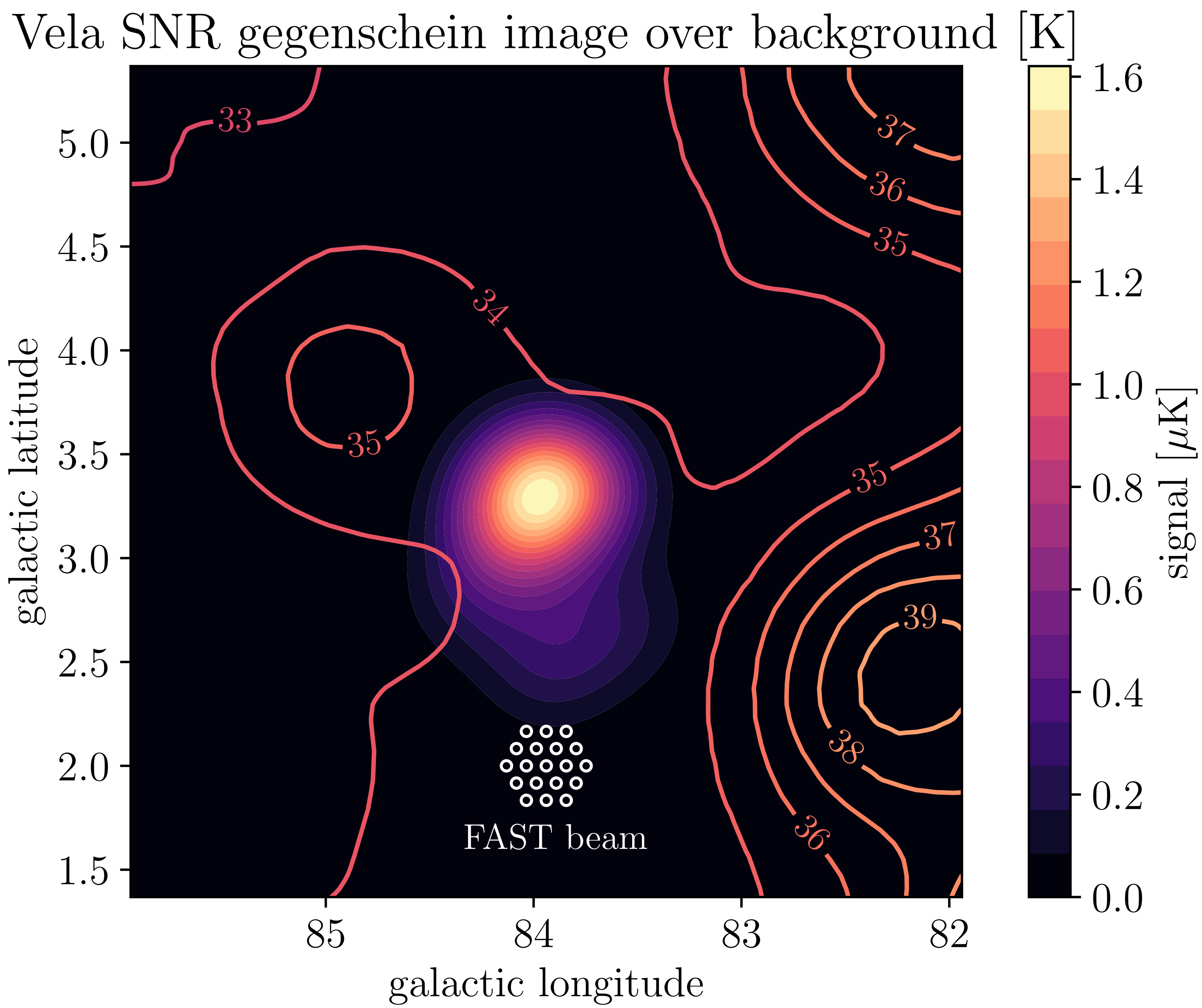


- Data obtained from SNRcat and Green's SNR catalog
- We vary the B field amplification time, electron model, spectral index, age, distance, etc.
- We conservatively assume no growth of the luminosity prior to the magnetic field amplification (observed light curves of young SNe suggest these should be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

Sun, KS, et al. PRD (2022)

UPSHOT: SUPERNOVA REMNANT BRIGHTNESS EVOLUTION CAN BE MODELED, CAN MAKE CONSERVATIVE ASSUMPTIONS

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

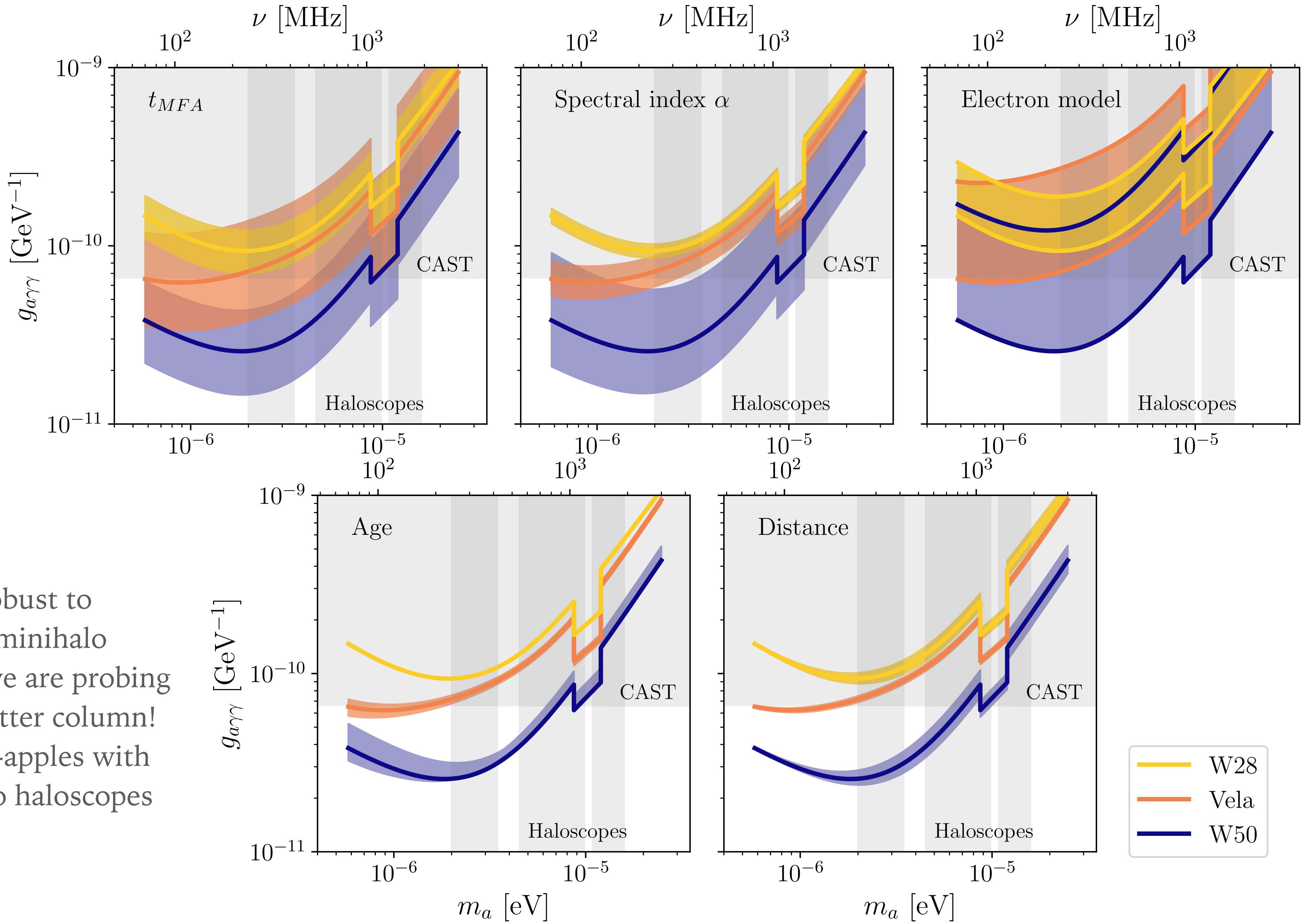


Five-hundred-meter Aperture Spherical Telescope (FAST)

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)

Sun, KS, et al. PRD (2022)

FAST projected sensitivity



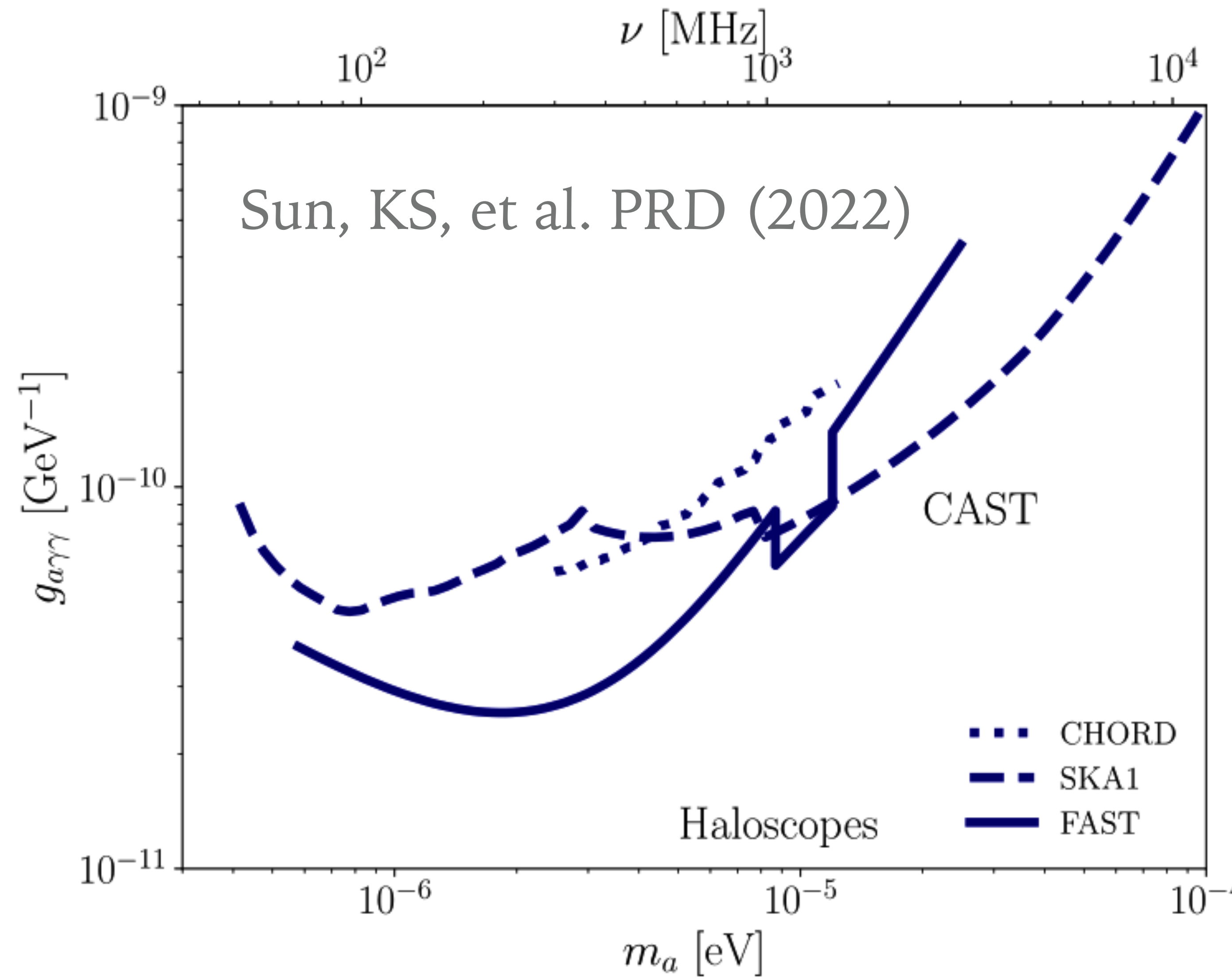
Note this is robust to substructure/minihalo effects since we are probing ~kpc dark matter column! Not apples-to-apples with terrestrial halo haloscopes

➤ 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

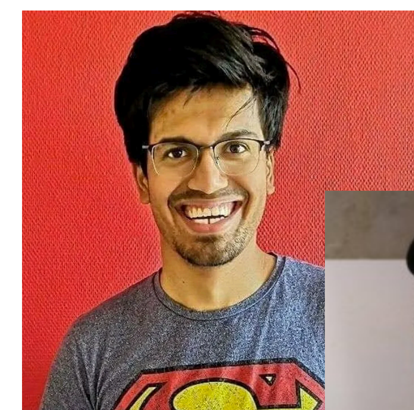


Fiducial sensitivity for W50 SNR

- 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

What about other astrophysical sources?

- Point sources unlikely to do better than supernova remnants, coincidence of their lifetime and light-crossing timescale of Milky Way
  - Shorter transients have signal decoherence over deep DM column due to time of flight effects
  - No "constant" radio point source is brighter than local supernova remnant in first ~100s of years of evolution
- (fairly) exhaustive search by MSc student Rohan Kulkarni and Yitian Sun over different kinds of point sources (including stellar basins; see talk by DeRocco!) and different parts of EM spectrum finding nothing imminently detectable (but let's chat if you have an idea!)

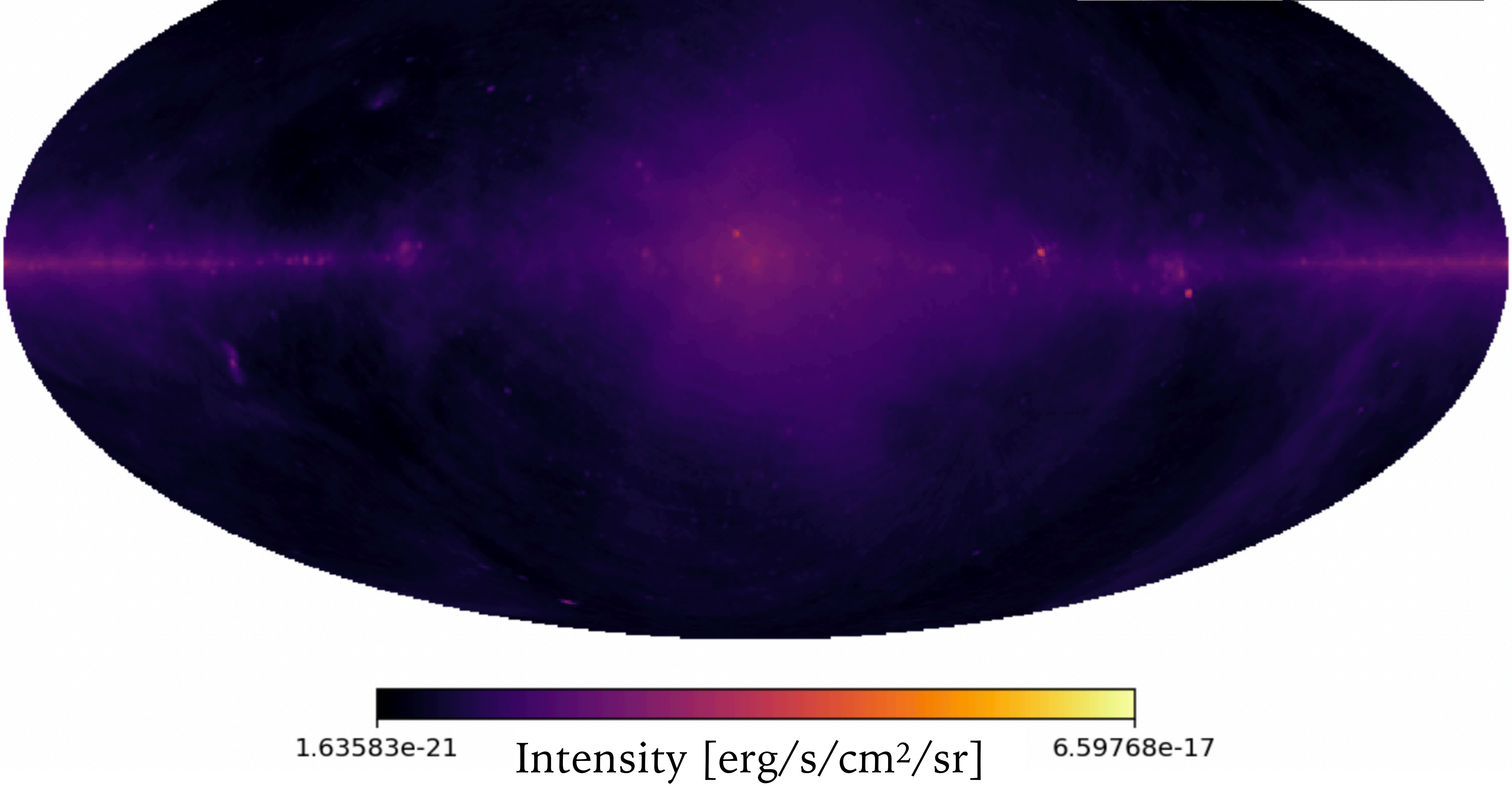


- What about extended objects… like the whole sky??? Can we win by looking at less optimal targets in a larger field of view for a longer time? ("collateral science" since people already doing 21 cm surveys, other radio observations)

Gegenschein of Haslam Map @408 MHz

led by McGill BSc student Harper Sewalls, Yitian Sun

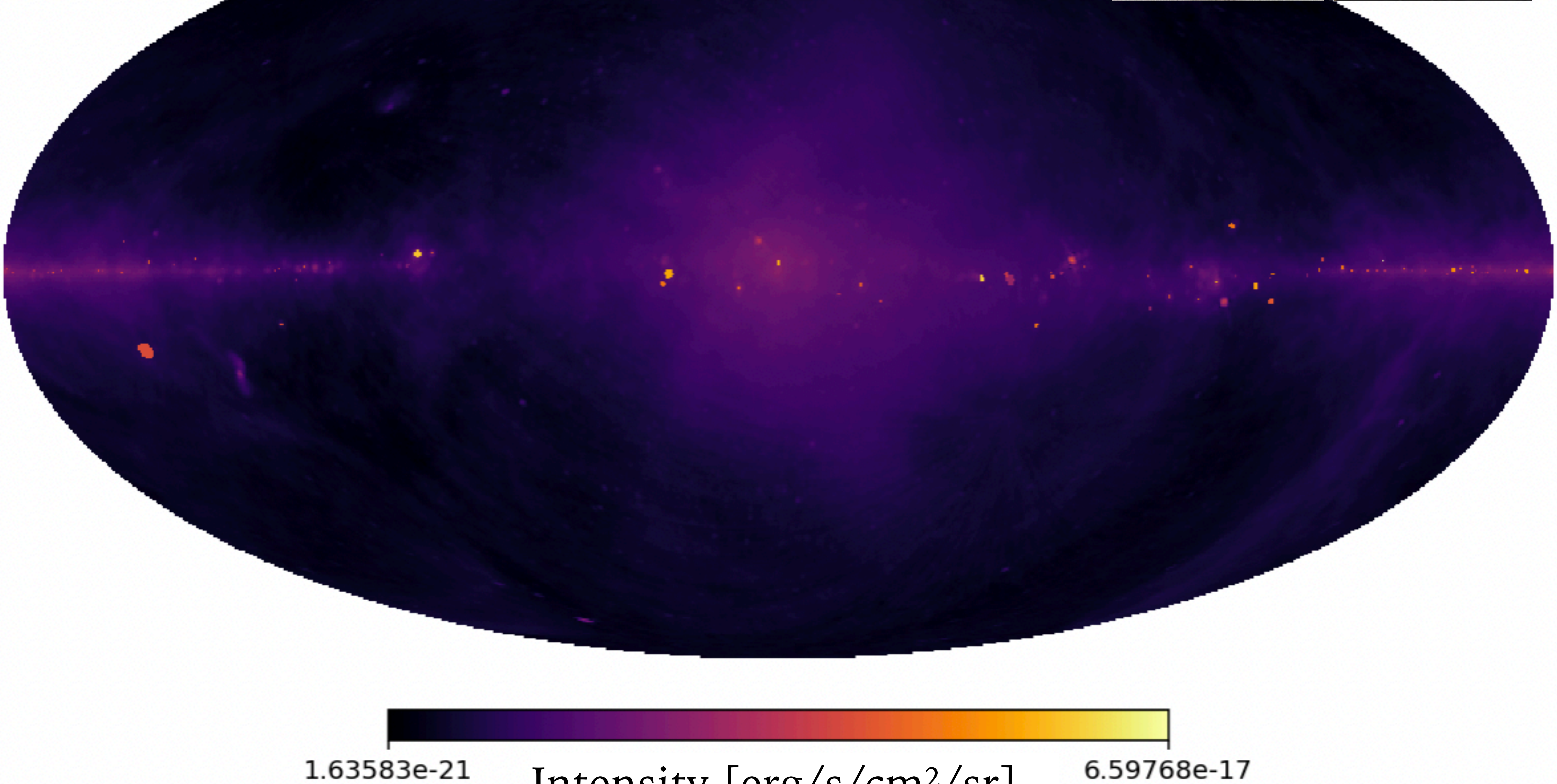
PRELIMINARY!



...adding in supernova remnants

led by McGill BSc student Harper Sewalls, Yitian Sun

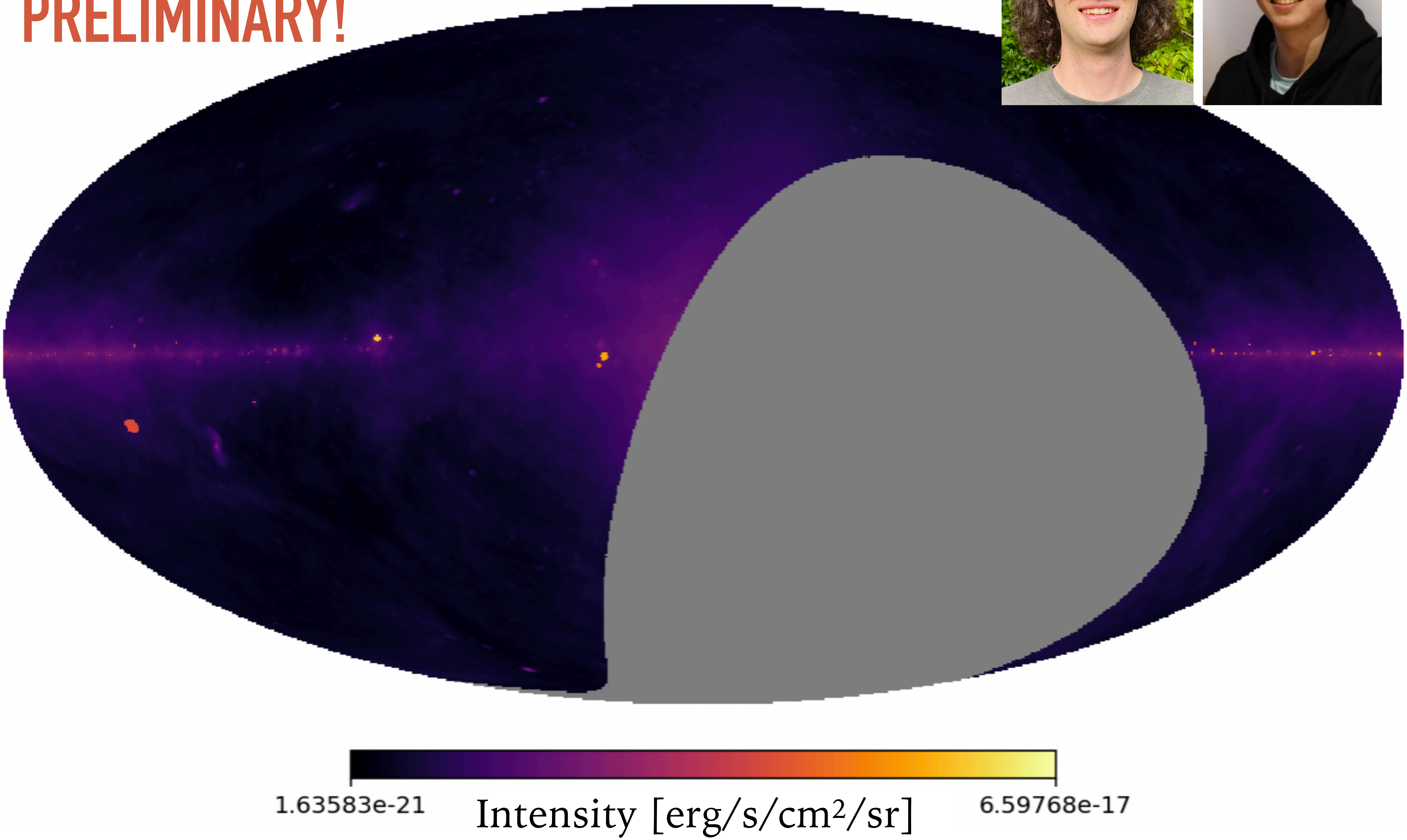
PRELIMINARY!



. . .in the CHIME field of view

led by McGill BSc student Harper Sewalls, Yitian Sun

PRELIMINARY!



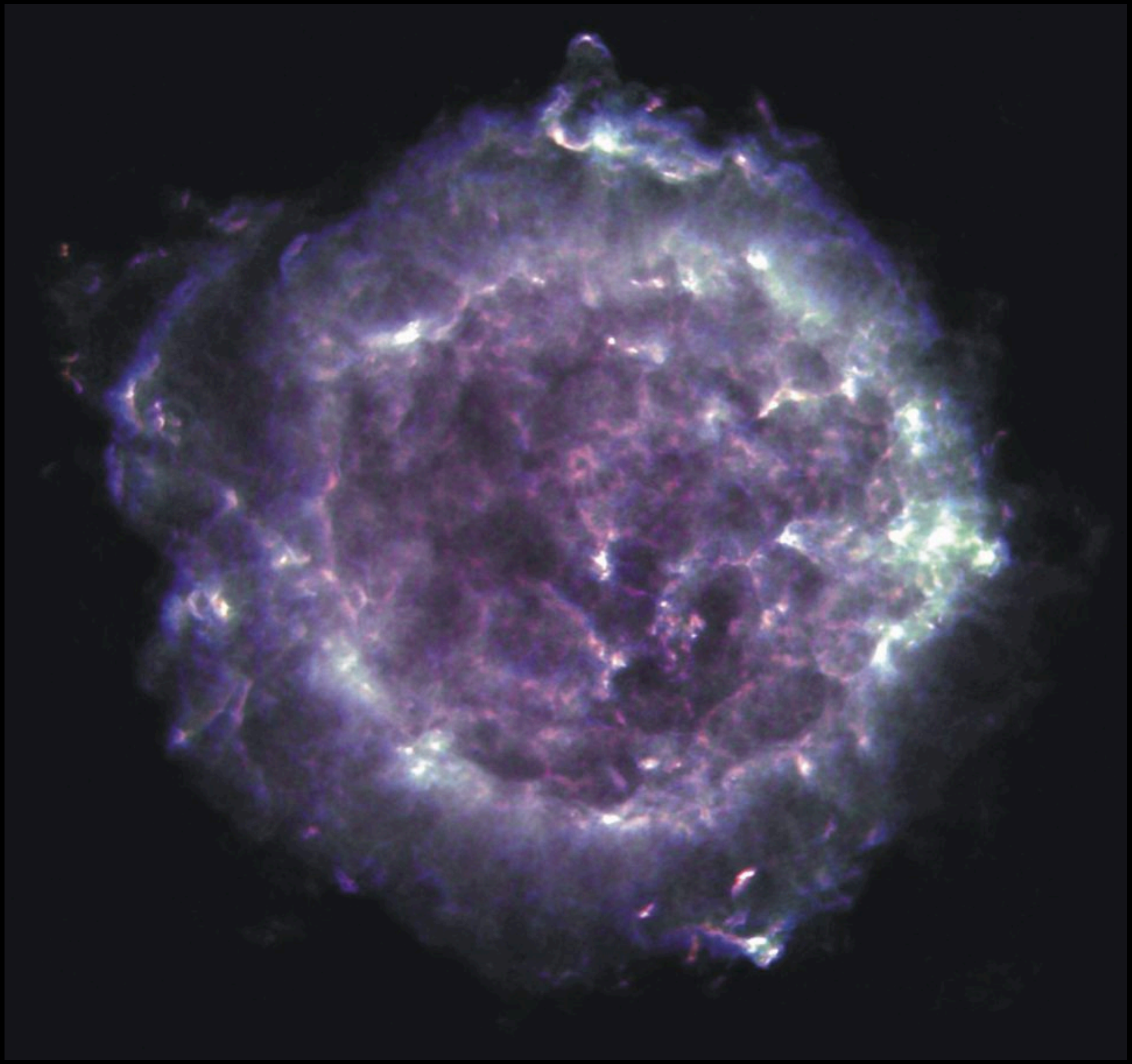
. . .in the CHIME field of view

led by McGill BSc student Harper Sewalls, Yitian Sun

PRELIMINARY!

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 and CHIME, we may have immediate sensitivity to new axion parameter space despite conservative modeling choices



THANK YOU!