Title: CHIME is secretly an axion experiment - VIRTUAL

Speakers: Katelin Schutz

Series: Particle Physics

Date: April 23, 2024 - 1:00 PM

URL: https://pirsa.org/24040114

Abstract: In the presence of radiation from bright astrophysical sources at radio frequencies, axion dark matter can undergo stimulated decay to two nearly back-to-back photons, meaning that bright sources could have faint counterimages in other parts of the sky. The counterimages will be spectrally distinct from backgrounds, taking the form of a narrow radio line centered at half the axion mass with a spectral width determined by Doppler broadening in the dark matter halo. In essence, axions behave as an imperfect monochromatic mirror. The morphology of the induced images can be nontrivial, with blurring due to the geometry of the source and image as well as spatial smearing due to the galactic kinematics of axion dark matter. I will show that the axion decay-induced counterimages of galactic sources may be bright enough to be detectable with archival data from CHIME and other ongoing or planned radio surveys. CHIME therefore can run as a competitive axion experiment simultaneously with other science objectives, requiring no new hardware.

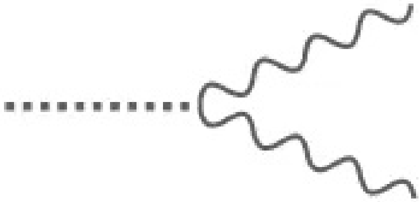
Zoom link

CHIME IS SECRETLY* AN AXION EXPERIMENT

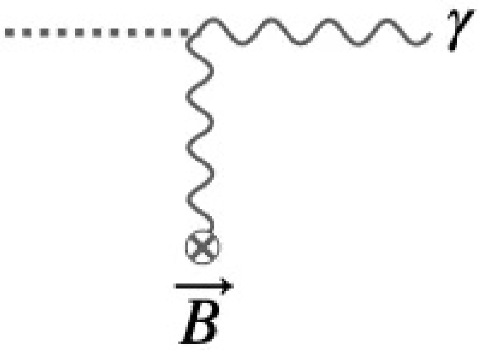
Katelin Schutz
Perimeter Particle Seminar, April 23 2024

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

AXION COUPLING TO PHOTONS

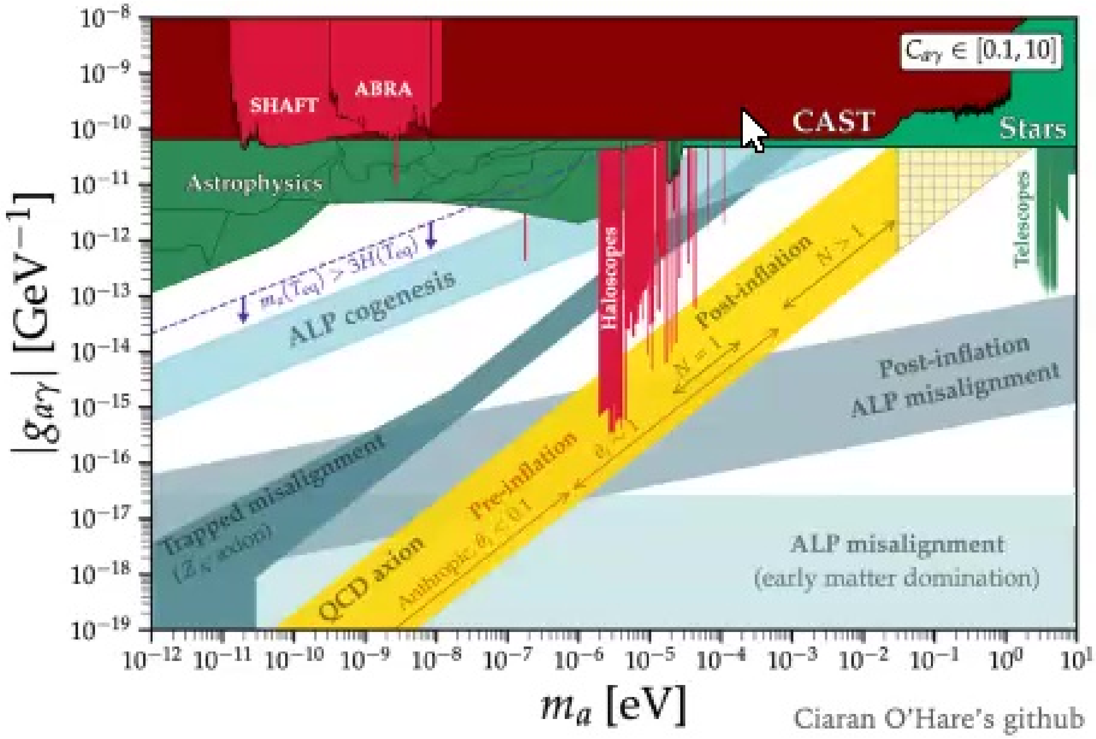


$$\mathscr{L} \supset g_{a\gamma\gamma}\, a(\vec{E} \cdot \vec{B})$$



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

AXION DARK MATTER COUPLING TO PHOTONS

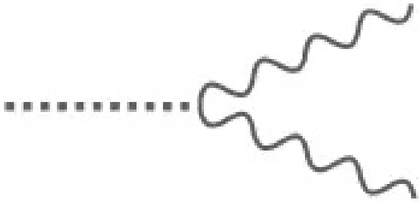


Ciaran O'Hare's github

The need for complementarity in axion searches

- All searches for axion-photon coupling in sub-eV mass range are subject to astrophysical uncertainty, whether in interpreting observations with systematics or in modeling/simulating astrophysical systems (e.g. neutron stars)
- Even terrestrial direct detection searches are not safe, some axion cosmologies lead to most of the axions being in compact mini-halos (e.g. Buschmann et al. 2019) with an O(1) survival rate inside the Milky Way (e.g. Shen et al. 2022), so terrestrial density could be substantially lower than the mean Galactic density
- Multiple independent searches with different observational systematics, different modeling requirements, and less sensitivity to the local axion density are extremely useful!

AXION SPONTANEOUS DECAY



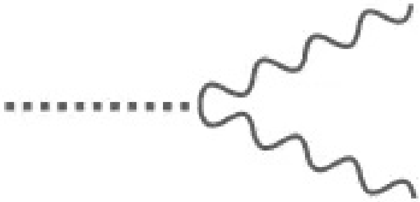
$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\, (\vec{E} \cdot \vec{B})$$

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



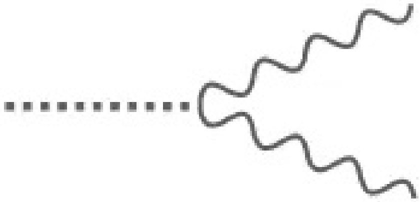
$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\,(\vec{E}\cdot\vec{B})$$

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

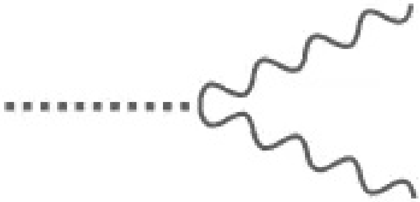
This is Bose enhanced

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

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

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

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“Gegenschein”

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

$\omega = m_a/2$ 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

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

e.g. Arza & Sikivie (2019)

THE UPSHOT:

AXIONS ARE AN IMPERFECT MONOCHROMATIC MIRROR.

CAN SHOOT RADIATION AT IT AND WAIT FOR ECHO, OR USE EXISTING ASTROPHYSICAL RADIATION!

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THE UPSHOT:

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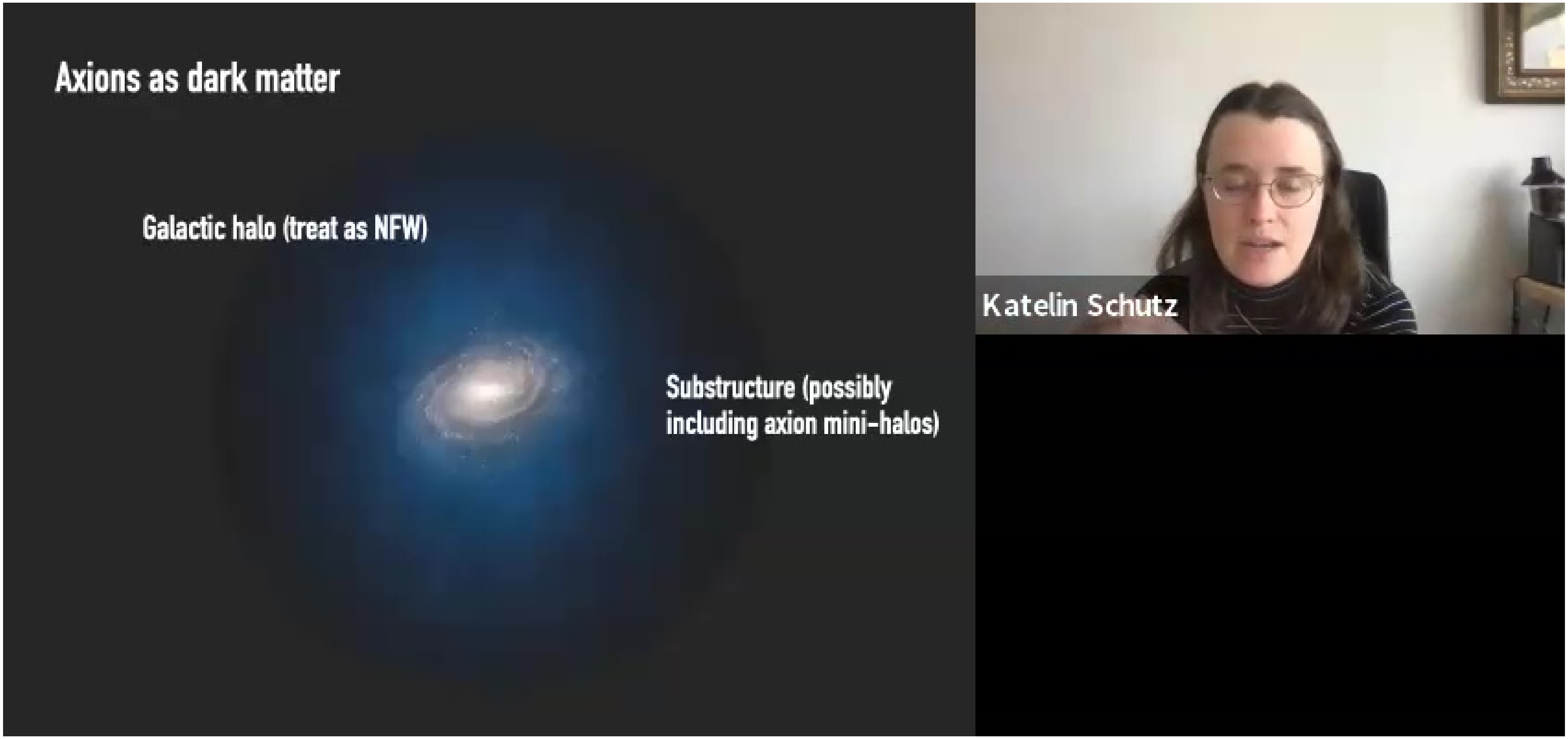
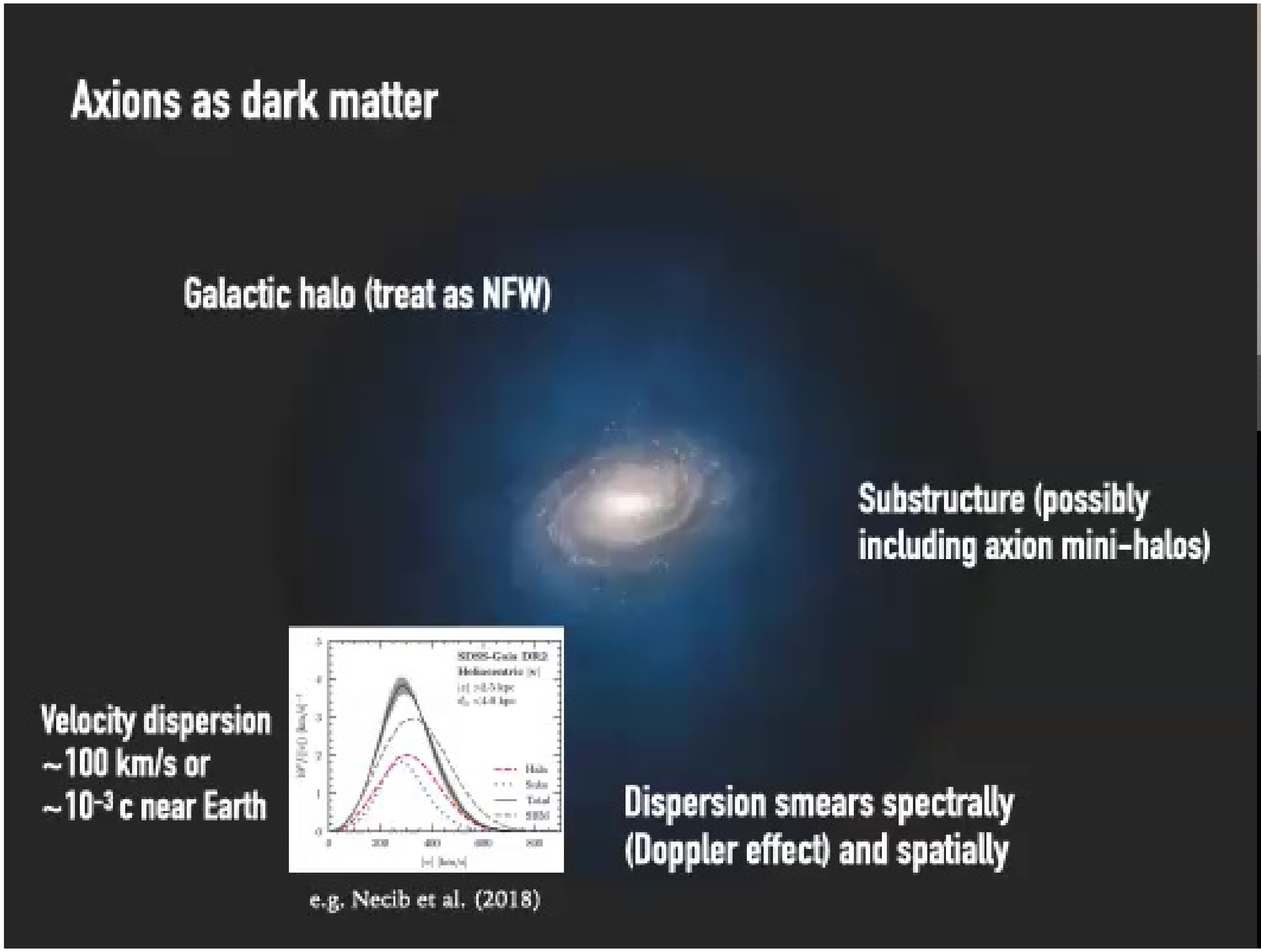
e.g. Ghosh et al. (2020), Buen-Abad et al. (2022), Sun, KS et al. (2022)



Axions as dark matter

Galactic halo (treat as NFW)

Substructure (possibly including axion mini-halos)



Axions as dark matter

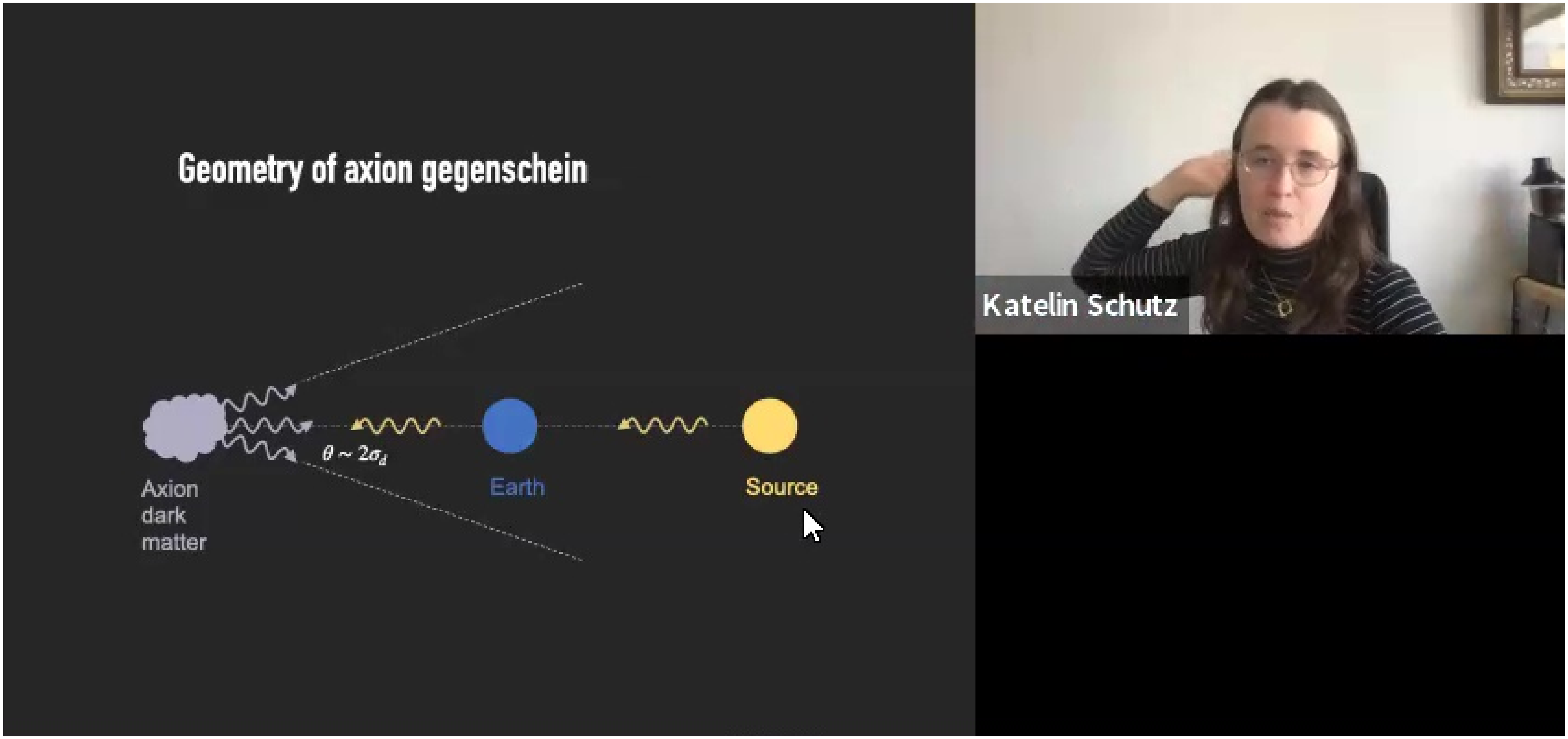
Galactic halo (treat as NFW)

Substructure (possibly including axion mini-halos)

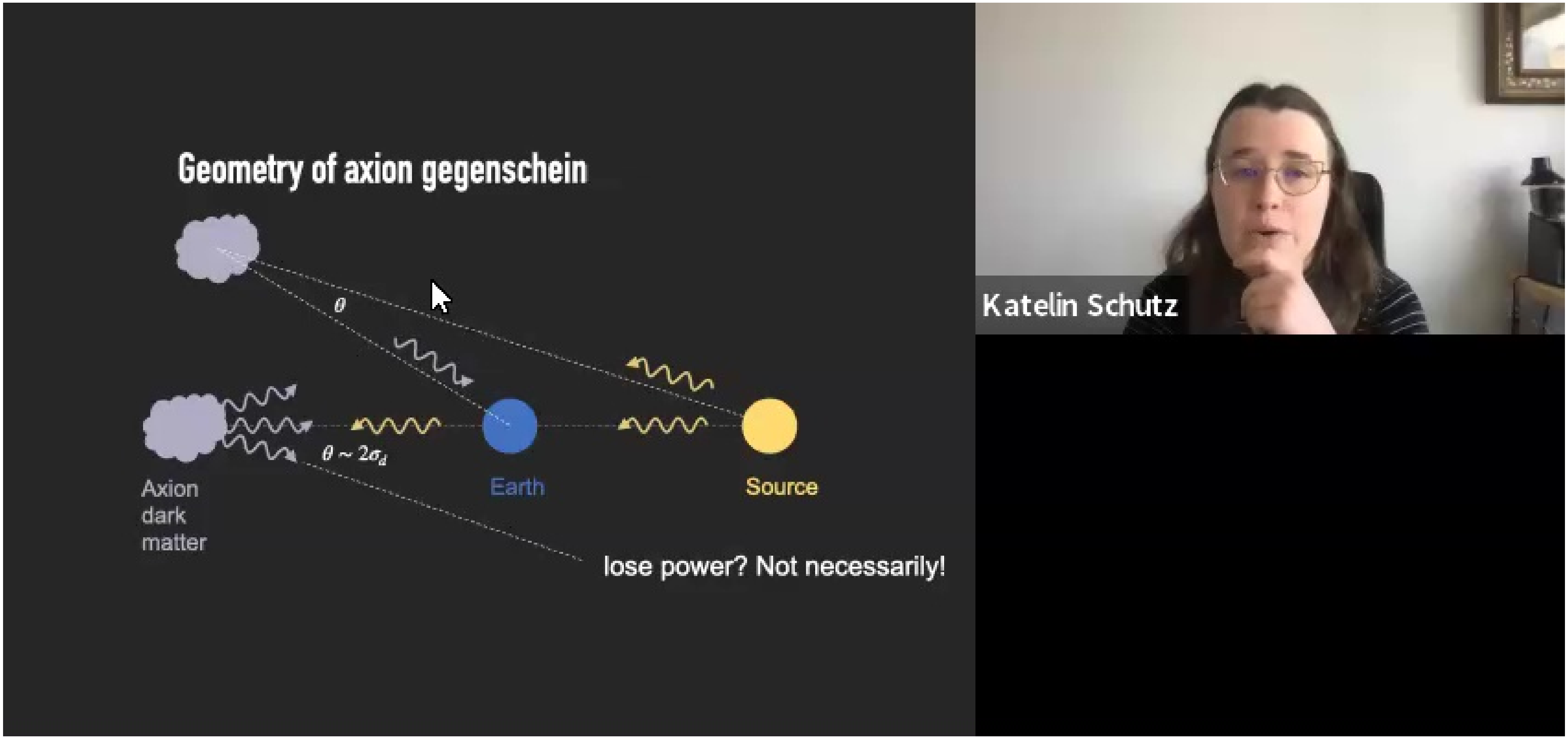
Velocity dispersion ~100 km/s or ~10^{-3} c near Earth

e.g. Necib et al. (2018)

Dispersion smears spectrally (Doppler effect) and spatially



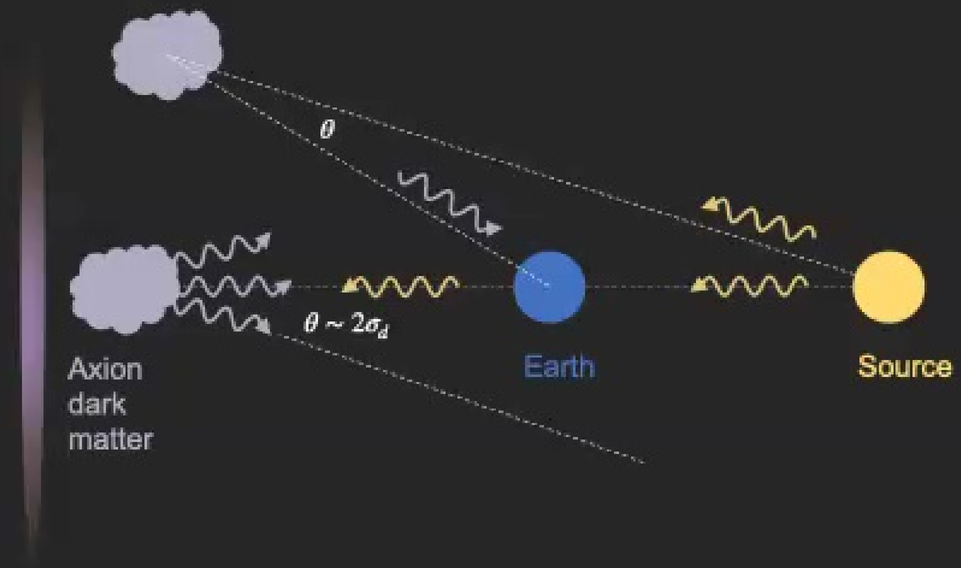
Geometry of axion gegenschein

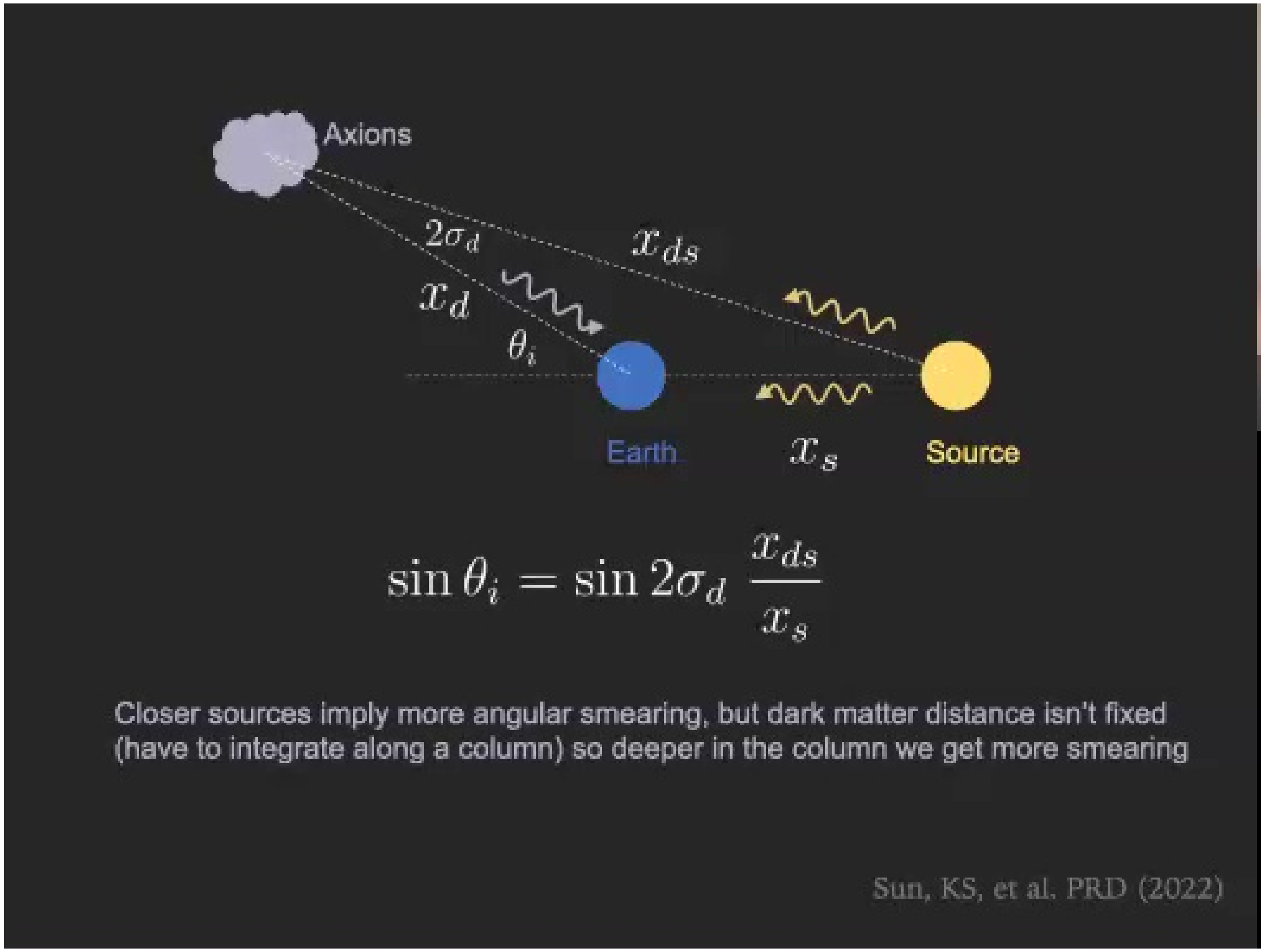


Geometry of axion gegenschein

lose power? Not necessarily!

Geometry of axion gegenschein

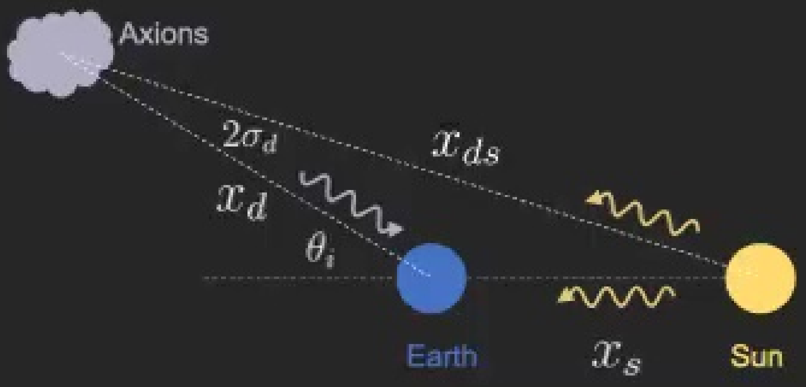




$$\sin\theta_i = \sin 2\sigma_d \, \frac{x_{ds}}{x_s}$$

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)



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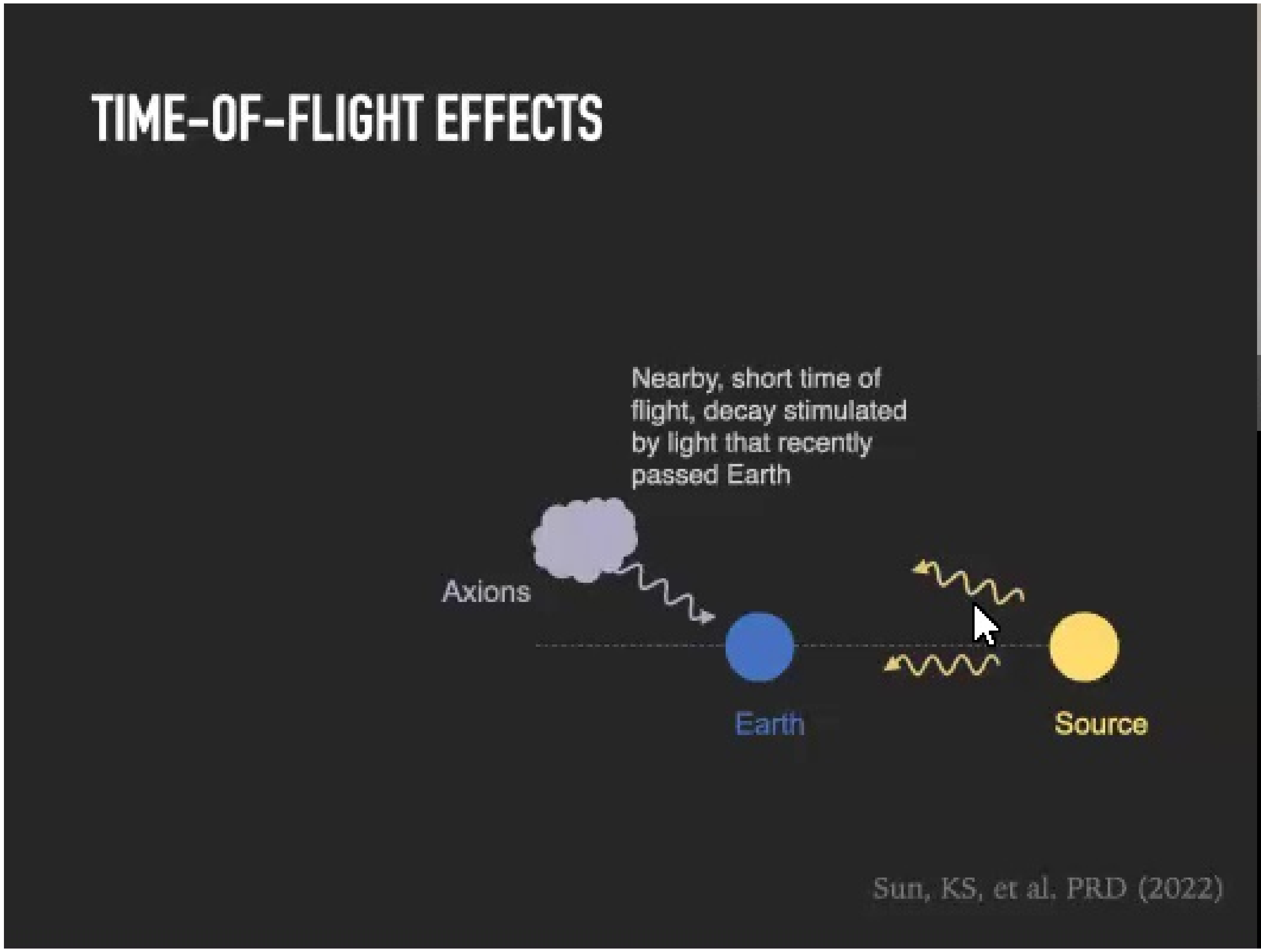
The Sun is very bright in radio waves but is not a very good source! Given ~10^{-3} velocity dispersion, once you get a dark matter column deeper than ~10^3 a.u. the image fills the entire sky… not easy to recover diffuse signal and we don't get to benefit much from deeper ~10 kpc dark matter column!

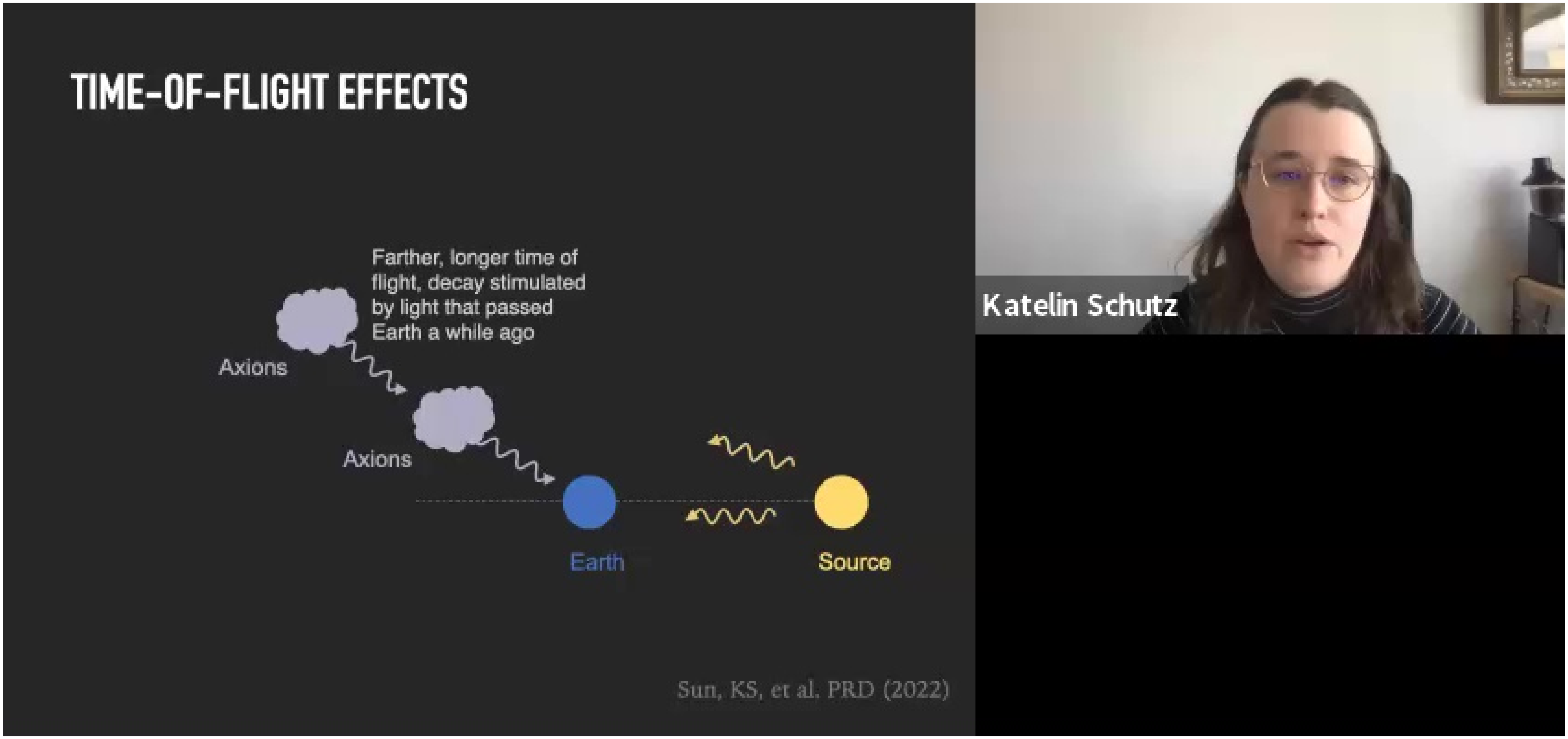
Sun, KS, et al. PRD (2022)

TIME-OF-FLIGHT EFFECTS



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

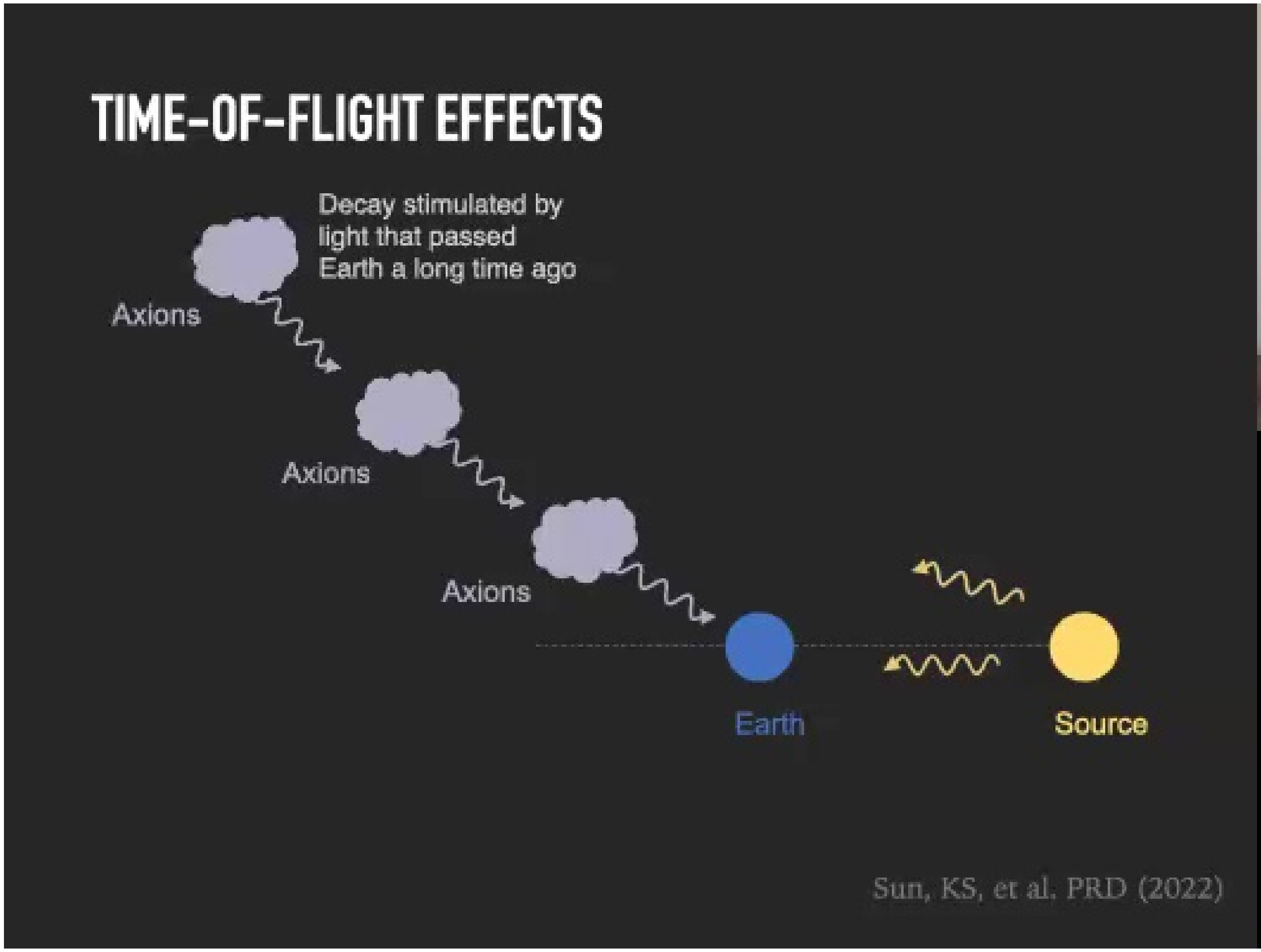
Sun, KS, et al. PRD (2022)



TIME-OF-FLIGHT EFFECTS

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

Sun, KS, et al. PRD (2022)



TIME-OF-FLIGHT EFFECTS

Decay stimulated by
light that passed
Earth a long time ago

Axions

Axions

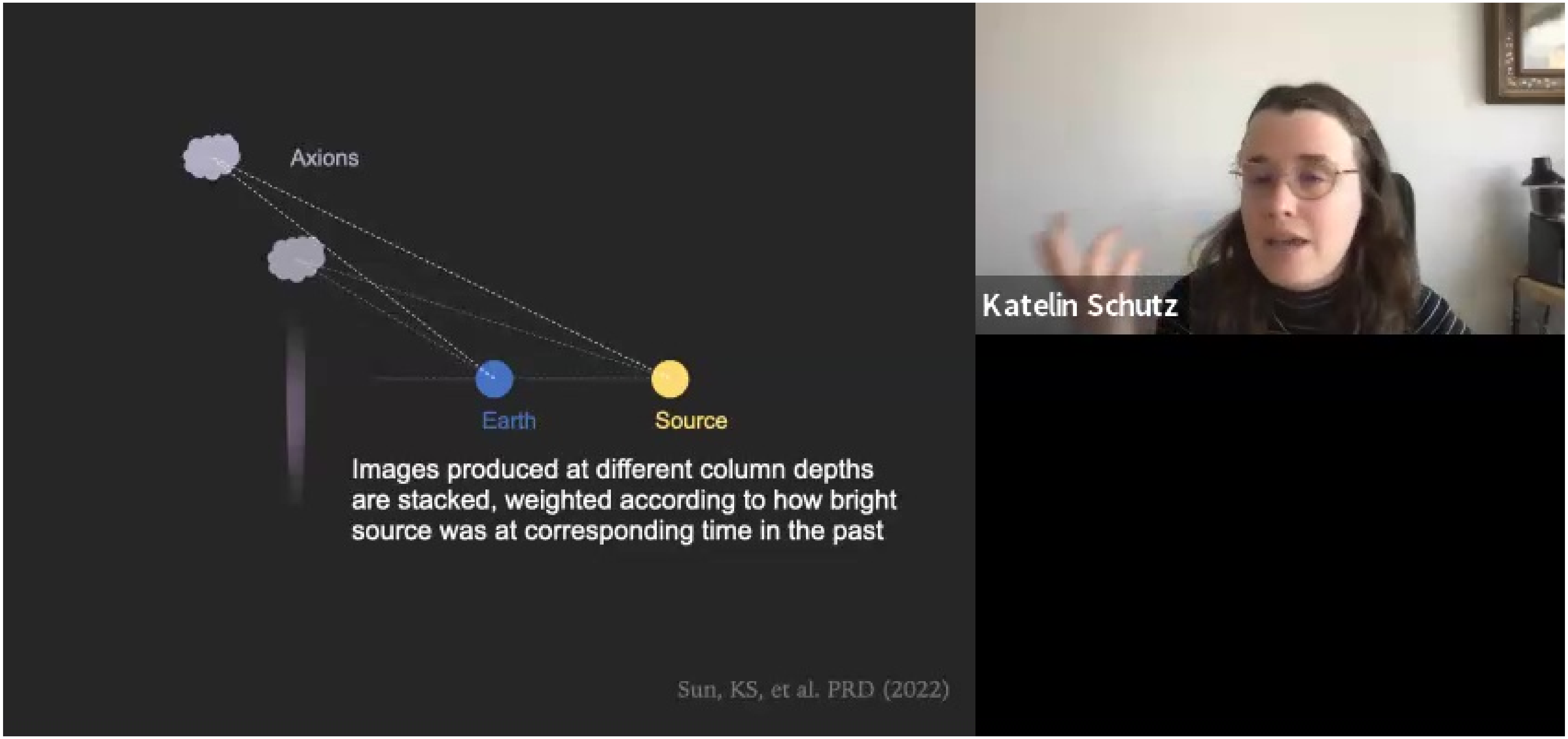
Axions

Earth

Source

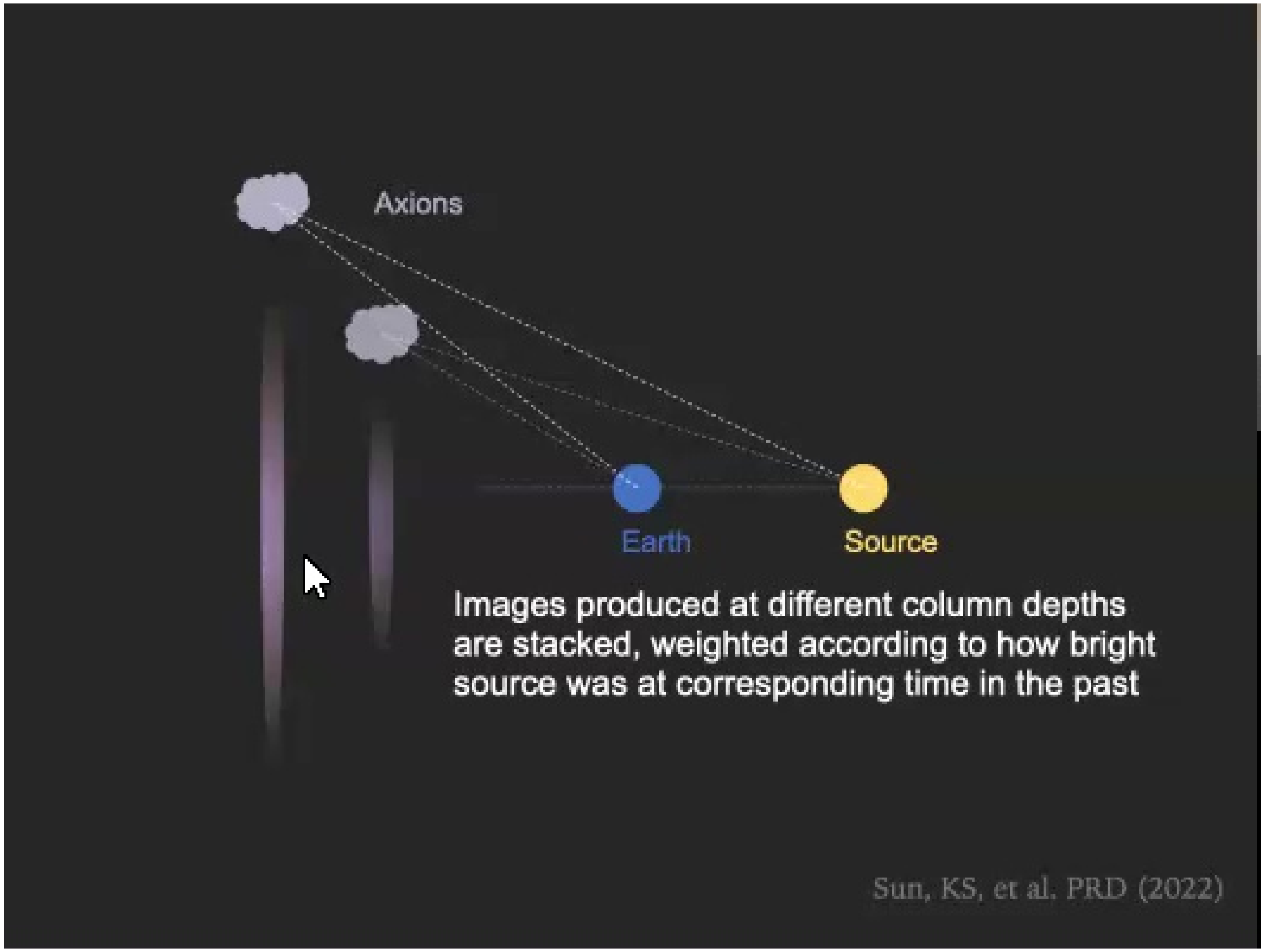
Sun, KS, et al. PRD (2022)


Katelin Schutz



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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Sun, KS, et al. PRD (2022)


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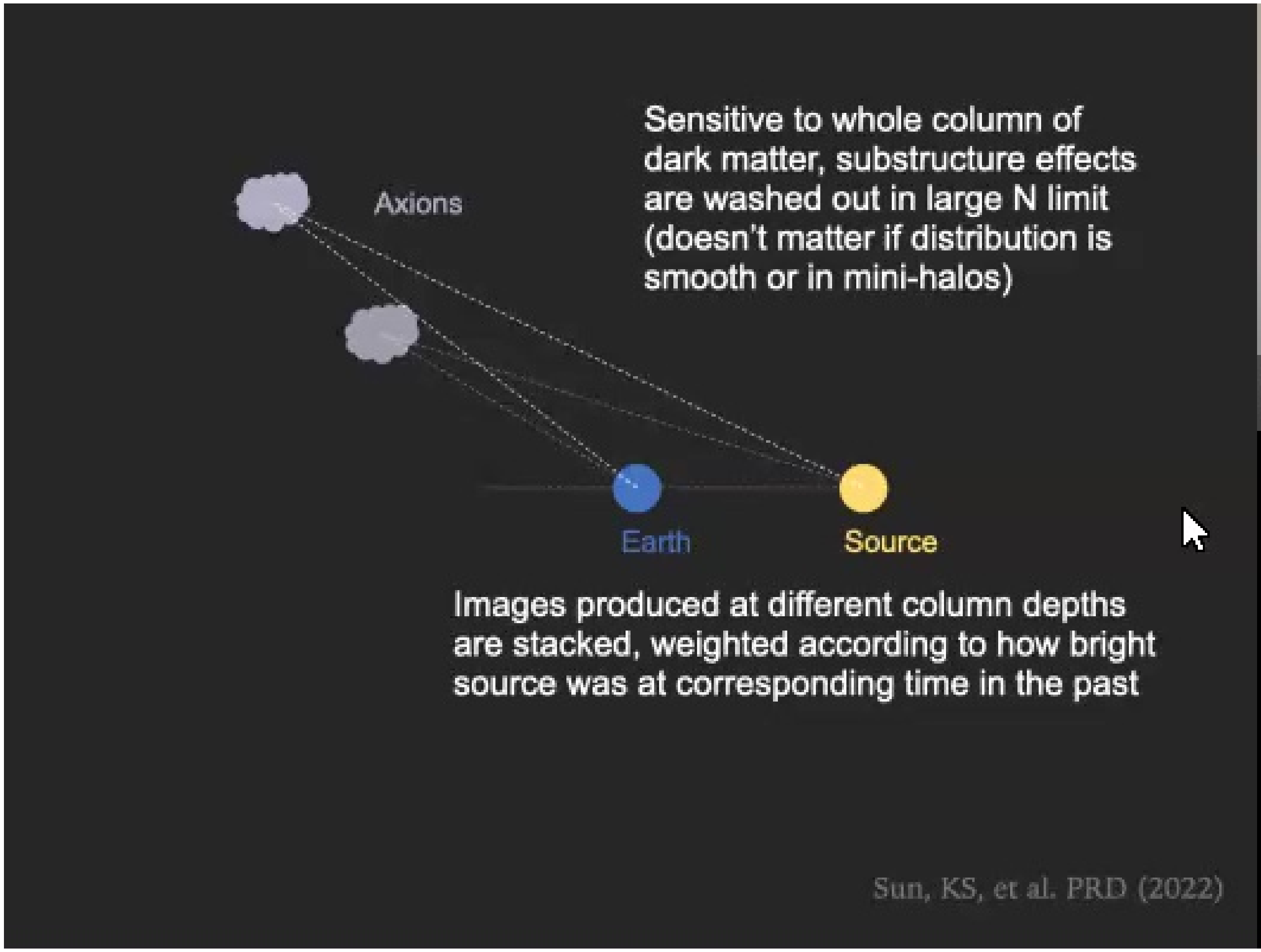

Sensitive to whole column of dark matter, substructure effects are washed out in large N limit (doesn't matter if distribution is smooth or in mini-halos)

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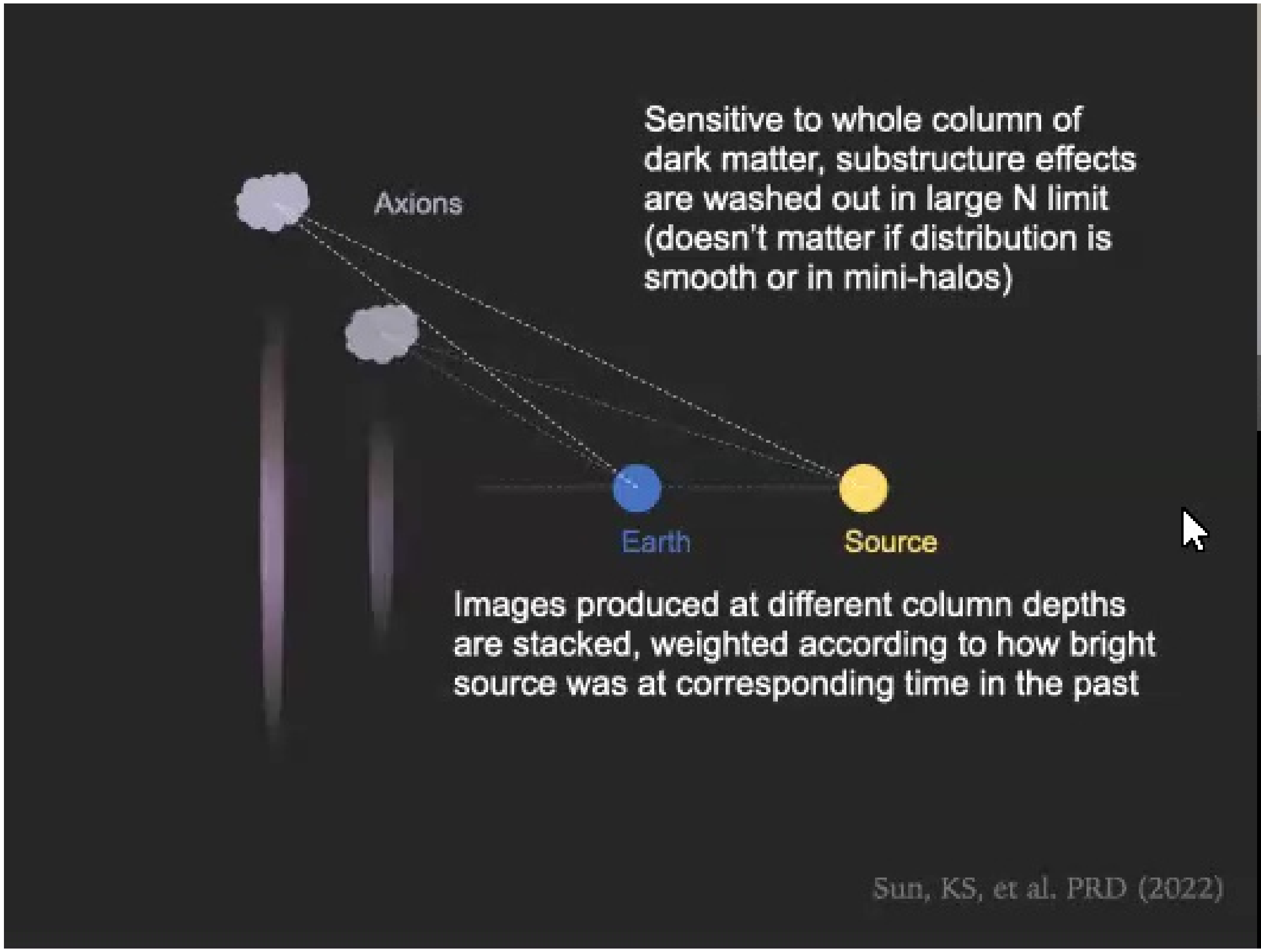

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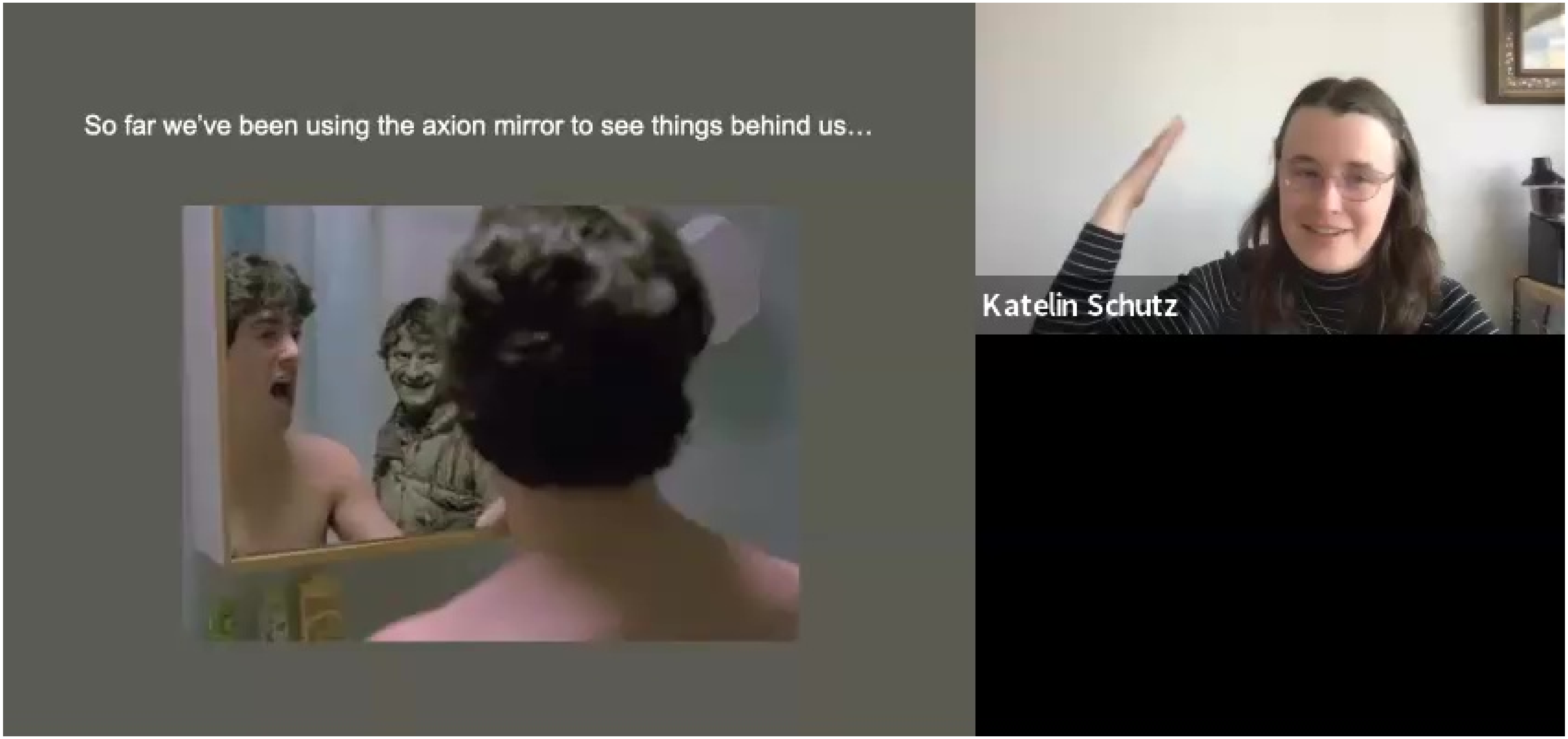
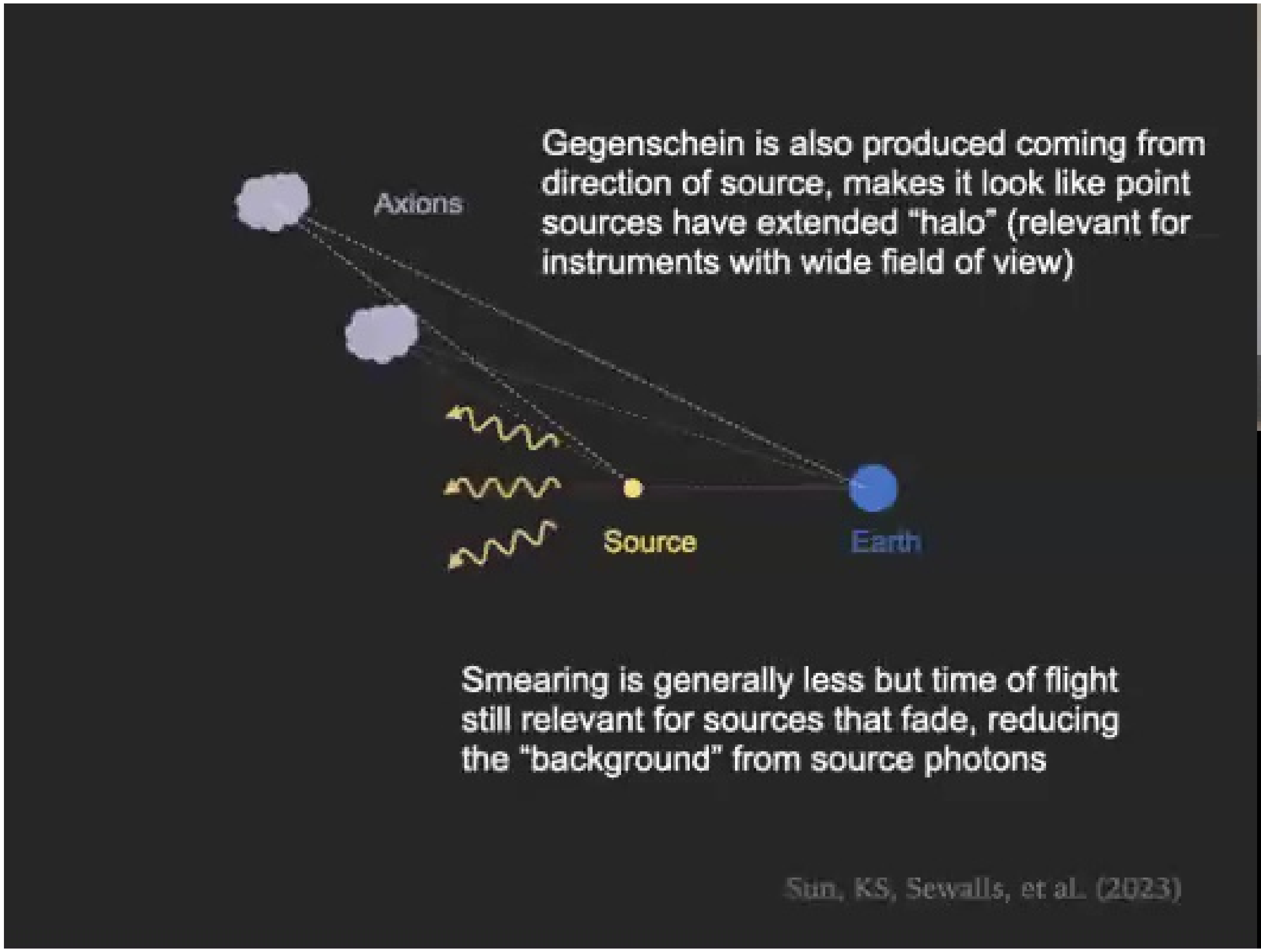


So far we've been using the axion mirror to see things behind us…

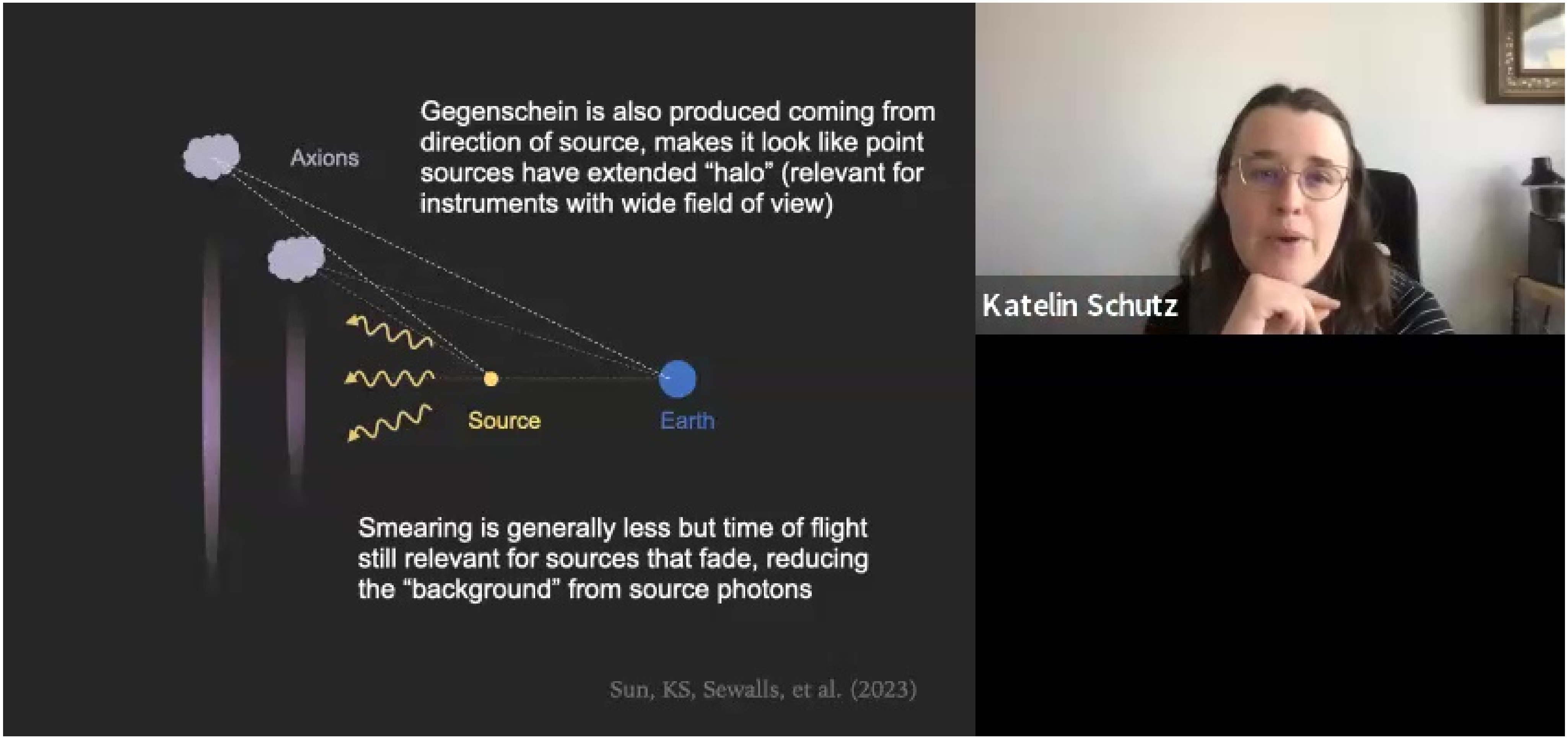
…. but you can also see things in front of your eyes (with time delay)



Gegenschein is also produced coming from direction of source, makes it look like point sources have extended “halo” (relevant for instruments with wide field of view)

Smearing is generally less but time of flight still relevant for sources that fade, reducing the “background” from source photons

Sun, KS, Sewalls, et al. (2023)



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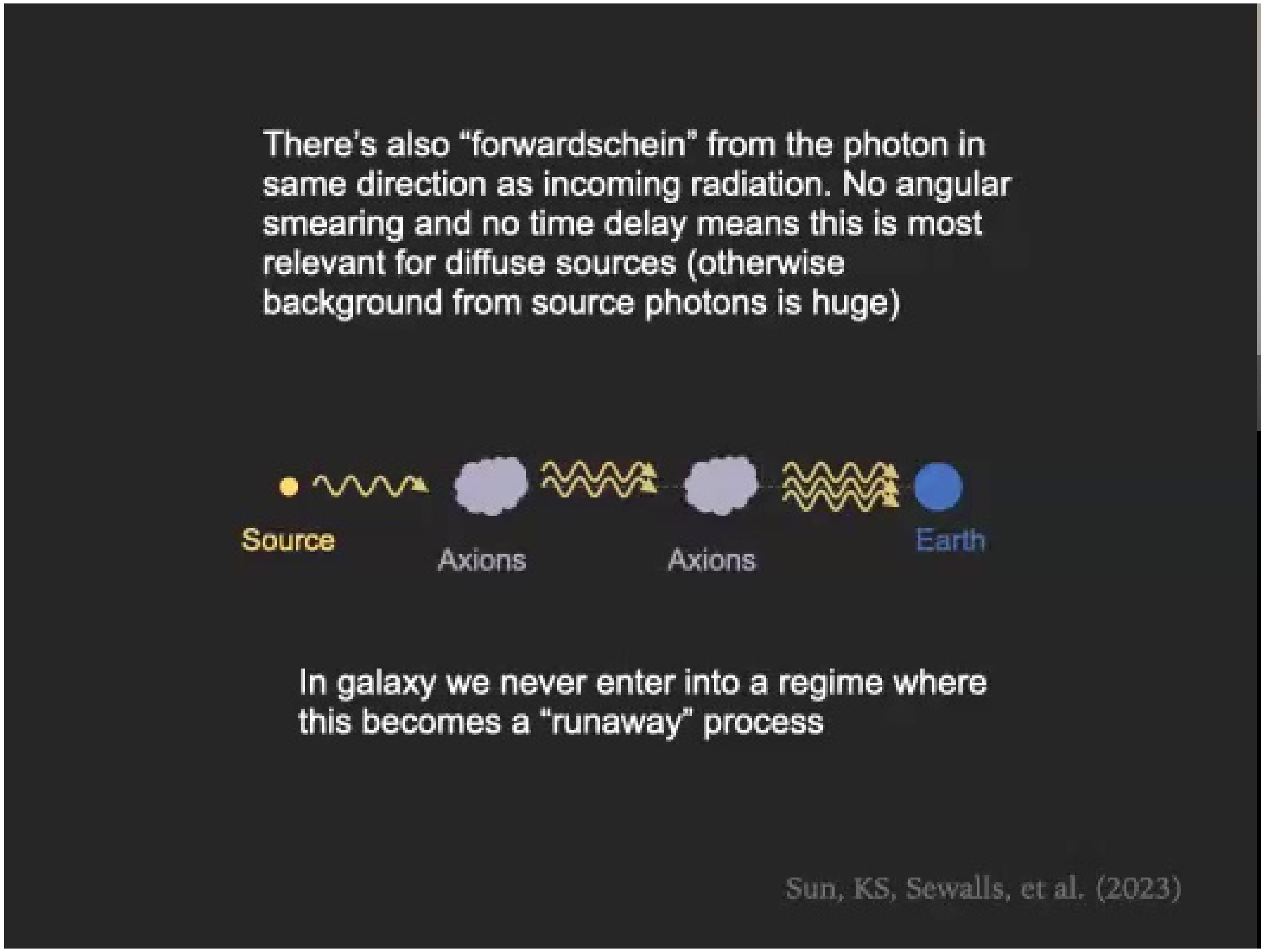


There's also "forwardschein" from the photon in same direction as incoming radiation. No angular smearing and no time delay means this is most relevant for diffuse sources (otherwise background from source photons is huge)

In galaxy we never enter into a regime where this becomes a "runaway" process

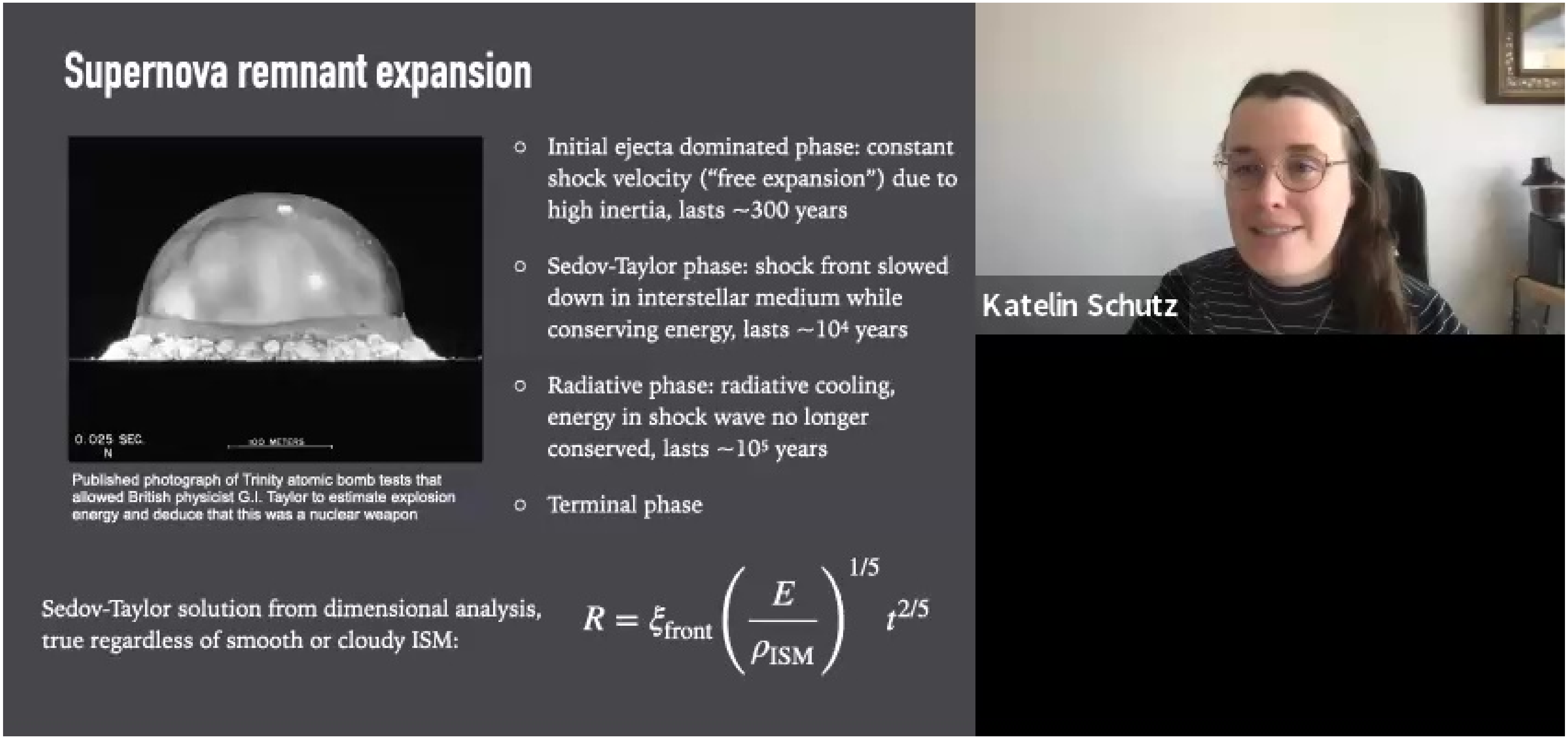
Sun, KS, Sewalls, et al. (2023)

UPSHOT: OPTIMAL SOURCES OF STIMULATING RADIATION WERE THE BRIGHTEST RADIO SOURCES AT SOME POINT WITHIN THE LAST GALACTIC LIGHT-CROSSING TIME

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 ~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



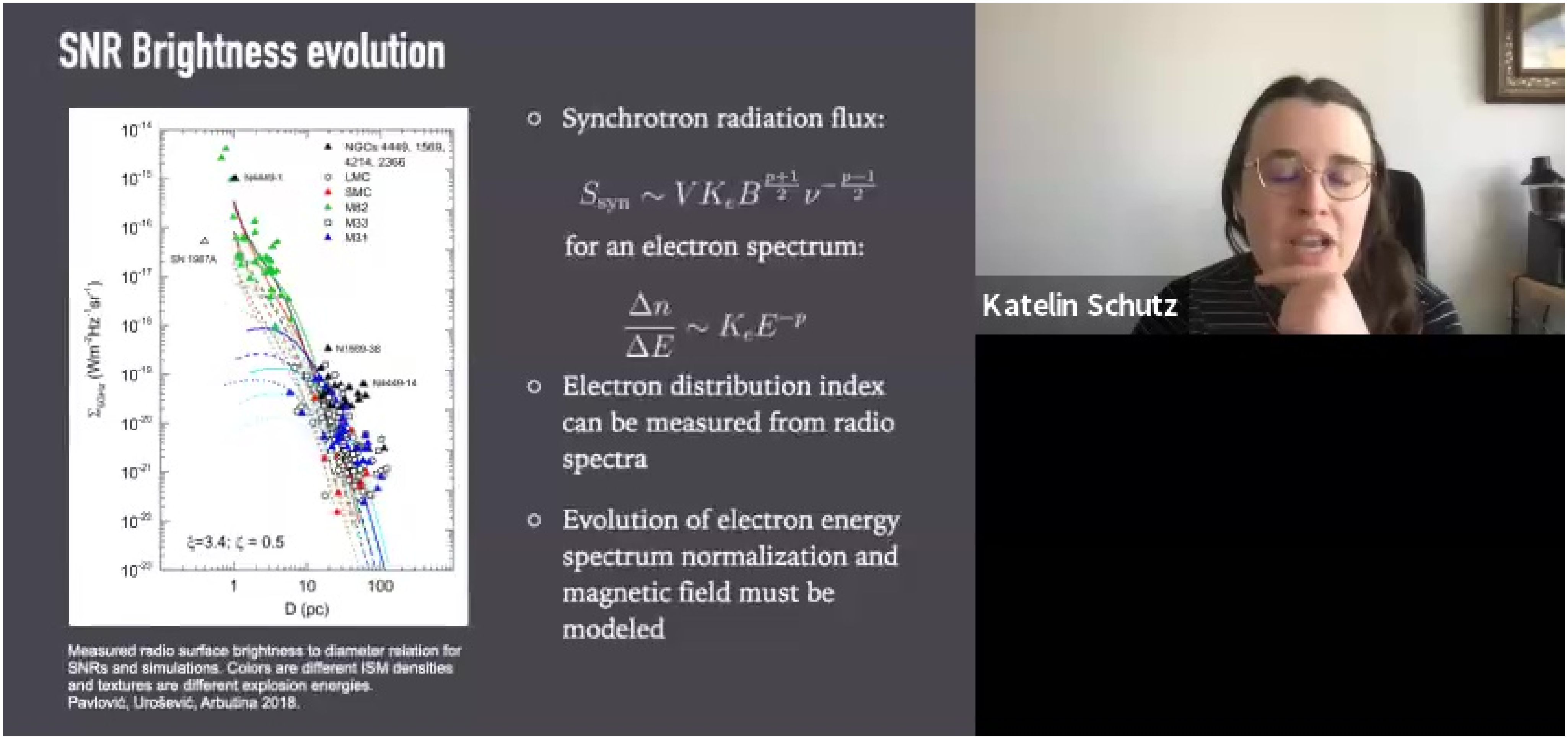
Supernova remnant expansion

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:

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



SNR Brightness evolution

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

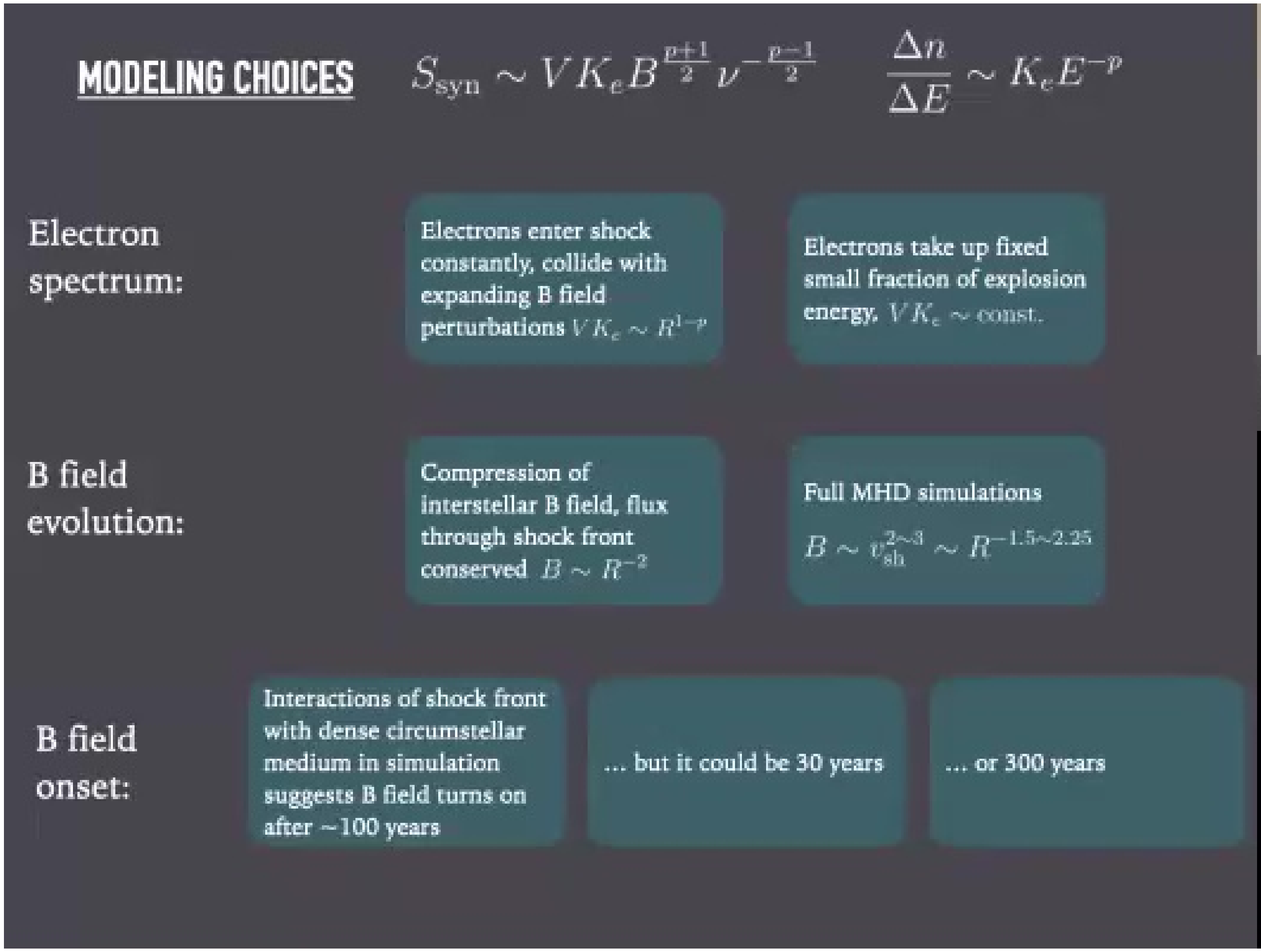
- Synchrotron radiation flux:

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

for an electron spectrum:

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

- Electron distribution index can be measured from radio spectra
- Evolution of electron energy spectrum normalization and magnetic field must be modeled



MODELING CHOICES

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

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, $V K_e \sim \text{const.}$

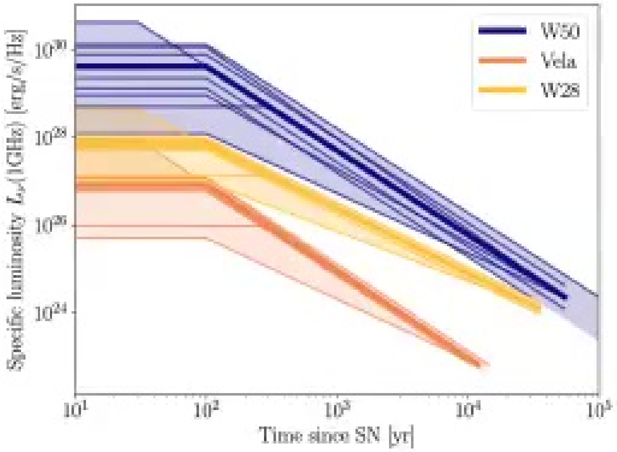
B field evolution:

- Compression of interstellar B field, flux through shock front conserved $B \sim R^{-2}$
- Full MHD simulations $B \sim v_{\text{sh}}^{2\sim3} \sim R^{-1.5\sim2.25}$

B field onset:

- Interactions of shock front with dense circumstellar medium in simulation suggests B field turns on after ~100 years
- … but it could be 30 years
- … or 300 years

MODELING CHOICE EFFECTS ON OUR BEST SOURCES

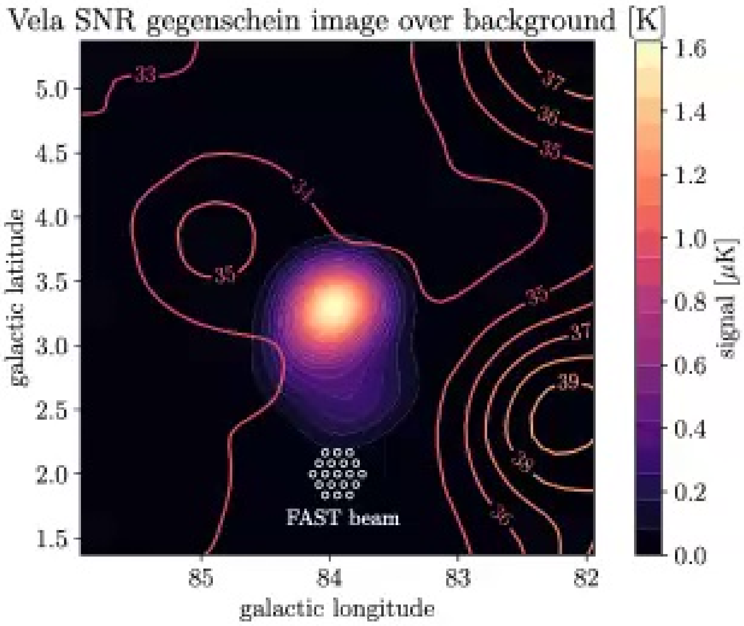


- Data obtained from UManitoba SNRcat and Green's SNR catalog
- We vary the B field amplification time, electron model, spectral index, age, distance, etc.
- We conservatively assume no growth of the luminosity prior to the magnetic field amplification (observed light curves of young SNe suggest these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

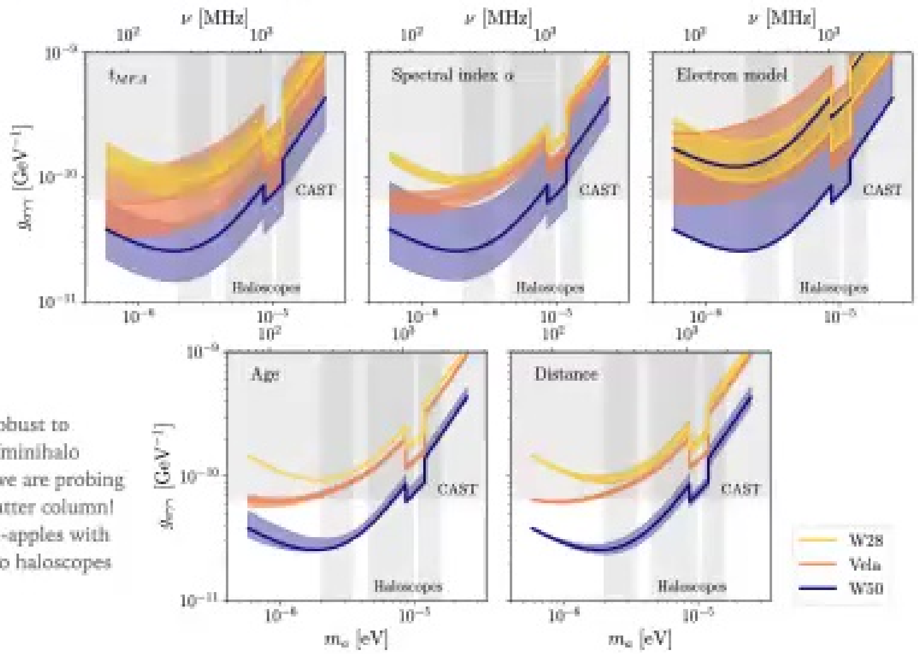


Sun, KS, et al. PRD (2022)

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



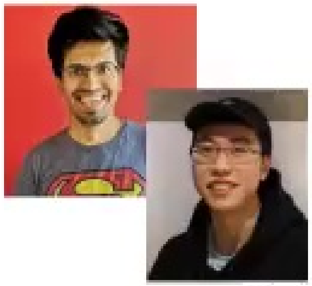
Note this is robust to substructure/minihalo effects since we are probing ~kpc dark matter column! Not apples-to-apples with terrestrial halo haloscopes

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

Sun, KS, et al. PRD (2022)

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) and different parts of EM spectrum finding nothing imminently detectable (but let's chat if you have an idea!)



What about other telescopes?


Canadian Hydrogen Intensity Mapping Experiment (CHIME)

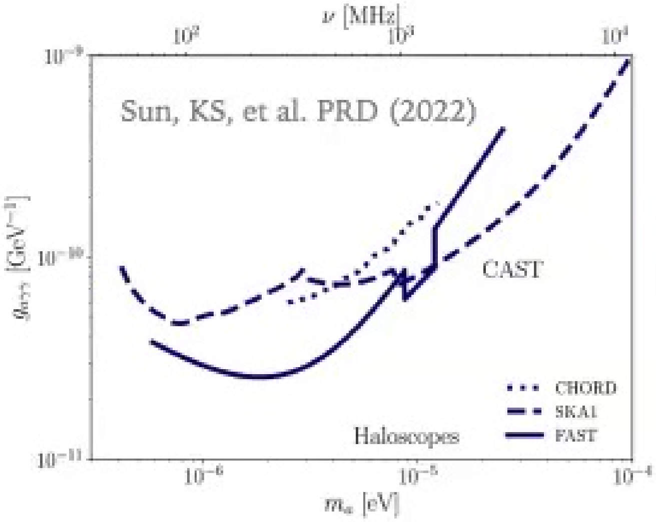

Canadian Hydrogen Observatory and Radio-Transient Detector (CHORD)


Hydrogen Intensity and Real-Time Analysis eXperiment (HIRAX)


Square Kilometre Array (SKA)

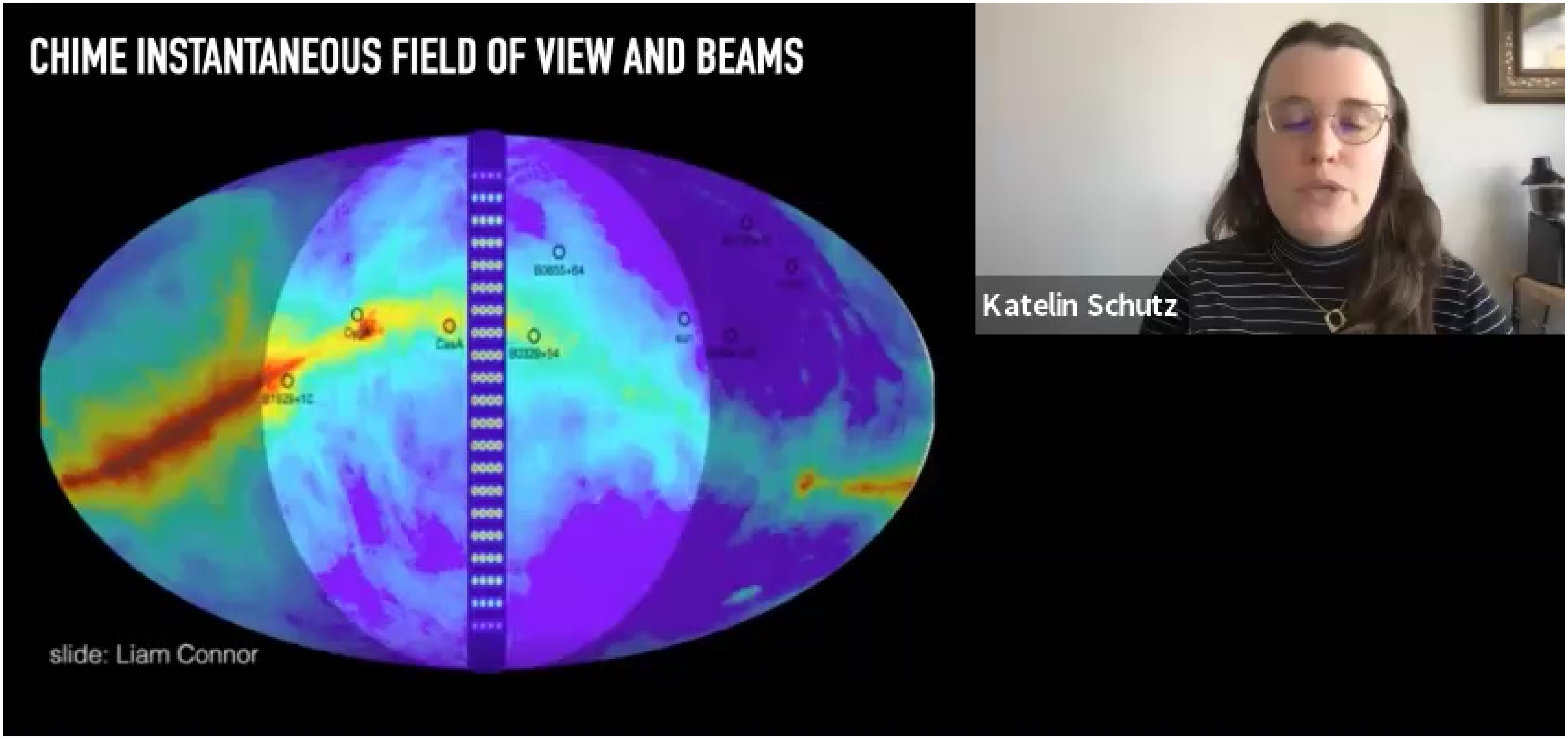
What about other telescopes?

- 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 and using **large field of view that can simultaneously monitor large fraction of the sky with multiple SNRs**



CHIME INSTANTANEOUS FIELD OF VIEW AND BEAMS

slide: Liam Connor

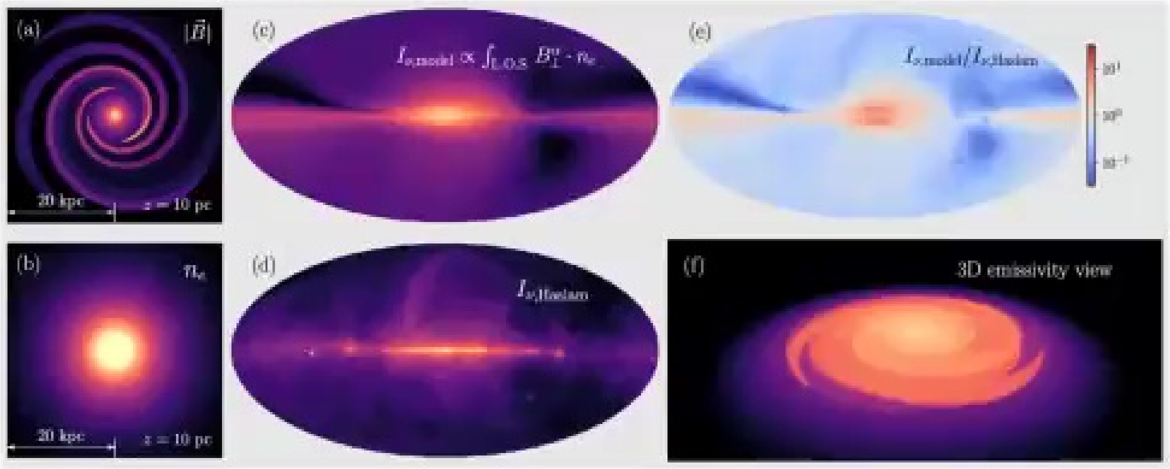
Katelin Schutz

What are the ingredients for making all-sky map?

- ☑ 3D map of dark matter density and its velocity dispersion (influences spatial smearing)
- ☑ 3D model for galactic synchrotron radiation (GSR)

Sun, KS, Sewalls, et al. PRD (2023)

Normalizing GSR intensity based on 3D spatial models using Haslam map



Upshot: total effect of finite distances/3D model is at few percent level
(robust to modeling uncertainty!)

Sun, KS, Sewalls, et al. PRD (2023)

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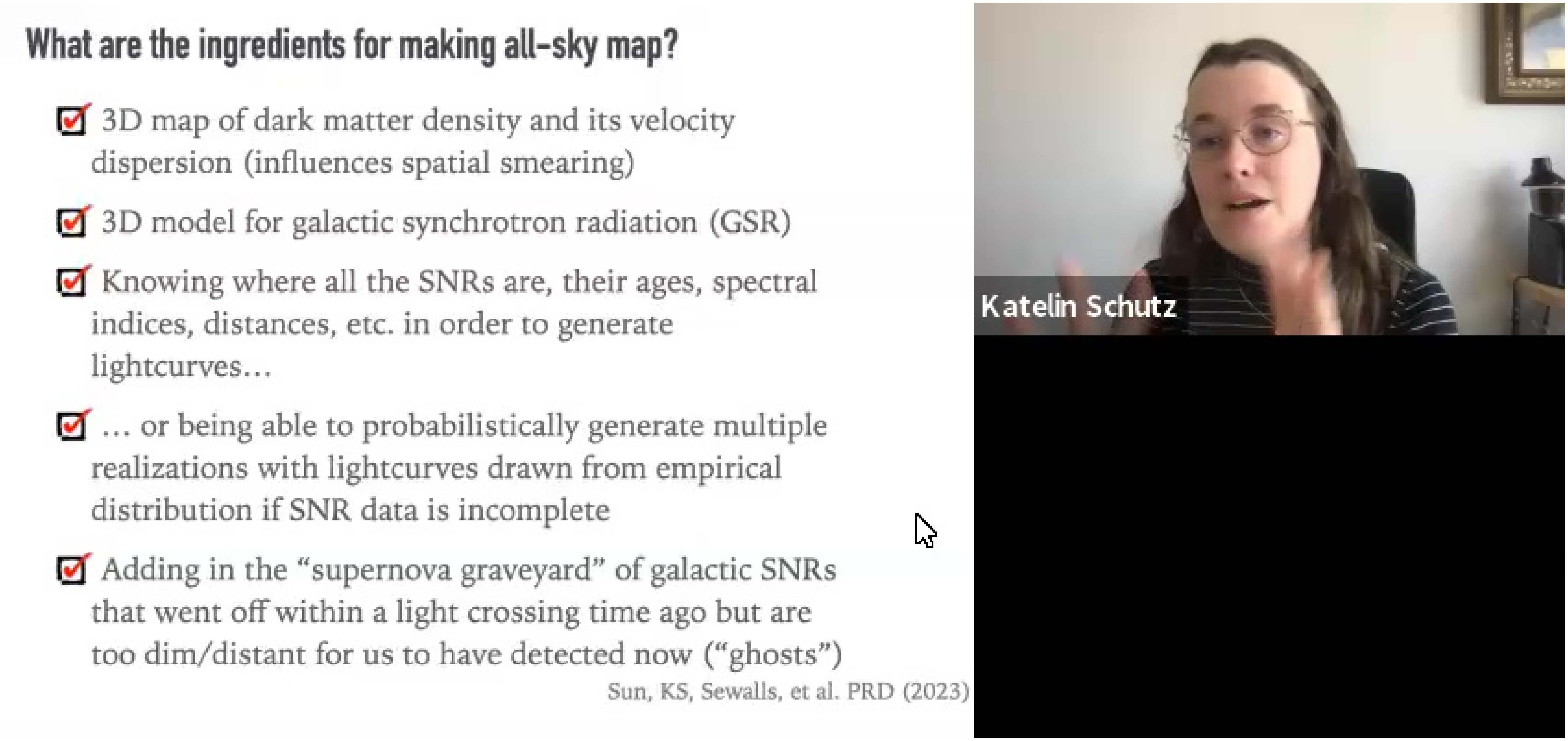
- ☑ … or being able to probabilistically generate multiple realizations with lightcurves drawn from empirical distribution if SNR data is incomplete

Sun, KS, Sewalls, et al. PRD (2023)



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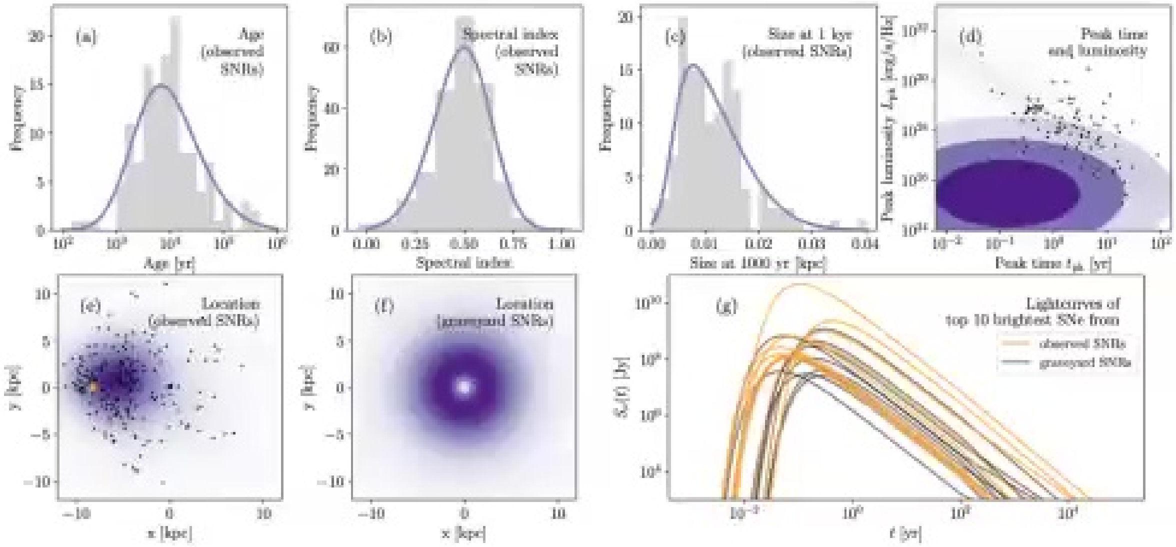
- ☑ Knowing where all the SNRs are, their ages, spectral indices, distances, etc. in order to generate lightcurves…
- ☑ … or being able to probabilistically generate multiple realizations with lightcurves drawn from empirical distribution if SNR data is incomplete
- ☑ Adding in the “supernova graveyard” of galactic SNRs that went off within a light crossing time ago but are too dim/distant for us to have detected now (“ghosts”)

Sun, KS, Sewalls, et al. PRD (2023)


Katelin Schutz

Distributions for sampling any unknown SN remnant properties



Sun, KS, Sewalls, et al. PRD (2023)

What are the ingredients for making all-sky map?

- ☑ 3D map of dark matter density and its velocity dispersion (influences spatial smearing)
- ☑ 3D model for galactic synchrotron radiation (GSR)
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Sun, KS, Sewalls, et al. PRD (2023)

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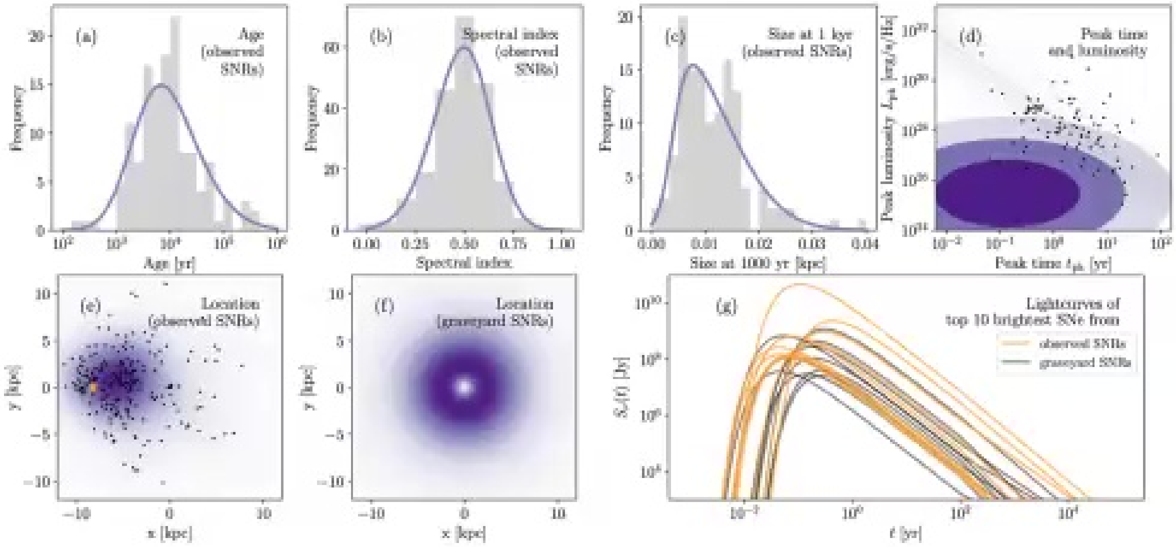

Sun, KS, Sewalls, et al. PRD (2023)

Generating probabilistic realizations of gegenschein map from supernova graveyard

Drawing from empirically derived SNR rates, spatial distributions, lightcurves, spectral indices, angular size, etc.

Sun, KS, Sewalls, et al. PRD (2023)

COMPARING DIFFERENT TELESCOPES

$$(S/N)^2 = \sum_{\text{pixels}} \left(\frac{T_{\text{sig}}}{T_{\text{sky}} + T_{\text{rec}}/\eta_S} \right)^2 n_{\text{pol}}\, \Delta\nu\, t_{\text{obs}}$$

Sun, KS, Sewalls, et al. PRD (2023)

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Sky background dominates over receiver at low frequencies

Sun, KS, Sewalls, et al. PRD (2023)

COMPARING DIFFERENT TELESCOPES

$$(S/N)^2 = \sum_{\text{pixels}} \left(\frac{T_{\text{sig}}}{T_{\text{sky}} + T_{\text{rec}}/\eta_S} \right)^2 n_{\text{pol}}\, \Delta\nu\, t_{\text{obs}}$$

sky-dependent

instrument-dependent

Sun, KS, Sewalls, et al. PRD (2023)

COMPARING DIFFERENT TELESCOPES

$$(S/N)^2 = \sum_{\text{pixels}} \left(\frac{T_{\text{sig}}}{T_{\text{sky}} + T_{\text{rec}}/\eta_S} \right)^2 n_{\text{pol}}\, \Delta\nu\, t_{\text{obs}}$$

Figure of merit for comparison:

$$(S/N)^2 \propto n_{\text{pol}} \nu N_{\text{pix,FOV}} \propto n_{\text{pol}} \nu \frac{\Omega_{\text{FOV}}}{\Delta\Omega} \propto n_{\text{pol}} \nu^3 A_{\text{eff}} \Omega_{\text{FOV}} \propto n_{\text{pol}} \nu N_{\text{element}}$$

Effective beam solid angle
$\Delta\Omega = \lambda^2 / A_{\text{eff}}$

Étendue

Elements in compact array

Sun, KS, Sewalls, et al. PRD (2023)

COMPARING DIFFERENT TELESCOPES

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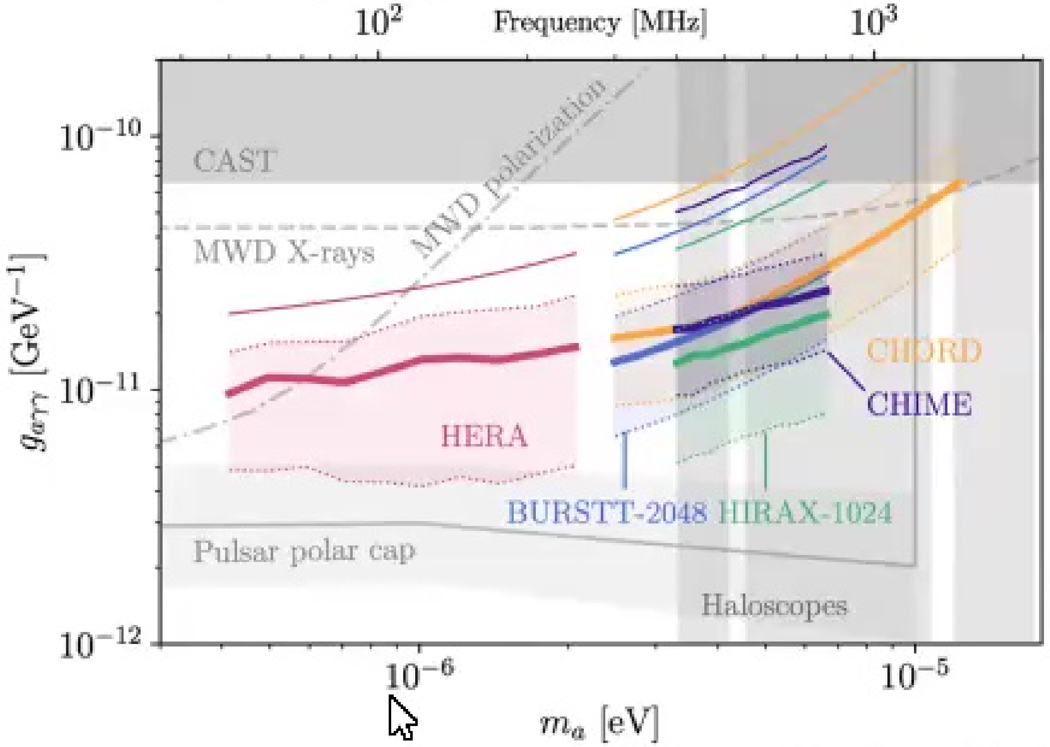
$\Delta\Omega = \lambda^2/A_{\text{eff}}$

Étendue

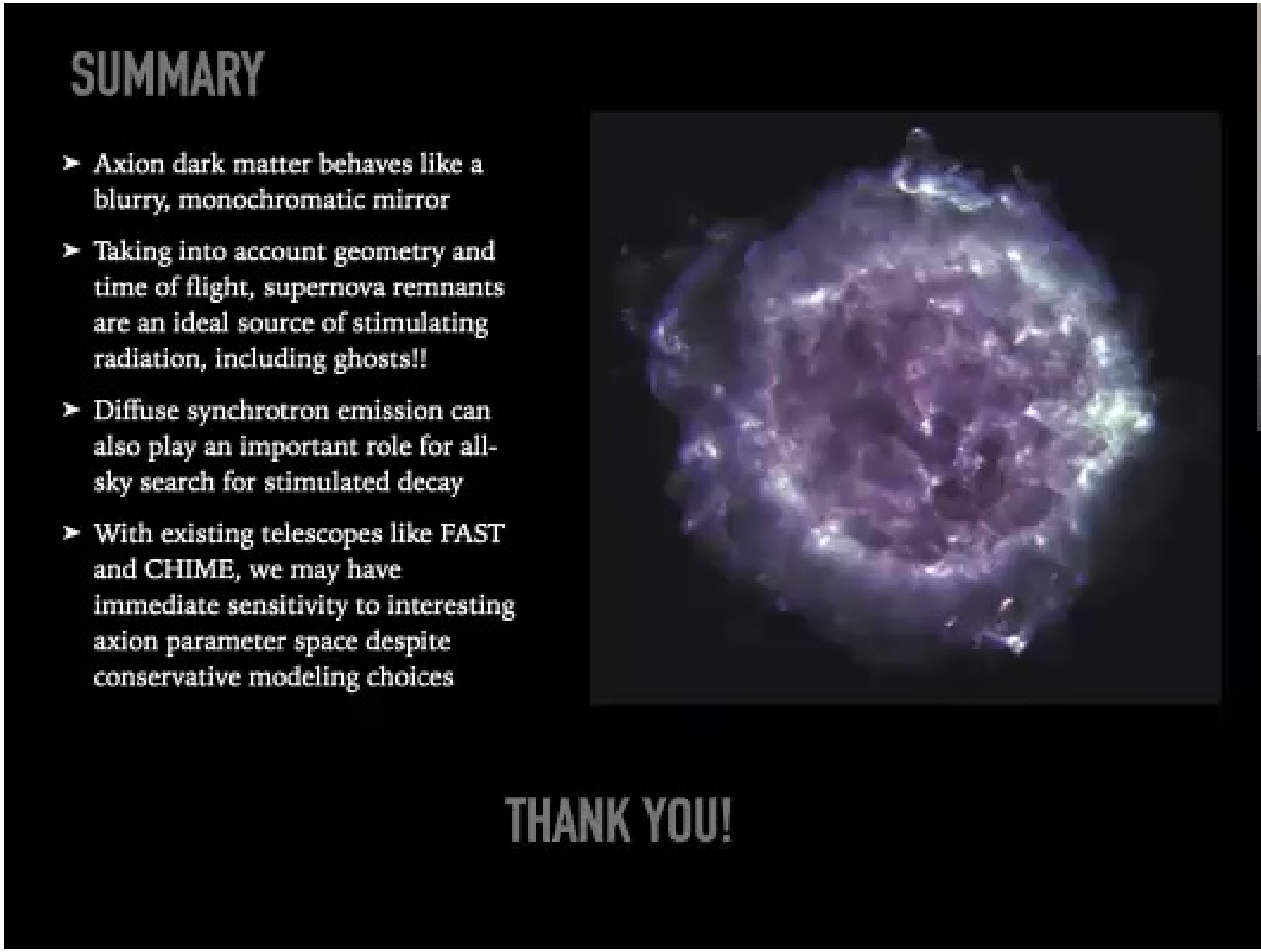
Elements in compact array

Sun, KS, Sewalls, et al. PRD (2023)

Forecast Axion Echo Sensitivity with ~5 years (corresponding to CHIME **archival** data)



Sun, KS, Sewalls, et al. (2023)



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, including ghosts!!
- Diffuse synchrotron emission can also play an important role for all-sky search for stimulated decay
- With existing telescopes like FAST and CHIME, we may have immediate sensitivity to interesting axion parameter space despite conservative modeling choices

THANK YOU!