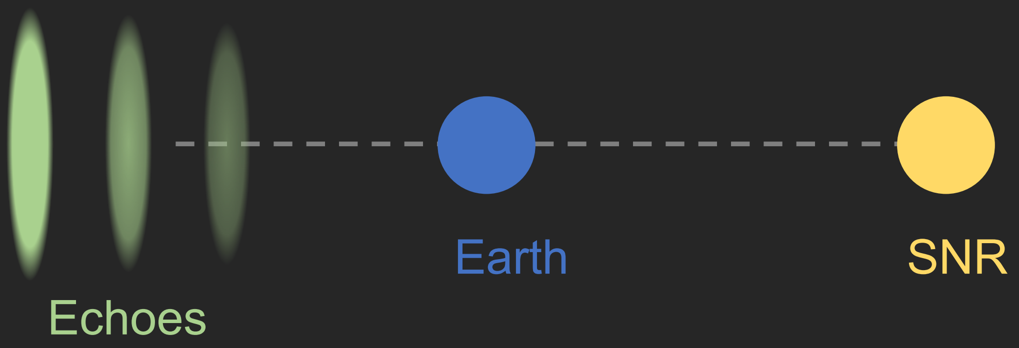
Axion dark matter-induced echo of supernova remnants

Yitian Sun

with Katelin Schutz, Anjali Nambrath

Calvin Leung, Kiyoshi Masui, Harper Sewalls

Based on 2110.13920



TeVPA 2022 | Aug 11th

Axion like particles (coupling to γ)

$$L \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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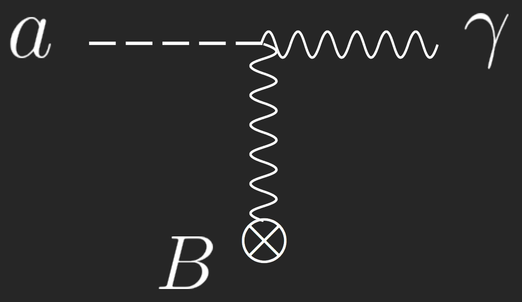
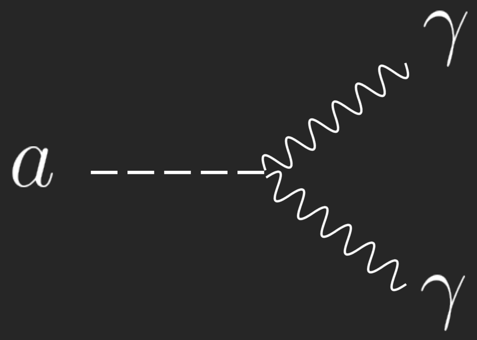


Decay:



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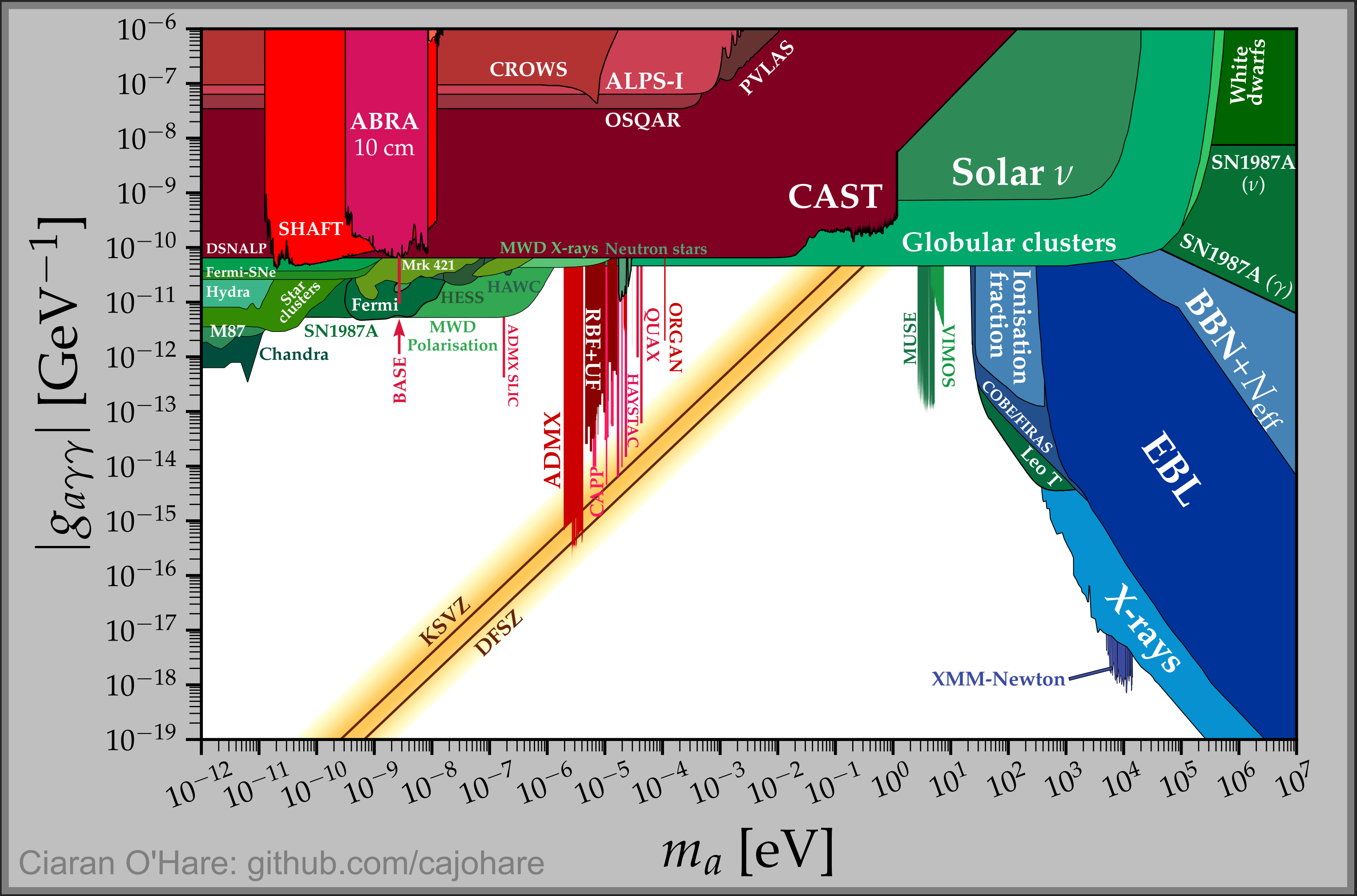

Ciaran O'Hare: github.com/cajohare

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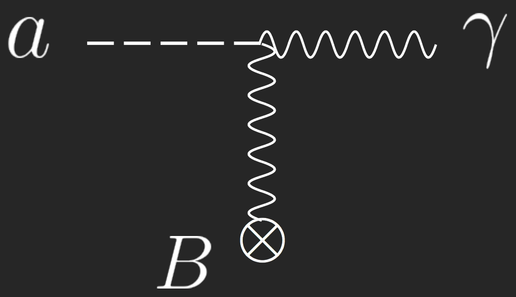
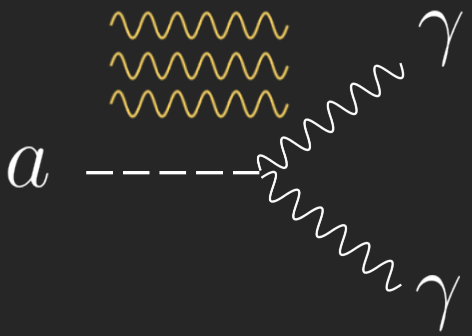


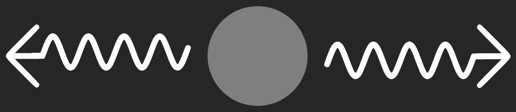
Stimulated decay:



Outline

- Axion echo via stimulated decay
- Making use of the axion echo
- Supernova remnants as sources

Axion spontaneous decay



$m_a/2$ spectral line in axion rest frame

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

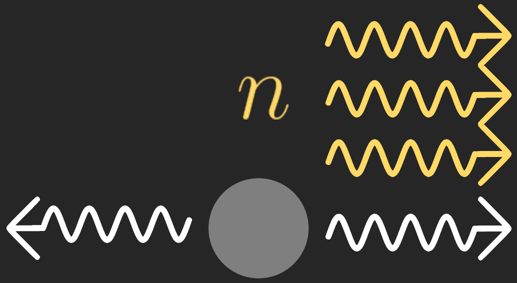
Axion
spontaneous decay

$$\text{rate} = \Gamma$$

Axion spontaneous decay

$$\text{rate} = \Gamma$$

Axion stimulated decay



$$\text{rate} = n\Gamma$$

Axion spontaneous decay

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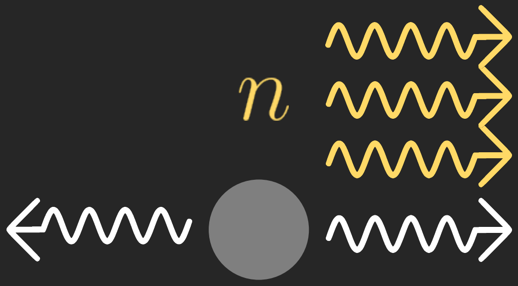
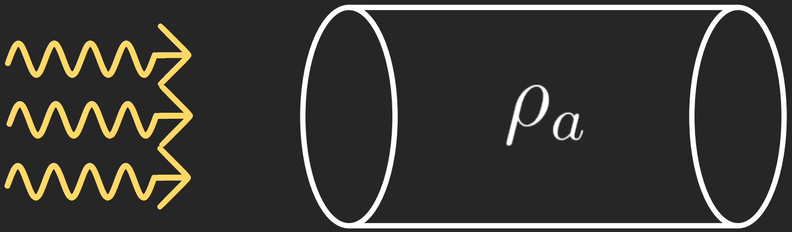
Axion stimulated decay



$$\text{rate} = n\Gamma$$

radio waves
(lots of photons)



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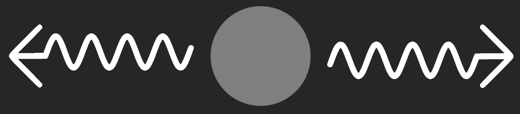

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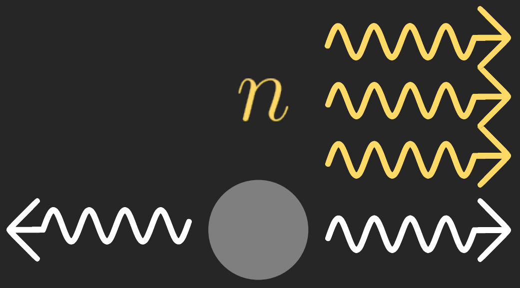
Axion stimulated decay



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Axions: a mirror for radio sources

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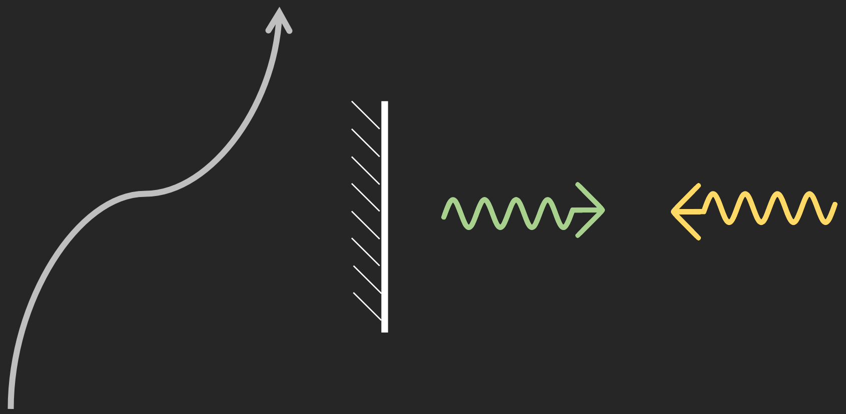
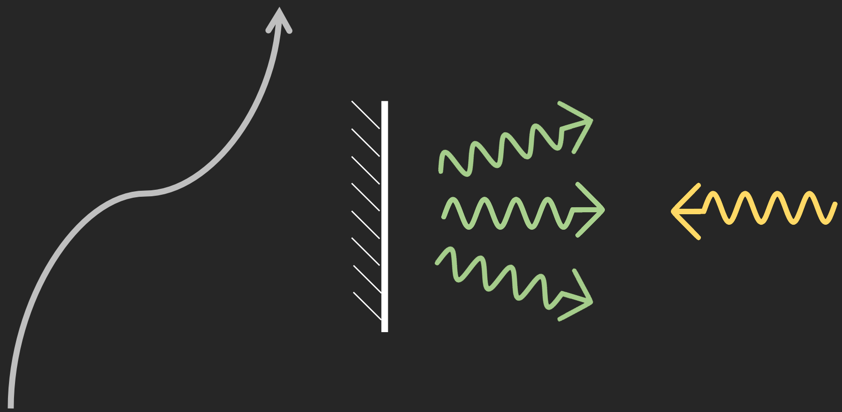


(monochromatic)

Decay line at $m_a/2$

Axions: a mirror for radio sources



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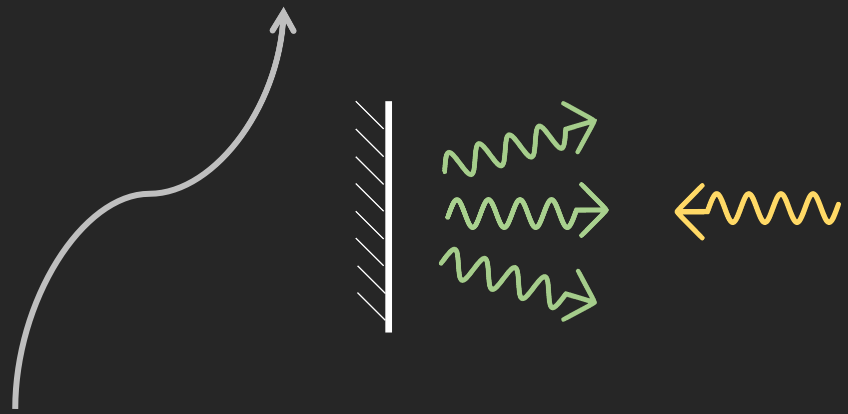
Decay line at $m_a/2$

Due to DM velocity dispersion σ_d

Axions: a mirror for radio sources

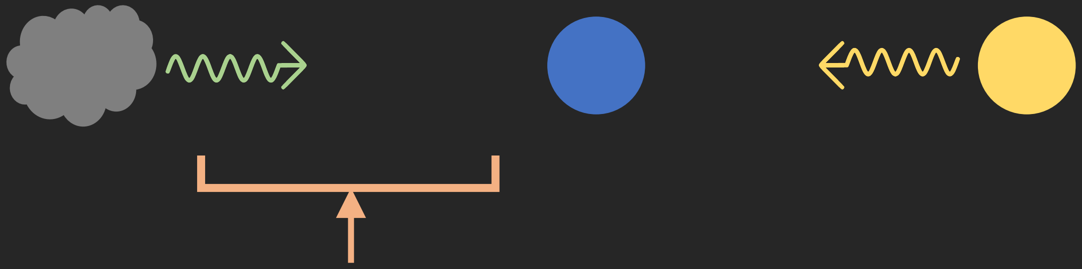


(monochromatic, blurry)

Decay line at $m_a/2$

Due to DM velocity dispersion σ_d

→ How to use this effect to look for axions?



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- Making use of the axion echo
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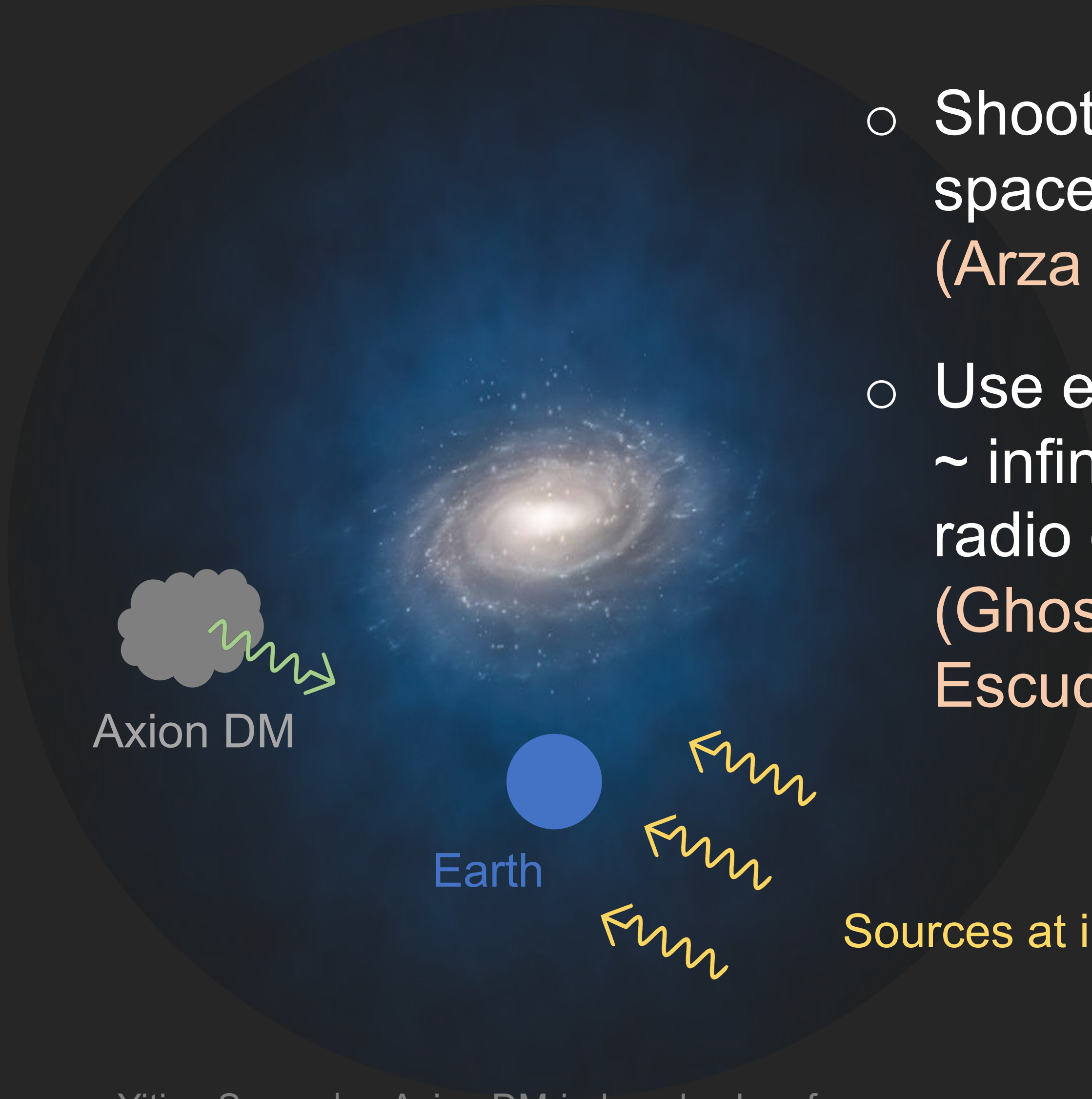
Making use of the axion echo

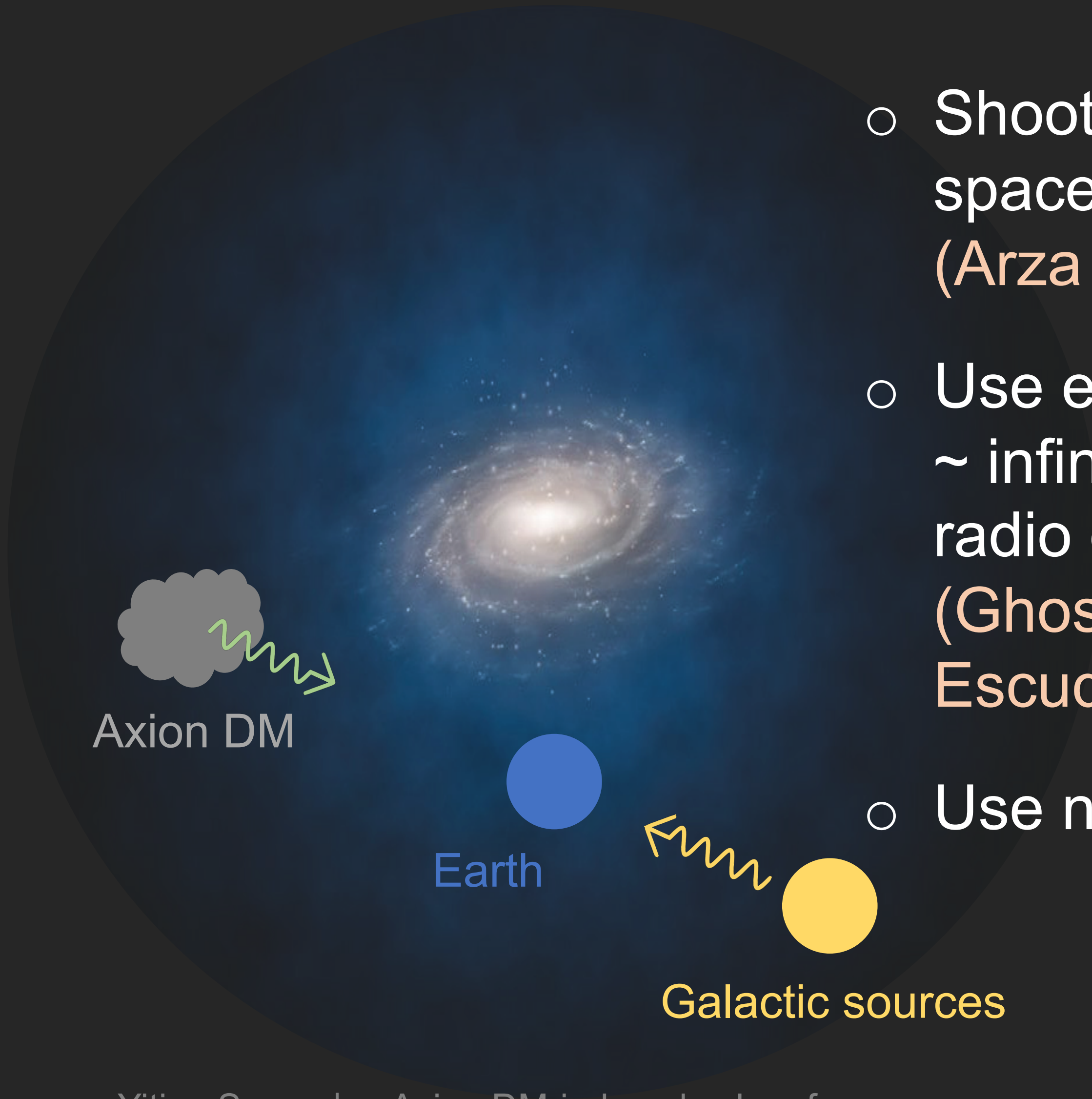
- Shoot a radio beam into space and look for echo (Arza & Sikivie 2019)

Making use of the axion echo



- Shoot a radio beam into space and look for echo (Arza & Sikivie 2019)
- Use extragalactic sources ~ infinitely far away, like radio galaxy Cyg A. (Ghosh, Salvado, Miralda-Escudé 2020)

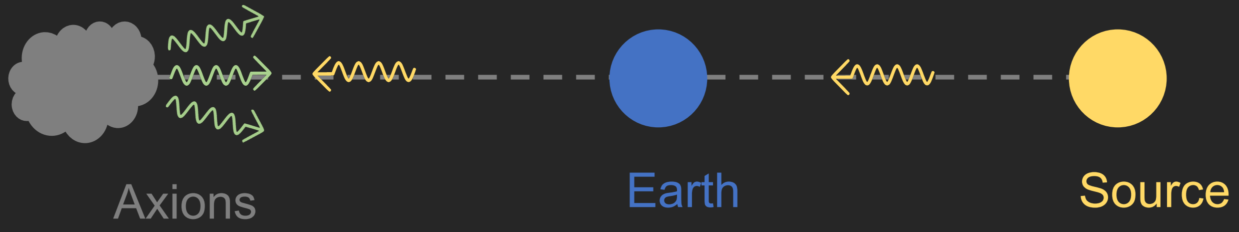
Making use of the axion echo



- Shoot a radio beam into space and look for echo (Arza & Sikivie 2019)
- Use extragalactic sources ~ infinitely far away, like radio galaxy Cyg A. (Ghosh, Salvado, Miralda-Escudé 2020)
- Use nearby sources…

Geometry of the axion echo

(from a nearby source)



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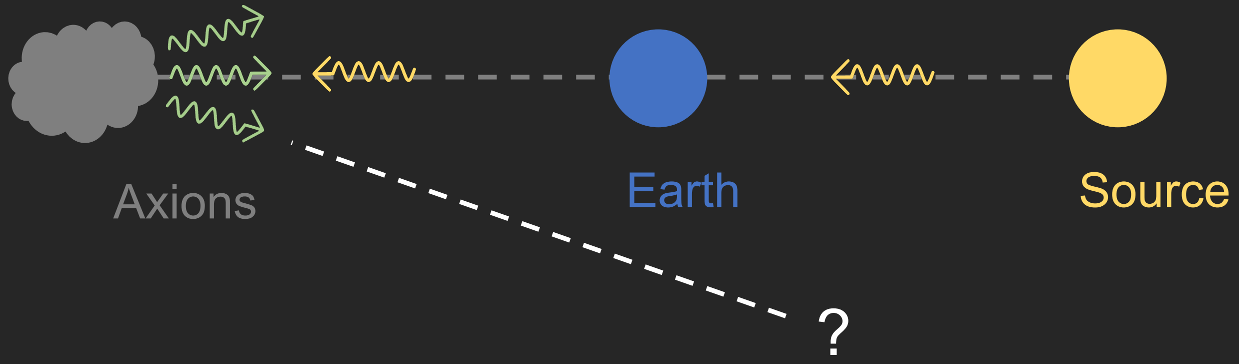

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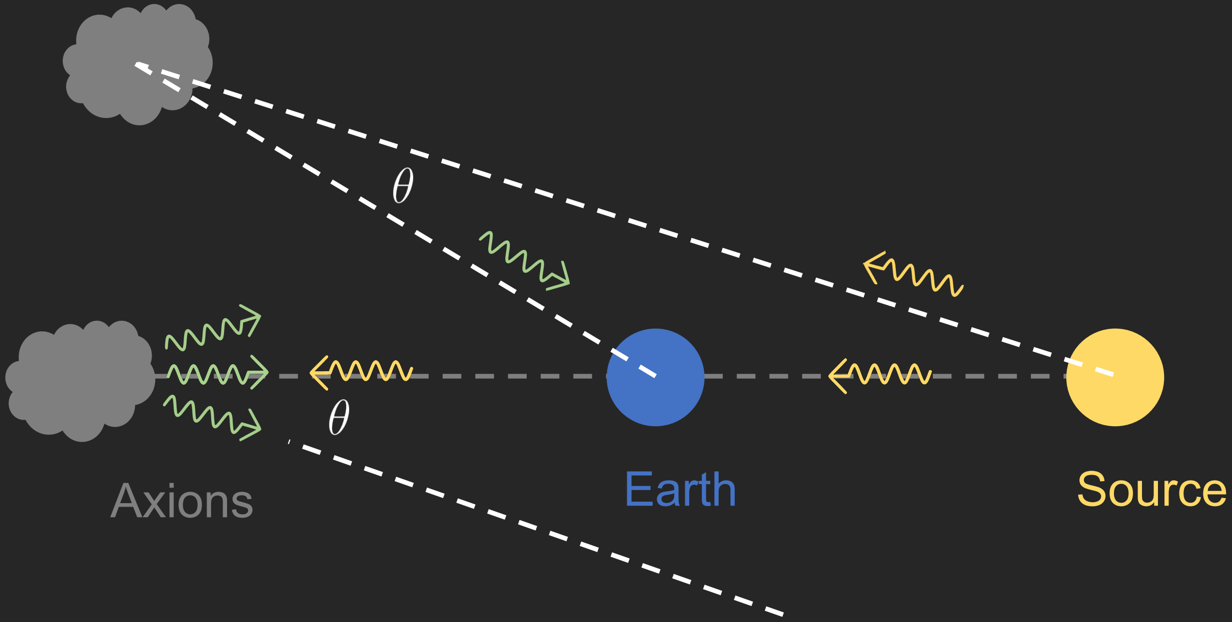

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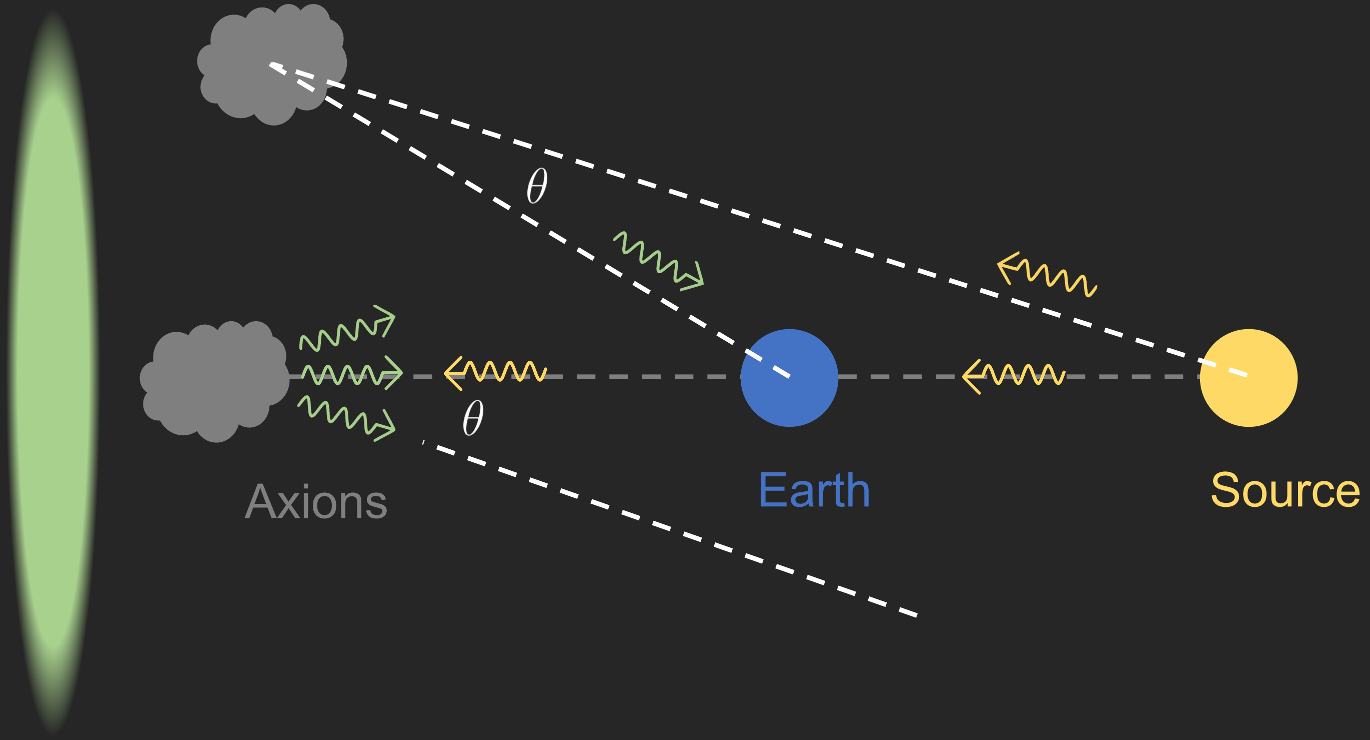
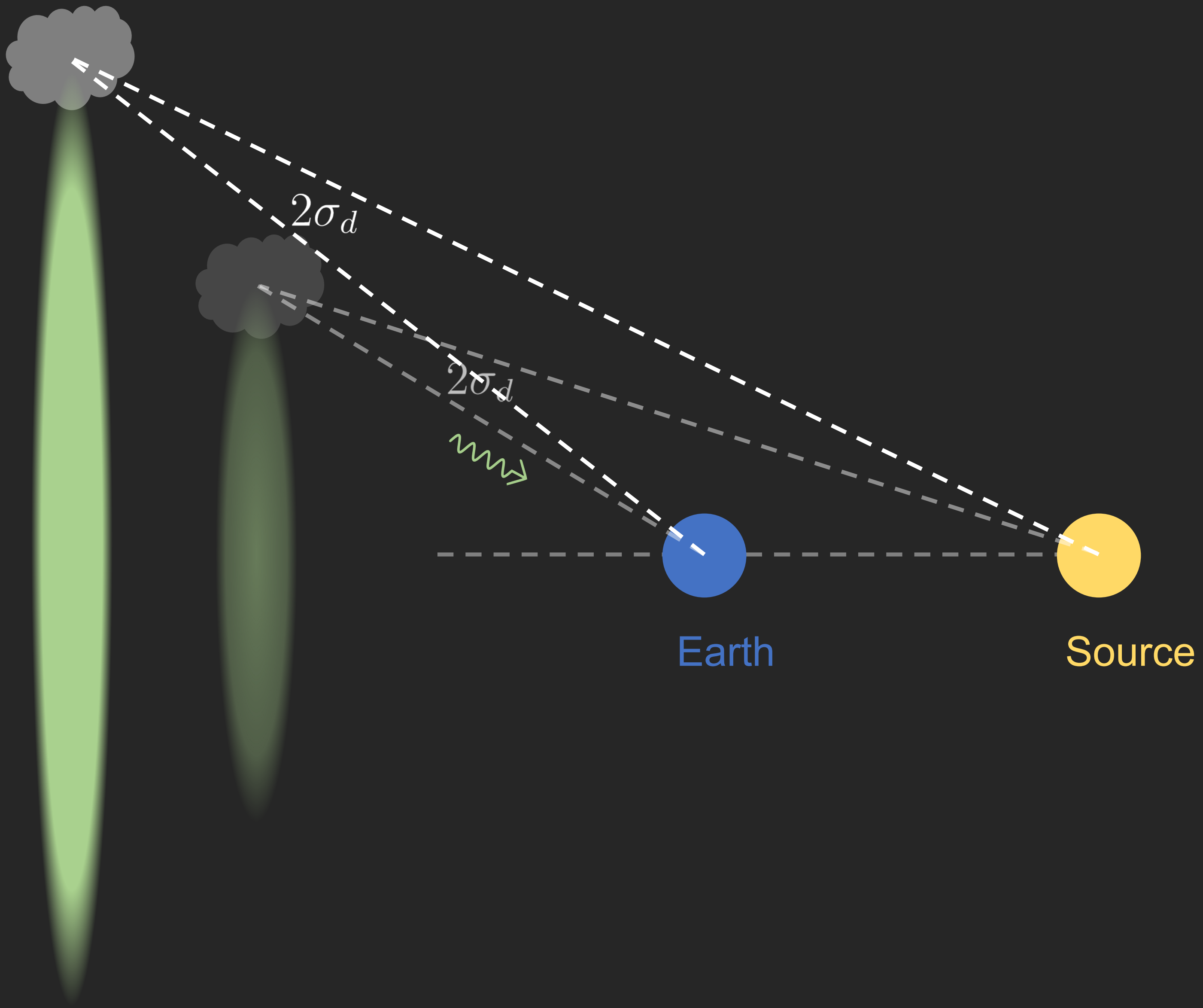
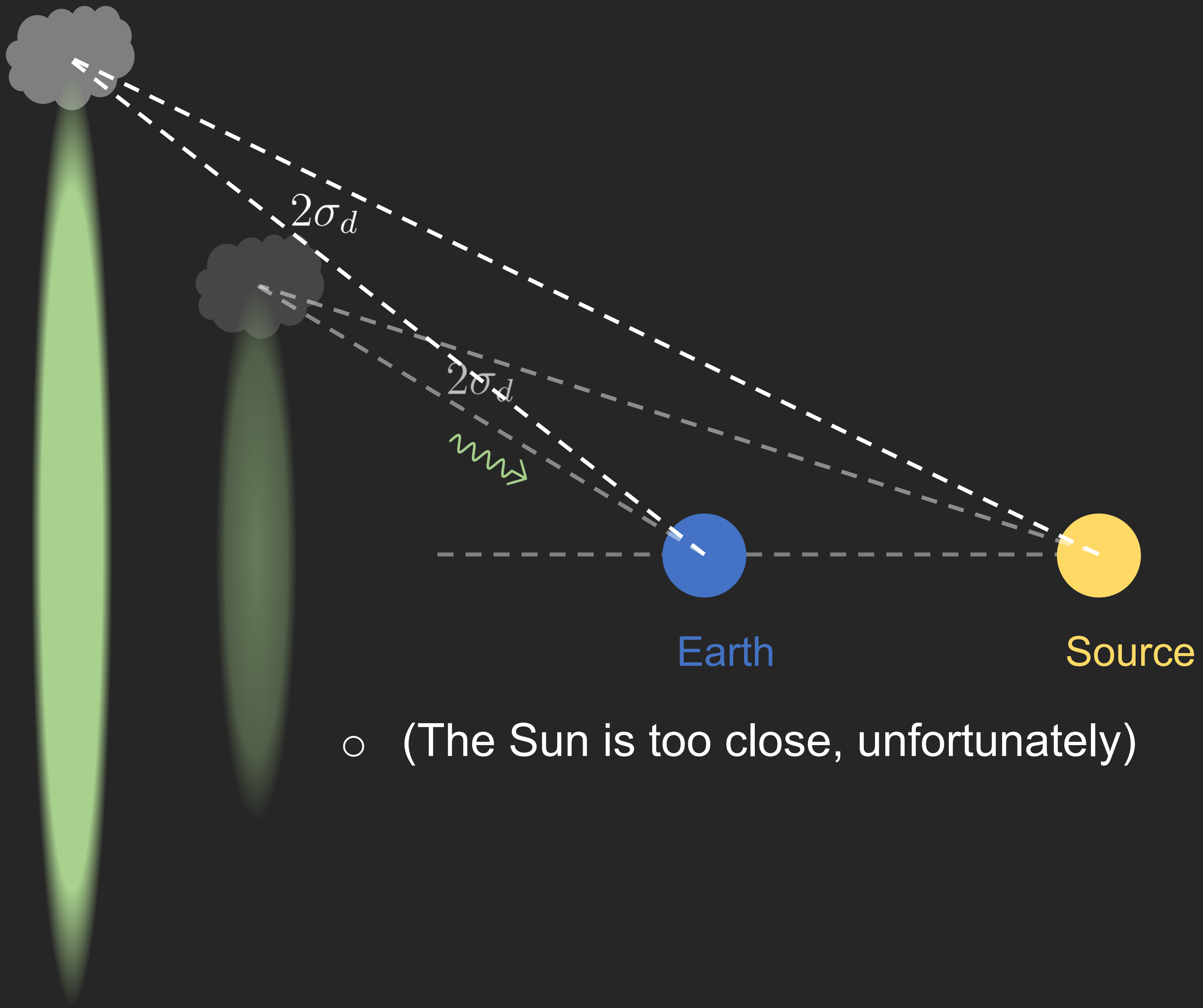
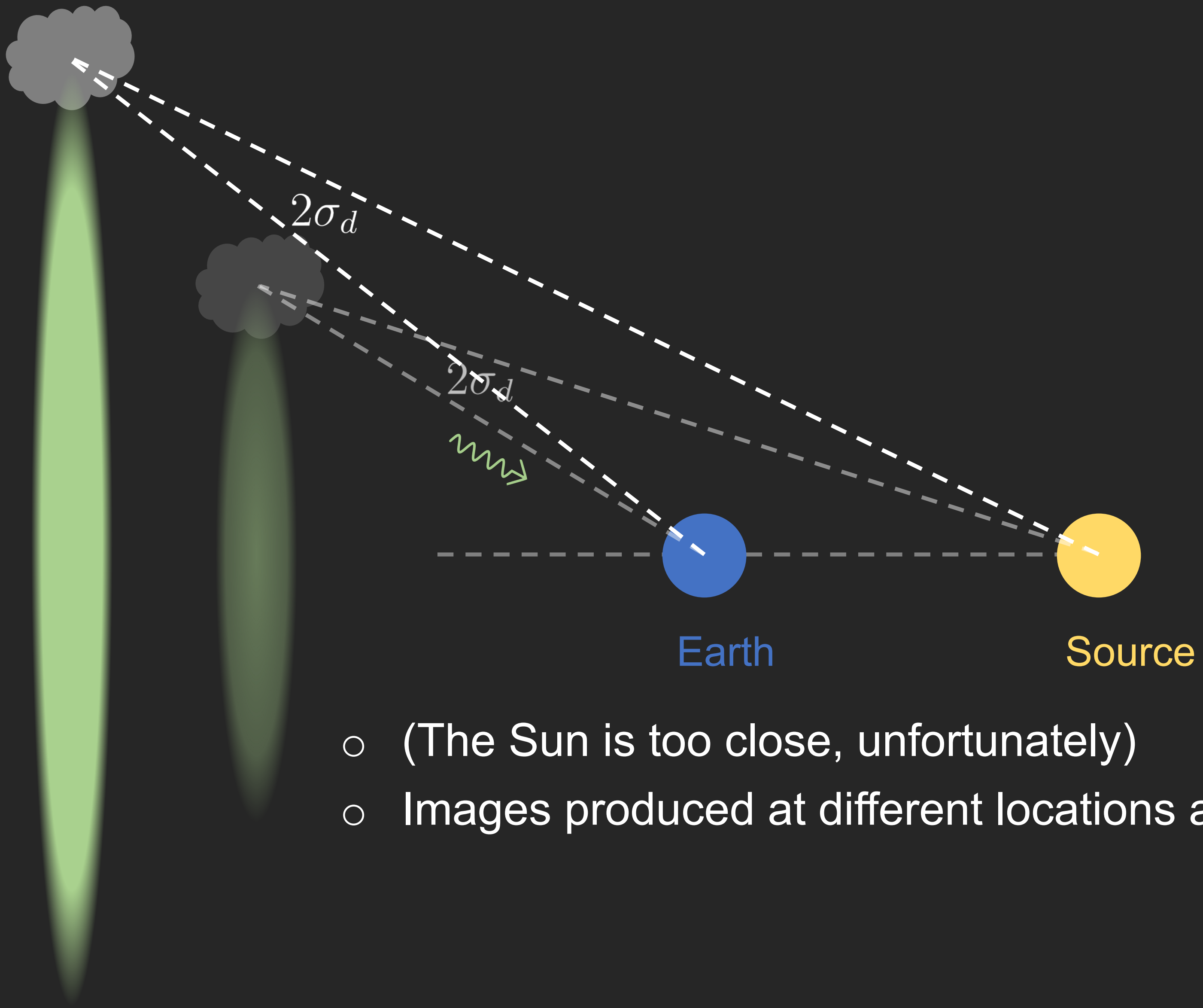



$2\sigma_d$
$2\sigma_d$
Earth
Source



- (The Sun is too close, unfortunately)



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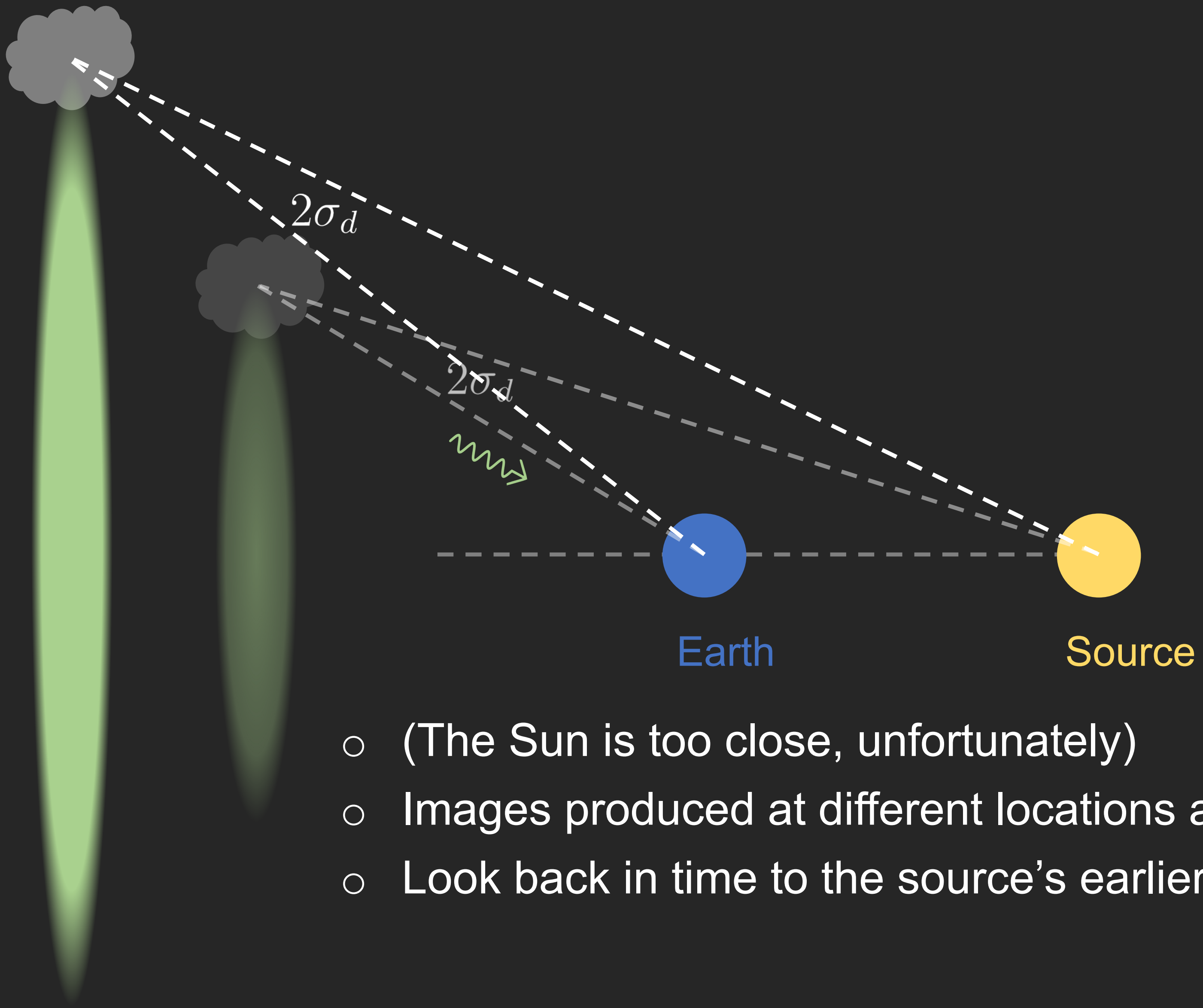
- Images produced at different locations are stacked



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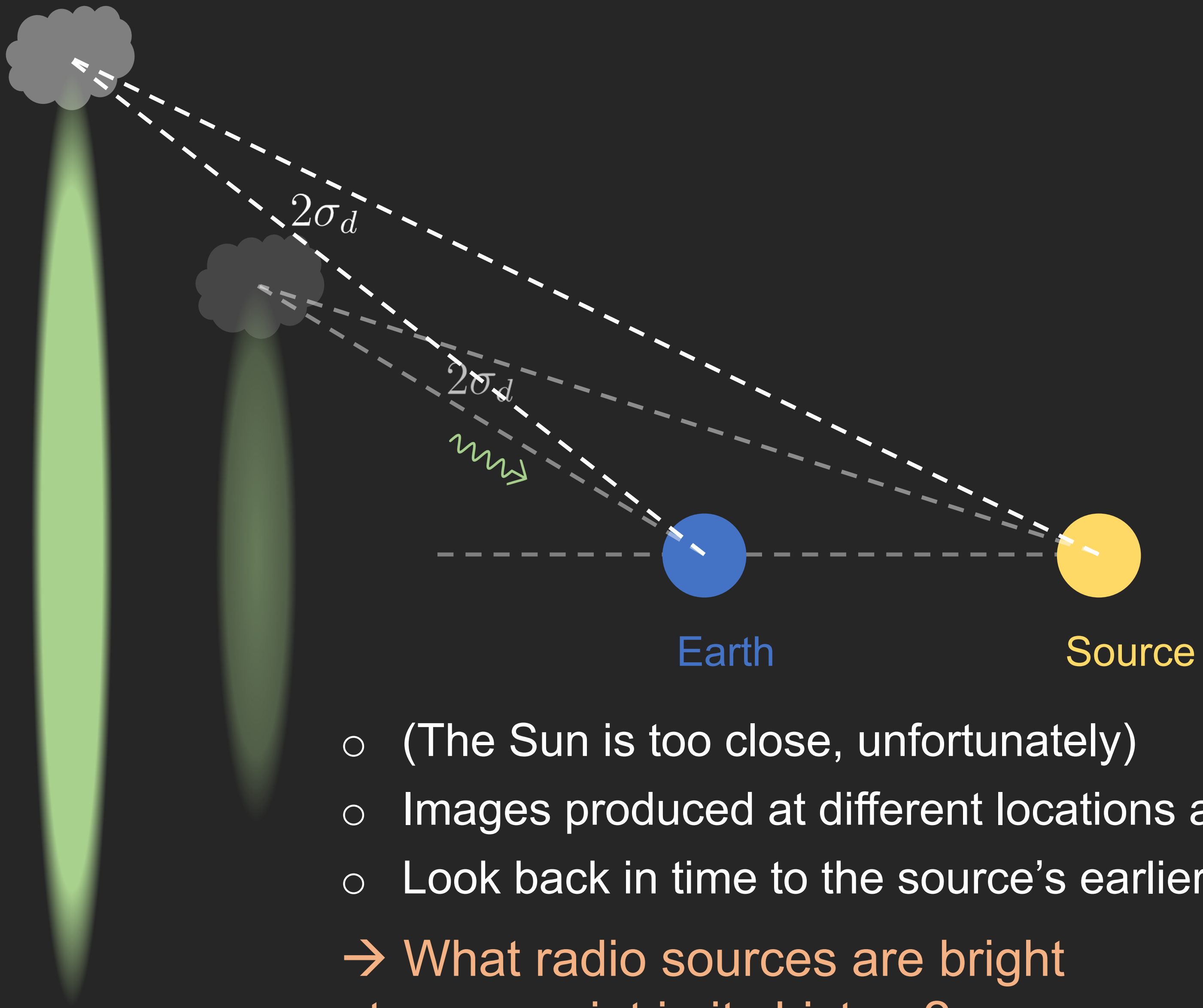

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→ What radio sources are bright <u>at some point in its history</u>?

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Supernova Remnants 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.

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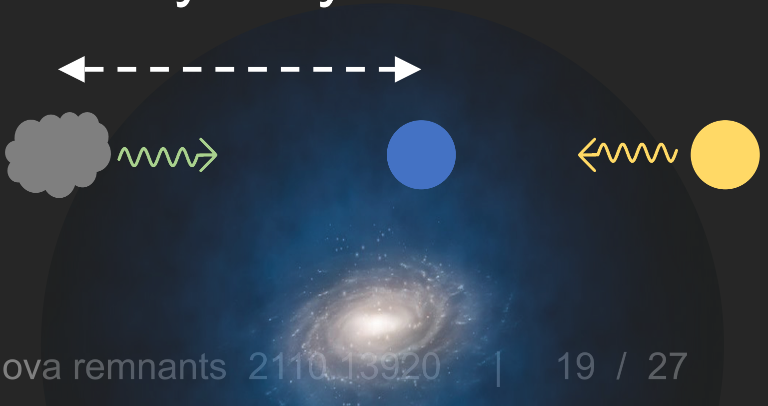

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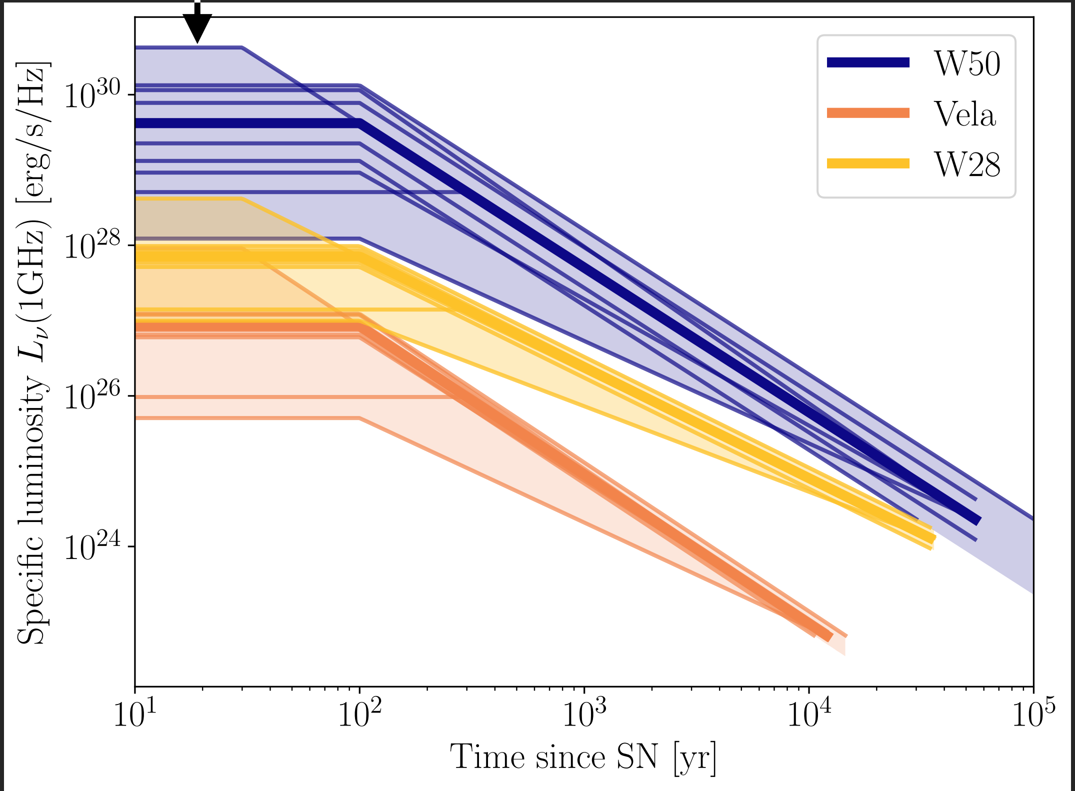
- Age ~ 10^4 years, close to the light crossing time of the Milky Way halo.
- Luminosity history can be modelled

Modeling of SNR luminosity history

1. Ejecta dominated expansion



Modeling of SNR luminosity history

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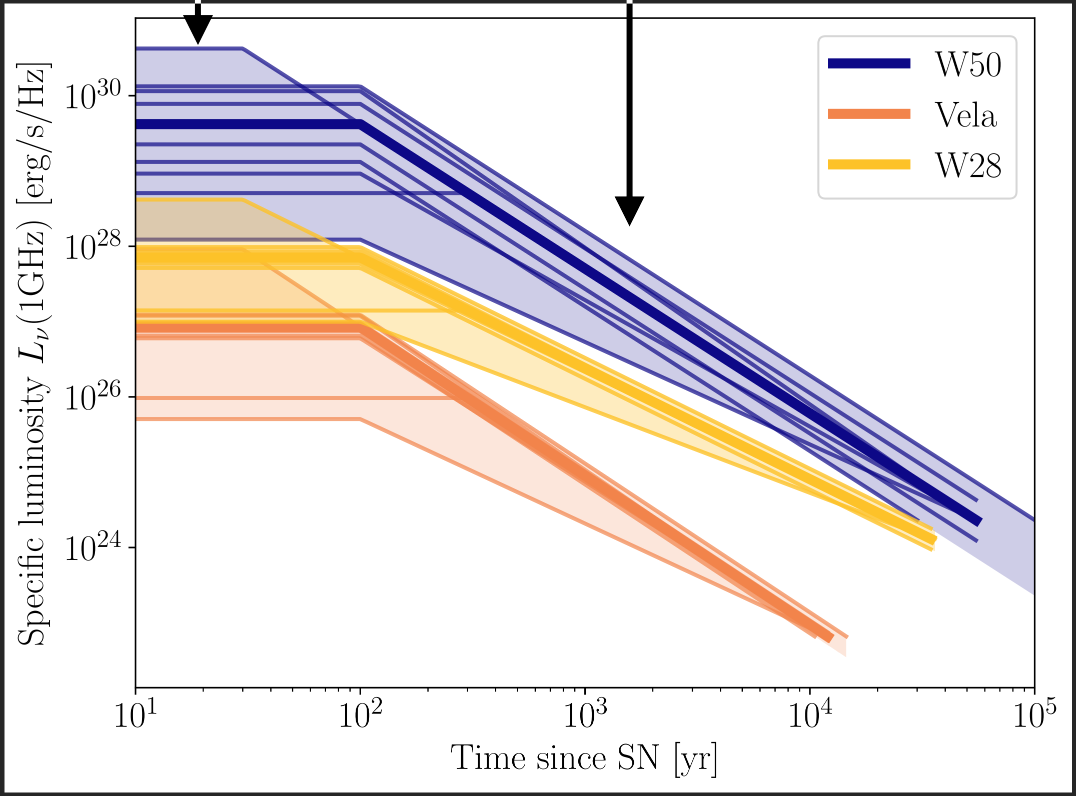


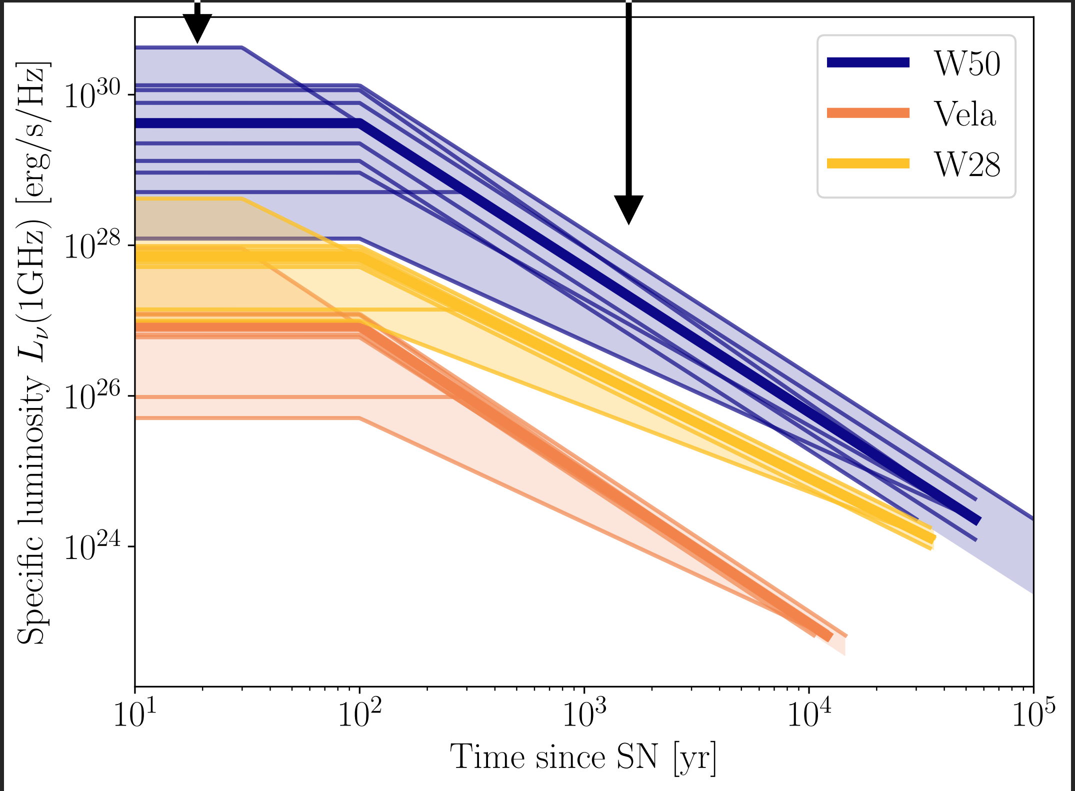
Modeling of SNR luminosity history

1. Ejecta dominated expansion

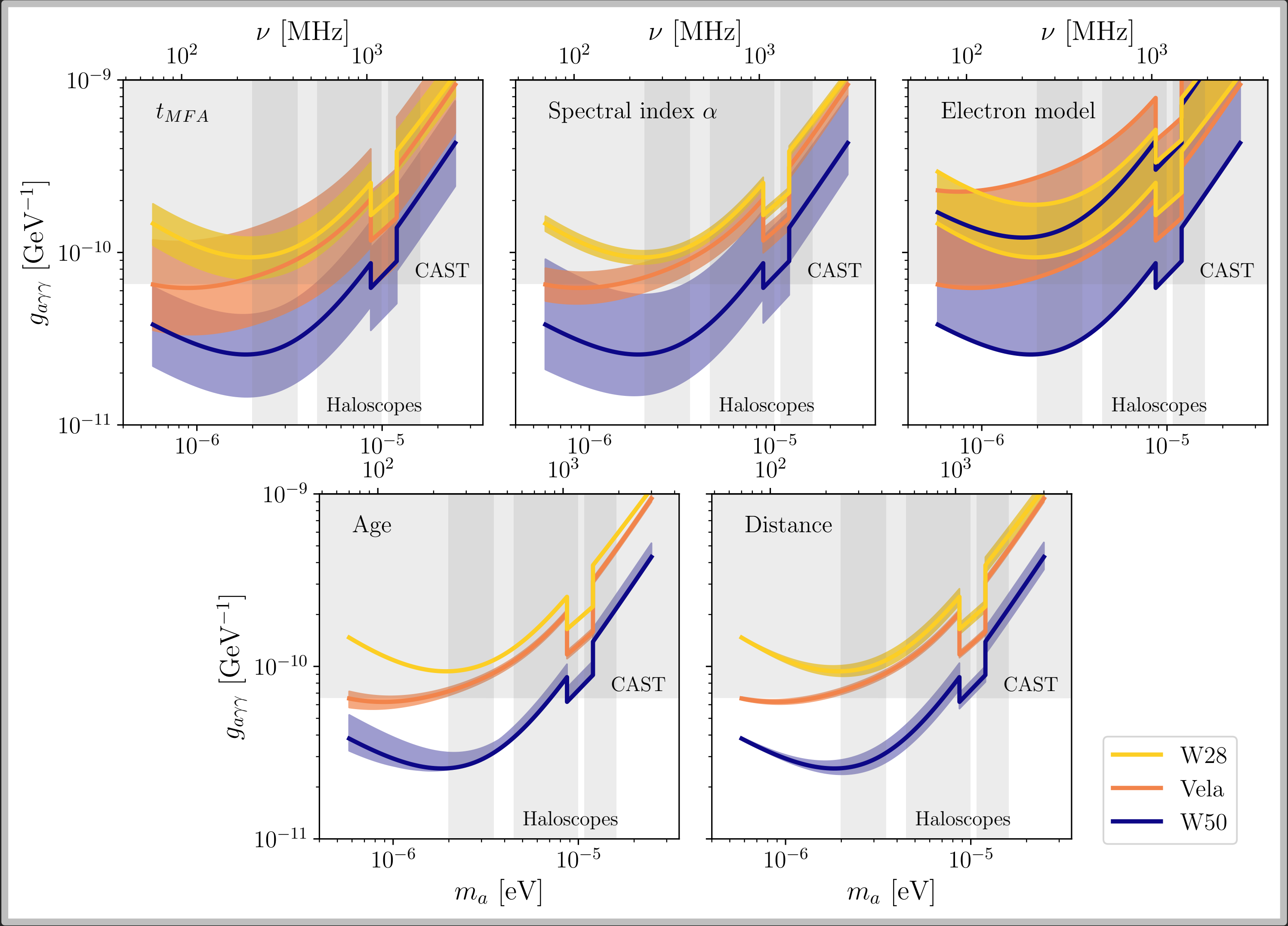
2. Adiabatic expansion

3. Radiative expansion

✕



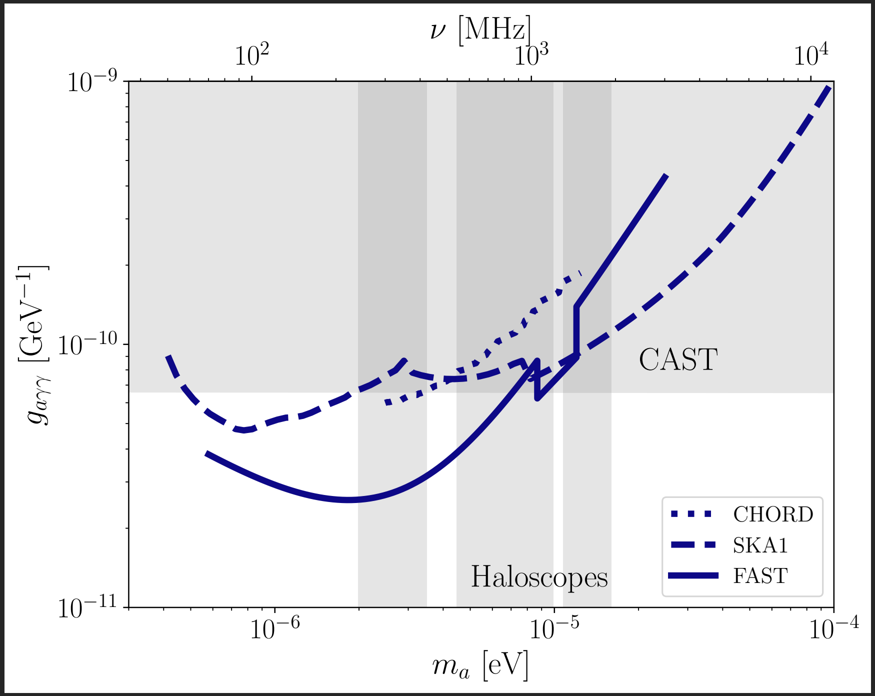
Projected limits & uncertainties



Telescopes: FAST, SKA-I, CHIME…

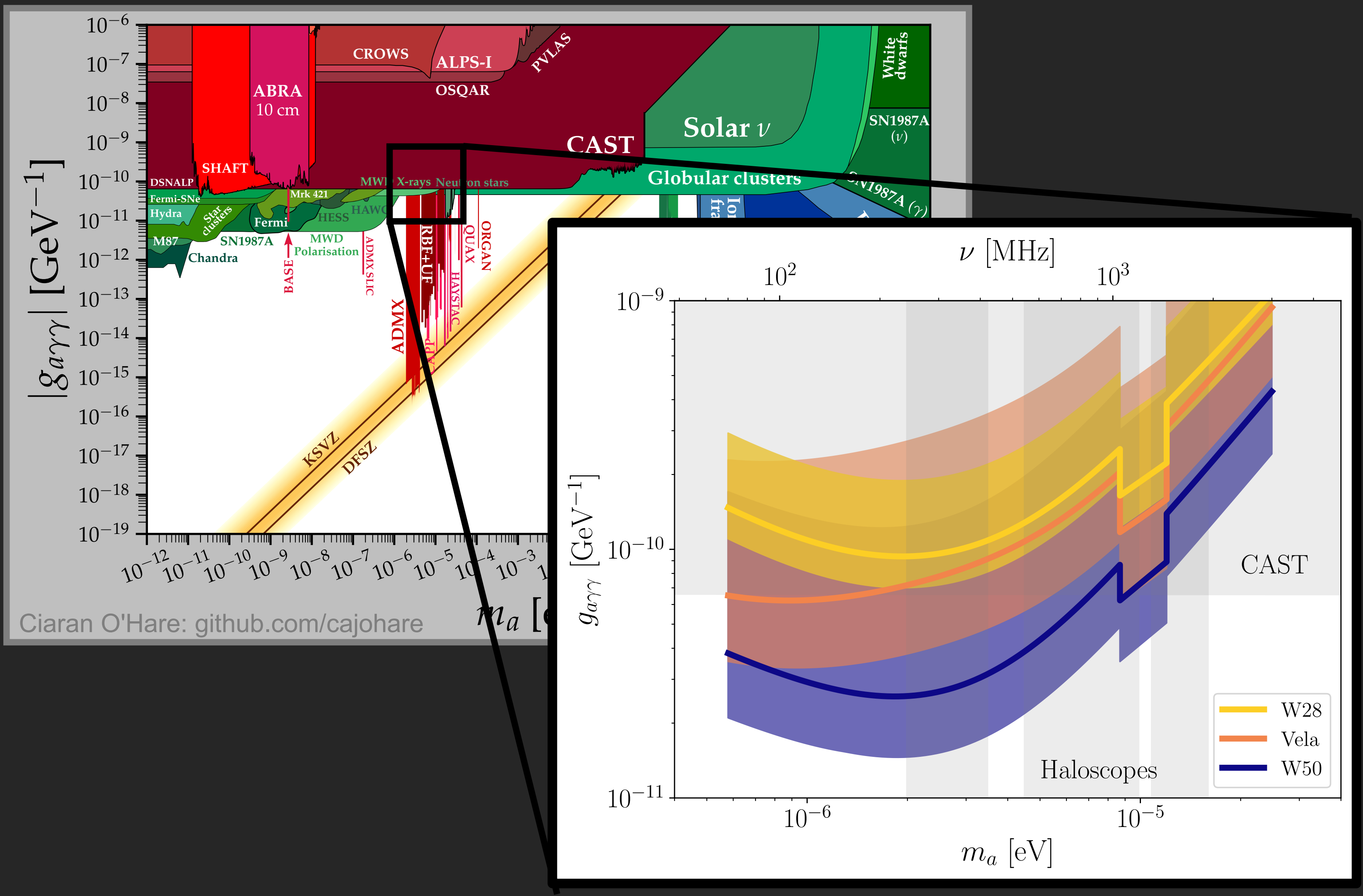
Five-hundred-meter Aperture Spherical Telescope (FAST)

Xinhua



Sensitivity for W50 SNR

Combined limits & uncertainties



Ciaran O'Hare: github.com/cajohare

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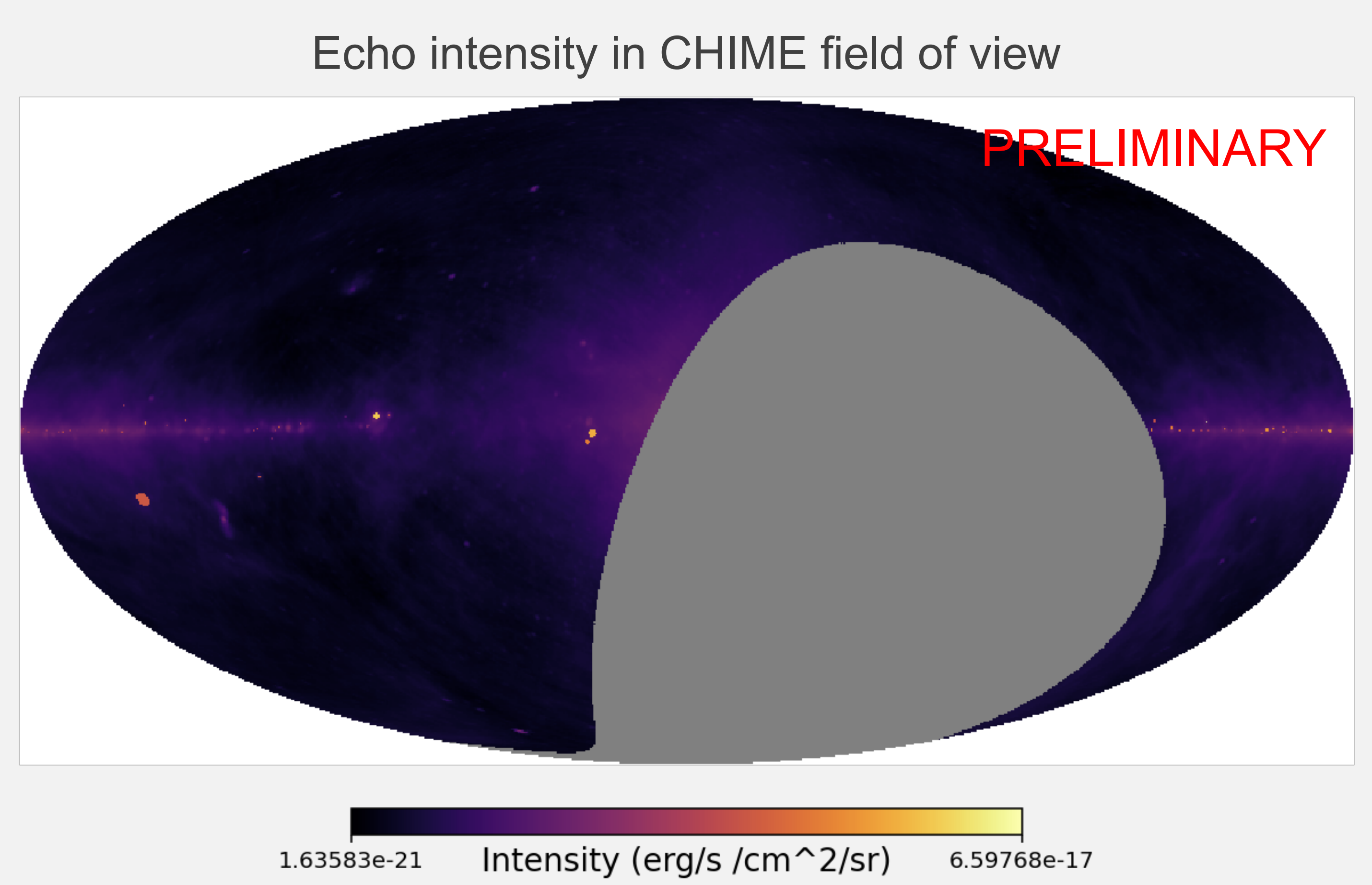
- Galactic synchrotron emission as source

Galactic synchrotron radiation as source

Work led by Harper Sewalls from McGill U.



Summary

- Axion dark matter behaves like a blurry, monochromatic mirror for radio sources.
- Supernova remnants are great sources because they are once bright in the past, and not too close to us.
- With existing telescope like FAST and CHIME, we have sensitivity to new parameter space despite conservative modeling choice.

Summary

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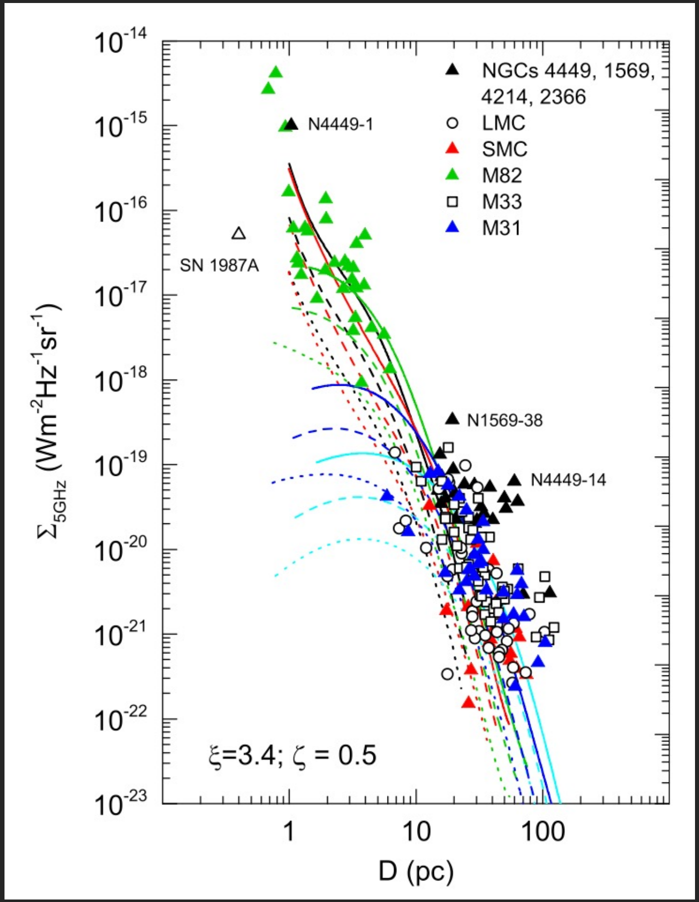
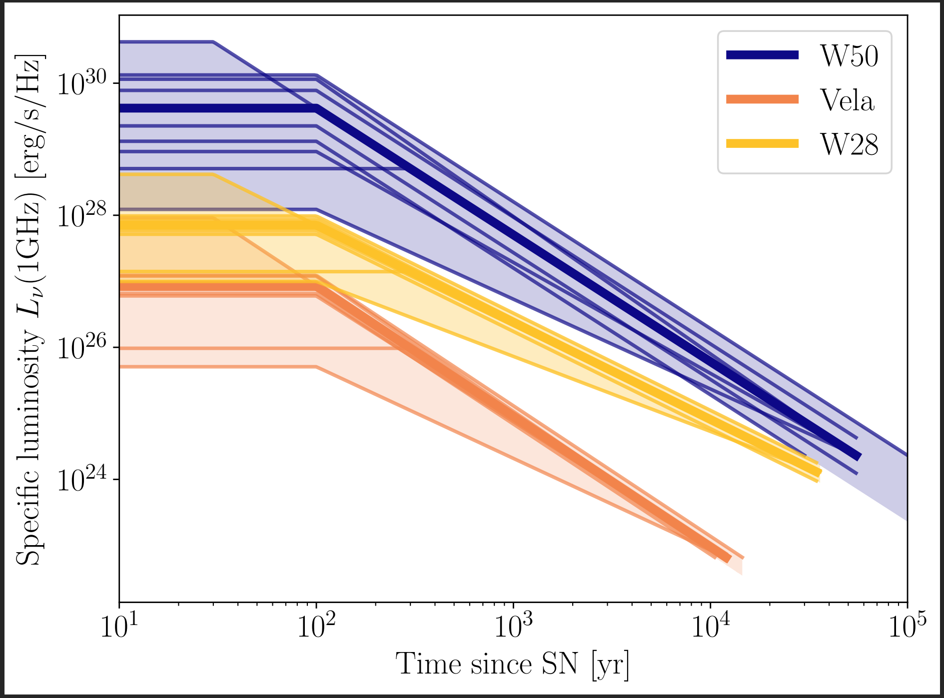
Thank you for your attention!

Backup slides

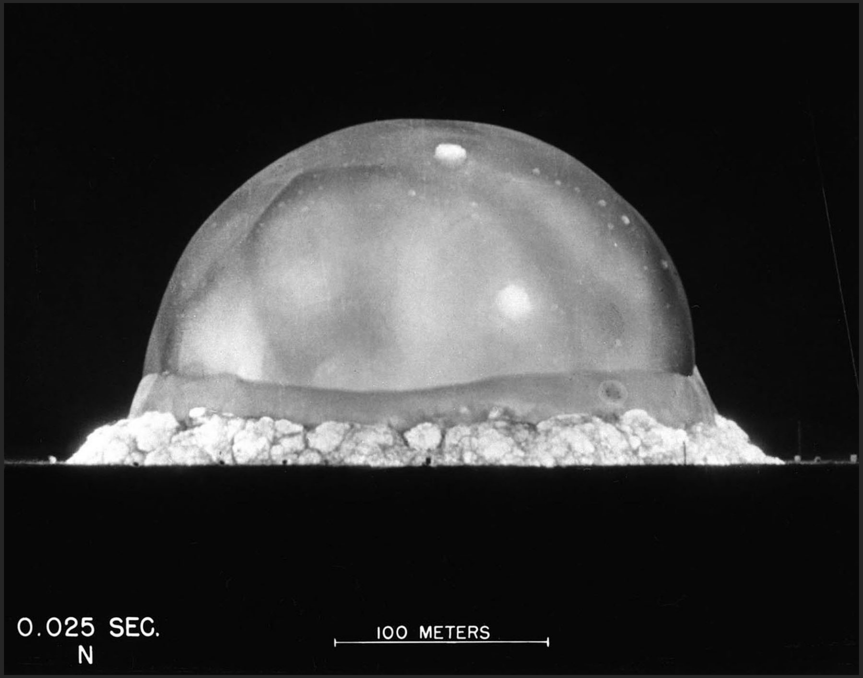
Comparison with observations





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

Supernova Remnant Dynamics $R - t$

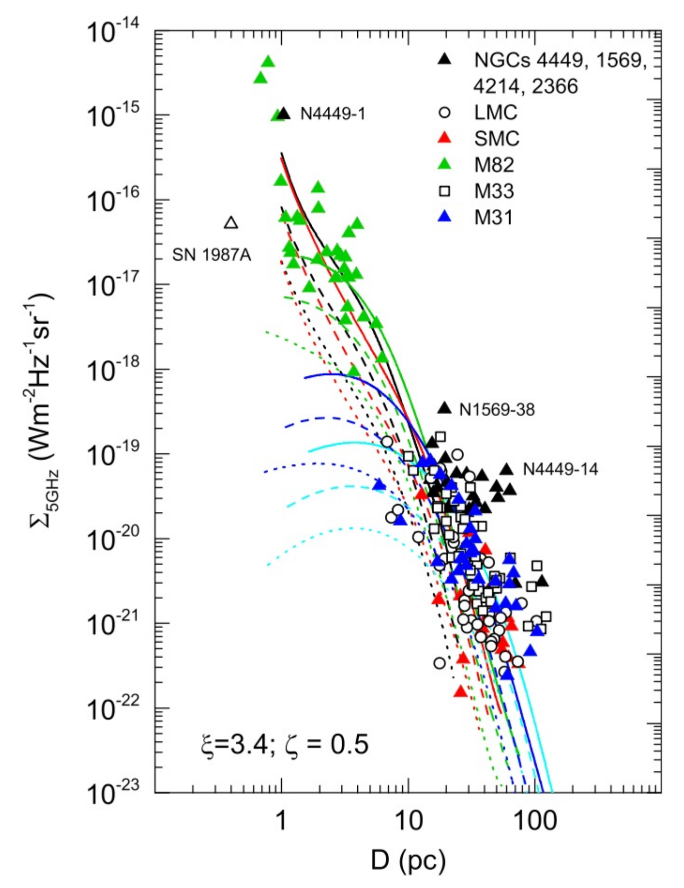


One of the published photograph of the Trinity atomic bomb tests that allowed British physicist G. I. Taylor to estimate the explosion energy.

- Ejecta dominated phase
  ~ 300 yr.
- Sedov-Taylor phase
  ~ 10^4 yr.
- Radiative phase
  ~ 10^5 yr.
- Terminal phase.

Sedov-Taylor solution: $R = \xi_{\mathrm{front}} \left(\frac{E}{\rho_{\mathrm{ISM}}} \right)^{1/5} t^{2/5}$

SNR Brightness evolution $\Sigma - D$



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 p can be measured from radio spectra.
- Total electron energy VK_e and magnetic field evolution must also be modelled.

SNR modelling: electrons

- Electron spectral index p:
  - Uncertainty can arise from a nonlinear synchrotron spectrum, or different portions of the SNR having different.
  - 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 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:

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

- MFA onset time:
  - Core-collapse supernovae have dense circumstellar medium, which interacts with shock front very early on.
  - Simulations (spherical SN [1], planar shock wave [2]) suggests

$$t_{\mathrm{MFA}} < 100\ \mathrm{yr}$$

[1] Shklovskii 1960