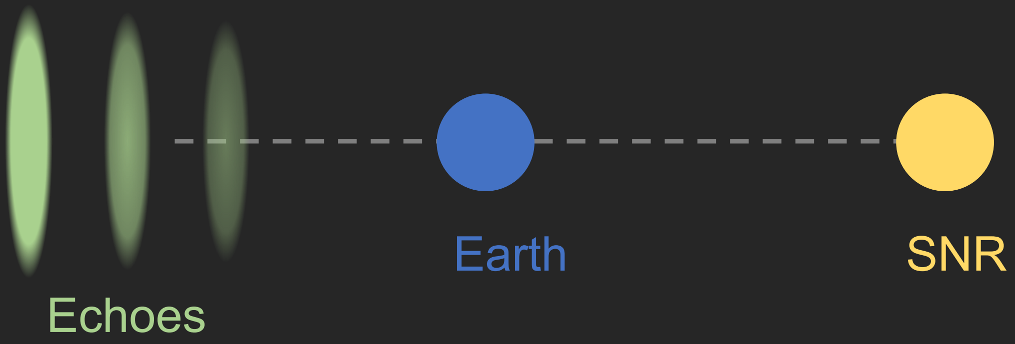
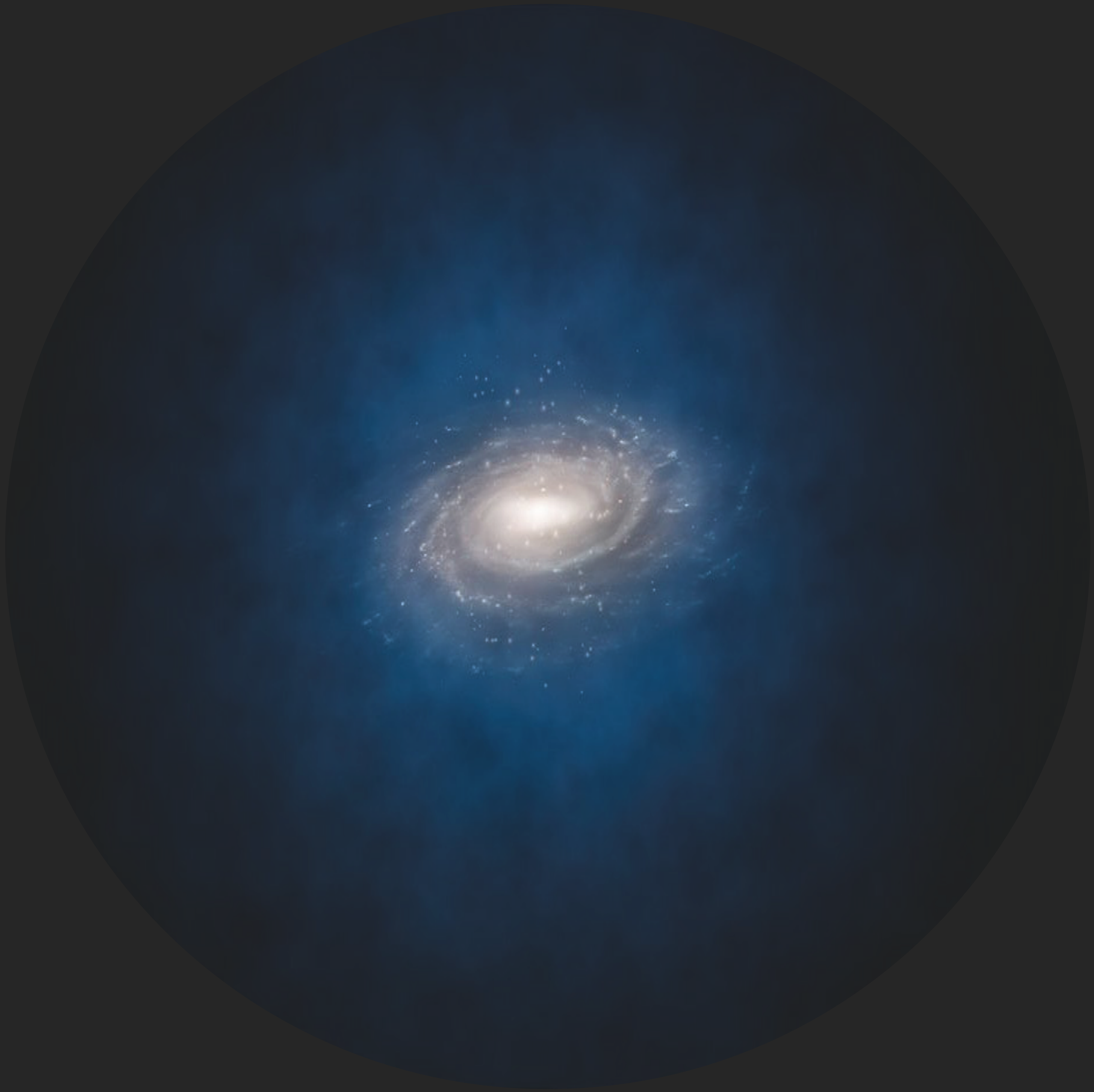
Axion dark matter-induced echo of supernova remnants

Yitian Sun, Katelin Schutz, Anjali Nambrath
Calvin Leung, Kiyoshi Masui



Pheno 2022 | May 9th | Yitian Sun

Dark Matter



Dark Matter

Axion like particles

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

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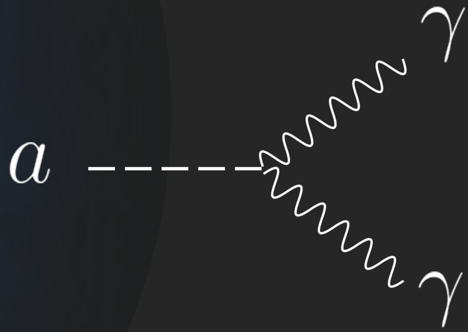
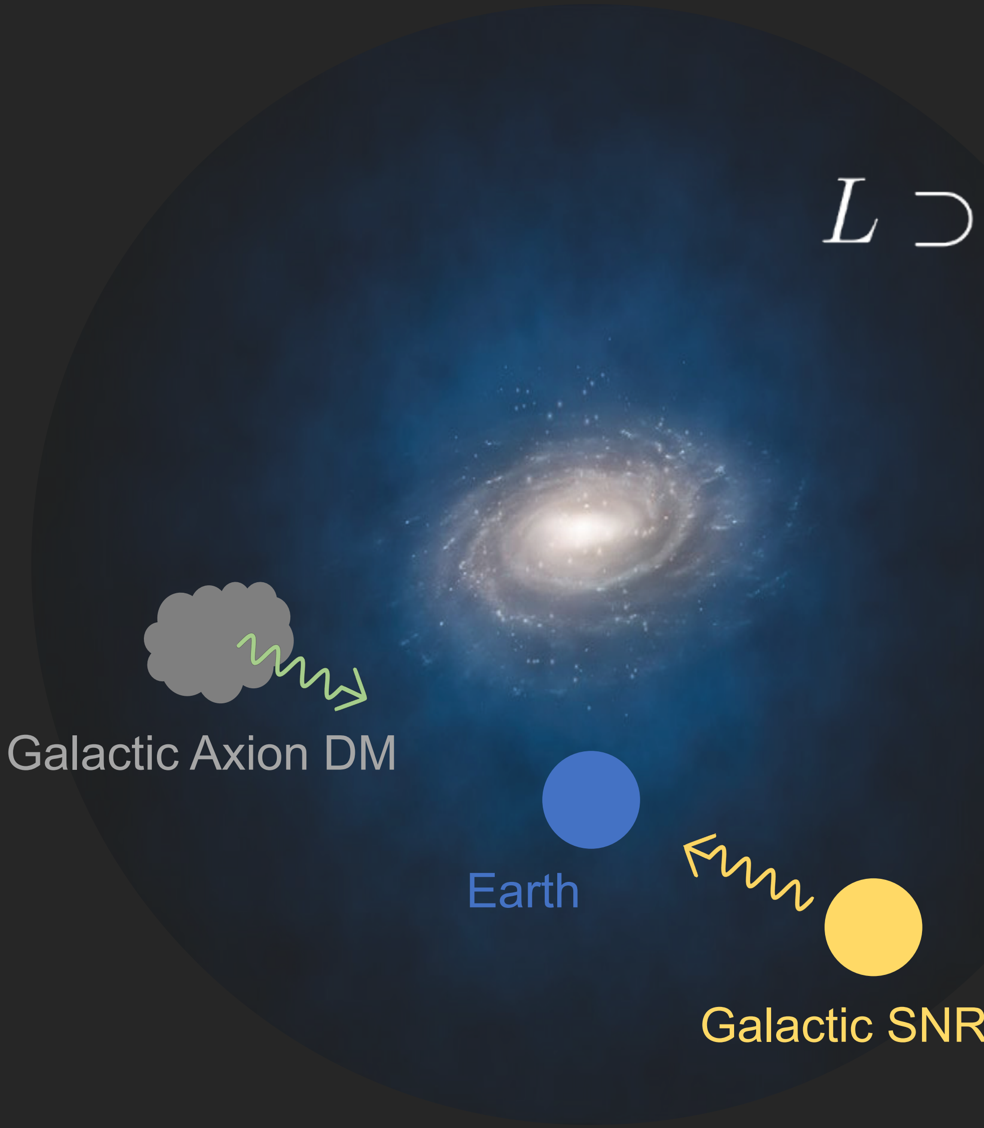


Dark Matter



Axion like particles

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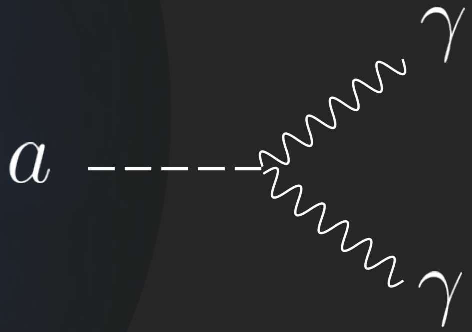
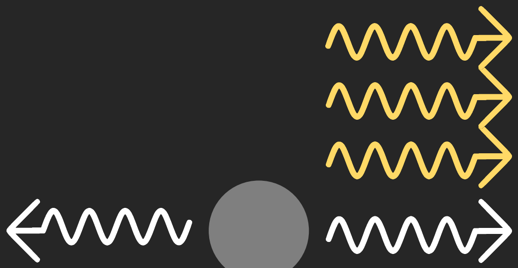


Outline

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

Axion
spontaneous decay

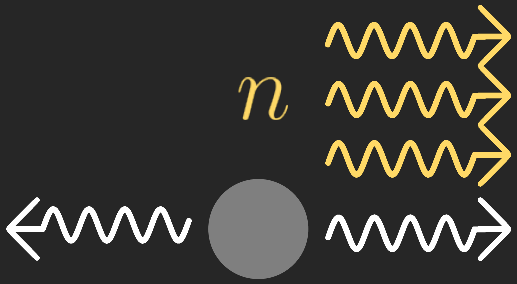
Axion
stimulated decay



Axion spontaneous decay

$$\mathrm{rate} = \Gamma$$

Axion stimulated decay

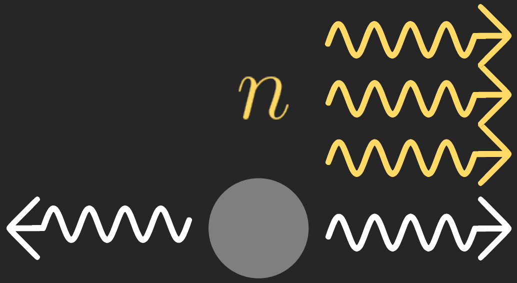


$$\mathrm{rate} = n\Gamma$$

Axion
spontaneous decay

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

Axion
stimulated decay

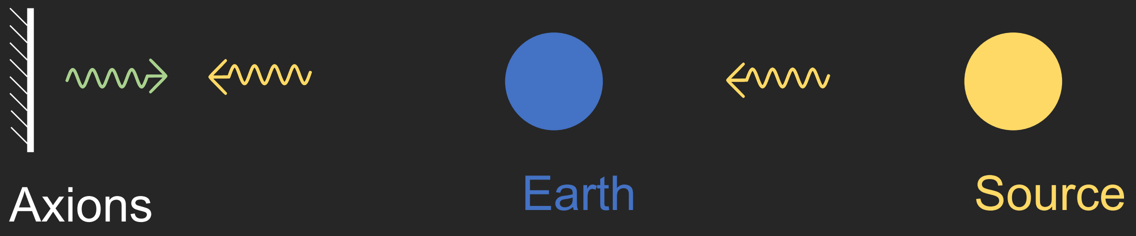


$$\text{rate} = n\Gamma$$

Radio waves
(lots of photons)

Signal

Axions act like a mirror for radio sources



Signal

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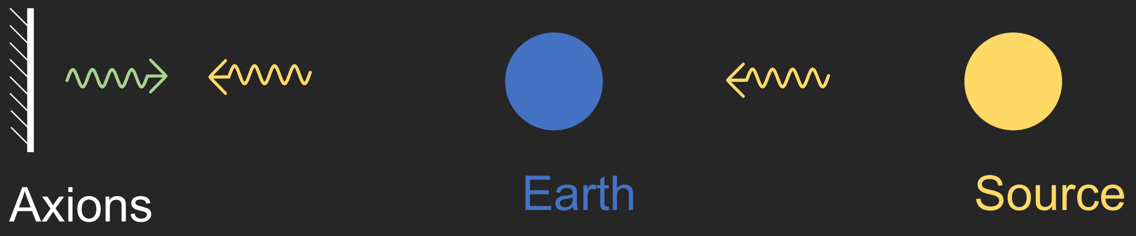

(monochromatic)

↓

Decay line at $m_a/2$

Signal

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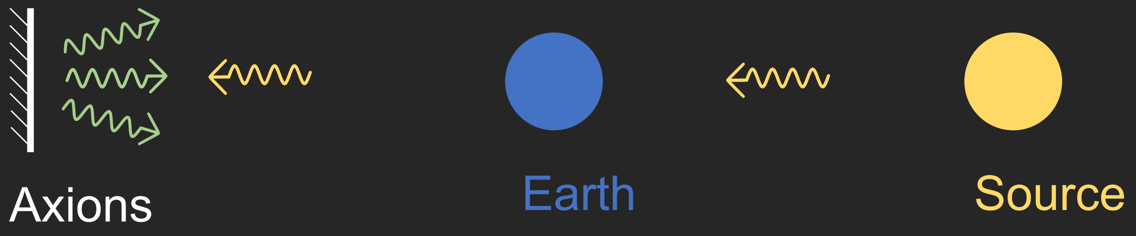


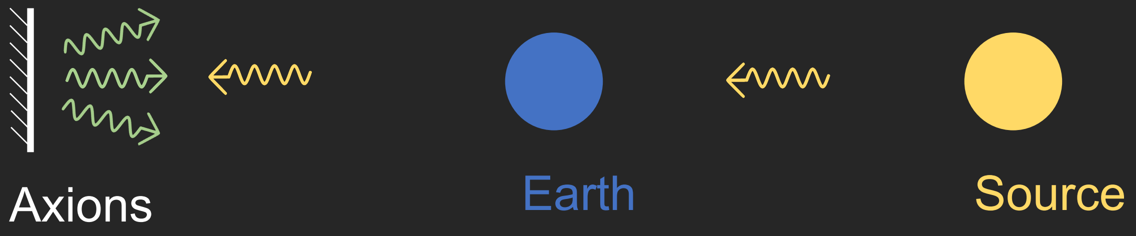
(monochromatic, foggy)

Decay line at $m_a/2$

Due to DM velocity dispersion σ_d

Signal

Axions act like a mirror for radio sources



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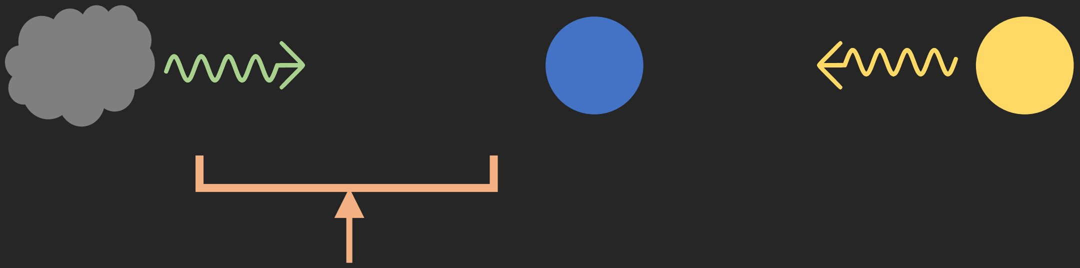
Decay line at $m_a/2$

Due to DM velocity dispersion σ_d

Echo counter-image: what does it look like?



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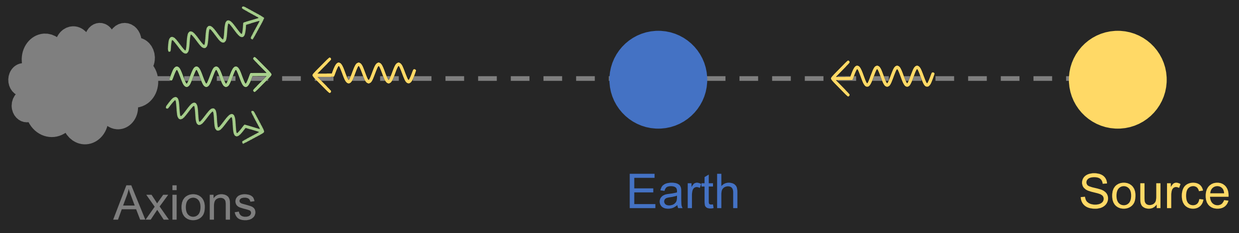
Geometry of the axion echo



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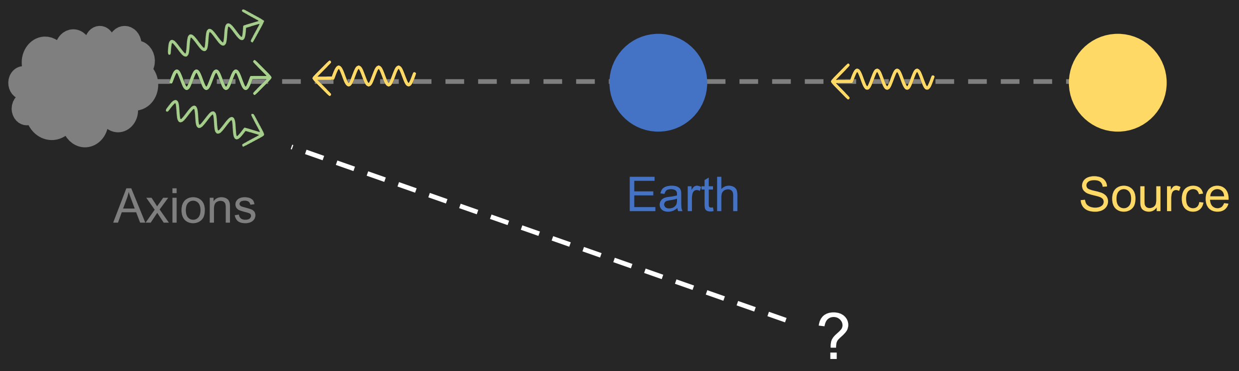

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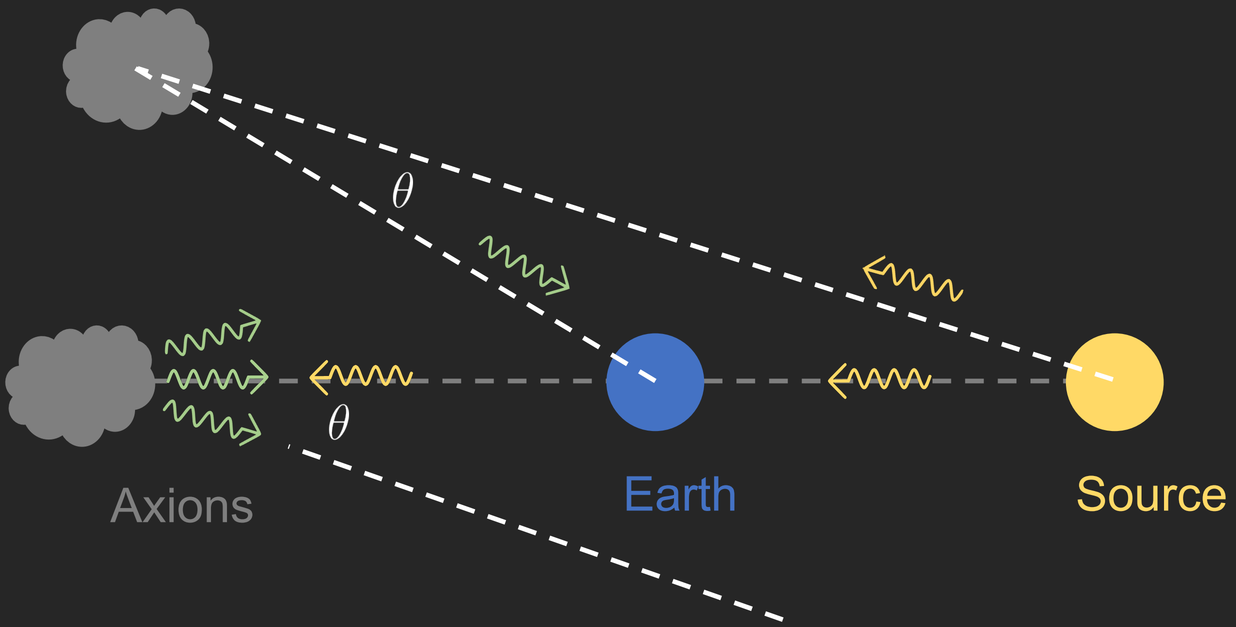

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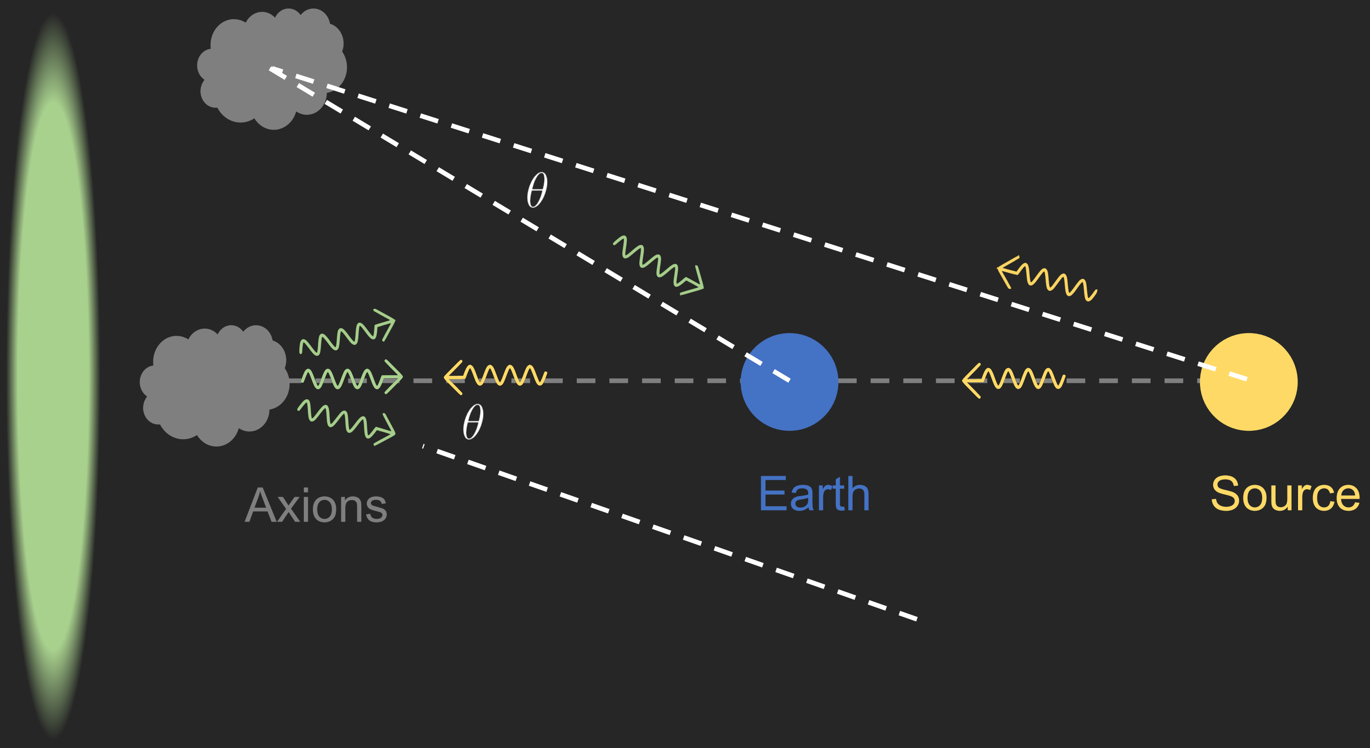
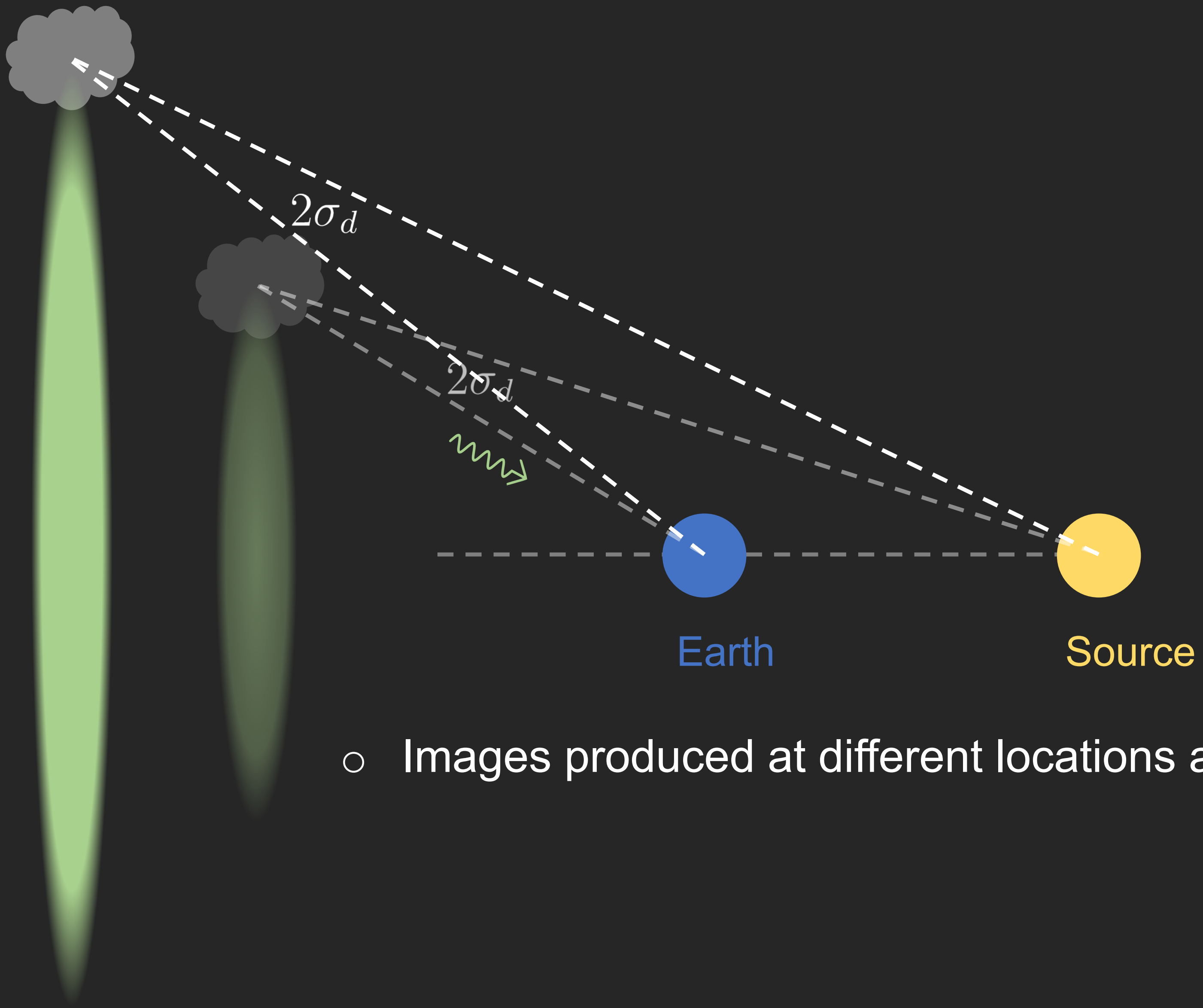
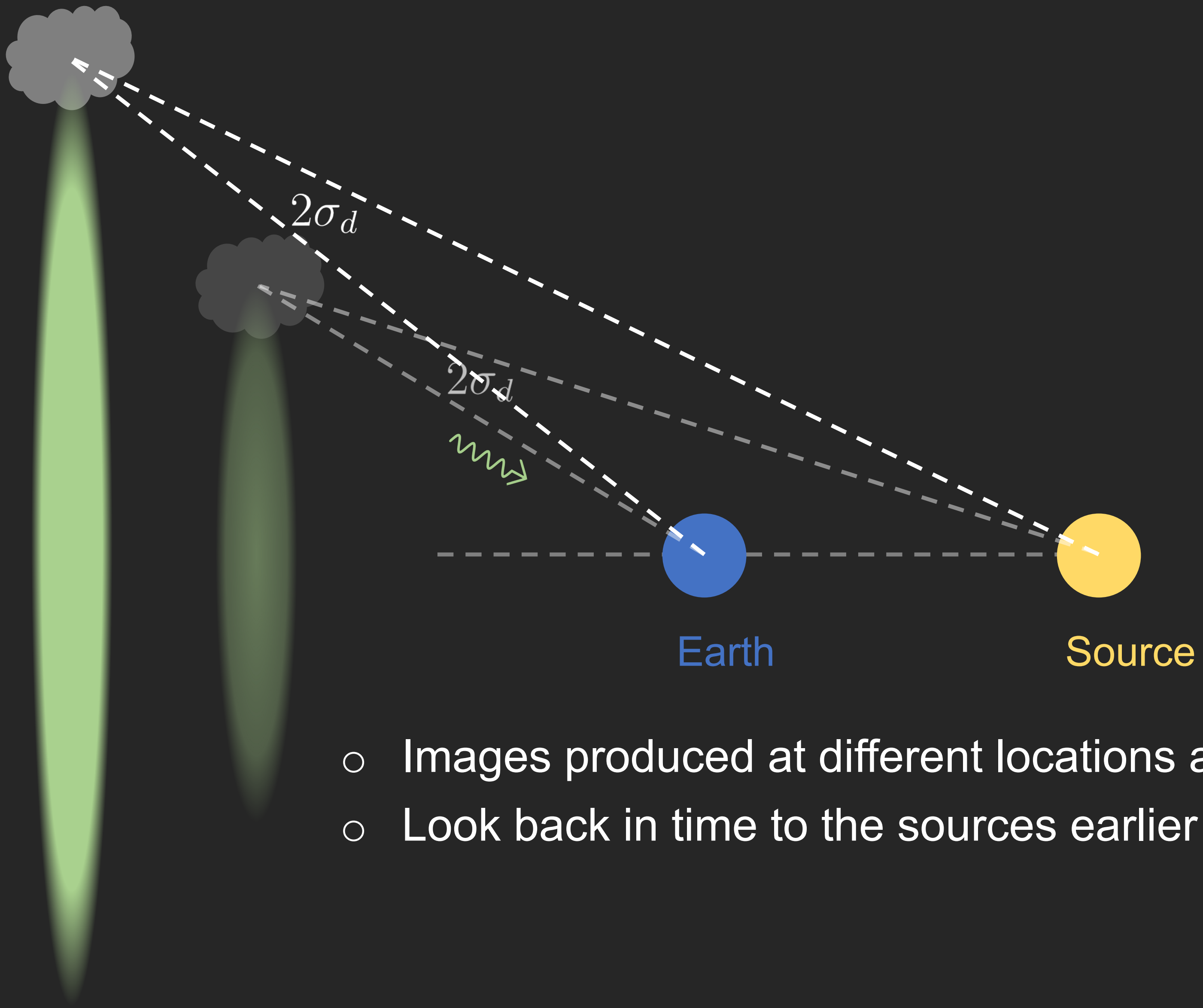




- Images produced at different locations are stacked



- Images produced at different locations are stacked
- Look back in time to the sources earlier stages

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Supernova Remnants as radio 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.

- Synchrotron radiation from shocked e^-.

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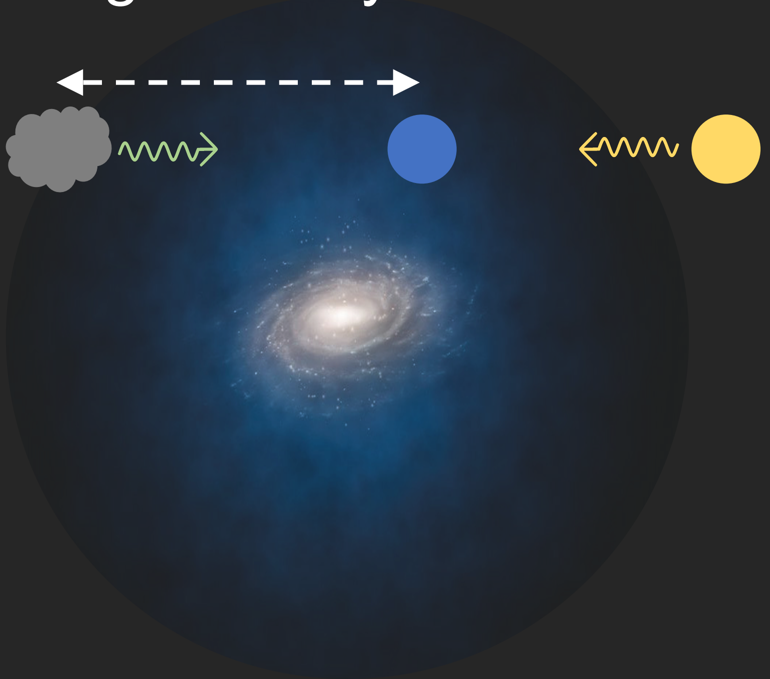

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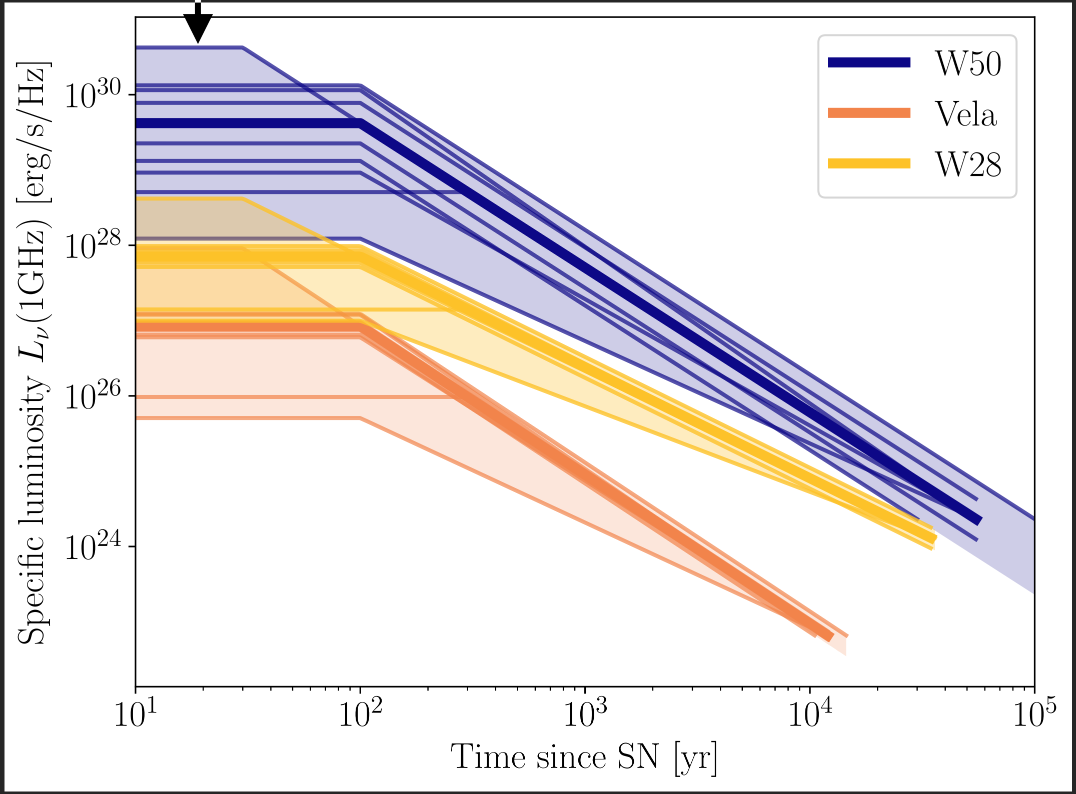
- Synchrotron radiation from shocked e^-.
- Brighter in the past.
- Age ~ 10^4 years.
- Luminosity history can be modelled.

Modeling of SNR luminosity history

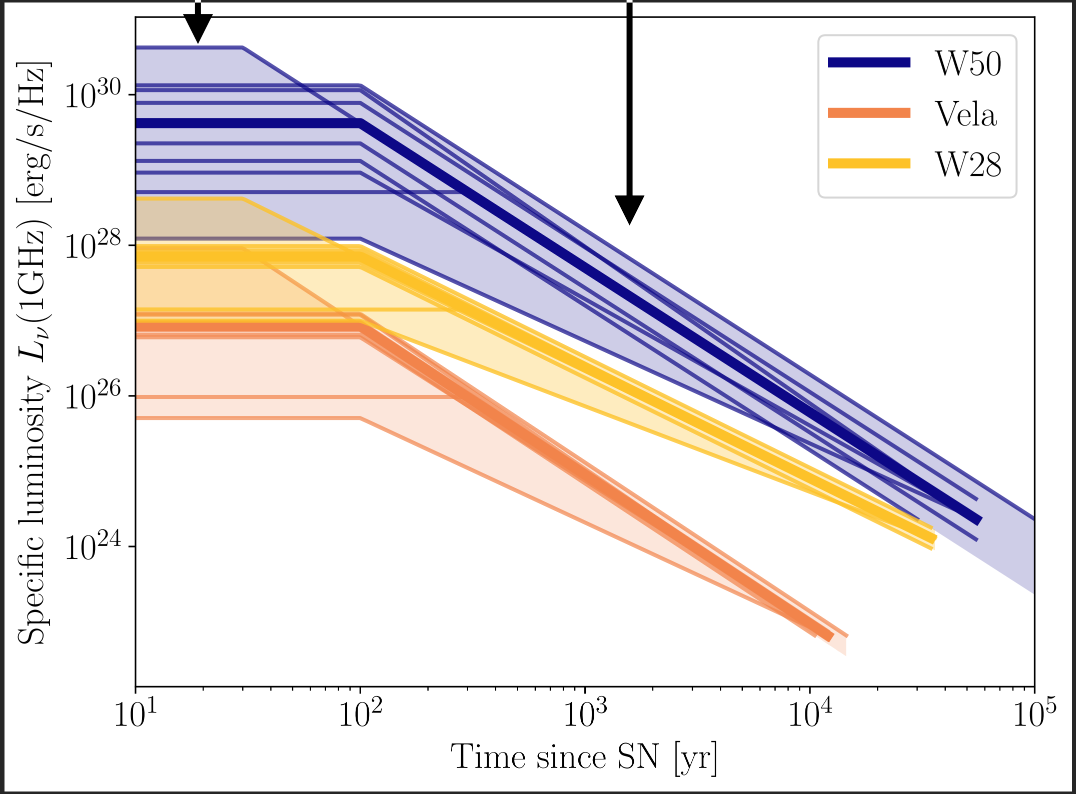
1. Ejecta dominated expansion



Modeling of SNR luminosity history

1. Ejecta dominated expansion

2. Adiabatic expansion



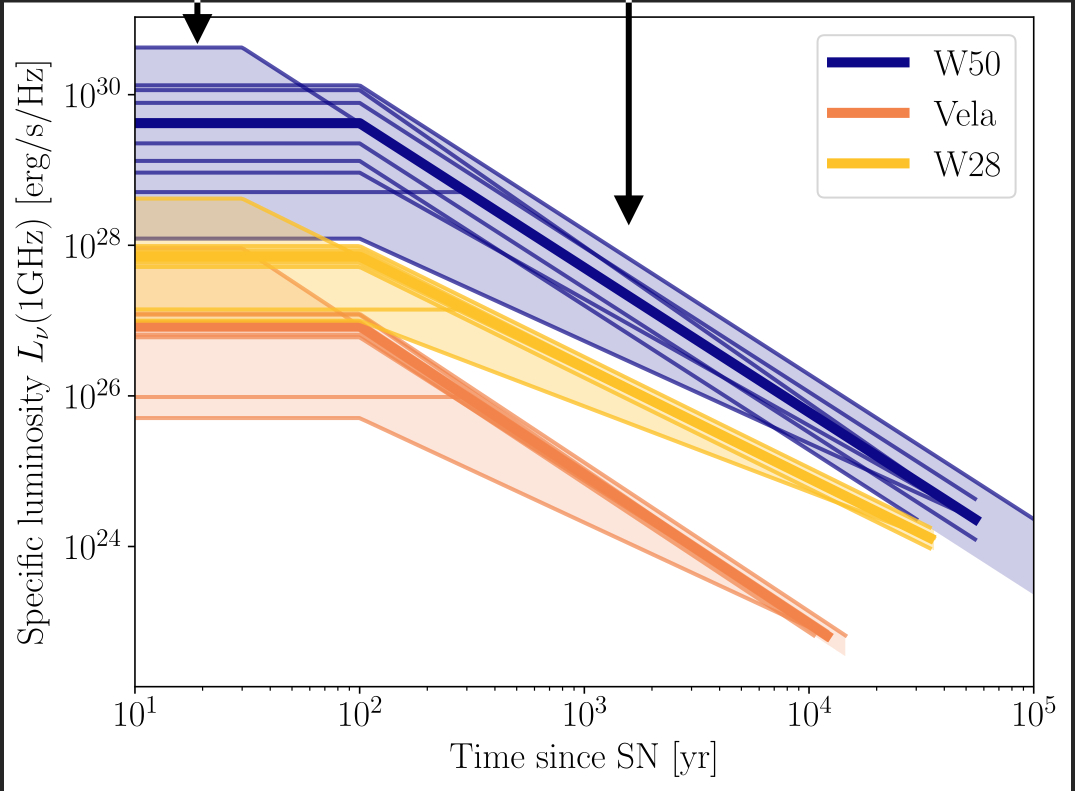
Modeling of SNR luminosity history

1. Ejecta dominated expansion

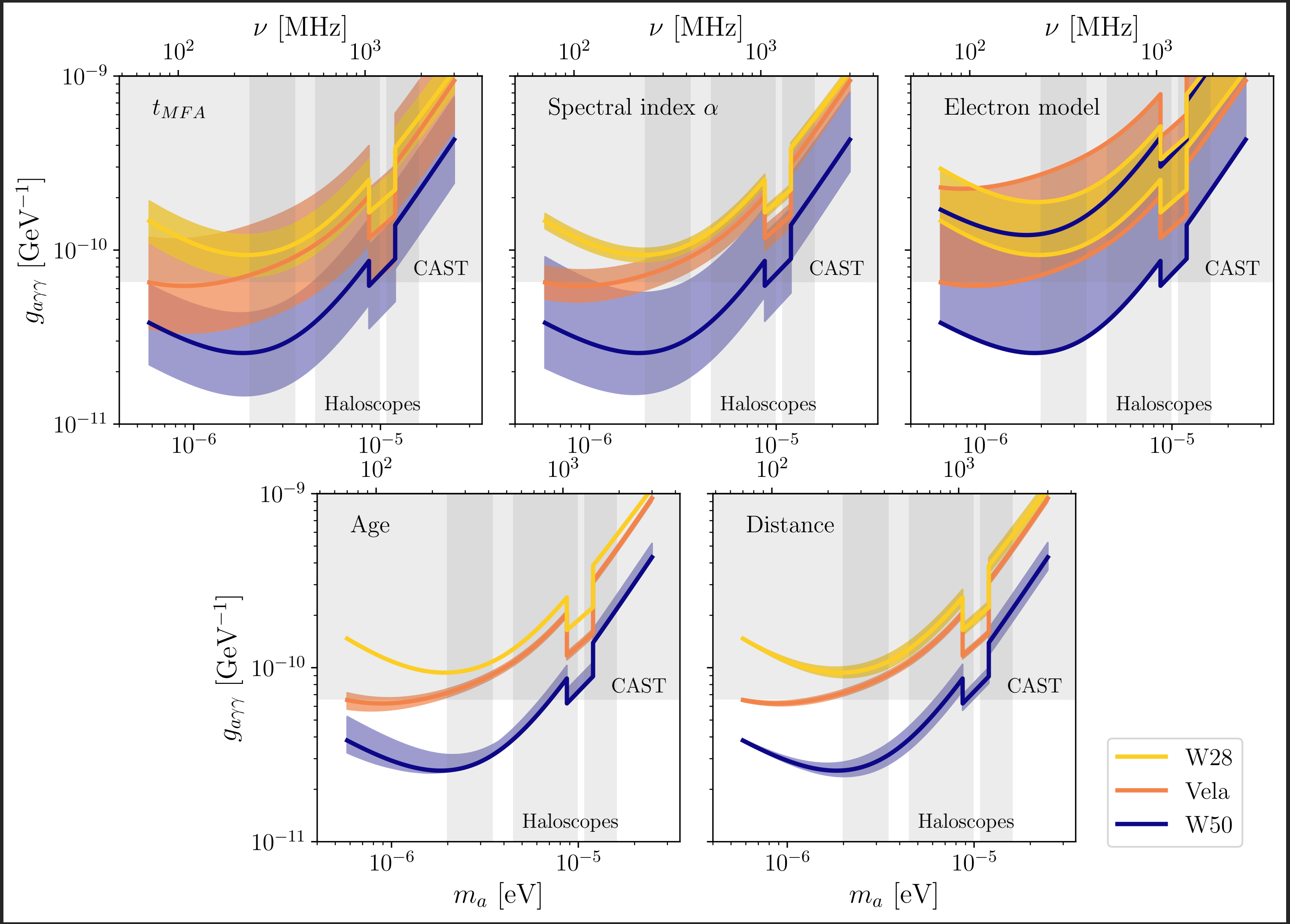
2. Adiabatic expansion

3. Radiative expansion

✕



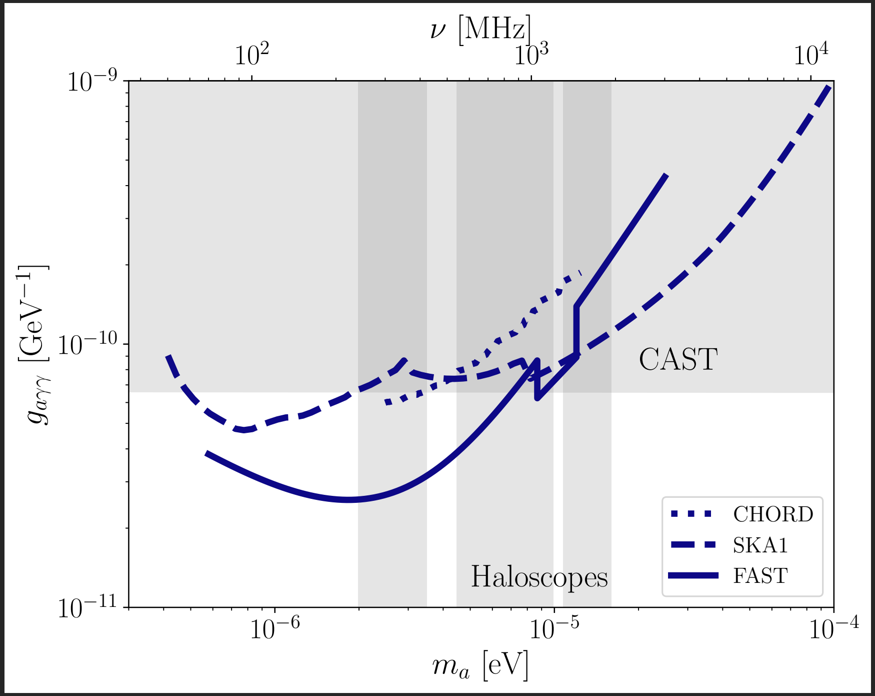
Projected limits & uncertainties



Telescopes: FAST, SKA-I, CHIME…

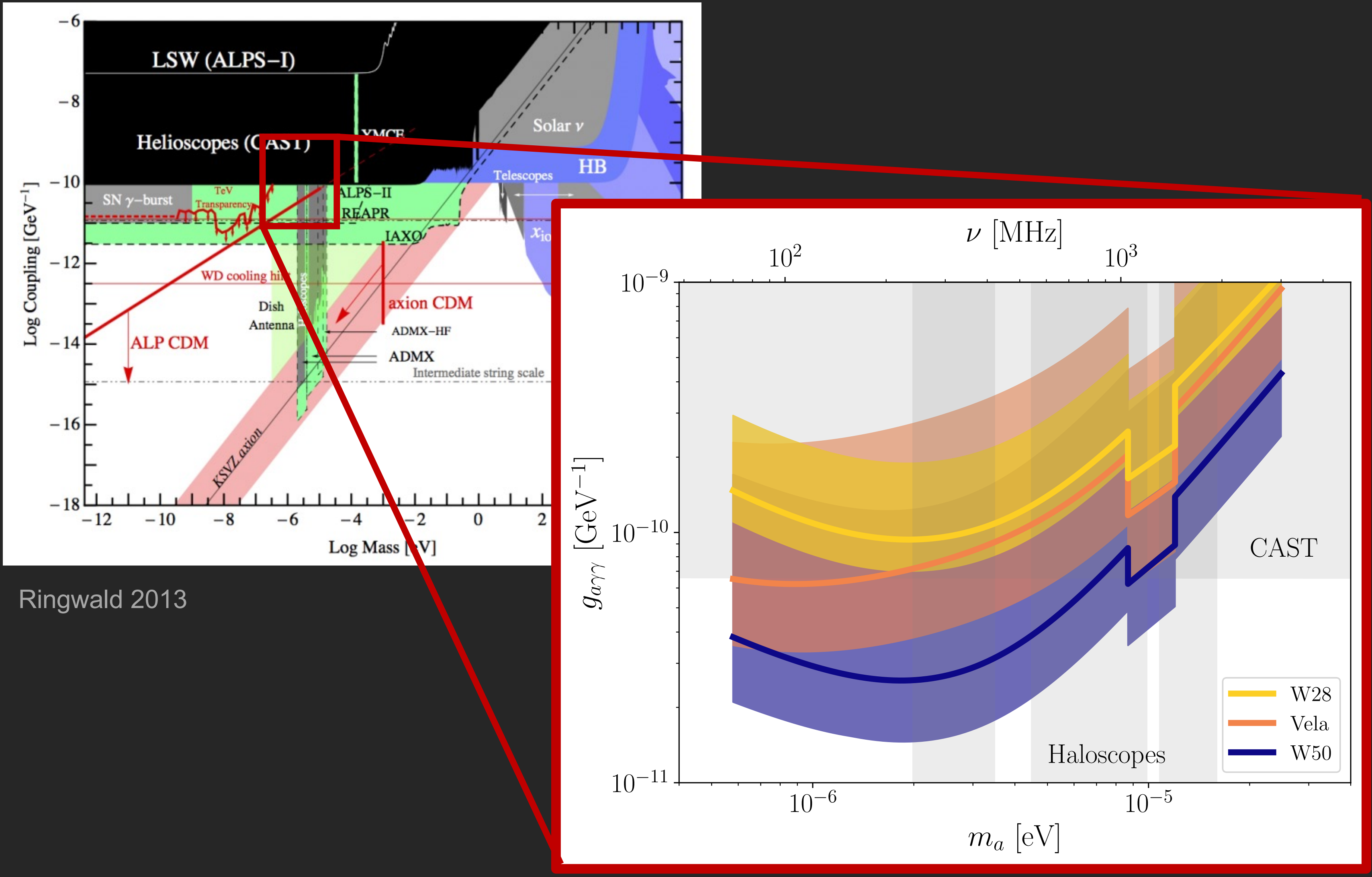
Five-hundred-meter Aperture Spherical Telescope (FAST)

Xinhua



Sensitivity for W50 SNR

Projected limits & compounded uncertainties



Ringwald 2013

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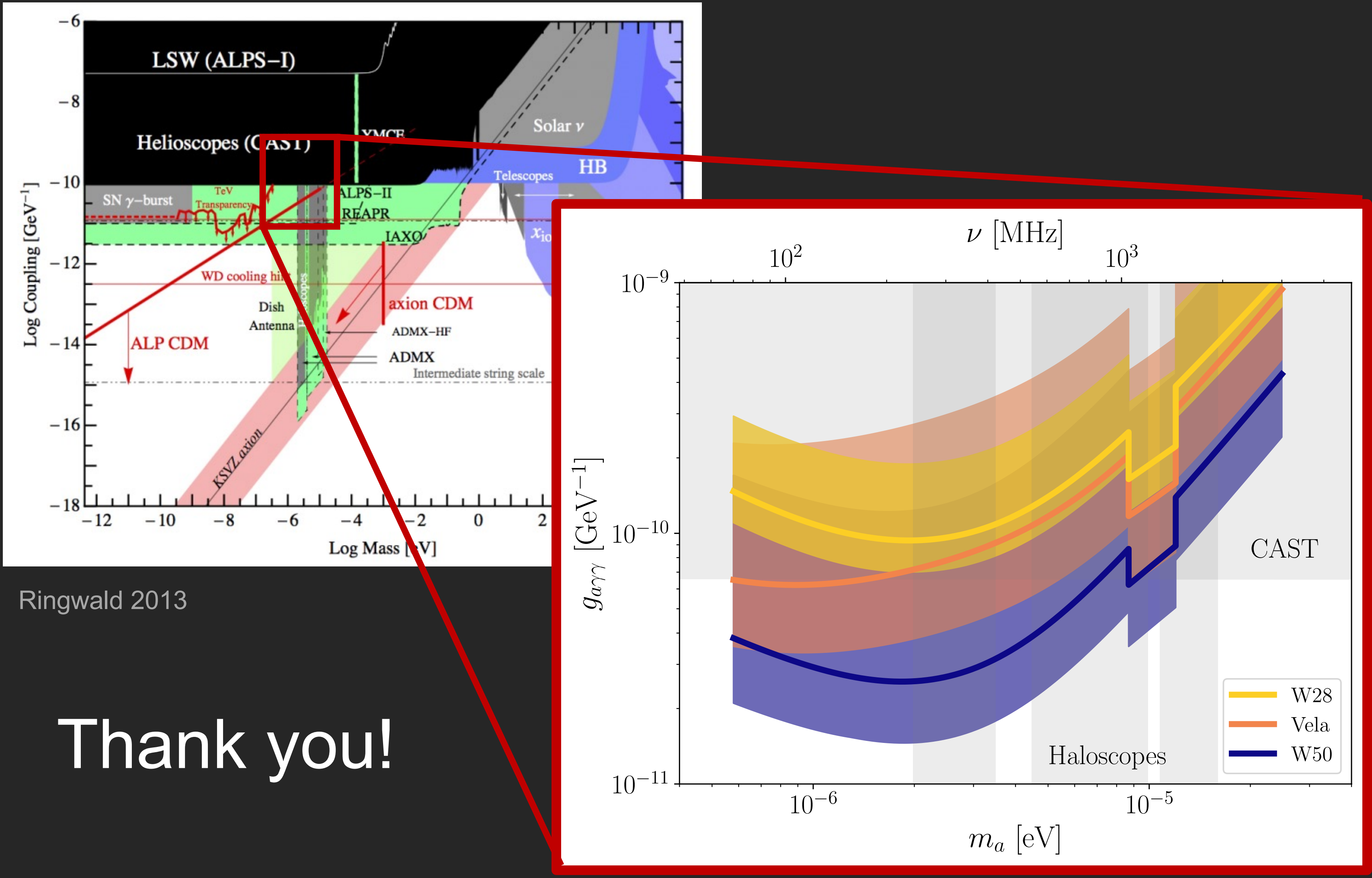
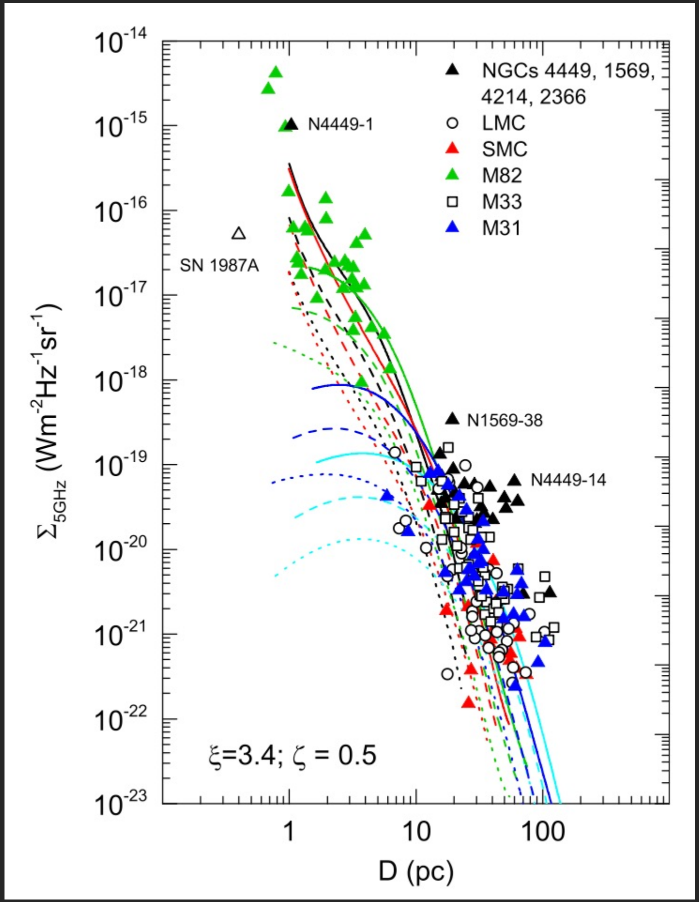


Ringwald 2013

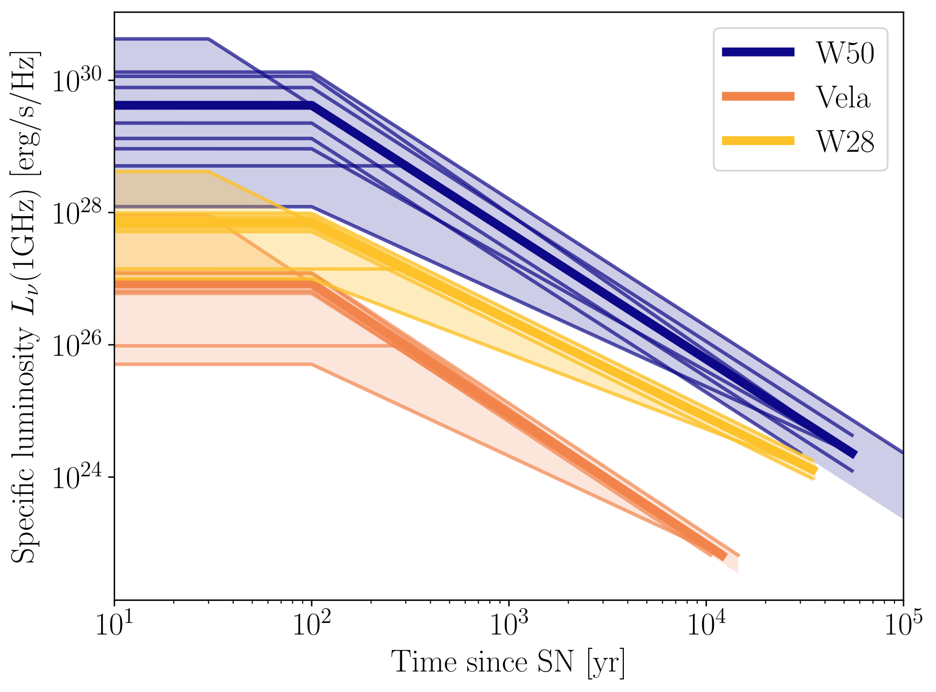
Thank you!

Backup slides

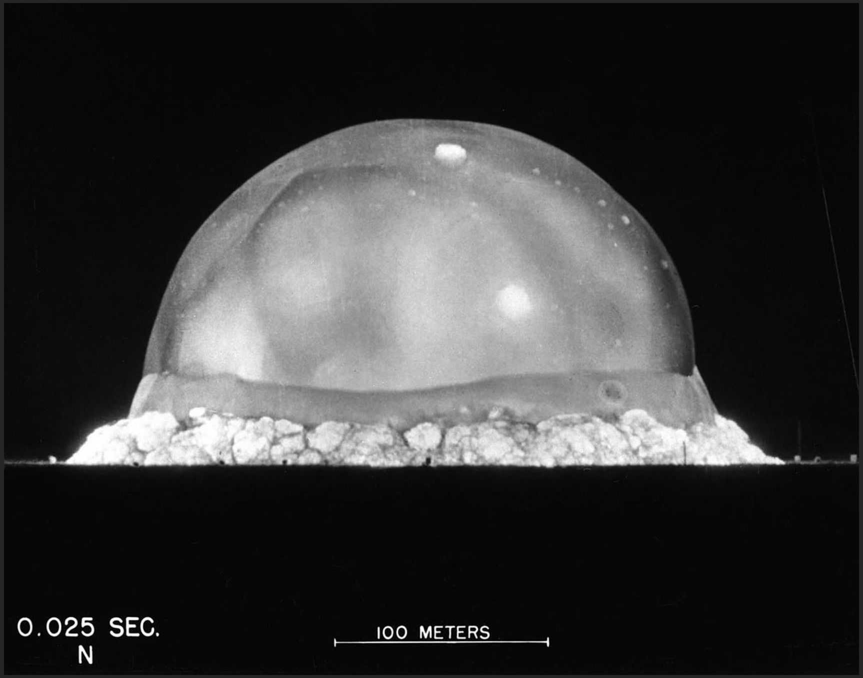
Comparison with observations



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



Supernova Remnant Dynamics $R - t$

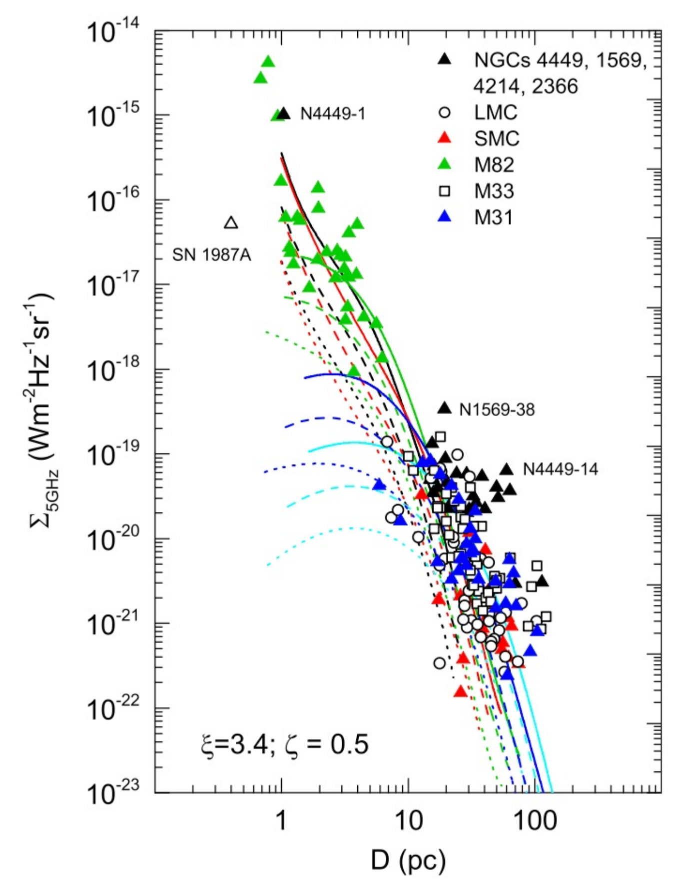


One of the published photograph of the Trinity atomic bomb tests that allowed British physicist G. I. Taylor to estimate the explosion energy.

- ○ 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 $\Sigma - D$



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- 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:

$$V K_e \sim R^{1-p}$$

  - Alternative model: total electron energy is conserved:

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

[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