McGill UNIVERSITY

MIT

Axions against the world:
An all-sky analysis of axion dark matter echoes

Yitian Sun
with Katelin Schutz, Harper Sewalls, Anjali Nambrath
Calvin Leung, and Kiyoshi Masui

Based on **YS**, Schutz et al, PRD and *upcoming work*

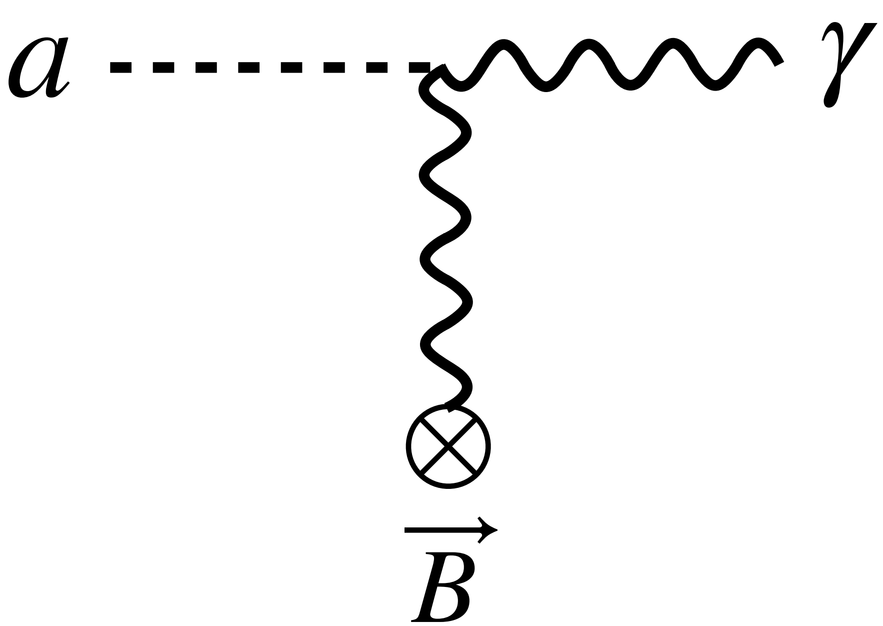
Jun 26 | PASCOS 2023 | UC Irvine

Background images generated by Midjourney

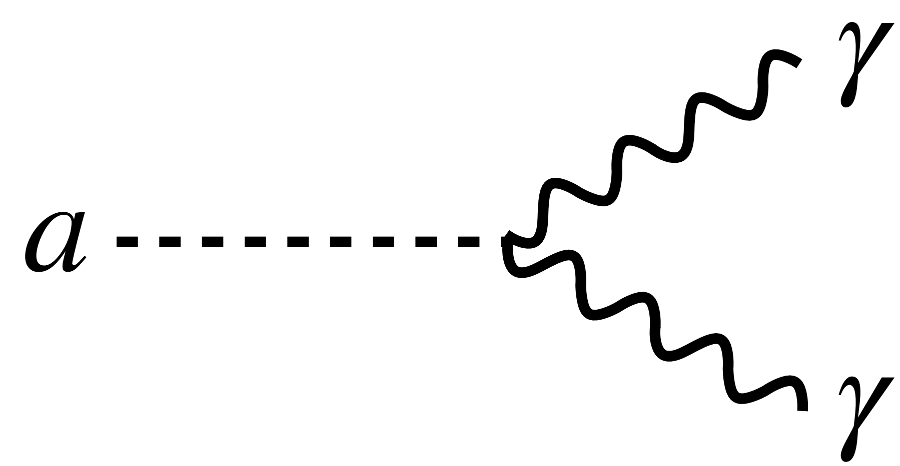
Axion (-like particles) couples to photon

via $$L \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \sim g_{a\gamma\gamma} a \overrightarrow{E} \cdot \overrightarrow{B}$$

Primakoff process



Decay



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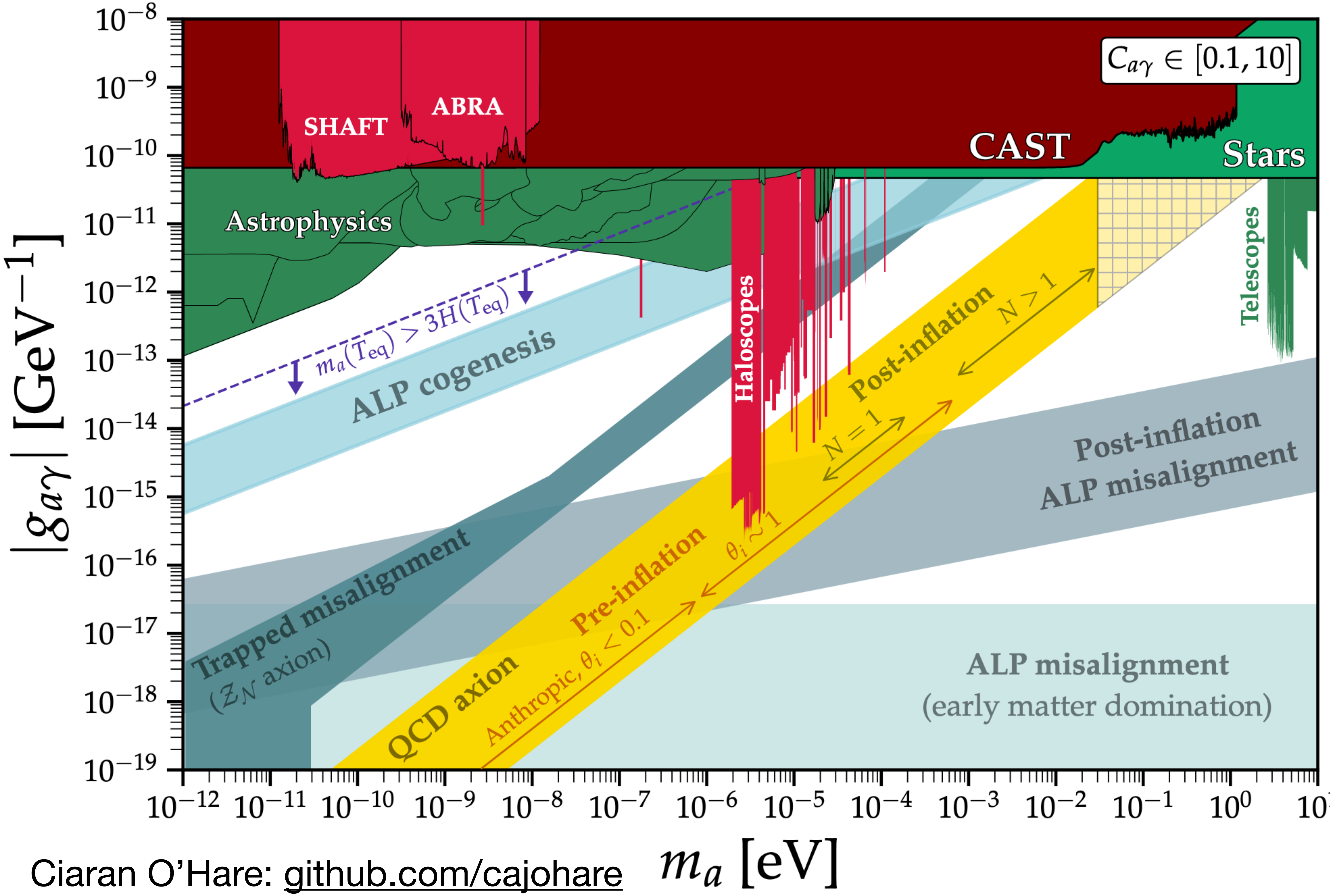

Ciaran O'Hare: github.com/cajohare

Need for complementarity in axion searches

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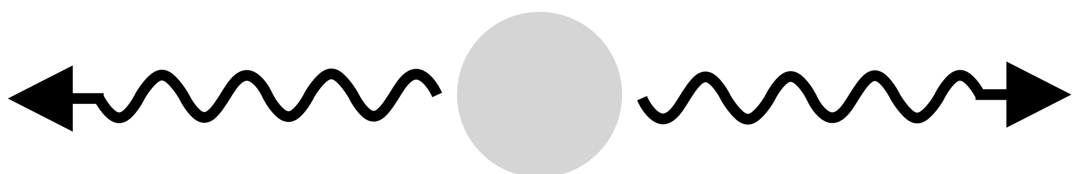
  - Local variation of axion dark matter density: some axion cosmologies lead to compact mini-halos (e.g. Buschmann *et al.* 2019) with an O(1) survival rate inside the Milky Way (e.g. Shen *et al.* 2022).
- Motivates multiple independent searches with different modeling and observational systematics, and less sensitivity to local axion density.

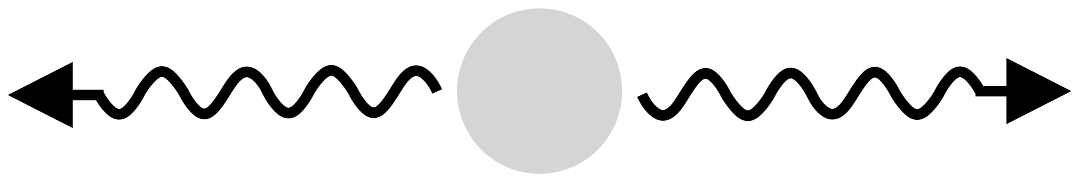
Axions can decay spontaneously



will produce a spectral line at $m_a/2$ in the axion rest frame, with a very long lifetime:

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

Axions can undergo stimulated decay



Rate $\sim \Gamma$

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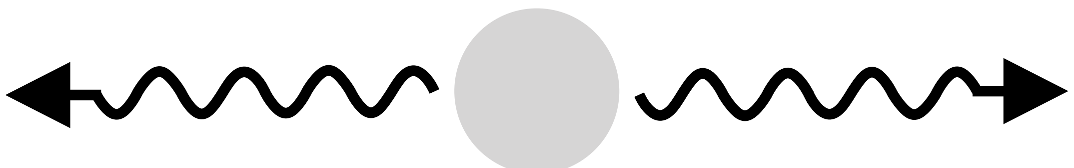

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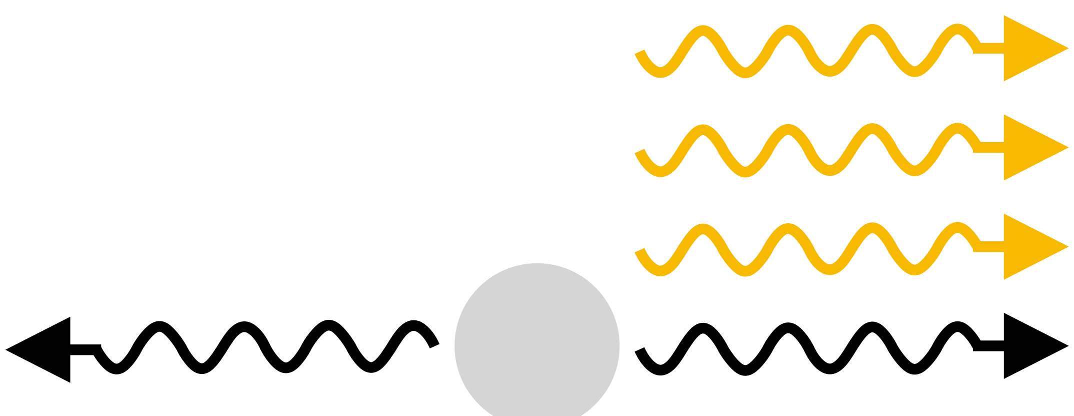

Rate $\sim f \cdot \Gamma$, where f is the phase space occupation #.
This is because of Bose enhancement.
In radio frequencies, this enhancement can be $\gtrsim 10^5$

Axion stimulated decay produces "echoes" aka "gegenschein"

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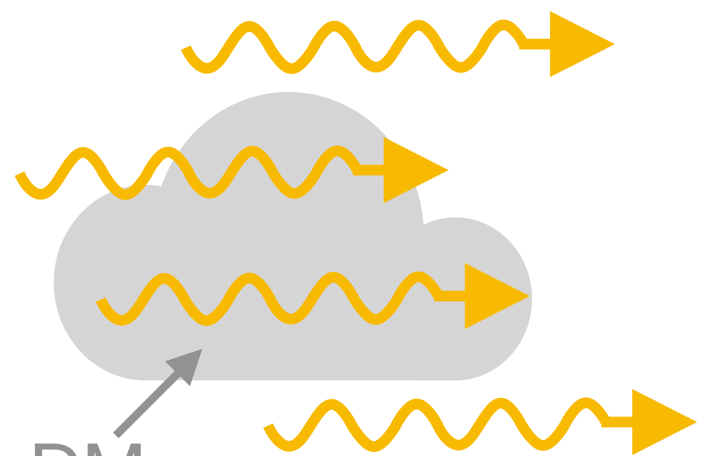

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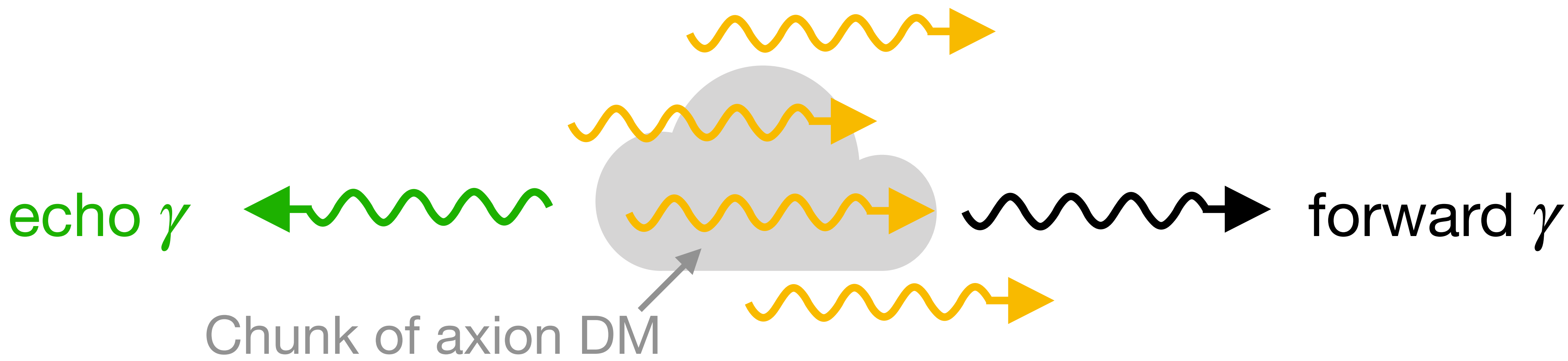

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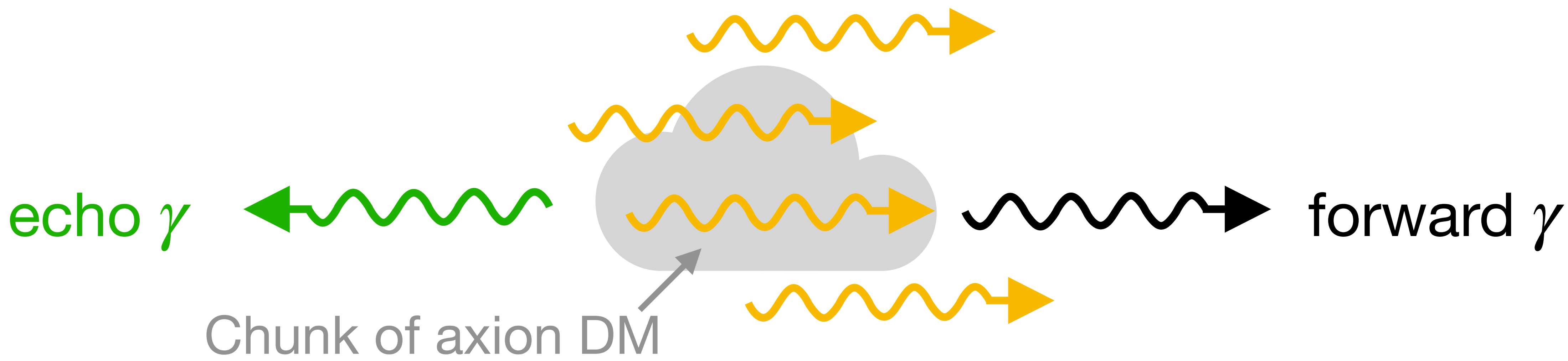
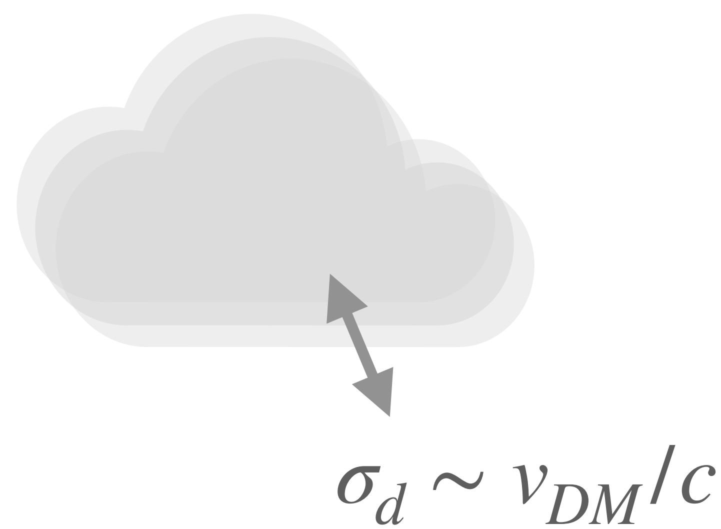


Integrating along the antipodal line of sight:

$$S_{\rm echo} = \frac{g_{a\gamma\gamma}^2}{16} \frac{{\rm d}S_{\rm in}}{{\rm d}E}\bigg|_{m_a/2} \int \rho_a \, dx$$

e.g. Arza & Sikivie (2019)

Axion echoes aligned with antipodal direction only in axion rest frame



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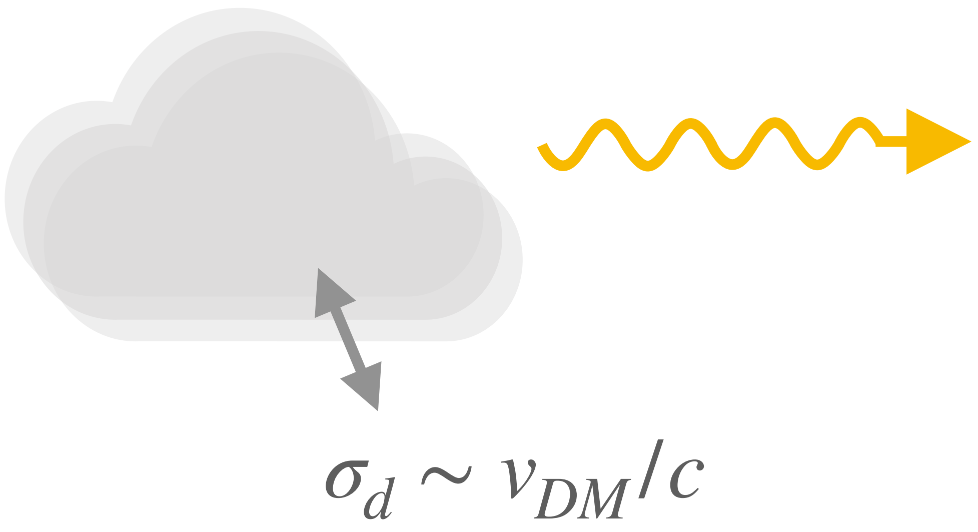

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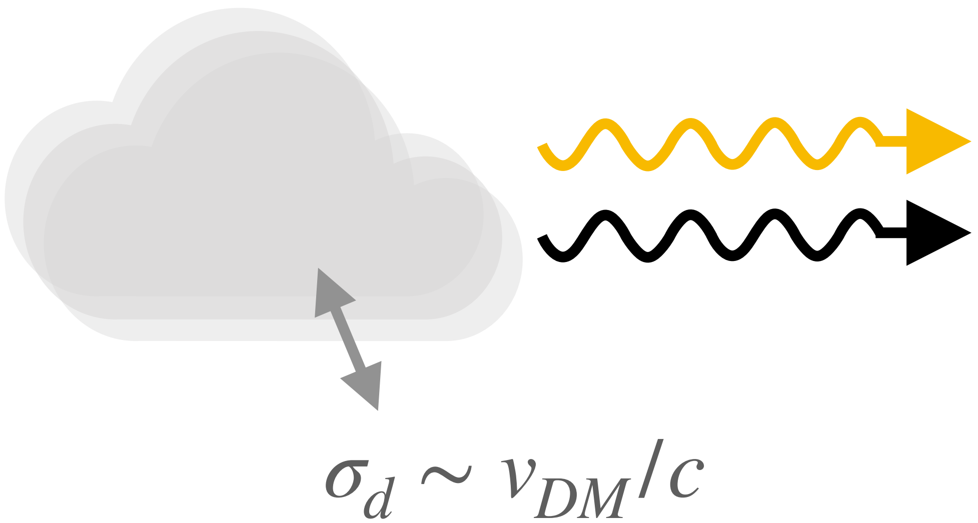

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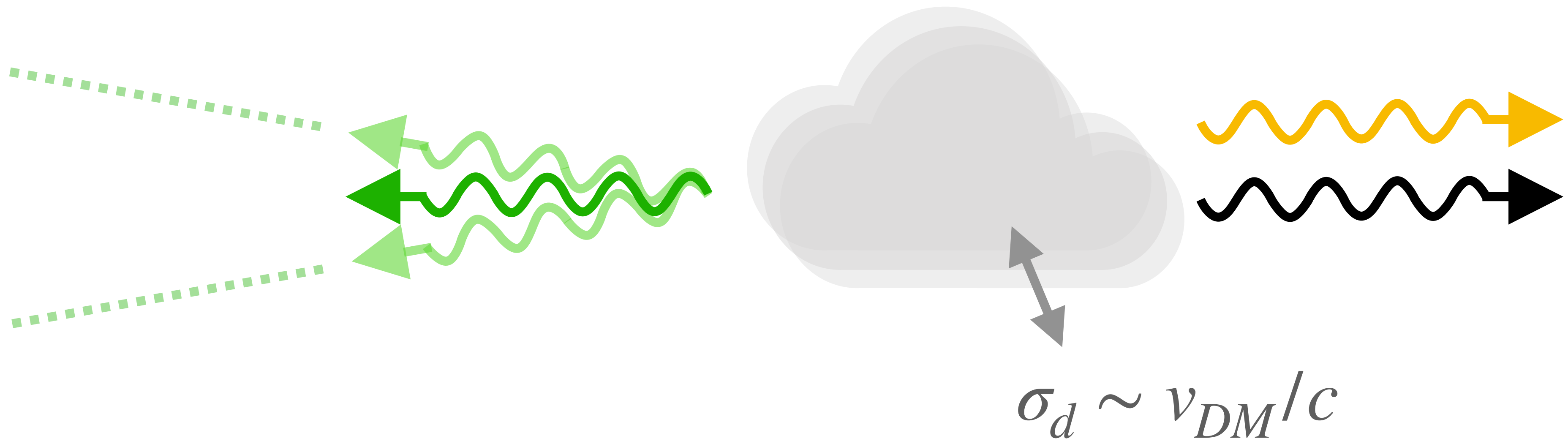

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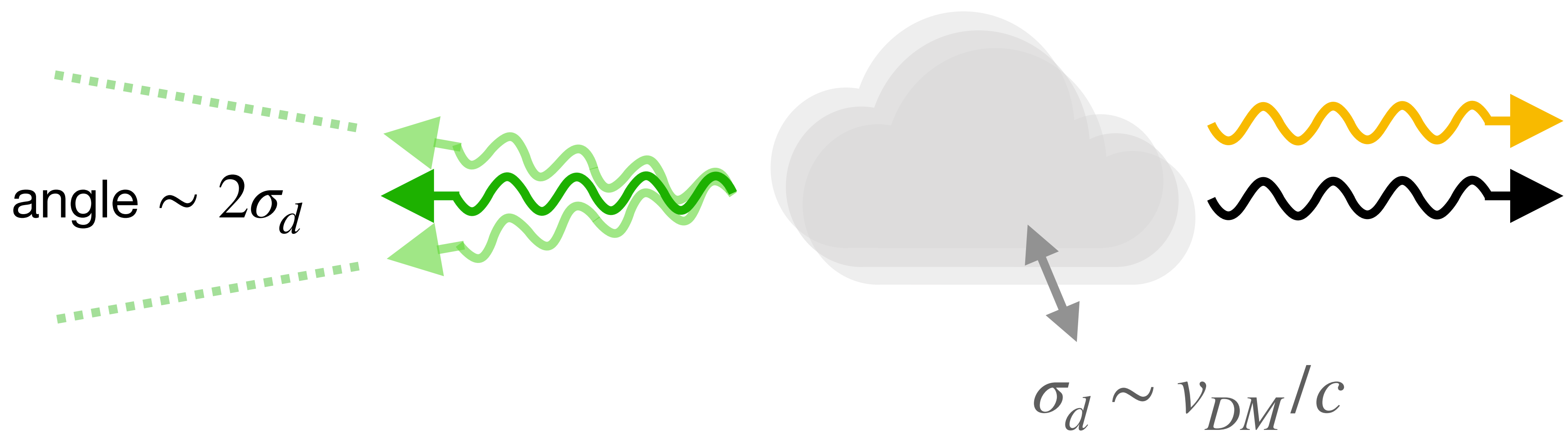
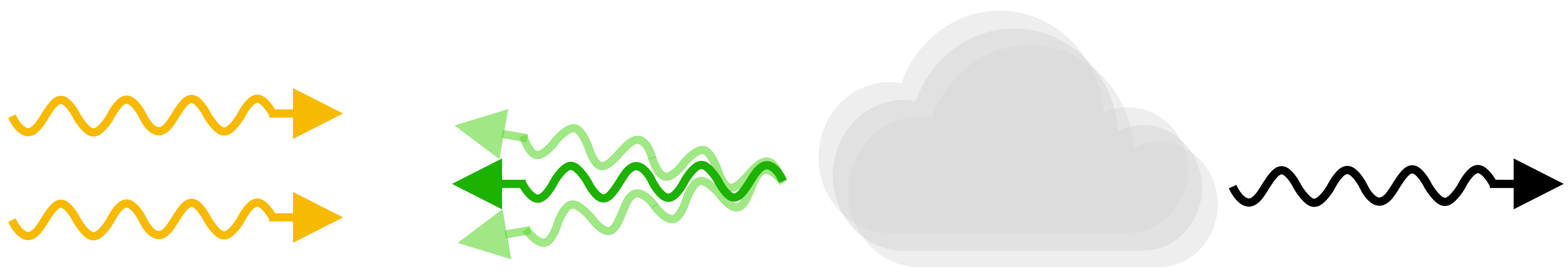


Part I: Summary



Axion Dark Matter is a blurry, monochromatic mirror.

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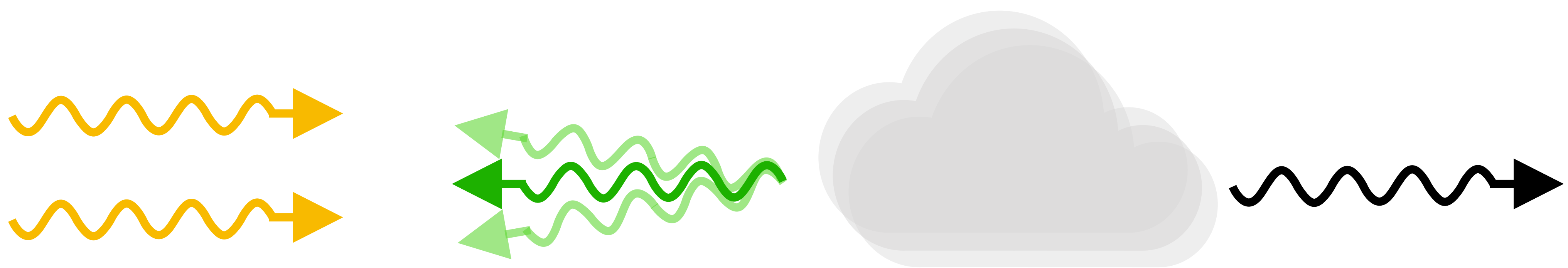

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We can shoot radiation at it and wait for the echo, or look for echoes of astrophysical sources

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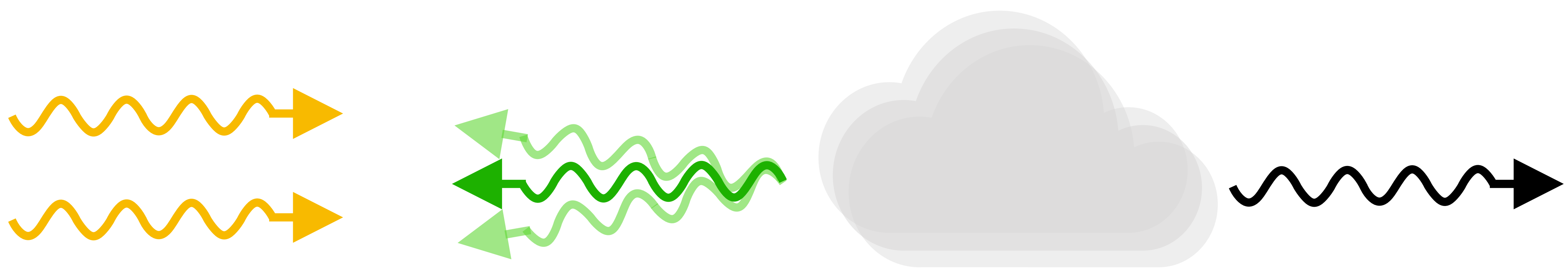

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Ghosh et al. (2020), Buen-Abad et al. (2022), **YS**, Schutz et al. (2022)

Part II: What are the best astrophysical sources?

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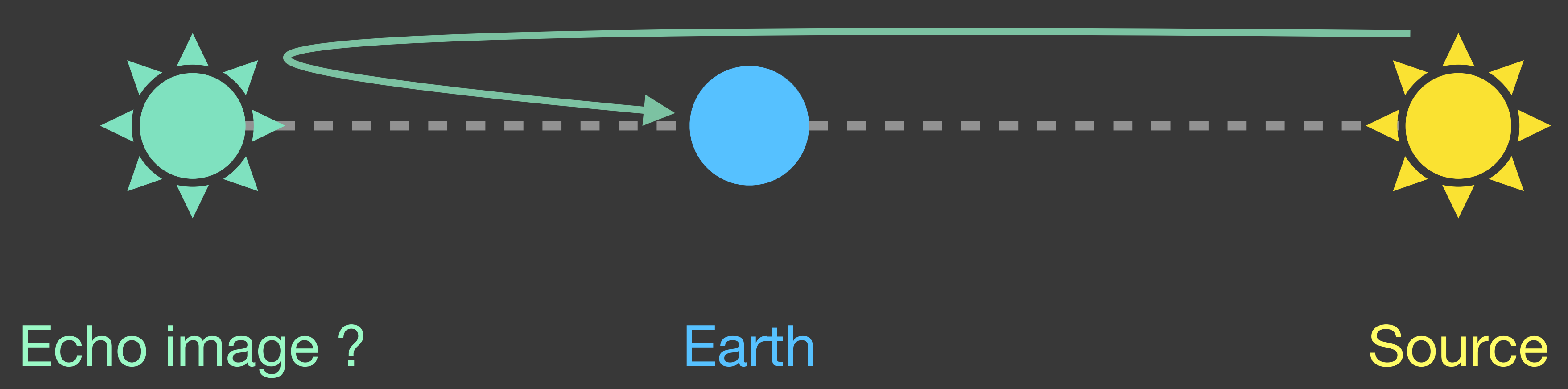
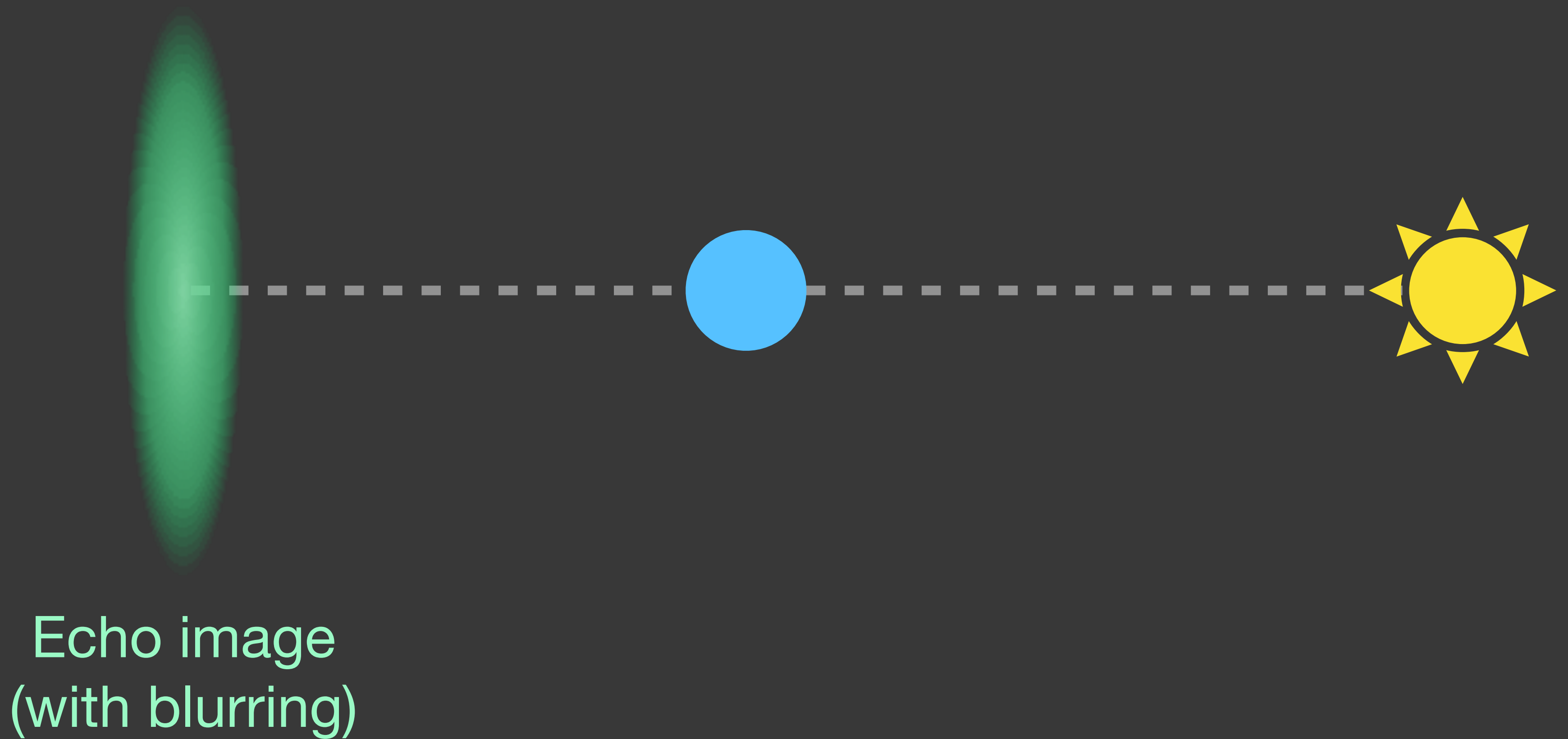
The brightest radio source in the sky is the Sun.
However it turns out to not be a good source
We need to understand the echo geometry.



Echo geometry



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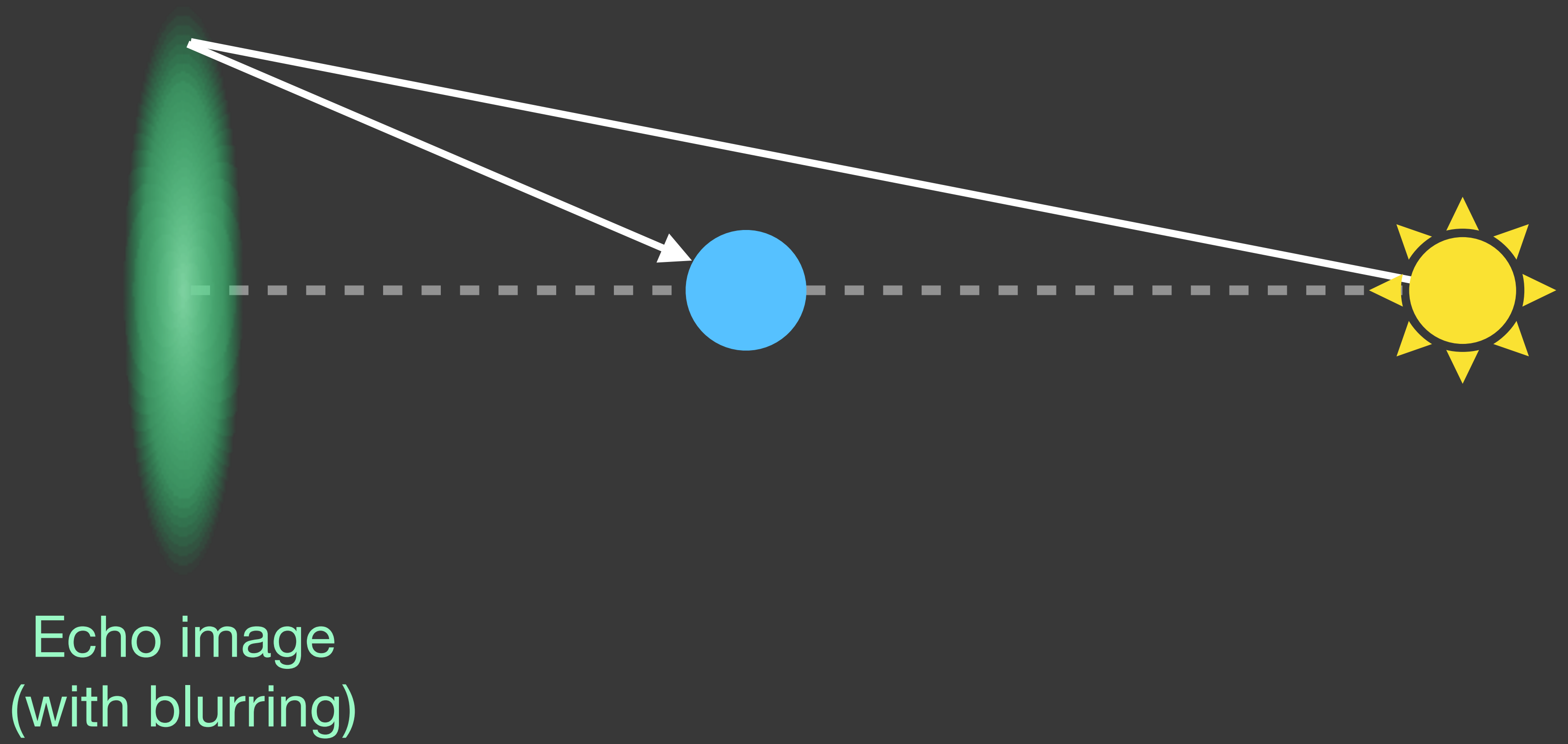

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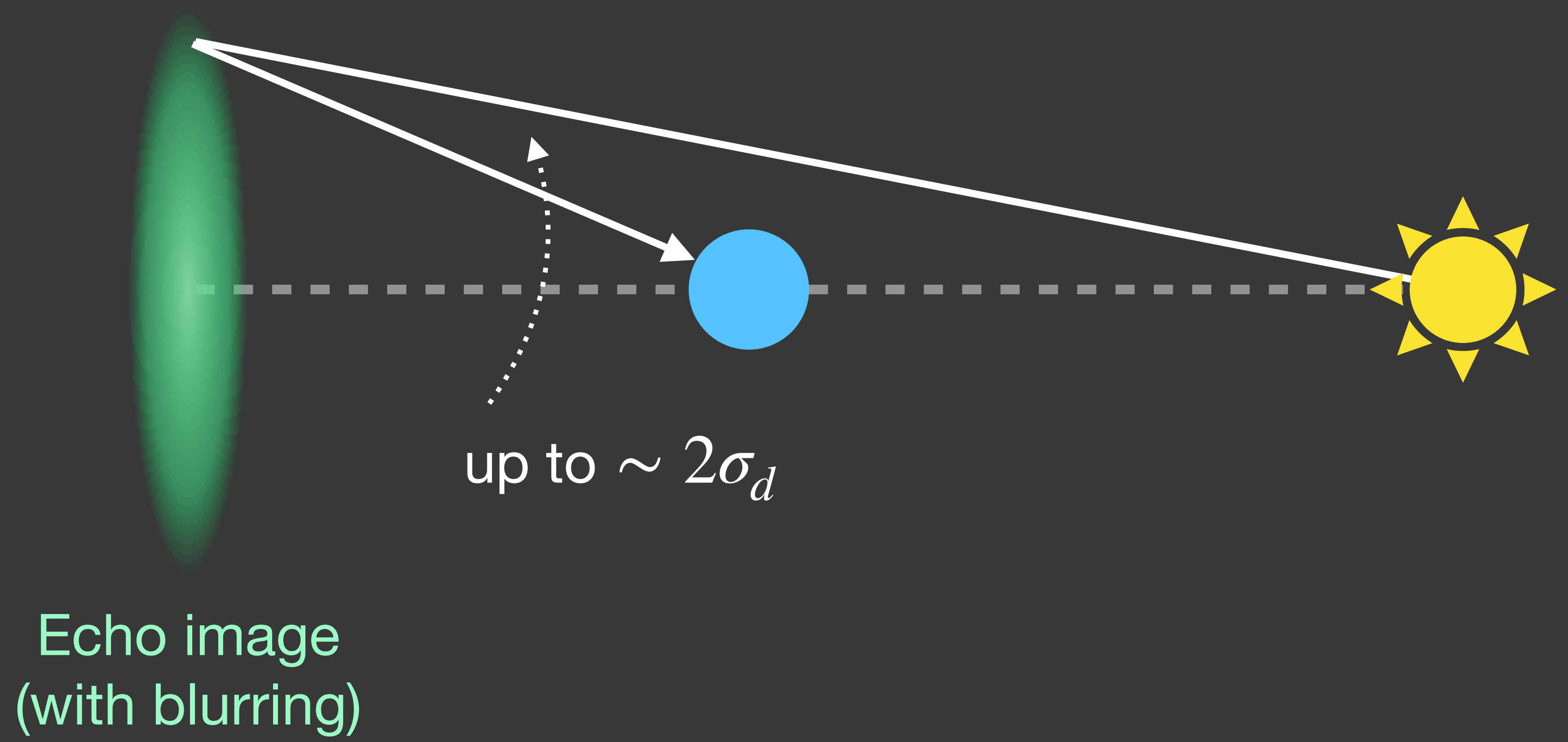

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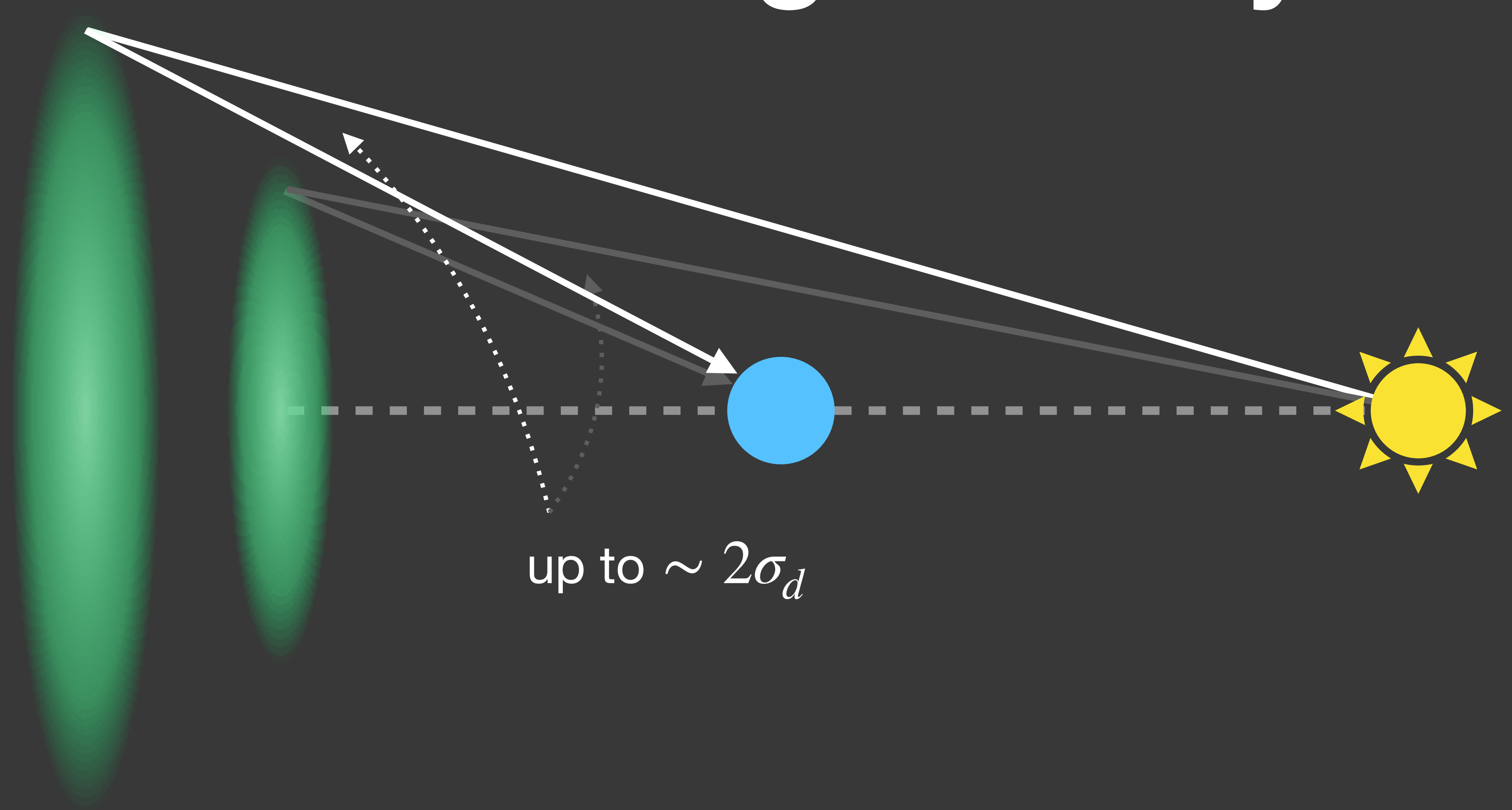

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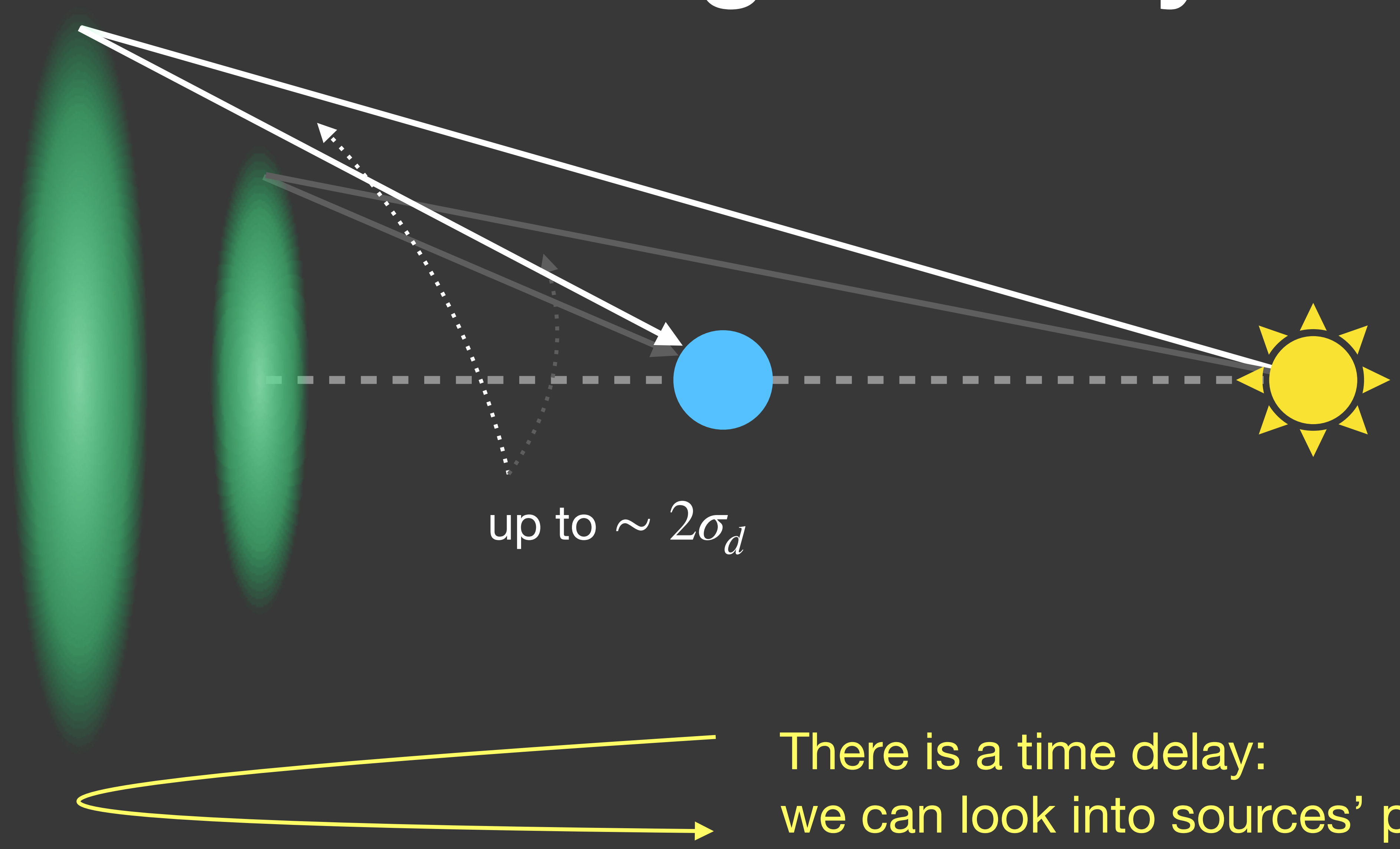
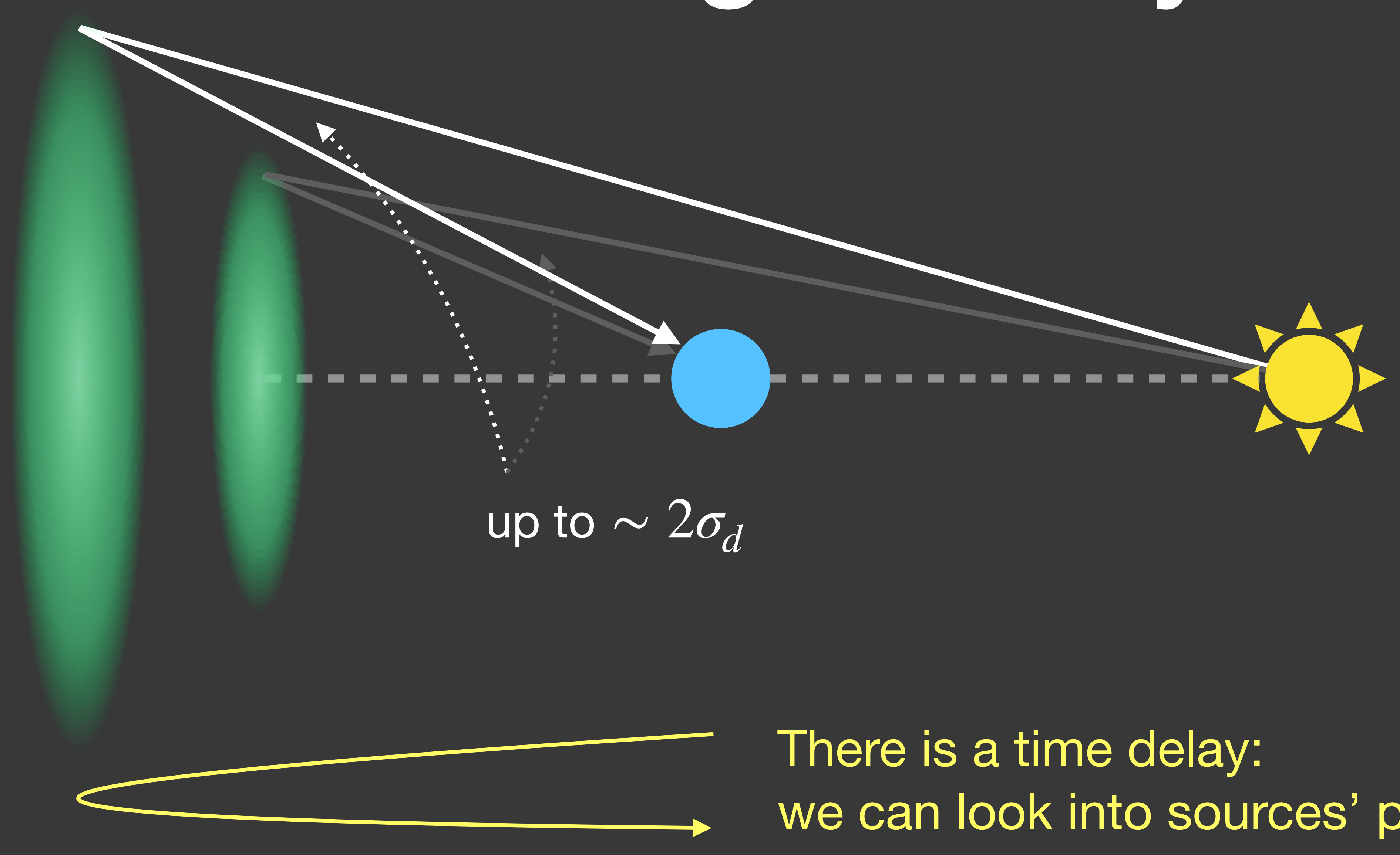


There is a time delay:
we can look into sources' past brightness

Echo geometry



There is a time delay:
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What radio sources have been the brightest
at some point in the galactic halo 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.

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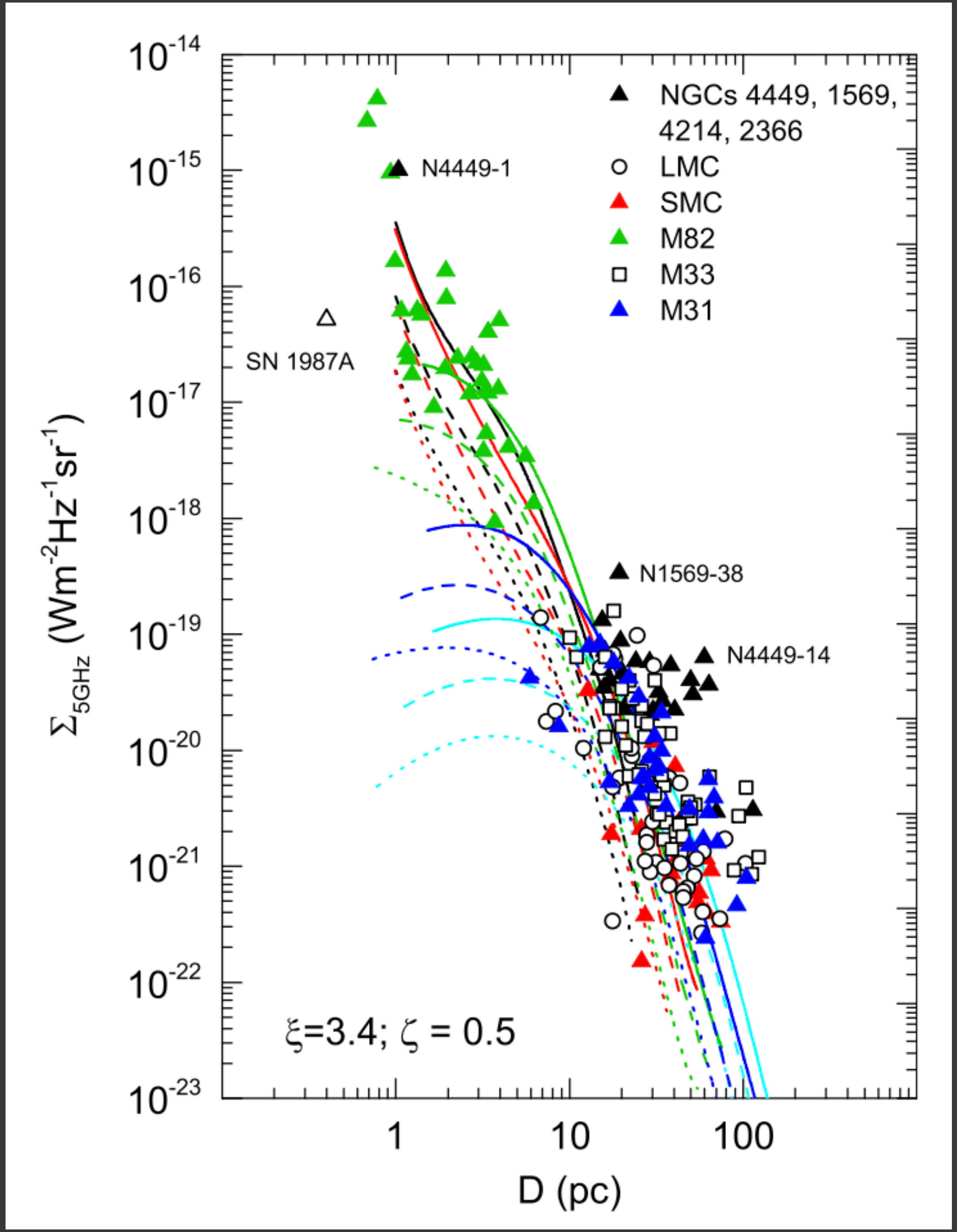
- Brightness decrease steeply → much brighter in the past
- Age $\sim 10^4$ years, close to the light crossing time of the Milky Way halo.
- Luminosity history can be modeled and compared to observation.

SNR: adiabatic expansion



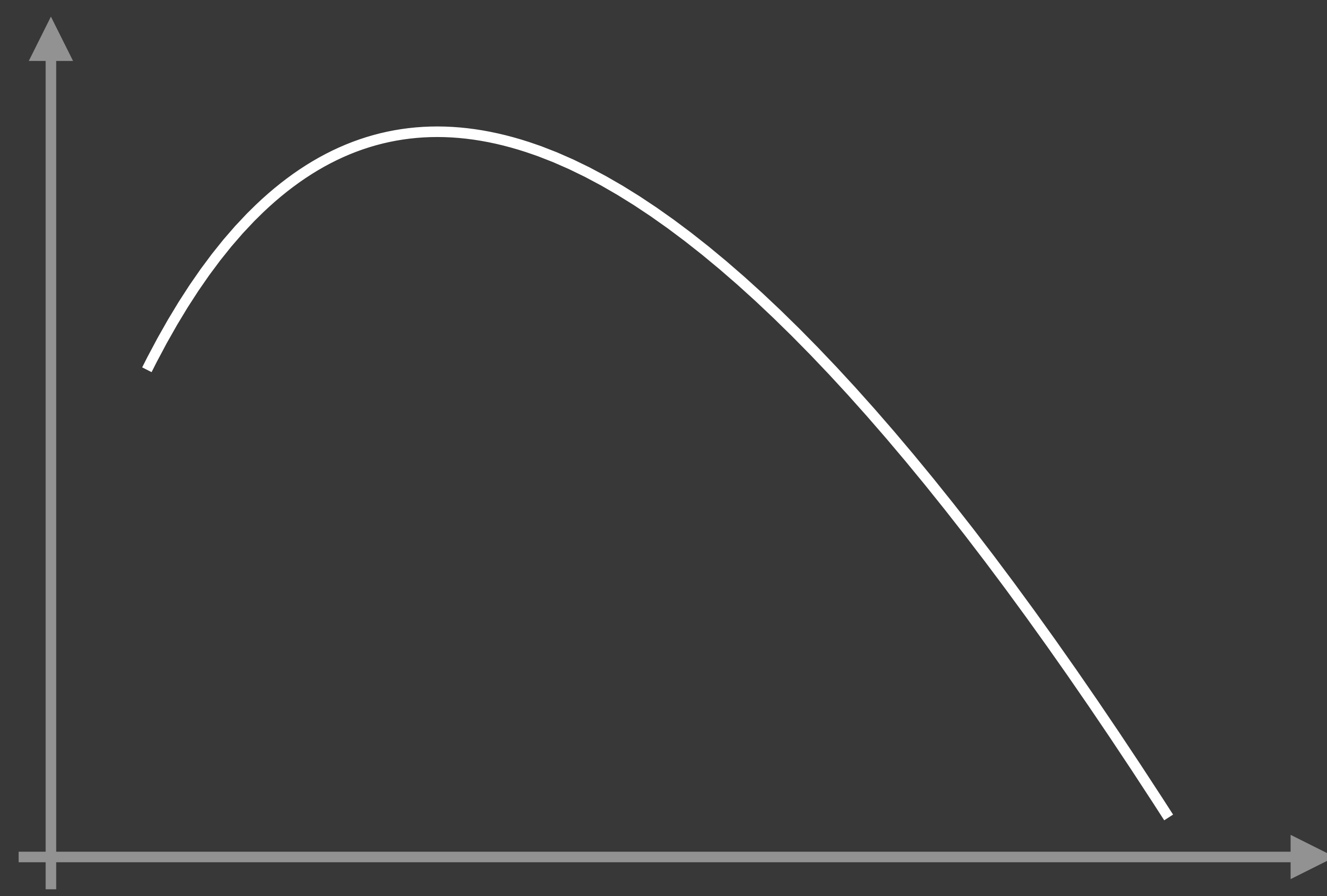
- Radius scaling: Sedov-Taylor solution from dimensional analysis

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

- Flux $S \sim t^{-1.6}$ for a typical SNR, comparable to observations.

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.

SNR: free expansion



From observation of extragalactic SNRs:

$$L(t) = L_{\text{peak}}\ e^{\frac{3}{2}(1 - t_{\text{peak}}/t)} \left(t/t_{\text{peak}}\right)^{-\frac{3}{2}}$$

Bietenholz et al. (2021)

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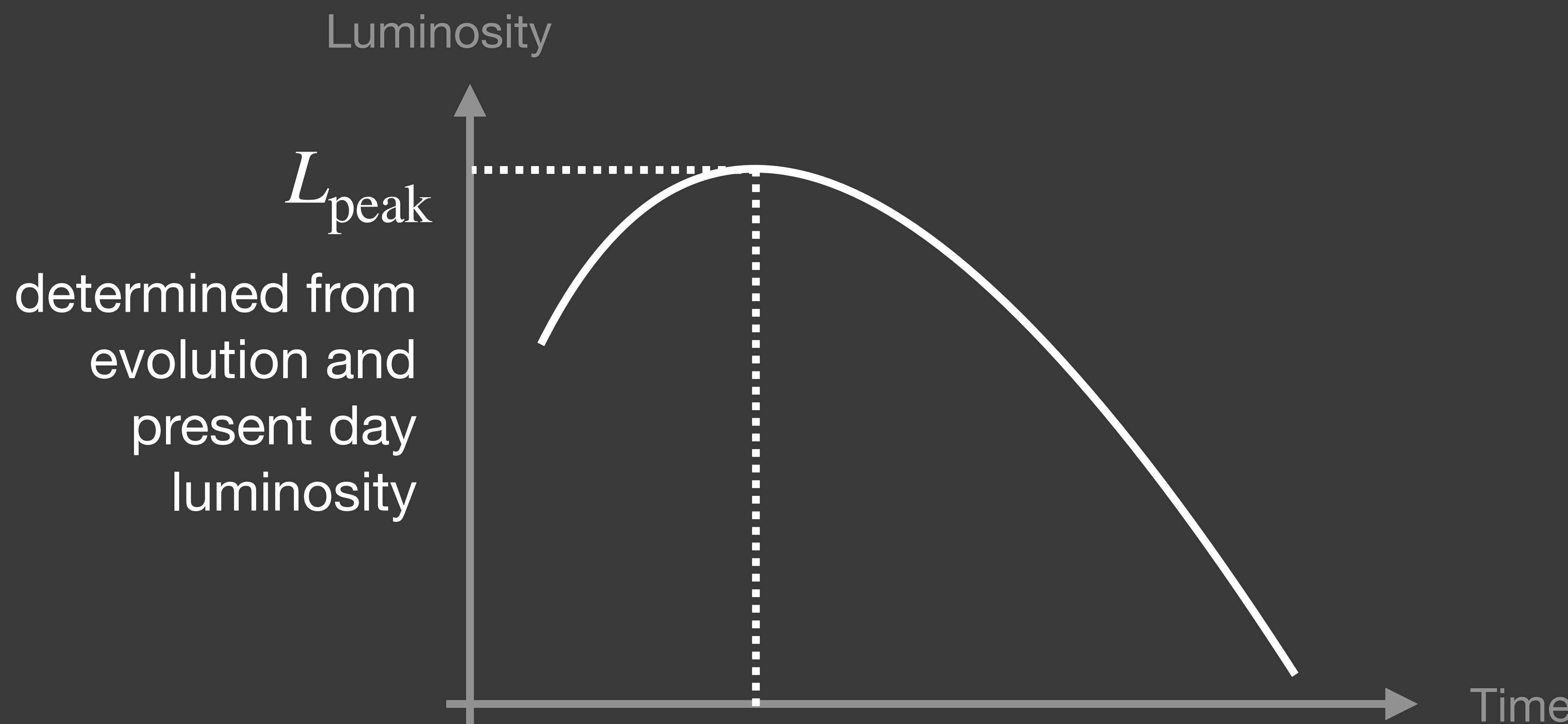

$$t_{\mathrm{peak}} \sim 50 \text{ days}$$

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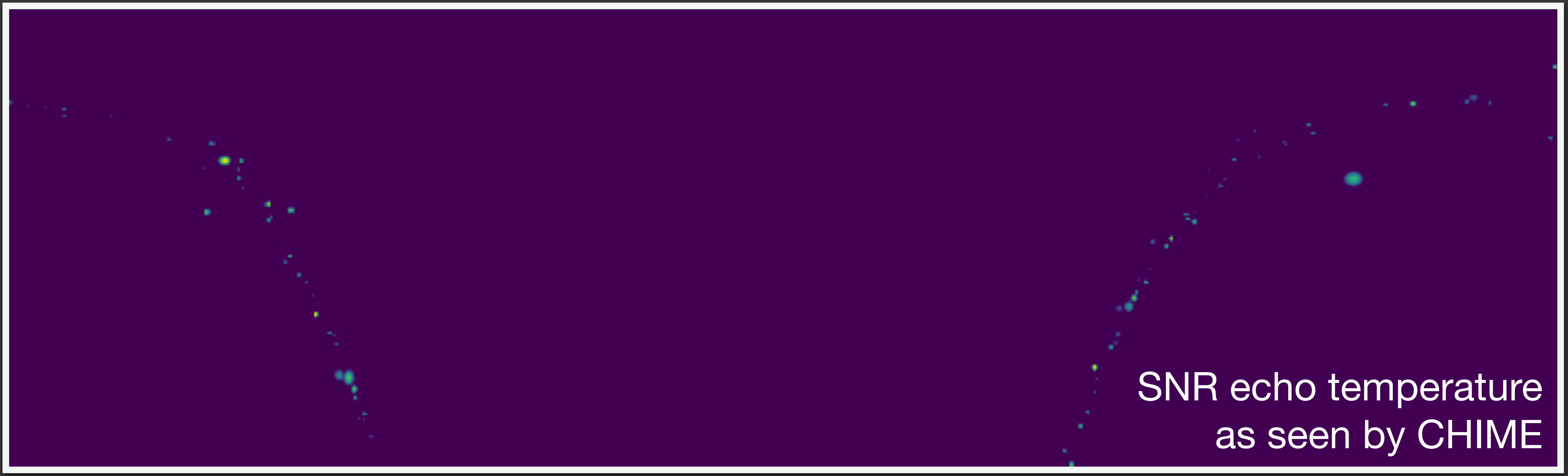
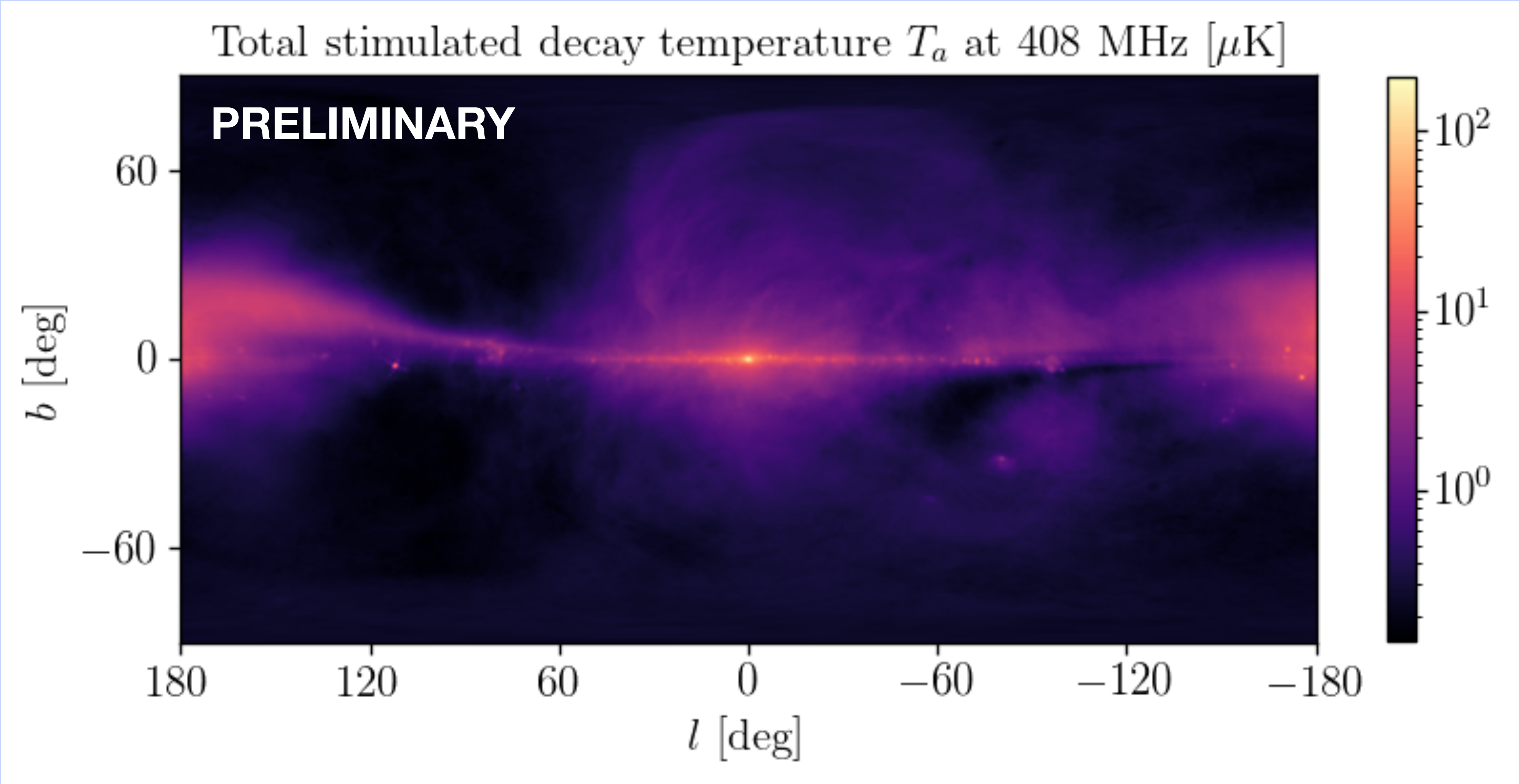
Part II Summary



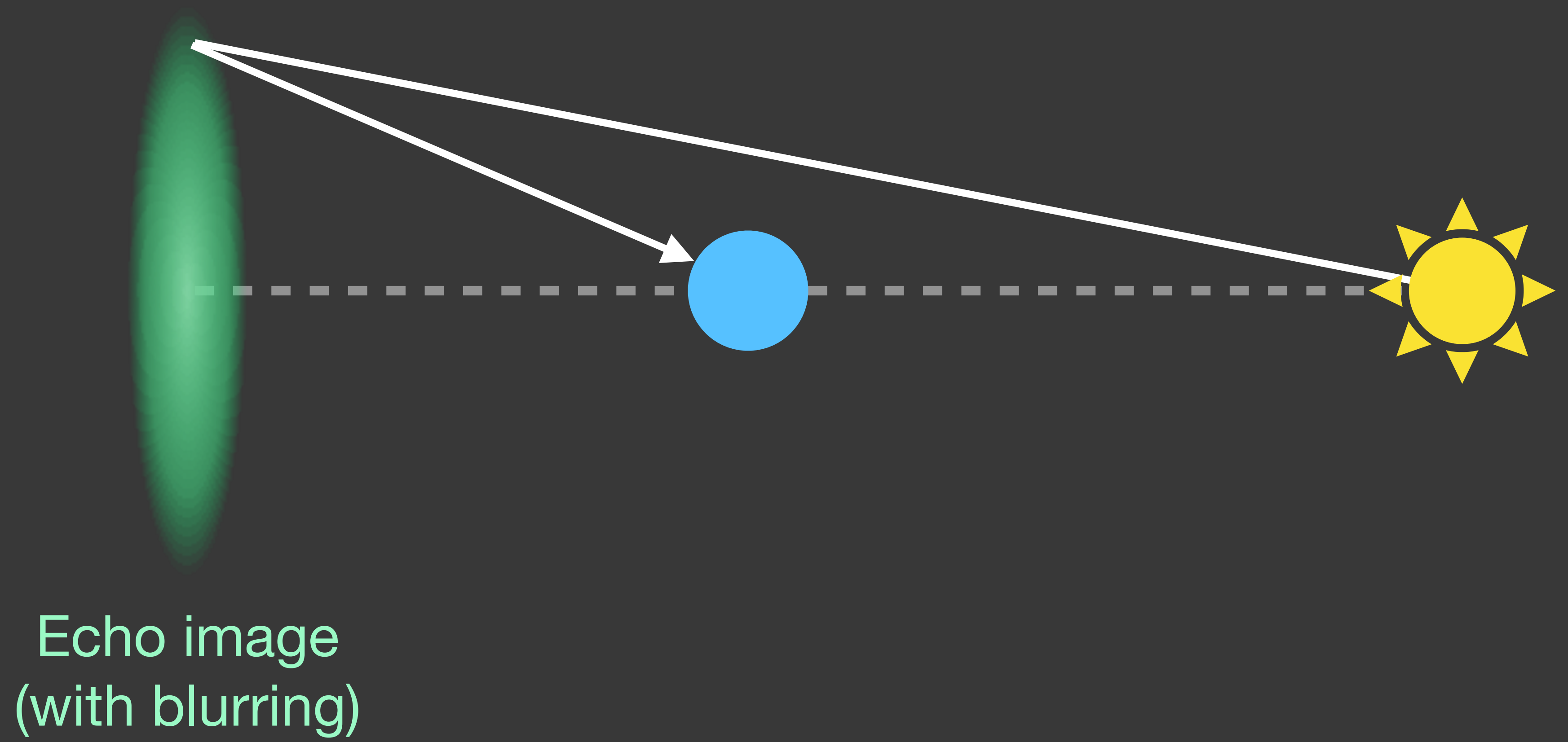
SNRs are optimal sources of stimulating radiation since they were the brightest radio sources at some point within the last light-crossing time of the galactic halo.

Part III: An all-sky analysis of sources

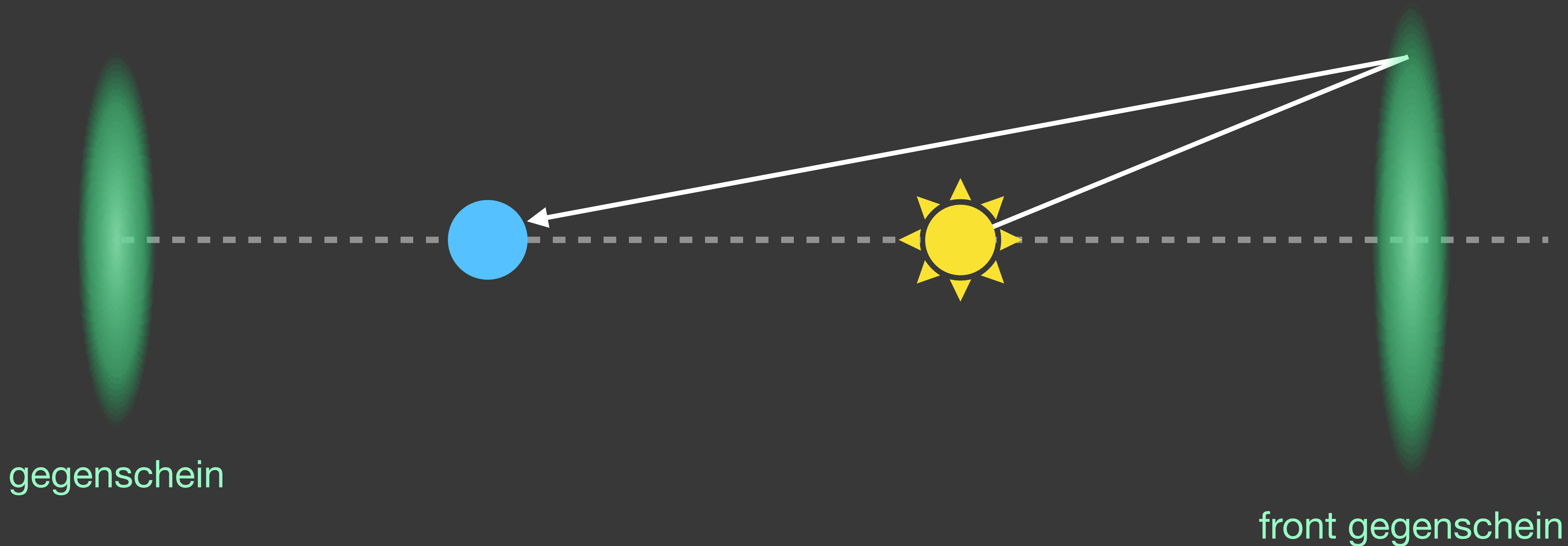
Galactic Synchrotron Radiation (GSR) as a source



Echo (gegenschein)



Echo from behind the source (front gegenschein)



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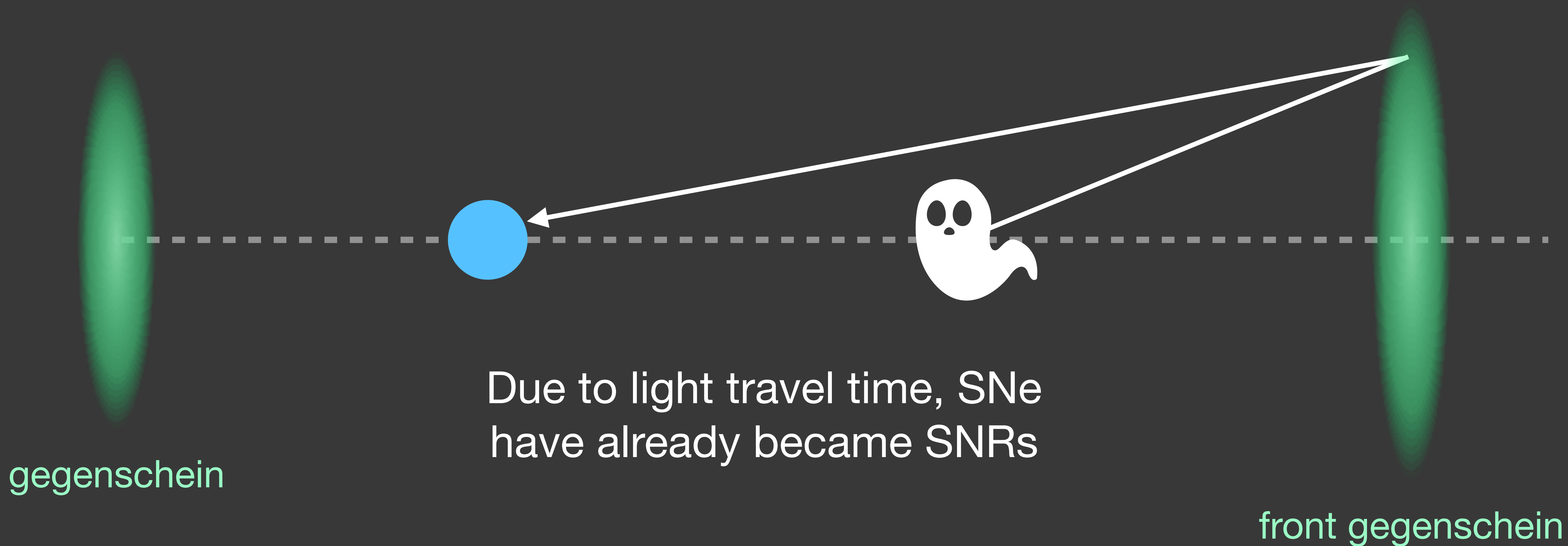
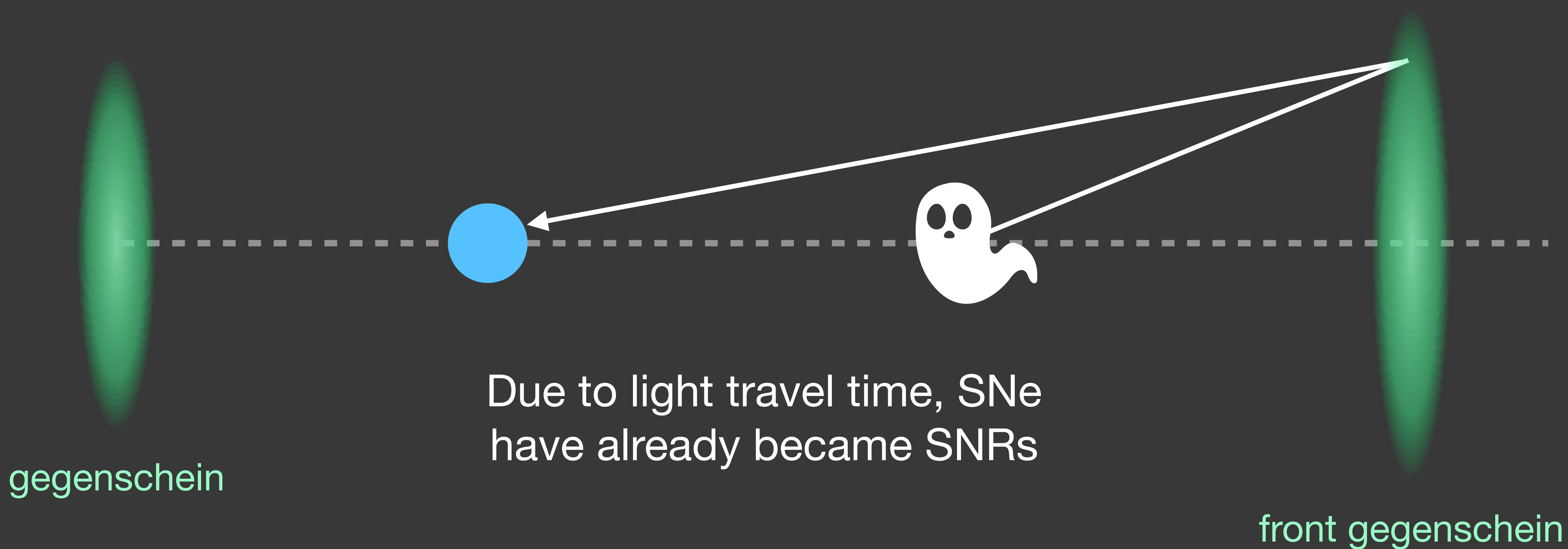


Due to light travel time, SNe have already became SNRs

Echo from behind the source (front gegenschein)



Buen-Abad et al. (2022) discussed constraints from observation from a general SNR: “SNR graveyard”

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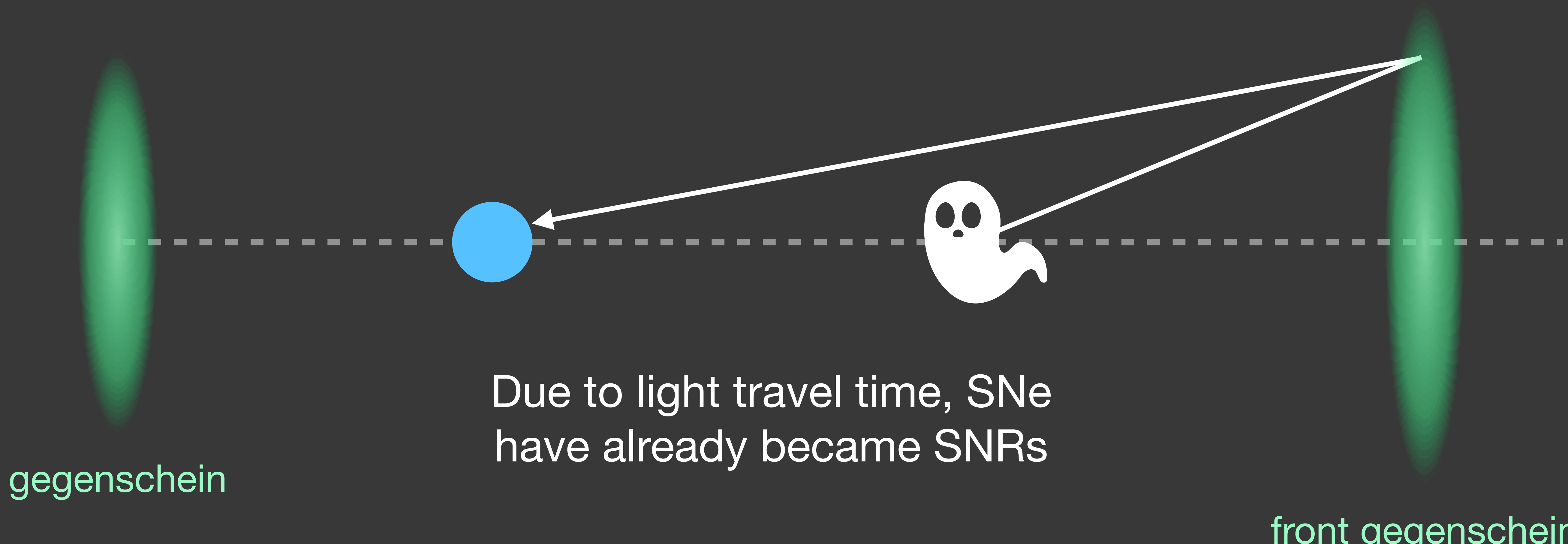

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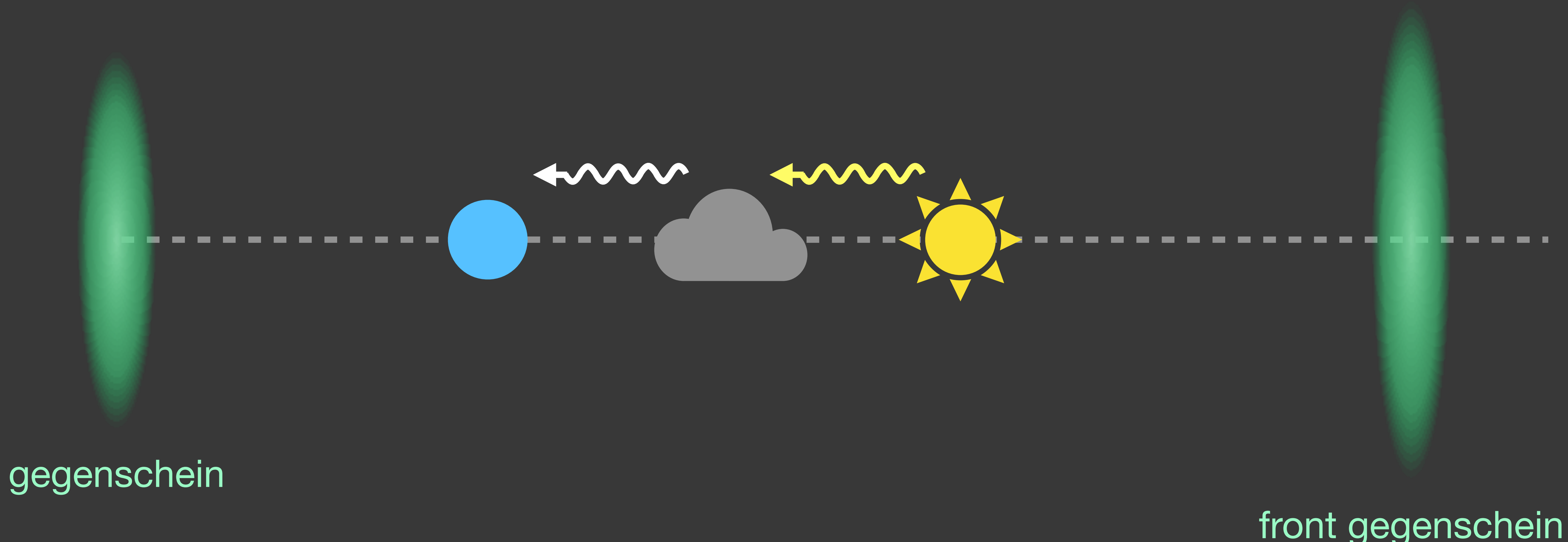
We should include potential unobserved SNRs in our analysis!

There is also the forward decay photon (forwardschein)



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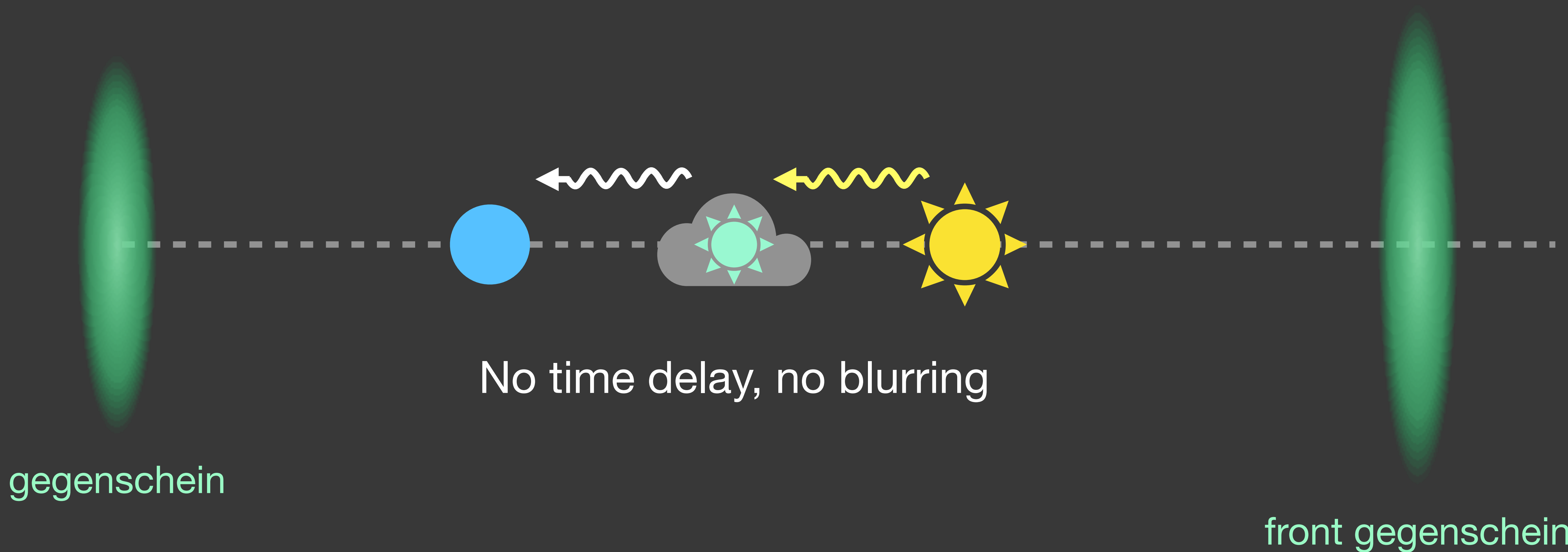

Echoes from unobserved SNRs (graveyard)

We need to sample the SNRs' age, distance, spectral indices, size etc…
Above is some of the realizations.

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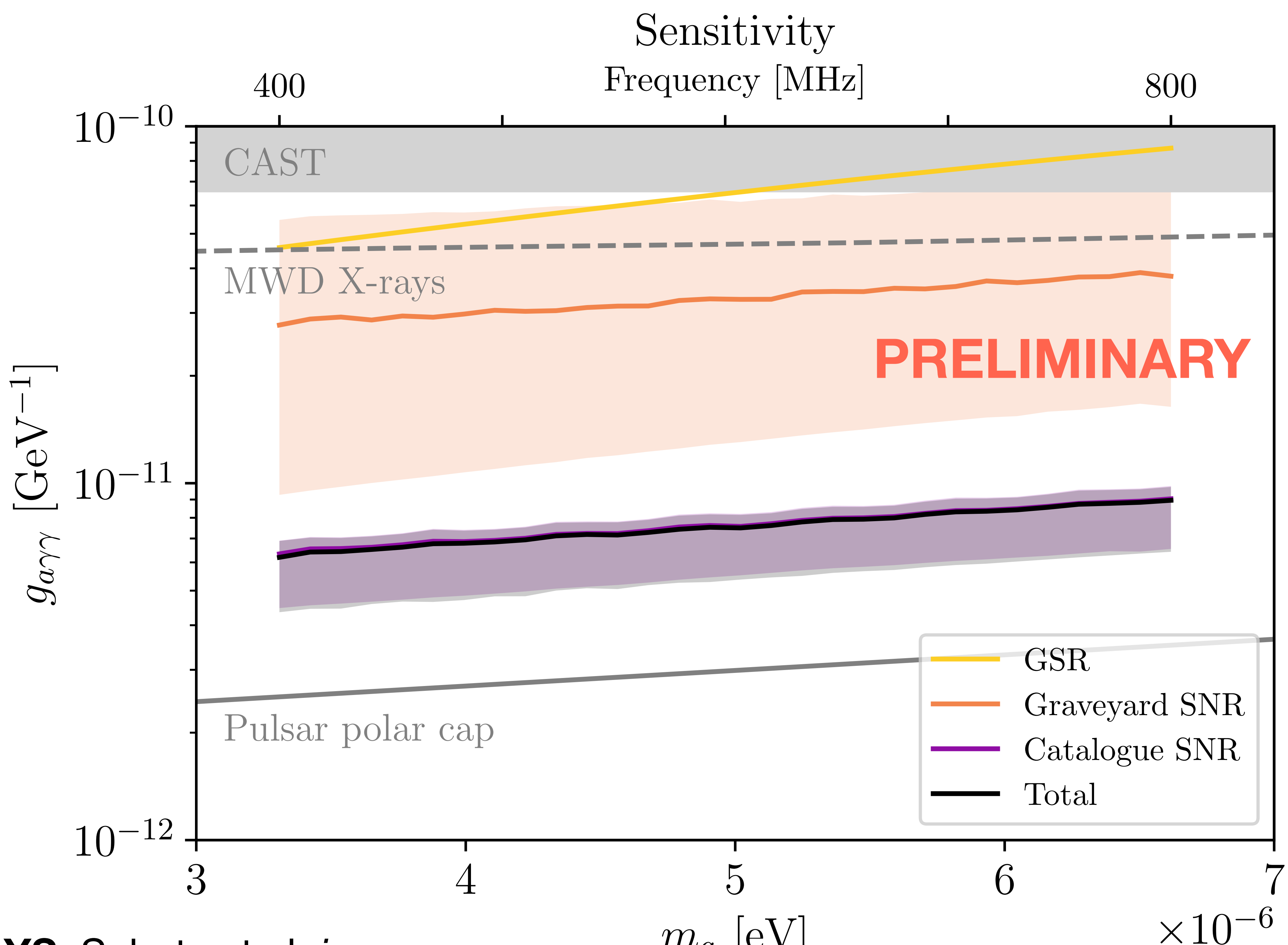
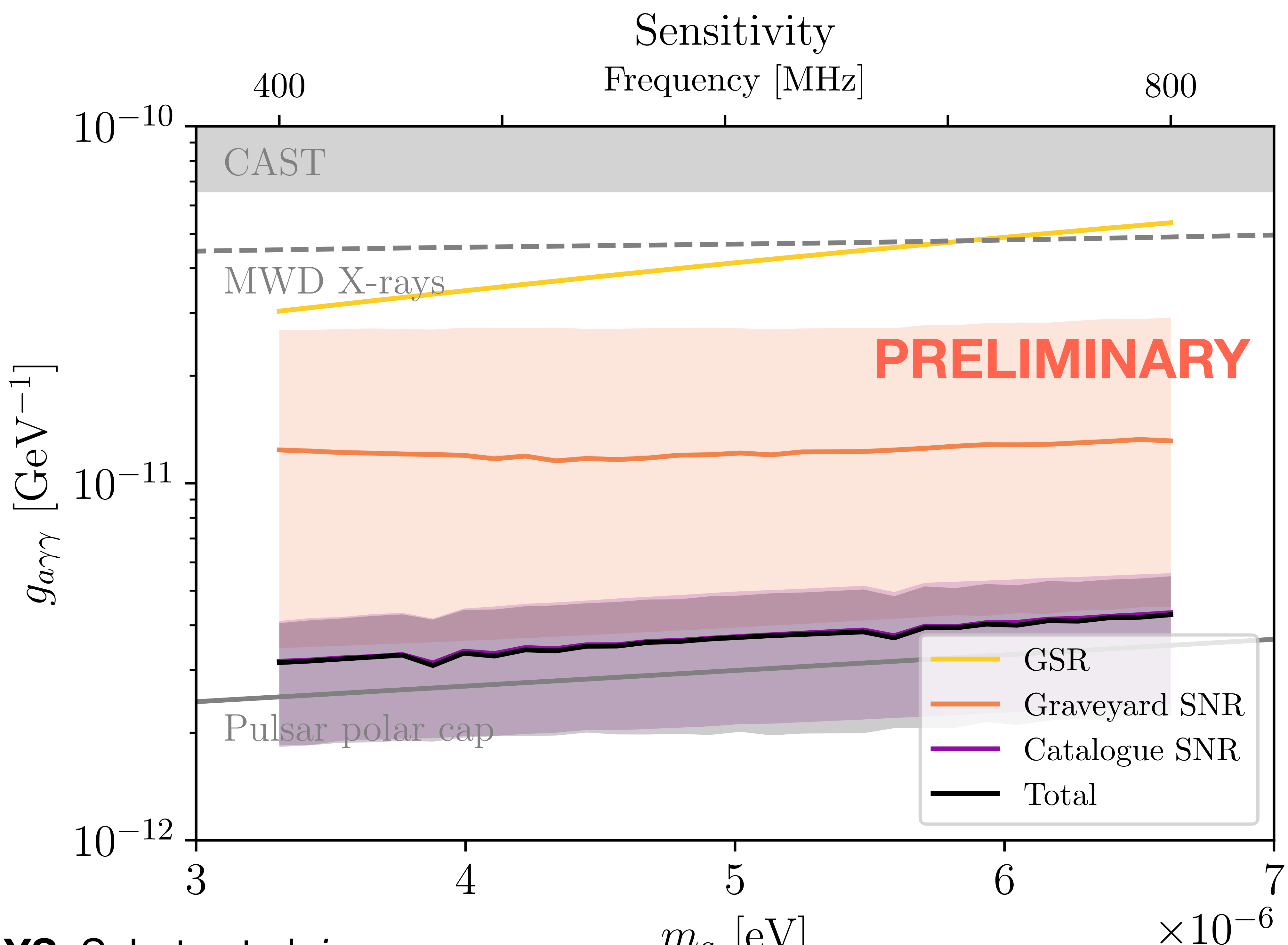
Projection for CHIME archival data (5 years)



YS, Schutz et al. *in prep*

Slightly better with HIRAX-1024 (2 years up time)



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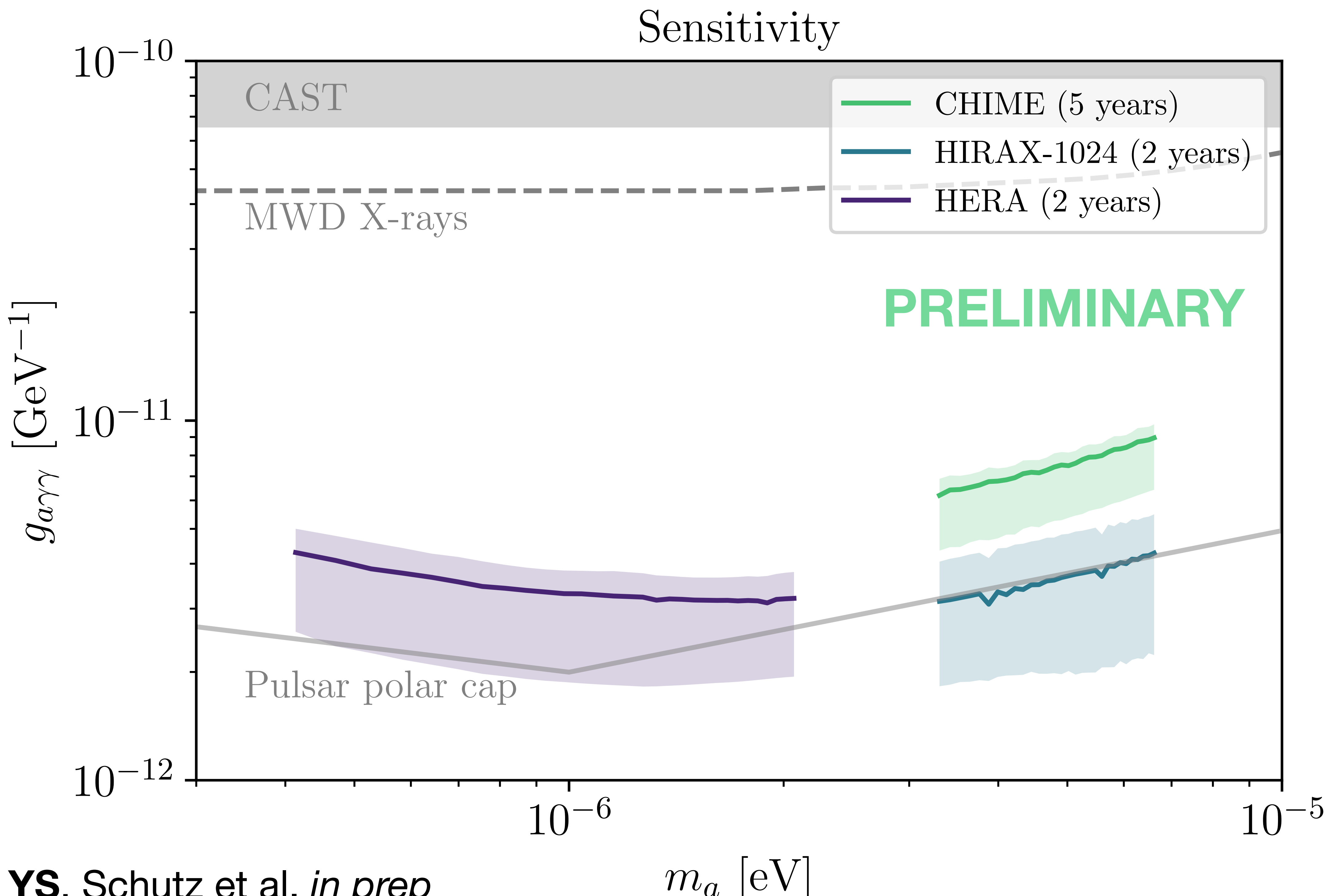
...and (full) HERA



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Thank you!