Title: Axion echos from supernovae remnants

Speakers: JiJi Fan

Series: Particle Physics

Date: February 22, 2022 - 1:00 PM

URL: https://pirsa.org/22020069

Abstract: Stimulated decays of axion dark matter, triggered by a source in the sky, could produce a photon flux along the continuation of the line of sight, pointing backward to the source. The strength of this so-called axion "echo" signal depends on the entire history of the source and could still be strong from sources that are dim today but had a large flux density in the past, such as supernova remnants (SNRs). This echo signal turns out to be most observable in the radio band. I will present the sensitivity of radio telescopes such as the Square Kilometer Array (SKA) to echo signals generated by SNRs that have already been observed. In addition, I will show projections of the detection reach for signals from newly born supernovae that could be detected in the future. Intriguingly, an observable echo signal could come from old "ghost" SNRs which were very bright in the past but are now so dim that they haven't been observed.

Zoom Link: https://pitp.zoom.us/j/91076203387?pwd=UzNva3N4Zi9mV3BkMlJvUnhtRXRZdz09

Axion Echos from Supernovae Remnants

JiJi Fan
Brown University

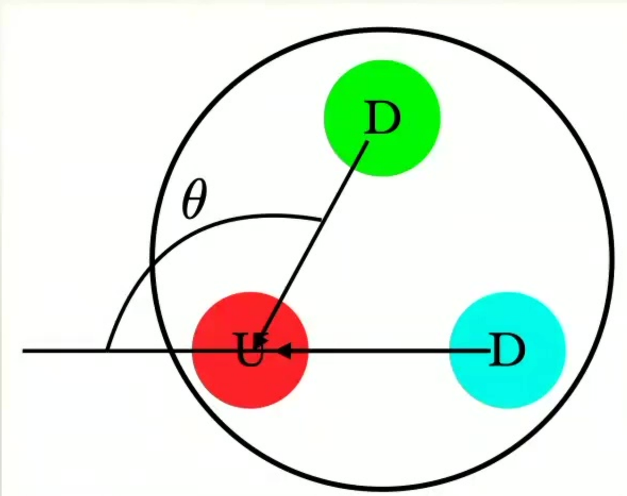
Perimeter Institute, 02/22/2022

What is an axion ?

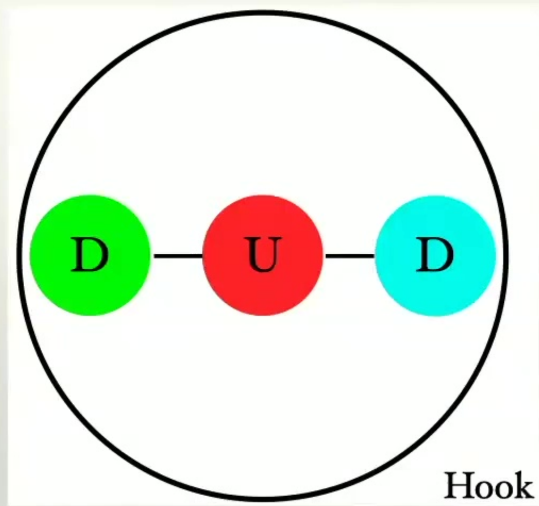
a periodic pseudo-scalar field

$$a \cong a + 2\pi f_a$$

Strong CP problem: QCD axion

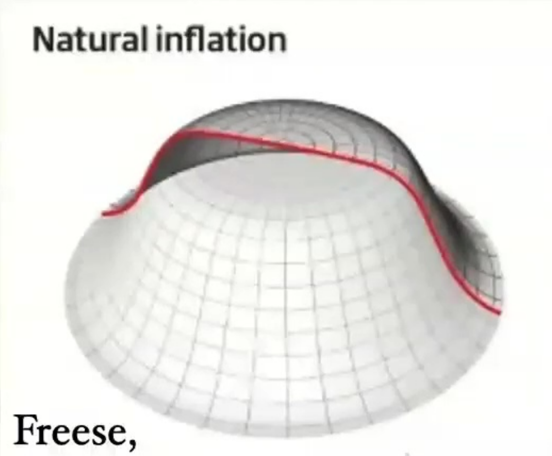


$$\theta \rightarrow a$$

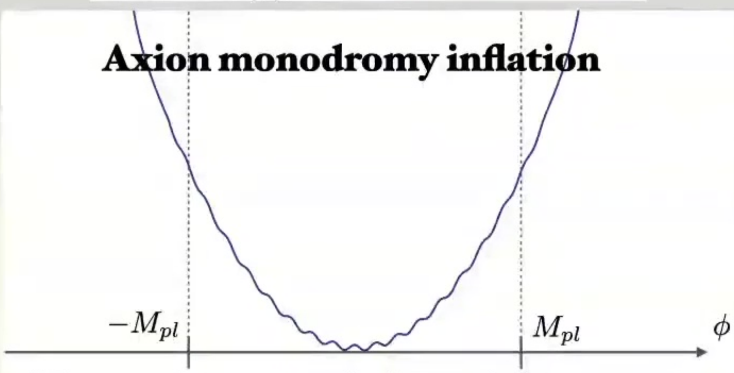


Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki 1977 - 1981

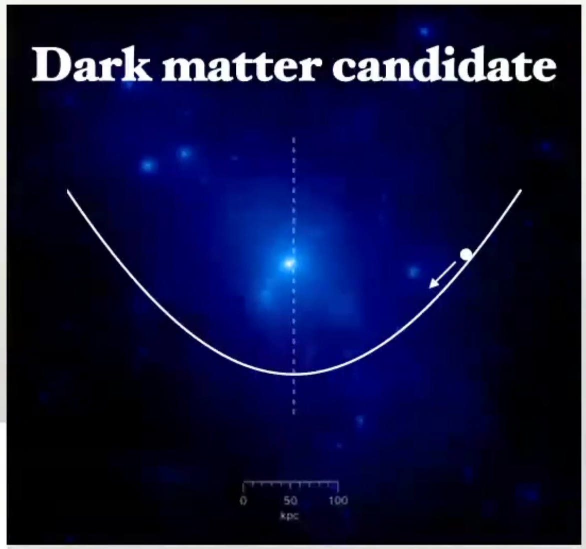
Other applications



Freese,
Frieman,
Olinto 1990

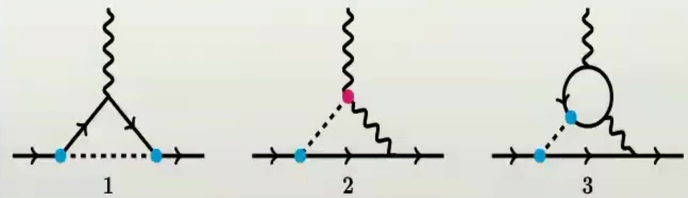


Silverstein, Westphal, McAllister 2008



Preskill, Wise, Wilczek; Dine, Fischler; Abbott, Sikivie 1983

Muon g-2



Marciano, Masiero, Paradisi, Passera 2016; Bauer, Neubert, Thamm 2017; Buen-Abad, Fan, Reece, Sun 2021

Terrestrial Experiments: DM radio, Casper, ABRACADABRA, ADMX...

Model Building:
go beyond vanilla models

Axion (ALP and QCD axion)

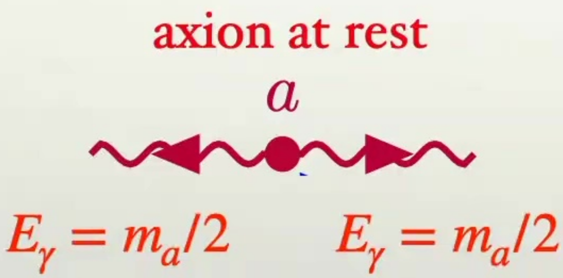
Astrophysical/Cosmic Probes:
CMB, gravitational waves, stars, galaxies....

A new astrophysical probe of couplings of axion DM

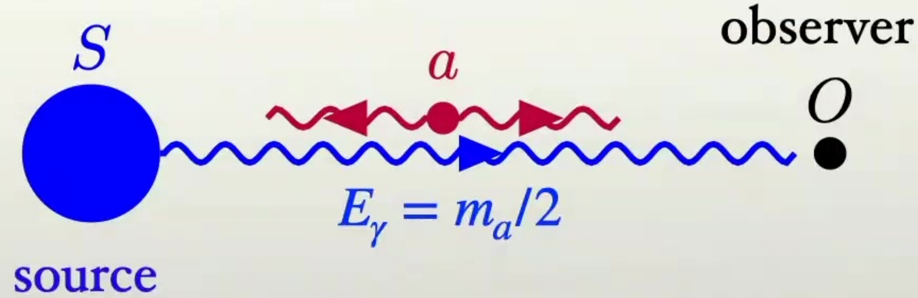
Buen-Abad, Fan, Sun;   Sun, Schutz, Nambrath, Leung, Masui   2021

Axion-photon coupling: $-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

Spontaneous decays



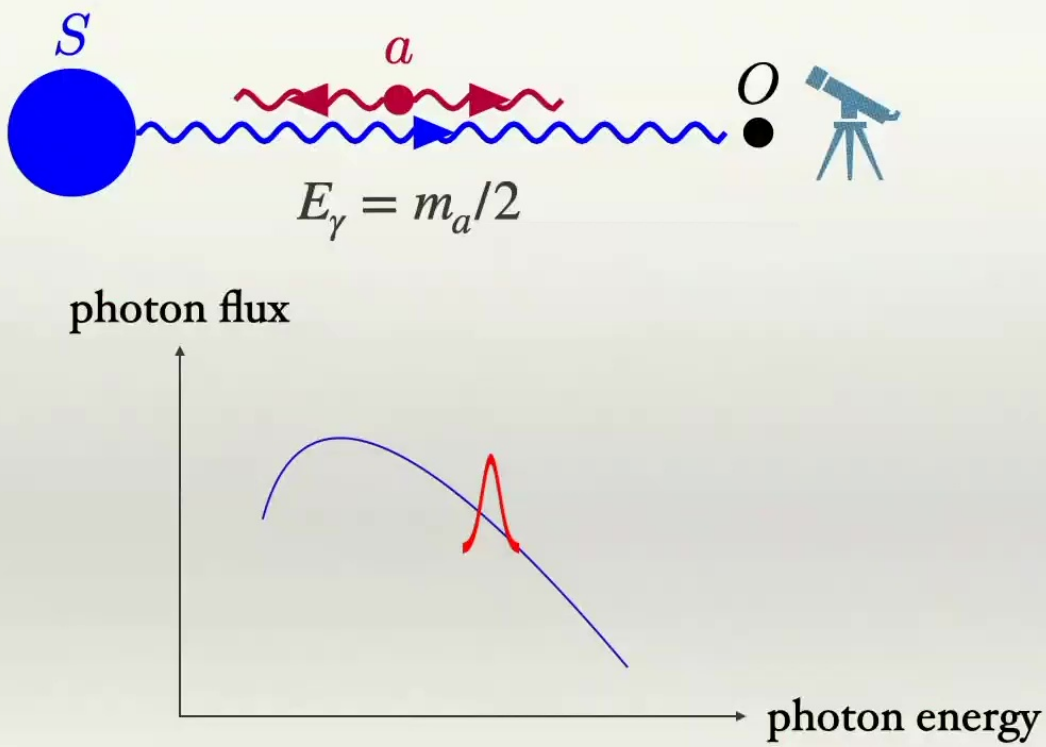
Stimulated decays



Analogous to laser, decay rate enhanced by the large occupation number of the external photon flux.

All wavy lines: photons; red wavy lines: photons from axion decays; blue wavy lines: photons emitted by the source.

Stimulated axion DM decays



Caputo, Regis, Taoso and Witte 2018

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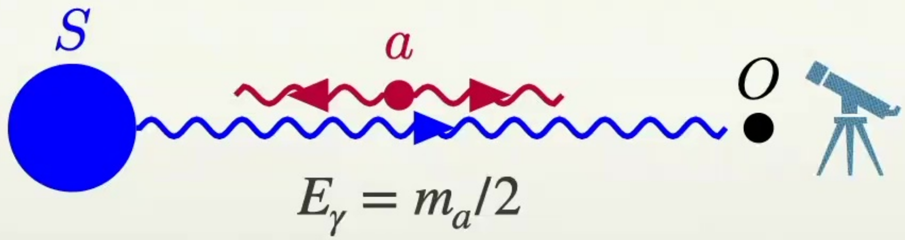

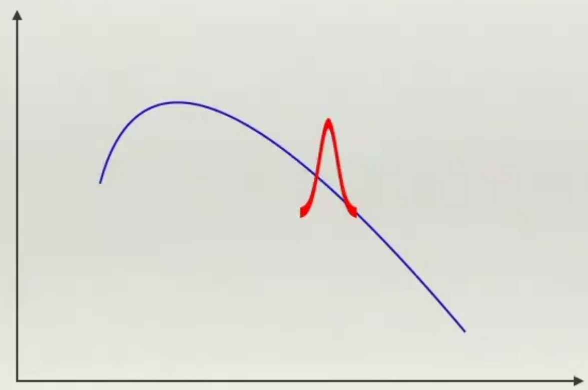

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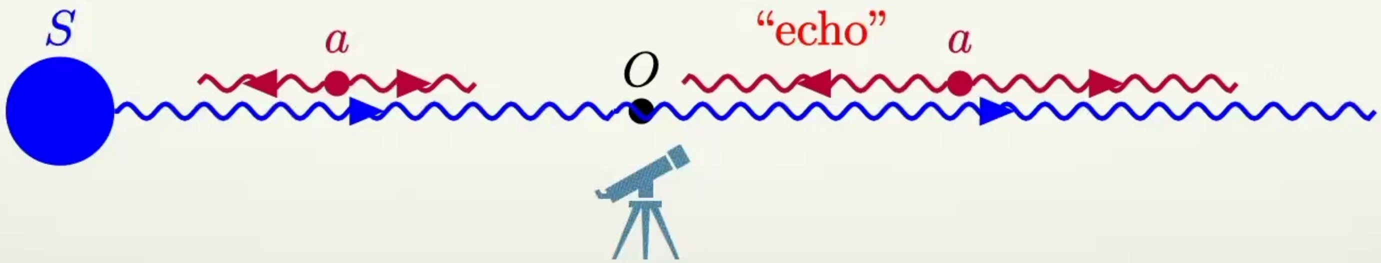
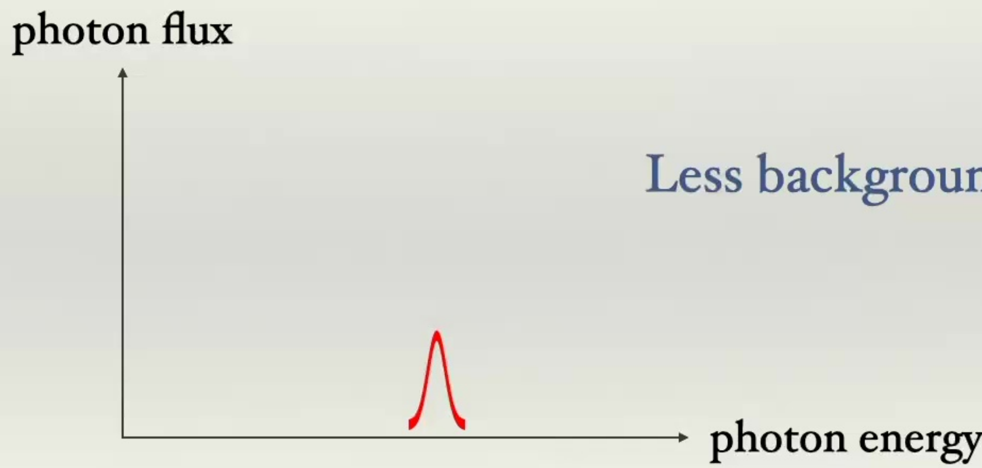
Axion echos

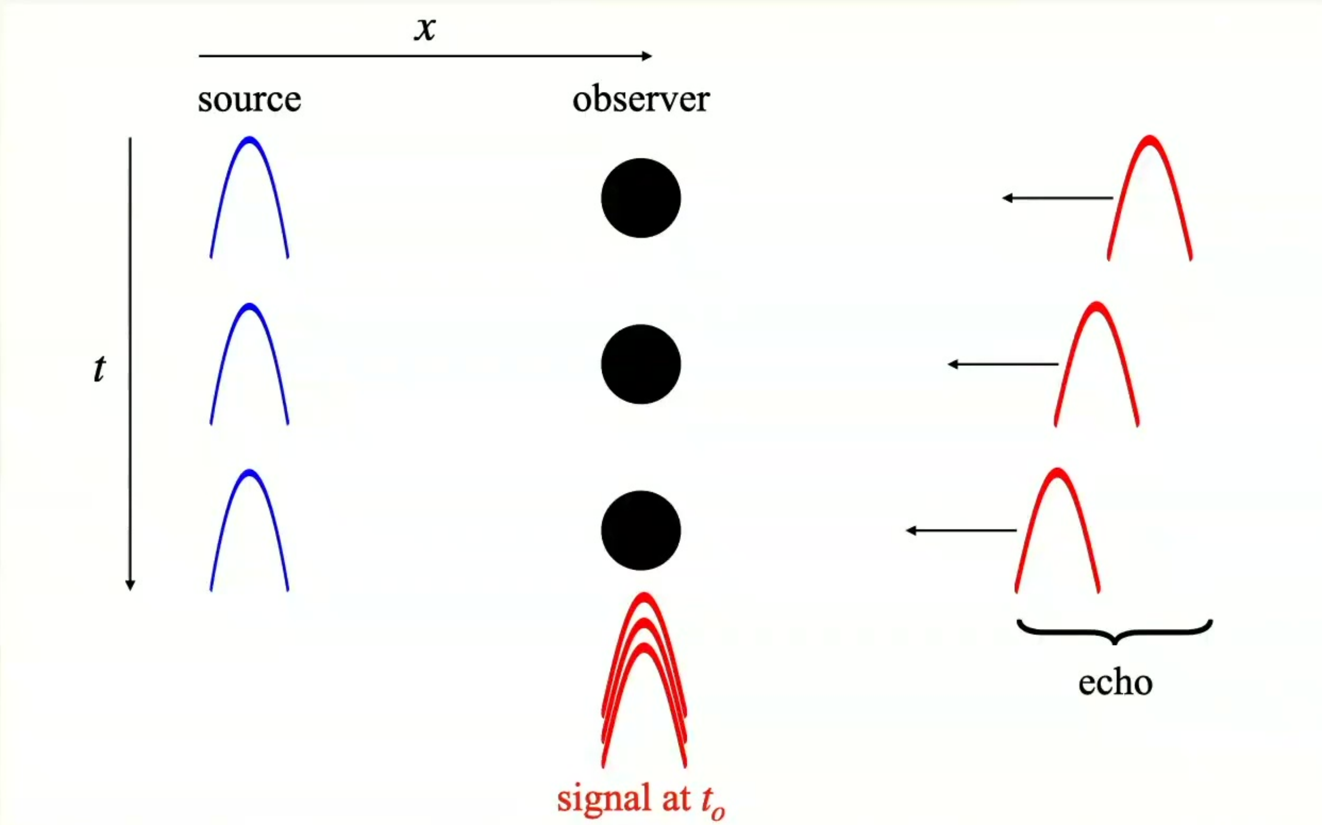


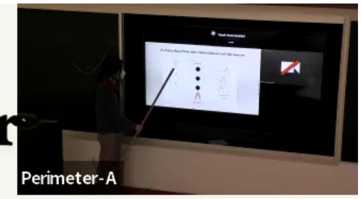


Less background !

Arza, Sikivie 2019 (S: very powerful microwave beam); Ghosh, Salvado and Miralda-Escude 2020 (S: Cygnus A radio galaxy, one of the most powerful constant radio sources in the sky)

Axion echos from the entire history of the sour





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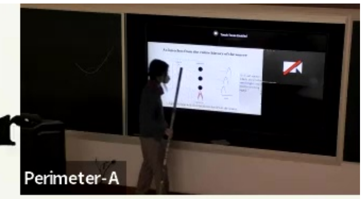
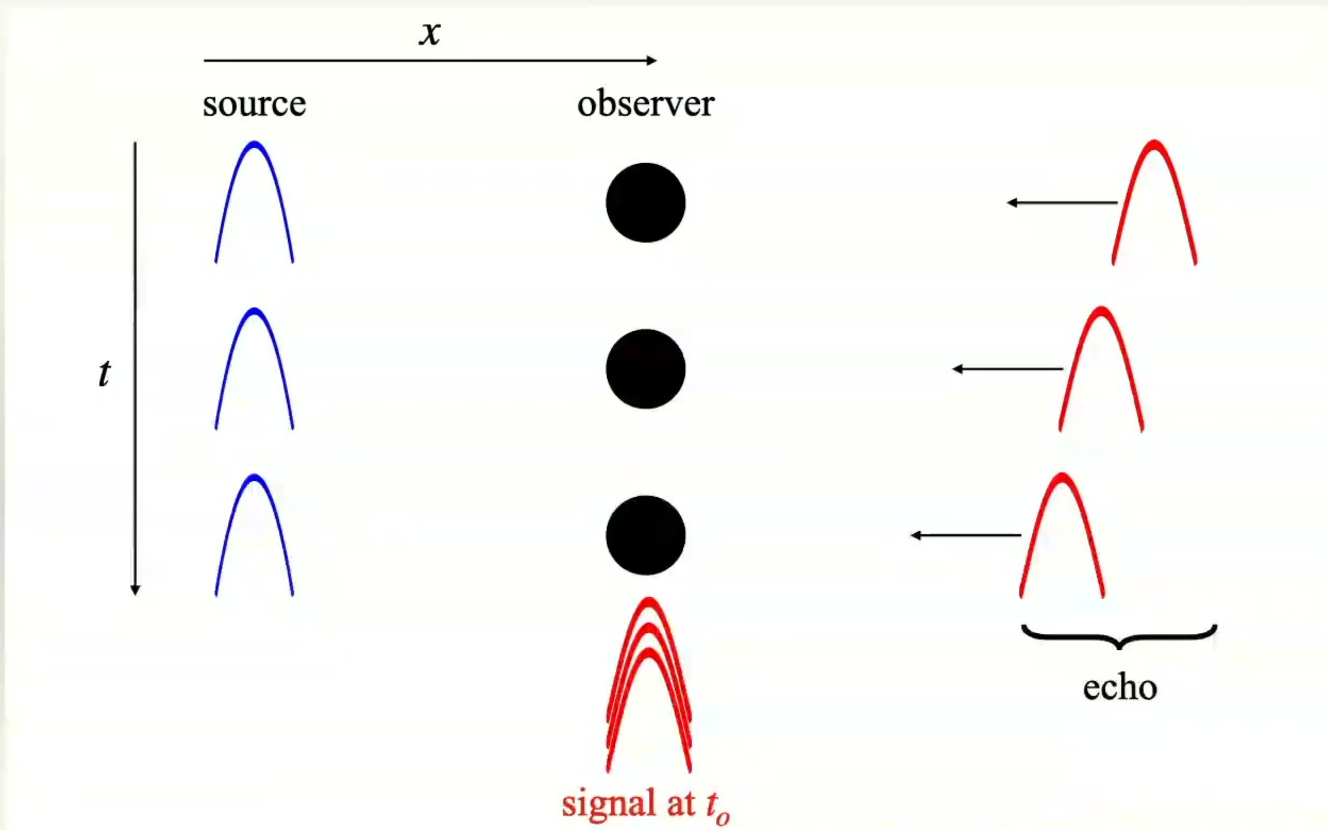
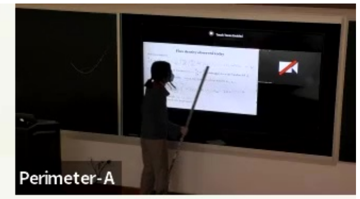




Dim old source which used to be very bright could lead to a strong signal !

Signal is integrated over the entire history of the source



Flux density observed today

Boltzmann equation:

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = C[f_\gamma] \quad C[f_1] = \frac{1}{2E_1}\int \frac{\mathrm{DP}_a}{2E_a}\int \frac{\mathrm{DP}_2}{2E_2}\, |\overline{\mathcal{M}}|^2 \left(f_a(1+f_1+f_2) - f_1 f_2\right) (2\pi)^4 \delta^4(p_a - p_1 - p_2)$$

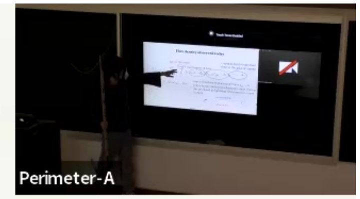
⇒ Echo flux density at frequency $\nu_a = \frac{E_a}{2\pi} = \frac{m_a}{4\pi}$, averaged over the bandwidth Δ_ν

fraction of signal within bandwidth

axion spontaneous decay width (m_a , $g_{a\gamma\gamma}$)

$$\overline{S}_{\nu_a,\mathrm{e}} = f_\Delta \frac{\pi \Gamma_a}{2E_a^3 \Delta\nu} \int_0^{t_{\mathrm{age}}/2} \mathrm{d}x\ \rho_a(x, -\hat{\mathbf{n}}_*)\ S_{\nu_a,\mathrm{s}}(t_{\mathrm{age}} - 2x)\ \mathrm{e}^{-\tau(\nu, x, -\hat{\mathbf{n}}_*)}$$

bandwidth $\Delta_\nu \sim \nu_a\, \sigma_v$ (σ_v : DM velocity dispersion)



Flux density observed today

age of the source

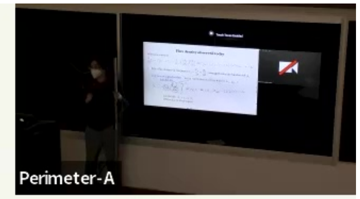
dark matter density

τ: optical depth (important close to the galactic center)

$$\overline{S}_{\nu_a,\mathrm{e}} = f_\Delta \frac{\pi \Gamma_a}{2E_a^3 \Delta\nu} \int_0^{t_{\mathrm{age}}/2} \mathrm{d}x\, \rho_a(x, -\hat{\mathbf{n}}_*)\, S_{\nu_a,\mathrm{s}}(t_{\mathrm{age}} - 2x)\, \mathrm{e}^{-\tau(\nu, x, -\hat{\mathbf{n}}_*)}$$

$t_{\mathrm{age}} \sim (10^4 - 10^5)$ years $\Rightarrow x_{\mathrm{max}} \sim 10\,\mathrm{kpc}$

source flux density at an earlier time $t_{\mathrm{age}} - 2x$: echo photon emitted at a distance x away from us was produced by light that first passed us a time $2x$ away.



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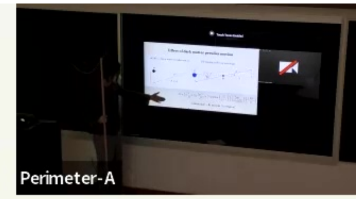
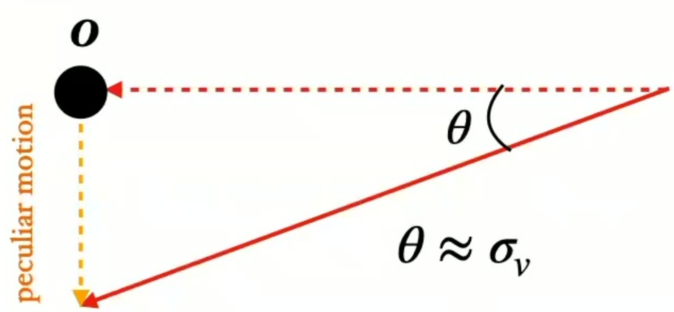
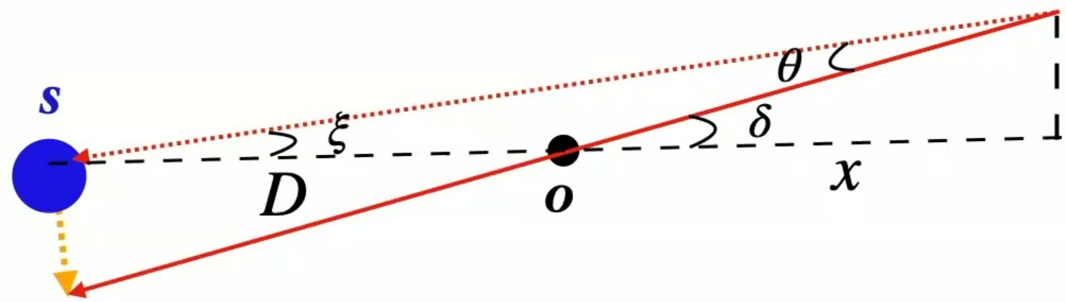


Effect of dark matter peculiar motion

a) Effect of dark matter peculiar motion

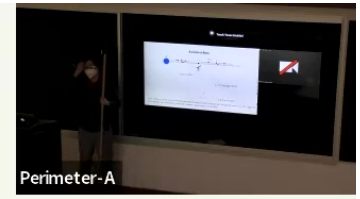


b) Enlarging collecting solid angle

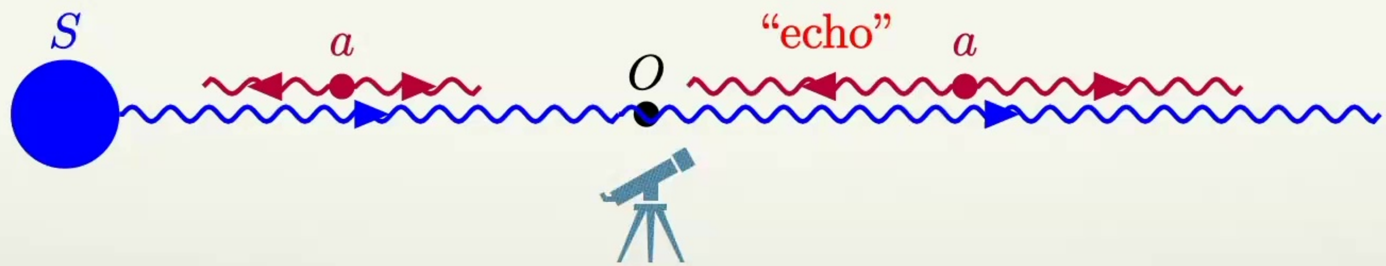


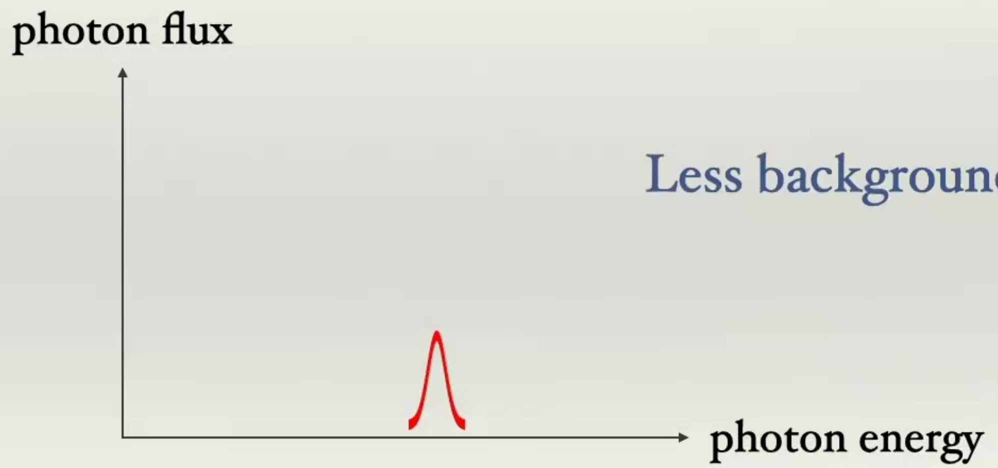
$$2\delta \approx 2\sigma_v \frac{x}{D} \approx 2\sigma_v \frac{t_{\rm age}/2}{D} \approx 10\,\text{arcmin}\left(\frac{\sigma_v}{10^{-3}}\right)\left(\frac{t_{\rm age}}{10^4\,\text{years}}\right)\left(\frac{1\,\text{kpc}}{D}\right)$$

source size: ~ 85 arcmin (1.7 degree)



Axion echos





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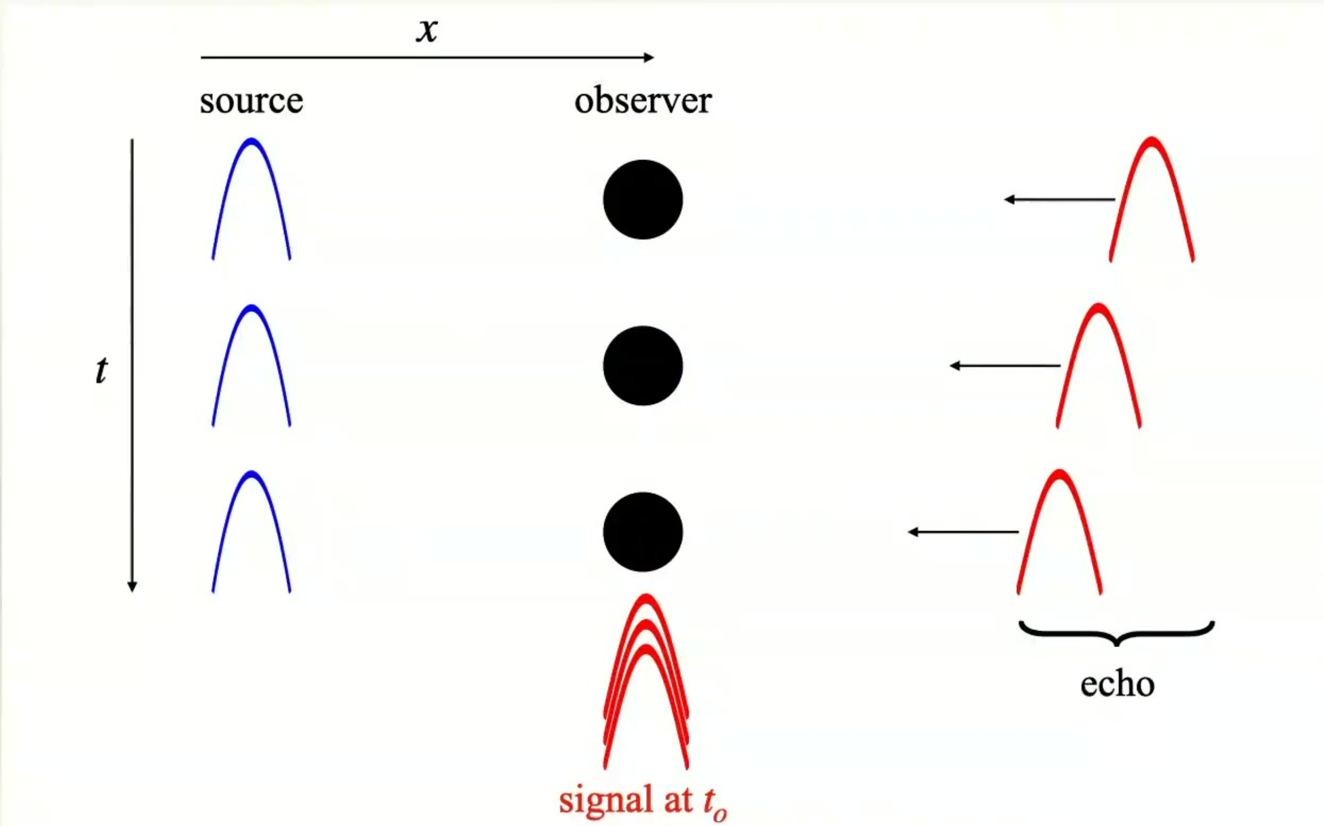

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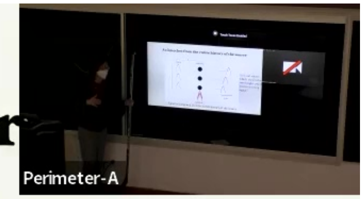
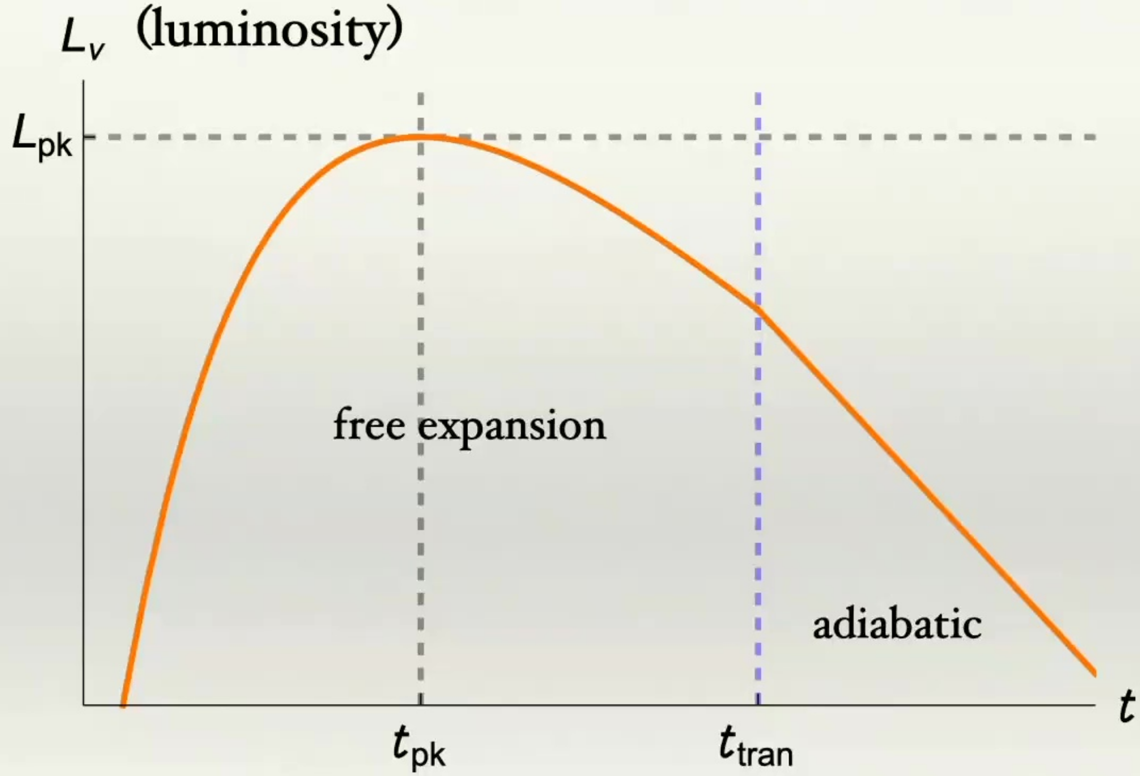
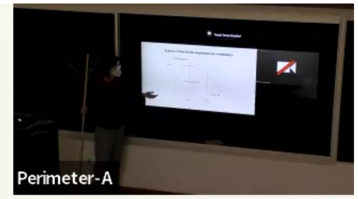



Supernova: powerful stellar explosion
SN2016aps
M.Weiss
Perimeter-A

Axion echos from supernovae remnants





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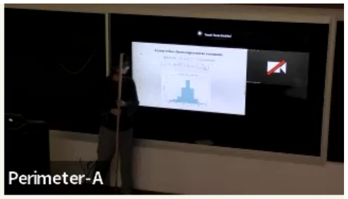
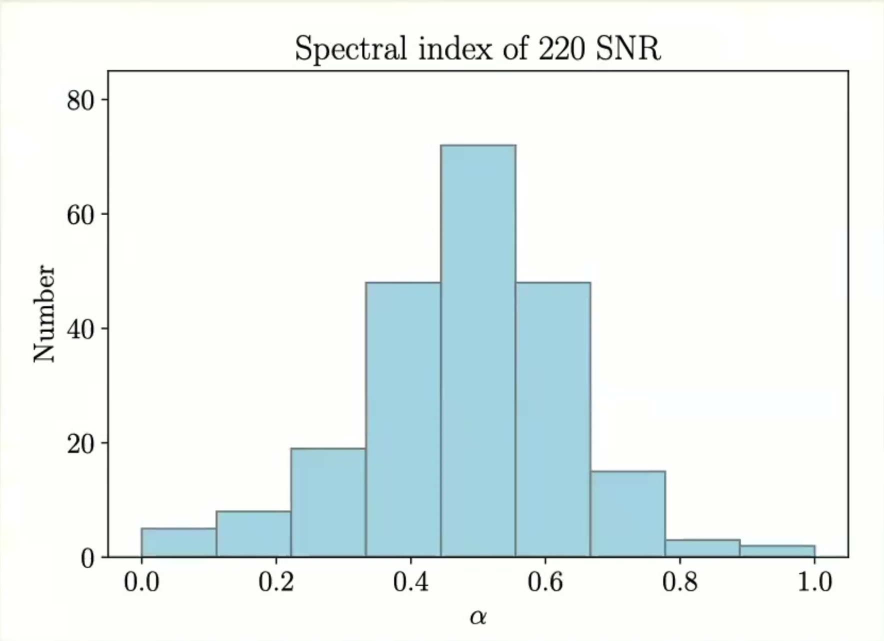
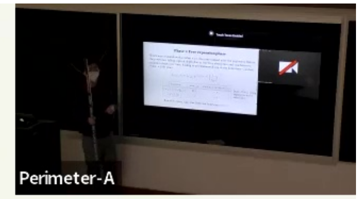


Spectrum: $S_\nu \propto E_\gamma^{-\alpha}$ α: spectral index

$$L_\nu = S_\nu\,(4\pi D^2) = L_{1\mathrm{GHz}}\left(\frac{\nu}{1\ \mathrm{GHz}}\right)^{-\alpha}$$





Phase 1: Free expansion phase

Shock wave expands with a radius $r \propto t$, the time elapsed after the explosion. Before the power law falling, optical depth due to free-free absorption and synchrotron radiation drops over time, leading to an exponential rise in the luminosity. Can last $\mathcal{O}(\text{few} \times 100)$ years.

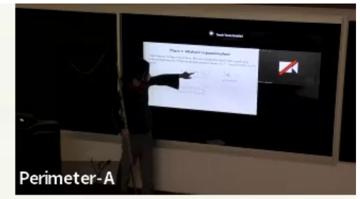
$$L_{\nu,\mathrm{free}}(t) \equiv L_{\nu,\mathrm{pk}}\ e^{\frac{3}{2}(1-t_{\mathrm{pk}}/t)} \left(\frac{t}{t_{\mathrm{pk}}}\right)^{-1.5}$$

Parameter	mean (μ)	standard deviation (σ)
$\log_{10}\left(\frac{L_{\nu,\mathrm{pk}}}{\mathrm{erg\ s^{-1}\ Hz^{-1}}}\right)$	25.5	1.5
$\log_{10}\left(\frac{t_{\mathrm{pk}}}{\mathrm{days}}\right)$	1.7	0.9

from ~ O(100) young supernovae in the radio band

Bietenholz, Bartel, Argo, Dua, Ryder and Soderberg 2011.11737

Phase 2: Adiabatic expansion phase



Approximate energy conservation. Pressure behind the shock waves push away surrounding material. Hydrodynamical estimates show $r \propto t^{2/5}$. Can last $\mathcal{O}(\text{few} \times 10^4)$ years.

$$L_{\nu,\mathrm{ad}}(t) \equiv L_{\nu,\mathrm{tran}} \left(\frac{t}{t_{\mathrm{tran}}}\right)^{-\gamma}$$

$$L_{\nu,\mathrm{tran}} \equiv L_{\nu,\mathrm{free}}(t_{\mathrm{tran}}) \ ,$$

$$\gamma = \frac{4}{5}(2\alpha + 1) > 0$$

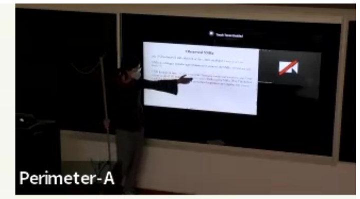
spectral index

Or

$$L_{\nu,\mathrm{ad}}(t) \equiv L_{\nu,0} \left(\frac{t}{t_{\mathrm{age}}}\right)^{-\gamma} \ ,$$

$$L_{\nu,\mathrm{ad}}(t_{\mathrm{tran}}) = L_{\nu,\mathrm{free}}(t_{\mathrm{tran}}) \ .$$

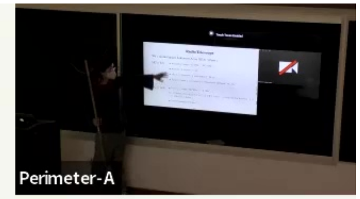
Observed SNRs



294 SNRs observed and collected in the Green catalogue. Green 2014-2019

SNRcat catalogue includes age estimates for some of the SNRs. Ferrand and Safi-Harb 2012

SNR formation rate: ~ 0.02 - 0.03/ year (Tammann, Loeffler and Schroeder 1994). Over a time scale of 10^5 years, about 2000 - 3000 SNRs in the Milky Way. The deficit could be due to selection criteria on surface brightness and angular size (Green, 2005 - 2019).



Radio Telescope

We consider Square Kilometer Array (SKA) - phase 1.

SKA1-low:

- frequency range: 50 MHz – 350 MHz;
- number of stations: 512;
- effective diameter of each station: 38 m;
- longest baseline (separation between two stations): 80 km,

SKA1-mid:

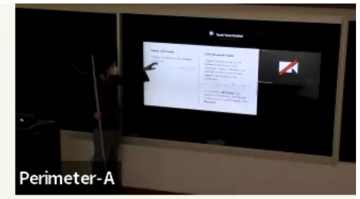
- frequency range: 350 MHz – 15.4 GHz;
- 133 dishes with a diameter of 15 m (SKA dishes), 64 dishes with a diameter of 13.5 m (MeerKAT dishes);
- longest baseline: 150 km.

Single-dish mode

Angular resolution set by *diameter* of the dish:

$$\theta_{\rm res} = 1.22\left(\frac{\lambda}{d}\right)\,\text{rad} \approx 1.4^\circ\left(\frac{\text{GHz}}{\nu}\right)\left(\frac{15\text{ m}}{d}\right)$$

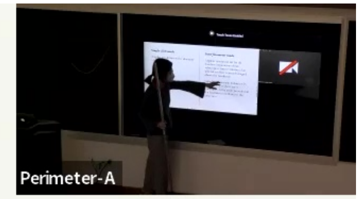
Interferometer mode



Angular resolution set by the *baseline* (separation of two telescopes): finer resolution; but will fail to detect an extended signal with size above the resolution.

$$\theta_b = \left(\frac{\lambda}{B}\right)\,\text{rad} = 0.17^\circ\left(\frac{\text{GHz}}{\nu}\right)\left(\frac{100\text{ m}}{B}\right)$$

As frequency ***increases***, the number of baselines contributing to detection of a given signal could ***decrease***!



Single-dish mode

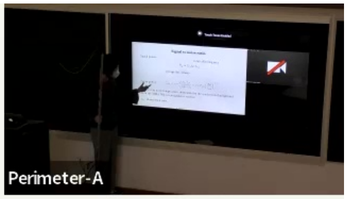
Angular resolution set by diameter of the dish;

Signal to noise ratio enhanced by $\sqrt{N}$ if there are N single dishes.

Interferometer mode

Angular resolution set by the baseline (separation of two telescopes): finer resolution; but will fail to detect extended signal above the resolution.

Signal to noise ratio enhanced by $\sqrt{N(N-1)/2}$ if there are N telescopes in the array, provided all the baselines contribute to the detection.



Signal to noise ratio

Signal power:

total collecting area

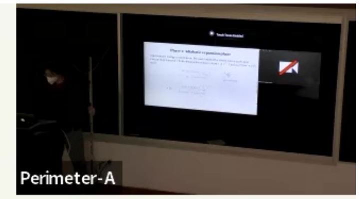
$$P_{\rm sig} \propto \bar{S}_{\nu,e} \Delta\nu \, A_{\rm tot}$$

average flux density

Noise power:
$$P_{\rm noi,\,unit} = \frac{2\,T_{\rm sys}\Delta\nu}{\sqrt{2\Delta\nu\,t_{\rm obs}}} = \sqrt{2}\,T_{\rm sys}\left(\frac{\Delta\nu}{t_{\rm obs}}\right)^{1/2} .$$

$T_{\rm sys}$: system noise temperature, dominated by the synchrotron background from the Milky Way or extragalactic sources

$t_{\rm obs}$: observation time.



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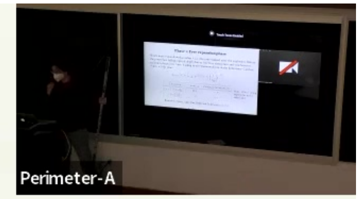

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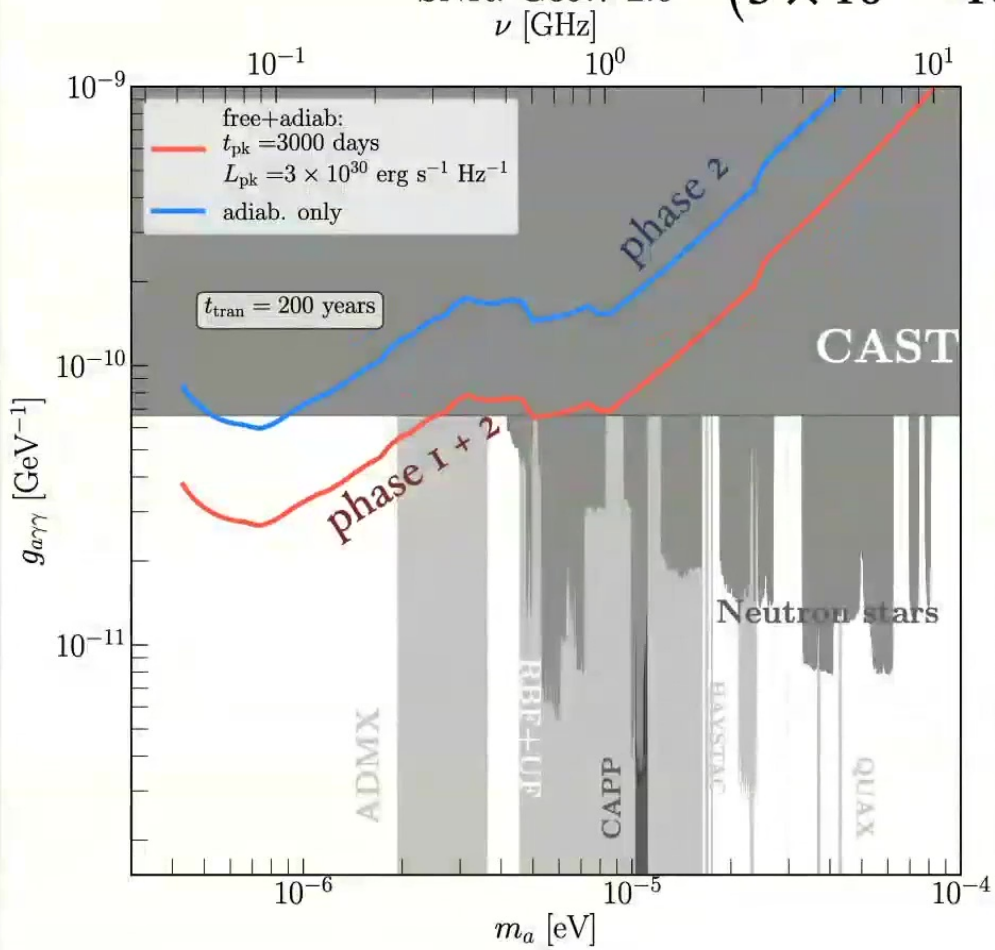
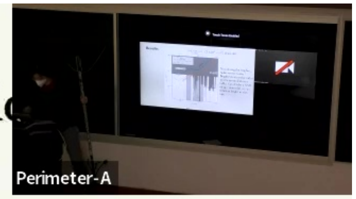
Bietenholz, Bartel, Argo, Dua, Ryder and Soderberg 2011.11737

Results

SNR: G39.7-2.0 $(3 \times 10^4 - 10^5)$ years old

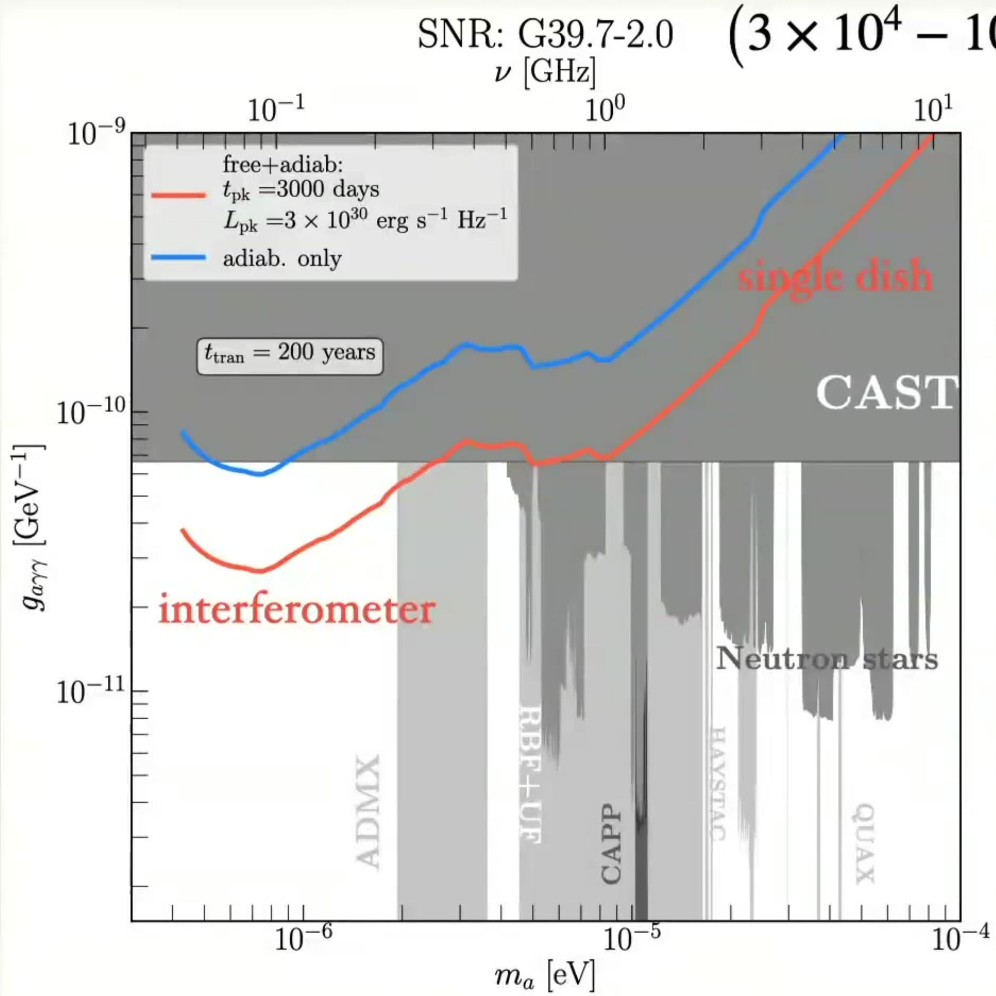


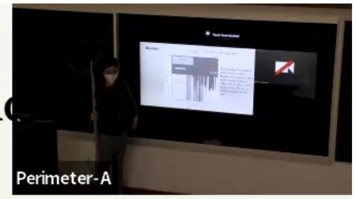


Not among the brightest radio source today ! Brightest extrasolar radio source around/above 1 GHz, Cas A (also a SNR of 340 years old), is ~ 30 times as bright as this one.

Results

$(3 \times 10^4 - 10^5)$ years ol





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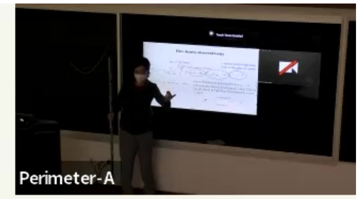


Flux density observed today

age of the source

dark matter density

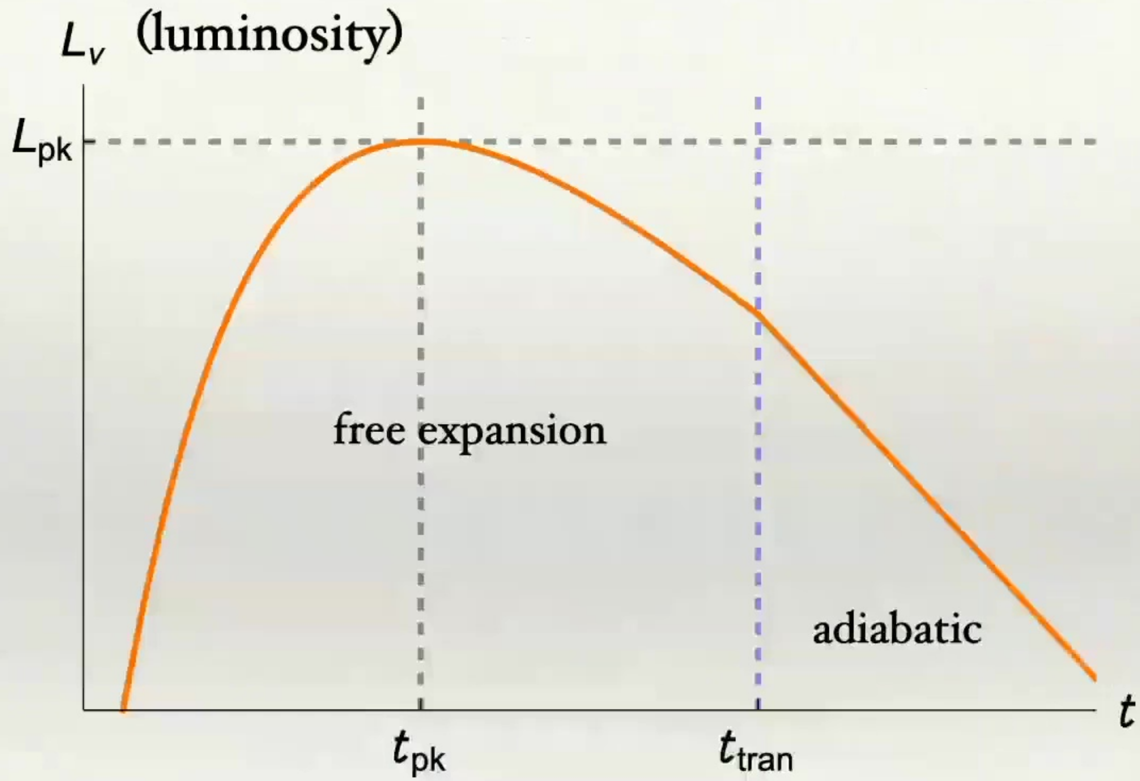
τ: optical depth (important close to the galactic center)

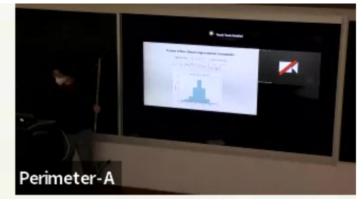
$$\overline{S}_{\nu_a,\mathrm{e}} = f_\Delta \frac{\pi \Gamma_a}{2E_a^3 \Delta\nu} \int_0^{t_{\mathrm{age}}/2} \mathrm{d}x\, \rho_a(x, -\hat{\mathbf{n}}_*)\, S_{\nu_a,\mathrm{s}}(t_{\mathrm{age}} - 2x)\, \mathrm{e}^{-\tau(\nu, x, -\hat{\mathbf{n}}_*)}$$

$t_{\mathrm{age}} \sim (10^4 - 10^5)$ years $\Rightarrow x_{\mathrm{max}} \sim 10\,\mathrm{kpc}$

source flux density at an earlier time $t_{\mathrm{age}} - 2x$: echo photon emitted at a distance x away from us was produced by light that first passed us a time $2x$ away.

Axion echos from supernovae remnants





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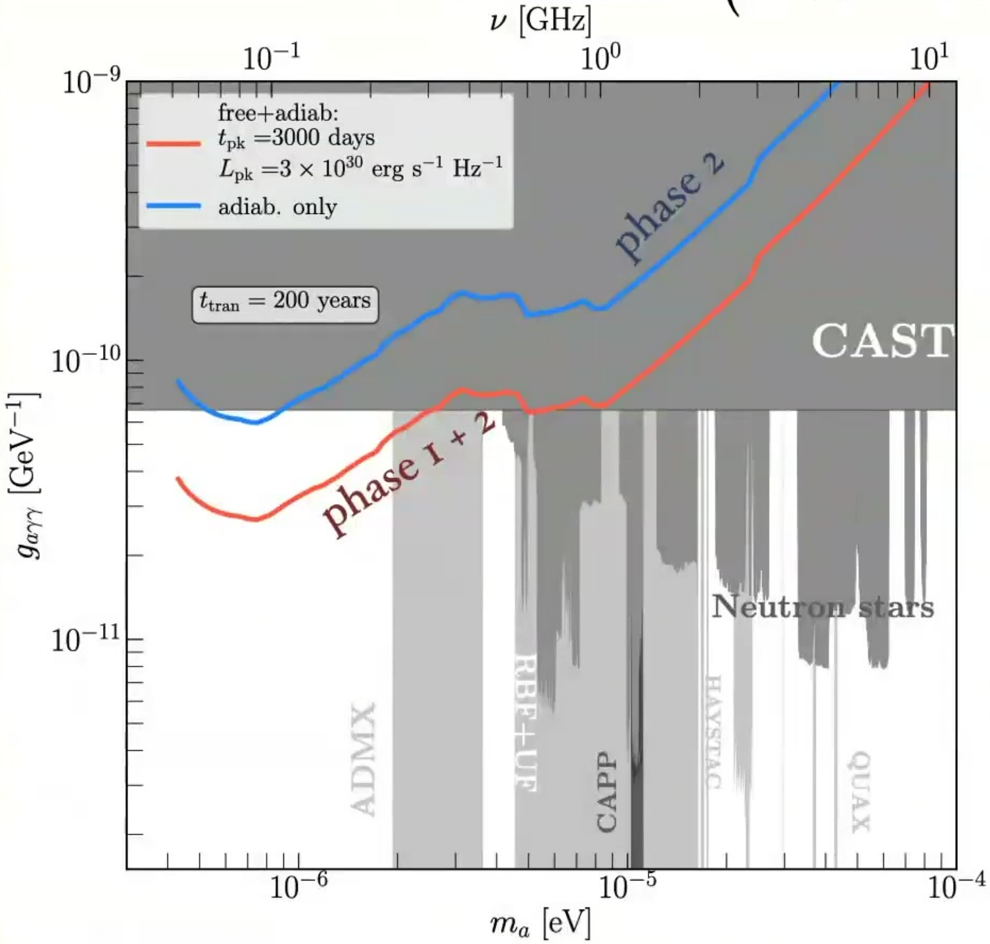
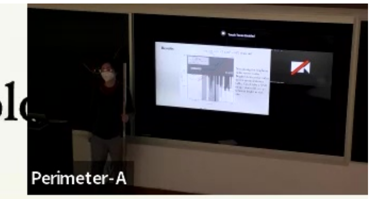
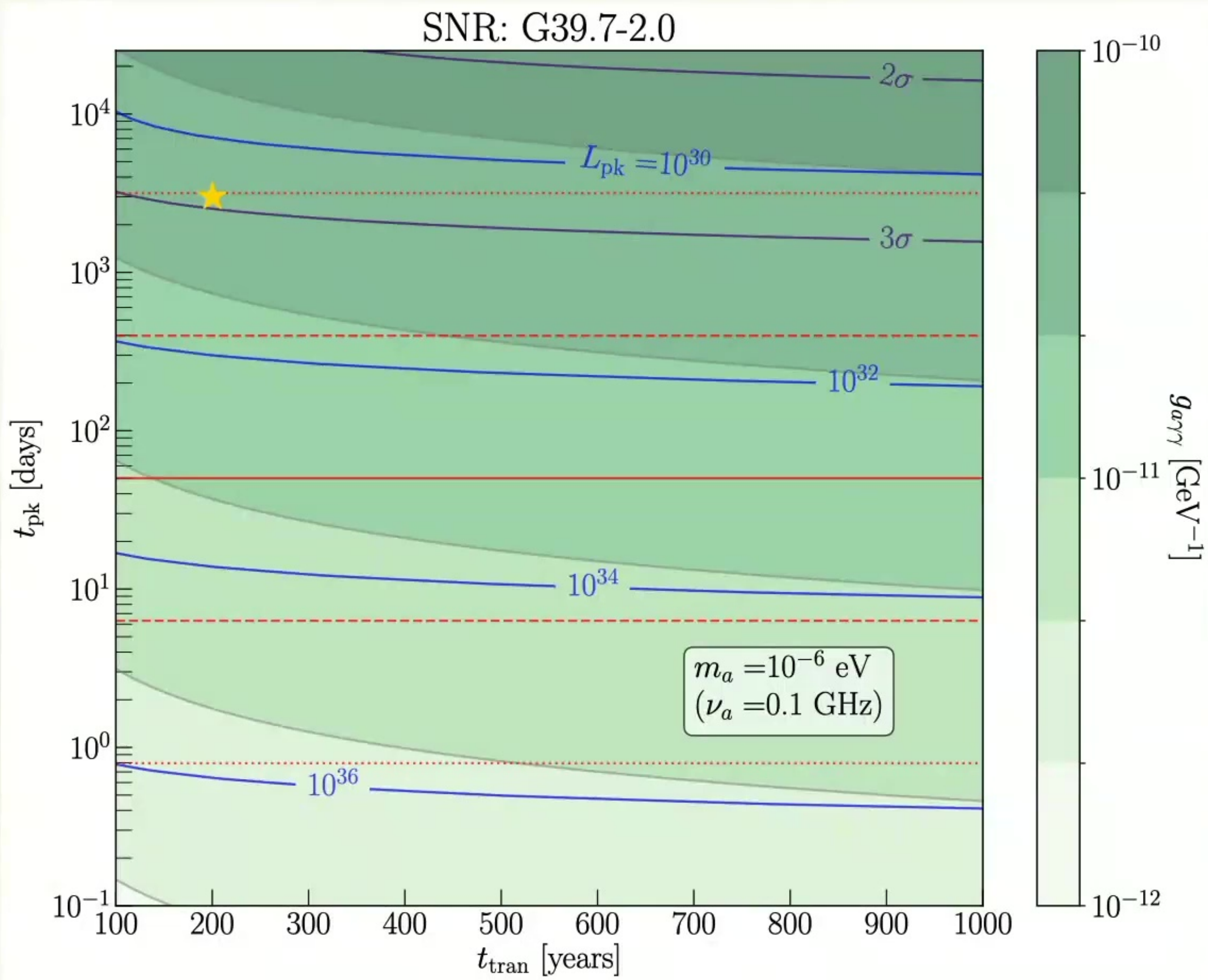
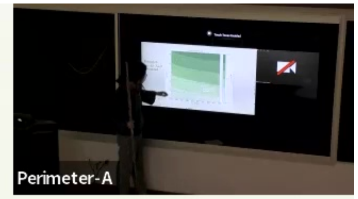




Not among the brightest radio source today ! Brightest extrasolar radio source around/above 1 GHz, Cas A (also a SNR of 340 years old), is ~ 30 times as bright as this one.

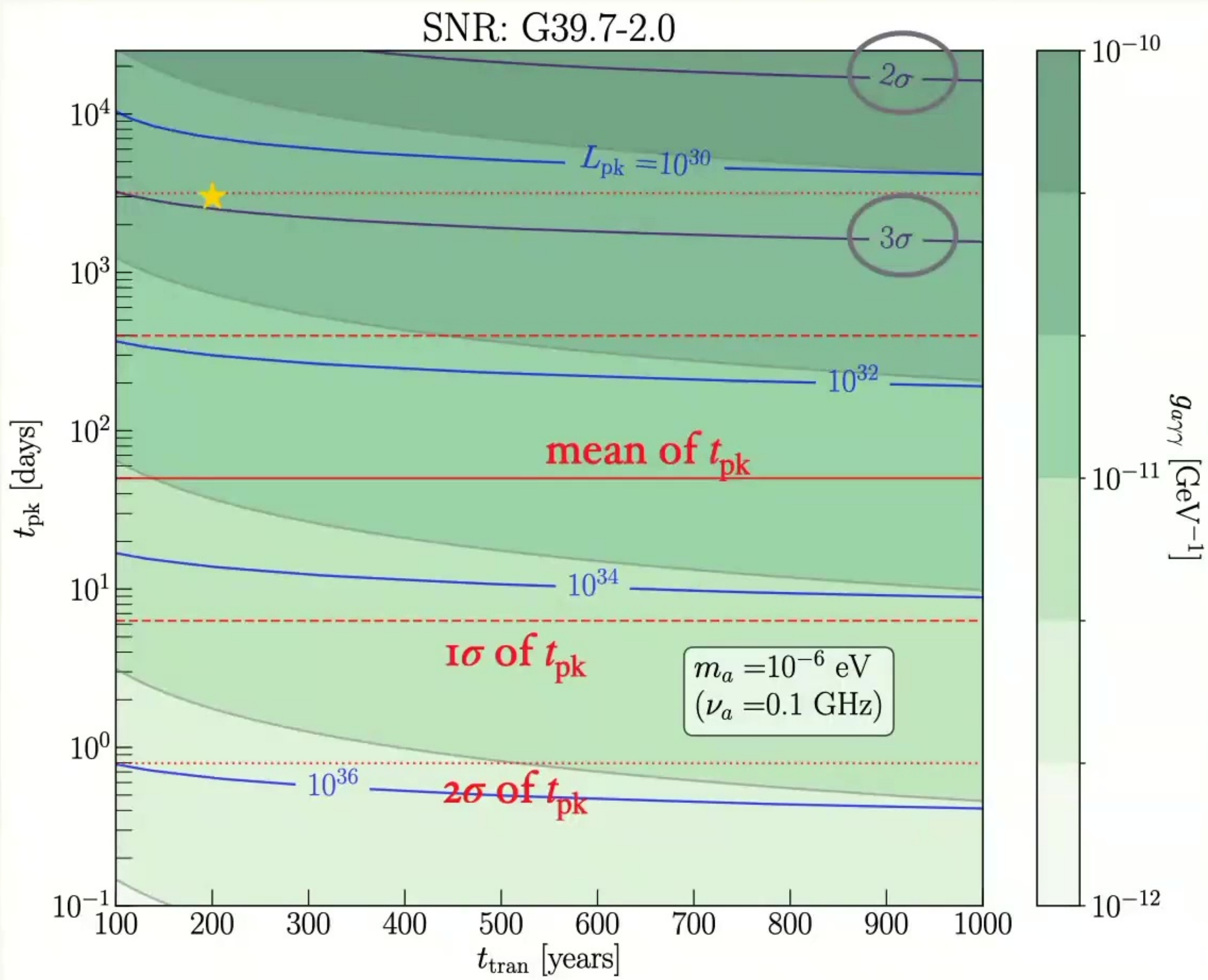
For a given $(t_{\rm tran}, t_{\rm pk})$, $L_{\rm pk}$ is determined.

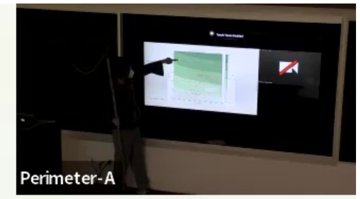




$L_{\rm pk}$: erg s^{-1} Hz^{-1}

For a given ($t_{\rm tran}$, $t_{\rm pk}$) , $L_{\rm pk}$ is determined.





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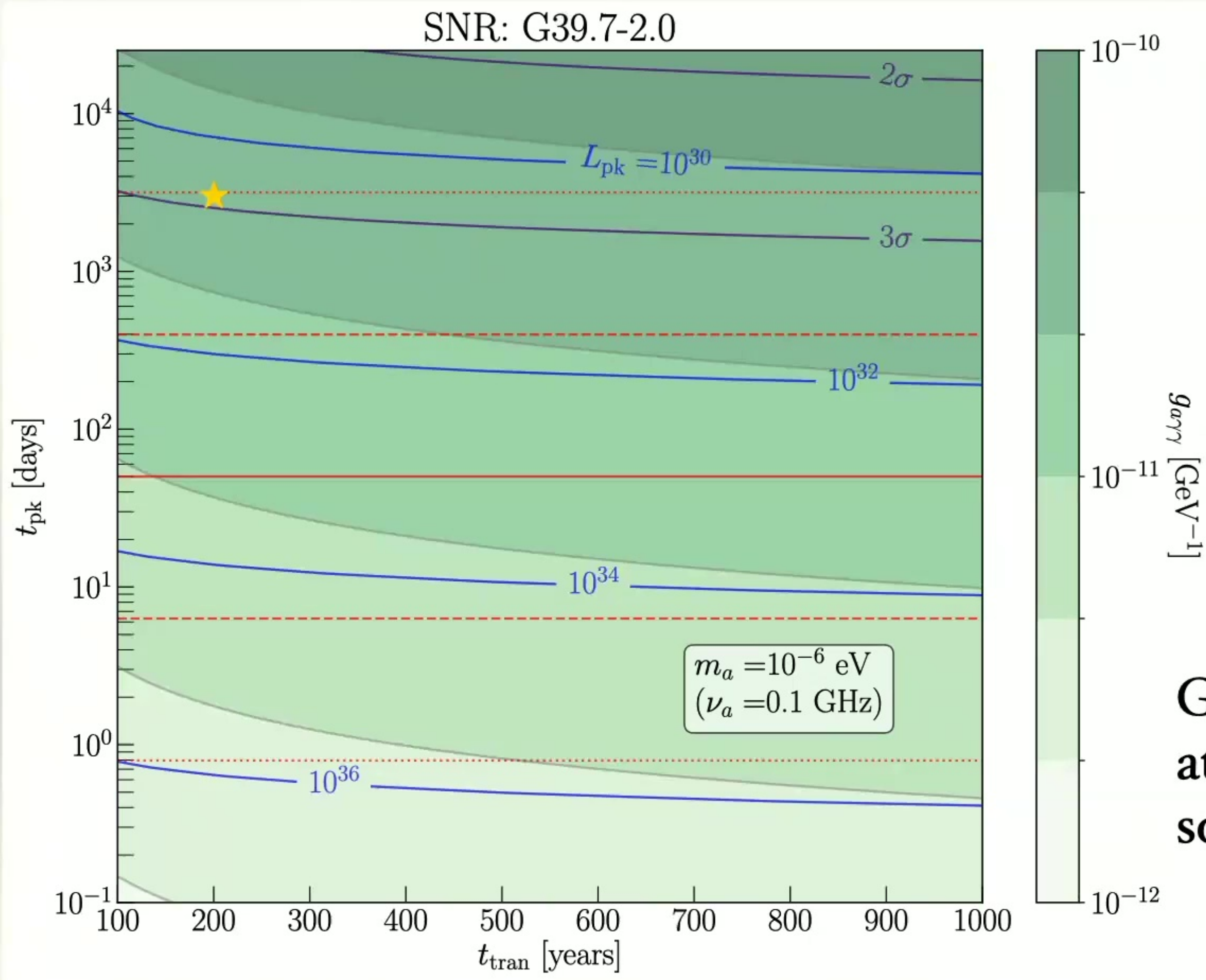
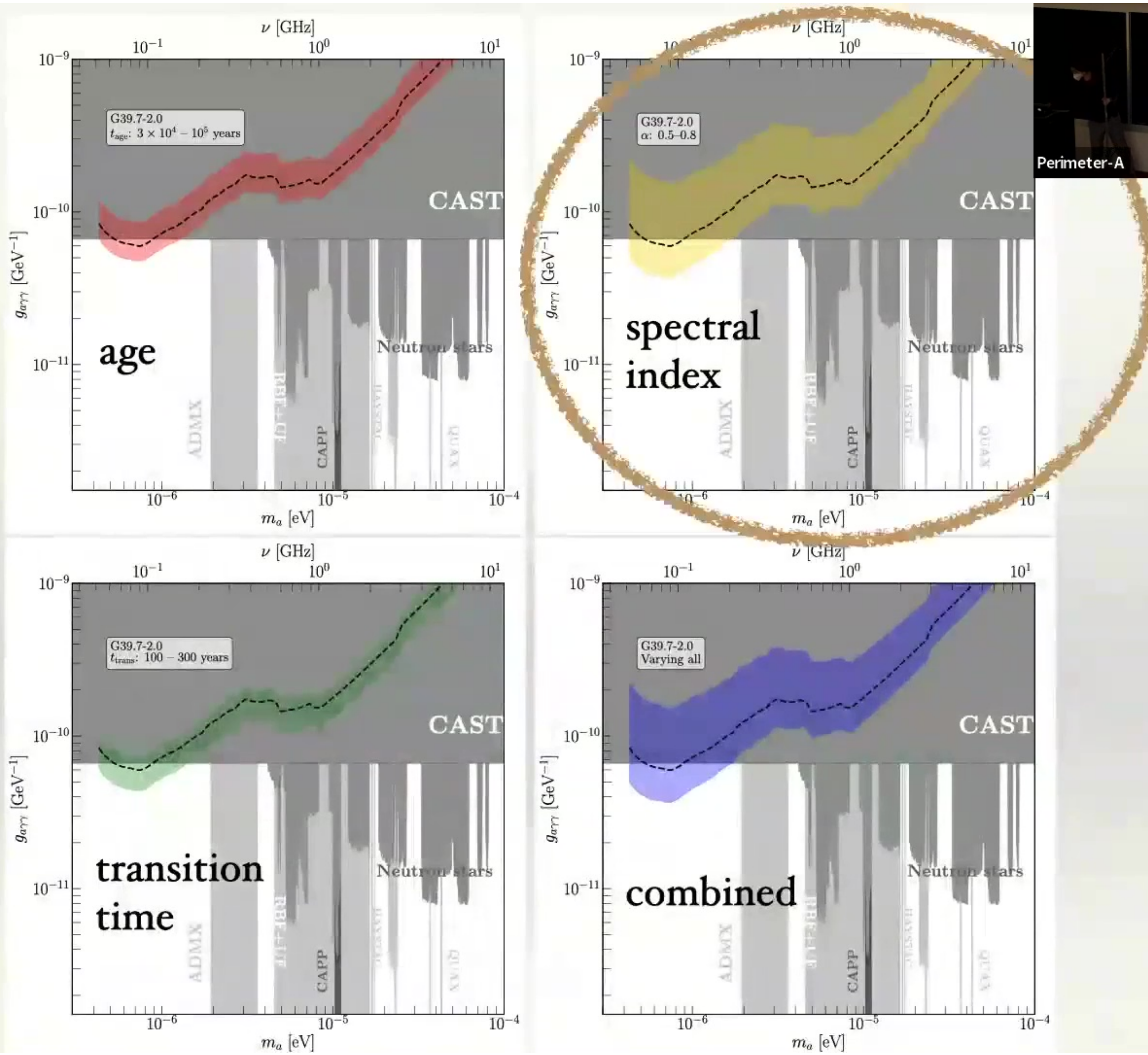


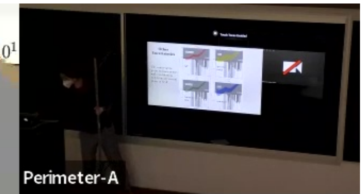
$L_{\rm pk}$: erg s^{-1} Hz^{-1}

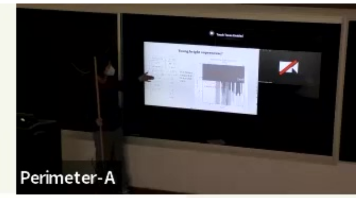
G39.7-2.0 is an atypical bright source in the past!

Other Uncertainties

The conservative projected sensitivities with contribution only from the second phase of SNR



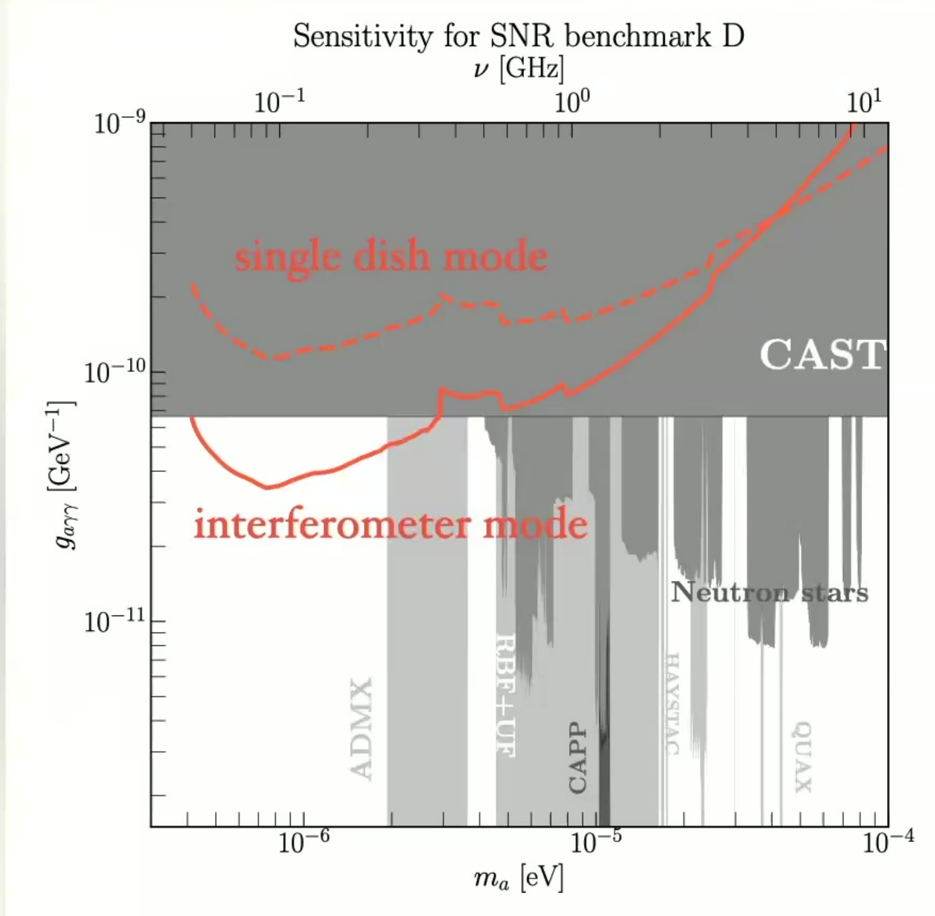


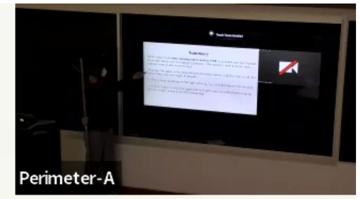


Young bright supernovae?

Benchmark	D (new)
(l, b)	$(40°, 0°)$
θ_s [arcmin]	$1.0(*)$
$S^{(0)}_{1\mathrm{GHz,s}}$ [Jy]	$2.1 \times 10^6(*)$
$L_{1\mathrm{GHz,pk}}$ [cgs]	1.2×10^{29}
t_{pk} [day]	50
t_{tran} [year]	4.1
D [kpc]	0.5
t_{age} [year]	10
α	0.65
γ	$1.84(*)$

Flux density comparable to the solar burst





Summary

Axion echoes from ***time-varying source such as SNR*** is a possible new way to probe axion dark matter and its coupling to photons. The sensitive could be better than constant sources such as from Cyg A.

A strong echo signal, in the opposite direction of the source, could be from an old dim source which was very bright in the past.

— More precise modeling of SNR light curve $(t_{\rm pk}, L_{\rm pk}, \alpha)$ could improve the estimate.

— “Ghost” source: a radio line signal with no bright source in either direction along the line of sight. A way to do SNR archaeology ?