Axion Archaeology

Echos from Ancient Supernova Remnants

Chen Sun

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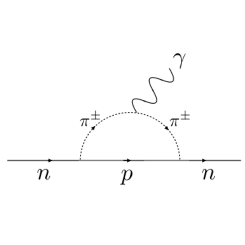
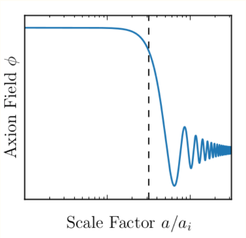
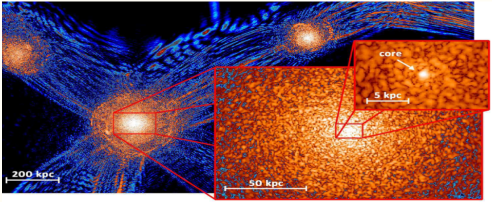
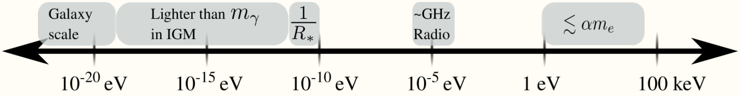




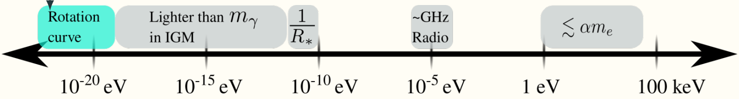


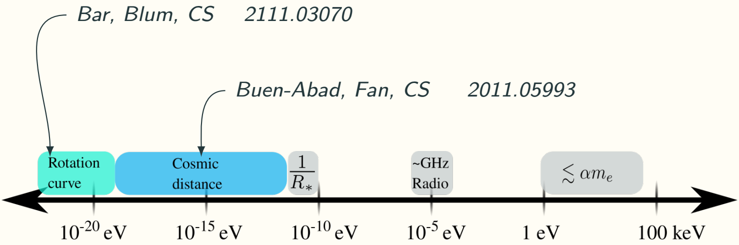
Axions

- are originally motivated by the strong CP problem;
- are natural light states that appear in many UV models;
- provide interesting non-thermal DM candidates.


Galaxy scale
Lighter than m_γ in IGM
$\frac{1}{R_*}$
~GHz Radio
$\lesssim \alpha m_e$
10^{-20} eV
10^{-15} eV
10^{-10} eV
10^{-5} eV
1 eV
100 keV

Bar, Blum, CS   2111.03070




Bar, Blum, CS 2111.03070
Buen-Abad, Fan, CS 2011.05993
Rotation curve
Cosmic distance
$\frac{1}{R_*}$
~GHz Radio
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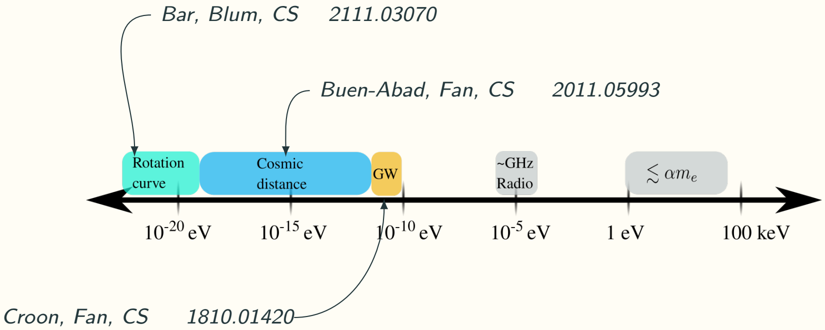
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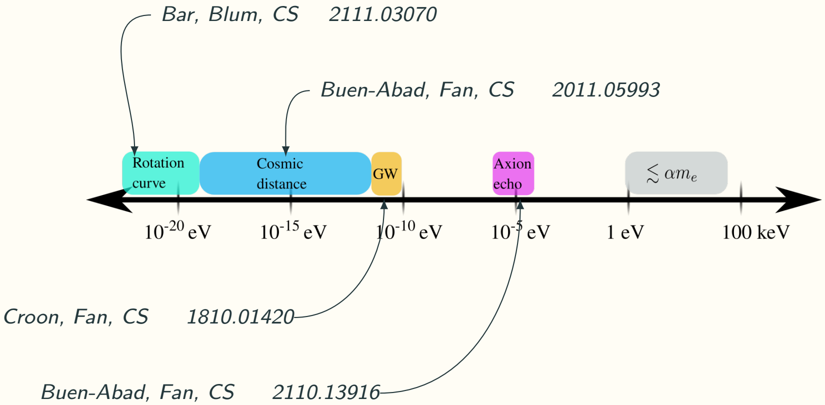
Croon, Fan, CS 1810.01420


Bar, Blum, CS 2111.03070
Buen-Abad, Fan, CS 2011.05993
Rotation curve
Cosmic distance
GW
Axion echo
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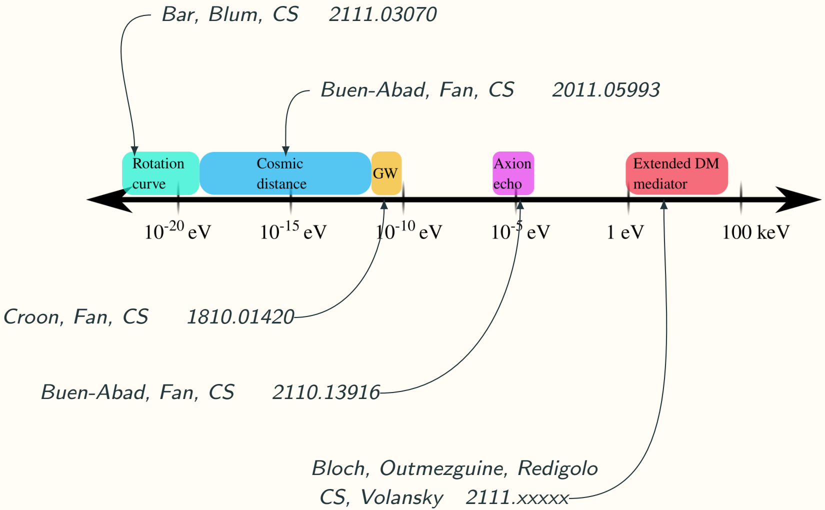
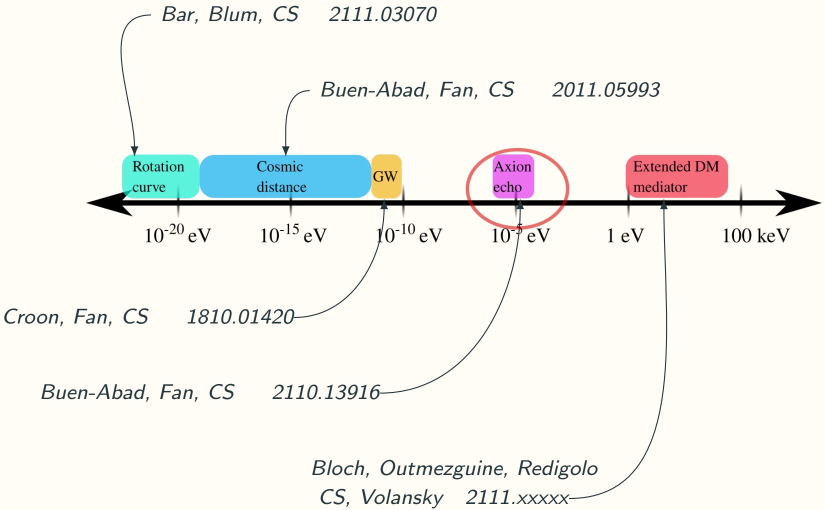
Croon, Fan, CS 1810.01420
Buen-Abad, Fan, CS 2110.13916


Bar, Blum, CS 2111.03070
Buen-Abad, Fan, CS 2011.05993
Rotation curve
Cosmic distance
GW
Axion echo
Extended DM mediator
10^{-20} eV
10^{-15} eV
10^{-10} eV
10^{-5} eV
1 eV
100 keV
Croon, Fan, CS 1810.01420
Buen-Abad, Fan, CS 2110.13916
Bloch, Outmezguine, Redigolo
CS, Volansky 2111.xxxxx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Axion(-like particles)

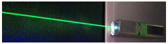
$$-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$

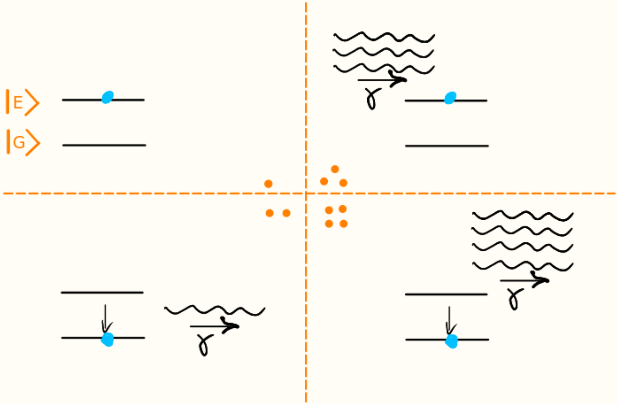
- One of the most studied axion couplings probed in lab.
- Astrophysical environments provide perfect conditions to study effects during γ propagation:
  - magnetic field at large scale
  - long "γ baseline"
  - high γ occupation number

SNIa/GC dist. meas. (2011.05993) — magnetic field at large scale; long "γ baseline"

This talk — long "γ baseline"; high γ occupation number

Spontaneous Decay v.s. Stimulated Decay





Spontaneous Decay v.s. Stimulated Decay

$$\begin{cases} |E\rangle : \text{excited atom}, \\ |G\rangle : \text{ground state atom} \end{cases} \Rightarrow \text{LASER (Light Amp. by Stimulated Emission of Radiation)}$$

$$\begin{cases} |E\rangle : \text{axion}, \\ |G\rangle : \text{photon} \end{cases} \Rightarrow \text{"ASER" (Axion Stimulated dEcay Radiation)}$$

Transition: axion state decays to a single photon state by emitting another photon.

Axion Stimulated Decay

S_ν: flux density [Jansky], power per area per frenquency

f: occupation number

Conditions:

- $E = m_a/2$ (decay, momentum conservation)
- large occupation number ($S_\nu \propto E^3 \cdot \Omega \cdot f$)
- reasonable background (detectable)

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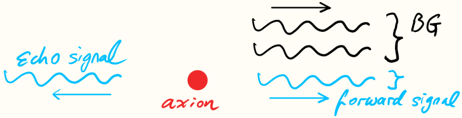
Signal dependence:

- stimulating source S_ν (astro)
- axion DM density (astro)
- $g_{a\gamma}$, m_a (fundamental)

Where to look for signals

Two photons, flying back-to-back in line of stimulating photon ($\mathbf{p}$ conservation)



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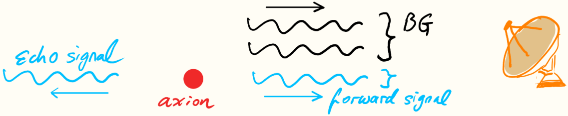

γ along original

- Galaxy center
- dwarf galaxies
- M87

(Caputo et al. 1811.08436)

Where to look for signals

Two photons, flying back-to-back in line of stimulating photon (**p** conservation)

γ flying backward "echo"

- Artificial photon beam (Arza and Sikivie, 1902.00114; Arza and Todarello 2108.00195)
- Cygnus A (Ghosh et al. 2008.02729)
- Time-varying radio sources (our work)

γ along original

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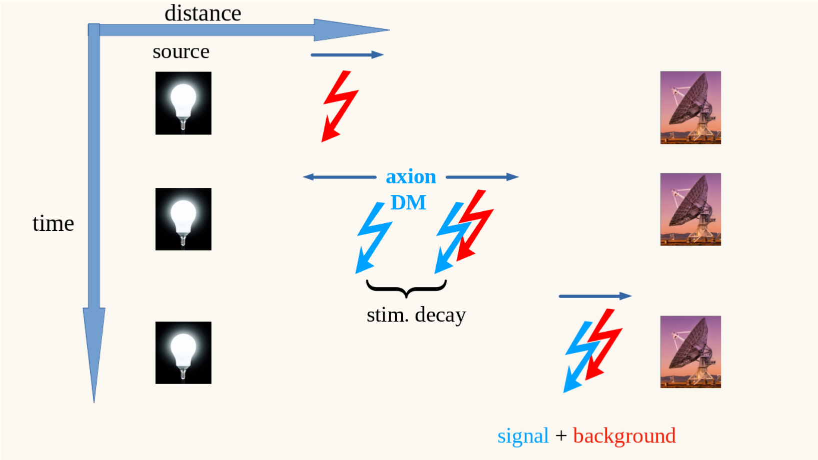
- dwarf galaxies
- M87

(Caputo et al. 1811.08436)

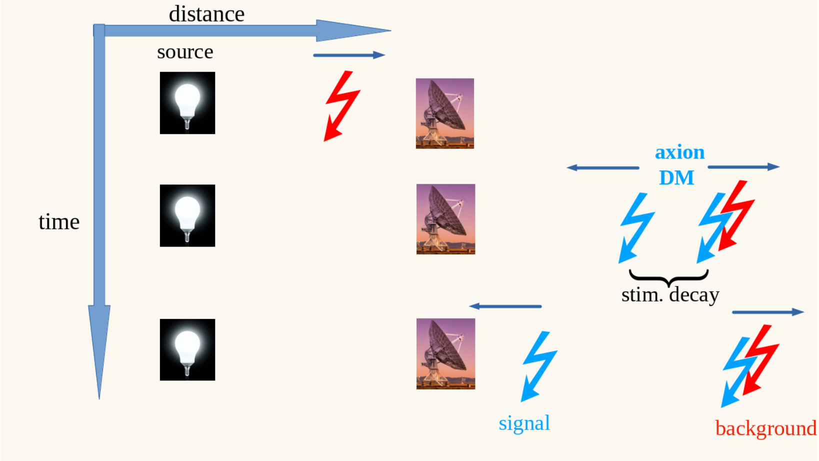
Benefit of echo signal?

Hints:

- Low background
- Strong signal from sources that look dim today



- Forward signal: arrives together with γ triggering the decay



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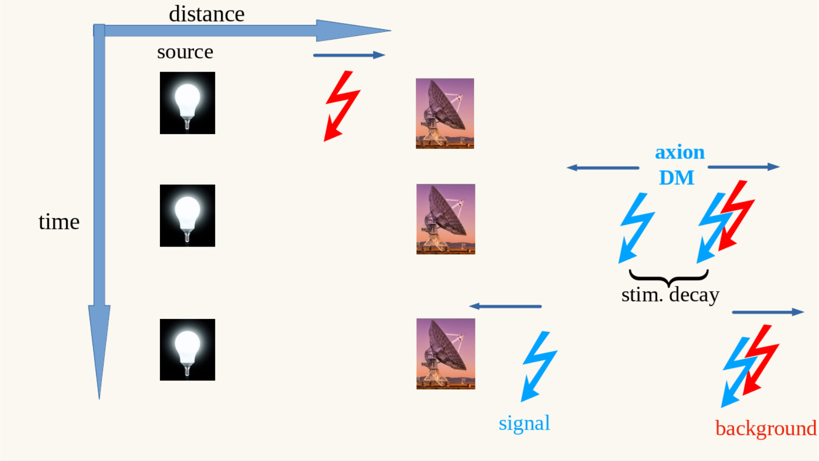
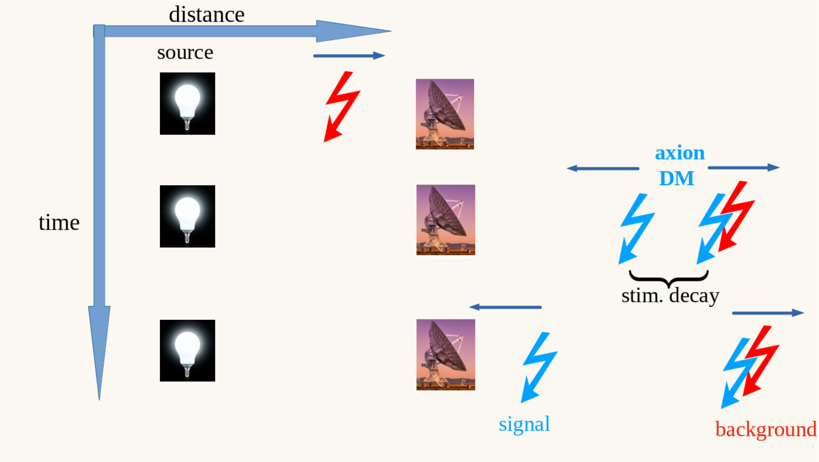


- Forward signal: arrives together with γ triggering the decay
- Backward signal:
  - separated from γ that generate them
  - not directly related to the radio source brightness at detection time



- Forward signal: arrives together with γ triggering the decay
- Backward signal:
  - separated from γ that generate them
  - not directly related to the radio source brightness at detection time → good candidates: Supernova Remnants

axion decay width

stimulating γ

$$S_{\nu,\mathrm{echo}} = \frac{16\pi^2 \Gamma_a}{m_a^4 \sigma_a} \int_0^{t_{\mathrm{age}}/2} dx\, \rho_a(x)\, S_\nu(t_{\mathrm{age}} - 2x)$$

axion DM density

Interlude Summary

- Axion stimulated decay
- Echo: historically bright radio sources

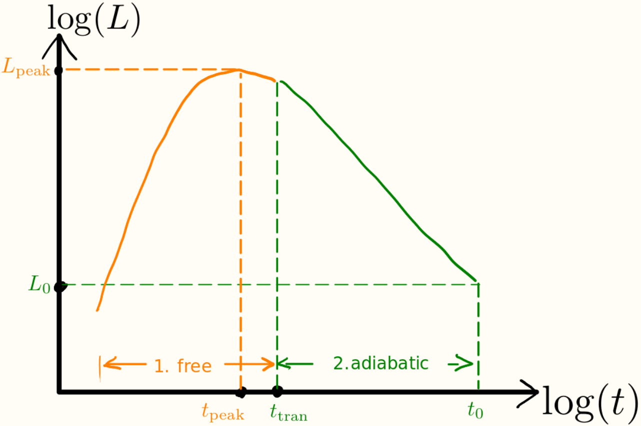
Interlude Summary

- Axion stimulated decay
- Echo: historically bright radio sources

Next:

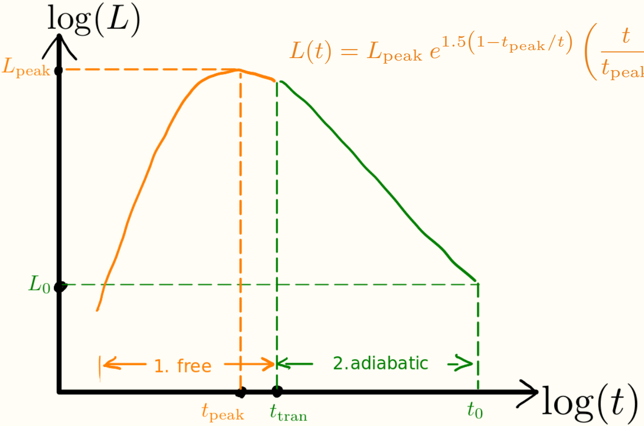
- Supernova evolution
- Signal and noise at SKA
- Results and discussions

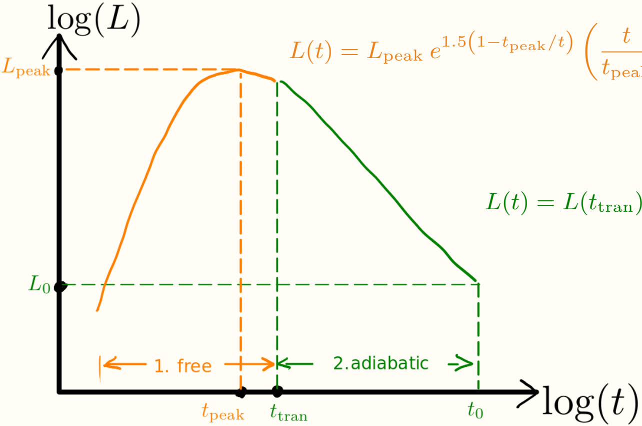
SN Remnant Evolution



$\log(L)$
$L_{\rm peak}$
L_0
1. free
2.adiabatic
$t_{\rm peak}$
$t_{\rm tran}$
t_0
$\log(t)$

$$L(t) = L_{\rm peak}\, e^{1.5(1-t_{\rm peak}/t)} \left(\frac{t}{t_{\rm peak}}\right)^{-1.5},$$

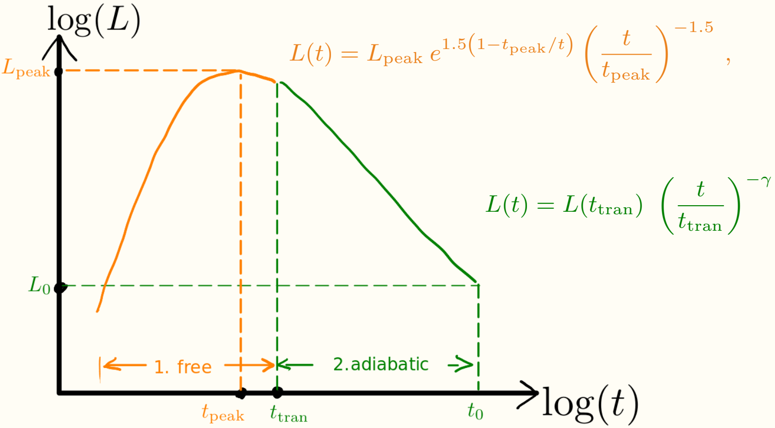




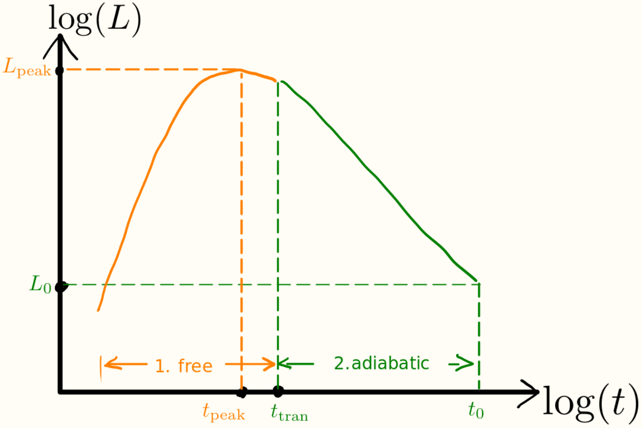
$$L(t) = L_{\rm peak}\, e^{1.5(1-t_{\rm peak}/t)} \left(\frac{t}{t_{\rm peak}}\right)^{-1.5},$$

$$L(t) = L(t_{\rm tran}) \left(\frac{t}{t_{\rm tran}}\right)^{-\gamma}$$

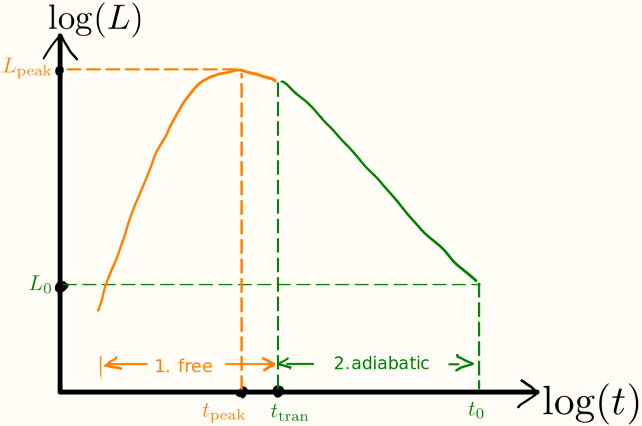
Phases of SNR Evolution



- 1. Free expansion, $\sim \mathcal{O}(100)$ yr
- 2. Adiabatic, $\sim \mathcal{O}(10^4)$ yr
- 3. Snow plough, $\sim \mathcal{O}(10^5)$ yr
- 4. Dispersion phase, $\sim \mathcal{O}(10^6)$ yr

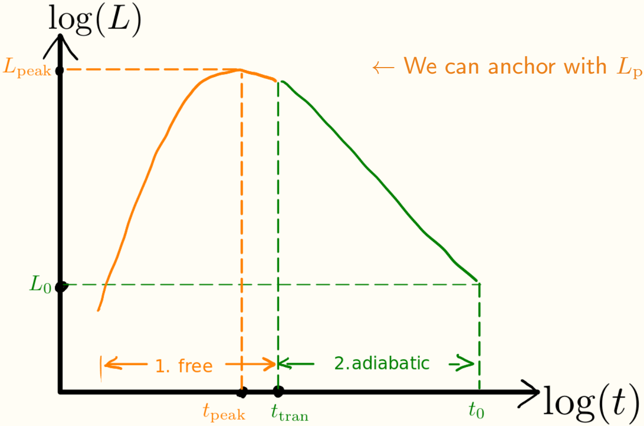


log(L)
L_{peak}
L_0
1. free
2.adiabatic
t_{peak}
t_{tran}
t_0
log(t)



↑ ↑ ↑

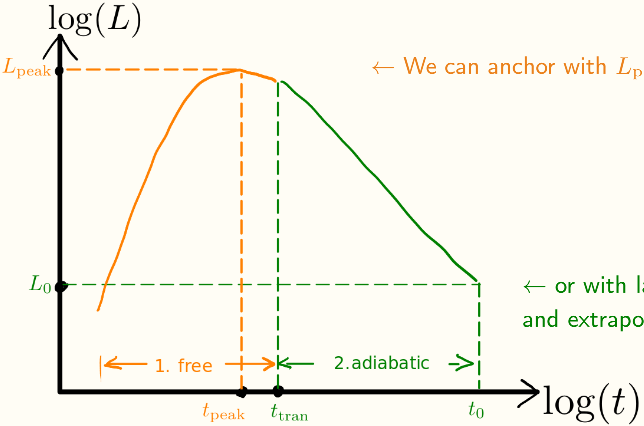
shape parameter



← We can anchor with $L_{\rm peak}$

↑ ↑ ↑

shape parameter

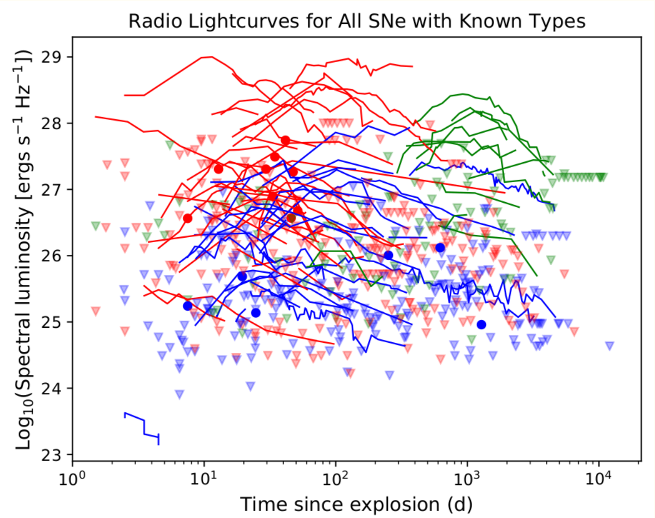


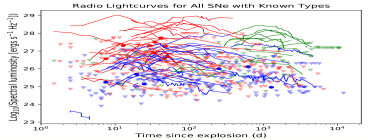
$\leftarrow$ We can anchor with $L_{\rm peak}$

$\leftarrow$ or with late time L_0,
and extrapolate backward

$\uparrow$ $\uparrow$ $\uparrow$

shape parameter


Radio Lightcurves for All SNe with Known Types
Log$_{10}$(Spectral luminosity [ergs s^{-1} Hz^{-1}])
29
28
27
26
25
24
23
10^0
10^1
10^2
10^3
10^4
Time since explosion (d)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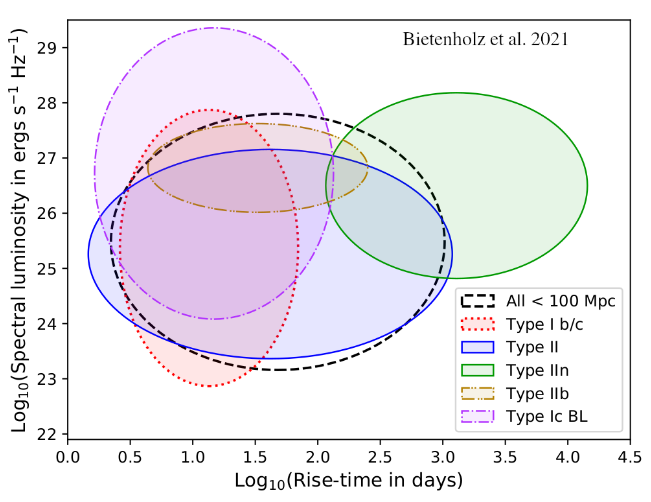
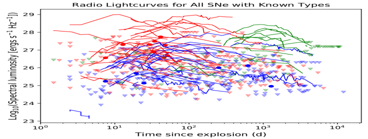
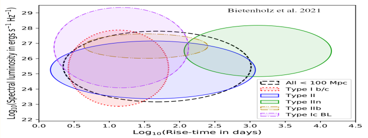

Bietenholz et al. 2021
All < 100 Mpc
Type I b/c
Type II
Type IIn
Type IIb
Type Ic BL
Log10(Spectral luminosity in ergs s−1 Hz−1)
Log10(Rise-time in days)

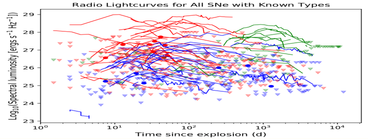


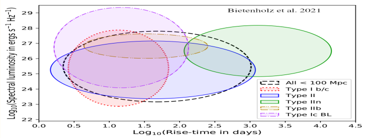


Green 2019

Table 1. 294 Galactic supernova remnants: summary data.

l	*b*	RA (J2000) (h m s)	Dec (° ′)	size /arcmin	type	Flux at 1 GHz/Jy	spectral index	other name(s)
0.0	+0.0	17 45 44	−29 00	3.5×2.5	S	100?	0.8?	Sgr A East
0.3	+0.0	17 46 15	−28 38	15×8	S	22	0.6	
0.9	+0.1	17 47 21	−28 09	8	C	18?	varies	
1.0	−0.1	17 48 30	−28 09	8	S	15	0.6?	
1.4	−0.1	17 49 39	−27 46	10	S	2?	?	
1.9	+0.3	17 48 45	−27 10	1.5	S	0.6	0.6	
3.7	−0.2	17 55 26	−25 50	14×11	S	2.3	0.65	
3.8	+0.3	17 52 55	−25 28	18	S?	3?	0.6	
4.2	−3.5	18 08 55	−27 03	28	S	3.2?	0.6?	
4.5	+6.8	17 30 42	−21 29	3	S	19	0.64	Kepler, SN1604,
4.8	+6.2	17 33 25	−21 34	18	S	3	0.6	
5.2	−2.6	18 07 30	−25 45	18	S	2.6?	0.6?	
5.4	−1.2	18 02 10	−24 54	35	C?	35?	0.2?	Milne 56
5.5	+0.3	17 57 04	−24 00	15×12	S	5.5	0.7	
5.9	+3.1	17 47 20	−22 16	20	S	3.3?	0.4?	
6.1	+0.5	17 57 29	−23 25	18×12	S	4.5	0.9	
6.1	+1.2	17 54 55	−23 05	30×26	F	4.0?	0.3?	
6.4	−0.1	18 00 30	−23 26	48	C	310	varies	W28
6.4	+4.0	17 45 10	−21 22	31	S	1.3?	0.4?	
6.5	−0.4	18 02 11	−23 34	18	S	27	0.6	
7.0	−0.1	18 01 50	−22 54	15	S	2.5?	0.5?	
7.2	+0.2	18 01 07	−22 38	12	S	2.8	0.6	





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SNRcat - *High Energy Observations of Galactic Supernova Remnants*

Image (GAL alignment)	ID	names	context	age (years)	distance (kpc)	type	keV	MeV	GeV	TeV	CHANDRA	XMM
	all	all	all	all	all	all	all	all	all	all	all	all
	G000.0+00.0	Sgr A East, *CXOGC J174545.5-285829, 1FGL J1745.6-2900c, 2FGL J1745.6-2858, 1FHL J1745.6-2900, 3FGL J1745.6-2859c, 2FHL J1745.7-2900, 3FHL J1745.6-2900, HESS J1745-290, VER J1745-290*	contains CXOGC J174545.5-285829 = the Cannonball = NS candidate and possibly PWN, close to BH Sgr A* interacts with molecular cloud	1200 - 10000	8	thermal composite	keV		GeV	TeV	CHANDRA	XMM
	G000.1-00.1	G0.13-0.12, *1FGL J1746.4-2849c, 2FGL J1746.6-2851c, 1FHL J1746.3-2851, 3FGL J1746.3-2851c, VER J1746-289*	contains PWN G0.13-0.11 interacts with molecular cloud??			thermal & plerionic composite?	keV		GeV	TeV	CHANDRA	XMM
	G000.3+00.0	~~G0.33+0.04~~, ~~G0.4+0.1~~		≤ 500000	8.5	shell			GeV	TeV		
			contains PSR									

Early phase: statistics of 262 SNe measured in the range of 2-10 GHz leads to

$$L_{\rm peak} = 10^{1.7\pm0.9}{\rm erg\,s^{-1}\ Hz^{-1}}, \qquad t_{\rm peak} = 10^{25.5\pm1.5}\ {\rm d}$$

Bietenholz et al. (2011.11737)

Late phase: statistics of 294 SN remnants from Green and SNRcat:

- $L_0 \sim \mathcal{O}(10)$ Jy
- $\alpha \sim 0.5$ (spectral index)
- angular size $\sim \mathcal{O}(10)$ arcmin
- galactic coordinate
- distance $\sim \mathcal{O}(\rm kpc)$
- age (X-ray observation etc.) $\sim \mathcal{O}(10^3) - \mathcal{O}(10^5)$ years

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$$S_{\nu_a} = \frac{16\pi^2 \Gamma_a}{m_a^4\ \sigma_a} \int dx\ \rho_a\ S_{\nu_a,stim}$$

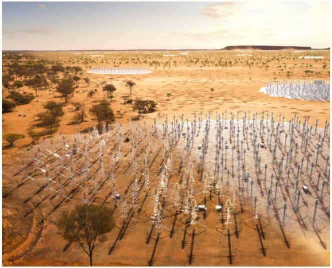
Detectability at SKA

SKA-mid SKA-low

“SKA is two telescopes”

SKA1-low (Australia)

- frequency: 50 MHz – 350 MHz;
- number of stations: 512;
- effective diameter of each station: 38 m;
- longest baseline: 80 km,



SKA1-mid (South Africa)

- frequency: 350 MHz – 15.4 GHz;
- 133 dishes $D = 15$ m (SKA dishes),
- 64 dishes $D = 13.5$ m (MeerKAT dishes);
- longest baseline: 150 km.

Signal/ Noise

$$P_{\text{signal}} = S_\nu \cdot \Delta\nu \cdot A \cdot \eta$$

Signal/ Noise

$$P_{\text{signal}} = S_\nu \cdot \Delta\nu \cdot A \cdot \eta$$

signal flux density

[power/area/freq]

$$S_{\nu_a} = \frac{16\pi^2 \Gamma_a}{m_a^4\ \sigma_a} \int dx\ \rho_a\ S_{\nu_a,stim}$$

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line width $\sim 10^{-3}(m_a/4\pi)$

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Signal/ Noise

signal flux density

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telescope area

$\sum$ (unit area)

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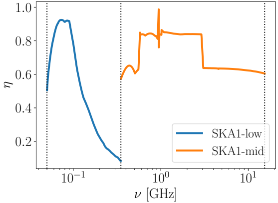
telescope efficiency



telescope area

$\sum$ (unit area)

$$P_{\rm noise,inst} = T_{\rm sys}\, \Delta\nu$$

- $T_{\rm cmb} \approx 2.73$ K
- $T_{\rm atm} \approx 3$ K at 1 GHz, $\sim \mathcal{O}(100)$ K at 100 MHz.
- $T_{\rm gal} \sim \mathcal{O}(10)$ K (inhomogeneous, Haslam 408 MHz map),
- $T_{\rm rcv} \approx 40$ K for SKA-low, and $T_{\rm r} \sim \mathcal{O}(10)$ K for SKA-mid
- $T_{\rm spl} \lesssim 3$ K

Signal/ Noise

$$P_{\text{noise}} = \frac{\sum_{\text{units}} \left(T_{\text{sys}}\, \Delta\nu\right)}{\left(\#\ \text{of meas.}\right)^{1/2}}$$

- $\sum_{\text{units}}$ is over all stations/dishes that receives the signal
- (# of meas.) is the number of independent measurements
  - 2 polarizations
  - $(\Delta\nu\, t_{\text{obs}})$ during t_{obs}
  - # of dishes (single-dish mode)
  - # of baselines (interferometry mode)

Signal of finite size, $\theta_{\rm sig}$

Single dish mode:

$$P_{\rm signal} \to P_{\rm signal}$$

$$P_{\rm noise} \to P_{\rm noise}\left(\frac{\theta_{\rm sig}}{\theta_{\rm res}}\right)$$

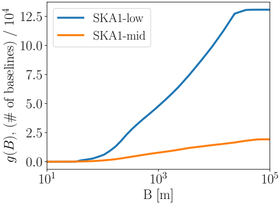
Signal of finite size, $\theta_{\rm sig}$

Interferometry mode:

$$P_{\rm signal} \to P_{\rm signal}\Theta(\lambda/B - \theta_{\rm sig})$$

$$P_{\rm noise} \to P_{\rm noise}/(\#\text{ of meas.})^{1/2}$$

Signal of finite size, θ_{sig}



Baseline length

Interferometry mode:

$$P_{\text{signal}} \to P_{\text{signal}} \Theta(\lambda/B - \theta_{\text{sig}})$$

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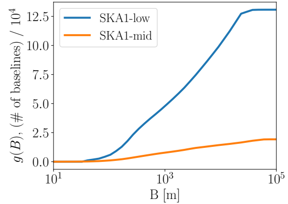
Signal of finite size, $\theta_{\rm sig}$



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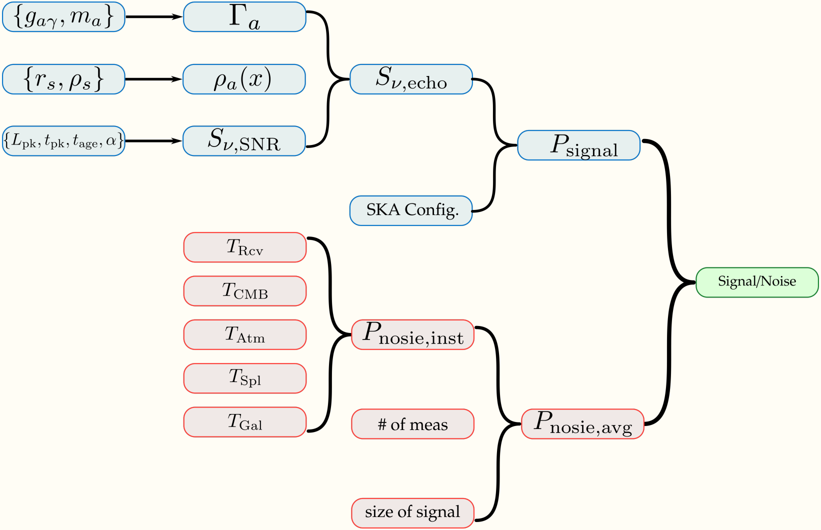
"active" baselines


$\{g_{a\gamma}, m_a\}$
Γ_a
$\{r_s, \rho_s\}$
$\rho_a(x)$
$\{L_{\rm pk}, t_{\rm pk}, t_{\rm age}, \alpha\}$
$S_{\nu,\rm SNR}$
$S_{\nu,\rm echo}$
$P_{\rm signal}$
SKA Config.
$T_{\rm Rcv}$
$T_{\rm CMB}$
$T_{\rm Atm}$
$T_{\rm Spl}$
$T_{\rm Gal}$
$P_{\rm nosie,inst}$
# of meas
$P_{\rm nosie,avg}$
size of signal
Signal/Noise

Results

G39.7-2.0 (W50)
$(l, b) = (39.7^\circ, -2^\circ)$
$\theta_s = 85$ arcmin
$S^{(0)}_{1\mathrm{GHz,s}} = 85$ Jy $(*)$
$D = 4.9$ kpc
$t_{\mathrm{age}} = 30,000$–$100,000$ years
$\alpha = 0.7$ $(*)$
$\gamma = 1.92$

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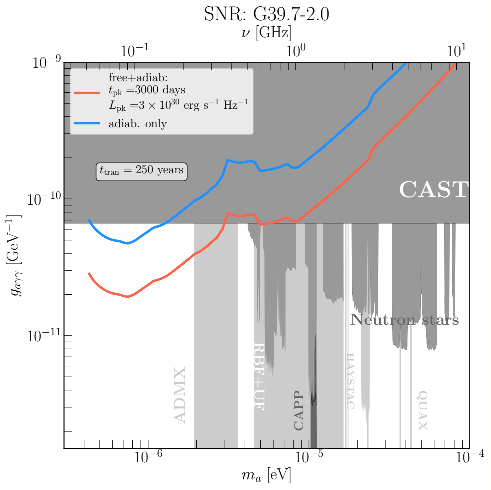
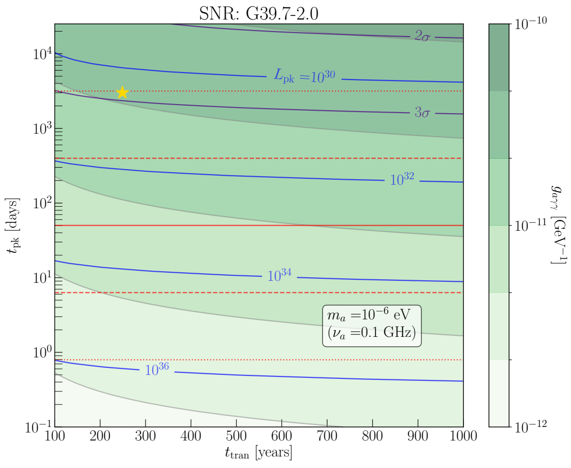
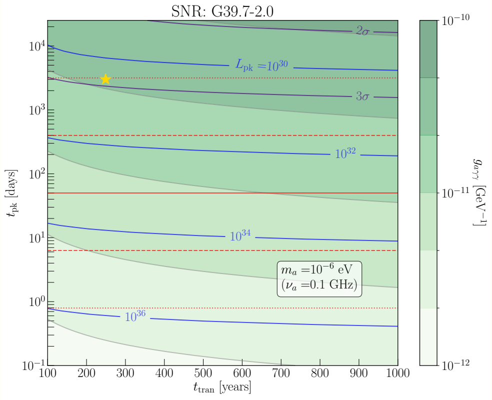


Dependence on Early Properties





- G39.7-2.0 not a very typical SNR (selection bias)

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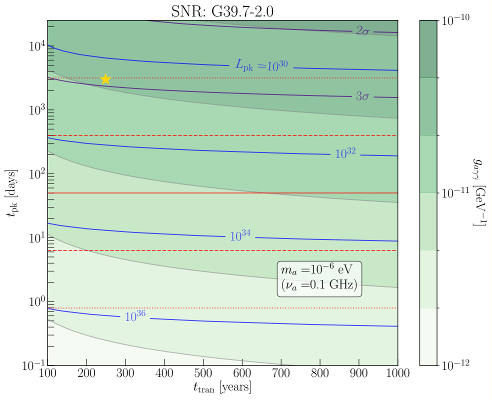

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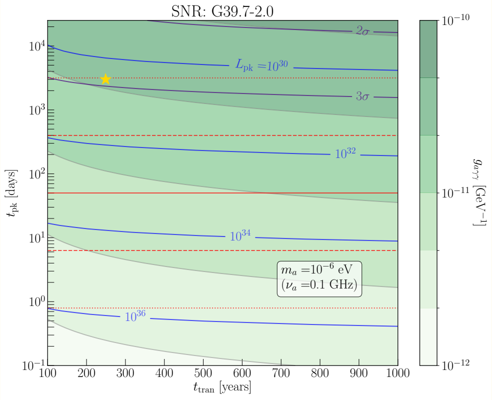

- G39.7-2.0 not a very typical SNR (selection bias)
- Current it is only 1/30 of Cas A
- Early brightness is the key

Projections

G6.4-0.1 like
$(l,b) = (64^\circ, -0.1^\circ)$
$\theta_\mathrm{s} = 48$ arcmin
$S^{(0)}_{1\mathrm{GHz,s}} = 310$ Jy $(*)$
$D = 1.9$ kpc
$t_\mathrm{age} \sim 35,000$ years
$\alpha = 0.65\ (*)$
$\gamma = 1.84$

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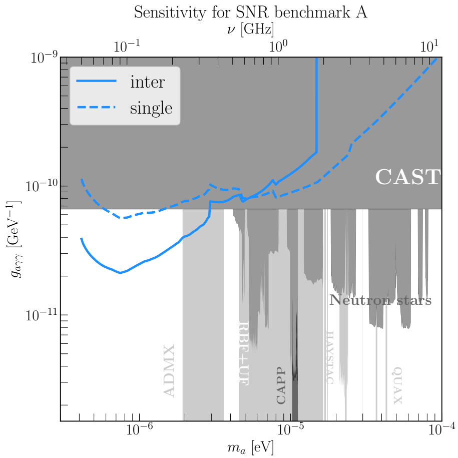

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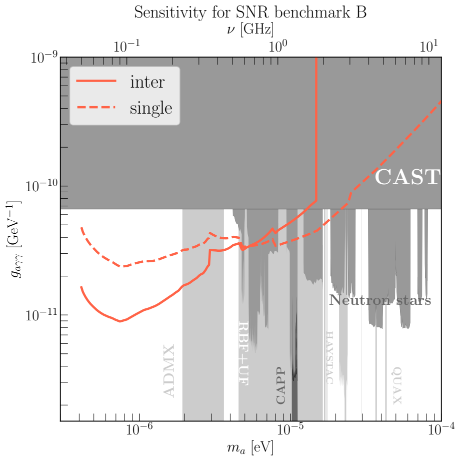

Results – anchor with Early data

Undiscovered old SNR
$(l,b) = (175°, 5°)$
$\theta_s = 16$ arcmin
$L_{1GHz,peak} = 1.2 \times 10^{29} \mathrm{erg} \cdot \mathrm{s}^{-1} \cdot \mathrm{Hz}^{-1}$
$t_{pk} = 50\,\mathrm{days}$
$S^{(0)}_{1GHz,s} = 6$ Jy (derived)
$D = 0.5$ kpc
$t_{age} \sim 55,000$ years
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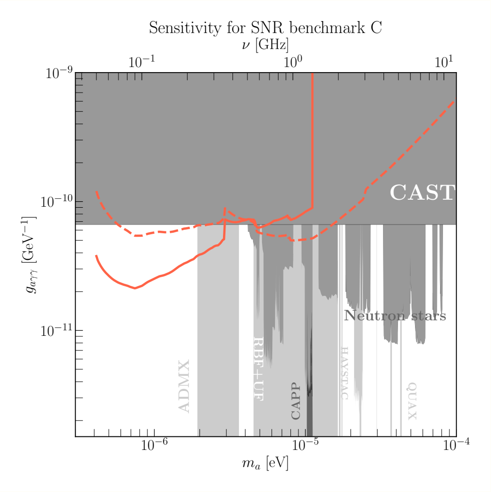
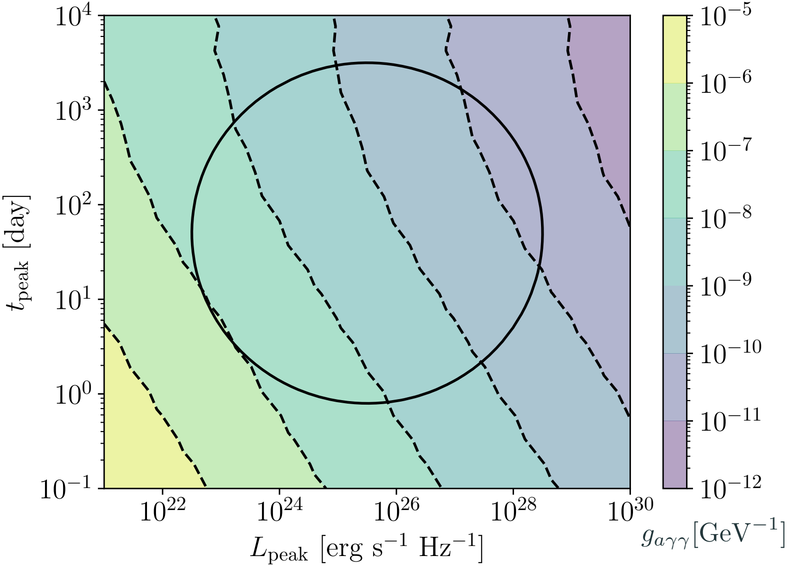
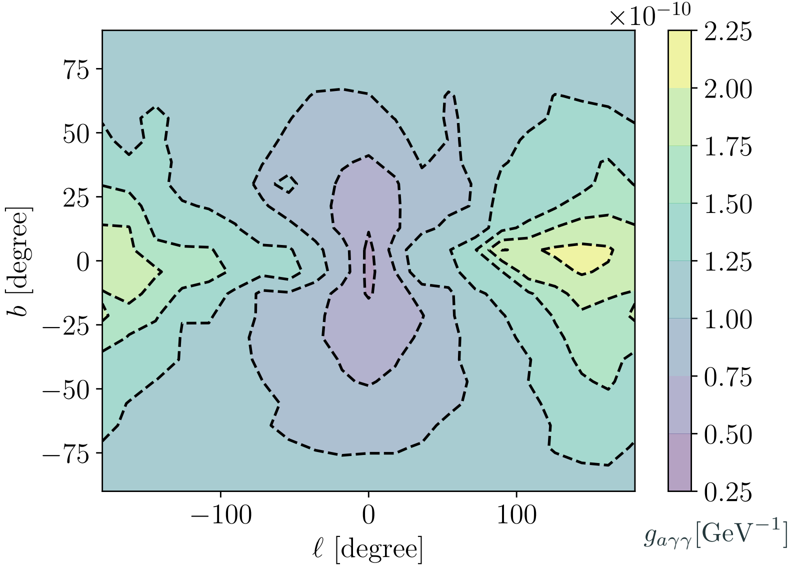
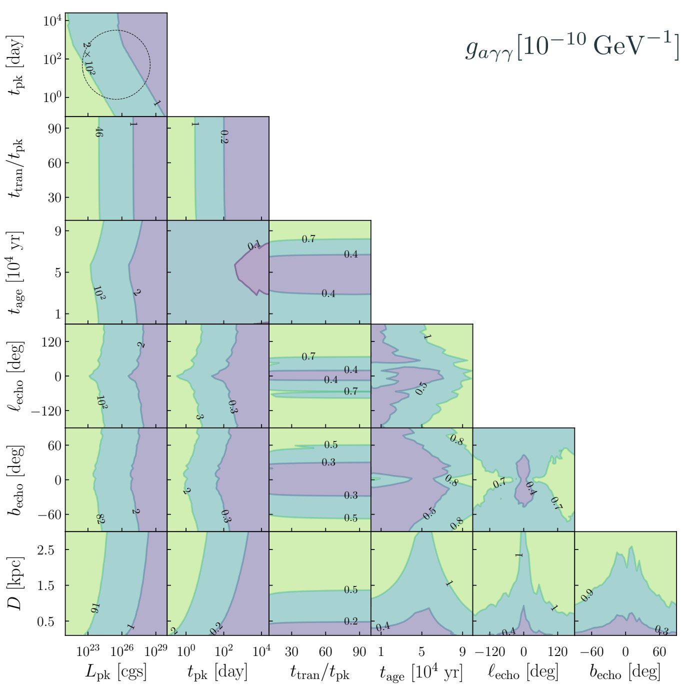


Results – Dependence on Early Properties



Results – Dependence on SNR Location




$g_{a\gamma\gamma}[10^{-10}\,\mathrm{GeV}^{-1}]$
$L_{\rm pk}$ [cgs]
$t_{\rm pk}$ [day]
$t_{\rm tran}/t_{\rm pk}$
$t_{\rm age}$ [10^4 yr]
$\ell_{\rm echo}$ [deg]
$b_{\rm echo}$ [deg]
D [kpc]

Bonus – if we get lucky

Future SN explosion
$(l, b) = (40°, 0°)$
$\theta_s = 1.0$ arcmin
$L_{1\text{GHz,peak}} = 1.2 \times 10^{29} \text{erg} \cdot \text{s}^{-1} \cdot \text{Hz}^{-1}$
$S^{(0)}_{1\text{GHz,s}} = 2.1 \times 10^6$ Jy (derived)
$D = 0.5$ kpc
$t_{\text{age}} \sim 10$ years
$\alpha = 0.65$ $(*)$
$\gamma = 1.84$

Bonus – if we get lucky

Future SN explosion
$(l, b) = (40^\circ, 0^\circ)$
$\theta_s = 1.0$ arcmin
$L_{1\mathrm{GHz,peak}} = 1.2 \times 10^{29}\mathrm{cgs}$
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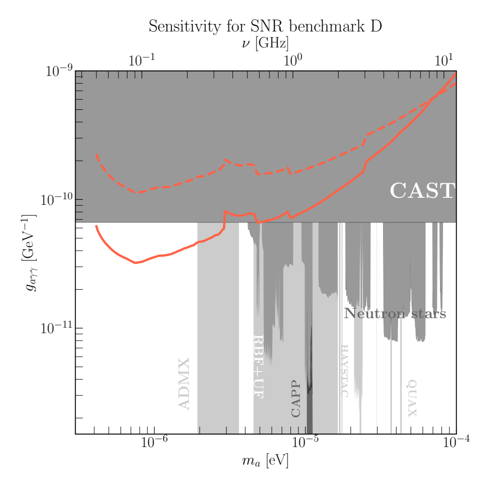

Summary

- Axion stimulated decay provides an important way to examine $g_{a\gamma}$

  Large γ occupation number is a must!

- $a \to \gamma_f + \gamma_b$

  γ_b: **depends on historical source brightness; has low background.**

- Supernova Remnants are bright (transient) radio sources

  Include the very old ones and those not detected yet

- Statistically normal SNR can probe axion DM parameter space beyond CAST

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https://github.com/ChenSun-phys/snr_ghosts

Time varying radio sources...
... are important for echo signals from stimulated decay of axions.

Backup slides

Light curve model

$$L_\nu(t) = \begin{cases} L_{\nu,\mathrm{free}}(t) & (t \le t_{\mathrm{tran}}) \\ L_{\nu,\mathrm{adia}}(t) & (t > t_{\mathrm{tran}}) \end{cases}$$

where

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

$$L_{\nu,\mathrm{adia}}(t) \equiv L_{\nu,0} \left(\frac{t}{t_0}\right)^{-\beta}$$

$$L_{\nu,\mathrm{adia}}(t_{\mathrm{tran}}) = L_{\nu,\mathrm{free}}(t_{\mathrm{tran}}) \quad \text{(matching condition)}$$

Master Formula

$$S_{\nu_a} = \frac{16\pi^2\Gamma_a}{m_a^4\ \sigma_a} \int_0^{t_0/2} dx\ \rho_a(x, -\Omega_*)\ S_{\nu_a,stim}(t_0 - 2x)\mathrm{e}^{-\tau(\nu,x,-\Omega_*)}\ ,$$

Optical Depth

$$\tau(\nu) \approx 9.5 \times 10^{-7} \left(\frac{\mathrm{EM}}{\mathrm{cm^{-6}\,pc}}\right) \left(\frac{T_e}{5000\ \mathrm{K}}\right)^{-1.38} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.08} ,$$

$\mathrm{EM} = \int n_e^2\, d\ell$ is the emission measurement

- away from the galaxy center (pulsar measurements)

$$\mathrm{EM} \approx 0.23\ \mathrm{cm^{-6}\ pc} \left(\frac{n_{e,0}}{0.015\ \mathrm{cm^{-3}}}\right)^2 \left(\frac{\ell}{\mathrm{kpc}}\right) ,$$

- at the galaxy center (Sgr A*)

$$\tau \sim \mathcal{O}(1) \text{ at } 300\ \mathrm{MHz}$$

Gregory and Seaquist 1973,
Pedlar et al. 1989,
Schnitzeler 2021,
...

Population Estimate

SN rate in our Galaxy is

$$0.02 \sim 0.03 \text{ per year}$$

SNRs younger than 10^5 years are

$$2000 \sim 3000$$

Distribution inside our galaxy

$$\Sigma(R) \propto \left(\frac{R}{R_\odot}\right)^a \exp\left(-b\frac{(R-R_\odot)}{R_\odot}\right),$$

$R_\odot = 8.5 \text{ kpc}$, $a = 1.09, b = 3.87$ ***(Green 2015)***
$\Rightarrow \mathcal{O}(10)$ within 1 kpc of the Sun.

Noise of radio telescopes

$$\rho_\gamma \sim \int fE\, d^3p \sim \int fE^3 dE d\Omega$$

$$I_\nu \equiv \frac{dP}{dA d\nu d\Omega} \sim \frac{d\rho_\gamma}{dE d\Omega} \sim fE^3 \sim TE^2$$

$$P_{\text{noise}} = I_\nu \cdot \Omega \cdot \Delta\nu \cdot (A\eta) \sim TE^2 \left(\frac{1}{\nu^2 A\eta}\right) \cdot \Delta\nu \cdot (A\eta) \sim T\Delta\nu$$

For a given telescope, the equivalent temperature is denoted as T_{sys}.

Aberration, dispersion, and signal reduction

Three different motions:

- coherent motion of the source
- coherent motion of the observer
- dispersion of dark matter

Aberration, dispersion, and signal reduction

Three different motions:

- coherent motion of the source

$$\theta_{\rm ab} \approx \frac{d_s}{D} \approx 10\,\mathrm{arcmin}\,\left(\frac{v_s}{10^{-3}}\right)\left(\frac{t_{\rm age}}{10^4\ \mathrm{years}}\right)\left(\frac{1\ \mathrm{kpc}}{D}\right)$$

Aberration, dispersion, and signal reduction

Three different motions:

- coherent motion of the source
- coherent motion of the observer

$$1 - \left(\frac{D}{d_o + D}\right)^2 \approx \frac{2d_o}{D} = 6 \times 10^{-3} \, \left(\frac{v_o}{10^{-3}}\right) \left(\frac{t_{\rm age}}{10^4 \text{ years}}\right) \left(\frac{1 \text{ kpc}}{D}\right)$$

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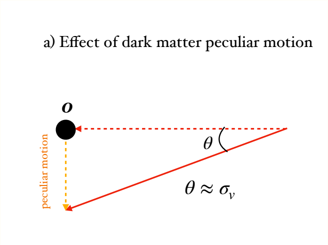

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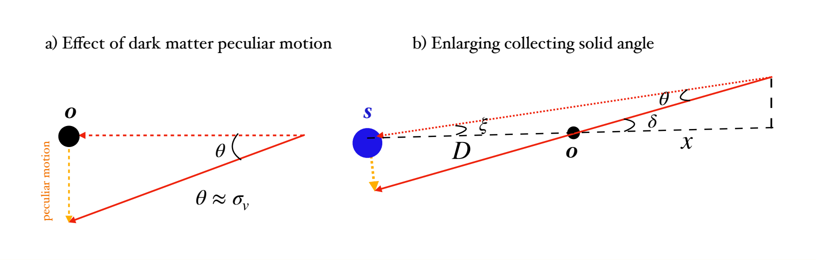

$$2\delta \approx 2\sigma_v \frac{x+D}{D} \approx 2\sigma_v \frac{t_{\rm age}/2+D}{D} \ ,$$

Shadow of the Earth

Had the Earth not been moving:

- stimulated decays of axions located within the Earth's shadow are prevented;
- the echo photons from axion decays outside the shadow will not pass the Earth

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Eppur si muove!

$$\ell_{\rm sd} \approx \frac{2R_\oplus}{\theta_{\rm s}} \approx 0.06\,{\rm au}\left(\frac{5\,{\rm arcmin}}{\theta_s}\right)$$

$$t \sim R_\oplus / v_\odot \sim 21\,{\rm s}$$