New Developments in Cosmological and Astrophysical searches of Dark Sectors

An <u>Incomplete</u> & <u>Biased</u> Perspective

Manuel A. Buen-Abad

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arXiv:2208.xxxxx: **MBA**, Z. Chacko, C. Kilic, G. Marques-Tavares, & T. Youn **[Monday]**

Aug 12 2022


US WAITING FOR THE
WAITING FOR THE
SPEAKER TO SHUT
UP ABOUT DARK SECTORS
imgflip.com

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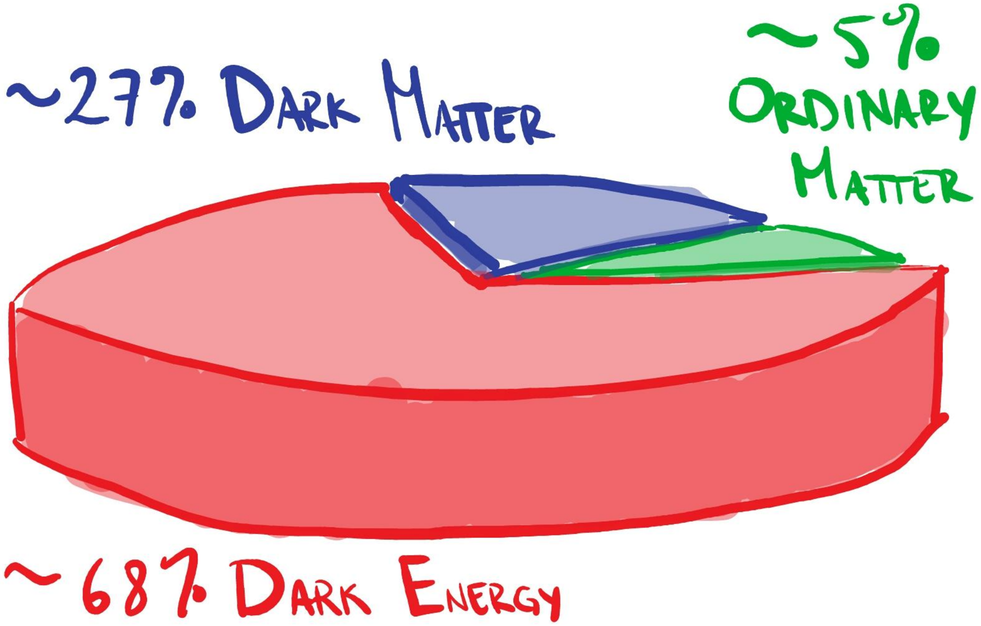
Outline

1. Motivation
2. Dark Sectors & Precision Cosmology
3. Conclusions

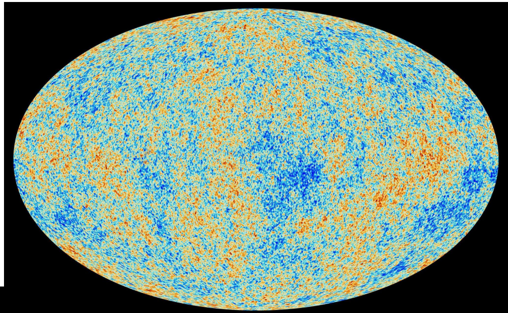
I. Motivation

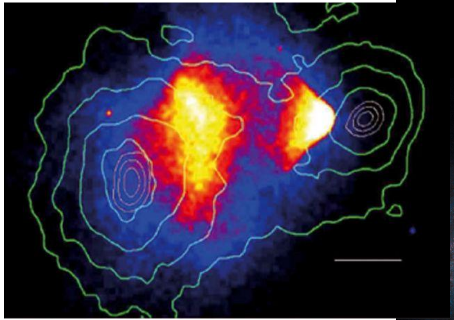
Energy components of the Universe

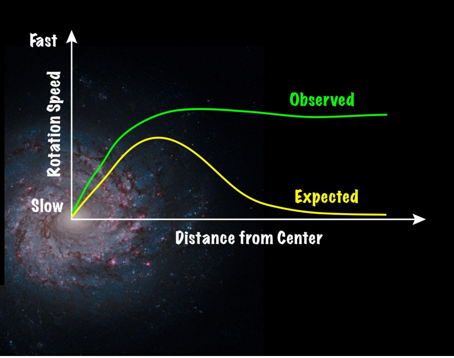


Hello Darkness, my old friend...

- Dark Energy (DE)
  - Lots of evidence
  - Really exciting & puzzling
  - Lots of cool ideas ...
  - ... but could just be cosmological constant
- Dark Matter (DM)
  - *Also* lots of evidence
  - *Also* really exciting & puzzling
  - Likely **not** MOND [Grudic et al. 1910.06345, etc]
  - Need **more** particles ⇒ **BSM**

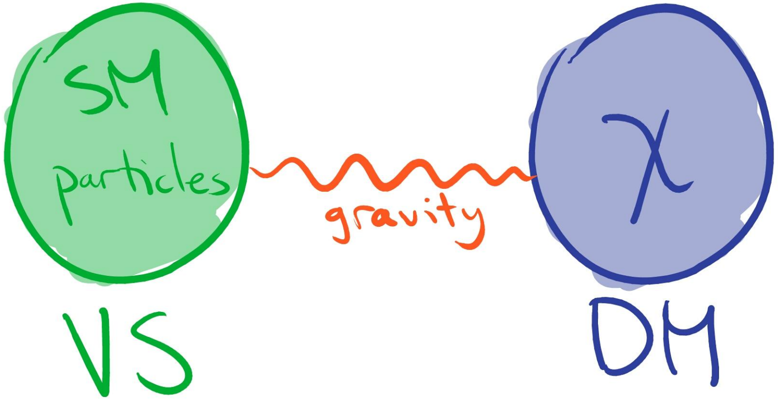






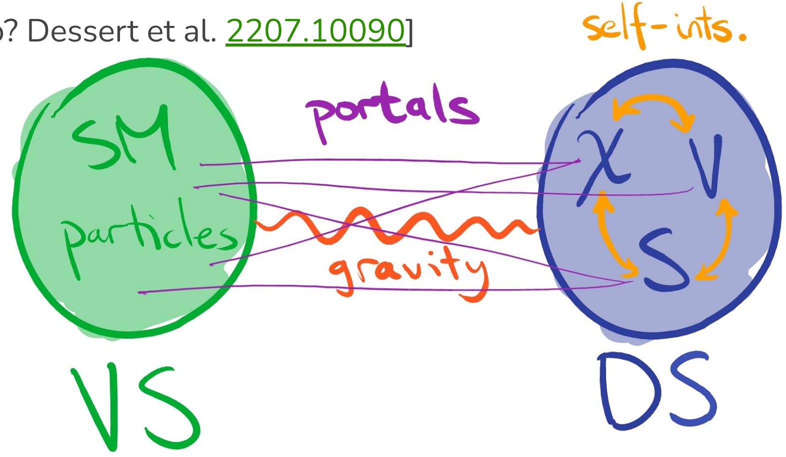
Dark Matter (DM)

- Could be just the one particle… [e.g. higgsino? Dessert et al. 2207.10090]



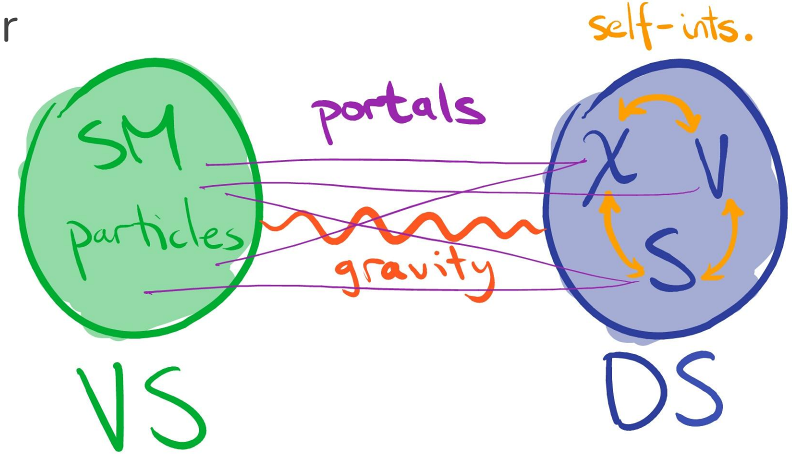
Dark Matter (DM)

- Could be just the one particle… [e.g. higgsino? Dessert et al. 2207.10090]
- … but it doesn't have to
  - E.g. in SM, ***three*** almost-dark particles
  - Could there be more than one DM?
  - With dark interactions?



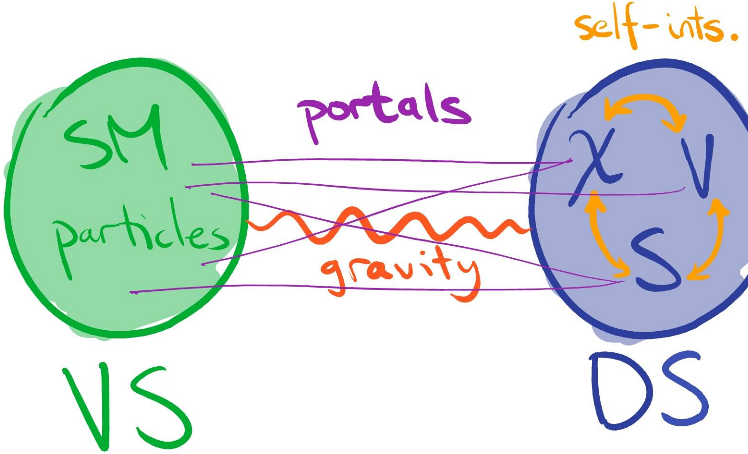
Dark Sectors (DS)

- Dark Matter could be part of Dark Sector
- Search for signals of these sectors
  - Colliders
  - Direct Detection experiments **[Kim, Mukul (Tu); Victor (Th); Peizhi & Robert (next week)]**
  - **Cosmology**
  - **Astrophysics**



Dark Sectors (DS)

- Observables (**where?**)
  - CMB? LSS? BBN? GW?
  - Black Holes? SNe? NS **[Davood (M)]**? Stars? **[Jae (next week)]** Galaxies?
  - Experimental anomalies?



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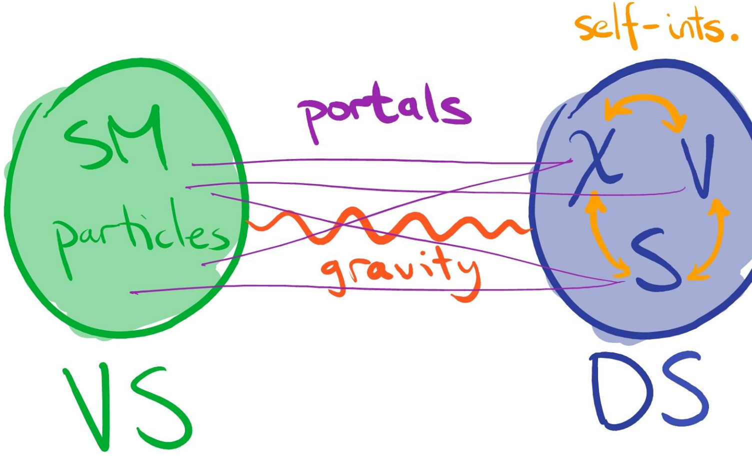
  - Experimental anomalies?
- Nature (**what?**)
  - Bosonic? Fermionic?
  - Dark Radiation? Interactions? **[Lan]** Portals?
  - Species: 1, 10^{32}? **[Peter (Tu)]**
  - Cold, warm?
  - Light **[Peter (Tu)]**, heavy, macro? **[Danny (M), Chuck (W)]**



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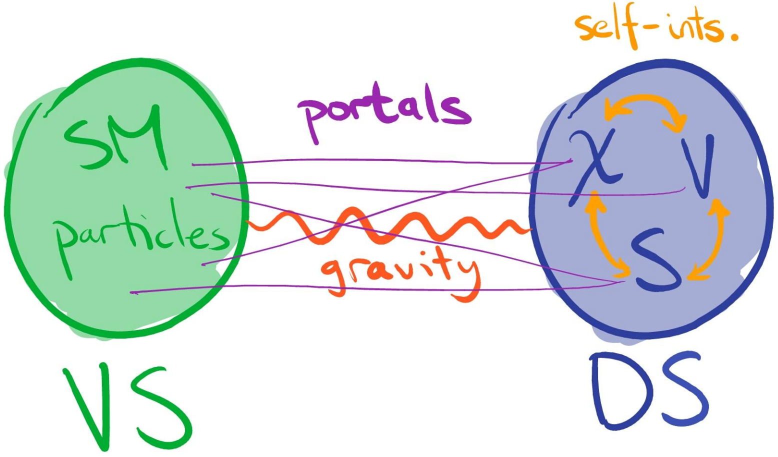
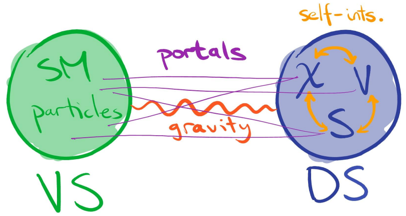
  - Species: 1, 10^{32}? **[Peter (Tu)]**
  - Cold, warm?
  - Light **[Peter (Tu)]**, heavy, macro? **[Danny (M), Chuck (W)]**
- Phenomena (**how?**)
  - Decays? Annihilations?
  - Collective phenomena? Phase Transitions?
  - New cosmic evolution?
  - ??????????????????????



DS: Interactions



- **Astrophysics:** Dark stuff is hard to probe: go to *extremes*
  - *Strong* gravitational interactions (e.g. superradiance in BHs **[Peter (Tu)]**, NS **[Davood (M)]**)
  - *Long* distances/times
    - E.g. axion dark matter decays stimulated by powerful radio sources over galactic distances [***MBA***, Fan, Sun 2110.13916, **github.com/ManuelBuenAbad/snr_ghosts**]
    - E.g. axion-photon conversion in intergalactic magnetic fields [***MBA***, Fan, Sun 2011.05993, **github.com/ManuelBuenAbad/cosmo_axions**]

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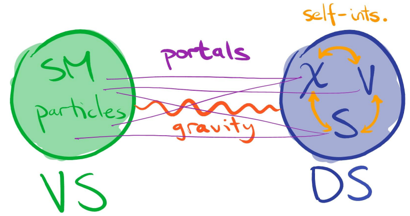

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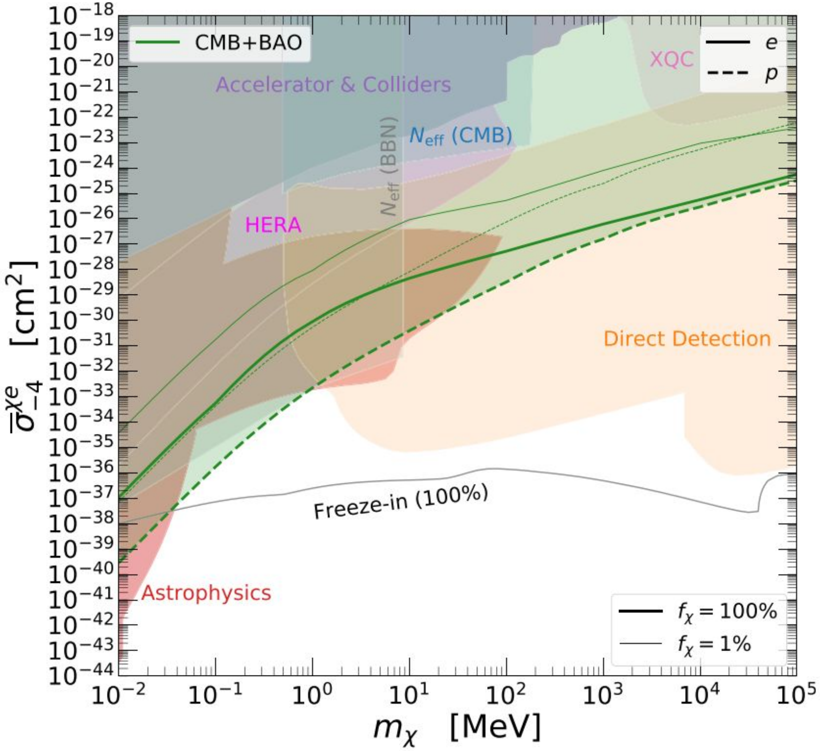
    - E.g. axion-photon conversion in intergalactic magnetic fields [***MBA***, Fan, Sun 2011.05993, **github.com/ManuelBuenAbad/cosmo_axions**]
- **Cosmology:** Dark Matter plays a central role in the evolution of the Universe
  - Age of precision cosmology: DS interactions with VS and within itself!
  - Vanilla (inert) CDM seems to work… but there are signs of cracks

II. Dark Sectors & Precision Cosmology

DM interactions with VS

- In ΛCDM: CDM and VS are coupled via gravity only
- Beyond ΛCDM: DM could interact with VS
  - Eg. via heavy/light mediator
  - Complicated thermal & perturbation history
- **DM–p:** early focus [Dvorkin et al. 1311.2937, Xu et al. 1802.06788, Boddy et al. 1808.00001]
- **DM–e:** recent developments [Ali-Haimoud 2101.04070, ***MBA*** et al. 2107.12377, Nguyen et al. 2107.12380]



Interactions within Dark Sectors

Remaining of This Talk

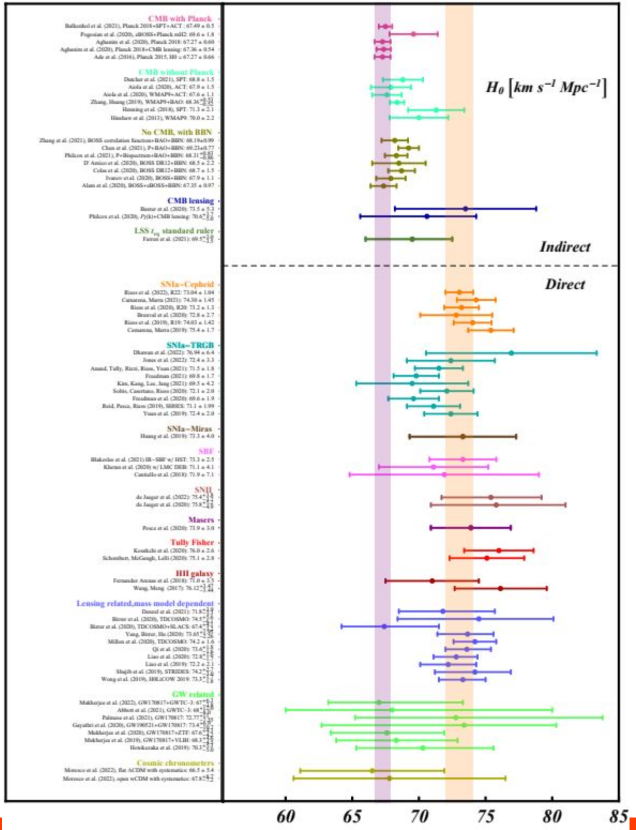
DS interactions with itself

MBA, **Chacko, Kilic, Marques-Tavares, Yuon [2208.xxxxx] (Monday!)**

- *Precision* cosmology: probe DS interactions
- Already signs of cracks in ΛCDM
  - ***H_0* tension:** rate of expansion of the Universe today
  - ***S_8* tension:** amplitude of mass fluctuations on scales of ***8 Mpc/h***

(O) Cosmological Tensions: H_o (~5σ)

- Early Universe
  - ΛCDM fits to CMB
  - **~68 km/s/Mpc** [Planck '18 1807.06209]
- Late Universe
  - Direct measurement w/ standard candles
  - **~73 km/s/Mpc** [Riess et al. 2112.04510]
- 200+ pages of Snowmass



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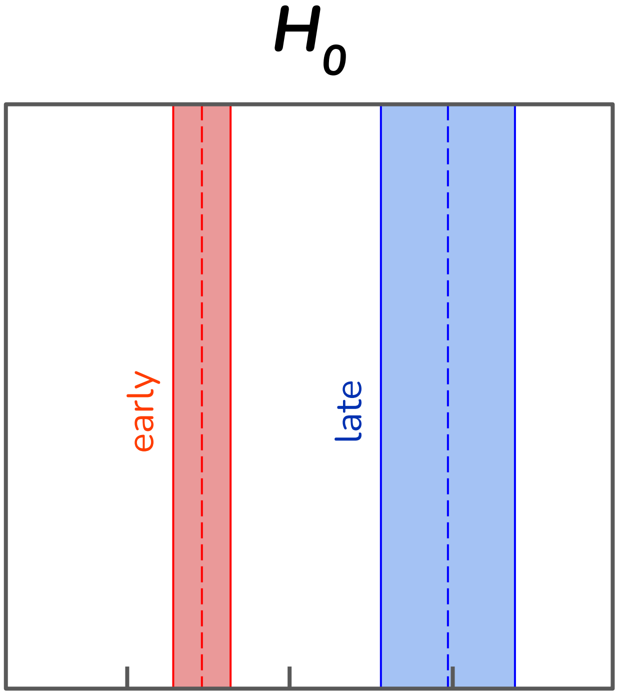
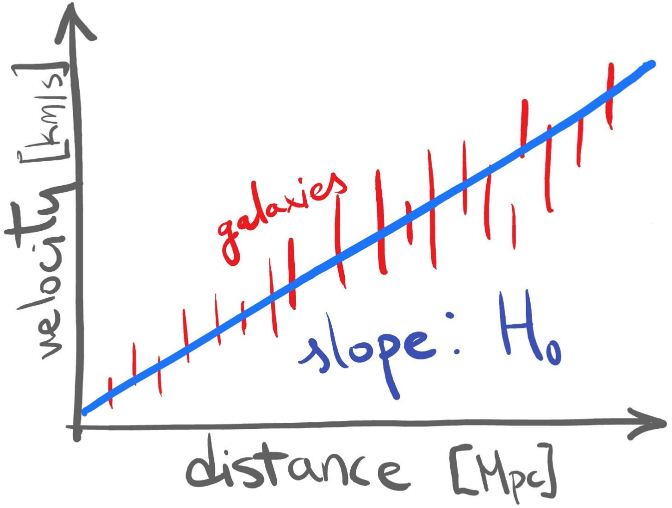
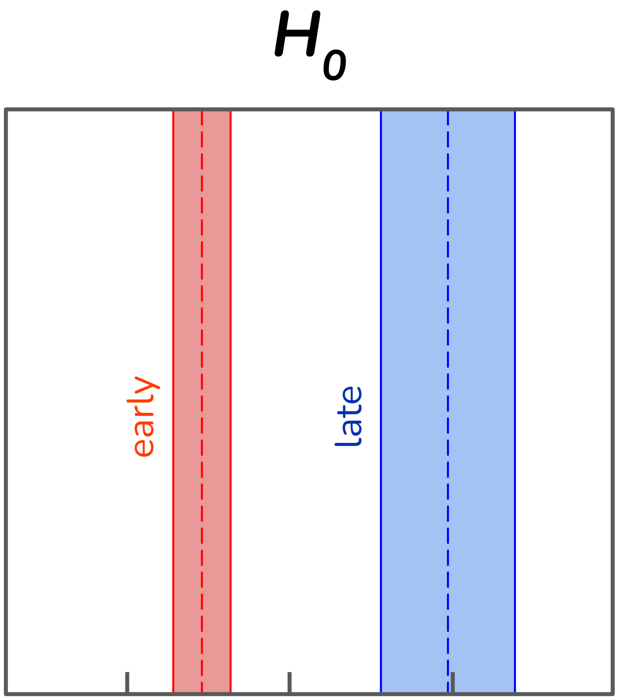
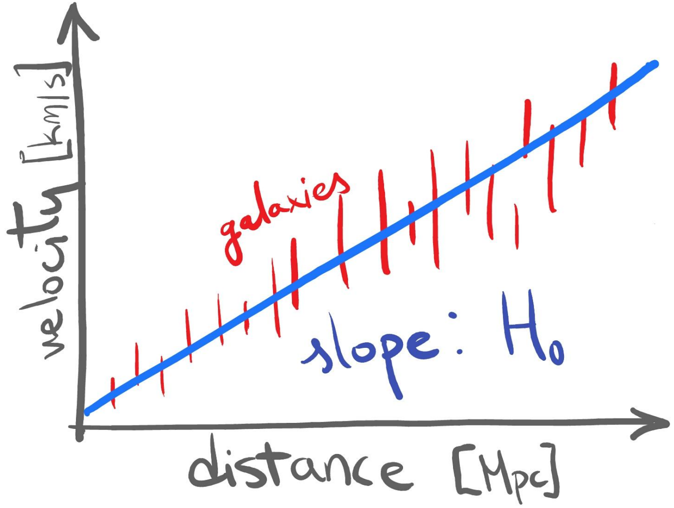


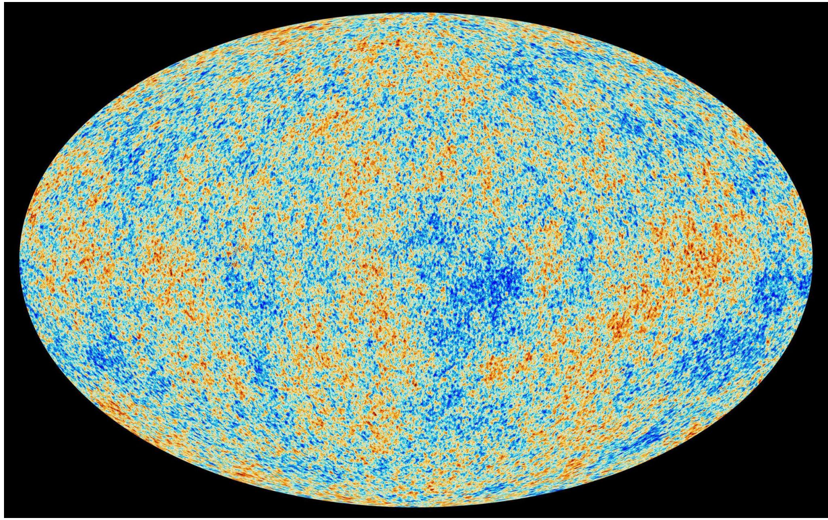
H_0 & r_s



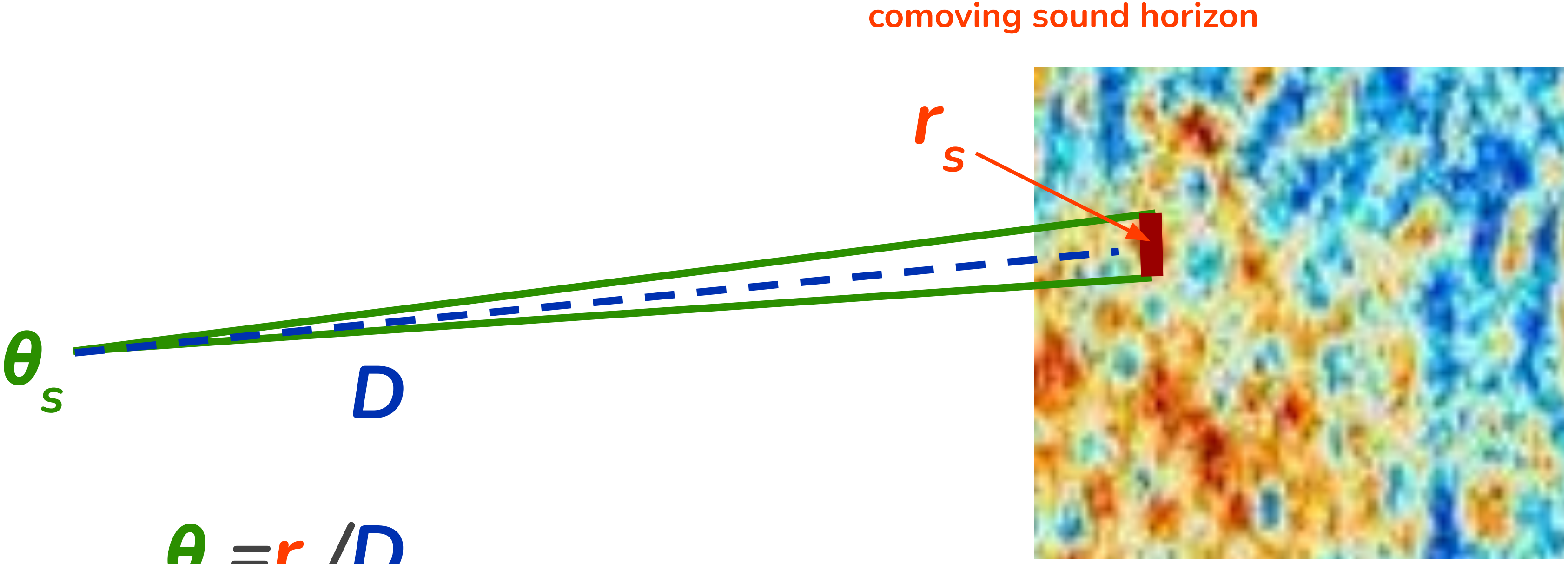


H_o & r_s





H_o & r_s

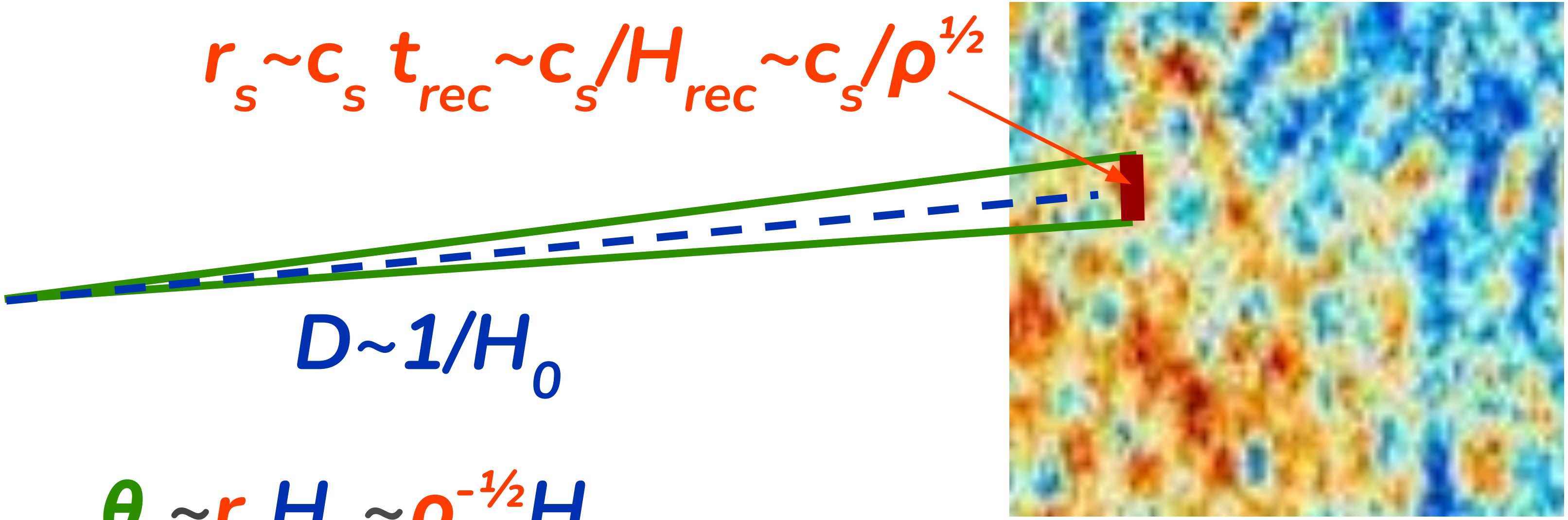


$\theta_s = r_s / D$

H_o & r_s

comoving sound horizon

$$r_s \sim c_s\, t_{rec} \sim c_s / H_{rec} \sim c_s / \rho^{1/2}$$

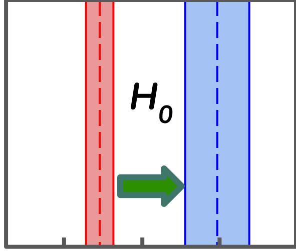


θ_s

$$D \sim 1/H_0$$

$$\theta_s \sim r_s H_0 \sim \rho^{-1/2} H_0$$

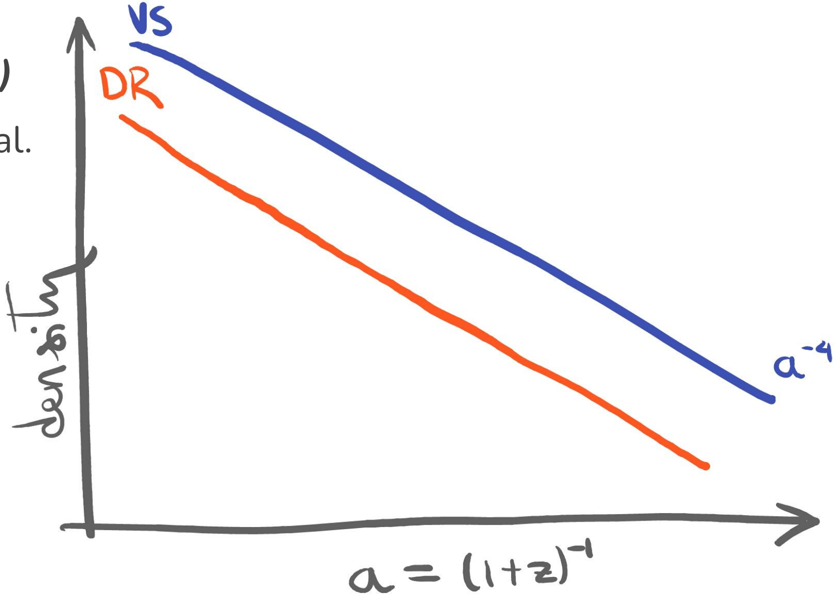
(N) A family of H_0 solutions



Enhance early H_0 measurement?

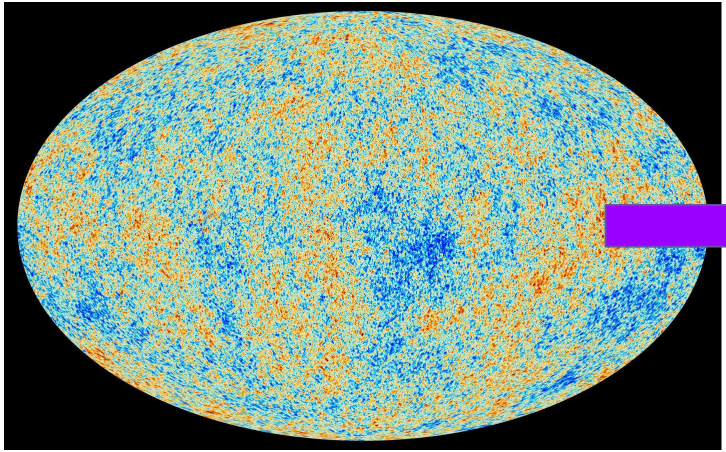
Additional energy density, most relevant around $z \sim O(10^3)$

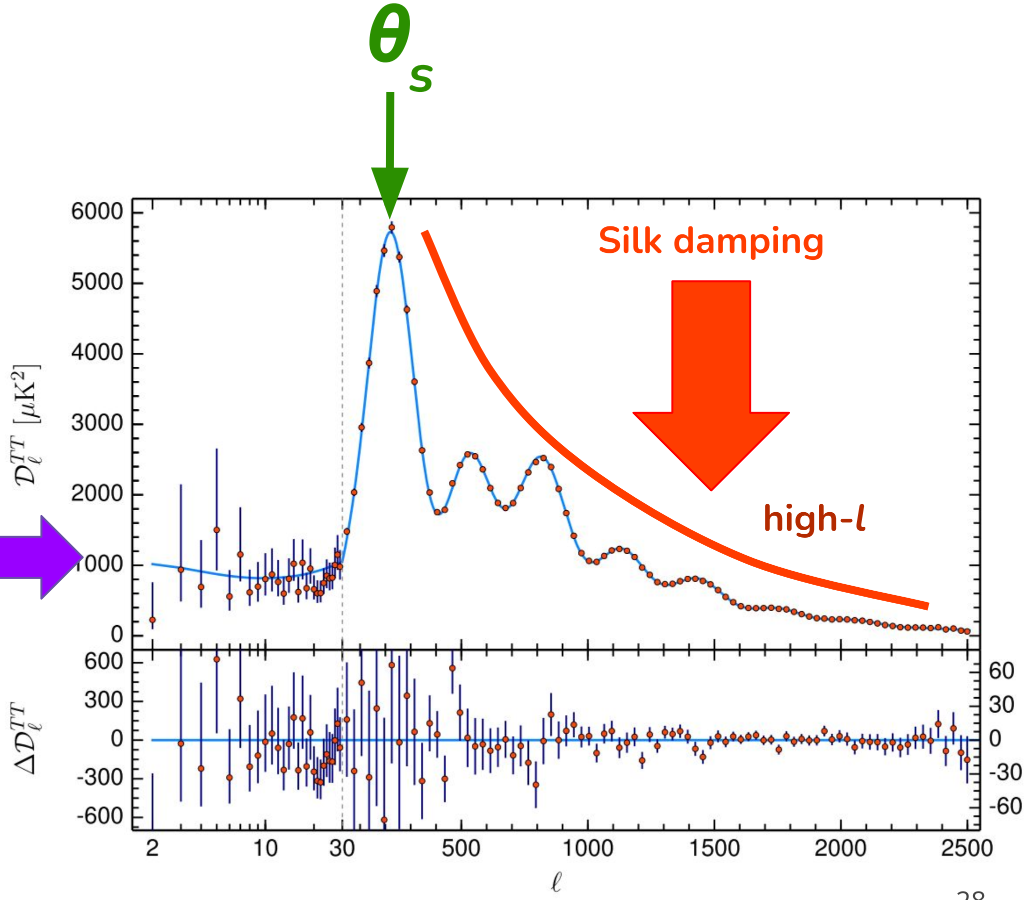
- E.g. Self-interacting Dark Radiation (DR) [Blinov et al. 2003.08387]



$$\theta_s \sim r_s H_0 \sim \rho^{-1/2} H_0$$

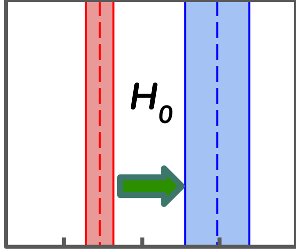
But…





θ_s
Silk damping
high-ℓ
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

(N) A family of H_0 solutions



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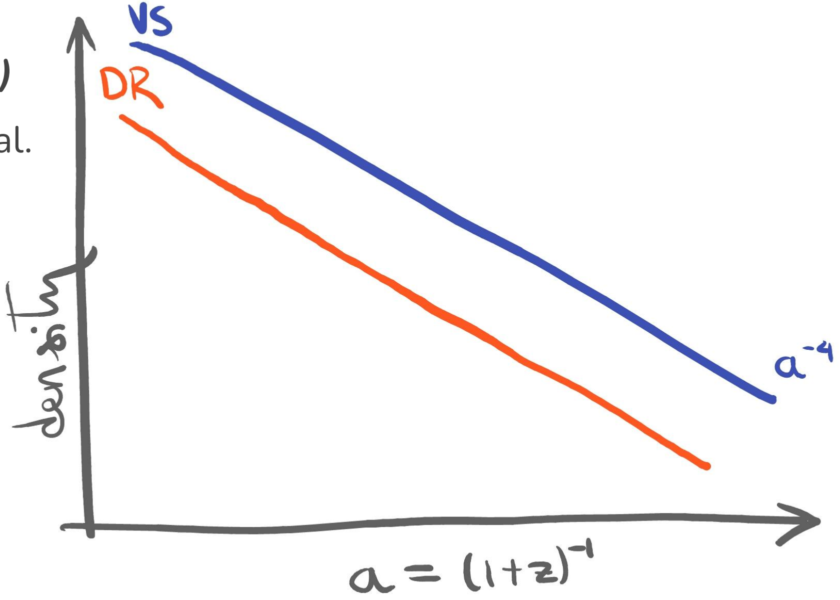
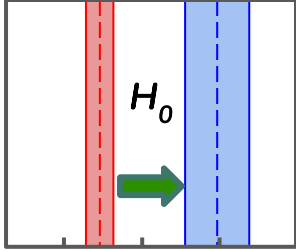
$$\theta_s \sim r_s H_0 \sim \rho^{-1/2} H_0$$



(N) A *better* family of H_0 solutions

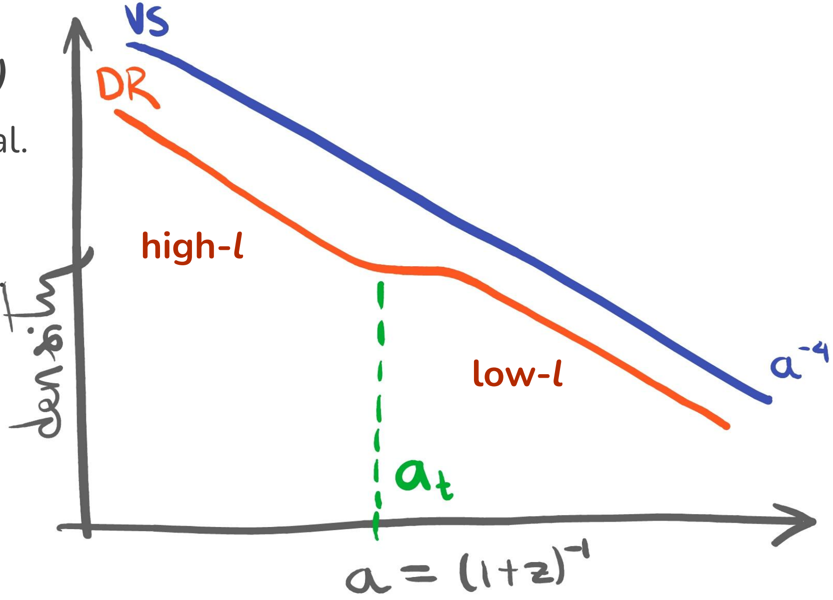


Enhance early H_0 measurement?

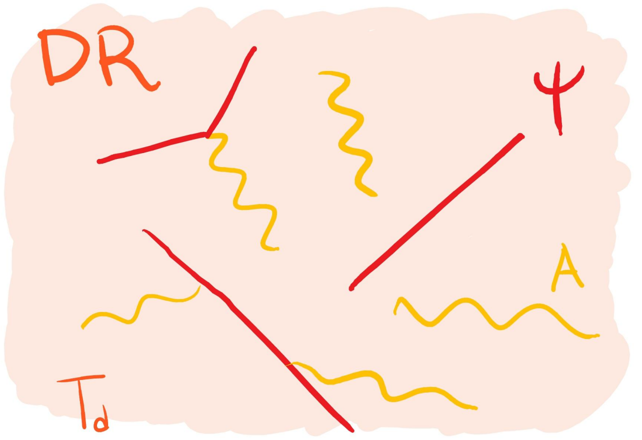
Additional energy density, most relevant around $z \sim O(10^3)$

- E.g. Self-interacting Dark Radiation (DR) [Blinov et al. 2003.08387]
- **Better**: with a **"*step*"** (preferred by data) [Aloni et al. 2111.00014]

$$\theta_s \sim r_s H_0 \sim \rho^{-1/2} H_0$$

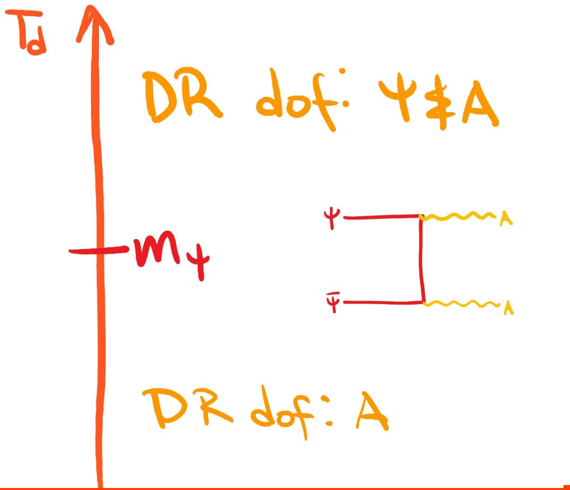


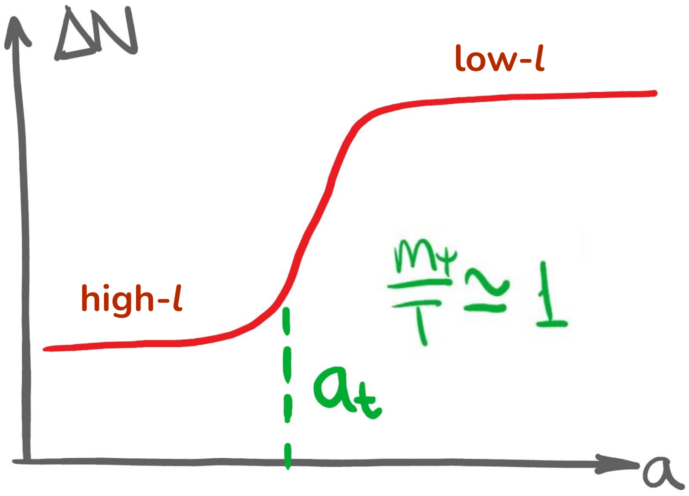
(P) Steps in DR



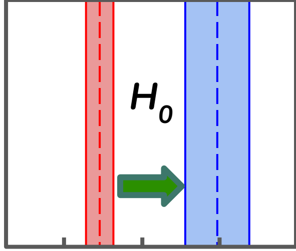
Entropy dump in DR sector

- Typical of mass thresholds in thermal baths (à la freeze-out)
- ⇒ implies multi-particle DR

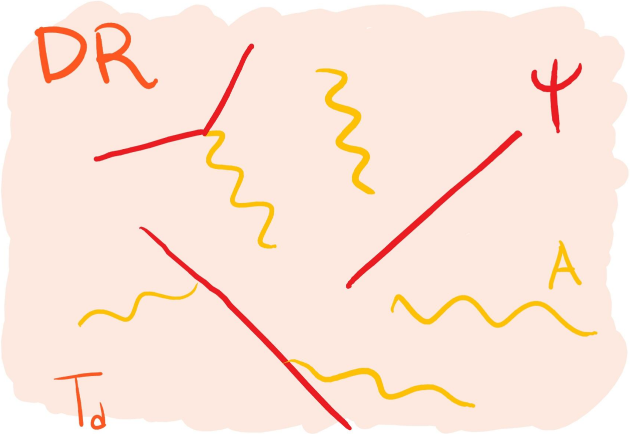


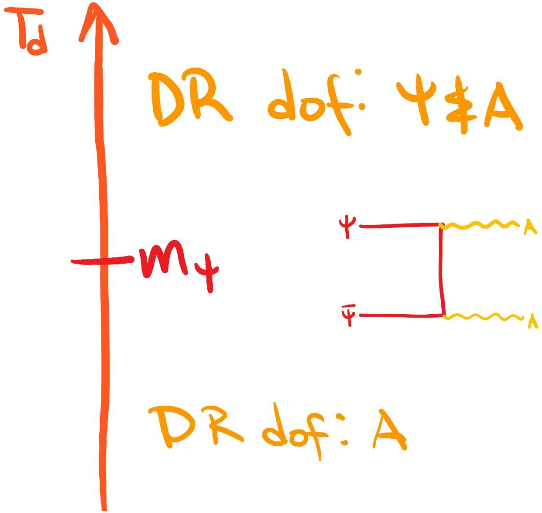


H_0 summary



- **(O)** H_0, ultimately r_s (CMB)
- **(N)** Extra DR, with a step
- **(P)** DR with multiple interacting components, and a mass threshold





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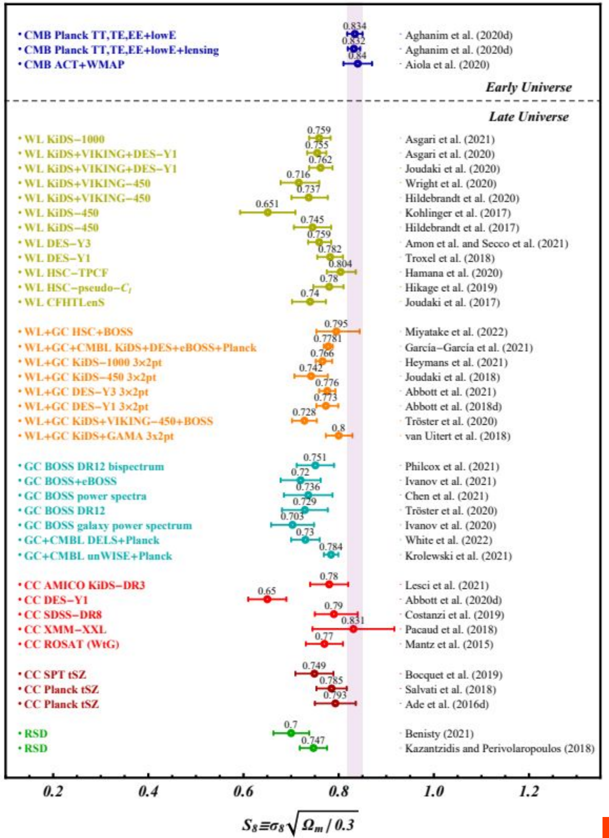
- Early Universe
  - ΛCDM fits to CMB
  - ~**0.83** [Planck '18 1807.06209]
- Late Universe
  - Direct measurements (e.g. weak lensing)
  - ~**0.76** [KiDS '21 2010.16416; DES '21 2105.13544 2105.13543]
- 200+ pages of Snowmass



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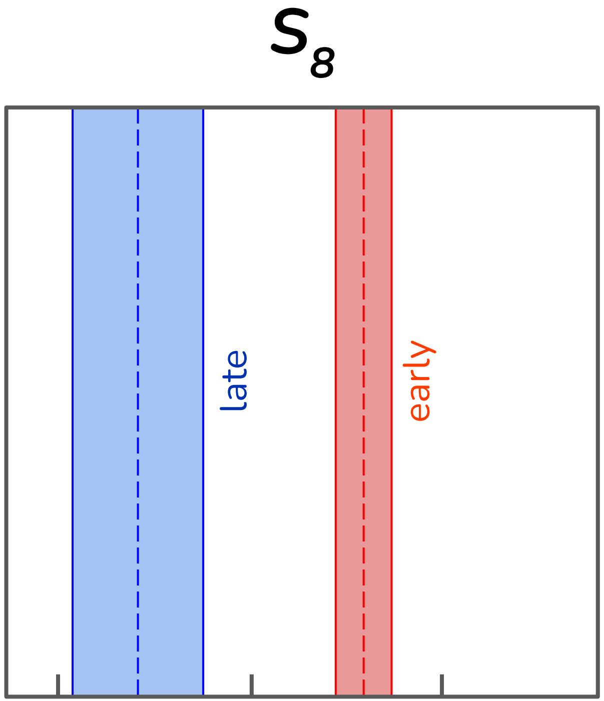
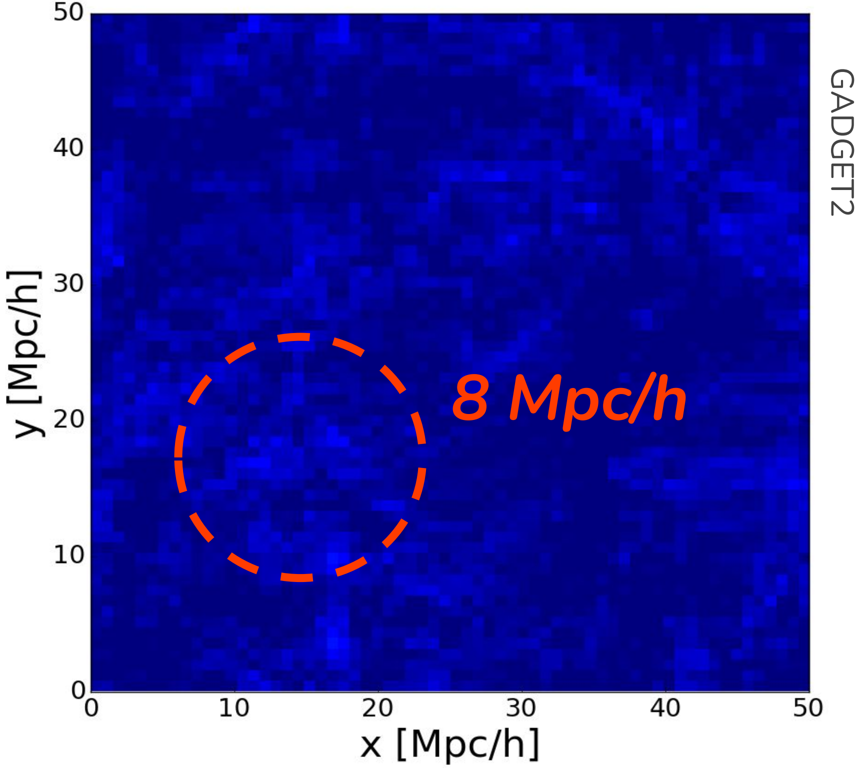
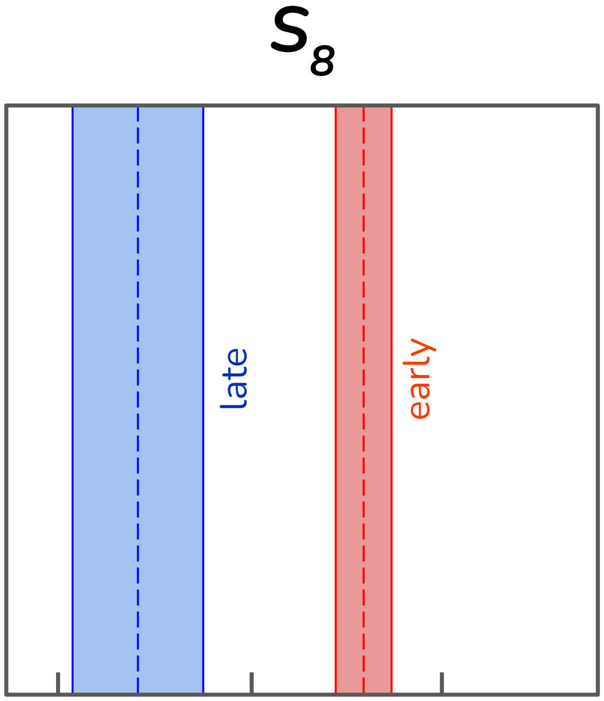


Structure formation





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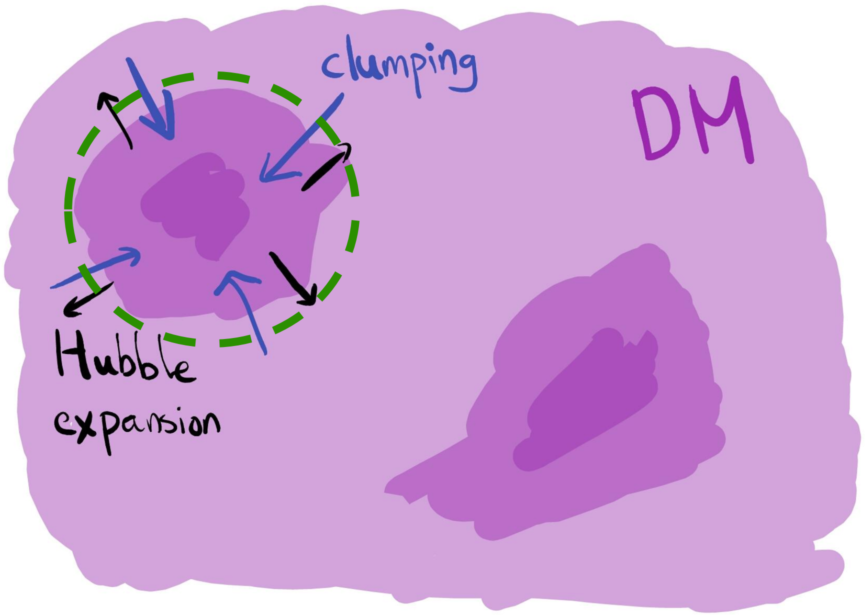
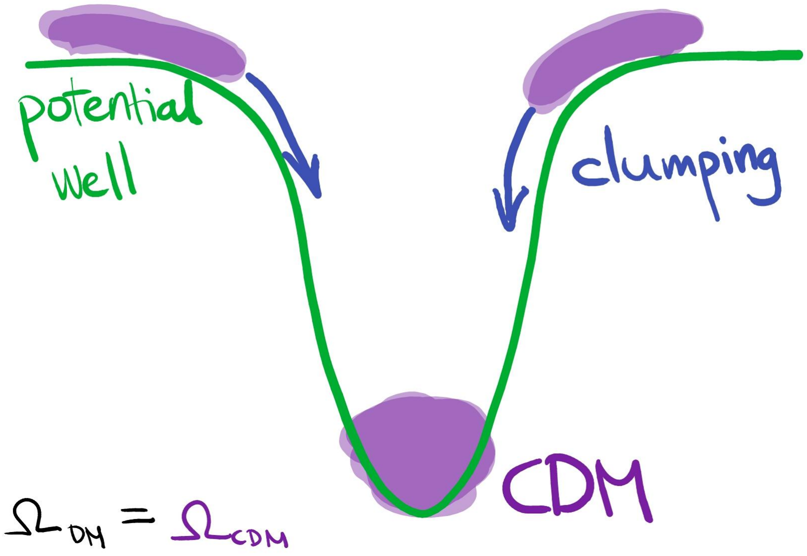
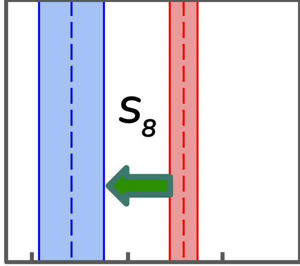
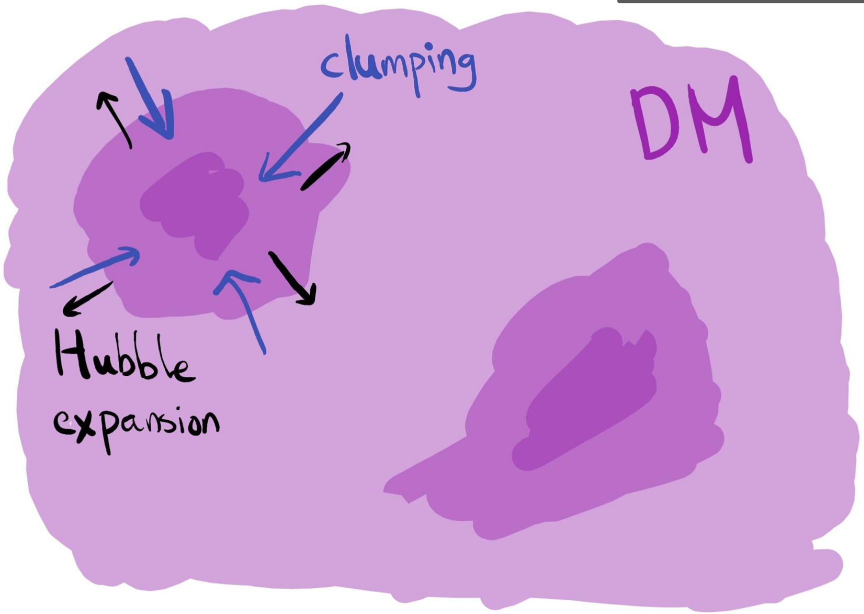




(N) A family of S_8 solutions





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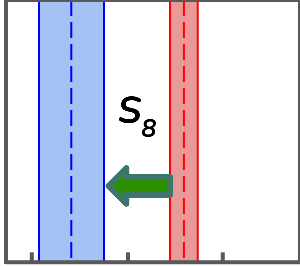
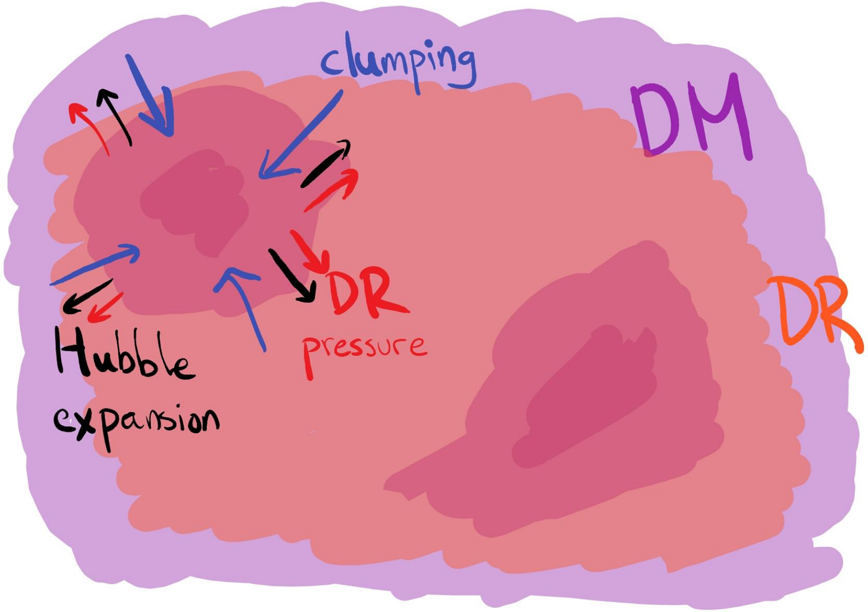
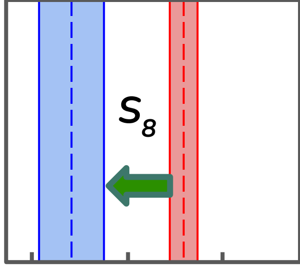


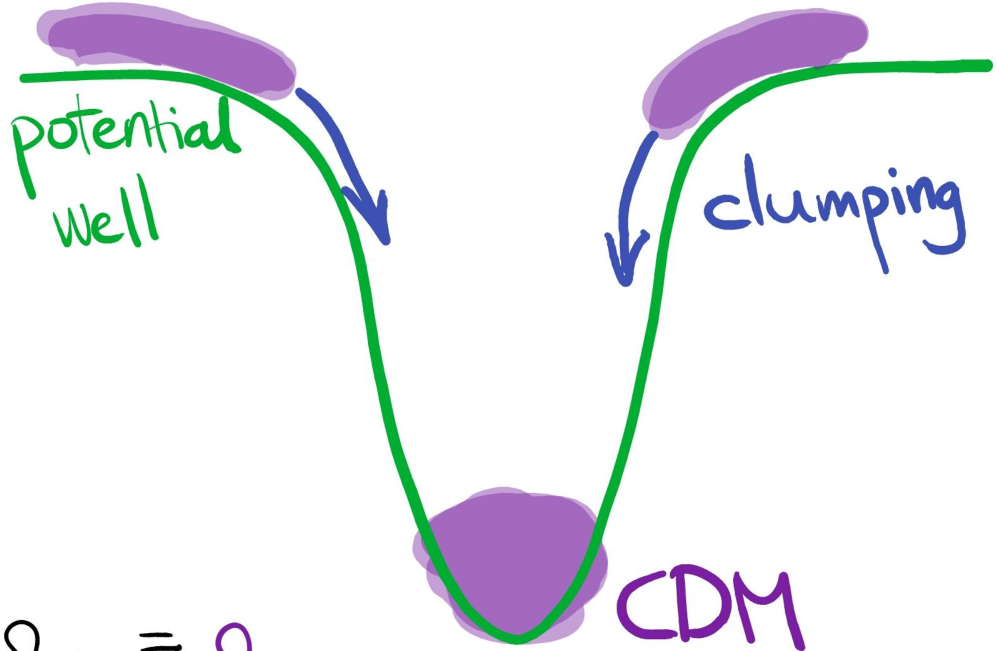
Dark Matter interacting with Dark Radiation: DR provides *pressure* on DM

- ***Weakly-coupled limit*** [**MBA** et al. 1505.03542, Lesgourgues et al. 1507.04351]
- ***Tightly-coupled limit***: [Chacko et al. 1609.03569, **MBA** et al. 1708.09406]



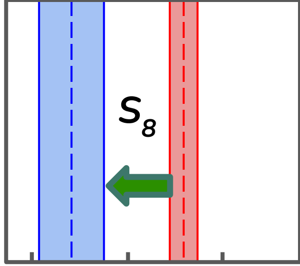
Tightly-coupled DM–DR

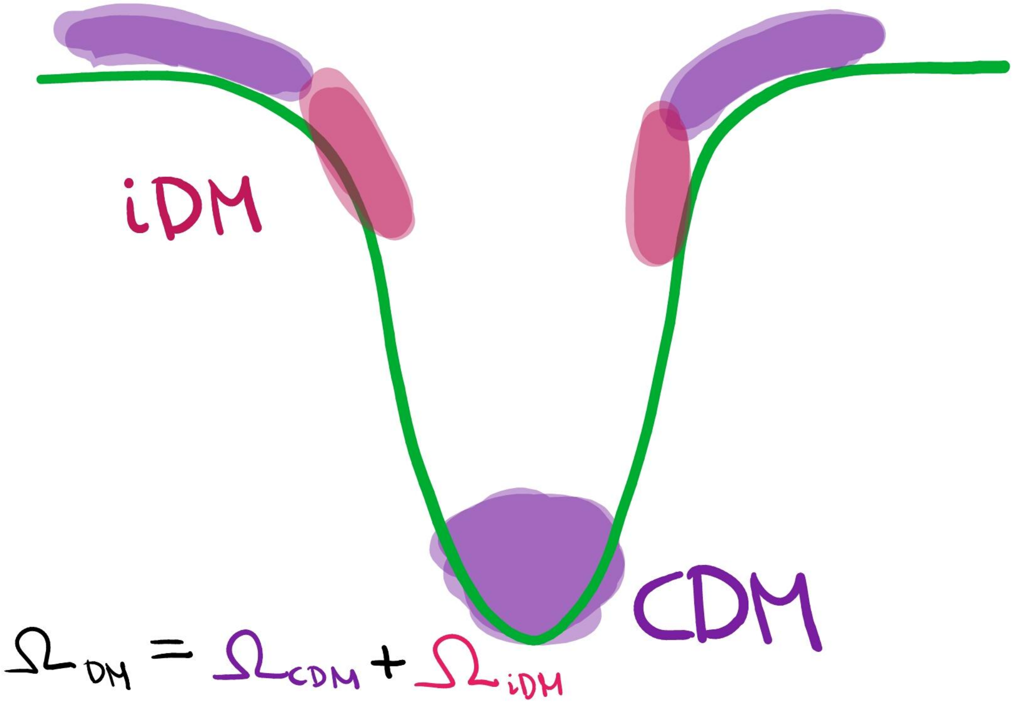




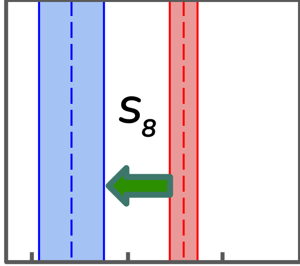
$\Omega_{DM} = \Omega_{CDM}$

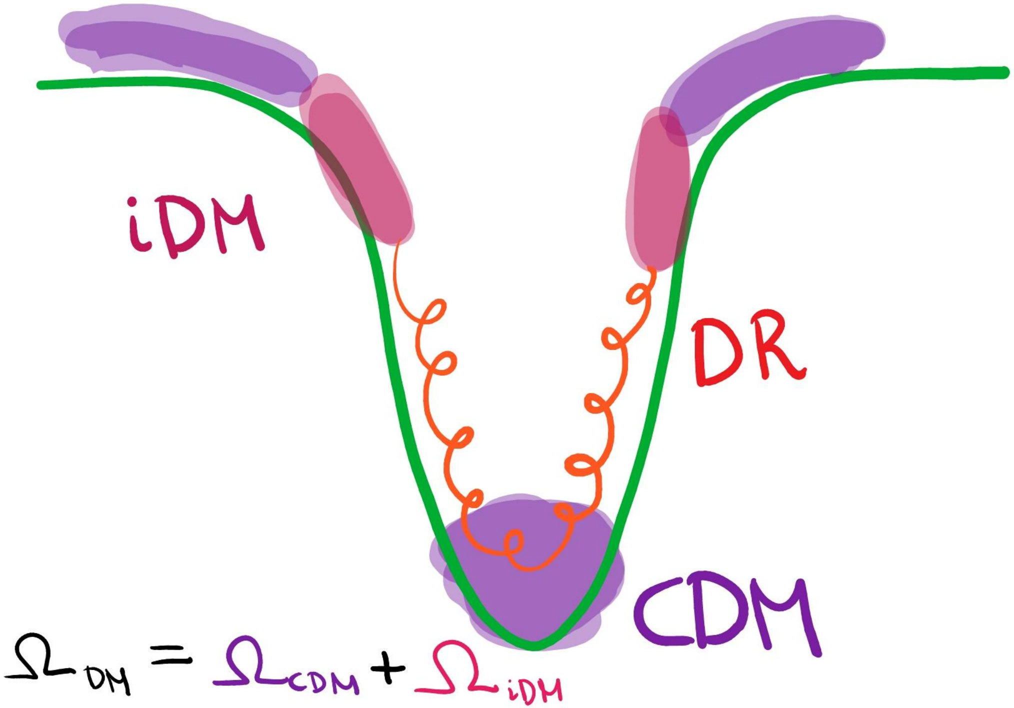
Tightly-coupled DM–DR



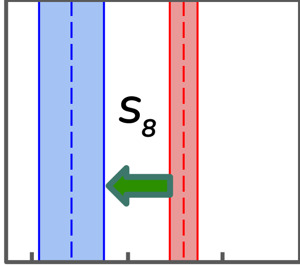


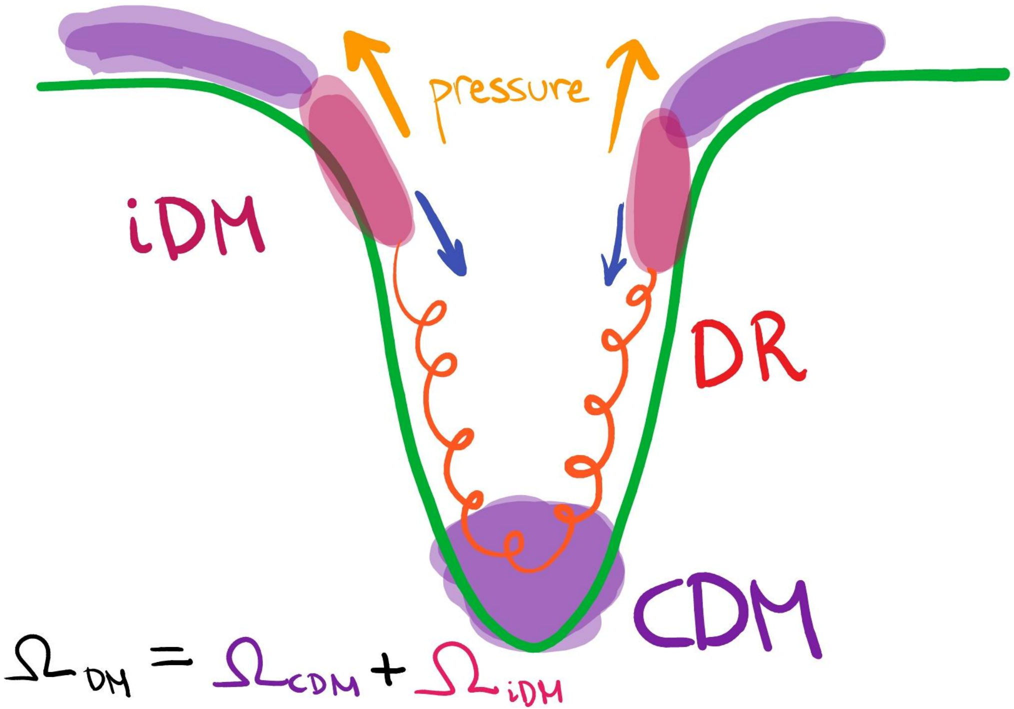
Tightly-coupled DM–DR



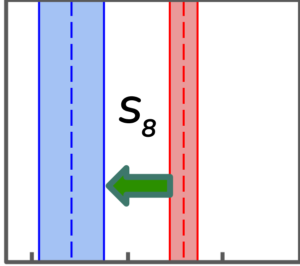


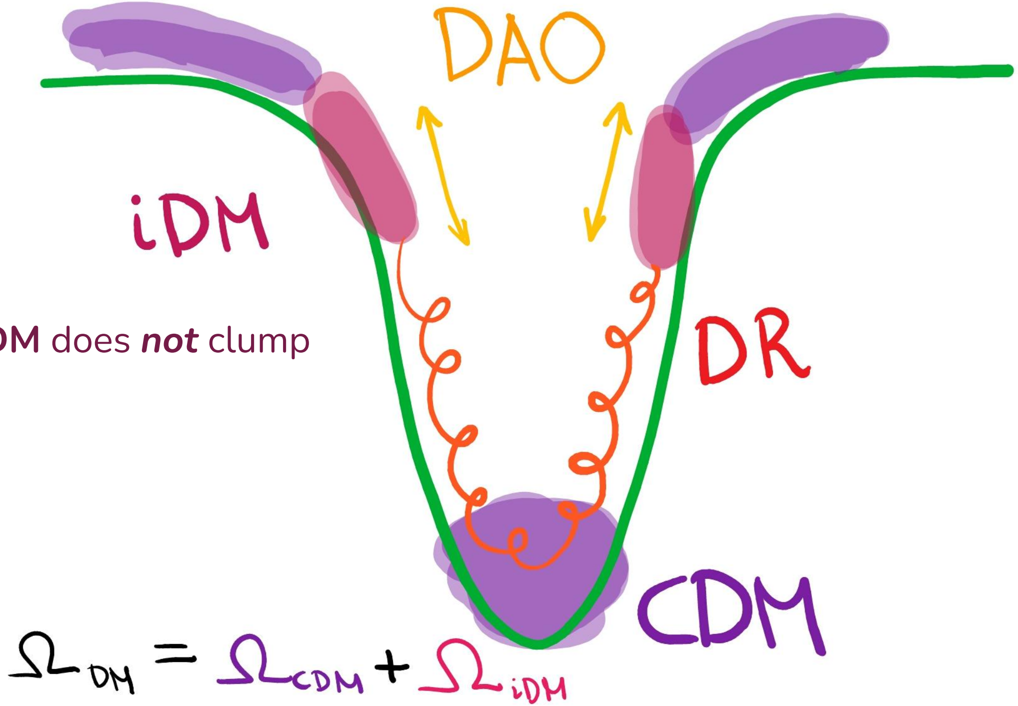
Tightly-coupled DM–DR





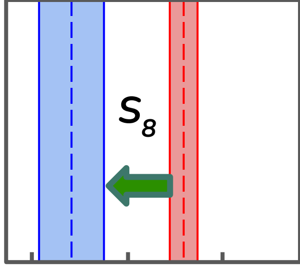
Dark Acoustic Oscillations

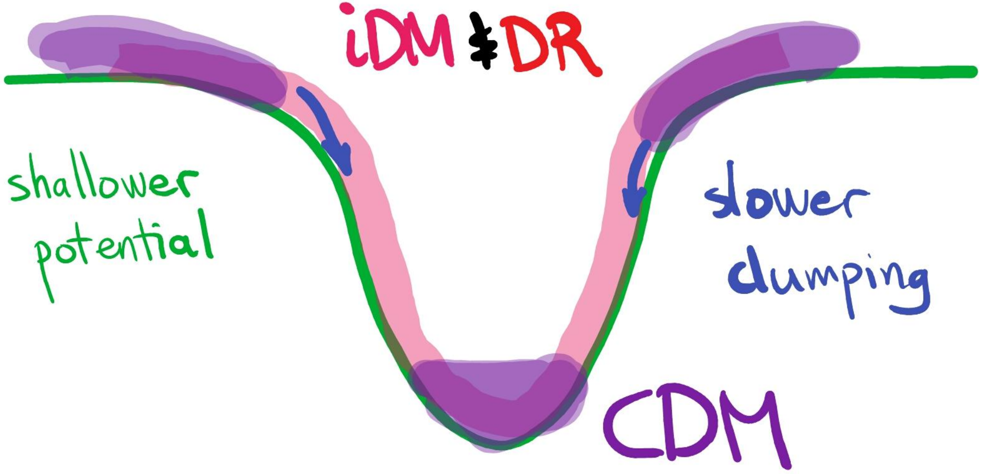




⇒ **iDM** does ***not*** clump

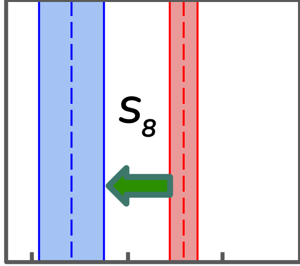
Structure Suppression



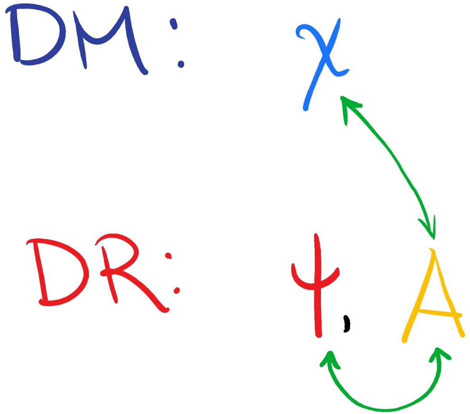


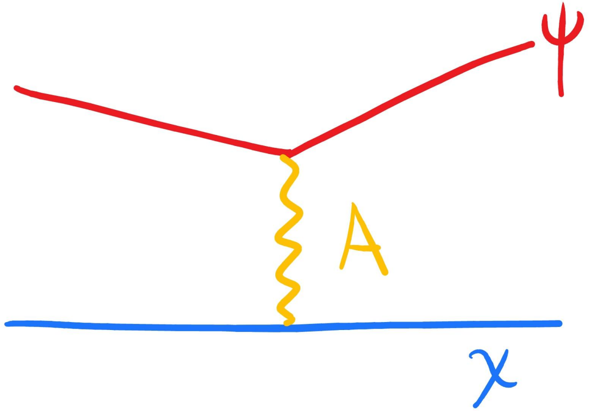
$$\Omega_{DM} = \Omega_{CDM} + \Omega_{iDM}$$

(P) Dark Acoustic Oscillations

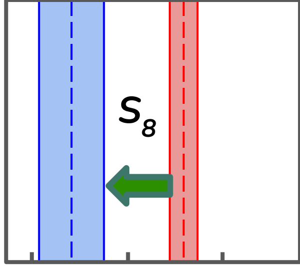


- DM charged under gauge bosons making up DR:
  - Sufficiently large coupling: DR pressure prevents clumping of DM

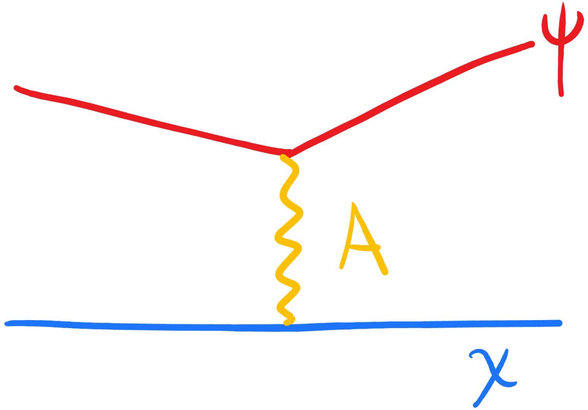


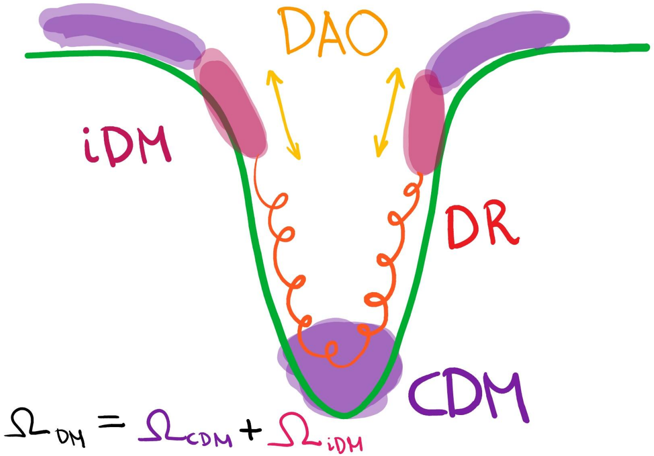


S_8 summary



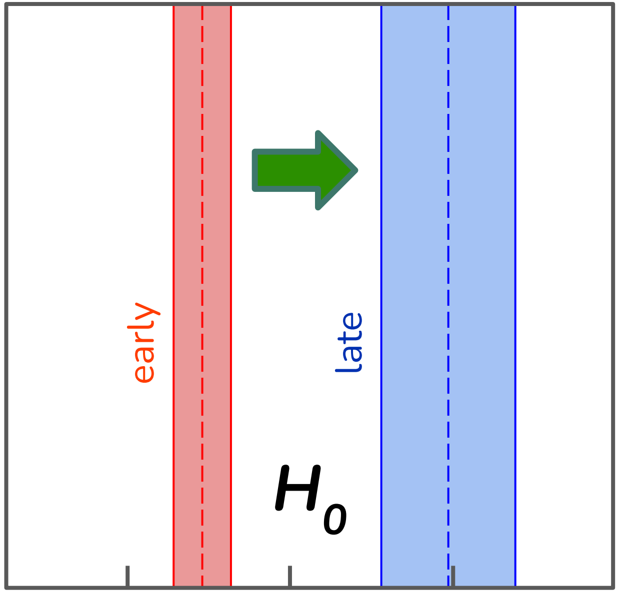
- **(O)** S_8: suppression of large-scale structure (LSS)
- **(N)** Tightly-coupled DM–DR
- **(P)** DM charged under DR

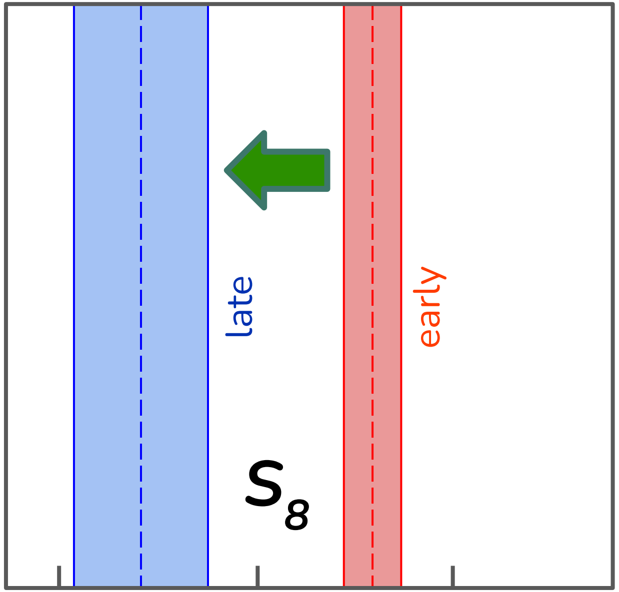




H_0 & S_8 together?

Enhance early measurement of H_0 & *decrease* early measurement of S_8?





H_0 & S_8 together: SPartAcous

Enhance early measurement of H_0 & *decrease* early measurement of S_8?

Stepped Partially Acoustic Dark Matter

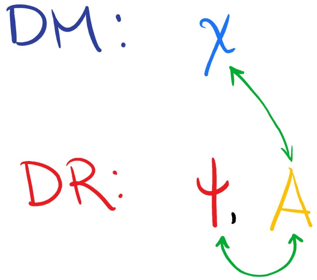
MBA, Chacko, Cilic, Marques-Tavares, Yuon [2208.xxxxx] (Monday!)

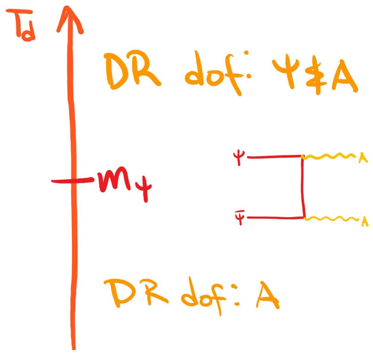
A good step with dark acoustics!

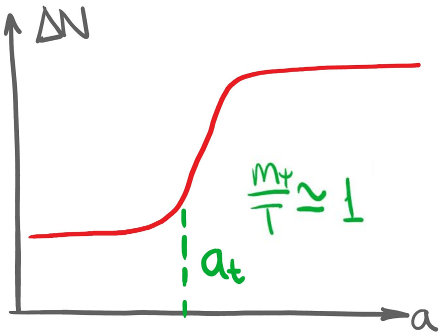
- **(O)** CMB, LSS; cosmological H_0 & S_8 tensions
- **(N)** DS=tightly-coupled DM+DR; DR has mass threshold
- **(P)** Late-time entropy dump in DS; DAOs

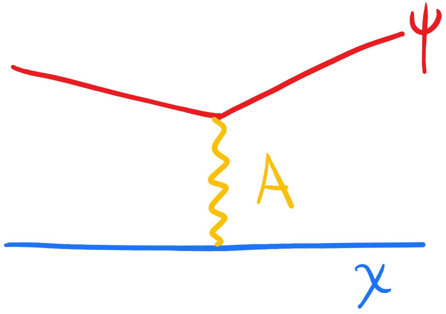
SPartAcous

Stepped **Part**ially **Acous**tic Dark Matter



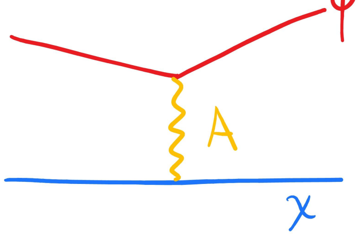




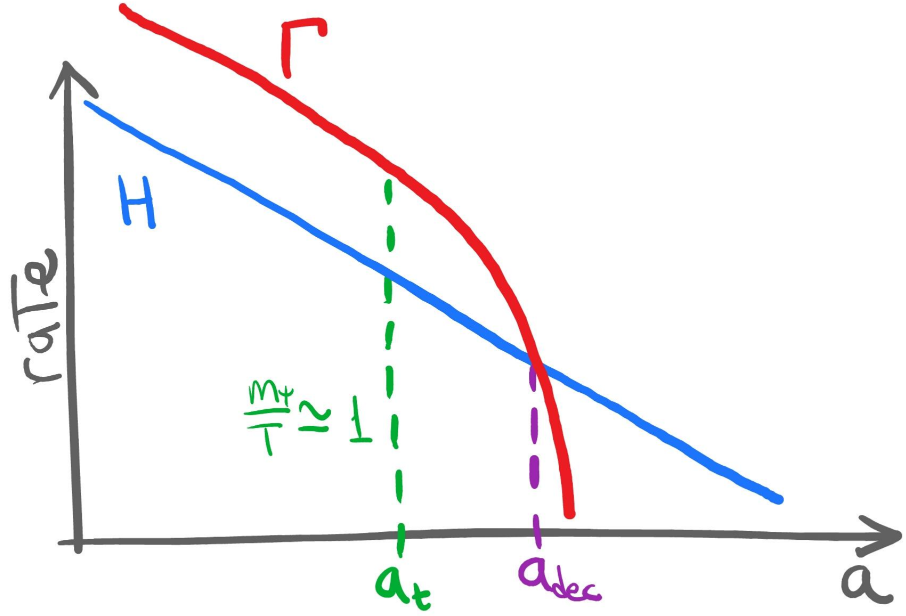


$$\delta\mathcal{L}_{\rm dark} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{\psi}(i\not{D} - m_\psi)\psi + |D\chi|^2 - m_\chi^2|\chi|^2$$

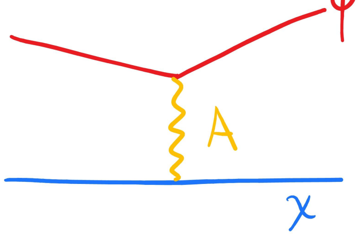
SPartAcous



$$\Gamma = \frac{4}{3\pi}\,\alpha_d^2\,\ln(4/\langle\theta_{\min}\rangle^2)\,\frac{T_d^2}{m_\chi}\,e^{-m_\psi/T_d}\left[2+\frac{m_\psi}{T_d}\left(2+\frac{m_\psi}{T_d}\right)\right]$$



SPartAcous



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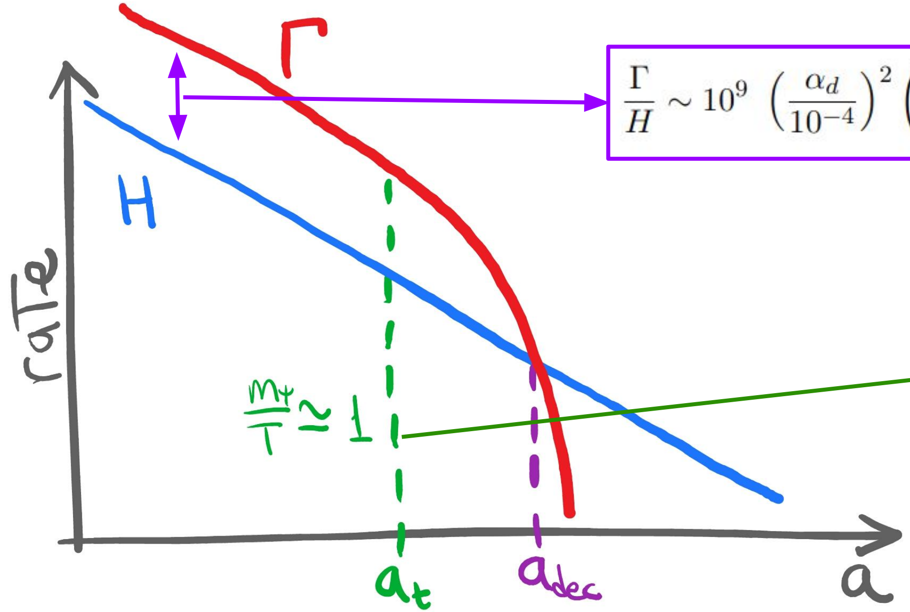
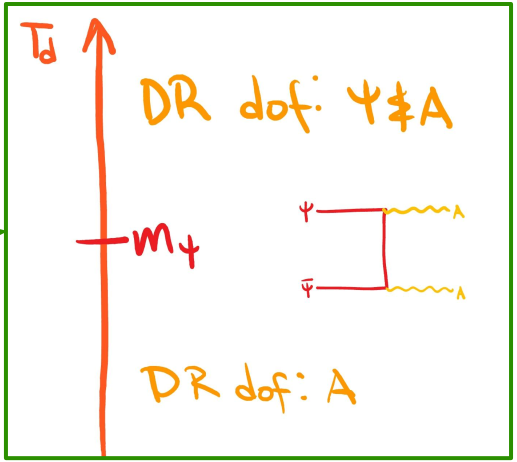
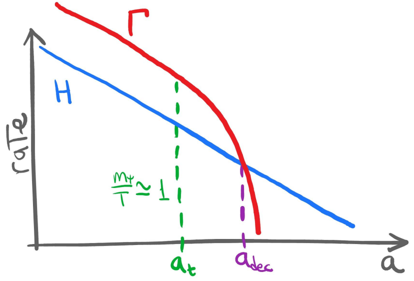
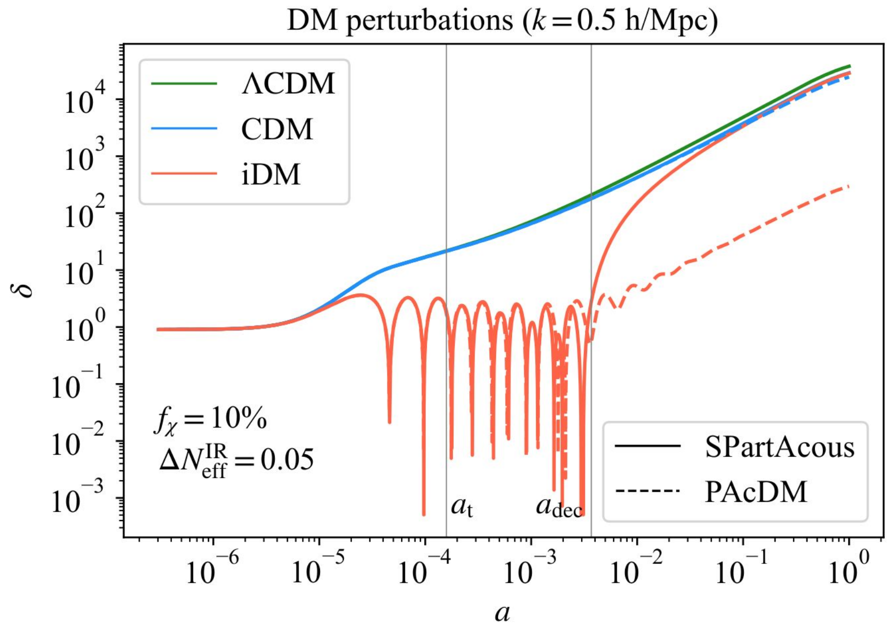


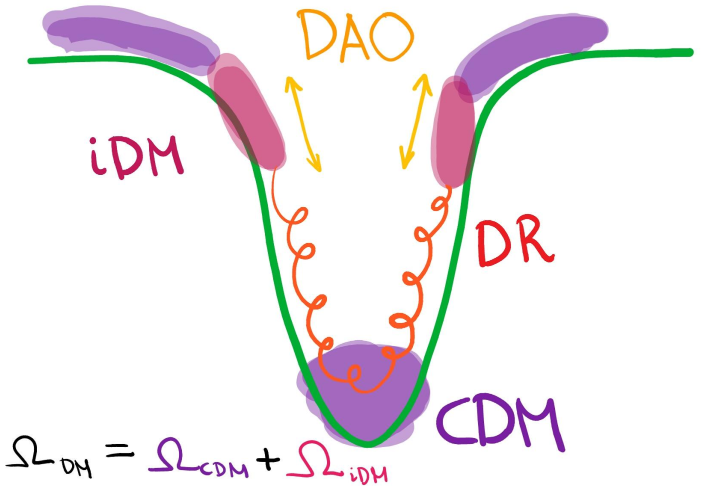
$$\frac{\Gamma}{H} \sim 10^9 \left(\frac{\alpha_d}{10^{-4}}\right)^2 \left(\frac{10^3\ \text{GeV}}{m_\chi}\right)$$



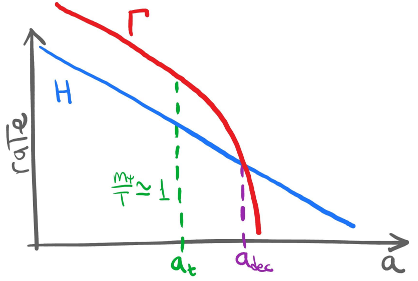
Dark Acoustic Oscillations

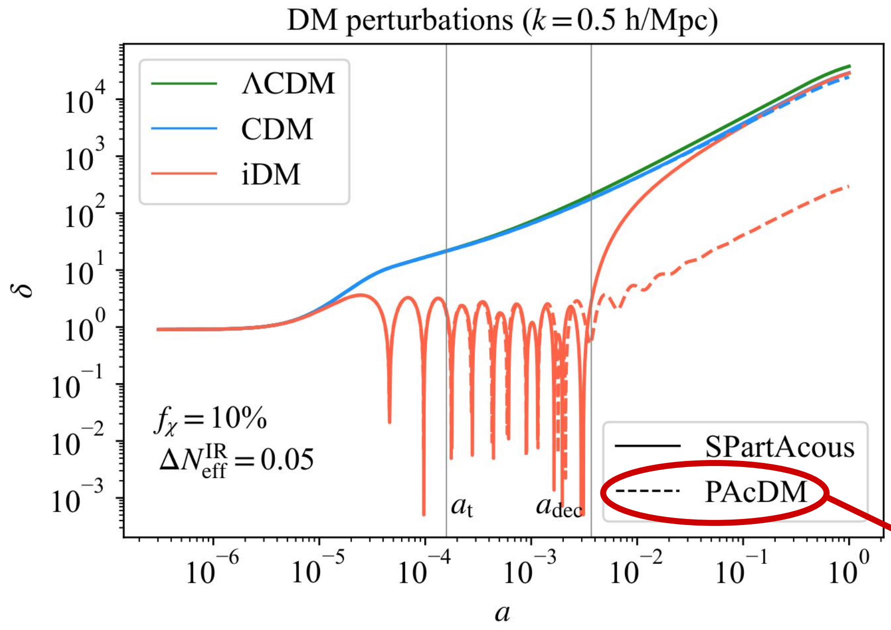


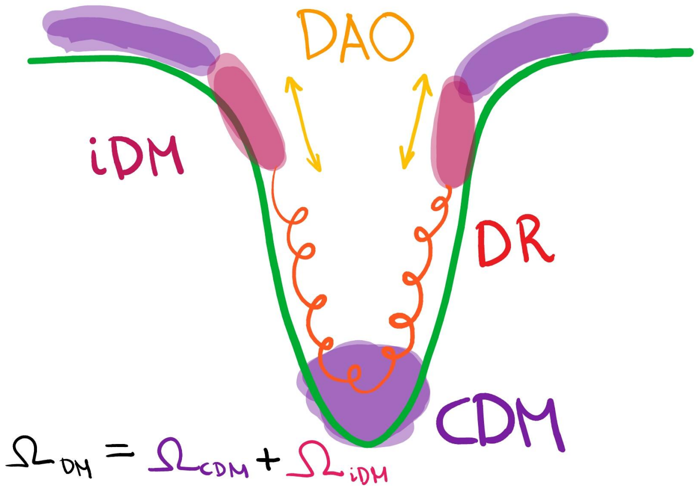




Dark Acoustic Oscillations







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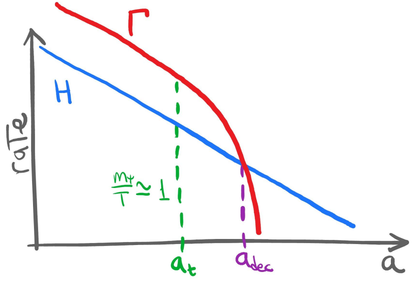
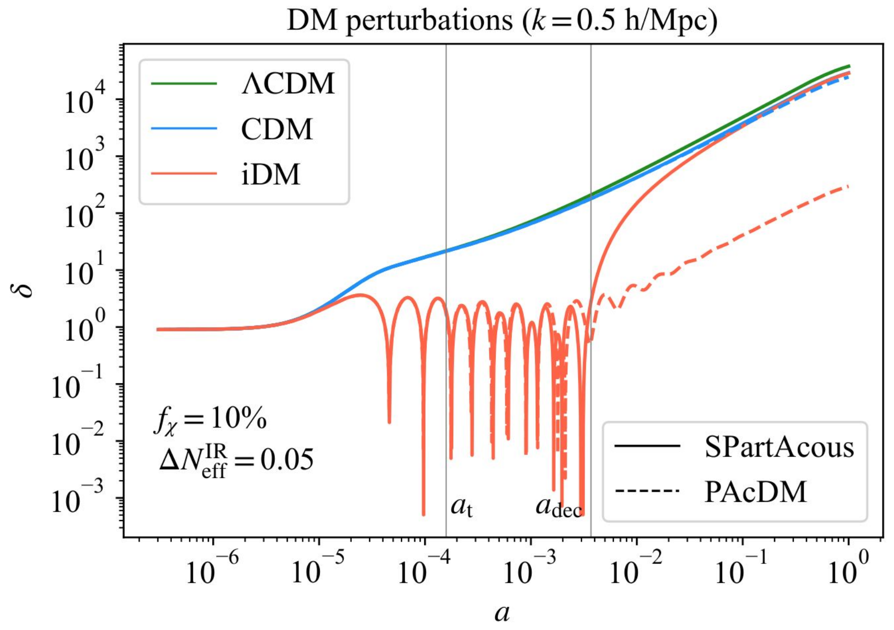
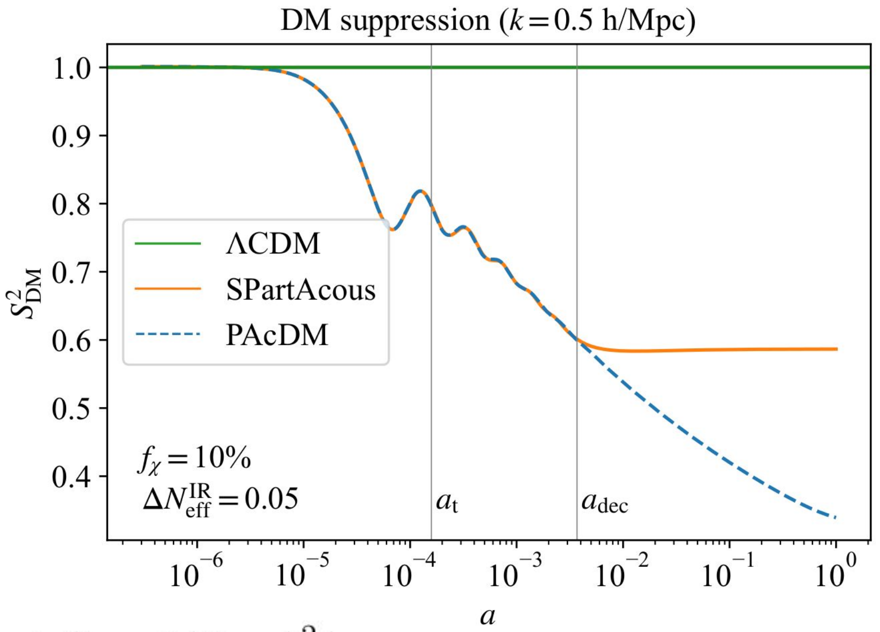
Dark Acoustic Oscillations

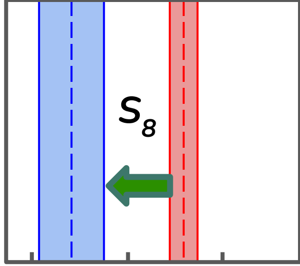


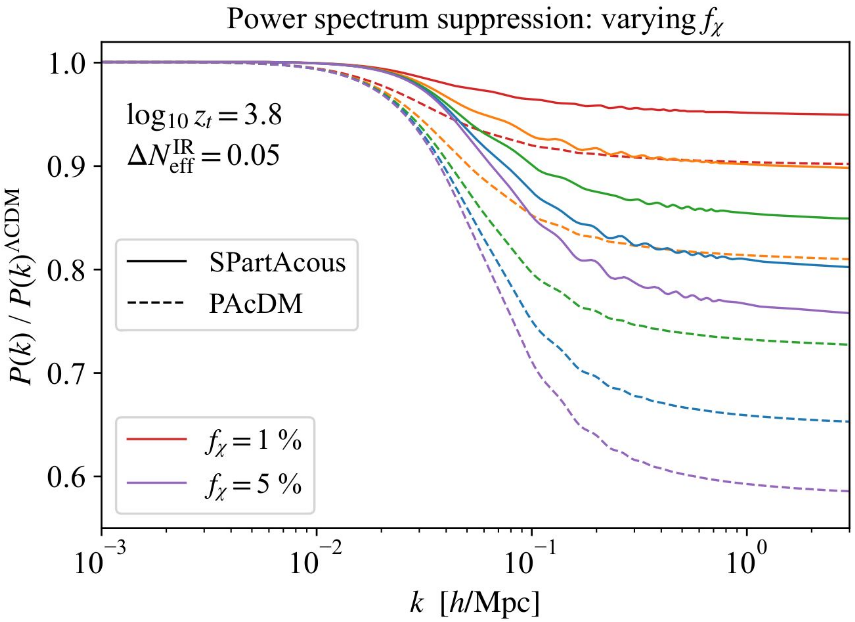


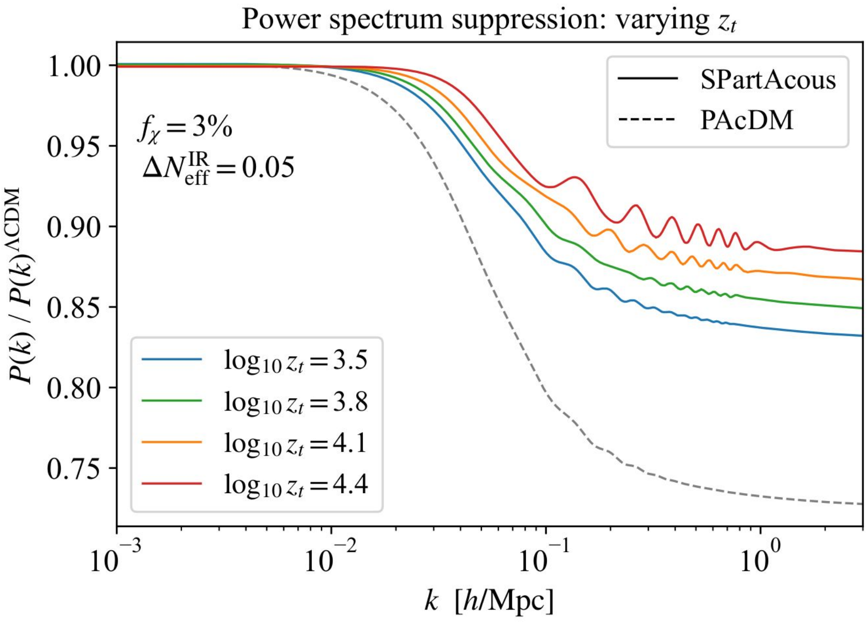


$$S^2_{\rm dm} \equiv \frac{(f_\chi \delta_{\rm idm} + (1 - f_\chi)\delta_{\rm cdm})^2 |_{\rm model}}{\delta^2_{\rm cdm}|_{\Lambda\rm CDM}}$$

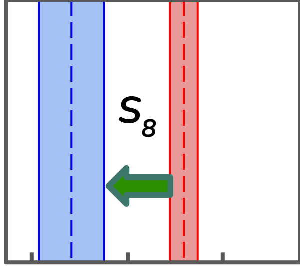
Dark Acoustic Oscillations

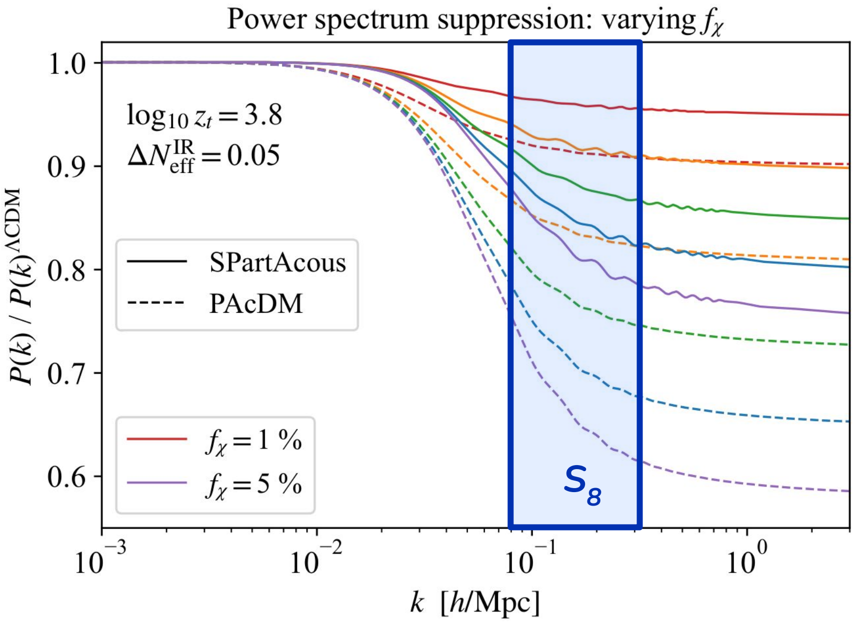


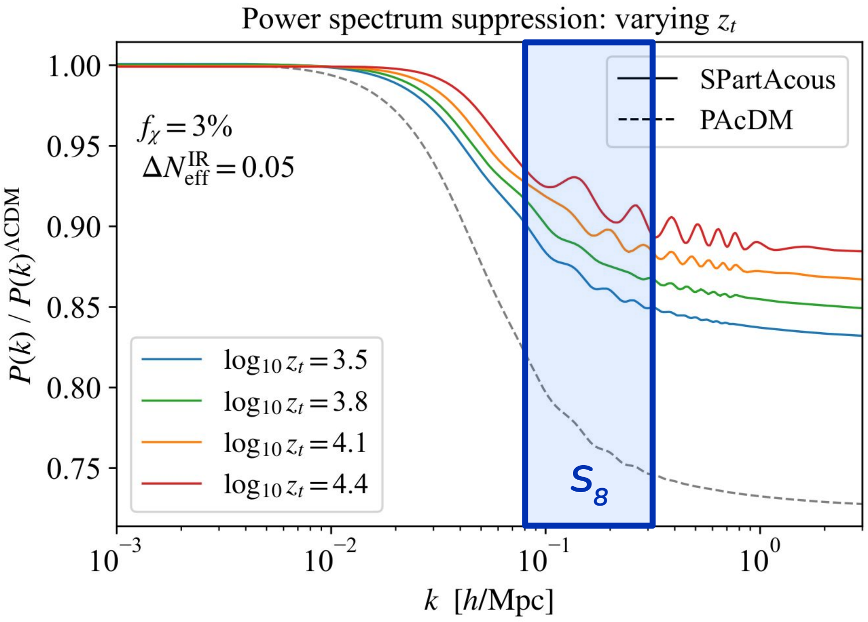




Dark Acoustic Oscillations







Conclusions

- Non-trivial Dark Sectors are well motivated
- Probing DS:
  - Astrophysics and Cosmology
  - DS–VS & DS–DS interactions
- Cracks in ΛCDM: H_0 (too small) & S_8 (too large)
  - Stepped DR
  - DM–DR interactions
- SPartAcous is promising (stay tuned for *premiere* Monday!)
- **SPartAcous Part II: MCMC** coming up in arXiv!

Backup Slides

Index

I: A Step with Dark Acoustics

arXiv:2208.xxxxx [Monday!]

II: Axion Echos from the Supernova Graveyard

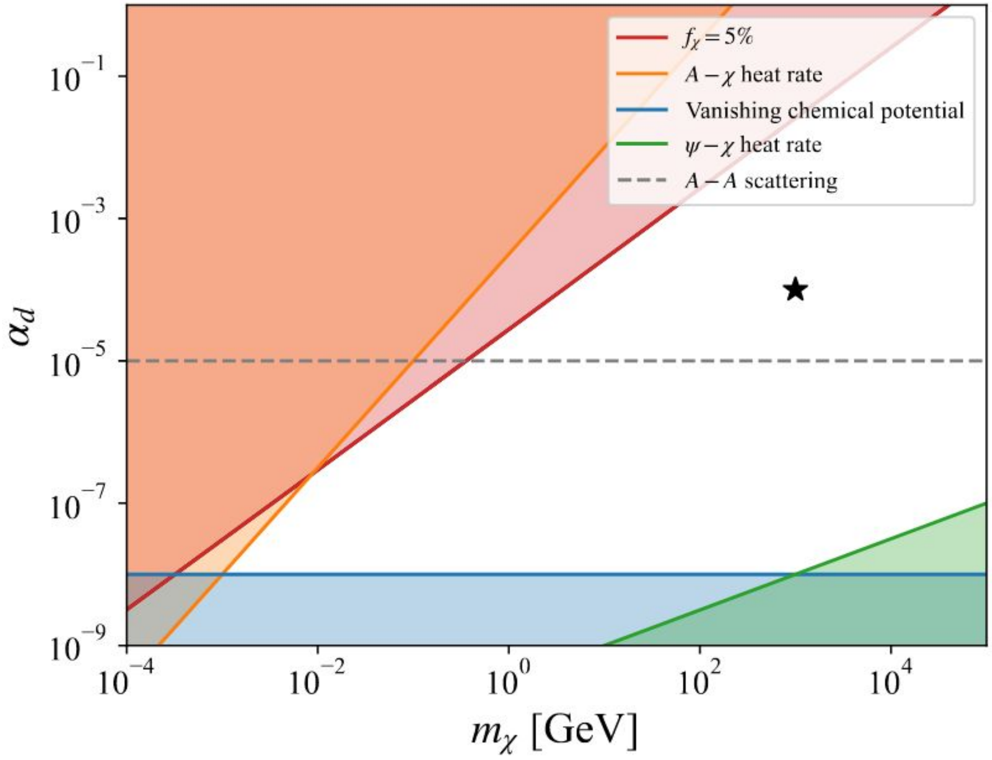
arXiv:2110.13916; PRD

I. Dark Acoustics

arXiv:2208.xxxxx [Monday]

MBA, Z. Chacko, C. Kilic, G. Marques-Tavares, & T. Youn

Parameter Space



Perturbation Equations

$$\dot{\delta}_{\rm idm} = -\theta_{\rm idm} + 3\dot{\phi}\,,$$

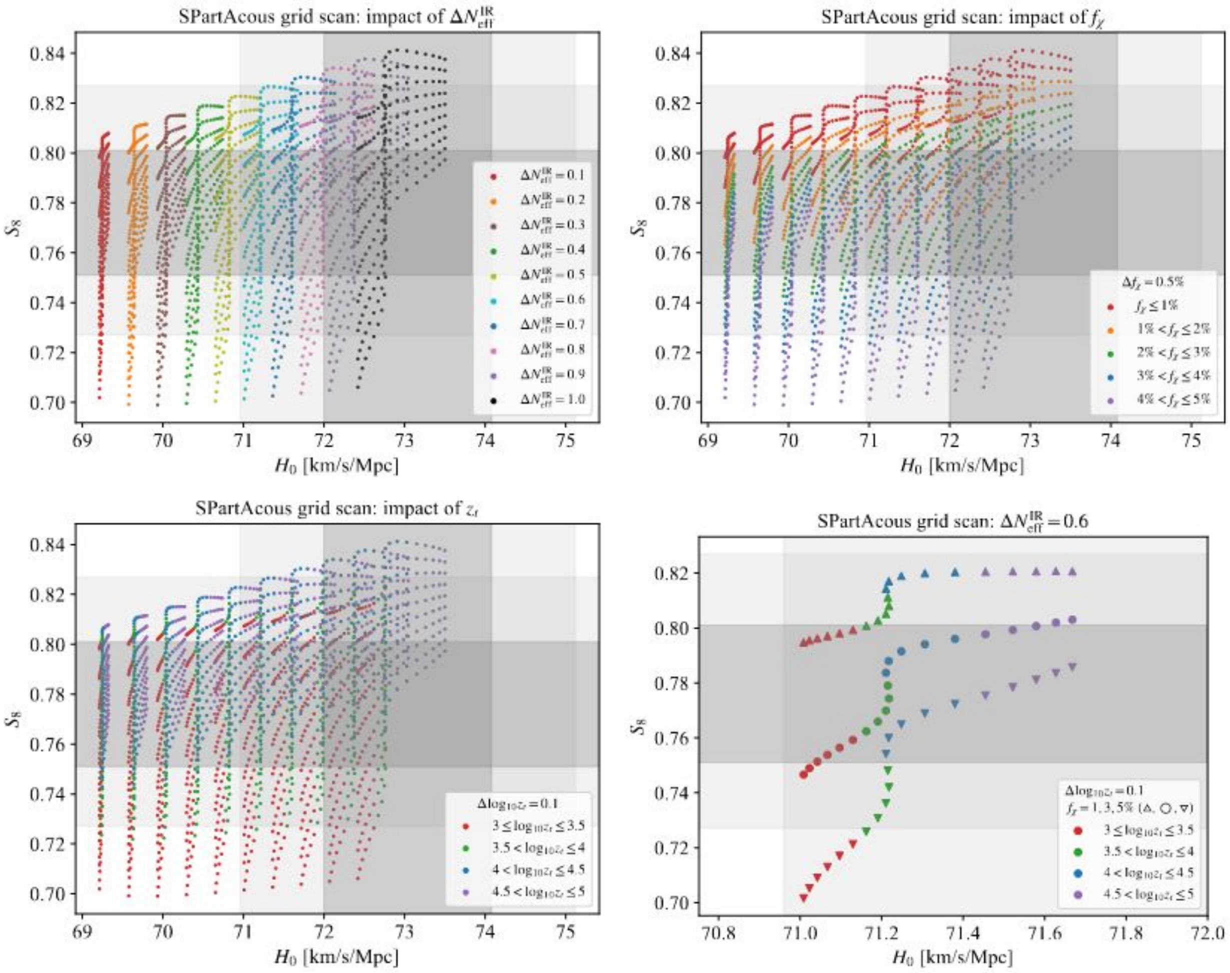
$$\dot{\theta}_{\rm idm} = -\mathcal{H}\theta_{\rm idm} + k^2\psi + a\Gamma\left(\theta_{\rm dr} - \theta_{\rm idm}\right),$$

$$\dot{\delta}_{\rm dr} = -(1+w)(\theta_{\rm dr} - 3\dot{\phi}) - 3\mathcal{H}\left(c_s^2 - w\right)\delta_{\rm dr}\,,$$

$$\dot{\theta}_{\rm dr} = -\left[(1-3w)\mathcal{H} + \frac{\dot{w}}{1+w}\right]\theta_{\rm dr} + k^2\left(\frac{c_s^2}{1+w}\delta_{\rm dr} + \psi\right) + \frac{\rho_{\rm idm}}{\rho_{\rm dr}(1+w)}\,a\Gamma(\theta_{\rm idm} - \theta_{\rm dr})\,.$$

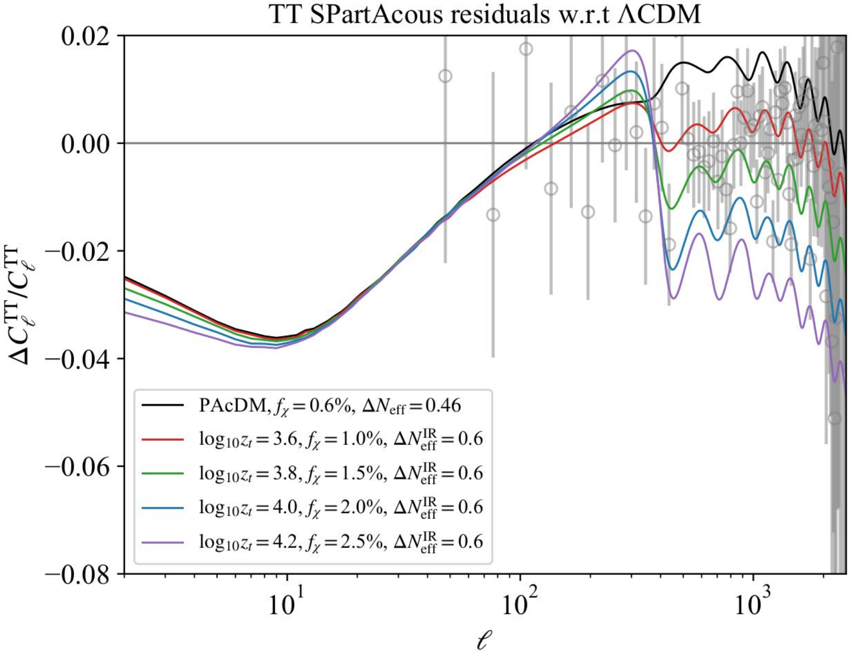
$$\Gamma = \frac{4}{3\pi}\,\alpha_d^2\,\ln(4/\langle\theta_{\rm min}\rangle^2)\,\frac{T_d^2}{m_\chi}\,e^{-m_\psi/T_d}\left[2 + \frac{m_\psi}{T_d}\left(2 + \frac{m_\psi}{T_d}\right)\right]$$

H_o & S_8

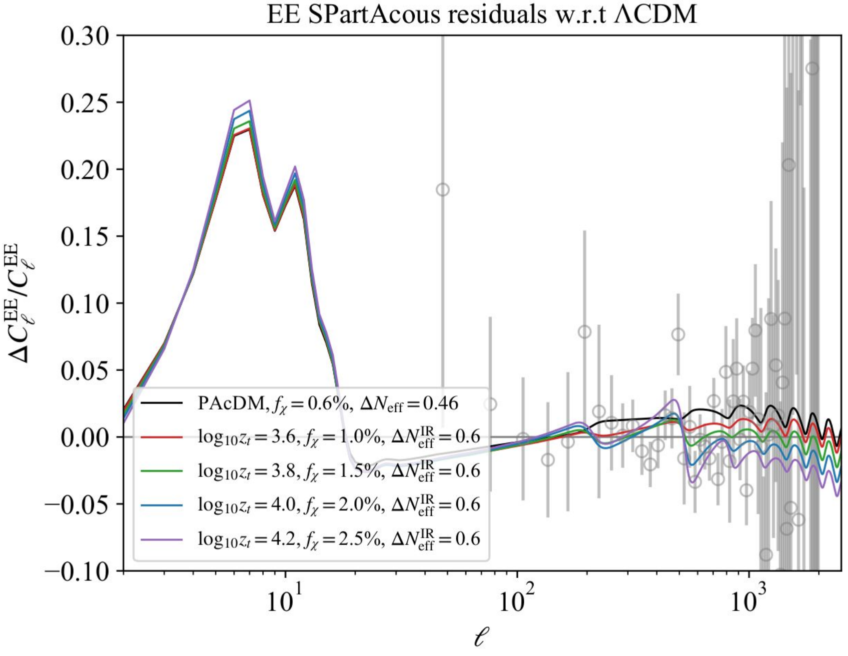


SPartAcous grid scan: impact of $\Delta N_{\rm eff}^{\rm IR}$
$\Delta N_{\rm eff}^{\rm IR} = 0.1$
$\Delta N_{\rm eff}^{\rm IR} = 0.2$
$\Delta N_{\rm eff}^{\rm IR} = 0.3$
$\Delta N_{\rm eff}^{\rm IR} = 0.4$
$\Delta N_{\rm eff}^{\rm IR} = 0.5$
$\Delta N_{\rm eff}^{\rm IR} = 0.6$
$\Delta N_{\rm eff}^{\rm IR} = 0.7$
$\Delta N_{\rm eff}^{\rm IR} = 0.8$
$\Delta N_{\rm eff}^{\rm IR} = 0.9$
$\Delta N_{\rm eff}^{\rm IR} = 1.0$
SPartAcous grid scan: impact of f_χ
$\Delta f_\chi = 0.5\%$
$f_\chi \leq 1\%$
$1\% < f_\chi \leq 2\%$
$2\% < f_\chi \leq 3\%$
$3\% < f_\chi \leq 4\%$
$4\% < f_\chi \leq 5\%$
SPartAcous grid scan: impact of z_t
$\Delta \log_{10} z_t = 0.1$
$3 \leq \log_{10} z_t \leq 3.5$
$3.5 < \log_{10} z_t \leq 4$
$4 < \log_{10} z_t \leq 4.5$
$4.5 < \log_{10} z_t \leq 5$
SPartAcous grid scan: $\Delta N_{\rm eff}^{\rm IR} = 0.6$
$\Delta \log_{10} z_t = 0.1$
$f_\chi = 1, 3, 5\%$ (△, ○, ▽)
$3 \leq \log_{10} z_t \leq 3.5$
$3.5 < \log_{10} z_t \leq 4$
$4 < \log_{10} z_t \leq 4.5$
$4.5 < \log_{10} z_t \leq 5$
S_8
H_0 [km/s/Mpc]

CMB



TT SPartAcous residuals w.r.t ΛCDM
0.02
0.00
−0.02
−0.04
−0.06
−0.08
$\Delta C_\ell^{TT}/C_\ell^{TT}$
10^1
10^2
10^3
ℓ
PAcDM, $f_\chi = 0.6\%$, $\Delta N_{eff} = 0.46$
$\log_{10} z_t = 3.6$, $f_\chi = 1.0\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 3.8$, $f_\chi = 1.5\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 4.0$, $f_\chi = 2.0\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 4.2$, $f_\chi = 2.5\%$, $\Delta N_{eff}^{IR} = 0.6$



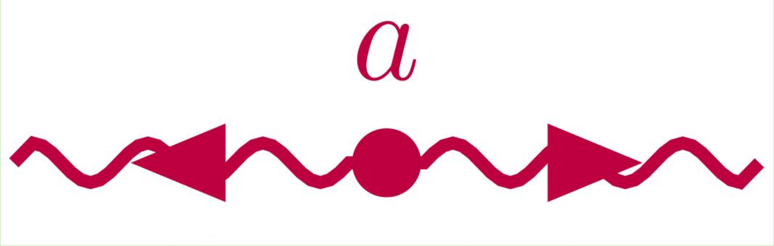
EE SPartAcous residuals w.r.t ΛCDM
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
$\Delta C_\ell^{EE}/C_\ell^{EE}$
10^1
10^2
10^3
ℓ
PAcDM, $f_\chi = 0.6\%$, $\Delta N_{eff} = 0.46$
$\log_{10} z_t = 3.6$, $f_\chi = 1.0\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 3.8$, $f_\chi = 1.5\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 4.0$, $f_\chi = 2.0\%$, $\Delta N_{eff}^{IR} = 0.6$
$\log_{10} z_t = 4.2$, $f_\chi = 2.5\%$, $\Delta N_{eff}^{IR} = 0.6$

II. Axion Echos from the Supernova Graveyard

arXiv:2110.13916; **PRD**

MBA JiJi Fan & Chen Sun

Axion Dark Matter & Stimulated Decays



Axions & ALPs

- Periodic pseudo-scalars $a \cong a + 2\pi f_a$
- Originally postulated to solve Strong CP problem
  - Peccei & Quinn; Weinberg & Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki ‘77-’81
- Interesting in their own right!
  - Muon g-2
    - Marciano, Masiero, Paradisi, Passera ‘16; Bauer, Neubert, Thamm ‘17; **MABA**, Fan, Reece, Sun ‘21]
  - Inflation
    - Freese, Frieman, Olinto ‘90; Silverstein, Westphal, McAllister ‘08]
  - **Dark Matter** (misalignment mechanism): non-thermal candidate
    - [Preskill, Wise, Wilczek; Dine, Fischler, Abbott, Sikivie ‘83]
    - ***This talk***

arXiv:2110.13916

Axion-Photon interactions

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

Spontaneous decay rate

$$\Gamma_a \equiv g_{a\gamma\gamma}^2 m_a^3/(64\pi)$$

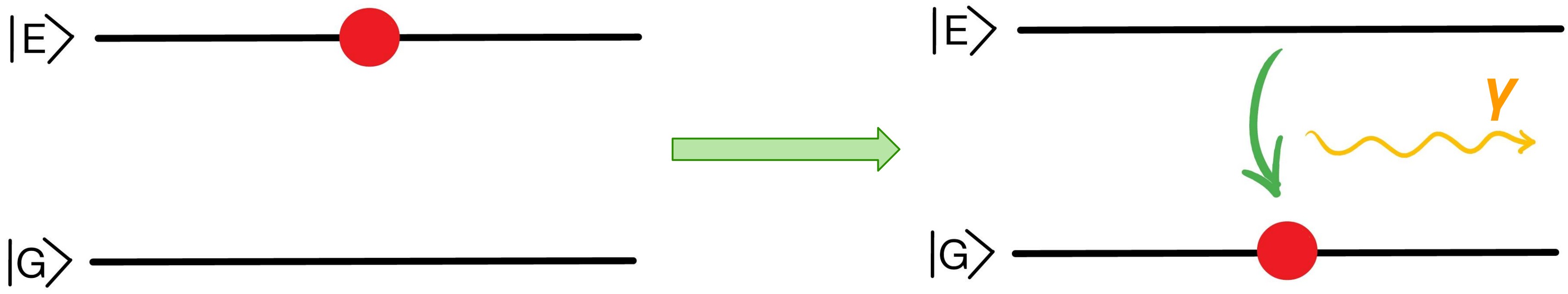
$E_\gamma = m_a/2$

Axion-Photon interactions

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

Spontaneous decay rate $$\Gamma_a \equiv g_{a\gamma\gamma}^2 m_a^3/(64\pi)$$

$E_\gamma = m_a/2$



Axion–Photon interactions

$$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

However: **γ** are bosons: ***BOSE ENHANCEMENT***.

Axion–Photon interactions

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

However: **γ** are bosons: ***BOSE ENHANCEMENT***.

Condition: same quantum numbers between **incoming** and **outgoing γ**!

$$a|f_i\rangle = \sqrt{f_i}|f_i - 1\rangle$$

$$a^\dagger|f_i\rangle = \sqrt{f_i + 1}|f_i + 1\rangle$$

f_i: initial occupation number

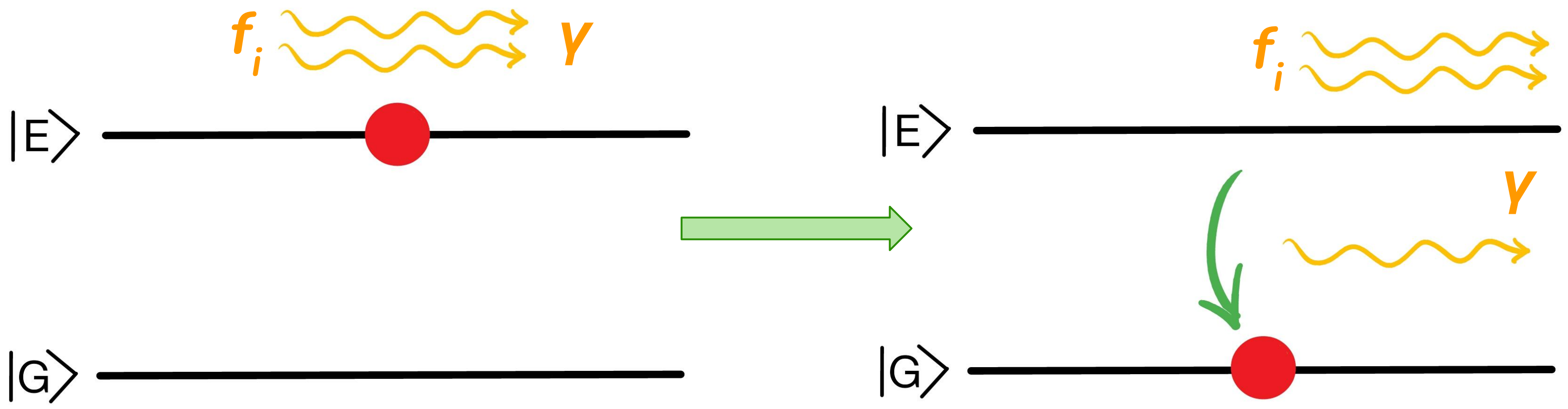
Axion-Photon interactions

$$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

However: **γ** are bosons: ***BOSE ENHANCEMENT***.

Condition: same quantum numbers between **incoming** and **outgoing γ**!

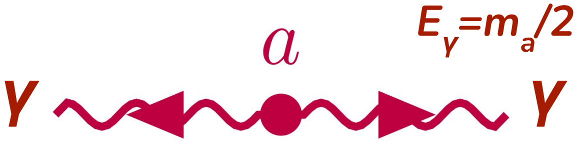
LASERs work like that. [**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation]



Axion-Photon interactions

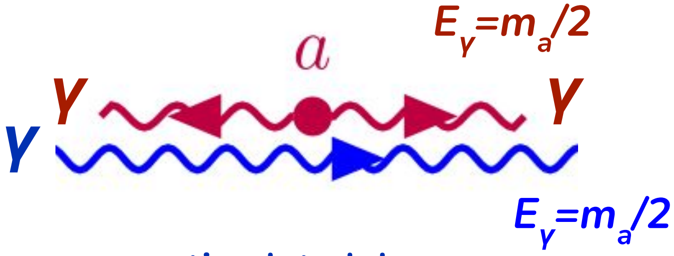
$$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

"ASER": Axion Stimulated dEcay Radiation [credit/blame: Chen Sun]



spontaneous decay

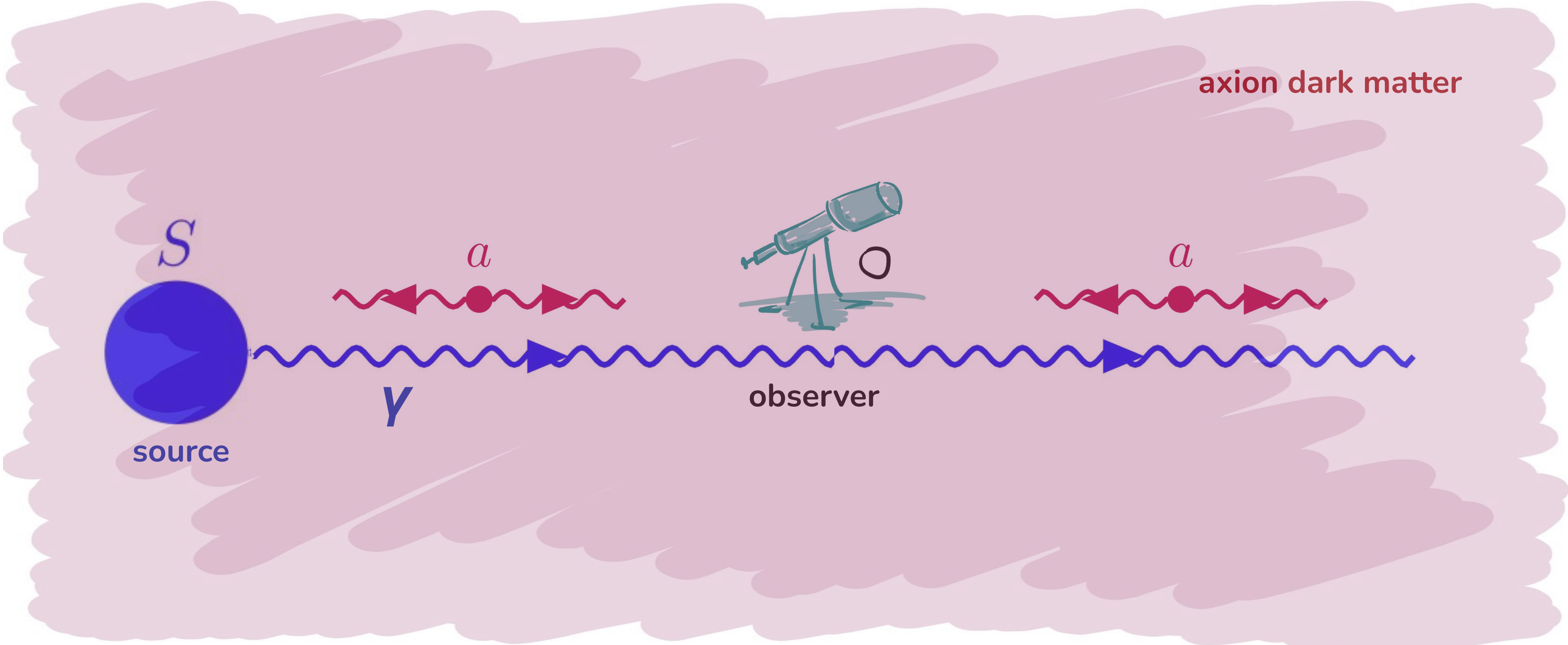
Γ_a



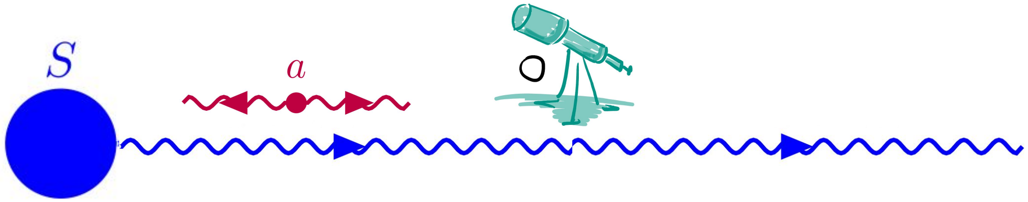
stimulated decay

$\Gamma_a \rightarrow \Gamma_a(1+f_\gamma)$

Axion Dark Matter Stimulated Decays

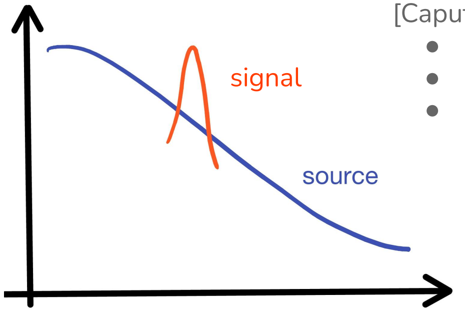


Axion Dark Matter Stimulated Decays



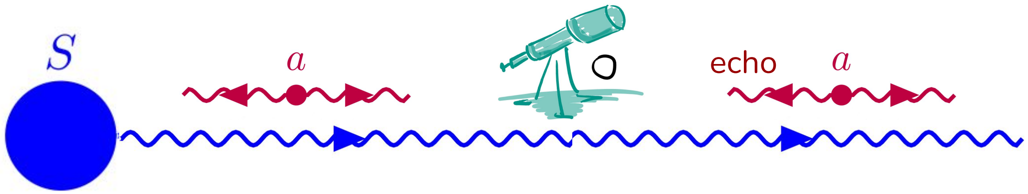
Forward

- Arrives at same time as source ***γ***
- Signal on top of bright source
- Distance-limited



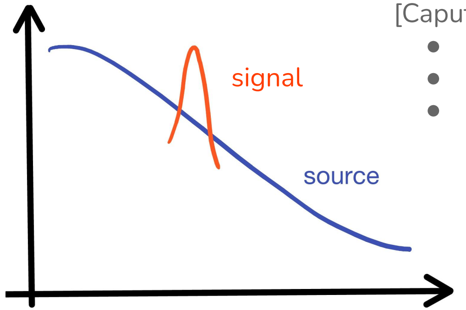
[Caputo et al. '18]
- Galaxy Center
- Dwarf Galaxies
- M87

Axion Dark Matter Stimulated Decays



<u>Forward</u>

- Arrives at same time as source ***γ***
- Signal on top of bright source
- Distance-limited



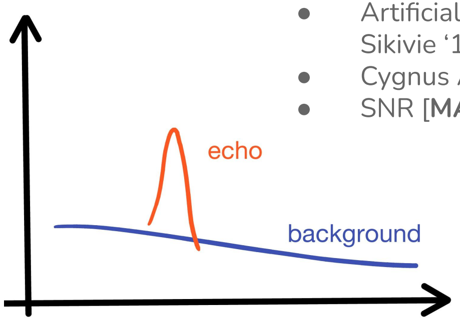
[Caputo et al. '18]

- Galaxy Center
- Dwarf Galaxies
- M87

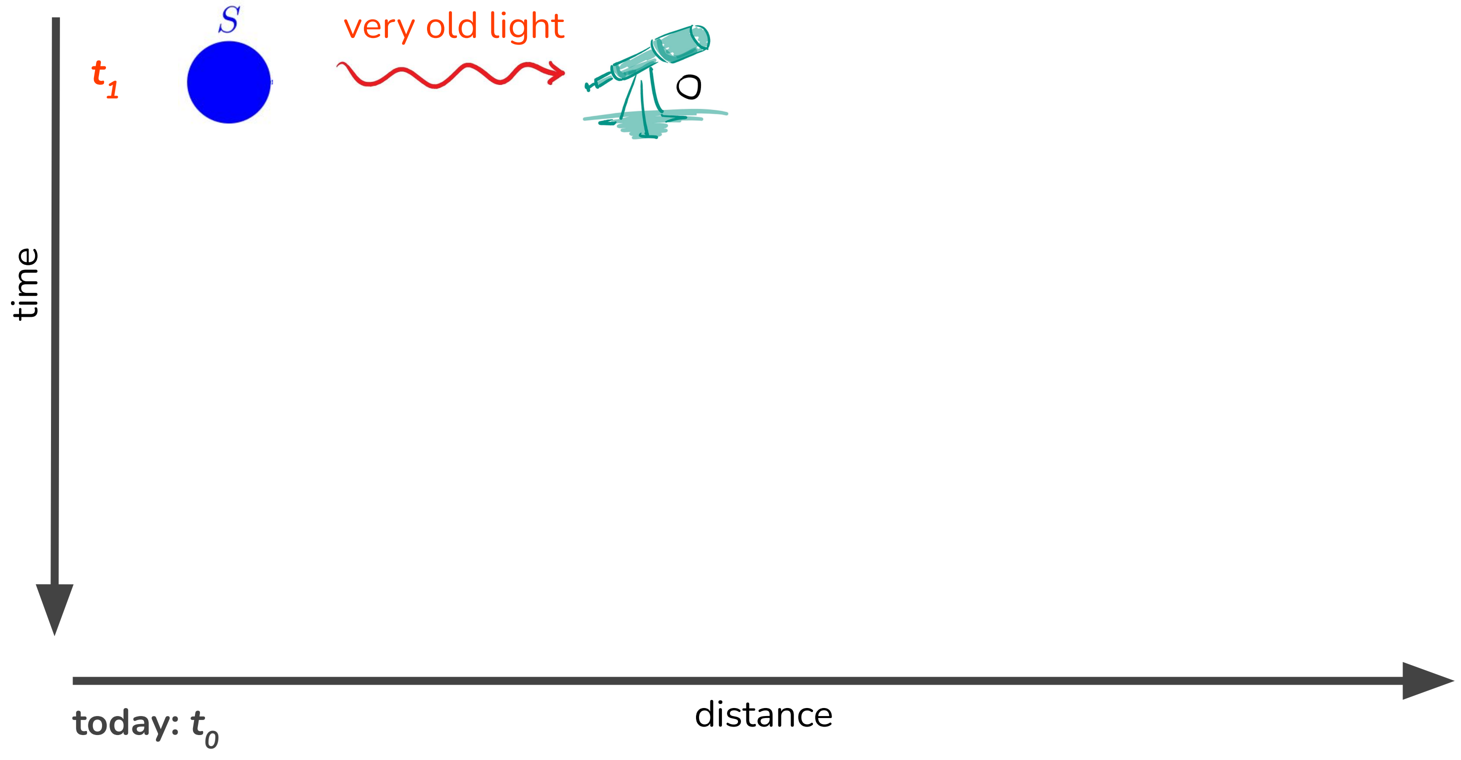
<u>Backward</u> (***echo***)

- Arrives delayed w.r.t. source ***γ***
- Potentially low background
- Age-limited

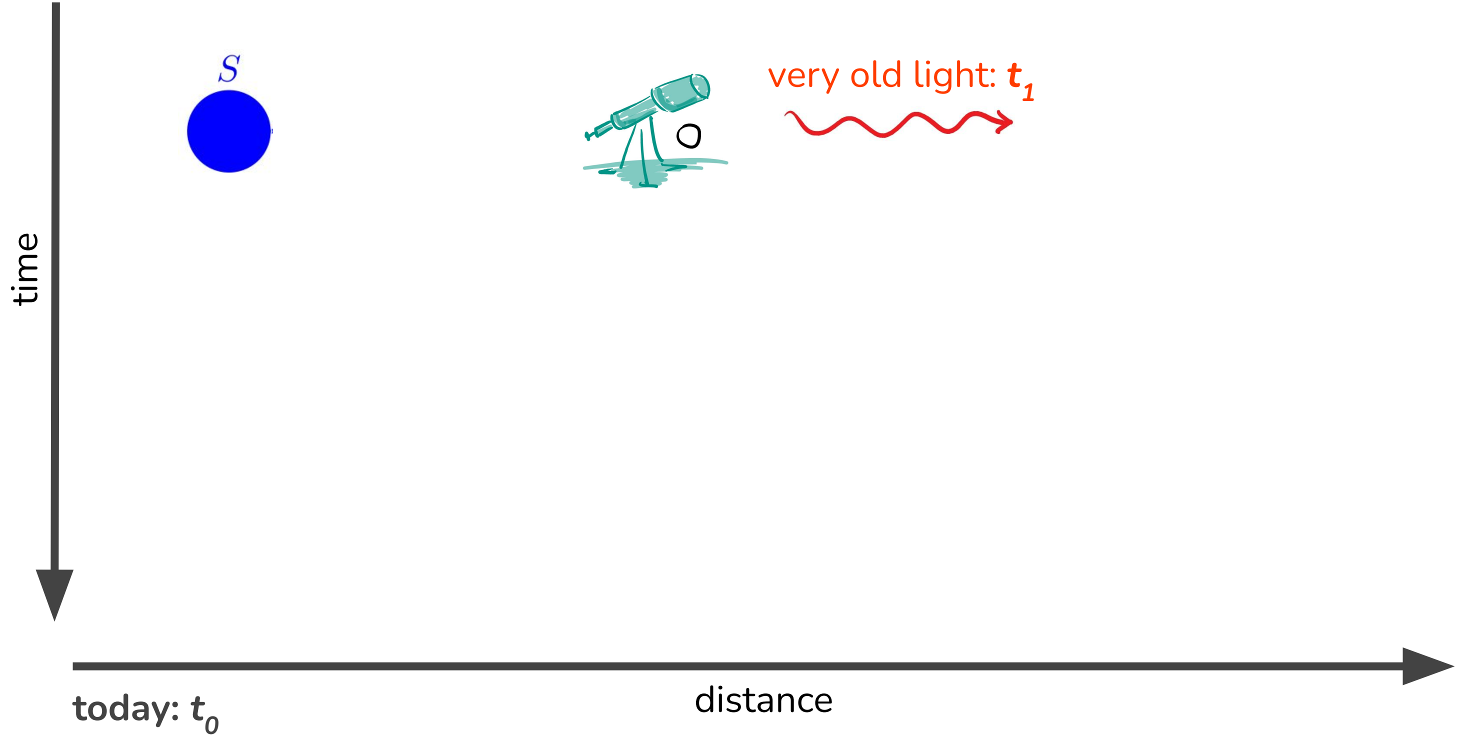
- Artificial photon beam [Arza, Sikivie '19; Arza, Todarello '21];
- Cygnus A [Ghosh et al. '20];
- SNR [**MABA**, Fan, Sun '21]



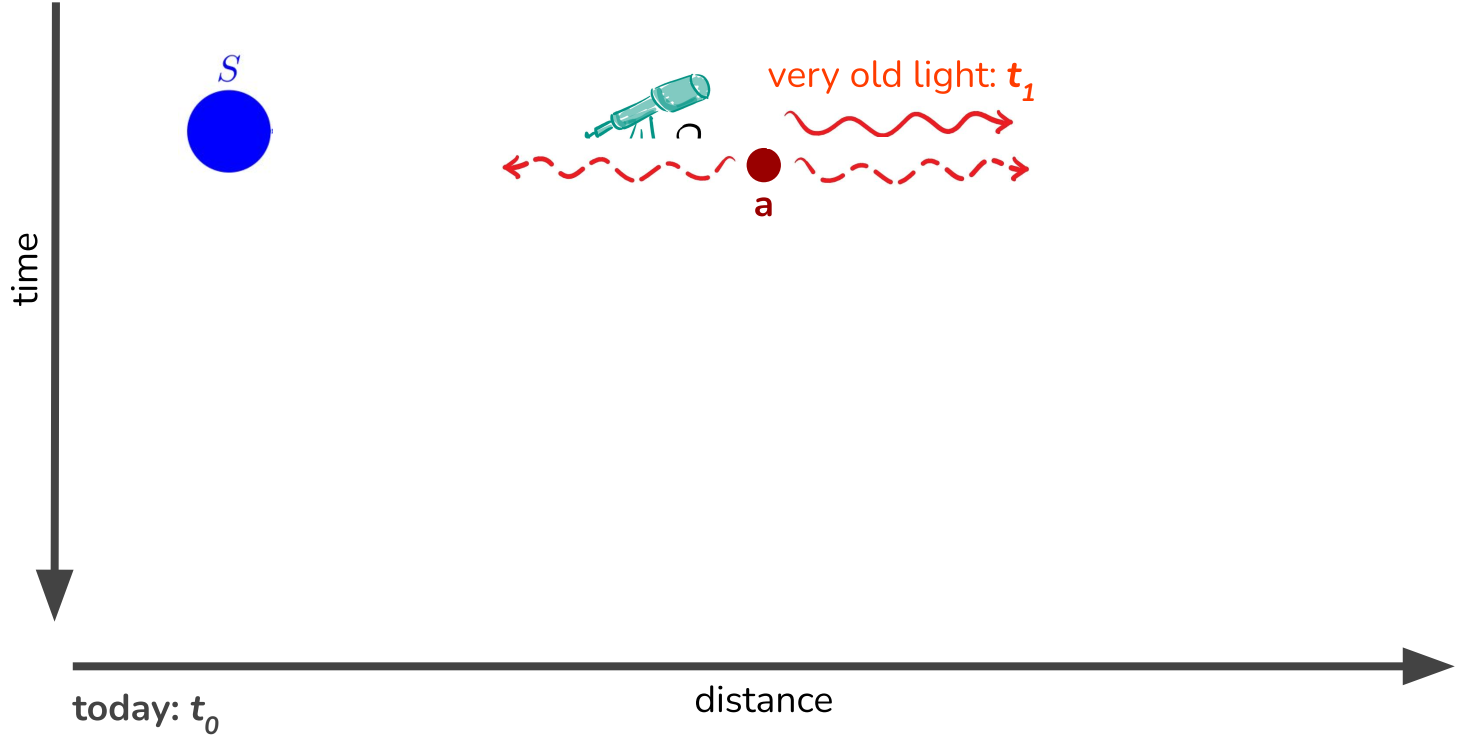
Axion echo: intuition



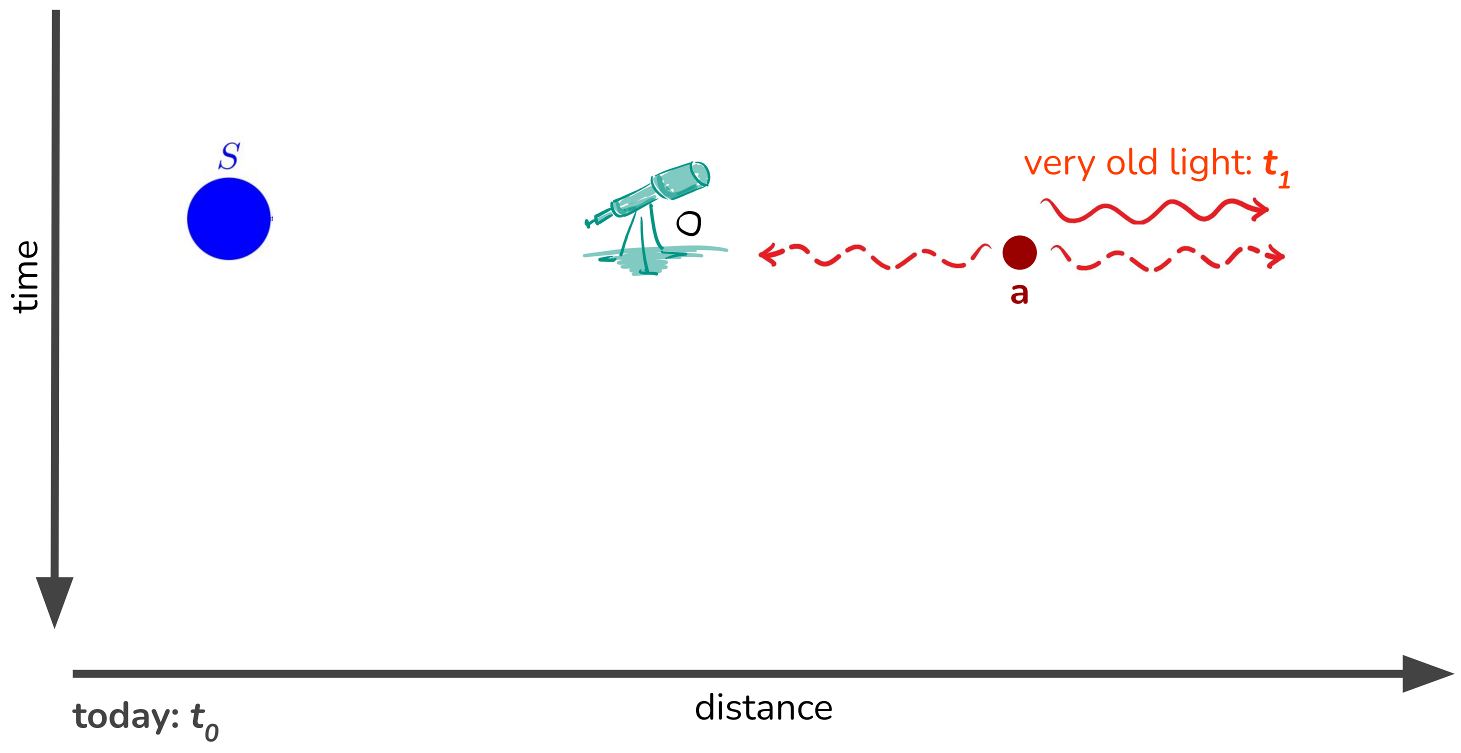
Axion echo: intuition



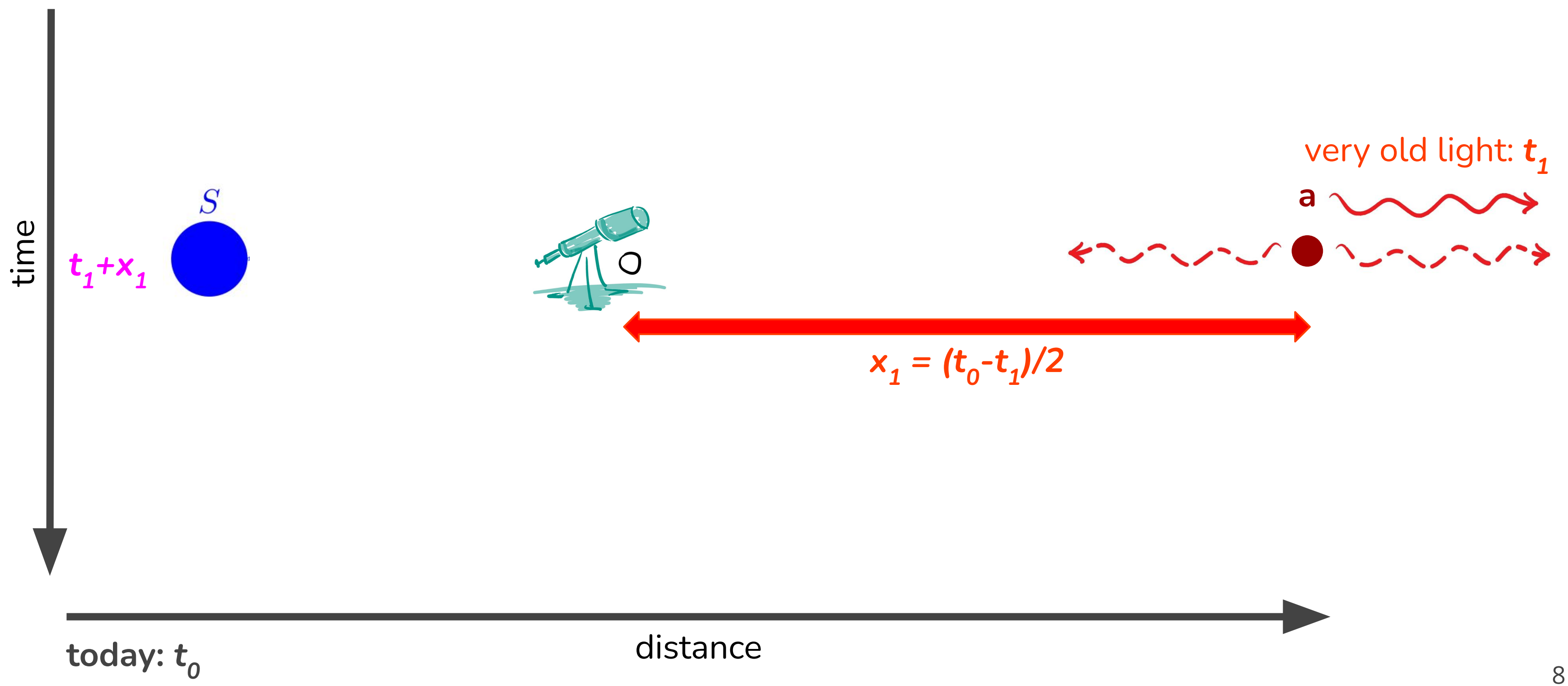
Axion echo: intuition



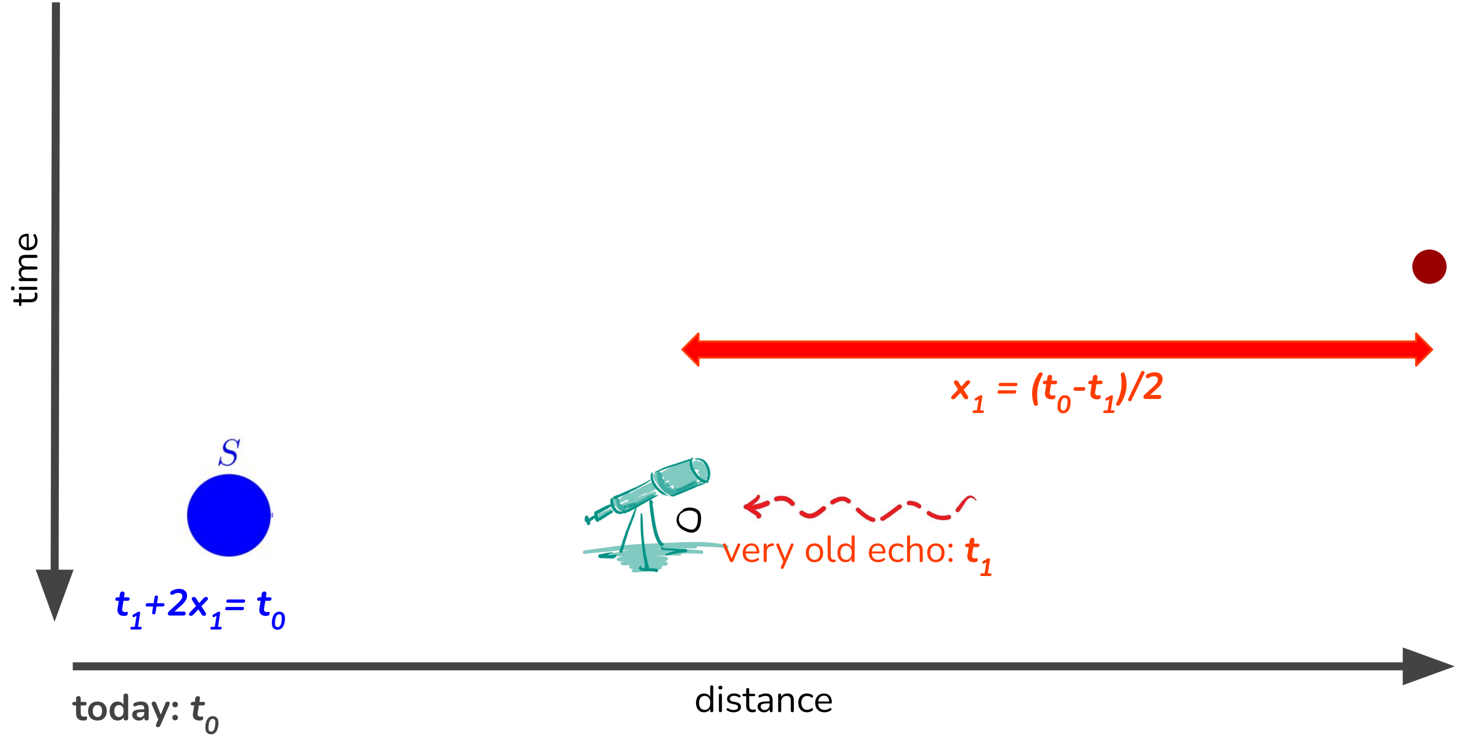
Axion echo: intuition



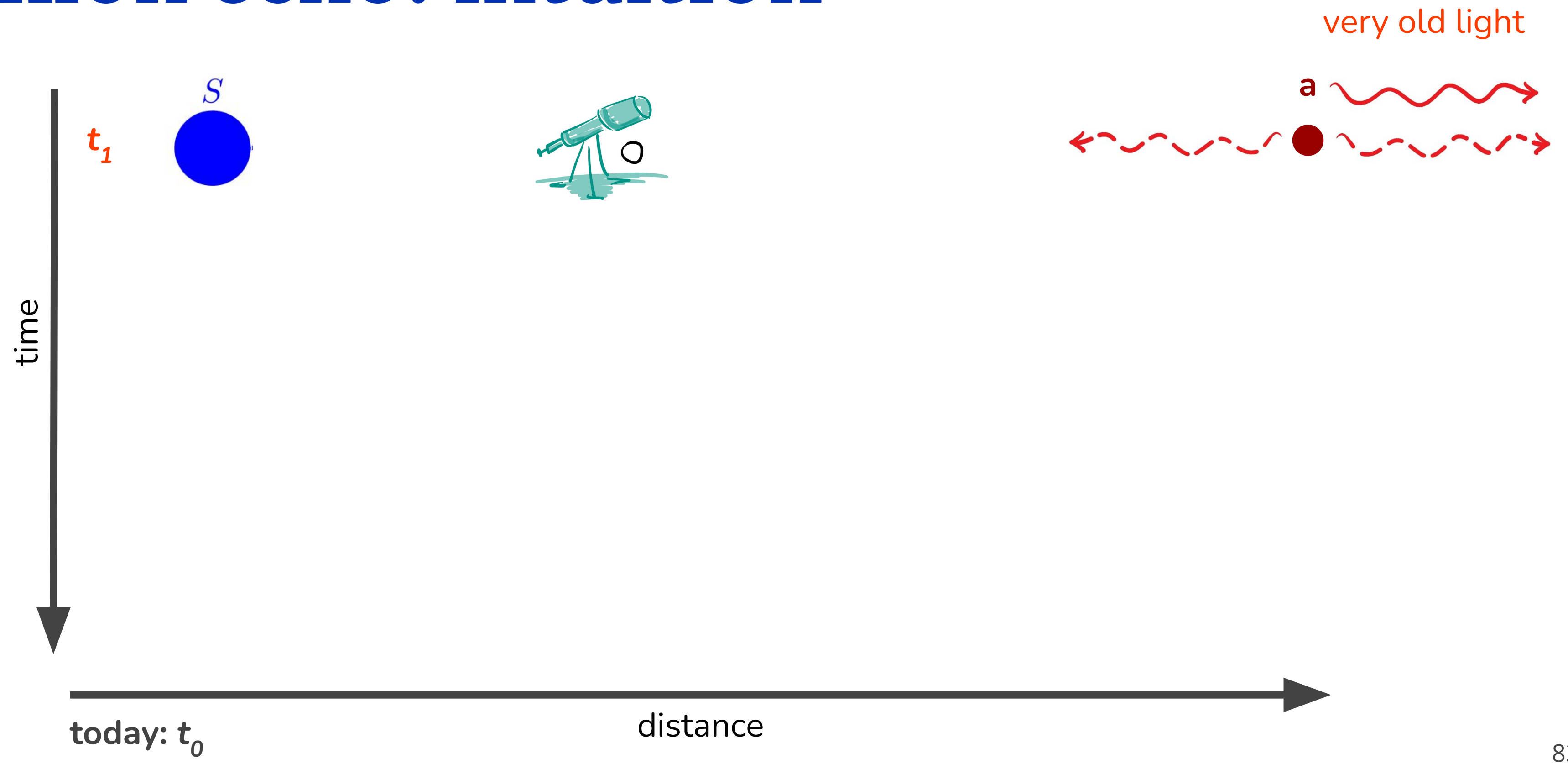
Axion echo: intuition



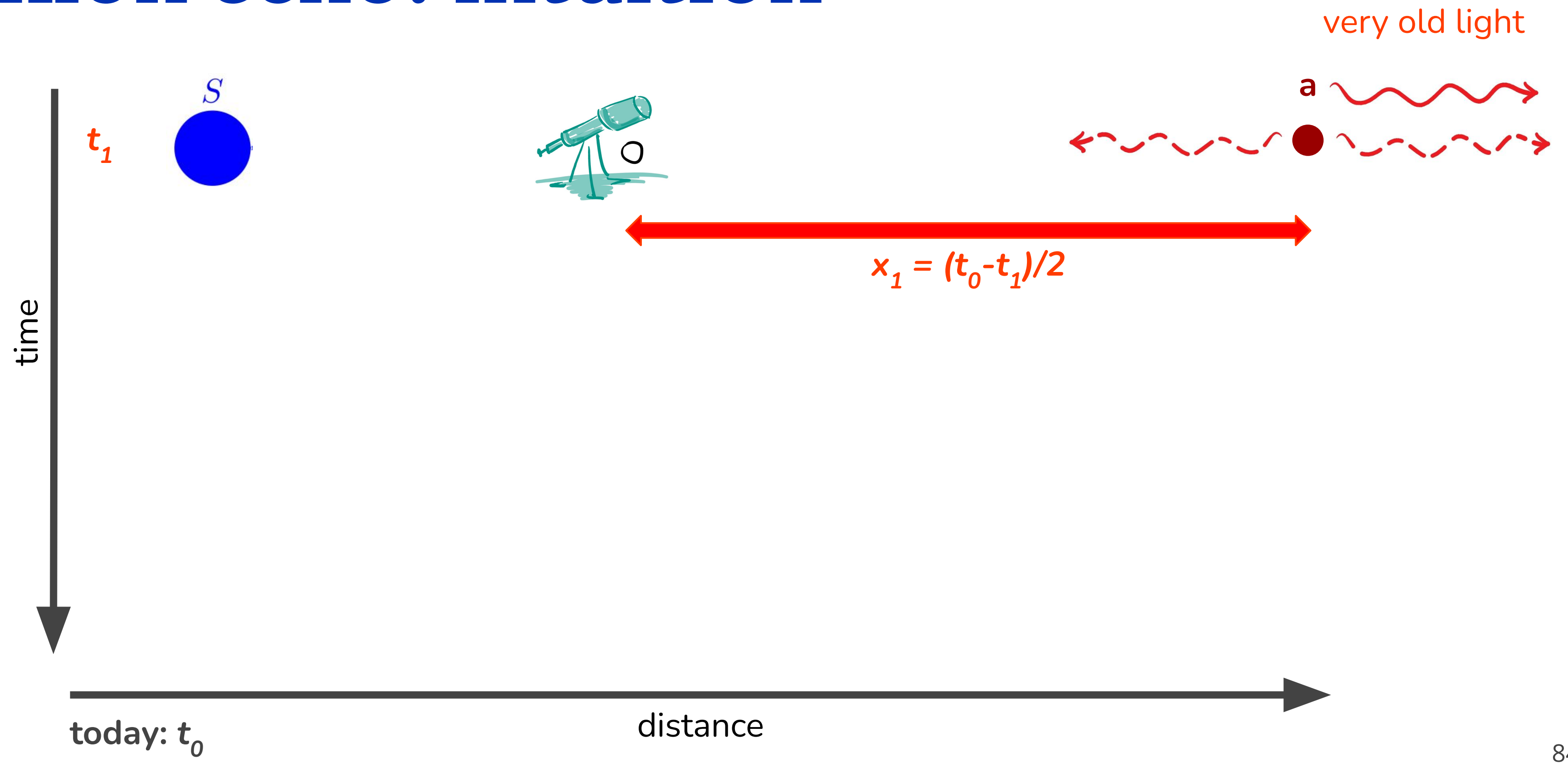
Axion echo: intuition



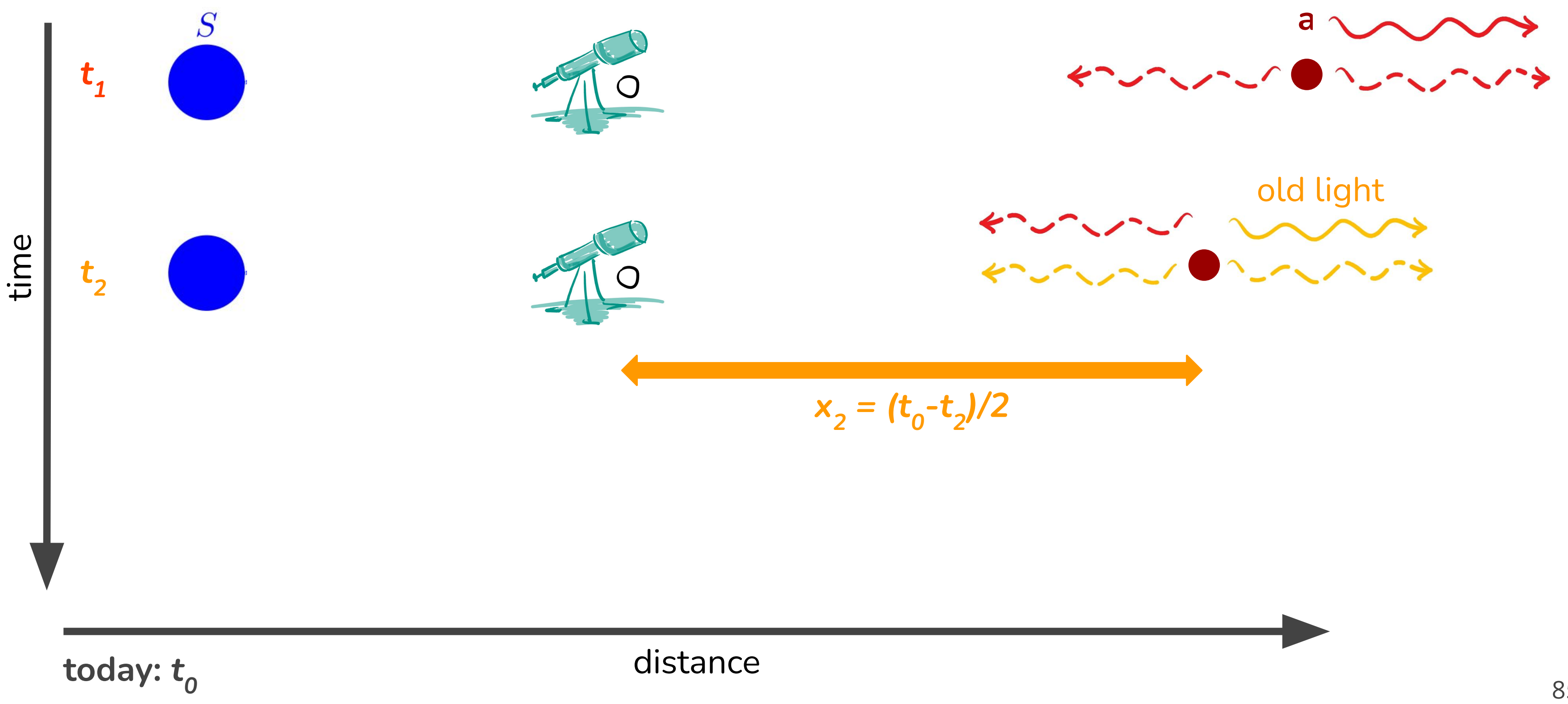
Axion echo: intuition



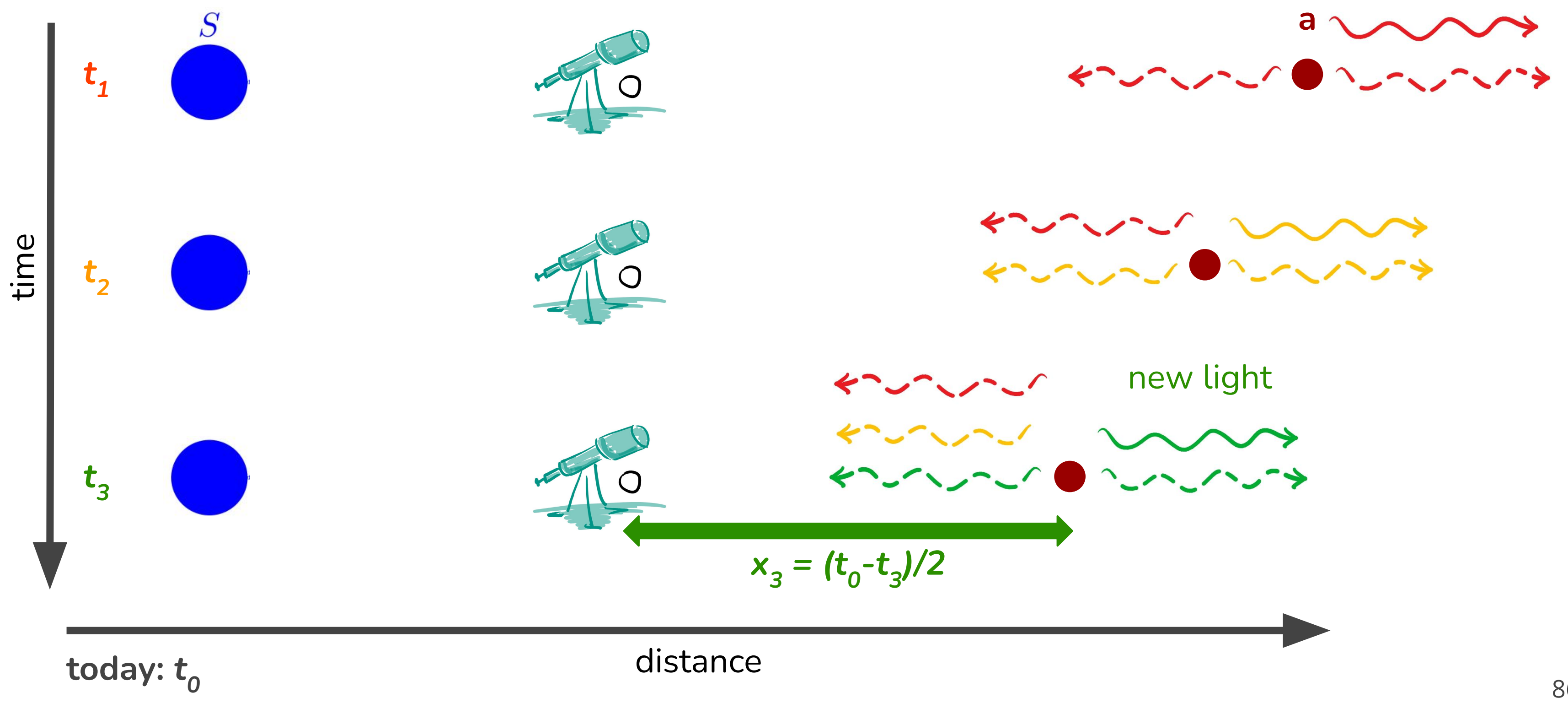
Axion echo: intuition



Axion echo: intuition

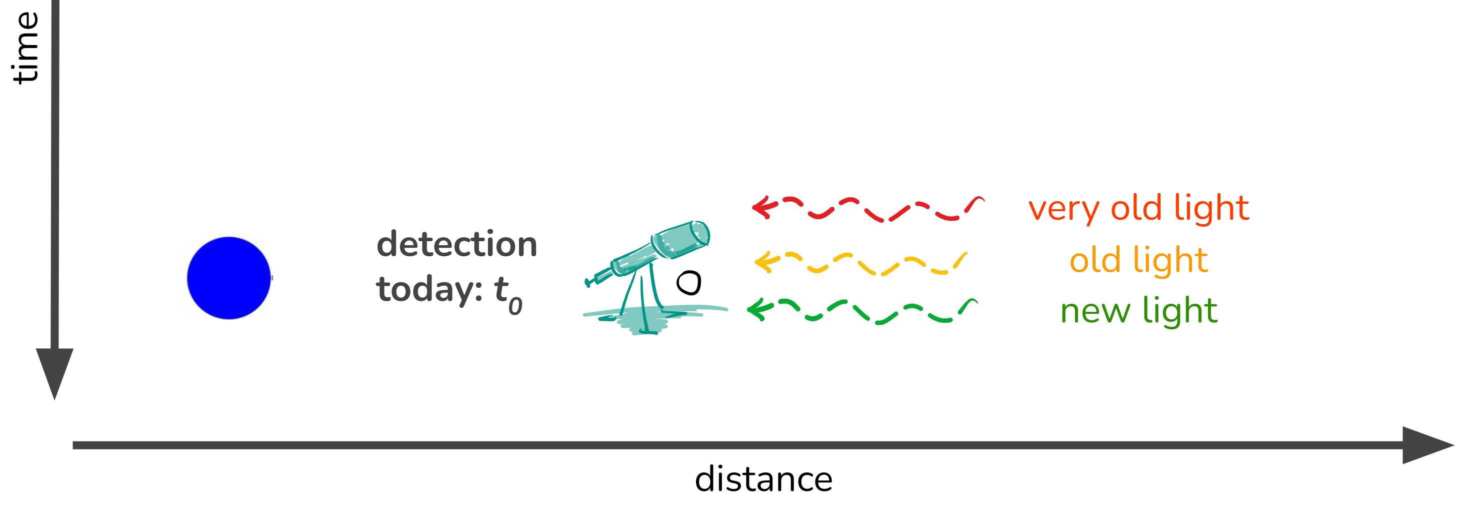


Axion echo: intuition



Axion echo: intuition

Echo depends on source's history: ***dim sources <u>today</u> could still produce bright echos***



Axion echo: formulas

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = C[f_\gamma]$$

Boltzmann equation

"Collision" term: *a*↔*γγ* process

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

Axion echo: formulas

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = C[f_\gamma]$$

Boltzmann equation

“Collision” term: *a*↔*γγ* process

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decay amplitude

inverse process

4-momentum conservation

Bose enhancement

spontaneous decay

momentum-space integrals

$$\mathrm{DP} \equiv g \mathrm{d}^3 p / (2\pi)^3$$

Axion echo: formulas

$$\overline{S}_{\nu_a,\mathrm{e}} = f_\Delta \frac{\pi \Gamma_a}{2 E_a^3 \Delta\nu} \int\limits_0^{t_{\mathrm{age}}/2} \mathrm{d}x \; \rho_a(x, -\hat{\mathbf{n}}_*) \; S_{\nu_a,\mathrm{s}}(t_{\mathrm{age}} - 2x) \; \mathrm{e}^{-\tau(\nu, x, -\hat{\mathbf{n}}_*)}$$

Axion echo: formulas

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

Axion echo: formulas

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

$$S_\nu = \frac{E^3}{2\pi^2} \int \mathrm{d}\Omega \; f(E, \Omega)$$

flux density **[1 Jy = 10^{-23} erg·s^{-1}·cm^{-2}·Hz^{-1}]**

Axion echo: formulas

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

$$\Gamma_a \equiv g_{a\gamma\gamma}^2 m_a^3 / (64\pi)$$

spontaneous decay rate

Axion echo: formulas

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

$$\boxed{\nu_a = E_a/(2\pi) = m_a/(4\pi)}$$

photon frequency

Axion echo: formulas

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

DM velocity dispersion: $\sigma_v \approx 5\times 10^{-4} c$

$$\Delta\nu \approx 2.8\,\nu_a \sigma_v \,, \qquad f_\Delta \approx 0.84$$

optimal bandwidth

signal fraction in bandwidth

Axion echo: formulas

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

axion decay at position *x*, integrate along l.o.s.
over source history

Axion echo: formulas

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

axion DM density (NFW)
in opposite direction to source

Axion echo: formulas

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

source flux density in the past

Axion echo: formulas

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

optical depth

Axion echo: requirements

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

- Stimulation condition: $E_\gamma = m_a/2$...
- ... large occupation number f_γ (OK if *historically!*)
- ... low background: **RADIO**

[1 Jy = 10^{-23} erg·s^{-1}·cm^{-2} ·Hz^{-1}]

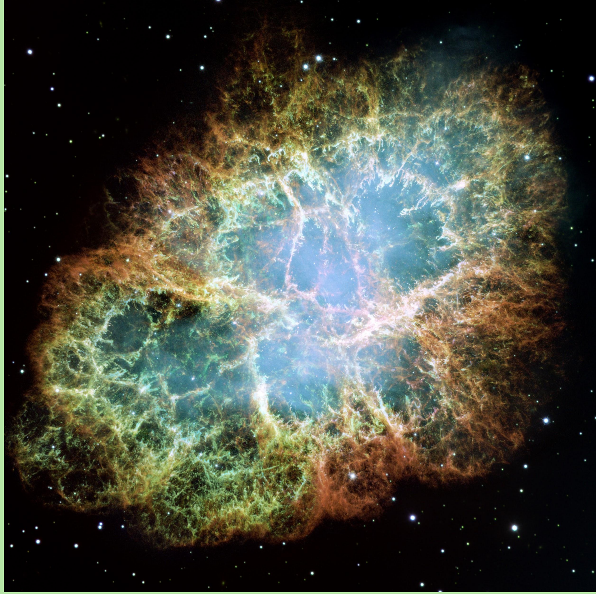
Benchmarks:

$m_a \sim 10^{-5}$ eV ⇒ $\nu \sim 1$ GHz

$\nu \sim 1$ GHz & $S_\nu \sim 10$ Jy & $\Omega \sim 10^{-5}$ sr ⇒ $f_\gamma \sim 100$

$t_{age} \sim 10^4$ yr ⇒ $x \sim 1.5$ kpc

Supernova Remnants



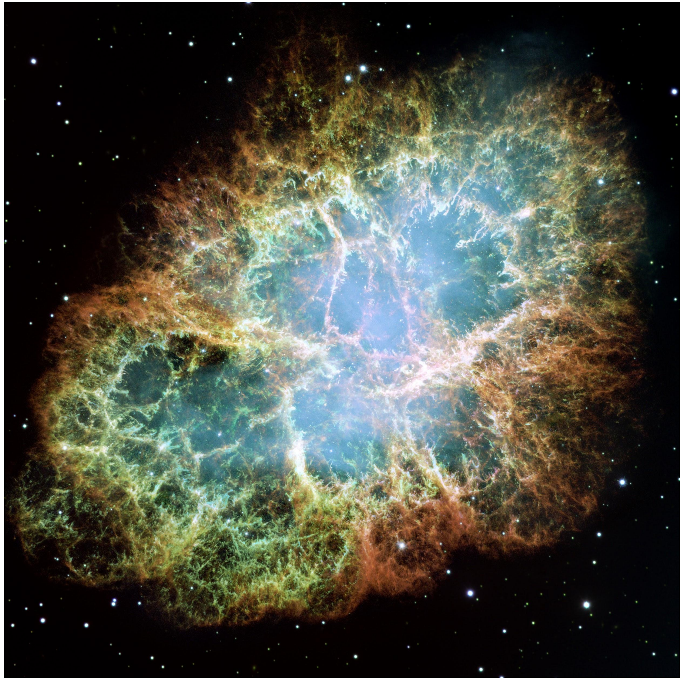
SN 1054 Crab Nebula

G39.7-2.0 Manatee Nebula

Supernova Remnants (SNRs)

OK with requirements!

- ***f_γ***: brightness OK today, better in the *past*!
- ***$E_\gamma = m_a/2$***: spectrum in radio
- Could have reasonable backgrounds

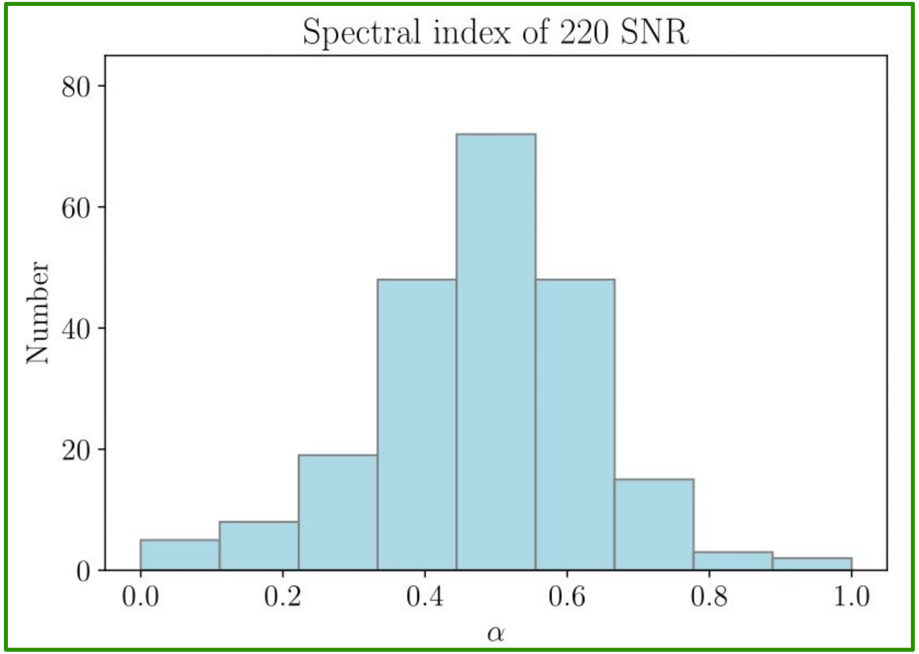


SN 1054 Crab Nebula

SNRs: *spectrum*

$$S_\nu \sim E^{-\alpha}$$

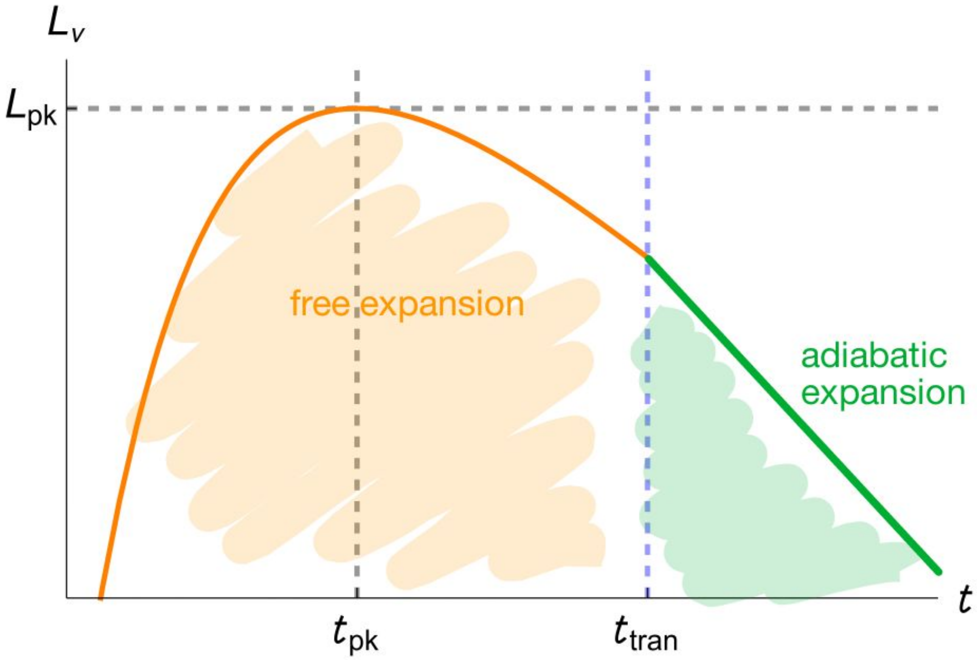
spectral index



Common normalization:

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

SNRs: evolution & *light curves*

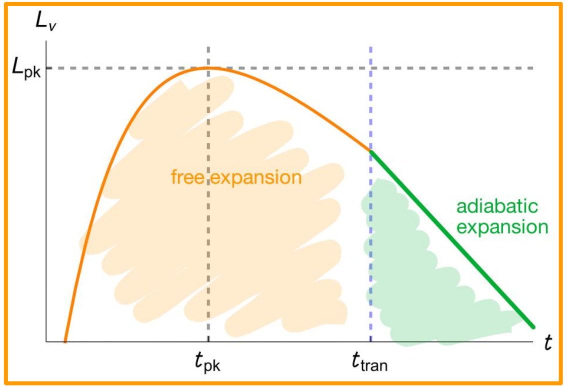


$$L_\nu(t) = \begin{cases} L_{\nu,\mathrm{free}}(t) & t \leq t_{\mathrm{tran}} \\ L_{\nu,\mathrm{ad}}(t) & t > t_{\mathrm{tran}} \end{cases}$$

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

1. Free expansion: ***O(100 yr)***
2. Adiabatic expansion: ***O(10^4 yr)***
3. Snow plough: ***O(10^6 yr)***
4. Dispersion: ***> O(10^6 yr)***

SNR evolution: *free expansion*



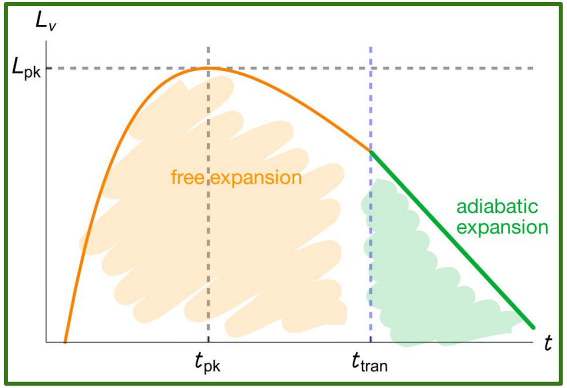
$$L_{\nu,\mathrm{free}}(t) \equiv L_{\nu,\mathrm{pk}}\ e^{\frac{3}{2}(1-t_{\mathrm{pk}}/t)} \left(\frac{t}{t_{\mathrm{pk}}}\right)^{-1.5}$$

57 SN with peak data

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

[Bietenholz et al. ‘21]

SNR evolution: *adiabatic expansion*



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

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

adiabatic index

SNR catalogs: 294 in Green Catalog [Green '14, '19; c.f. Ferrand, Safi-Harb '12]

- ***$S_\nu \sim O(10)$ Jy***
- ***$D \sim O(1)$ kpc***
- ***$\Omega \sim O(10^{-5})$ sr***
- ***$\alpha \sim 0.5$***
- ***$t_{age} \sim O(10^3) – O(10^4)$ yr***

[Shklovsky '60; Wilson, Rohlfs, Huttemeister '09]

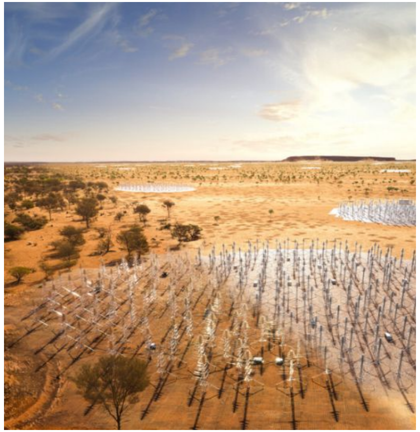
Echo Detection

SKA: Square Kilometer Array

SKA1-low

- *ν*: 50 MHz – 350 MHz
- # stations: 512 dishes ∅ 38 m
- longest baseline: 80 km

Australia



SKA1-mid

- *ν*: 350 MHz – 15.4 GHz
- # stations: 133 (SKA dishes) ∅ 15m, 64 (MeerKAT dishes) ∅ 13.5 m
- longest baseline: 150 km

South Africa

s/n: signal-to-noise ratio

$$\mathrm{s/n} = \frac{P_{\mathrm{sig}}}{P_{\mathrm{noi}}}$$

Signal power: 1 unit

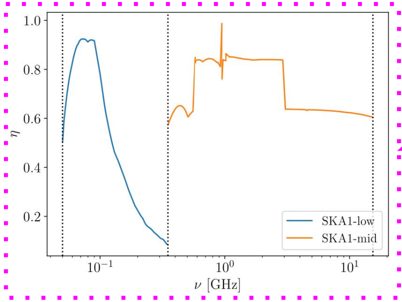
$$P_{\mathrm{sig,\,unit}} = \overline{S}_{\nu_{\mathrm{a}},\mathrm{e}}\ \Delta\nu\ \eta\ A_{\mathrm{unit}}$$

Signal power: 1 unit

echo flux density

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

$$P_{\mathrm{sig,\,unit}} = \overline{S}_{\nu_\mathrm{a},\mathrm{e}}\ \Delta\nu\ \eta\ A_\mathrm{unit}$$



efficiency

area of single unit dish

Noise power: 1 unit

$$P_{\text{noi, unit}} = 2\, T_{\text{sys}}\, \Delta\nu$$

T_{sys}: system temperature

- T_{cmb} **= 2.73 K**
- T_{atm} **~ 3 K** @ 1 GHz, **O(100) K** @ 100 MHz
- T_{gal} **~ O(10) K** (inhomogeneous, Haslam 408 MHz map)
- T_{rcv} **~ 40 K** @ SKA1-low, **O(10) K** @ SKA1-mid
- T_{spl} **~ 3 K**

Noise power: 1 unit

$$P_{\text{noi, unit}} \rightarrow \frac{P_{\text{noi, unit}}}{\sqrt{\#\ \text{meas.}}}$$

measurements includes:

- 2 polarizations
- $\Delta\nu \cdot t_{obs}$ observations (time domain)
- # pixels (angular resolution)
- From units to arrays:
    - ***single-dish*** mode
    - ***interferometry*** mode

Noise power: 1 unit

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

measurements includes:

- 2 polarizations
- $\Delta\nu \cdot t_{obs}$ observations (time domain)
- # pixels (angular resolution)
- From units to arrays:
  - ***single-dish*** mode
  - ***interferometry*** mode

Single-Dish mode

Each dish/unit works on its own; then add them up.

$$P_{\mathrm{sig;\,SD}} = P_{\mathrm{sig,\,unit}} \times N_{\mathrm{dishes}}$$

$$P_{\mathrm{noi;\,SD}} = P_{\mathrm{noi,\,unit}} \times \frac{N_{\mathrm{dishes}}}{\sqrt{N_{\mathrm{dishes}}}}$$

Single-Dish mode

Each dish/unit works on its own; then add them up.

$$P_{\mathrm{sig;\,SD}} = P_{\mathrm{sig,\,unit}} \times N_{\mathrm{dishes}}$$

$$P_{\mathrm{noi;\,SD}} = P_{\mathrm{noi,\,unit}} \times \frac{N_{\mathrm{dishes}}}{\sqrt{N_{\mathrm{dishes}}}}$$

$$P_{\mathrm{noi,\,unit}} = \sqrt{2}\,\bar{T}_{\mathrm{sys}} \left(\frac{\Delta\nu}{t_{\mathrm{obs}}}\right)^{1/2} \underbrace{\max\left(\frac{\theta_{\mathrm{echo}}}{\theta_{\mathrm{res}}}, 1\right)}_{\text{pixels}}$$

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

Interferometry mode

One pair of dishes/units (a “**baseline**”) working in tandem (à *la* Young double-slit experiment). More baselines than dishes ⇒ less noise!

$$P_{\text{sig; IN}} = P_{\text{sig, unit}} \times N_{\text{active}}$$

$$P_{\text{noi; IN}} = P_{\text{noi, unit}} \times \frac{N_{\text{active}}}{\sqrt{N_{\text{baselines}}}}$$

Interferometry mode

One pair of dishes/units (a “**baseline**”) working in tandem (à *la* Young double-slit experiment). More baselines than dishes ⇒ less noise!

$$P_{\mathrm{sig;\,IN}} = P_{\mathrm{sig,\,unit}} \times N_{\mathrm{active}}$$

$$P_{\mathrm{noi;\,IN}} = P_{\mathrm{noi,\,unit}} \times \frac{N_{\mathrm{active}}}{\sqrt{N_{\mathrm{baselines}}}}$$

$$\theta_{\mathrm{echo}} \lesssim \theta_{\mathrm{b}}$$

active units

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

Interferometry mode

One pair of dishes/units (a “**baseline**”) working in tandem (à *la* Young double-slit experiment). More baselines than dishes ⇒ less noise!

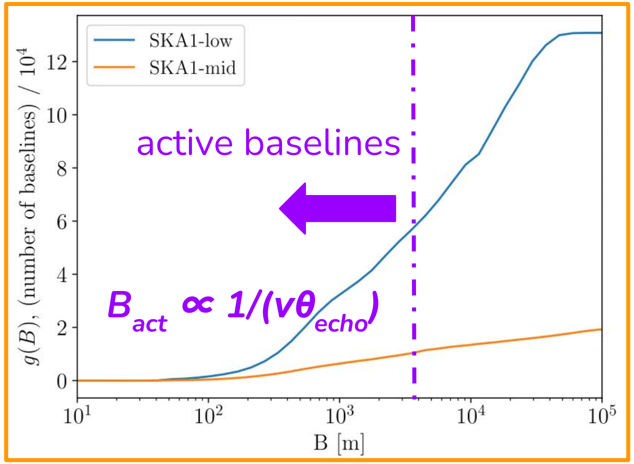
$$P_{\mathrm{sig;\,IN}} = P_{\mathrm{sig,\,unit}} \times N_{\mathrm{active}}$$

$$P_{\mathrm{noi;\,IN}} = P_{\mathrm{noi,\,unit}} \times \frac{N_{\mathrm{active}}}{\sqrt{N_{\mathrm{baselines}}}}$$

$$\theta_{\mathrm{echo}} \lesssim \theta_{\mathrm{b}}$$

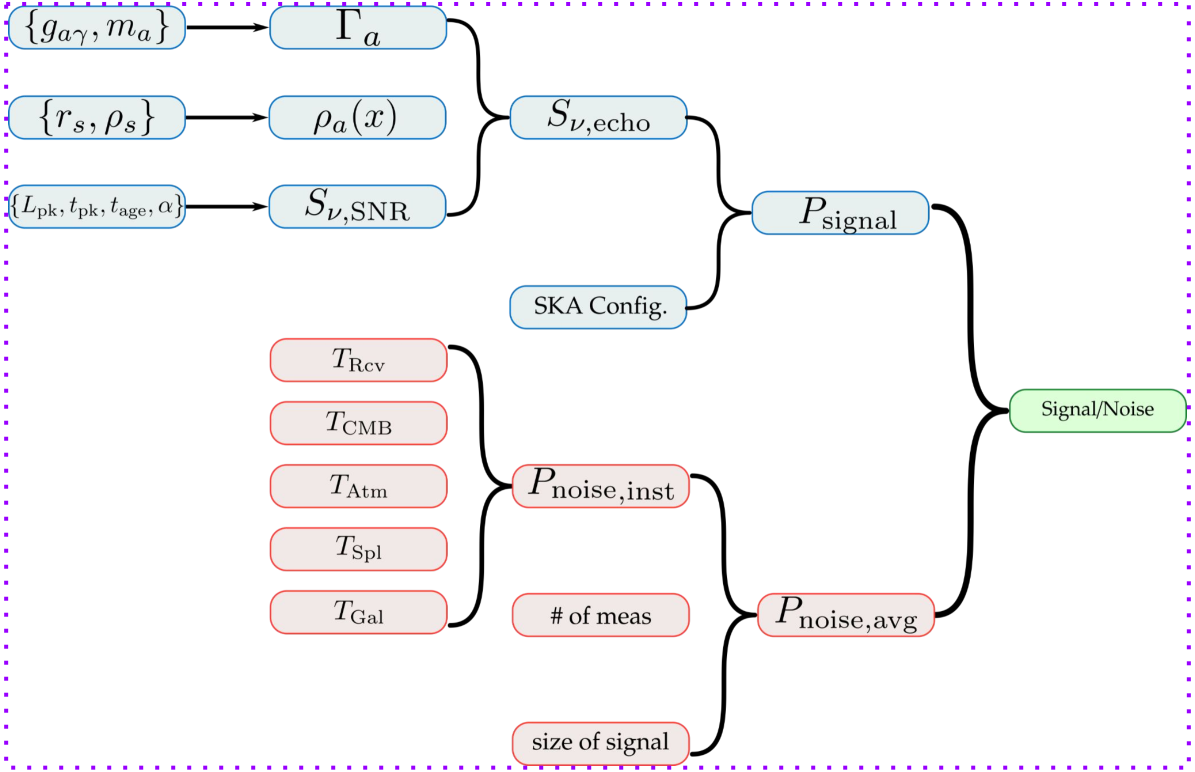
active units

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



$$N_{\mathrm{baselines}} \approx N_{\mathrm{active}}(N_{\mathrm{active}} - 1)/2$$

Pipeline



[image credit: Chen Sun]

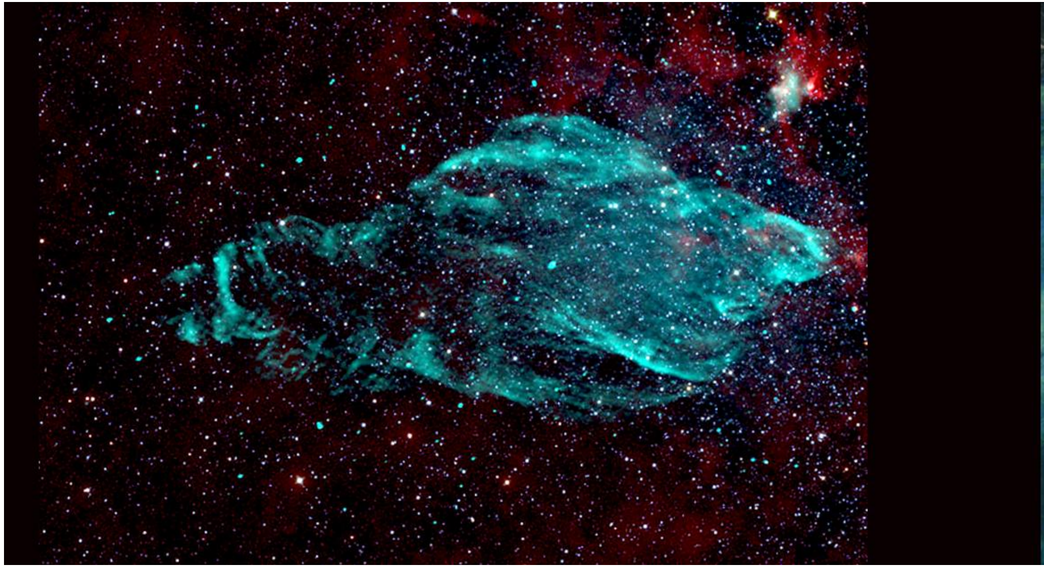
Analysis

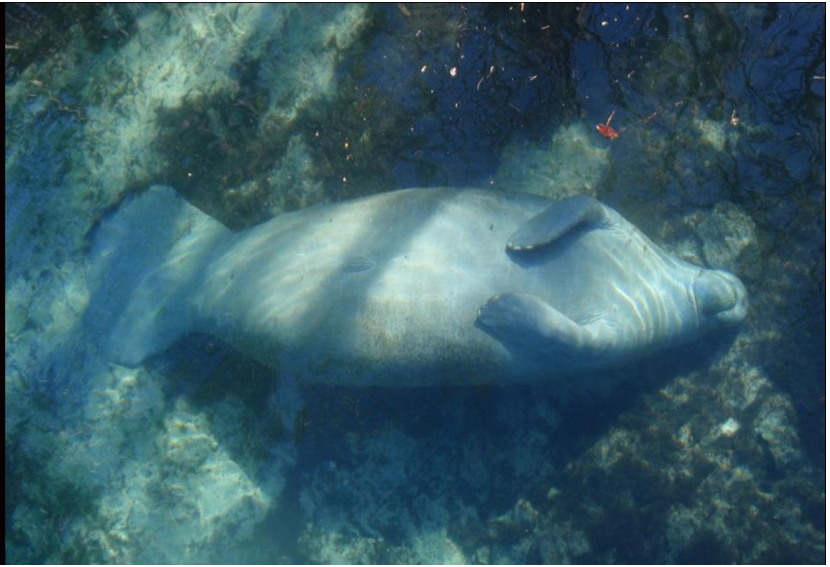
- **60 SNRs** with data on: flux density, spectral index, age, coordinates, distance.
- SNR evolution: **free** expansion & **adiabatic** expansion
- Axion **DM**: **NFW** profile
- **Echo signal** for axion DM parameters
- SKA1 **s/n**
- Full analysis: **github.com/ManuelBuenAbad/snr_ghosts**

Results

SNR G39.7-2.0

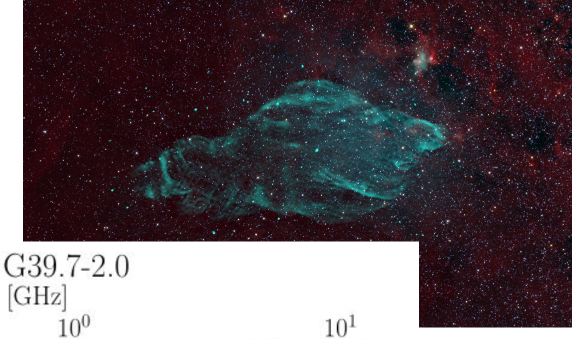
Manatee Nebula (W50)



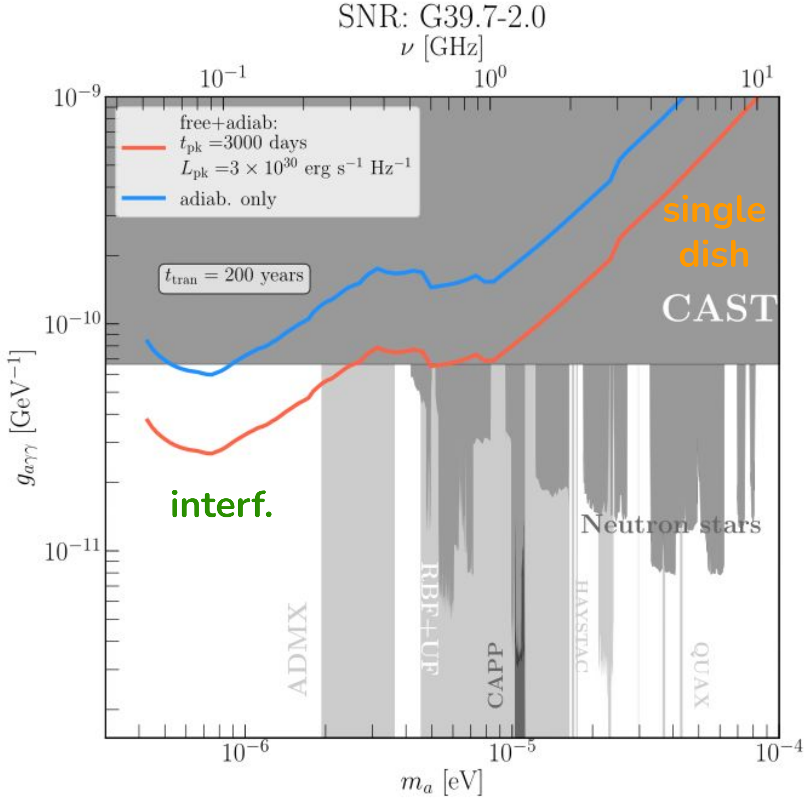


(1/30 brightness of Cassiopeia A)

SNR G39.7–2.0

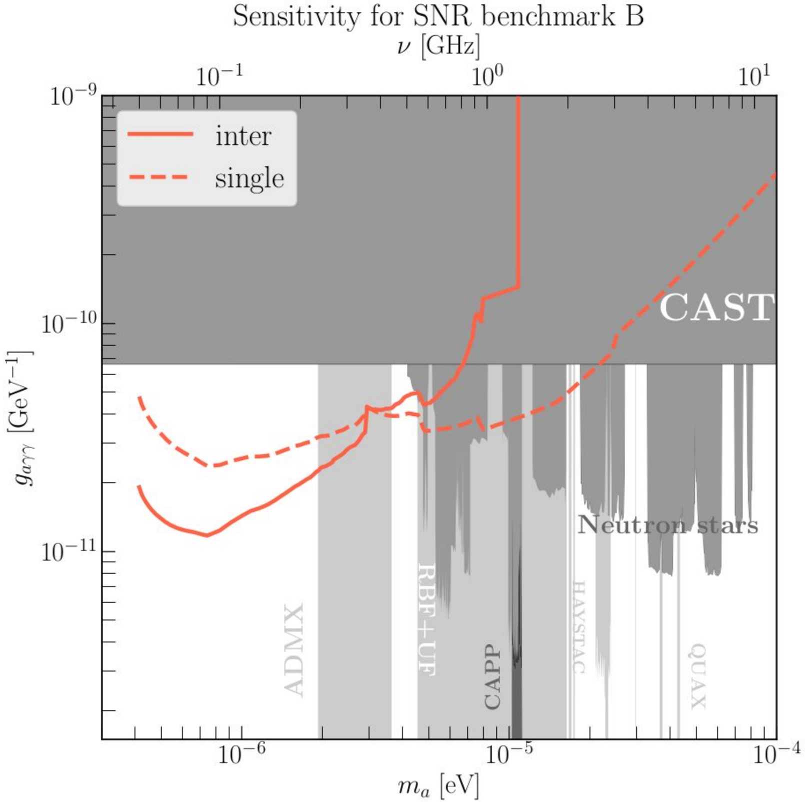


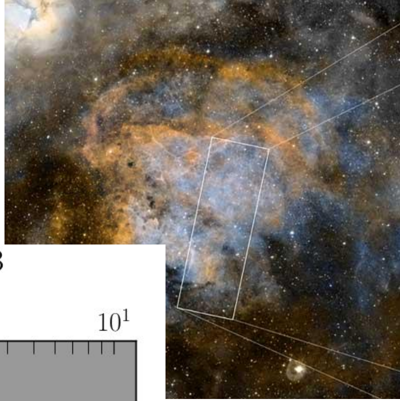
G39.7-2.0
$(l, b) = (39.7°, -2°)$
$\theta_s = 85$ arcmin
$S^{(0)}_{1\mathrm{GHz,s}} = 85$ Jy
$D = 4.9$ kpc $(4.5 - 5.5$ kpc$)$
$t_{age} = 30,000 - 100,000$ years
$\alpha = 0.7\ (0.5 - 0.8)$
$\gamma = 1.92\ (1.6 - 2.08)$



SNR G6.4-0.1-like

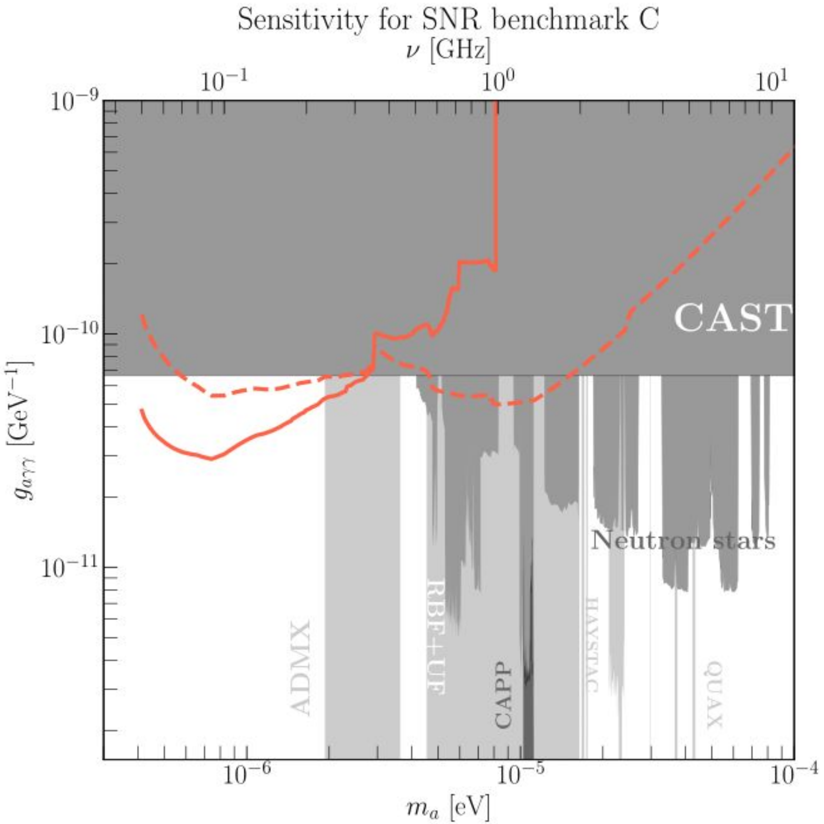
Benchmark	B (free+adiabatic)
(l, b)	$(64°, -0.1°)$
θ_s [arcmin]	48
$S^{(0)}_{1\mathrm{GHz,s}}$ [Jy]	310
$L_{1\mathrm{GHz,pk}}$ [cgs]	$2.5 \times 10^{30}(*)$
t_{pk} [day]	$t_{\mathrm{tran}}/30$
t_{tran} [year]	100
D [kpc]	1.9
t_{age} [year]	35,000
α	0.65
γ	$1.84(*)$





Ghost SNR

Benchmark	C (old)
(l, b)	$(175°, 5°)$
θ_s [arcmin]	$16(*)$
$S^{(0)}_{1GHz,s}$ [Jy]	$6.3(*)$
$L_{1GHz,pk}$ [cgs]	1.2×10^{29}
t_{pk} [day]	50
t_{tran} [year]	4.1
D [kpc]	0.5
t_{age} [year]	$55,000$
α	0.65
γ	$1.84(*)$



Conclusions

- Stimulated decays: forward & backward signals (***echo***)
- Transient vs. constant sources: dim today, *bright yesterday*
- Old and/or undetected dim SNR "*ghosts*": **detectable echos**
    - **SNR archaeology!**
- Better SNR light curve understanding: better estimates
- **Axion DM stimulated decays** via **SNR**s with **SKA1**:
    - beyond CAST
    - $g_{a\gamma\gamma} \sim 10^{-11}\ \mathrm{GeV}^{-1}$ @ $m_a \sim 10^{-6}\ \mathrm{eV}$

Backup Slides

Effects due to motion…

1. **… of the source w.r.t. dark matter:**

   echo points towards "historic" source position; the stacked echo image of source's history is then blurred/smeared with aberration

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

Effects due to motion...

1. ... of the source w.r.t. dark matter,

2. **of the Earth w.r.t. the source:**

the Earth can move away from the source, decreasing the flux density:

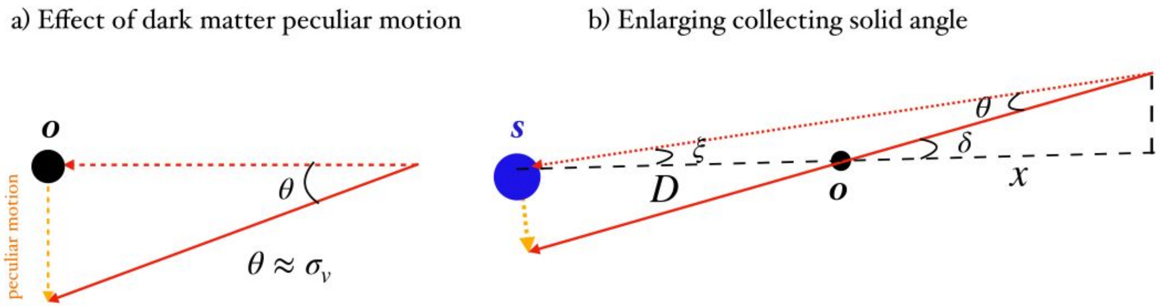
$$1 - \left(\frac{D}{d_o + D}\right)^2 \approx \frac{2d_o}{D} = 6 \times 10^{-3} \left(\frac{v_o}{10^{-3}}\right) \left(\frac{t_{\rm age}}{10^4 \,\rm years}\right) \left(\frac{1\,\rm kpc}{D}\right)$$

Effects due to motion…

1. … of the source w.r.t. dark r

2. of the Earth w.r.t. the sourc

3. **of the dark matter particles:**



*photons from decay of DM axions w/ vel. dispersion **σ_v** will not make it back to detector: need a **wider collection angle***

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

Effects due to motion...

1. ... of the source w.r.t. dark matter,
2. of the Earth w.r.t. the source,
3. of the dark matter particles:

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

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

$$\theta_{\rm echo} = \max(\theta_{\rm s}, \theta_{\rm ab}, 2\delta)$$

Earth’s shadow

1. The Earth’s shadow prevents photons from stimulating axion DM decays

$$\ell_{\rm sd} \approx \frac{2R_\oplus}{\theta_{\rm s}}$$

shadow’s length << l.o.s. for typical source sizes

2. Source photons are physically **blocked** by the Earth from stimulating axion DM on ... ource

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

timescale in which the Earth moves **“out of the way”** of the light rays << l.o.s.

SN rates

- **0.02 – 0.03 SN/yr ⇒ 2000 – 3000** SNRs in **10^5 yr.** [Tammann et al. '94]
- GC: 294 SNRs only, rest could be dim and at tail of observational capabilities

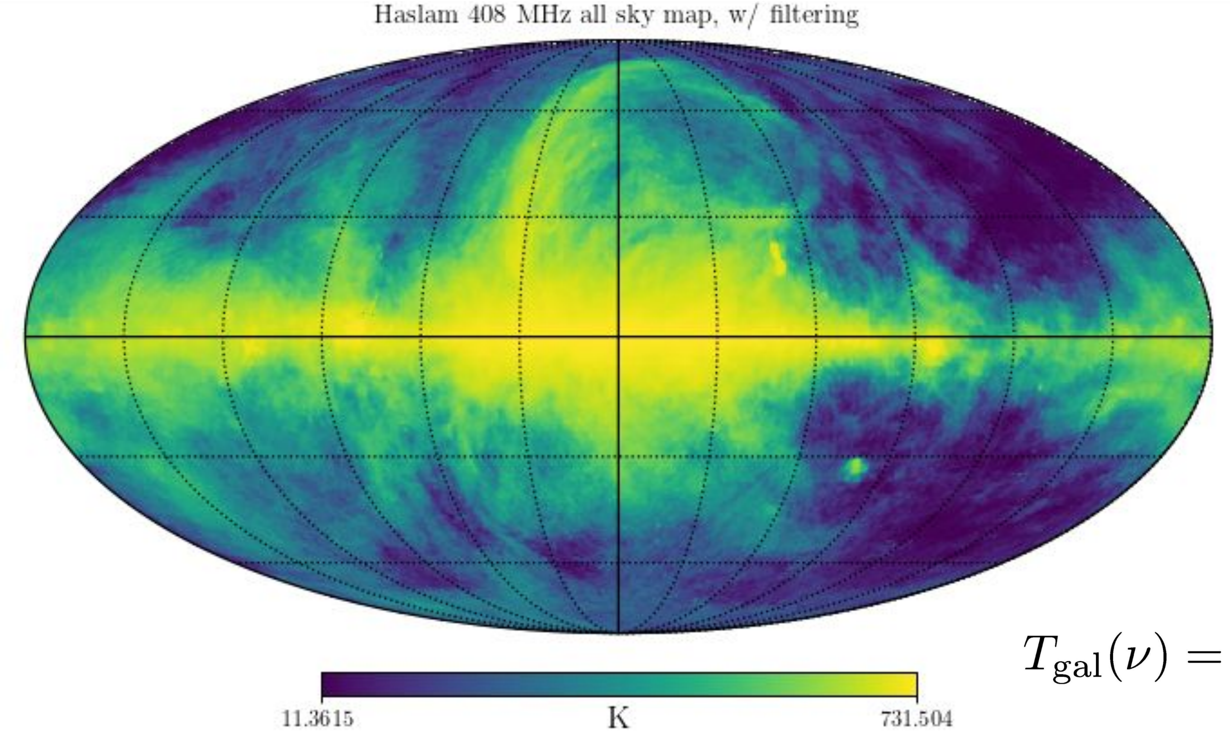
$$\Sigma(R) \propto \left(\frac{R}{R_\odot}\right)^a \exp\left(-b\frac{(R-R_\odot)}{R_\odot}\right)$$

$a = 1.09, b = 3.87.$

2D SNR density distribution
[Green '15]

- ⇒ ***O(10)*** SNRs within ***1 kpc*** of the Sun

$T_{gal}(\nu)$



$$T_{\rm gal}(\nu) = T_{408}\left(\frac{\nu}{0.408\ \rm GHz}\right)^{-2.55}$$

$$\mathrm{DP} \equiv g\mathrm{d}^3p/(2\pi)^3$$

Axion Dark Matter Echo

$$\frac{\mathrm{d}}{\mathrm{d}t}f_\gamma = C[f_\gamma]$$

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

Boltzmann equation

$$\mathrm{DP} \equiv g\mathrm{d}^3p/(2\pi)^3$$

Axion Dark Matter Echo

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

photon p.s.d. function

$$f_1 = f_\gamma(|\mathbf{p}_1|) h(\hat{\mathbf{p}}_1)$$

$$h(\hat{\mathbf{p}}_1) \approx \delta^2(\Omega_1 \hat{\mathbf{p}}_1 + \Omega_* \hat{\mathbf{n}}_*)$$

axion p.s.d. function

$$f_a = n_a (2\pi)^3 \delta^3(\mathbf{p}_a).$$

$$\rho_a = n_a m_a$$

Axion Dark Matter Echo

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = \frac{\pi^2 \Gamma_a}{E_a^3} \rho_a \Big(1 + f_\gamma h(\hat{\mathbf{p}}_1) + f_\gamma h(-\hat{\mathbf{p}}_1)\Big) \delta(E_\gamma - E_a)$$

photon p.s.d. function

$$f_1 = f_\gamma(|\mathbf{p}_1|) h(\hat{\mathbf{p}}_1)$$

$$h(\hat{\mathbf{p}}_1) \approx \delta^2(\Omega_1 \hat{\mathbf{p}}_1 + \Omega_* \hat{\mathbf{n}}_*)$$

Axion Dark Matter Echo

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = \frac{\pi^2 \Gamma_a}{E_a^3} \rho_a \Big(1 + f_\gamma h(\hat{\mathbf{p}}_1) + f_\gamma h(-\hat{\mathbf{p}}_1) \Big) \delta(E_\gamma - E_a)$$

isotropic

forward

backward (***echo***)

photon p.s.d. function

$$f_1 = f_\gamma(|\mathbf{p}_1|) h(\hat{\mathbf{p}}_1)$$

$$h(\hat{\mathbf{p}}_1) \approx \delta^2(\Omega_1 \hat{\mathbf{p}}_1 + \Omega_* \hat{\mathbf{n}}_*)$$

Axion Dark Matter Echo

$$\frac{\mathrm{d}}{\mathrm{d}t} f_\gamma = \frac{\pi^2 \Gamma_a}{E_a^3} \rho_a \Big(1 + f_\gamma h(\hat{\mathbf{p}}_1) + f_\gamma h(-\hat{\mathbf{p}}_1)\Big) \delta(E_\gamma - E_a)$$

isotropic

forward

backward (***echo***)

photon p.s.d. function

$$f_1 = f_\gamma(|\mathbf{p}_1|) h(\hat{\mathbf{p}}_1)$$

$$h(\hat{\mathbf{p}}_1) \approx \delta^2(\Omega_1 \hat{\mathbf{p}}_1 + \Omega_* \hat{\mathbf{n}}_*)$$

integrating over solid angle along the **backwards l.o.s.**, and integrating over (emission!) time...

Axion Dark Matter Echo

$$S_{\nu_a,\mathrm{e}} = \frac{\pi^2 \Gamma_a}{E_a^3} \delta(E_\gamma - E_a) \int_0^{t_{\mathrm{age}}/2} \mathrm{d}x \; \rho_a(x, -\hat{\mathbf{n}}_*) \; S_{\nu_a,\mathrm{s}}(t_{\mathrm{age}} - 2x)$$

$$S_\nu = \frac{E^3}{2\pi^2} \int \mathrm{d}\Omega \; f(E, \Omega)$$

Optical Depth

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

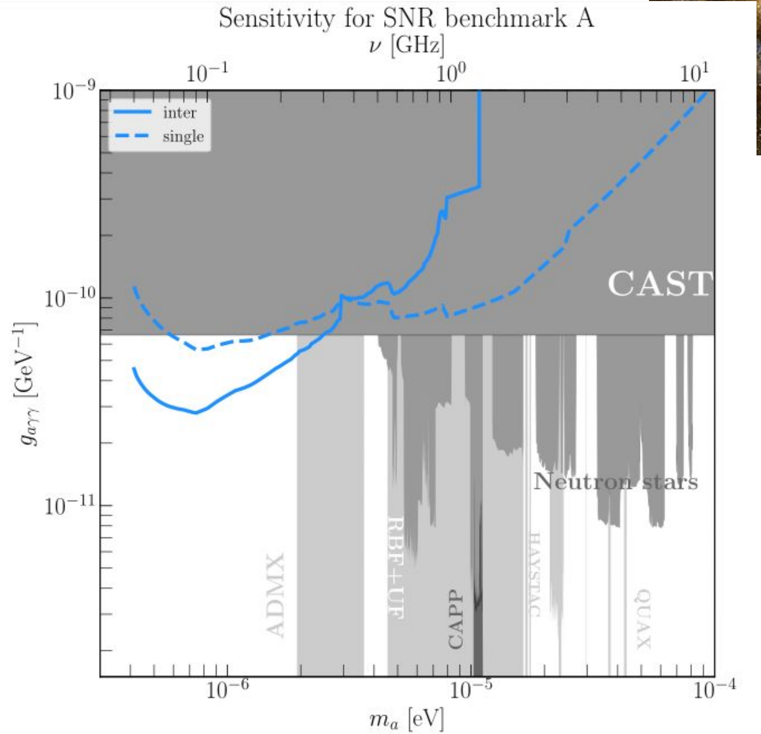
$\mathrm{EM} = \int n_e^2\, d\ell$ emission measure of electrons along the photon's propagation

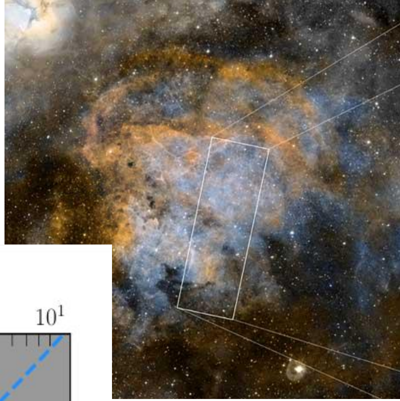
$$\mathrm{EM} \approx 0.23\ \mathrm{cm^{-6}\ pc} \left(\frac{n_{e,0}}{0.015\ \mathrm{cm^{-3}}}\right)^2 \left(\frac{\ell}{\mathrm{kpc}}\right)$$

midplane, away from galactic center

SNR G6.4-0.1-like

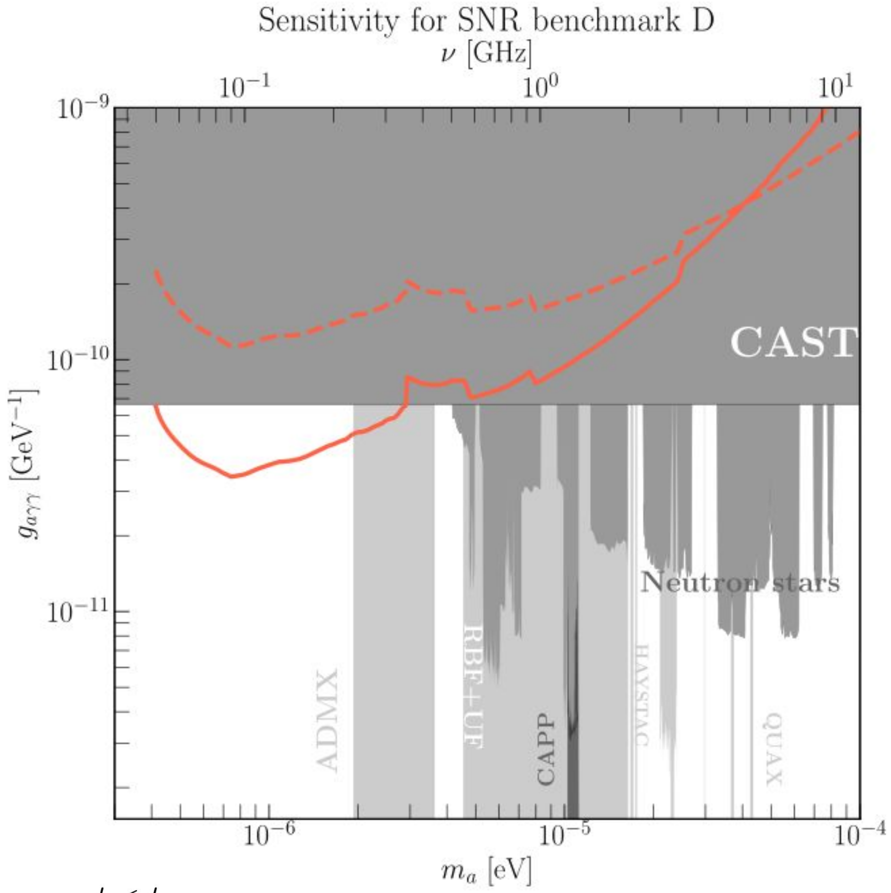
Benchmark	A (adiabatic only)
(l, b)	$(64°, -0.1°)$
θ_s [arcmin]	48
$S^{(0)}_{1\mathrm{GHz,s}}$ [Jy]	310
$L_{1\mathrm{GHz,pk}}$ [cgs]	(n/a)
t_{pk} [day]	(n/a)
t_{tran} [year]	100
D [kpc]	1.9
t_{age} [year]	35, 000
α	0.65
γ	1.84(*)



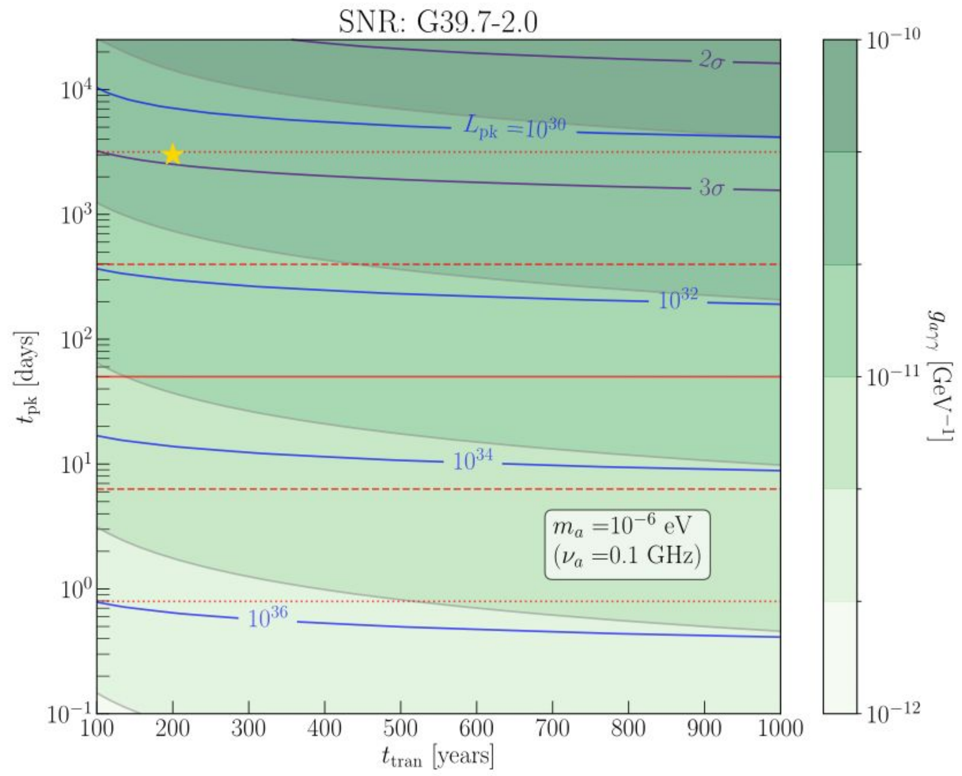


Baby SN

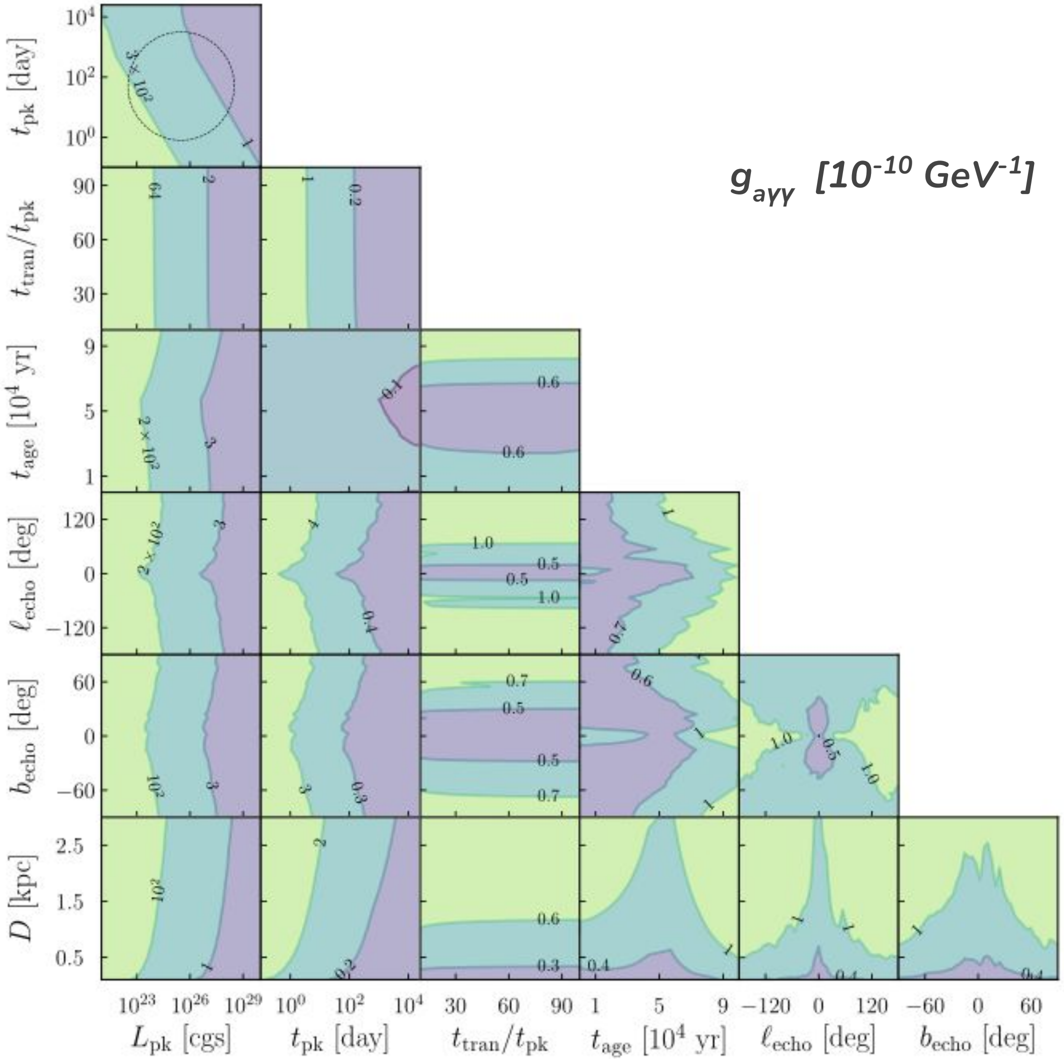
Benchmark	D (new)
(l, b)	$(40°, 0°)$
θ_s [arcmin]	1.0(*)
$S^{(0)}_{1\mathrm{GHz,s}}$ [Jy]	$2.1 \times 10^6(*)$
$L_{1\mathrm{GHz,pk}}$ [cgs]	1.2×10^{29}
t_{pk} [day]	50
t_{tran} [year]	4.1
D [kpc]	0.5
t_{age} [year]	10
α	0.65
γ	1.84(*)



$$R(t) = \begin{cases} v_{hom} t, & t < t_{tran} \\ v_{hom} t_{tran} \left(\frac{t}{t_{tran}} \right)^{2/5}, & t \geq t_{tran} \end{cases}$$

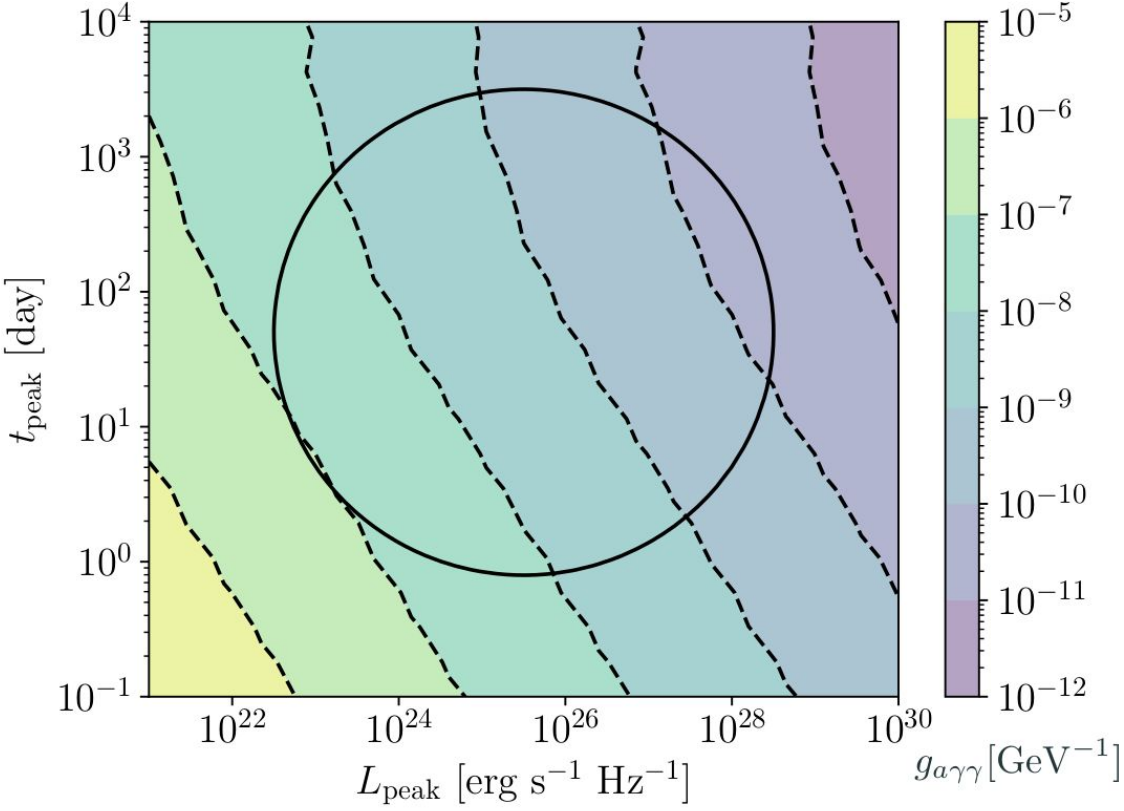


G39.7-2.0 free expansion

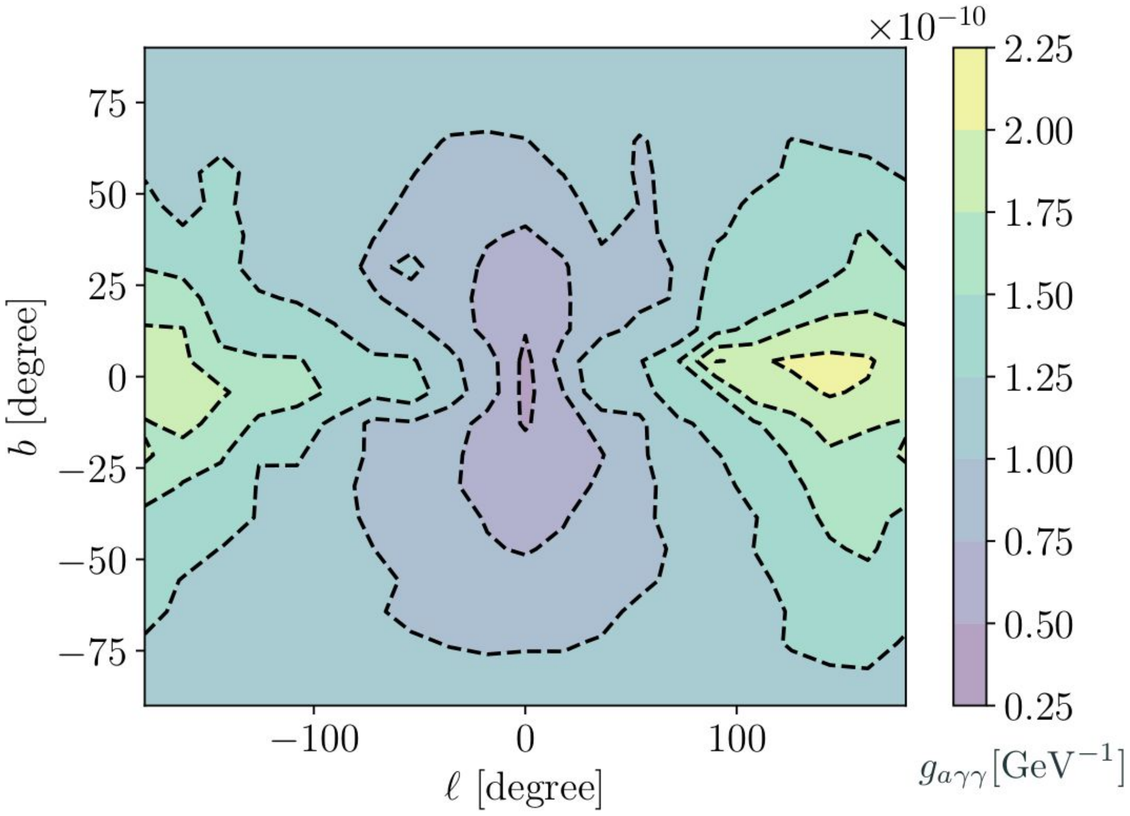


$g_{a\gamma\gamma}$ [10^{-10} GeV^{-1}]
t_{pk} [day]
t_{tran}/t_{pk}
t_{age} [10^4 yr]
ℓ_{echo} [deg]
b_{echo} [deg]
D [kpc]
L_{pk} [cgs]

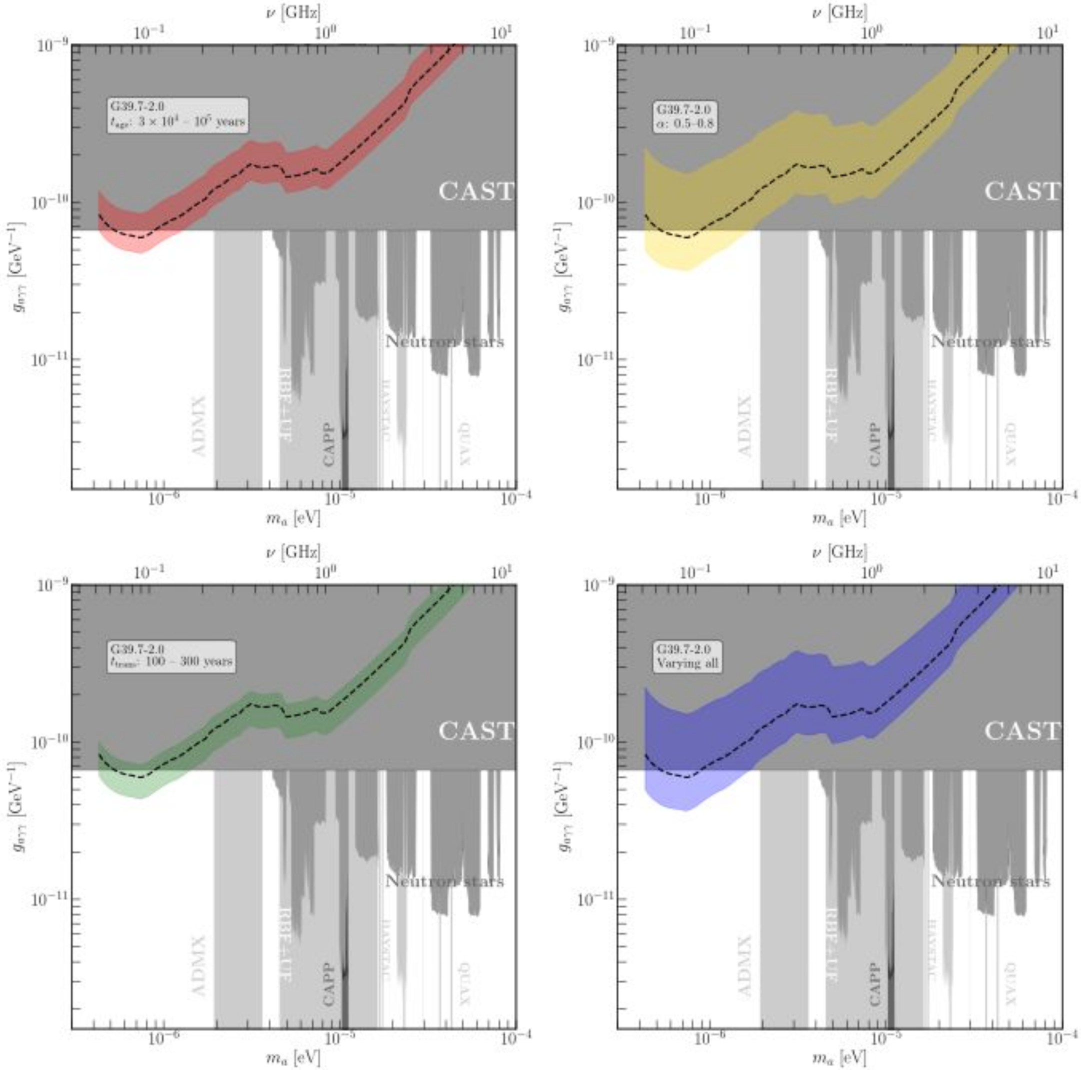
Ghost SNR



Free expansion

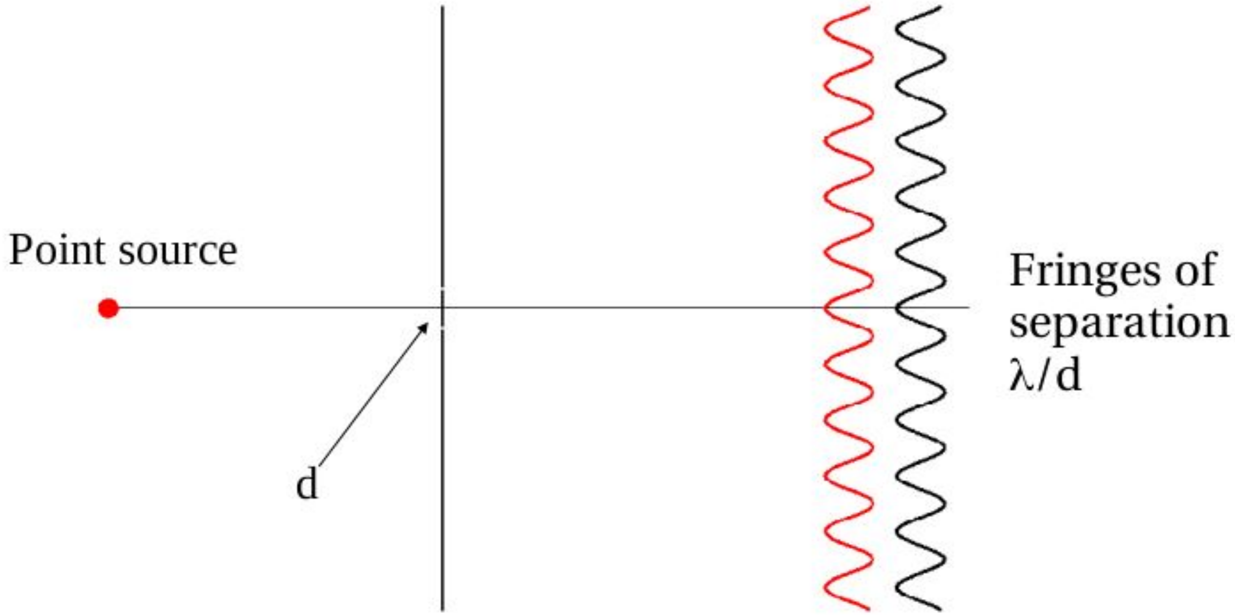


Echo location

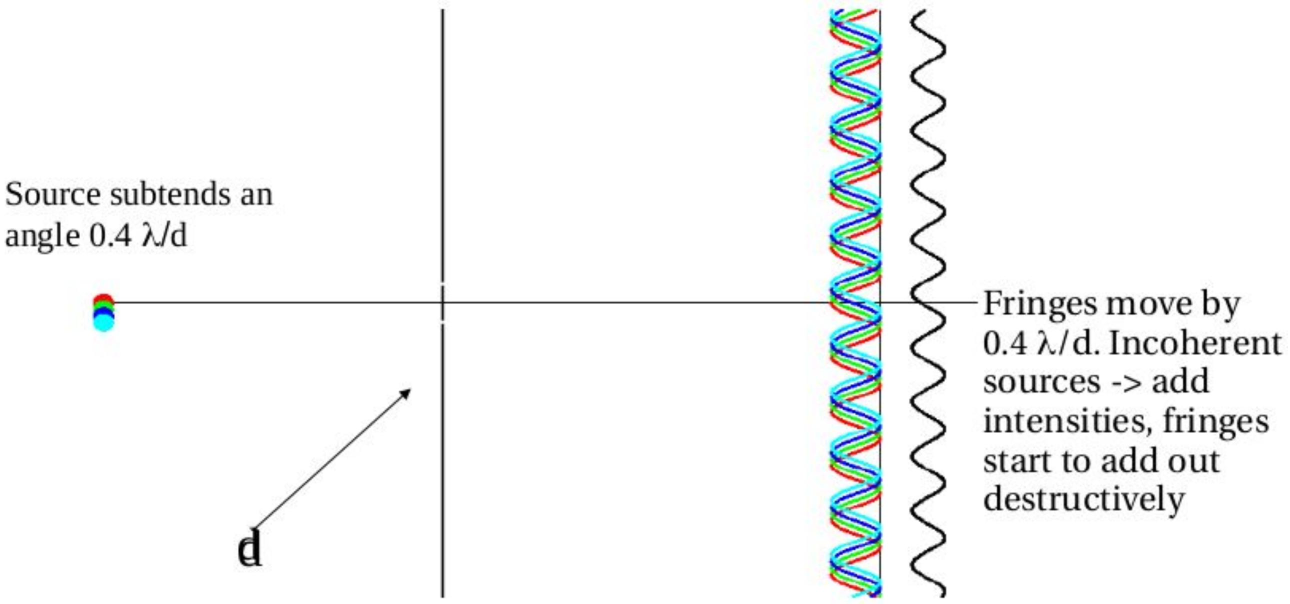


Uncertainties

Young Experiment



Young Experiment



Define |fringe visibility| as $(I_{max}-I_{min})/(I_{max}+I_{min})$

Young Experiment