Astro & Cosmo Searches for (QCD) axions

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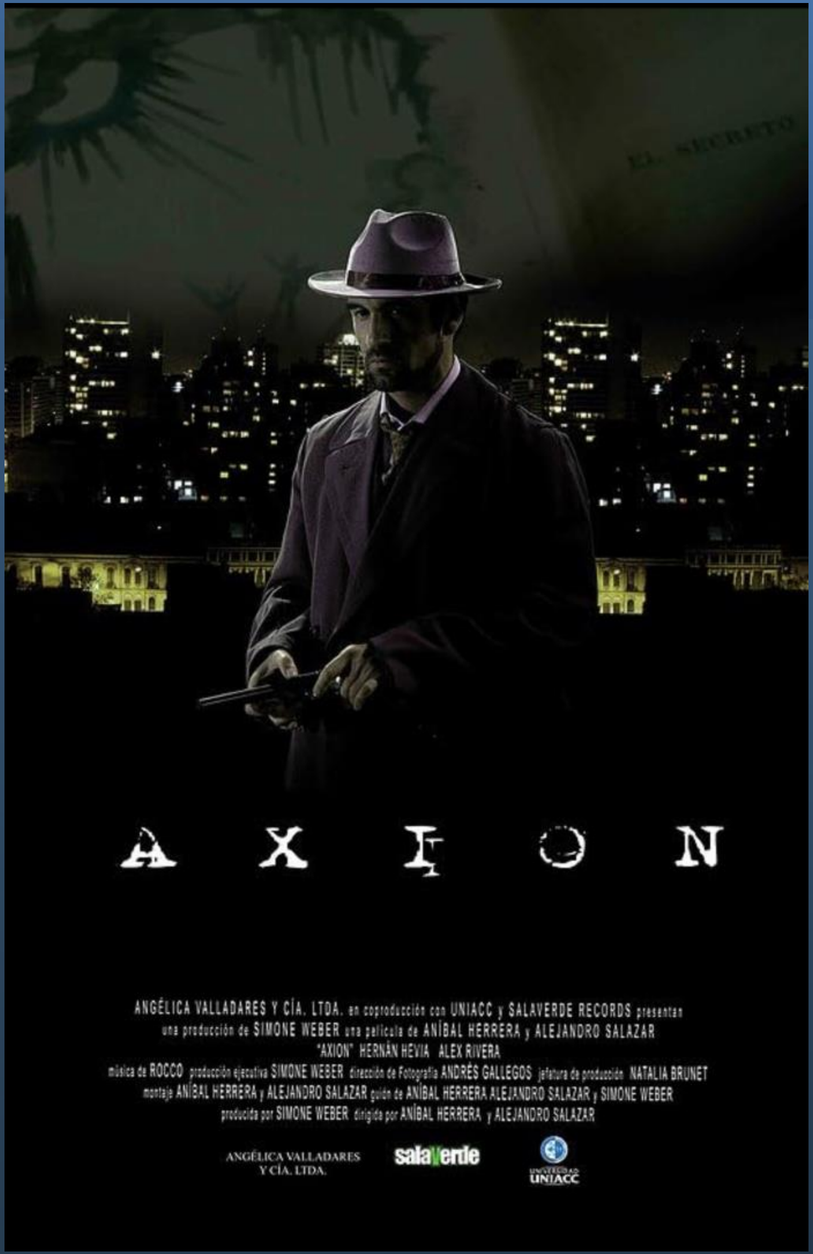
Outline

- **CMB** searches
- **SN1987A** bound
- Signatures of **Axionic Defects**


EL SECRETO
AXION
ANGÉLICA VALLADARES Y CÍA. LTDA. en coproducción con UNIACC y SALAVERDE RECORDS presentan
una producción de SIMONE WEBER una película de ANÍBAL HERRERA y ALEJANDRO SALAZAR
"AXION" HERNÁN HEVIA ALEX RIVERA
música de ROCCO producción ejecutiva SIMONE WEBER dirección de Fotografía ANDRÉS GALLEGOS jefatura de producción NATALIA BRUNET
montaje ANÍBAL HERRERA y ALEJANDRO SALAZAR guión de ANÍBAL HERRERA ALEJANDRO SALAZAR y SIMONE WEBER
producida por SIMONE WEBER dirigida por ANÍBAL HERRERA y ALEJANDRO SALAZAR
ANGÉLICA VALLADARES Y CÍA. LTDA.
salaverde
UNIVERSIDAD UNIACC

Axion Detection: Building blocks

- Direct coupling to **SM particles**:

  - Above QCDPT (T $> \sim$ 1 GeV)

$$\mathcal{L}_{a-SM} = \frac{c_y}{2f}\partial_\mu a J^\mu_y + \sum_{X=G,Y,Z} \frac{\alpha_X}{8\pi f} a X \tilde{X}$$

Hard to probe! Except for colliders (and perhaps CMB-S4)

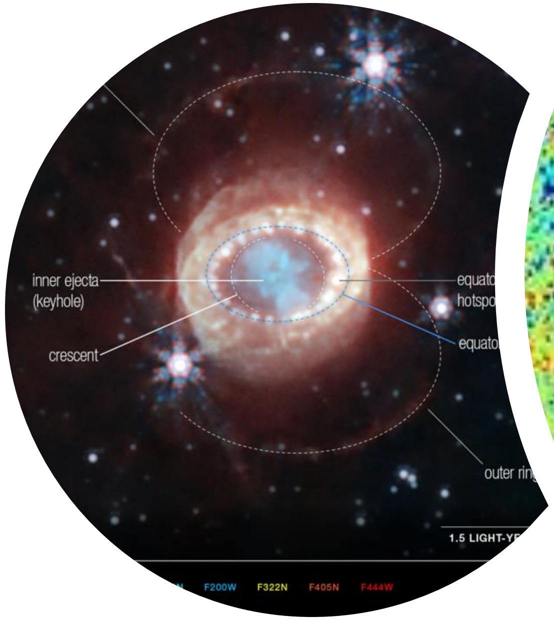
  - Below QCDPT (T $<$ 150 MeV)

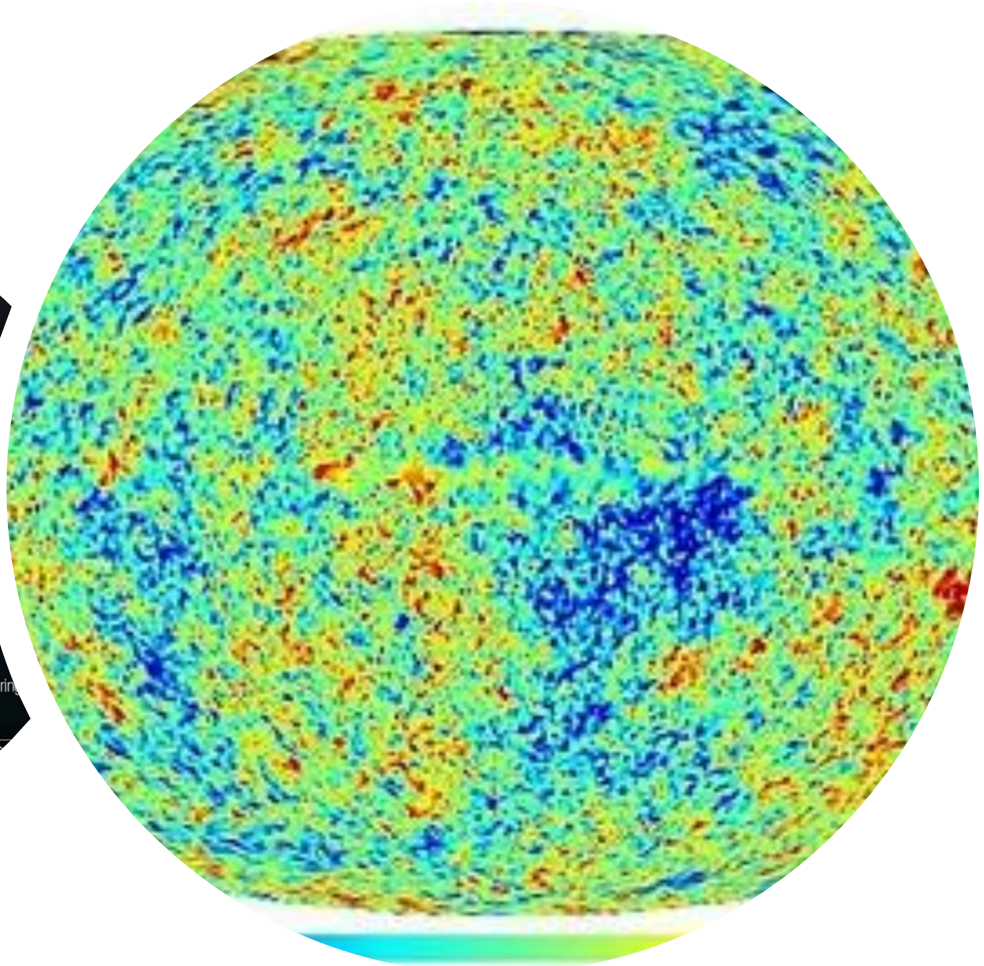
$$\mathcal{L}_{a-SM} = c_{a\pi}\partial a \partial\pi\pi\pi + +c_{aN}\partial_\mu a N S^\mu N + \frac{\alpha_{EM}}{8\pi f} a F\tilde{F} + \sum_{i=e,\mu} \frac{c_i}{2f}\partial_\mu a J^\mu_i$$

Easier to probe in astro&cosmo environments

- **Gravitational Probes**:

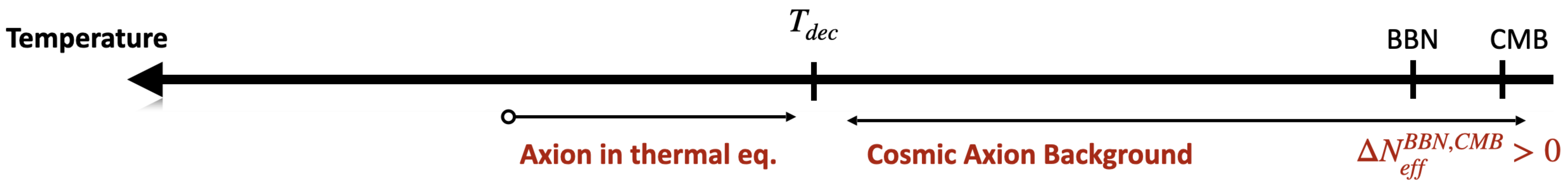
  CMB; Gravitational Waves; Primordial Black Holes.





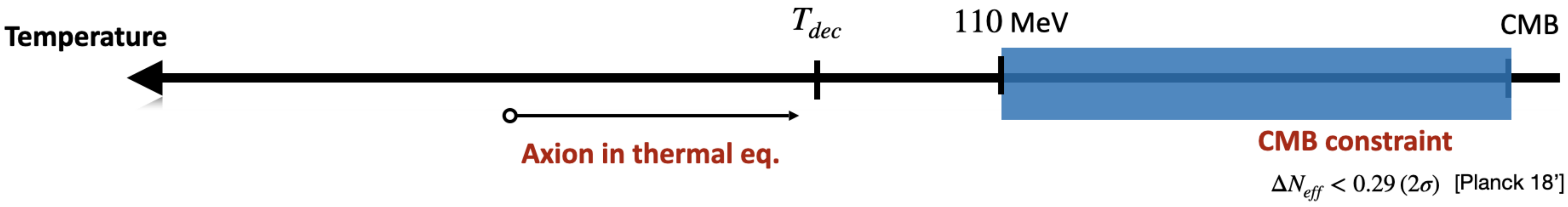
Cosmic Microwave Background

Hot Axions in the CMB



- **Thermal axion production** contributes to ΔN_{eff} at CMB and BBN.
- Later decoupling (smaller T_{dec}) $\rightarrow$ larger signal: $\Delta N_{eff} \propto g_*(T_{dec})^{-4/3}$

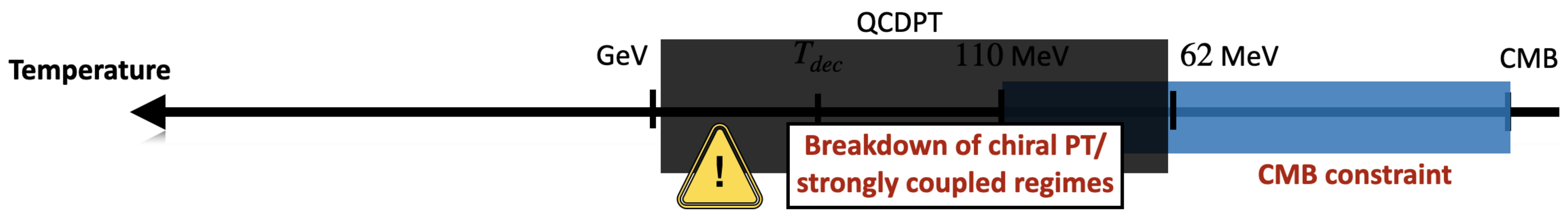
[Turner 88', Chang 93', Hannestad 05', Brust 13', Di Valentino 15', Baumann 16' ....]



- Current data is is now sensitive to relativistic species that are produced close to the QCD PT ($T_c \sim 110$ MeV)

- Recent **developments**:
  - Beyond instantaneous decoupling approximation,
  - Boltzmann equations,
  - Full momentum distribution, etc.

[**RZF**&Notari 17', Arias-Aragon 20', +,
D'Eramo et al. 18', 20',+,
Green&Wallisch 21,
...]



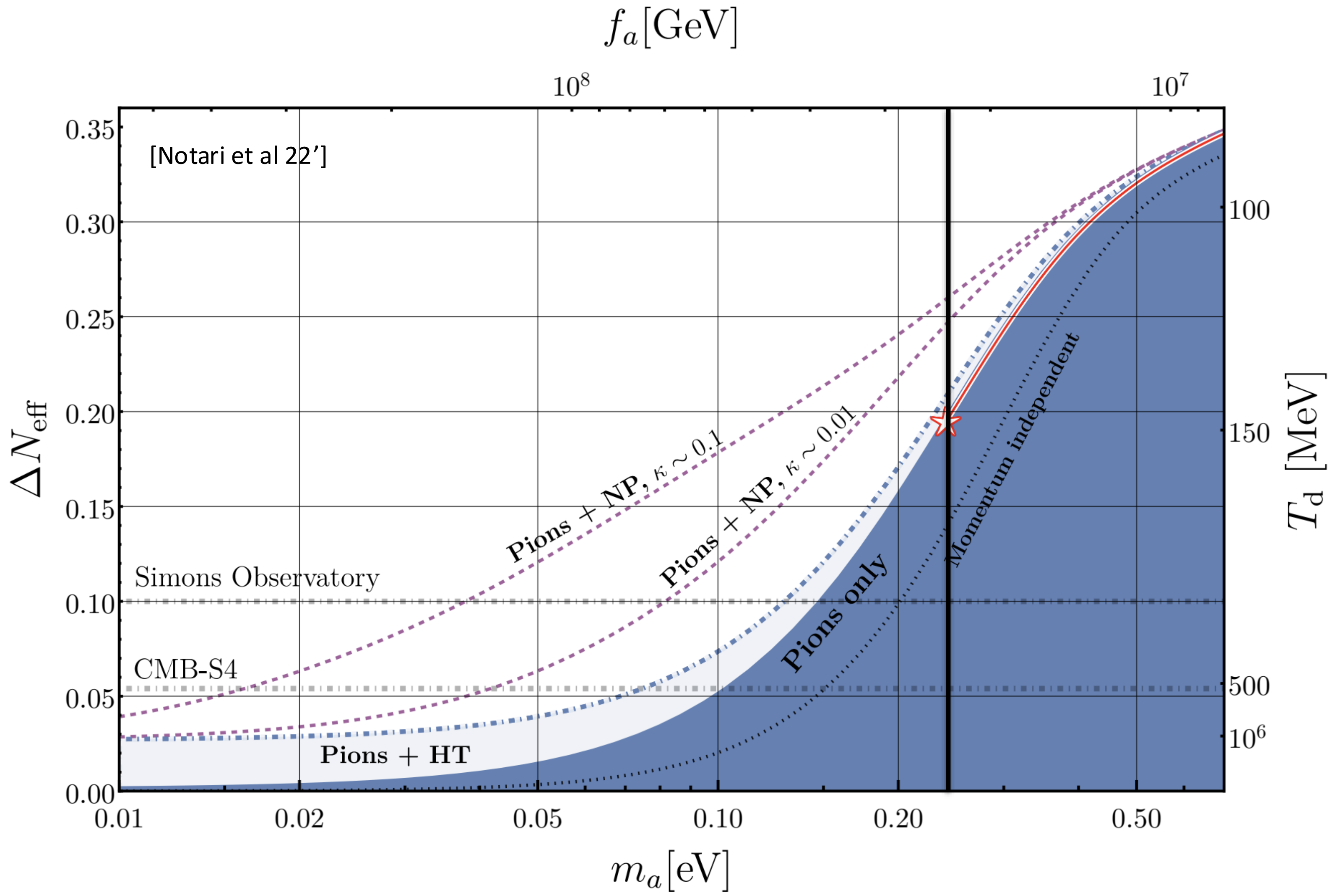
QCD axion case:

- Leading process for <u>axion production</u> at T < GeV: $\pi\pi \rightarrow \pi a$
- **Obstacle**: breakdown of chiral EFT at $T < 60$ MeV. [Di Luzio et al. 21']
- Recent ideas:
  - 1) use observed pion cross-section; [Notari et al 22']
  - 2) go to higher order in the EFT [Di Luzio et al. 22', Bianchini et al. 23']

CMB bound on the QCD axion:

$$f_a > 2.4 \times 10^7 \mathrm{GeV}$$

(95% CL)

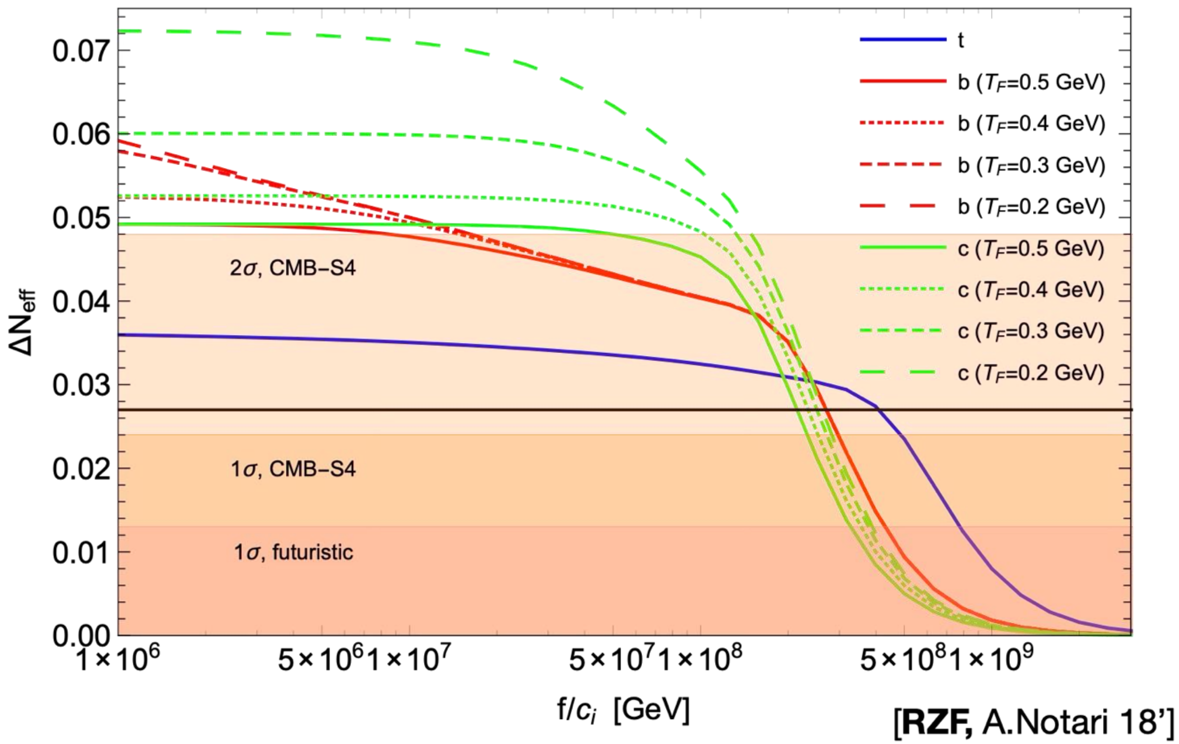


[See also talks by Nicola Barbieri and Marcin Badziak]

Future:

- CMB-S4 can test the QCD axion at $f_a > 10^8$ GeV if:
  - Axion couples to <u>heavy quarks</u>
  - Axion has <u>Flavor Violating</u> couplings

[**RZF**&Notari 17', Arias-Aragon 20', +, D'Eramo et al. 18', 20',+, Green&Wallisch 21, ..., Badziak et al. 24', ...]



[**RZF**, A.Notari 18']

- Use the CMB to probe each coupling in the ALP-SM EFT.

[Caloni et al. 22', ...]

[See also talks by Nicola Barbieri and Marcin Badziak]

Future:

- CMB-S4 can test the QCD axion at $f_a > 10^8$ GeV if:
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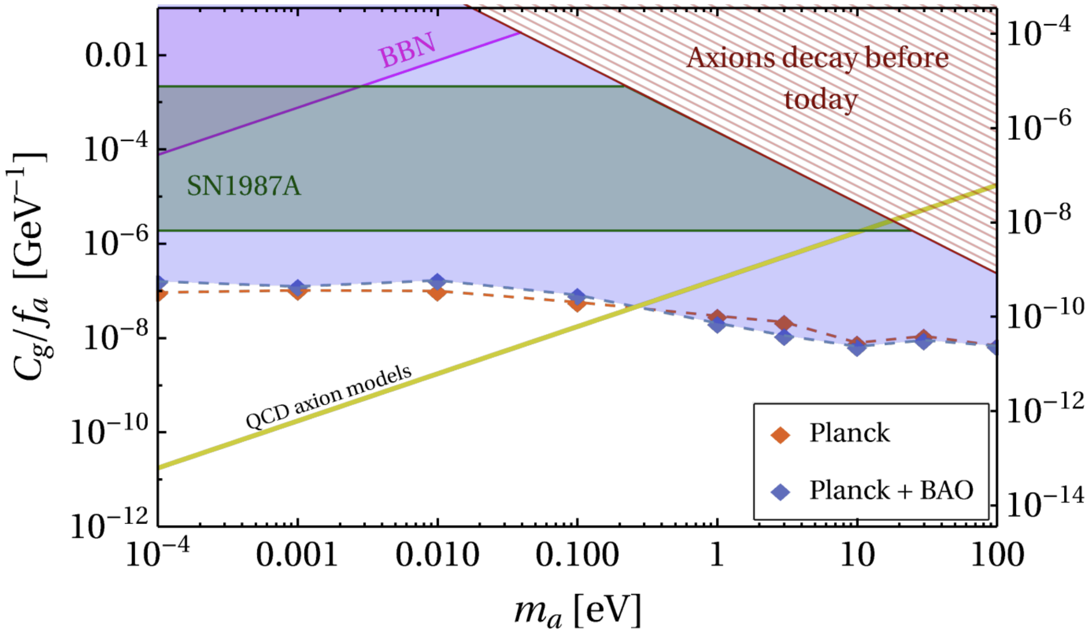
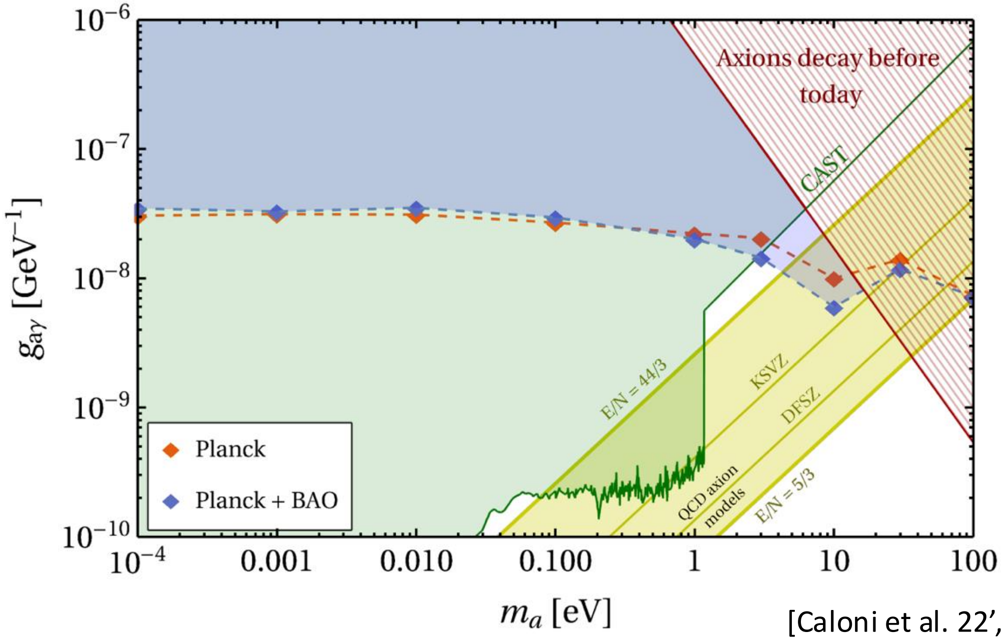
[**RZF**&Notari 17', Arias-Aragon 20', +, D'Eramo et al. 18', 20',+, Green&Wallisch 21, …]

- Probe each coupling in the ALP-SM EFT!

[D'Eramo, **RZF,** Notari, Bernal 18', Caloni et al. 22', Badziak et al. 24',…]

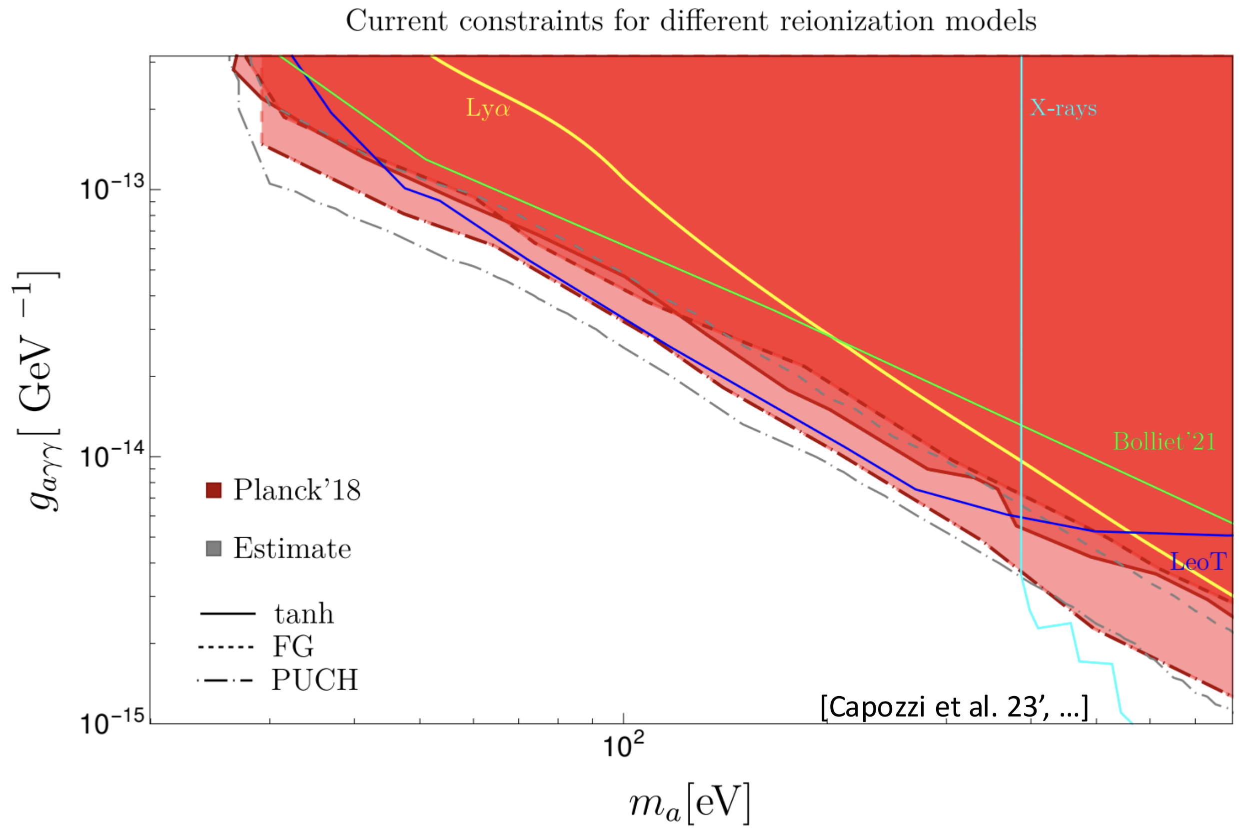




[Caloni et al. 22', …]

CMB also probes **Axion DM decaying to photons/electrons:**

- Decay to photons/electrons affects:
  - the ionization fraction x_e (optical depth) → CMB
  - IGM temperature → Lyman-alpha



[See also Bolliet et al. 20', H. Liu et al. 23']

Astrophysical factories of axions

- White Dwarfs

[Talk by Ben Safdi]

- Pulsars

[Talk by Jorge Calvo, Mariia Khelashvili]

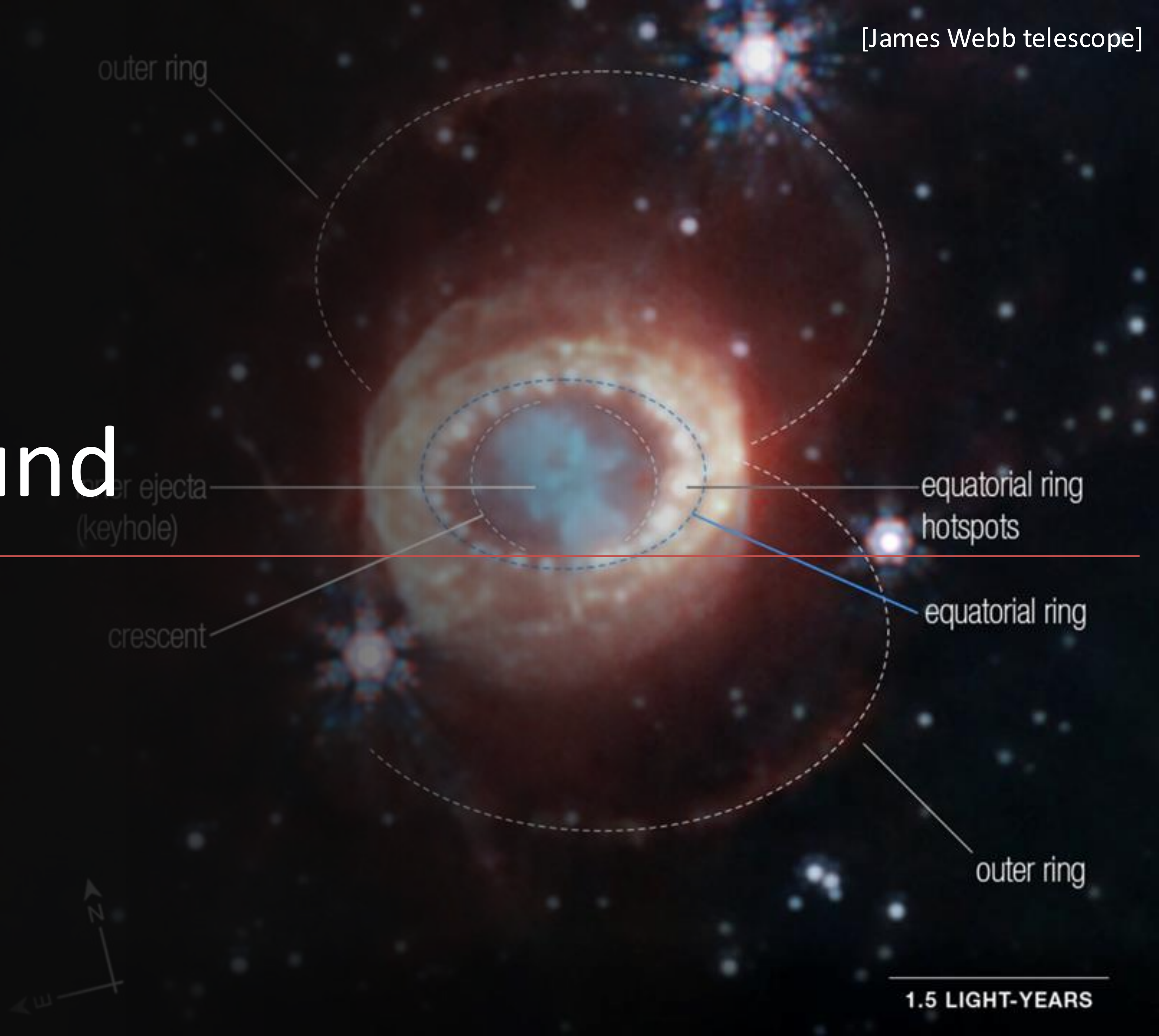
- Neutron Stars

[Talk by Topi Sirkiä, Ben Safdi]

- Core-collapse Supernovae
- Diffuse backgrounds
- Black Hole superradiance

[Talk by Thomas Spieksma]

[See also Orion Ning's talk]

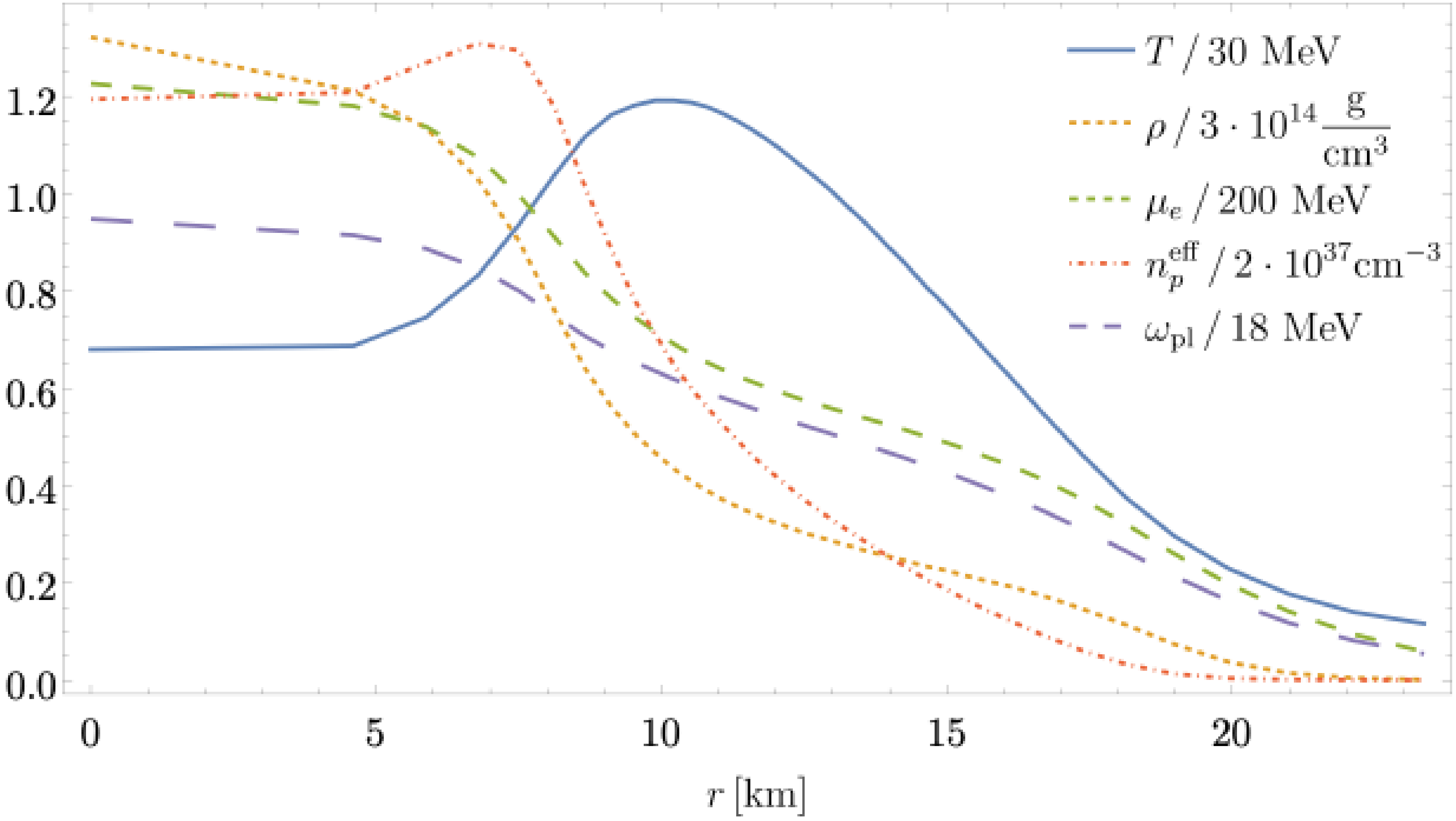


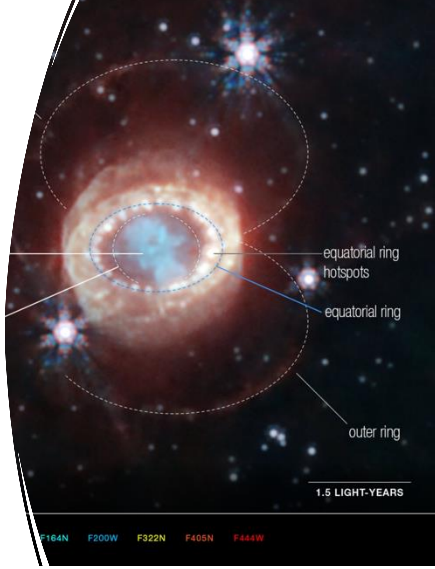
[James Webb telescope]

SN1987A bound

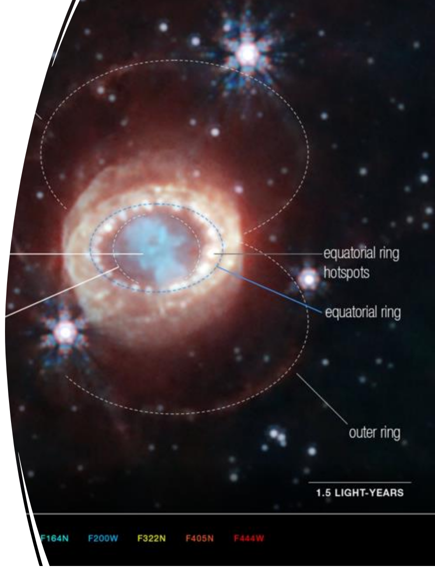
(as of 2025)

SN1987A bound on the QCD Axion
(as of 2025)





SN1987A bound on the QCD Axion
(as of 2025)



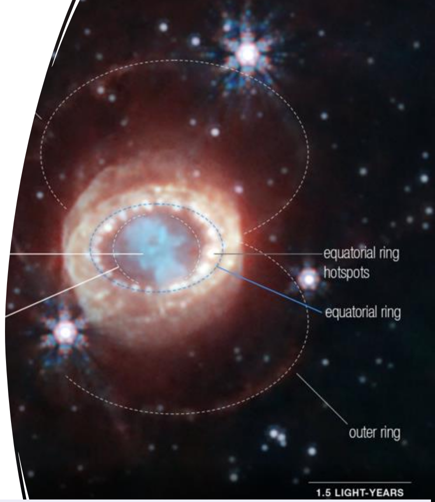
- **Step 2**, calculate axion production:

  - **N + N → N + N +a** (nucleon-nucleon bremsstrahlung) [Chang et al. 18', Carenza et al. 19,...]

  or

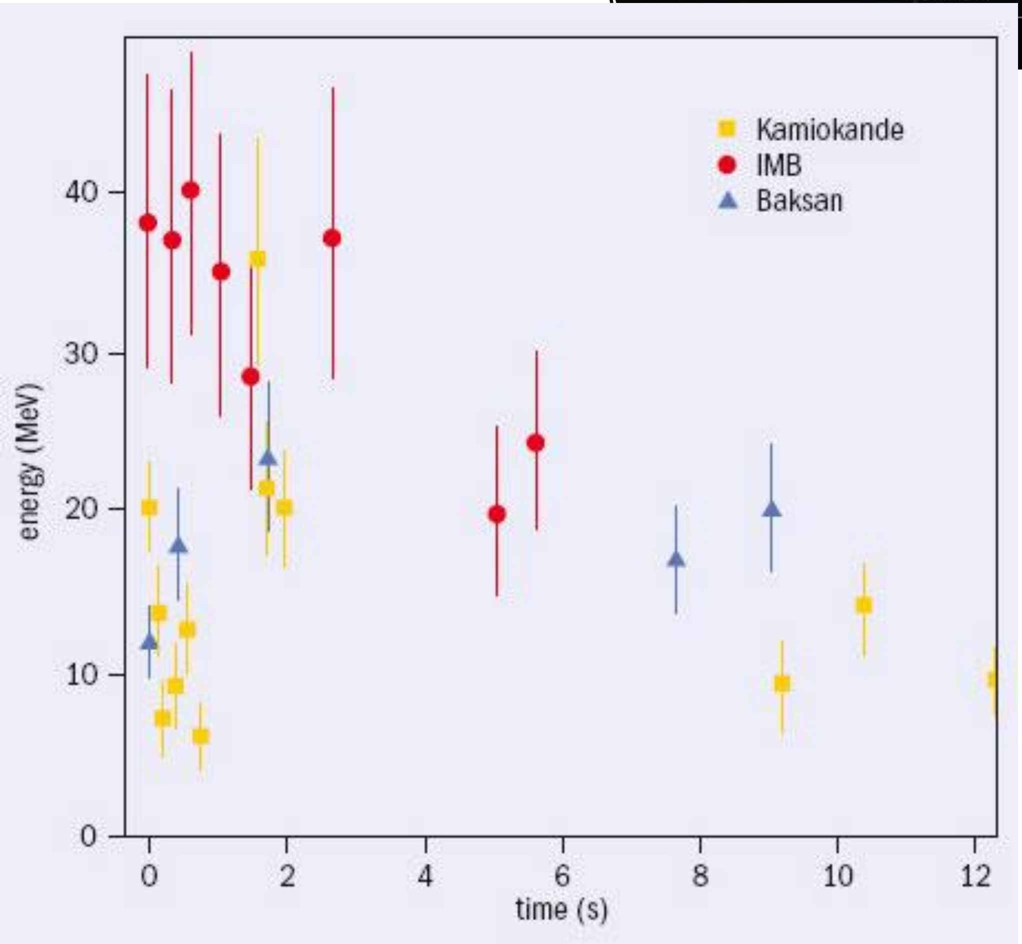
  - **π^- + p → n + a** (if pion densities are large enough) [Carenza et al. 20]

SN1987A bound on the QCD Axion (as of 2025)

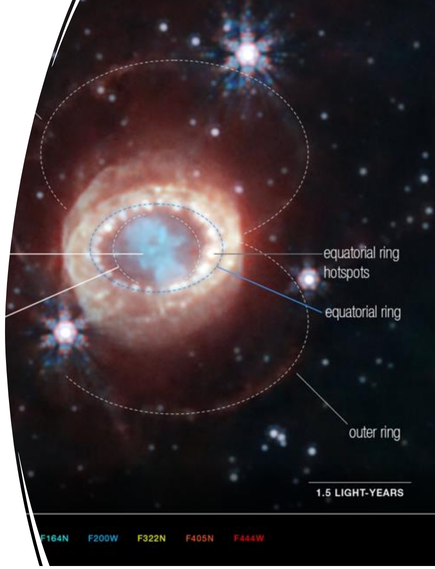


- **Step 3**, the cooling bound:
  - SN1987A neutrino burst lasted around 10 sec
  - $$L_a < L_\nu \simeq 3 \cdot 10^{52} \frac{\text{erg}}{\text{s}}$$ [Raffelt and Seckel 88']

    Otherwise neutrino burst has been estimated to be shortened in **half**!



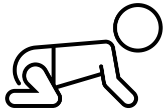
SN1987A bound on the QCD Axion
(as of 2025)



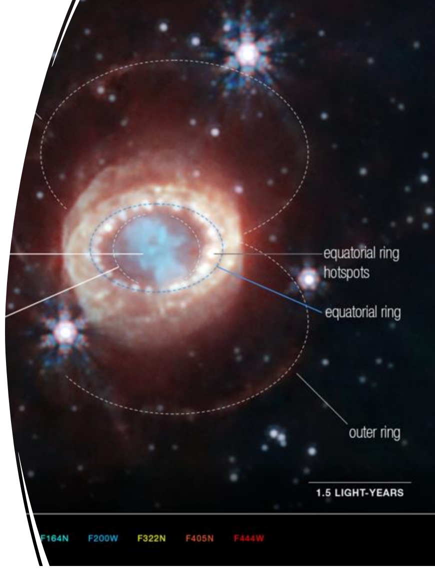
- **Step 1 + 2 + 3** give the bound:

$$f_a > few \times 10^8 \mathrm{GeV}$$
$$(m_a < few \times 10^{-2} eV)$$

[Chang et al. 18',
Carenza et al. 19,…]

- But… what about the **error bars**?
  – Let's go a few steps back  (3 → 2 → 1)

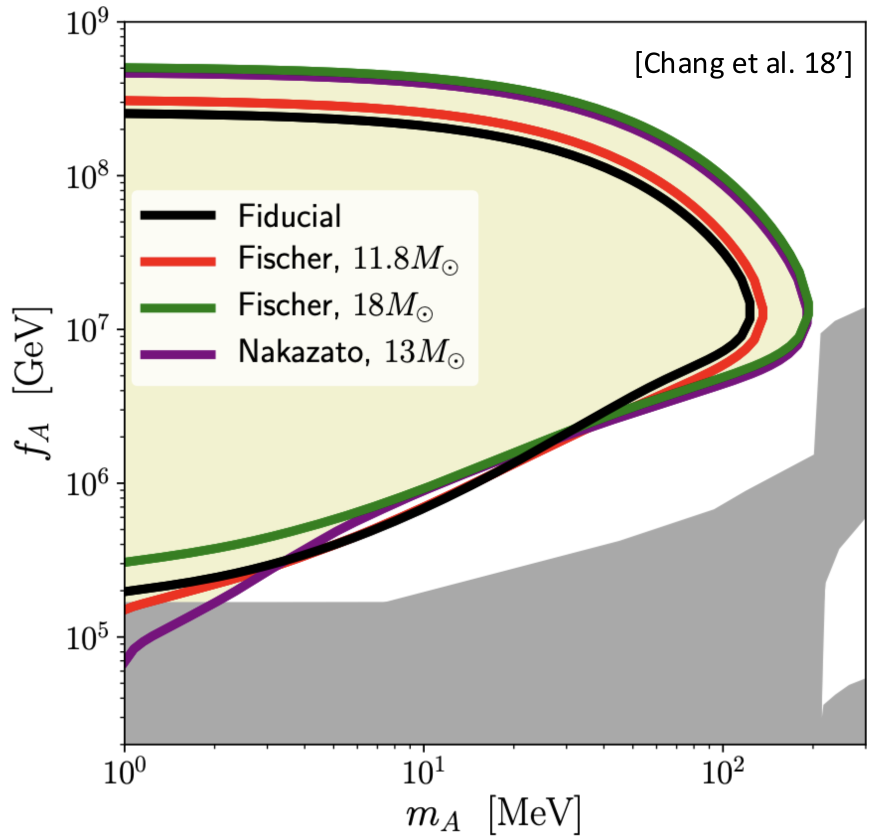
SN1987A bound on the QCD Axion
(as of 2025)



Recap of uncertainties:

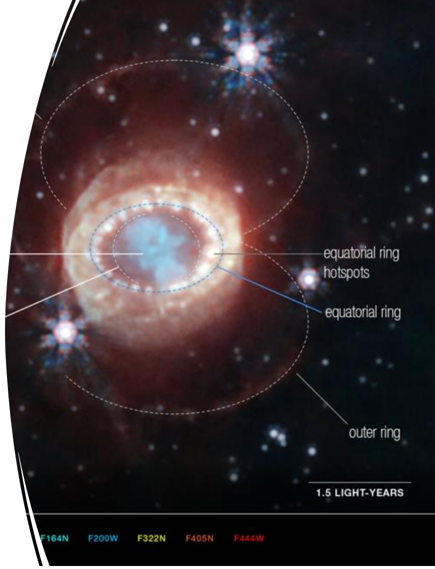
1 - Different simulations + different EoS for the SN core yield bounds that can vary within

$$\frac{\Delta f_a}{f_a} \sim 2, 3$$



Important to marginalize over these effects + other astrophysical parameters

SN1987A bound on the QCD Axion
(as of 2025)



Recap of uncertainties:

2 - Model **dependence** of the **coupling to nucleons:** (KSVZ vs DFSZ vs nucleophobic axions).
Bounds on f_a can change by $O(10)$.

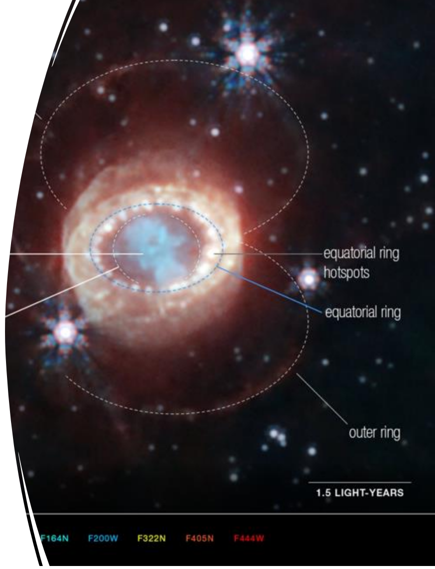
3 – **Finite density effects**

[Springmann et al. 2024]

in the Heavy baryon chiral EFT of axion-nucleons.

Sizeable corrections (and associated errors of 50%)

SN1987A bound on the QCD Axion (as of 2025)



- To summarize:

> ➢ $\boldsymbol{f_a \sim 10^8}$ **GeV** is likely still **compatible** with data **at $\boldsymbol{2\sigma}$**.
>
> (Similar conclusion for axion bounds from NS cooling).
>
> ➢ A complete dedicated analysis of **uncertainties** missing!

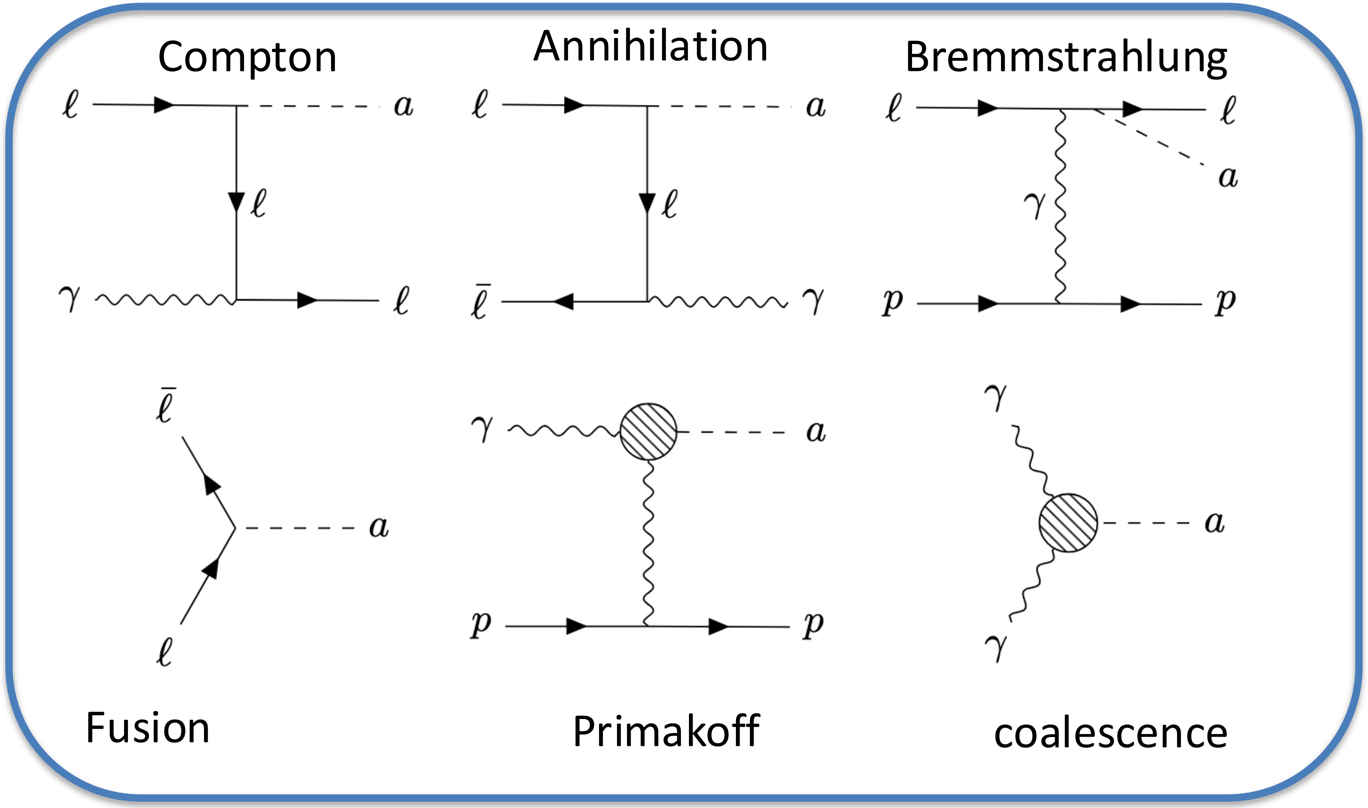
Core-colapse SNe: Beyond QCD Axion

- Two main directions:
  - **Heavier** axions
  - Couplings with **other SM particles** in the core (pions, photons, electrons, muons)

Core-colapse SNe: Beyond QCD Axion

- Example: ALP-electron/muon coupling $\partial_\mu(a/f)\bar{\psi}\gamma^\mu\gamma^5\bar{\psi}$

Production Channels:



(see Eike Ravensburg's talk)

Core-colapse SNe: Beyond QCD Axion

- Example: ALP-electron/muon coupling

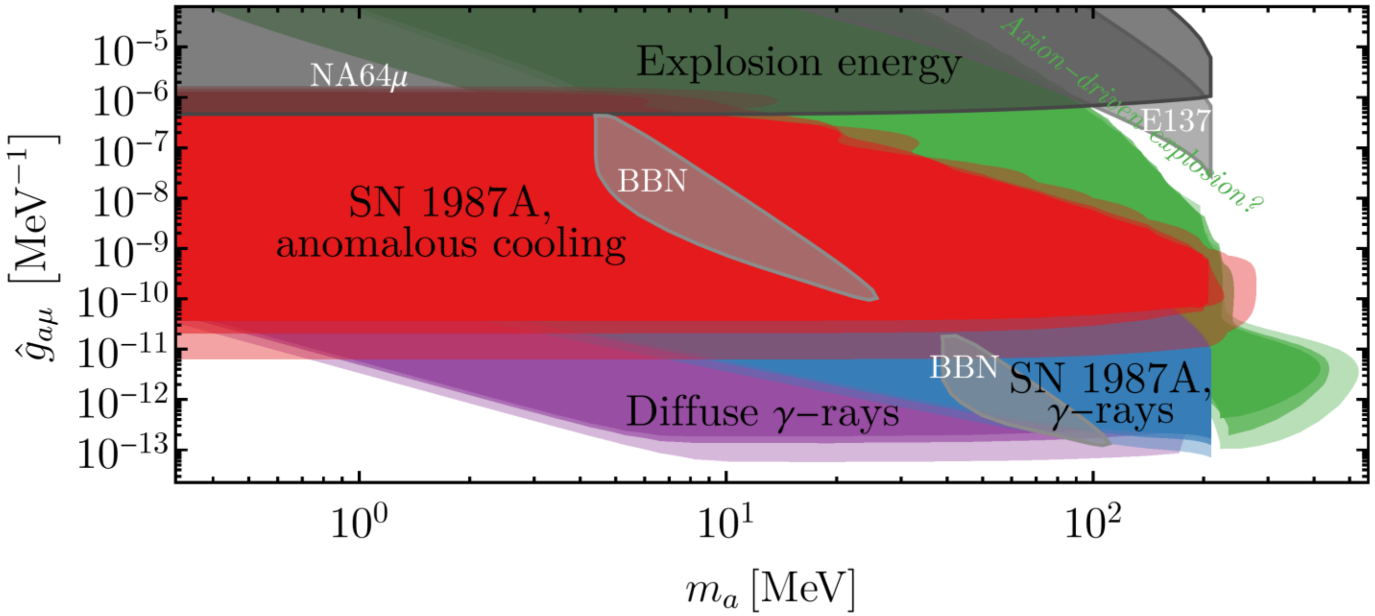
$$\partial_\mu (a/f)\bar{\psi}\gamma^\mu\gamma^5\bar{\psi}$$

<u>Detection Channels:</u>

- Cooling bound
- Explosion energy bound
- Gamma-ray emission
(from SN1987A, or integrated)
- 511 keV line

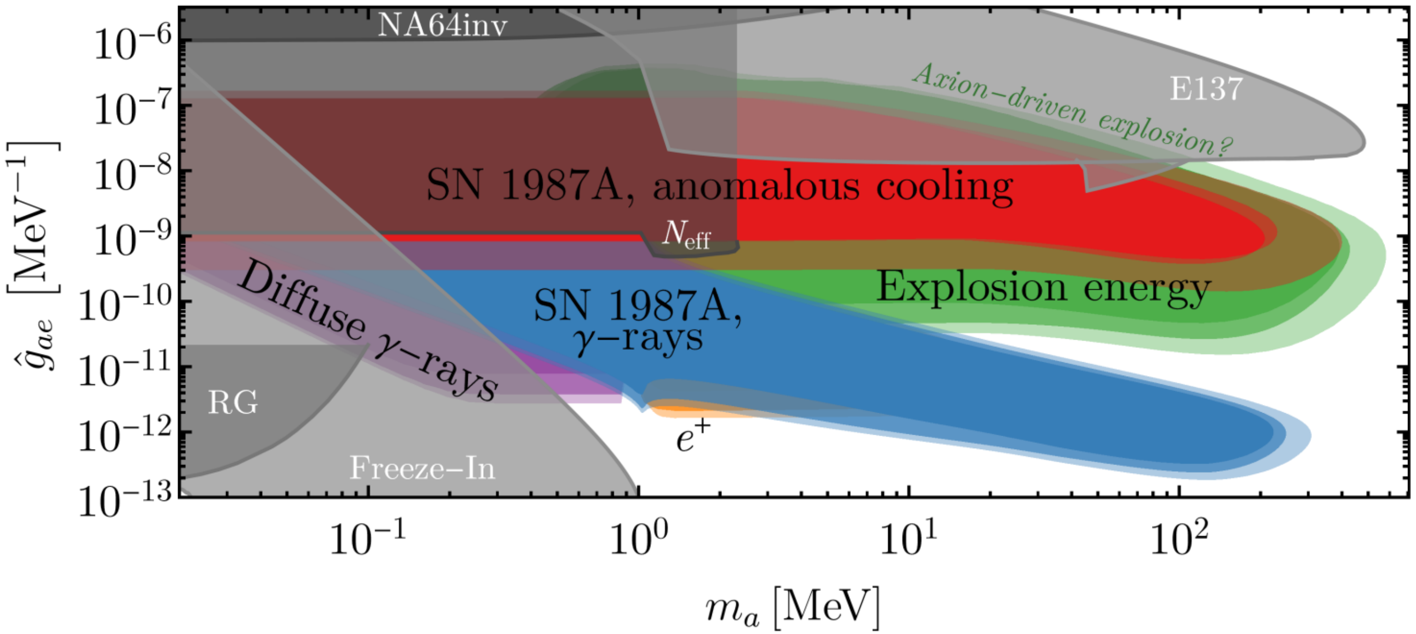
(see Eike Ravensburg's talk)

Axion-Muon



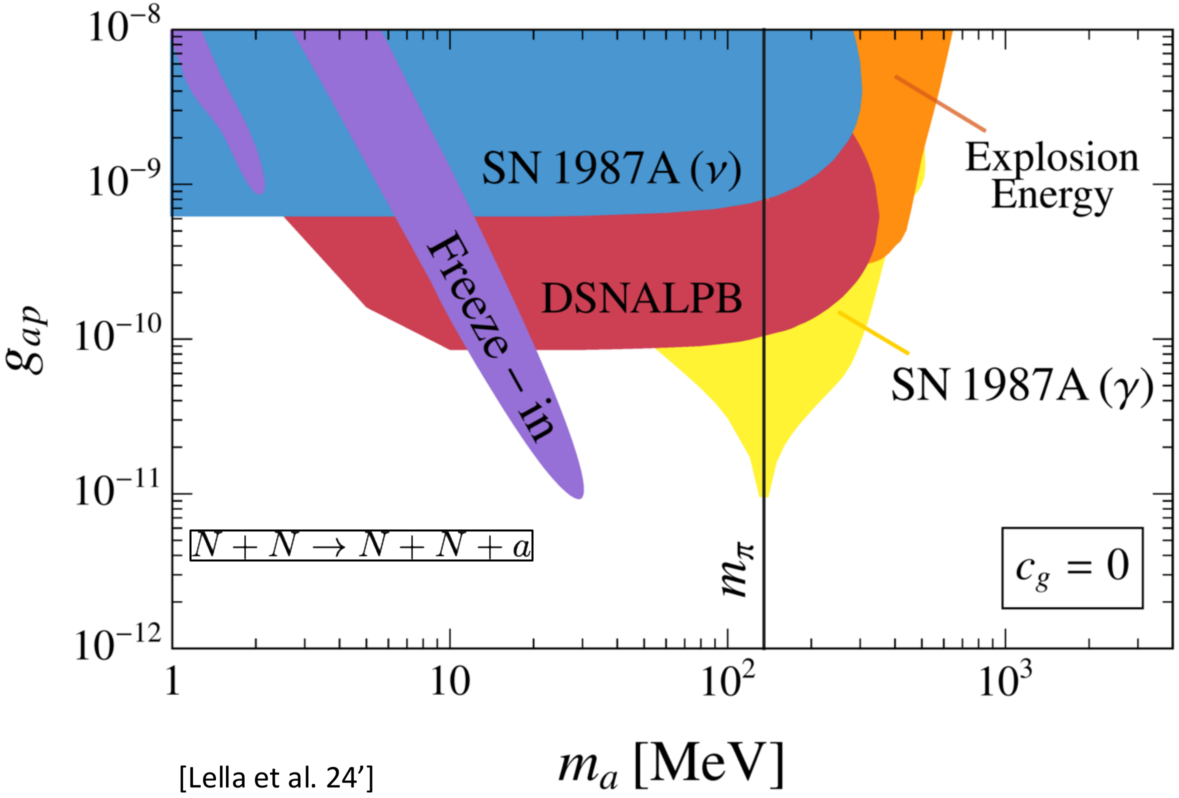
[Ferreira, Marsh, Muller 22'
+ Eike's PhD thesis 23']

Axion-Electron



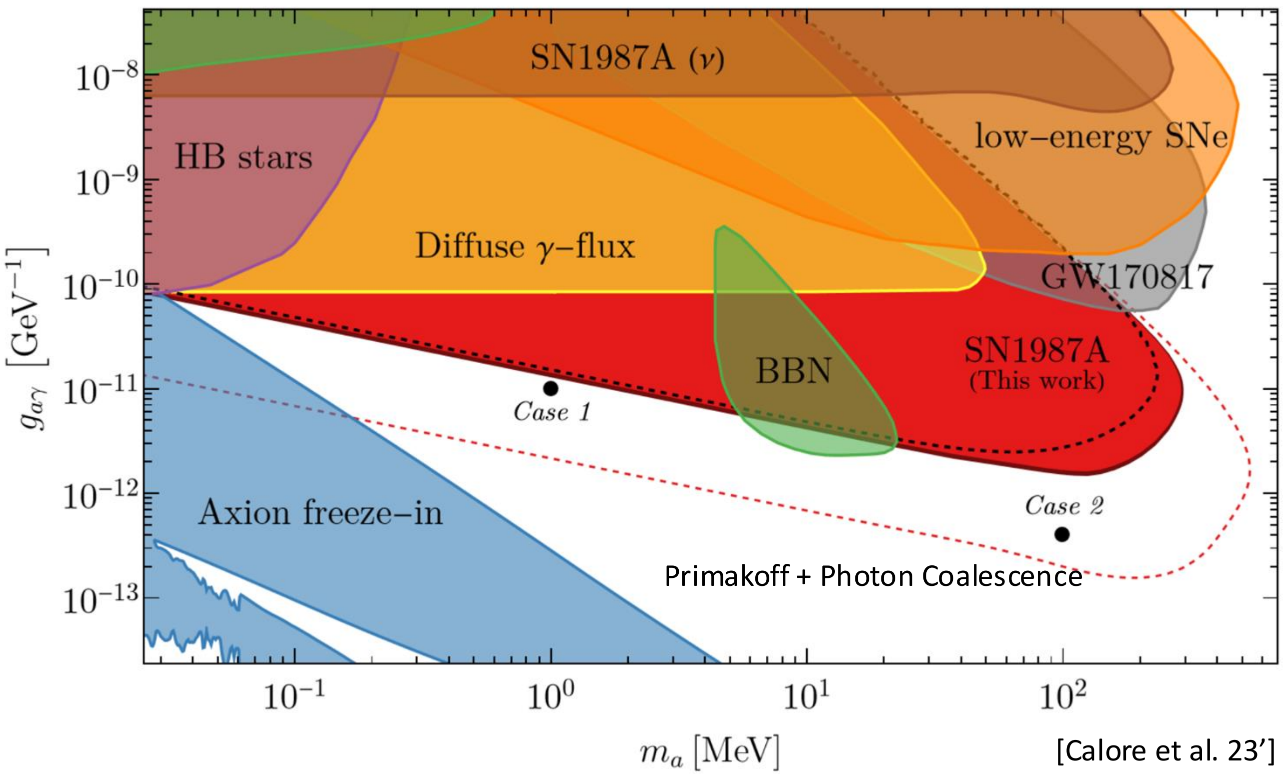
[see also Caputo et al. 21'
Fiorillo et al. 25']

Axion-Proton

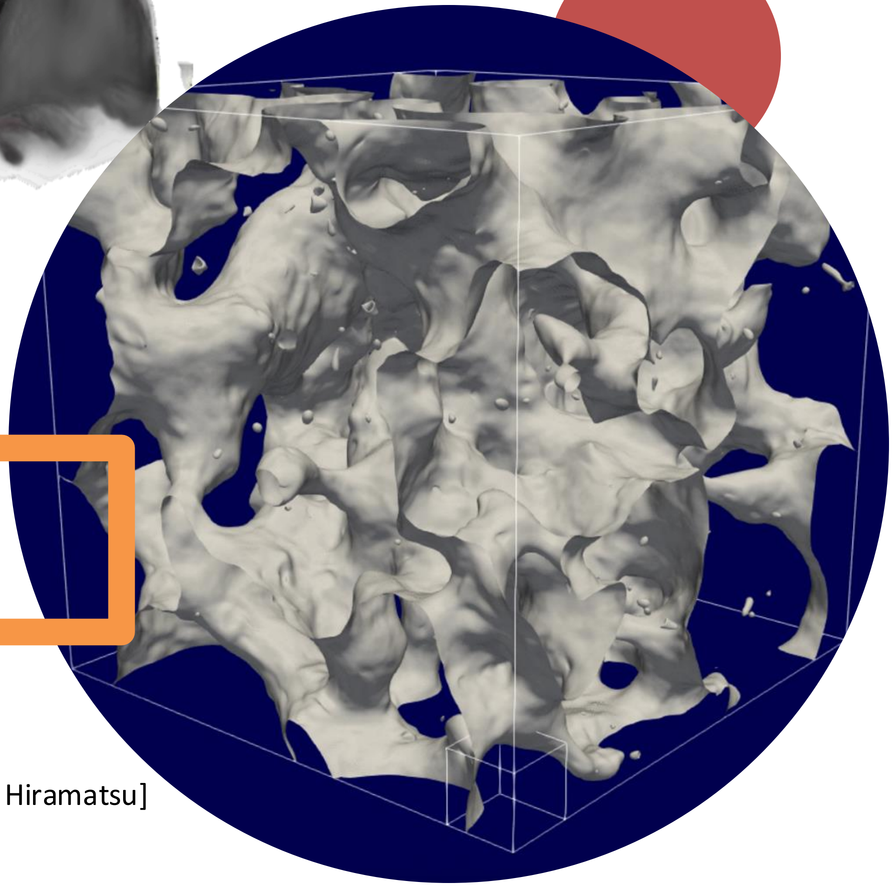


[Lella et al. 24']

Axion-Photon



[Calore et al. 23']



[courtesy of T. Hiramatsu]

Cosmo Probes of Axionic Defects

Axionic Defects

- **Cosmic Strings** and **Domain Walls** are intrinsic to axion models.
  (U(1) symmetry breaking) (Discrete shift symmetry)

- Common to **post-inflationary** models (but not only....)

- Interesting cosmological signatures: →

GWs

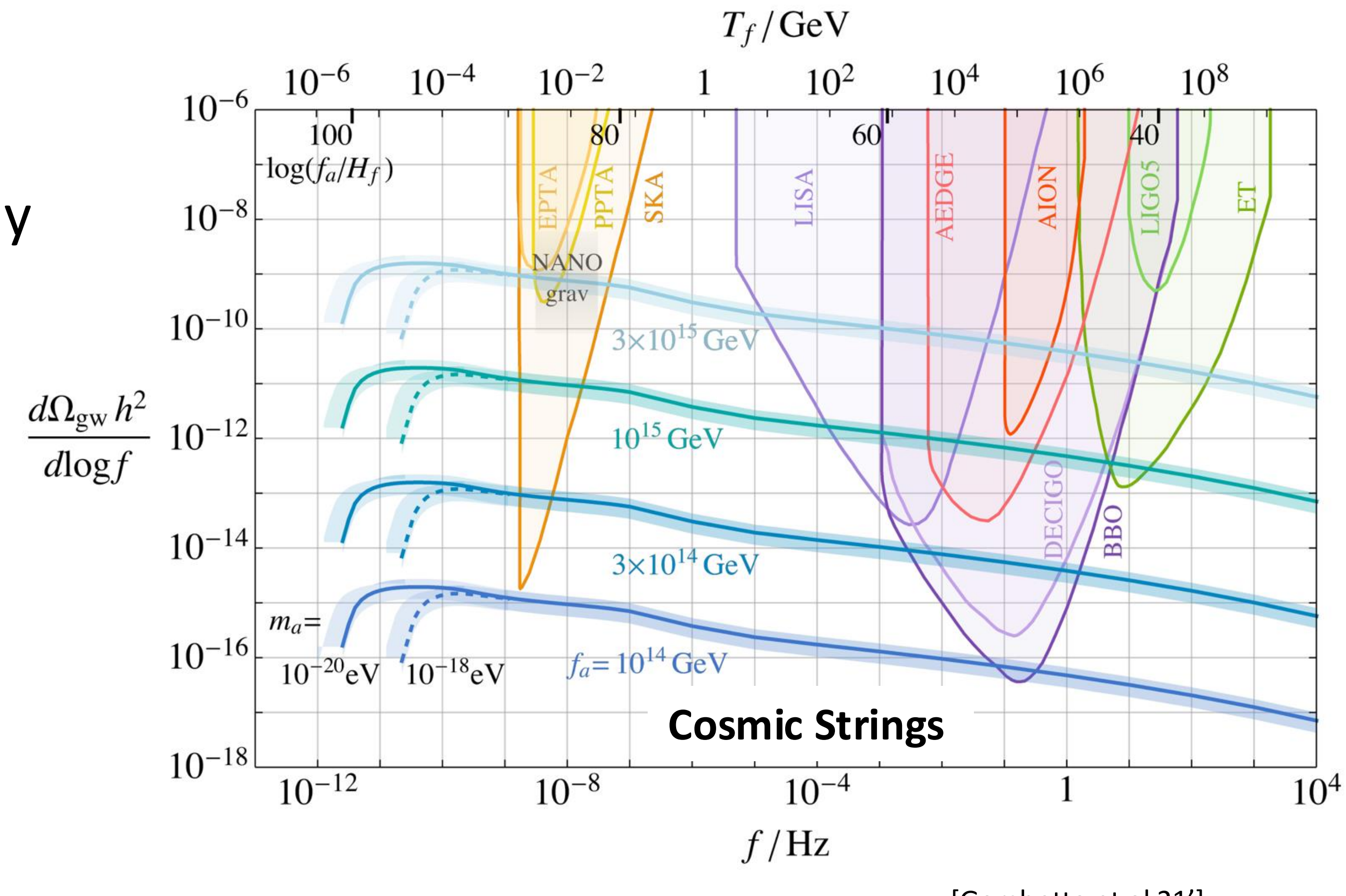
Cosmic Birefringence

PBH

[Zeldovich 74’, Vilenkin&Everett 82’, Sikivie 82’, Davies 86’,...]

Axionic Defects: 1- Gravitational Waves

- **Detectable** GWs require:
  - strings and DWs to **decay** before today (CMB constraints)



[Gorghetto et al 21']

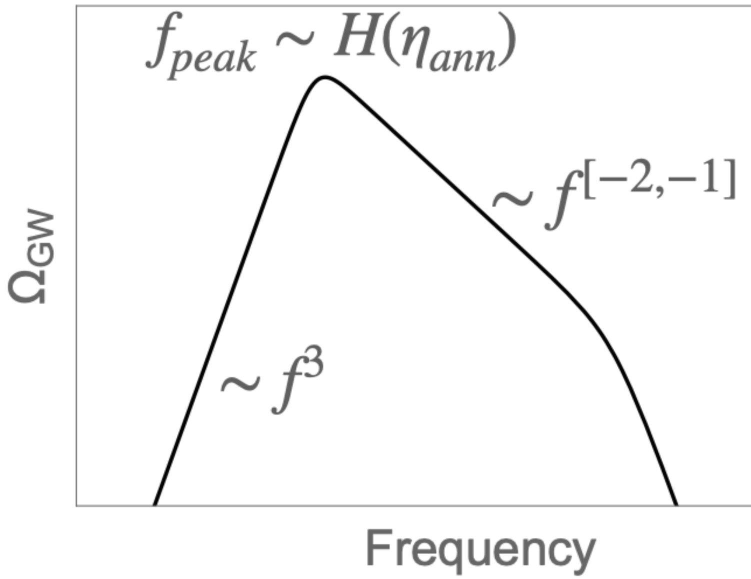
Gravitational Waves from Domain Walls

- **Domain Walls** tendency for domination makes them natural sources

- **GW emission maximal** around the time of annihilation.

  Spectrum:

$$\Omega_{GW}(f) \sim 10^{-10} \left(\frac{\rho_{DW}/\rho_{tot}}{0.01} \right)^2_{ann} S(f)$$



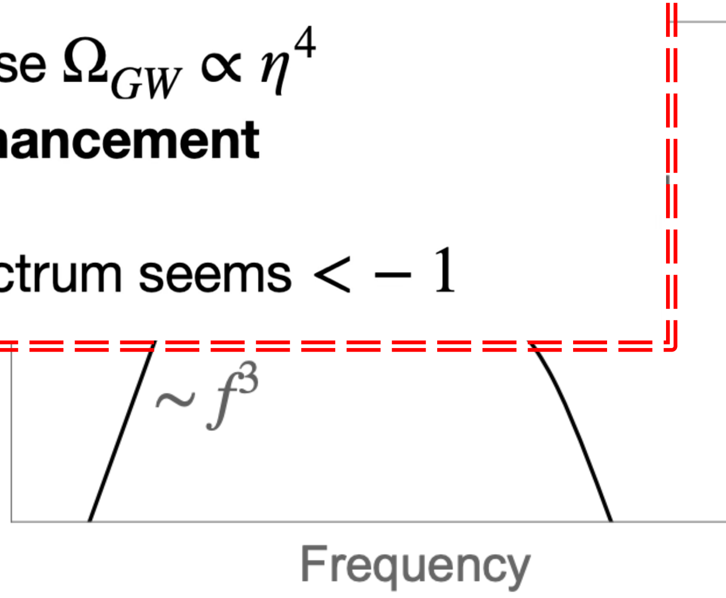
[Hiramatsu et al. 2013', …
[**RZF**, Notari, Pujolas, Rompineve 21', 22']

Gravitational Waves from Domain Walls

- **Domain Walls** tendency for domination makes them natural sources

Some updates…

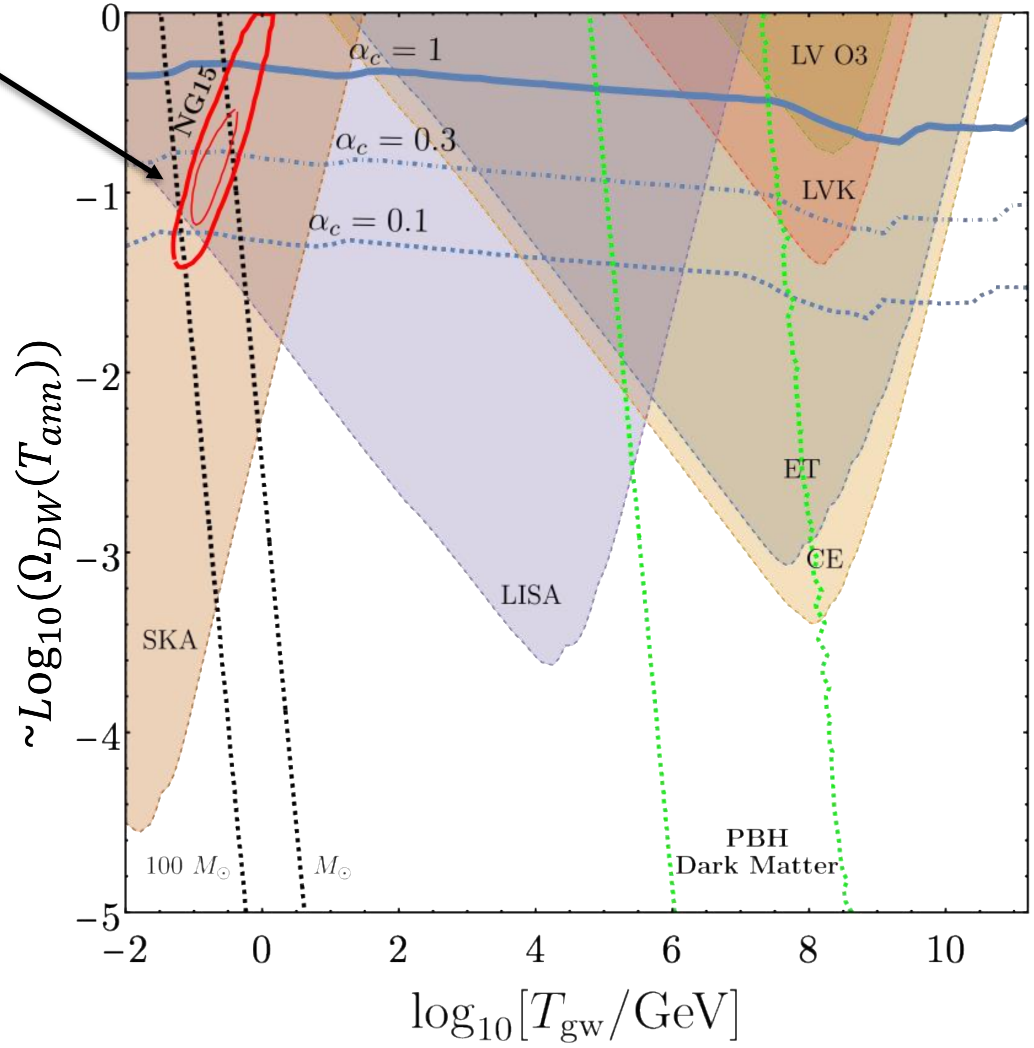
- GW emission is efficient until the time $\eta \sim 2\eta_{\Delta V}$ instead of $\eta_{\Delta V}$ as previously thought.
- Large impact because $\Omega_{GW} \propto \eta^4$ $\Rightarrow 2^4 \sim \mathcal{O}(10)$ **enhancement**
- UV slope of the spectrum seems < -1



[**RZF**, Gasparotto, Hiramatsu, Obata, Pujolàs 23’;
RZF, Notari, Pujolas, Rompineve 24’
[Kitajima et al. 23’, Dankovsky et al. 24’, Notari et al. 25’]

Gravitational Waves from Domain Walls

GWs at PTAs



[**RZF**, Notari, Pujolas, Rompineve 22', 24']

Axionic Defects: 2- Primordial Black Holes

- Domain Walls (or string-Wall) networks can colapse into **Black Holes**

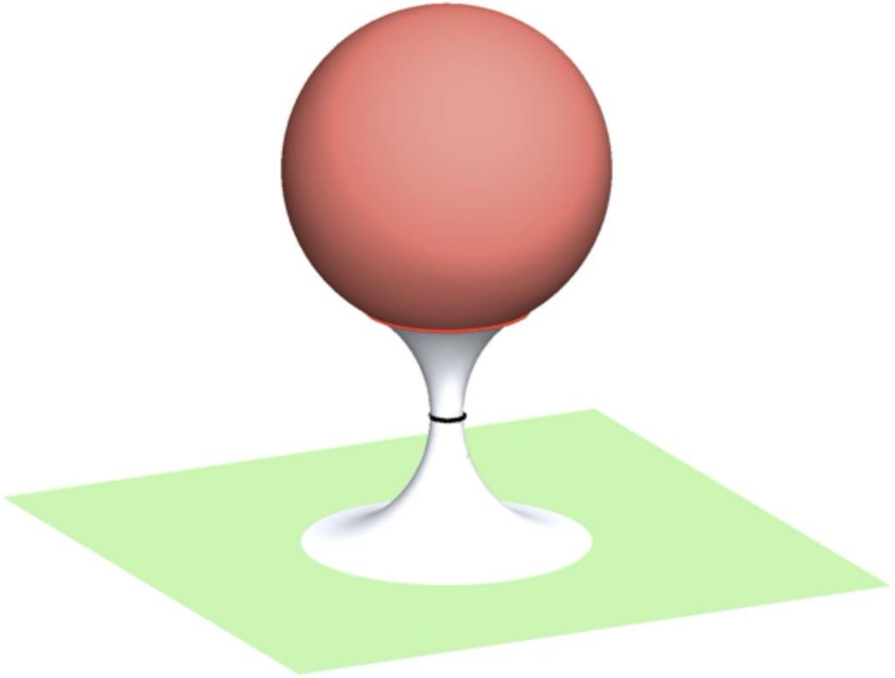
- How?

    1. If they are **very** spherical,
       (e.g. bubble nucleation)

       [Garriga & Vilenkin 16']

    2. Or **supercritical** (r_{Sch} > 1/H),
       (e.g. superhorizon DWs)

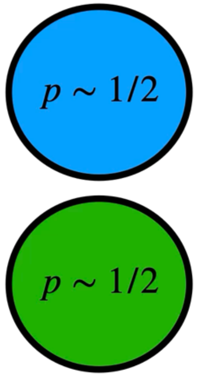
       [T. Vachaspati 17'; Ferrer et al. 18'
       Gelmini et al 22', **RZF** et al. 24',25']

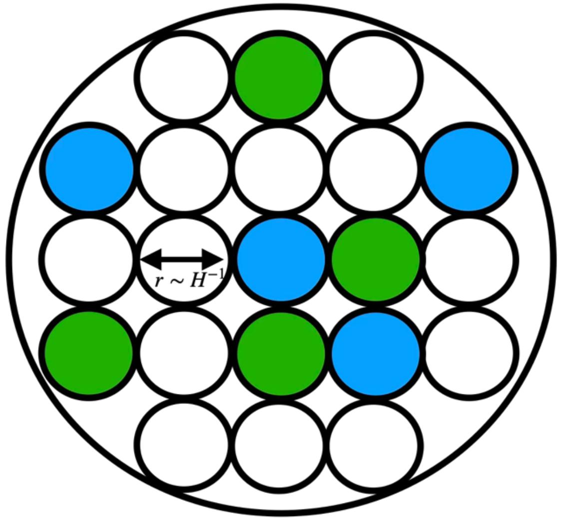


Case 1: Network Annihilation → PBH

- **Before annihilation,** network is composed of:
    - Hubble-size Domains, vacua equally distributed

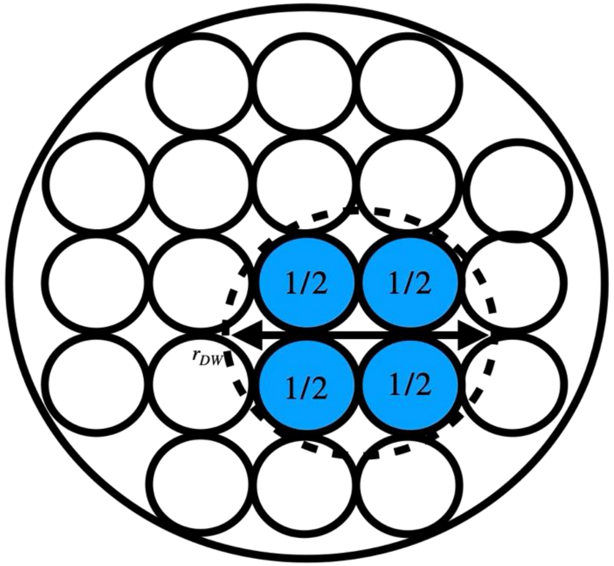
For a Z_2 symmetry





Annihilation

A few large and rare DWs survive

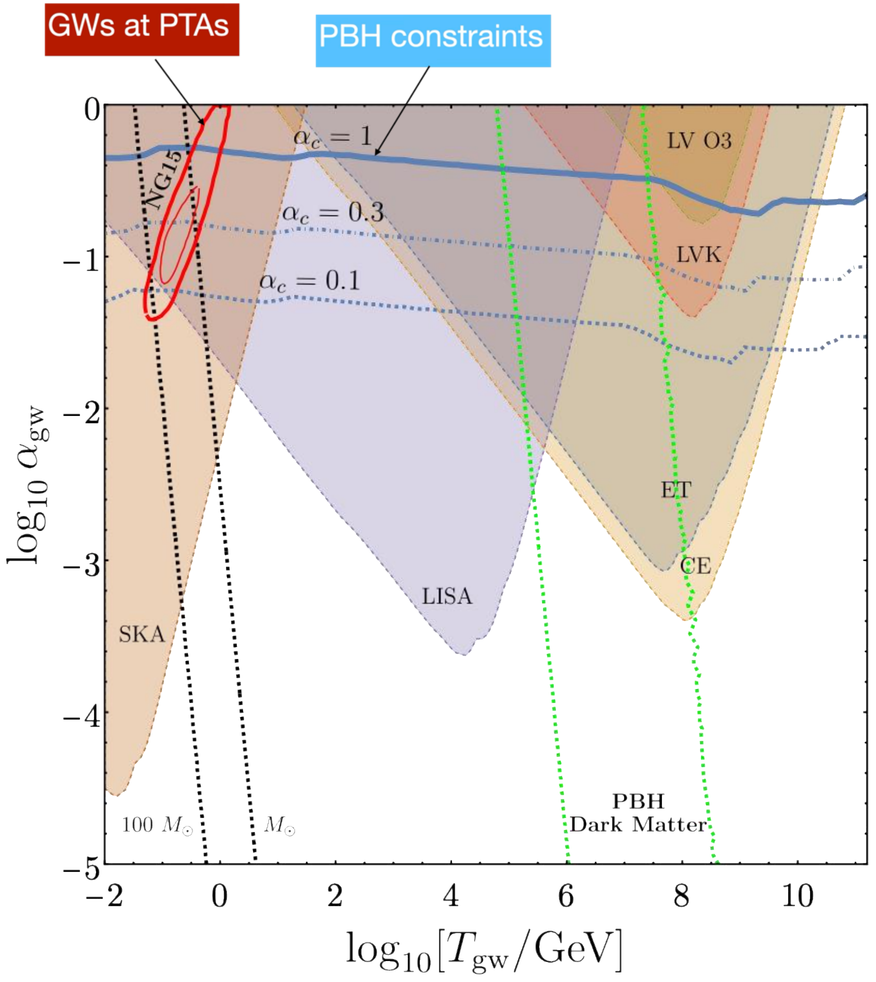


PBHs at horizon reentry

Case 1: Network Annihilation → PBH

– Large **Domain Wall abundance** at annihilation can give:

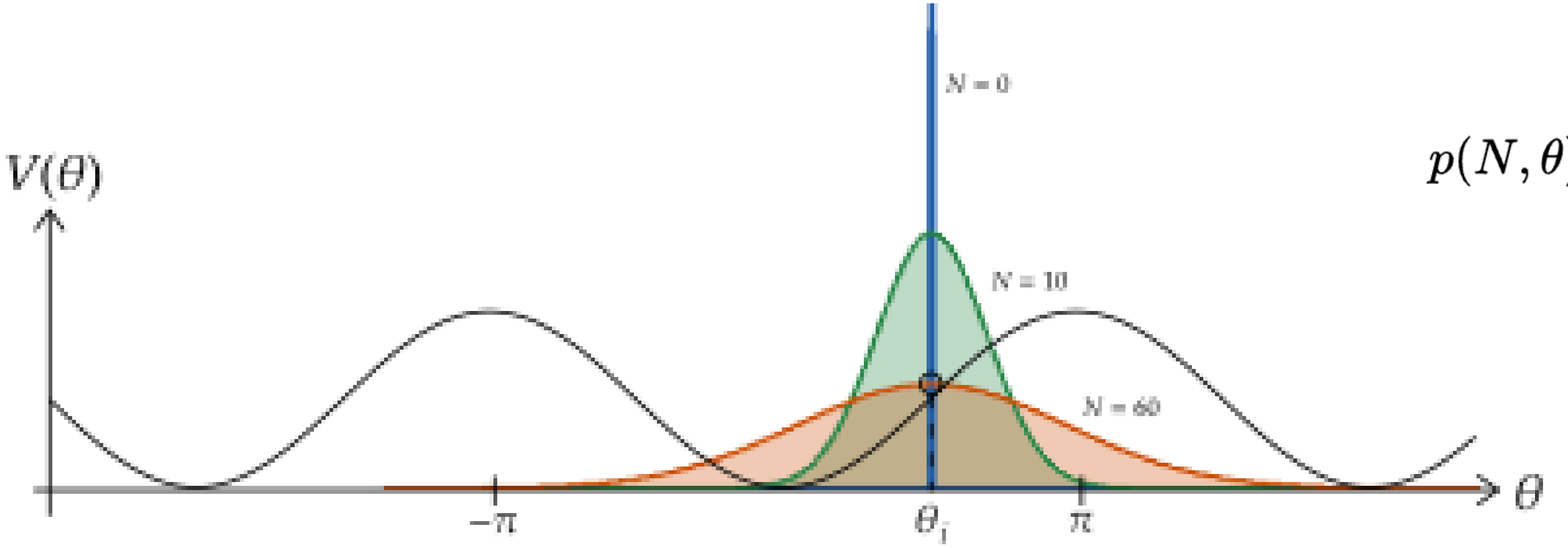
- Sizeable **PBH abundance**
- **PBH dark matter** if $T_{ann} \sim 10^6 - 10^8$ GeV
  Correlated GWs expected at LVK-ET-CE
- Possibility of GWs **and** Solar Mass PBH at PTAs.



Case 2: *vanilla* QCD axion and DWs

- Back to the standard pre-inflationary QCD axion:
  - Can we form DWs there? Old idea...
  - Mechanism is based on inflationary diffusion:

[Linde 90', Linde and Lyth' 94',... Kitajima&Takahashi 20']



$$p(N,\theta) = \frac{1}{\sqrt{2\pi}\sigma_\theta(N)} \exp\left(-\frac{(\theta-\theta_i)^2}{2\sigma_\theta^2(N)}\right)$$

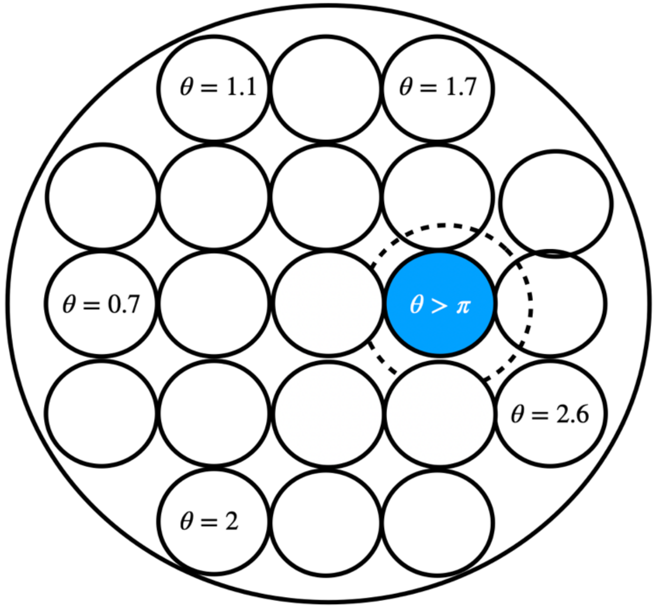
$$\sigma_\theta(N) = \frac{H}{2\pi f_a}\sqrt{N}$$

[Faria, **RZF** and Rompineve 25']

Isocurvatures → DW formation

[Faria, Ferreira and Rompineve 25']

- After inflation:
  - when $m_a(T) > H$, the regions of space where $\theta > \pi$ the oscillates the nearest minimum (2π).
  - **Superhorizon DWs** are formed (even for KSVZ!)
  - At horizon reenter, the DWs colapse into:
    - **Dark Matter** axions
    - **PBHs**, If DWs are supercritical ($r_s > 1/H$)



$$\rho_{\rm dm}^{\rm dw}(t_0) = \int_{N_{\rm eq}}^{N_{\rm osc}} \beta(N_*)\, \rho_{\rm dw} \left(\frac{a(H_*)}{a_0}\right)^3 dN_*$$

$$M_{\rm dw} = 4\pi\sigma/H^2 + 4\pi\Delta V/(3H^3)\,.$$

Observational signatures

1. **Isocurvatures at CMB scales**

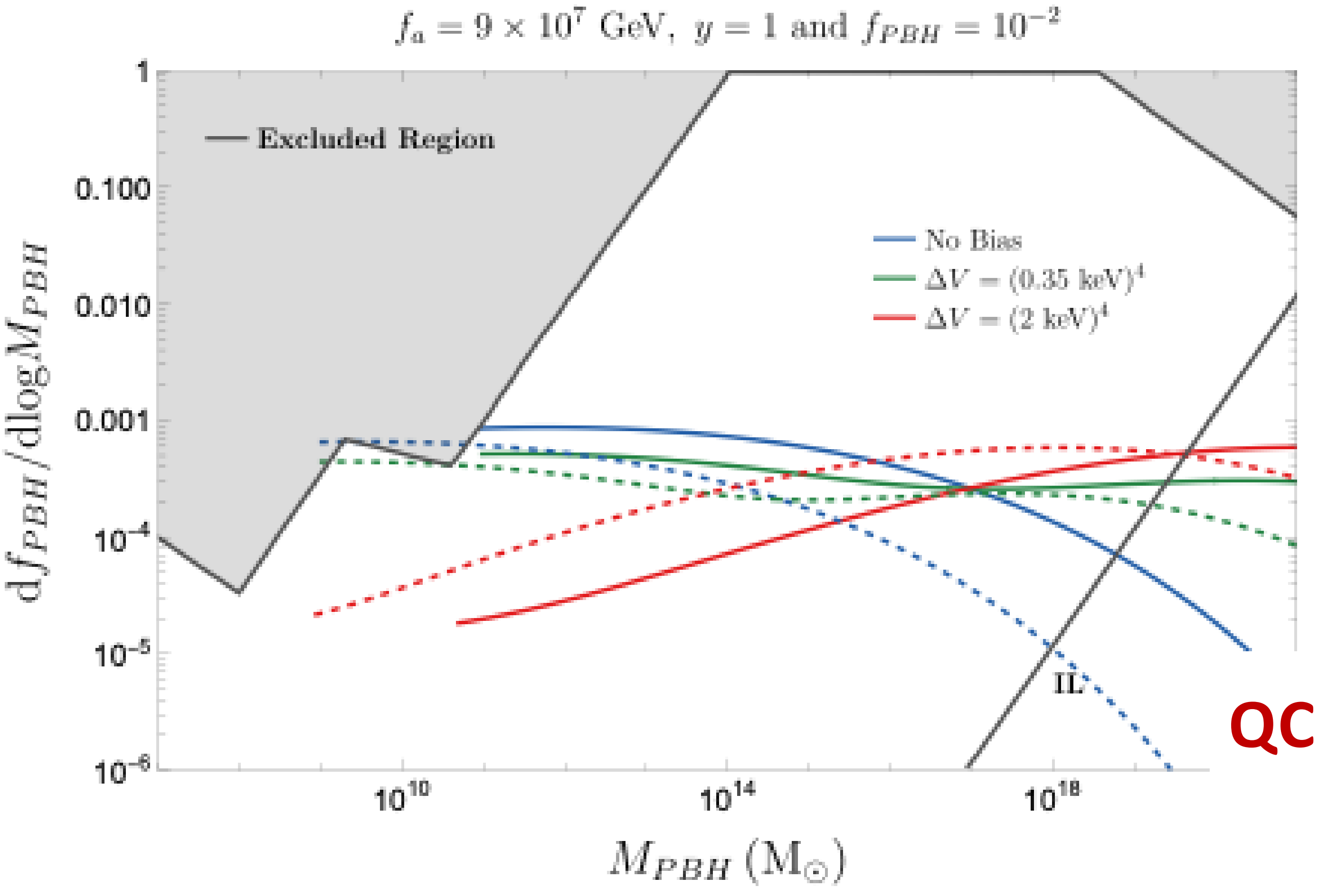
$$y = H/f_a \overset{(\theta \ll 1)}{\lesssim} \left(\frac{f_a}{10^8\ \mathrm{GeV}} \right)^{-\frac{7}{6}} \theta_i^{-1}$$

- Although maybe erasable with additional assumptions (eg 2-step inflation).

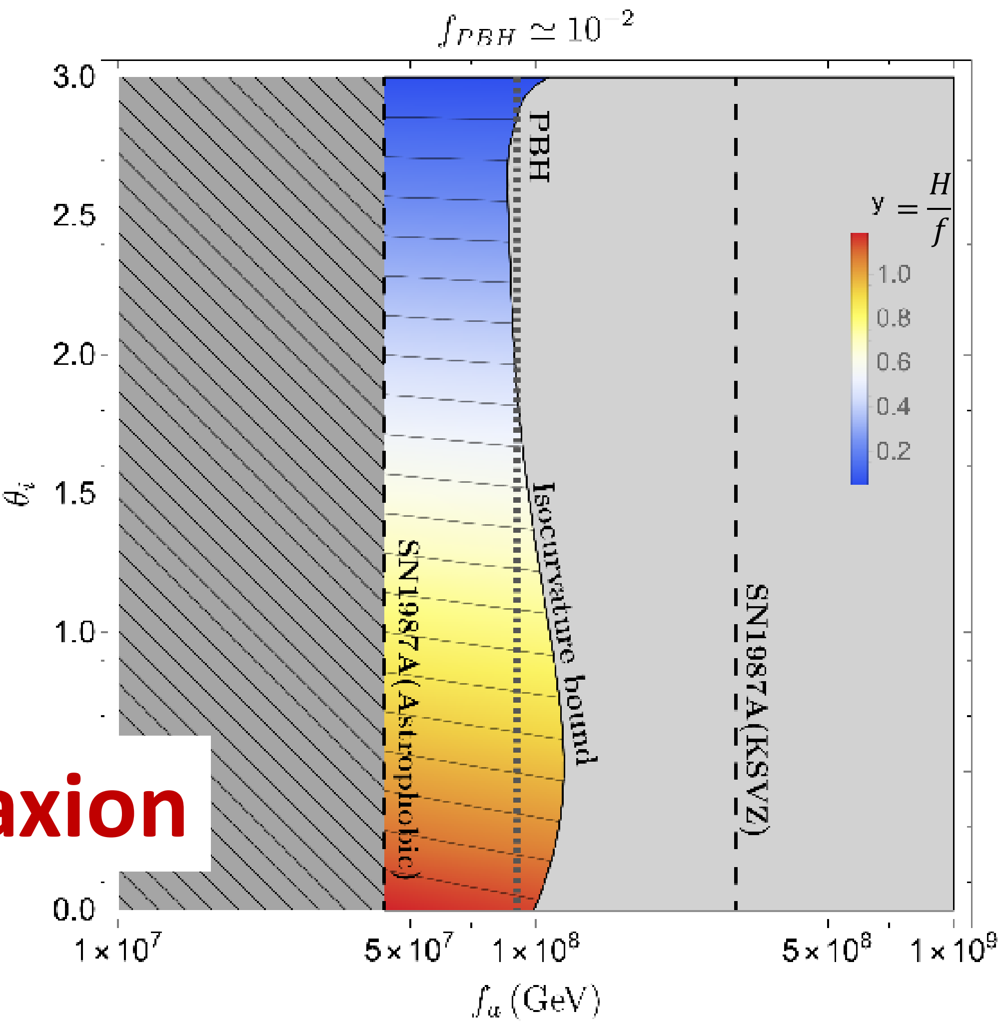
2. **Stupendeously large PBH**

- **Large DM abundance** seems to come with **large PBH abundance**.
- Broad mass spectrum

PBH mass distribution



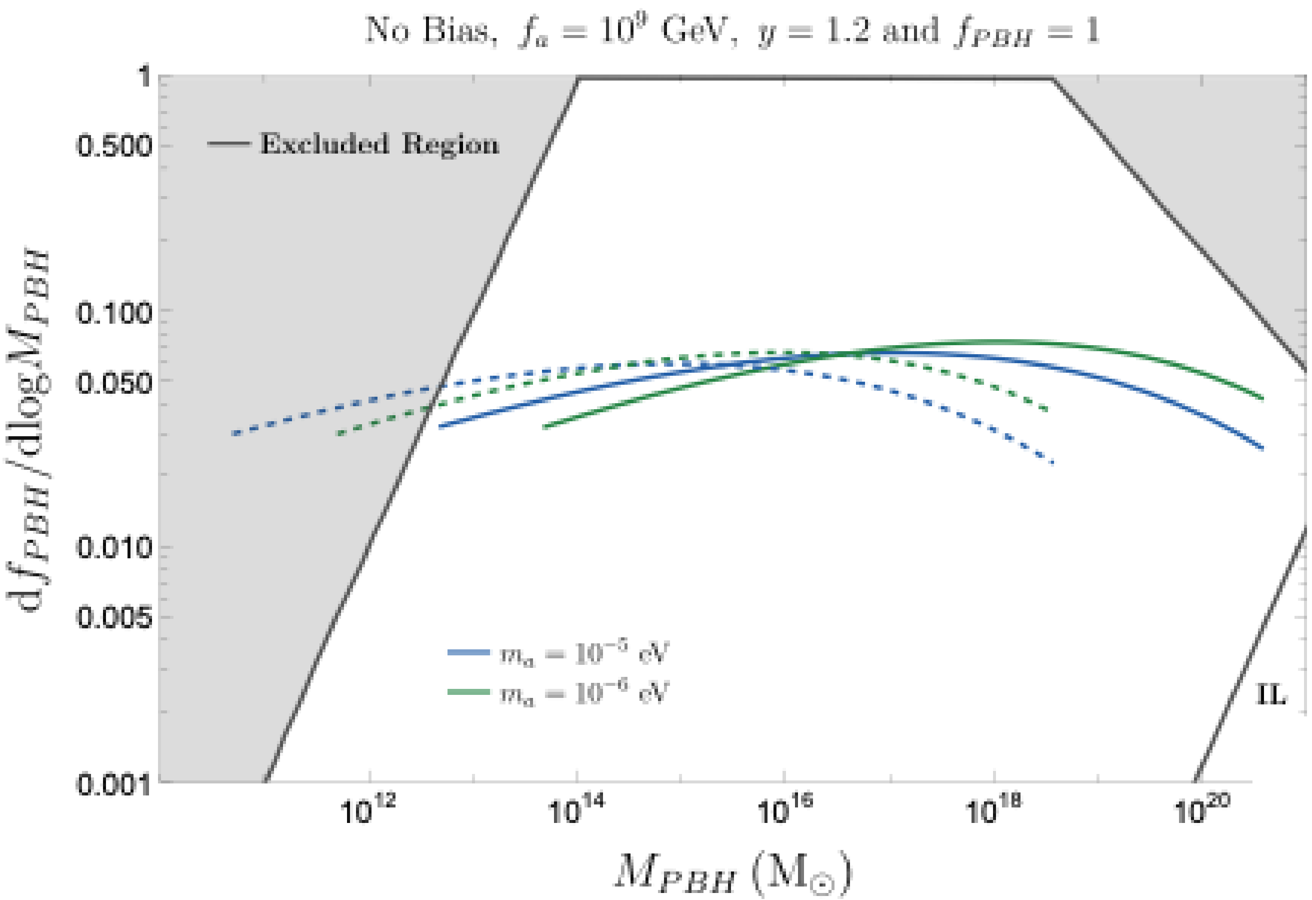
Parameter space



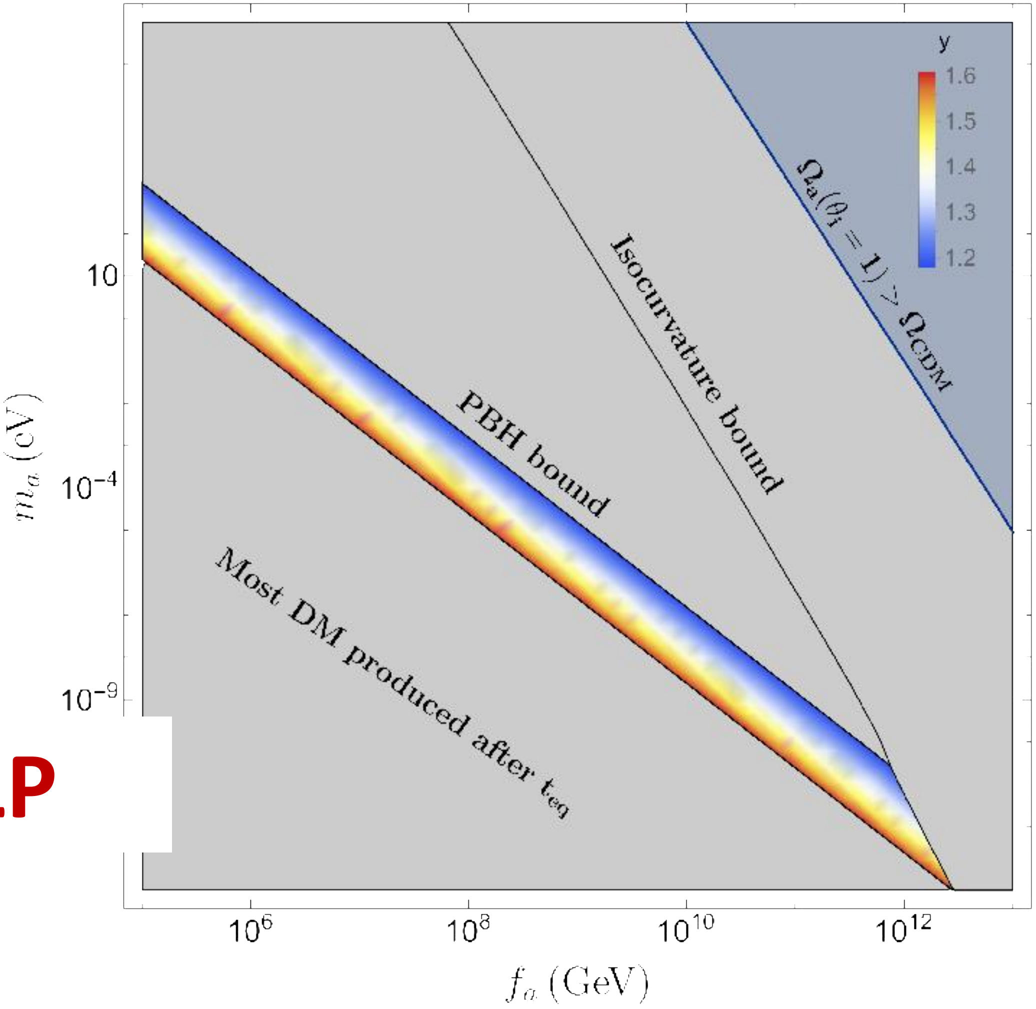
QCD axion

[Faria, Ferreira and Rompineve 25']

PBH mass distribution



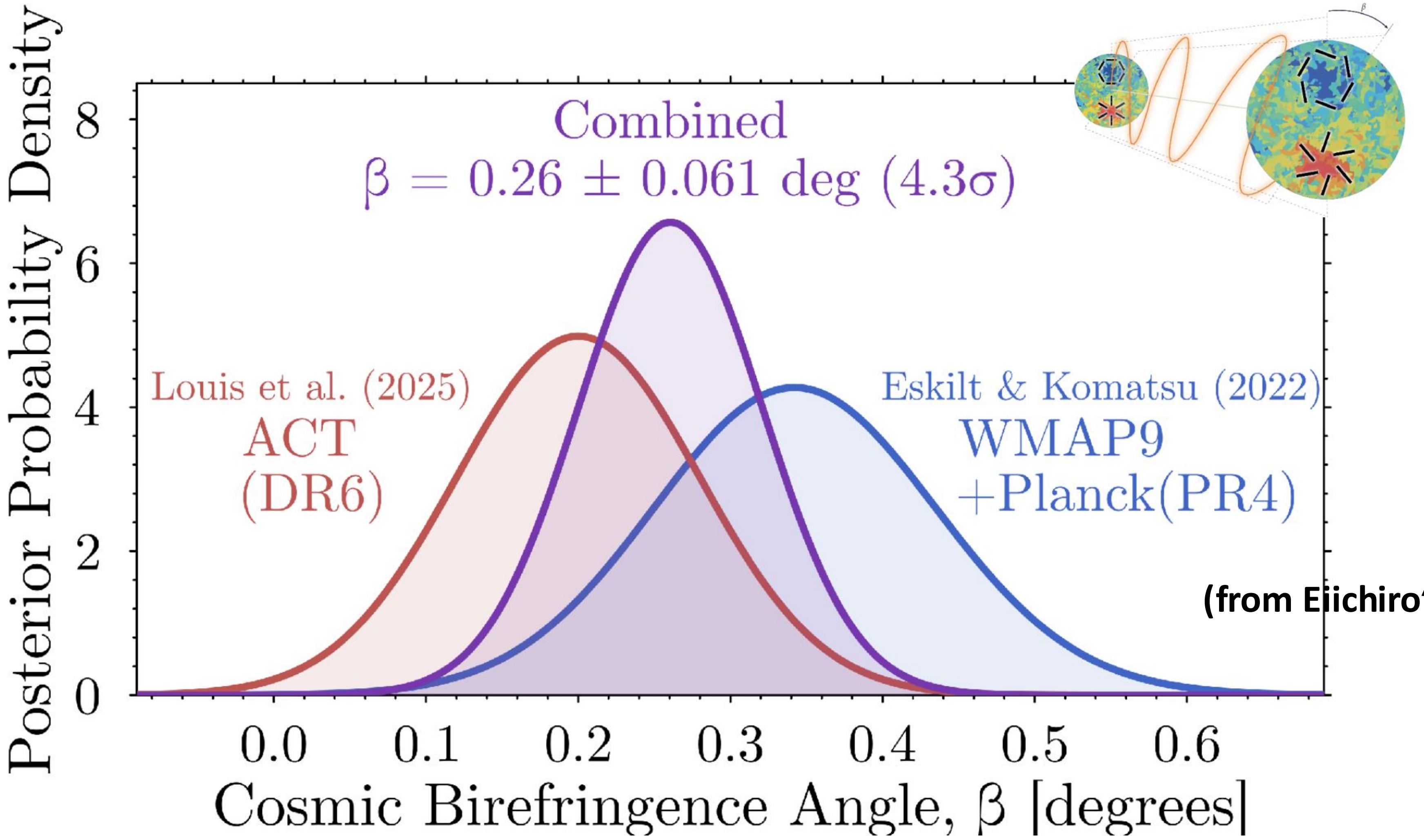
Parameter space



ALP

[Faria, Ferreira and Rompineve 25']

CMB Birefringence and Axion Defects



(from Eiichiro's talk)

- No *obvious* astrophysical or late-time explanation.
  Clean case for **new physics**. Main **ingredients** (if produced from scalar field):

1. **Parity violating coupling** to photons $\longrightarrow$ $c_\gamma \frac{\alpha_{\rm em}}{8\pi} \frac{\phi}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$
2. **Sizeable field excursion**, $\longrightarrow$ $\beta^{\rm iso}(\eta) = c_\gamma \frac{\alpha_{\rm em}}{4\pi} \left[\langle \theta(\eta, \hat{n})\rangle - \theta(\eta_0)\right]$ $(\theta = \phi/f)$

Axionic defects (DWs and strings): [This talk]

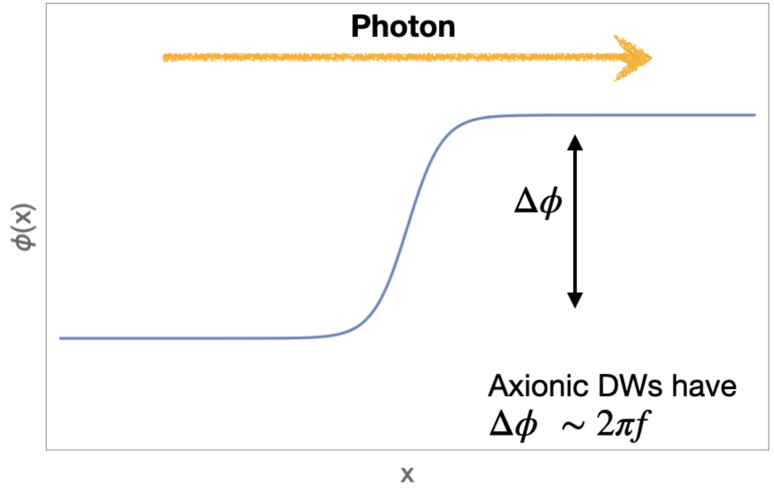
[Takahashi and Yin 20', Kitajima+,…, **RZF**+ 23]'

- DWs made of scalar field ϕ,
- When photon crosses **one** DW:

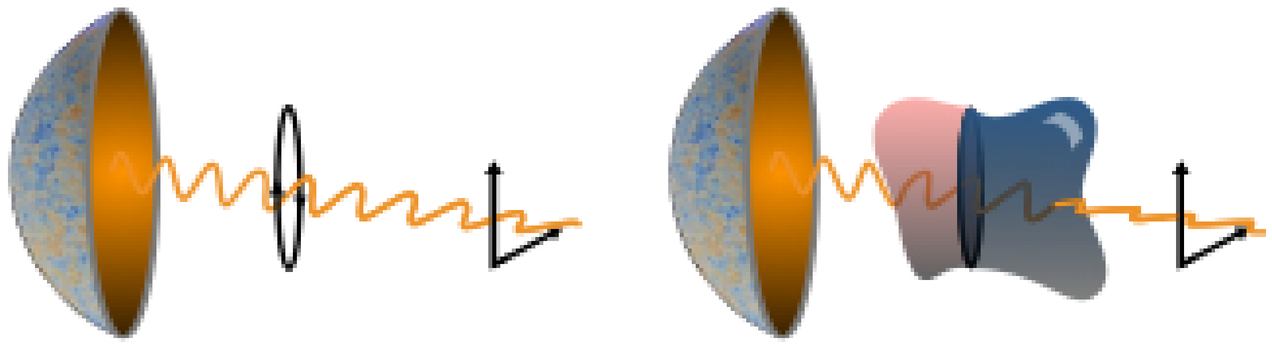
$$\beta = 0.21 c_\gamma \frac{\Delta\phi/f}{2\pi} \text{ deg}$$

(similar when photon crosses <u>strings loops</u>)

[Agrawal et al. 19', M. Jain et al. 21,22']

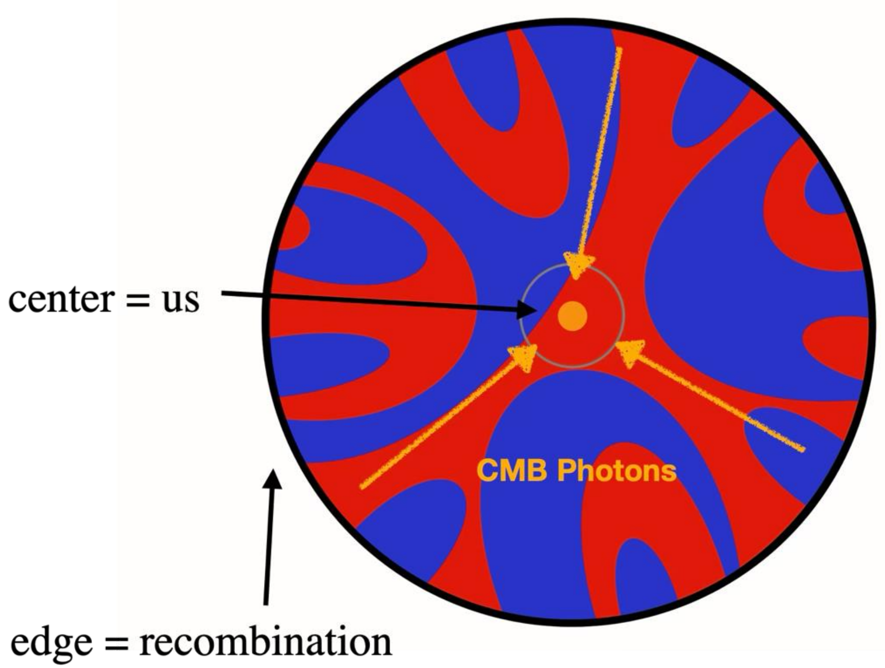


String-(Wall) network



(from Andrew Long's talk)

DW network



What about strings-wall networks?

- Axionic domain walls often (though not always…) come attached to **cosmic strings.** **Is the birefringence signal affected?**

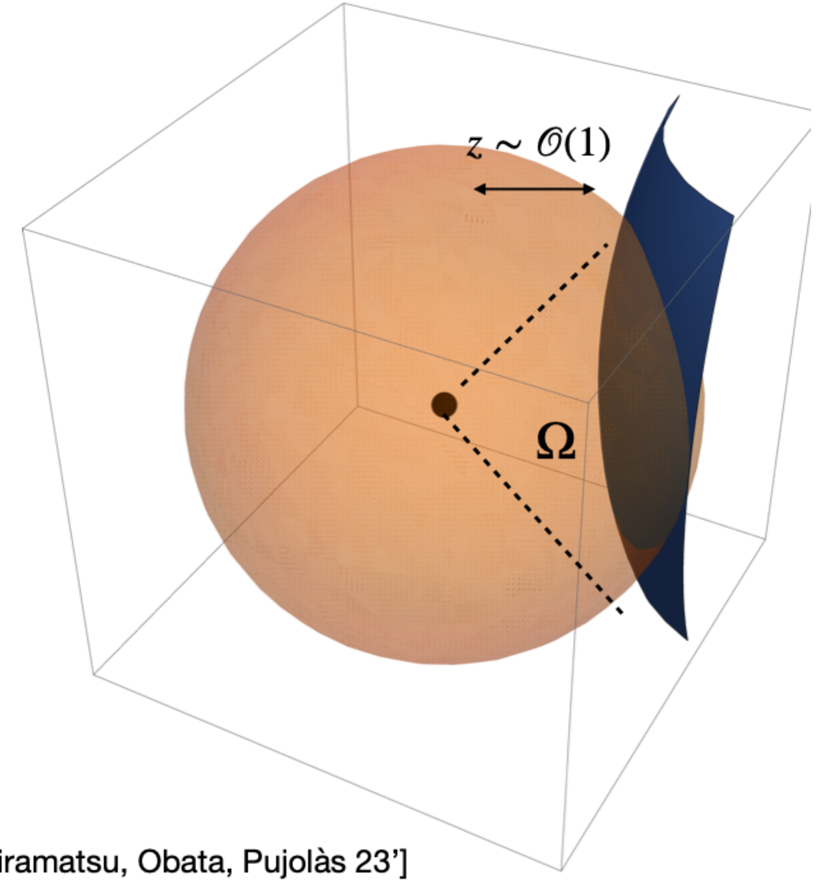
[Agrawal et al. 19']
[M. Jain et al. 21,22']

- **Yes! Wash-out** of isotropic signal at high redshift: strings (loops) provide an **axis of symmetry,** photons come from regions with $\phi \gtrless 0$ with equal probability.

- **However…** if defect is relatively nearby ($z \lesssim 1$) as in scaling $\Rightarrow$ **no washout! Environmental effect**

$$\beta^{iso}_{env} \sim 0.21 c_\gamma \left(\frac{\Omega}{4\pi}\right) \text{deg}$$

Striking feature, β^{iso} should vary significantly at low z!



[**RZF**, Gasparotto, Hiramatsu, Obata, Pujolàs 23']

Conclusions

- $f_a \sim 10^8$ GeV is **not** excluded.

  Uncertainties in the bound derived from SN1987A (or neutron star) bound are still large. It is important to have all effects into account.

- **CMB probes** are weaker but very robust.
  They are slowly reaching the 10^8 GeV region.

- **Topological defects** open up other cosmo probes of axions:
  GWs, PBH, birefringence

Extra slides

- **Annihilation** leftovers:

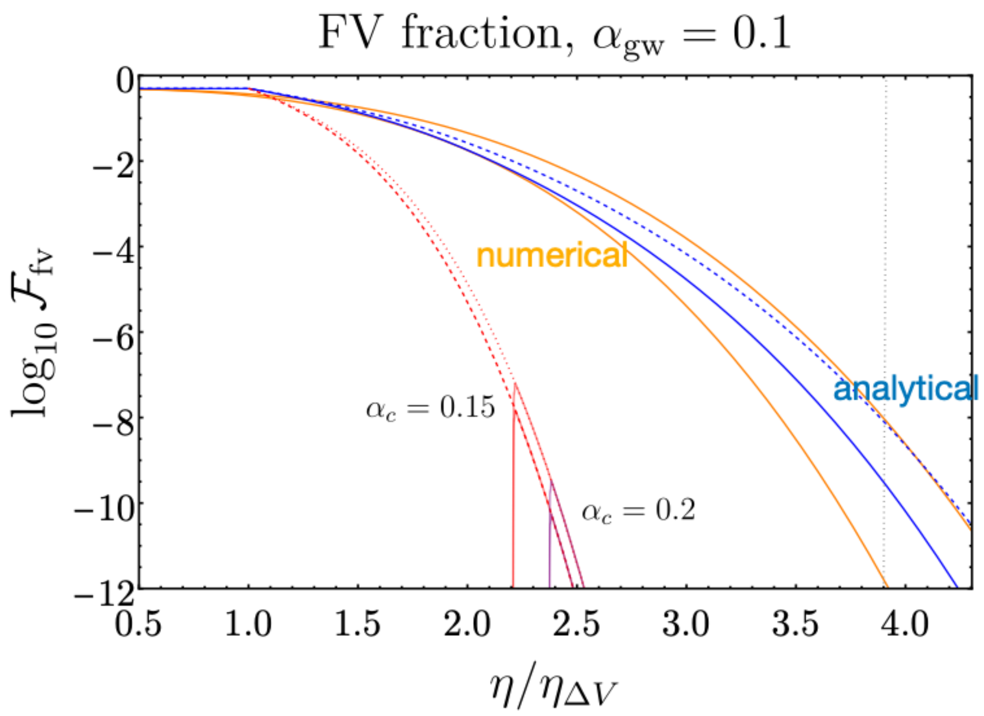
- **FV** Pockets with $R_{DW} \gtrsim 1/H_{ann}$ that collapse at horizon reentry.

- **Distribution** of large pockets *inherited* from the scaling regime. For a Z_2 symmetry:

after solving Nambu-Goto eq. for $R_{dw}(\eta)$ and integrating over pockets

$$p(R_{DW}) \sim \left(\frac{1}{2}\right)^{\frac{Vol(R_{DW})}{Vol(1/H_{ann})}} \sim \left(\frac{1}{2}\right)^{-(R_{DW}H_{ann})^3} \quad \rightarrow \quad \mathcal{F}_{fv}(R_{DW} > 1/H) \sim \left(\frac{1}{2}\right)^{-(1.8\eta/\eta_{\Delta V})^3}$$

- Good agreement between semi-analytics and numerics!



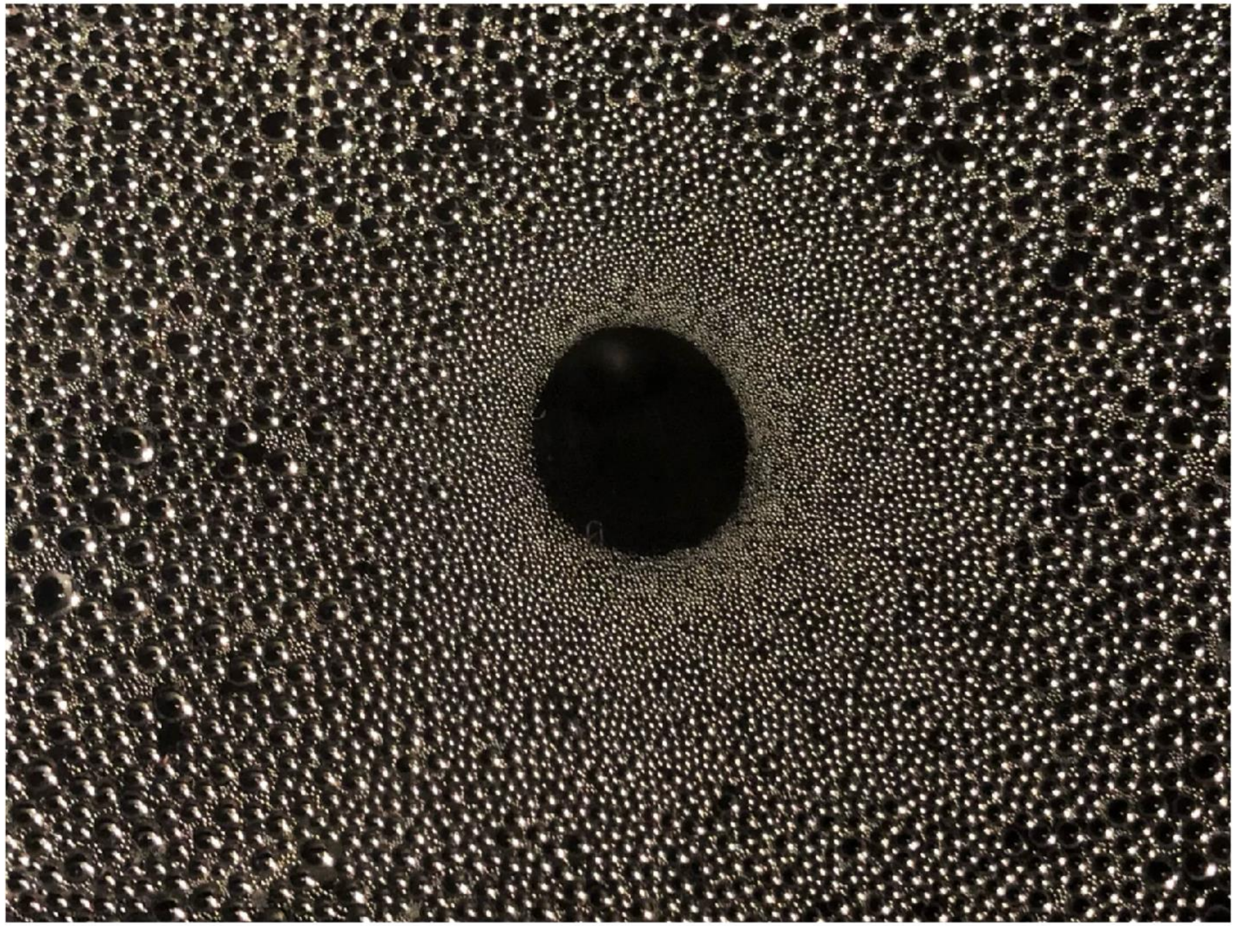
[RZF, Notari, Pujolas, Rompineve 24']

MAY 2, 2024 | 8 MIN READ

Collapsing Sheets of Spacetime Could Explain Dark Matter and Why the Universe 'Hums'

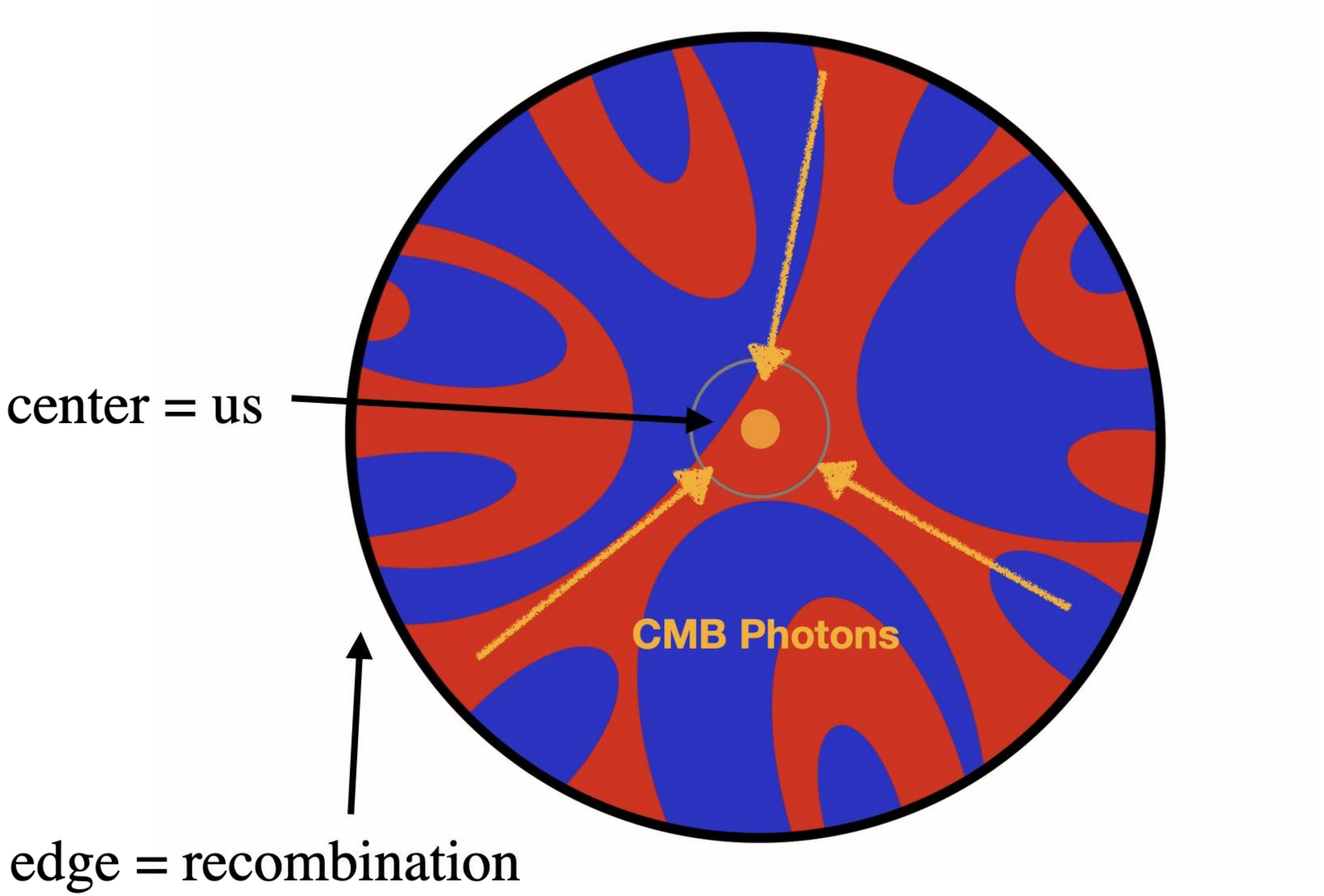
Domain walls, long a divisive topic in physics, may be ideal explanations for some bizarre cosmic quirks

BY ANIL ANANTHASWAMY



If hypothetical cosmic structures called domain walls formed shortly after the big bang, at very large scales the early universe could have resembled a foamy froth—a network of domain wall–bounded bubbles of spacetime. jpgfactory/Getty Images

DW network



Additional signatures?

- **Anisotropic Birefringence**:

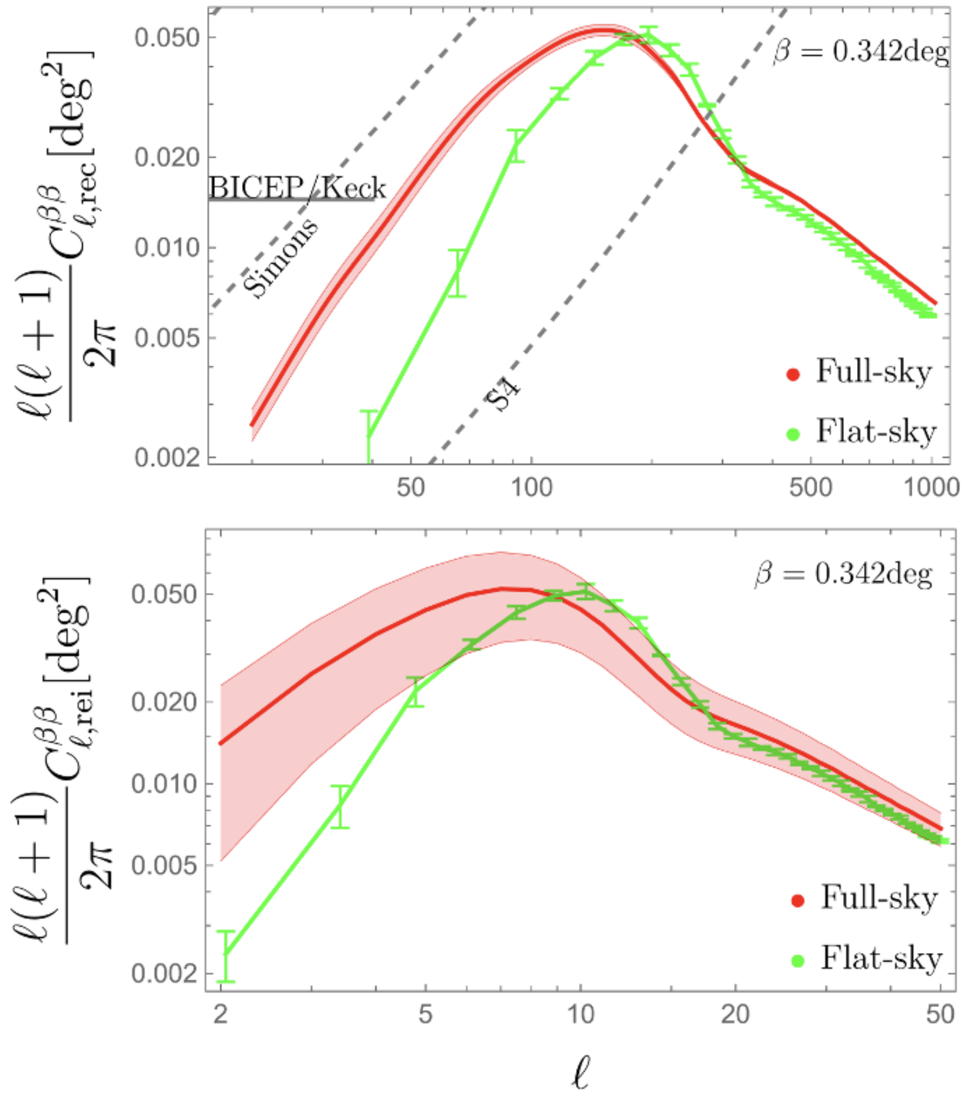
$$\langle \beta^*_{\ell_1 m_1}(\eta_1)\beta_{\ell_2 m_2}(\eta_2)\rangle = C^{\beta\beta}_{\ell_1}(\eta_1,\eta_2)\delta_{\ell_1\ell_2}\delta_{m_1 m_2},$$

[Greco et al. 23']

- **Time-dependent $\beta^{iso}(\eta)$**
  E.g. If network **forms/annihilates** in between recombination and today.

- Stochastic **GWs** at CMB scales:
  - **Evidence for** a UV spectral of around -1.7/-1.8, (common lore was -1)
  - **New probes for $T_{ann} < eV$**

[**RZF**, Gasparotto, Hiramatsu, Obata, Pujolàs 23']



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Annihilation / Formation	$z_{\rm rec} > z_{\rm ann} > z_{\rm rei}$	$z_{\rm rei} > z_{\rm ann} \geq 0$
Isotropic Birefringence:		
	$\beta_{\rm rec} \neq \beta_{\rm rei} = 0$	$\beta_{\rm rec} \simeq \beta_{\rm rei} \neq 0$
Anisotropic Birefringence:		
$z_{\rm f} > z_{\rm rec}$	$C^{\beta\beta}_{\rm DW}\vert_{\rm rec}$, $C^{\beta\beta}_{\rm DW}\vert_{\rm rei} \sim 0$	$C^{\beta\beta}_{\rm DW}\vert_{\rm rec}$, $C^{\beta\beta}_{\rm DW}\vert_{\rm rei}$
$z_{\rm rec} > z_{\rm f} > z_{\rm rei}$	$C^{\beta\beta}_{\rm IC}\vert_{\rm rec}$, $C^{\beta\beta}_{\rm DW}\vert_{\rm rei} \sim 0$	$C^{\beta\beta}_{\rm IC}\vert_{\rm rec}$, $C^{\beta\beta}_{\rm DW}\vert_{\rm rei}$
$z_{\rm rei} > z_{\rm f} > 0$	//	$C^{\beta\beta}_{\rm IC}\vert_{\rm rec}$, $C^{\beta\beta}_{\rm IC}\vert_{\rm rei}$

[**RZF**, Gasparotto, Hiramatsu, Obata, Pujolàs 23']

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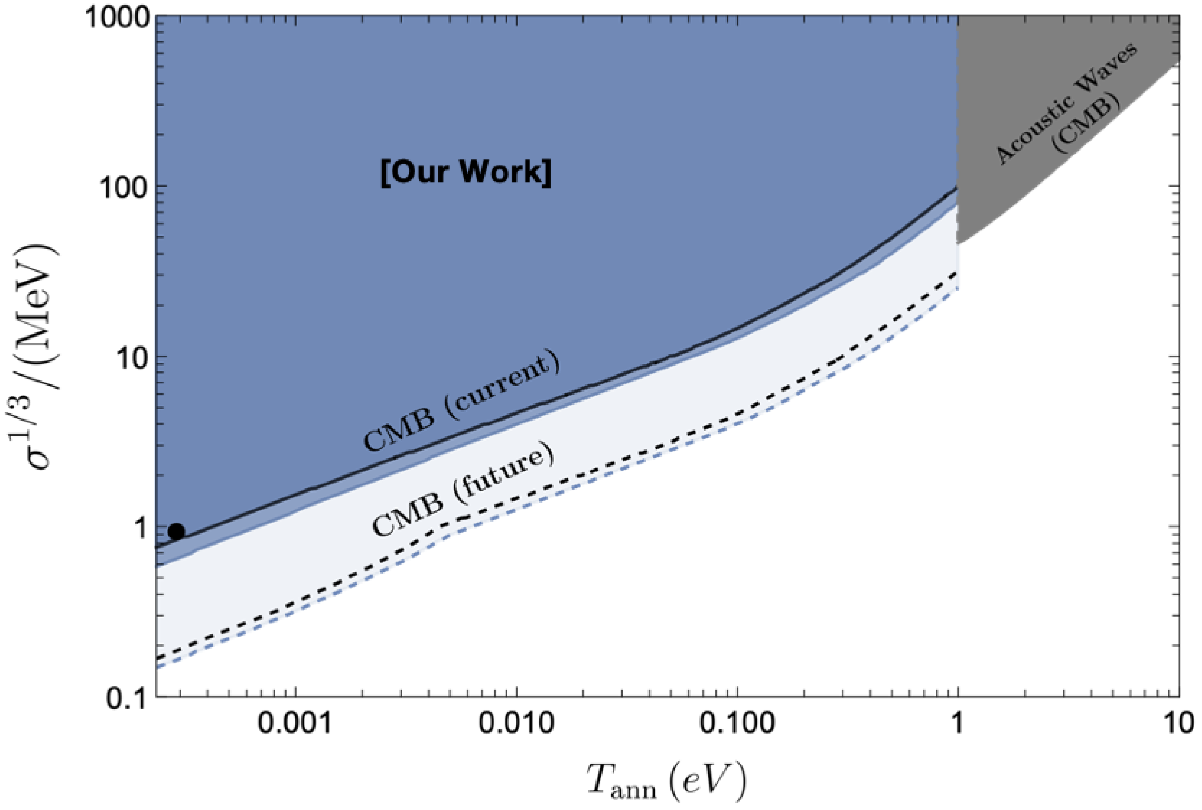

[**RZF**, Gasparotto, Hiramatsu, Obata, Pujolàs 23']