Cosmological Roles of Dark Photons in Axion-Induced Electroweak Baryogenesis

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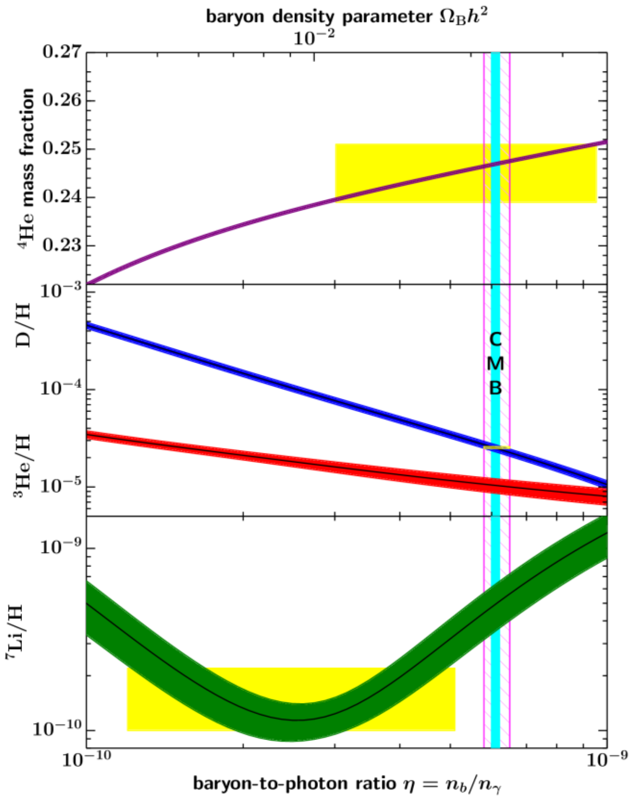
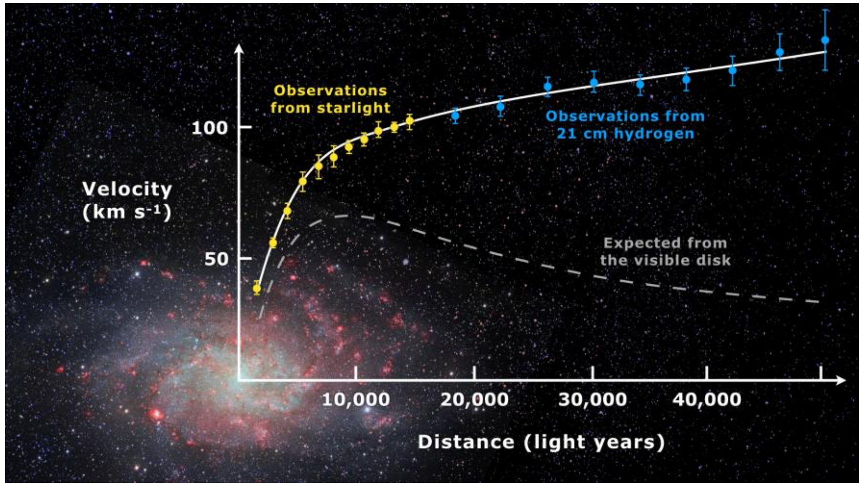
Motivation

Physics Beyond the Standard Model

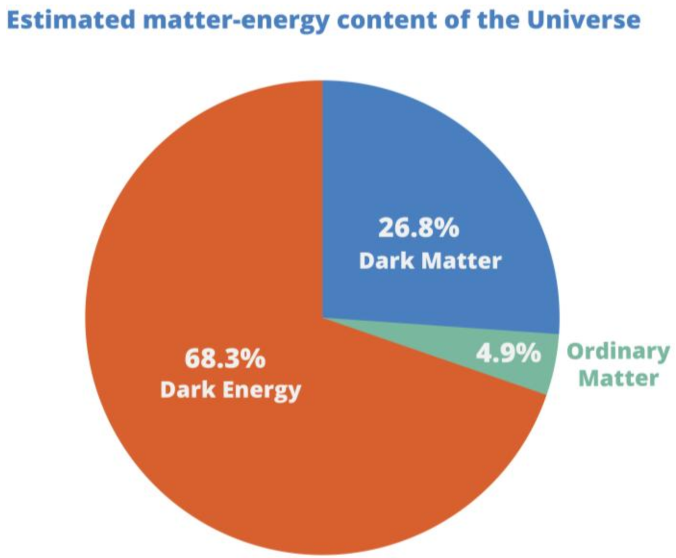
- Standard Model: Excellent description of the nature up to TeV $(\sim 10^{-18}\ \mathrm{m})$ scale;
  unresolved problems require BSM physics



B.D. Fields *et al.* 2022



Mario De Leo 2018



Planck 2018

Axion

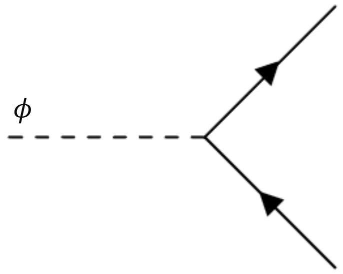
- Axion: pseudo Nambu–Goldstone boson of spontaneously broken global $\mathrm{U}(1)$
  - Shift symmetry: $\phi = \phi + \mathrm{constant}$
  - Periodicity: $\phi = \phi + 2\pi f$

- Mass from shift symmetry breaking at the energy scale Λ

$\rightarrow m_\phi \sim \frac{\Lambda^2}{f}$

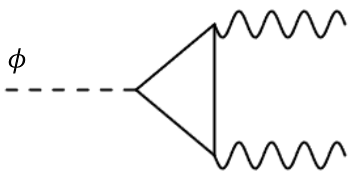
- Axion–SM couplings

Yukawa couplings to fermions

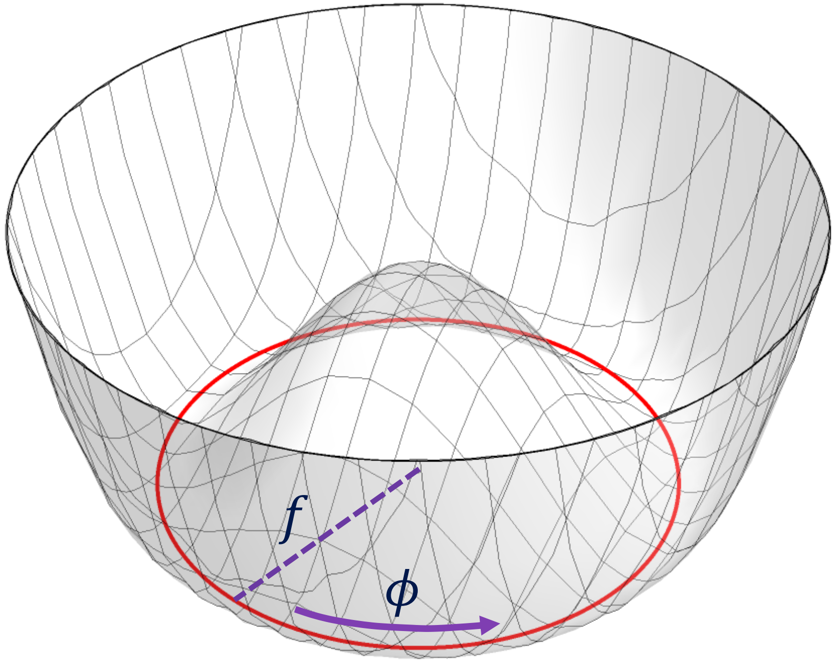


$y_\psi \propto \frac{m_\psi}{f}$

Anomalous gauge couplings



$g_\phi \propto \frac{\alpha_{\mathrm{EM}}}{2\pi f}$



Dark Photon

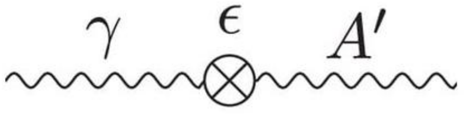
- Dark photon: Gauge boson of an extra $\mathrm{U}(1)$ symmetry

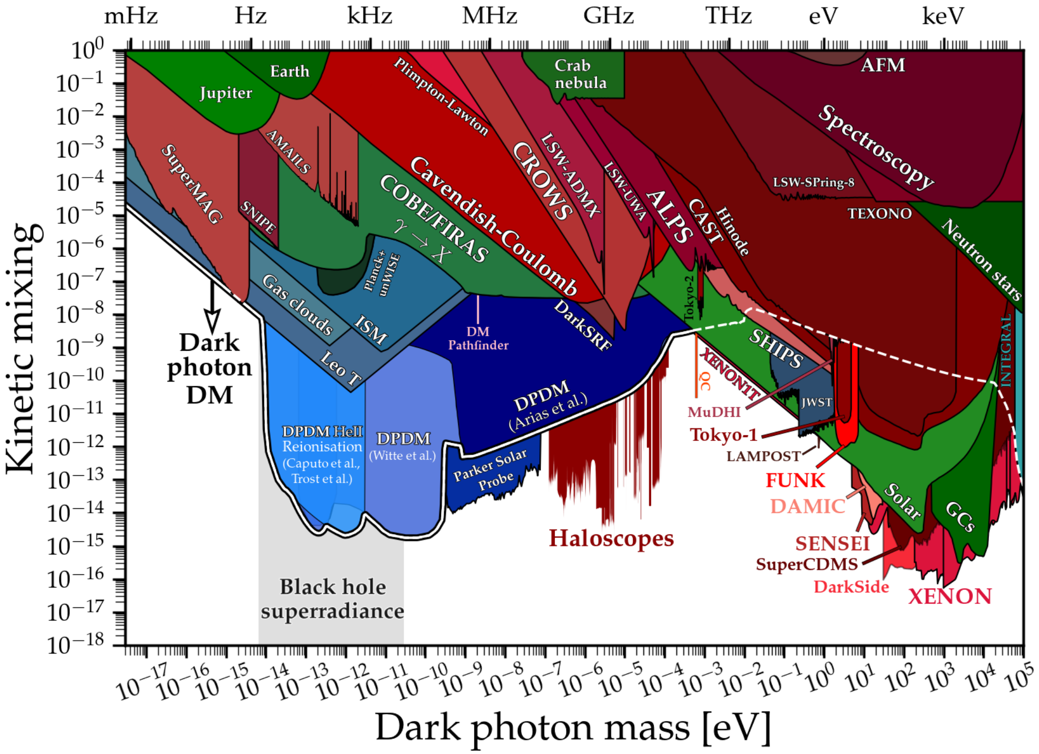
- Interact with SM via kinetic mixing

  $\rightarrow \mathcal{L} \supset -e\epsilon J_\mu A'^\mu$ (ϵ: mixing strength)

- Dark photon–SM couplings

Kinetic mixing



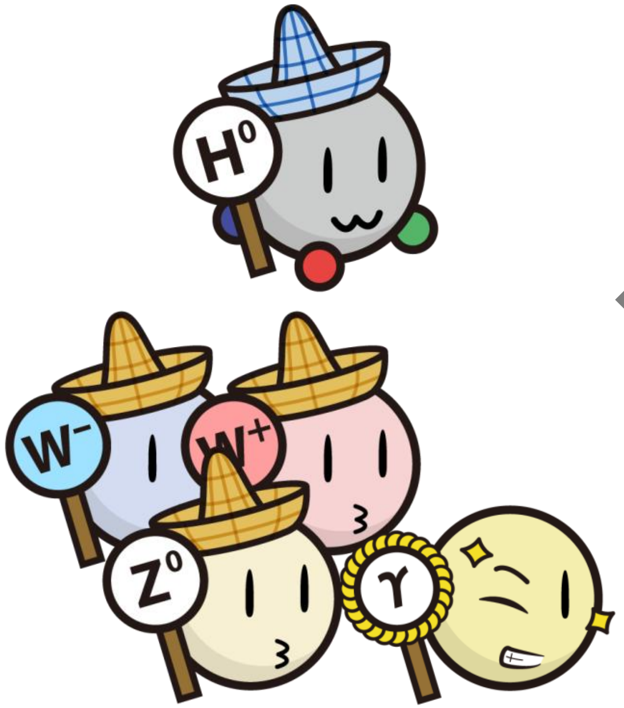


A. Caputo *et al.* 2021

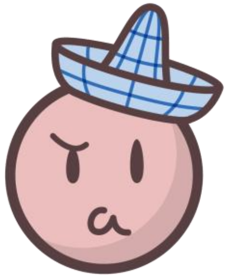
Model

Model

SM sector

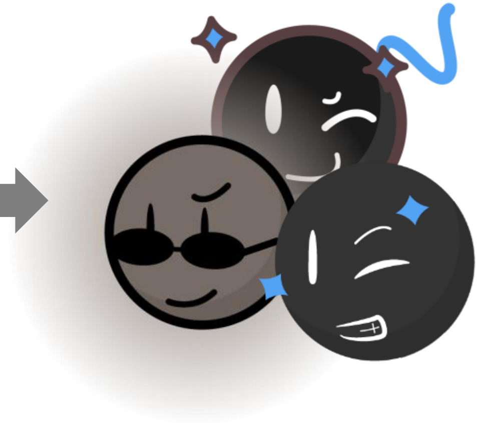


Axion



- Mediator between SM and dark sector
- Matter–antimatter asymmetry via electroweak baryogenesis

Dark sector
(Dark photons)



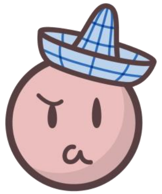
- Dark matter candidate

A single model simultaneously explains baryogenesis and dark matter!

pictures from higgstan.com

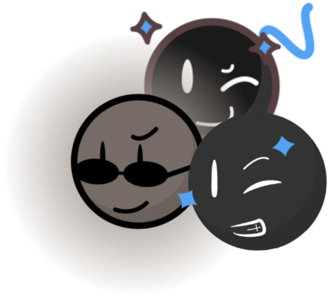
Key Questions

Axion



- How can an axion enable electroweak baryogenesis to explain the observed matter-antimatter asymmetry?

Dark sector



- How does the axion produce dark photons that could account for dark matter?

pictures from higgstan.com

Axion-Induced Electroweak Baryogenesis

Sakharov Conditions

- Conditions required for producing baryon asymmetry

  1. Baryon number B violation
  2. C and CP symmetry violation
  3. Interactions out of thermal equilibrium

- SM fails to sufficiently satisfy these conditions

  → Need BSM extensions

Axion-Extended Higgs Sector

- Axion coupled to the Higgs sector

$$\mu_{\text{eff}}^2(\phi)h^2$$

- Scalar potential

$$V = \frac{1}{2}\left(\mu^2 - M^2\cos\left(\frac{\phi}{f}+\alpha\right) + c_h T^2\right)h^2 + \frac{\lambda}{4}h^4 - \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

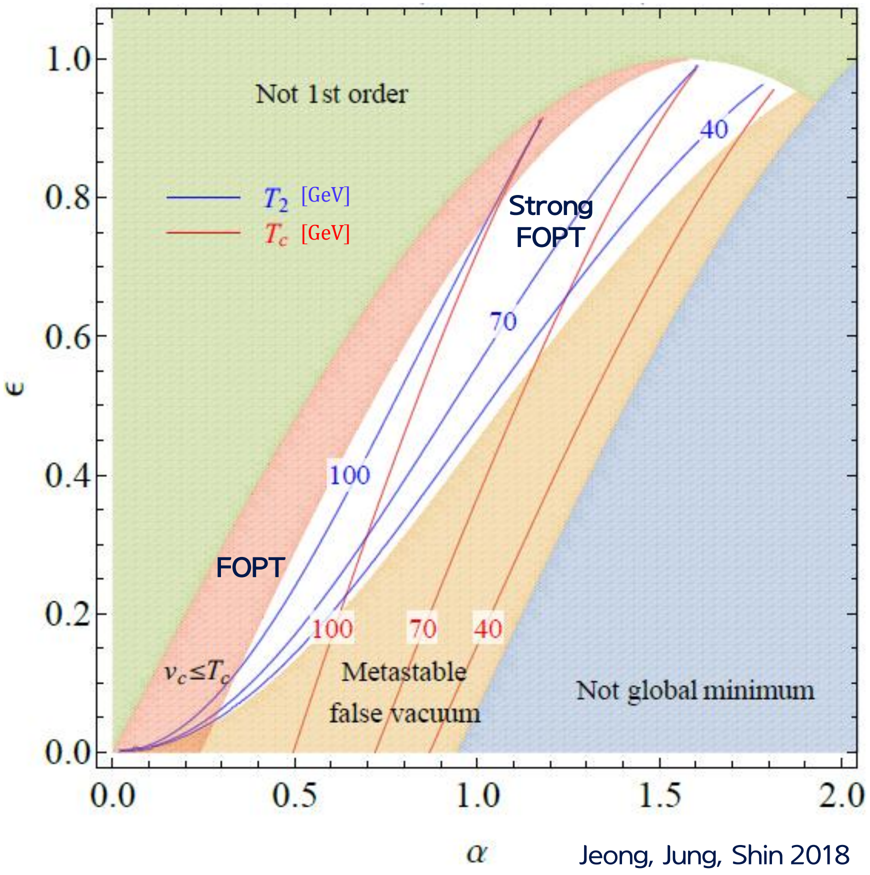
μ, M, Λ : around the EW scale

- Tunneling occurs dominantly along the axion direction

- Axion can induce a strong first-order electroweak phase transition

→ Provides out-of-equilibrium condition

Pattern of EWPT



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Axion-Induced Electroweak Baryogenesis

- Axion coupling to the EW gauge sector

$$\frac{\phi}{f} W_{\mu\nu}\widetilde{W}^{\mu\nu} \leftrightarrow (\partial_\mu \phi) J^\mu$$

- $\frac{d\phi}{dt}$ serves as a chemical potential for B

→ Spontaneous baryogenesis

Cohen, Kaplan 1988

- Observed baryon asymmetry obtained for

10^5 GeV $\lesssim f \lesssim 10^7$ GeV

corresponding to axion mass range:

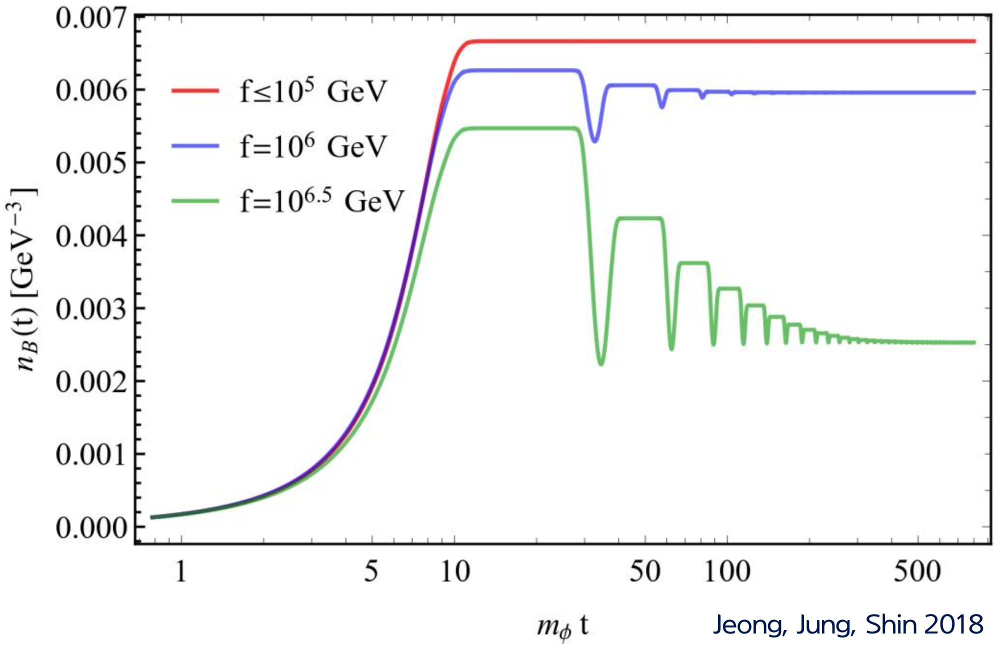
$\mathcal{O}(1)$ MeV $\lesssim m_\phi \lesssim \mathcal{O}(100)$ MeV

Axion mass

$m_\phi \sim \frac{m_h^2}{f}$

$(m_h = 125$ GeV$)$

Evolution of Baryon Number Density

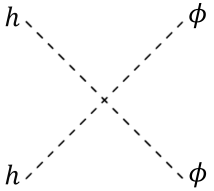


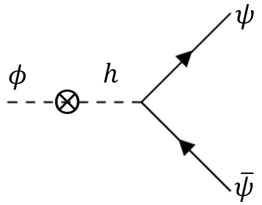
Jeong, Jung, Shin 2018

Axion Interactions with SM Particles

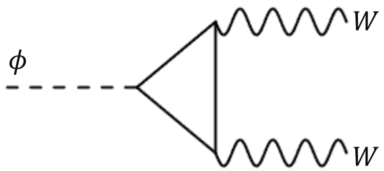
Interaction channels

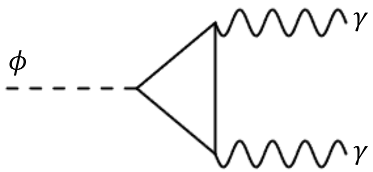
$\mu_{\text{eff}}^2(\phi)h^2 \quad \Rightarrow$





$\frac{\phi}{f} W_{\mu\nu}\widetilde{W}^{\mu\nu} \quad \Rightarrow$





Axion–Higgs mixing

$$\sin\theta_{\text{mix}} \sim \frac{m_h}{f}$$

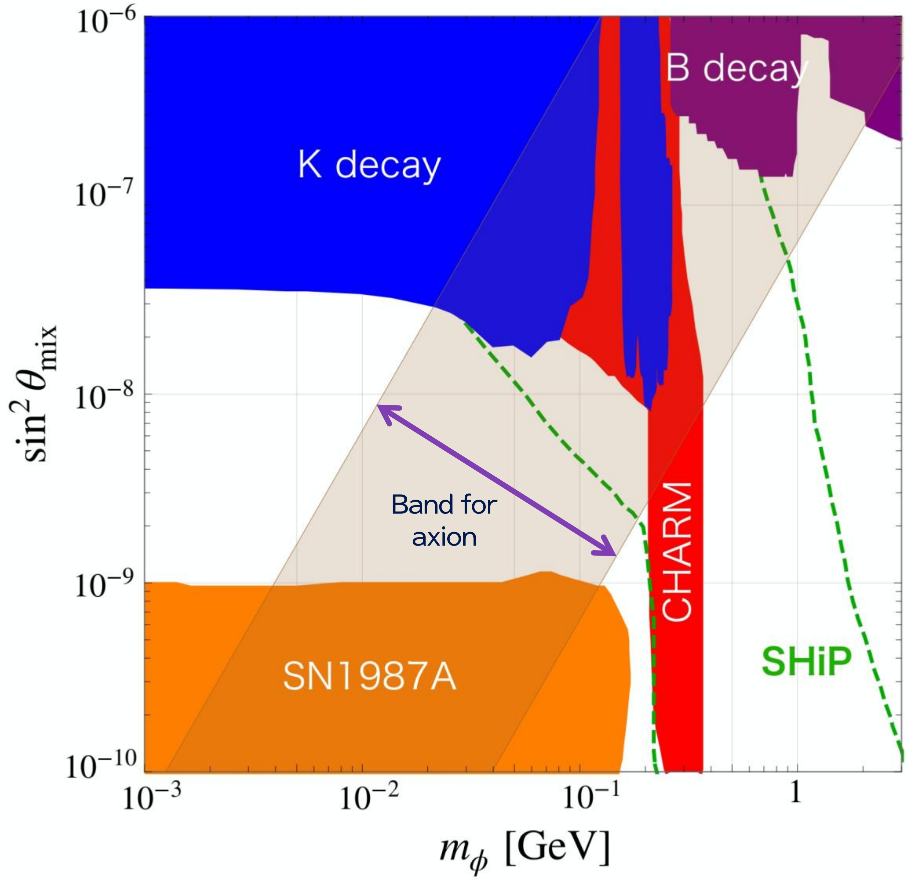
$(m_h = 125 \text{ GeV})$

Axion–Photon coupling

$$g_{\phi\gamma} \sim \frac{\alpha_{\text{EM}}}{2\pi f}$$

Constraints on Axion

Axion−Higgs Mixing

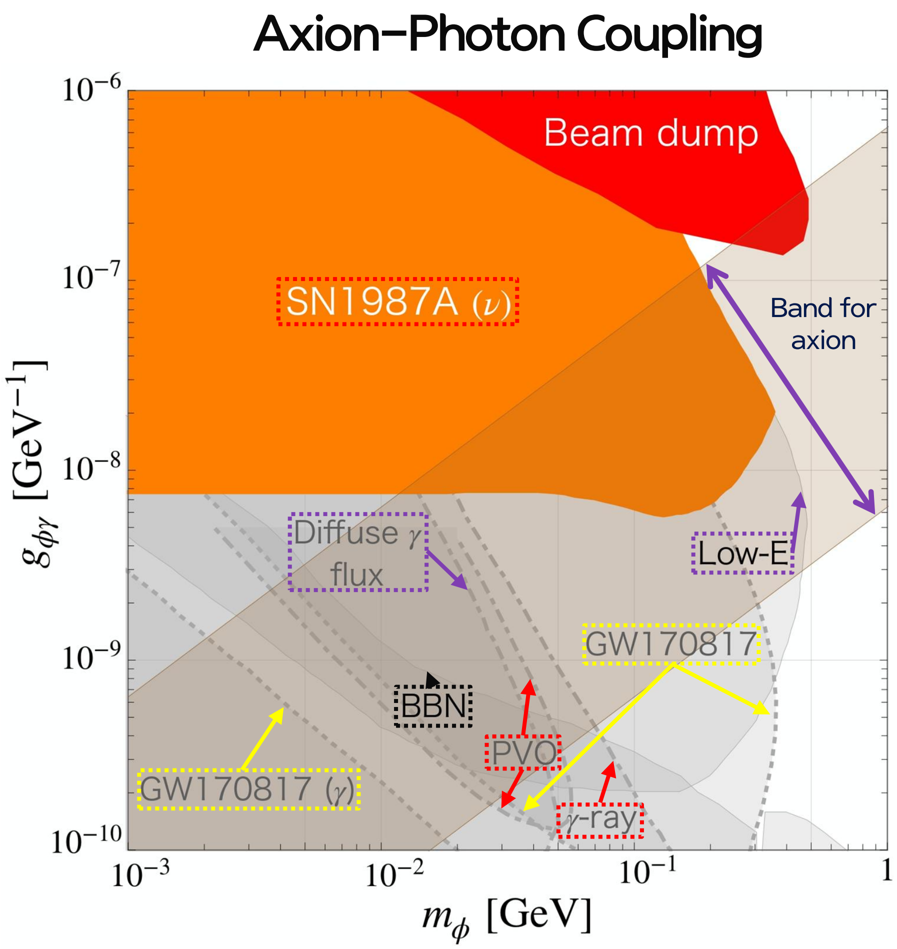


Jeong, Kang, Nakagawa 2024

- Bounds arise from rare meson decays, beam dump experiments, and supernova cooling

- Future searches such as SHiP can probe the remaining parameter space

Constraints on Axion



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---, --- : supernovae / --- : neutron star merger / --- : cosmology

- Bounds arise from supernova explosions, binary neutron star merger, and BBN
- Astrophysical bounds strongly constrain the axion proposed to realize electroweak baryogenesis

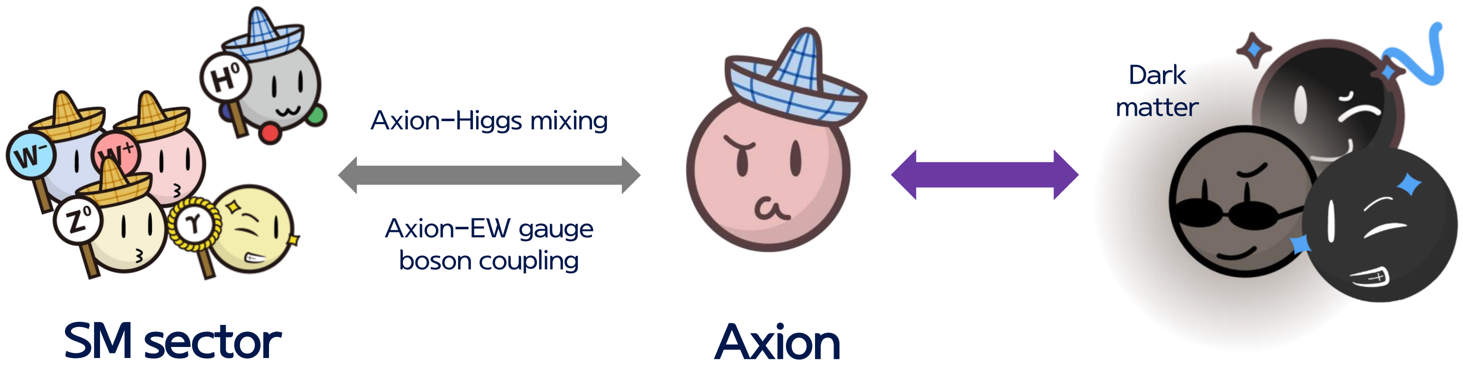
Axion-Induced EWBG: Limits and the Path Forward

- Result of axionic extension

  Axion coupled to both the Higgs and the EW gauge sectors can account for the baryon asymmetry

- Key limitations
  - Severe constraints on the axion-photon coupling
  - No dark matter candidate

- **Possible solution: Axion-coupled dark photons may resolve these difficulties!**



Dark sector (Dark photons)

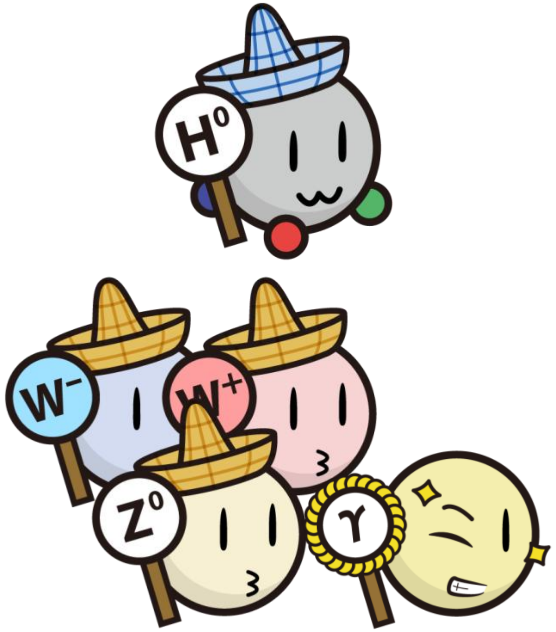
- Constraint relief
- Dark matter candidate

pictures from higgstan.com

Dark Photons

Dark Photons

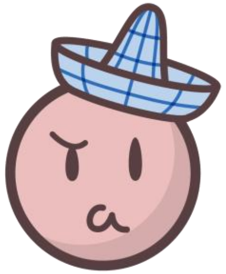
SM sector



Axion–Higgs mixing

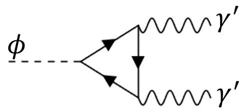
Axion–EW gauge boson coupling

Axion



Interaction

$\frac{g_{\phi\gamma'}}{4}\phi F'_{\mu\nu}\tilde{F}'^{\mu\nu}$



Dark photons

(3 types)

Type I: $\gamma'_{\rm M}$

Mass: $m_{\gamma'_{\rm M}} < m_\phi/2$

Role: constraint relaxation (astrophysical bounds)

Type II: $\gamma'_{\rm DM}$

Mass: $10\ {\rm keV} < m_{\gamma'_{\rm DM}} < m_\phi/2$

Role: dark matter (cold dark matter)

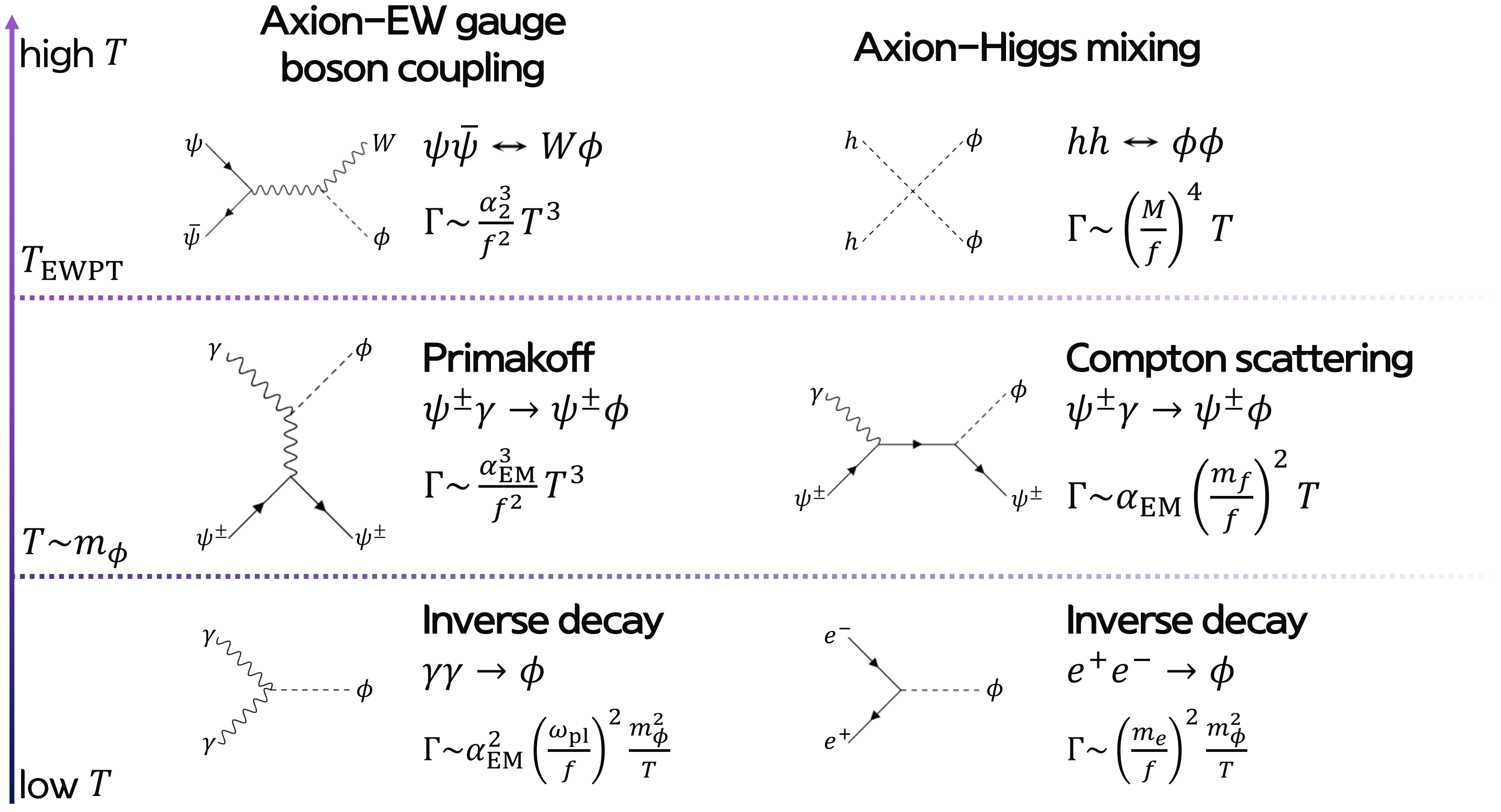
Type III: $\gamma'_{\rm DR}$

Mass: $m_{\gamma'_{\rm DR}} \lesssim 1\ {\rm eV}$

Role: dark radiation (hot dark matter)

pictures from higgstan.com

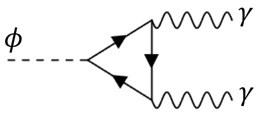
Thermal Production of Axions



- Axions remain in thermal equilibrium at high temperatures
- Axions freeze out once they become non-relativistic

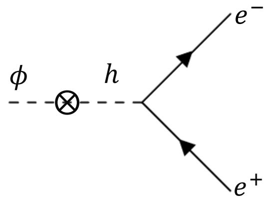
Type I Dark Photon: Invisible Axion Decay

- Alleviating constraints on the axion–photon coupling
  - Constraints on $g_{\phi\gamma}$ depend on $\mathrm{BR}(\phi \to \mathrm{SM})$
  - Invisible decay into dark photons makes $\mathrm{BR}(\phi \to \mathrm{SM}) \ll 1$



Axion–photon coupling

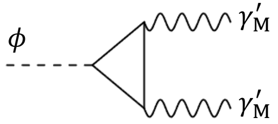
$$\frac{\alpha_{\mathrm{EM}}}{f}$$



Axion–electron coupling

$$\sin\theta_{\mathrm{mix}} \frac{m_e}{f}$$

$<$



Axion–dark photon coupling

$$\frac{\alpha'}{f}$$

- Gauge coupling $g_{\phi\gamma'_{\mathrm{M}}}$ must remain perturbative
  - Implies $g_{\phi\gamma'_{\mathrm{M}}} \lesssim \frac{1}{f}$ and therefore $\mathrm{BR}(\phi \to \mathrm{SM}) \gtrsim 10^{-4} \left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{-2}$

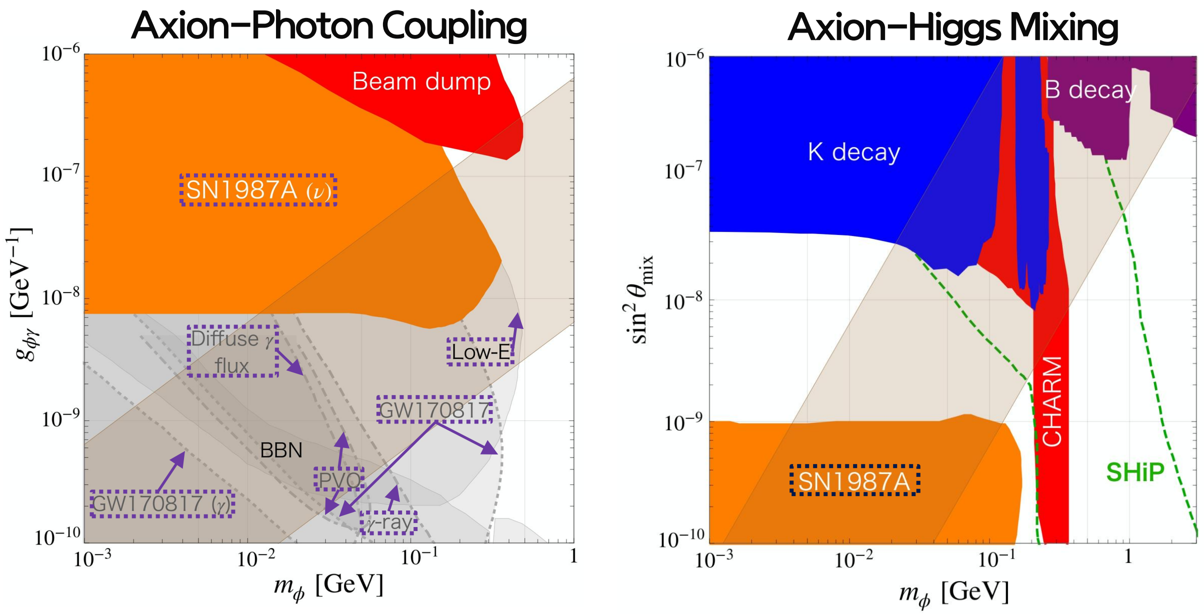
Type I Dark Photon: Invisible Axion Decay

- Constraints on $g_{\phi\gamma}$ from SN explosions and NS merger
  - Axion coupling to dark photons should be much larger than the coupling to electrons

    $\rightarrow g_{\phi\gamma'_{\rm M}} \gtrsim 10^{-7}\ \mathrm{GeV}^{-1}$

- Constraints on $\sin^2\theta_{\rm mix}$ from SN cooling
  - Axion should be trapped inside the SN core

    $\rightarrow g_{\phi\gamma'_{\rm M}} < 10^{-6}\ \mathrm{GeV}^{-1} \left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{-3/2}$



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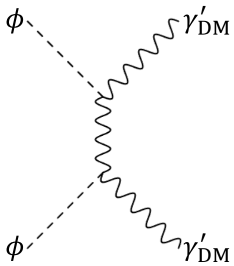
Type II Dark Photon: Dark Matter

- Dark matter candidate
- To prevent dark photon overproduction, γ'_{DM} should not be thermalized

Scattering

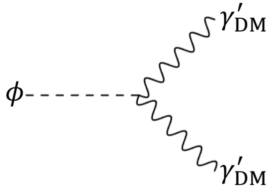
$\phi\phi \leftrightarrow \gamma'_{\mathrm{DM}}\gamma'_{\mathrm{DM}}$



$$T_{\mathrm{reh}} < 10^{6}\ \mathrm{GeV}\left(\frac{g_{\phi\gamma'_{\mathrm{DM}}}}{10^{-9}\ \mathrm{GeV}^{-1}}\right)^{-4/3}$$

Decay, inverse decay

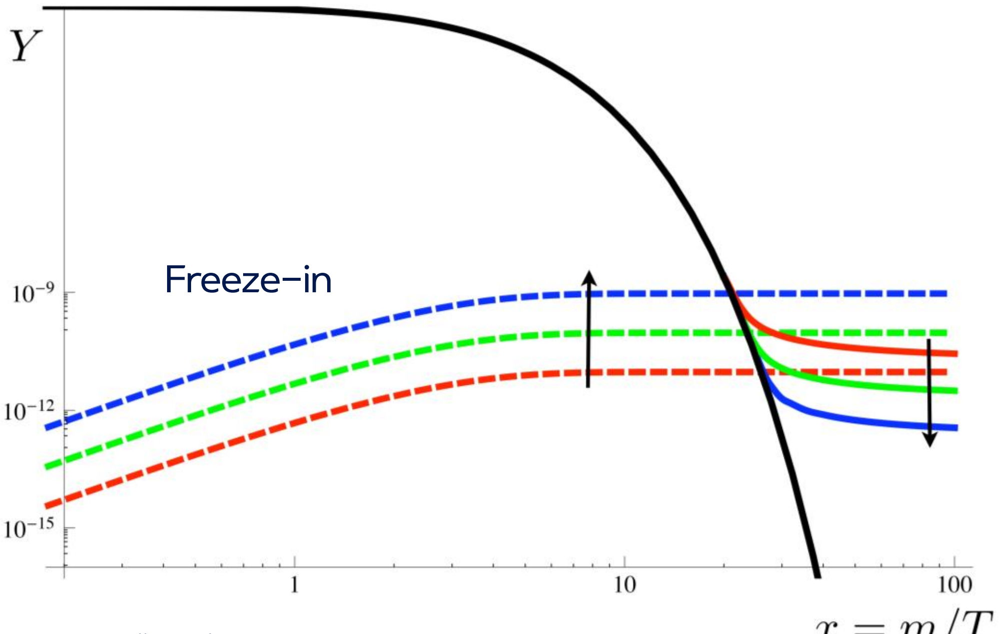
$\phi \leftrightarrow \gamma'_{\mathrm{DM}}\gamma'_{\mathrm{DM}}$



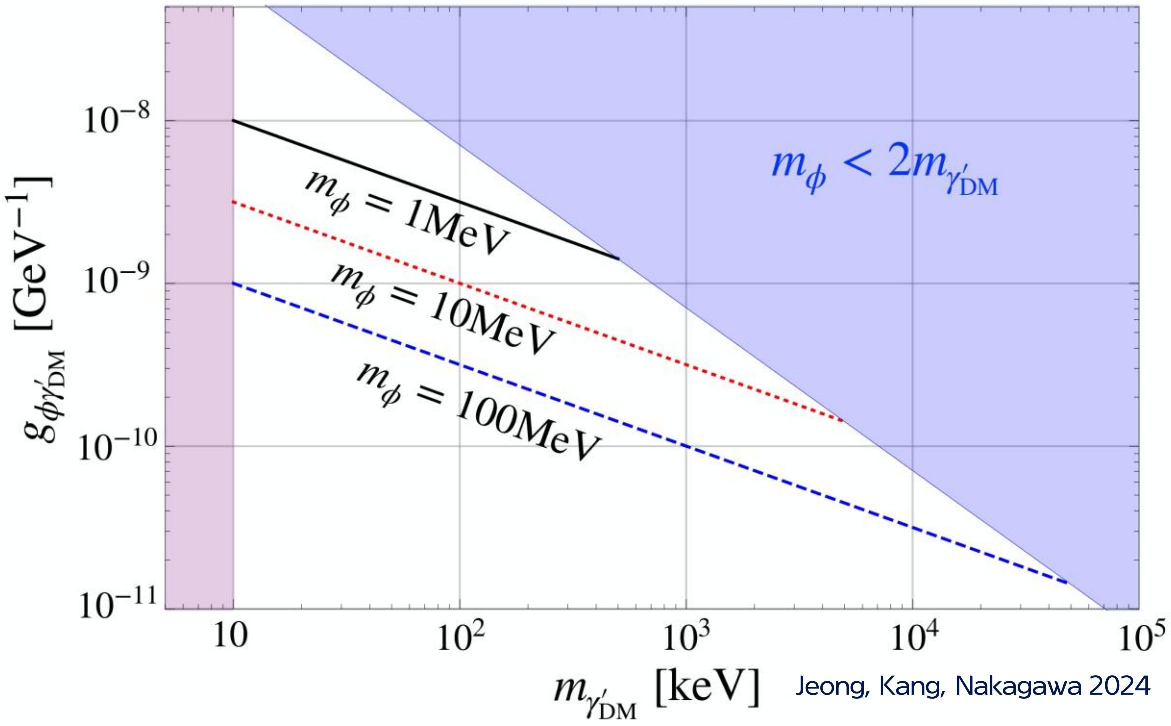
$$g_{\phi\gamma'_{\mathrm{DM}}} < 10^{-8}\ \mathrm{GeV}^{-1}\left(\frac{m_{\phi}}{10\ \mathrm{MeV}}\right)^{-1/2}$$

Type II Dark Photon: Dark Matter

- Freeze-in production of γ'_{DM} can account for the observed dark matter abundance
- DM density: $\Omega_{\gamma'_{\mathrm{DM}}} \mathrm{h}^2 \approx 0.12 \left(\frac{m_{\gamma'_{\mathrm{DM}}}}{100 \text{ keV}}\right) \left(\frac{g_{\phi\gamma'_{\mathrm{DM}}}}{10^{-10} \text{ GeV}^{-1}}\right)^2 \left(\frac{m_\phi}{10 \text{ MeV}}\right)$



L. J. Hall *et al.* 2009



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Type III Dark Photon: Dark Radiation

- Sub−eV dark photon γ'_{DR} may contribute to dark radiation

$$\Delta N_{\mathrm{eff}} = \frac{4g}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{*s}(T)}{g_{*s}(T_{\mathrm{decDR}})}\right)^{4/3}$$

(T_{decDR}: γ'_{DR} decoupling temperature)

- ΔN_{eff} from γ'_{DR} decoupled before EWPT

$\Delta N_{\mathrm{eff}} \approx 0.07 < 0.3$ Planck constraints

G. Efstathiou, S. Galli, A. Lewis *et al.* 2018

Conclusions

Conclusions

- Axion coupled to both the Higgs and the electroweak gauge sectors can account for the observed baryon asymmetry

- Stringent astrophysical bounds on axion-photon coupling and the absence of dark matter candidates motivate additional extension

Axion-coupled dark photons mitigate astrophysical constraints while explaining the observed dark matter abundance

Back-Up

Axion–Higgs Coupling for 1st order EWPT

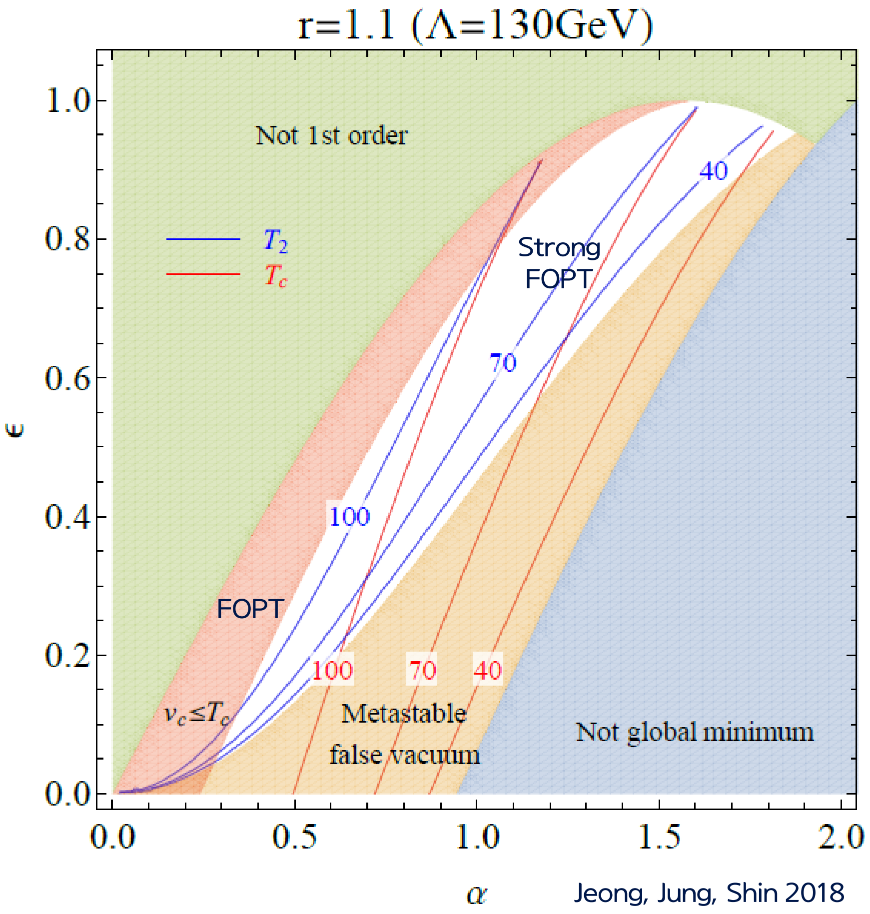
$$V = \frac{1}{2}\underbrace{\left(\mu^2 - M^2\cos\left(\frac{\phi}{f}+\alpha\right) + c_h T^2\right)}_{\equiv\, \mu_{\rm HT}^2(\phi)} h^2 + \frac{\lambda}{4}h^4 - \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

For $f \gg$ EW scale, tunneling occurs dominantly along the axion direction

$$\left.\frac{\partial V}{\partial h}\right|_{h=\hat{h}(\phi)} = 0$$

$$\hat{h}(\phi) \simeq \begin{cases} 0 & \text{if } \mu_{\rm HT}^2(\phi) \geq 0 \\ \sqrt{-\frac{1}{\lambda}\,\mu_{HT}^2(\phi)} & \text{if } \mu_{\rm HT}^2(\phi) < 0 \end{cases}$$

$$V_{\rm eff} = \Lambda^4(\cos\theta_0 - \cos\theta) - \frac{\lambda}{4}\left(\hat{h}^4(\phi) - v_0^4\right)$$



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Three dimensionless parameters

$$\alpha, \epsilon \equiv \frac{\sqrt{2\lambda}\Lambda^2}{M^2}, r \equiv \frac{\sqrt{2}\Lambda^2}{\sqrt{\lambda}v^2}$$

Bubble Nucleation

Bubble nucleation rate per unit volume $\Gamma \propto T^4 e^{-S_3/T}$

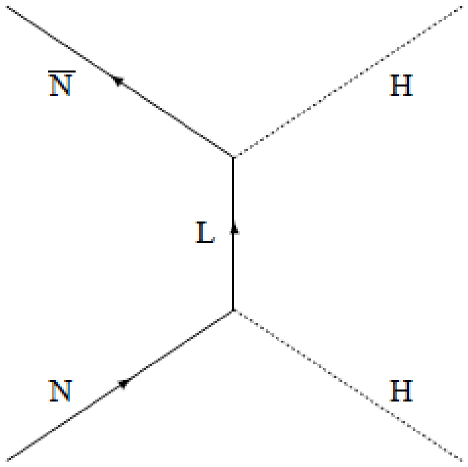
Euclidean action $S_3 \simeq 4\pi f^3 \int_0^\infty dx\, x^2 \left[\frac{\theta'^2}{2} + V_{\text{eff}}(\theta)\right]$ $x \equiv r/f$

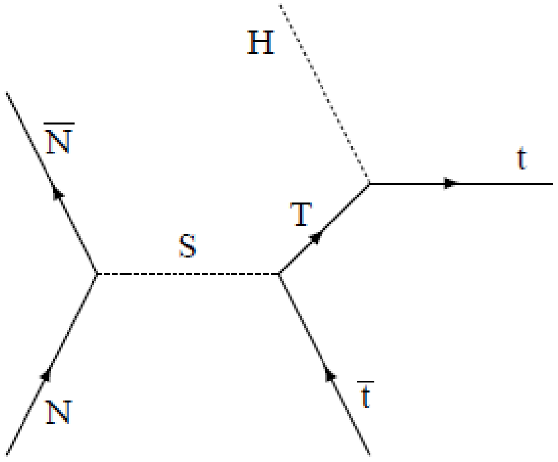
Around the T_n, $\frac{S_3}{T} \propto (T - T_2)^n f^3$ n: positive constant, order unity

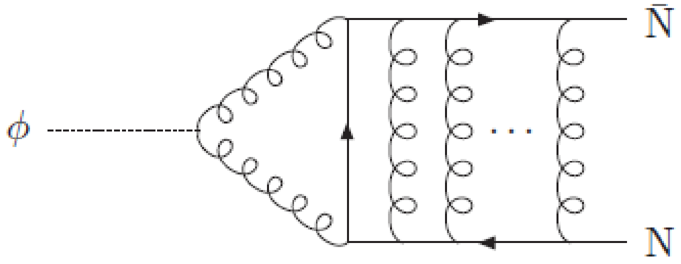
→ $T_n \sim T_2$

Bubble nucleation starts when $S_3/T \lesssim 140$

UV Completion







Jeong, Jung, Shin 2018

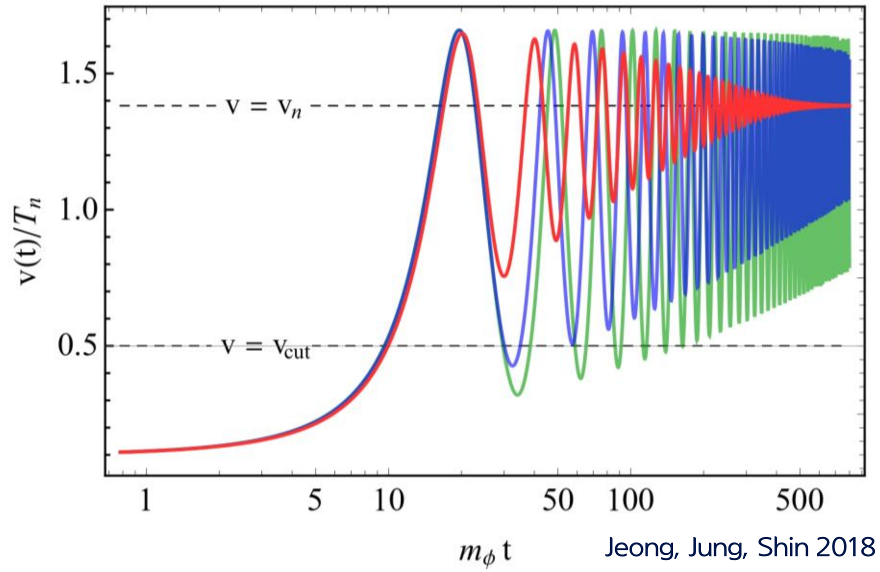
Axion-Induced Baryogenesis

Axion coupled to the EW gauge sector

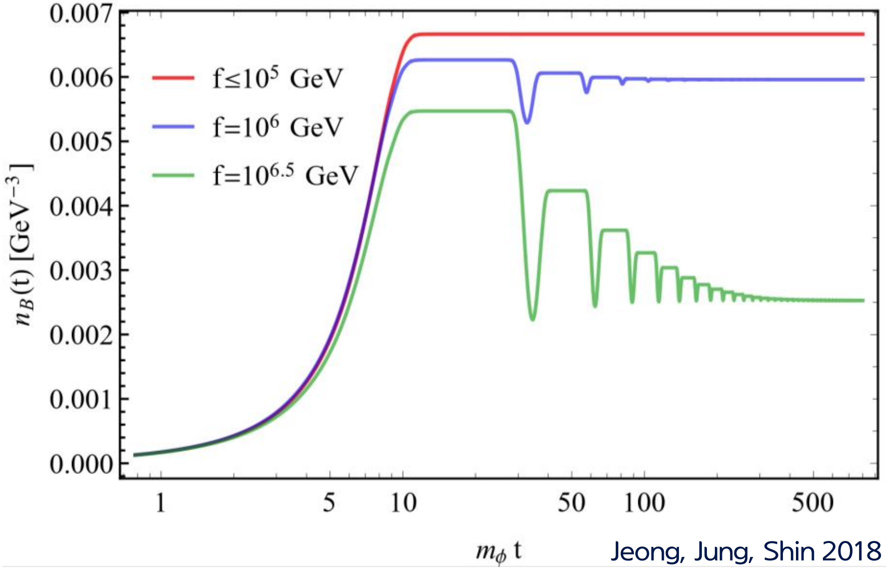
$$\frac{\phi}{f} W_{\mu\nu}\widetilde{W}^{\mu\nu} \rightarrow \frac{dn_B}{dt} \approx \frac{N_g}{2}\frac{\Gamma_{\rm sph}}{T}\frac{d}{dt}\frac{\phi}{f} - \frac{13N_g}{4}\frac{\Gamma_{\rm sph}}{T^3}n_B$$

$$\rightarrow n_B(t) = \int_0^t dt' \frac{3\Gamma_{\rm sph}}{2T}\dot{\theta}\,{\rm Exp}\left[-\int_{t'}^{t} dt'' \frac{39\Gamma_{\rm sph}}{4T^3}\right]$$

$$= n_0 e^{-K_\phi}$$



Jeong, Jung, Shin 2018



Jeong, Jung, Shin 2018

Axion Properties

Axion mass

$$m_\phi = \kappa_1 \frac{m_h^2}{f}$$

$(m_h = 125\mathrm{GeV})$

$$\kappa_1 \simeq \sqrt{\frac{r(1+2r\epsilon\cos\alpha + r^2\epsilon^2)^{3/2} - r^4\epsilon\sin^2\alpha}{8\lambda\epsilon(1+2r\epsilon\cos\alpha + r^2\epsilon^2)}}$$

Axion–Higgs mixing

$$\sin\theta_{\mathrm{mix}} = \kappa_2 \frac{m_h}{f}$$

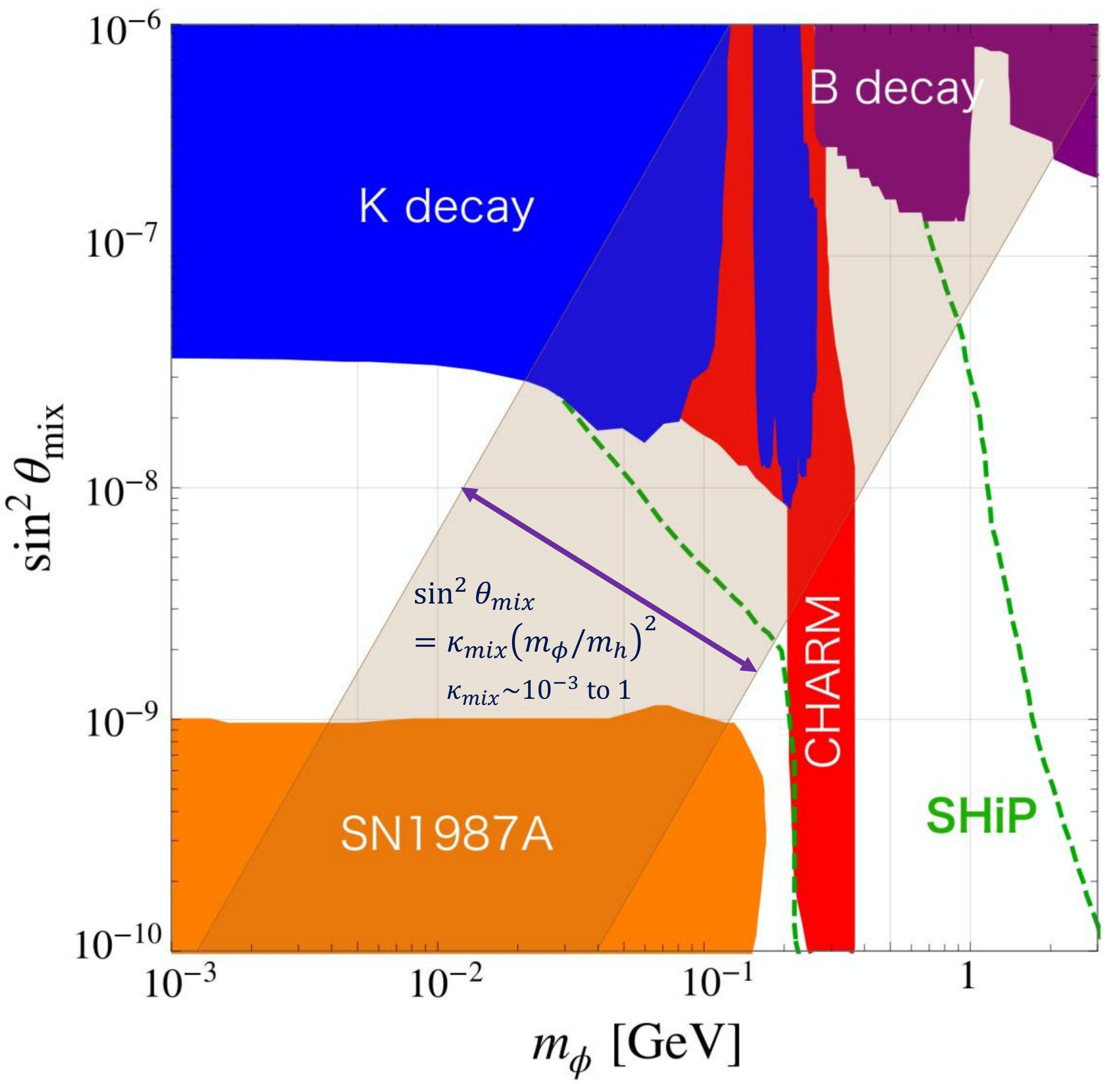
$$\kappa_2 \simeq \frac{r^2\sin\alpha}{\sqrt{8\lambda(1+2r\epsilon\cos\alpha + r^2\epsilon^2)}}$$

Constraints on Axion–Higgs Mixing

Rare meson decays: invisible state
– K decay: $K^+ \to \pi^+ \nu \bar{\nu}$
– B decay: $B^+ \to K^+ \mu^+ \mu^-$, $B^0 \to K^0 \mu^+ \mu^-$

Axion searches: beam dump experiments
– CHARM: proton beam dump
– SHiP: future experiment

Astrophysical bounds: PNS cooling
– SN 1987A



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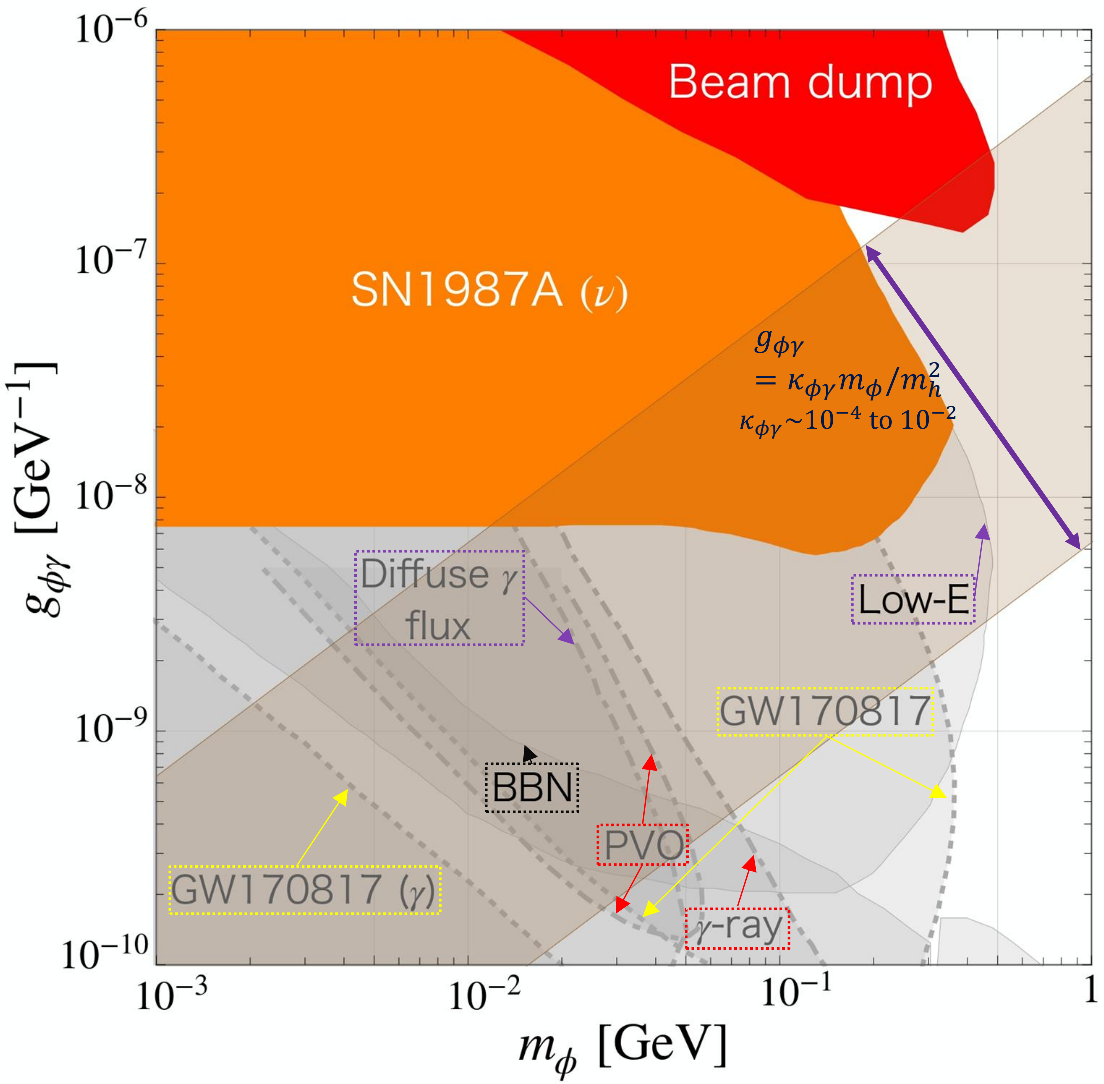
Constraints on Axion-Photon Coupling

Supernovae (Astro)
- SN 1987A: PNS cooling
- γ-ray: SN 1987A SMM (γ-burst)
- PVO: SN 1987A (fireball)
- Low-E: low-energy SN explosion energy

Binary merger (Astro)
- GW170817: neutron star merger (fireball)
- GW170817(γ): neutron star merger (γ-burst)

Cosmological bound
- BBN: dilution effects on the baryon and neutrino densities



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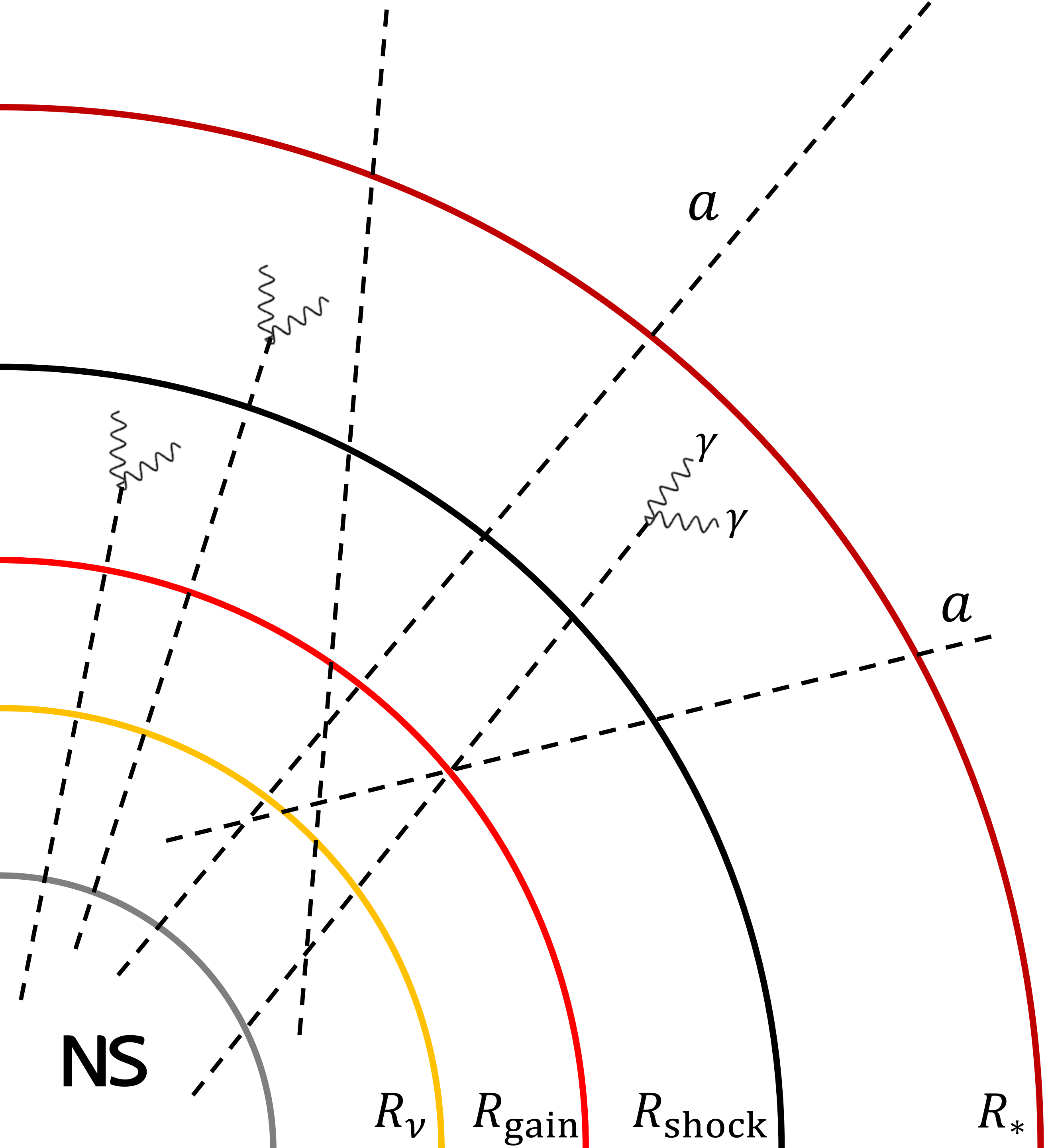
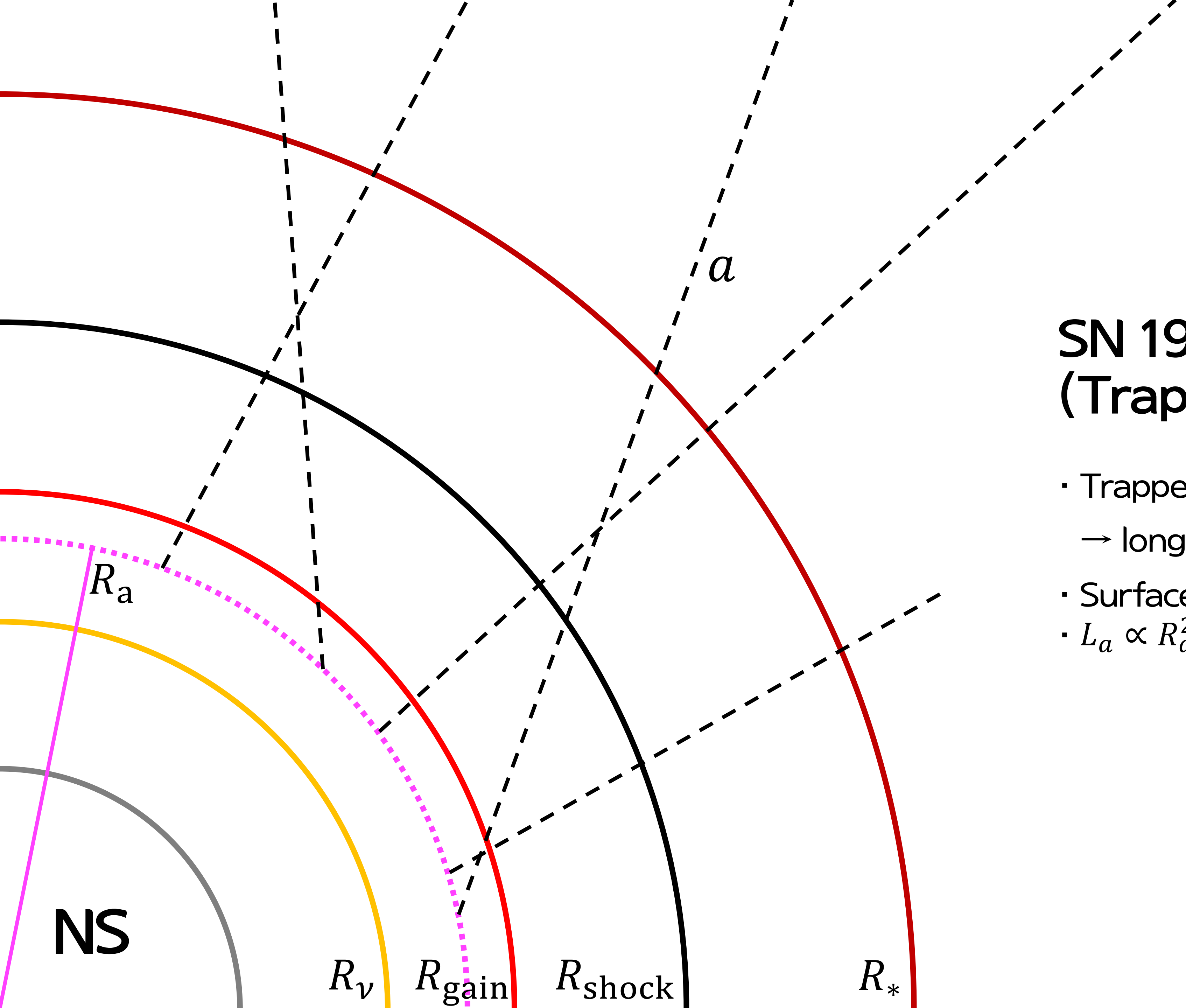


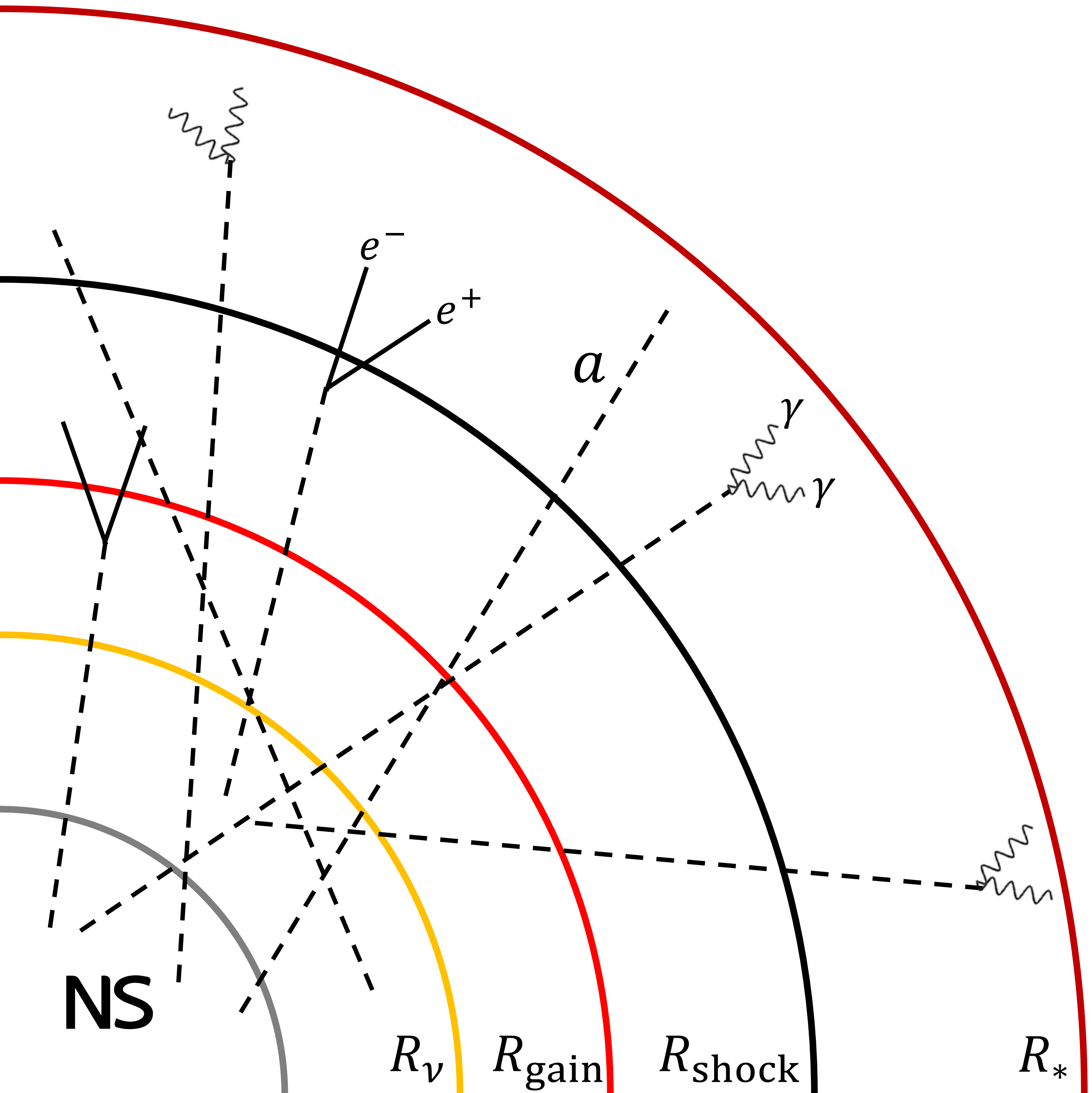
SN 1987A Cooling (Free-Streaming)

- Freely escape from the supernova
  → short $t_{\text{diff}} = \frac{\lambda_a}{c}\frac{R_*^2}{\lambda_a^2}$
- Volume emission
- $L_a \propto g_a^2$



SN 1987A Cooling (Trapping)

- Trapped inside the supernova
  → long $t_{\text{diff}} = \frac{\lambda_a}{c}\frac{R_*^2}{\lambda_a^2}$
- Surface emission
- $L_a \propto R_a^2 T^4(R_a)$



Low-Energy Supernovae (Type II-P)

- Energy deposition by axion should be below about 10^{50} erg

$$E_{\rm mantle} = \int dt \int_0^{R_{\rm NS}} dR \int_{m'_a(R)}^{\infty} dE_a \frac{dL_a(R, E_a, t)}{dR dE_a} \times \{\exp[-(R_{\rm NS} - R)/\lambda_a] - \exp[-(R_* - R)/\lambda_a]\}$$

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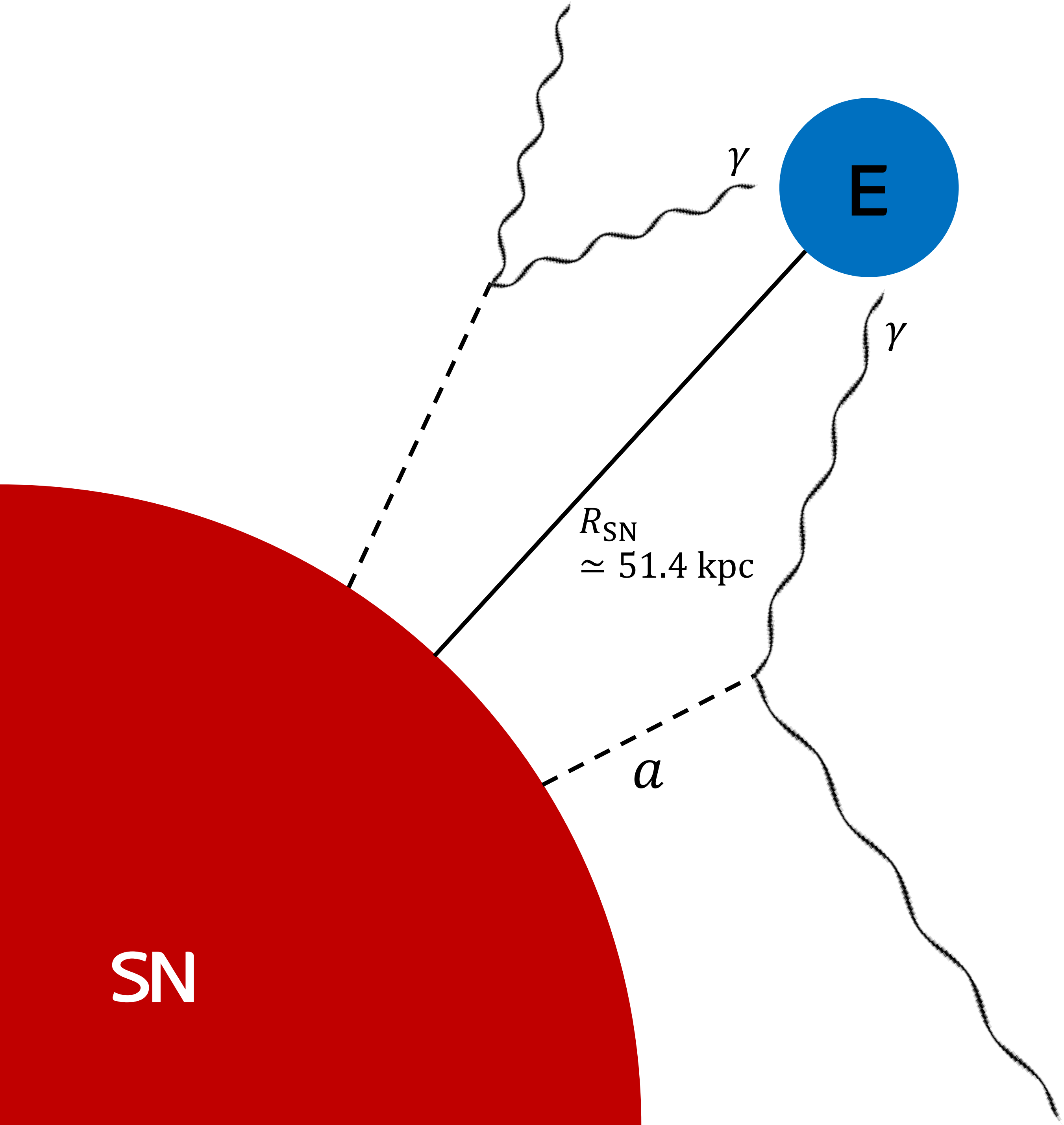

γ-ray Burst (SN 1987A)

- Axion-induced γ-ray flux from SN 1987A → SMM ($E_\gamma \gtrsim 25$ MeV, $t \sim 223$ s)

$$F_\gamma = \frac{1}{2\pi R_{\mathrm{SN}}^2} \int_{m_a}^{\infty} \mathrm{d}\omega_a \int_{\omega_\gamma^{\min}(p_a)}^{\omega_\gamma^{\max}(p_a)} \mathrm{d}\omega_\gamma \, p_a^{-1} \frac{\mathrm{d}N_a}{\mathrm{d}\omega_a} \left(e^{-\frac{R_* m_a}{\tau_a p_a}} - e^{-\frac{t^{\max}}{\tau_a}\frac{2\omega_\gamma}{m_a}} \right) \Theta\left(\Delta\omega_\gamma(p_a)\right)$$

$$= \frac{1}{2\pi R_{\mathrm{SN}}^2} \int_{m_a}^{\infty} \mathrm{d}\omega_a \left[\Delta\omega_\gamma(p_a) e^{-\frac{R_* m_a}{\tau_a p_a}} - \frac{\tau_a}{t^{\max}} \frac{m_a}{2} \left(e^{-\frac{t^{\max}}{\tau_a}\frac{2\omega_\gamma^{\min}(p_a)}{m_a}} - e^{-\frac{t^{\max}}{\tau_a}\frac{2\omega_\gamma^{\max}(p_a)}{m_a}} \right) \right] \times p_a^{-1} \frac{\mathrm{d}N_a}{\mathrm{d}\omega_a} \Theta\left(\Delta\omega_\gamma(p_a)\right) ,$$

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e.g. [18, 19, 30]. The ALPs produced in the SN are constrained to induce a photon fluence of $F_\gamma < 1.78\ \mathrm{cm}^{-1}$ at the satellite to be consistent with the (null) observation at the 3 sigma level, or $F_\gamma < 1.19\ \mathrm{cm}^{-1}$ at the 2 sigma level [18].

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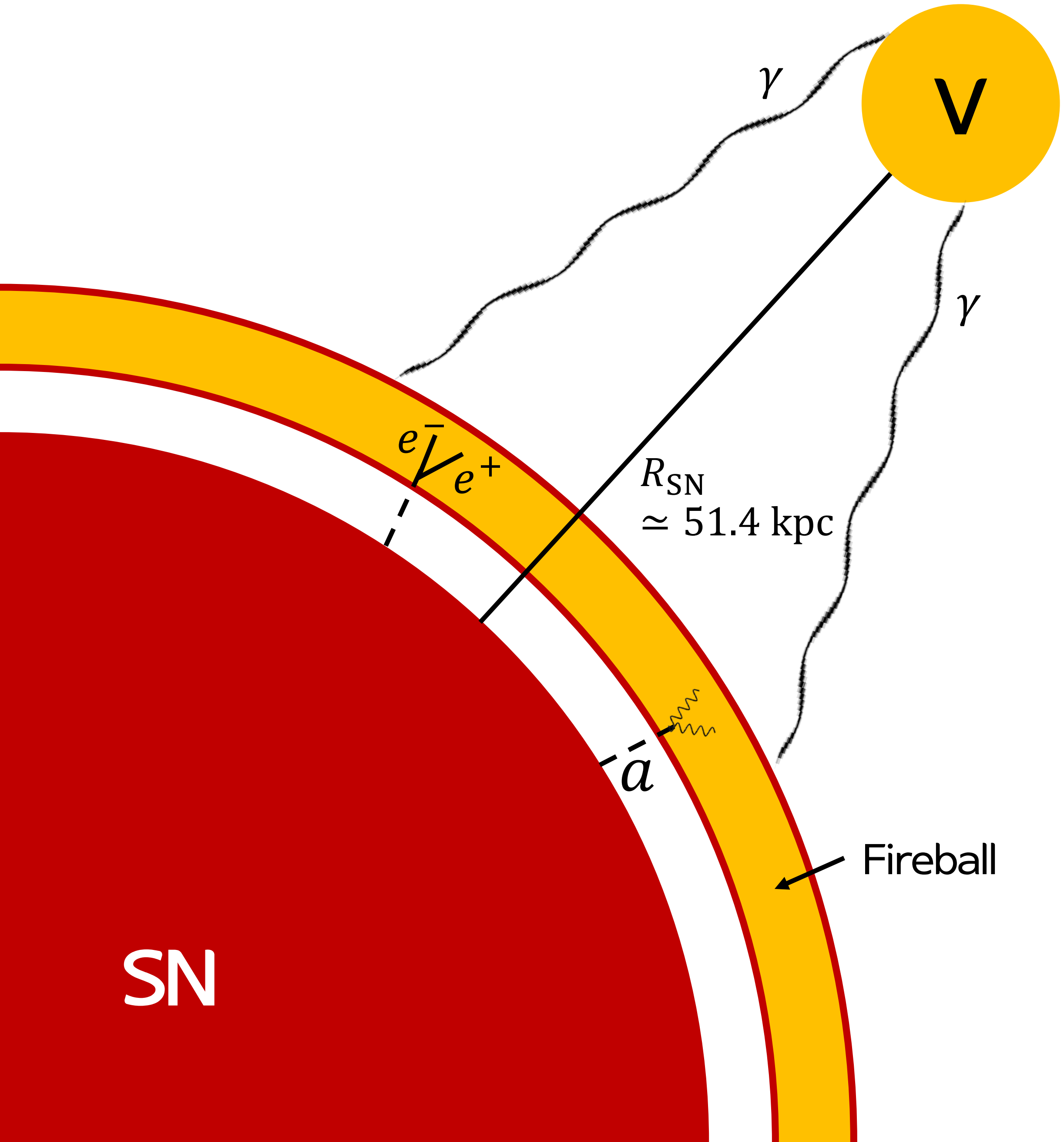

Fireball γ−ray (SN 1987A)

- γ−ray flux from axion−induced fireball → PVO $(E_\gamma \sim \mathcal{O}(0.1-1)\ \mathrm{MeV})$
- Boltzmann−shape spectrum

$$f_{\text{spectrum}} = \int_{E_{\min}}^{+\infty} e^{-E/2\gamma T} E^3 dE \Big/ \int_0^{+\infty} e^{-E/2\gamma T} E^3 dE = e^{-E_{\min}/2\gamma T}\left[1 + \frac{E_{\min}}{2\gamma T} + \frac{1}{2}\left(\frac{E_{\min}}{2\gamma T}\right)^2 + \frac{1}{6}\left(\frac{E_{\min}}{2\gamma T}\right)^3\right]$$

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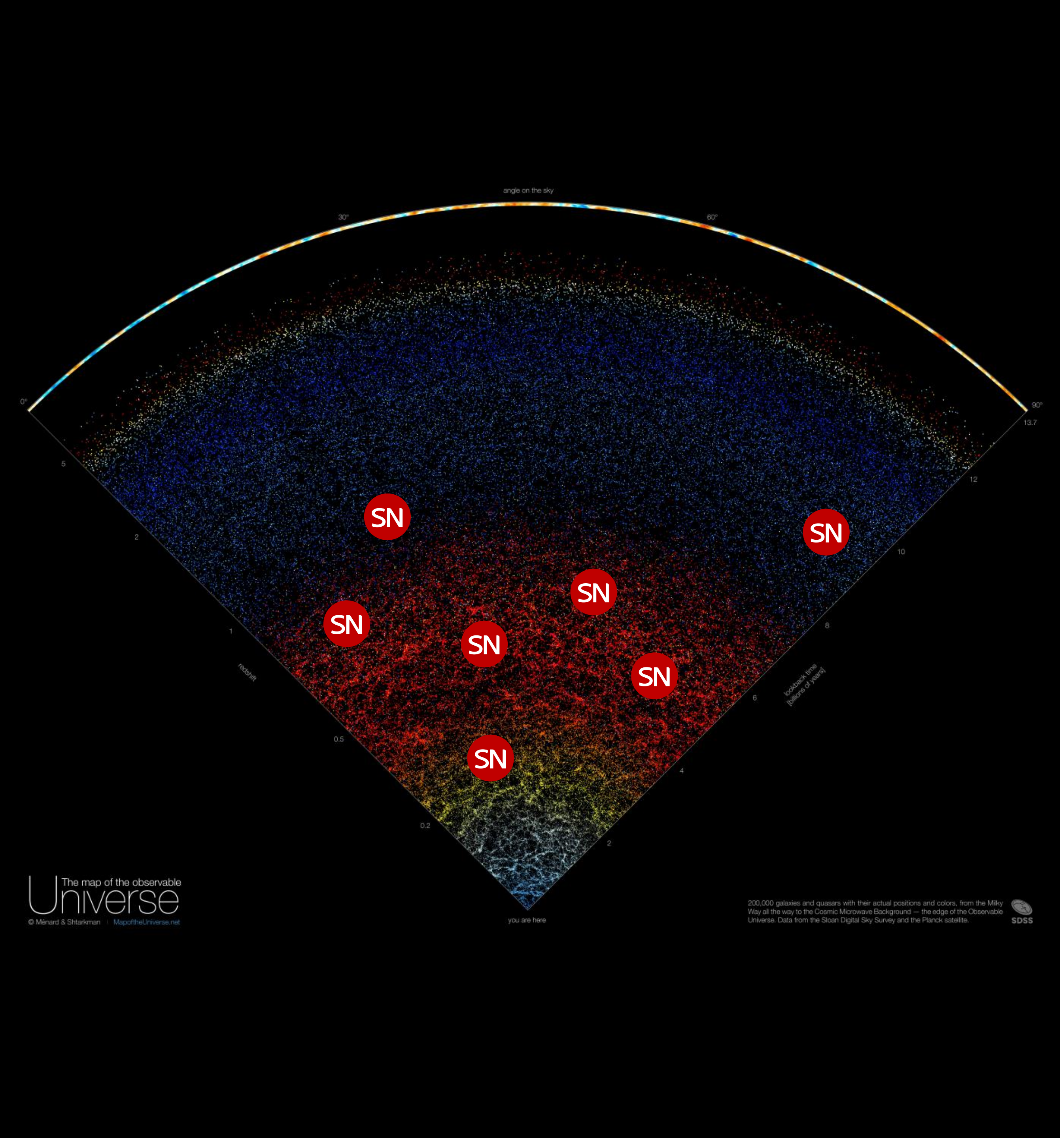
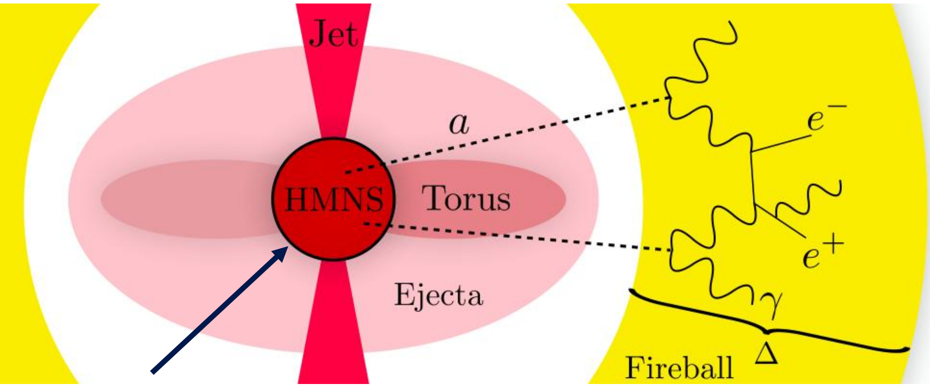


Diffuse γ−ray (All past SNe)

- Axions produced by all past supernovae form the DSAB
- If $\lambda_a \lesssim \mathrm{H}_0^{-1}$, axions can produce a diffuse γ−ray flux observable from Earth
- Axions should not affect the observed diffuse γ−ray flux

Fireball and Low-E SNe



Hypermassive
Metastable
Neutron
Star

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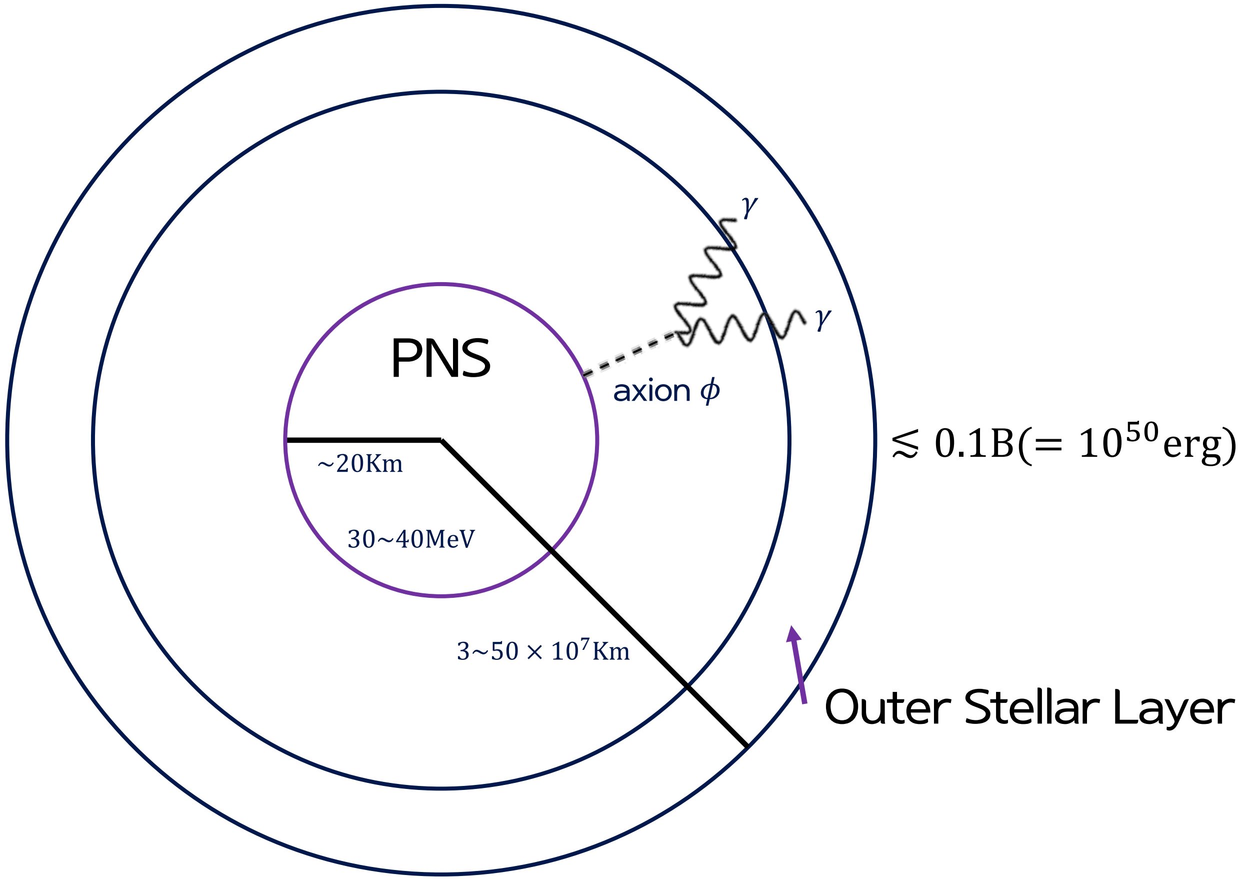


Reference: A. Caputo *et al.* 2022

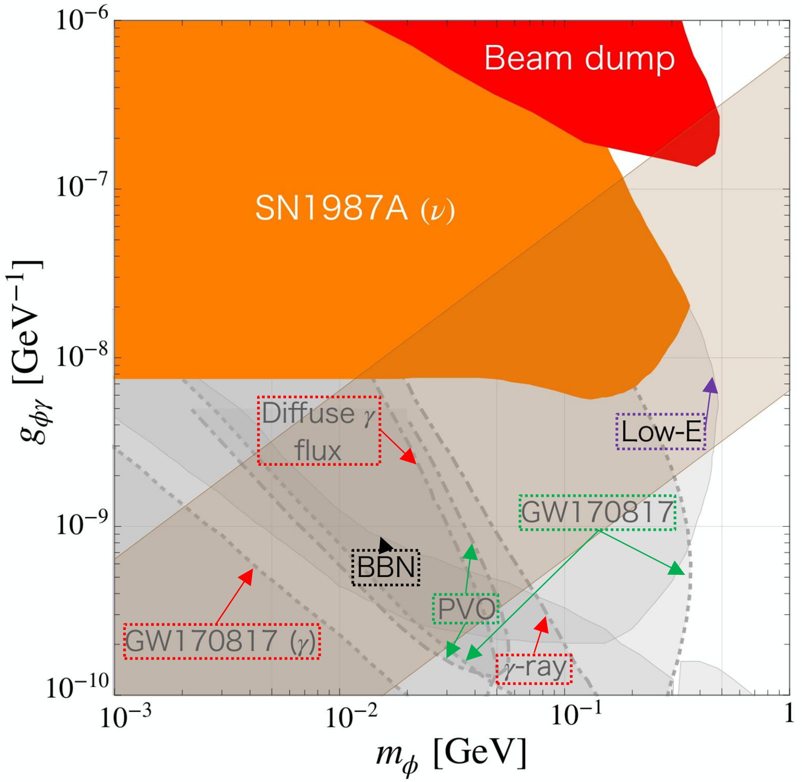
Type I Dark Photon: Invisible Axion Decay

$$\frac{\Gamma_{\phi\to\gamma\gamma}}{\Gamma_{\phi\to e^+e^-}} \sim \frac{10^{-5}}{\kappa_2^2}\left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^2$$ γ−ray signal

$$g_{\phi\gamma'_M} > \frac{2\kappa_2 m_e}{m_\phi f} \simeq \left(\frac{\kappa_2}{\kappa_1}\right) \times 10^{-7}\ \mathrm{GeV}^{-1}$$
$$\to \mathrm{BR}(\phi \to \mathrm{SM}) \gtrsim 10^{-4}\left(\frac{\kappa_2}{0.1}\right)^2\left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{-2}$$ SN explosion and GW170817

$$g_{\phi\gamma'_M} < 10^{-6}\mathrm{GeV}^{-1}\left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{-3/2}$$ Low−E

$$g_{\phi\gamma'_M} > 4 \times 10^{-9}\mathrm{GeV}^{-1}\left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{-1}$$ BBN



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Type I Dark Photon: Dark Fermion

$\Gamma_{\phi\leftrightarrow\gamma'_{\rm M}\gamma'_{\rm M}} > \Gamma_{\phi\leftrightarrow e^+e^-}$ case

$\gamma'_{\rm M}$ decays into ultralight dark fermion χ (below $\rm eV$ scale)

$$\Delta N_{\rm eff} \approx \left(\frac{T_{\rm fo}}{T_{\rm decay}}\right)\left(\frac{m_{\gamma'_{\rm M}}}{T_{\rm fo}}\right)^{5/2} e^{-m_{\gamma'_{\rm M}}/T_{\rm fo}} \sim \mathcal{O}(0.1)$$

assumption: $T_{\rm decay} < T_{\rm fo} \lesssim m_{\gamma'_M}/3$

$m_\phi/15 \lesssim T_{\rm fo} \lesssim m_\phi/5$

$$\mathcal{L} = \epsilon A'_\mu \bar{\chi}\gamma^\mu\chi$$

$$\rightarrow \epsilon < 10^{-9}\left(\frac{m_{\gamma'_{\rm M}}}{10{\rm MeV}}\right)^{1/2}$$

Naturally achievable via kinetic mixing between $\gamma'_{\rm M}$ and hidden $\rm U(1)$ gauge boson