A review of Axion physics

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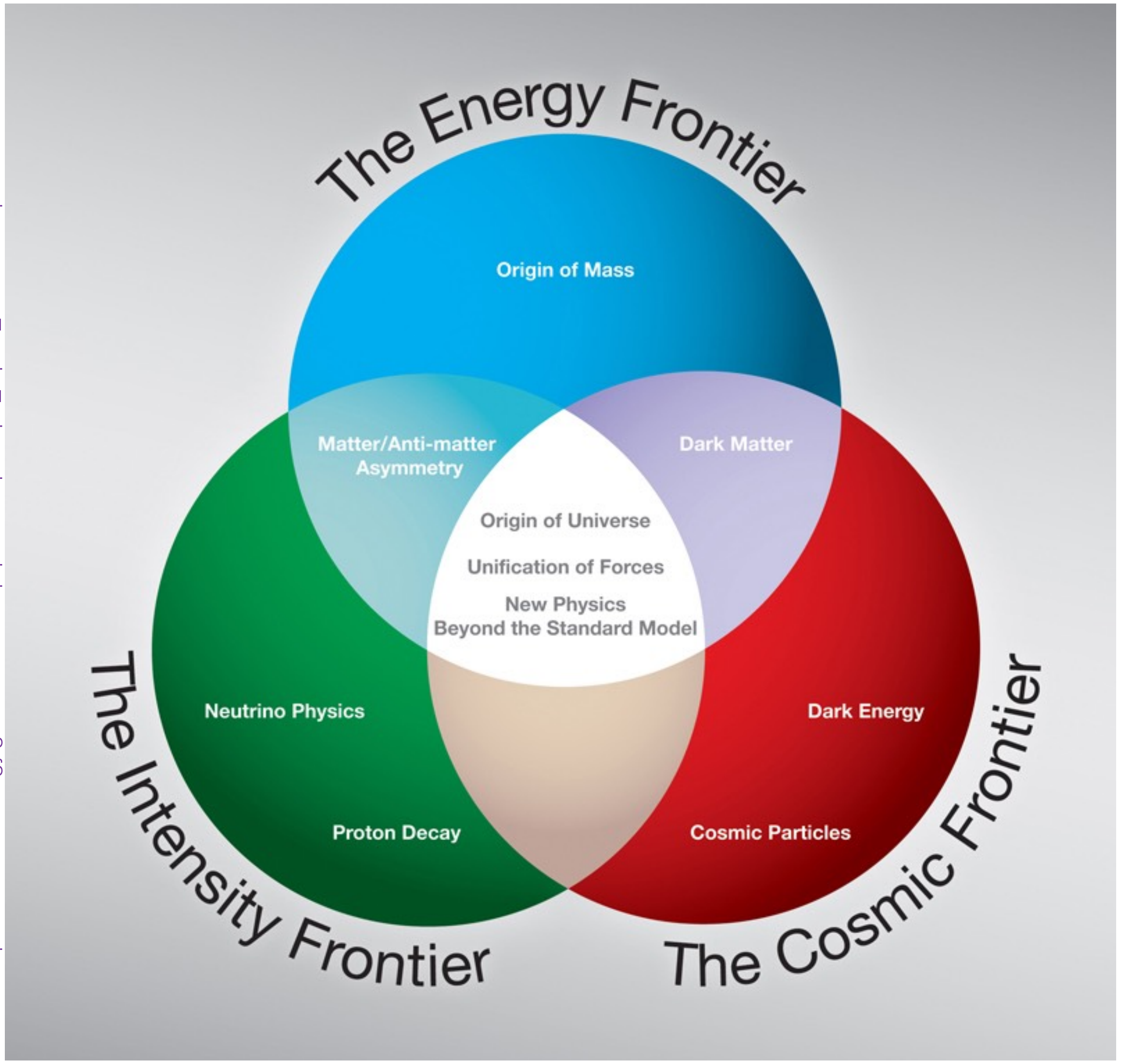
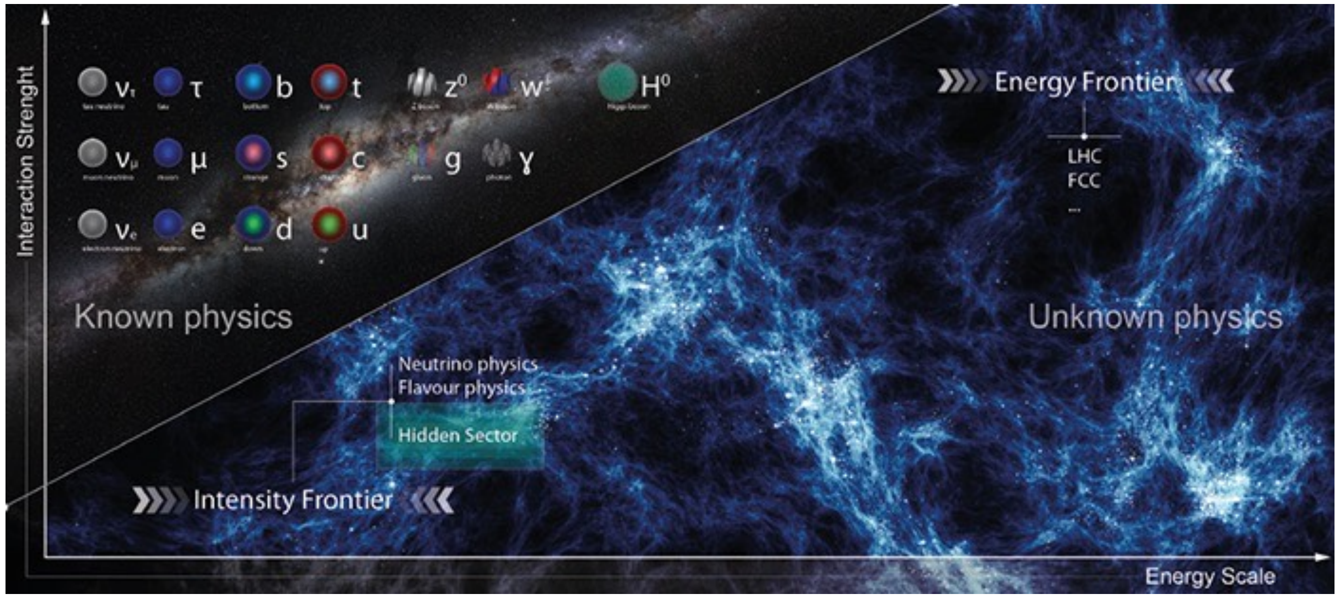
Frontiers of particle physics

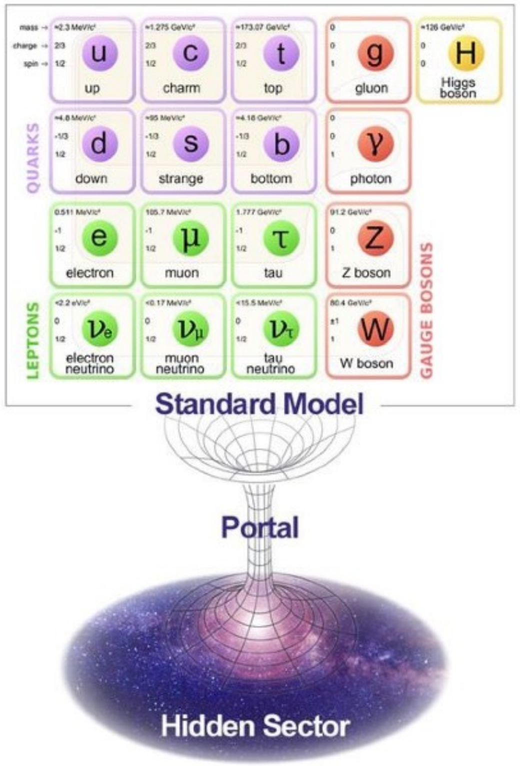


https://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf

- Energy frontier
  - high-energy high-collision rate accelerators (e.g., LHC)
- Intensity frontier
  - medium or low-energy ultra-high-collision rate
- Cosmic frontier
  - universe & astroparticle



Portal physics



01	02	03	04
Higgs portal	**Axion portal**	**Vector portal**	**Neutrino portal**
spin-0 scalar	spin-0 pseudoscalar	spin-1 vector	spin-1/2 fermion
$\lvert S \rvert^2 H^\dagger H$	$(a/f_a)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$ $(\partial_\mu a/2f_a)\, \bar{\psi}\gamma^\mu\gamma^5\psi$	$F_{\mu\nu}X^{\mu\nu}$	$\bar{L}HN$

Outline

01 Strong CP problem: the motivation of axions

02 QCD axion (KSVZ & DFSZ) | Axion-like particles

03 Effective field theory framework on axions

e.g., anomalous coupling to the electromagnetic field ($g_{a\gamma}$)

04 Current statue of searches

- *Experimental*
- *Astrophysical*
- *Cosmological*

Low energy QCD

- The QCD Lagrangian around the confinement scale

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{4} G^{a\mu\nu} G^{a}_{\mu\nu} + i\bar{q}\gamma^{\mu} D_{\mu} q - \frac{g_s^2}{32\pi^2} \theta_{\mathrm{QCD}} G^{a\mu\nu} \tilde{G}^{a}_{\mu\nu} - \left(\bar{q}_L M_q q_R + \mathrm{h.c.}\right)$$

$$q_{L,R} = P_{L,R} \left(u, d, s\right)^{\mathrm{T}}, \ M_q = \mathrm{diag}\left[m_u, m_d, m_s\right]$$

- CP violation in the strong interactions

$$\bar{\theta} = \theta_{\mathrm{QCD}} + \arg \mathrm{Det}\, M_q$$

Naturally $\mathcal{O}(1)$?

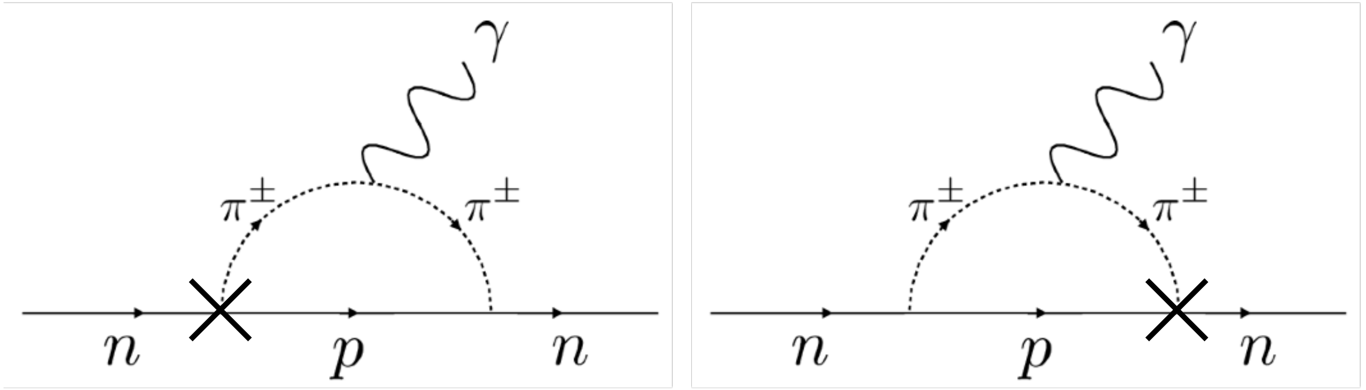
Strong CP problem @ quantum level

- P & T violating pion-nucleon coupling for $\bar{\theta} \ll 1$

$$\mathscr{L}_{\bar{\theta}\pi N} = -\bar{\theta}\frac{c_+\mu}{f_\pi}\pi^a N\sigma^a N, \quad \text{where } \mu = \frac{m_u m_d}{m_u + m_d} \ \& \ c_+ \approx 1.7$$

baryon mass spliting

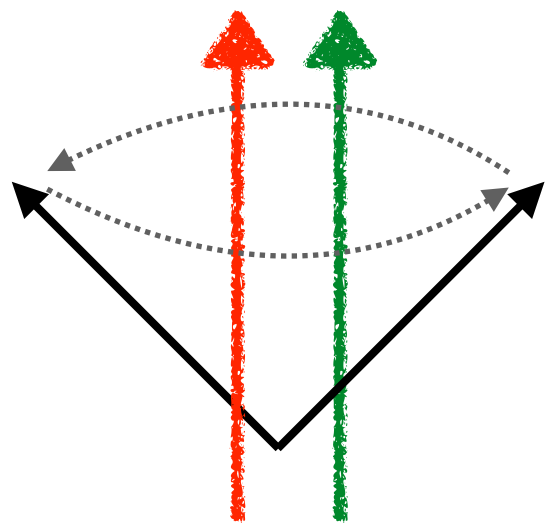
- Electric dipole moment of the neutron



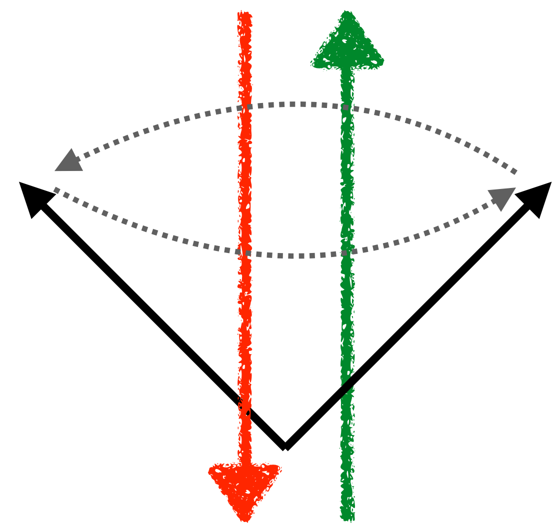
$$d_n F_{\mu\nu}\bar{n}\gamma^{\mu\nu}i\gamma^5 n \quad \text{with} \quad d_n \sim 3\times 10^{-16}\,\bar{\theta}\, e\,\text{cm}$$

Experimental bound on d_n

- Conceptual way to measure d_n via a (Larmor) precession in $\vec{E}$ & $\vec{B}$



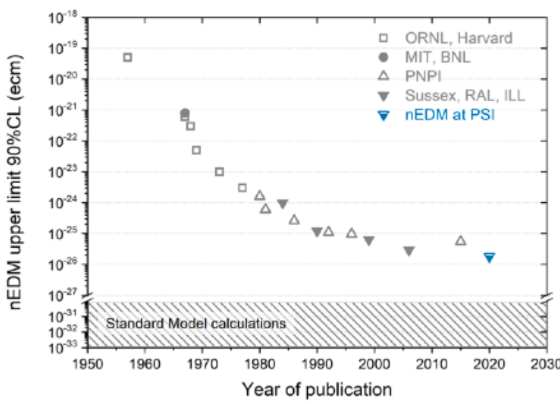
$$\nu = 2\mu B + 2dE$$



$$\nu = 2\mu B - 2dE$$

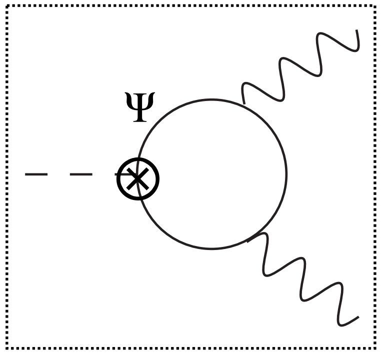
- Bound on electric dipole moment of the neutron

$$\boxed{d_n \sim 3 \times 10^{-16}\,\bar{\theta}\, e\,\text{cm} \leq 10^{-26} e\,\text{cm} \qquad ☞ \qquad \bar{\theta} < 10^{-10}}$$



[Wikipedia]

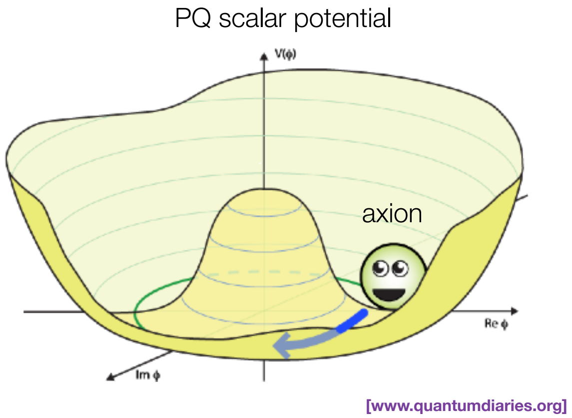
Axion



- Solution for the strong CP problem
- Global Peccei-Quinn symmetry anomalous to the SM - **PQ fermions**

$$\Psi \to e^{i\alpha\gamma^5/2}\Psi \quad ☞ \quad \frac{g_s^2}{32\pi^2}\alpha G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Spontaneous breaking of the PQ symmetry - **PQ scalar field**



$$V_\varphi = \lambda_\varphi \left(|\varphi|^2 - f_a^2/2 \right) \quad ☞ \quad \varphi \to \left(f_a/\sqrt{2} \right) e^{ia/f_a}$$

- NG boson a, the so-called '*axion*'

$$\mathscr{L}_{\mathrm{PQ}} \supset -y_\Psi \varphi \bar{\Psi}_L \Psi_R + \mathrm{h.c.} \quad ☞ \quad \boxed{\bar{\theta} \to \bar{\theta} + a/f_a}$$

- With the minimum of $V_{\bar{\theta}}$ at $\bar{\theta} + a/f_a = 0$,

"The strong CP problem is solved dynamically"

Axion models & properties

PQ scalar

☞ axion (axial degree)

KSVZ	DFSZ
[J.E. Kim, 1979] [M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, 1980]	[M. Dine, W. Fischler and M. Srednicki, 1980] [A.R. Zhitnitsky, 1980]
Fermion extension of SM	Scalar extension of SM
e.g., heavy PQ colored fermion	e.g., multi Higgs doublets

- Goldstone boson nature ☞ axion mass and coupling $\propto f_a^{-1}$

Axion mass $\simeq 5.7\,\mathrm{meV}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$ **Coupling to SM** $\propto \frac{v_{\mathrm{EW}}}{f_a} \sim \frac{100\,\mathrm{GeV}}{f_a}$

- Axion mass independent of f_a (but still light), if there is an explicit breaking of PQ symmetry

"Axion-like particles"

Effective axion couplings

- In the non-linearly realized PQ-symmetry basis
  i.e., invariant under the shift $a \to a + \text{constant}$

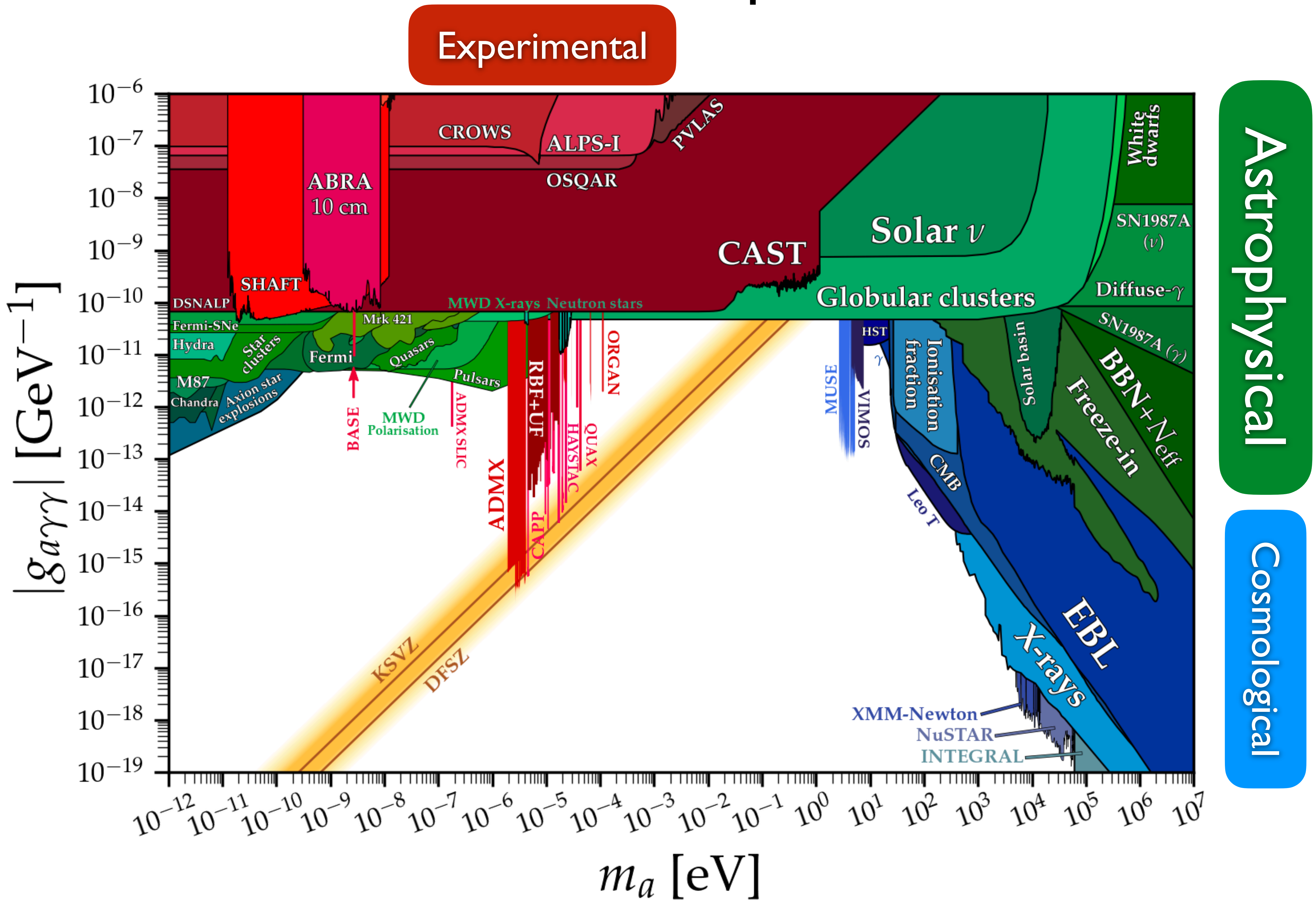
$$\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = - g_{a\gamma} a \vec{E} \cdot \vec{B}$$

$$\underbrace{\frac{\partial_\mu a}{2 f_a} \left(\sum_\psi c_\psi \bar{\psi} \gamma^\mu \psi + \sum_\phi c_\phi \phi^\dagger i \overleftrightarrow{\partial}_\mu \phi \right)}_{\equiv J^\mu_{\rm PQ}} + \frac{a}{f_a} \sum_V c_V \frac{g_V^2}{32\pi^2} F_V^{\mu\nu} \tilde{F}_{V\mu\nu}$$

- Can be converted into the linearly-realized basis through the axionic rotation, which relies on the conservation of PQ-current (i.e., $\partial_\mu J^\mu_{\rm PQ}$)

☞ Effective operators with non-vanishing PQ-charge contribute to axion physics

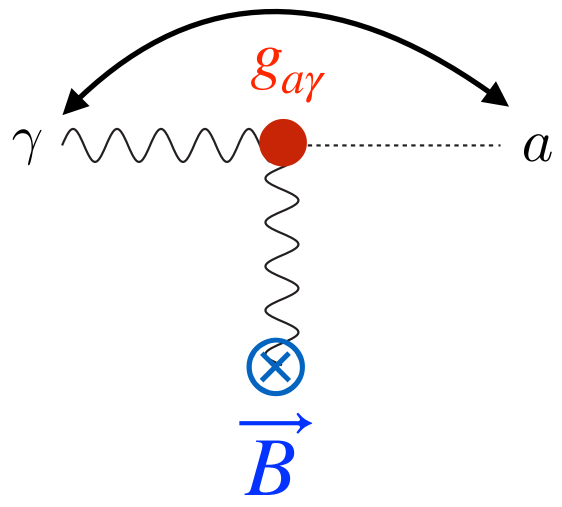
Current status on $\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$



Experimental searches

- Axion-photon conversion in a magnetic background
- Light-Shining-Through-Walls
- Photon polarizations (Dichroism & Birefringence)

Axion-Photon oscillation



"Primakoff" process

- Equation of motion in the presence of a background (transverse) magnetic field $\vec{B}$

$$\mathcal{L}_{a\,\&\,\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= g_{a\gamma}\vec{E}\cdot\vec{B}a$$

$$\partial_\mu F^{\mu\nu} = g_{a\gamma}\tilde{F}^{\mu\nu}\partial_\mu a$$

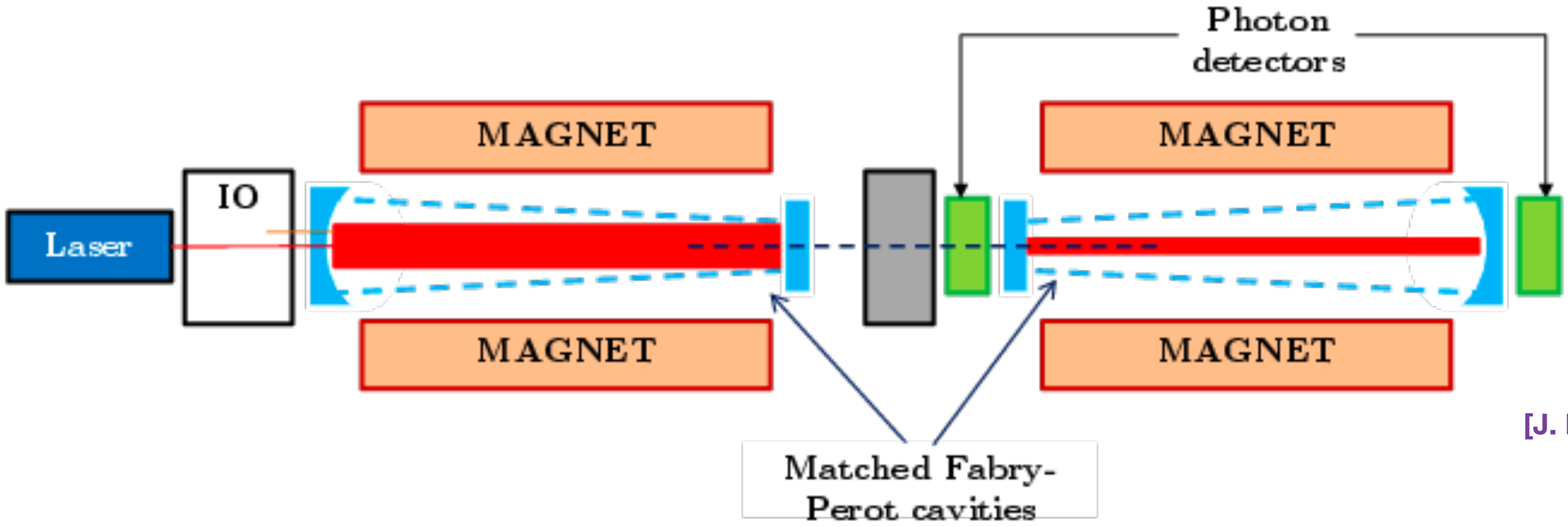
$$\partial_\mu\partial^\mu a = -m_a^2 a - \frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

☞

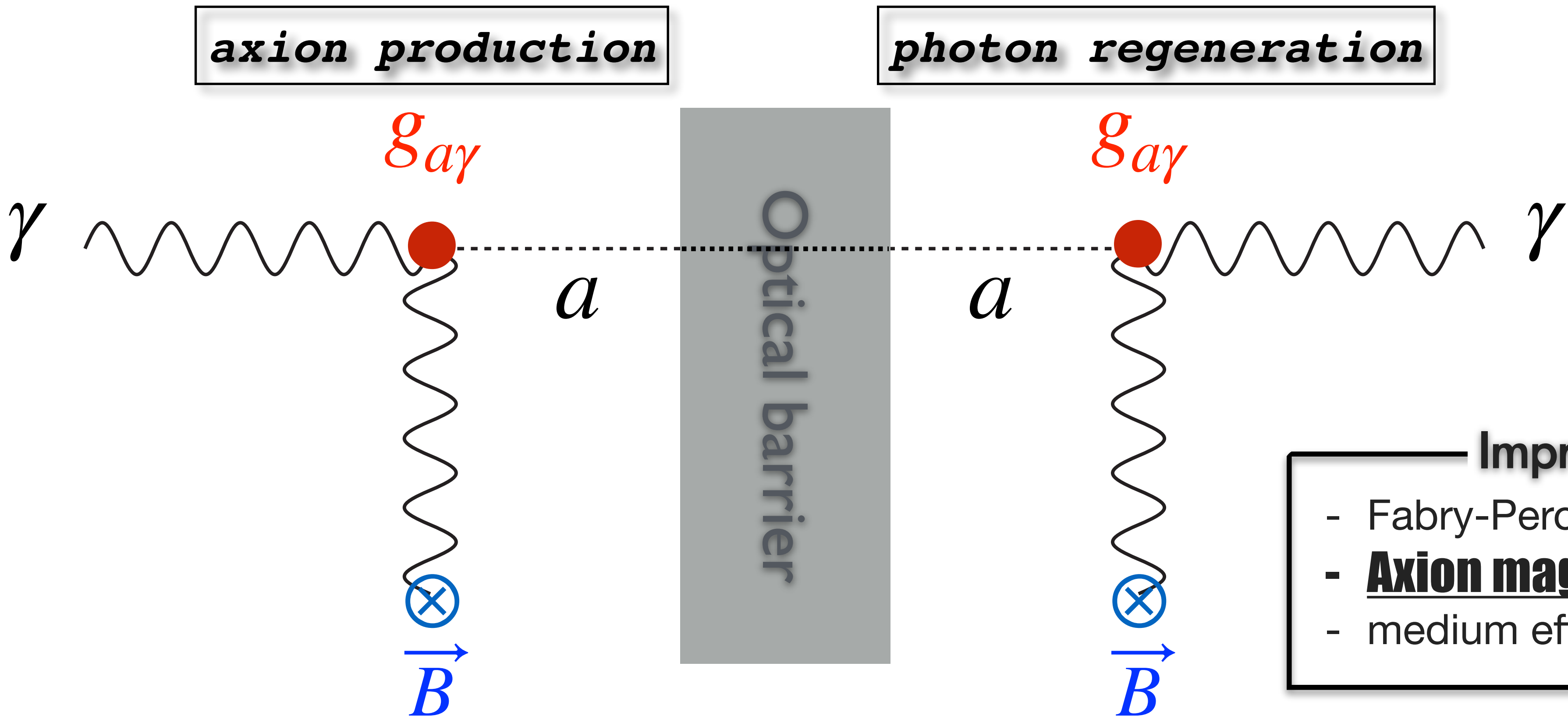
$$\partial_\mu\partial^\mu\vec{A} = g_{a\gamma}\vec{B}\partial_t a$$

$$\partial_\mu\partial^\mu a = -m_a^2 a - g_{a\gamma}\vec{B}\cdot\partial_t\vec{A}$$

Light-Shining-Through-Walls



[J. Redondo et al, 18]

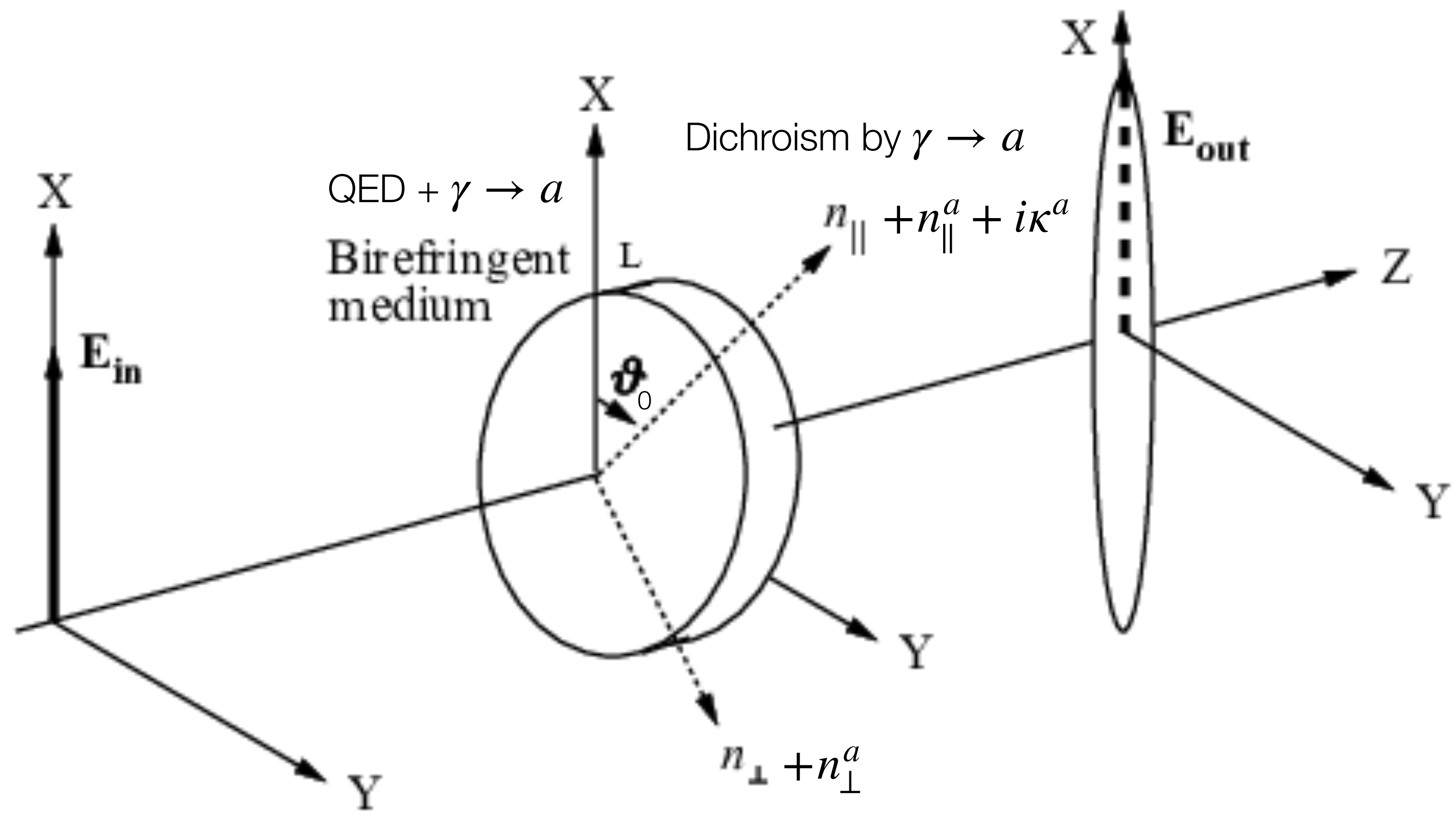


Improvement?

- Fabry-Perot cavities
- **Axion magnetic resonance**
- medium effect, etc

Photon polarization

[PVRAS, arXiv:2005.12913]

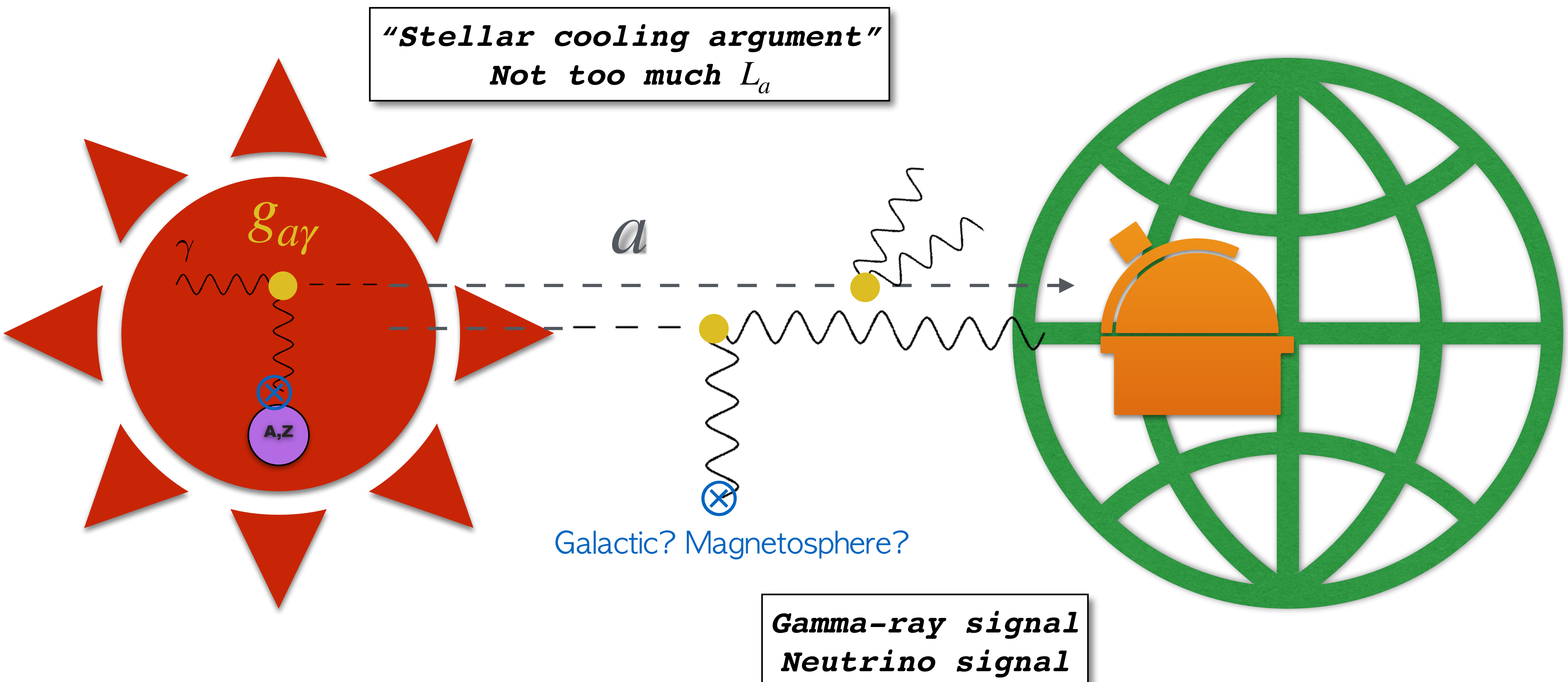


1. Initial linearly polarized light to the $\hat{x}$-direction & propagating to the $\hat{z}$-direction
2. Passing through a magnetic field background
   - **Birefringence: ellipticity of the γ-polarization (phase retardation by QED & $\gamma \to a$)**
   - **Dichroism: rotation of the γ-polarization (depletion by $\gamma \to a$)**

Astrophysical searches

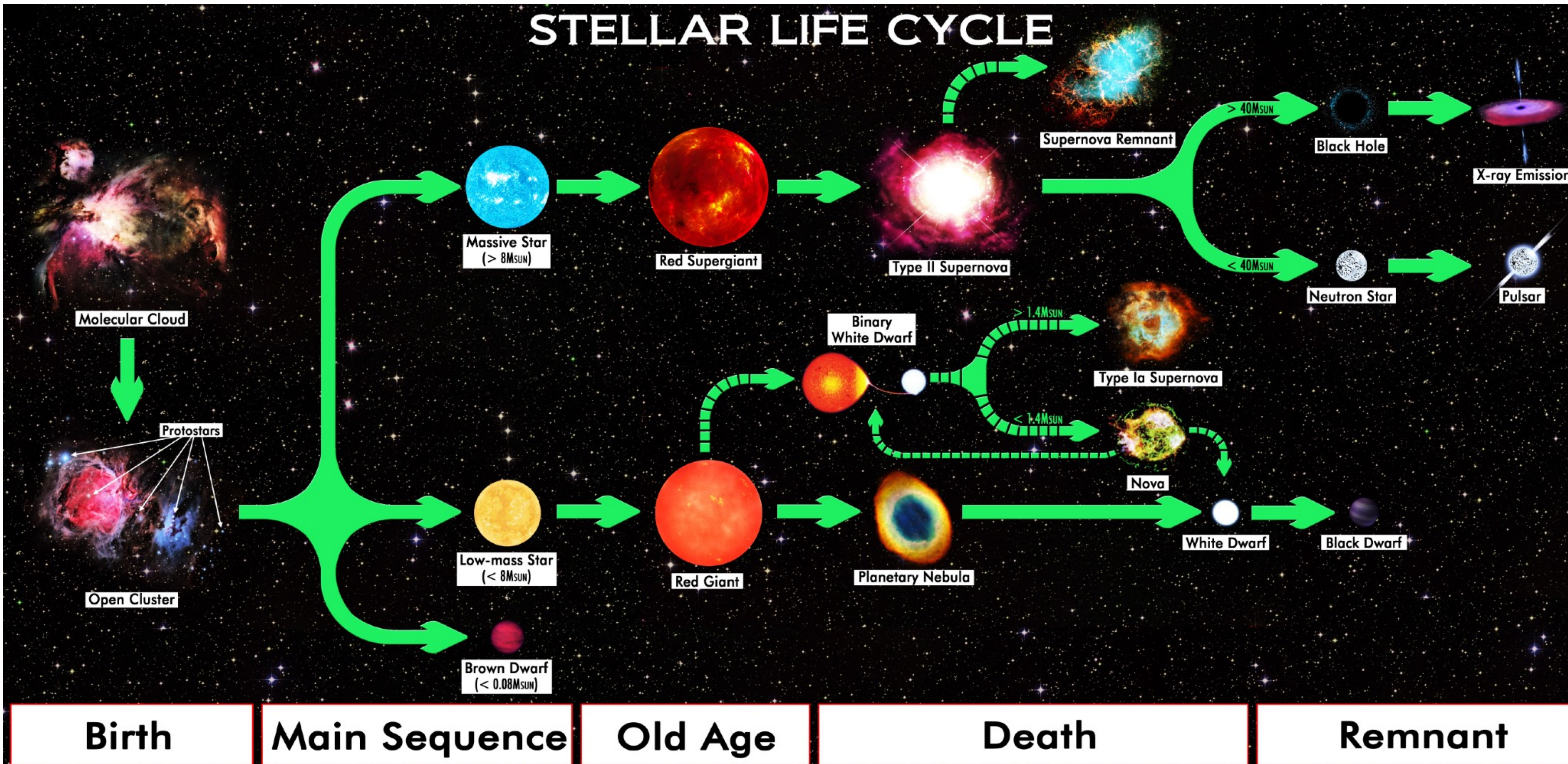
- Axion production: Primakoff process
- Implications:
  1) Stellar cooling argument
  2) γ-ray signal from axion-photon conversion in a magnetic field
  3) γ-ray signal from axion decay into 2γ

Astrophysical searching scheme



Stellar evolution

[image from Wikipedia]

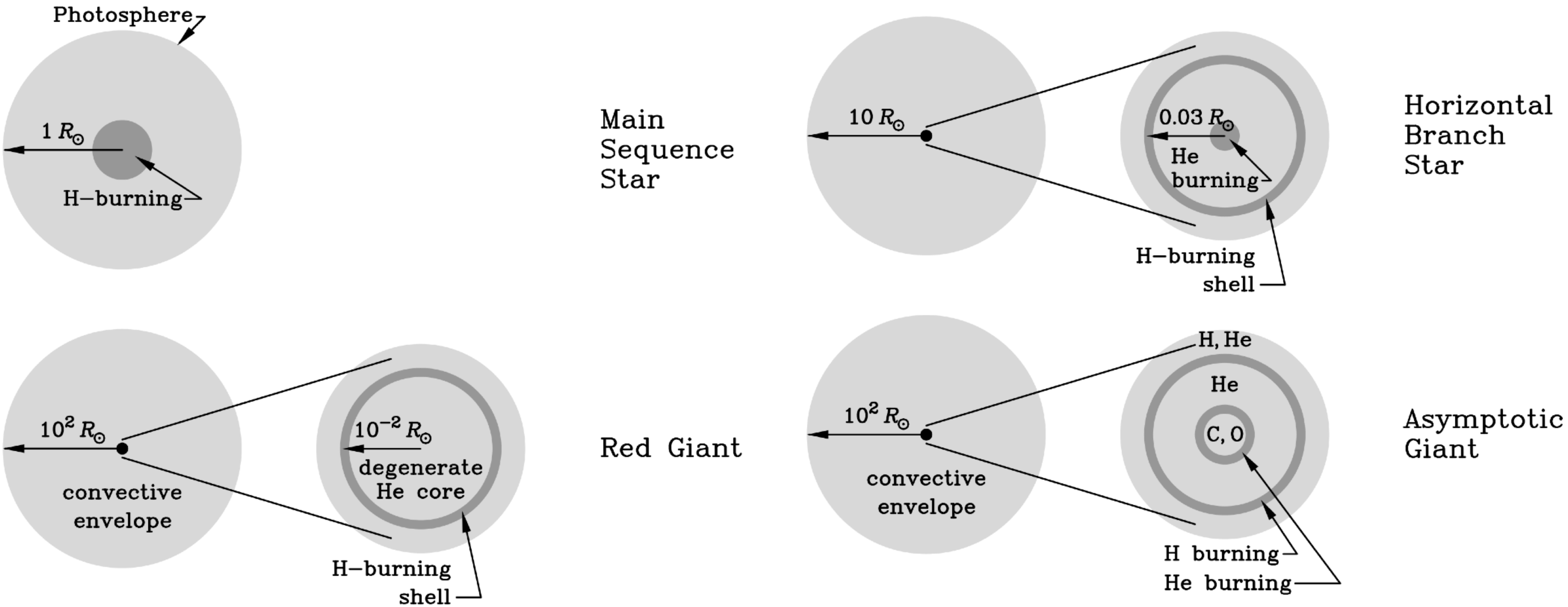


mass

time

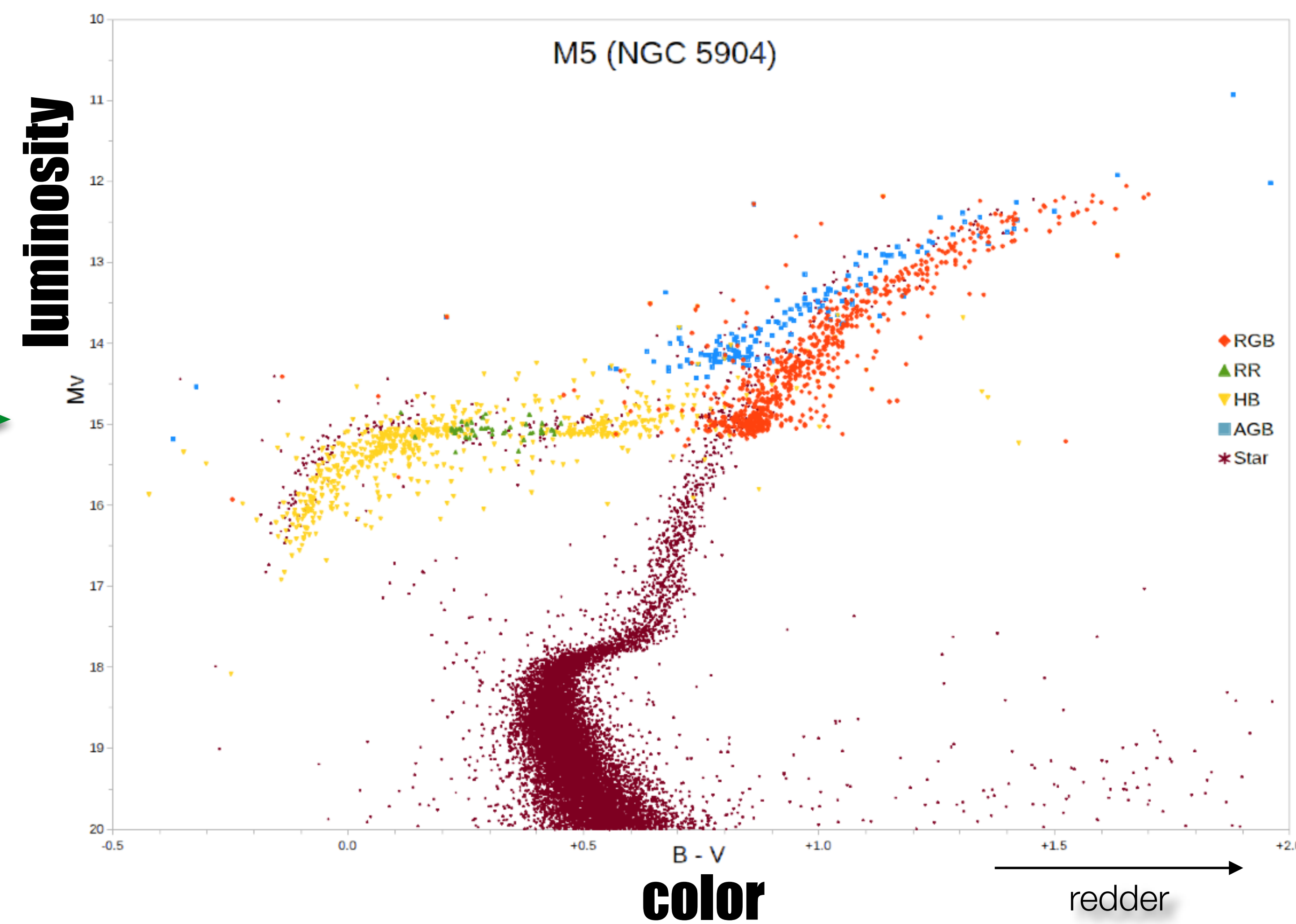
Stellar evolution for low ρ_c

[Raffelt, “Stars as laboratories for Fundamental Physics”]

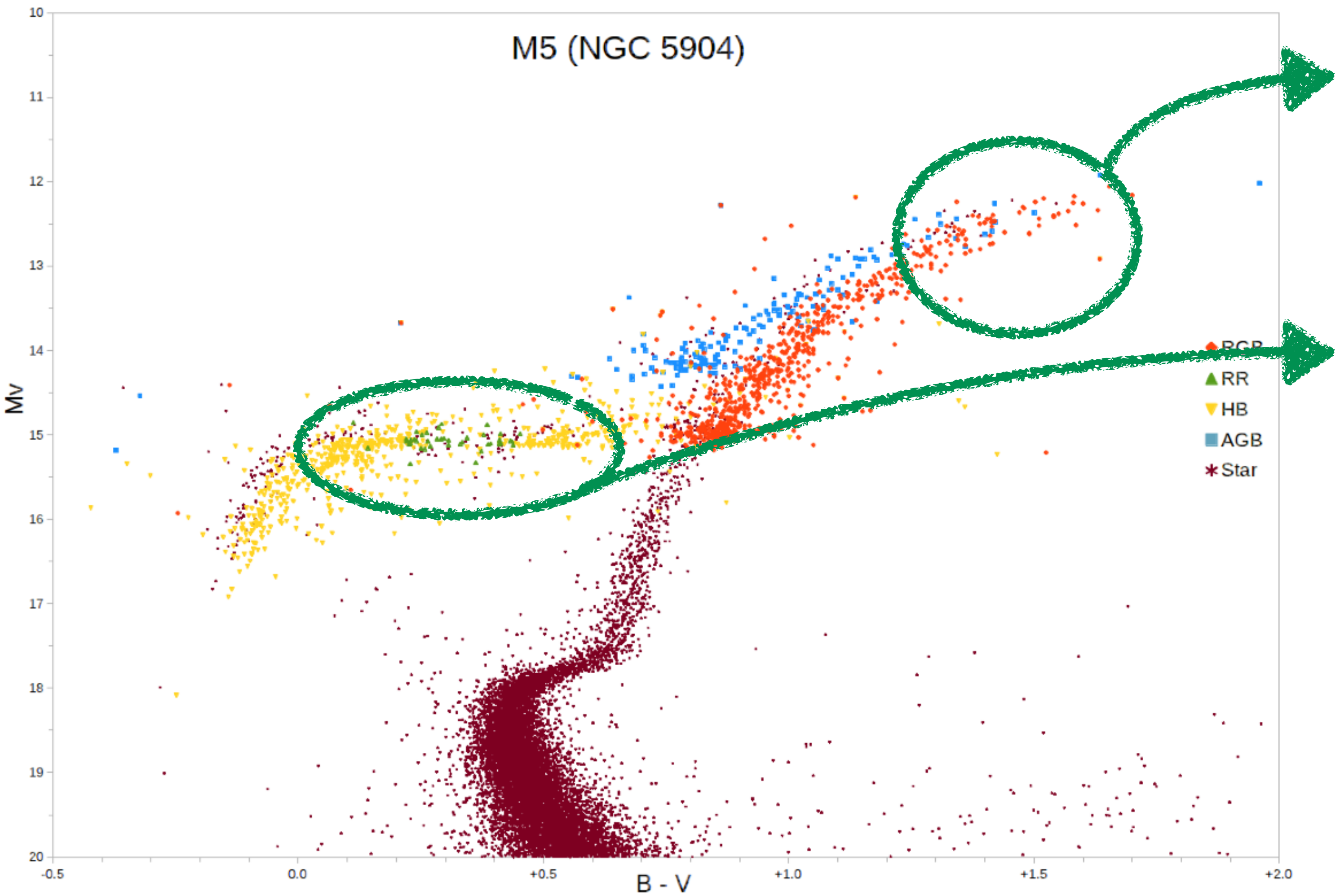


Globular cluster

- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass



Stellar cooling argument on GC



- Delay of helium ignition in red-giant
  - brightness of the tip of a red-giant branch
  - core mass increase at helium ignition
- Lifetime of stars on horizontal-branch
  - duration of helium burning
  - the number ratio of stars on HB vs. RGB
- Dominantly neutrino emission channel

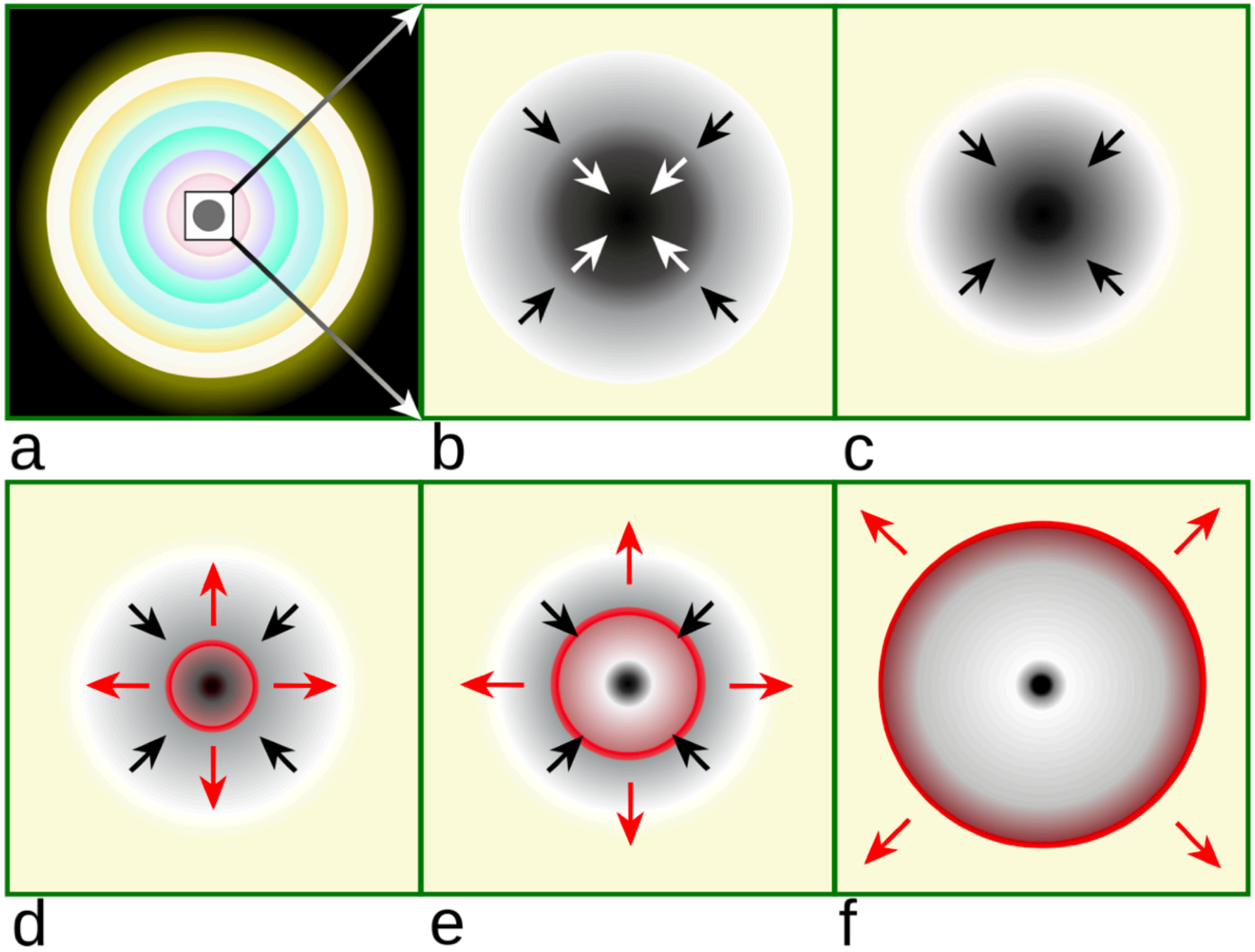
$$\epsilon_x \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$$

"Raffelt's criterion"

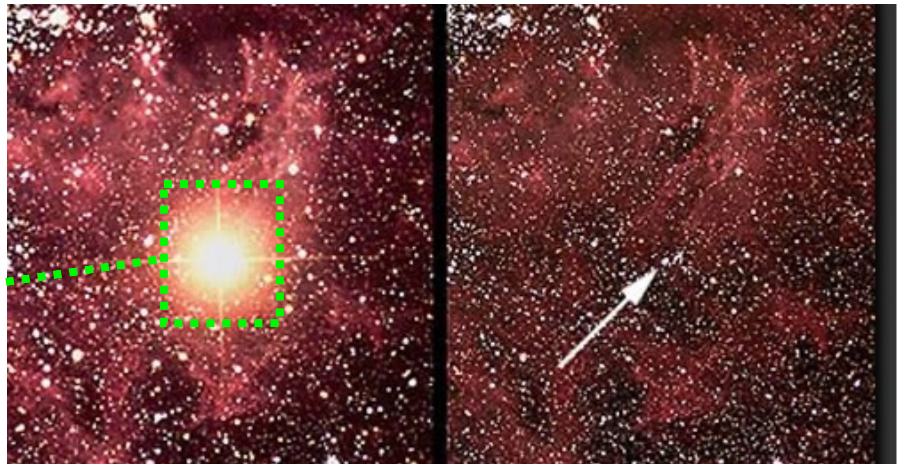
ν VS x

Core-collapse supernovae

[image from Wikipedia]

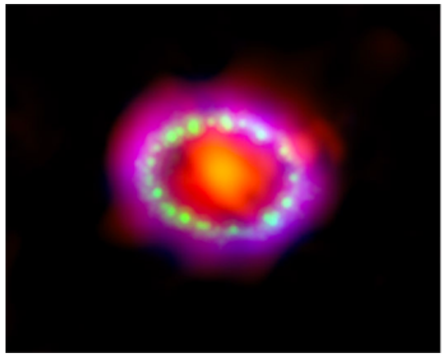


SN1987A

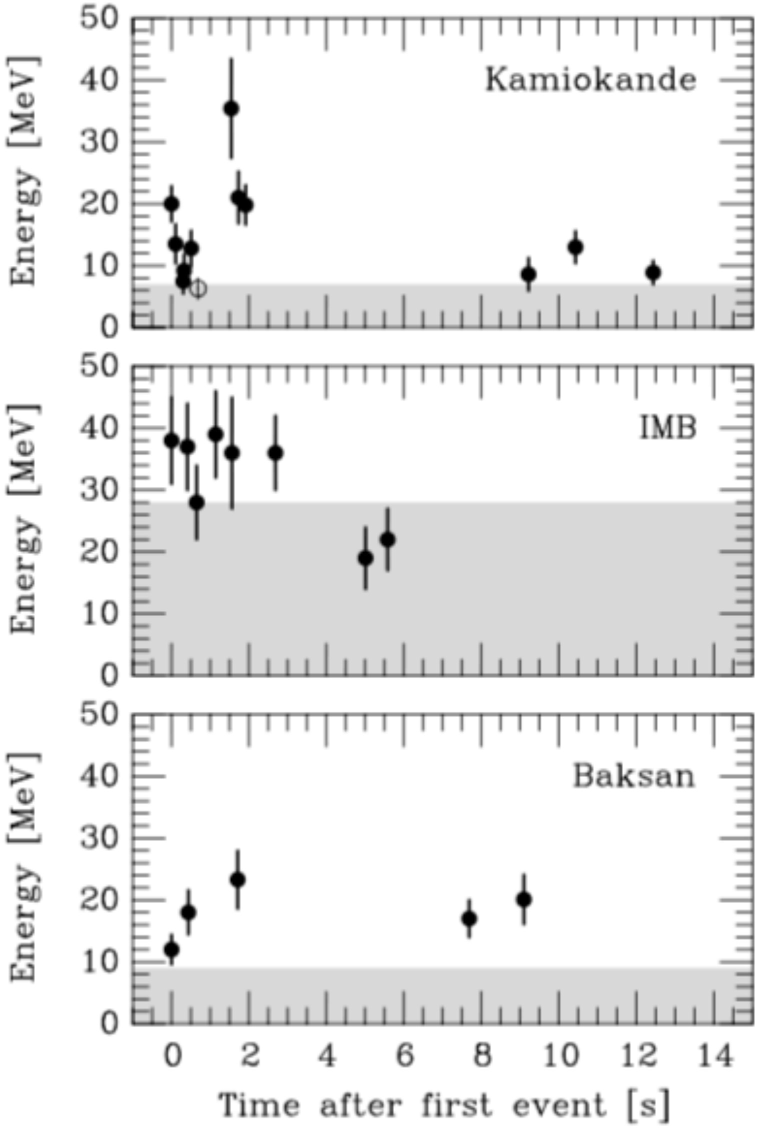


Remnant?

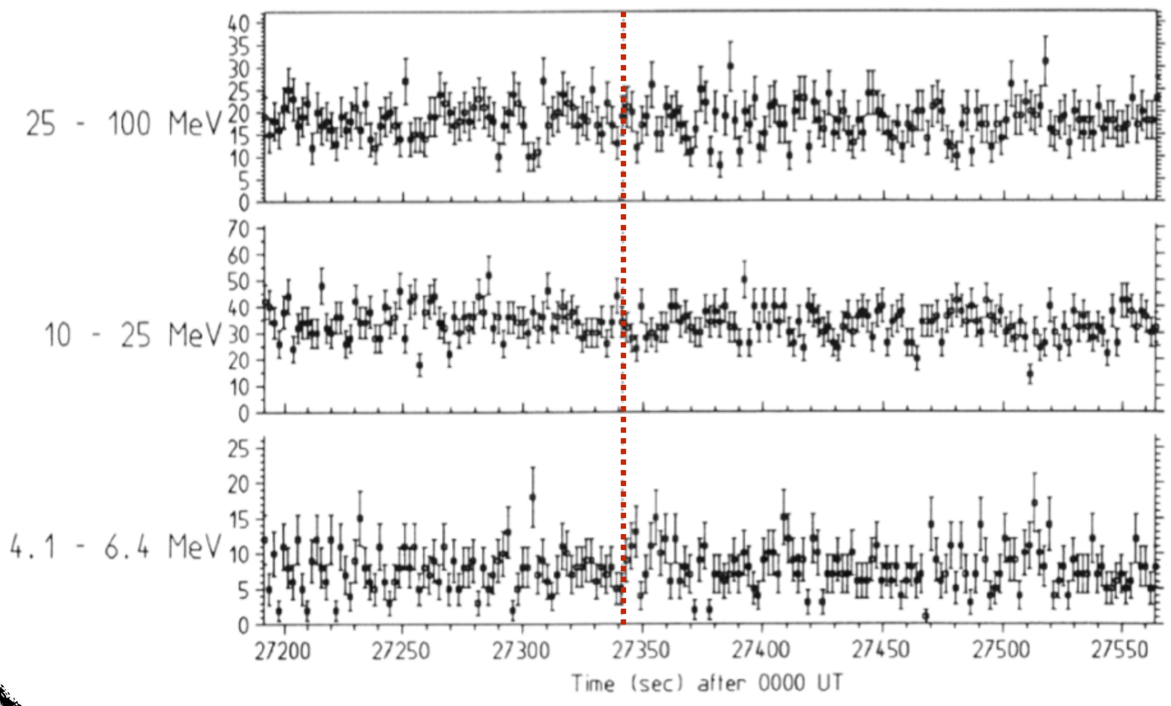
[Chandra, 17]



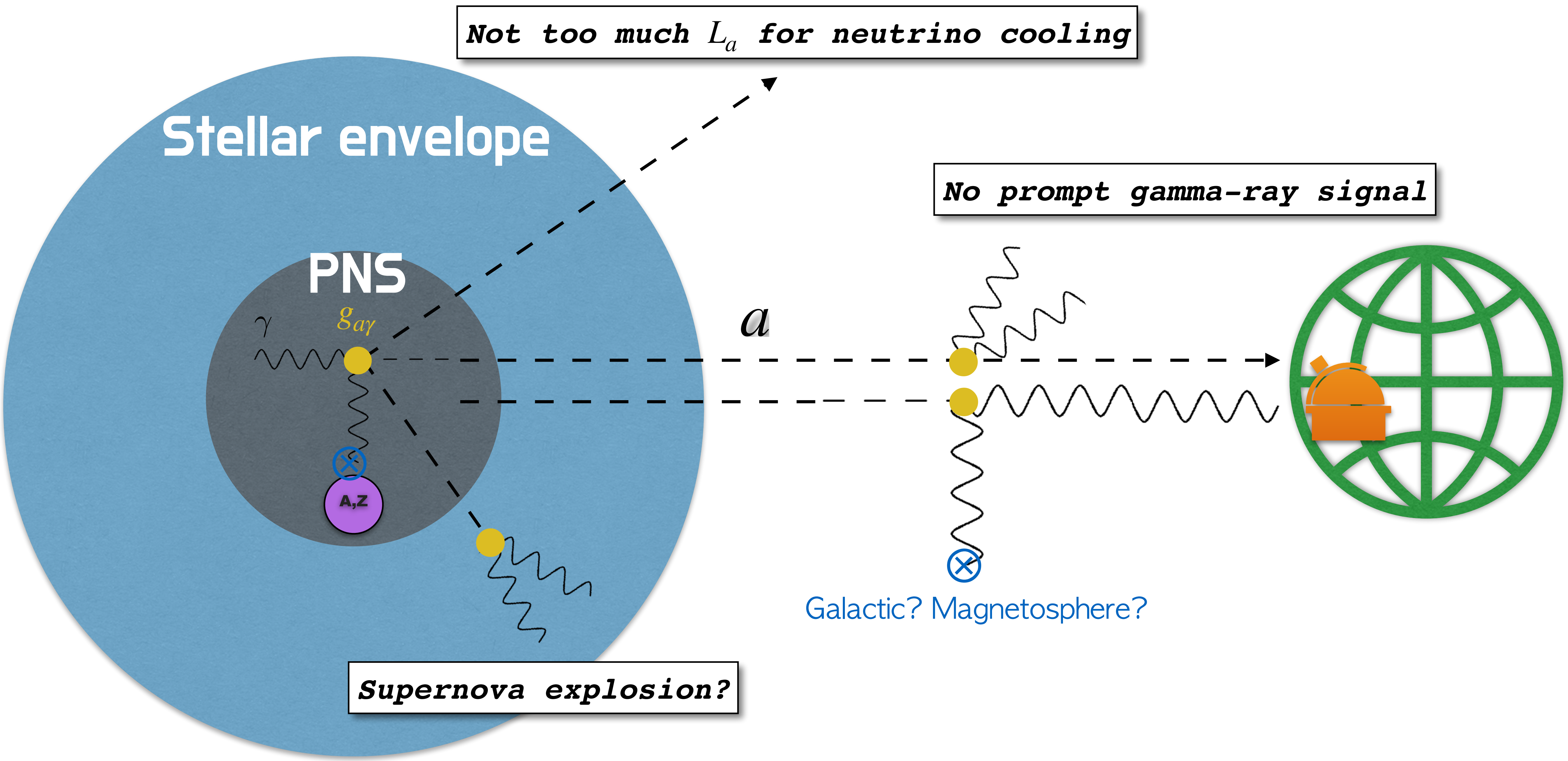
Observed neutrino signal



Lack of prompt gamma-ray signal



Searches on supernova axions

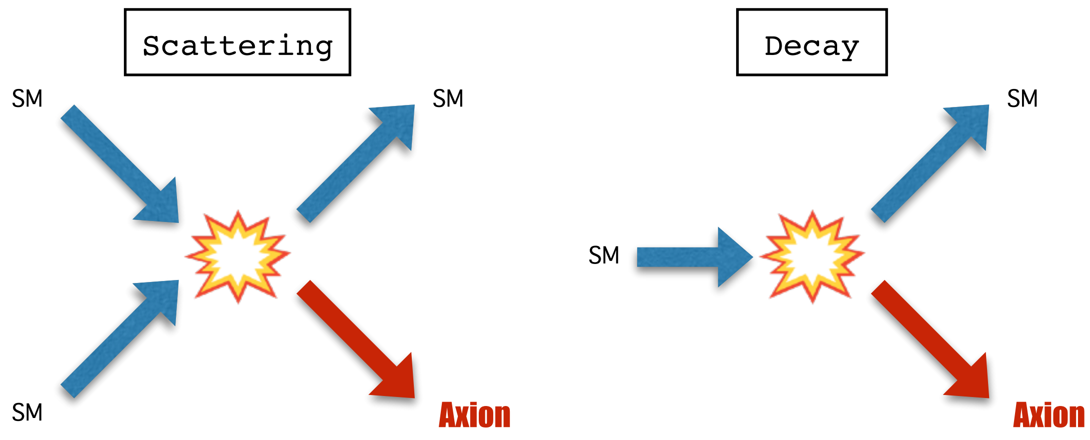


Cosmological searches

- Cosmic axions
  - particles (dark radiation) ☞ CMB spectrum, BBN, etc
  - waves (dark matter) ☞ Microwave cavities, atomic clock, etc

Cosmological axion relic

Cosmic axion background

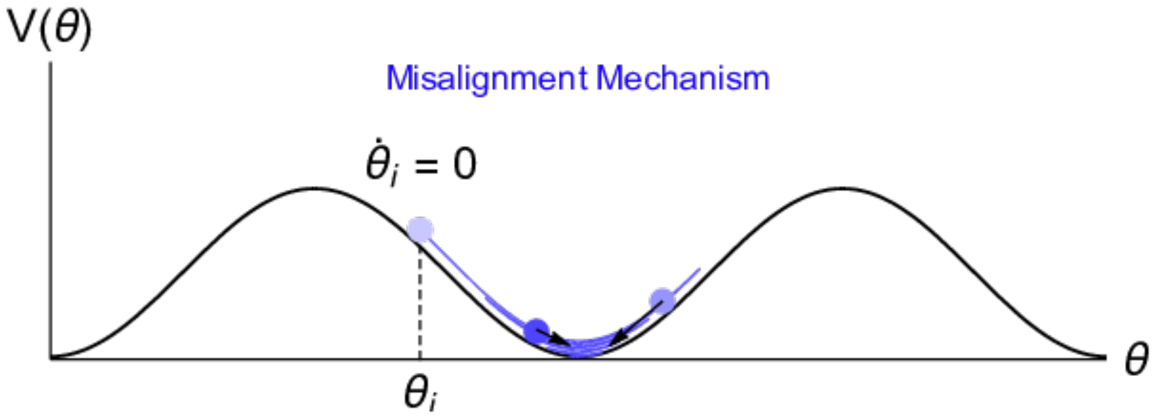


[SY et al, 21][SY et al, 22], etc

- Thermally or non-thermally
- Additional radiation degree
- CMB spectrum, BBN, etc

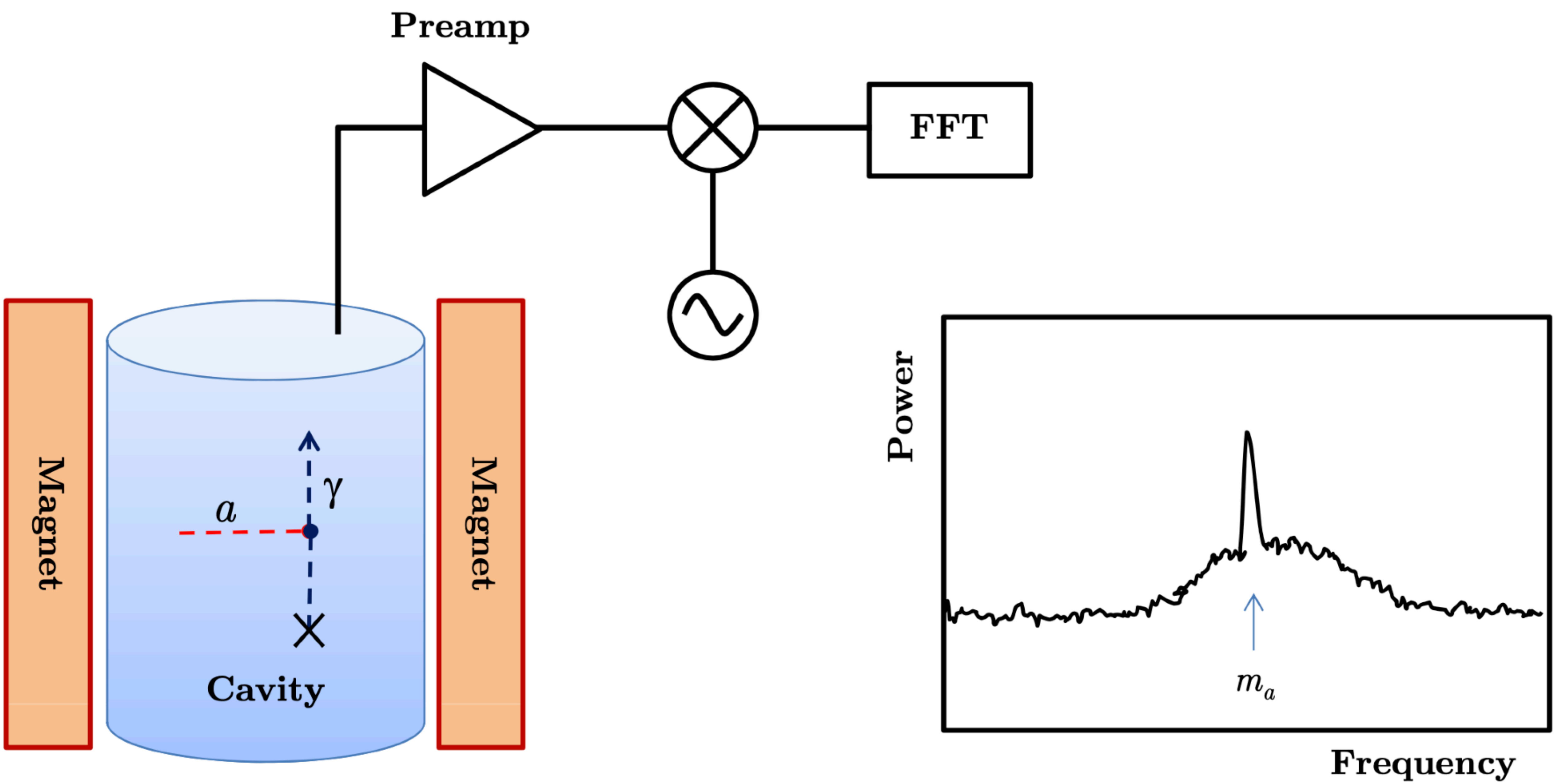
Wave dark matter

[image from R. T. Co et al, 2019]



- Ultra light dark matter
- (coherent) Wave feature
- Microwave cavity, atomic clock, etc

Microwave cavity



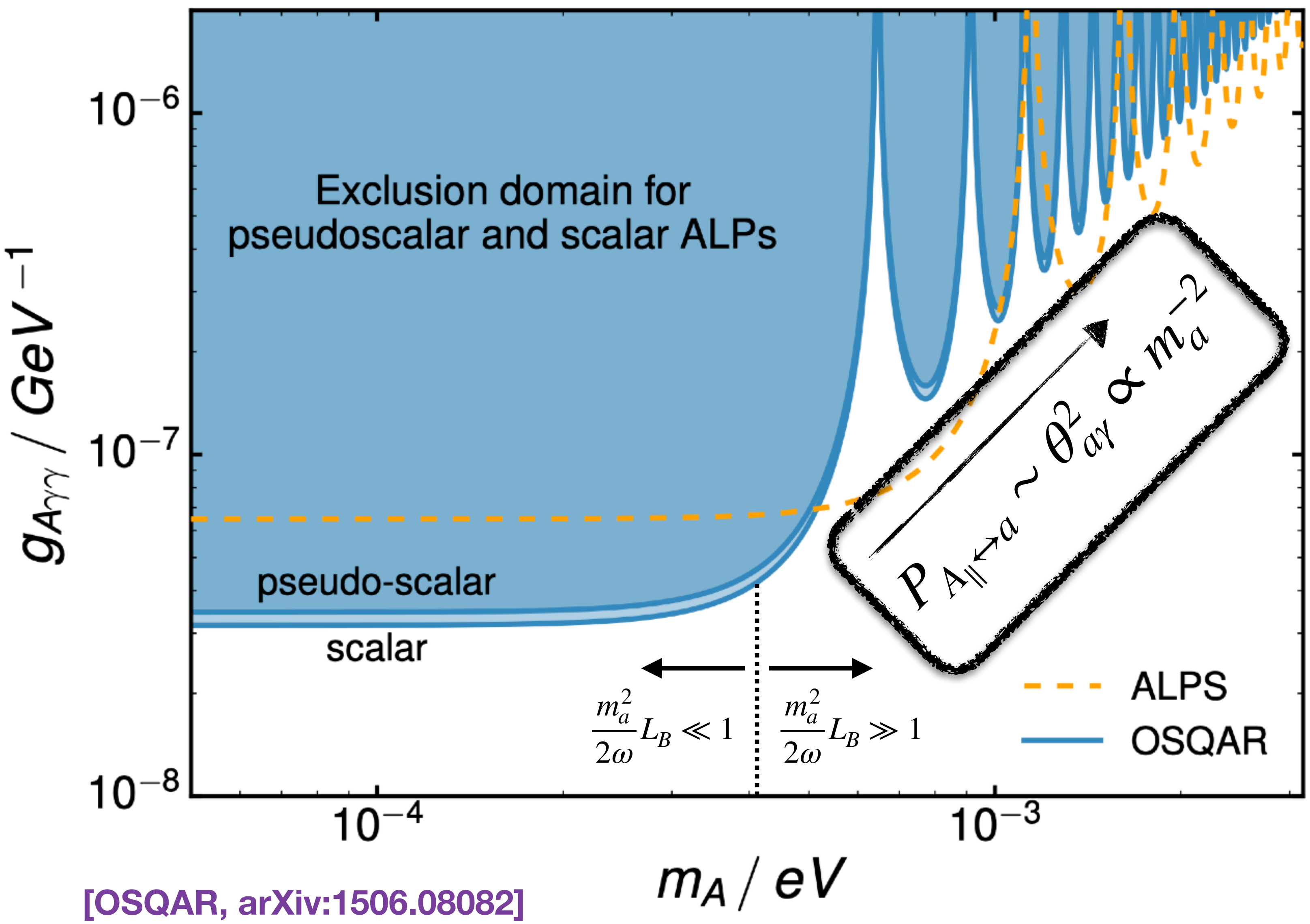
[C. Sun, H. Seong, SY, 23]

Axion magnetic resonance

- Enhancement of axion-photon conversion in a spatially/temporally ***rotating*** magnetic field
- Applications to LSTW & Helioscope

Light-Shining-Through-Walls

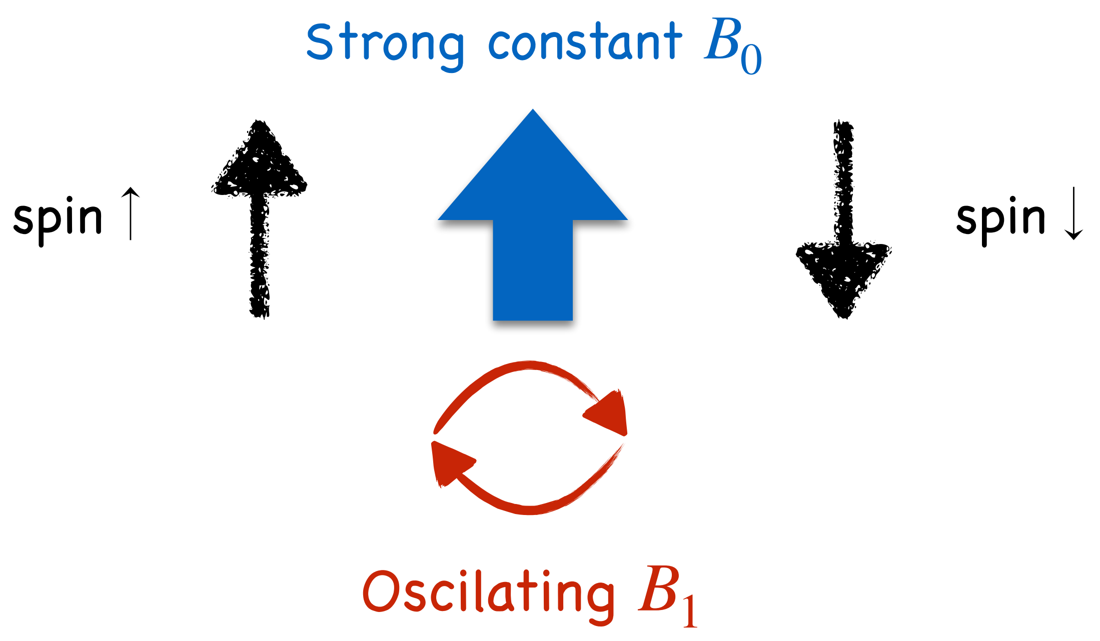
- In the conventional setups, a background magnetic field is constant



[OSQAR, arXiv:1506.08082]

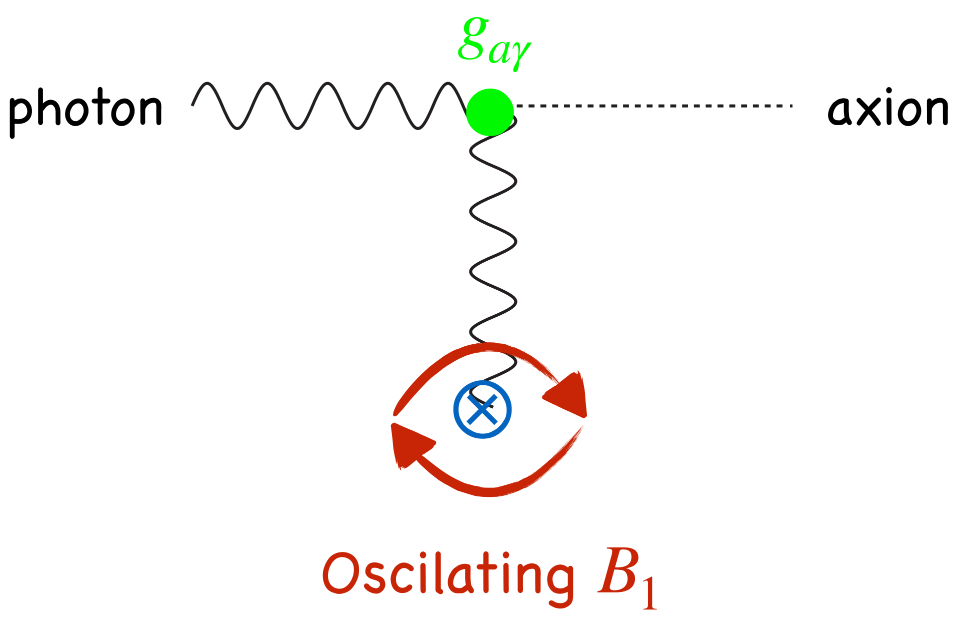
Axion magnetic resonance

Nuclear magnetic resonance



- Two states: spin ↑↓
- Larmor precession frequency $\omega_0 = \mu B_0$
- Transition in oscillating B_1 with $\dot{\theta} = d\hat{B}_1/dt$
- Rabi frequency $\sqrt{(\omega_0 - \dot{\theta})^2 + (\mu B_1)^2}$

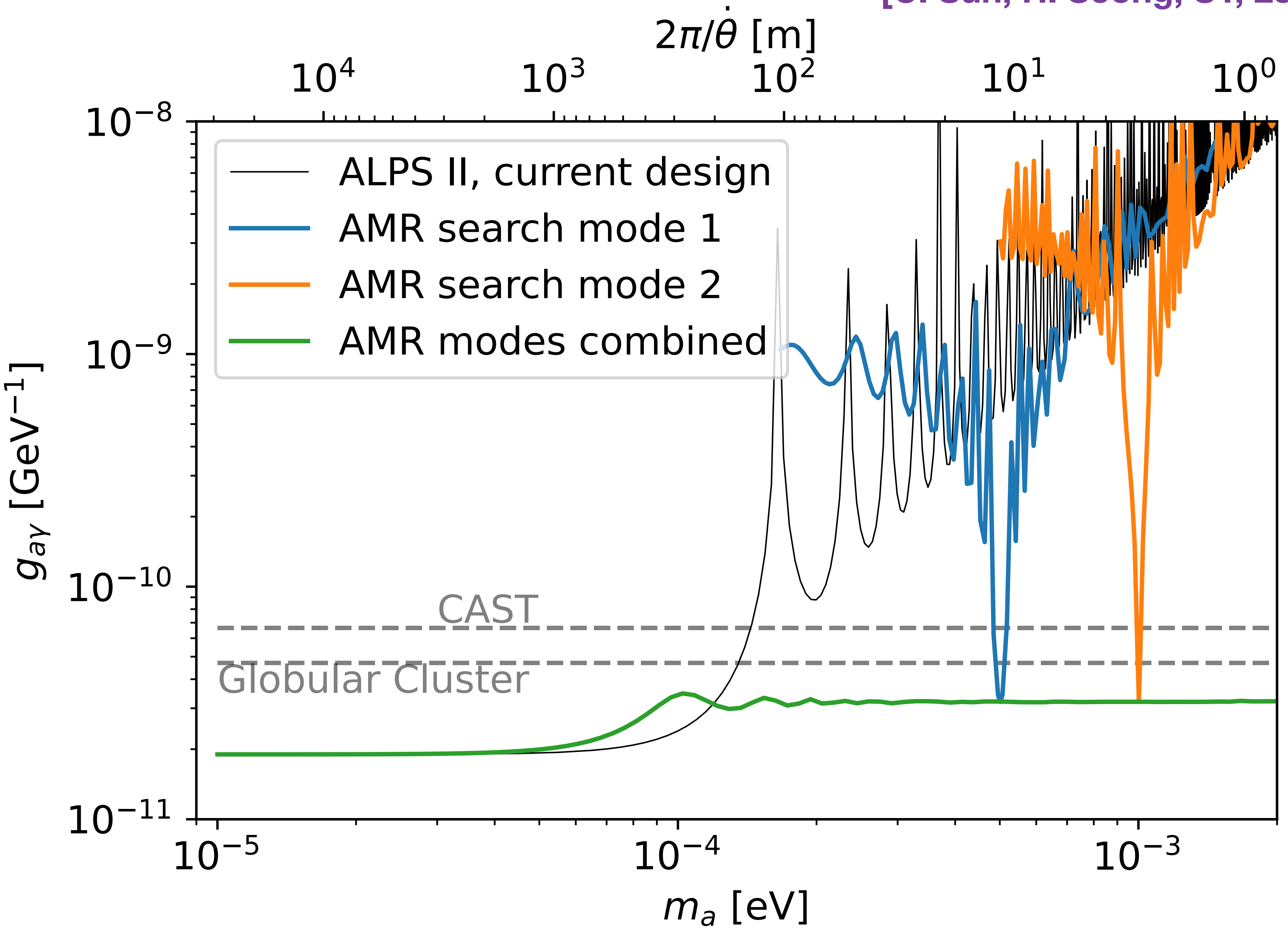
Axion magnetic resonance



- Two state: photon & axion
- Axion momentum transfer $\omega_a = m_a^2/2E$
- Transition in oscillating B_1 with $\dot{\theta} = d\hat{B}_1/dt$
- Rabi frequency $\sqrt{(\omega_a - \dot{\theta})^2 + (g_{a\gamma}B/2)^2}$

Axion magnetic resonance

[C. Sun, H. Seong, SY, 23]



Thank you!

Back up

Effective Chiral Lagrangian

- Quark-antiquark condensation as the chiral breaking

$$\begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix} + \frac{2}{\sqrt{6}}\eta'$$

$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD}\Sigma$ where $\Sigma = e^{i\Phi}$ with Φ the meson-field matrix (octet+singlet)

- Effective theory of mesons **"Chiral perturbation theory"**

$q_L \to L q_L, \quad q_R \to R q_R$

$$M_q \to L M_q R^\dagger, \quad \bar{\theta} \to \bar{\theta} + \arg {\rm Det}\left[L R^\dagger\right], \quad \Sigma \to R\,\Sigma\,L^\dagger$$

- Meson potential at the leading order - based on the symmetry argument

$$-V = \left(\Lambda^4 e^{i\bar{\theta}}\,{\rm Det}\,\Sigma + {\rm h.c.}\right) + \left(\frac{m_\pi^2 f_\pi^2}{2(m_u+m_d)}\,{\rm tr}\left[M_q\,e^{i\Phi}\right] + {\rm h.c.}\right)$$

$$U(1)_A \Rightarrow \eta'$$

The vacuum in the meson space

- Meson vacuum in the presence of $\bar{\theta} \neq 0$, i.e., $\left.\frac{\partial V}{\partial \Phi}\right|_{\bar{\theta}} = 0$

$$\langle \Phi \rangle = \mathrm{diag}\ \left[\phi_u, \phi_d, \phi_s\right] \quad \Rightarrow \quad -V = \Lambda^4 \cos\left(\sum \phi_q + \bar{\theta}\right) + \frac{m_\pi^2 f_\pi^2}{m_u + m_d} \sum m_q \cos \phi_q$$

- In the limit of $m_{u,d} \ll m_s \ll \Lambda_{\rm QCD}$,

i) $\bar{\theta} + \sum \phi_q \approx 0$, ii) $m_u \sin \phi_u = m_d \sin \phi_d = m_s \sin \phi_s$

$$\sin \phi_u \simeq -\frac{m_d \sin \bar{\theta}}{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos \bar{\theta}}}, \quad \sin \phi_d \simeq -\frac{m_u \sin \bar{\theta}}{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos \bar{\theta}}}, \quad \sin \phi_s \simeq -\frac{m_u m_d \sin \bar{\theta}}{m_s \sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos \bar{\theta}}}$$

if $\bar{\theta} \ll 1$

☞ $$\langle \Phi \rangle = -\frac{M_q^{-1}}{\mathrm{tr}\, M_q^{-1}} \bar{\theta}$$

The potential of $\bar{\theta}$ (leading to axion potential)

$$-V = \Lambda^4 \cos\left(\sum \phi_q + \bar{\theta}\right) + \frac{m_\pi^2 f_\pi^2}{m_u + m_d} \sum m_q \cos\phi_q$$

$$\sin\phi_u \simeq -\frac{m_d \sin\bar{\theta}}{\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos\bar{\theta}}}, \quad \sin\phi_d \simeq -\frac{m_u \sin\bar{\theta}}{\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos\bar{\theta}}}, \quad \sin\phi_s \simeq -\frac{m_u m_d \sin\bar{\theta}}{m_s\sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos\bar{\theta}}}$$

$$\Rightarrow \quad \boxed{V_{\bar{\theta}} = -f_\pi^2 m_\pi^2 \sqrt{\frac{m_u^2 + m_d^2 + 2m_u m_d \cos\bar{\theta}}{\left(m_u + m_d\right)^2}}}$$

Stellar object

> “ **Star**
>
> From Wikipedia, the free encyclopedia
>
> *This article is about the astronomical object. For other uses, see Star (disambiguation).*
>
> A **star** is an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity. ”

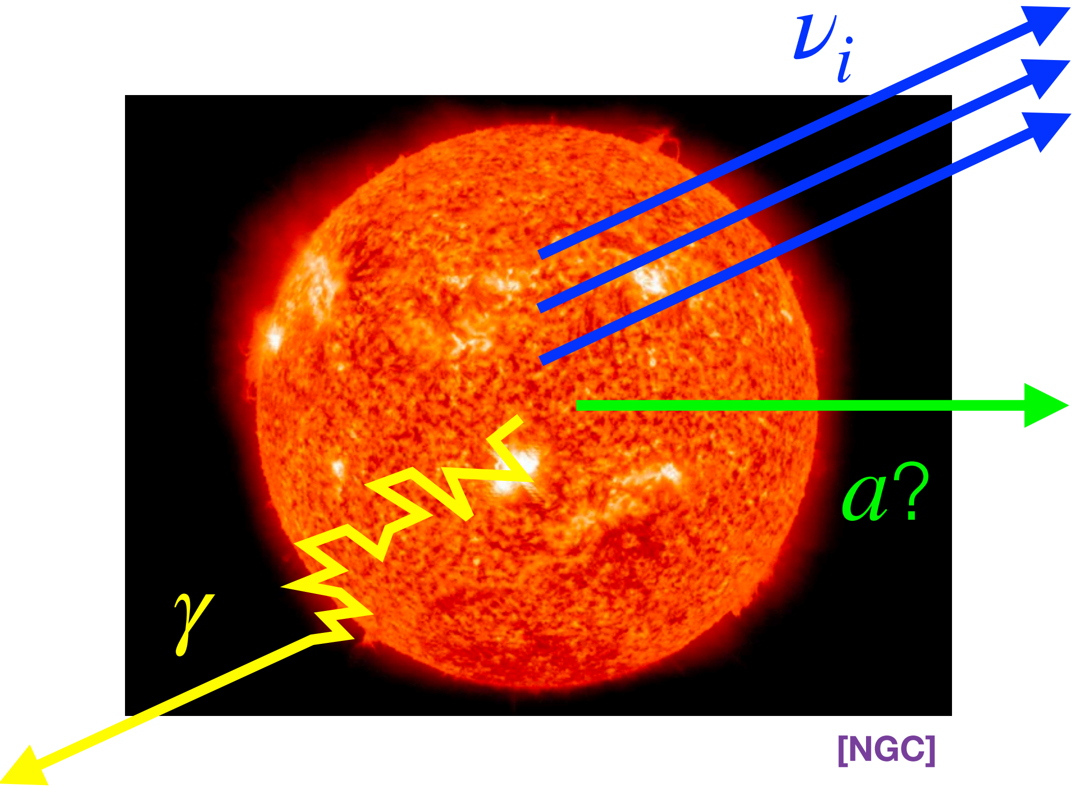
- can be used as laboratories to probe fundamental interactions.
  - observed photon or neutrino signal

    e.g. γ-ray spectral modulation which can be explained by axion-photon oscillations

  - Stellar evolution

    extra energy leakage could change the evolutionary path
    which fits well to the standard scenario

Stellar argument on Sun



- Standard solar model calibrated to match the present-day solar radius & luminosity

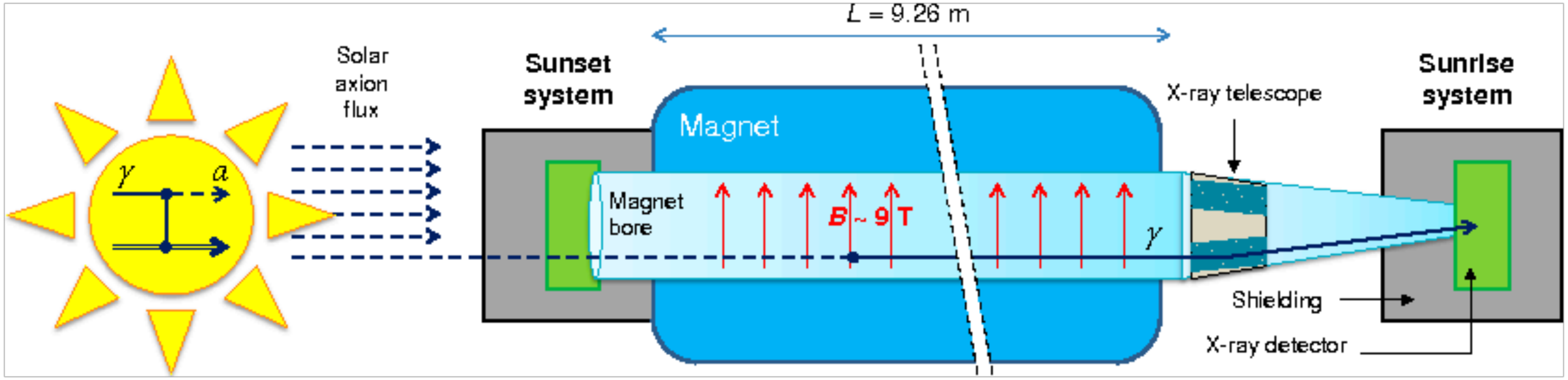
$$R_\odot = 6.9598 \times 10^{10}\,\mathrm{cm} \qquad L_\odot = 3.8418 \times 10^{33}\,\mathrm{erg\,s^{-1}}$$

- Observables:
  1) Helioseismology (sound speed, surface helium)
  2) Solar neutrino fluxes $\Phi\left({}^8\mathrm{B}\right)$ and $\Phi\left({}^7\mathrm{Be}\right)$

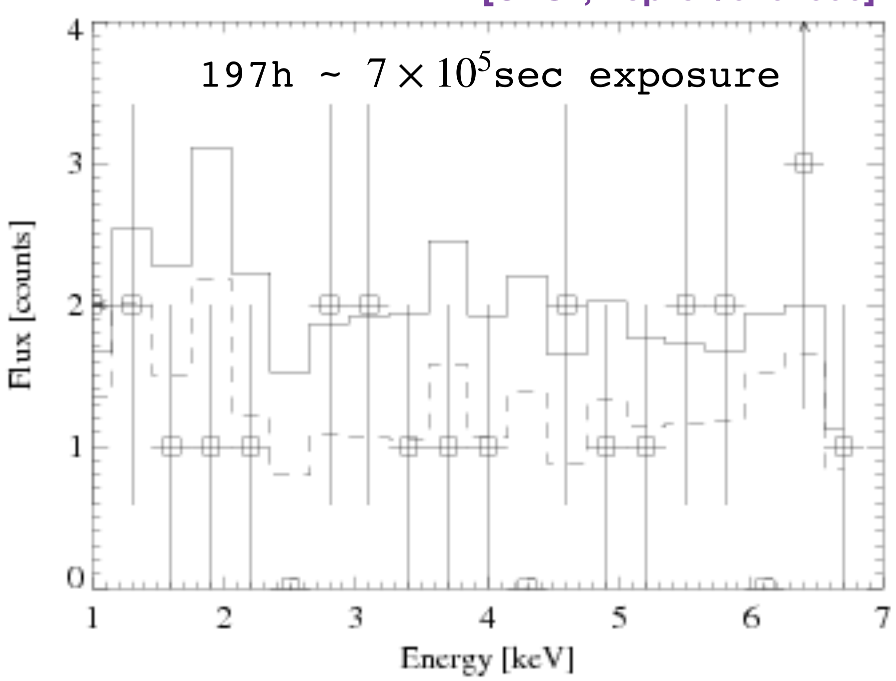
Axion cooling leading to observable deviations

Axion helioscope

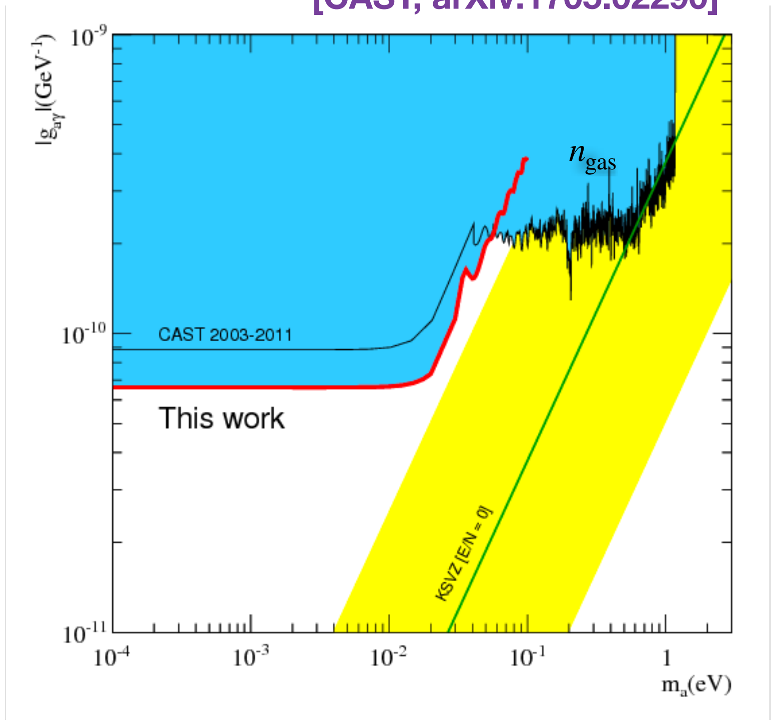
[CAST, arXiv:1705.02290]



[CAST, hep-ex/0702006]



[CAST, arXiv:1705.02290]



Stellar cooling argument on HB

triple-α reaction

- A helium-burning core and a hydrogen-burning shell after the tip of red-giants

$$\rho \approx 10^4\,\mathrm{g\,cm^{-3}} \qquad T \approx 10^8\,\mathrm{K}$$

- The number ratio R of HB vs. RGB in Globular clusters agreed with standard predictions to within 10%

- Lifetime of HB t_{He} (i.e., duration of helium burning phase) agrees within 10%

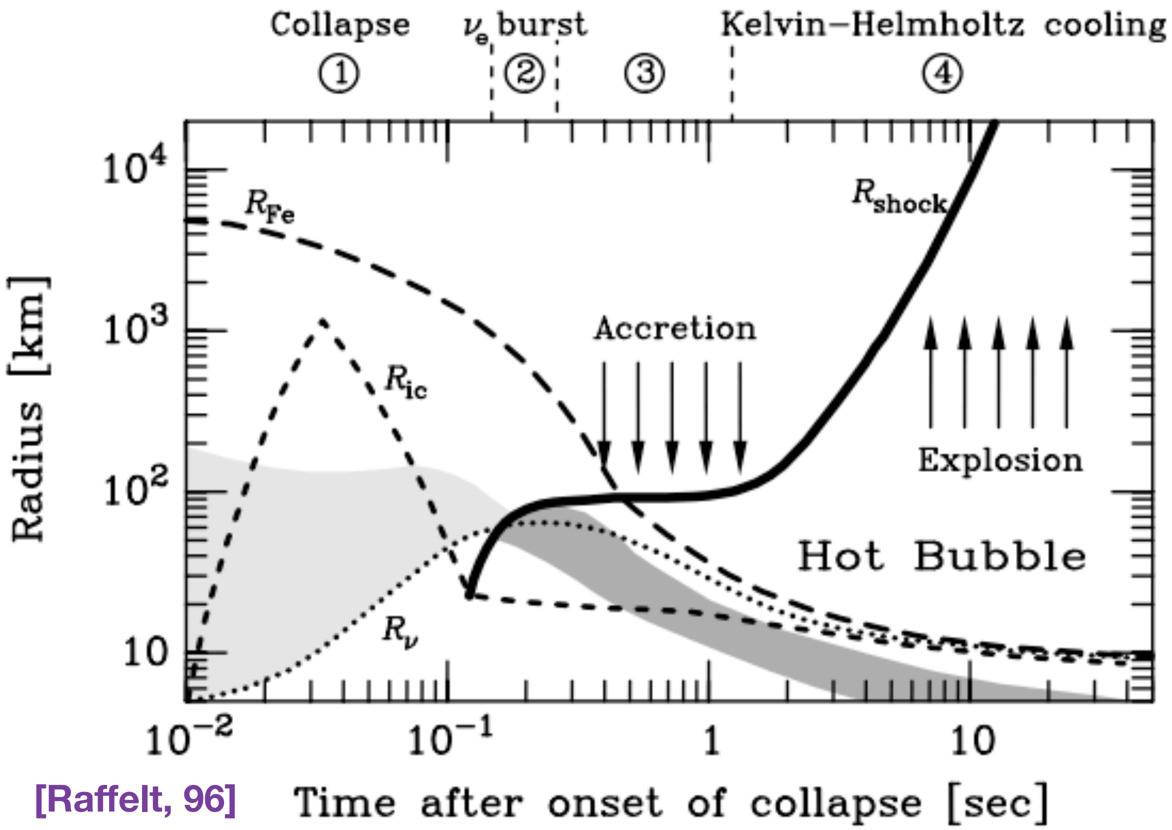
[Raffelt]

t_{He} **reduced by** $\dfrac{L_{3\alpha}}{L_a + L_{3\alpha}}$ → $L_a \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$

$L_{3\alpha} \sim 20 L_\odot \approx 8 \times 10^{34}\,\mathrm{erg\,s^{-1}}$

$M_c^{\mathrm{HB}} \sim 0.5\,M_\odot$

Stellar cooling argument on SN



[Raffelt, 96]

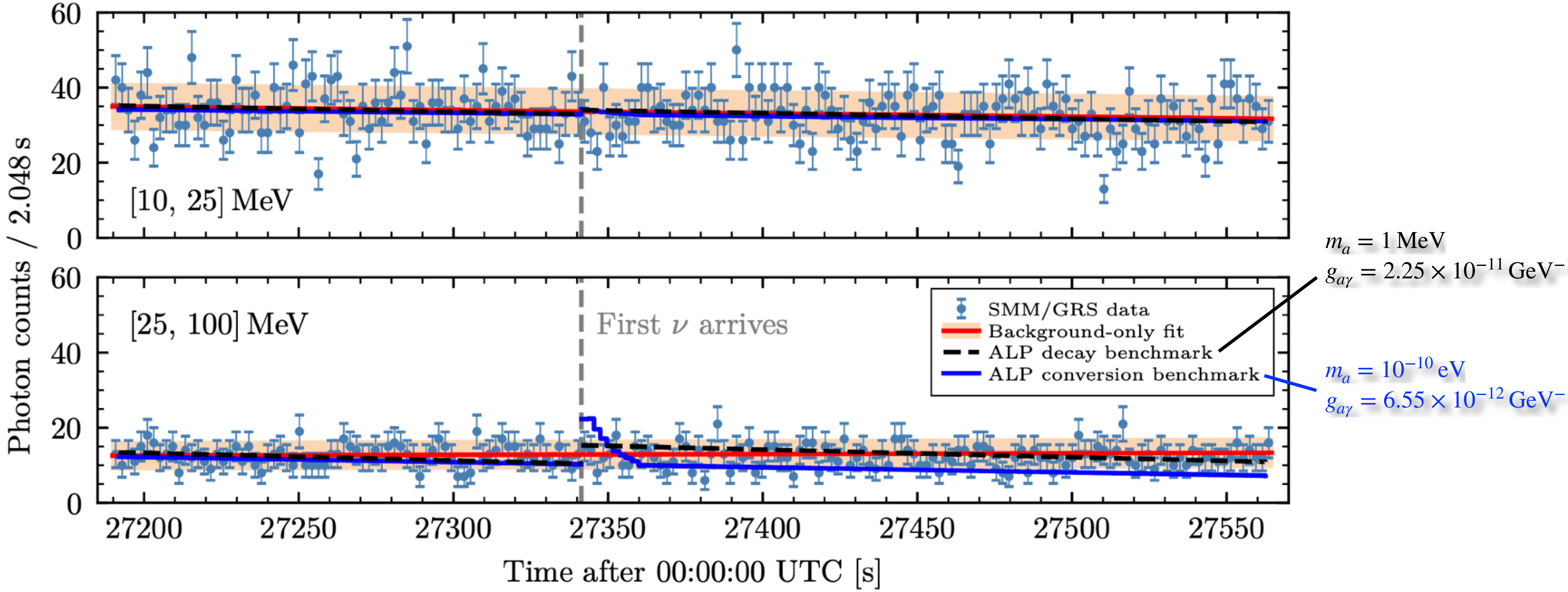
- The "***delayed explosion scenario***" (***DνM***)
  - Thermal relaxation of the proto-neutron star as the source of neutrino emission for > 5sec
  - the energy deposition of the neutrino flow causes the explosion ($\mathcal{O}(1)$% of total neutrino bulk energy)

$$\Rightarrow \quad L_x \lesssim 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

"Raffelt's criterion"

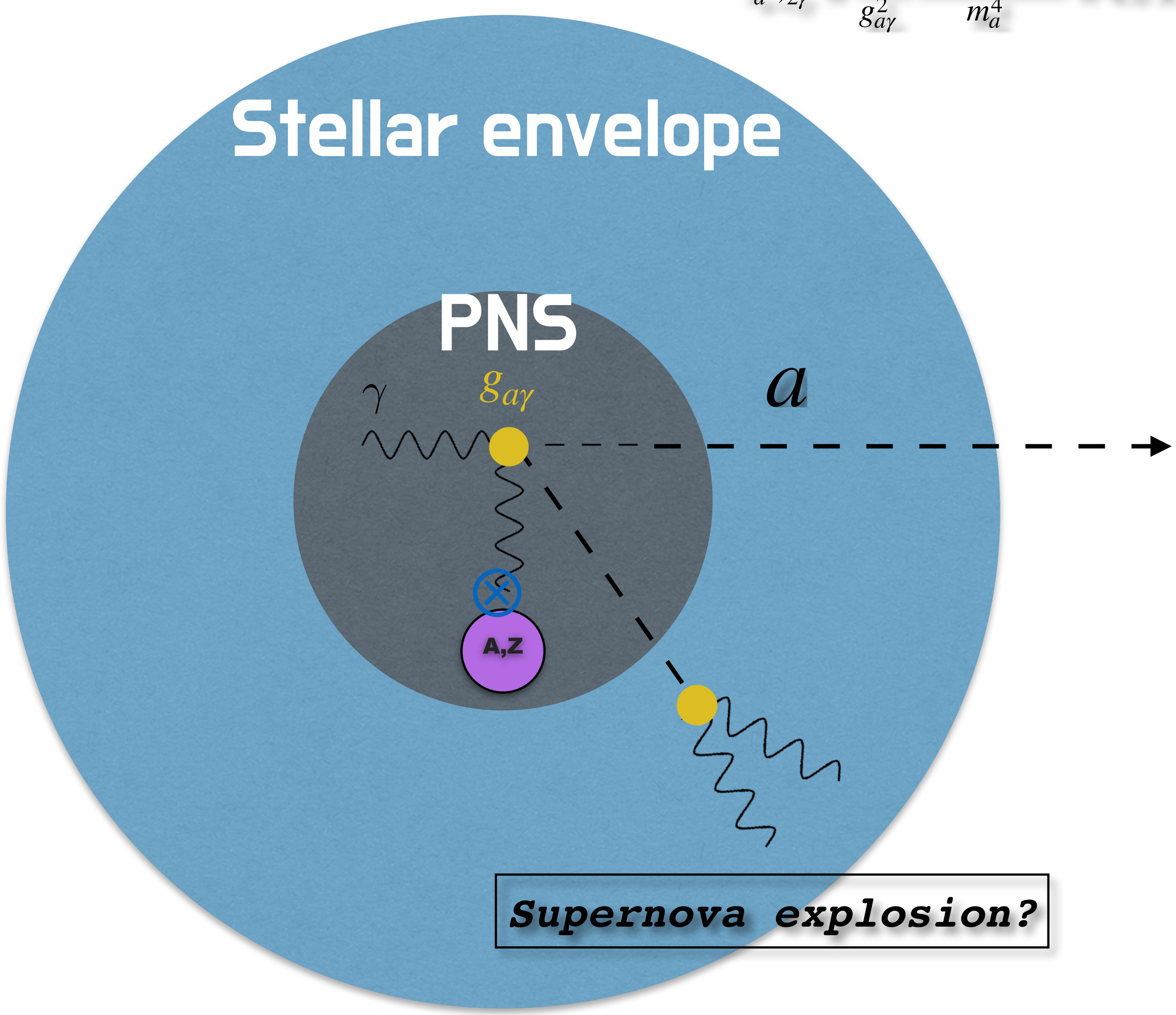
SN1987A gamma-ray burst bound

[arXiv:2212.09764]



Low energy supernova?

$$\lambda_{a\to 2\gamma} = \frac{64\pi}{g_{a\gamma}^2}\frac{\sqrt{\omega^2 - m_a^2}}{m_a^4} = 4.0\times 10^{13}\,\mathrm{cm}\left(\frac{g_{a\gamma}}{10^{-9}\,\mathrm{GeV}^{-1}}\right)^{-2}\left(\frac{\omega}{100\,\mathrm{MeV}^{-1}}\right)\left(\frac{m_a}{10\,\mathrm{MeV}}\right)^{-4}$$

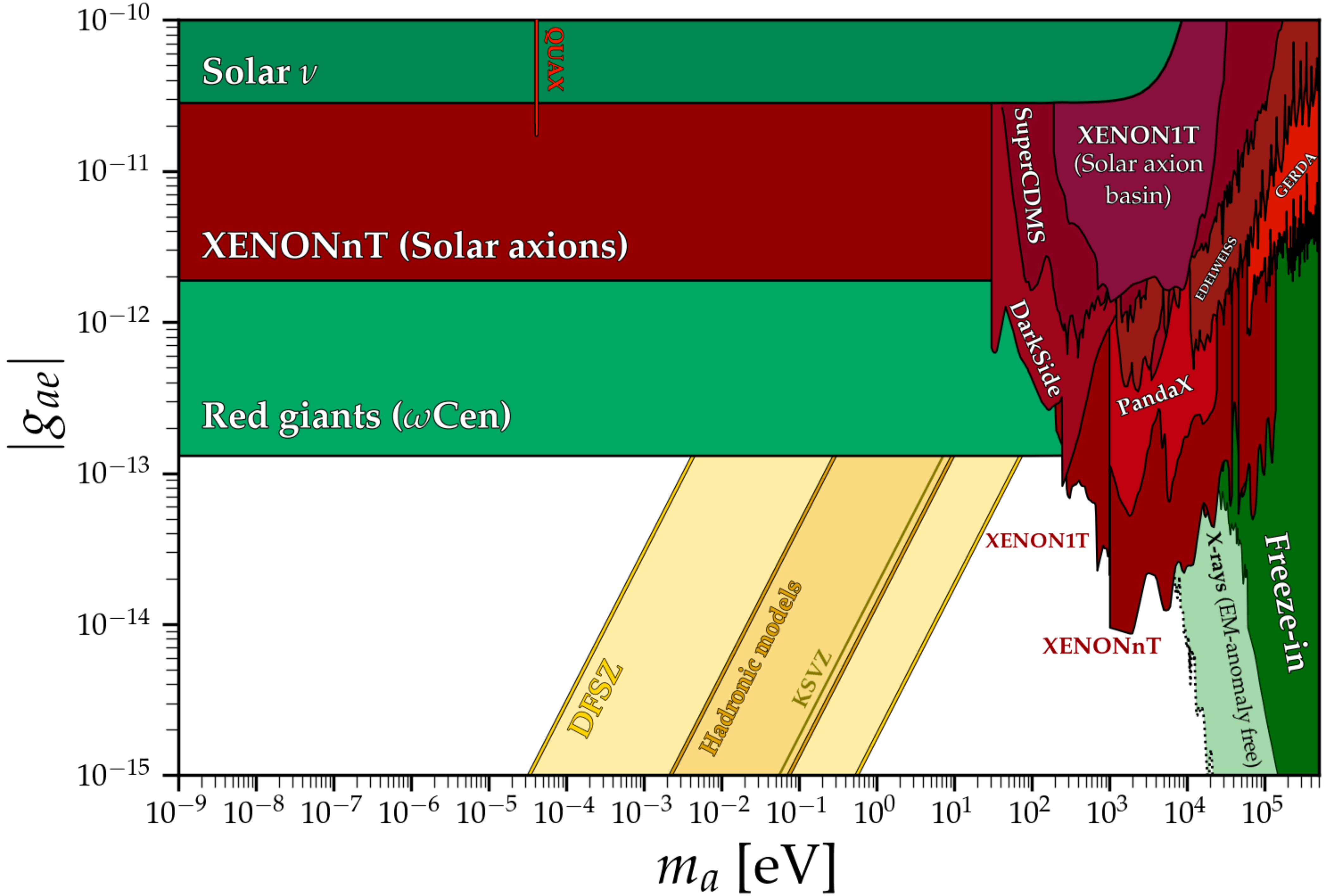


- Observables:
  1) Light curves
  2) Spectroscopic ejecta velocities

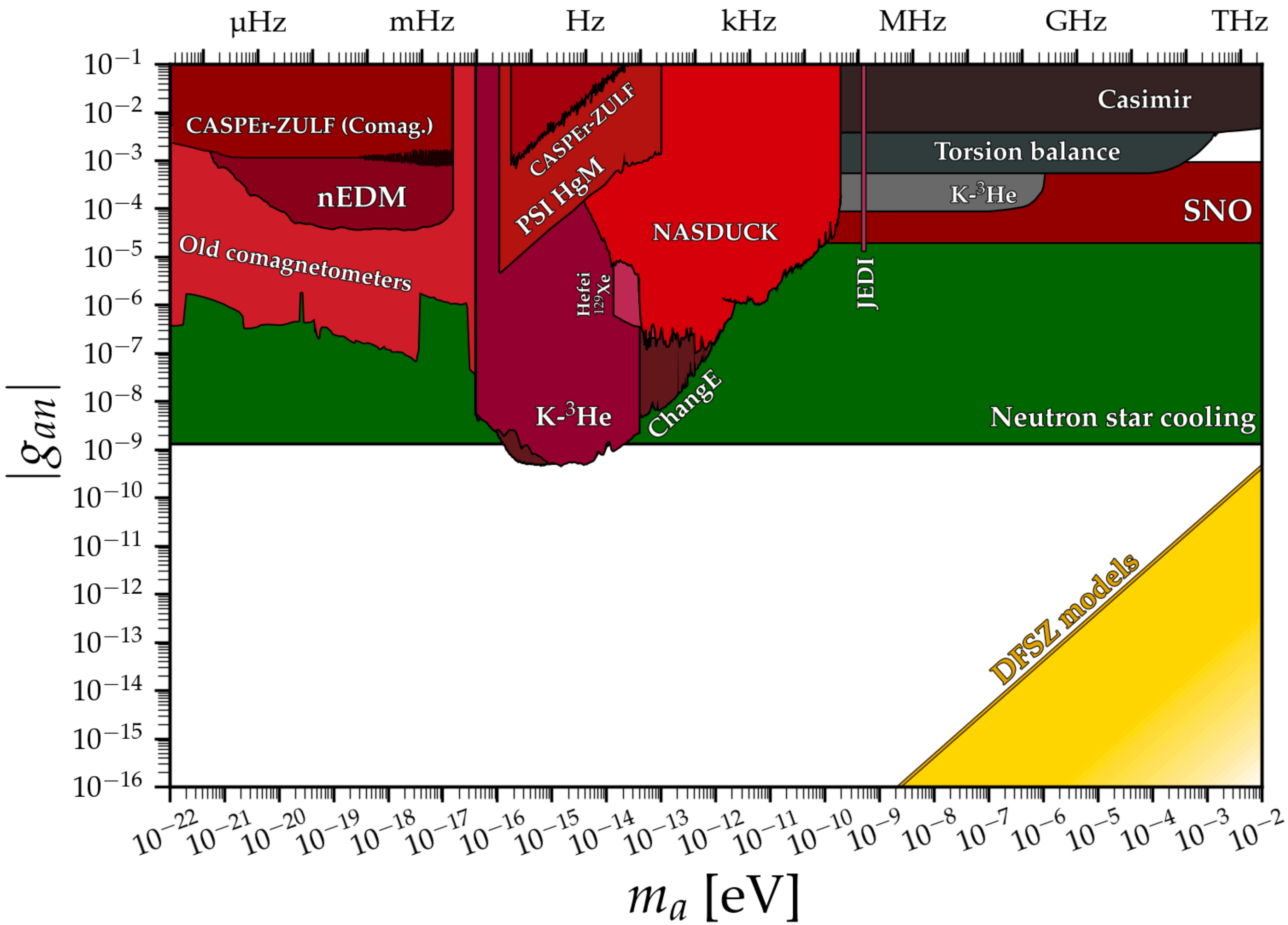
[arXiv:2201.09890]

$$E_{\mathrm{exp}} < 0.1\,\mathrm{Bethe} = 10^{50}\,\mathrm{erg}$$

Current status on $ig_{aee}a\bar{e}\gamma^5 e$



Current status on $ig_{ann}a\bar{n}\gamma^5 n$



Current status on $ig_{ann}a\bar{n}\gamma^5 n$