Light BSM Particles from Stars

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@ Summer Institute 2025

Introduction Myself

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- Faculty @ IBS-CTPU-PTC
- Particle Phenomenology & Cosmology:

  Cosmological & Astrophysical aspects of light particles
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Outline

01 Preliminary

- Current status of New Light Bosons
- Stages of Stellar Evolution
- Production & Absorption rates
- Particle Dispersion in Media

02 Low-M Stellar Evolution

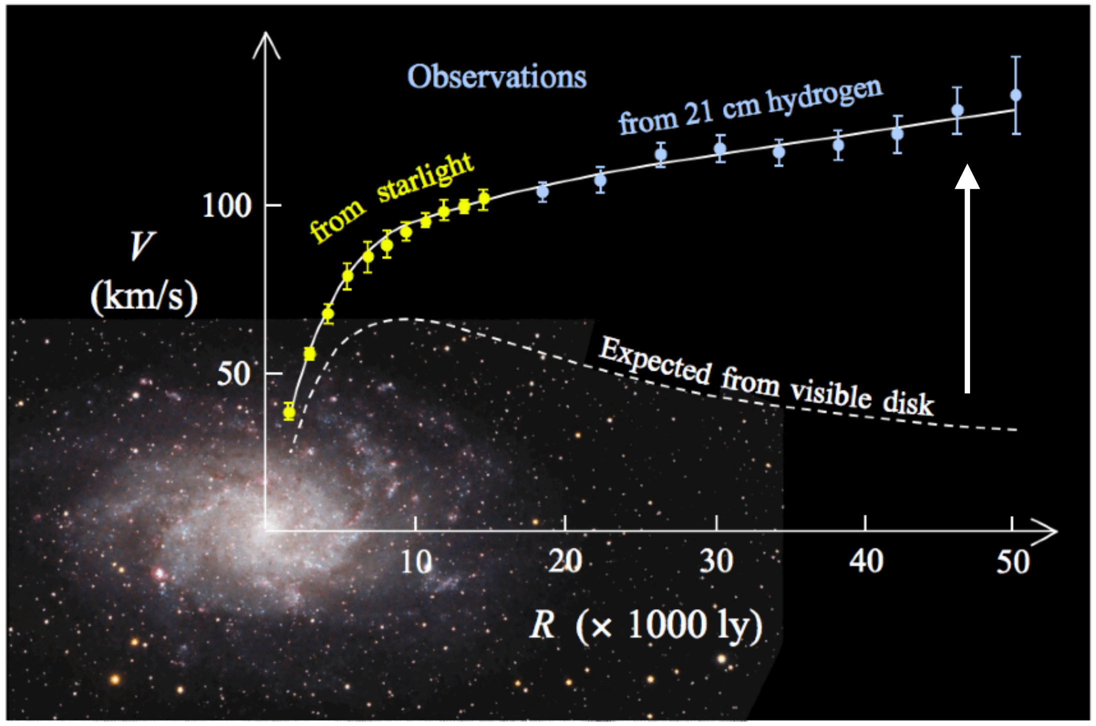
◉ Stellar Cooling Argument

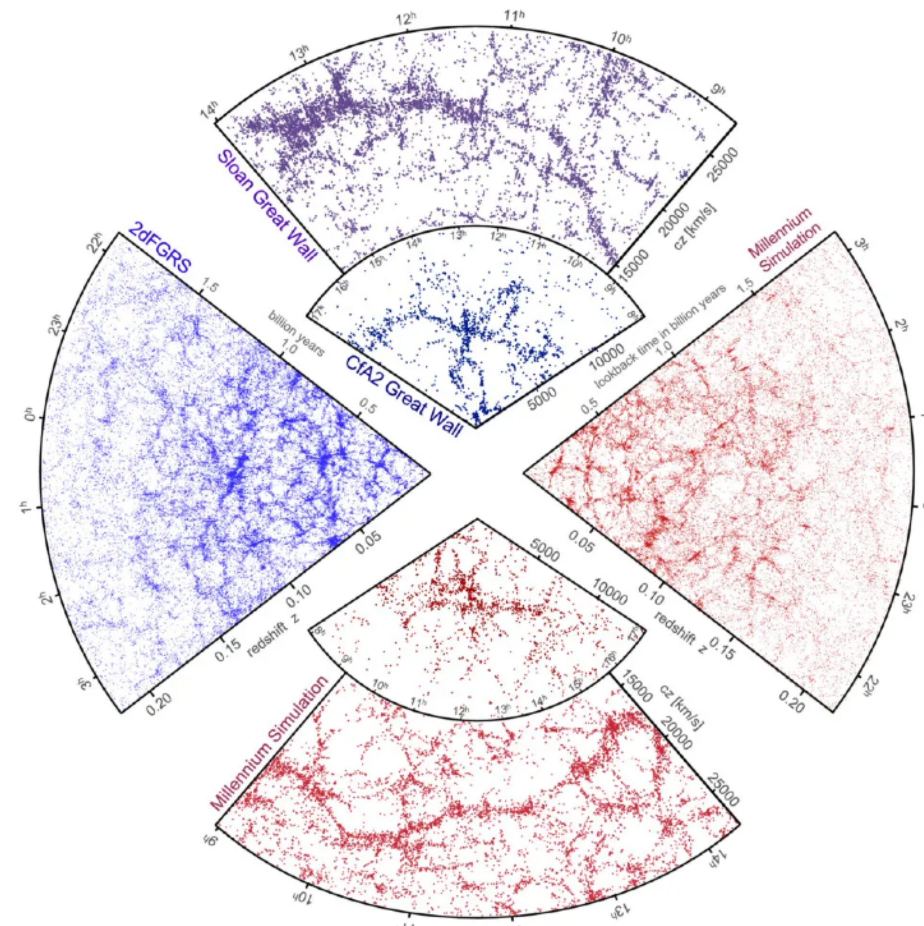
- Sun (Main Sequence) - solar ν
- Red Giants - luminosity @ tip
- Horizontal Branches - lifetime

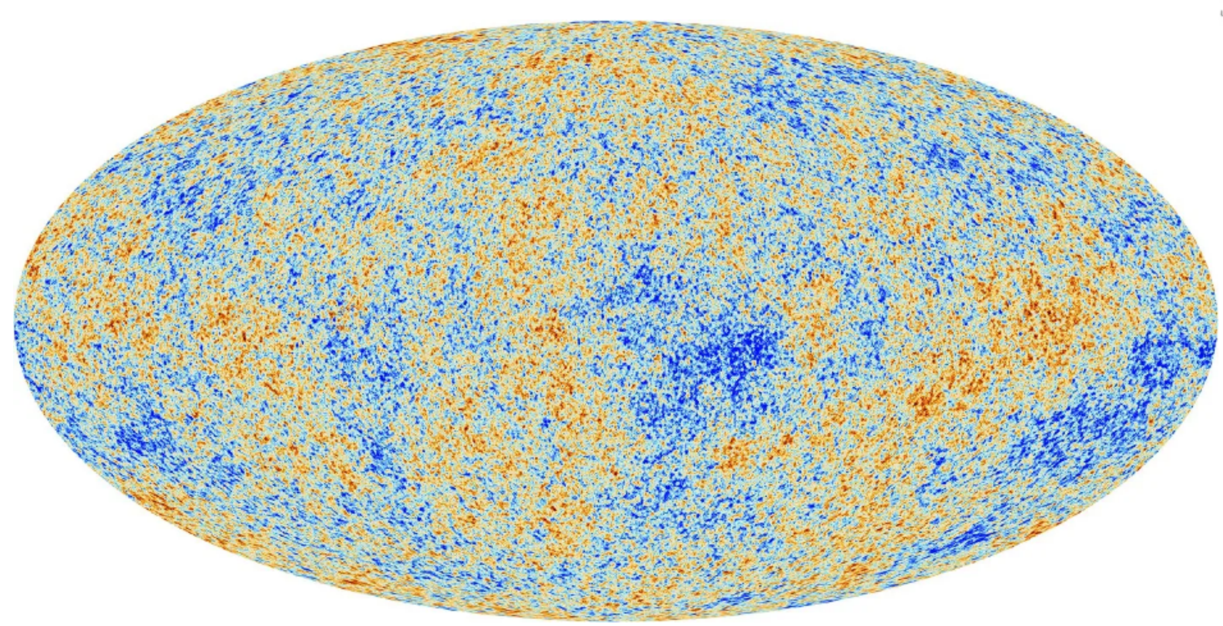
03 Supernova & Neutron Stars

- Core-Collapse of massive stars
- SN1987A Observations
  - Duration of ν signals & No prompt γ-ray
- Phenomena associated with SN
- ν-driven explosion

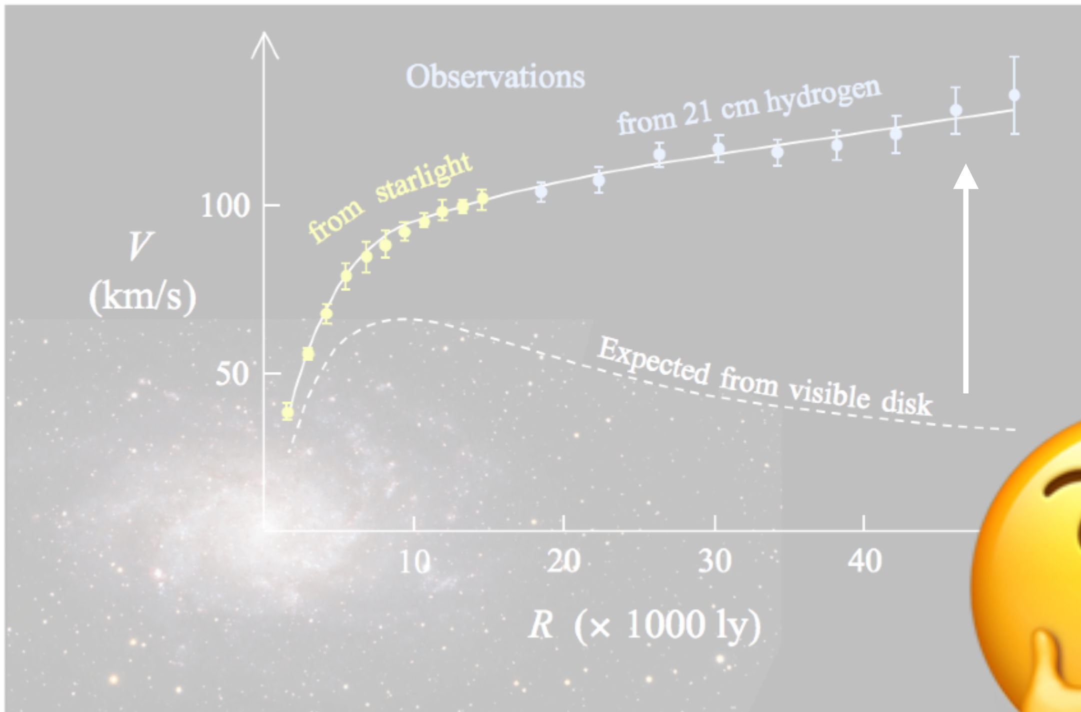
Evidences of Dark Matter

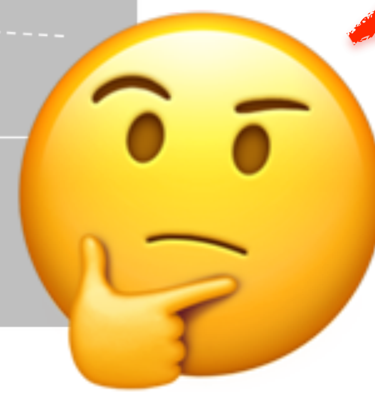




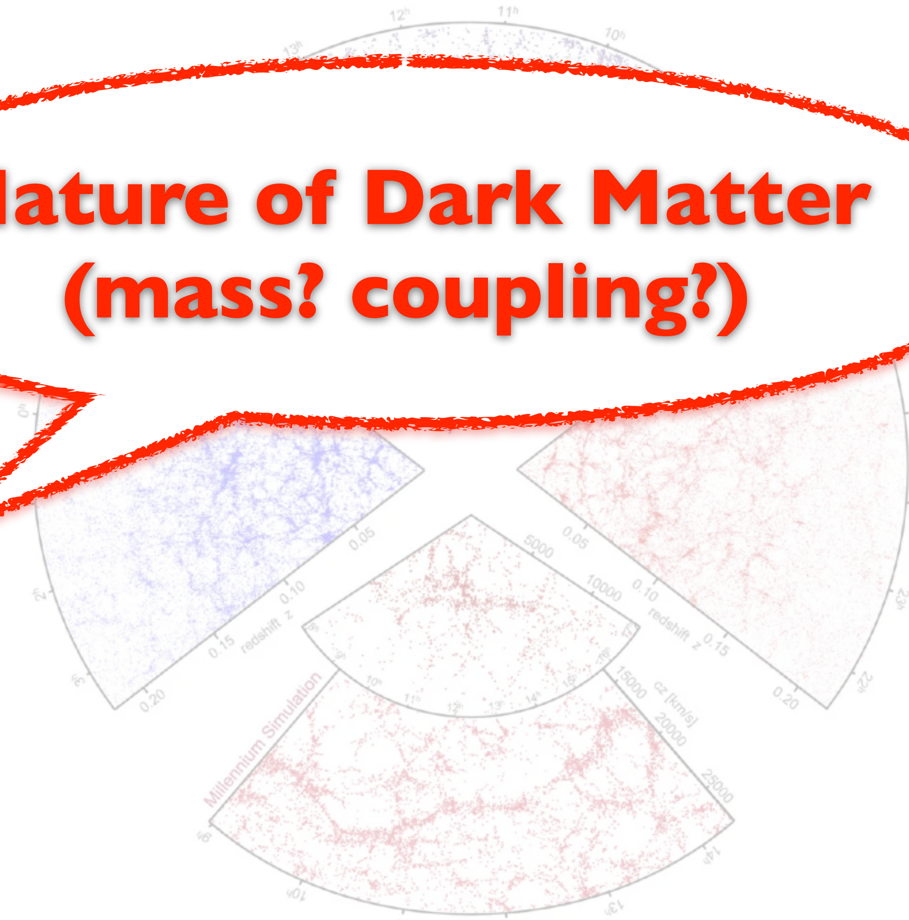


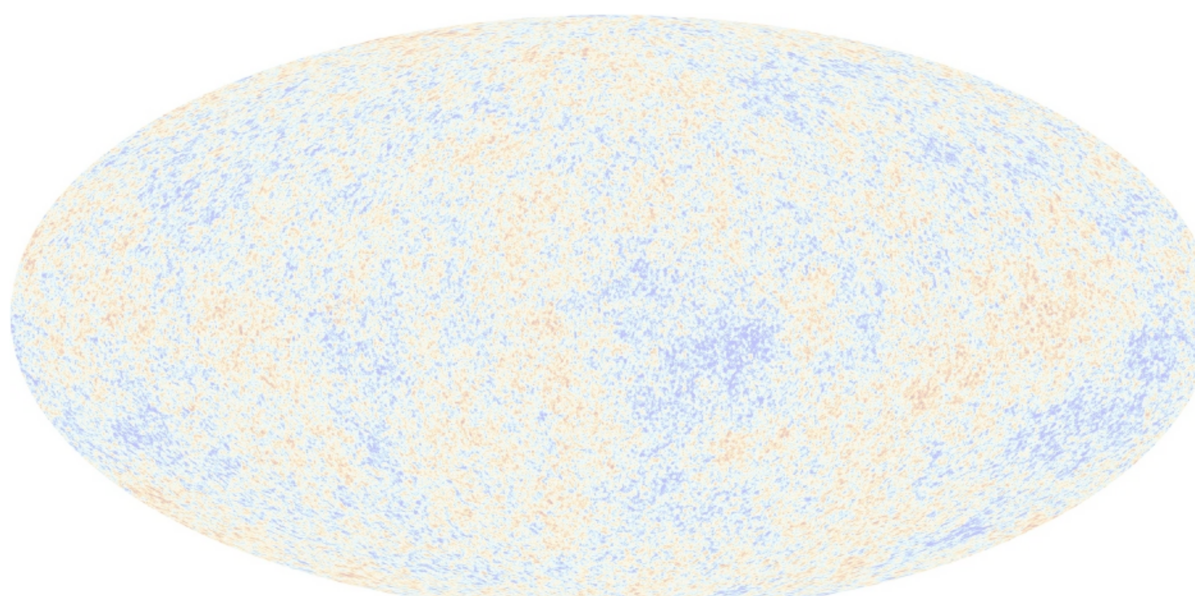
Evidences of Dark Matter



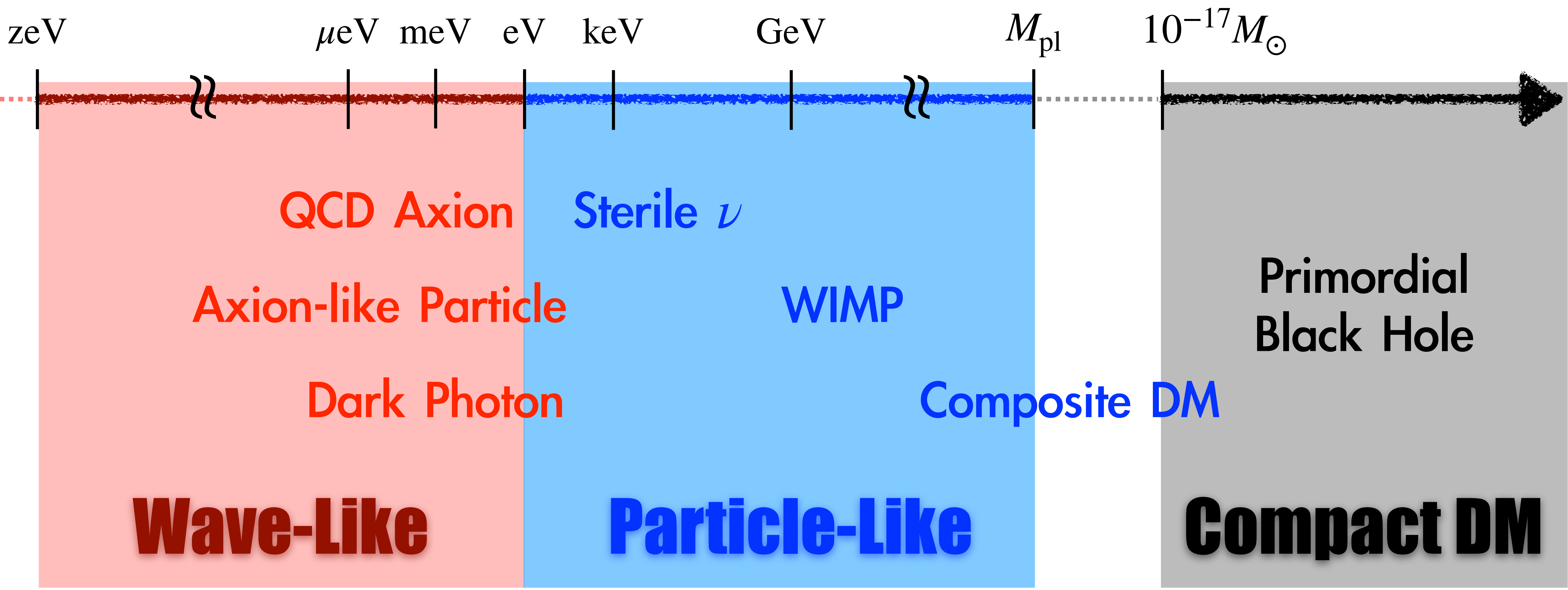


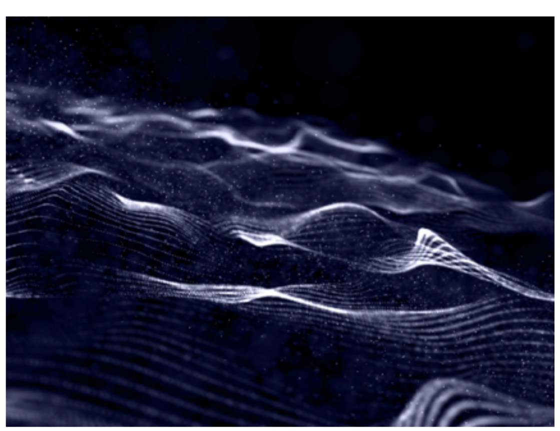
Nature of Dark Matter
(mass? coupling?)



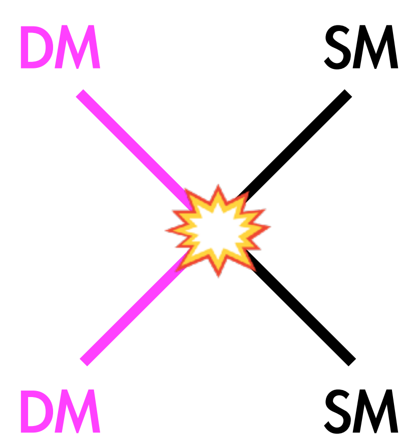


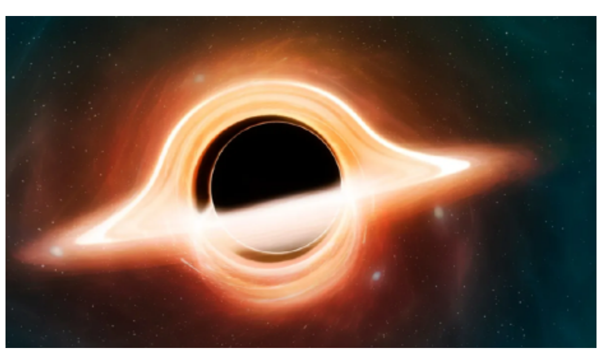
Dark Matter Candidates



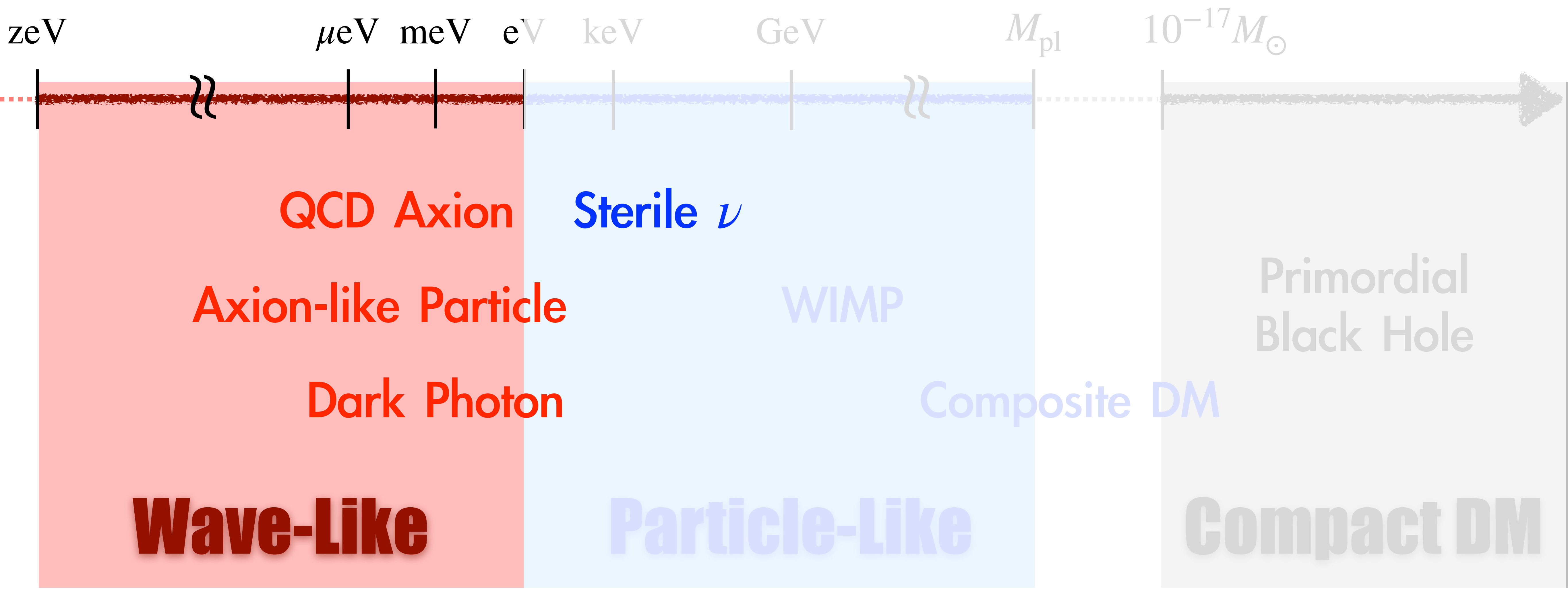


[Medium]





Dark Matter Candidates



Low-E frontier

✓ Intensity: ultra-high collision rate
✓ Cosmic: universe & astroparticle

Feebly-interacting Particles (FIPs)
Weakly-interacting Slim Particles (WISPs)

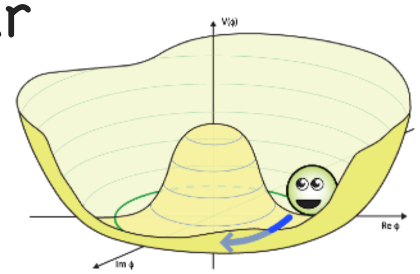
Feebly-Interacting Light Bosons

- **Ubiquitous in several extensions of the Standard Model**
- **Can be a good dark matter candidate**

Axion / Axion-Like Particle

✓ Spin-0 Pseudoscalar

✓ Strong CP problem



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

Dark Photon

✓ Spin-1 Vector

✓ $(g-2)_\mu$, $\cdots$

$$\frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu}$$

Axion

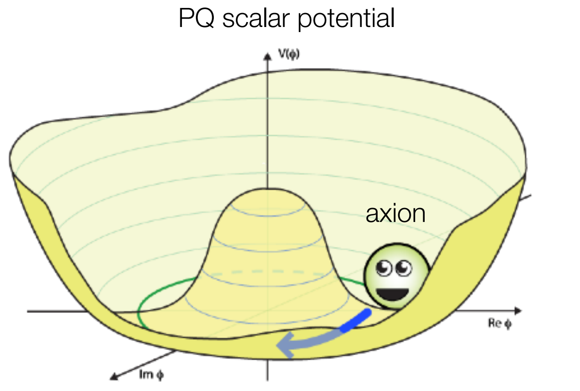
$\bar{\theta} < \mathcal{O}(10^{-10})$

- 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**



[www.quantumdiaries.org]

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

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

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

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

"The strong CP problem is solved dynamically"

Axion Models

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]
<u>Fermion</u> extension of SM	<u>Scalar</u> 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 $\simeq 5.7\,\mathrm{meV}\left(\dfrac{10^9\,\mathrm{GeV}}{f_a}\right)$ **Coupling to SM** $\propto \dfrac{v_{\rm EW}}{f_a} \sim \dfrac{100\,\mathrm{GeV}}{f_a}$

- 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 $a \to a + \text{constant}$

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

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

- 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

Gauged U(1) Extension of the SM

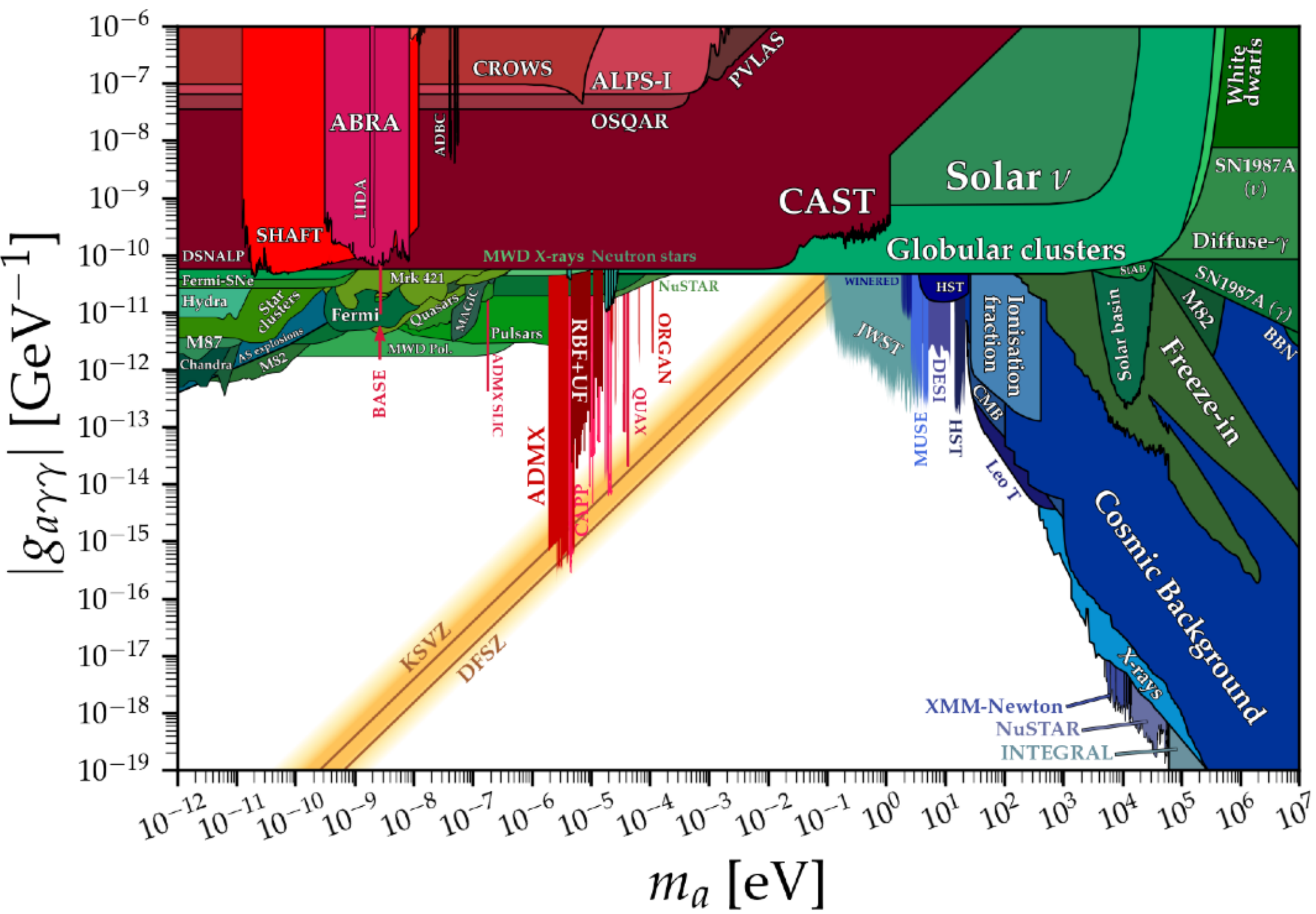
- General interactions of ***dark gauge bosons*** (γ' or A'_μ) to SM particles
  - *U(1) charge assignment* $\mathscr{L}_{\gamma'\text{-}\psi} = g_\psi A'_\mu \bar{\psi}\Gamma^\mu\psi$ $\qquad \Gamma^\mu = [\gamma^\mu, \gamma^\mu\gamma^5, \cdots]$
  - *Kinetic mixing* $\mathscr{L}_{\gamma'\text{-}\gamma} = \dfrac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}$ ☞ $g_\psi = e\varepsilon q_\psi$ & $\Gamma^\mu = \gamma^\mu$ in vacuum
- Anomaly-free Abelian symmetries
  - flavor universal: $B-L$, $\cdots$
  - flavor dependent: $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$, $\cdots$
  - only kinetic mixing: dark photon

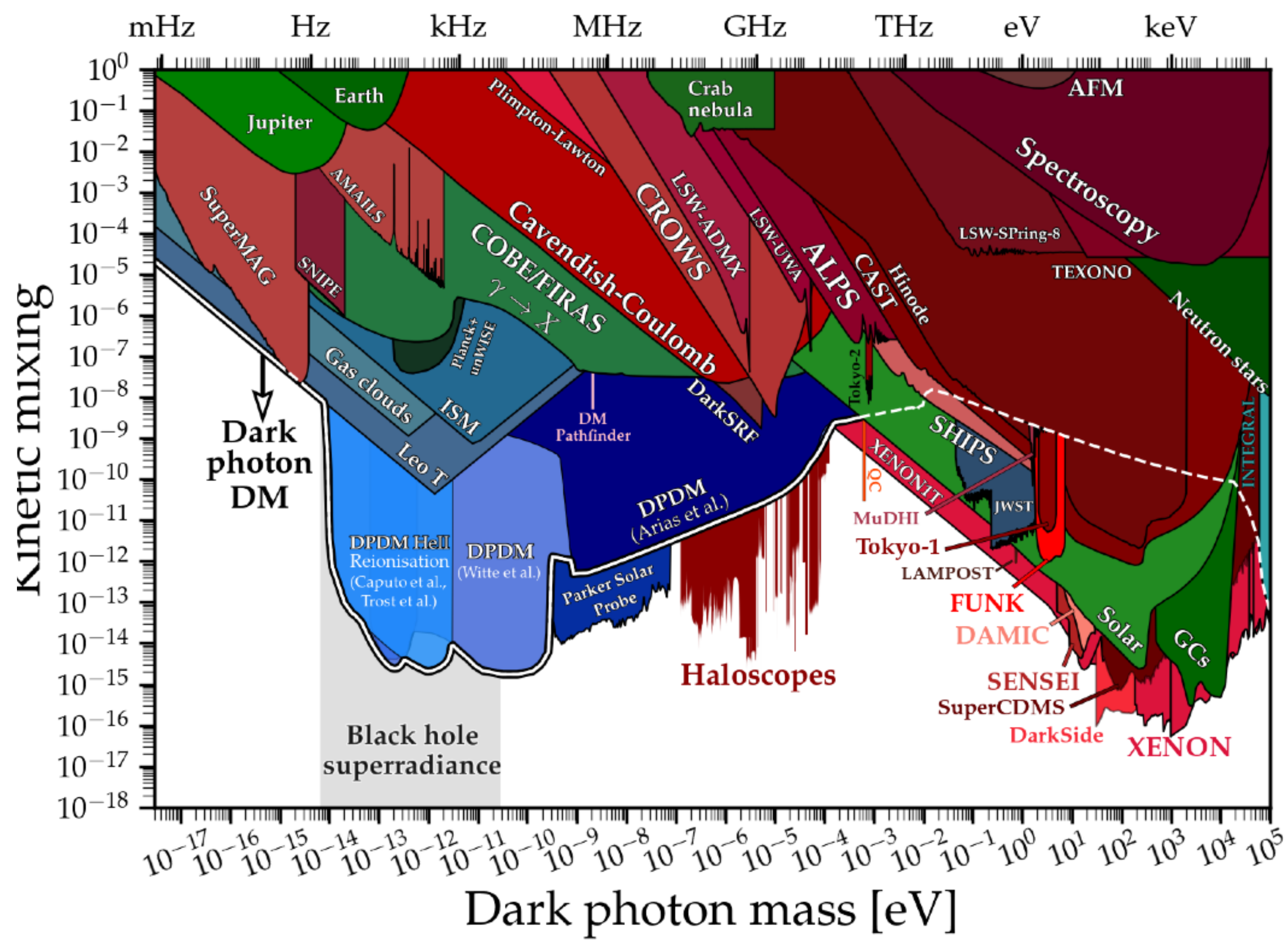
Current Status

Experimental

Astrophysical

Cosmological





[https://cajohare.github.io/AxionLimits/]

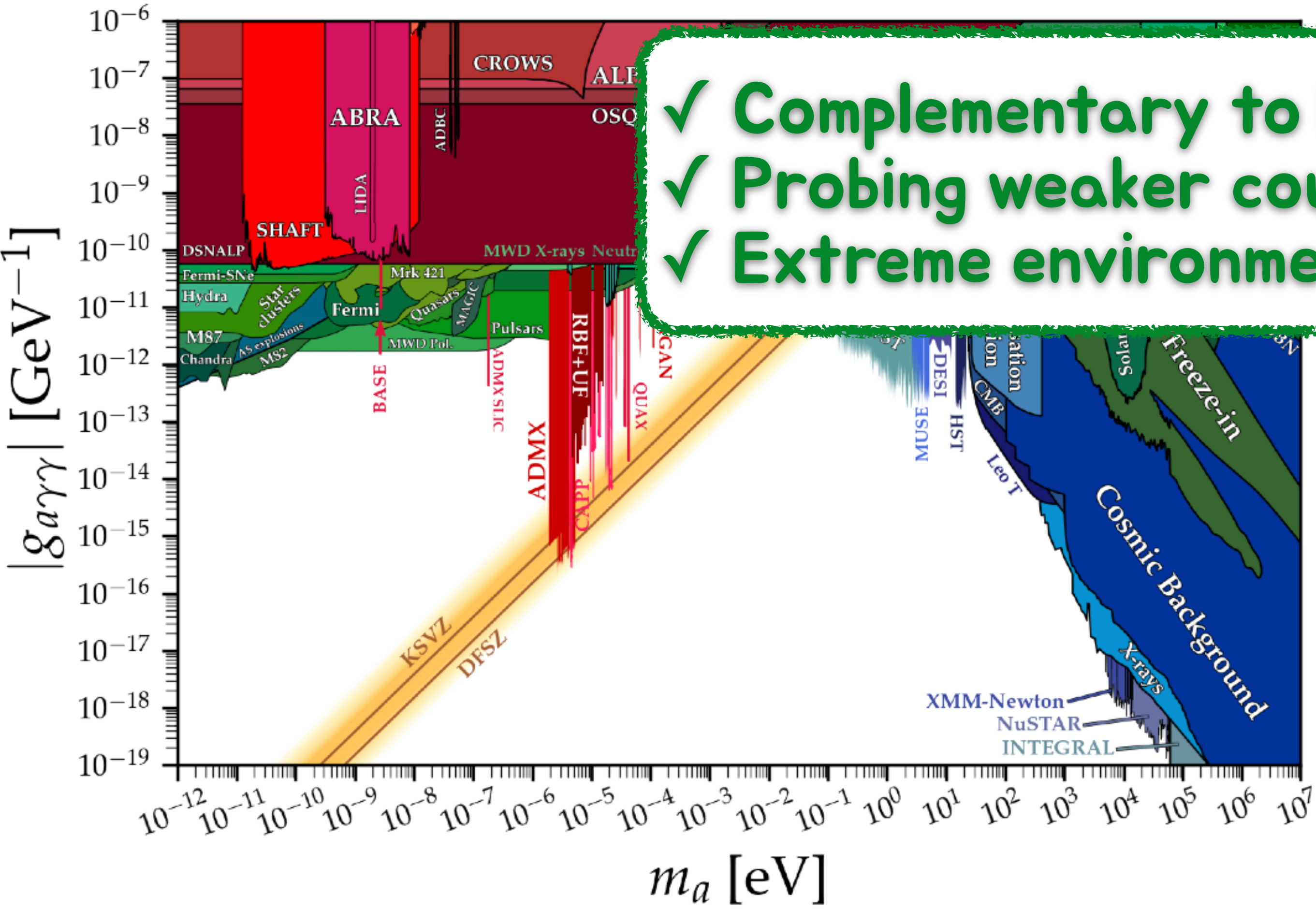
Current Status

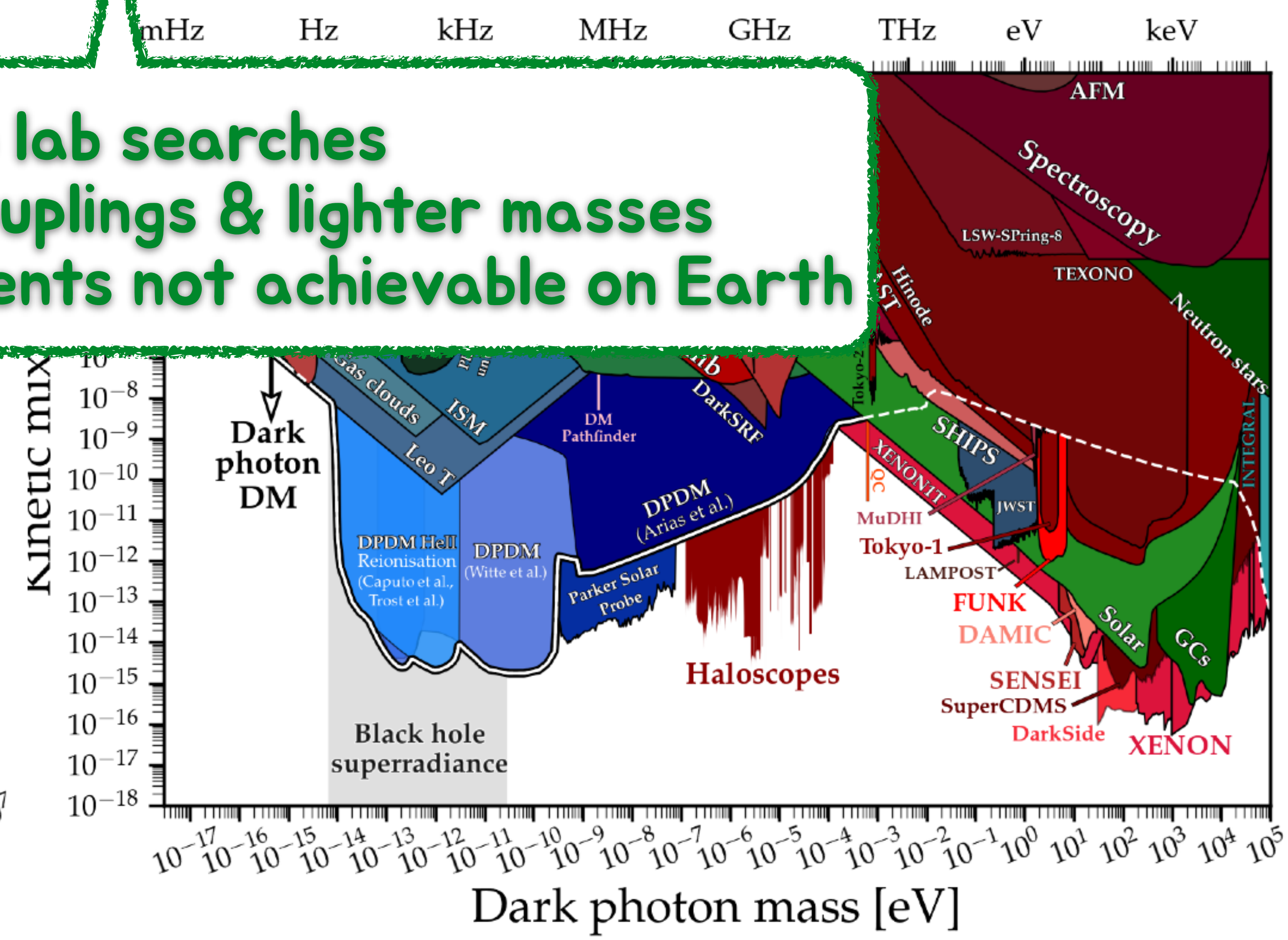
Experimental

Astrophysical

Cosmological

- ✓ Complementary to lab searches
- ✓ Probing weaker couplings & lighter masses
- ✓ Extreme environments not achievable on Earth





[https://cajohare.github.io/AxionLimits/]

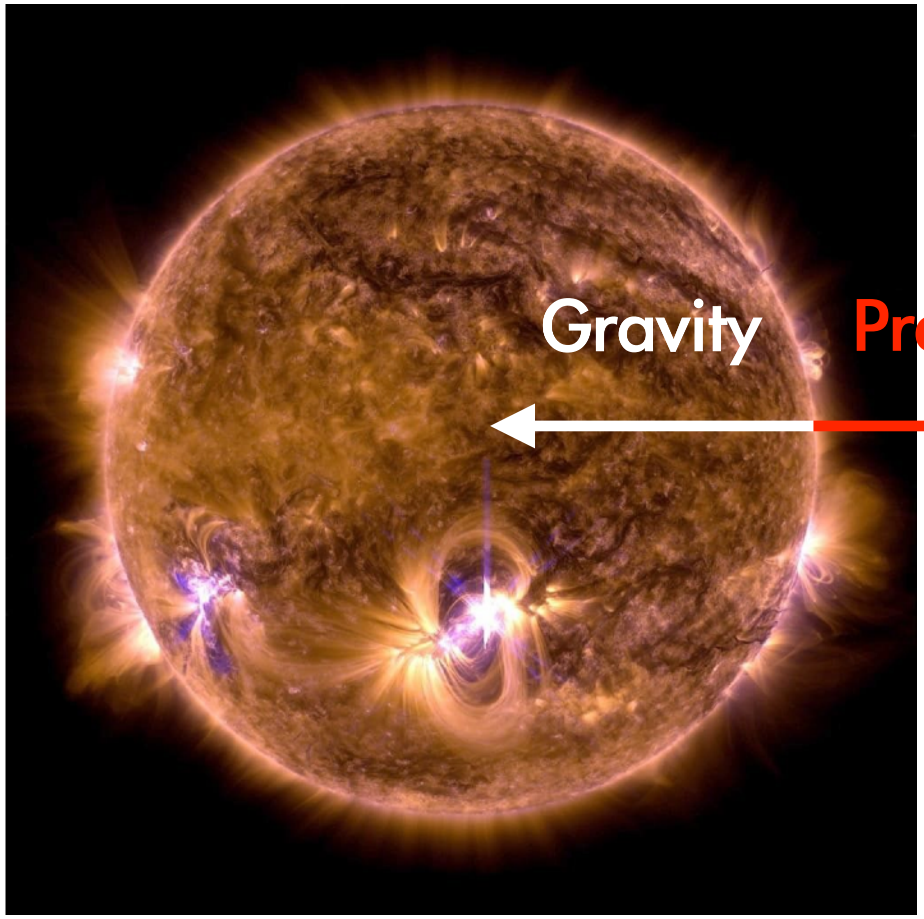
Stars

“ **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. ”

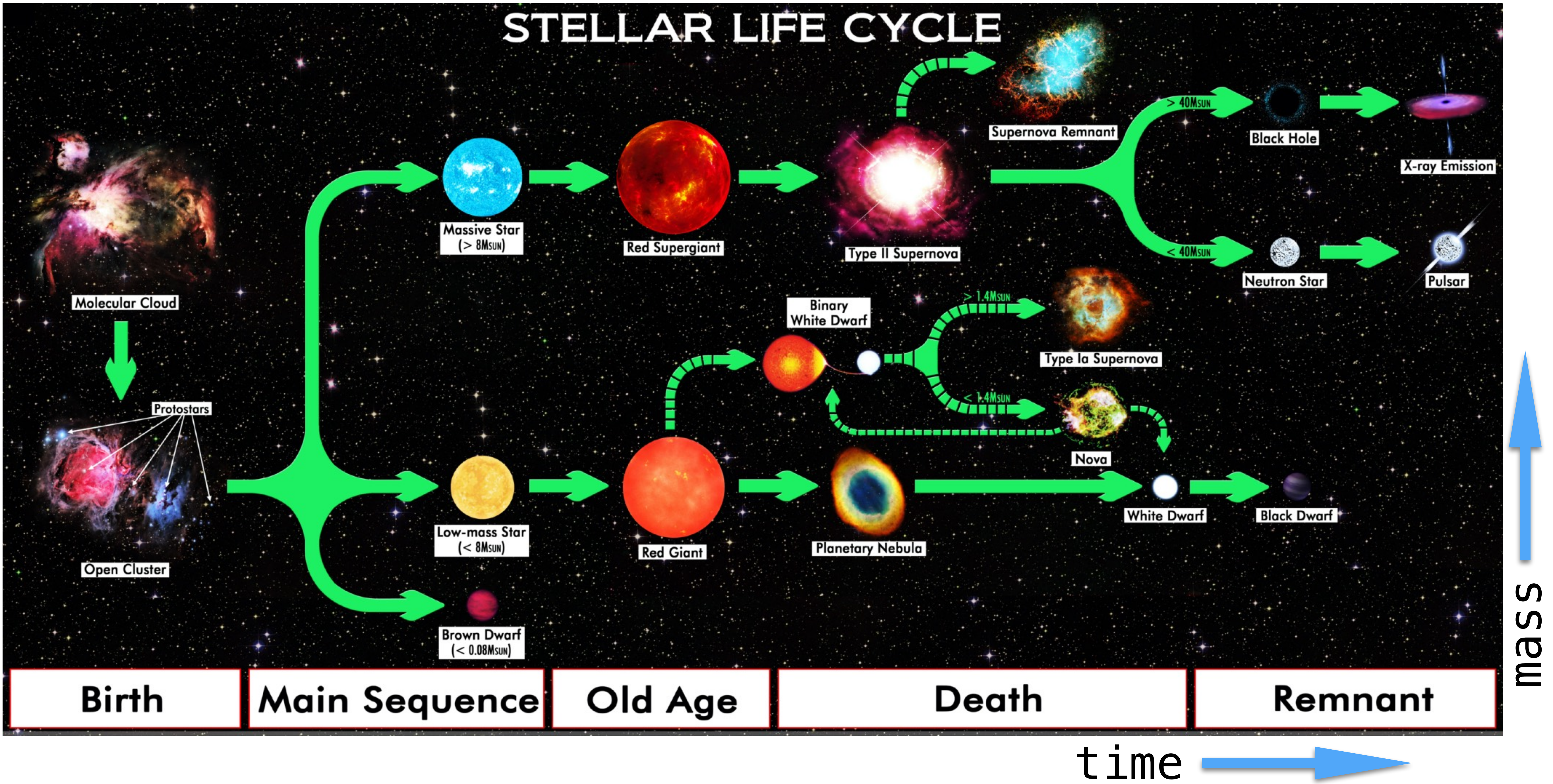


(thermal? degeneracy?)

+ Energy conservation & transfer

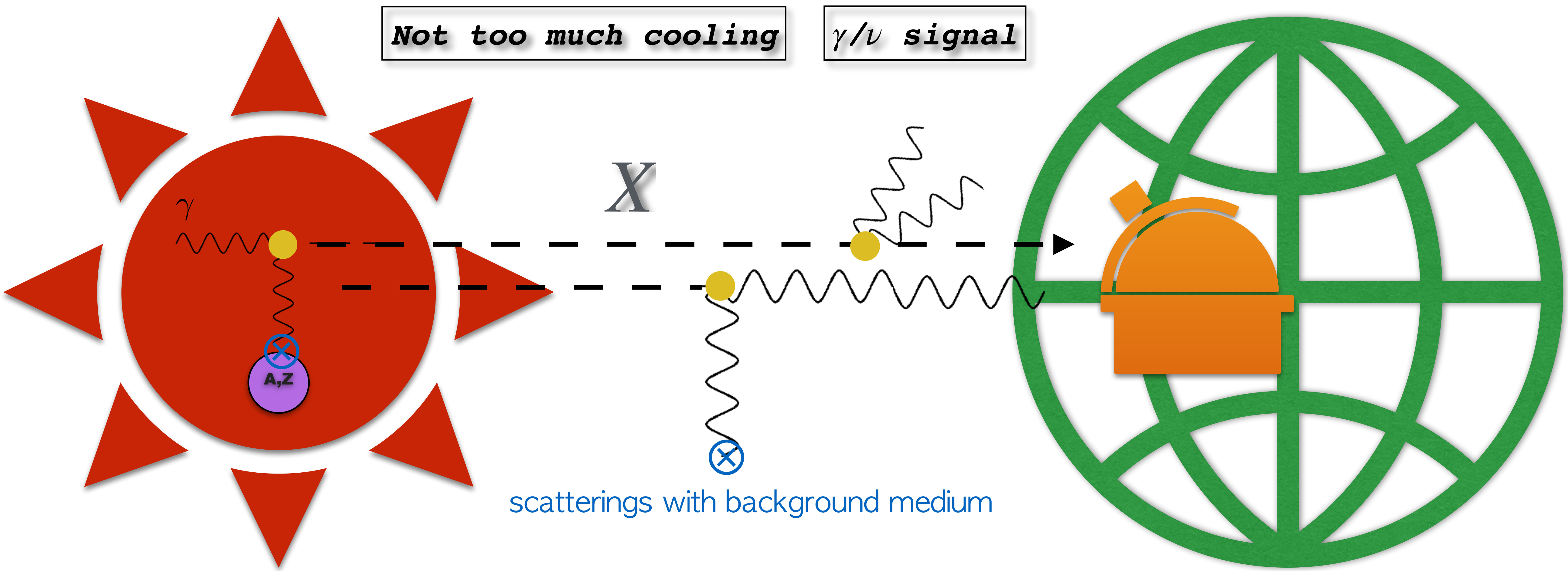
Stellar Evolution

[image from Wikipedia]



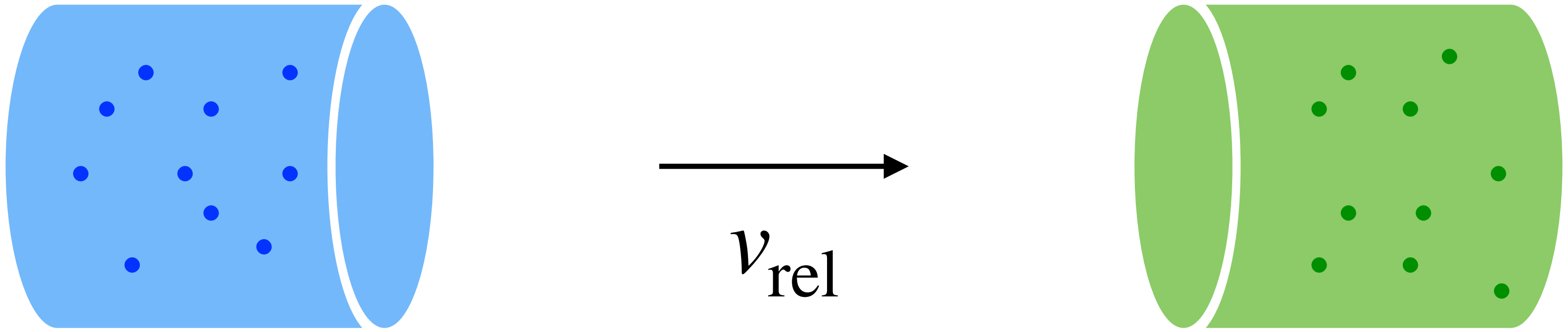
Astrophysical Searching Scheme

- Stars as ***laboratories*** to probe light bosons in extreme circumstances
  - ✓ Detection opportunity (e.g., ν spectrum from Sun or Supernovae)
  - ✓ Backreaction on stellar properties



Production & Absorption

Cross Section



$$\sigma \equiv \frac{N_{\text{event}}}{(n_A l_A)(n_B l_B) S}$$

✓ n_i: # density of i particles
✓ l_i: length of the i bunch
✓ S: common area

Event Rate per Volume

$$\frac{dn_{\text{event}}}{dt} = \frac{N_{\text{event}}}{Vt} = n_A n_B \sigma v$$

Scattering amplitude

$$\sigma v = \frac{1}{2E_A}\frac{1}{2E_B}\underbrace{\left(\prod_f \int \frac{d^3\overrightarrow{p}_f}{(2\pi)^3 2E_f}\right)}_{\text{Phase space integral}} |\mathscr{M}|^2 \underbrace{(2\pi)^4\,\delta^{(4)}\left(p_A + p_B - \sum_f p_f\right)}_{\text{Energy-momentum conservation}}$$

Production Rate

- Production from $i_1 + i_2 \to \sum_i f_i + X$

Differential production rate

$$\Gamma_{\text{prod}} = \frac{1}{2\omega}\left(\prod_i \int \frac{d^3\overrightarrow{p}_i}{(2\pi)^3 2E_i} f_i\right)\left(\prod_f \int \frac{d^3\overrightarrow{p}_f}{(2\pi)^3 2E_f}(1 \pm f_f)\right)$$
$$\times |\mathscr{M}|^2 (2\pi)^4 \delta^{(4)}\left(p_1 + p_2 - \sum_f p_f - k\right)$$

- Quantum statistical factor for the final states $(1 \pm f_f)$

✓ Boson (+): $a^+ |n\rangle = \sqrt{1+n}\,|n+1\rangle$ & $a\,|n\rangle = \sqrt{n}\,|n-1\rangle$

✓ Fermion (-): probability for a state to be occupied

$$|\psi\rangle = \sqrt{1-f}\,|0\rangle + \sqrt{f}\,|1\rangle$$

Absorption Rate

- Absorption from $\sum_i f_i + X \to i_1 + i_2$ (i.e., inverse production)

$$\Gamma_{\text{abs}} = \frac{1}{2\omega}\left(\prod_i \int \frac{d^3\overrightarrow{p}_i}{(2\pi)^3 2E_i}(1 \pm f_i)\right)\left(\prod_f \int \frac{d^3\overrightarrow{p}_f}{(2\pi)^3 2E_f} f_f\right)$$
$$\times |\mathscr{M}|^2 (2\pi)^4 \delta^{(4)}\left(p_1 + p_2 - \sum_f p_f - k\right)$$

- Boltzmann equation

$$\frac{df_X}{dt} = \Gamma_{\text{prod}}\left(1 \pm f_X\right) - \Gamma_{\text{abs}} f_X$$

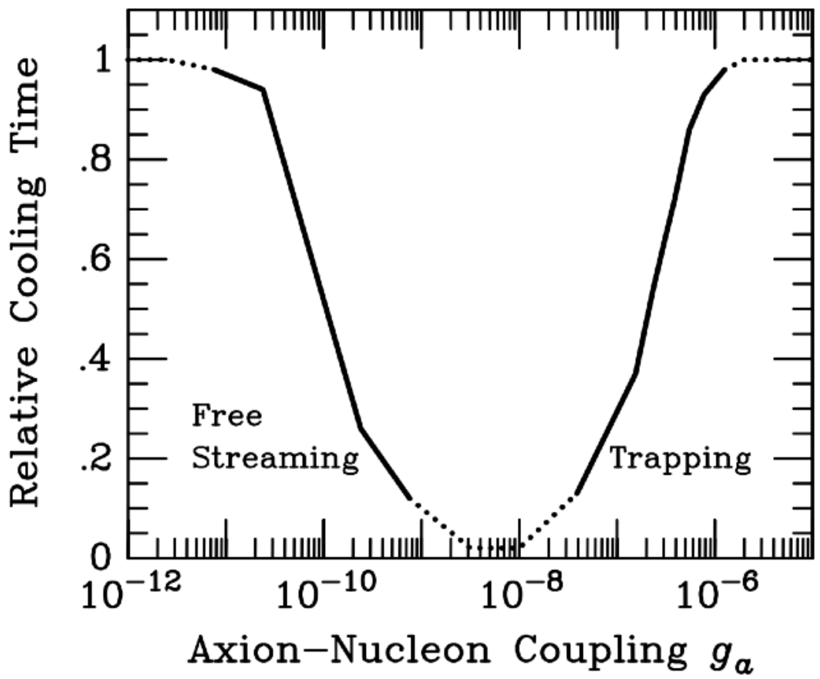
✓ Trap ($df_X/dt = 0$) & Equilibrium ☞ $\Gamma_{\text{abs}} = \Gamma_{\text{prod}} e^{\omega/T}$ (i.e., detailed balance)

✓ Actual absorption rate in medium: $\Gamma_{\text{abs}} \mp \Gamma_{\text{prod}} = \left(1 \pm e^{-\omega/T}\right)\Gamma_{\text{abs}}$

Effective Luminosity

$$L_X = \int dV \, \frac{d^3\vec{k}}{(2\pi)^3} \, \Gamma_{\text{prod}} \, \omega \, e^{-\tau}$$

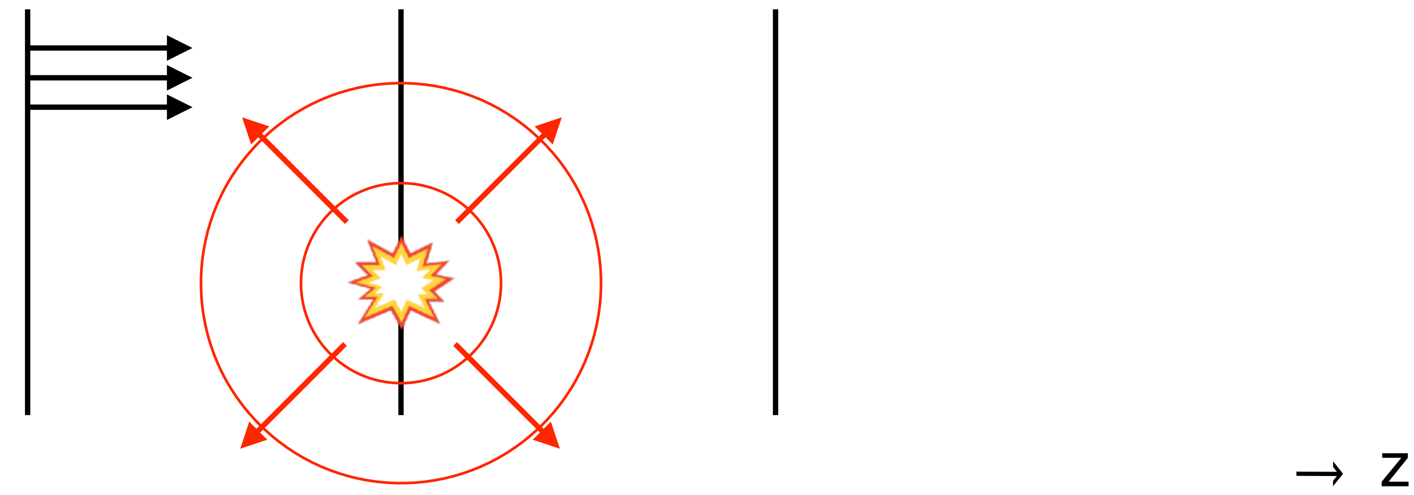
- ✓ Optical depth $\tau = \int d\vec{l} \, \Gamma_{\text{abs}} \mp \Gamma_{\text{prod}}$ along the line of sight $\vec{l}$
- ✓ $\tau \ll 1$: free-streaming (volume emission)
- ✓ $\tau \gg 1$: trapping (surface emission)



[Raffelt]

Particle Dispersion In Media

Wave Form with a Scatterer

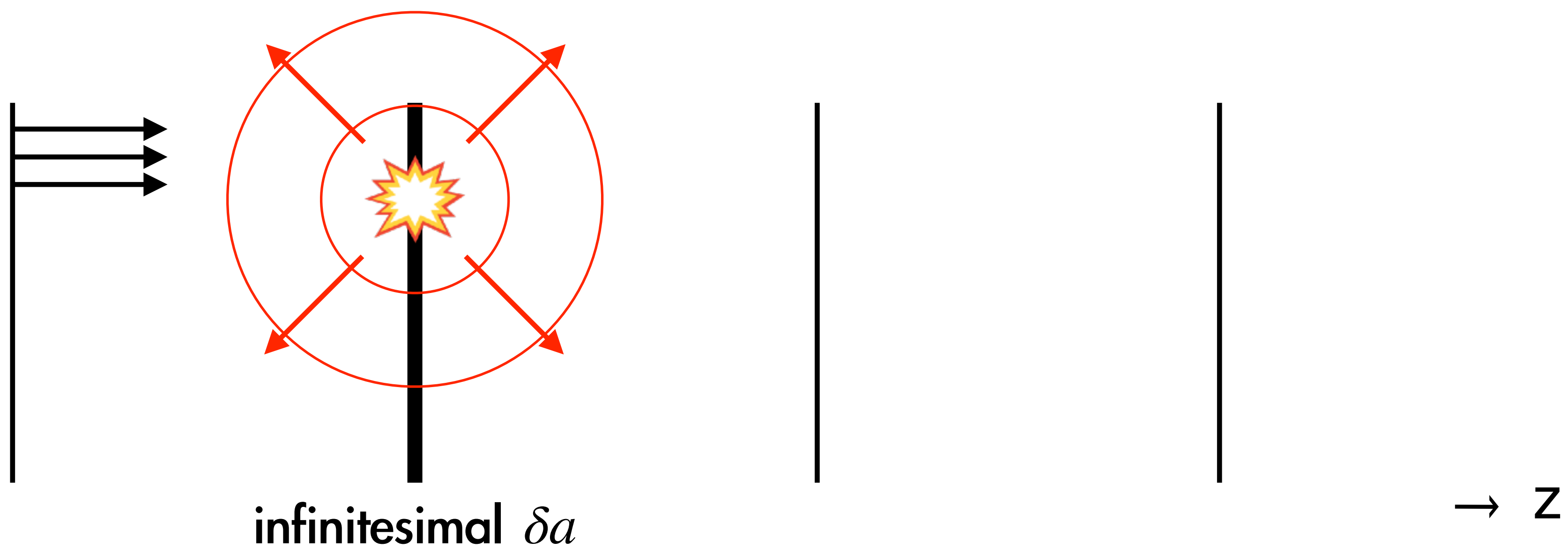


$$\Phi(r,t) \propto e^{-i\omega t}\left(e^{ikz} + f(\omega,\theta)\frac{e^{ikr}}{r} \right)$$

Original wave Scattered wave

✓ $\dfrac{d\sigma}{d\Omega} = f(\omega,\theta)$

Forward Scattering

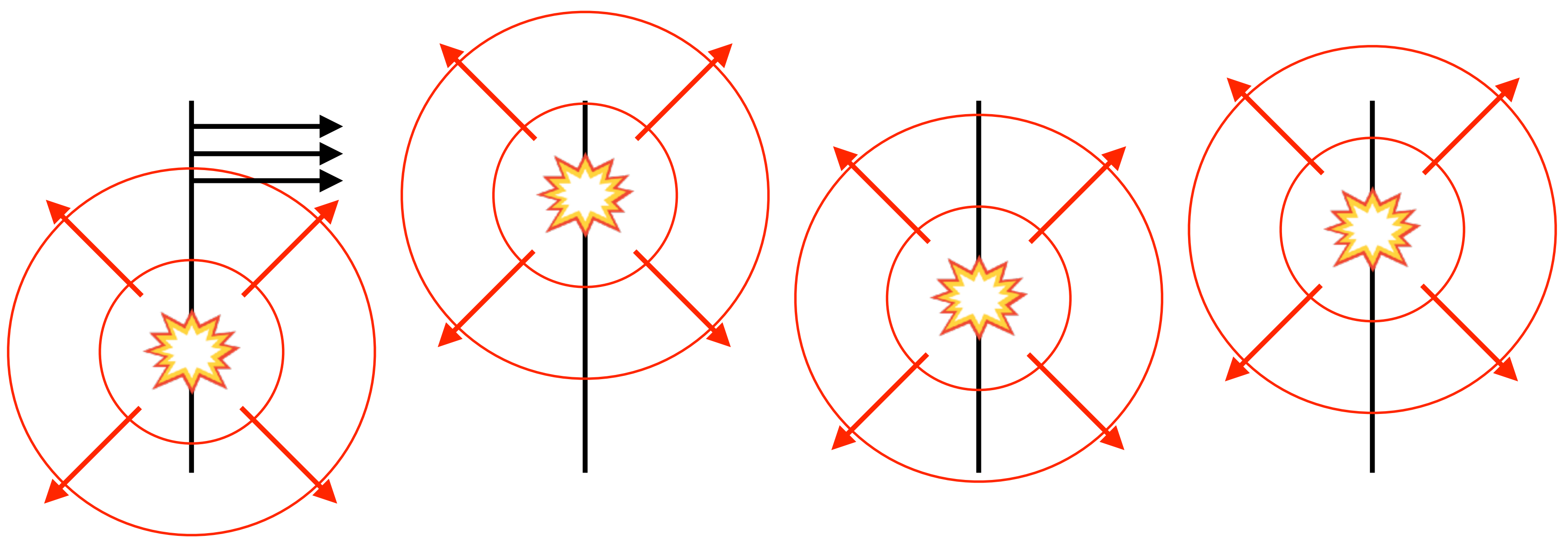


$$\Phi(z) \propto e^{ikz}\left(1+ n\delta a \int_0^{\infty} \frac{e^{ik\sqrt{\rho^2+z^2}}}{\sqrt{\rho^2+z^2}} f(\omega,\theta) 2\pi\rho d\rho\right)$$

$$\sim e^{i\omega z}\left(1+ \frac{2\pi n\delta a}{\omega} f(\omega,0)\right)$$

✓ Coherent sum of forward scatterings

Forward Scattering & Refraction



$$\lim_{j\to\infty}\left[1+\frac{2\pi n}{\omega}\frac{z}{j}f(\omega,0)\right]^j = e^{i(2\pi n/\omega)f(\omega,0)z}$$

$$\boxed{\Phi(t,z) \propto e^{-i\omega t}e^{iz\left(\omega+\frac{2\pi n}{\omega}f(\omega,0)\right)}}$$

✓ $n_{\text{refr}} = 1 + \dfrac{2\pi}{\omega^2}nf(\omega,0)$

Photon Dispersion in non-rel medium

- Thompson scattering

$$f(\omega,0) = \sqrt{\frac{d\sigma}{d\Omega}} = \sqrt{\left(\frac{\alpha}{m_e}\right)^2 \left|\epsilon \cdot \epsilon'\right|^2} = \frac{\alpha}{m_e}$$

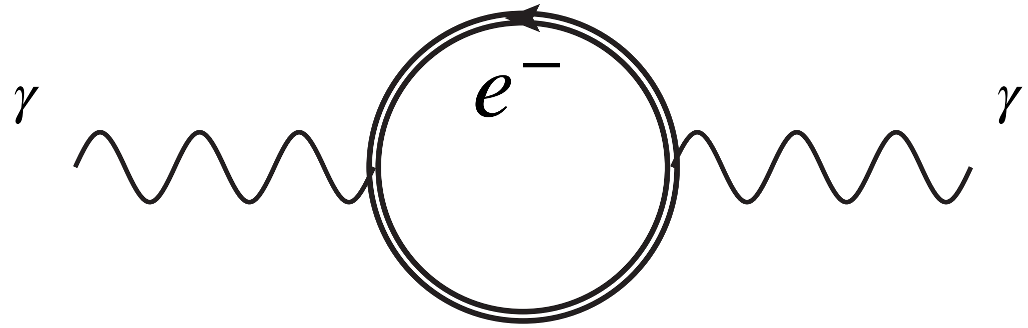
=1 forward scattering

$$\boxed{e^{-i\omega t} e^{iz\left(k + \frac{1}{2k}\frac{4\pi\alpha n_e}{m_e}\right)}}$$

✓ $\omega^2 - \left(k + \frac{1}{2k}\frac{4\pi\alpha n_e}{m_e}\right)^2 = 0$ ☞ $\omega^2 - k^2 \approx \frac{4\pi\alpha n_e}{m_e}$

Plasma frequency

Photon Dispersion



$$\mathscr{L}_{\text{medium}} = \frac{1}{2} A_\mu \Pi^{\mu\nu} A_\nu$$

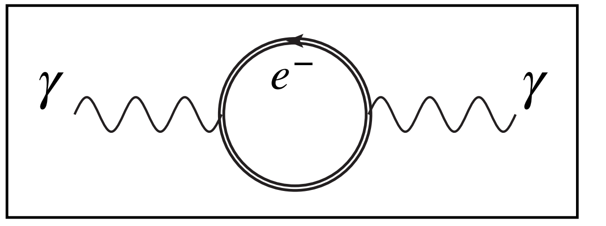
Polarization tensor

$$\checkmark\ \Pi^{\mu\nu} = \left\langle J^\mu_{\text{EM}} J^\nu_{\text{EM}} \right\rangle = \sum_{i=\text{T,L}} \pi_i \left(-\epsilon_i^\mu \epsilon_i^{*\nu} \right)$$

$$= 16\pi\alpha \int \frac{d^3\overrightarrow{p}}{(2\pi)^3 2E_p} f_e \frac{(P\cdot K)^2 g^{\mu\nu} + K^2 P^\mu P^\nu - P\cdot K(K^\mu P^\nu + K^\nu P^\mu)}{(P\cdot K)^2 - (K^2)^2/4}$$

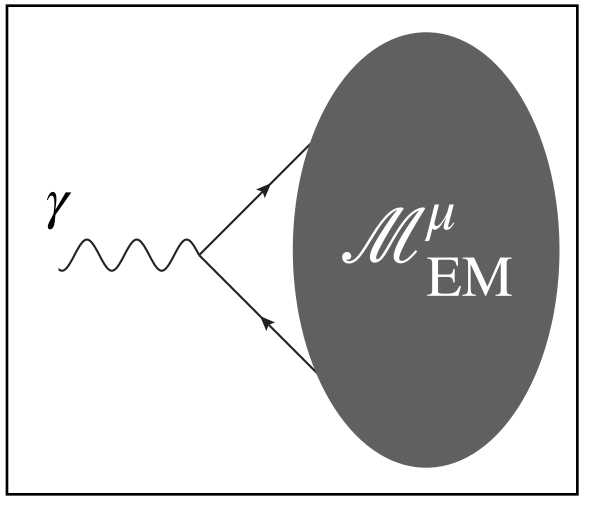
Polarization Tensor $\pi_{\mathrm{T,L}}$

- Real part: photon refractive index (i.e., effective photon mass)
  - from coherent forward scatterings
  - parametrized by plasma frequency $\omega_{\mathrm{pl}} \propto \sqrt{n_e}$
  - in Lorentz gauge $\partial_\mu A^\mu = 0$



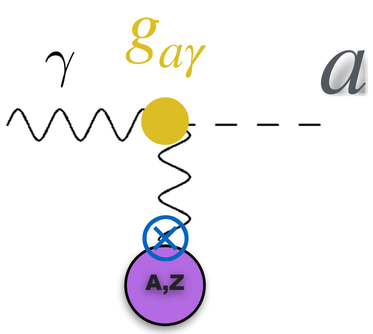
$$\mathrm{Re}\left[\pi_{\mathrm{T}}\right] = \frac{1}{2}\left(\mathrm{tr}\left[\Pi\right] - \pi_{\mathrm{L}}\right) \sim \omega_{\mathrm{pl}}^2 \qquad \mathrm{Re}\left[\pi_{\mathrm{L}}\right] = \left(1 - \omega^2/k^2\right)\Pi^{00} \sim \frac{\omega^2 - k^2}{\omega^2}\omega_{\mathrm{pl}}^2$$

- Imaginary part: photon absorption width
  - detailed balance ☞ $\mathrm{Im}\,\pi_{\mathrm{T,L}} = -\,\omega\left(e^{\omega/T} - 1\right)\Gamma^{\mathrm{P}}_{\gamma_{\mathrm{T,L}}}$
  - $\mathrm{Im}\,\pi_{\mathrm{T,L}} \ll \mathrm{Re}\,\pi_{\mathrm{T,L}}$ in typical



Screening Effects

- Regulate IR divergence of scatterings involving long-range interactions



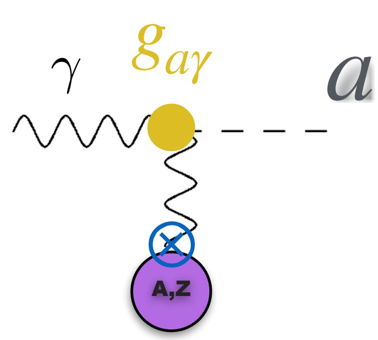
"Primakoff" process

- In the static limit for background

$$\left(k^2 + \pi_{\mathrm{L}}(0,k)\right)\Phi(k) = \rho_k$$
$$\left(k^2 + \pi_{\mathrm{T}}(0,k)\right)\overrightarrow{A}(k) = \overrightarrow{J}_k$$

Screening Effects

- Regulate IR divergence of scatterings involving long-range interactions



“Primakoff” process

- In the static limit for background

✓ No screening for magnetic field

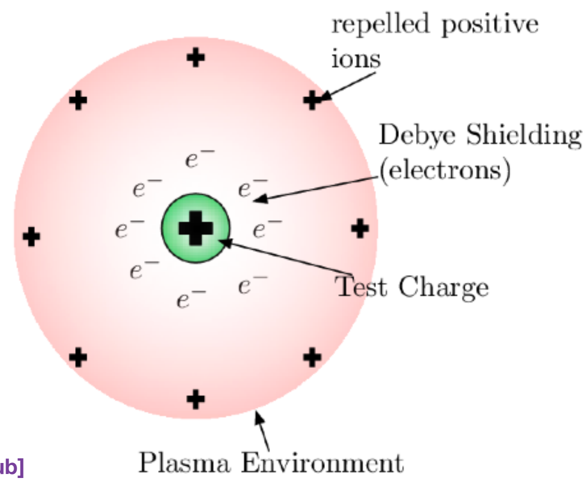
$$\left(k^2 + \pi_{\mathrm{L}}(0,k)\right)\Phi(k) = \rho_k$$
$$\left(k^2 + \cancel{\pi_{\mathrm{T}}(0,k)}\right)\overrightarrow{A}(k) = \overrightarrow{J}_k$$

Screening Effects

$$\left(k^2 + \pi_{\mathrm{L}}(0,k)\right)\Phi(k) = \rho_k$$

$\equiv \kappa_s^2$

- Rearrangement of electric charges



[Hanspeter Schaub]

$$\checkmark\ \Phi \propto \frac{1}{r} e^{-\kappa_s r}$$

- Classical limit: $$\kappa_s^2 = \kappa_{\mathrm{D}}^2 = \frac{4\pi\alpha n}{T}$$

Debye screening

✓ Independent of mass
✓ Including all ions

- Degenerate limit: $$\kappa_s^2 = \kappa_{\mathrm{TF}}^2 = \frac{4\alpha}{\pi} E_{\mathrm{F}} p_{\mathrm{F}}$$

Thomas-Fermi