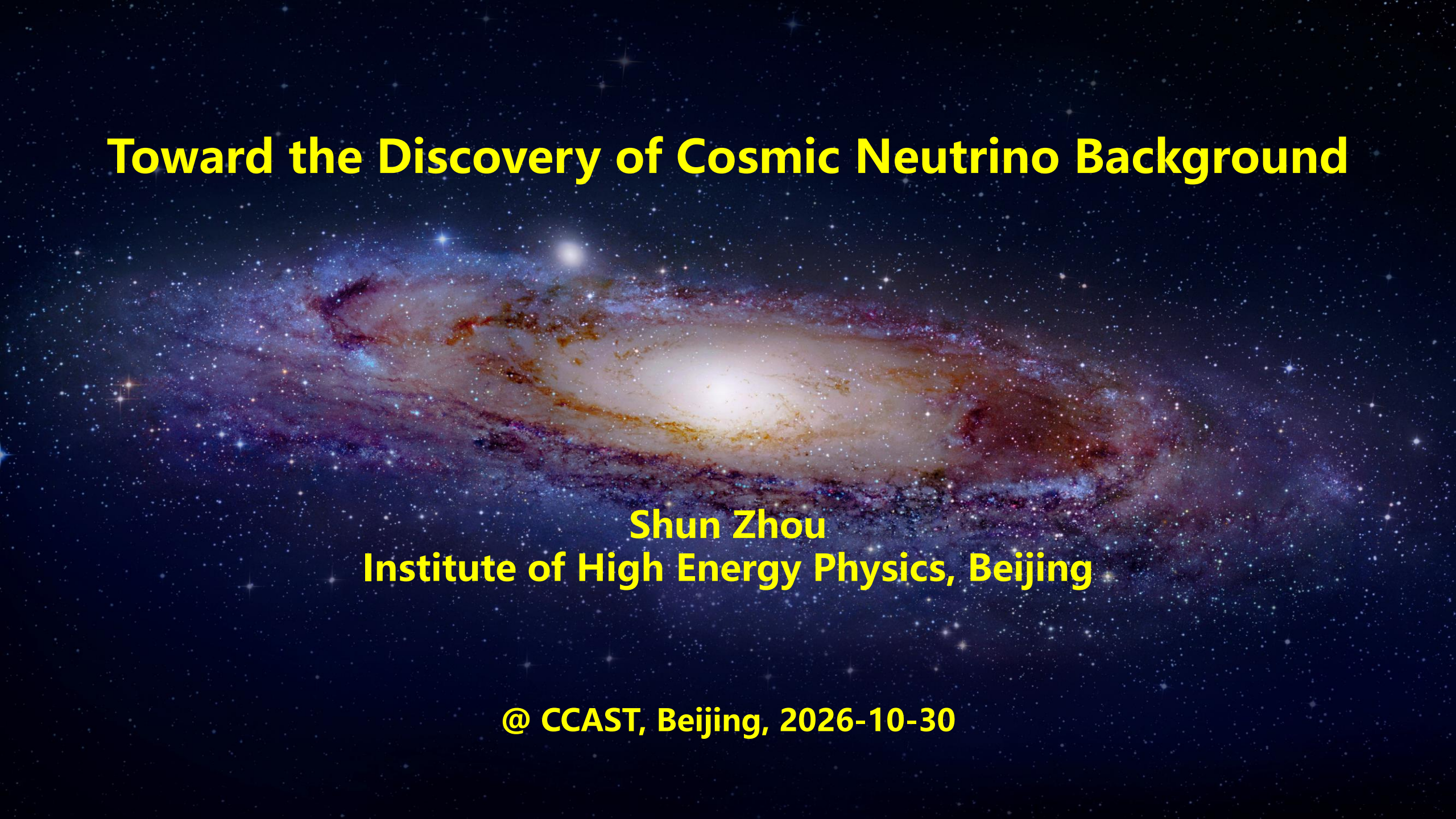
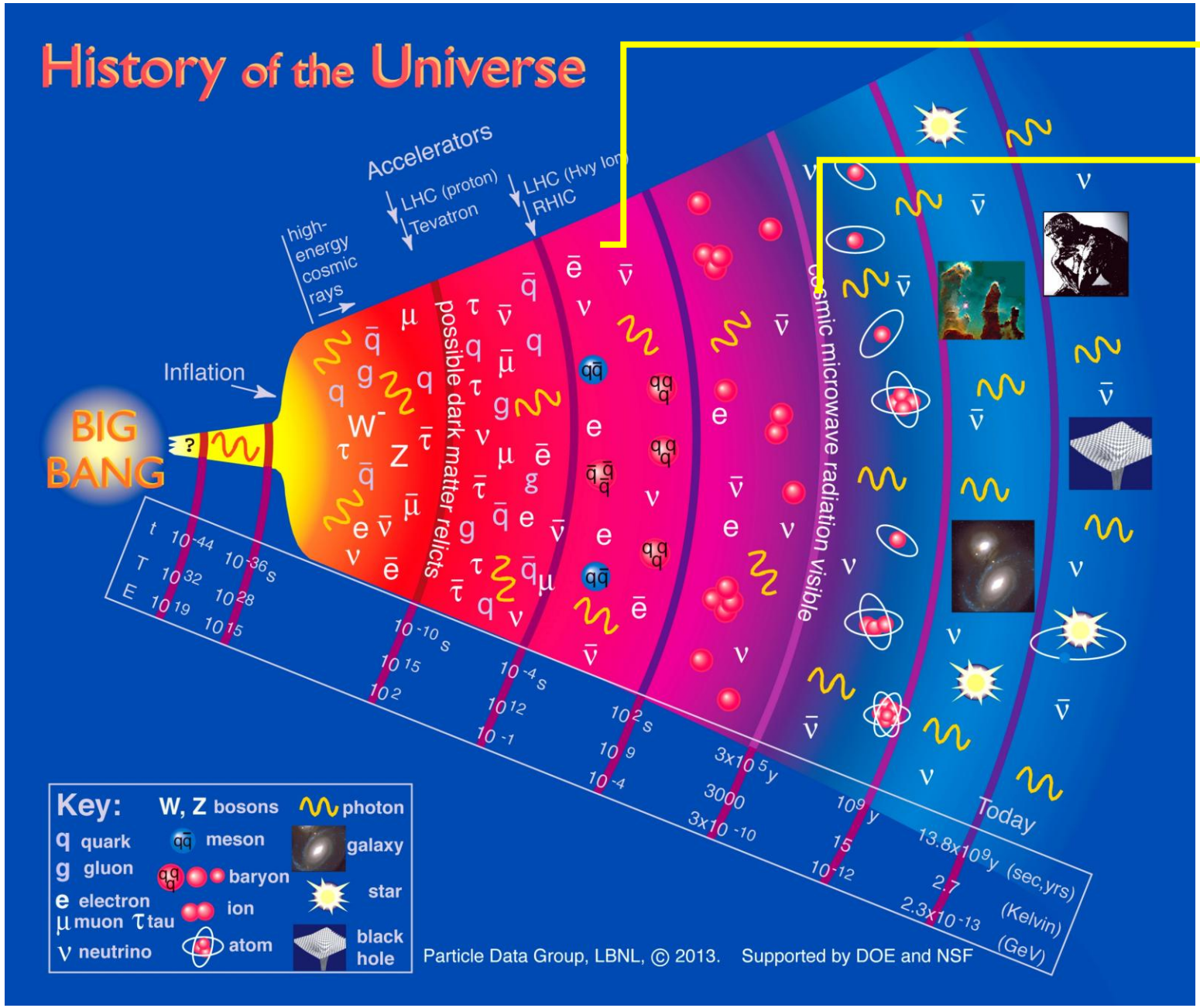
Toward the Discovery of Cosmic Neutrino Background



Shun Zhou
Institute of High Energy Physics, Beijing

@ CCAST, Beijing, 2026-10-30

Relic neutrinos from the Big Bang



Cosmic ν Background (CνB or CNB)

neutrino decoupling@ t =1 second

Cosmic Microwave Background (CMB)

photon decoupling@ t =10^5 years

◆ **Why is the CνB detection important?**

① **test standard model of cosmology**

② **evolution of the early Universe (1s)**

③ **probe ν masses & Majorana nature**

Temperature today

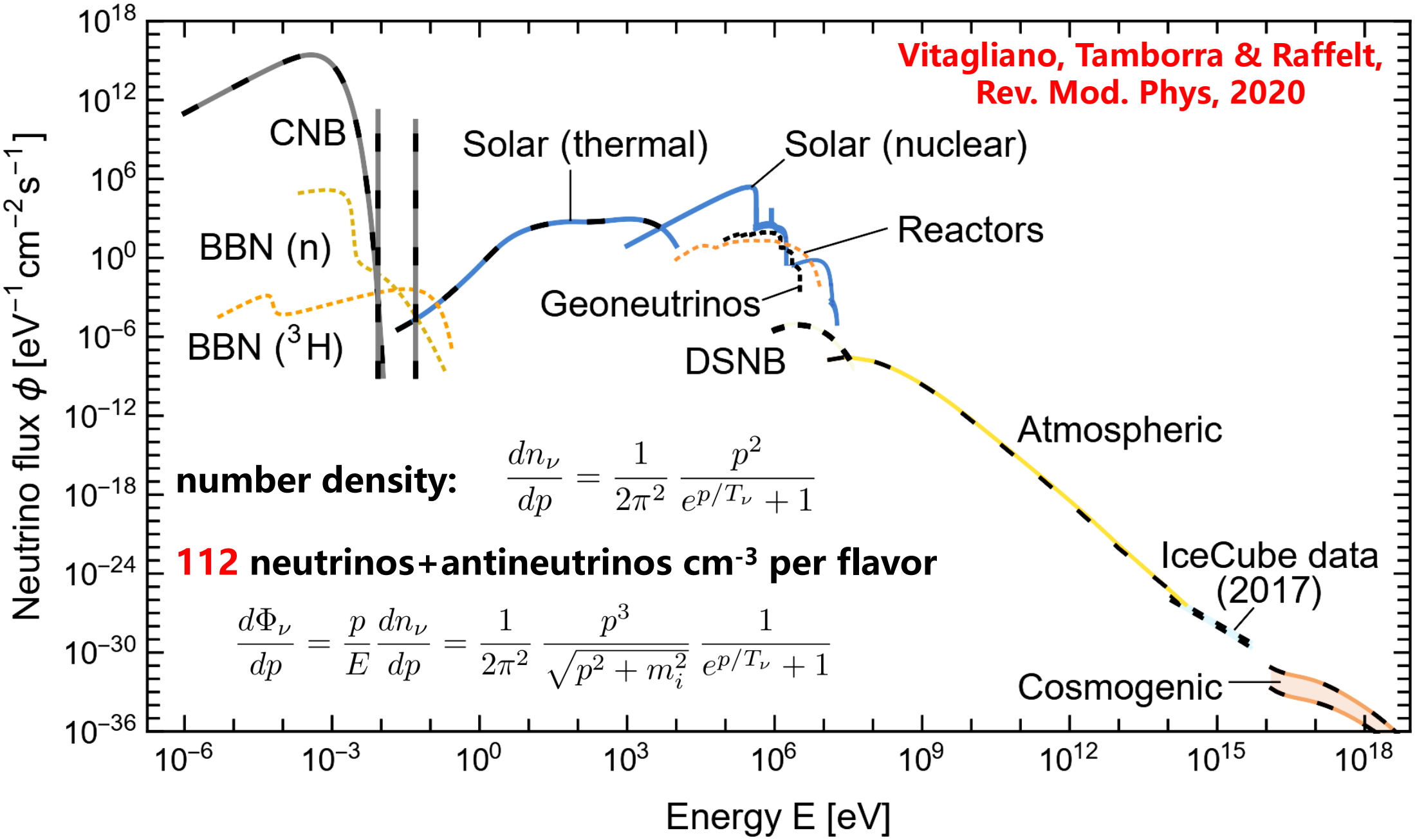
$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

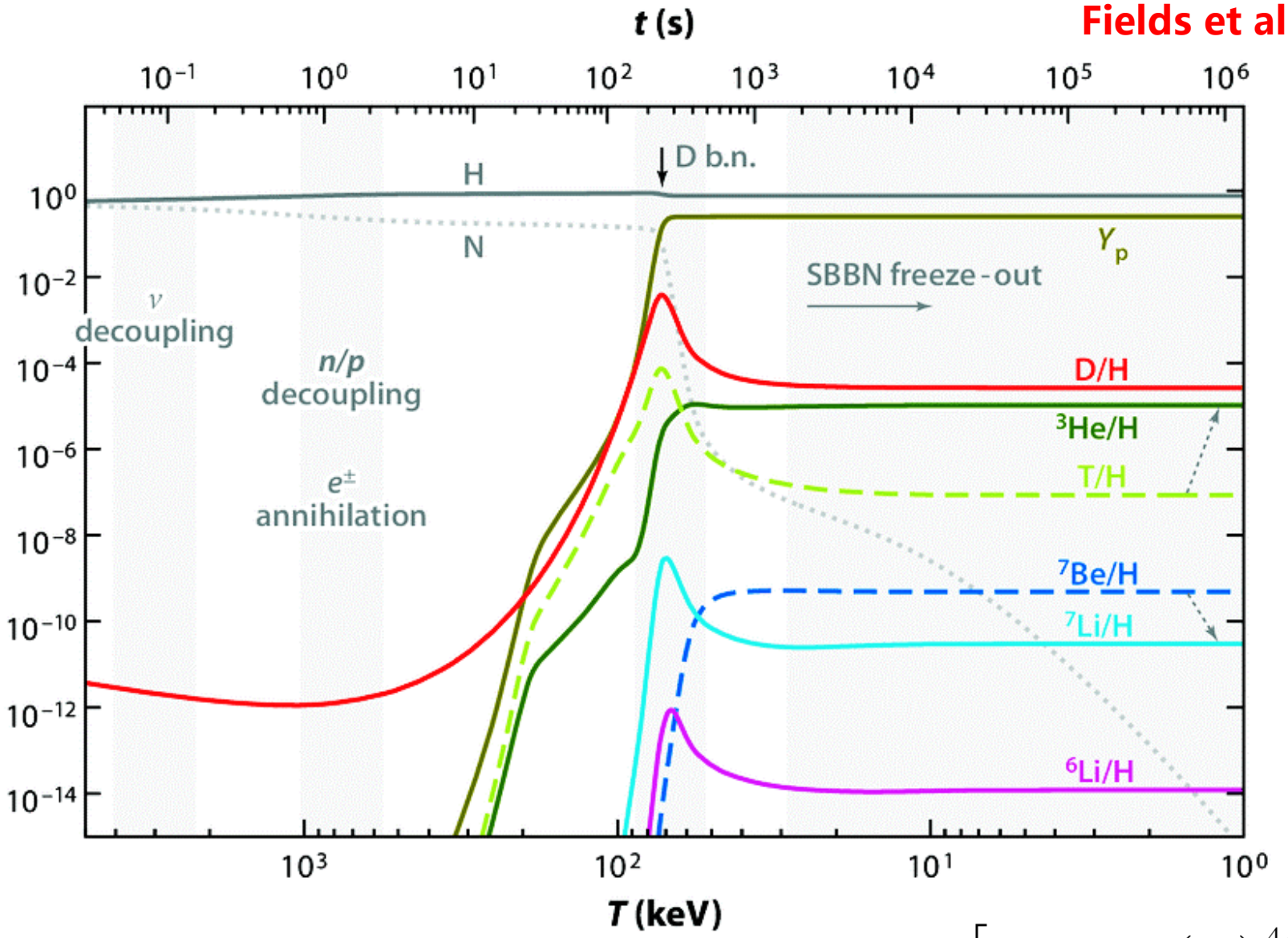
the only source of non-relativistic ν's

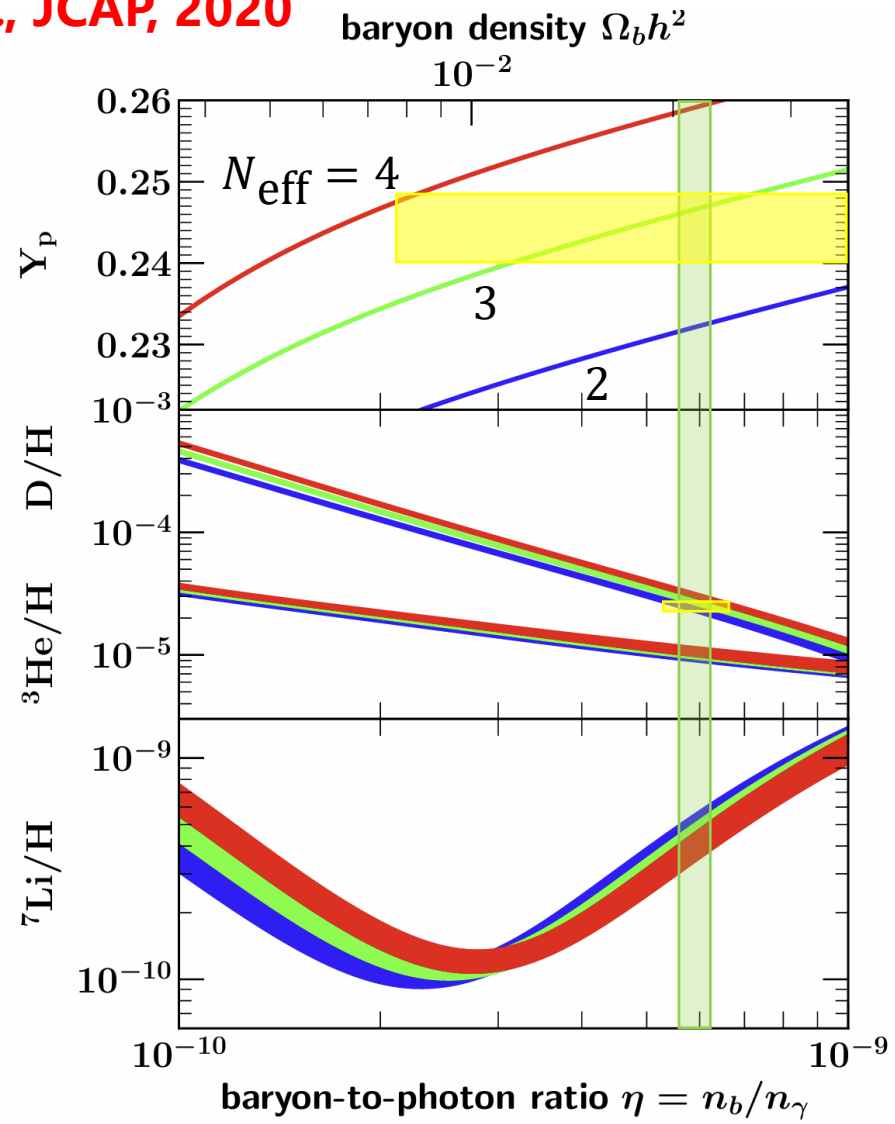
Relic neutrinos from the Big Bang



Big Bang Nucleosynthesis (BBN): indirect evidence for CνB

Fields et al., JCAP, 2020



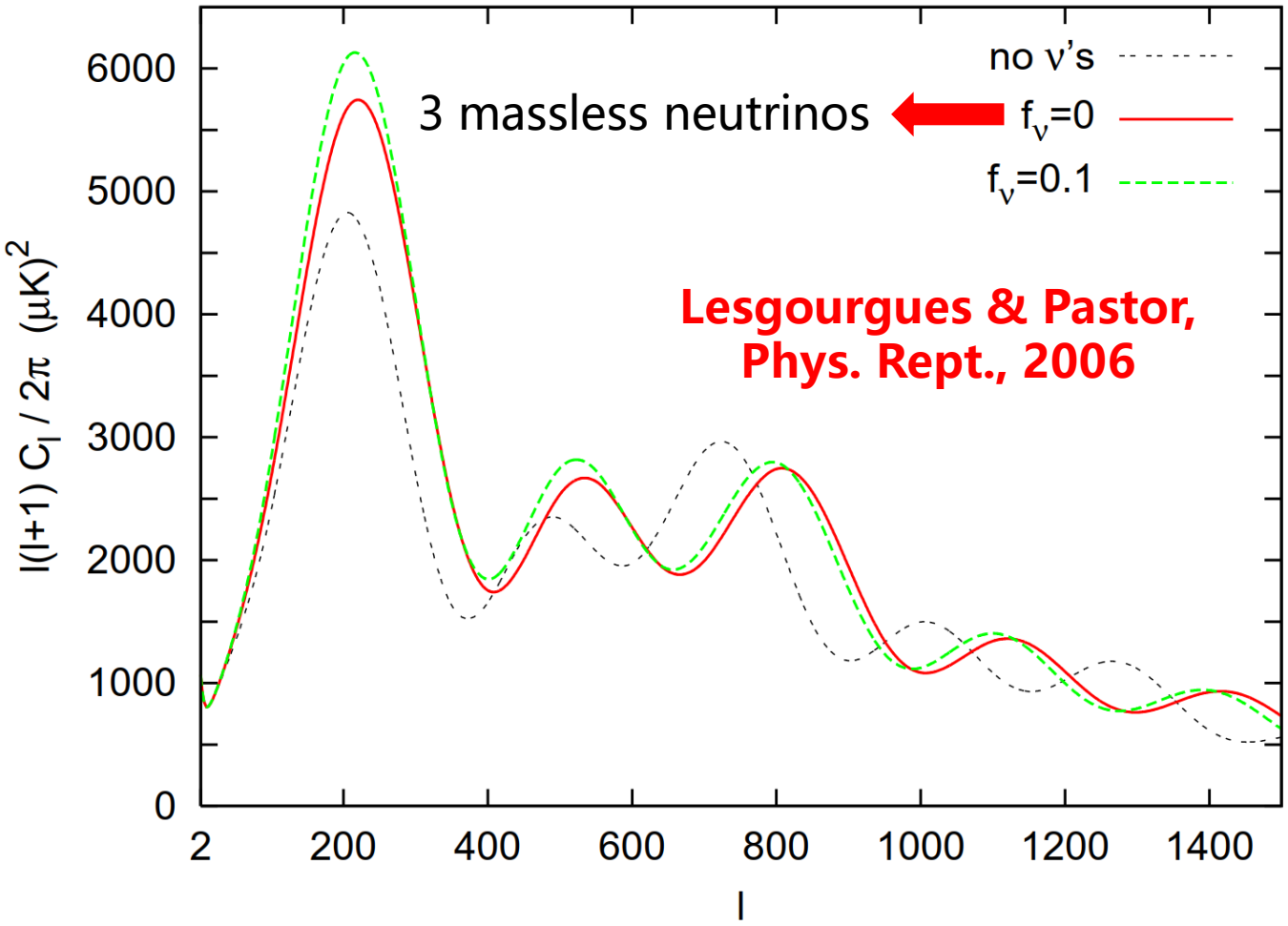


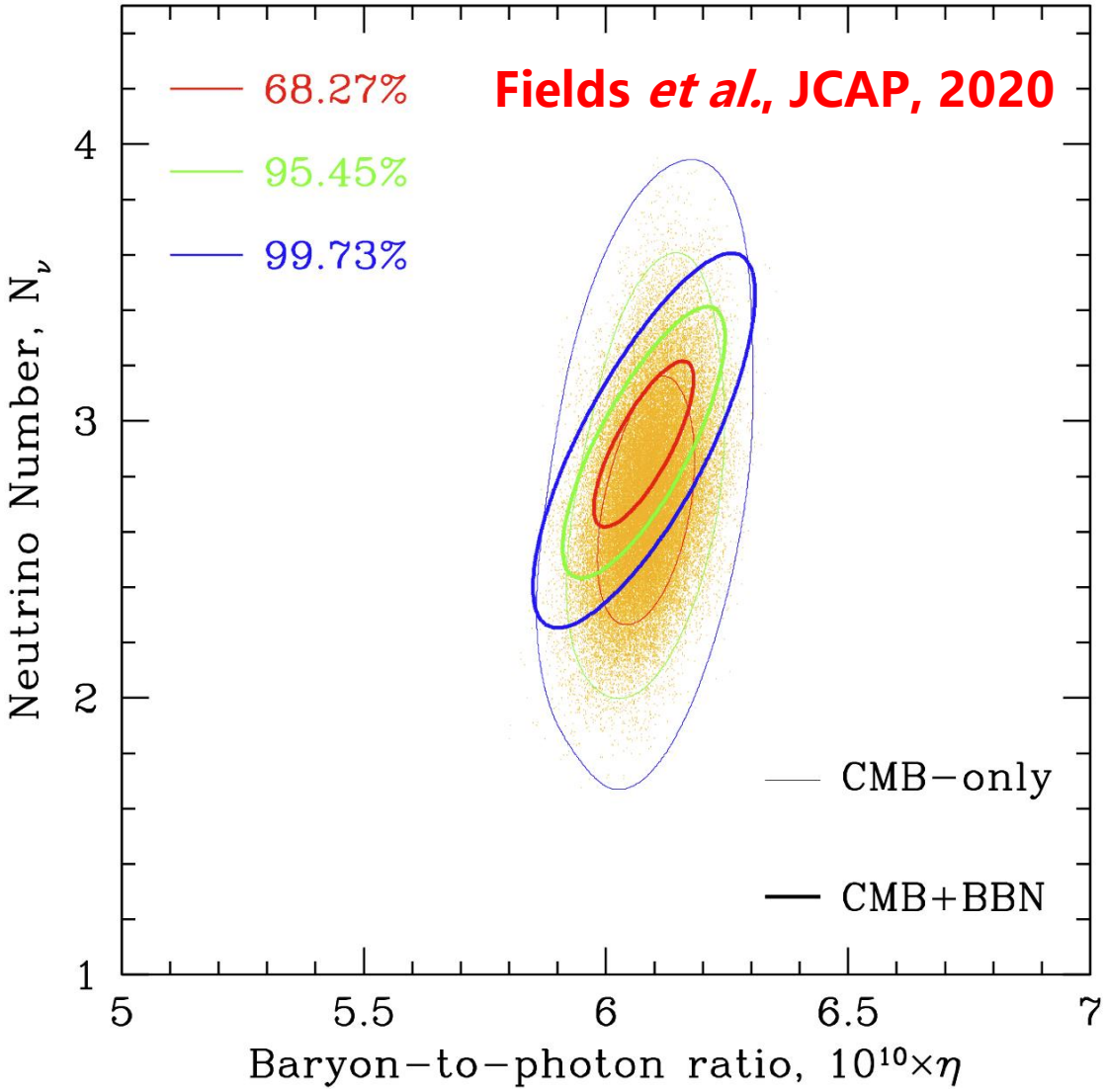
Effective number of neutrino generations: $\rho_{\rm rad} = \left[1 + N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma$

Standard value: $N_{\rm eff} = 3.044$

Drewes et al., 2402.18481

CMB: indirect evidence for CνB

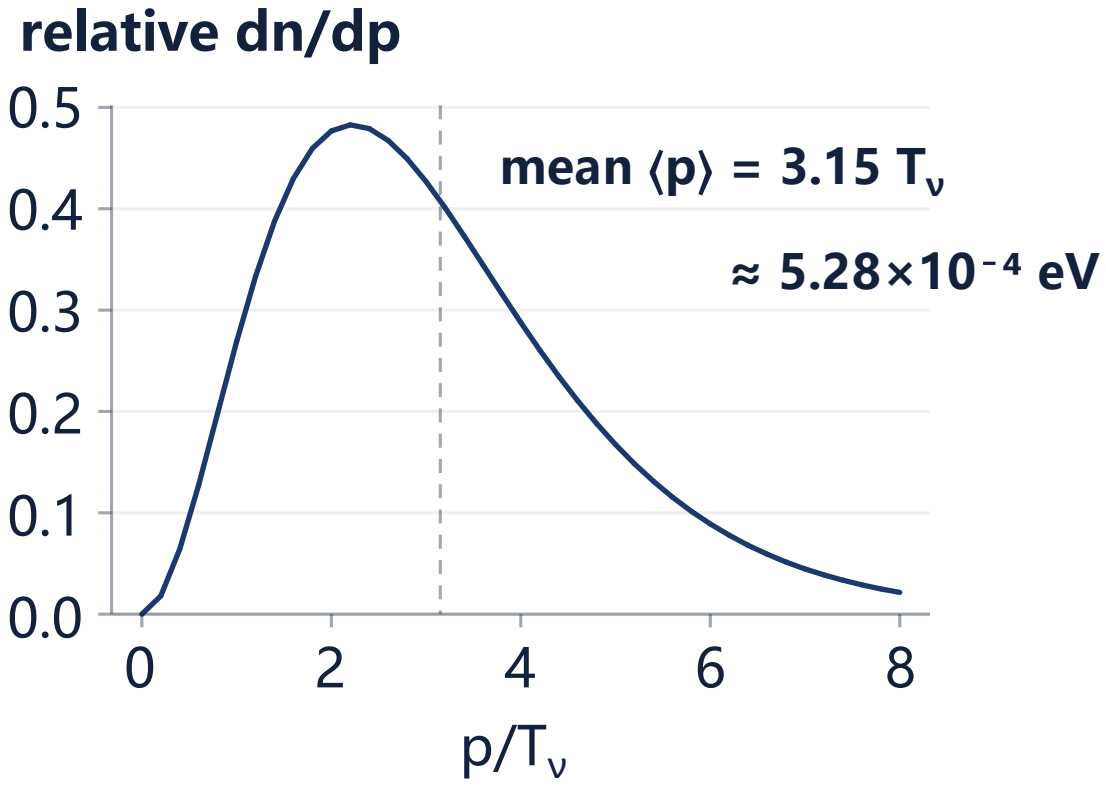




Energy density fraction: $f_\nu \equiv \dfrac{\rho_\nu}{(\rho_{\rm cdm}+\rho_{\rm b}+\rho_\nu)} = \dfrac{\Omega_\nu}{\Omega_{\rm m}}$

sensitive to effective number & neutrino masses

◆Why is the CνB detection so difficult?



Heavy nucleus, $Q_W \approx 100$:

$\sigma \approx$ **10^{-54} cm²**

Mean free path in a solid:

$\lambda = 1/(n\sigma) \approx$ **10^{14} light-years**

Tiny energy

meV

Sub-meV spectroscopy far below any useful detector threshold; there is no sharp energy edge to trigger on

Tiny cross section

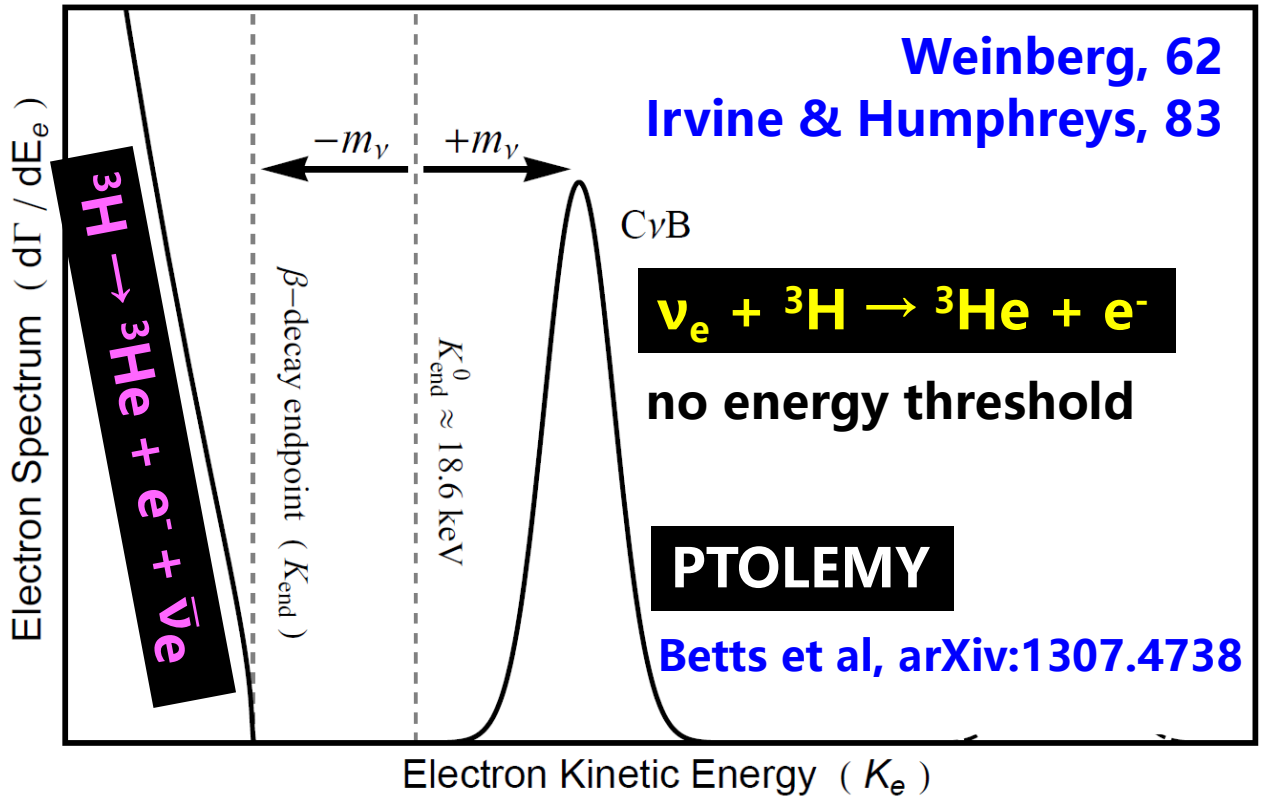
10^{-54} cm²

For non-relativistic coherent scattering on a nucleus — a mean free path of order 10^{14} light-years in a solid

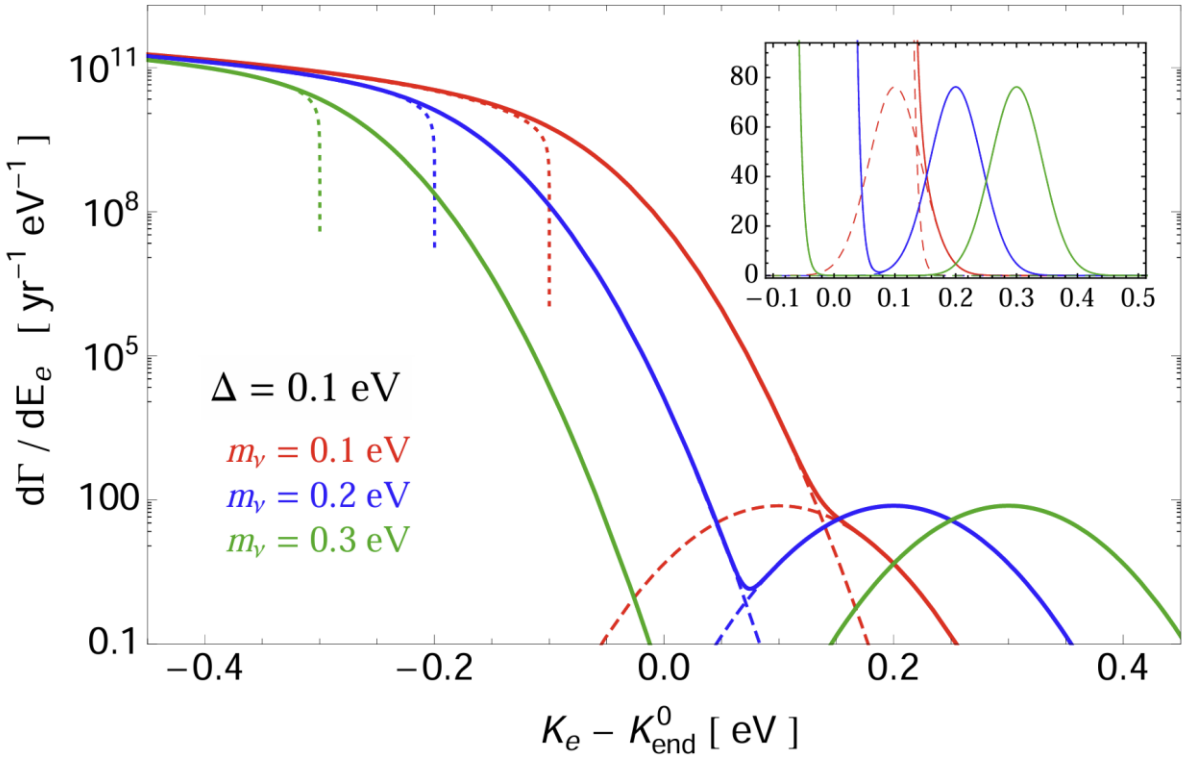
$$\sigma = (2/\pi)\, G_F^2\, Q_W^2\, m_\nu^2$$

Summary of Direct-detection Methods

➢ Capture on tritium



Long *et al*, arXiv:1405.7654



★ first experiment

★ 100 g of tritium

★ graphene target

★ planned energy resolution 0.15 eV

★ CνB capture rate

D = Dirac $\quad \Gamma^{\rm D}_{\rm C\nu B} \sim 4\ {\rm yr}^{-1}$

M = Majorana $\quad \Gamma^{\rm M}_{\rm C\nu B} \sim 8\ {\rm yr}^{-1}$

signal-to-background ratio:

$$r_{\rm SN} \gtrsim 1 \qquad \text{for} \qquad \Delta \lesssim 0.7 m_\nu$$

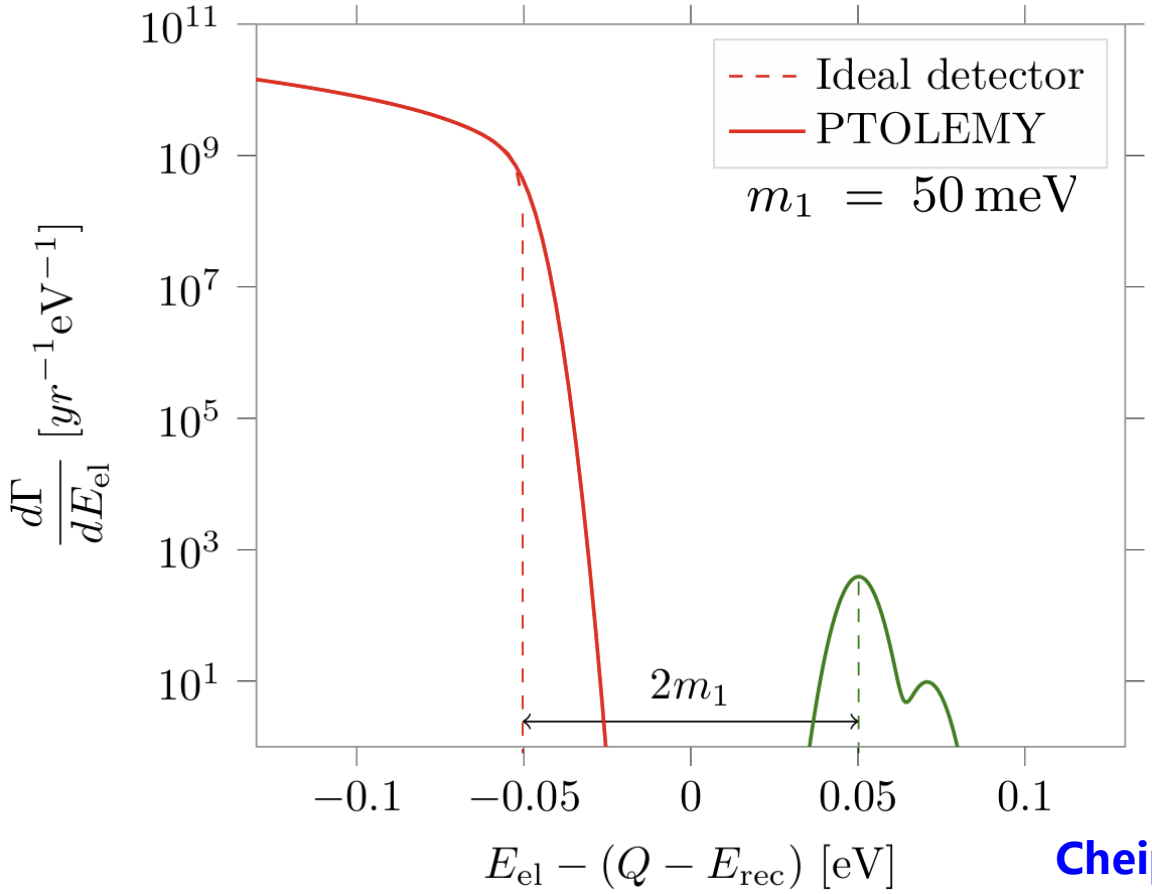
cf. only 60 μg tritium in KATRIN

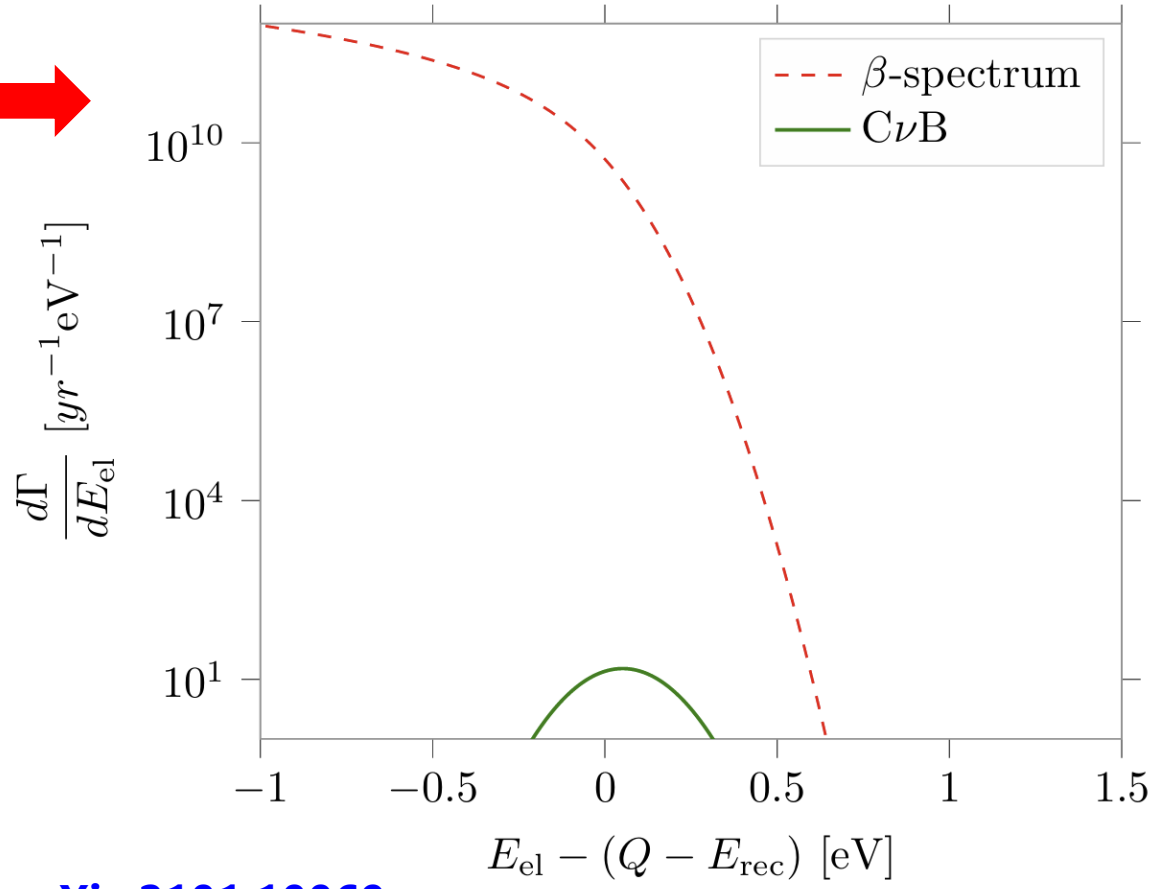
Challenges for PTOLEMY

Potential perpendicular to the graphene $U(z) = \kappa z^2/2 + U_0$ localized nuclei cannot be at rest

Potential	Source	κ, $\left[\mathrm{eV/Å}^2\right]$	λ, [Å]	ΔE, [eV]
Chemisorption	[23]	2.15	0.16	0.60
	[21], GGA	4.62	0.13	0.73
	[21], vdW-DF	4.9	0.13	0.75

$$\Delta E \approx \frac{\hbar c}{\lambda_{\mathrm{el}}}\gamma \qquad \gamma = \left[\frac{Q^2 m_{\mathrm{el}}}{m_{\mathrm{nucl}}^3 c^4}\right]^{1/4}$$ uncertainty in electron energy

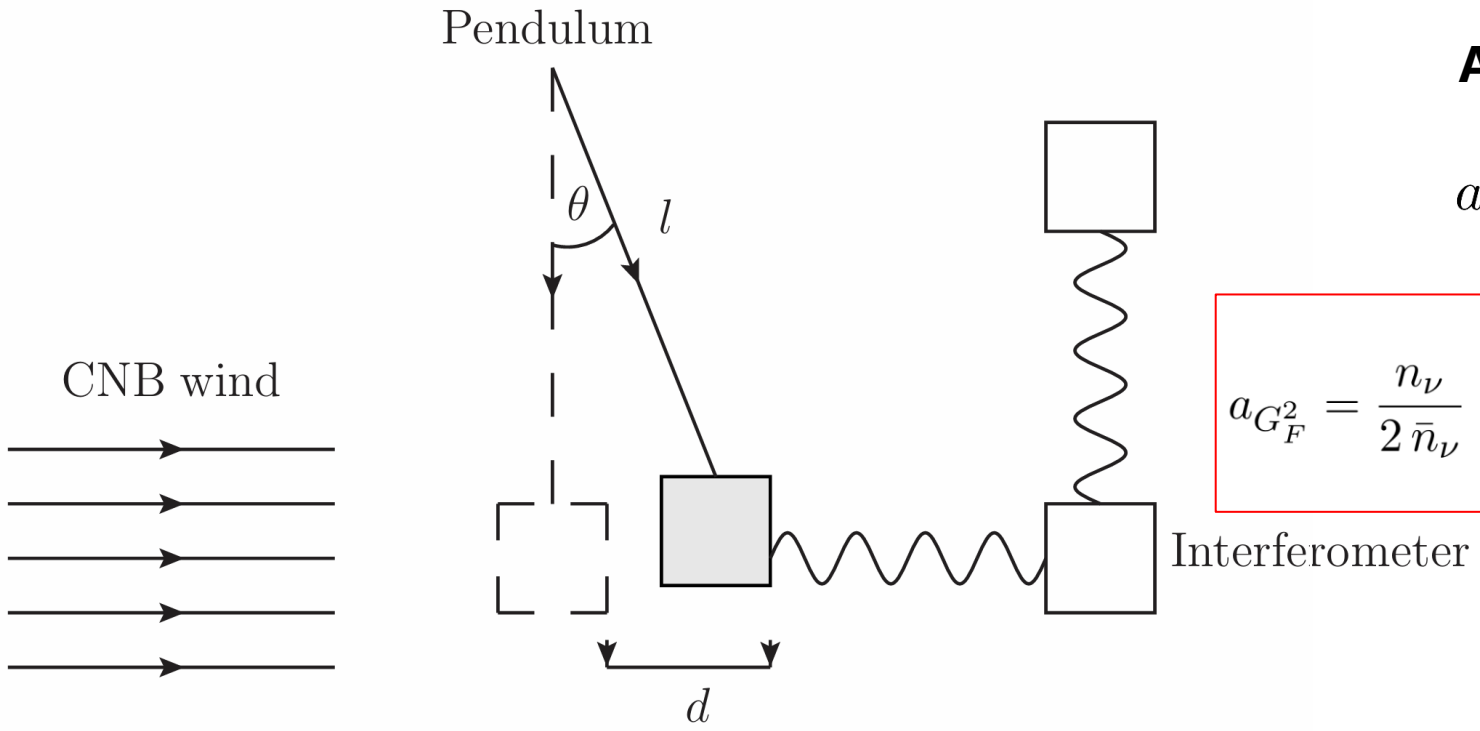




Cheipesh *et al*, arXiv:2101.10069

➢ Laser Interferometers

Domcke & Spinrath, arXiv:1703.08629



Acceleration of the test mass

$$a_{G_F^2} = \frac{2\,\pi^2\,G_F^2}{\hbar\,c^2}\,n_\nu\,\frac{N_{AV}^2(A-Z)^2\,\rho}{A^2\,m_{AV}^2}\,\frac{\langle\Delta p\rangle E_\nu}{p_\nu^2}$$

$$a_{G_F^2} = \frac{n_\nu}{2\,\bar{n}_\nu}\begin{cases} 3\cdot 10^{-33}\,\mathrm{cm/s^2} & \text{for (R)}\,, \\ 5\cdot 10^{-31}\,(m_\nu/0.1\ \mathrm{eV}/c^2)\,\mathrm{cm/s^2} & \text{for (NR-NC)}\,, \\ 2\cdot 10^{-27}\,(10^{-3}/\beta_{\mathrm{vir}})\,\mathrm{cm/s^2} & \text{for (NR-C)}\,, \end{cases}$$

relevant parameters for lead:

$$\rho \approx 11.34\ \mathrm{g/cm^3} \quad A = 208 \quad Z = 82$$

smaller by more than 10 orders of magnitude

★ **Coherent scattering of CνB with nuclei: enhancement**

★ **Cross section of weak interactions suppressed by G_F*G_F**

★ **Average momentum transfer from CνB to the test mass**

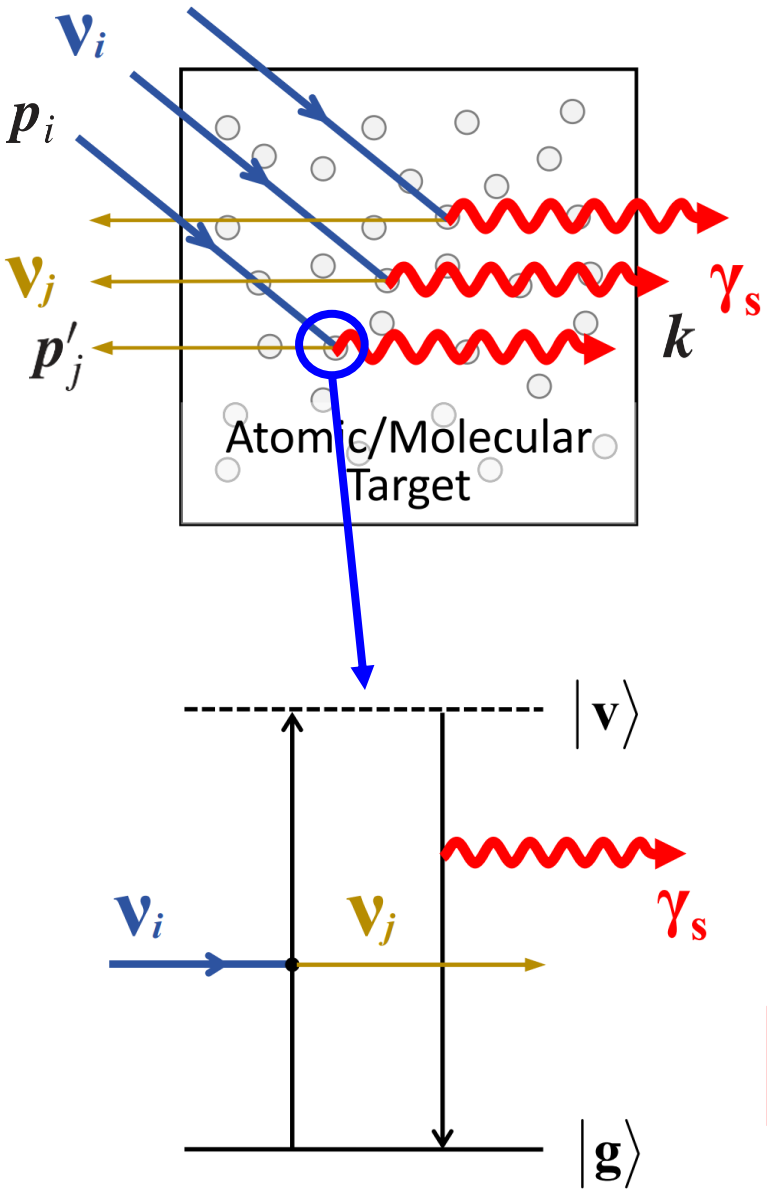
★ **Current sensitivity a_{min} = 10^{-16} cm s^{-2} & future 10^{-18} cm s^{-2}**

➢ *Z*-burst: EHE neutrinos

$$E_{\nu_i}^{\mathrm{res}} = \frac{m_Z^2}{2m_{\nu_i}} = 4.2\times 10^{21}\left(\frac{\mathrm{eV}}{m_{\nu_i}}\right)\ \mathrm{eV}$$

Weiler, PRD, 1982

A New Method: parametric fluorescence



☑ Coherent scattering

G.Y. Huang & S. Zhou, PRL, 2026

$$\mathcal{M}_{\rm tot} = \sum_{r=1}^{N} \mathcal{M}_r \cdot \mathrm{e}^{\mathrm{i}(\boldsymbol{p}_i - \boldsymbol{p}'_j - \boldsymbol{k})\cdot \boldsymbol{x}_r}$$

phase matching $\boldsymbol{p}_i - \boldsymbol{p}'_j - \boldsymbol{k} = 0$

the amplitudes for each radiant added coherently, leading to the enhancement by a factor of *N* (number of radiants)

☑ On resonance

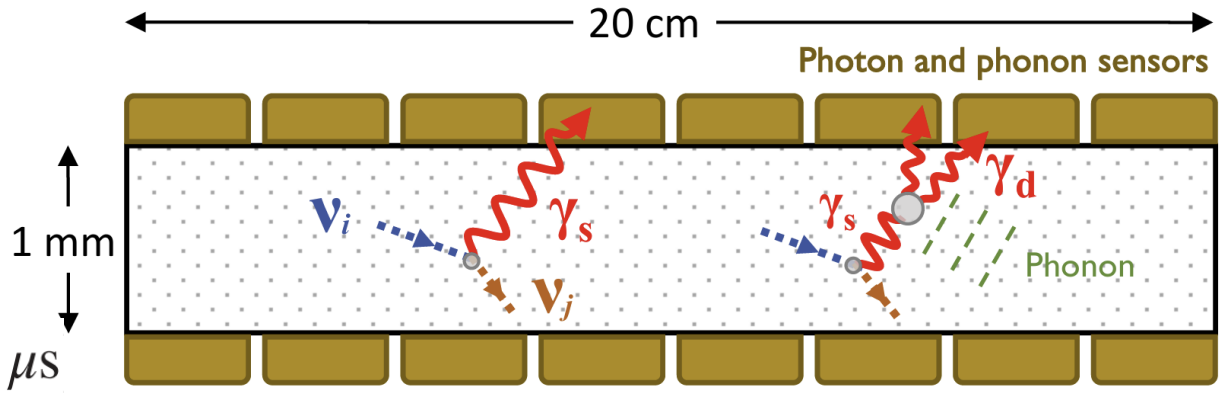
$E_{\rm vg} = E_i - E'_j$

further resonant enhancement of the emission rate

☑ Detection

$R_{\nu_3 \to \nu_1} \sim 8\ \mathrm{yr}^{-1}$

$V = 40\ \mathrm{cm}^3 \quad T_c = 10\ \mu\mathrm{s}$



Theoretical Framework

Response of the dielectric medium to the applied electric field

Nonlinear Optics

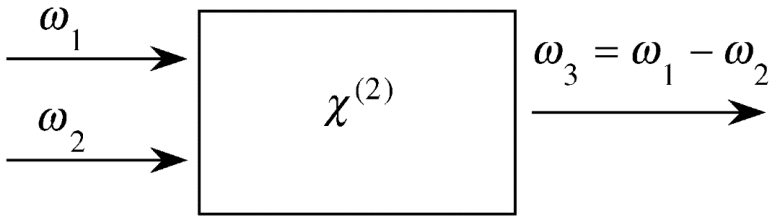
Boyd, 2008

$$P_i \supset \chi_{ij}^{(1)}\mathcal{E}_j + \chi_{ijk}^{(2)}\mathcal{E}_j\mathcal{E}_k + \chi_{ijkl}^{(3)}\mathcal{E}_j\mathcal{E}_k\mathcal{E}_l + \cdots$$

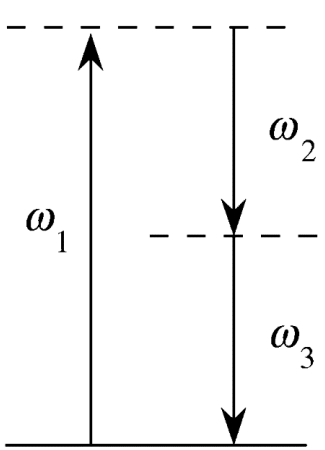
polarization **linear and nonlinear susceptibilities**

(a)

second-order susceptibility



(b)

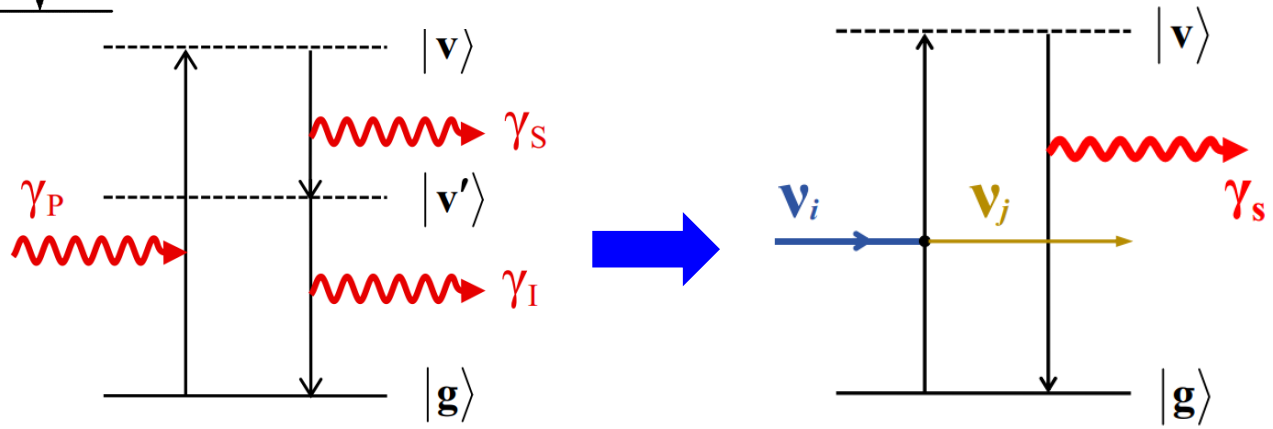


Parametric fluorescence

Byer & Harris, 1968

- **The quantum state of the atom remains the same**
- **The virtual states are involved and no energy transfer to the media**

nonlinear susceptibility



- **Frequency-difference generation**
- **Lower-frequency input photons are created**
  optical parametric amplification
- **Occurs also without lower-frequency photons**

Theoretical Framework

Calculating the susceptibilities in quantum mechanics

Nonlinear Optics

Boyd, 2008

$$|\Psi(t)\rangle = C_{\mathrm{g}}(t)|\mathrm{g}\rangle + \sum_{\mathrm{v}} C_{\mathrm{v}}(t)|\mathrm{v}\rangle$$

electric-dipole interaction $H_{\boldsymbol{d}} = -\boldsymbol{d}\cdot\boldsymbol{\mathcal{E}}$

$$\boldsymbol{\mathcal{E}}(t,\boldsymbol{x}) = \textstyle\sum_i \boldsymbol{\mathcal{E}}(\boldsymbol{k}_i)\cdot\exp(-i\omega_i t)$$

first-order result for the transition coefficient

$$C_{\mathrm{v}}^{(1)}(t) = -\mathrm{i}\int_{-\infty}^{t} \mathrm{d}\tilde{t}\,\langle \mathrm{v}|\,H_{\boldsymbol{d}}(\tilde{t})\,|\mathrm{g}\rangle = \sum_i \frac{\boldsymbol{d}_{\mathrm{vg}}\cdot\boldsymbol{\mathcal{E}}(\omega_i)}{E_{\mathrm{vg}}-\omega_i}\mathrm{e}^{\mathrm{i}(E_{\mathrm{vg}}-\omega_i)t}$$

expected value of the electric-dipole operator

$$\langle \boldsymbol{d}\rangle = \textstyle\sum_{\mathrm{v}} C_{\mathrm{v}}^{(1)}\,\langle \mathrm{g}|\,\boldsymbol{d}\,|\mathrm{v}\rangle + C_{\mathrm{v}}^{(1)*}\,\langle \mathrm{v}|\,\boldsymbol{d}\,|\mathrm{g}\rangle$$

$$\langle \boldsymbol{d}\rangle^{(1)} = \sum_{i,\,\mathrm{v}} \frac{\boldsymbol{d}_{\mathrm{vg}}^{*}\left[\boldsymbol{d}_{\mathrm{vg}}\cdot\boldsymbol{\mathcal{E}}(\omega_i)\right]}{E_{\mathrm{vg}}-\omega_i}\mathrm{e}^{-\mathrm{i}\omega_i t} + \mathrm{h.c.}$$

polarization density

$$\boldsymbol{P}^{(1)} = n_{\boldsymbol{d}}\,\langle \boldsymbol{d}\rangle^{(1)}$$

$$\mathcal{H}_{2\gamma}^{(1)} = -\boldsymbol{P}^{(1)}\cdot\boldsymbol{\mathcal{E}}(t,\boldsymbol{x})$$

$$\mathcal{H}_{2\gamma}^{(1)} = \sum_{i,\,j,\,\mathrm{v}} \frac{n_{\boldsymbol{d}}\left[\boldsymbol{d}_{\mathrm{vg}}^{*}\cdot\boldsymbol{\mathcal{E}}(\boldsymbol{k}_j)\right]\left[\boldsymbol{d}_{\mathrm{vg}}\cdot\boldsymbol{\mathcal{E}}(\boldsymbol{k}_i)\right]}{\omega_i - E_{\mathrm{vg}}}\mathrm{e}^{-\mathrm{i}(\omega_i+\omega_j)t} + \mathrm{h.c.}$$

$n_{\boldsymbol{d}} \sim N_{\mathrm{A}}\ \mathrm{cm}^{-3}$ **dipole density in the medium**

Now take the perturbation to be neutrino fields

Emission Rate

Weak interaction

$$\sum_{i,j=1}^{3} \frac{G_{\mathrm{F}} C_{ij}}{\sqrt{2}} \overline{\nu}_j \gamma^\mu \left(1-\gamma_5\right) \nu_i \cdot \overline{e} \gamma_\mu \left(1-\gamma_5\right) e \qquad C_{ij} \equiv U_{ei}^* U_{ej} \ (i \neq j)$$

Only charged-current interaction contributes to the off-diagonal transition

In the non-relativistic limit of electrons:

E1-transition Hamiltonian

$$-H_{\mathrm{I}}^{\mathrm{E1}}(t, \boldsymbol{x_d}) = \frac{G_{\mathrm{F}} C_{ij}}{\sqrt{2}\mathrm{i}} \hat{j}_{ij}^0(\boldsymbol{p}_i, \boldsymbol{p}'_j)\, \boldsymbol{x}_{\mathrm{vg}} \cdot (\boldsymbol{p}_i - \boldsymbol{p}'_j)\, \mathrm{e}^{\mathrm{i}(E_{\mathrm{vg}}+E'_j-E_i)t} \left|\mathrm{v}\right\rangle \left\langle\mathrm{g}\right| + \boldsymbol{d}_{\mathrm{vg}} \cdot \boldsymbol{\mathcal{E}}(\boldsymbol{k})\, \mathrm{e}^{\mathrm{i}(-E_{\mathrm{vg}}+\omega)t} \left|\mathrm{g}\right\rangle \left\langle\mathrm{v}\right| + \mathrm{h.c.}$$

M1-transition Hamiltonian

$$-H_{\mathrm{I}}^{\mathrm{M1}}(t, \boldsymbol{x_d}) = \frac{G_{\mathrm{F}} C_{ij}}{\sqrt{2}} \hat{\boldsymbol{j}}_{ij}(\boldsymbol{p}_i, \boldsymbol{p}'_j) \cdot \boldsymbol{\sigma}_{\mathrm{vg}}\, \mathrm{e}^{\mathrm{i}(E_{\mathrm{vg}}+E'_j-E_i)t} \left|\mathrm{v}\right\rangle \left\langle\mathrm{g}\right| + \boldsymbol{d}_{\mathrm{vg}} \cdot \boldsymbol{\mathcal{B}}(\boldsymbol{k})\, \mathrm{e}^{\mathrm{i}(-E_{\mathrm{vg}}+\omega)t} \left|\mathrm{g}\right\rangle \left\langle\mathrm{v}\right| + \mathrm{h.c.}$$

Neutrino current:

$j_{ij}^\mu = \overline{u}_{\boldsymbol{p}'_j} \gamma^\mu (1-\gamma_5) u_{\boldsymbol{p}_i}$ **Dirac case**

$j_{ij}^\mu = \overline{u}_{\boldsymbol{p}'_j} \gamma^\mu (1-\gamma_5) u_{\boldsymbol{p}_i} + \overline{v}_{\boldsymbol{p}_i} \gamma^\mu (1-\gamma_5) v_{\boldsymbol{p}'_j}$ **Majorana case**

Emission Rate

M1-transition: optimistic case

$$C_{\rm v}^{(1)}(t) = \frac{G_{\rm F} C_{ij}}{\sqrt{2}} \frac{\hat{\boldsymbol{j}}_{ij} \cdot \boldsymbol{\sigma}_{\rm vg}}{E_{\rm vg} + E'_j - E_i} {\rm e}^{{\rm i}(E_{\rm vg} + E'_j - E_i)t}$$

coefficient under the perturbation by neutrinos

Effective Hamiltonian:

$$\mathcal{H}^{\rm M1}_{\nu\nu\gamma} = -\frac{G_{\rm F} C_{ij}}{\sqrt{2}} \frac{n_d \left[\hat{\boldsymbol{j}}_{ij} \cdot \boldsymbol{\sigma}_{\rm vg}\right] \left[\boldsymbol{d}^*_{\rm vg} \cdot \boldsymbol{\mathcal{B}}(\boldsymbol{k})\right]}{E_{\rm vg} + E'_j - E_i} \times {\rm e}^{{\rm i}(\omega + E'_j - E_i)t} + {\rm h.c.}\,,$$

Differential rate:

$$\frac{{\rm d}\Gamma}{{\rm d}\Omega_\gamma} = \int {\rm d}|\boldsymbol{k}| \frac{\boldsymbol{k}^2 \left|\mathcal{M}\right|^2}{32\pi^2 m_i E'_j \omega} \delta(\omega + E'_j - E_i)$$

Total rate:

$$\Gamma \approx \frac{G_{\rm F}^2 |U^*_{ei} U_{ej}|^2}{2\pi} \frac{f_\theta^{\rm M1}\, n_{\boldsymbol{d}}^2\, |\boldsymbol{d}_{\rm vg}|^2 D_k}{(E_{\rm vg} + E'_j - E_i)^2 + \gamma_{\rm vg}^2/4} \frac{|\boldsymbol{k}|^4}{\omega}$$

$E_{\rm vg} = 0.025$ eV $\qquad \omega \sim m_3/2 \approx 0.025$ eV

$$R_{\nu_3 \to \nu_1} \sim 1\ {\rm yr}^{-1} \quad (V = 5\ {\rm m}^3,\ T_{\rm c} = 10\ {\rm ns})\,,$$
$$R_{\nu_3 \to \nu_1} \sim 8\ {\rm yr}^{-1} \quad (V = 40\ {\rm cm}^3,\ T_{\rm c} = 10\ \mu{\rm s})\,.$$

$D_k \equiv 1/[{\rm d}(\omega + E'_j - E_i)/{\rm d}|\boldsymbol{k}|]$

depending on photon dispersion in media and neutrino masses

$\gamma_{\rm vg} \equiv T_{\rm c}^{-1}$ **damping rate**

$T_1^{-1} + T_\phi^{-1}$

spontaneous decay **dephasing**

$|\boldsymbol{d}_{\rm vg}| \sim e/m_e$

Bohr magneton

Momentum Dispersion & Attenuation

The heaviest neutrino is not at rest $\nu_3 \to \nu_1 \gamma$

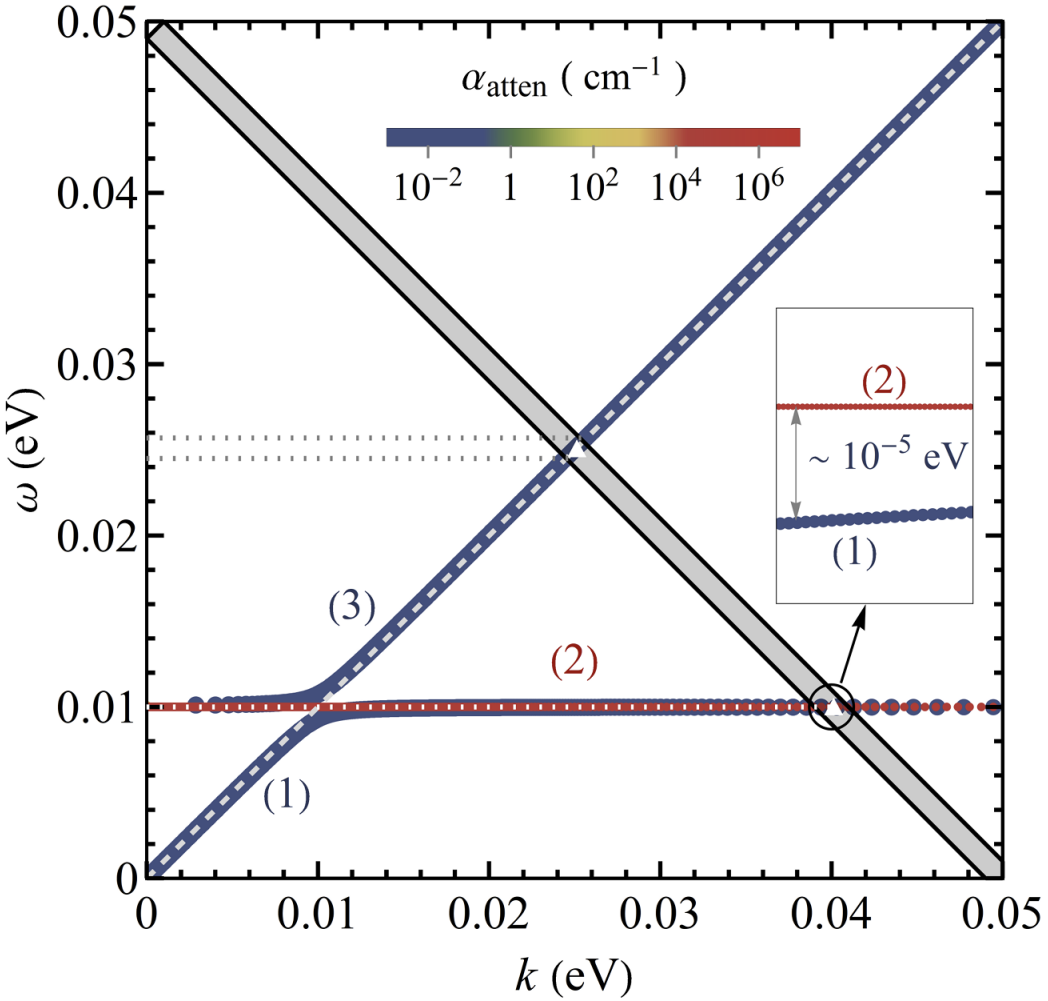
$$\Delta E_3 \approx \Delta p^2/(2m_3) \sim 10^{-6}\ \text{eV}$$

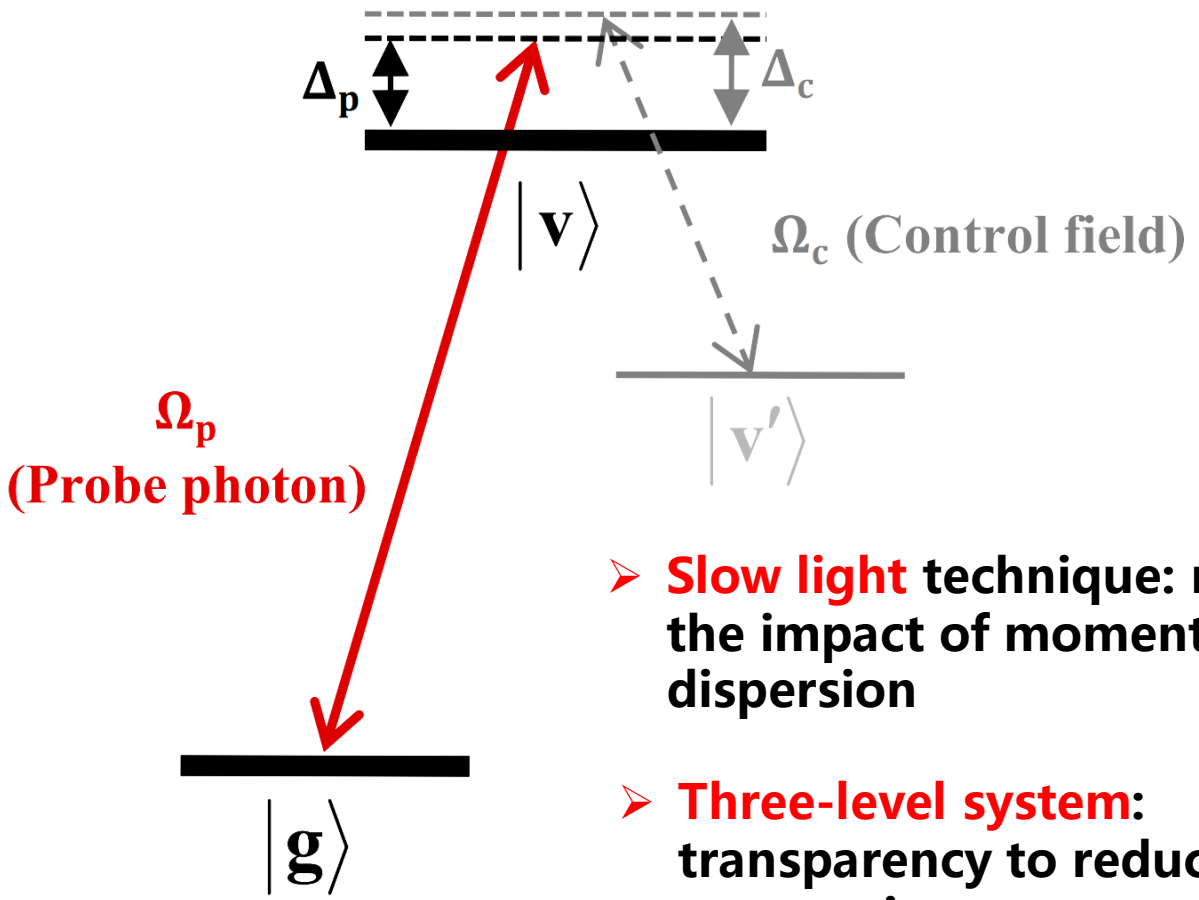
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \text{eV}$$

$$\boxed{p_i - p'_j - k = 0}$$

away from resonance

$$\Delta(E_3 - E'_1) \sim 10^{-4}\ \text{eV}$$





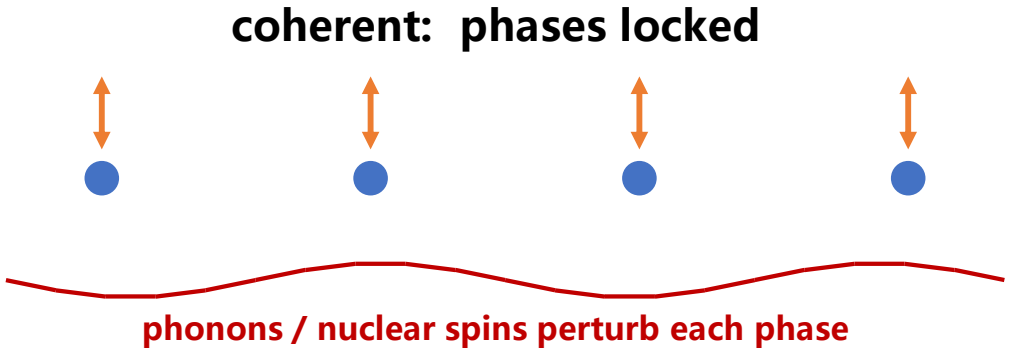
- **Slow light** technique: reduce the impact of momentum dispersion
- **Three-level system**: transparency to reduce the attenuation

Question A: what is coherence and what destroys it

Coherent emission

$N = n_d \cdot V$ target ions are driven by one neutrino field

their dipoles oscillate in step → amplitudes add; rate ∝ N^2



The coherence time T_2^*

each ion's dipole builds up for a time T_2^*

the rate scales as T_2^{*2} — long coherence is the whole game

What destroys it

dephasing: phonons, ion–ion dipolar, nuclear spins

$\gamma_1 \approx 0$ ($T_1 \gtrsim 10^3$ s)

γ_φ = dephasing (dominant)

The dephasing budget

$\gamma_{vg} = \gamma_1 + \gamma_\varphi = T_2^{*-1}$

γ_1 (spontaneous M1): $T_1 \gtrsim 10^3$ s — negligible

γ_φ (pure dephasing): the rate-limiter

T_2^* ~ 10 μs–ms at 1–4 K

Question B: candidate targets and event rates

Three neutrino channels

$\nu_2 \rightarrow \nu_1$: 4.33 meV (34.9 cm^{-1}), $|C|^2 = 0.204$

$\nu_3 \rightarrow \nu_2$: 24.32 meV (196.2 cm^{-1}), $|C|^2 = 0.0067$

$\nu_3 \rightarrow \nu_1$: 25.06 meV (202.1 cm^{-1}), $|C|^2 = 0.0150$

Operating point (all routes)

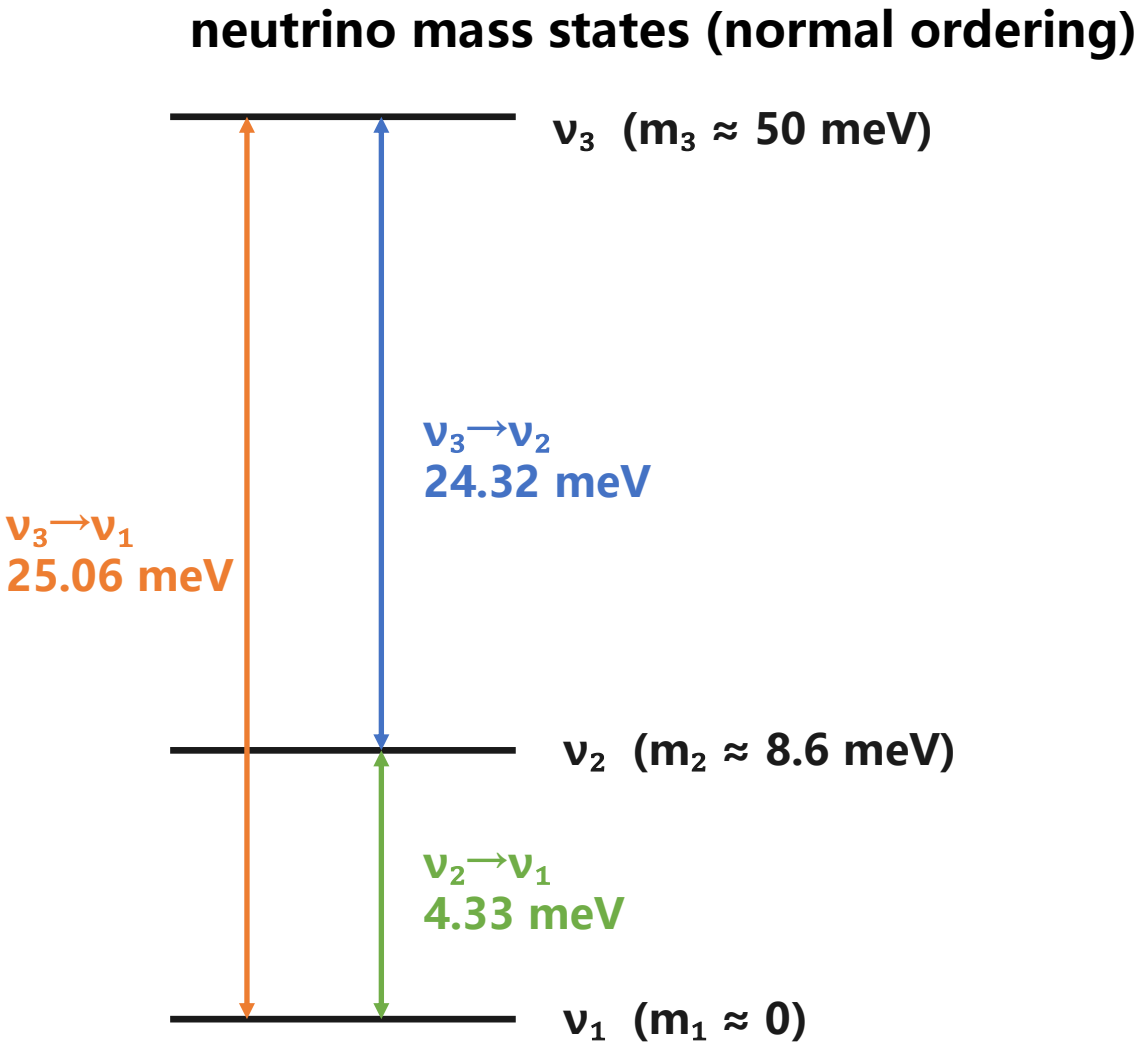
V = 9.3 L, T_2^* = 100 μs, α_0 = 20 cm^{-1}

Two routes + one fallback

Route A — **$Pr^{3+}:LaCl_3$**, $\nu_2 \rightarrow \nu_1$: R ≈ 22 yr^{-1}

Route B — **$Nd^{3+}:CaF_2$**, ν_3: R ≈ 22.8 / 54.2 yr^{-1}

Fallback — **$Nd^{3+}:SrF_2$**: cleanest phonon gap



Route A: $Pr^{3+}:LaCl_3$ on $\nu_2 \rightarrow \nu_1$ (4.4 meV)

Target

dilute Pr^{3+}-doped $LaCl_3$ ($P6_3/m$, C3h site)

Working transition

$^3H_4(0) \rightarrow {}^3H_4(4.1\ meV)$, M1 spin flip

$\mu_{vg} \approx \mu_B$, $E_{vg} = 4.36\ meV = 1.054\ THz$

Why it works

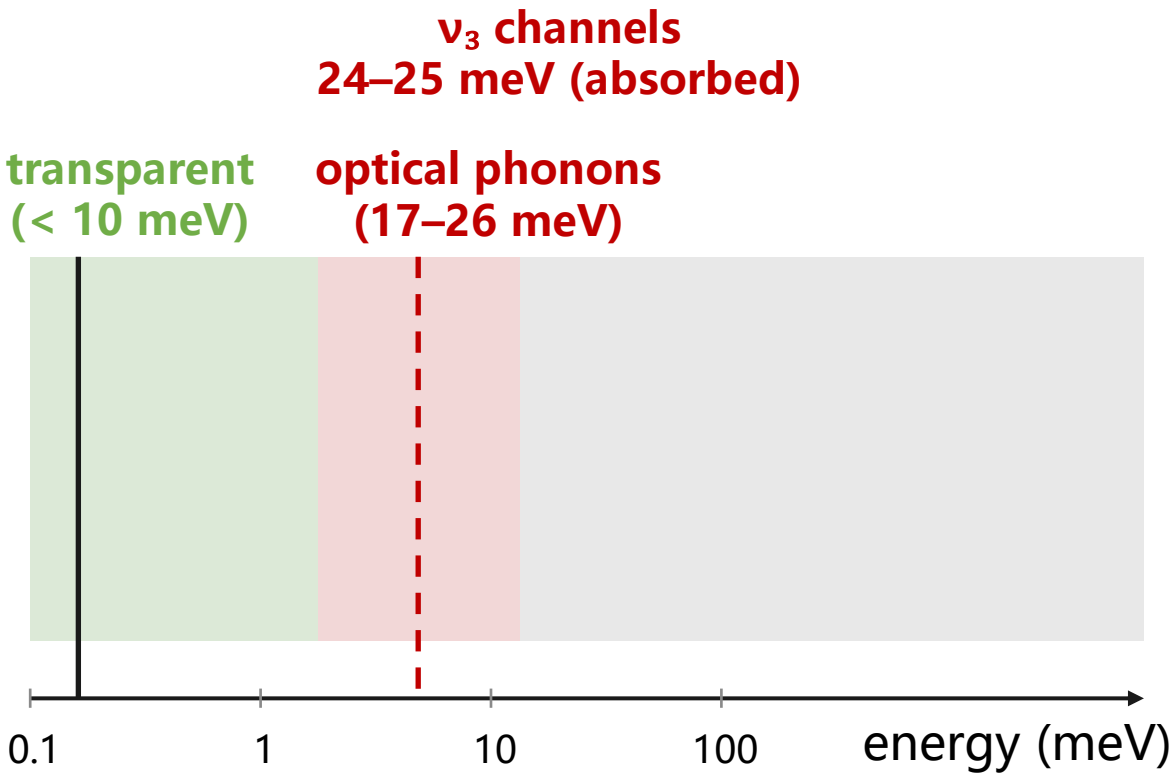
level known ($\approx 33\ cm^{-1}$); transparent < 10 meV

^{141}Pr I = 5/2 hyperfine pairs → EIT Λ

Rate & status

$R \approx 22\ yr^{-1}$ (Dirac, EIT); ×2 Majorana

T_2^* unmeasured — the decisive measurement



Λ system

$|g\rangle,\ |e\rangle = {}^3\mathrm{H}_4(0)\ (\mathrm{hf},\ \Delta_{\mathrm{hf}} \sim 1\text{–}20\ \mathrm{MHz}),\qquad |v\rangle = {}^3\mathrm{H}_4(4.1\ \mathrm{meV})$

Route B: $Nd^{3+}:CaF_2$ on the ν_3 channels (25 meV)

Target

dilute Nd^{3+}-doped CaF_2 (fluorite, C4v site)

Phonon window

transparent 24–32 meV (TO phonon 32 meV)

Levels

$^4I_{9/2}$: 0, 87, 152, ≈190–197 (Z_4), 273 cm^{-1}

Z_4 ≈ 196 cm^{-1} on-shell for $\nu_3 \rightarrow \nu_2$

Rates

R_{32} ≈ 22.8, R_{31} ≈ 54.2 yr^{-1} (Dirac, EIT)

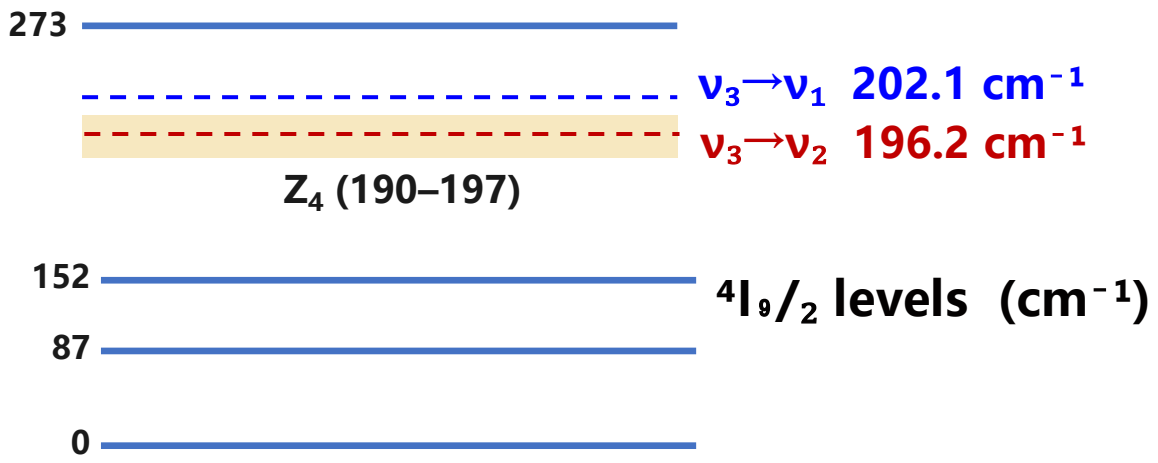
×2 Majorana; ÷1.1–1.7 site fraction

Status

conditional on Z_4; decisive: far-IR $Z_4 < 0.8$ cm^{-1}

Nd^{3+} EIT dark state needs $T_2 \gtrsim 1$–24 ms





Question C: the coherence volume

Longitudinal bound

phase matching: $L_{pm} = \pi / [(n_{ph}-1)\, E_{vg}]$

$L_{pm} \approx 0.06$ mm at 25 meV $(n_{ph}-1 \approx 0.4)$

$k = n_{ph} \cdot \omega \Rightarrow q = p_i - p'_j - k = (1 - n_{ph})\omega \neq 0$

coherence length ≪ target size (log scale)



$L_{pm} \approx 0.06$ mm target ≈ 21 cm

Transverse area

$A \rightarrow 10^{-2}$ cm²……10^{4} cm²

The coherent number

$V_{coh} = L_{coh} \cdot A$, $N_{coh} = n_d \cdot V_{coh}$

$N_{coh} \approx 10^{10}$–$10^{16} \ll n_d \cdot V \approx 4 \times 10^{18}$

rate $\propto N_{coh} \rightarrow R \approx$ **10^{-7}–0.2 yr^{-1}**

whole-target: $N_{coh} = n_d \cdot V \rightarrow$ 22–54 yr^{-1}

↓

coherence volume: $V_{coh} = L_{coh} \cdot A \ll V$

↓

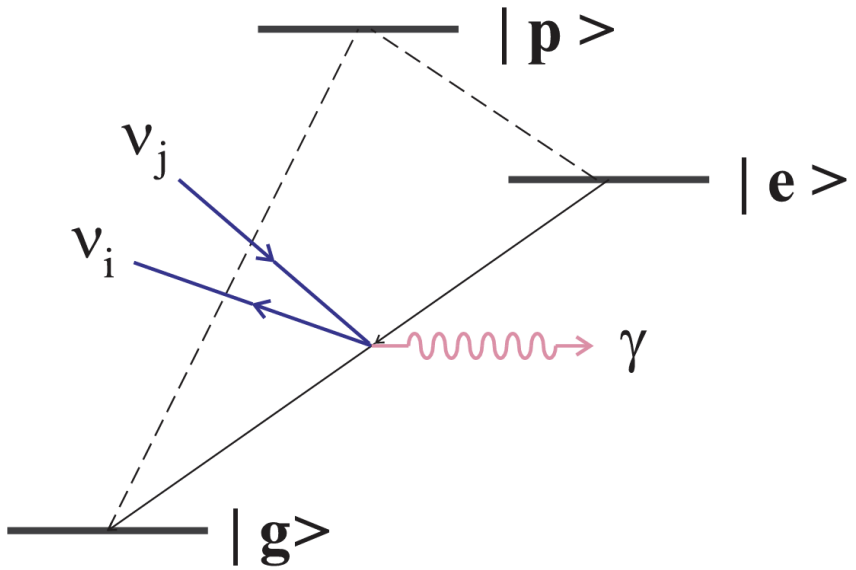
honest: $R \approx 10^{-7}$–0.2 yr^{-1}

the coherence volume cuts N_{coh} by 10^2–10^7

Summary and Outlook

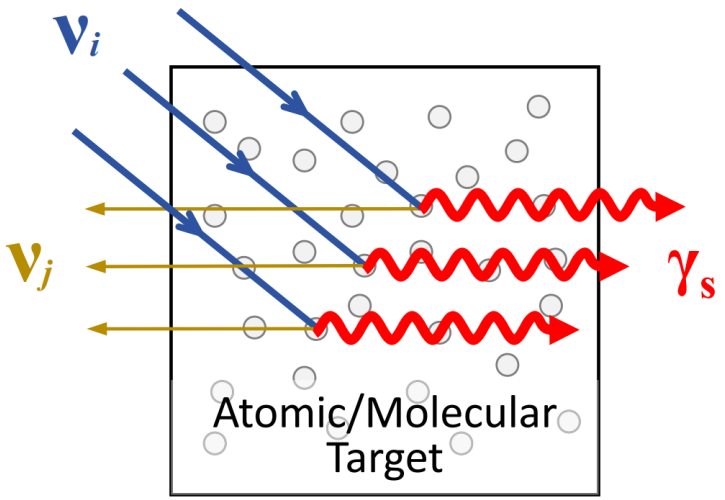
- The existence of CνB receives robust evidence from the BBN, CMB and LSS observations, but a direct detection is still lacking

- All the existing ideas towards a real detection are facing difficulties, and new ones are being proposed and studied seriously

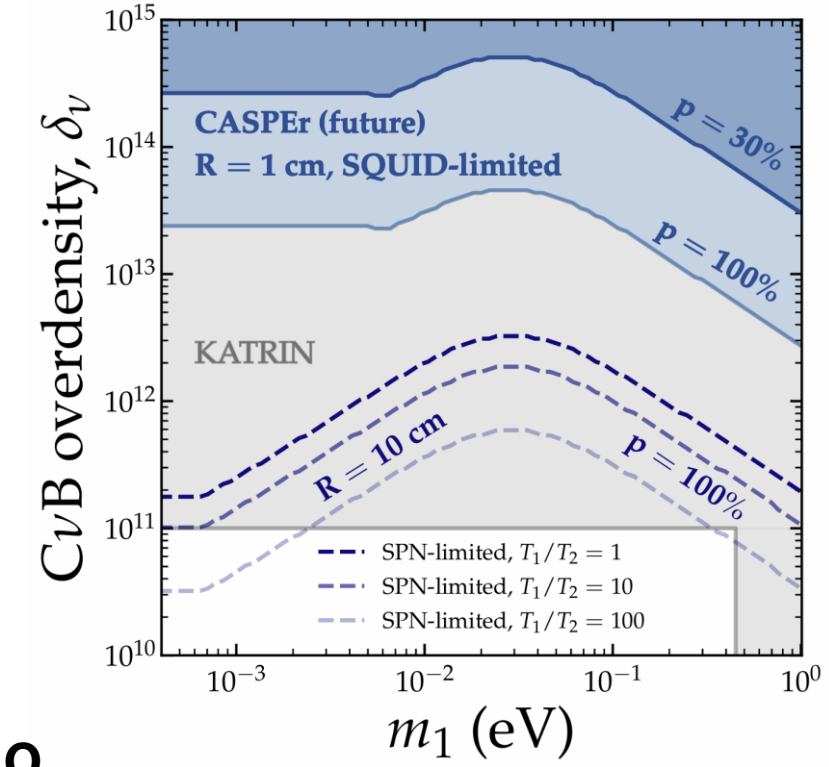


Sasao & Yoshimura

$$|e\rangle \rightarrow |g\rangle + \gamma + \nu_i \nu_j$$



- New technologies developed in the AMO may find applications to the detection of CνB and dark matter



Garcia del Castillo, Pierobon, Sengupta & Wong, PRD, 2026