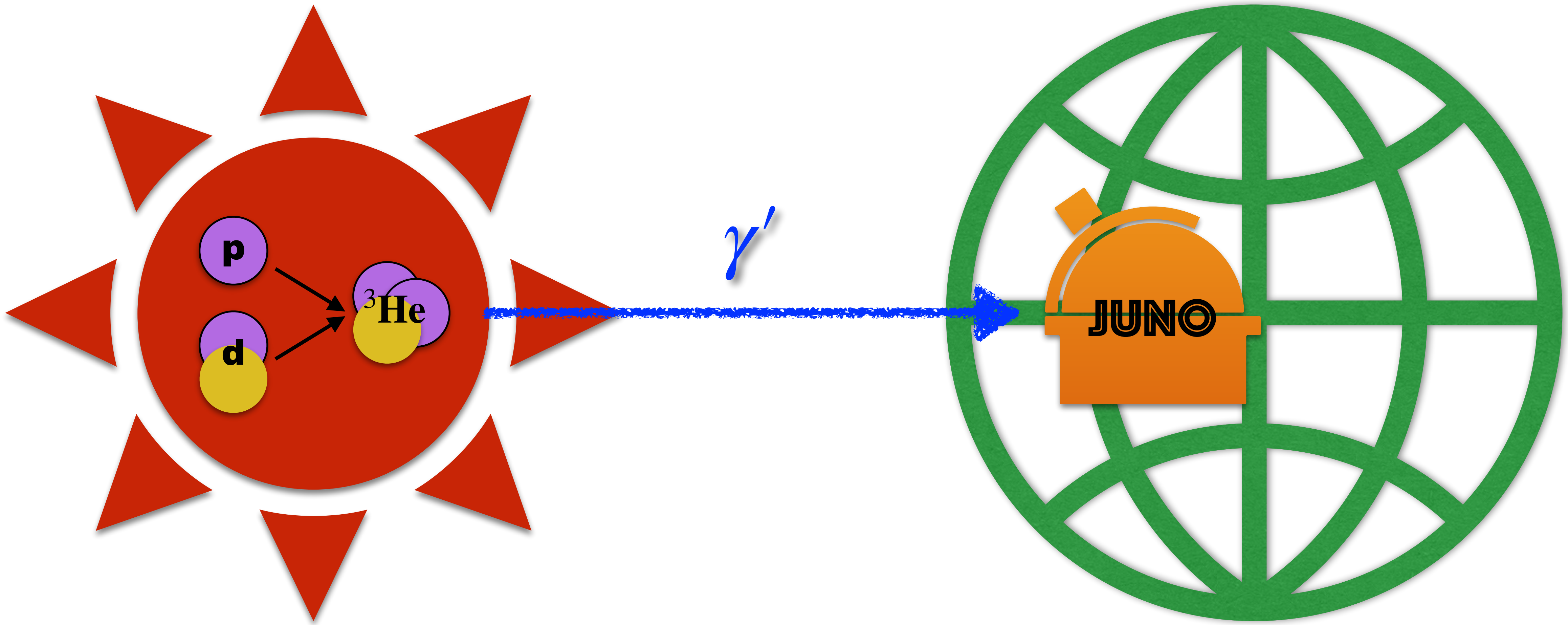
Solar hidden vectors at the JUNO detector

Seokhoon Yun

“*Terrestrial detection of hidden vectors produced by solar nuclear reactions*”
Francesco D’Eramo (U. Padova & INFN Padova), Giuseppe Lucente (INFN Bari), Newton Nath (INFN Bari), ***SY***
2305.14420



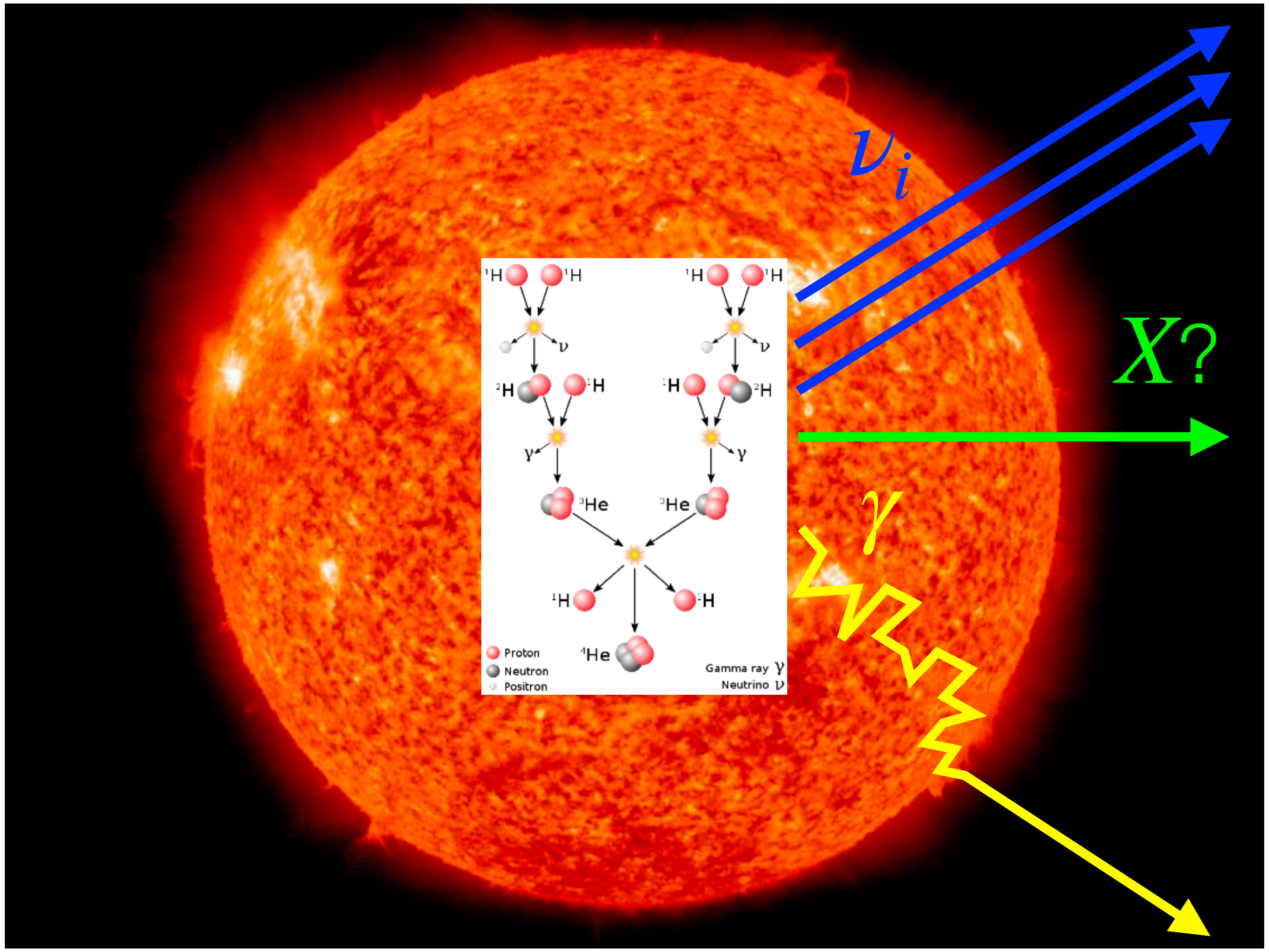
Production

- Effective theory of γ' in a medium
  - *i. Kinetic mixing*
  - *ii. Plasma mixing*
- $p + d \rightarrow {}^3\mathrm{He} + \gamma' \left(5.49\,\mathrm{MeV}\right)$
  - ✓ *Multipole expansion - (E1 & M1)*
  - ✓ *Isovector*

Detection

- Compton-like $e^-\gamma' \rightarrow e^-\gamma$
  - ✓ *Polarized cross-section*
- In-flight decay $\gamma' \rightarrow e^-e^+$
  - ✓ *allowed for* $m_{\gamma'} \geq 2m_e$

Sun



[NGC]

- Closest star to Earth
  - as a good and natural laboratory to probe new physics
- Dominant energy release by nuclear reaction (p-p chain)
  - **Neutrino** (volume emission)
  - **Photon** (surface emission)
  - ***Novel particles?***
    - thermal : $E \Downarrow$ ($\sim T = \mathcal{O}(1)\,\mathrm{keV}$), $\Phi \Uparrow$
    - N-reaction : $E \Uparrow$ ($\sim \mathcal{O}(1)\,\mathrm{MeV}$), $\Phi \Downarrow$

Effective theory of Hidden gauge boson

- Chiral perturbation theory framework
  - Hadronic interactions
- Thermal field theory framework
  - Plasma effect : refractive index & mixing effect

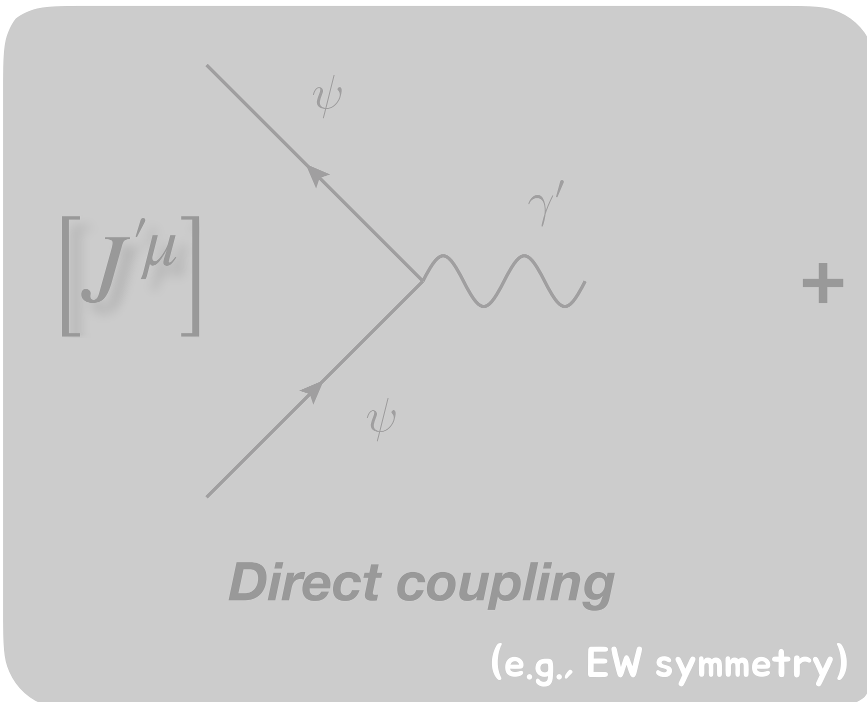
Kinetic & plasma mixing with γ

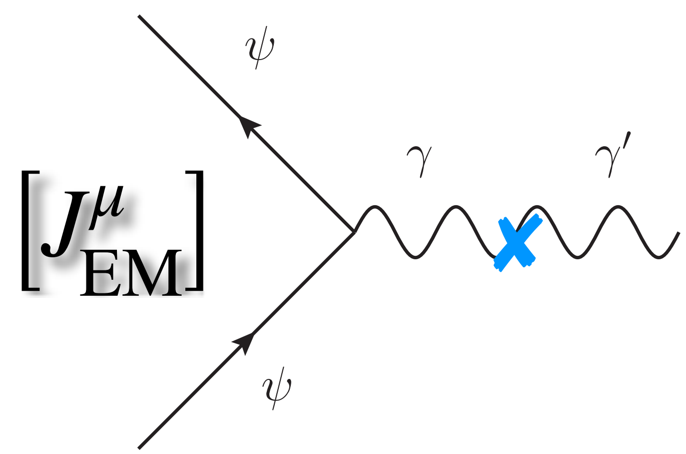
- Low-energy effective γ' couplings

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu + eA_\mu J^\mu_{\mathrm{EM}} + e'A'_\mu J'^\mu$$

EM field strength | DP field strength | **kinetic mixing** | γ' mass | EM current | γ' current
- hadron (ChPT)
- ***lepton***

- Effective γ' couplings: direct + indirect (mixing)



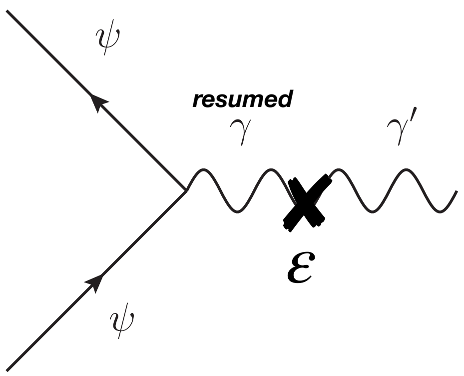


Indirect coupling

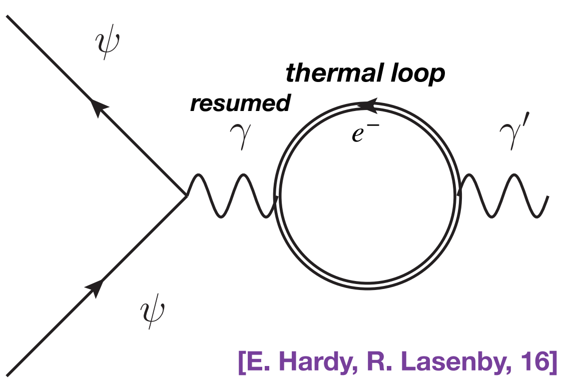
- kinetic mixing ε
- plasma mixing via q'_e

Effective coupling of γ' in medium

✓ Kinetic mixing (ε)



✓ Plasma mixing



[E. Hardy, R. Lasenby, 16]
[C. S. Shin, D. Hong, SY, 20]

$$\mathscr{L}_{\varepsilon}^{\text{eff}} = \varepsilon e \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\text{T,L}}} J_{\text{EM}}^{\mu} A'_{\mu}$$

$$\mathscr{L}_{\Pi}^{\text{eff}} = -e' q'_e \frac{\pi_{\text{T,L}}}{m_{\gamma'}^2 - \pi_{\text{T,L}}} J_{\text{EM}}^{\mu} A'_{\mu}$$

- q : EM charge
- q' : dark $U(1)$ charge

$\mu_e \ll T \,\&\, T \ll m_e$

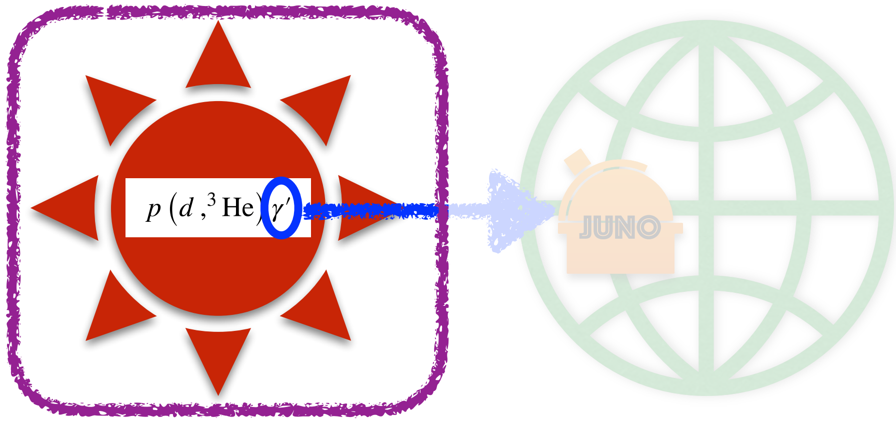
$$\text{Re}\left[\pi_{\text{T}}\right] = \omega_{\text{pl}}^2$$

$$\text{Re}\left[\pi_{\text{L}}\right] = \frac{m_{\gamma'}^2}{\omega^2}\omega_{\text{pl}}^2$$

In the solar medium

$$\omega_{\text{pl}} = 0.3\,\text{keV}\left(\frac{n_e}{n_\odot}\right)^{1/2}$$

$$\text{Im}\,\pi_{\text{T}} = -\,\omega\left(1 - e^{-\omega/T}\right)\frac{8\pi\alpha^2}{3m_e^2}n_e$$

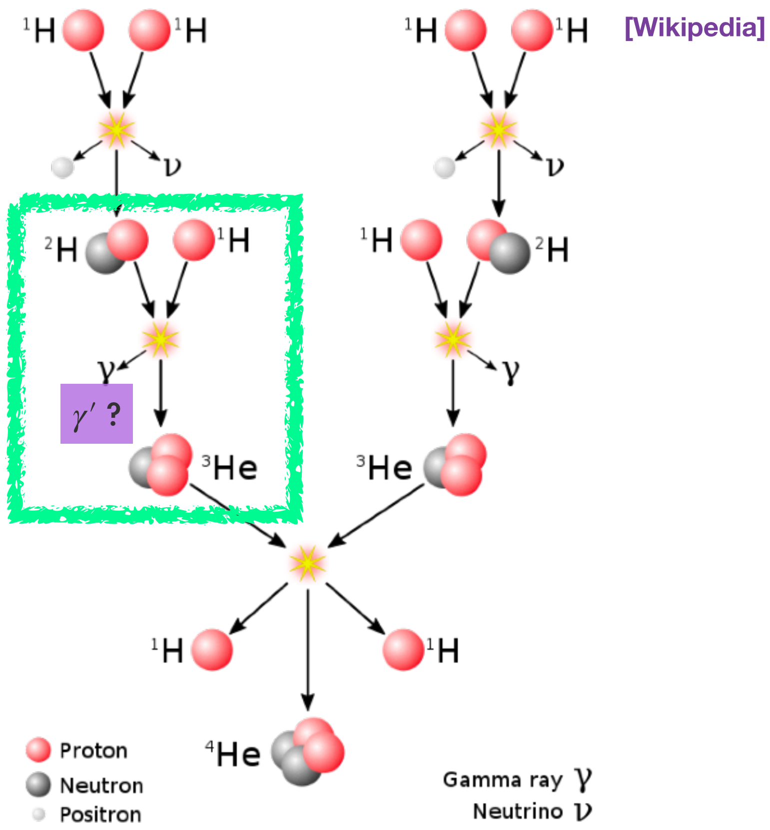


Solar γ' production via the nuclear reaction

- Deuterium fusion $p + d \to {}^{3}\mathrm{He} + \gamma' \left(5.49\,\mathrm{MeV}\right)$
- Predominantly isovector (i.e., isospin breaking)
- Kinetic mixing & In-medium mixing

Deuterium fusion

$$p + d \rightarrow {}^{3}\mathrm{He} + \gamma\,(5.49\,\mathrm{MeV})$$



- The second stage of solar pp fusion chain
  - $1.7 \times 10^{38}\,\mathrm{s}^{-1}$ at the innermost region (core) of the Sun

- 5.49 MeV energy release through the electromagnetic radiation
  - γ' instead of γ ? (possibility for axion have been discussed)

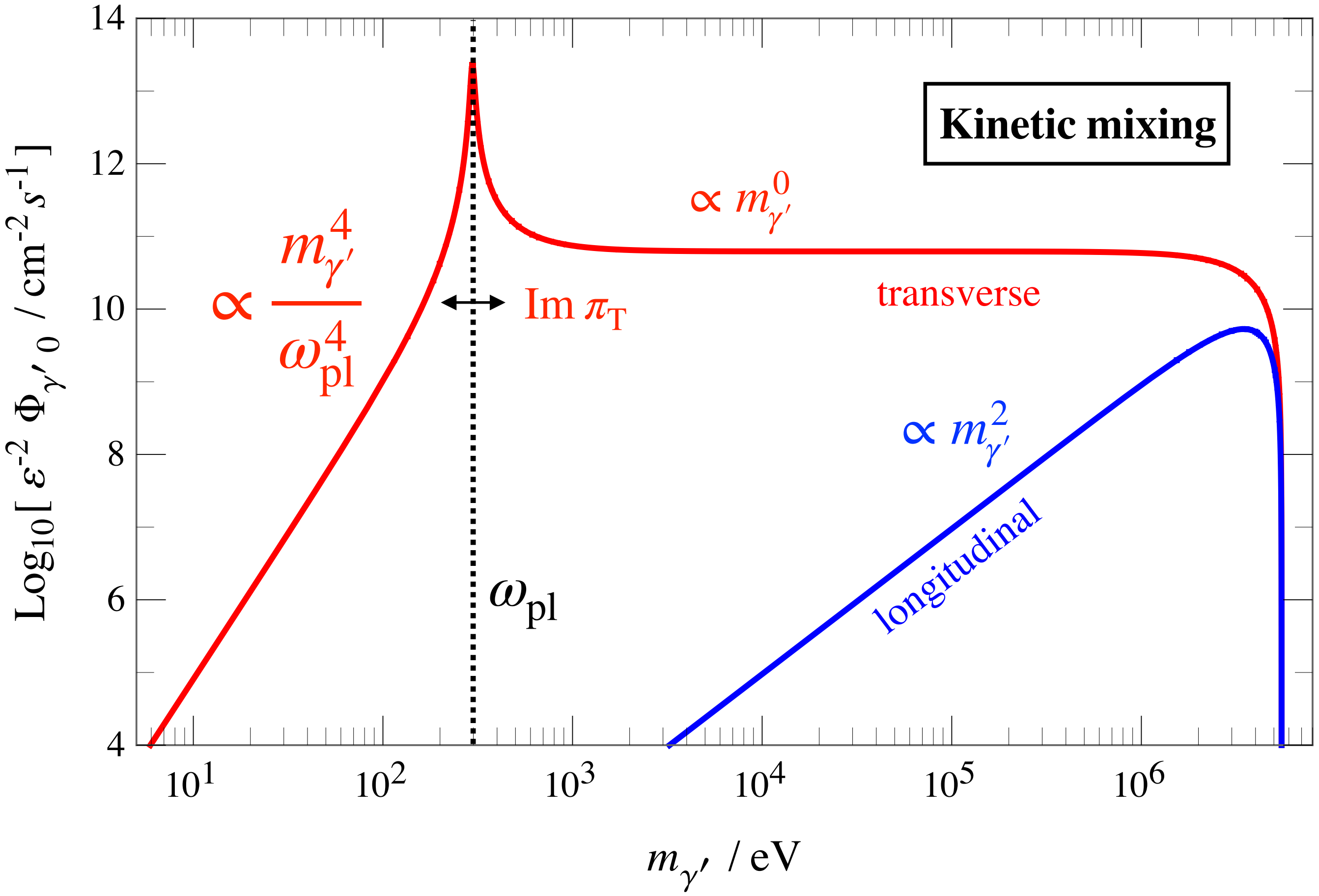
- In terms of multipole expansion (relevant to non-relativistic regime)
  - Electric- & Magnetic-dipole transition dominant
  - Due to the proton and deuteron as the pure isospin eigenstates
  - Controlled by **isovector** charge (i.e., difference between the couplings to nucleons)

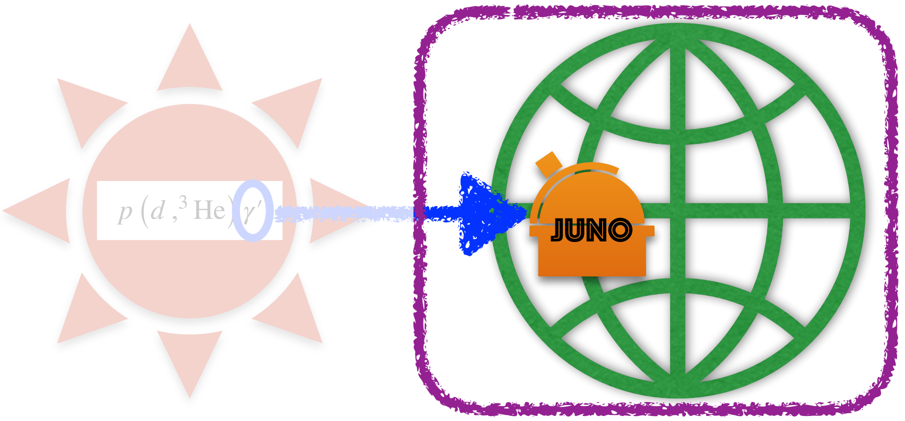
Solar $\mathbf{5.49\ MeV}$ γ' flux (kinetic mixing)

$\boxed{1.7\times 10^{38}\,\mathrm{s}^{-1}\ \textbf{for}\ p\,(d,{}^3\mathrm{He})\,\gamma}$ $\boxed{\gamma\text{-}\gamma'\ \textbf{mixing}}$

$$\left[\Phi_{\gamma'}\right]_{\mathrm{T,L}} = \frac{1}{4\pi d_\odot^2}\phi_\gamma \frac{k^3}{\omega^3}\left|\varepsilon\frac{m_{\gamma'}^2}{m_{\gamma'}^2-\pi_{\mathrm{T,L}}}\right|^2 \times \left[\frac{m_{\gamma'}^2}{\omega^2}\right]_{\mathrm{L}}$$

(current conservation)





Detection at JUNO

- Compton-like scattering $\gamma' + e^- \rightarrow \gamma + e^-$
- Decay $\gamma' \rightarrow e^- + e^+$ @ $m_{\gamma'} \geq 2m_e$

In the detector
Effective couplings with $\pi_{\mathrm{T,L}} = 0$
i.e., $\varepsilon e\, J^{\mu}_{\mathrm{EM}} A'_{\mu}$

Detection processes

◉ Scattering

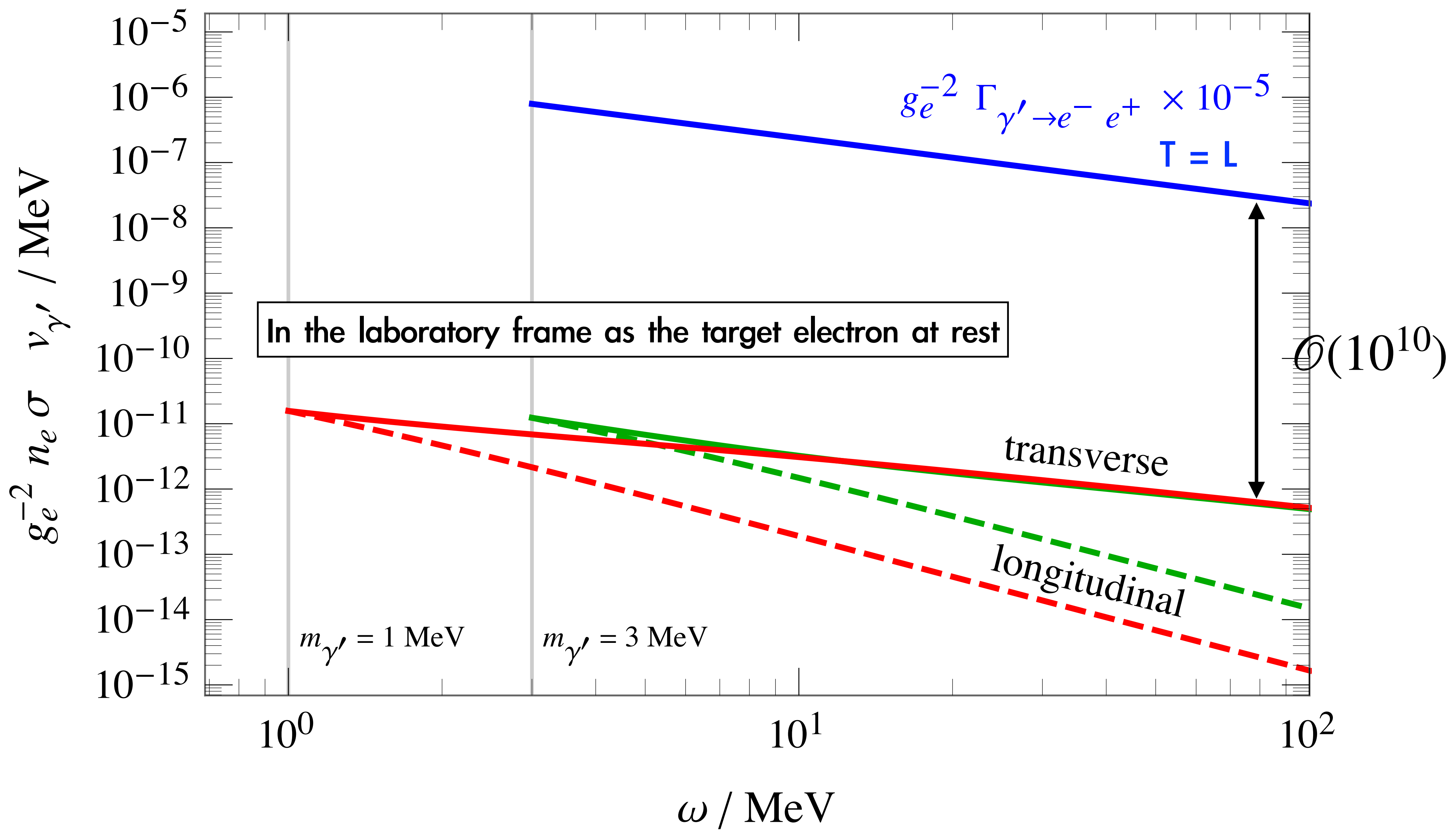
- Compton-like
  - $\gamma' + e^- \to \gamma + e^-$
  - **`dominant detection`** process at $m_{\gamma'} < 2m_e$
  - separate on the γ' polarization
- Similar to photoelectric effect
  - $\gamma' + e \to e^*$ instead of γ (sub-dominant)
- e^-e^+ pair production in the electric field
  - of nuclei or electrons
  - Bethe-Heitler (sub-dominant @ 5.49 MeV)

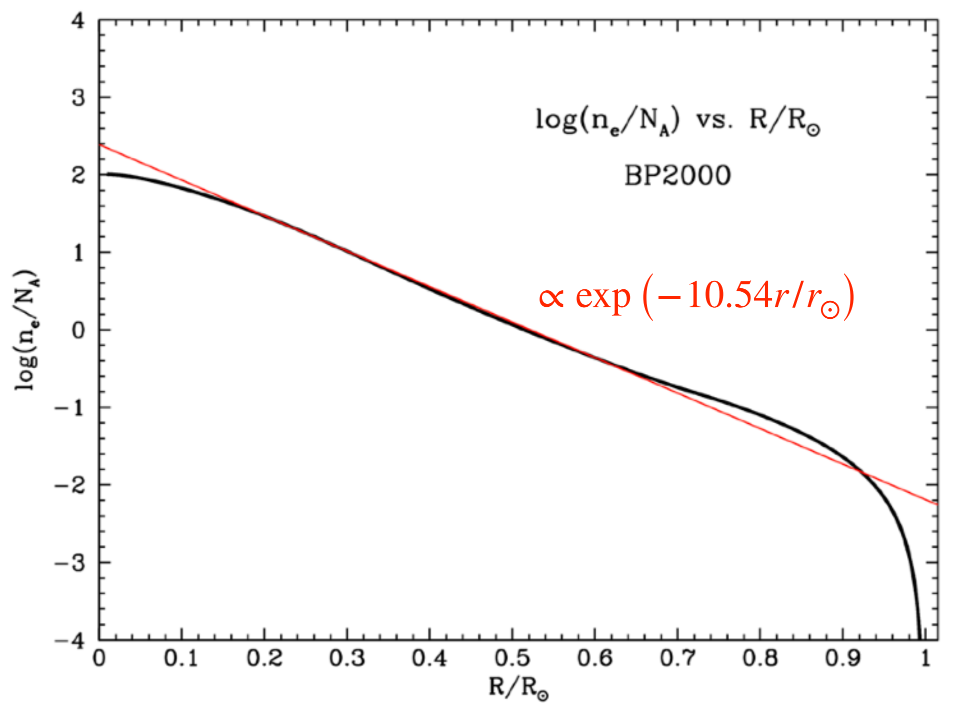
◉ Decay

- $\gamma' \to e^- e^+$
  - visible channel
  - dominant detection process at $m_{\gamma'} > 2m_e$
  - but, too much depletion of the γ' flux on Earth
- $\gamma' \to 3\gamma$
  - possible at $m_{\gamma'} < 2m_e$
  - loop & phase-space suppression (negligible)
- $\gamma' \to \nu\bar{\nu}$
  - invisible channel

Detection rate

In the detector
Effective couplings with $\pi_{\mathrm{T,L}} = 0$
i.e., $(-\varepsilon e)\,\bar{e}\gamma^{\mu} e A'_{\mu}$





Trapping limit

- Absorption into the solar medium?
  - scatterings with charged particles (e.g., electrons) $\propto n_e$
  - due to exponential decrease in r, mostly occurs near core
  - optical depth $\tau_{\gamma'} = \int_0^{r_\odot} dr\, n_e \sigma v_{\gamma'}$ ☞ $\Phi_{\gamma'} e^{-\tau_{\gamma'}}$

- Conversion $\gamma' \to \gamma$?
  - resonant at $m_{\gamma'}^2 = \omega_{\rm pl}^2(r) \propto n_e$ (only for $m_{\gamma'} < 0.3\,\mathrm{keV}$)
  - $P^{\rm res}_{\gamma' \leftrightarrow \gamma} = 1 - \exp\left(-\pi \gamma_{\rm ad}/2\right)$ (second term as level-crossing probability)
  - adiabaticity $\gamma_{\rm ad} = \dfrac{\Delta_{\rm osc}}{|\,d\theta/dr\,|}$

Expected # of solar γ' event signals

- Net flux reduced by decays
  - visible (e^-e^+ & 3γ) + invisible ($\nu\bar{\nu}$)

10 years

$$N_{\rm ev} = \sum_{i={\rm T,L}} \left[\Phi_{\gamma' 0} e^{-\tau_i}\right]_i e^{-\Gamma_{\gamma'} d_\odot / v_{\gamma'}} \left[N_e \sigma_i + \frac{V_f \Gamma_{\gamma'} \, {\rm Br}\left(\gamma' \to {\rm vis}\right)}{v_{\gamma'}}\right] t$$

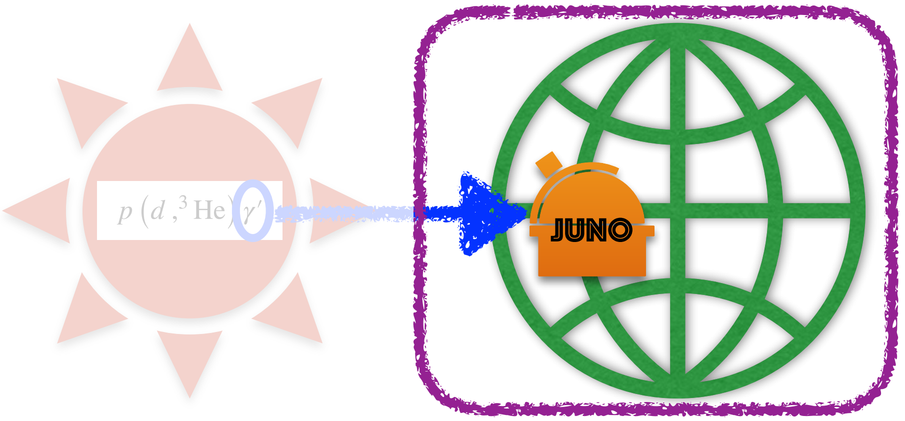
- Solar 5.49 MeV γ' flux on Earth
  - isovector deuterium fusion reaction
  - free-streaming out at $g_e < \mathcal{O}(10^{-7})$

    i.e., $\tau_i \ll 1$ [$g_e = \varepsilon e - e' q'_e$]

- Detection at JUNO
  - Compton-like scatterings (first)
  - in-flight decays into visible channels (second)
  - fiducial volume V_f of 16.2 kton for $E > 5\,\mathrm{MeV}$
  - the total # of electrons $N_e \simeq 5.5 \times 10^{33}$

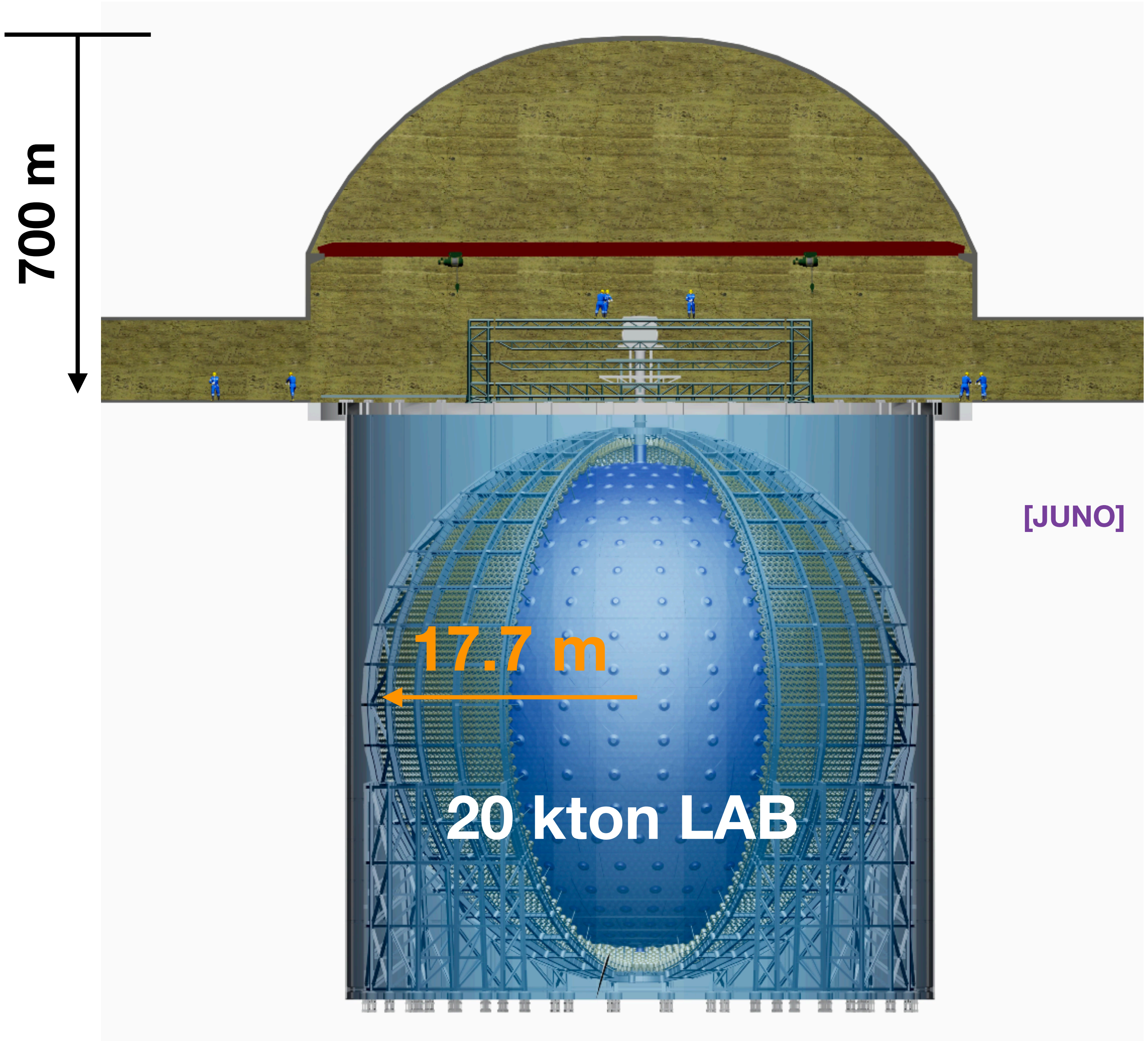
JUNO sensitivity

- Projected sensitivity in terms of N_{ev}
- Constraints on the kinetic mixing scenarios



JUNO detector

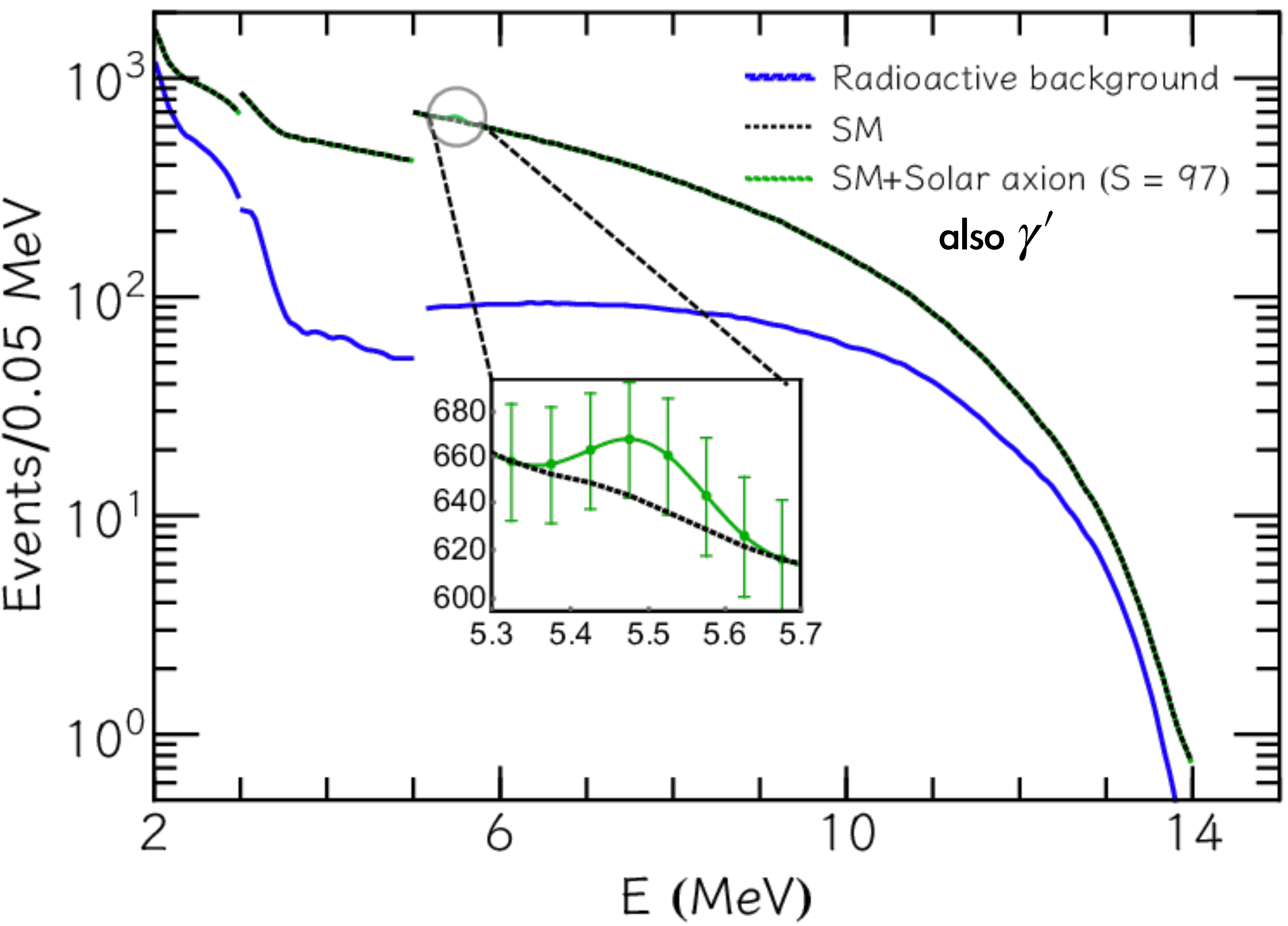
Jiangmen Underground Neutrino Observatory

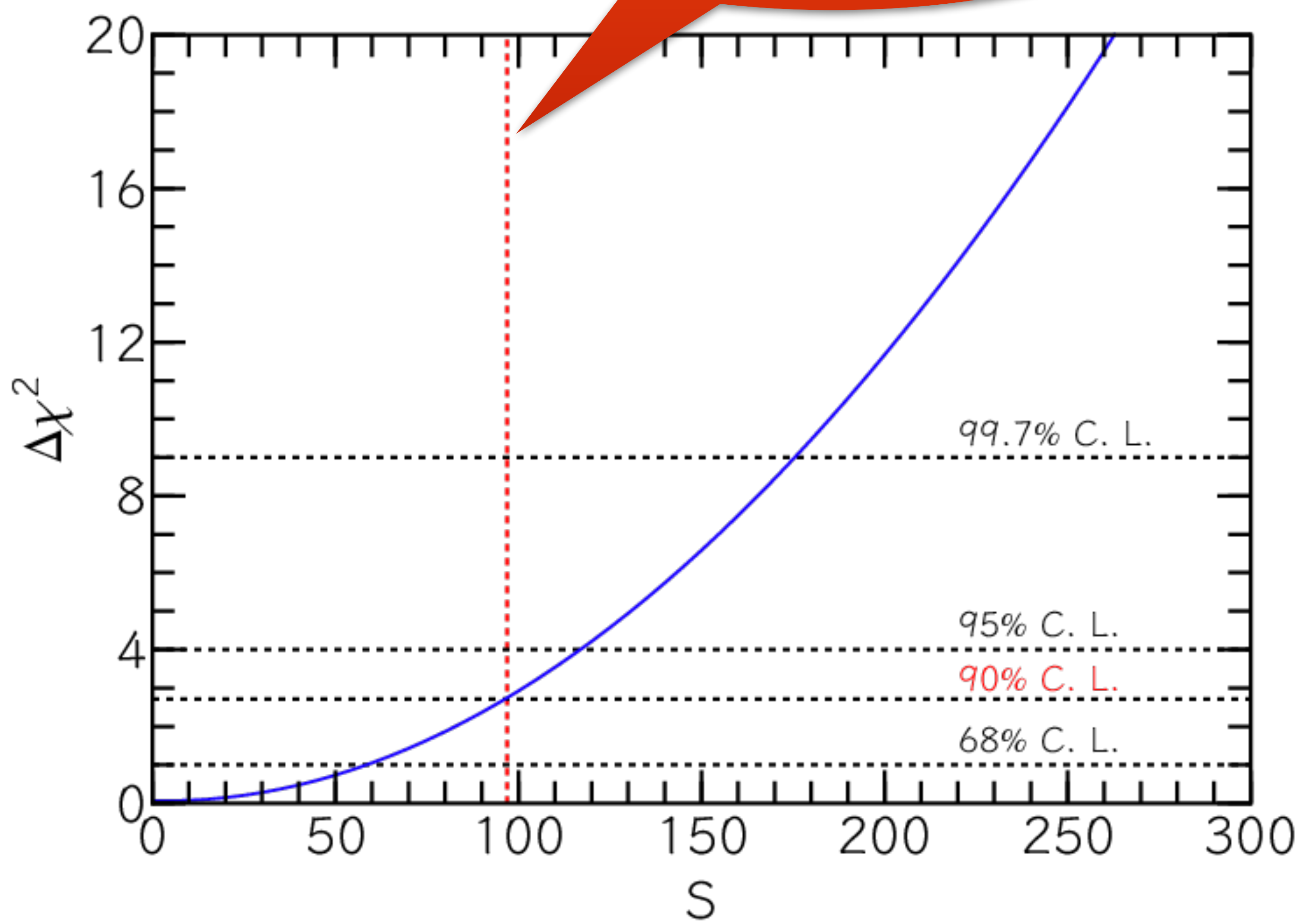


- Multi-purpose liquid scintillator detector
  - aims to determine neutrino mass ordering & precision measurement of PMNS parameters
  - SN, atmospheric, geo-ν
  - also exotic (astroparticle) searches
- Better sensitivity
  - than the previous ones such as Borexino
  - energy threshold $2\,\mathrm{MeV}$
  - under construction, begin taking data 2023

Fitting procedure

$N_{ev}^{lim} = 97$ at 90 % C.L.



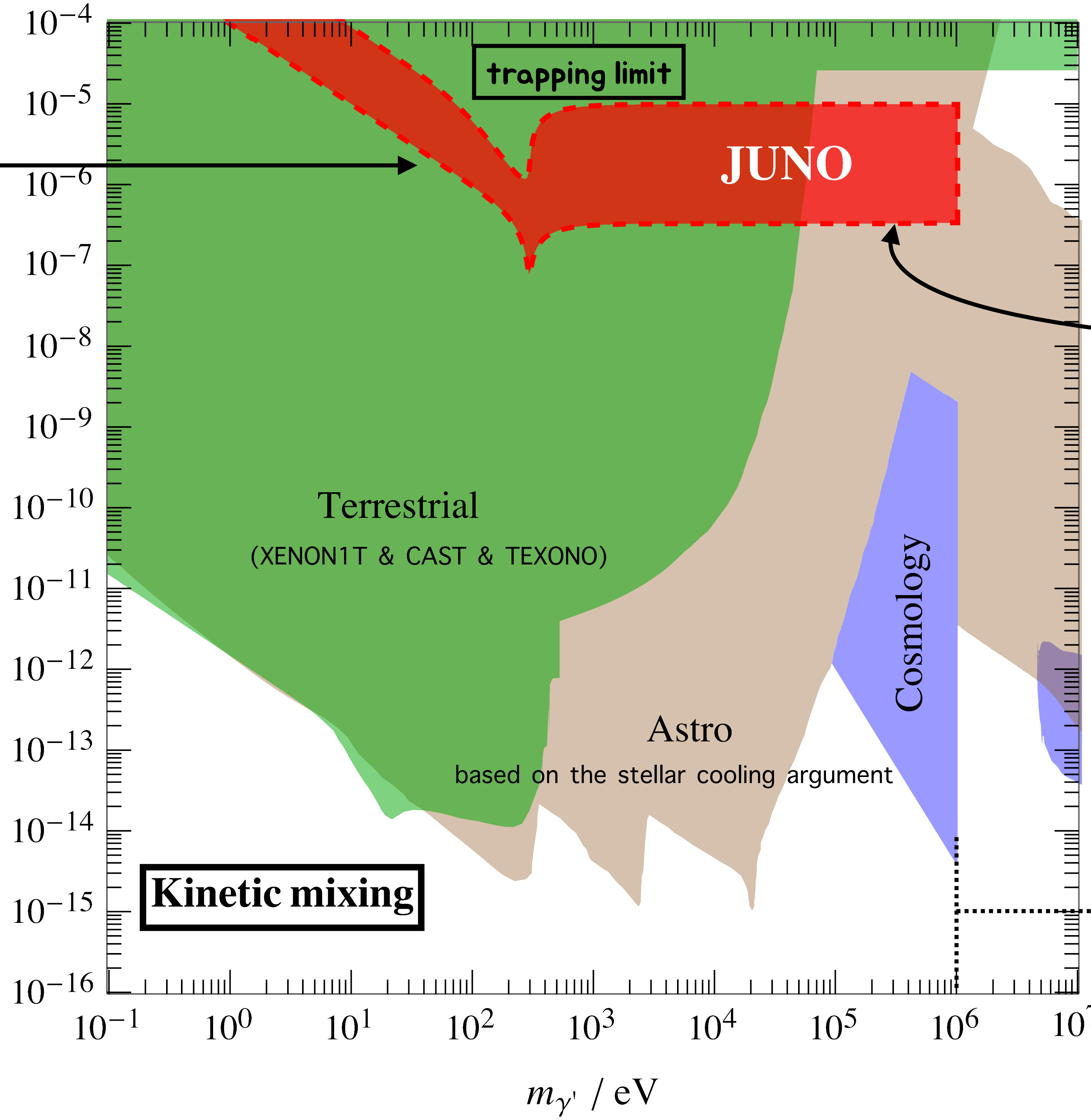


[G. Lucente et al., 22]

$$N_{\rm ev} < N_{\rm ev}^{\rm lim} = 97 \text{ @ } 90\,\% \text{ C.L.}$$

JUNO constraint on Kinetic mixing

$$N_{\rm ev} \propto \left(\varepsilon^2 m_{\gamma'}^4\right)\left(\varepsilon^2\right)$$



$$N_{\rm ev} \propto \left(\varepsilon^2 m_{\gamma'}^0\right)\left(\varepsilon^2\right)$$

$$\Phi_{\gamma'}\, e^{-\Gamma_{\gamma'} d_\odot / v_{\gamma'}}$$

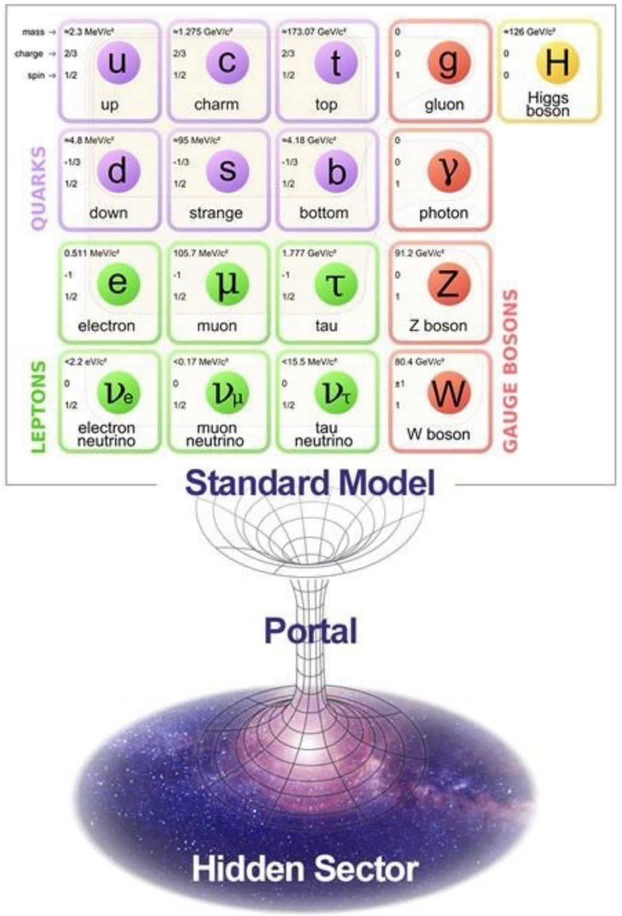
$$\gamma' \to e^- e^+$$

Conclusion

- Sun is an attractive natural object to probe fundamental interactions
- Solar 5.49 MeV γ' production via the deuterium fusion reaction
  - Isovector from γ'-γ mixing
  - Kinetic (ε) & In-medium (q_e')
- Solar 5.49 MeV γ' detection at JUNO
  - Compton-like ($\gamma' + e^- \to \gamma + e^-$)
  - In-flight decay ($\gamma' \to e^- e^+$) ☞ no bound at $m_{\gamma'} > 2m_e$
- Projected constraints from JUNO
  - $10^{-7} < \varepsilon < 10^{-5}$ @ $10\,\mathrm{keV} < m_{\gamma'} < 1\,\mathrm{MeV}$

Back up

Portal physics

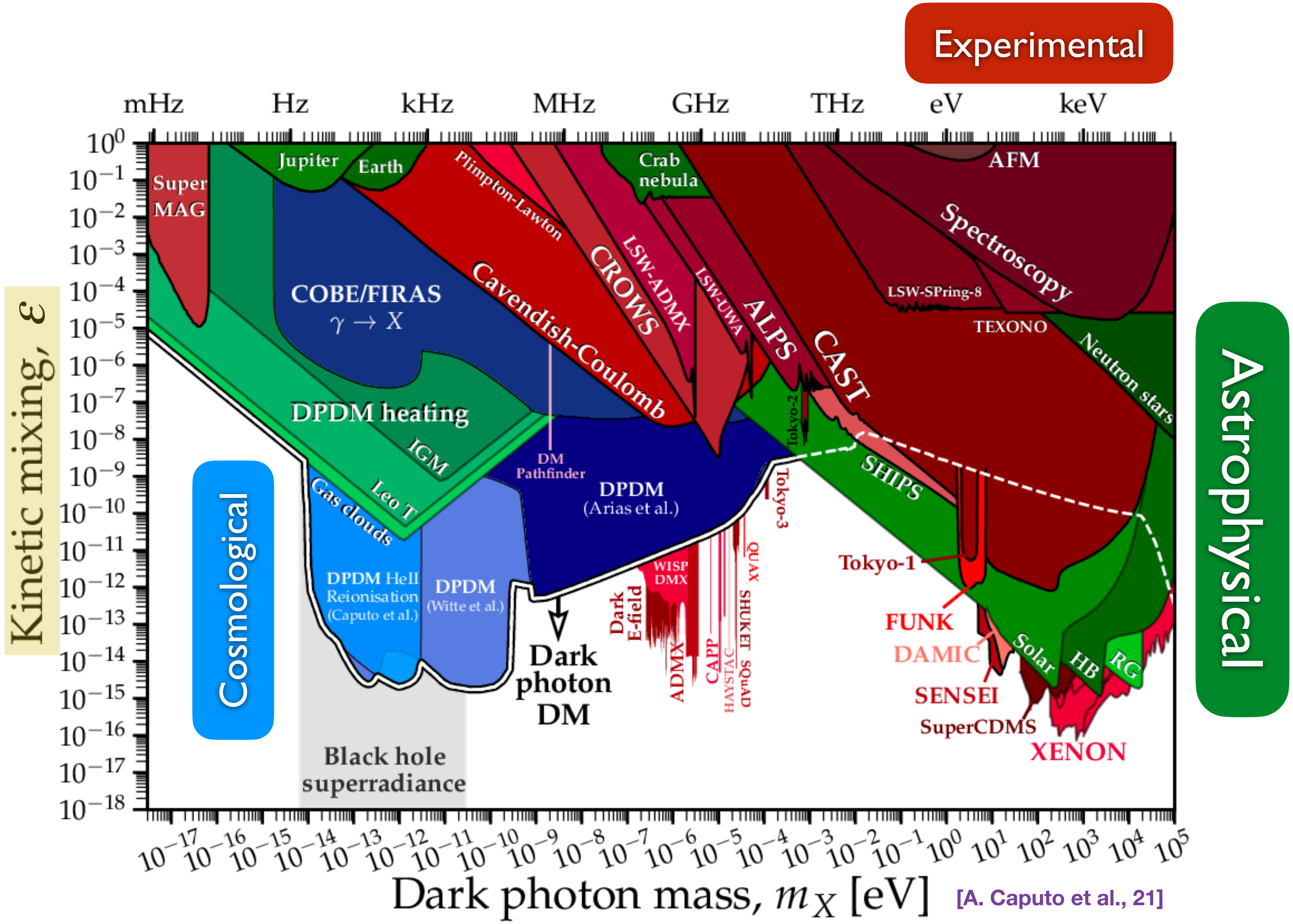


Higgs portal	***Axion portal***	***Vector portal***	***Neutrino portal***
spin-0 scalar	spin-0 pseudoscalar	spin-1 vector	spin-1/2 fermion
$\vert S \vert^2 H^\dagger H$	$(a/f_a)\, F_{\mu\nu}\tilde{F}^{\mu\nu}$ $(\partial_\mu a/f_a)\, \bar{\psi}\gamma^\mu\gamma^5\psi$	$\dfrac{\varepsilon}{2} F_{\mu\nu}X^{\mu\nu}$ $A'_\mu J^\mu_{\text{dark}}$	$\bar{L}HN$

Gauged U(1) extension of SM

- General interactions of dark gauge bosons (γ' & A'_μ) to SM particles
  - *U(1) charge assignment* $\mathscr{L}_{\gamma'\text{-}\psi} = g_\psi A'_\mu \bar{\psi}\Gamma^\mu \psi$ $\Gamma^\mu = [\gamma^\mu, \gamma^\mu\gamma^5, \cdots]$
  - *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 constraints



[A. Caputo et al., 21]

Dark $U(1)$ gauge boson

- Effective γ' couplings at $\mu > \Lambda_{\rm QCD}$ - *perturbative QCD*

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu + eA_\mu J^\mu_{\rm EM} + e'A'_\mu J'^\mu$$

EM field strength | DP field strength | kinetic mixing | γ' mass | EM current | γ' current
- quark
- lepton

- Effective γ' couplings at $\mu < \Lambda_{\rm QCD}$?

  ✓ Chiral perturbation theory (ChPT) with hadronic resonances (e.g., nucleons and mesons)

- Effective γ' couplings in a medium?

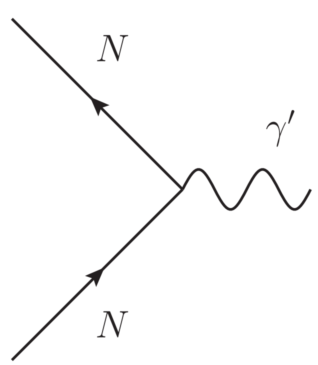
  ✓ Thermal field theory ☞ plasma effect

Hadronic interactions

- Basic principle in ChPT?
  - ➡ Matching currents with the same symmetry properties
- γ' couplings to hadrons from $e' A'_\mu J'^\mu$ $\boxed{J'_\mu = \sum q'_i \bar{\Psi}_i \gamma_\mu \psi_i}$

[Kroll-Ruderman, 1954]

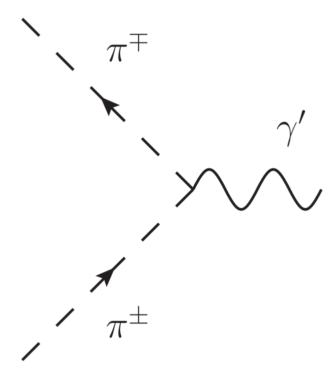
- Nucleon currents



$$e' A'_\mu \sum_N q'_N \bar{N} \gamma^\mu N$$

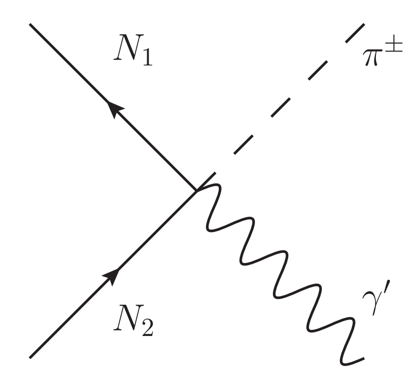
$$q'_p = 2q'_u + q'_d \quad q'_n = q'_u + 2q'_d$$

- Pion currents



$$e' A'_\mu \left(q'_p - q'_n\right) i\pi^- \overleftrightarrow{\partial^\mu} \pi^+$$

- N+Pion currents



$$-ie' A'_\mu \left(q'_p - q'_n\right) \frac{g_A}{f_\pi} \left[\pi^+ \bar{p} \gamma^\mu \gamma^5 n - \pi^- \bar{n} \gamma^\mu \gamma^5 p\right]$$

★ What is effective couplings in a dense medium?

$\left(q'_p \,\&\, q'_n\right)$

Hadronic interactions

- Basic principle in ChPT?
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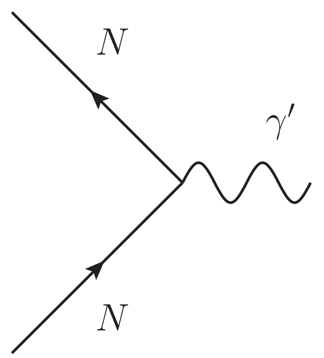
- γ' couplings to hadrons from $e'A'_\mu J'^\mu$ $\boxed{J'_\mu = \sum q'_i \bar{\Psi}_i \gamma_\mu \psi_i}$

[Kroll-Ruderman, 1954]

- Nucleon currents



$$e'A'_\mu \sum_N q'_N \bar{N}\gamma^\mu N$$

$q'_p = 2q'_u + q'_d \quad q'_n = q'_u + 2q'_d$

- Pion currents

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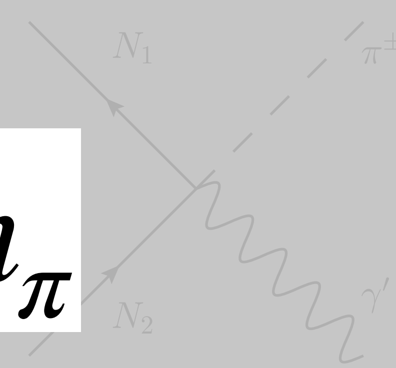
- N+Pion currents



$$-ie'A'_\mu \left(q'_p - q'_n\right) \frac{g_A}{f_\pi} \left[\pi^+ \bar{p}\gamma^\mu\gamma^5 n - \pi^- \bar{n}\gamma^\mu\gamma^5 p\right]$$

$$T \ll m_\pi$$

★ What is effective couplings in a dense medium?
$\left(q'_p \,\&\, q'_n\right)$

Isovector component

$$\mathscr{L}_{\gamma'} = \mathscr{L}' + \mathscr{L}_{\varepsilon} + \mathscr{L}_{\Pi}$$

Isovector component

$$\mathscr{L}_{\gamma'} = \underline{\mathscr{L}'} + \mathscr{L}_{\varepsilon} + \mathscr{L}_{\Pi}$$

$$e' J'^{\mu} A'_{\mu}$$

$$\boxed{J'^{\mu} = \sum q'_{\psi} \bar{\psi} \gamma^{\mu} \psi}$$

- If q'_{ψ} respect the SM symmetries
  - particularly, interchange of $SU(2)_W$ doublets
  - ***Isoscalar*** (i.e., $q'_u = q'_d$ leading to $q'_p = q'_n$)
  - e.g., gauging baryon number B
  - typically considered

Isovector component

$$\mathscr{L}_{\gamma'} = \mathscr{L}' + \underbrace{\mathscr{L}_{\varepsilon} + \mathscr{L}_{\Pi}}$$

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$$\left(\varepsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\mathrm{T,L}}} + \frac{e' q'_e}{e q_e} \frac{\pi_{\mathrm{T,L}}}{m_{\gamma'}^2 - \pi_{\mathrm{T,L}}} \right) e J^{\mu}_{\mathrm{EM}} A'_{\mu}$$

- From mixing with γ
  - following electromagnetic current J^{μ}_{EM}
  - ***Isovector***
  - source of γ' production via nuclear transition
  - at the leading dipole order

Multipole radiation

- Velocity as a good order parameter in expansion for scatterings
- Dipole radiation
  - Leading order
  - $\mathscr{M}_{\text{dipole}} \propto (e_{\text{eff}}^{N_1} - e_{\text{eff}}^{N_2})$ of ***isospin breaking*** combination
  - Center of charges ≠ Center of masses
- Quadrupole radiation
  - Next-leading order
  - $\mathscr{M}_{\text{quadrupole}}$ as $\left|\dfrac{\mathscr{M}_{\text{quadrupole}}}{\mathscr{M}_{\text{dipole}}}\right| \sim v_N$
  - Center of charges = Center of masses

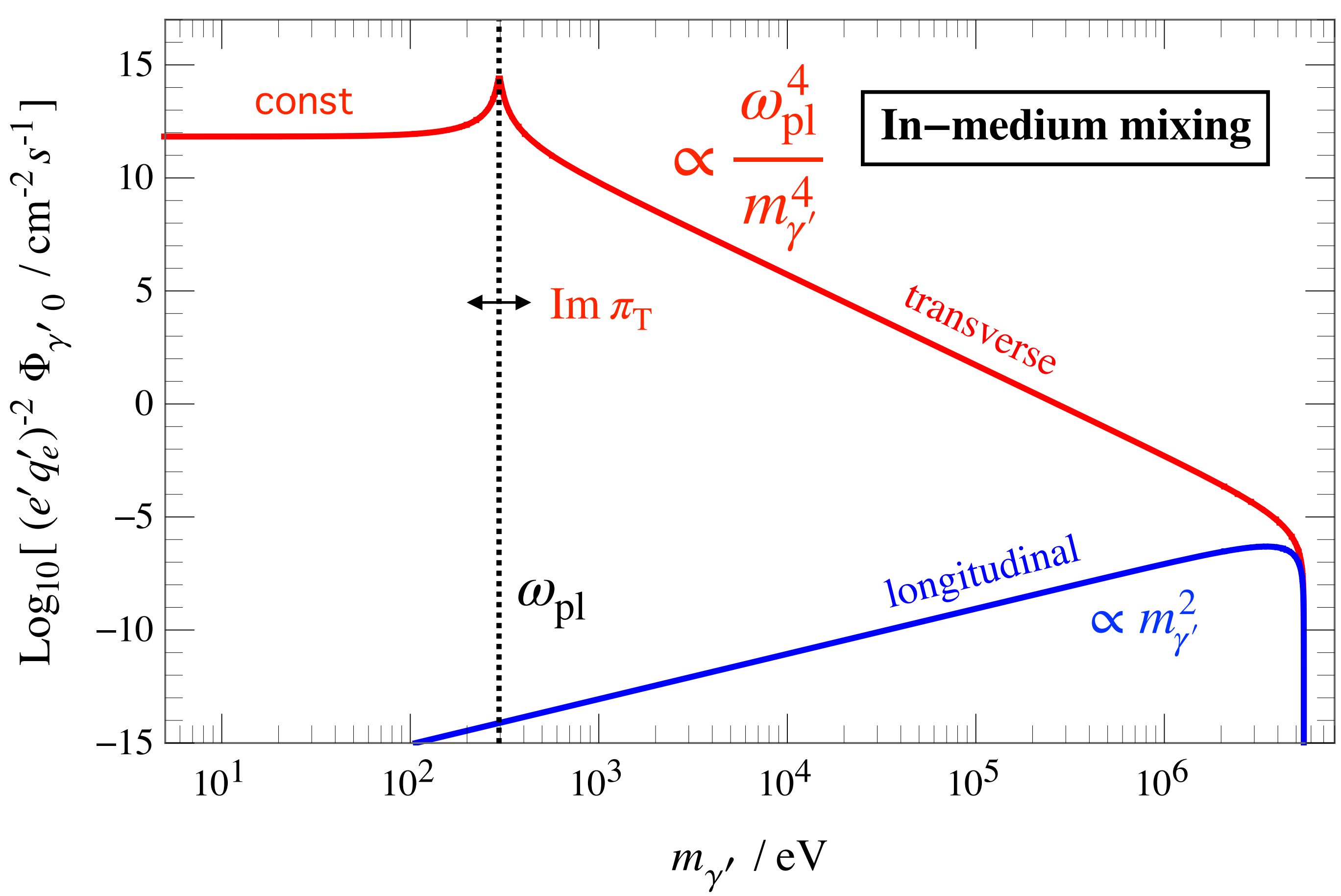
Solar **5.49 MeV** γ' flux (In-medium)

$1.7 \times 10^{38}\,\mathrm{s}^{-1}$ **for** $p\,(d\,,^3\mathrm{He})\,\gamma$

γ-γ' **mixing**

$$\left[\Phi_{\gamma'}\right]_{\mathrm{T,L}} = \frac{1}{4\pi d_\odot^2}\phi_\gamma \frac{k^3}{\omega^3}\left|\frac{e'q_e'}{eq_e}\frac{\pi_{\mathrm{T,L}}}{m_{\gamma'}^2-\pi_{\mathrm{T,L}}}\right|^2 \times \left[\frac{m_{\gamma'}^2}{\omega^2}\right]_{\mathrm{L}}$$

(current conservation)



Numerical Procedure: χ^2 is defined as

$$\chi^2 = 2 \times \sum_{i=1}^{240} \left(N^i_{pre} - N^i_{obs} + N^i_{obs} \times \log \frac{N^i_{obs}}{N^i_{pre}} \right) + \left(\frac{\varepsilon_s}{\sigma_s} \right)^2 + \left(\frac{\varepsilon_b}{\sigma_b} \right)^2 ,$$

$$N^i_{pre} = (1 + \varepsilon_s) \times T_i + (1 + \varepsilon_b) \times B_i + \frac{S}{\sqrt{2\pi}\sigma} \times e^{-\frac{(E_{5.5} - E_i)^2}{2\sigma^2}} ,$$

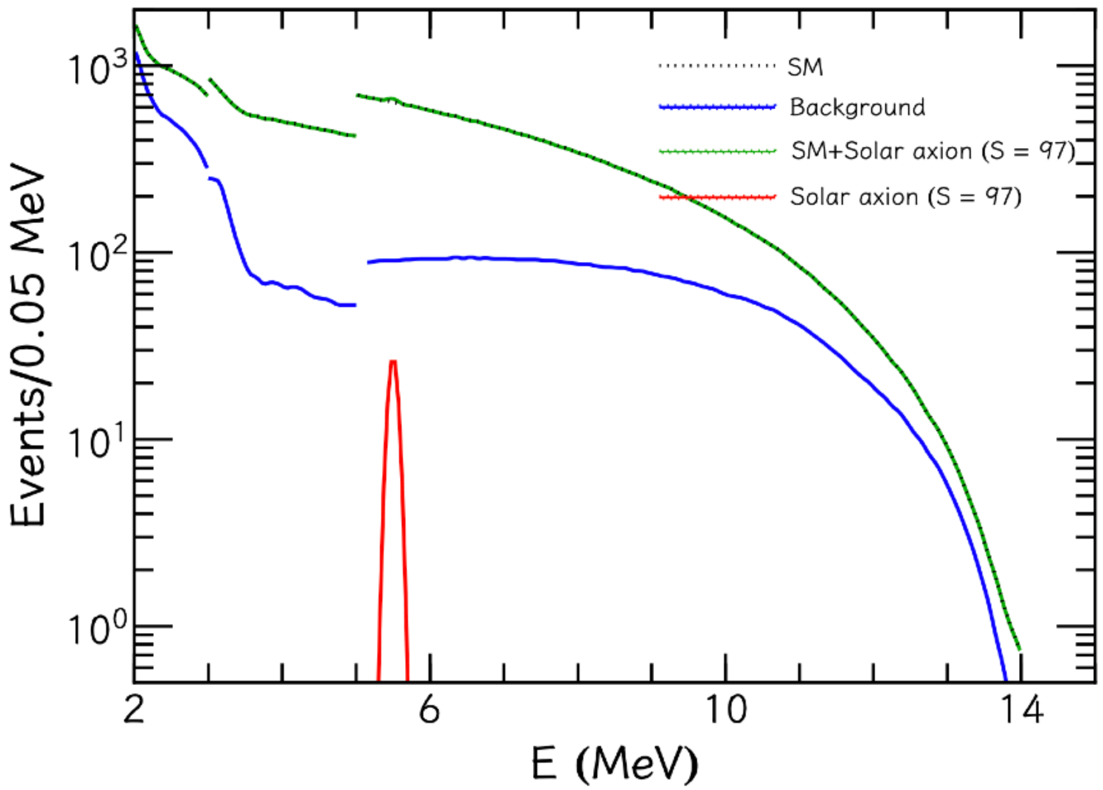
Total signal

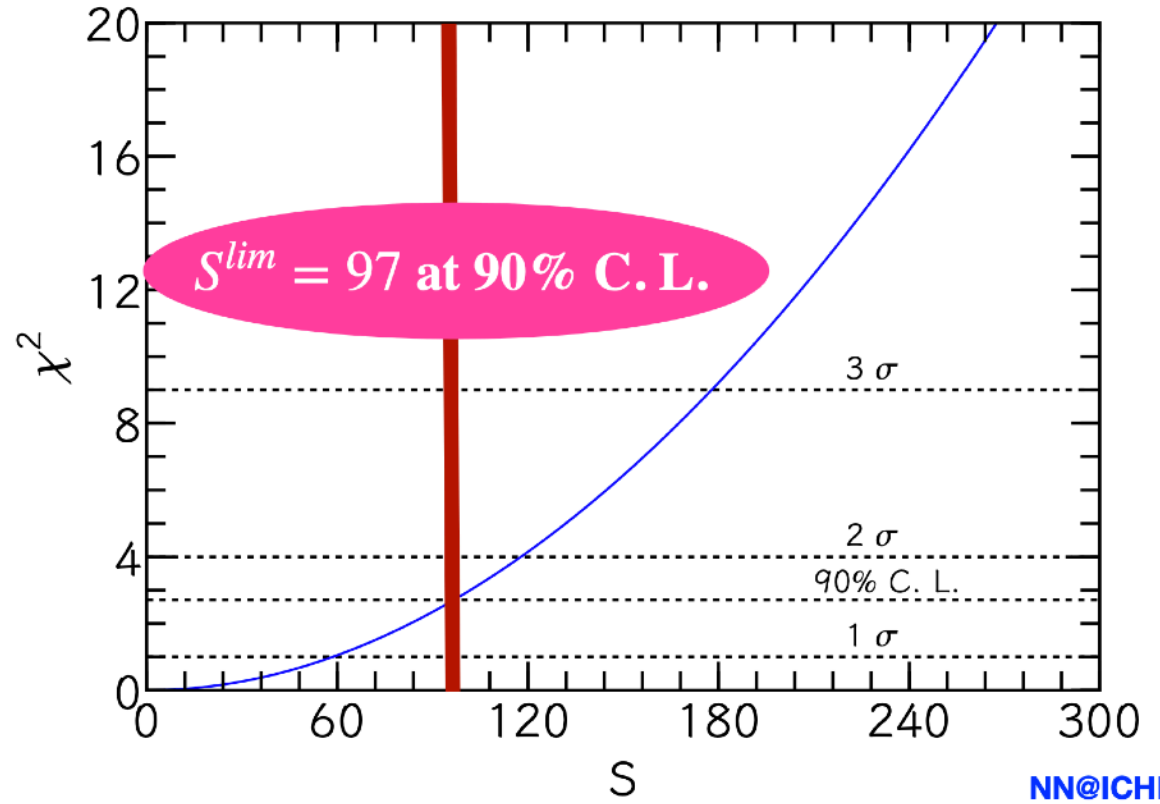
Total Background

Axion peak Intensity

Nuisance parameters

Signal and background Uncertainties, 5% & 15 %





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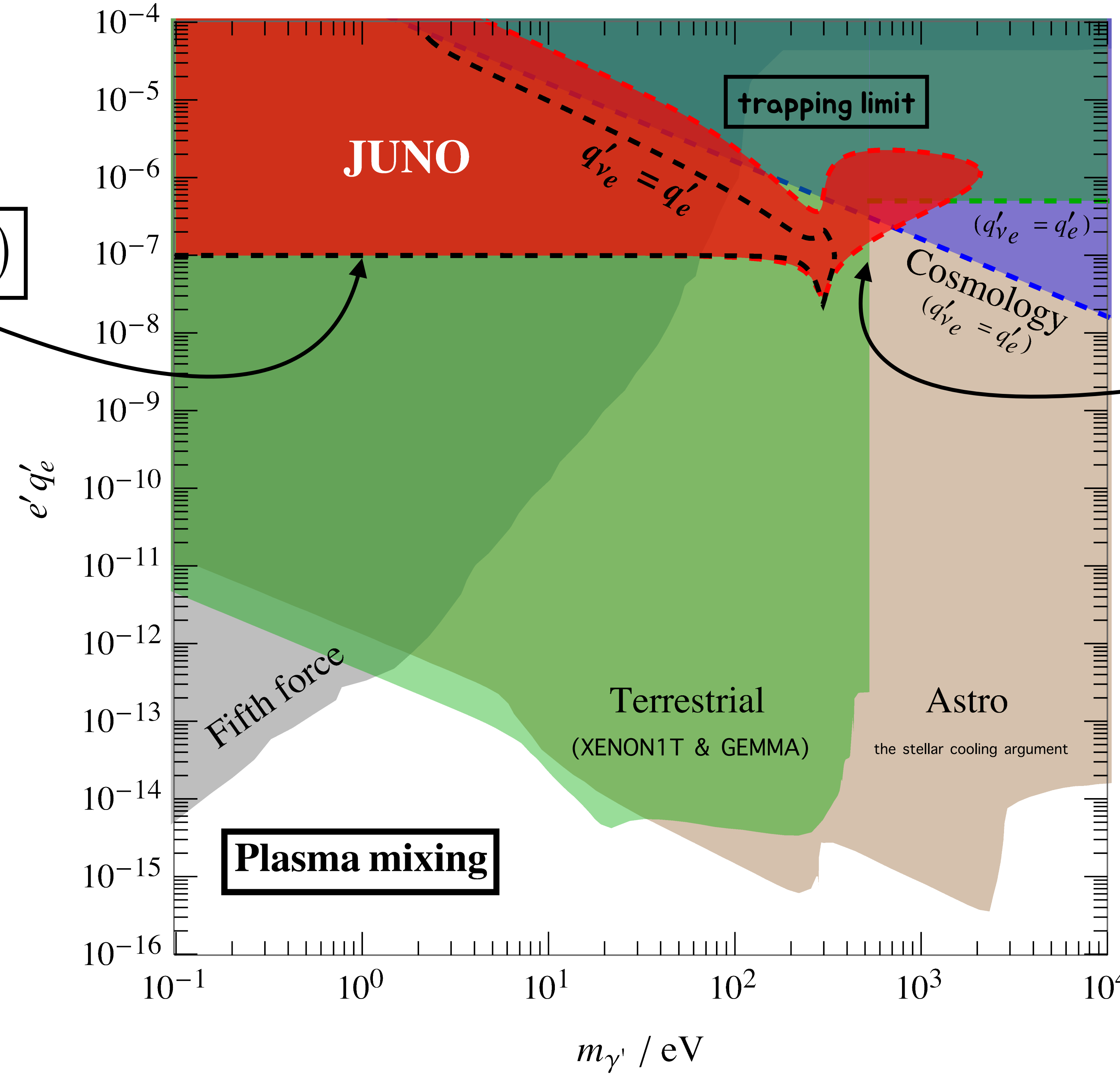
[N. Nath's slide]

$N_{ev} < N_{ev}^{lim} = 97$ @ 90 % C.L.

JUNO constraint on In-medium mixing



$N_{ev} \propto (e'^2 m_{\gamma'}^0)(e'^2)$

$N_{ev} \propto (e'^2 m_{\gamma'}^{-4})(e'^2)$