Phenomenology of Majorons

Julian Heeck

MPIK Heidelberg

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Fundamental Interactions .be

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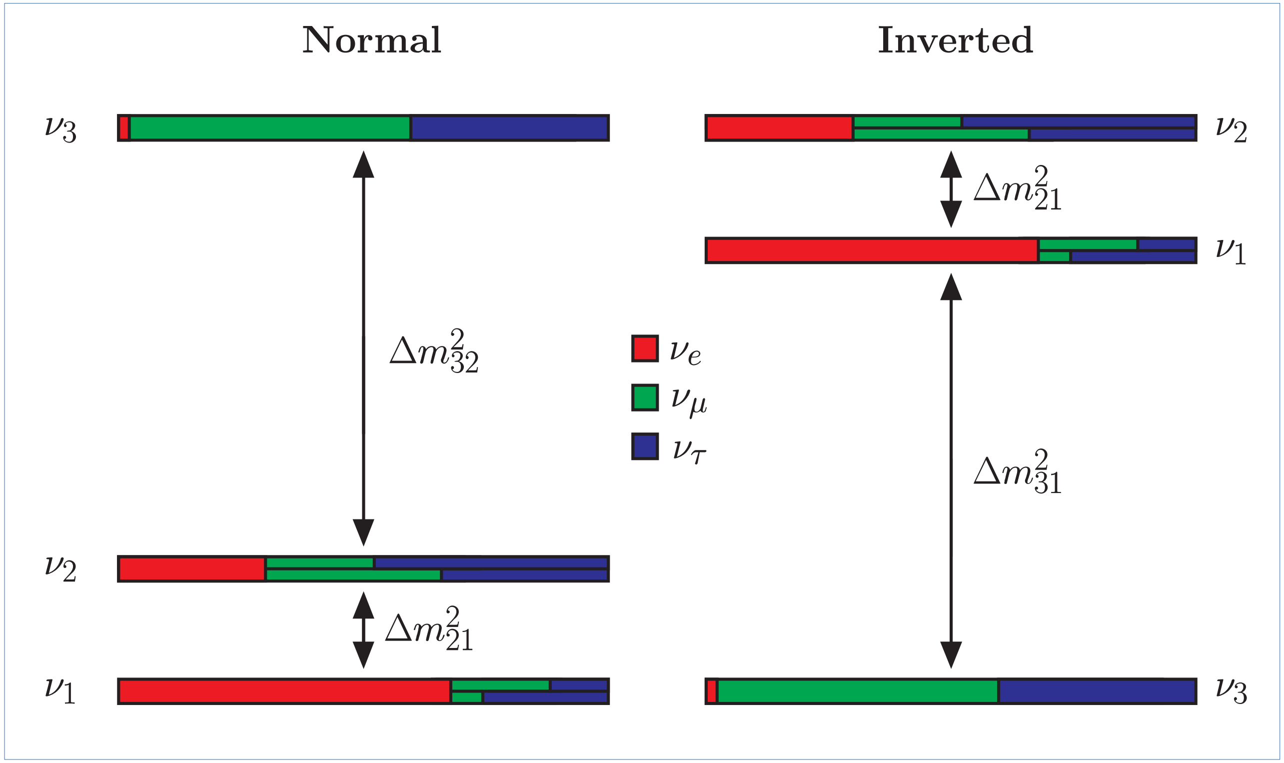
Neutrinos have masses and mix

- Mass splittings ✔
- Angles ✔
- Phase(s) ✘
- Ordering ✘
- Mass scale ✘
- Dirac vs. Majorana ✘
- Mass origin ✘



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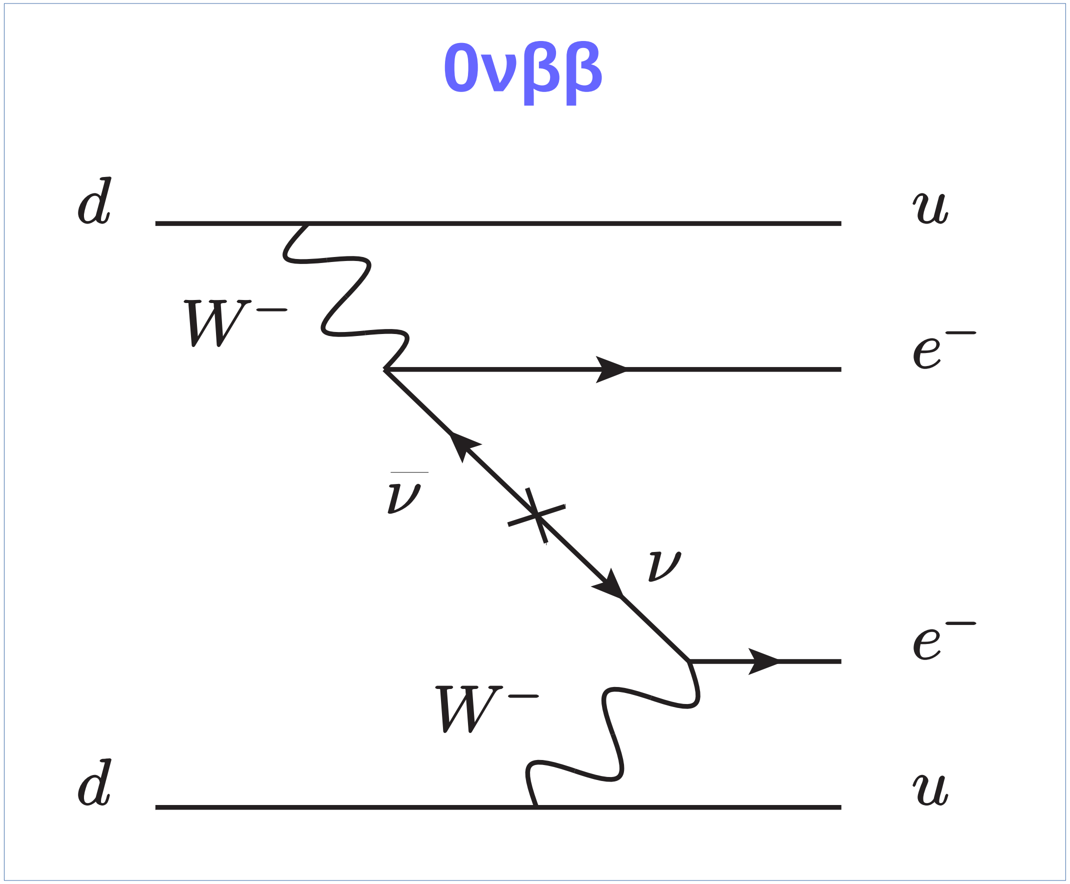
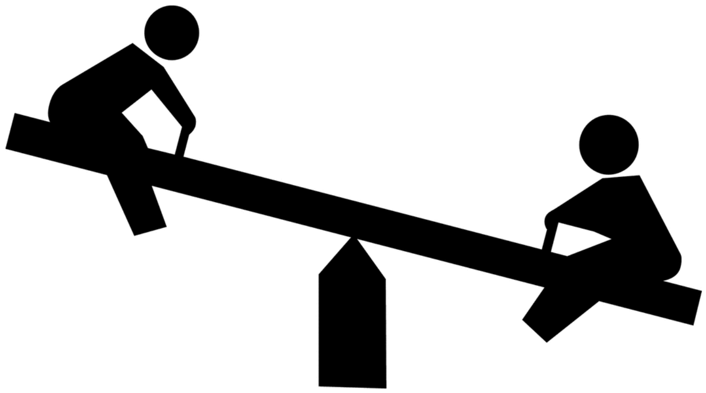


Mass origin via seesaw mechanism



- Introduce 3 singlets N_R:

$$\mathcal{L} = -\overline{L}\underbrace{yH}_{m_D}N_R - \frac{1}{2}\overline{N}_R^c M_R N_R + \text{h.c.}$$

- For $M_R \gg m_D$: $\boxed{M_\nu \simeq -m_D M_R^{-1} m_D^T}$

$$\simeq 1\text{eV}\left(\frac{m_D}{100\text{GeV}}\right)^2\left(\frac{10^{13}\text{GeV}}{M_R}\right).$$

- Majorana neutrinos: hope for $0\nu\beta\beta$!
- Bonus: leptogenesis (even with majoron).
  [Aristizabal Sierra, Tortola, Valle, Vicente, ‘14]

Parametrization of our ignorance

"Known": $\mathsf{M}_\nu = \mathsf{U}\,\mathsf{diag}(\mathsf{m}_1, \mathsf{m}_2, \mathsf{m}_3)\mathsf{U}^\mathsf{T} \simeq -\mathsf{m}_\mathsf{D}\mathsf{M}_\mathsf{R}^{-1}\mathsf{m}_\mathsf{D}^\mathsf{T}$

PMNS mixing matrix

Parametrization of our ignorance

“Known”: $M_\nu = U\,\mathrm{diag}(m_1, m_2, m_3) U^T \simeq -m_D M_R^{-1} m_D^T$

PMNS mixing matrix

9 parameters not known:

- M_R (3 parameters) and

$$m_D = iU\sqrt{\mathrm{diag}(m_j)}R^T\sqrt{M_R}$$

with $R^T R = 1$.

[Casas, Ibarra, hep-ph/0103065]

- $\{m_D, M_R\} \leftrightarrow \{M_\nu, M_R, R\}$.

Parametrization of our ignorance

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- $\{m_D, M_R\} \leftrightarrow \{M_\nu, M_R, R\}$.

or

- Just $m_D m_D^\dagger$.

[Davidson, Ibarra, hep-ph/0104076]

- Hermitian, contains 9 real parameters.
- $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.

Spontaneous B – L breaking

- Instead of explicitly, break $U(1)_{B\text{-}L}$ spontaneously:

$$\mathcal{L} = -\overline{L} y H N_R - \tfrac{1}{2} \underbrace{\overline{N_R^c} \lambda \sigma}_{} N_R + \text{h.c.}$$

$$M_R = \frac{\lambda f}{\sqrt{2}}$$

- New scalar $\sigma = (f + \sigma^0 + iJ)/\sqrt{2}.$

Breaking scale

Heavy scalar (inflaton?)

Majoron

[Chikashige, Mohapatra, Peccei, ‘81; Schechter, Valle, ‘82]

- Scalar potential:

$$V = V_H + \lambda_{H\sigma} \left(\frac{v^2}{2} - |H|^2 \right) \left(\frac{f^2}{2} - |\sigma|^2 \right) + \lambda_\sigma \left(\frac{f^2}{2} - |\sigma|^2 \right)^2 .$$

Pseudo-Goldstone

- Spontaneous global U(1) breaking gives $m_J = 0$.
- Non-zero mass from:
  - Breaking by quantum gravity, e.g. $\Delta V = \lambda \frac{\sigma^5}{M_{Pl}} + h.c.$

$$\Rightarrow \quad m_J \simeq \lambda \left(\frac{f}{10^8\,\mathrm{GeV}}\right)^{\frac{3}{2}} \mathrm{TeV}.$$

[Babu, Rothstein, Seckel, '93; Akhmedov, Berezhiani, Mohapatra, Senjanovic '93]

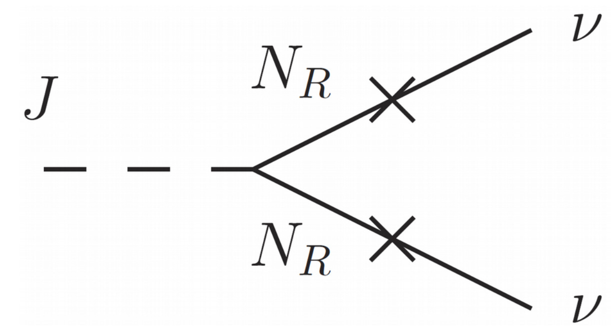
  - Anomalies, e.g. if $U(1)_{B-L} = U(1)_{PQ}$.

[Mohapatra, Senjanovic '83; Langacker, Peccei, Yanagida '86; SMASH '16]

  - Explicit breaking, e.g. $\Delta V = \frac{1}{2} m_J^2 J^2$.

Stay ignorant here, just put m_J.

Tree-level couplings



- $\mathrm{L} = \mathrm{i}J \sum_j \left(\frac{m_j}{2f}\right) \overline{\nu}_j \gamma_5 \nu_j + \ldots$

Tiny coupling: neutrino mass over B-L breaking scale!

- Long lifetime $\rightarrow$ majoron dark matter!

[Berezinsky, Valle ‘93; Lattanzi, Valle ‘07; Queiroz, Sinha, ‘14]

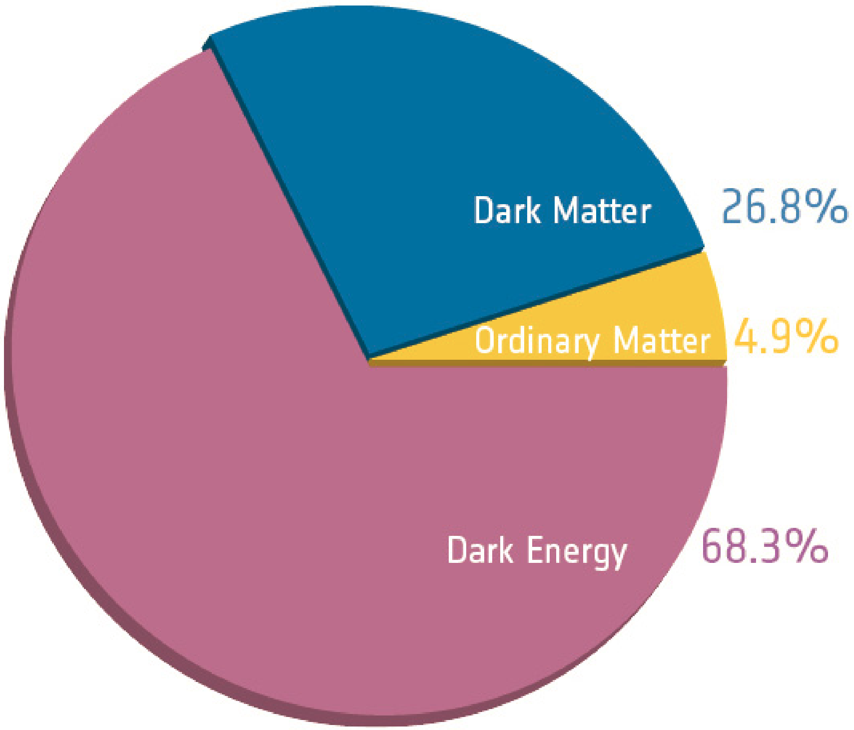
$$\boxed{\Gamma(J \to \nu\nu) \simeq \frac{1}{3\times 10^{19}\mathrm{s}} \left(\frac{m_J}{\mathrm{MeV}}\right) \left(\frac{10^9\,\mathrm{GeV}}{f}\right)^2 \left(\frac{\sum_j m_j^2}{10^{-3}\mathrm{eV}^2}\right)}$$

- General limit from DM $\rightarrow$ invisible: $\tau > \underbrace{5 \times 10^{18}\mathrm{s}}_{10\,\times\,\tau_{\mathrm{Universe}}}.$

[Audren, Lesgourgues, Mangano, Serpico, Tram, ‘14]

Dark matter abundance

- Freeze out via $\lambda J J \overline{H} H$:
  - $m_J \sim m_h/2$,
  - $m_J > 400$ GeV.



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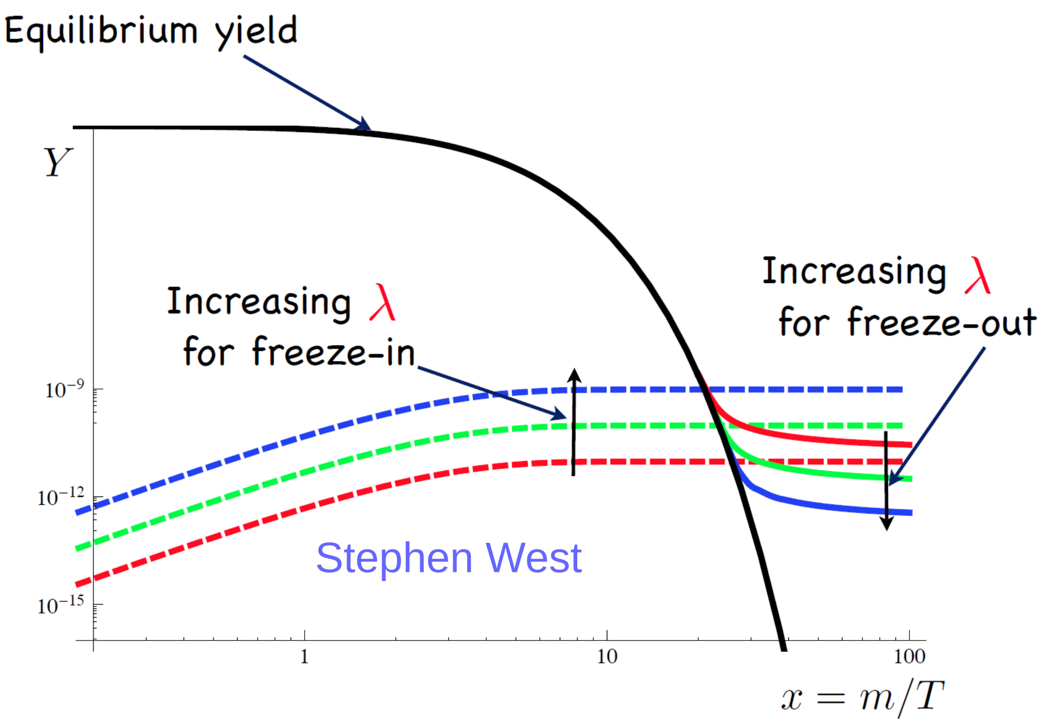
- Freeze in:

  $$\Omega_J \propto m_J \Gamma(h \to JJ)$$

$$\Rightarrow \quad \boxed{m_J \simeq \left(\frac{10^{-10}}{\lambda}\right)^2 \text{MeV.}}$$

[McDonald, '02; Hall, Jedamzik, March-Russell, West '10; Frigerio, Hambye, Masso, '11]



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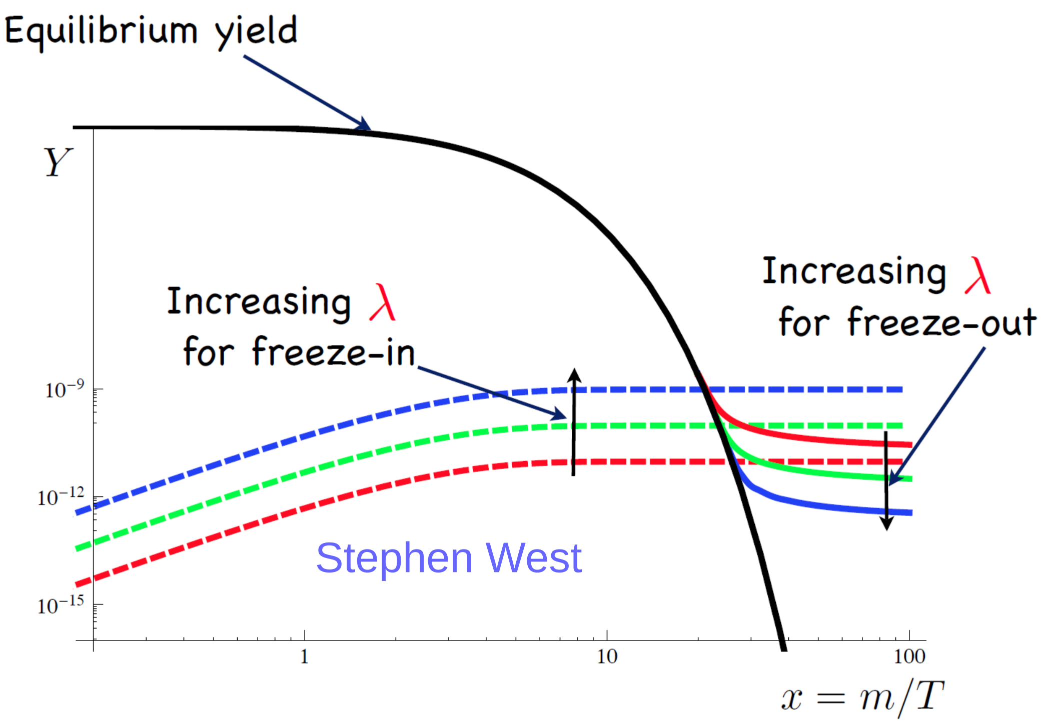

Lyman-α constraints below 12 keV!
Use different mechanism:
JH, D. Teresi, 1706.09909.

Indirect detection

$$\Gamma(J \to \nu\nu) \simeq \frac{1}{3\times 10^{19}\mathrm{s}} \left(\frac{m_J}{\mathrm{MeV}}\right) \left(\frac{10^9\,\mathrm{GeV}}{f}\right)^2 \left(\frac{\sum_j m_j^2}{10^{-3}\mathrm{eV}^2}\right)$$

- General limit from DM $\to$ invisible: $\tau > 5 \times 10^{18}\mathrm{s}$.

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- Can we observe the **neutrino lines**?
  - m_J > 10 TeV: **No.** Dominant decay is J $\to$ ννh(h).

    [Dudas, Mambrini, Olive, '15]

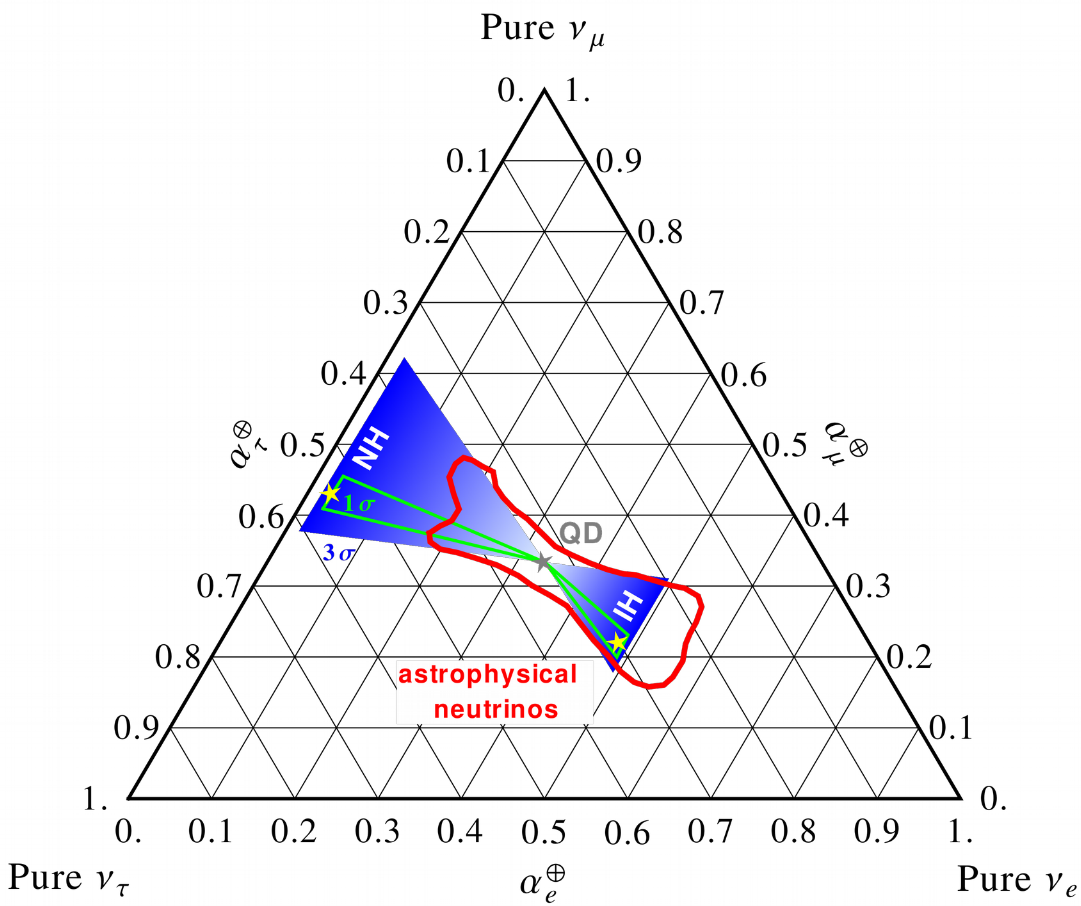
  - Also want to avoid electroweak Bremsstrahlung.

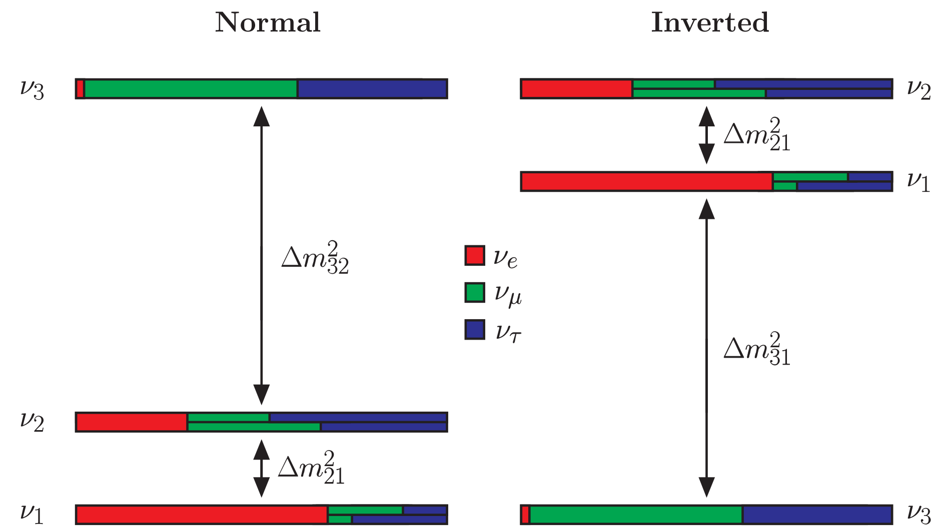
    [Kachelriess, Serpico, '07; Bell, Dent, Jacques, Weiler, '08; Queiroz, Yaguna, Weniger, '16]

  - For MeV < m_J < 100 GeV: **Yes!**

Flavor of J $\rightarrow \nu_j \nu_j$

No oscillations!

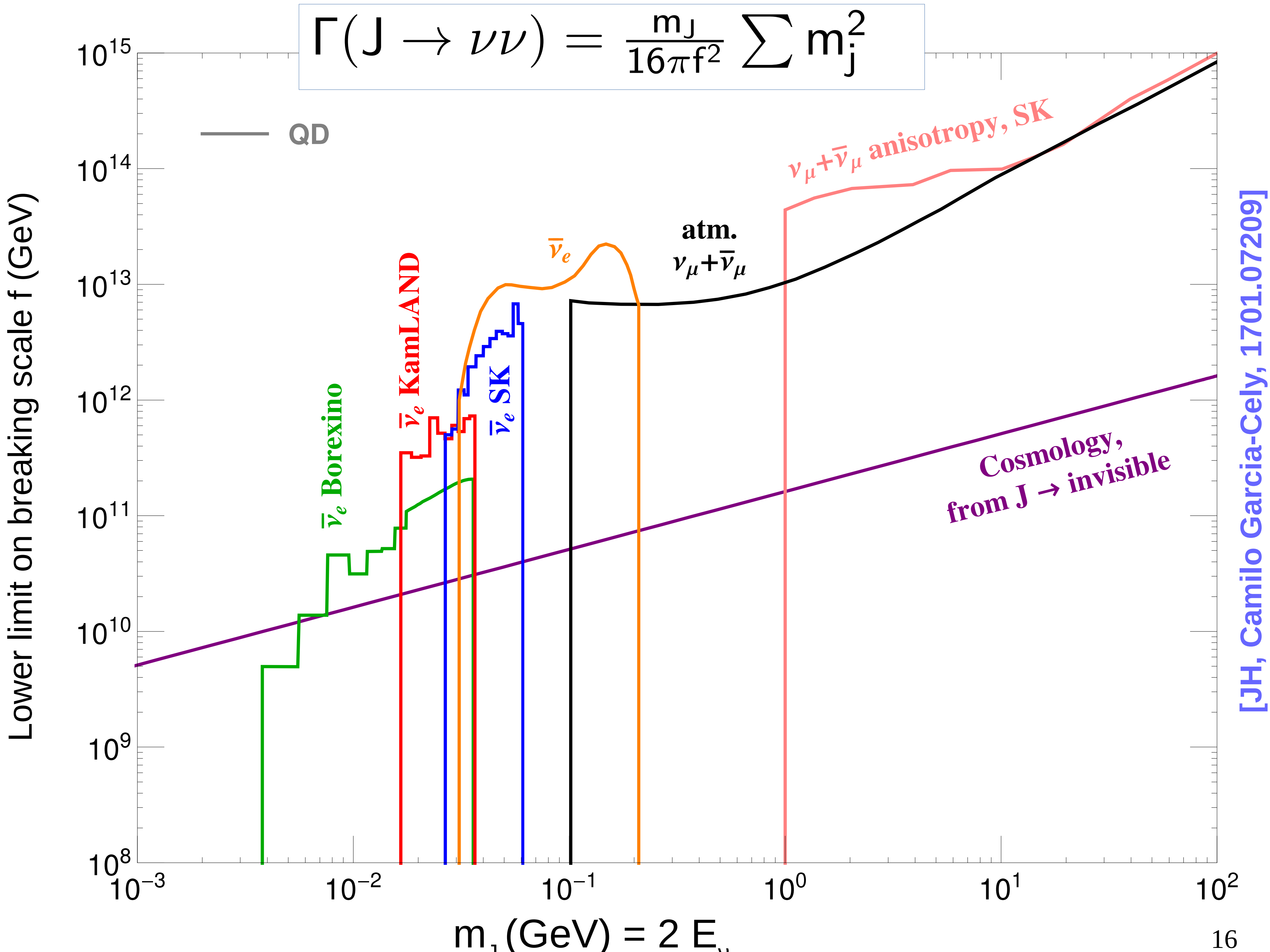




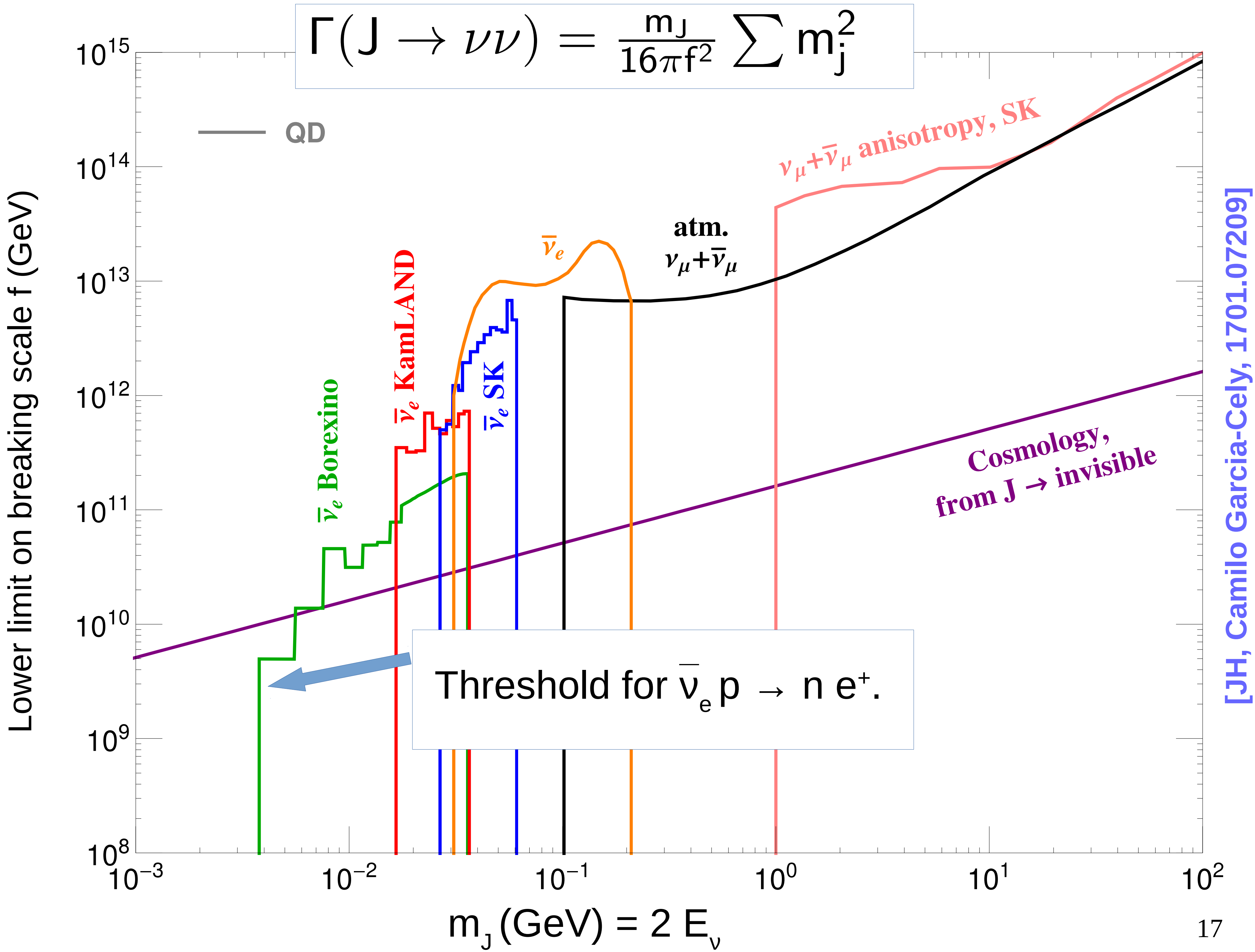
Flavor ratios:

$$
\begin{array}{lcccccc}
 & \alpha_e & : & \alpha_\mu & : & \alpha_\tau & \\
\text{NH}: & 0.03 & : & 0.43 & : & 0.54 & , \\
\text{IH}: & 0.48 & : & 0.22 & : & 0.30 & , \\
\text{QD}: & 0.33 & : & 0.33 & : & 0.33 & .
\end{array}
$$

[JH, Camilo Garcia-Cely, 1701.07209]



$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_j^2$
QD
$\nu_\mu + \bar{\nu}_\mu$ anisotropy, SK
$\bar{\nu}_e$
atm. $\nu_\mu + \bar{\nu}_\mu$
$\bar{\nu}_e$ KamLAND
$\bar{\nu}_e$ SK
$\bar{\nu}_e$ Borexino
Cosmology, from $J \to$ invisible
Lower limit on breaking scale f (GeV)
m_J (GeV) = 2 E_ν
[JH, Camilo Garcia-Cely, 1701.07209]



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atm. $\nu_\mu + \bar{\nu}_\mu$
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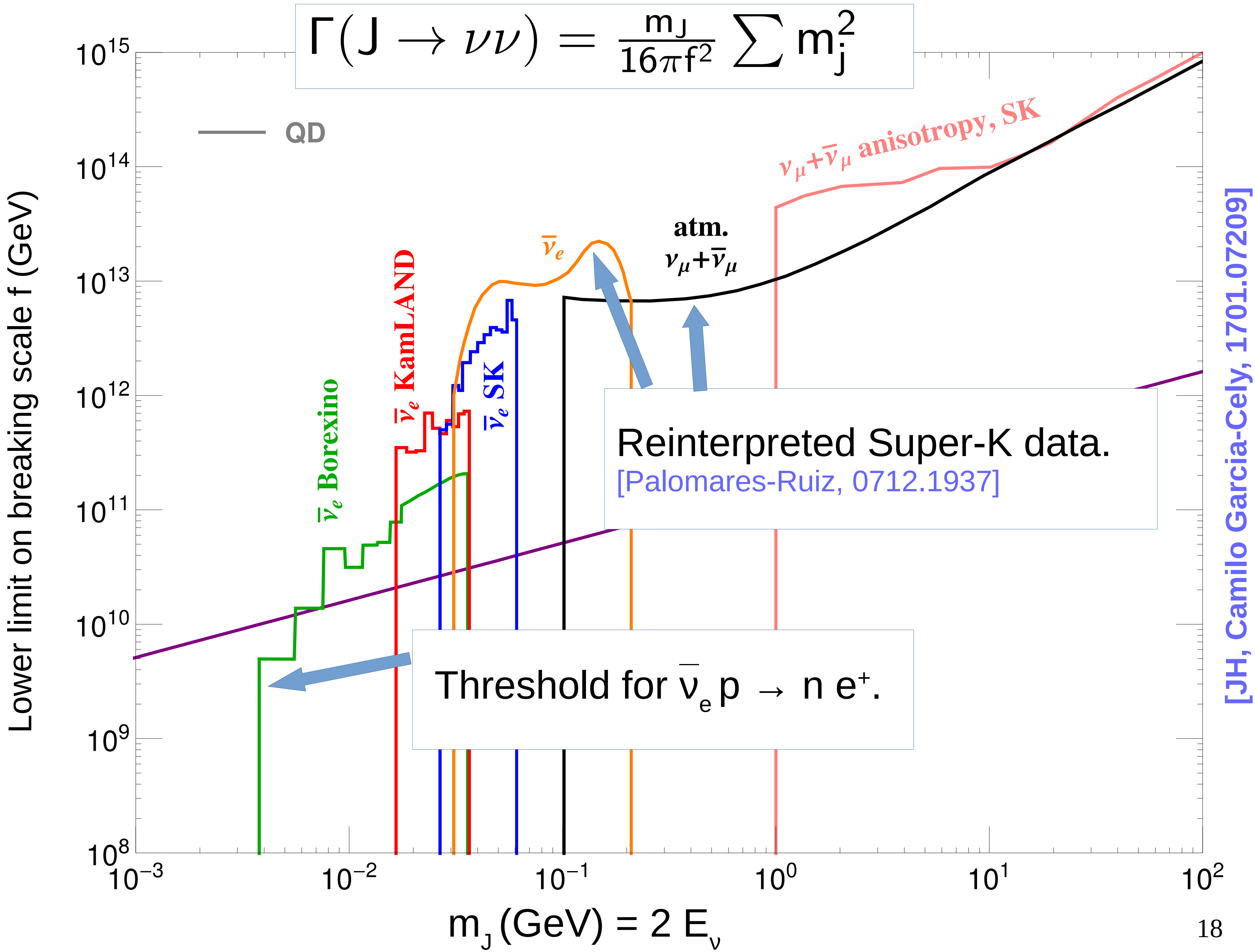
Cosmology, from J → invisible
Threshold for $\bar{\nu}_e\, p \to n\, e^+$.
[JH, Camilo Garcia-Cely, 1701.07209]



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Reinterpreted Super-K data.
[Palomares-Ruiz, 0712.1937]
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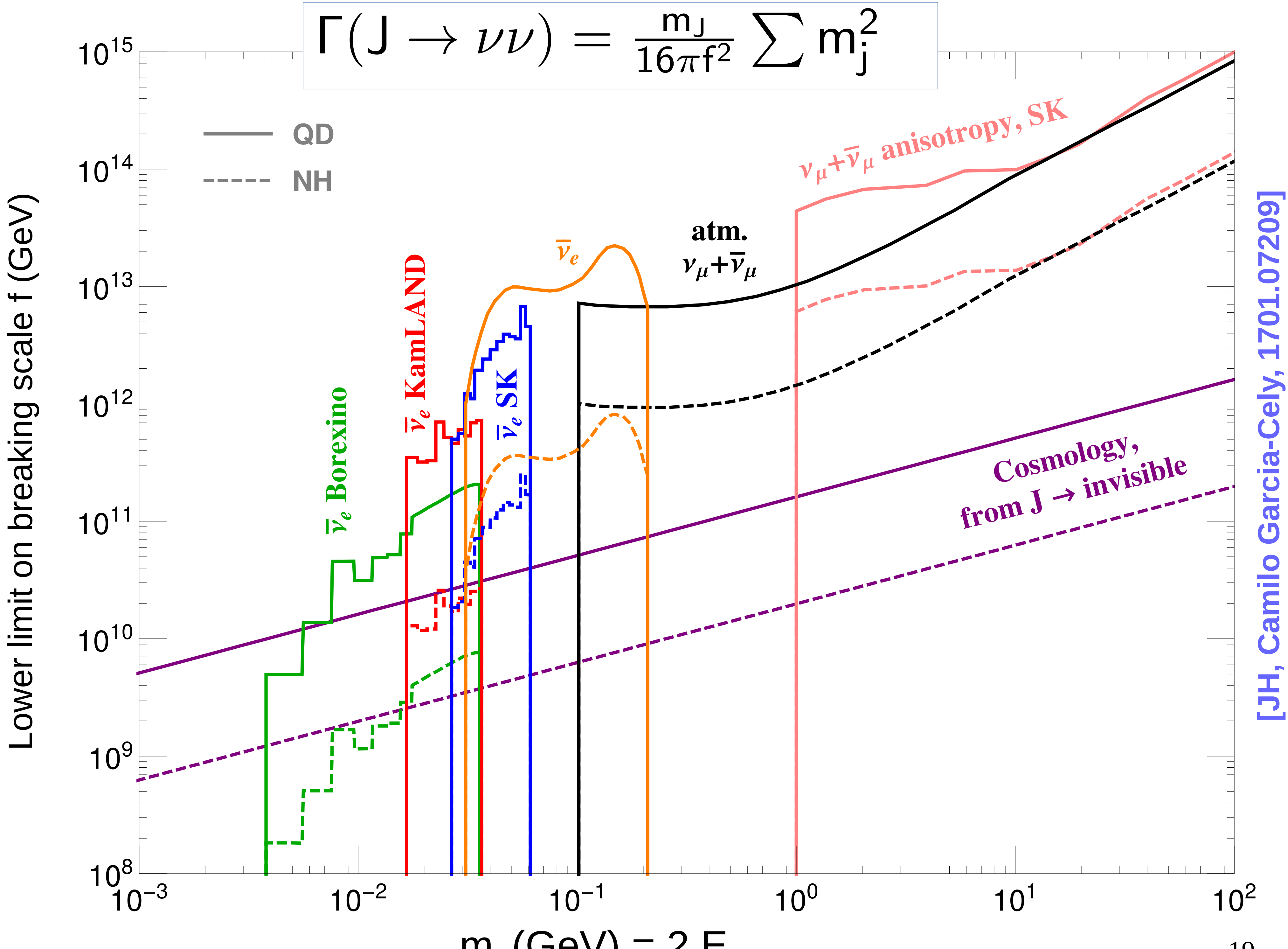

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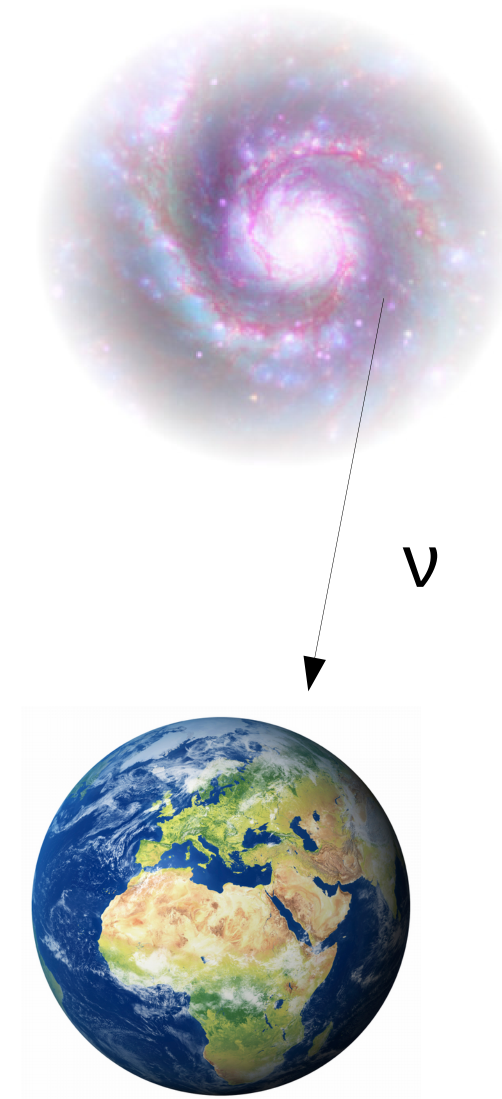
Look for neutrinos from light DM!

- ν lines detectable down to MeV.
- For free in searches for diffuse supernova neutrino background.
- Borexino = indirect DM detector.
- Future direct DM detectors (LZ, XENONnT) = indirect DM detectors.
- DM → ν easily dominant channel, no SU(2) argument as for multi-TeV.

[El Aisati, Garcia-Cely, Hambye, Vanderheyden, 1706.06600]



One-loop couplings

- Diagonal:

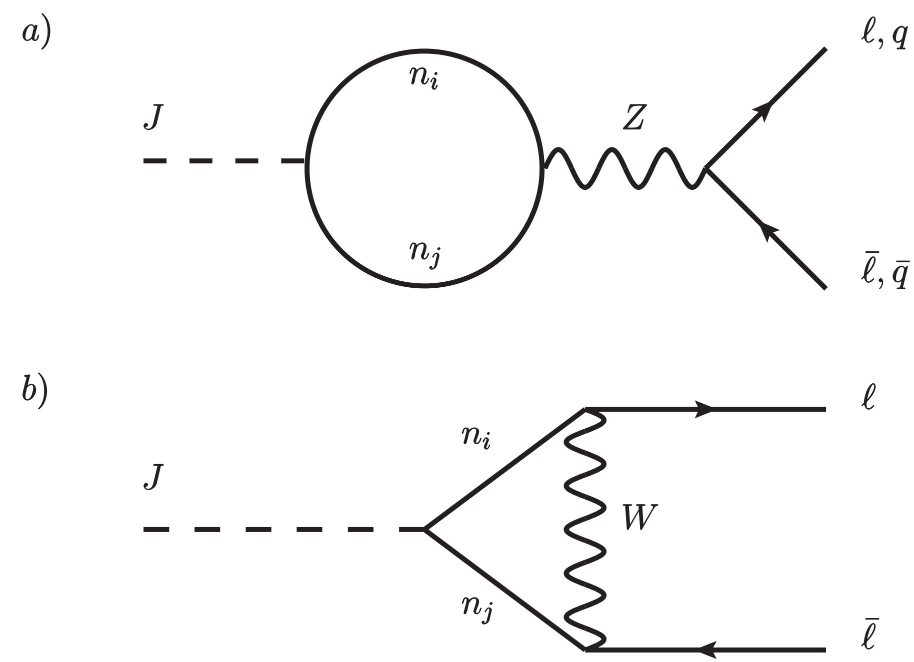
$$\mathcal{L} = iJ\overline{q}\gamma_5 q\,\frac{m_q}{8\pi^2 v}\left(T_3^q\,\mathrm{tr}\,K\right) + iJ\overline{\ell}\gamma_5\ell\,\frac{m_\ell}{8\pi^2 v}\left(T_3^\ell\,\mathrm{tr}\,K + K_{\ell\ell}\right).$$

- Off-diagonal:

$$\mathcal{L} = -iJ\overline{\ell}P_L\ell'\,\frac{m_\ell}{8\pi^2 v}K_{\ell\ell'}.$$

- New parameter:

$$\boxed{K \equiv \frac{m_D m_D^\dagger}{v\,f}.}$$



- K = rest of seesaw!
- $|K_{\ell\ell'}| \leq \mathrm{tr}\,K.$
- One generation:

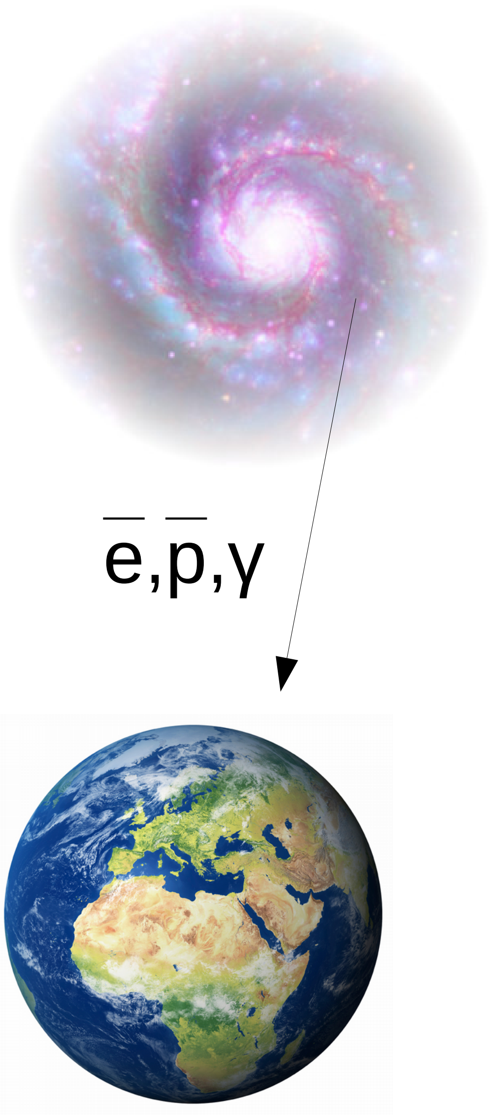
$$K \sim \frac{m_\nu M_R}{v\,f} \sim 10^{-13} M_R/f.$$

[Chikashige, Mohapatra, Peccei, ‘81; Pilaftsis ‘94]

Indirect detection II

$$\boxed{\Gamma(J \to \bar{f}f) \propto m_f^2 \mathcal{O}(K^2)}$$

- DM → ττ, bb, tt, … give
  - continuous γ spectrum: Integral, Fermi-LAT.
  - anti-protons and positrons: PAMELA, AMS-02.
- DM decay around z ~ 1000:
  - modification of CMB. [Slatyer, Wu, 1610.06933]
  - independent of DM profile.



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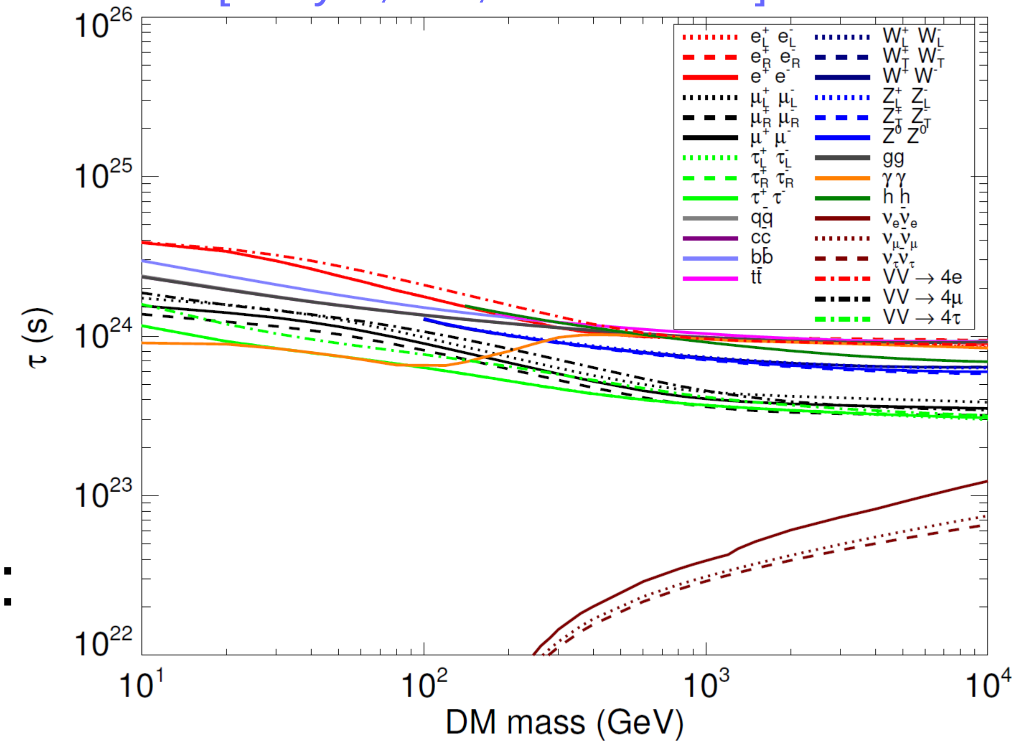
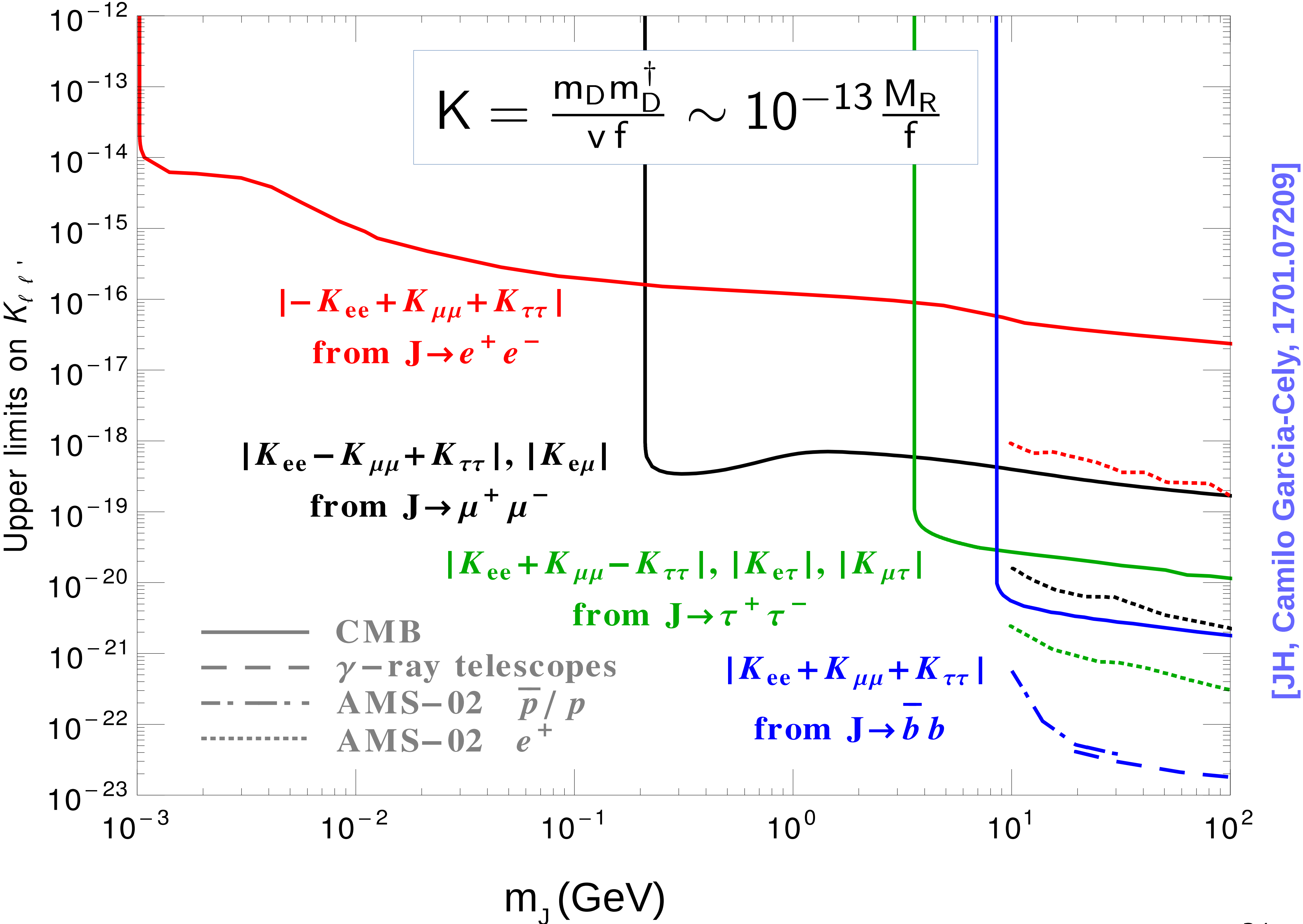
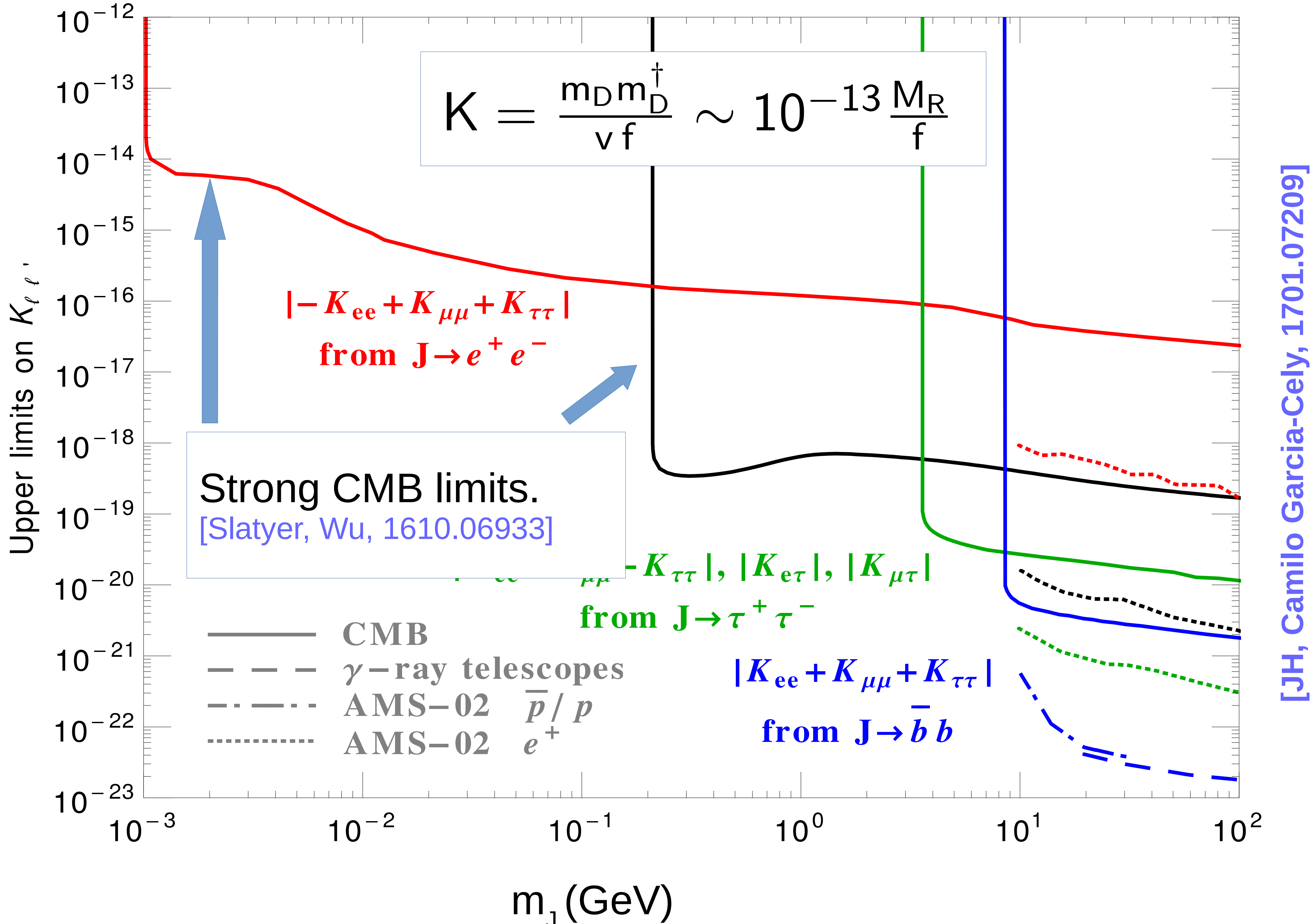




$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13} \frac{M_R}{f}$
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J \to e^+ e^-$
$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|, |K_{e\mu}|$
from $J \to \mu^+ \mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|, |K_{e\tau}|, |K_{\mu\tau}|$
from $J \to \tau^+ \tau^-$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J \to \bar{b}\, b$
CMB
γ-ray telescopes
AMS-02 $\bar{p}/p$
AMS-02 e^+
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
[JH, Camilo Garcia-Cely, 1701.07209]



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Strong CMB limits.
[Slatyer, Wu, 1610.06933]
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from $J \to e^+e^-$
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10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
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10^{-22}
10^{-23}
10^{-3}
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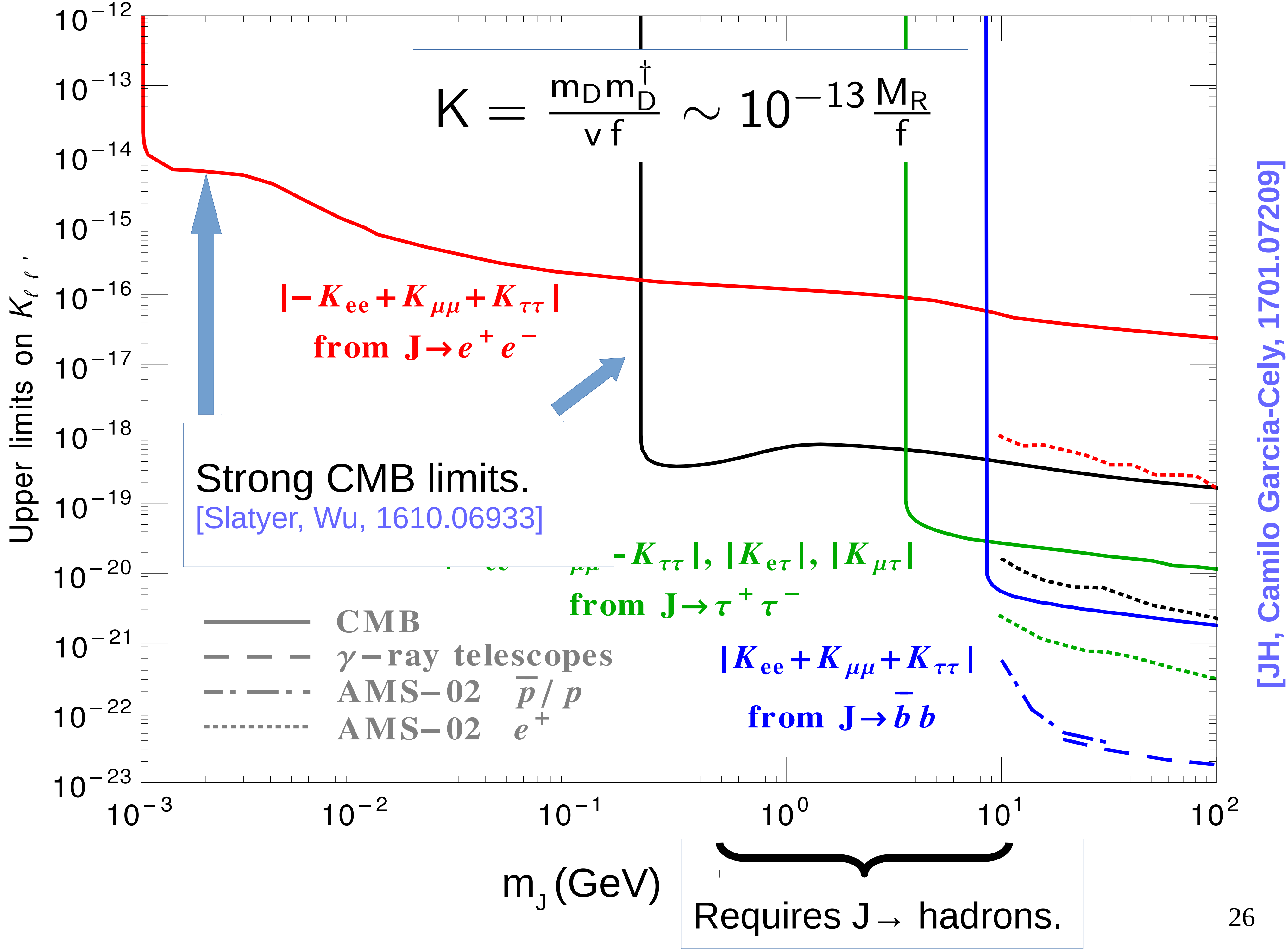
10^{-1}
10^{0}
10^{1}
10^{2}



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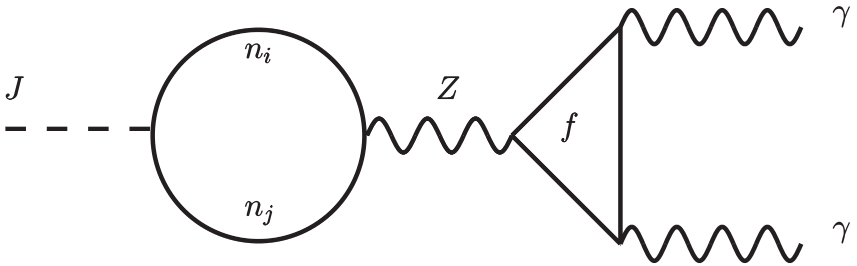
[JH, Camilo Garcia-Cely, 1701.07209]
Requires $J \to$ hadrons.

Two-loop couplings

- Full calculation highly non-trivial.

  [JH, Hiren Patel, in progress]



- J-Z mixing formally similar to triplet majoron:

  [Bazzocchi, Lattanzi, Riemer-Sørensen, Valle, 0805.2372]

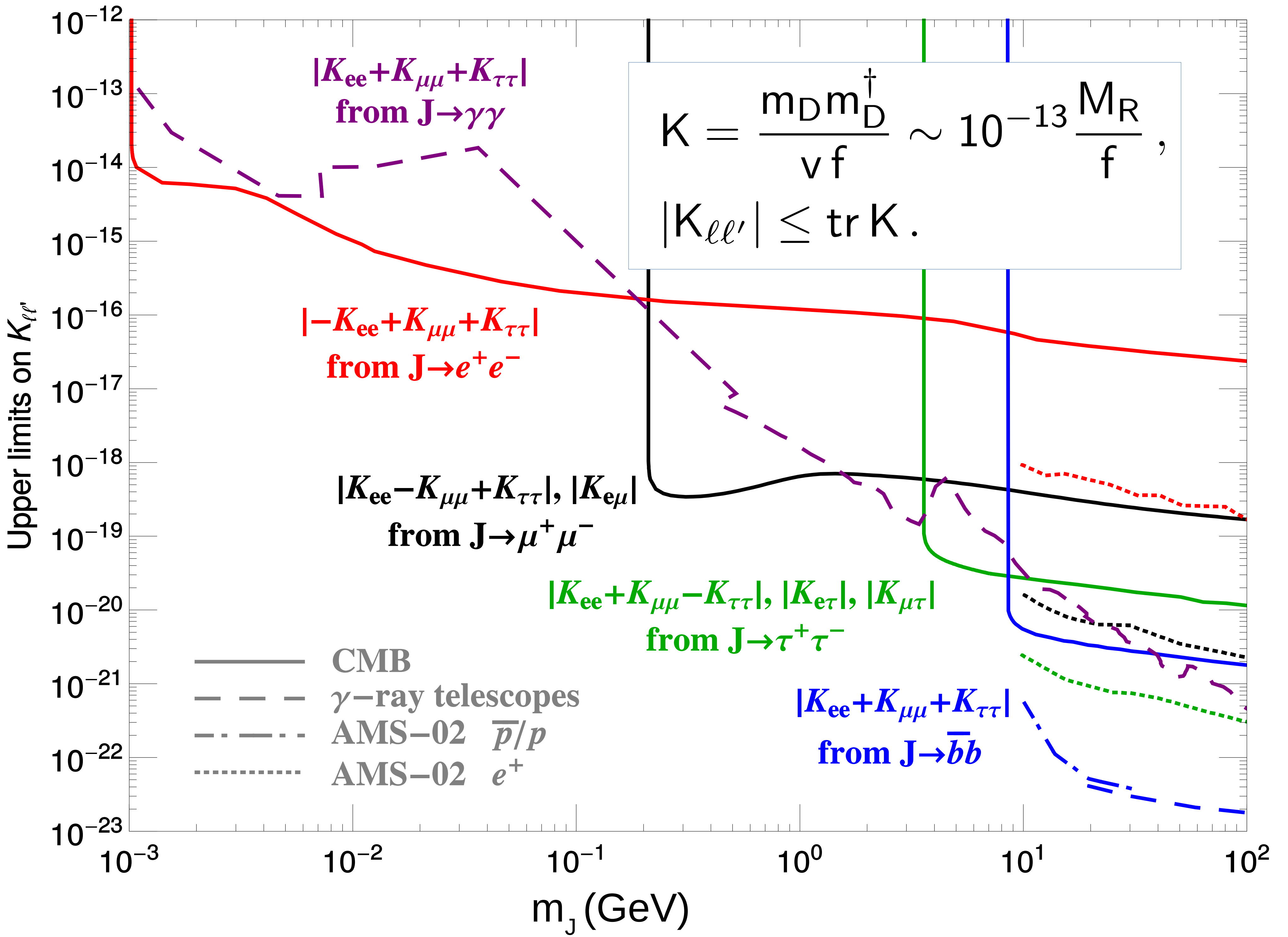
$$\text{(two loop)} \qquad \frac{\mathrm{tr}\, K}{16\pi^2} \leftrightarrow \frac{2v_T^2}{v\, f}\,. \qquad \text{(one loop)}$$

- Gives the only DM signature for m_J < MeV.

  [Lattanzi, Riemer-Sørensen, Tórtola, Valle, '13; Queiroz, Sinha, '14]

$$\Gamma(J \to \gamma\gamma) \simeq \frac{\alpha^2 (\mathrm{tr}\, K)^2}{4096\pi^7} \frac{m_J^3}{v^2} \left| \sum_f N_c^f T_3^f Q_f^2\, g\left(\frac{m_J^2}{4m_f^2}\right) \right|^2$$

[JH, Camilo Garcia-Cely, 1701.07209]



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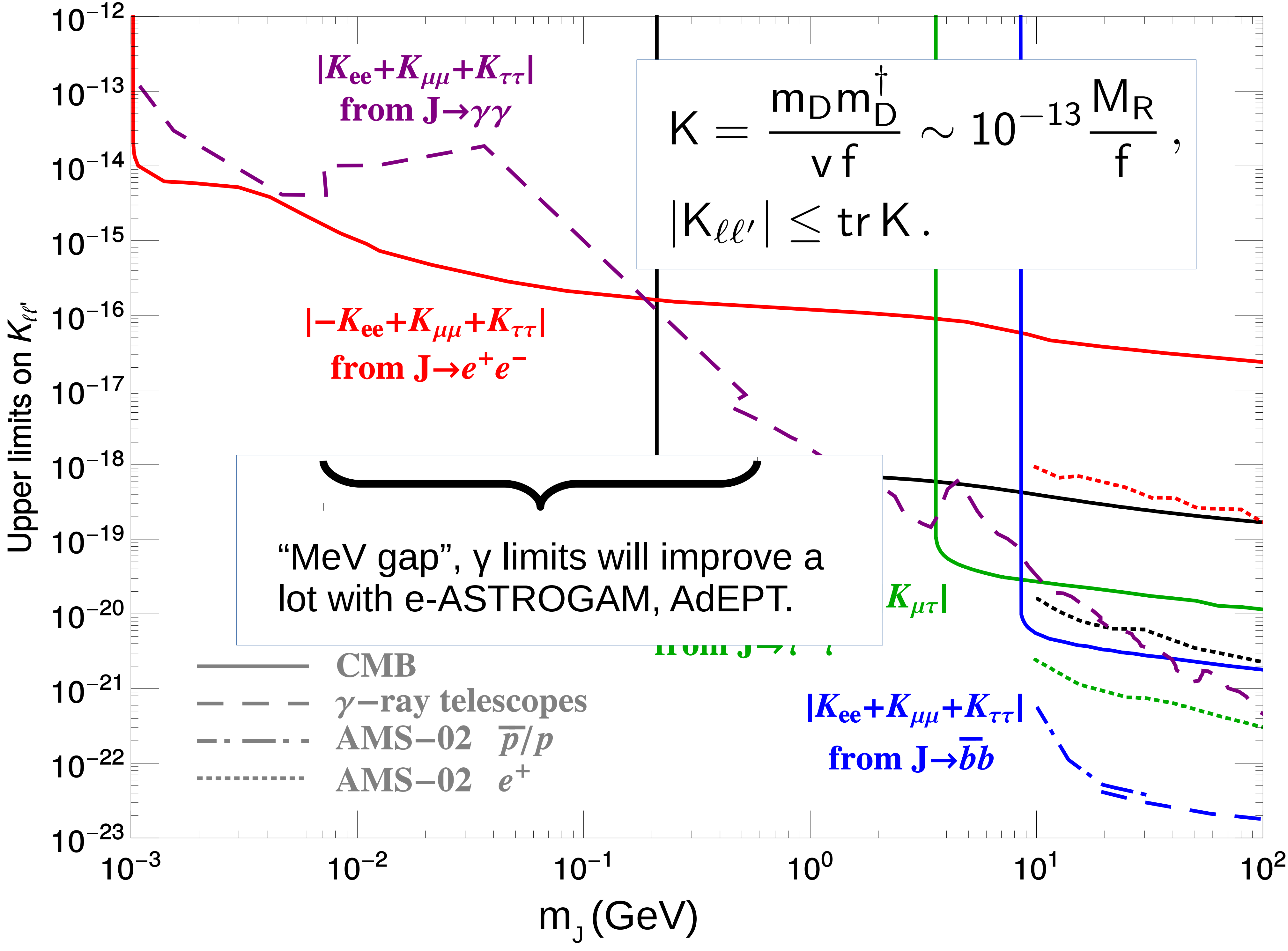

|Kee+Kμμ+Kττ| from J→γγ
|−Kee+Kμμ+Kττ| from J→e+e−
|Kee+Kμμ+Kττ| from J→b̄b
Kμτ|
K = mD mD† / v f ∼ 10−13 MR / f ,
|Kℓℓ′| ≤ tr K .
“MeV gap”, γ limits will improve a lot with e-ASTROGAM, AdEPT.
CMB
γ−ray telescopes
AMS−02 p̄/p
AMS−02 e+
Upper limits on Kℓℓ′
mJ (GeV)

Majoron = DM

- Naturally light, long-lived DM candidate.
- Indirect detection possible:
  - MeV < m_J: $J \to \nu\nu, \gamma\gamma, \bar{f}f$.
  - keV < m_J < MeV: $J \to \gamma\gamma$. Maybe warm DM.

    [JH, Daniele Teresi, 1706.09909]

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    [JH, Daniele Teresi, 1706.09909]

Majoron ≠ DM

- Increase couplings to produce J in lab.
- Measure seesaw parameters.

  [JH, work in progress]

Reconstruct seesaw?

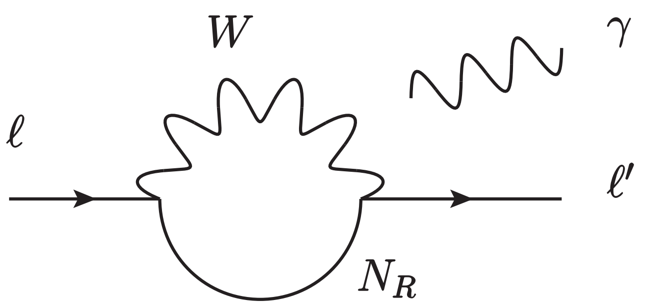
- $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.
- $J\nu\nu$ coupling to measure ~~U(1)~~$_L$ scale f.
- Use $J\bar{f}f$ couplings to reconstruct

$$(m_D m_D^\dagger)_{\alpha\beta} = K_{\alpha\beta} v\, f = \begin{pmatrix} K_{ee} & |K_{e\mu}|e^{ia} & |K_{e\tau}|e^{ib} \\ |K_{e\mu}|e^{-ia} & K_{\mu\mu} & |K_{\mu\tau}|e^{ic} \\ |K_{e\tau}|e^{-ib} & |K_{\mu\tau}|e^{-ic} & K_{\tau\tau} \end{pmatrix} v\, f.$$

- Diagonal K entries from e.g. Jee, $J\mu\mu$, and $J\gamma\gamma$.
- Off-diagonal $|K_{\alpha\beta}|$ from LFV: $\alpha \to \beta J$.
- Phase of off-diagonal $K_{\alpha\beta}$?

Take from axion/ALP searches.

Lepton flavor violation



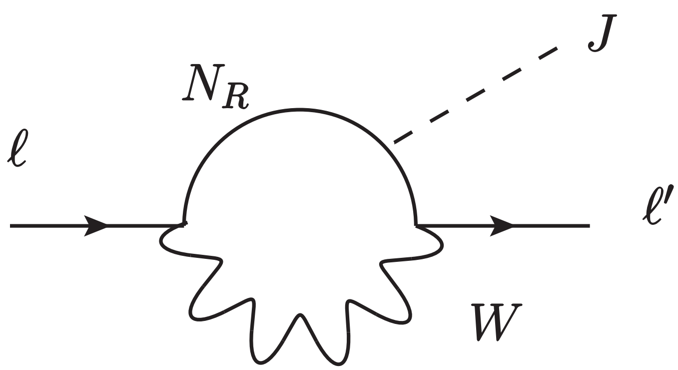
- Standard LFV in seesaw:

$$\frac{\Gamma(\ell \to \ell' \gamma)}{\Gamma(\ell \to \ell' \nu_\ell \overline{\nu}_{\ell'})} \simeq \frac{3\alpha}{8\pi} \left| \left(m_D M_R^{-2} m_D^\dagger \right)_{\ell\ell'} \right|^2 .$$

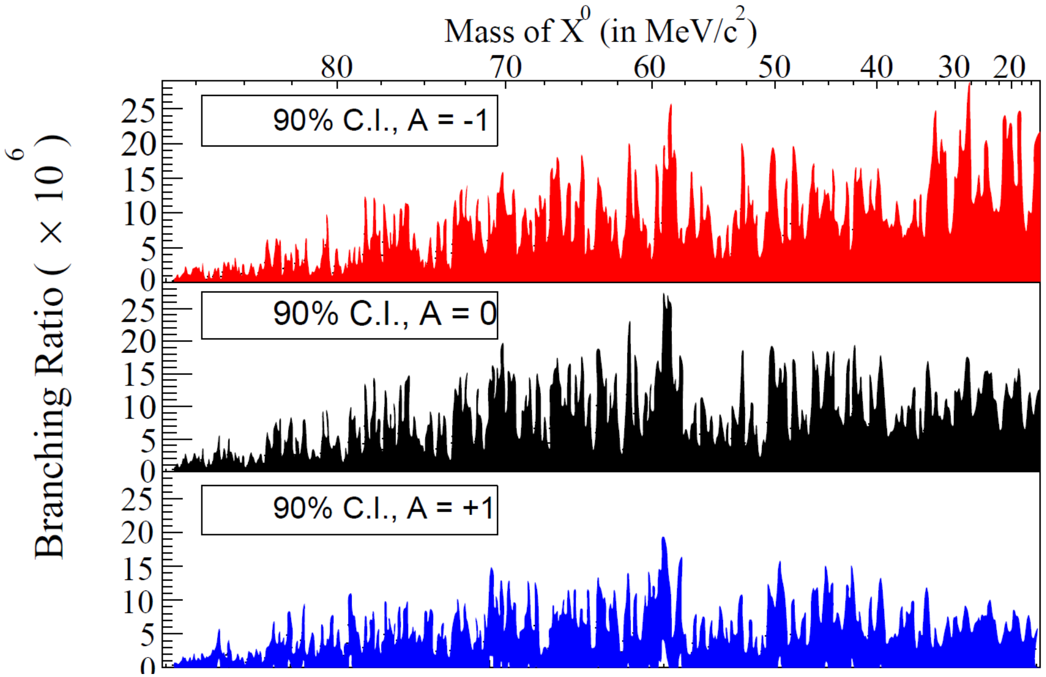
- Great signature, but requires light $N_{R.}$
- With majoron: look for mono-energetic lepton:

[Pilaftsis, '94; Feng, Moroi, Murayama, Schnapka, '98; Hirsch, Vicente, Meyer, Porod, '09]

$$\frac{\Gamma(\ell \to \ell' J)}{\Gamma(\ell \to \ell' \nu_\ell \overline{\nu}_{\ell'})} \simeq \frac{3}{16\pi^2} \frac{v^2}{m_\ell^2} \frac{\left| \left(m_D m_D^\dagger \right)_{\ell\ell'} \right|^2}{v^2 f^2} .$$



$\mu \to e\,J$ with $J \to$ invisible

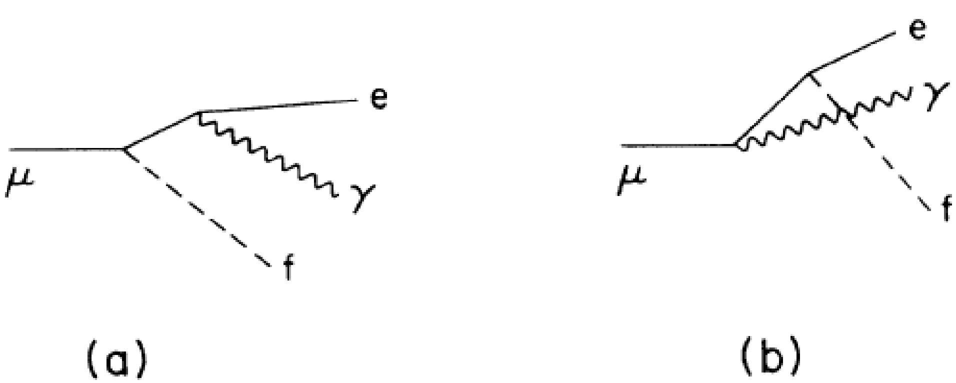


- TWIST, ‘15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [JH, Camilo Garcia-Cely, 1701.07209]
- Bremsstrahlung is competitive: $\mu \to e\,J\,\gamma$.

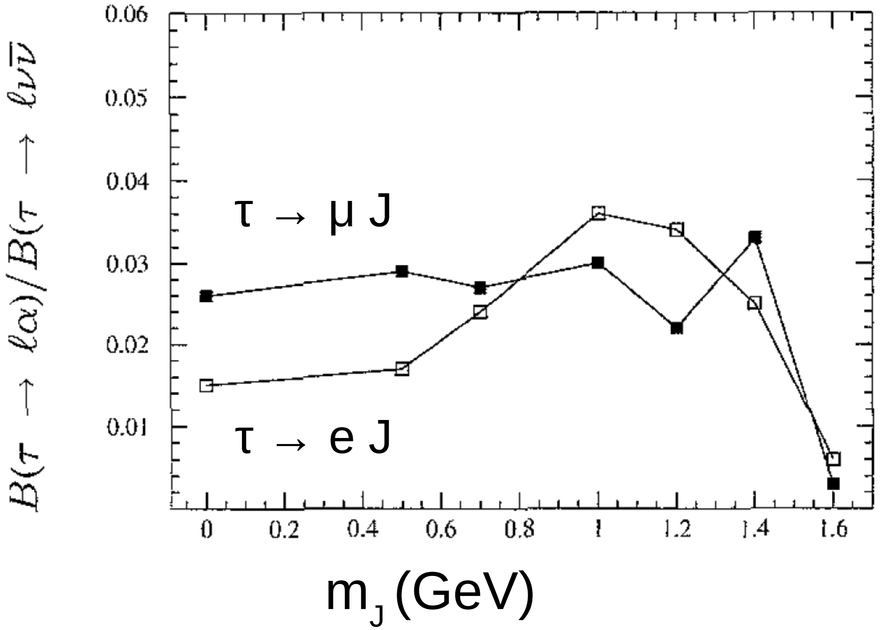
  [Goldman, Hallin, Hoffman, Piilonen, Preston, ‘87]
- Approximate limit

$$|K_{\mu e}| \lesssim 10^{-5}.$$

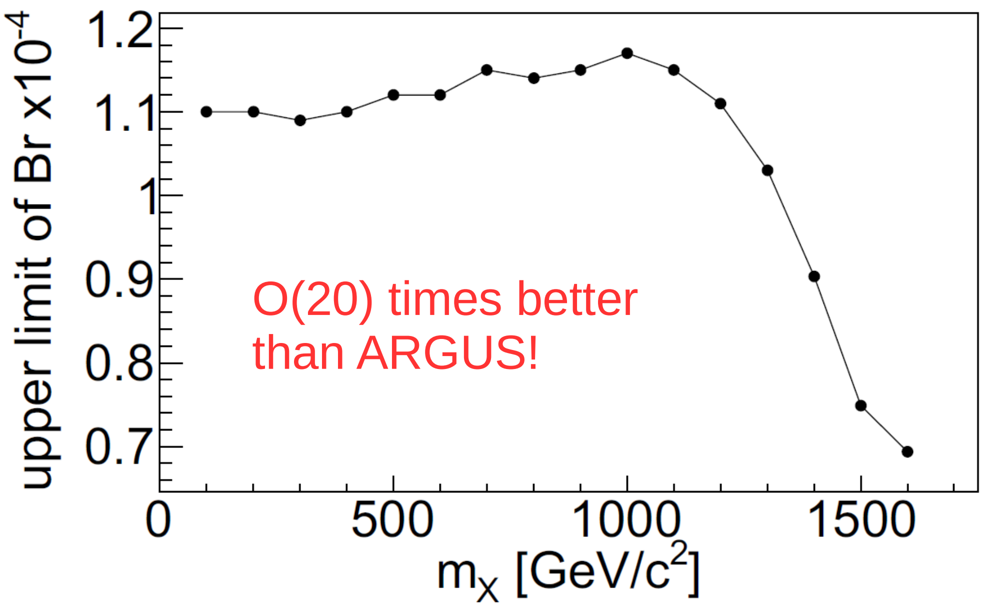


τ → ℓ J with J→ invisible

- ARGUS, '95; 5e5 taus.



- Belle, '16 prelim.; 1e9 taus.



- Also interesting for LFV Z'.
  [JH, 1602.03810; Altmannshofer, Chen, Dev, Soni, 1607.06832]
- Improvement with Belle-II.
- No limits yet on J→ visible or τ → ℓ J γ.

$$|K_{\tau e}| \lesssim 6\times 10^{-3},$$
$$|K_{\tau\mu}| \lesssim 10^{-3}.$$

Summary

- Majoron couplings suppressed by ~~U(1)~~$_L$ scale.
- Automatically long-lived DM candidate.
- Seesaw and leptogenesis for free.
- For MeV < m_J: $J \to \nu\nu$ in Borexino, Super-K,…
- Look for $J \to \gamma\gamma$, $\bar{\ell}\ell$, natural for m_J < 10 GeV.
- If not DM: LFV via $\ell' \to \ell\, J$, $\ell\, J\, \gamma$, …

Always look out for lines!