Neutrino Lines from Majoron Dark Matter

Julian Heeck

based on: JH, Camilo Garcia-Cely, JHEP 1705 (2017) 102 [1701.07209].

NUFACT2017

28.9.2017

Fundamental Interactions .be

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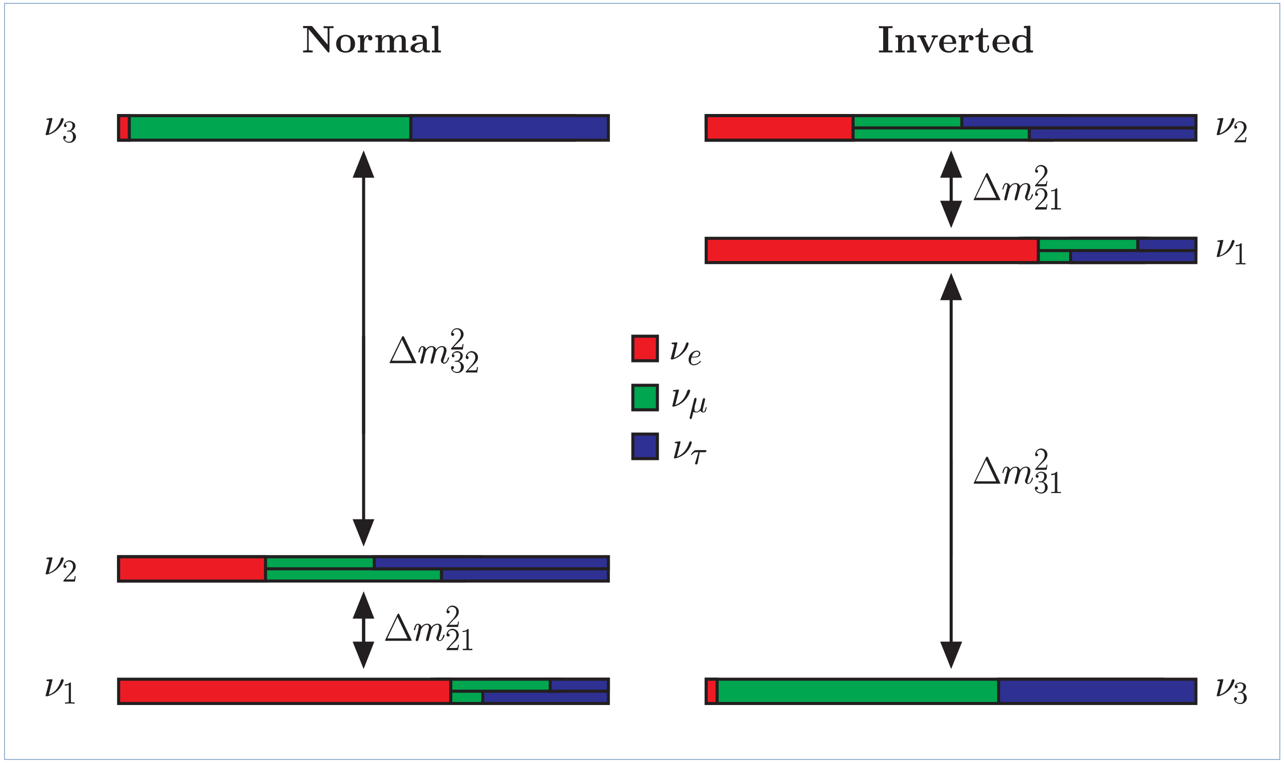
Is it possible to detect dark matter via neutrinos and not gamma-rays or anti-matter?

Neutrinos have masses and mix

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



Majoronic seesaw

- 3 singlets N_R + new scalar $\sigma = (f + \sigma^0 + iJ)/\sqrt{2}$.

B-L breaking scale — Heavy scalar (inflaton?) — **Majoron**

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

- Break $U(1)_{B-L}$ spontaneously:

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

$$L = -\overline{L}yHN_R - \frac{1}{2}\overline{N_R^c}\overbrace{\lambda\sigma}N_R + h.c.$$

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

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

Parametrization of our ignorance

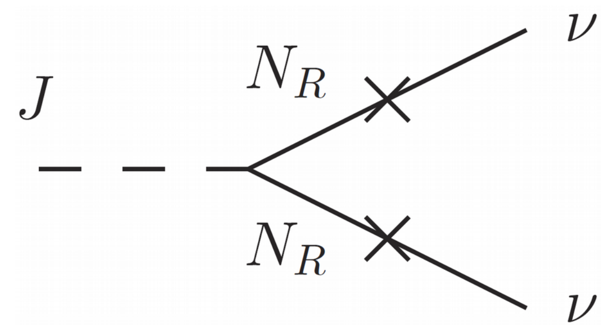
"Known": $M_\nu = U\,\mathrm{diag}(m_1, m_2, m_3) U^T \simeq -m_D M_R^{-1} m_D^T$

PMNS mixing matrix

- Leaves 9 unknown parameters.
- Here: hermitian $m_D m_D^\dagger$.

  [Davidson, Ibarra, hep-ph/0104076]
- One-to-one: $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.
- Useful: majoron loop couplings depend on $m_D m_D^\dagger$.

Tree-level couplings



- $L = iJ \sum_k \left(\frac{m_k}{2f}\right) \overline{\nu}_k \gamma_5 \nu_k + \dots$

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

- Long lifetime $\rightarrow$ majoron dark matter!

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

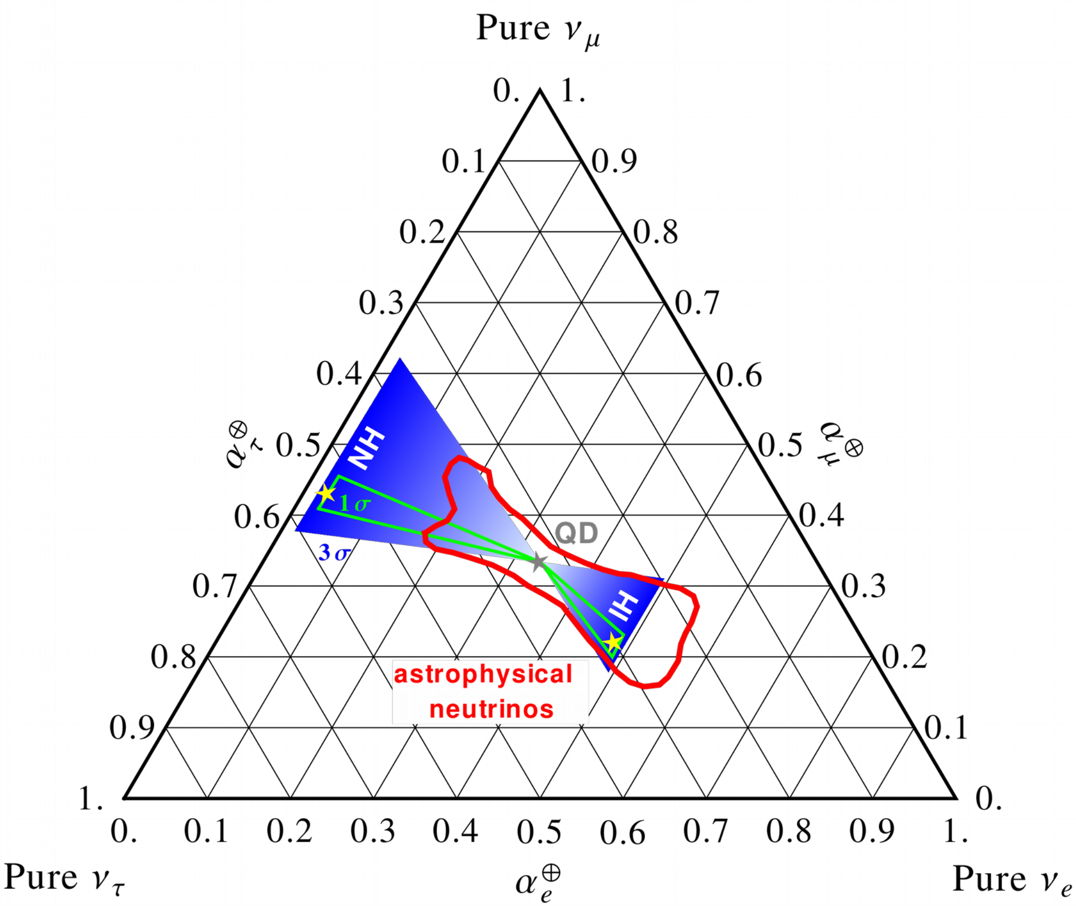
$$\Gamma(J \to \nu\nu) \simeq \frac{1}{3\times 10^{19}\text{s}} \left(\frac{m_J}{\text{MeV}}\right) \left(\frac{10^9\,\text{GeV}}{f}\right)^2 \left(\frac{\sum_k m_k^2}{10^{-3}\text{eV}^2}\right)$$

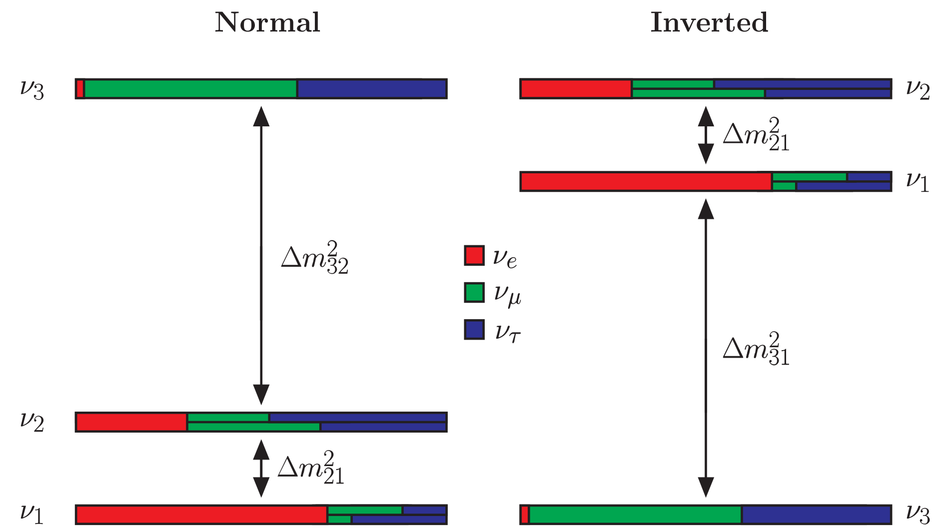
- DM abundance e.g. via freeze-in.

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

Flavor of J $\rightarrow \nu_k \, \nu_k$

Mass eigenstates → no oscillations!





Flavor ratios:

	α_e :	α_μ :	α_τ
NH :	0.03 :	0.43 :	0.54 ,
IH :	0.48 :	0.22 :	0.30 ,
QD :	0.33 :	0.33 :	0.33 .

[JH, Camilo Garcia-Cely, 1701.07209]

Indirect detection

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

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

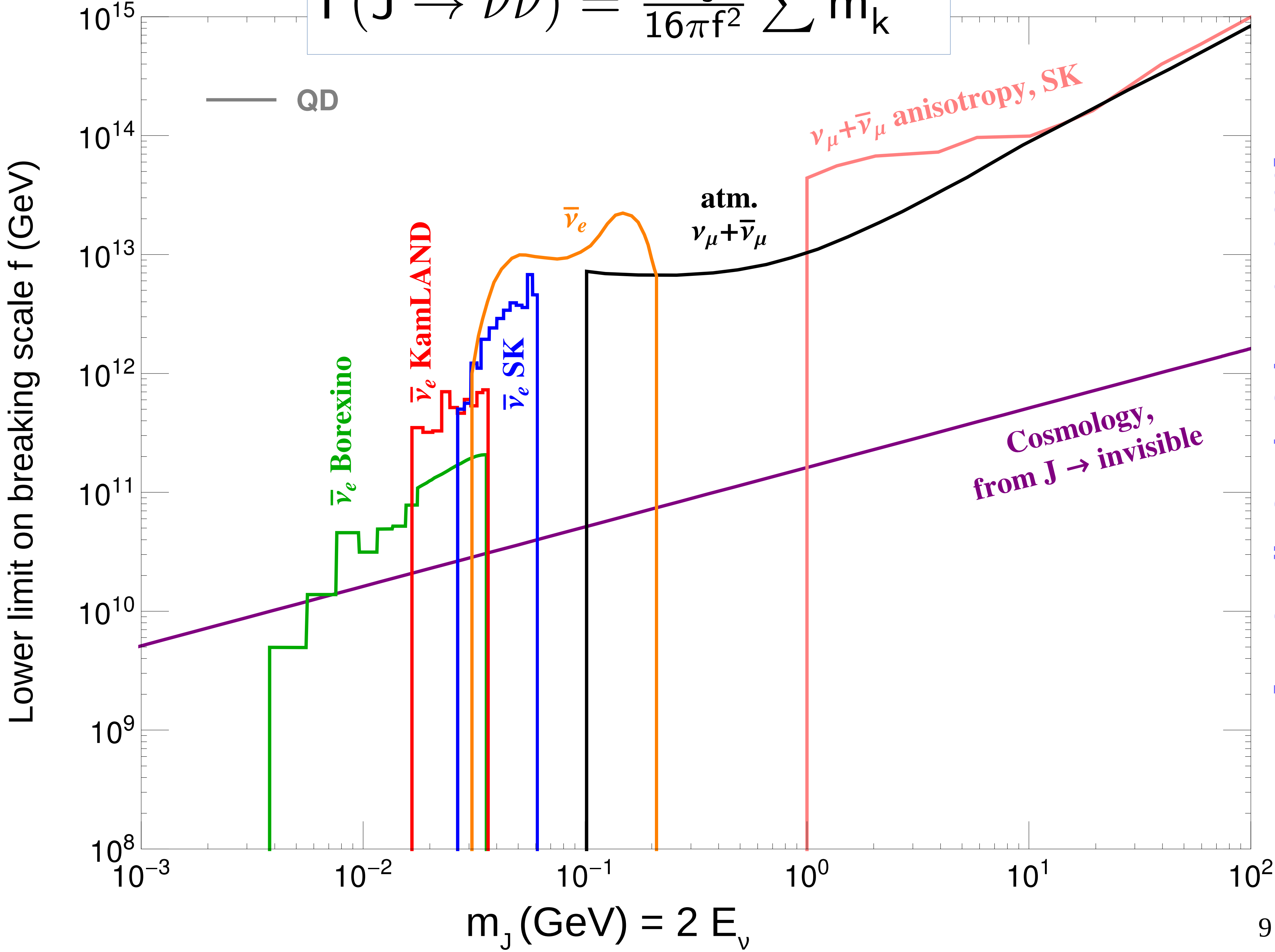
  [Audren, Lesgourgues, Mangano, Serpico, Tram, '14]

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

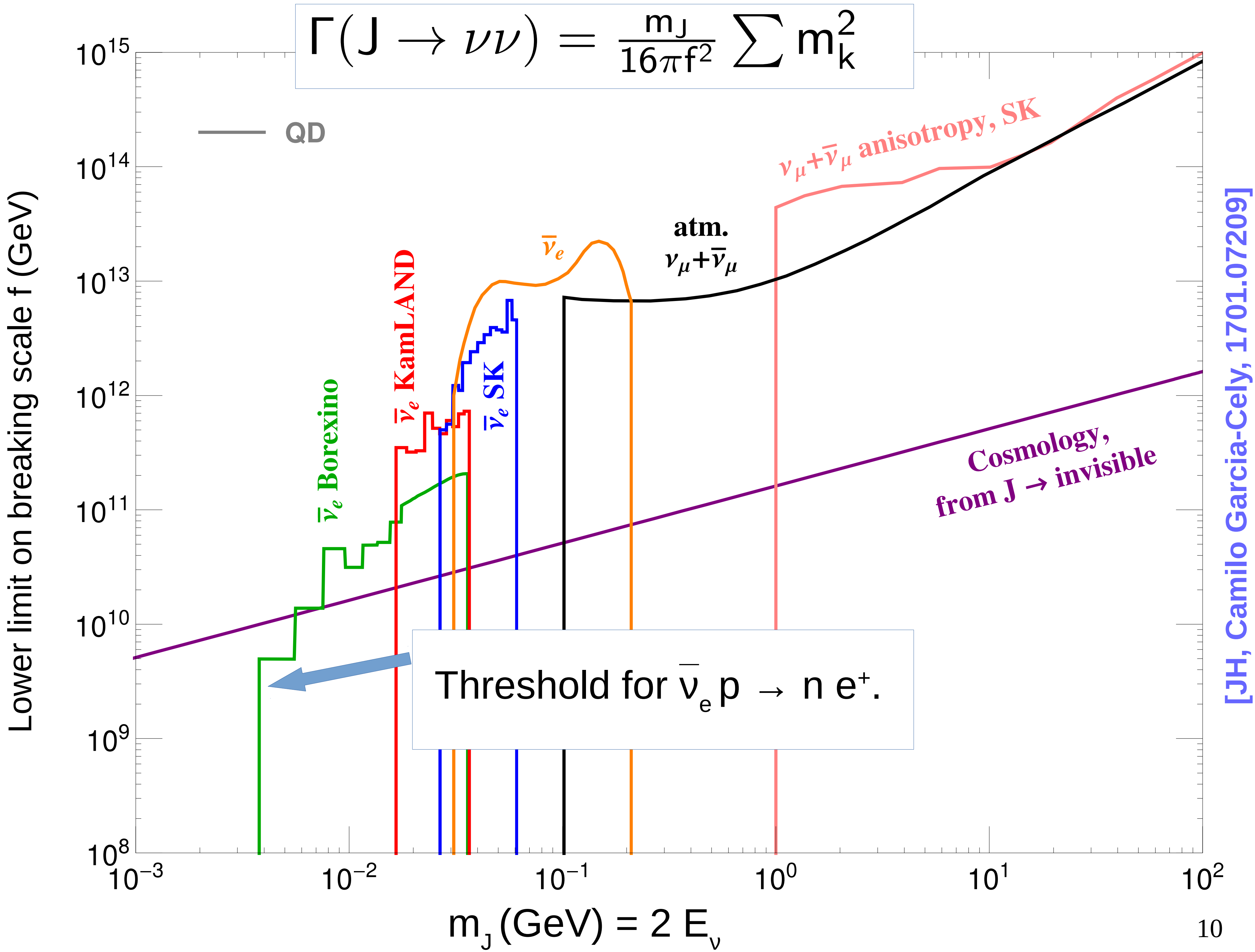
    [Dudas, Mambrini, Olive, '15]
  - Also want to avoid electroweak Bremsstrahlung.

    [Kachelriess, Serpico, '07; Bell, Dent, Jacques, Weiler, '08; Queiroz, Yaguna, Weniger, '16]
  - For MeV < m_J < 100 GeV: **Yes!**

$$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_k^2$$



[JH, Camilo Garcia-Cely, 1701.07209]



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

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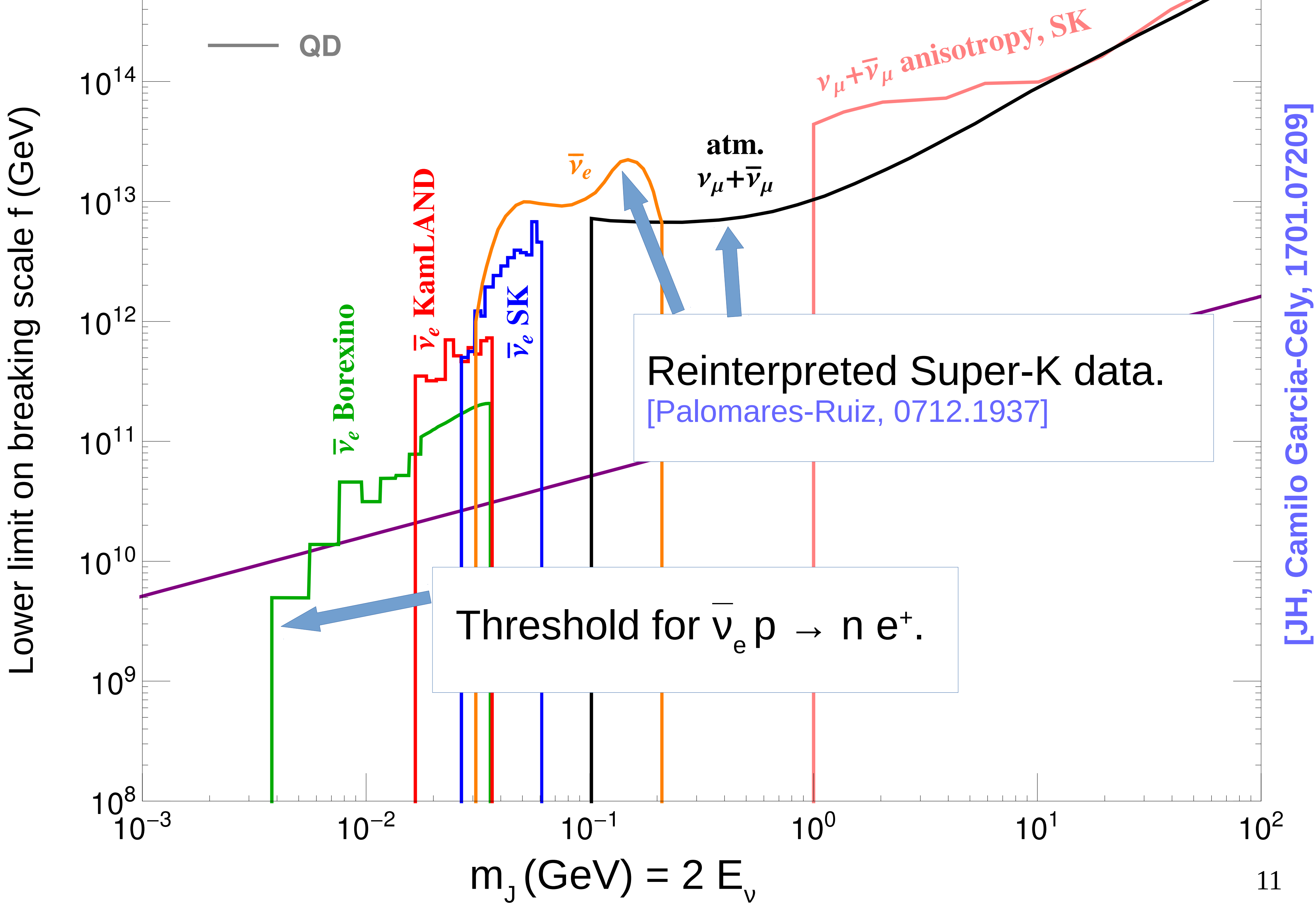

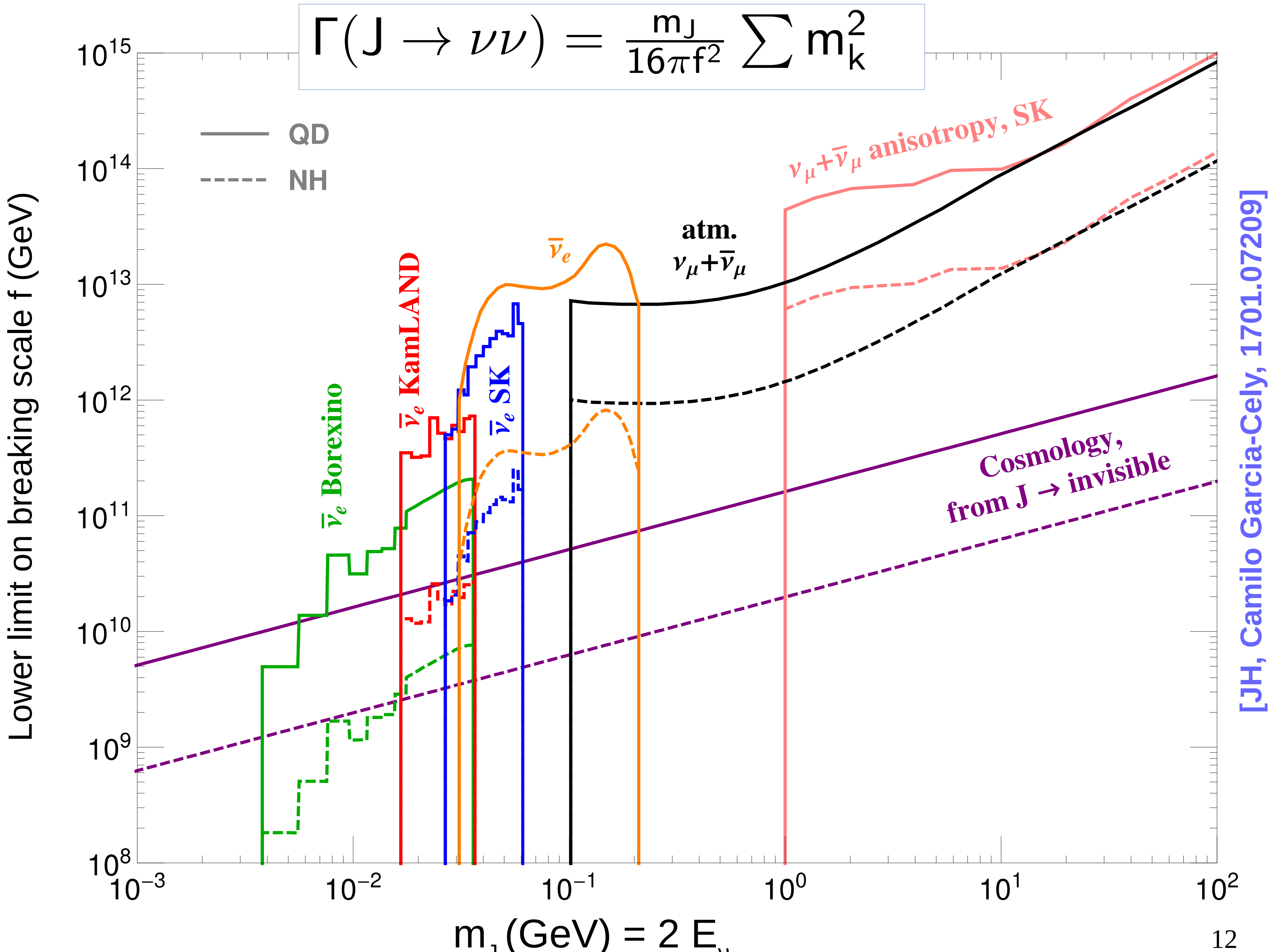
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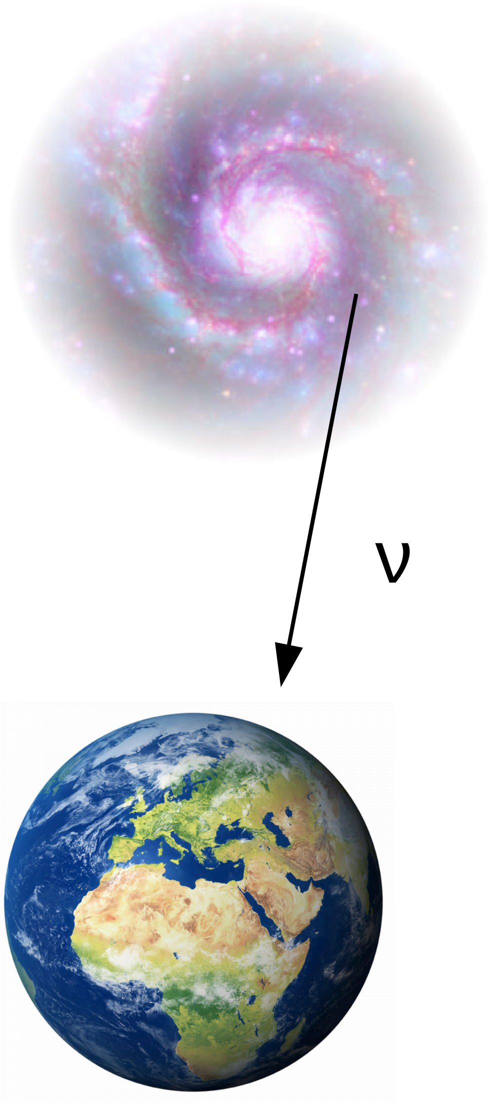
Lower limit on breaking scale f (GeV)
m_J (GeV) = 2 E_ν
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

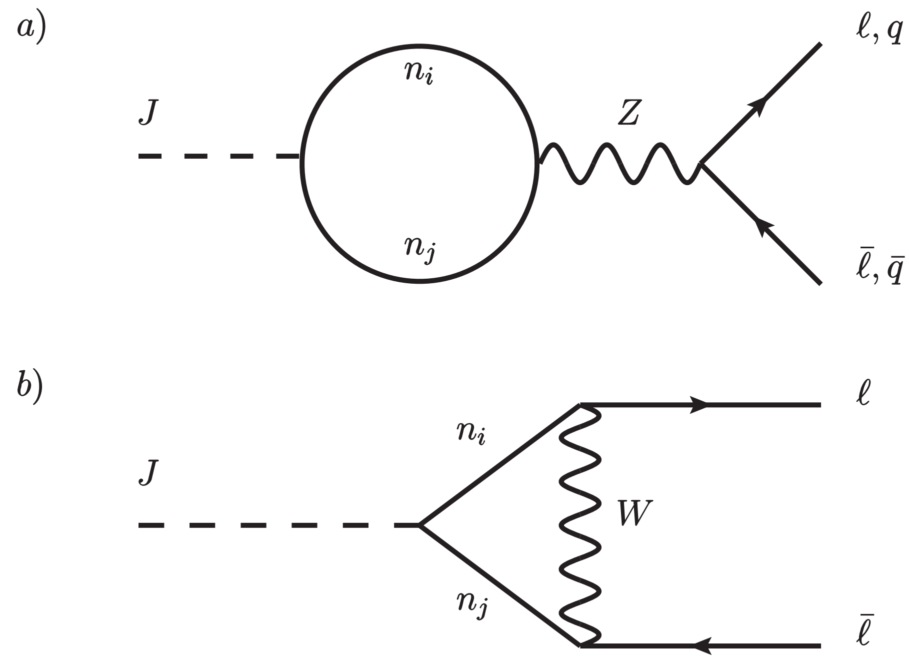
Look for neutrinos from light DM!

- 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.
- Also Hyper-K, JUNO,...
- DM → ν easily dominant channel, no SU(2) argument as for multi-TeV DM.

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



One-loop couplings



- Diagonal:

$$\mathrm{L} = i J \bar{q} \gamma_5 q \frac{m_q}{8\pi^2 v} \left(T_3^q \operatorname{tr} K \right) + i J \bar{\ell} \gamma_5 \ell \frac{m_\ell}{8\pi^2 v} \left(T_3^\ell \operatorname{tr} K + K_{\ell\ell} \right) .$$

- Off-diagonal:

$$\mathrm{L} = -i J \bar{\ell} P_L \ell' \frac{m_\ell}{8\pi^2 v} K_{\ell\ell'} .$$

- New parameter:

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

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

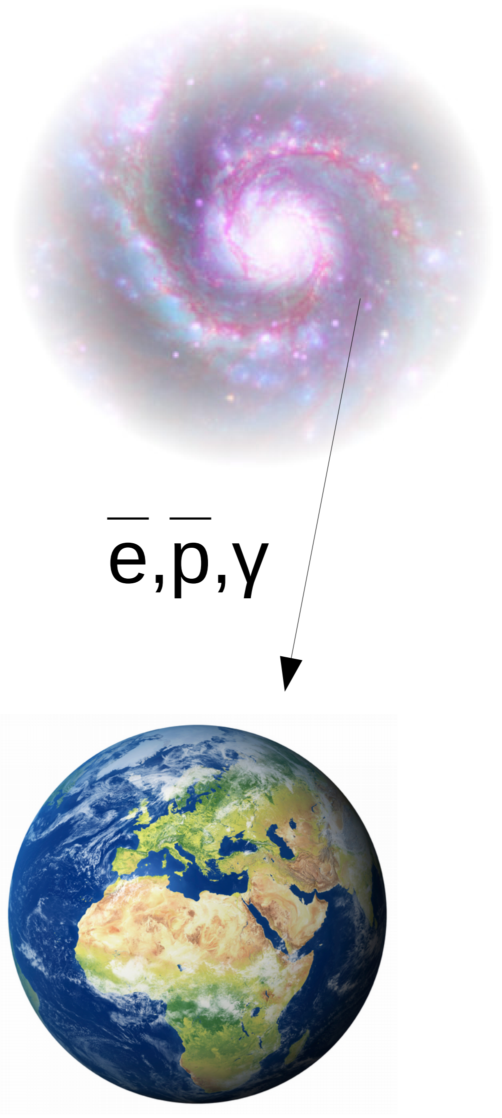
$$K \sim \frac{m_\nu M_R}{v f} \sim 10^{-13} M_R / f .$$

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

Indirect detection II

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

- 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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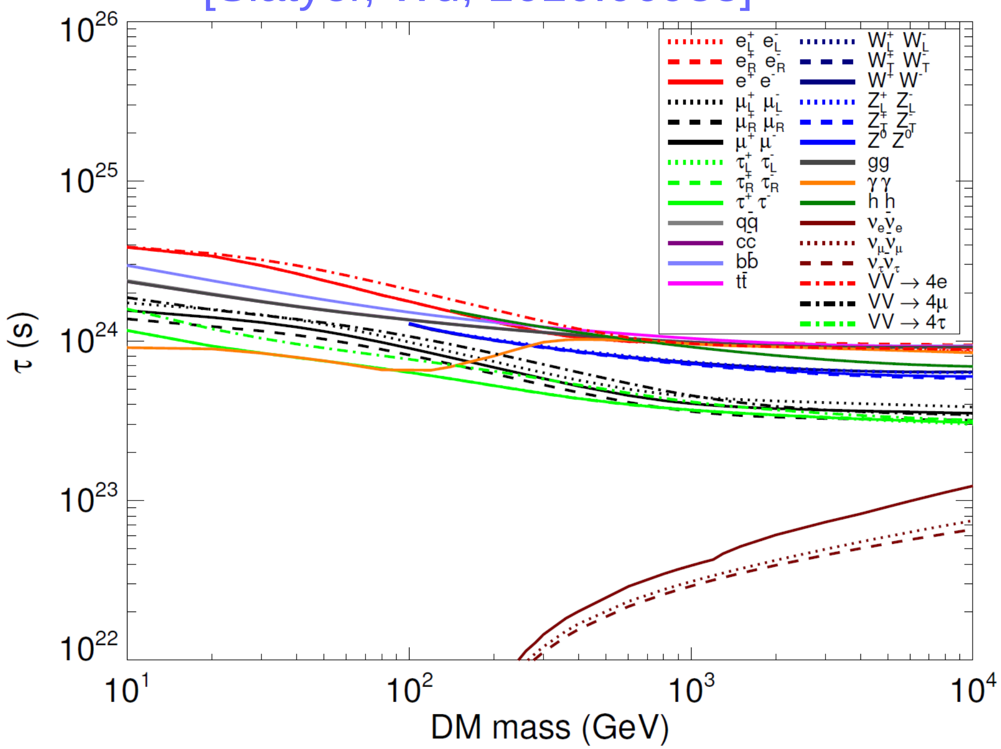
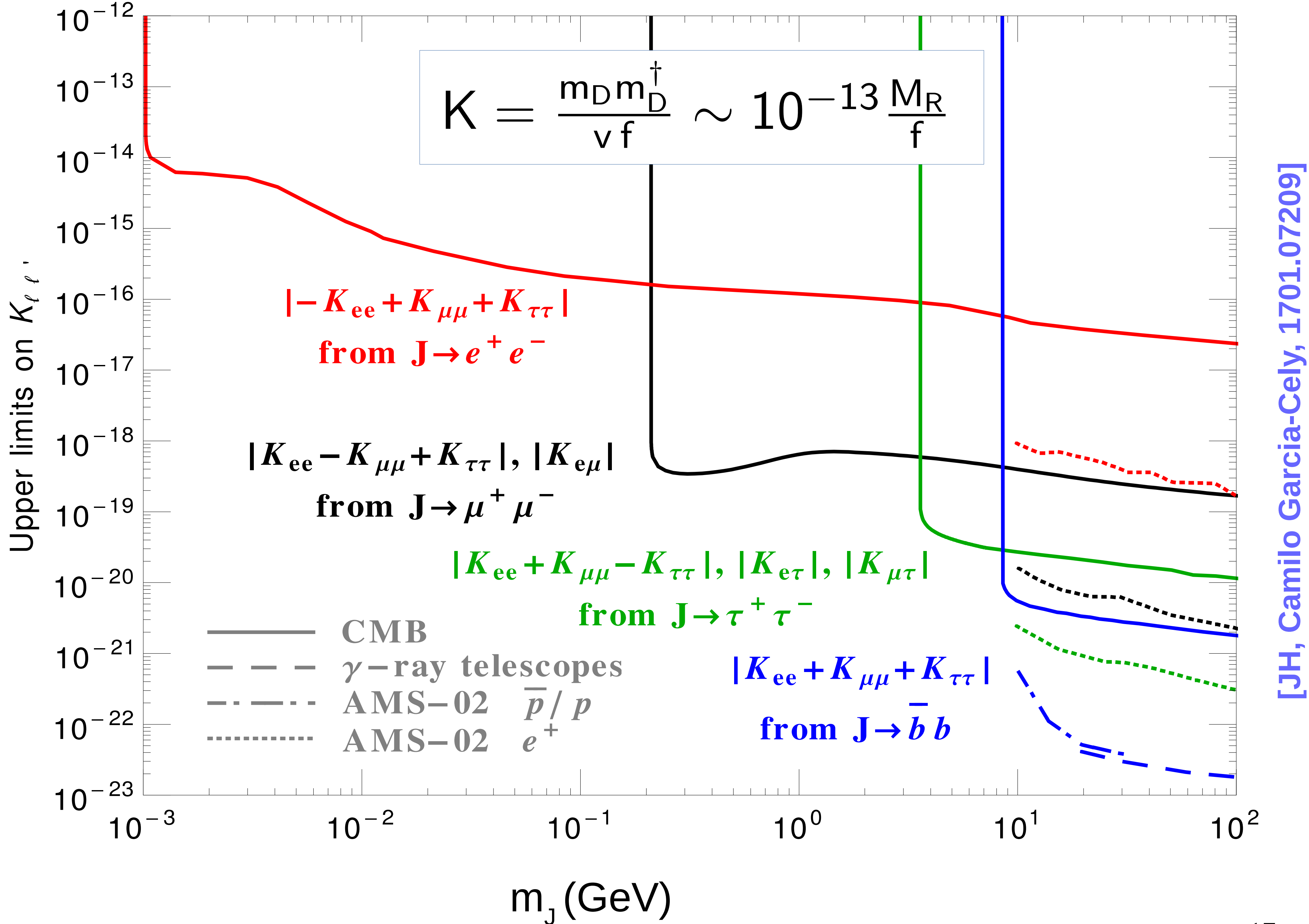
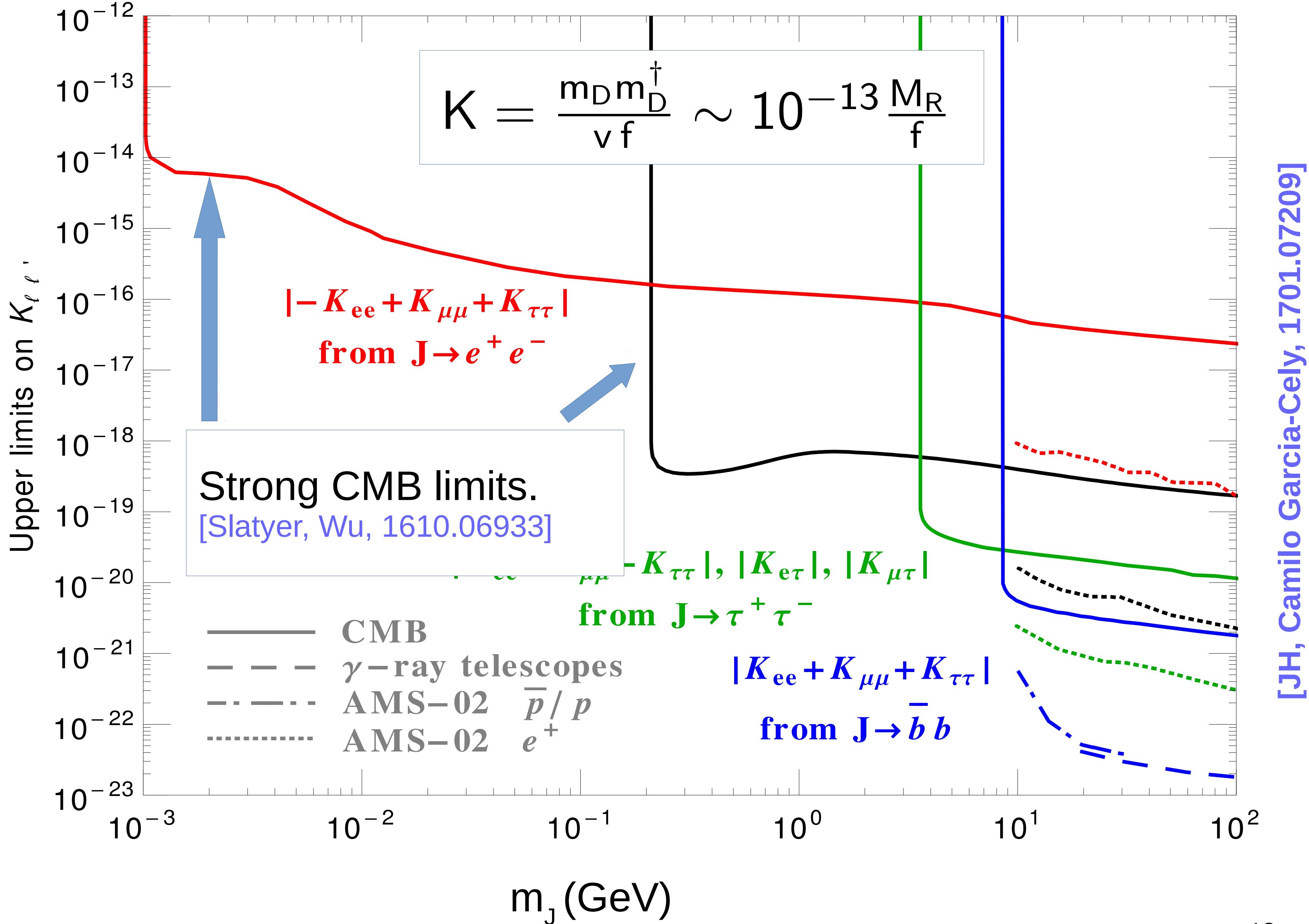
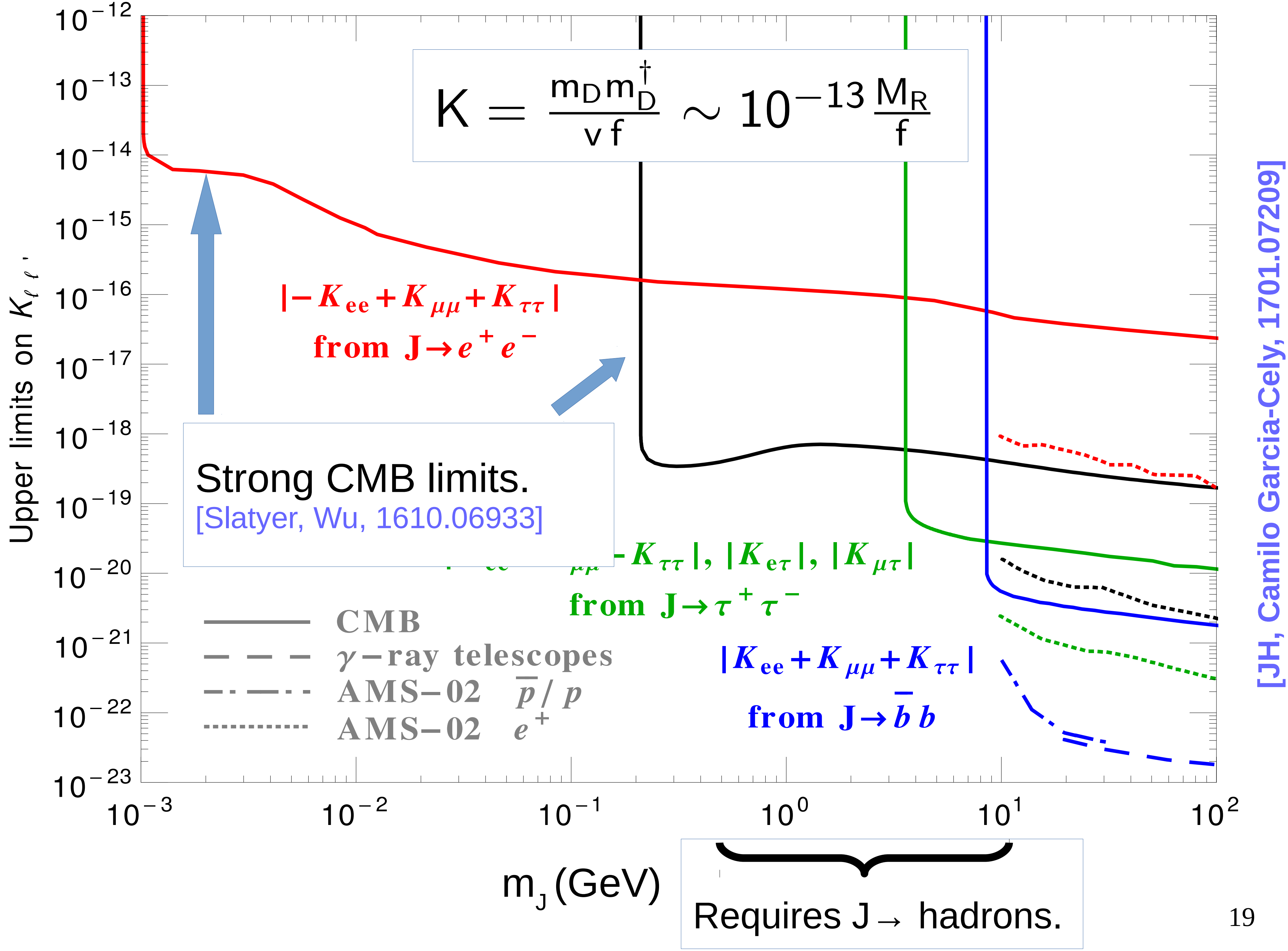




$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13} \frac{M_R}{f}$
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$ from $J \to e^+e^-$
$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|$, $|K_{e\mu}|$ from $J \to \mu^+\mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$ from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



K = m_D m_D^† / v f ∼ 10^−13 M_R / f
Strong CMB limits.
[Slatyer, Wu, 1610.06933]
|−K_ee + K_μμ + K_ττ|
from J → e^+ e^−
-K_ττ|, |K_eτ|, |K_μτ|
from J → τ^+ τ^−
|K_ee + K_μμ + K_ττ|
from J → b̄ b
CMB
γ−ray telescopes
AMS−02 p̄ / p
AMS−02 e^+
Upper limits on K_ℓℓ'
m_J (GeV)
10^−12
10^−13
10^−14
10^−15
10^−16
10^−17
10^−18
10^−19
10^−20
10^−21
10^−22
10^−23
10^−3
10^−2
10^−1
10^0
10^1
10^2
[JH, Camilo Garcia-Cely, 1701.07209]



$K = \frac{m_D m_D^\dagger}{v\,f} \sim 10^{-13}\,\frac{M_R}{f}$
Strong CMB limits.
[Slatyer, Wu, 1610.06933]
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
$\mu\mu - K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$
from $J\to\tau^+\tau^-$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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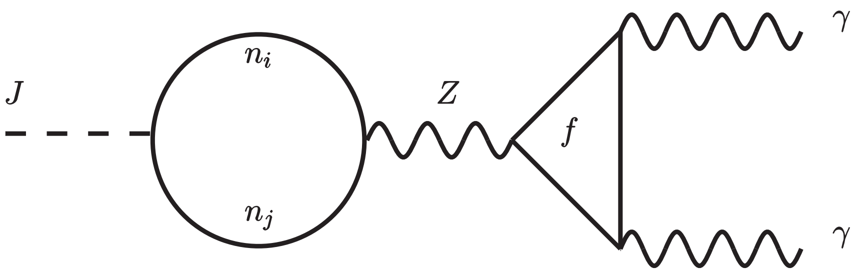
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Requires J→ hadrons.
[JH, Camilo Garcia-Cely, 1701.07209]

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]

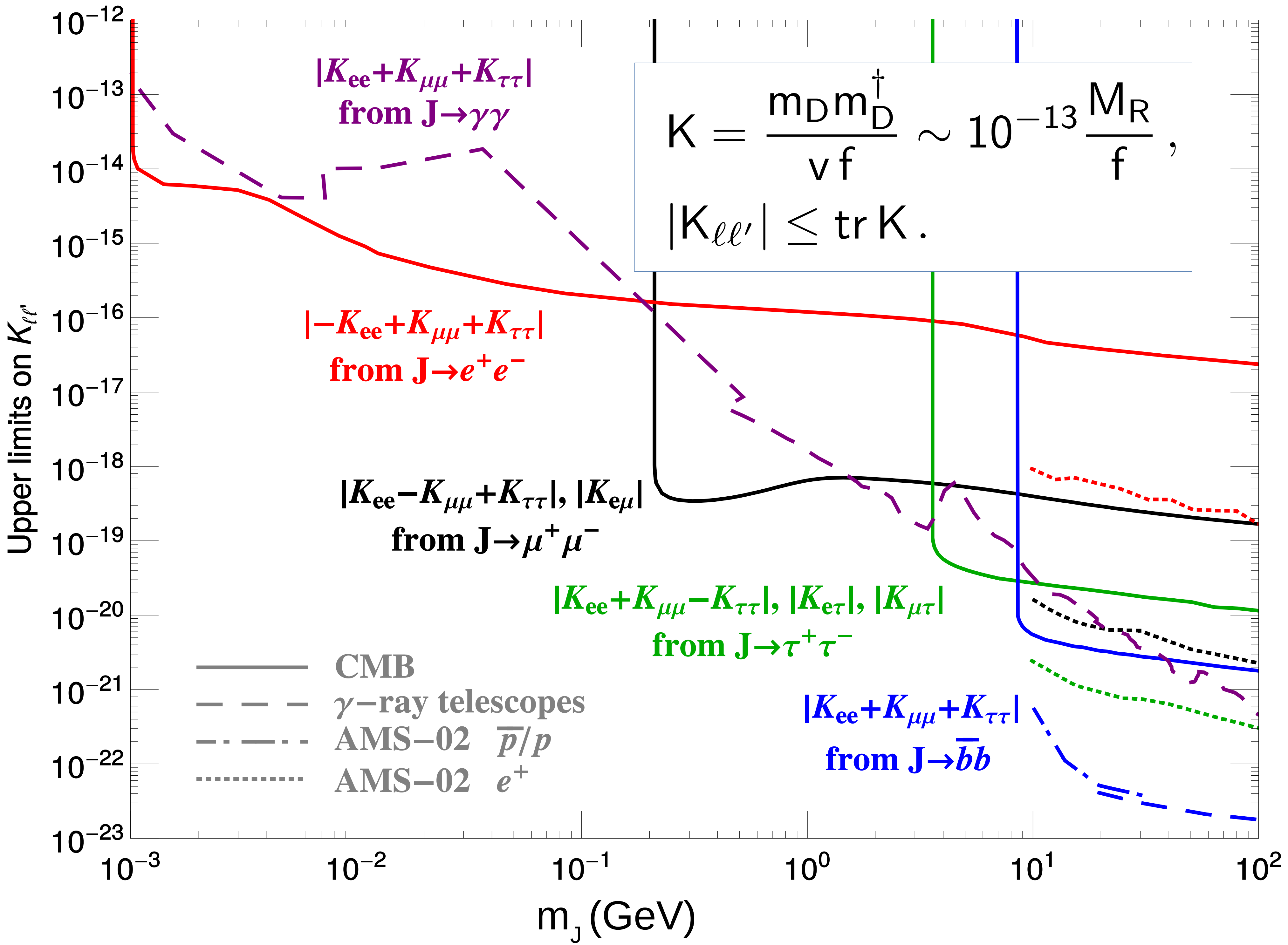
(two loop) $$\frac{\mathrm{tr}\, K}{16\pi^2} \leftrightarrow \frac{2 v_T^2}{v\, f}\,.$$ (one loop)

- Gives the only DM signature for $m_J <$ MeV.

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

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

[JH, Camilo Garcia-Cely, 1701.07209]



$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\, K$.
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|$, $|K_{e\mu}|$
from $J\to\mu^+\mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$
from $J\to\tau^+\tau^-$
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CMB
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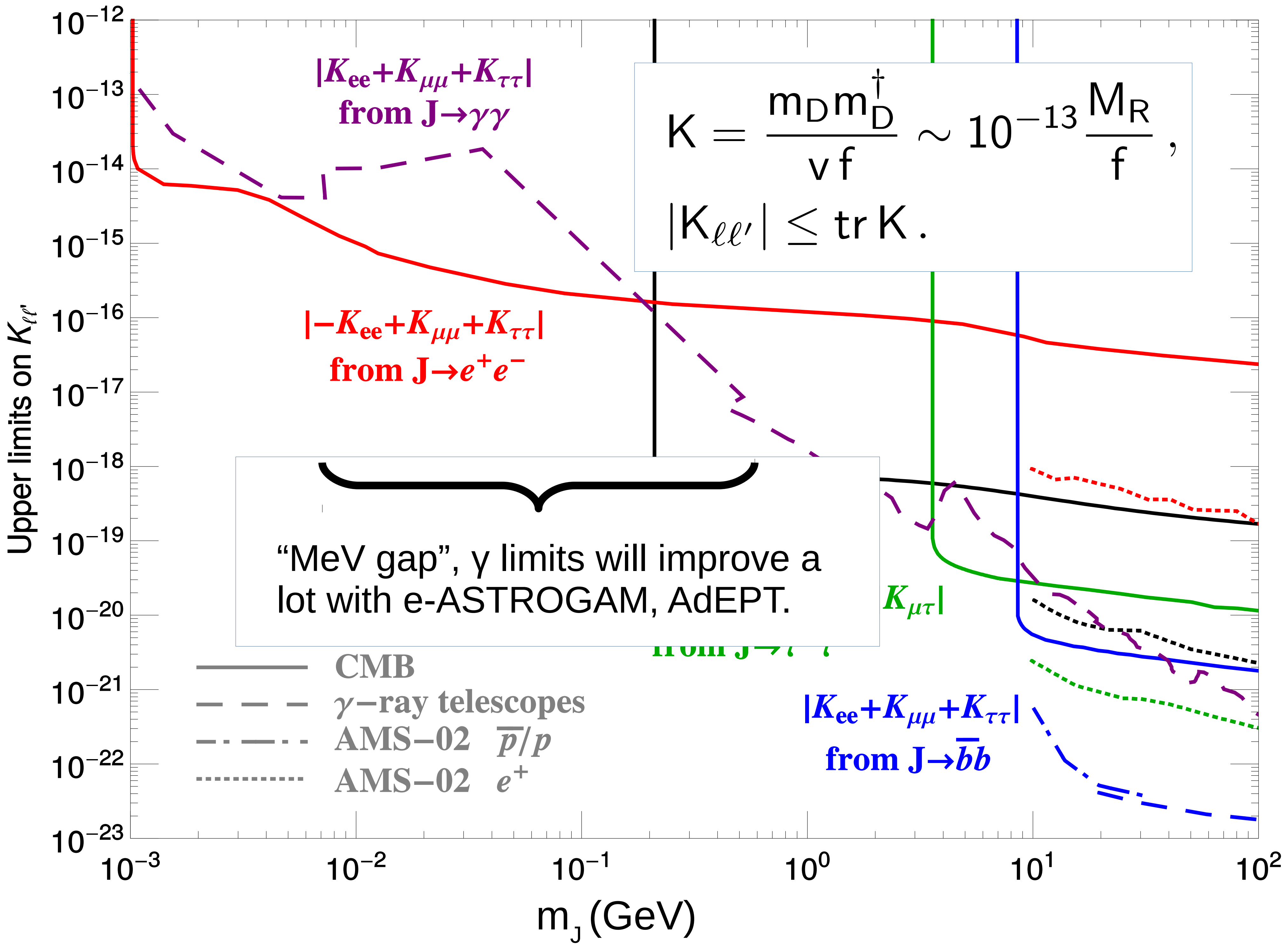
Upper limits on $K_{\ell\ell'}$
m_J (GeV)


$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\, K$.
"MeV gap", γ limits will improve a lot with e-ASTROGAM, AdEPT.
CMB
γ−ray telescopes
AMS−02 $\bar{p}/p$
AMS−02 e^+
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
10^{-12}
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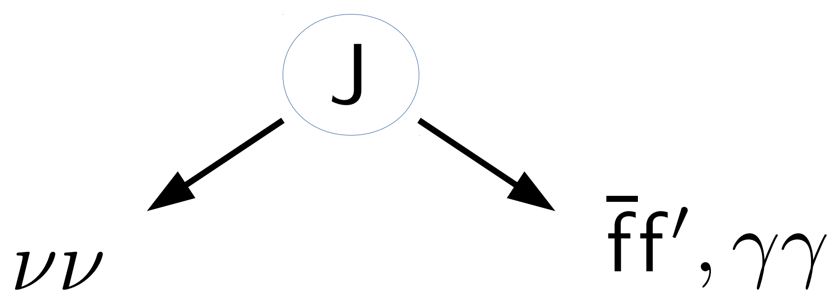
10^{2}

Is it possible to detect dark matter via neutrinos and not gamma-rays or anti-matter?

Yes!



depends on
$$\mathrm{M}_\nu \simeq -\mathrm{m_D} \mathrm{M_R}^{-1} \mathrm{m_D^T}.$$

depends on
$$\mathrm{m_D} \mathrm{m_D^\dagger}.$$

Independent / Complementary!

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,…
- Complementary to $J \to \gamma\gamma$, $\bar{\ell}\ell'$, $\bar{q}q$.

Always look out for lines!

Backup

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, 1709.07283]

Majoron ≠ DM

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

  [JH, work in progress]

Reconstruct seesaw?

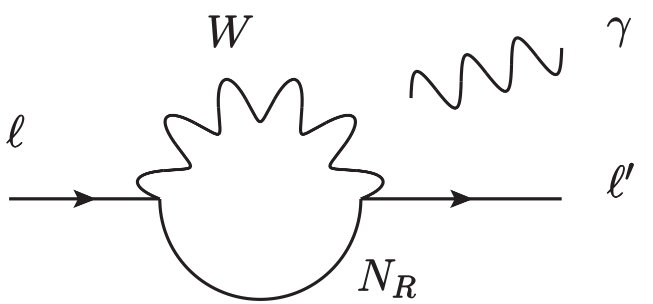
- $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.
- $J\nu\nu$ coupling to measure ~~U(1)~~$_L$ scale f.
- Use $J\bar{f}f$ couplings to reconstruct

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

- 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



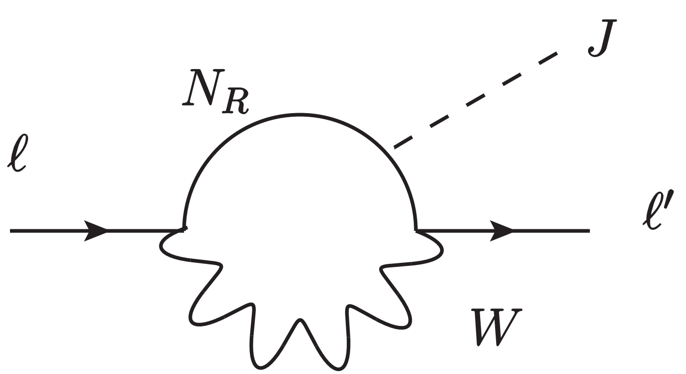
- Standard LFV in seesaw:

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

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

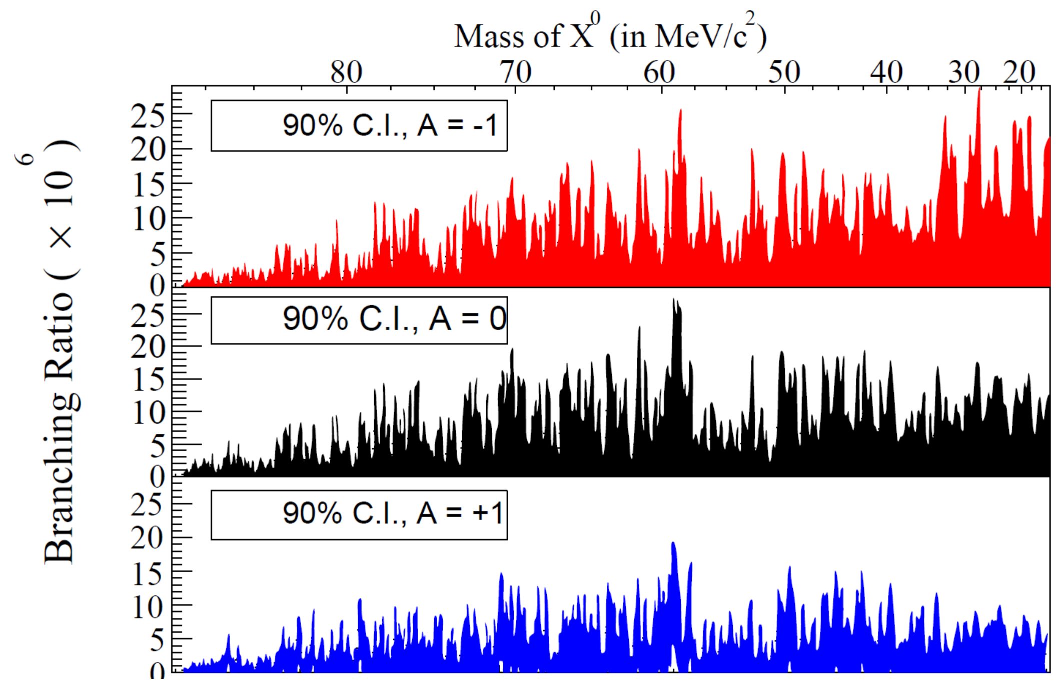
[Pilaftsis, '94; Feng, Moroi, Murayama, Schnapka, '98; Hirsch, Vicente, Meyer, Porod, '09]

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



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

- TWIST, '15: limits on different anisotropies.

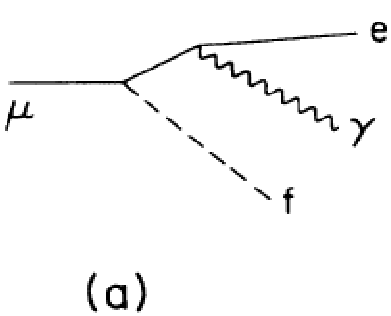


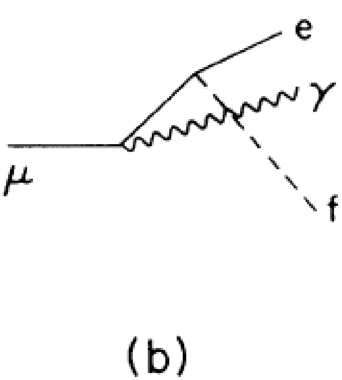
- Chiral coupling $\bar{\mu} P_L e J$ suppresses sensitivity!

  [JH, Camilo Garcia-Cely, 1701.07209]

- Bremsstrahlung is competitive: $\mu \to e\, J\, \gamma$.

  [Goldman, Hallin, Hoffman, Piilonen, Preston, '87]



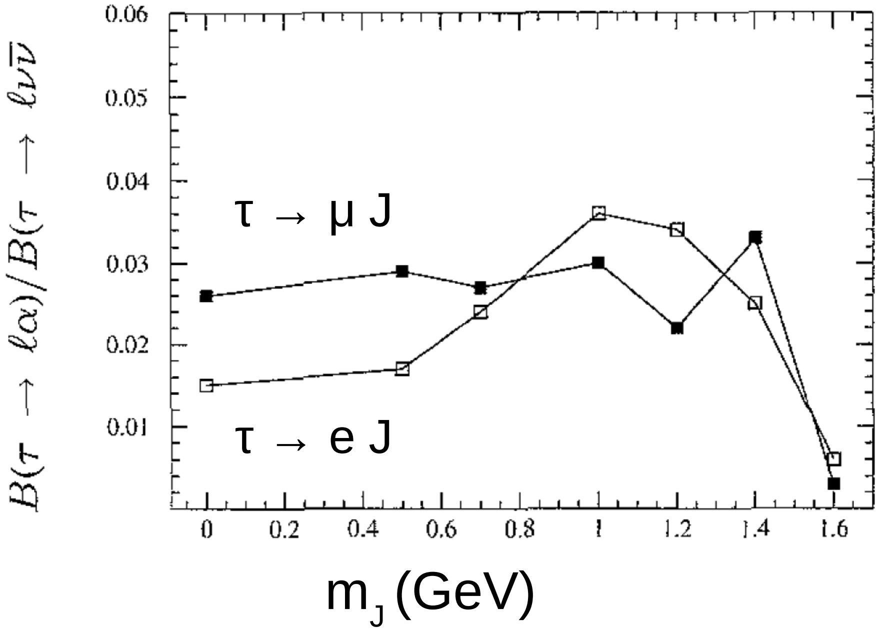


- Approximate limit

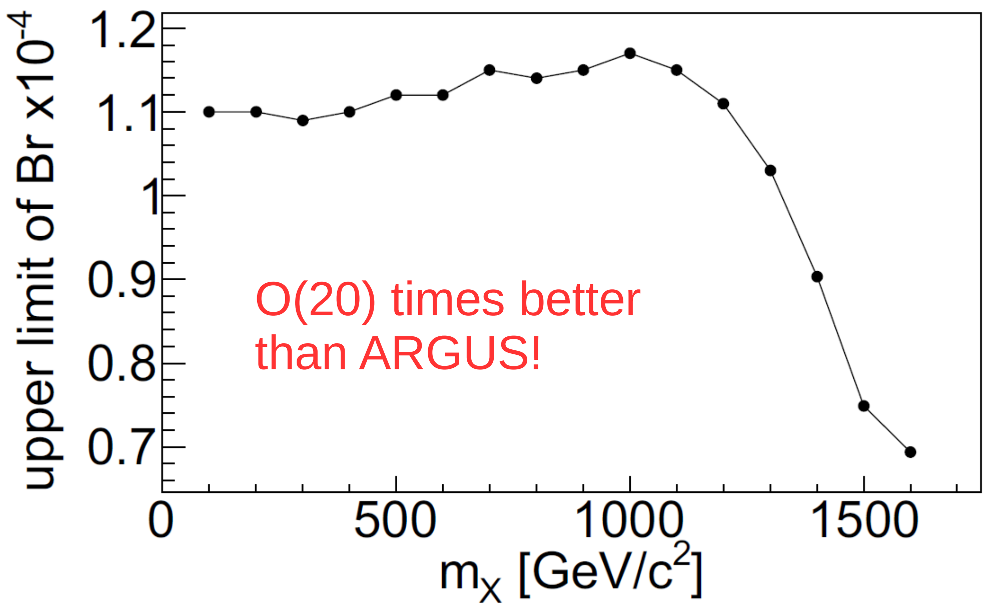
$$|K_{\mu e}| \lesssim 10^{-5}.$$

τ → ℓ J with J→ invisible

- ARGUS, '95; 5e5 taus.



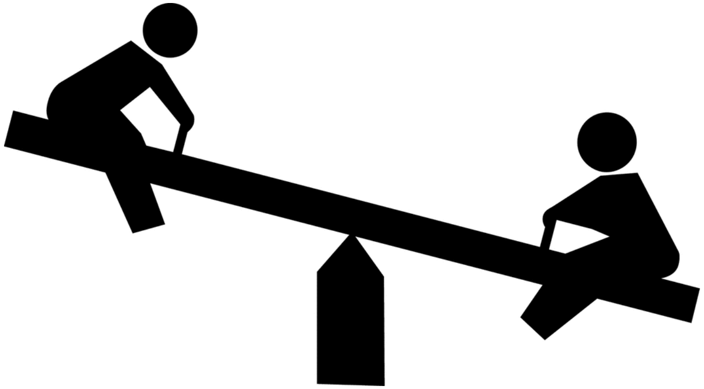
- Belle, '16 prelim.; 1e9 taus.



- 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.

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

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

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]

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

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:

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

- 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 gravity, e.g. wormholes,

$$m_J \sim M_{Pl} \exp\left[-\mathcal{O}(M_{Pl}/f)\right].$$

[Alonso, Urbano, 1706.07415]

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

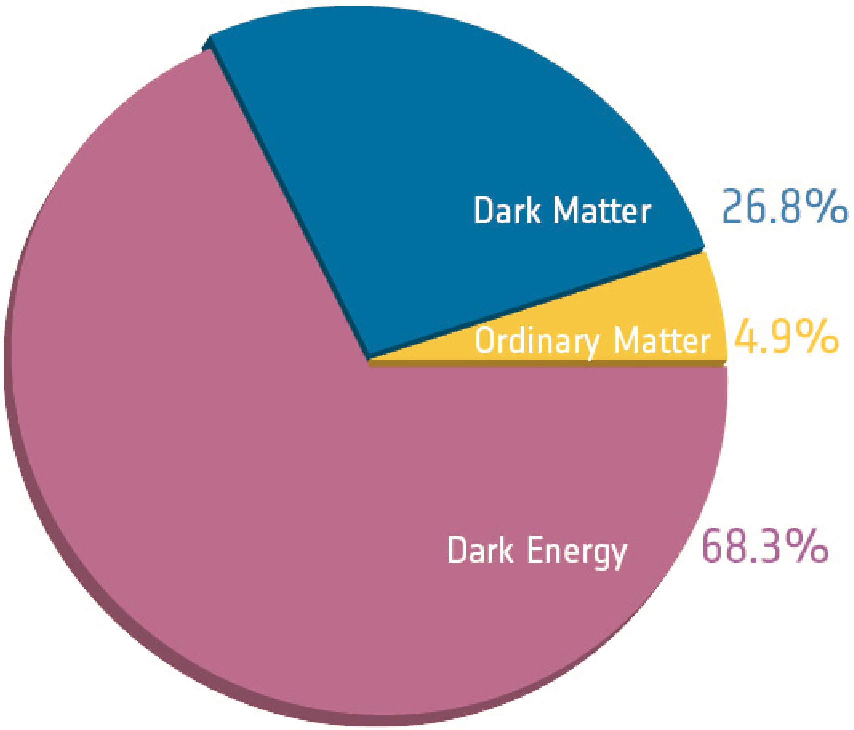
[Mohapatra, Senjanovic ‘83; Langacker, Peccei, Yanagida ‘86; SMASH ‘16]

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

Stay ignorant here, just put m_J.

Dark matter abundance

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



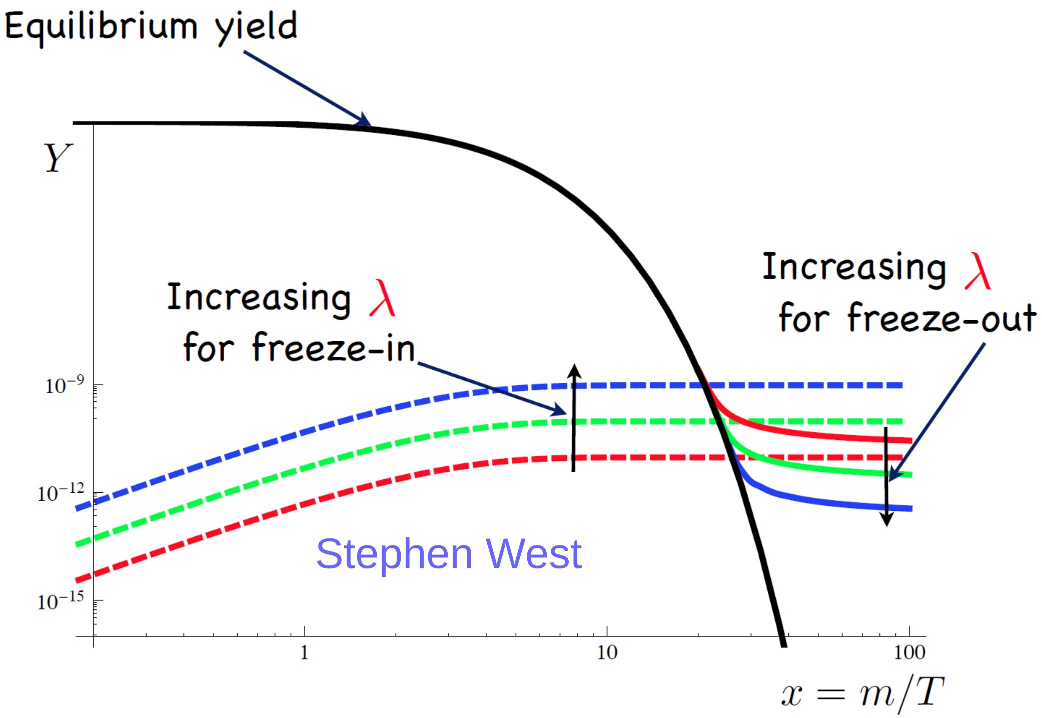
Dark matter abundance

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

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

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

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



Lyman-α constraints < 12 keV!
Use different mechanism:
JH, Teresi, 1706.09909, 1709.07283.