Majorons
in the Sky and in the Lab

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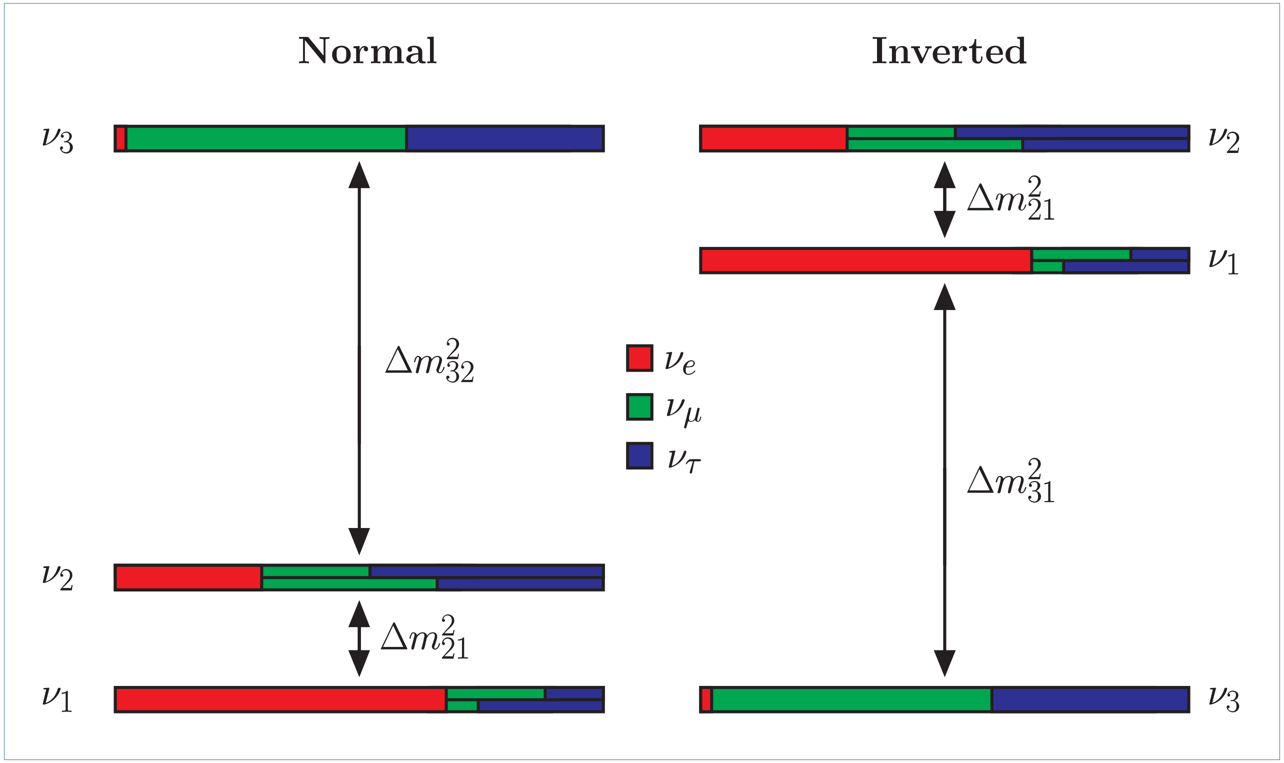
Neutrinos have masses and mix

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



Majoronic seesaw

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

Lepton number breaking scale Heavy scalar **Majoron**

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

- Break $U(1)_L$ spontaneously:

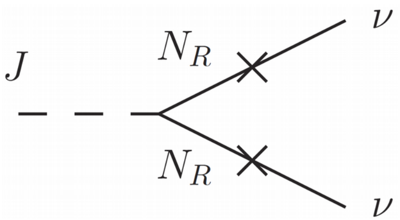
$$\mathcal{L} = -\underbrace{\overline{L} y H N_R}_{m_D = \frac{y}{\sqrt{2}} v} - \frac{1}{2} \overline{N_R^c} \underbrace{\kappa \sigma}_{M_R = \frac{\kappa f}{\sqrt{2}}} N_R + \text{h.c.} \quad \Rightarrow \quad \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

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

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

Majoron couplings

- Tree-level coupling only to neutrinos:



$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 (m_D M_R^{-1} m_D^T)^*_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k \gamma_5 m_k \nu_k$$

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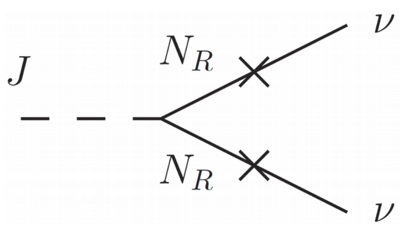


$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 (m_D M_R^{-1} m_D^T)^*_{\alpha\beta} \nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k \gamma_5 m_k \nu_k$$

- Assume *Pseudo*-Goldstone Majoron: $m_J \neq 0$.

[Rothstein, Babu, Seckel, '93]

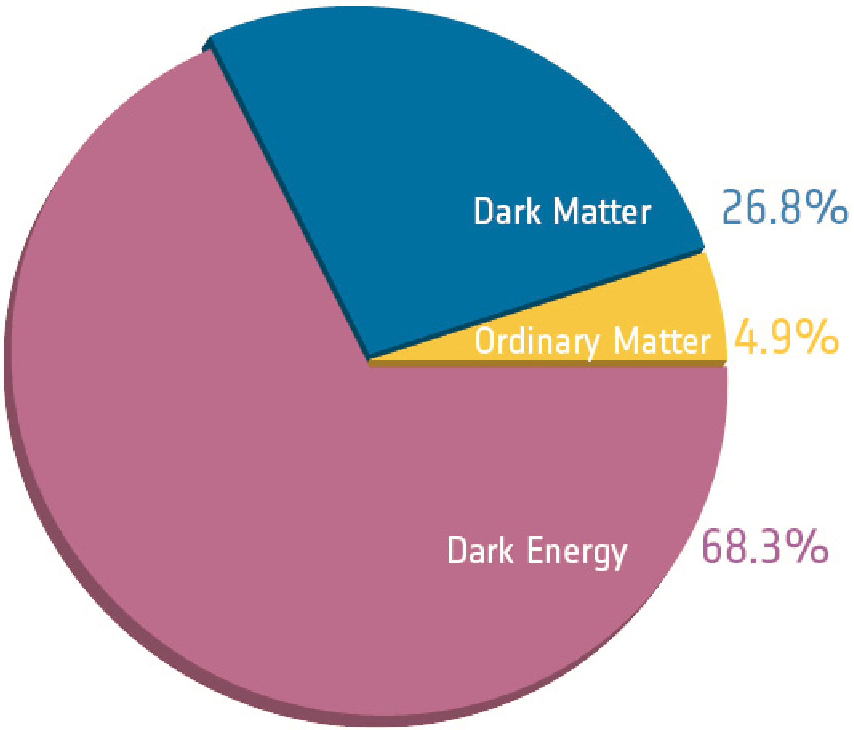
- Long lifetime → Dark matter!

[Berezinsky, Valle '93; Lattanzi, Valle '07; Bazzocchi et al, '08; Queiroz, Sinha, '14]

$$\tau(J \to \nu\nu) \simeq \tau_{\text{Universe}} \left(\frac{\text{MeV}}{m_J}\right) \left(\frac{f}{10^8\,\text{GeV}}\right)^2 \left(\frac{10^{-3}\,\text{eV}^2}{\sum_k m_k^2}\right)$$

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

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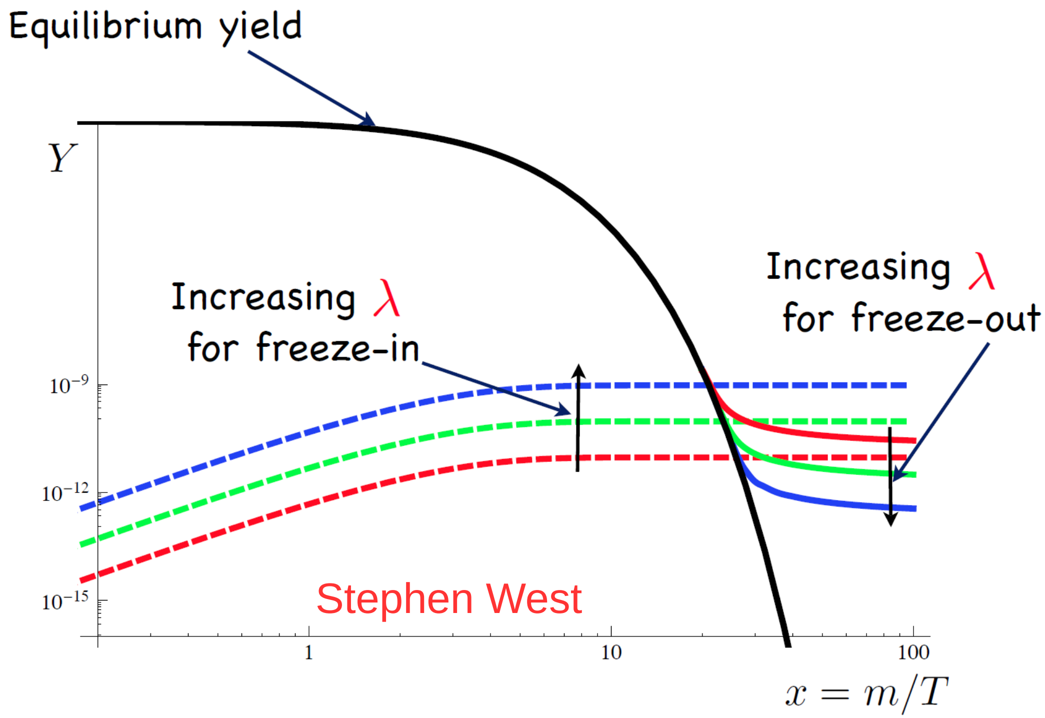
  - $m_J \sim m_h/2$,
  - $m_J > 400$ GeV.
- Freeze in:

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

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

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



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

Indirect detection

$$\tau(\mathrm{J} \to \nu\nu) \simeq \tau_{\text{Universe}} \left(\frac{\mathrm{MeV}}{\mathrm{m_J}}\right) \left(\frac{\mathrm{f}}{10^8\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-3}\mathrm{eV}^2}{\sum_k \mathrm{m}_k^2}\right)$$

- General limit from DM → invisible: $\tau \gtrsim 10 \times \tau_{\text{Universe}}$.

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

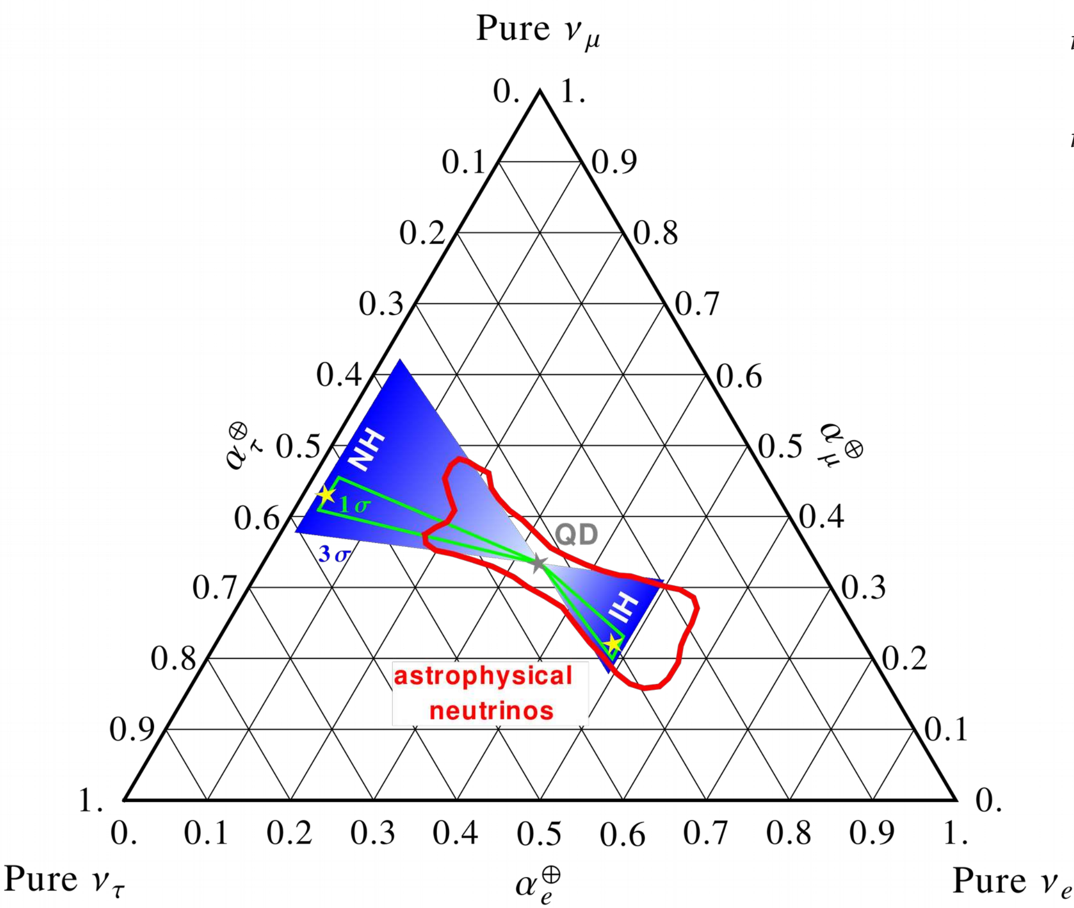
- Can we observe the **neutrino lines**?
  - m_J > 10 TeV: **No.** Dominant decay is J →ννh(h).
    - ► no line! [Dudas, Mambrini, Olive, ‘15]
  - Also want to avoid electroweak Bremsstrahlung.

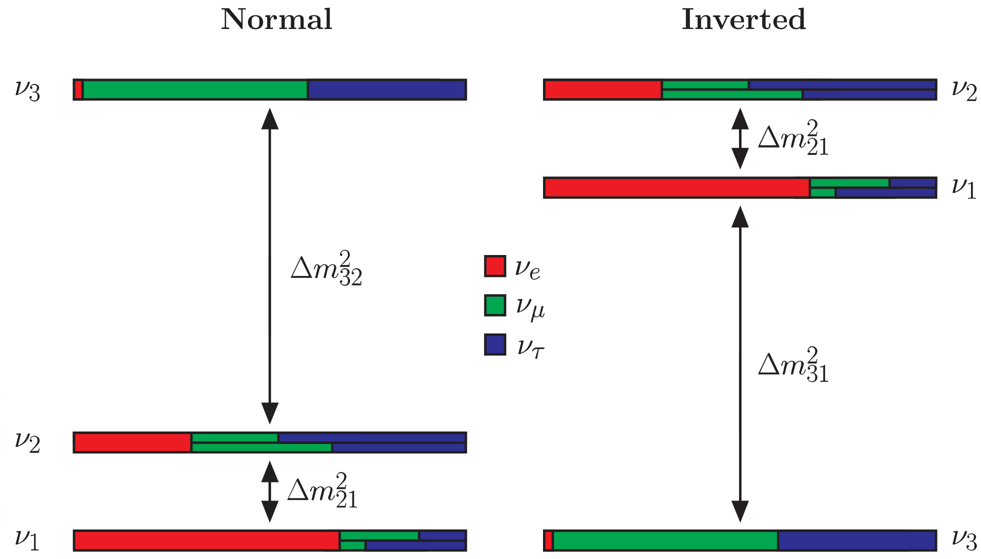
[Kachelriess, Serpico, ‘07; Bell, Dent, Jacques, Weiler, ‘08; Queiroz, Yaguna, Weniger, ‘16]

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

Flavor of J → $\nu_k \nu_k$

Mass eigenstates → no oscillations!





Flavor ratios:

$$\alpha_e : \alpha_\mu : \alpha_\tau$$

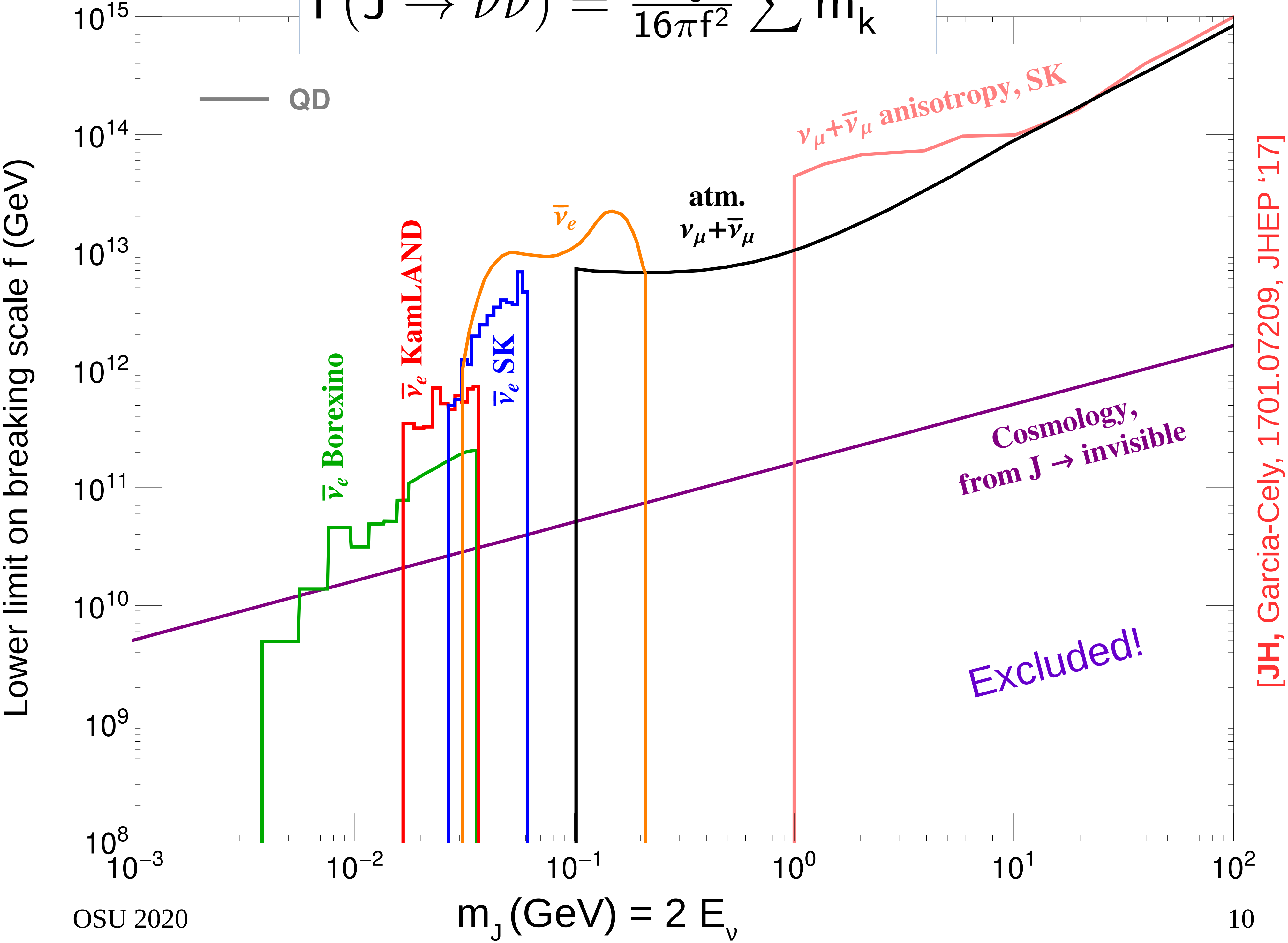
$$\text{NH} : 0.03 : 0.43 : 0.54\,,$$

$$\text{IH} : 0.48 : 0.22 : 0.30\,,$$

$$\text{QD} : 0.33 : 0.33 : 0.33\,.$$

[**JH,** Garcia-Cely, 1701.07209, JHEP '17]

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



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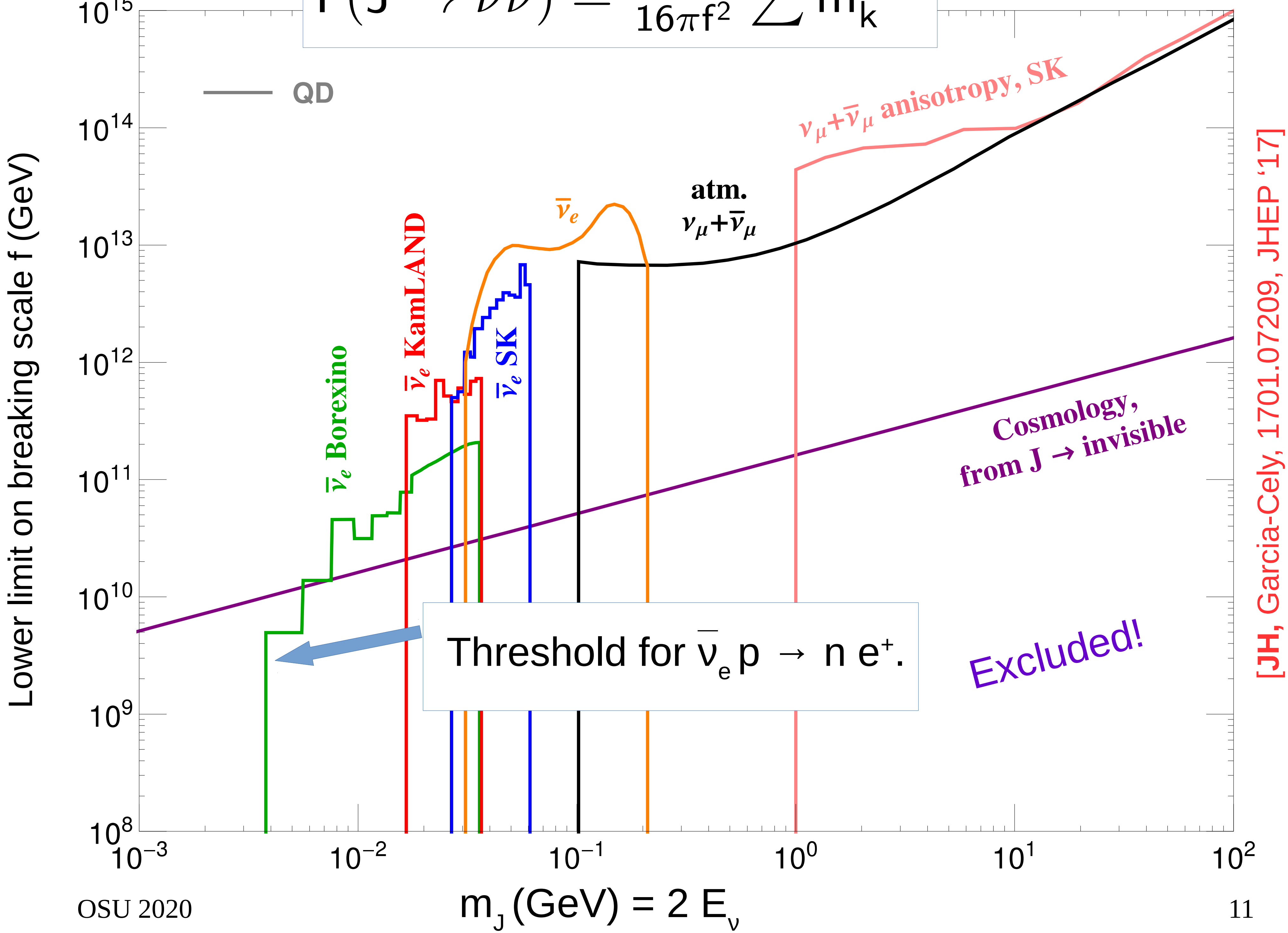
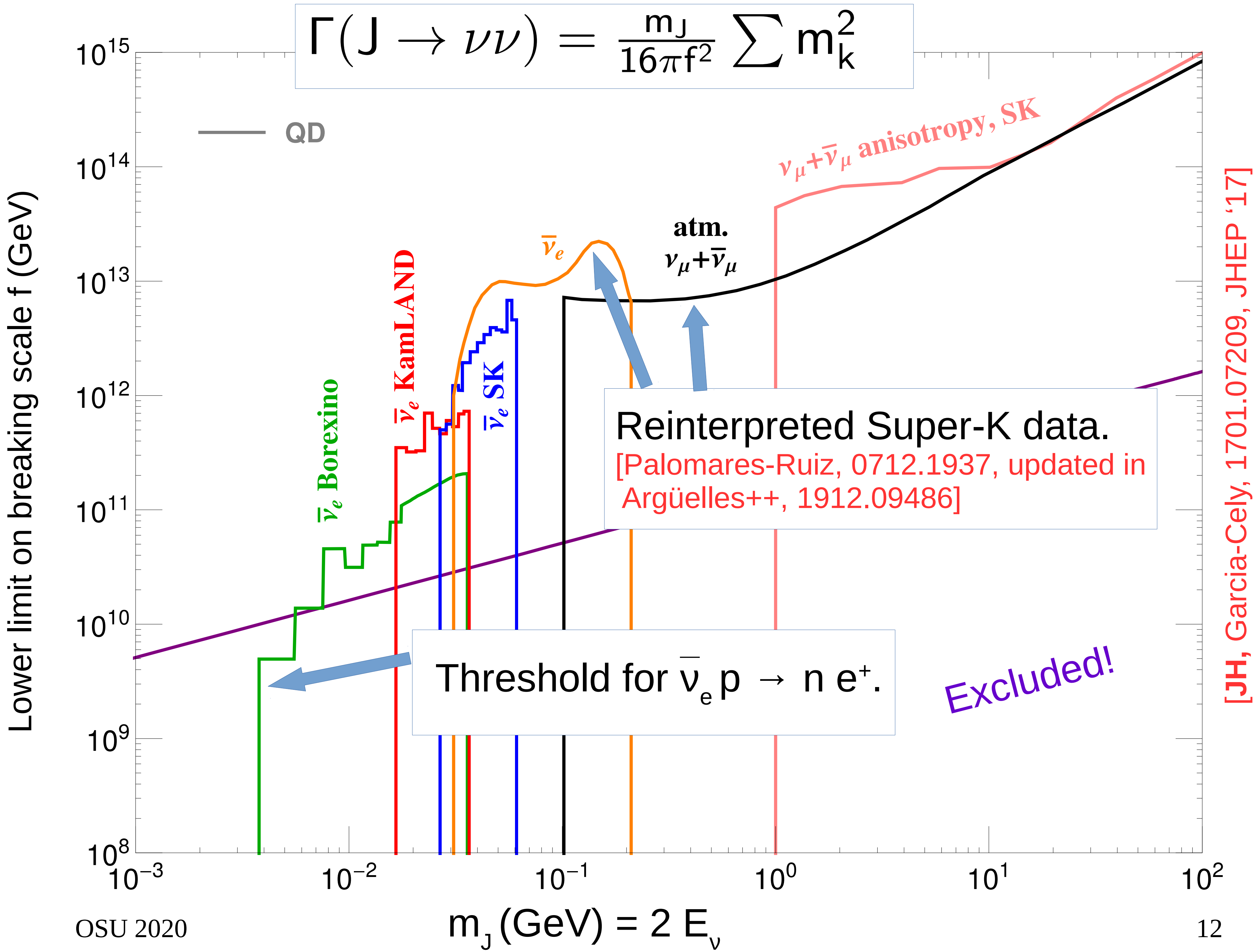
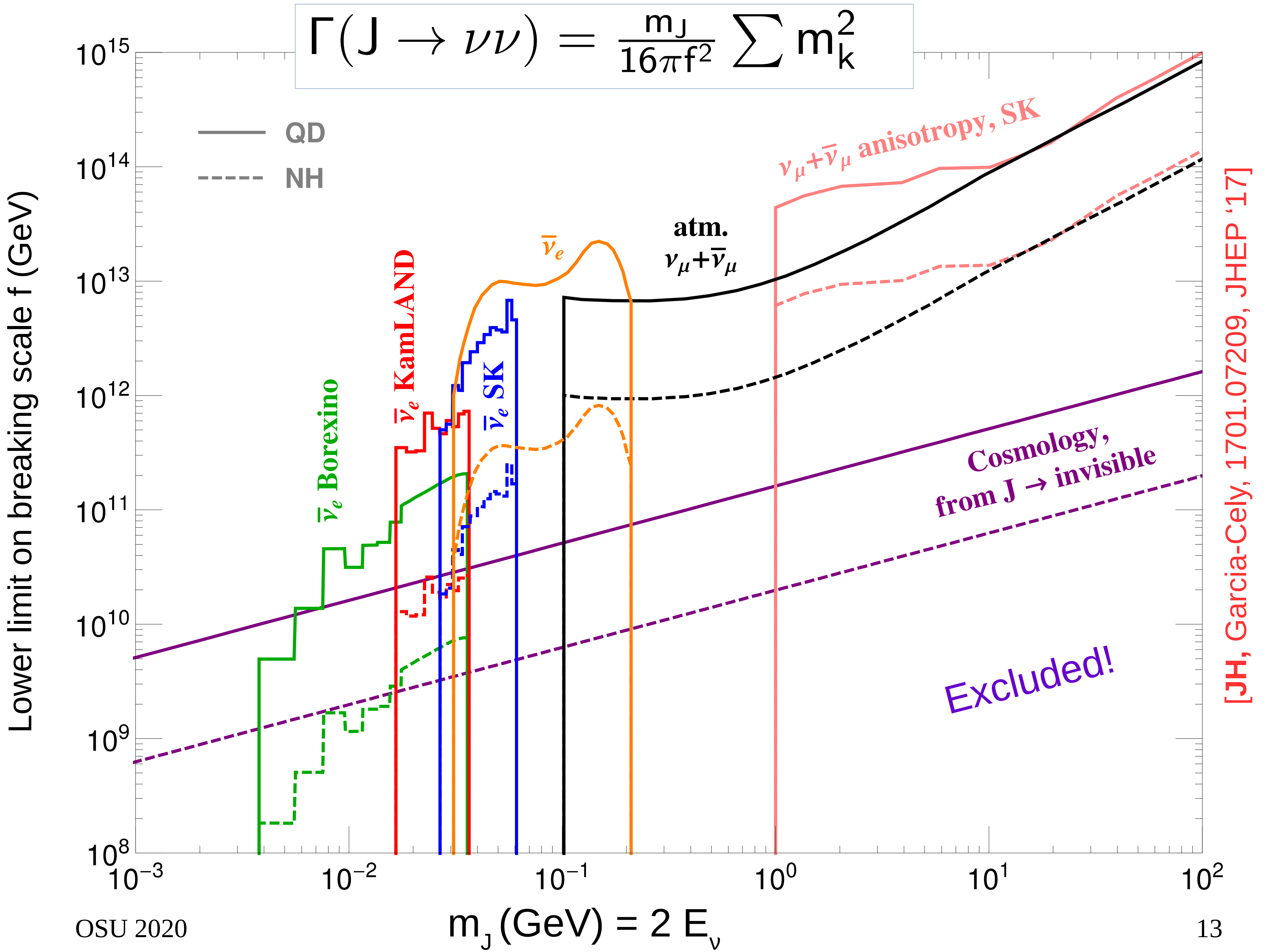




$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_k^2$
QD
$\bar{\nu}_e$ Borexino
$\bar{\nu}_e$ KamLAND
$\bar{\nu}_e$ SK
$\bar{\nu}_e$
atm.
$\nu_\mu + \bar{\nu}_\mu$
$\nu_\mu + \bar{\nu}_\mu$ anisotropy, SK
Reinterpreted Super-K data.
[Palomares-Ruiz, 0712.1937, updated in
Argüelles++, 1912.09486]
Threshold for $\bar{\nu}_e\, p \to n\, e^+$.
Excluded!
[JH, Garcia-Cely, 1701.07209, JHEP '17]
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}



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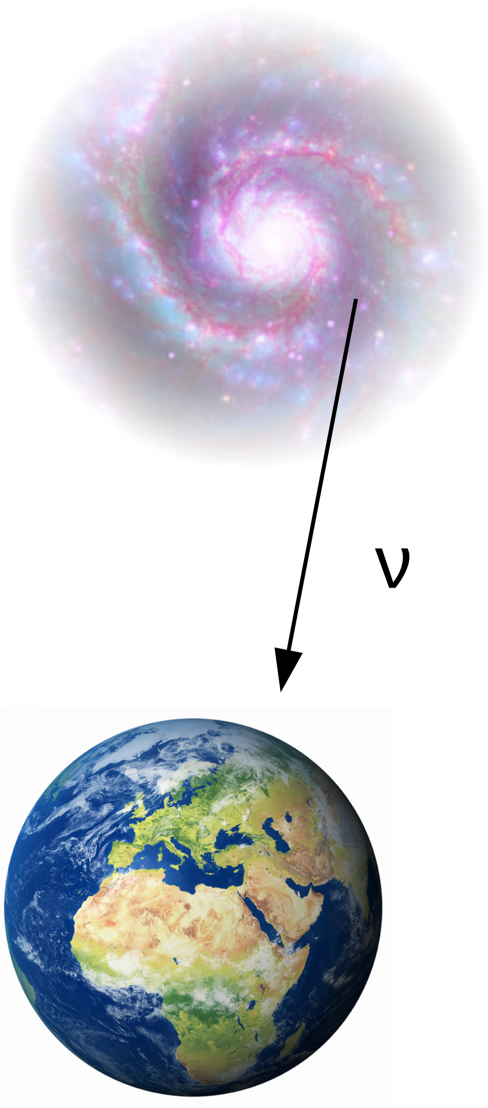
Cosmology, from J → invisible
Excluded!
[JH, Garcia-Cely, 1701.07209, JHEP '17]

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!
- Darwin, Hyper-K, JUNO,… = indirect DM detectors.
- DM → ν easily dominant channel, no SU(2) argument as for multi-TeV DM.

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



Majoron couplings

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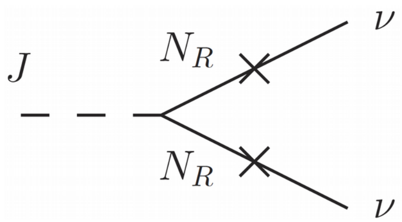
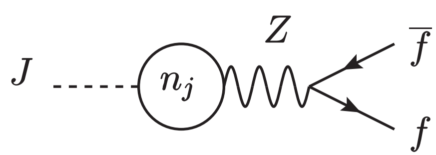
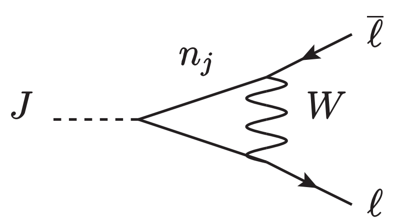


$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 \left(m_D M_R^{-1} m_D^T\right)^*_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k \gamma_5 m_k \nu_k$$

- One loop:



$$\frac{iJ}{f}\overline{f}\gamma_5 f\, \frac{m_f T_3^f}{8\pi^2 v^2}\, \mathrm{tr}\left(m_D m_D^\dagger\right)$$

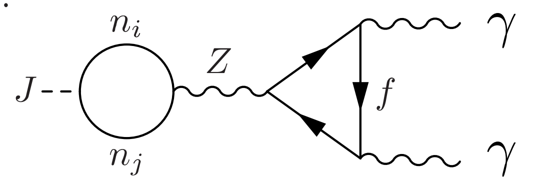


$$\frac{iJ}{f}\overline{\ell}_\alpha \left(\frac{m_\beta}{8\pi^2 v^2}P_R - \frac{m_\alpha}{8\pi^2 v^2}P_L\right)\ell_\beta \left(m_D m_D^\dagger\right)_{\alpha\beta}$$

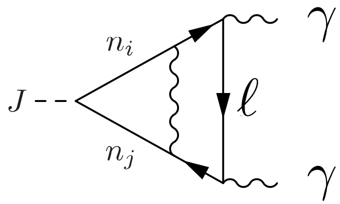
Off-diagonal!

[**JH**, Garcia-Cely, JHEP ‘17; see also Pilaftsis ‘94]

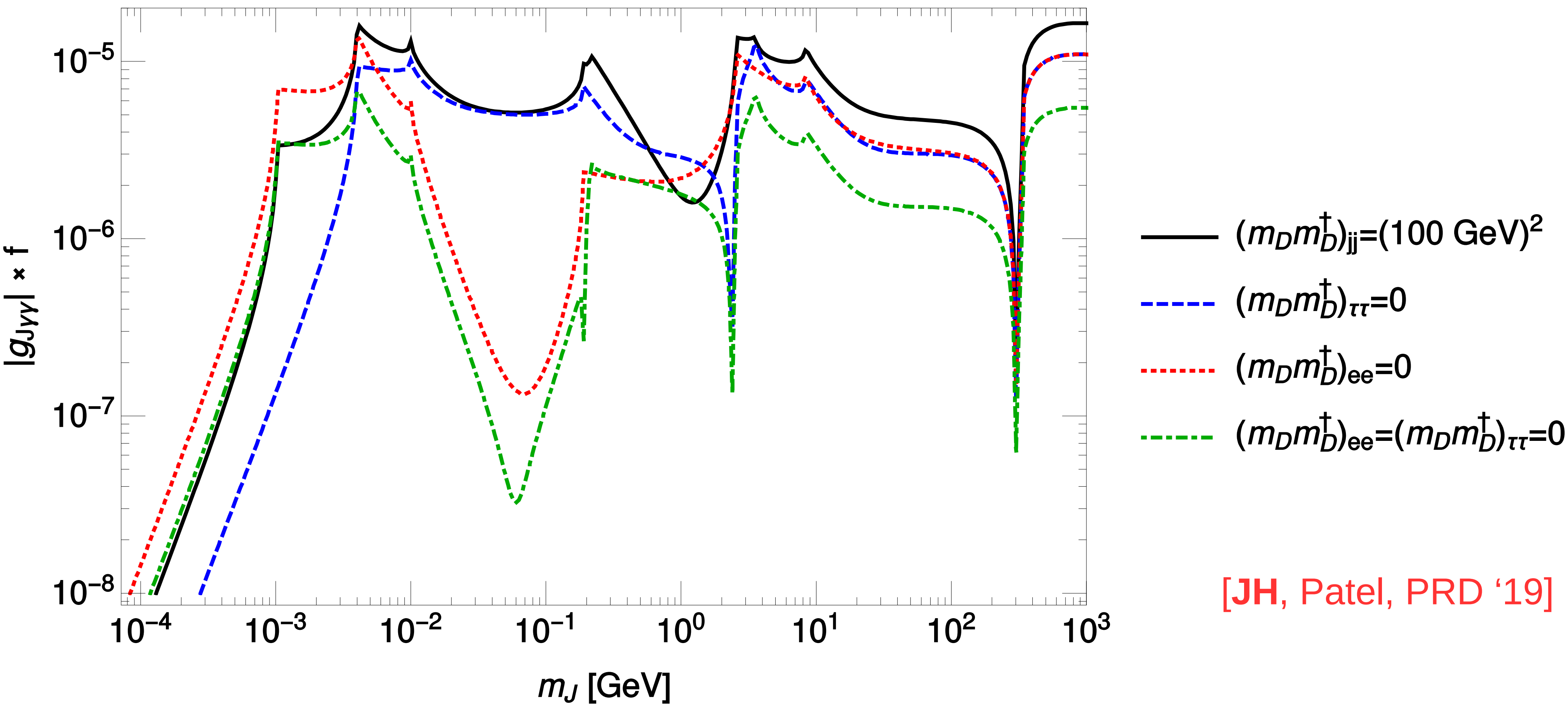
:



$$= \frac{\alpha}{8\pi^3 v^2 f} \, \mathrm{tr}(m_D m_D^\dagger) \sum_f N_c^f Q_f^2 T_3^f \; h\left(\frac{m_J^2}{4m_f^2}\right)$$



$$= \frac{\alpha}{8\pi^3 v^2 f} \sum_\ell (m_D m_D^\dagger)_{\ell\ell} \; h\left(\frac{m_J^2}{4m_\ell^2}\right)$$



[**JH**, Patel, PRD '19]

Loop induced $J \to \gamma\gamma, \bar{q}q, \bar{\ell}\ell'$

- Tree-level J couplings $\propto M_\nu$ while loop level $\propto m_D m_D^\dagger$.
- One-to-one mapping: $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.

[Davidson, Ibarra, hep-ph/0104076]

- Loop couplings contain unknown seesaw parameters!

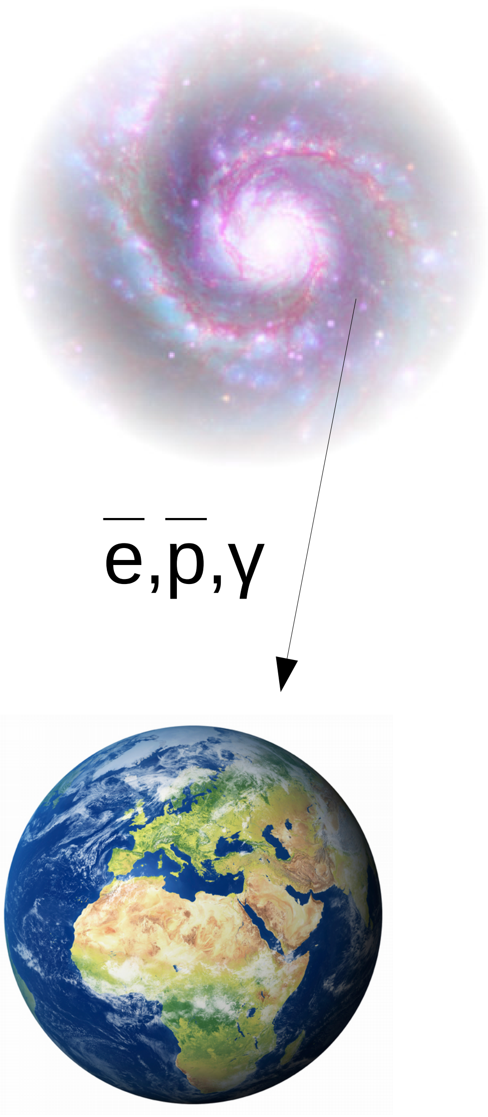
$J \to \gamma\gamma, \bar{q}q, \bar{\ell}\ell'$ are *complementary* to $\nu\nu$ channel!

- One generation: $K \equiv \frac{m_D m_D^\dagger}{v\, f} \sim \frac{m_\nu M_R}{v\, f} \sim 10^{-13} M_R/f$.

[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.
- DM → γγ gives lines.

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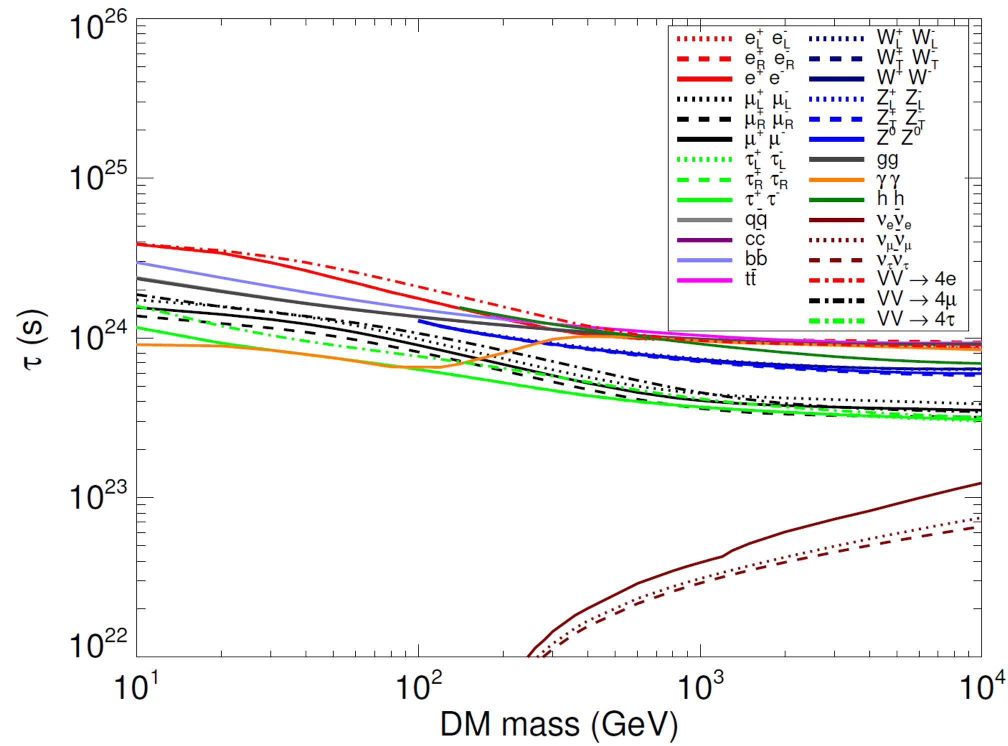

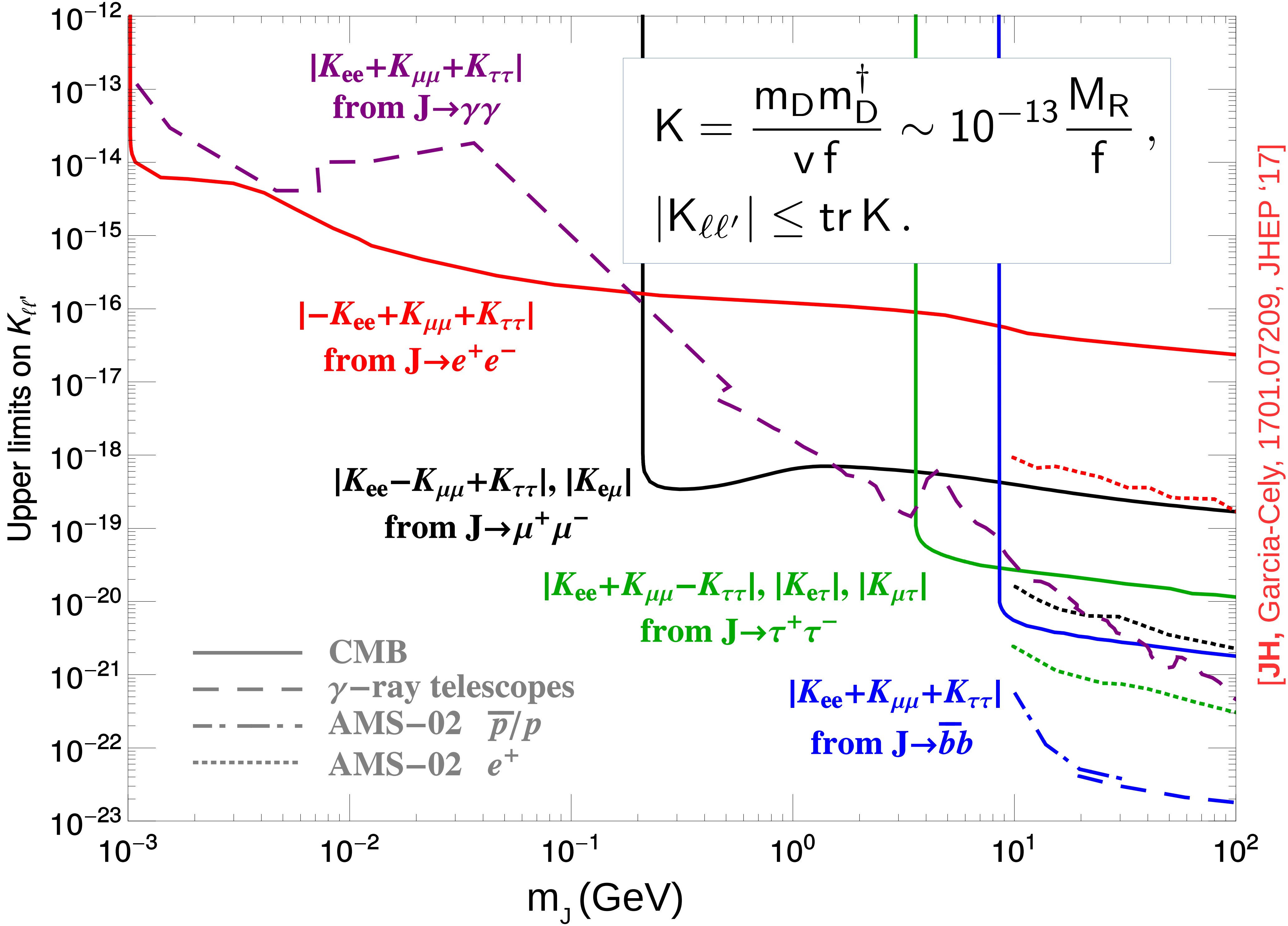

$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\, K$.
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|$, $|K_{e\mu}|$
from $J\to\mu^+\mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$
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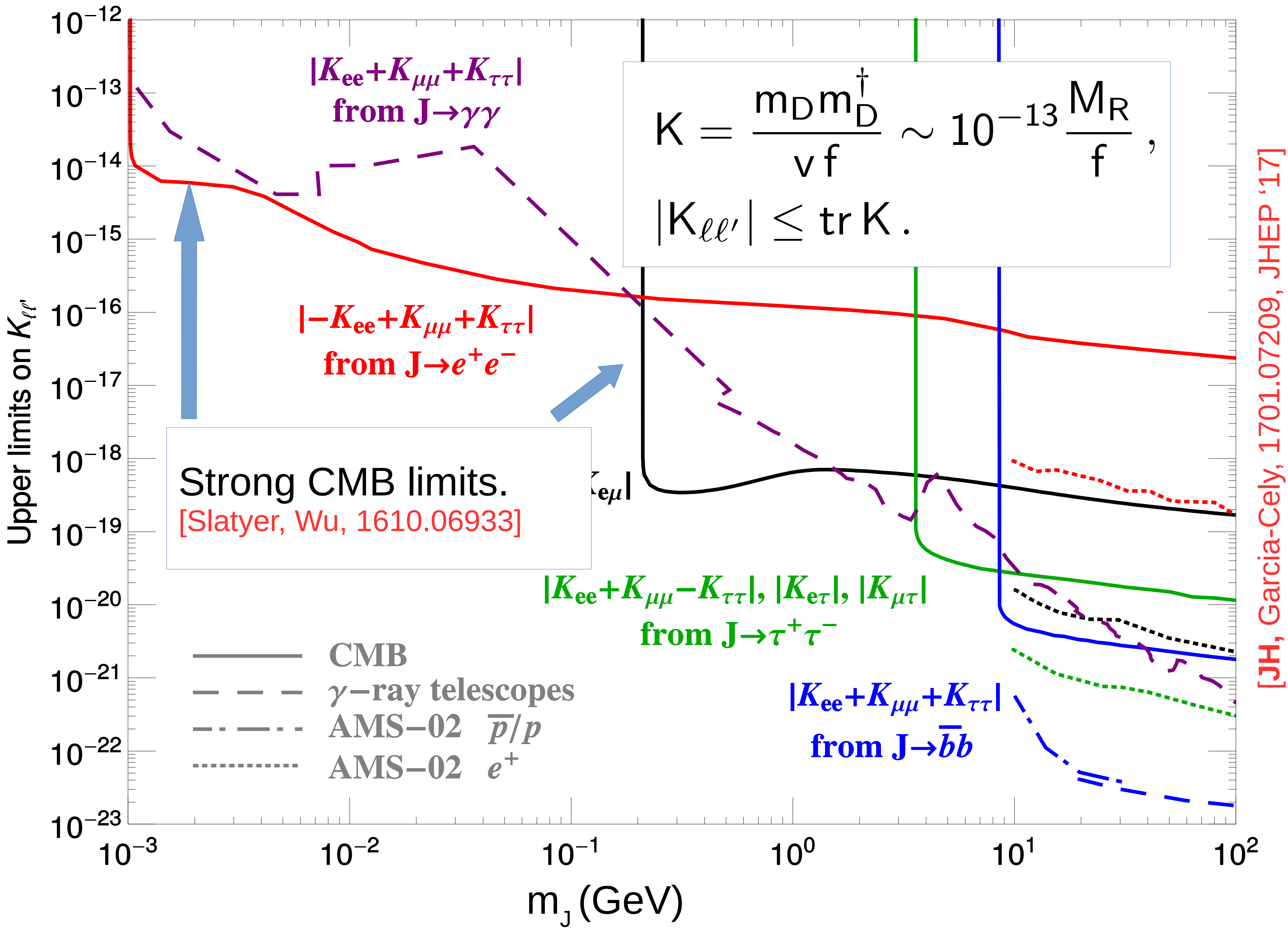
from $J\to\bar{b}b$
CMB
γ−ray telescopes
AMS−02 $\bar{p}/p$
AMS−02 e^+
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
[JH, Garcia-Cely, 1701.07209, JHEP '17]



$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$ from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
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$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$ from $J\to e^+e^-$
Strong CMB limits.
[Slatyer, Wu, 1610.06933]
$K_{e\mu}|$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$ from $J\to\tau^+\tau^-$
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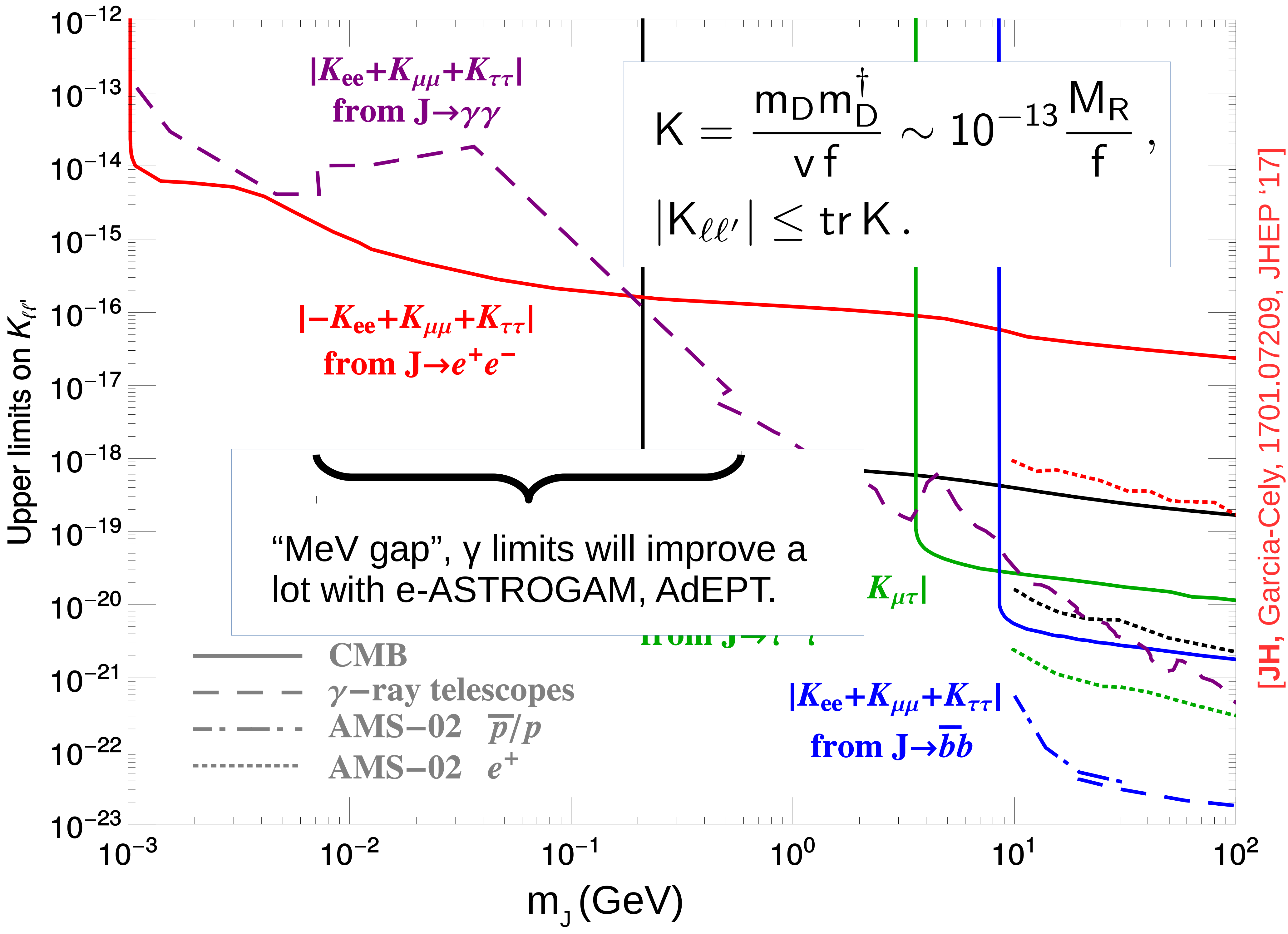

Upper limits on $K_{\ell\ell'}$
m_J (GeV)
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
$K_{\mu\tau}|$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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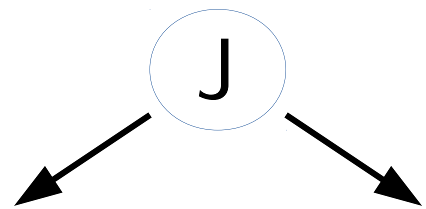
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\, K$.
"MeV gap", γ limits will improve a
lot with e-ASTROGAM, AdEPT.
CMB
γ−ray telescopes
AMS−02 $\bar{p}/p$
AMS−02 e^+
[JH, Garcia-Cely, 1701.07209, JHEP '17]

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

Yes!



$\nu\nu$

$\bar{f}f', \gamma\gamma$

depends on

$M_\nu \simeq -m_D M_R^{-1} m_D^T.$

depends on

$m_D m_D^\dagger.$

Independent / Complementary!

Majoron = DM

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

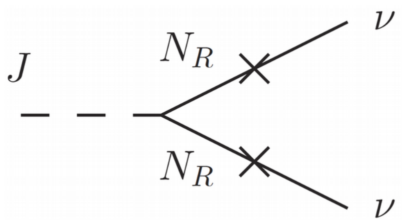
    [**JH**, Teresi, 1706.09909, 1709.07283]

Majoron ≠ DM

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

Majoron couplings

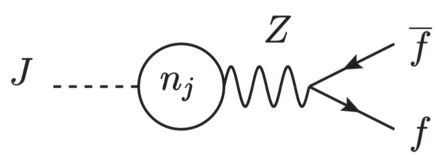
- Tree-level coupling only to neutrinos:



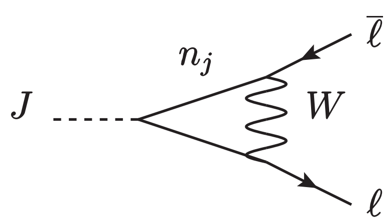
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha\gamma_5\left(m_D M_R^{-1} m_D^T\right)^*_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\underbrace{\sum_k \overline{\nu}_k\gamma_5 m_k\nu_k}$$

Too small for lab

- One loop:



$$\frac{iJ}{f}\overline{f}\gamma_5 f\,\frac{m_f T_3^f}{8\pi^2 v^2}\,\mathrm{tr}\left(m_D m_D^\dagger\right)$$



$$\frac{iJ}{f}\overline{\ell}_\alpha\left(\frac{m_\beta}{8\pi^2 v^2}P_R - \frac{m_\alpha}{8\pi^2 v^2}P_L\right)\ell_\beta\left(m_D m_D^\dagger\right)_{\alpha\beta}$$

Off-diagonal!

[**JH**, Garcia-Cely, JHEP ‘17; see also Pilaftsis ‘94]

Properties

- Crucial observation: the two matrices are independent!

$$\{m_D,\ M_R\} \leftrightarrow \{M_\nu = -m_D M_R^{-1} m_D^T,\ m_D m_D^\dagger\}.$$

[Davidson, Ibarra, JHEP ‘01]

- $J\bar{\ell}\ell'$ coupling can be *large* and of arbitrary structure.
- Similar couplings arise for familons or flavor Z’.

[Wilczek, ‘82; Reiss, ‘82; Grinstein, Preskill, Wise, 85; ...]

- Experimental signature depends on J decay channel:

$$\ell \to \ell' J, \quad J \to \text{inv}\,, \ell''\ell''', \underbrace{\gamma\gamma}, \ldots$$

[μ→e J, J→γγ: MEG, 2005.00339]

[**JH**, Rodejohann, PLB ‘18; Bauer et al., PRL ‘20; Cornella et al., JHEP ‘20]

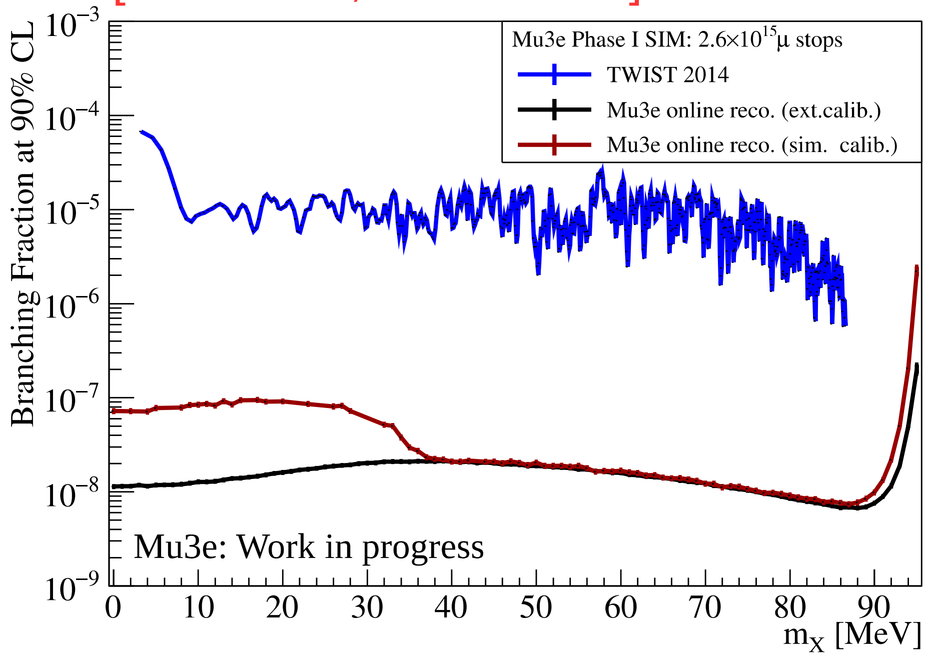
μ → e J

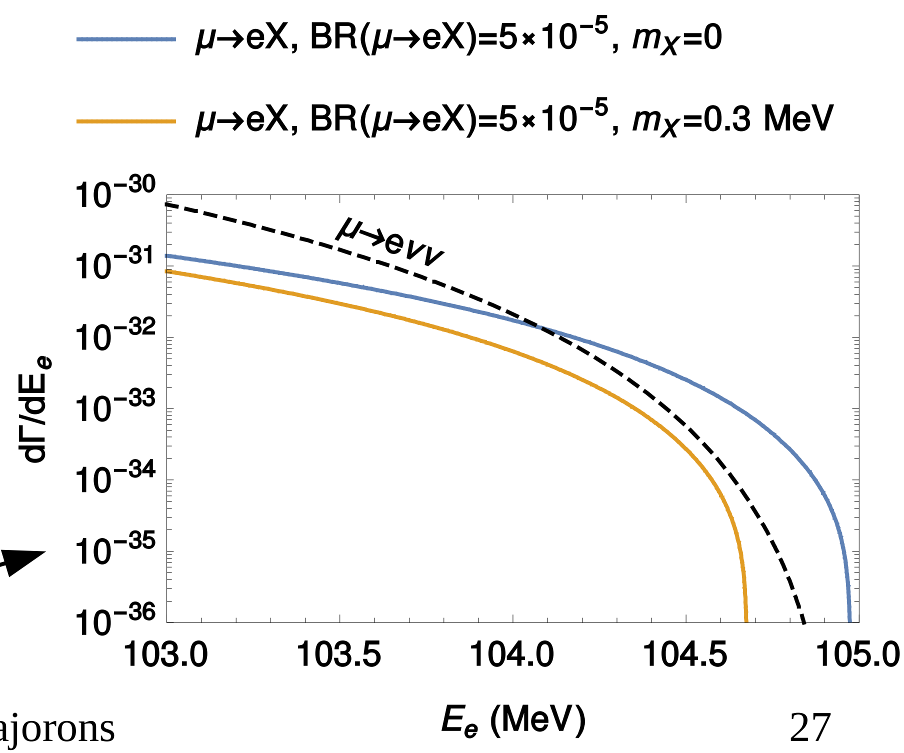
- Electron *line* on top of Michel spectrum.
- Good prospects @ Mu3e.
- In progress: signal in μ → e conversion exps. COMET, Mu2e(-II).
  - Many muons!
  - Nuclear recoil: E_e up to m_μ.
  - Suppression of tail...

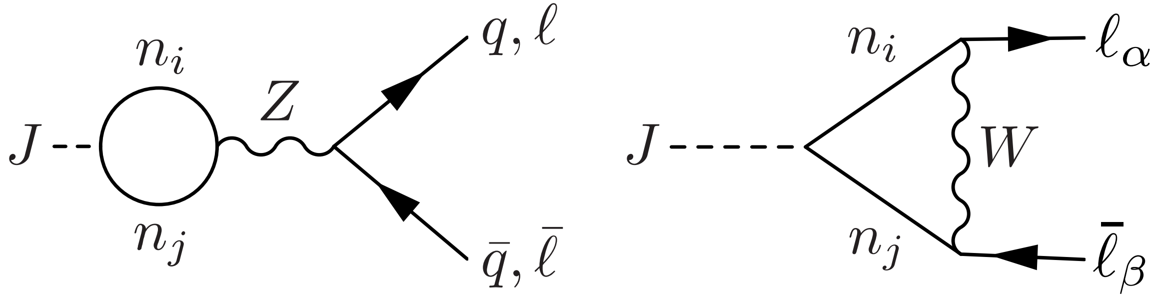
[Garcia i Tormo++, PRD '11; Uesaka, 2005.07894]

[**JH**++, Mu2e-II Snowmass LOI]

[Perrevoort, 1812.00741]

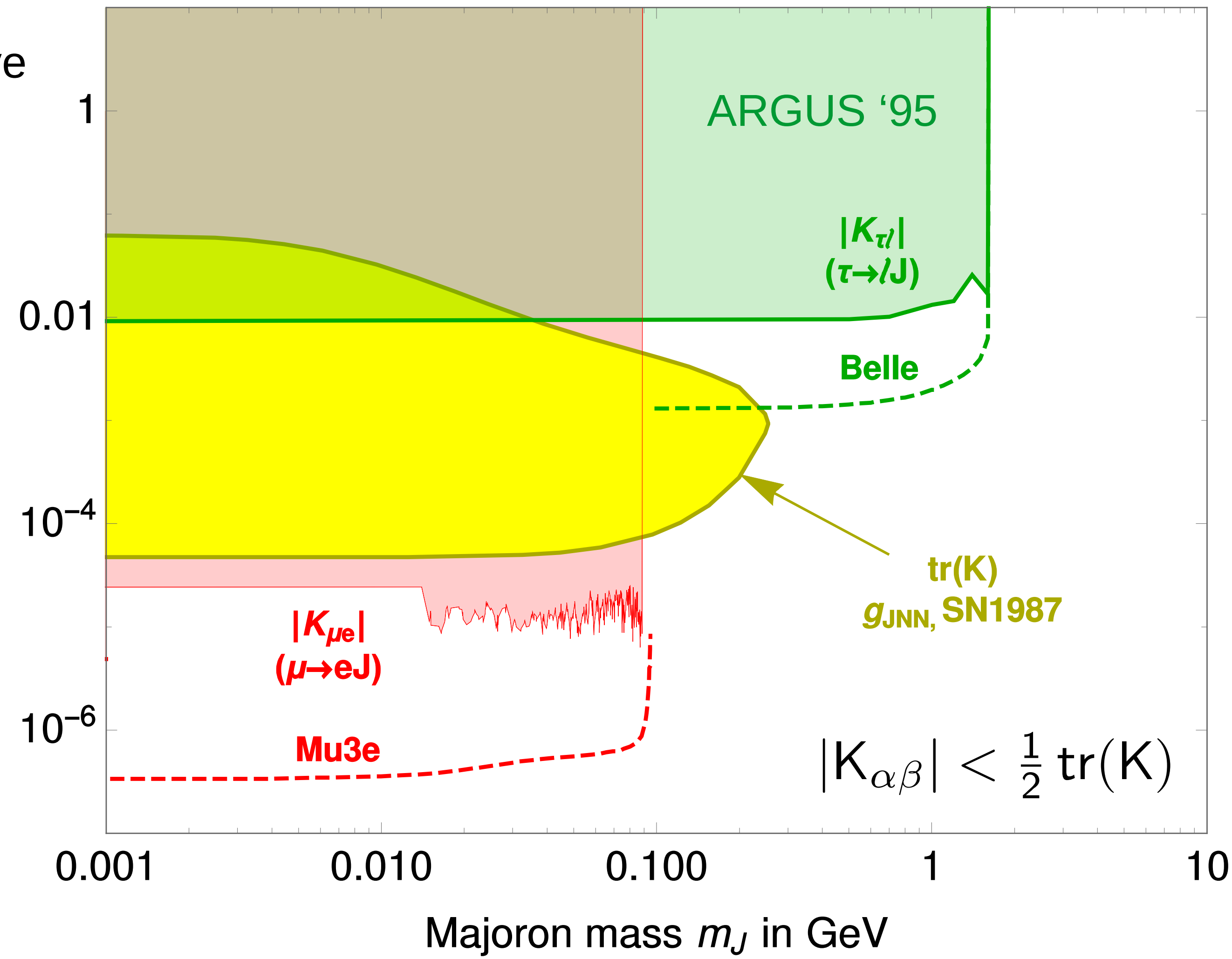






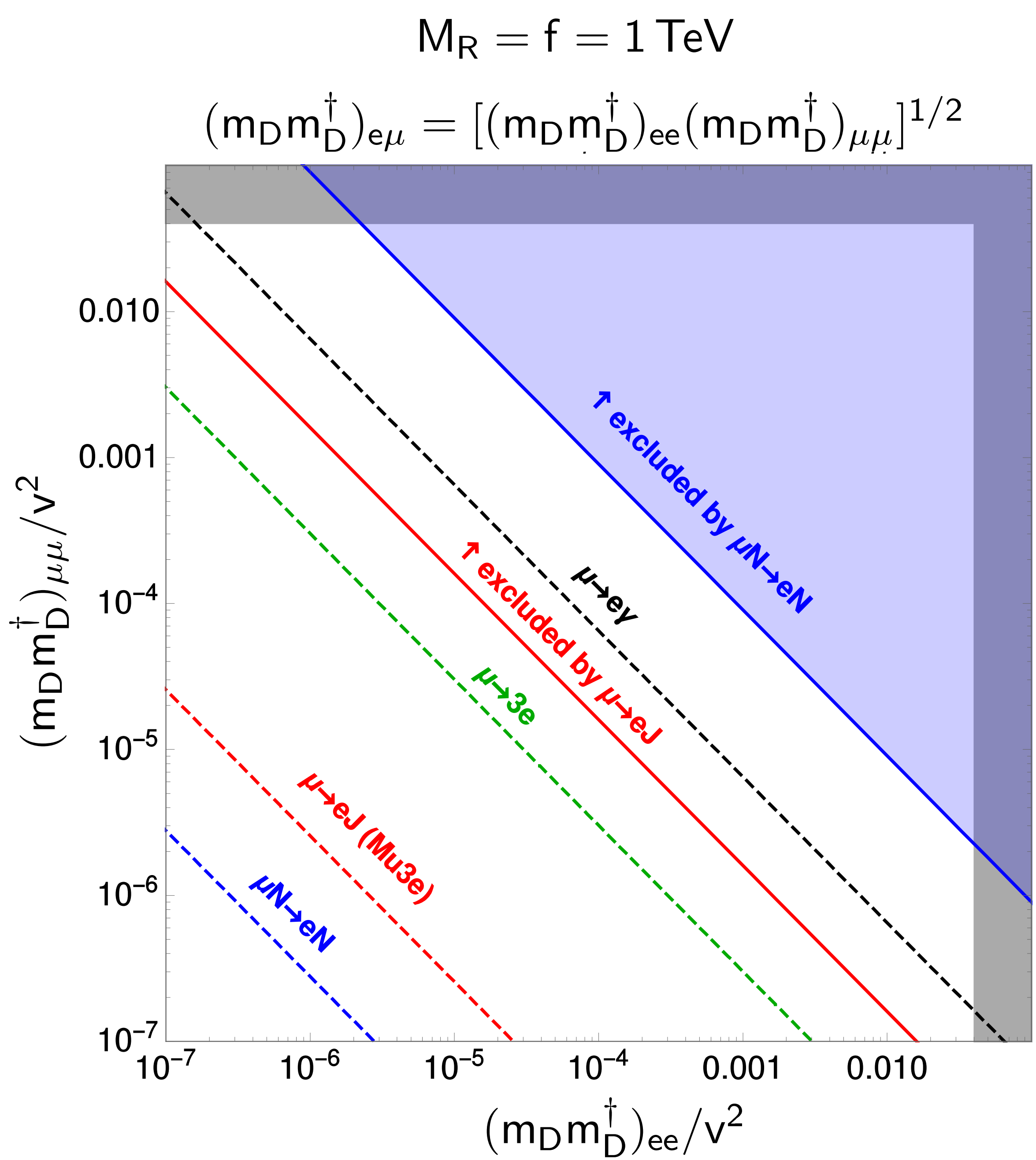
Limit on effective coupling

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



[**JH**, Garcia-Cely, JHEP '17]

- Comparison of Majoron and non-Majoron limits. [from Coy & Frigerio, PRD '19]
- $m_D M_R^{-2} m_D^\dagger$ vs. $\frac{m_D m_D^\dagger}{f}$.
- Sterile neutrinos modify EWPD & LFV.
- $\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell' J)} \simeq 2\pi\alpha \frac{m_\ell^2}{M_R^2}\frac{f^2}{M_R^2}$.
- Majoron wins for f ~ M_R.
- $\ell \to \ell'$ + J possible!
- Together with LFV in μ?



[**JH**, Patel, PRD '19]

- Comparison of Majoron and non-Majoron limits.
  [from Coy & Frigerio, PRD '19]
- $m_D M_R^{-2} m_D^\dagger$ vs. $\frac{m_D m_D^\dagger}{f}$.
- Sterile neutrinos modify EWPD & LFV.
- $\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell' J)} \simeq 2\pi\alpha \frac{m_\ell^2}{M_R^2}\frac{f^2}{M_R^2}$.
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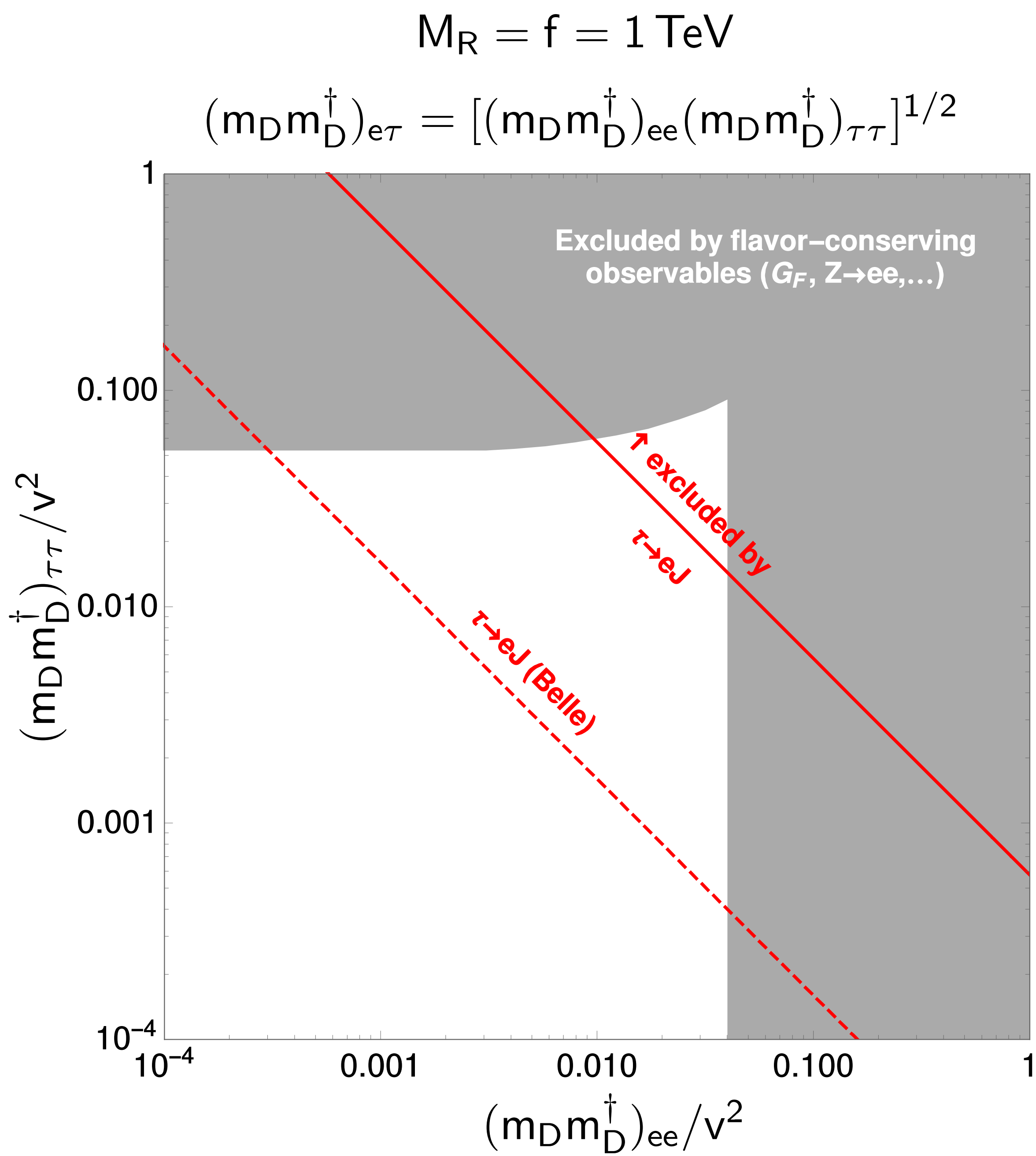
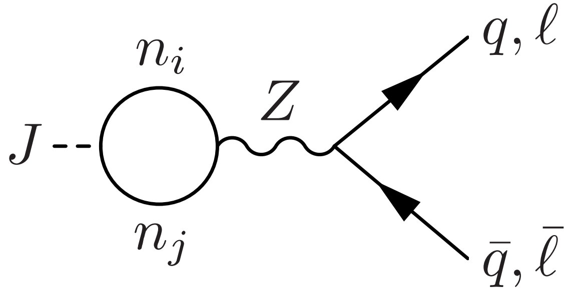
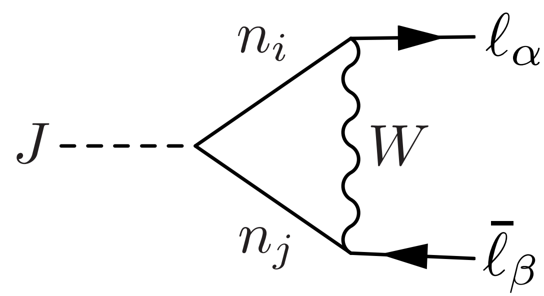


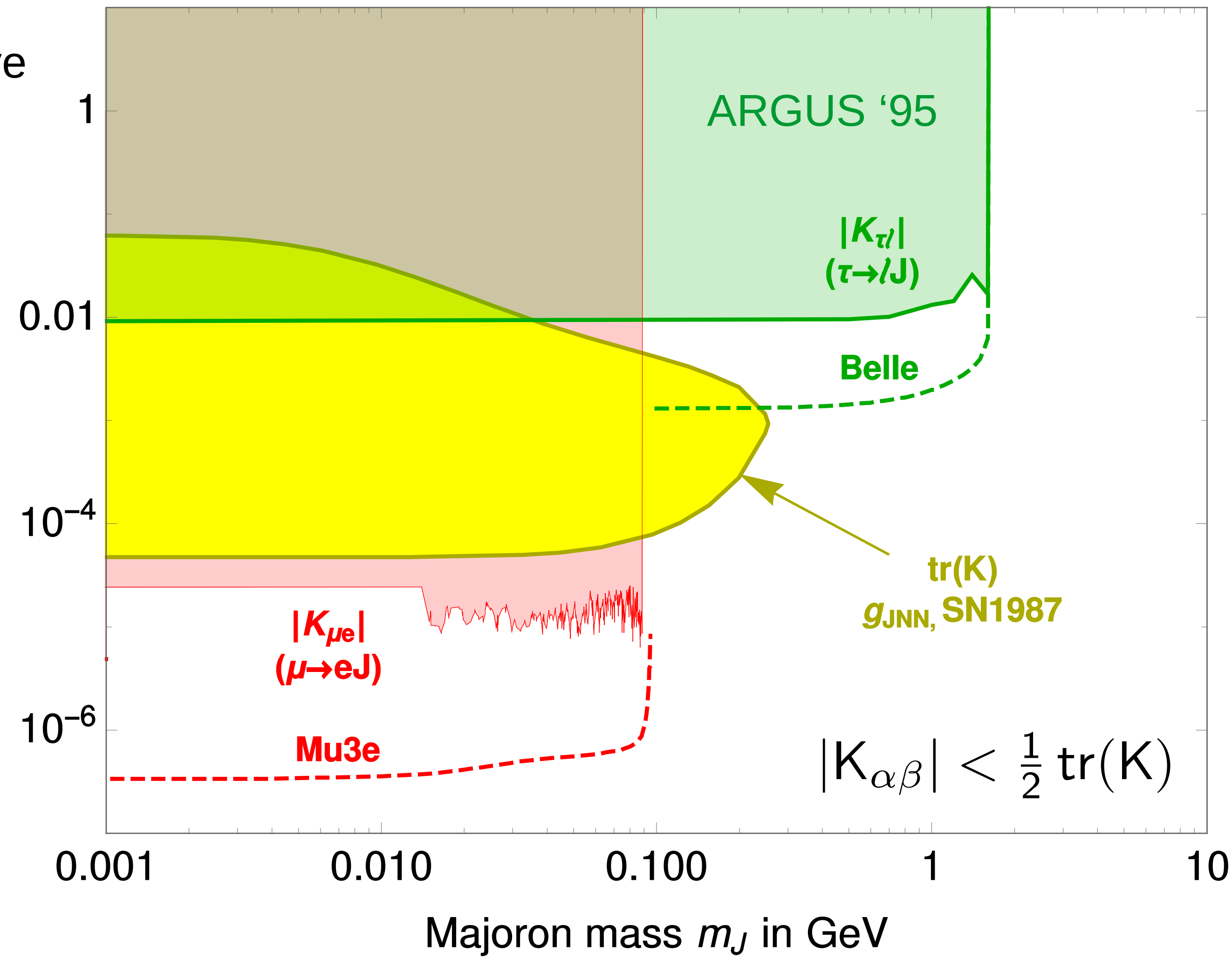
[**JH**, Patel, PRD '19]



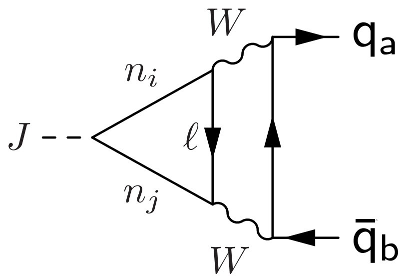


Limit on effective coupling

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



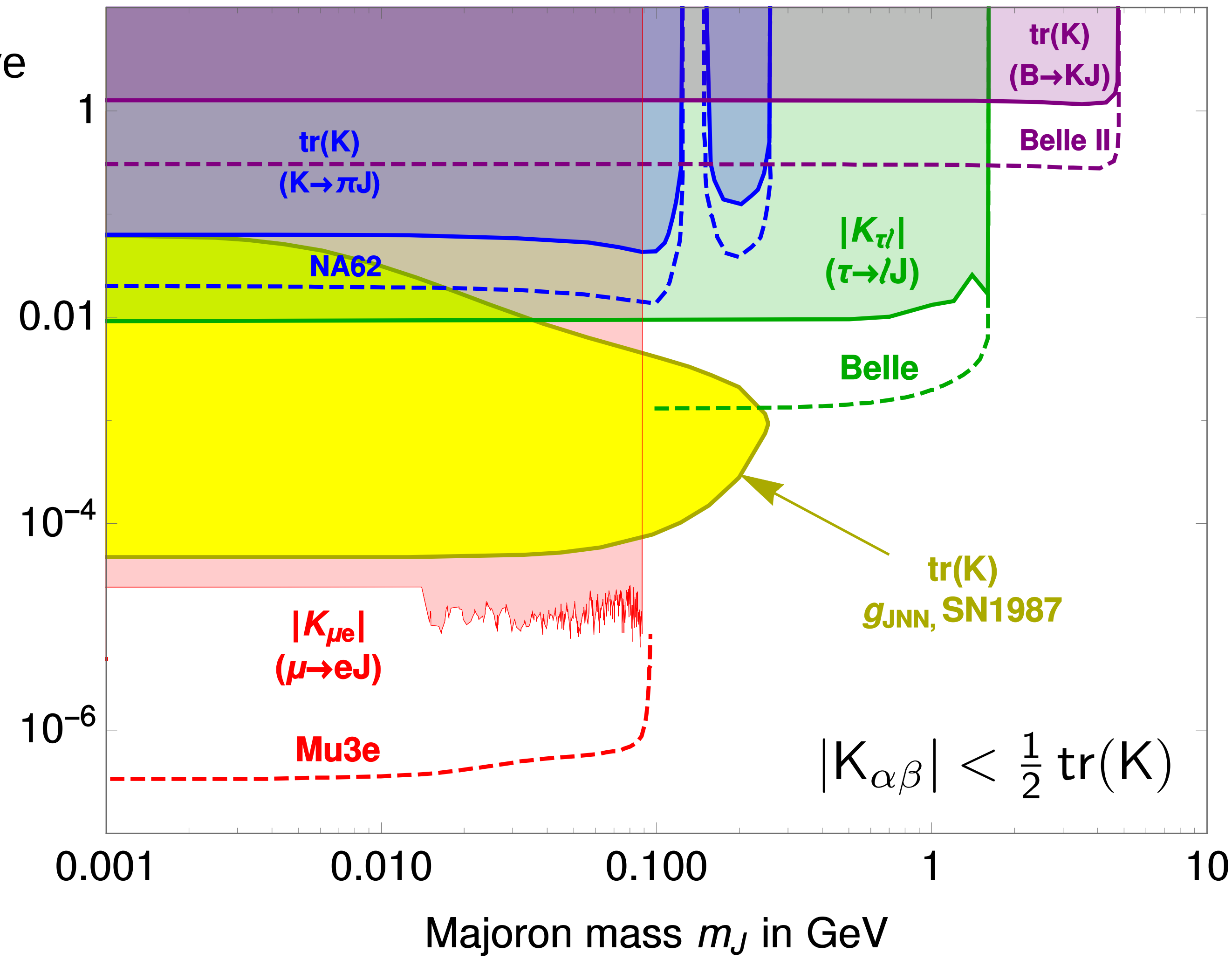
[**JH**, Garcia-Cely, JHEP '17]



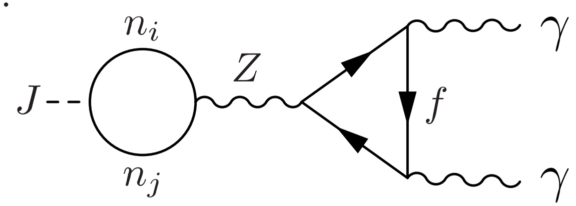
$$\simeq \frac{\mathrm{tr}\left(m_D \log\left(\frac{M_R}{m_W}\right) m_D^\dagger\right)}{128\pi^4 v^4 f}\, iJ\, \bar{d}_R M_d V_q^\dagger M_u^2 V_q\, d_L$$

Limit on effective coupling

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



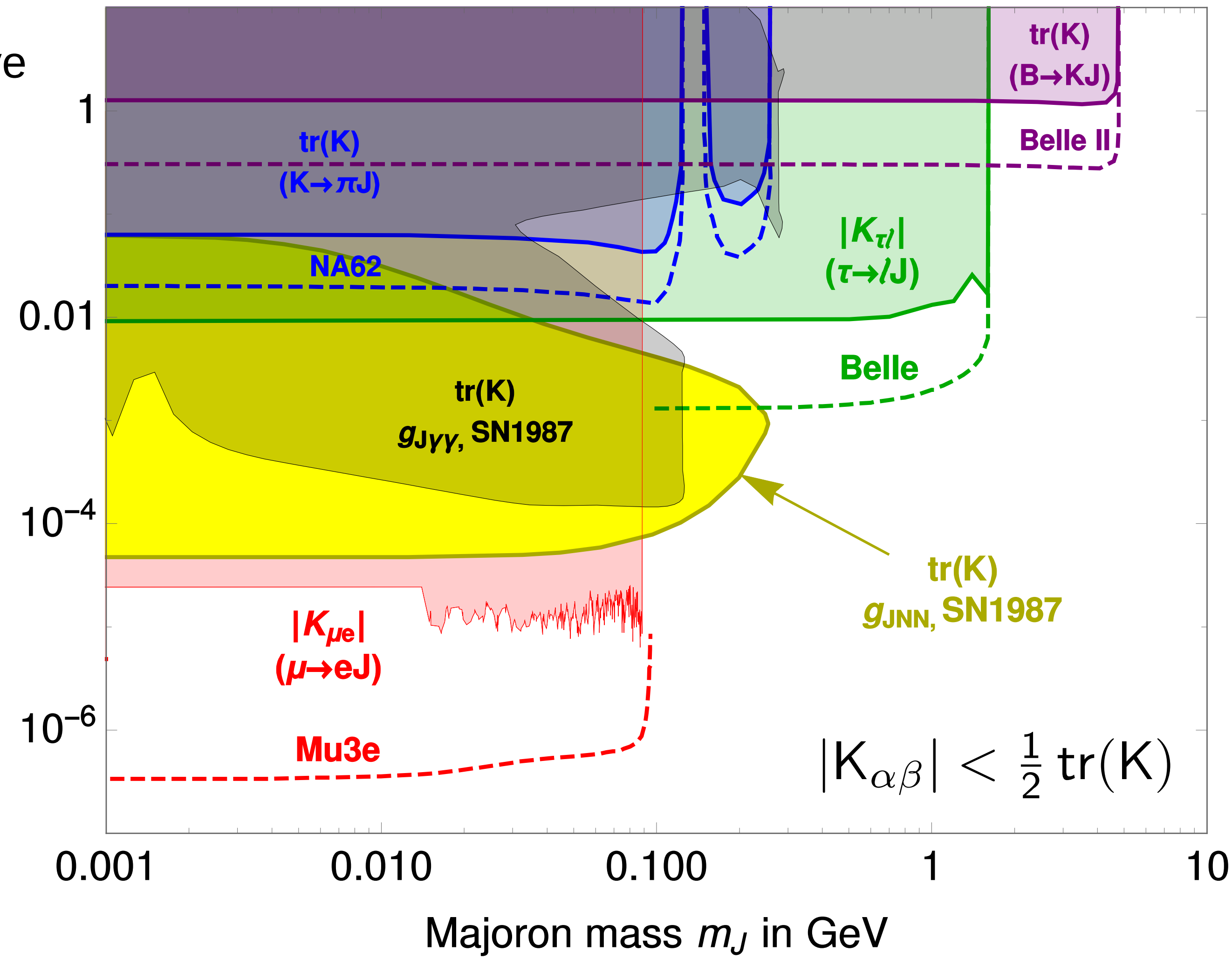
[**JH**, Patel, PRD '19]



$$\simeq \frac{\alpha}{8\pi^3 v^2 f}\, \mathrm{tr}(m_D m_D^\dagger) \sum_f N_c^f Q_f^2 T_3^f\, h\left(\frac{m_J^2}{4 m_f^2}\right) + \dots$$

Limit on effective coupling

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



[**JH**, Patel, PRD '19]

Summary

- Majoron = simple axion-like particle connected to seesaw.
- Seesaw parameters encoded in loop couplings ($J\bar{f}f$ & $J\gamma\gamma$).
- In the sky:
  - $DM \to \nu\nu$ @ JUNO, DUNE, Hyper-K, DARWIN,...
  - $DM \to \gamma\gamma$, $\bar{\ell}\ell'$, $\bar{q}q$ @ Fermi, CTA, e-ASTROGAM,...
- In the lab:
  - One loop: $\ell \to \ell' + J$ @ MEG, Mu3e, Mu2e, Belle II,…
  - Two loops: $K \to \pi J$, $B \to K J$ @ NA62, Belle II, LHCb.
- Next step: add prompt/displaced/delayed vertices, $J \to SM$.

Always look out for lines!

Backup

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. $\Delta V = \frac{1}{2} m_J^2 J^2$.

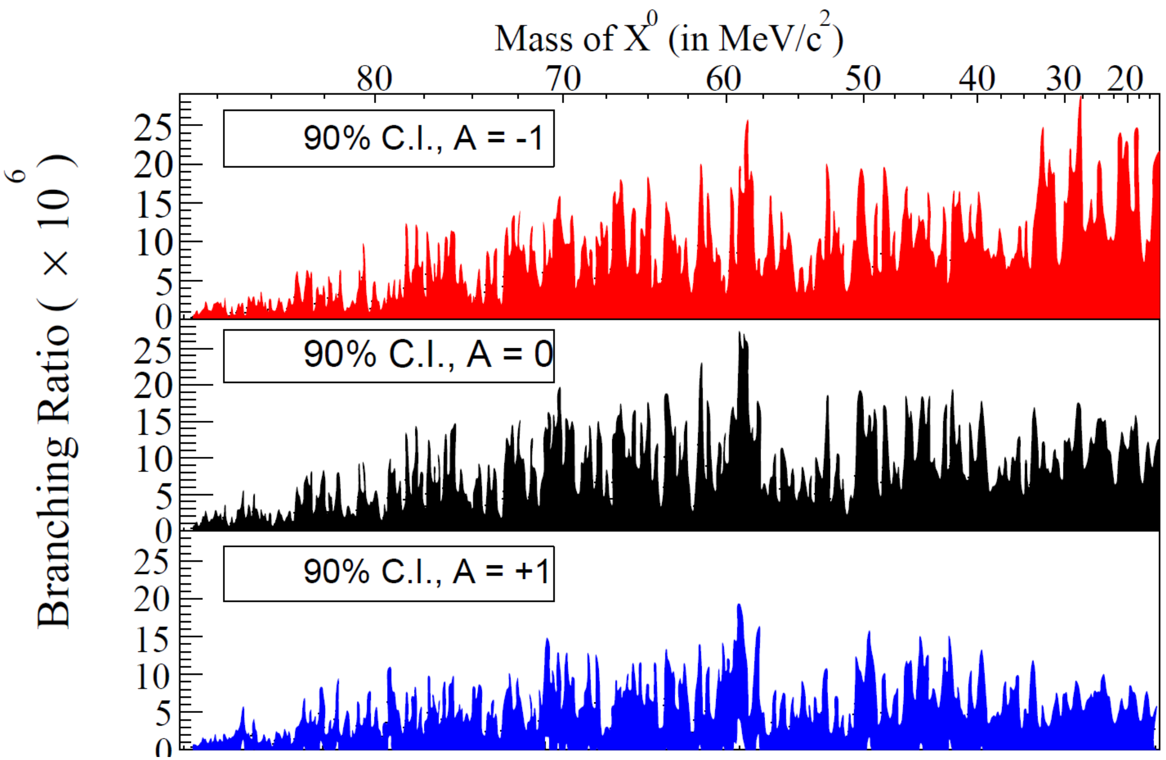
$\mu \to e\, J$ with $J \to$ invisible

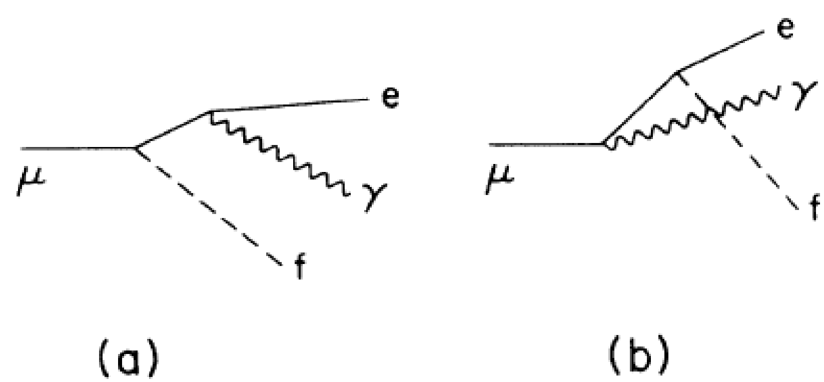
- TWIST, '15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [**JH**, Garcia-Cely, 1701.07209]

- Bremsstrahlung is competitive: $\mu \to e\, J\, \gamma$. [Goldman et al, '87]
- Approximate limit

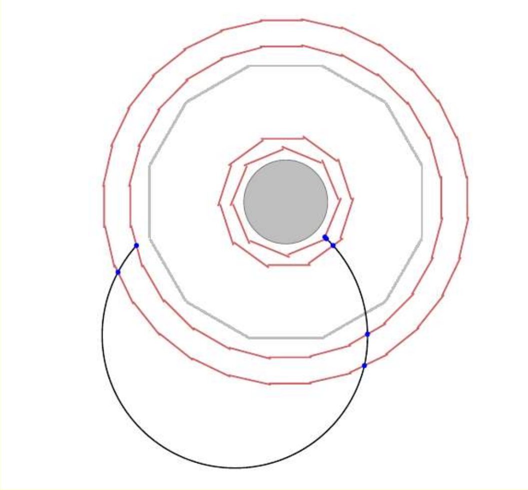
$$\frac{|(m_D m_D^\dagger)_{\mu e}|}{v\, f} \lesssim 10^{-5}.$$

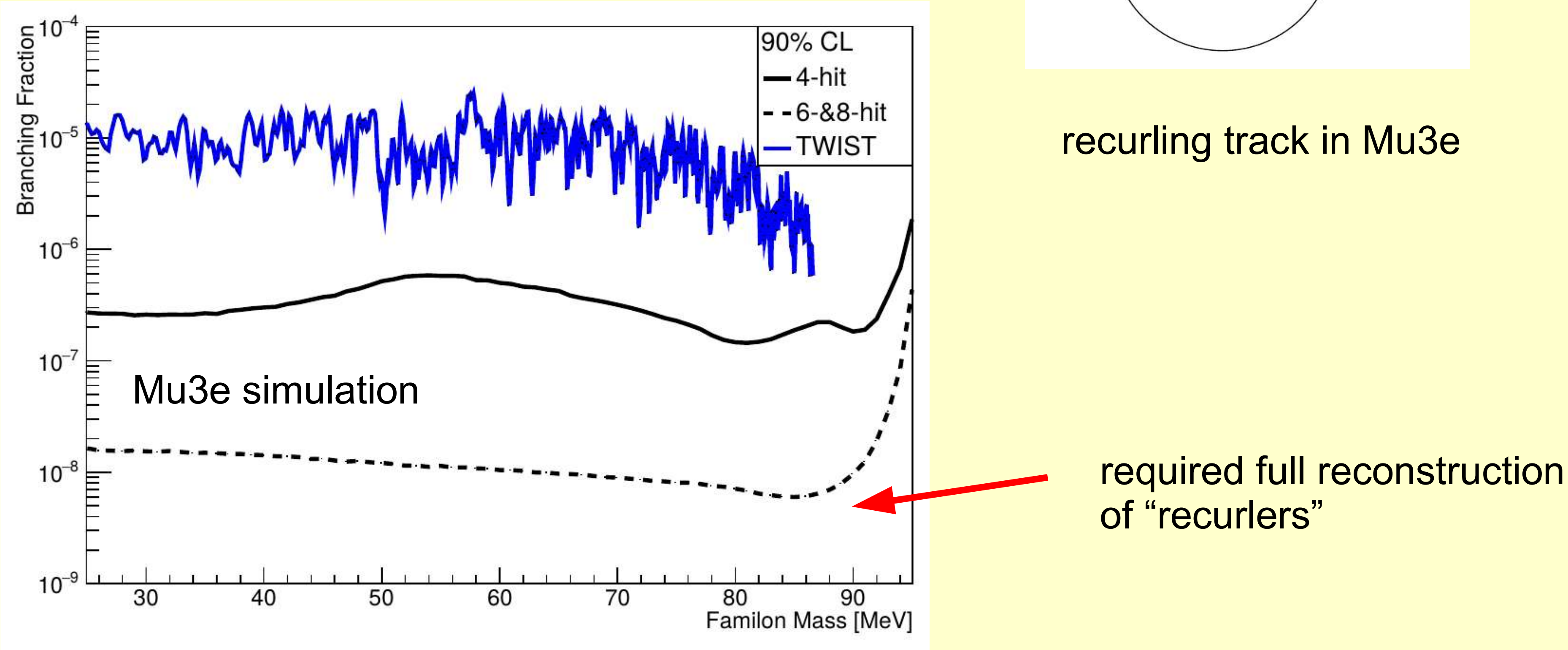




Searches for μ → e X with Mu3e

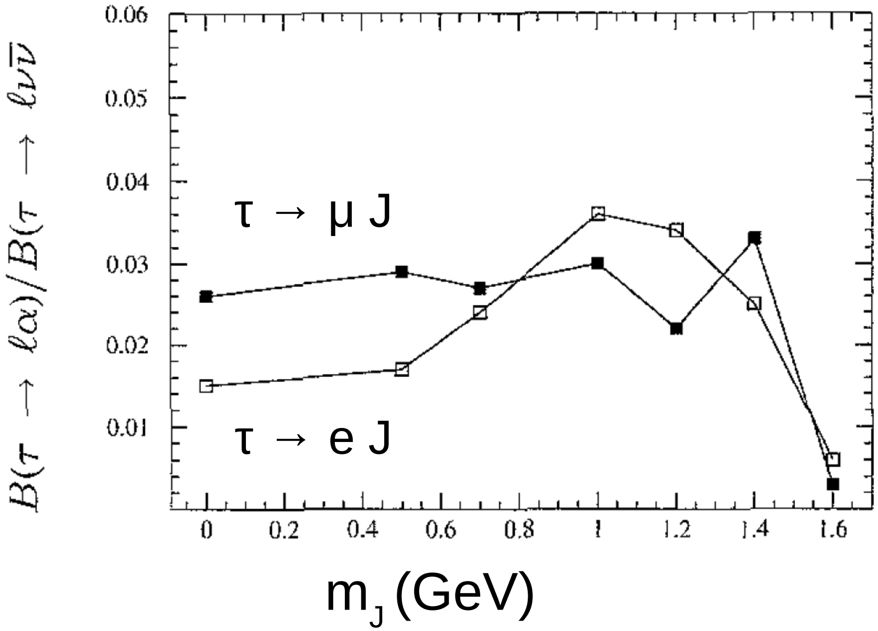
- Full reconstruction of all Michel decays is a big challenged for data acquisition
- B(μ → e X) ~ 10^{-8} at 90 % CL



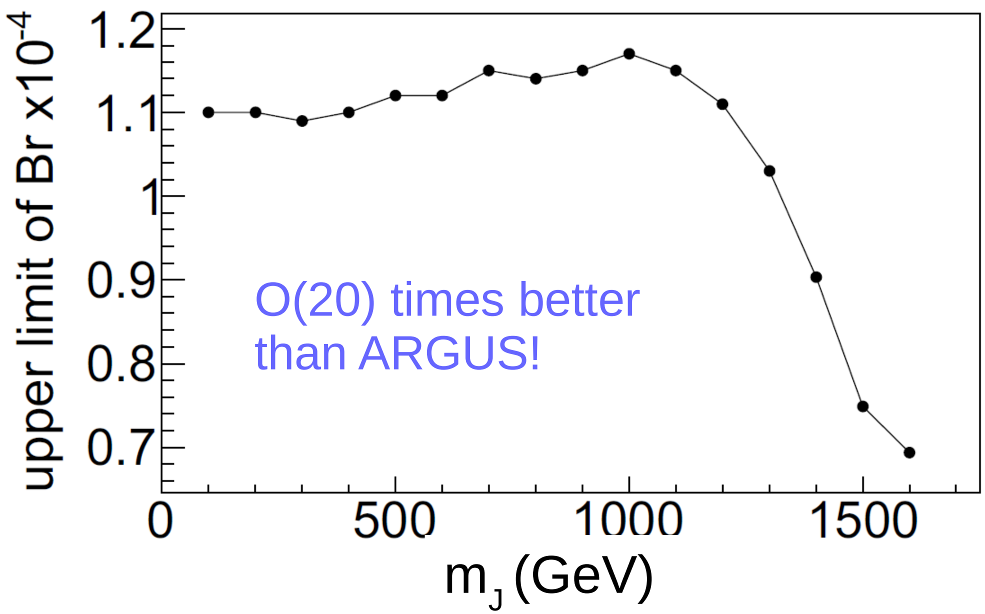


τ → ℓ J with J→ invisible

- ARGUS, '95; 5e5 taus.



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



- Also interesting for LFV Z'.

[**JH**, 1602.03810; Altmannshofer et al, 1607.06832]

- Improvement with Belle II.

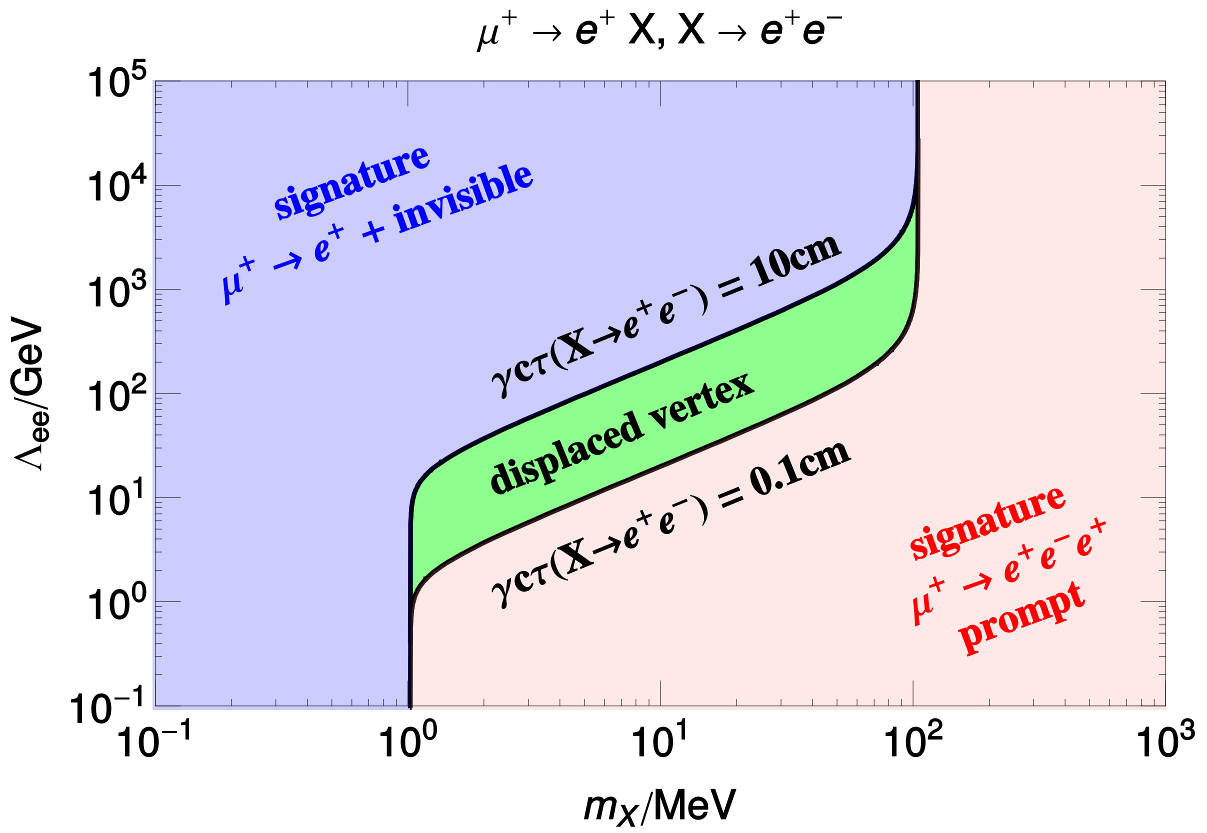
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{v\,f} \lesssim 6 \times 10^{-3},$$

$$\frac{|(m_D m_D^\dagger)_{\tau \mu}|}{v\,f} \lesssim 9 \times 10^{-3}.$$

$\mu \to e\, X$ with $X \to$ visible

- Take $X \bar{e} \gamma_5 e\; m_e/\Lambda_{ee}$.
- Decay length determines signature.
- Displaced vertex gives new observable.
  [**JH**, Rodejohann, PLB '18]
- Muon at rest:

$$\gamma c\tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm}\left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2\left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

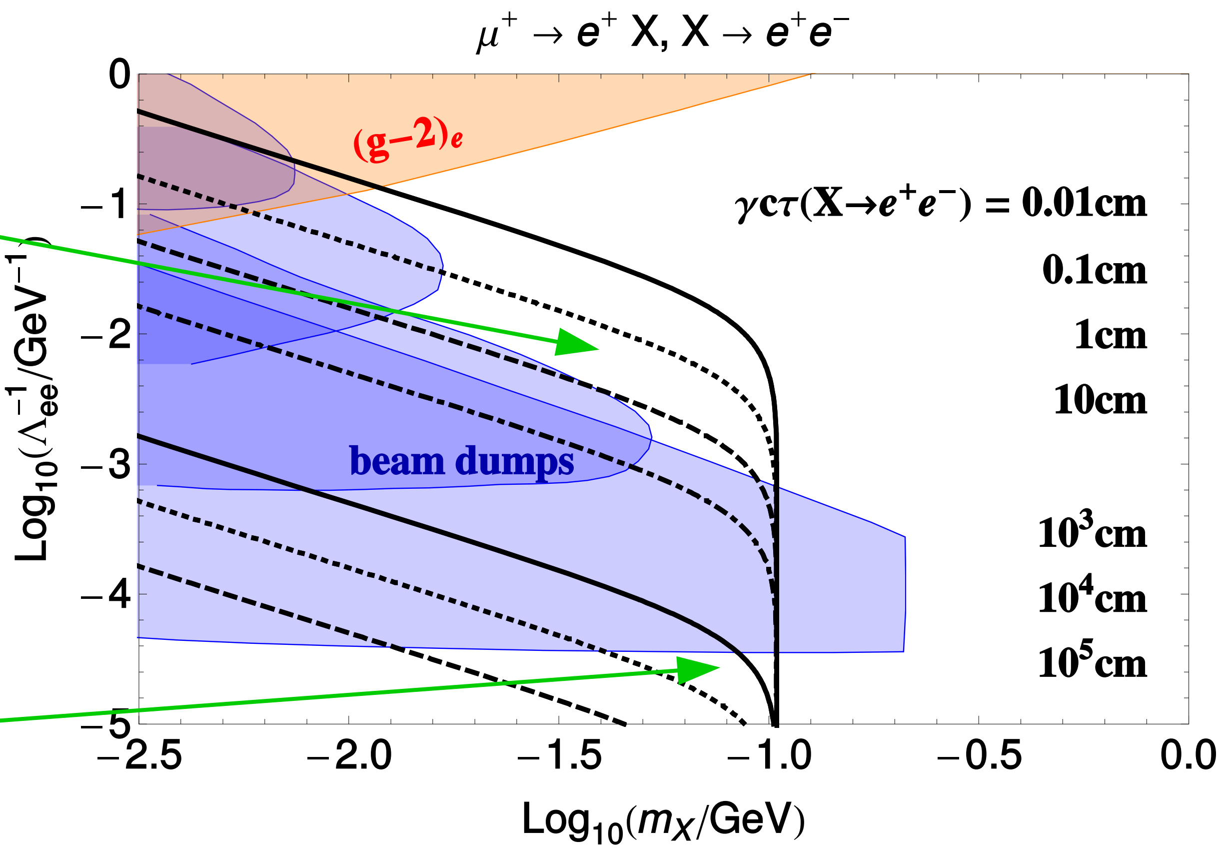


Sub-GeV X with ee coupling allowed?

$\mu \to e X$ with $X \to \overline{e}e$

[**JH**, Rodejohann, PLB '18]

- Decay length typically below cm. ⇒ looks prompt.
- Below beam dump: Λ_{ee} > 30 TeV; mostly invisible, but some DV!



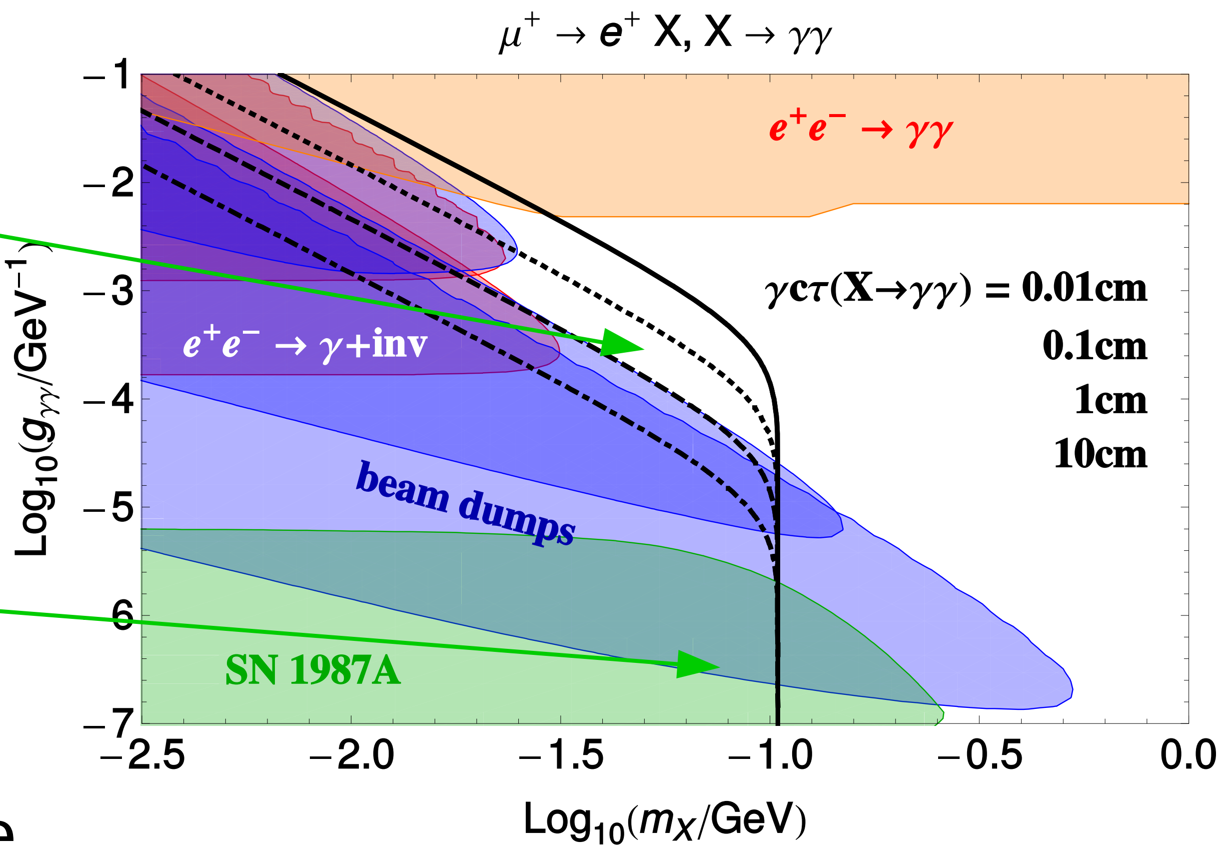
$$\text{BR}(\mu \to eX)\text{BR}(X \to ee)(1 - P(l_{\text{dec}}))$$
$$\simeq \text{BR}(\mu \to eX)\frac{l_{\text{dec}}}{\gamma c\tau}\,.$$

Possible in Mu3e!

$\mu \to e\, X$ with $X \to \gamma\gamma$

[**JH**, Rodejohann, PLB '18]

- Decay length always below cm. ⇒ looks prompt.
- Below beam dump: supernova constraints!
- Prompt channel still interesting, maybe MEG(II) or Mu3e extension?



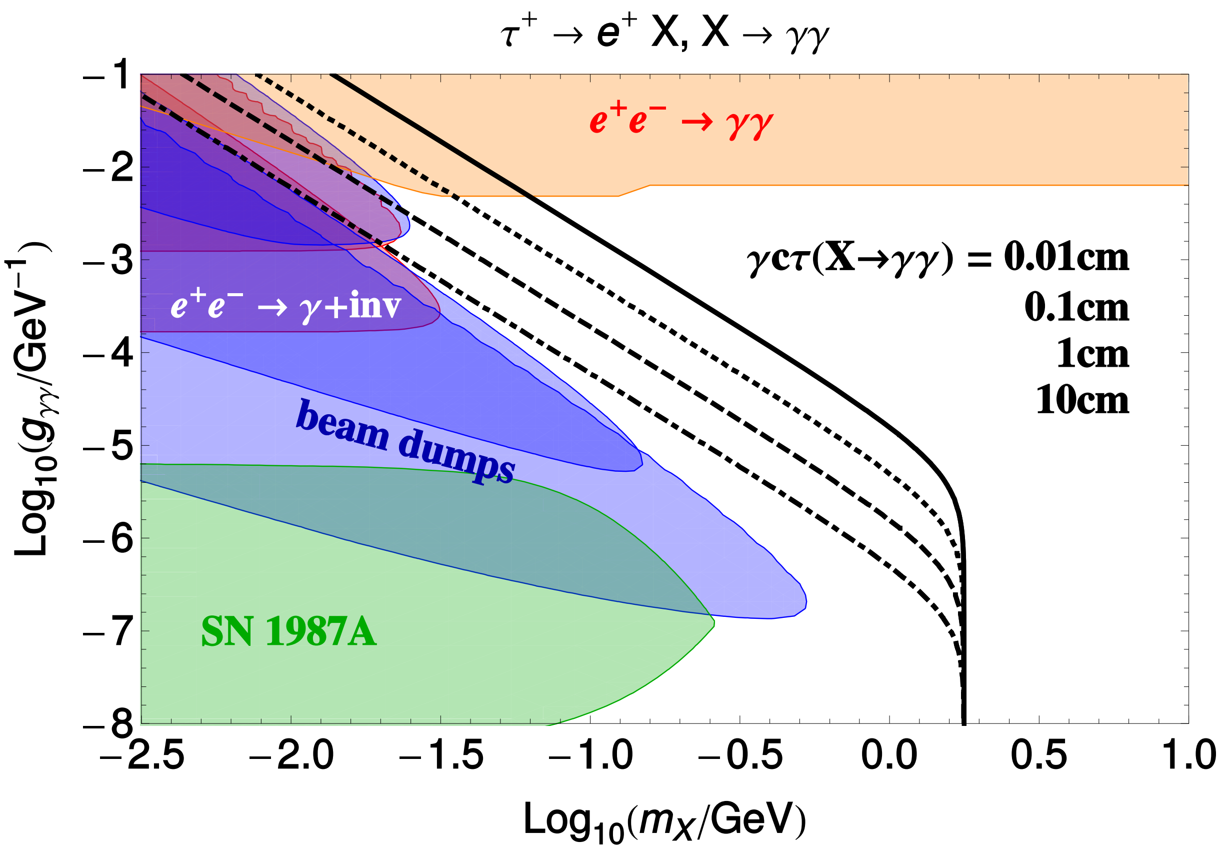
[Limits: Dolan et al, JHEP '17]

Muons difficult, taus easier.

τ→e X with X→ visible

[**JH**, Rodejohann, PLB '18]

- Tau at rest, higher X boost.
- Arbitrary decay lengths possible.
- Similar for X → ee, μμ, μe.
- Worthwhile in LHCb and Belle (II).



[Limits: Dolan et al, JHEP '17]

New signatures from light physics!

Quark Flavor Phenomenology of the QCD Axion

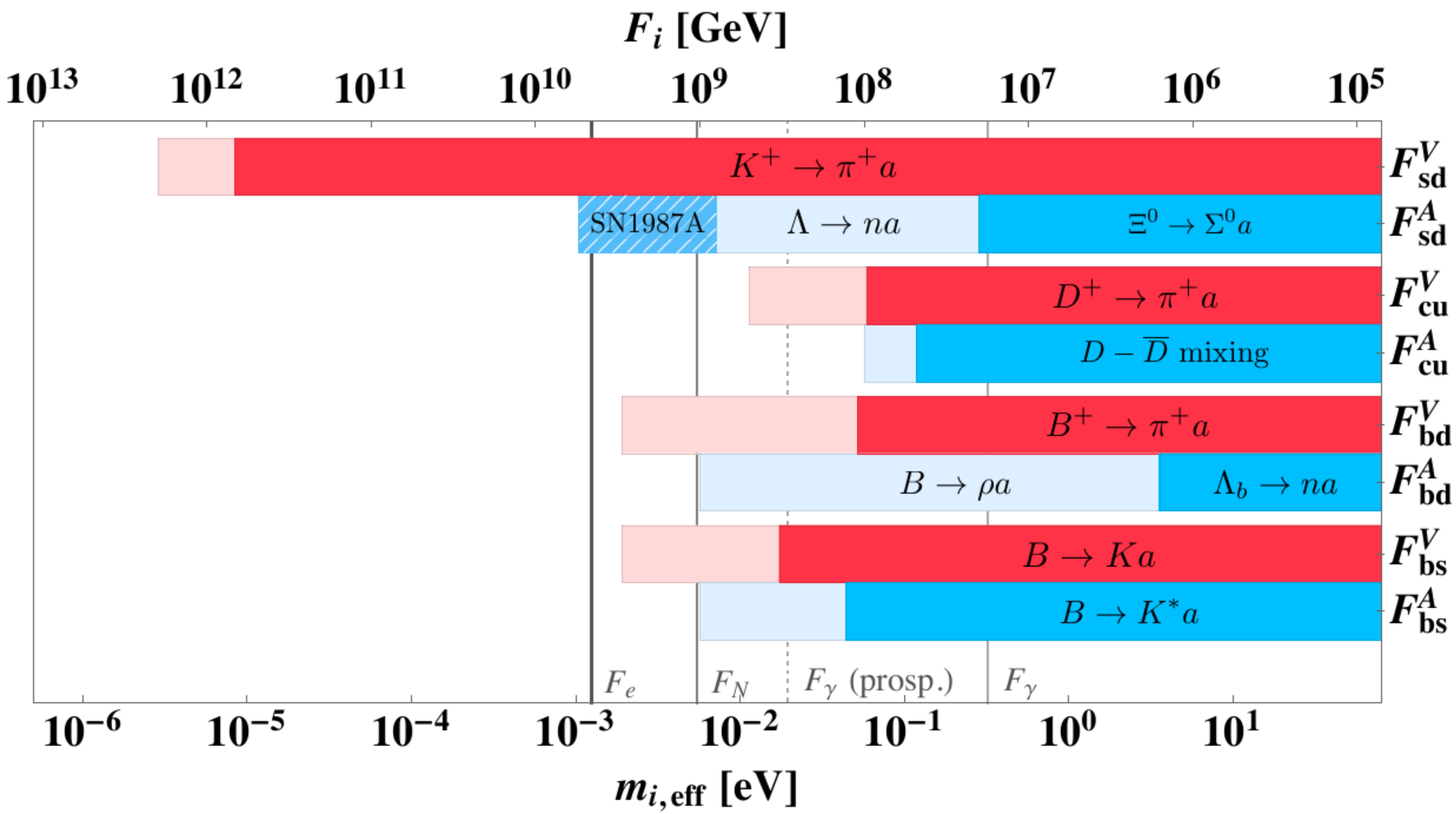


FIG. 4. Summary of the most important bounds for the different flavor sectors and for vectorial (red) and axial-vectorial (blue) couplings. On the lower axis we indicate the corresponding values for the effective axion mass defined by $m_{i,\mathrm{eff}} \equiv 4.69\,\mathrm{eV} \times 10^6\,\mathrm{GeV}/F_i$. Also shown as vertical gray lines are the bounds on axion couplings to electrons F_e (95%CL), nucleons F_N, and photons F_γ (95%CL), see Section V for details.

[Camalich, Pospelov, Vuong, Ziegler, Zupan, 2002.04623]