Beyond the 3x3 neutrino paradigm with majorons

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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, 3x3 paradigm!

seesaw mechanism

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seesaw mechanism

- Still 9 unknown parameters in type-I seesaw.
- Most common: couplings of N_R.

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PMNS mixing matrix, 3x3 paradigm!

seesaw mechanism

- Still 9 unknown parameters in type-I seesaw.
- Here: hermitian $m_D m_D^\dagger$.

  [Davidson, Ibarra, hep-ph/0104076]

Beyond 3x3 paradigm!

- One-to-one: $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.
- (More general: $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D M_R^n m_D^\dagger\}$).

Majoronic seesaw

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

B−L breaking scale

Heavy scalar (inflaton?)

Majoron

(Even more beyond 3x3 paradigm!)

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

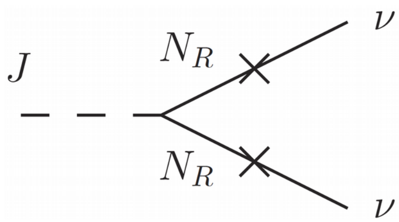
- Break $U(1)_{B\text{-}L}$ spontaneously:

$$\mathcal{L} = -\underbrace{\overline{L} y H}_{m_D = y\langle H\rangle} N_R - \frac{1}{2}\overline{N}_R^c \underbrace{\kappa \sigma}_{M_R = \frac{\kappa f}{\sqrt{2}}} N_R + h.c.$$

- Similar for *inverse* seesaw, *extended* seesaw,...
- Assume J is a *pseudo*-Goldstone: $m_J \neq 0$.

Majoron couplings

- Tree-level coupling only to neutrinos:



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

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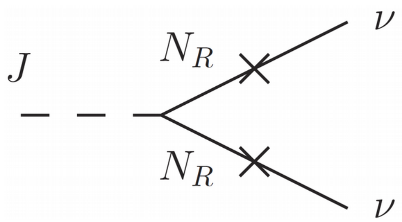

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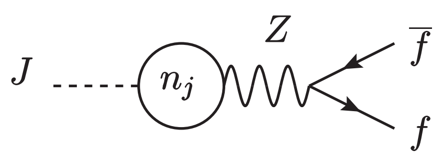
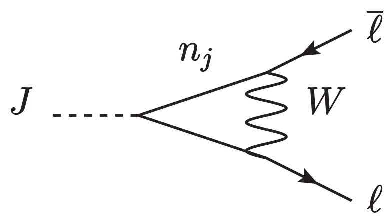
- One loop:



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

Off-diagonal!



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

[Heeck, Camilo Garcia-Cely, 1701.07209; see also Pilaftsis '94]

Majoron couplings

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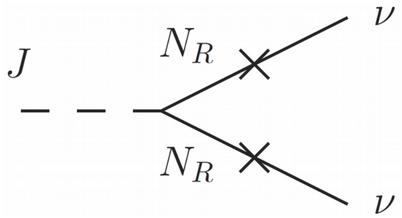

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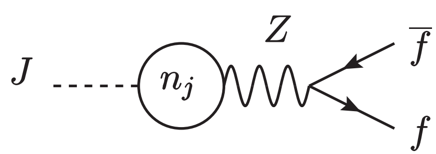

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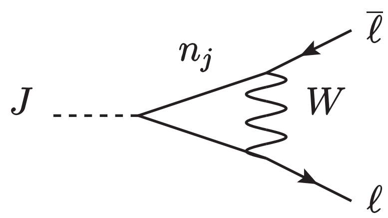

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- Two loop: $\Gamma(J\to\gamma\gamma) \simeq \frac{\alpha^2\,\mathrm{tr}\left(m_D m_D^\dagger\right)^2}{4096\pi^7}\frac{m_J^3}{v^4 f^2}\left|\sum_f N_c^f T_3^f Q_f^2\, g\left(\frac{m_J^2}{4m_f^2}\right)\right|^2$

[Heeck, Camilo Garcia-Cely, 1701.07209; see also Pilaftsis ‘94]

Reconstruct seesaw?

- $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$. [Davidson, Ibarra, hep-ph/0104076]
- Jνν 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, Jμμ, and Jγγ or Jqq.
- Light J: $|K_{\alpha\beta}| < 10^{-5}$ from stellar energy loss.

[Raffelt, e.g. 1205.1776]

$f \sim 10^7$ GeV

Take from axion/ALP searches.

Lepton flavor violation

- Off-diagonal $|K_{\alpha\beta}|$ from LFV: $\ell_\alpha \to \ell_\beta J$.
- (Phase of off-diagonal $K_{\alpha\beta}$?)
- $J\bar{\ell}\ell'$ coupling can be *large* and of arbitrary structure.
- Similar couplings arise for familons or flavor Z'.

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

- Boson not necessarily massless: *pseudo*-Goldstone.
- Experimental signature depends on decay channel:

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

[Heeck, Rodejohann, 1710.02062]

$\ell \to \ell'$ J with J$\to$ invisible

- 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]

$$\frac{\Gamma(\ell\to\ell' J)}{\Gamma(\ell\to\ell'\nu_\ell\overline{\nu}_{\ell'})} \simeq \frac{3}{16\pi^2}\frac{1}{m_\ell^2 f^2}\left|(m_D m_D^\dagger)_{\ell\ell'}\right|^2.$$

- If M_R= diag(M): $\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell' J)} \simeq 2\pi\alpha\frac{m_\ell^2}{M^2}\frac{f^2}{M^2}\begin{cases} \gg 1 \text{ for } M \ll f\,, \\ \ll 1 \text{ for } , M \sim f \gg m_\ell\,. \end{cases}$

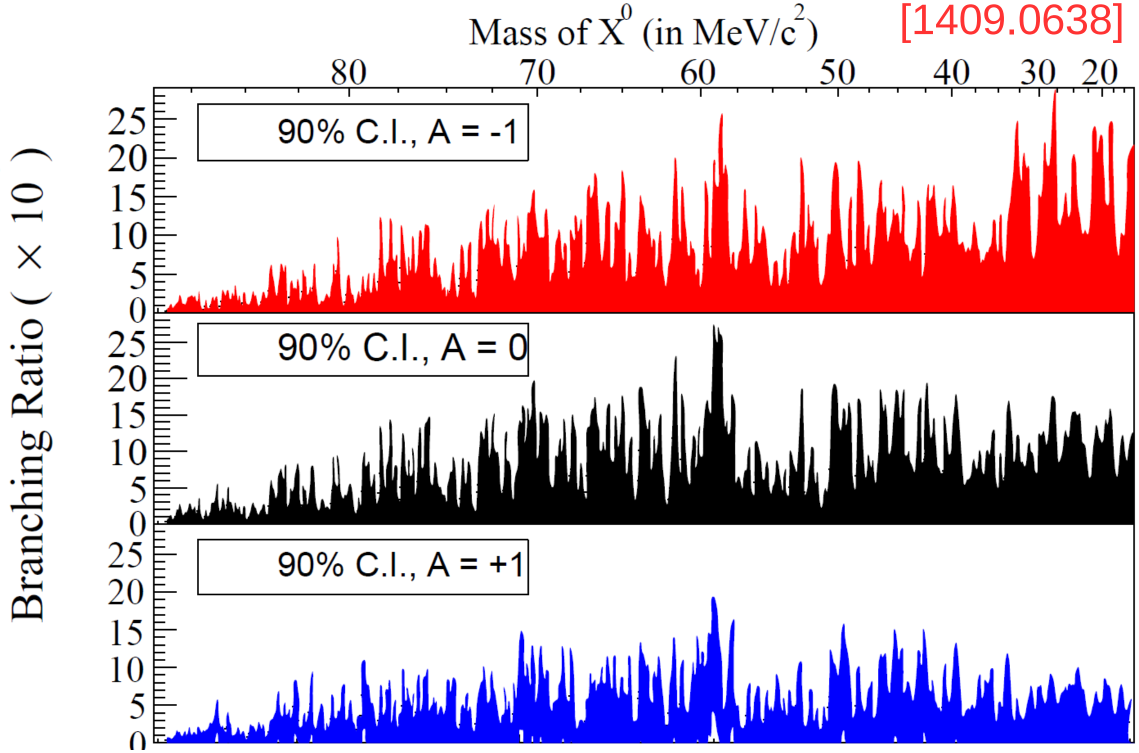
μ→e J with J→ invisible

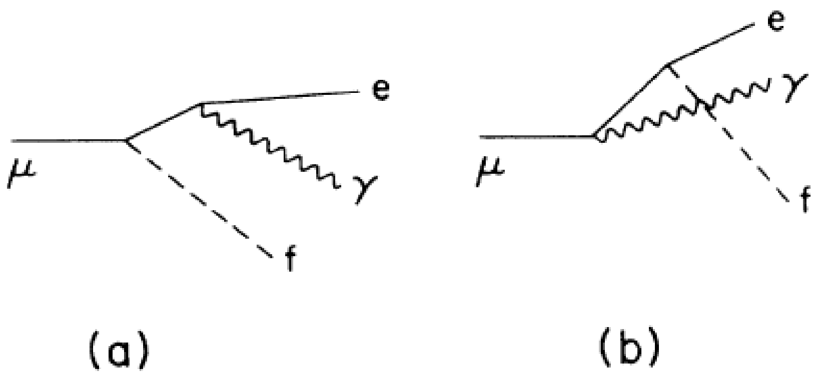
- TWIST, '15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [Heeck, Garcia-Cely, 1701.07209]
- Bremsstrahlung is competitive: μ→e J γ.
  [Goldman et al, '87]
- Approximate limit

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

[1409.0638]





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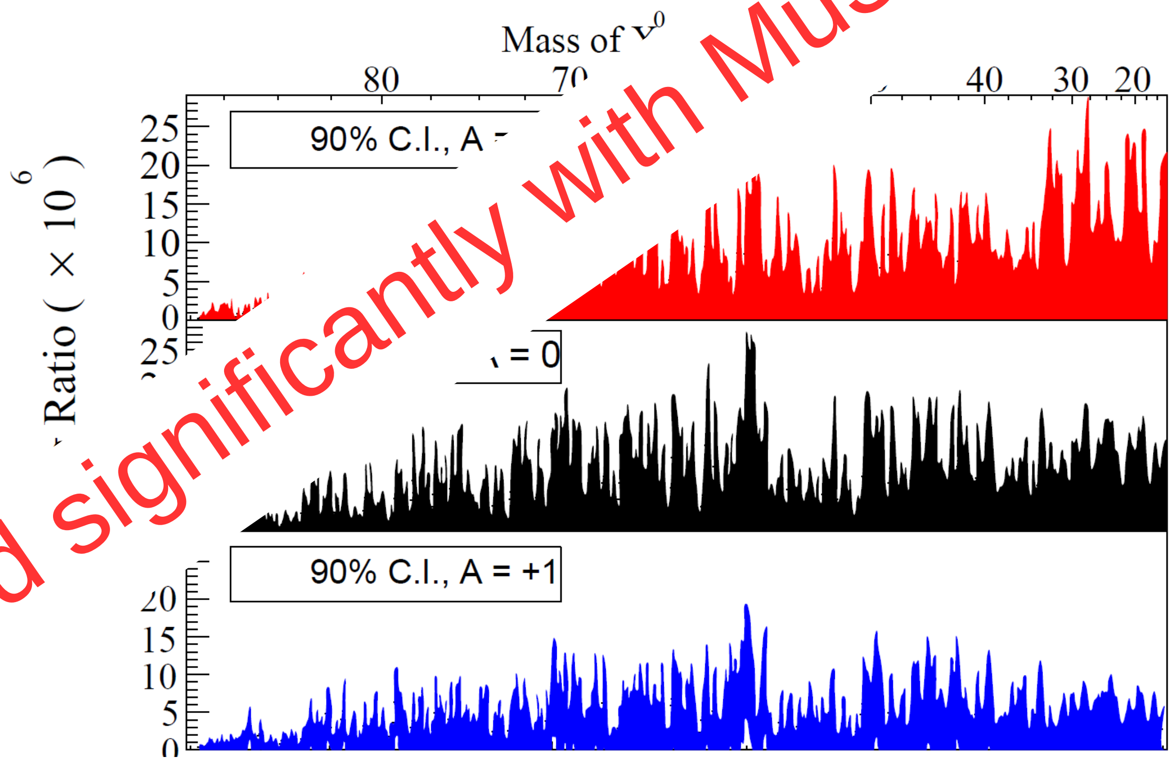
- Bremsstrahlun… competitive…

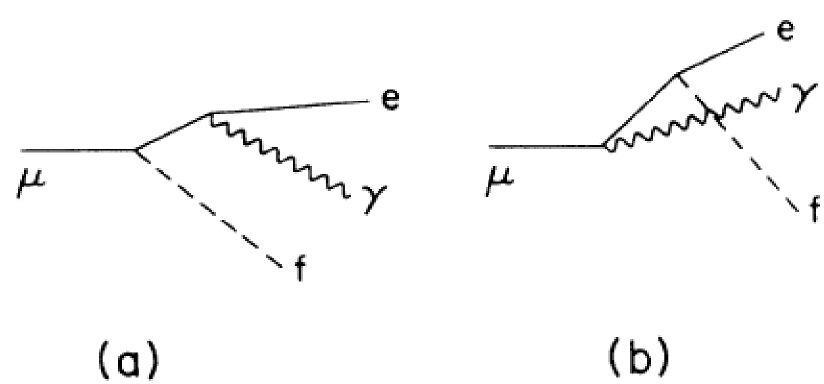
  [Goldman et …

- Ap… …imit

$$\ldots \frac{\ldots m_D^\dagger)_{\mu e}|}{vf} \lesssim 10^{-5}.$$

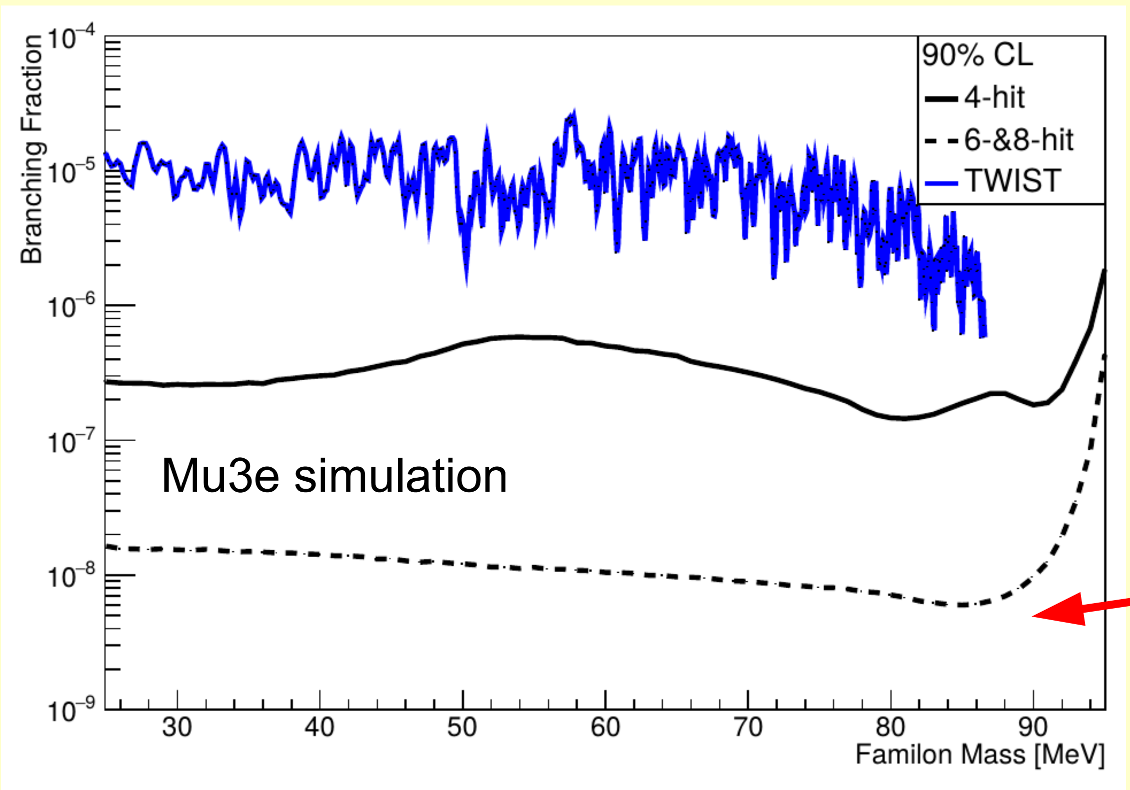
Can be improved significantly with Mu3e!

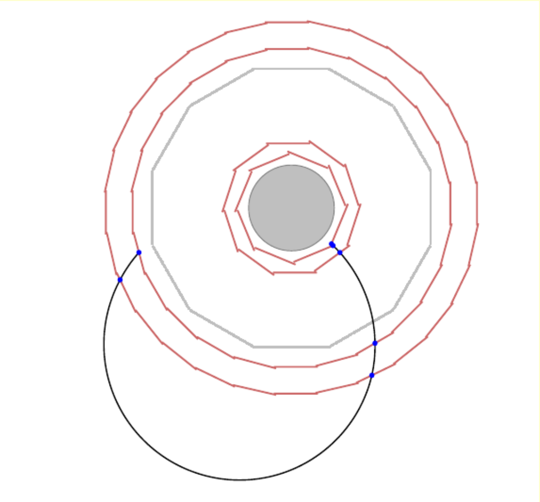




Searches for μ → e X with Mu3e

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



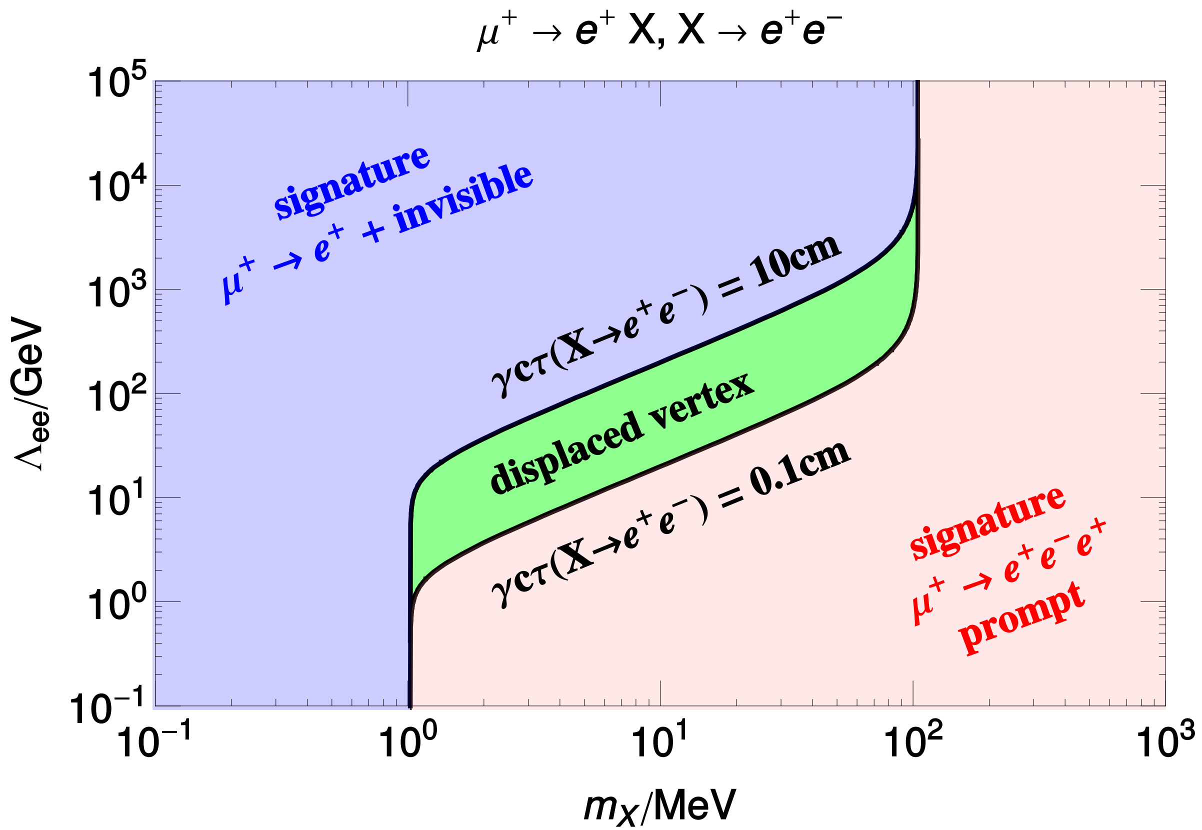


recurling track in Mu3e

required full reconstruction of “recurlers”

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

- Take $\overline{X e}\gamma_5 e\, m_e/\Lambda_{ee}$.
- Decay length determines signature.
- Displaced vertex gives new observable. [Heeck, Rodejohann, 1710.02062]
- Muon at rest:



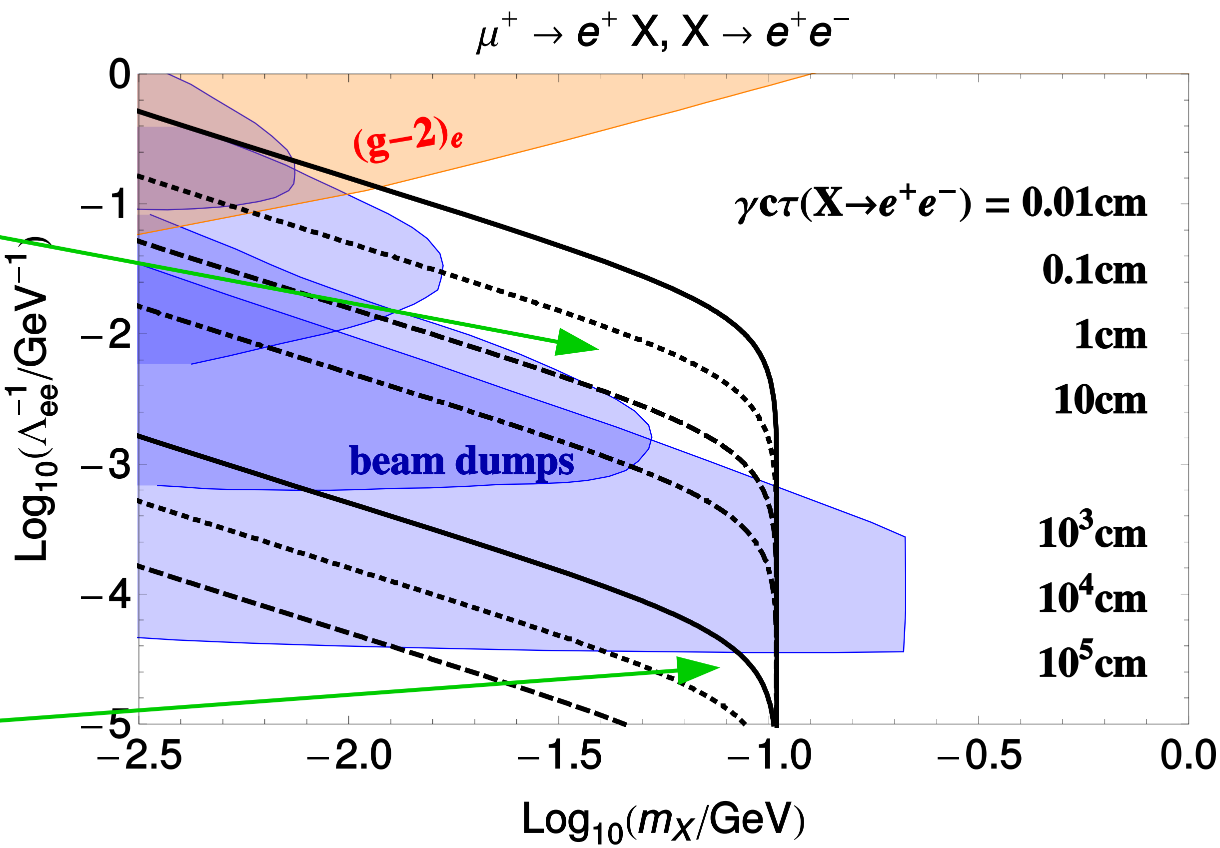
$$\gamma c\tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm}\left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

$\mu \rightarrow e\, X$ with $X \rightarrow \bar{e}e$

[Heeck, Rodejohann, 1710.02062]

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



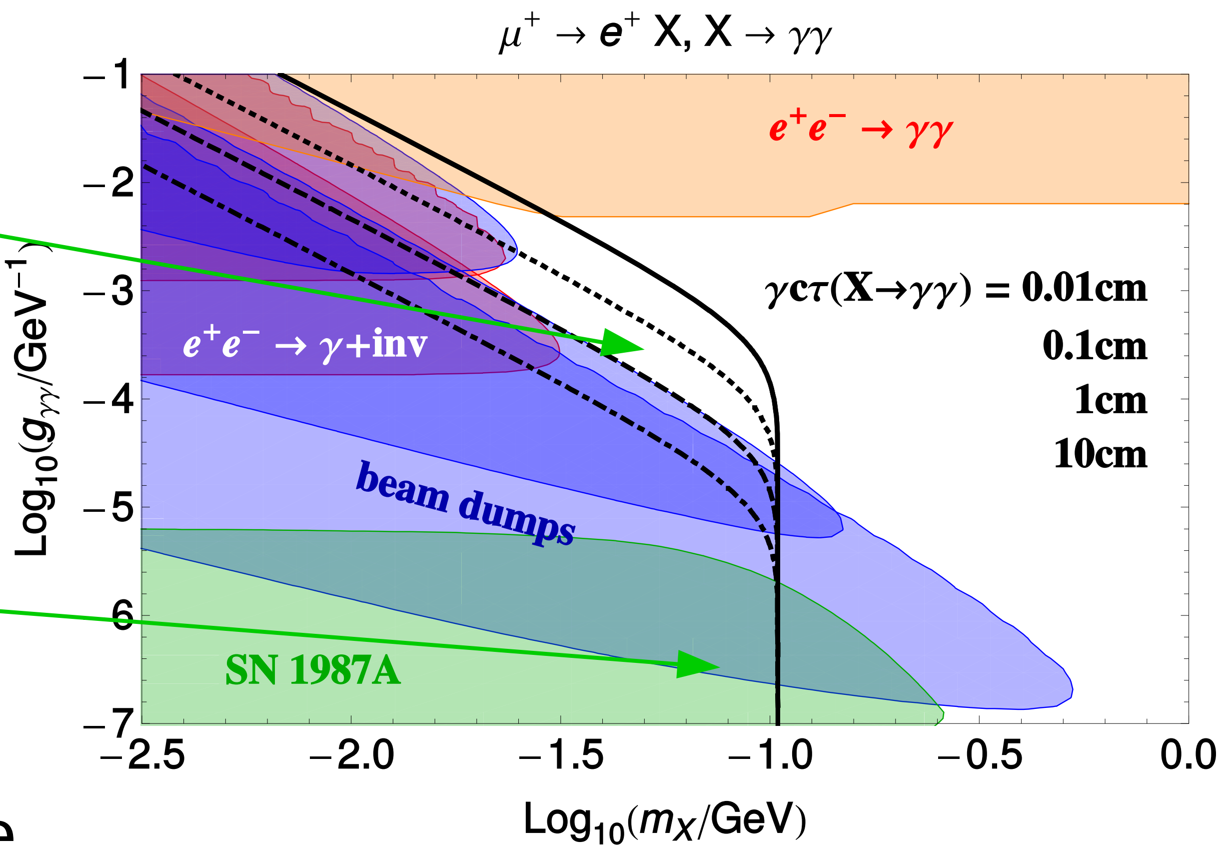
$$\mathrm{BR}(\mu \to eX)\mathrm{BR}(X \to ee)(1 - P(l_{\mathrm{dec}}))$$
$$\simeq \mathrm{BR}(\mu \to eX)\frac{l_{\mathrm{dec}}}{\gamma c \tau}\,.$$

Possible in Mu3e!

[Heeck, Rodejohann, 1710.02062]

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

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

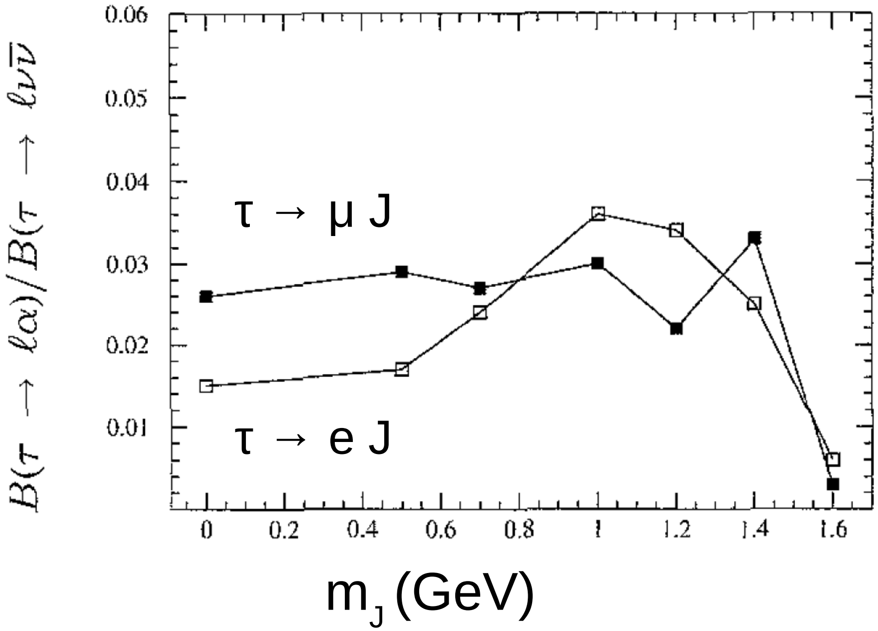


[Recent limits: Dolan et al, 1709.00009]

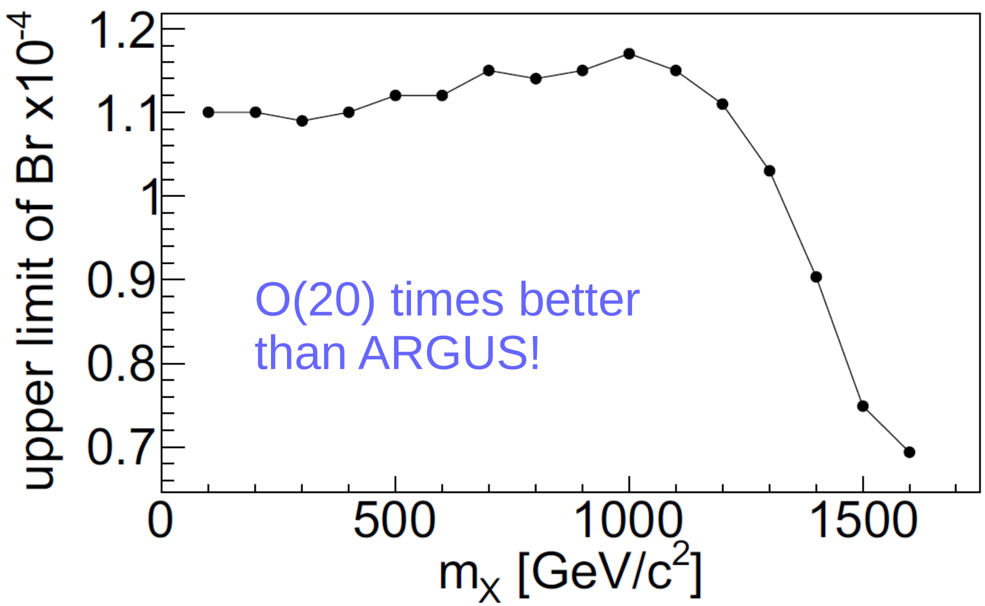
Muons difficult, taus easier.

$\tau \to \ell J$ with $J \to$ invisible

- ARGUS, ‘95; 5e5 taus.



- Belle, ‘16 prelim.; 1e9 taus.



- Also interesting for LFV Z’.

[Foot, He, Lew, Volkas, ‘94; Heeck, 1602.03810; Altmannshofer et al, 1607.06832]

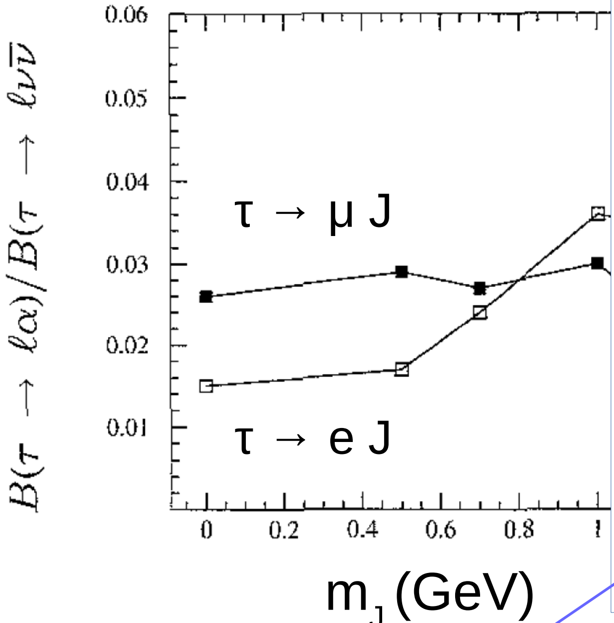
- Improvement with Belle-II.

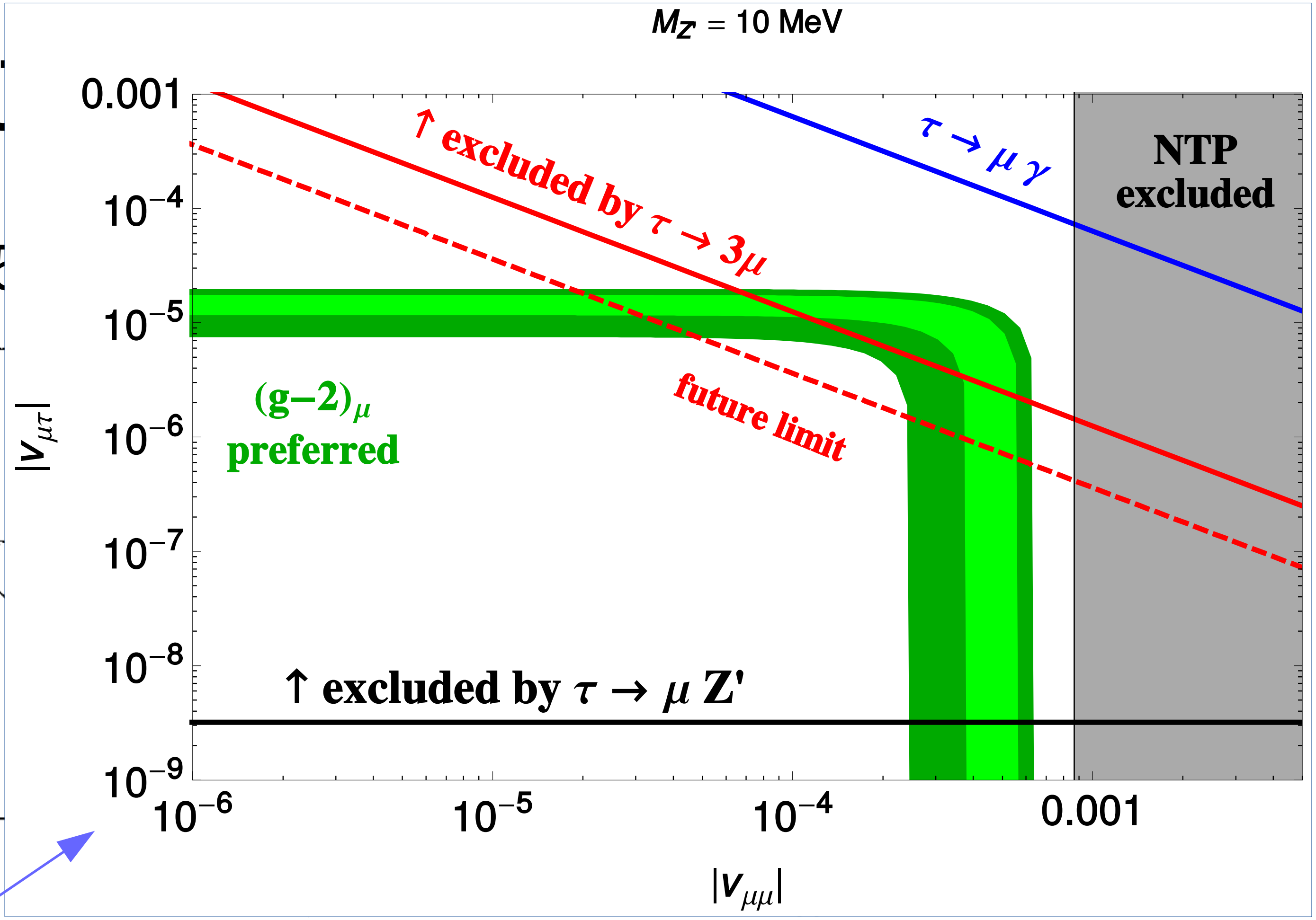
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

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

τ → ℓ J with J

- ARGUS, '95; 5e5





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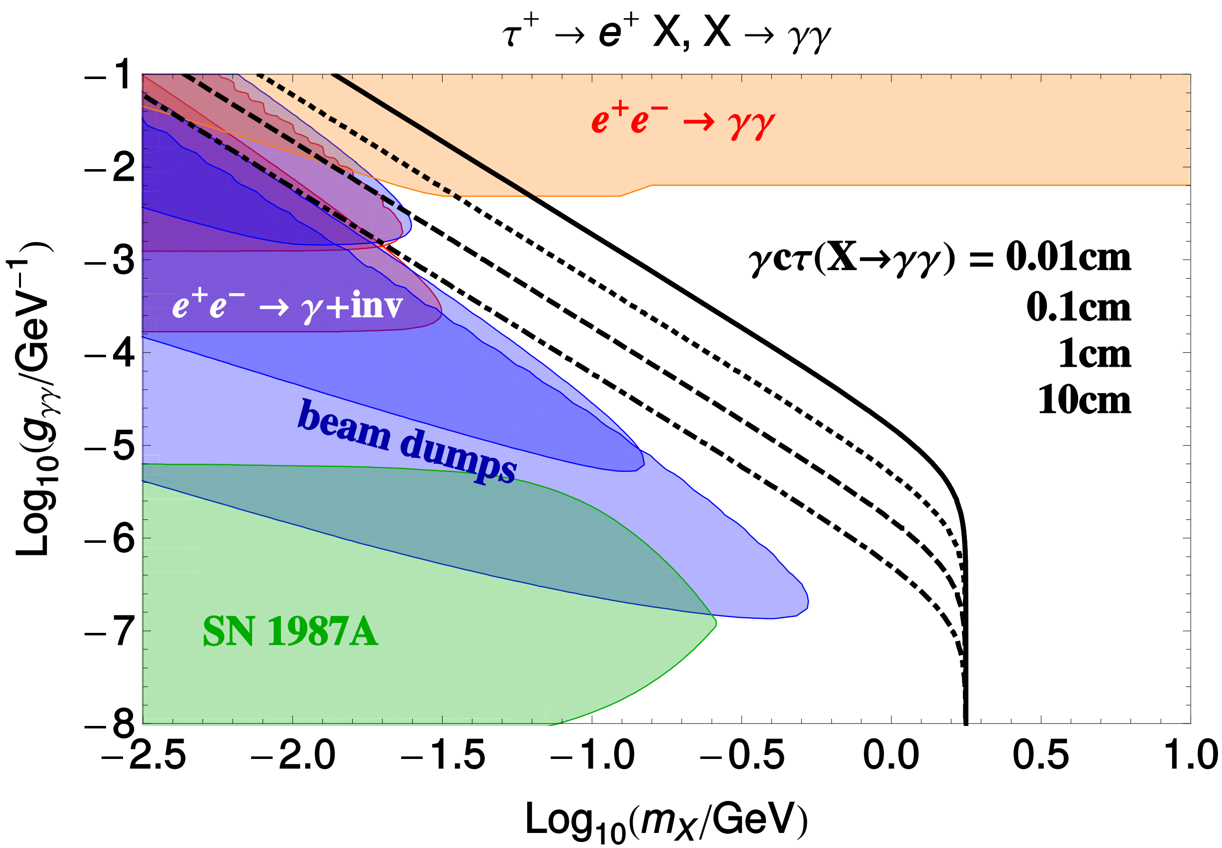
[Heeck, Rodejohann, 1710.02062]

τ → e X with X → visible

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



[Recent limits: Dolan et al, 1709.00009]

Muons difficult, taus easier...

Reconstruct seesaw

- $\{m_D, M_R\} \leftrightarrow \{M_\nu = -m_D M_R^{-1} m_D^T, m_D m_D^\dagger\}$. [Davidson, Ibarra, '01]
- Jνν coupling to measure ~~U(1)~~$_L$ scale f.
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Difficult to probe $f > 10^7$ GeV. What happens there?

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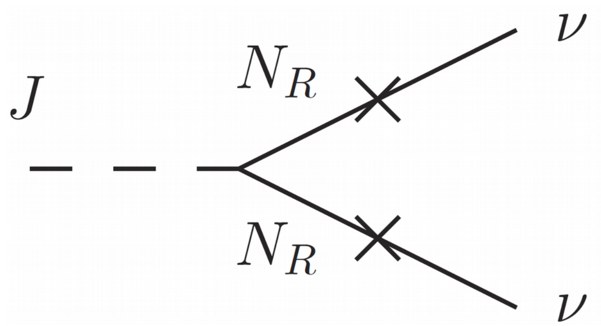
Majoron dark matter!

Tree-level couplings



- $\mathsf{L} = \mathsf{i}J \sum_k \left(\frac{m_k}{2f}\right) \overline{\nu}_k \gamma_5 \nu_k + \ldots$

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

- Long lifetime → majoron dark matter!

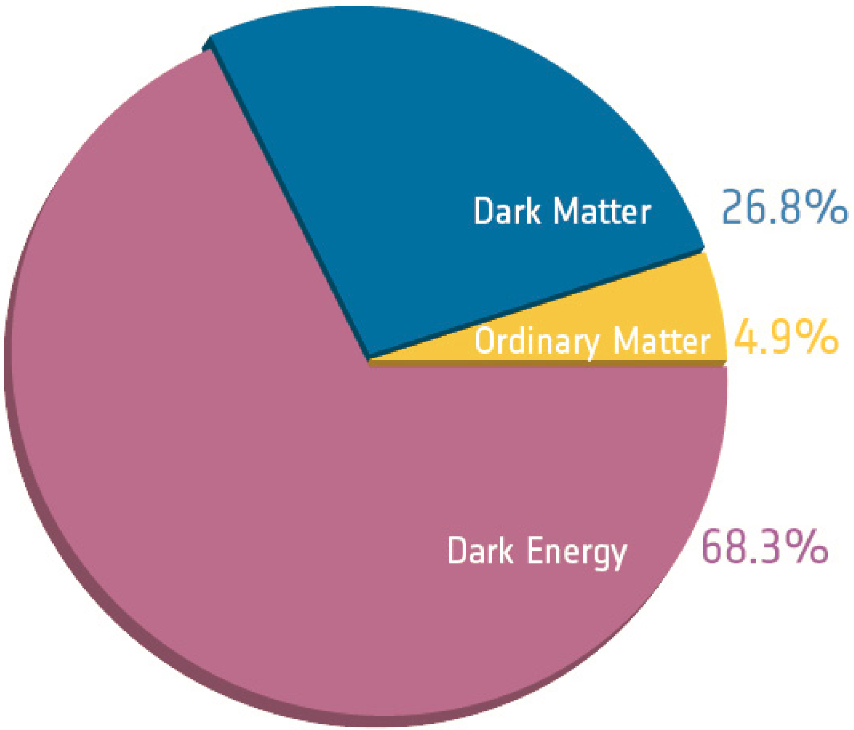
[Berezinsky, Valle ‘93; Lattanzi, Valle ‘07; Bazzocchi et al, ‘08; Queiroz, Sinha, ‘14]

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

- Signatures for MeV < m_J: J → νν, γγ, $\bar{f}f$.
- For keV < m_J < MeV: J → γγ. Maybe *warm* DM.

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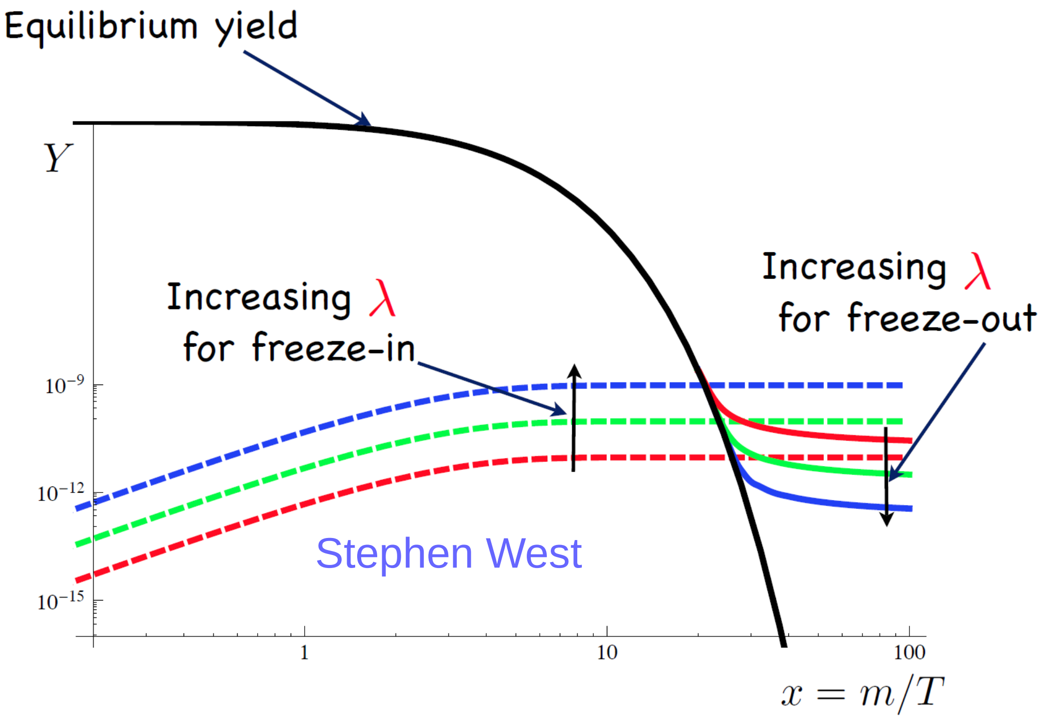
  - $m_J \sim m_h/2$,
  - $m_J > 400$ GeV.
- Freeze in:

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

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

[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

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

- General limit from DM → 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!

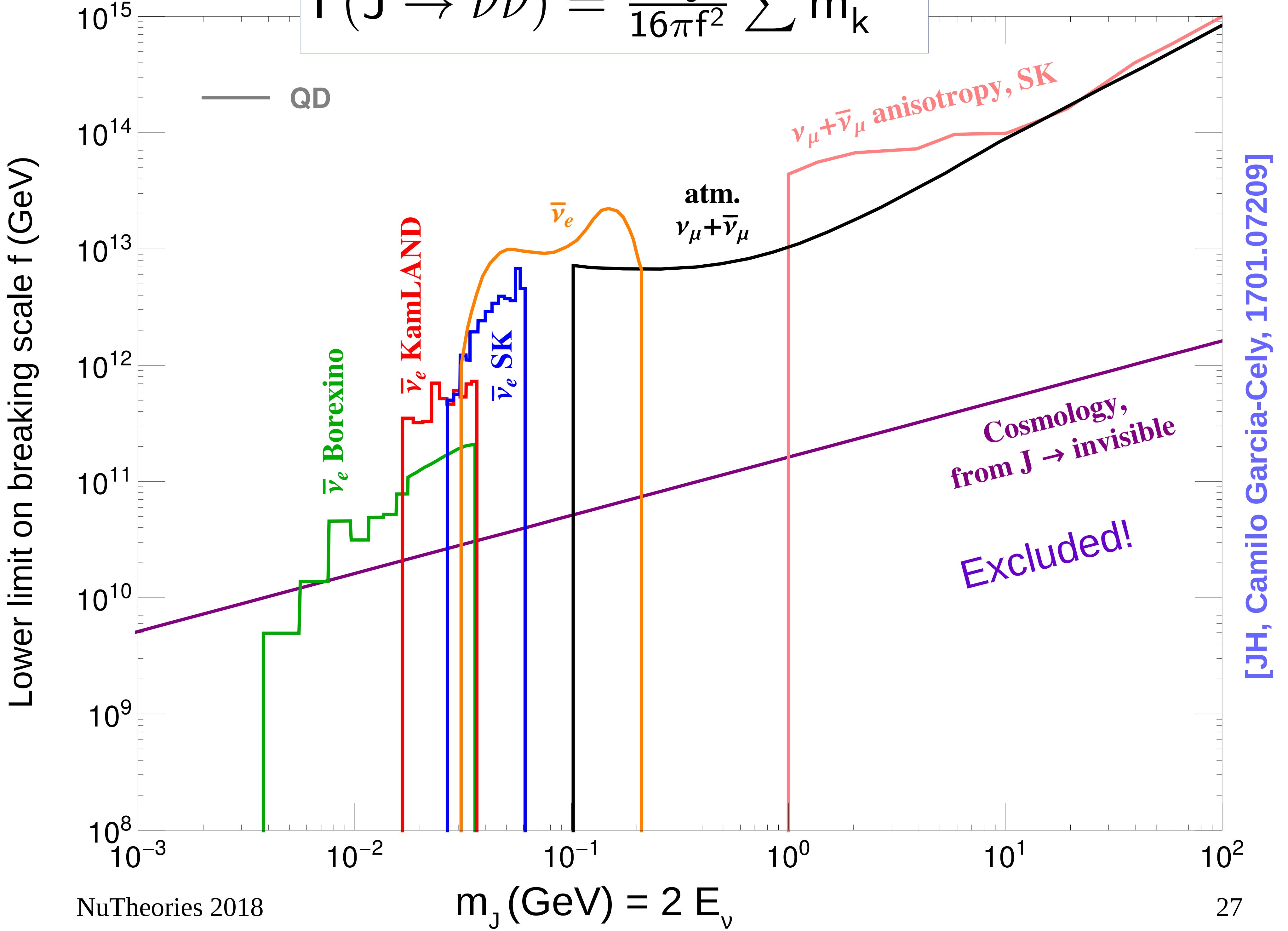
    [Dudas, Mambrini, Olive, '15]

  - 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!**

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



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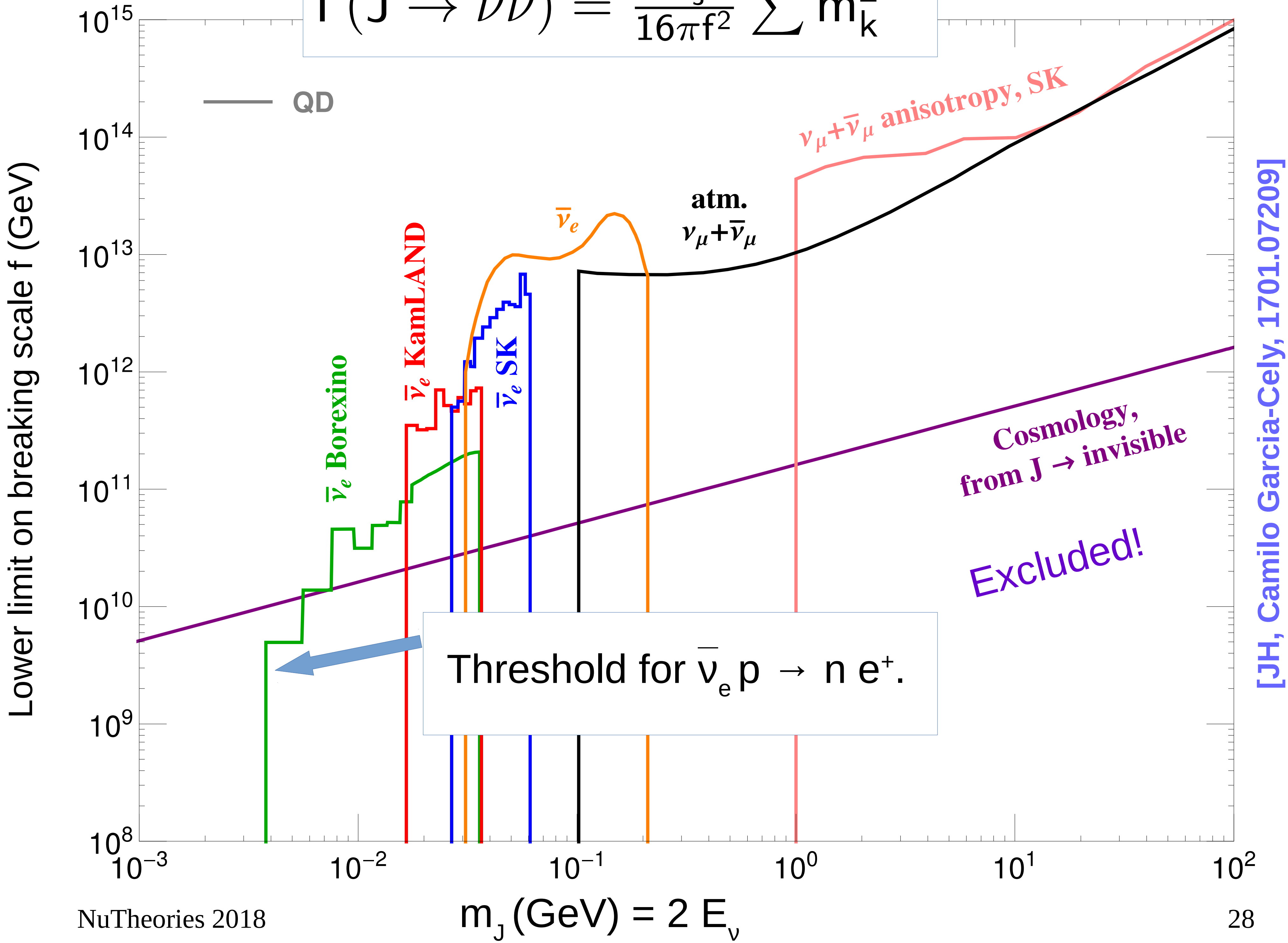
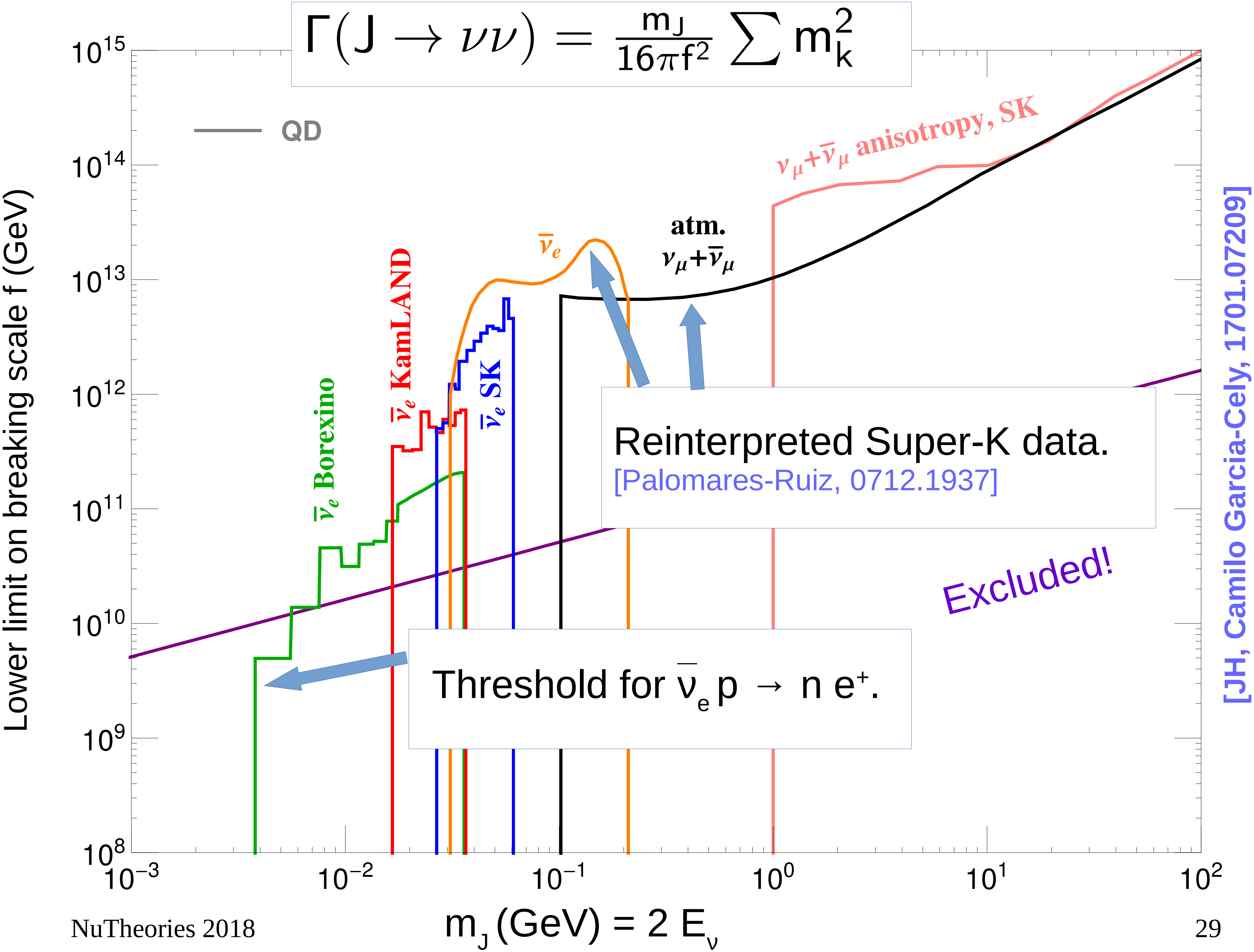
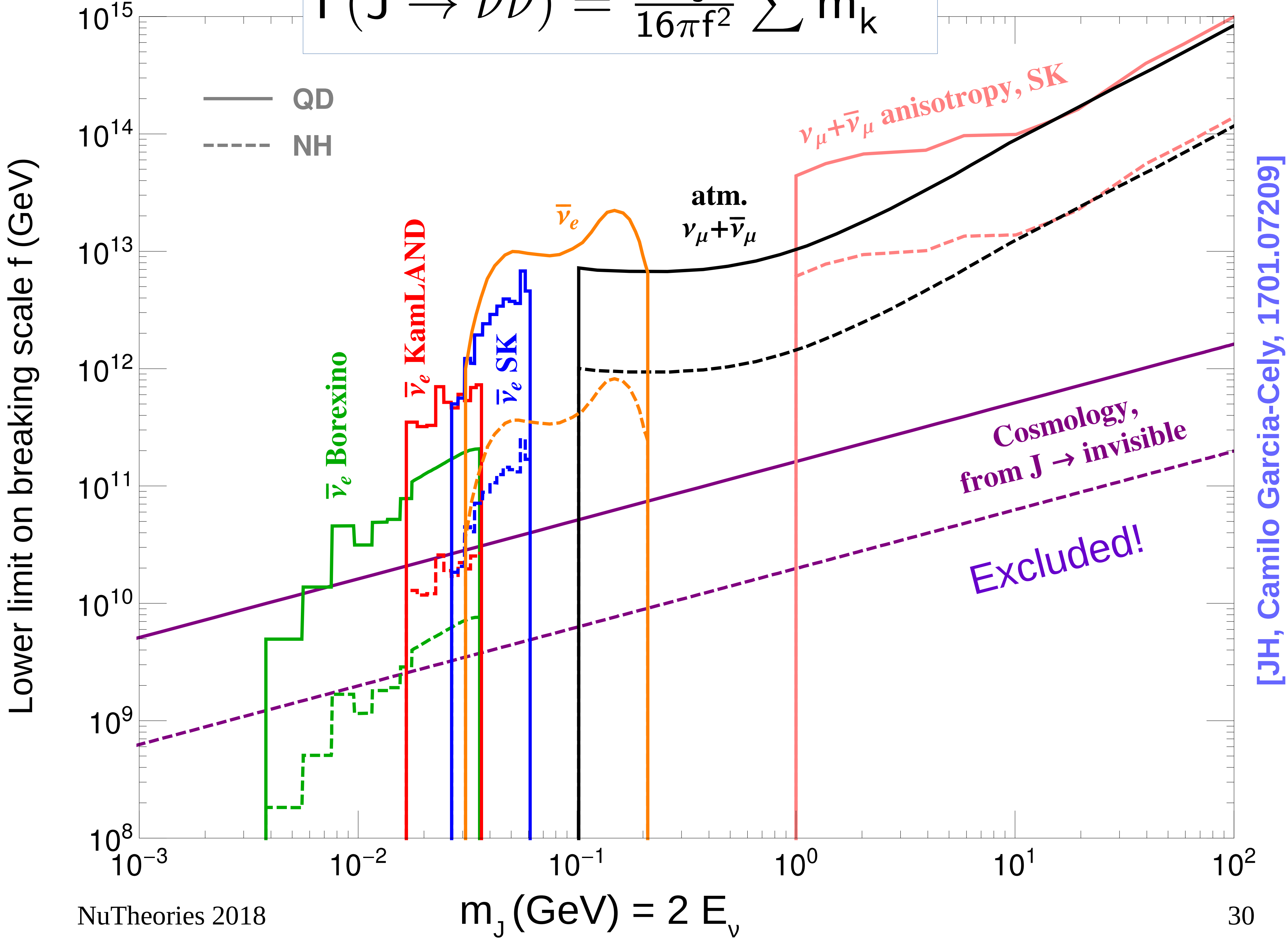




$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_k^2$
QD
$\nu_\mu+\bar{\nu}_\mu$ anisotropy, SK
atm. $\nu_\mu+\bar{\nu}_\mu$
$\bar{\nu}_e$
$\bar{\nu}_e$ KamLAND
$\bar{\nu}_e$ SK
$\bar{\nu}_e$ Borexino
Reinterpreted Super-K data.
[Palomares-Ruiz, 0712.1937]
Excluded!
Threshold for $\bar{\nu}_e\, p \to n\, e^+$.
[JH, Camilo Garcia-Cely, 1701.07209]
Lower limit on breaking scale f (GeV)
m_J (GeV) = 2 E_ν

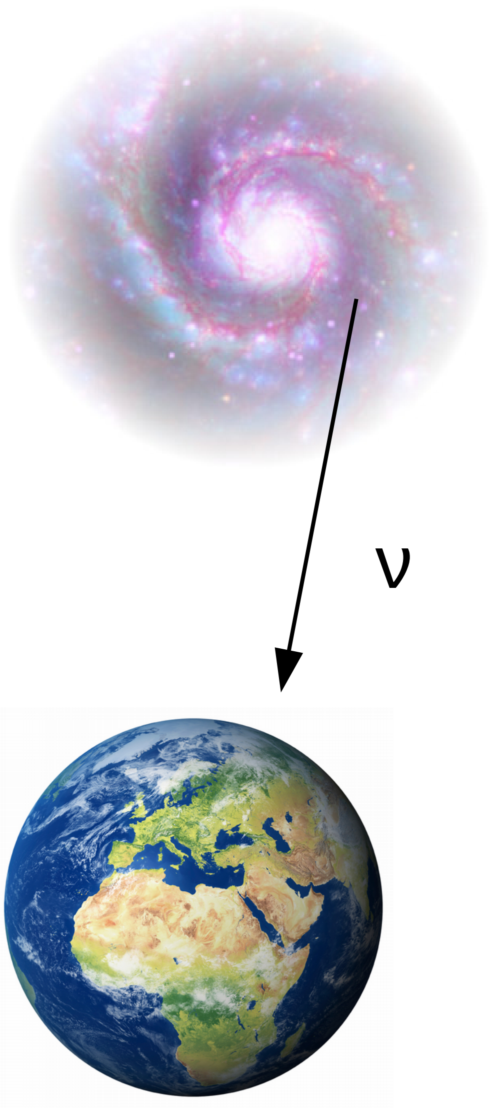
$$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_k^2$$



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!
- 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]



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

- Tree-level J couplings $\propto M_\nu$ while loop level $\propto m_D m_D^\dagger$.
- E.g. diagonal J-f-f couplings with $K \equiv \frac{m_D m_D^\dagger}{v\, f}$

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

- One-to-one mapping: $\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}$.

[Davidson, Ibarra, hep-ph/0104076]

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

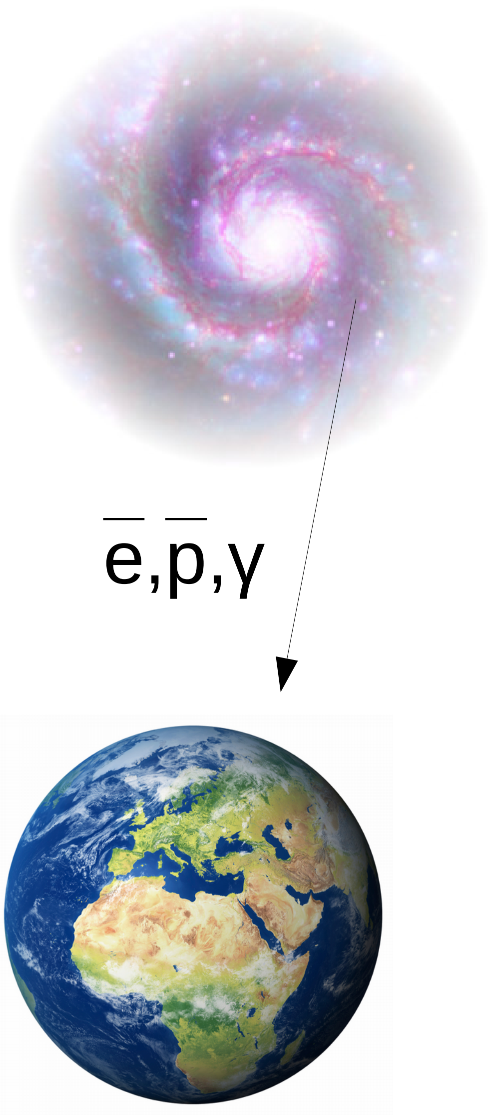
- One generation: $K \sim \frac{m_\nu M_R}{v\, f} \sim 10^{-13} M_R/f$.

[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.
- DM → γγ gives lines.



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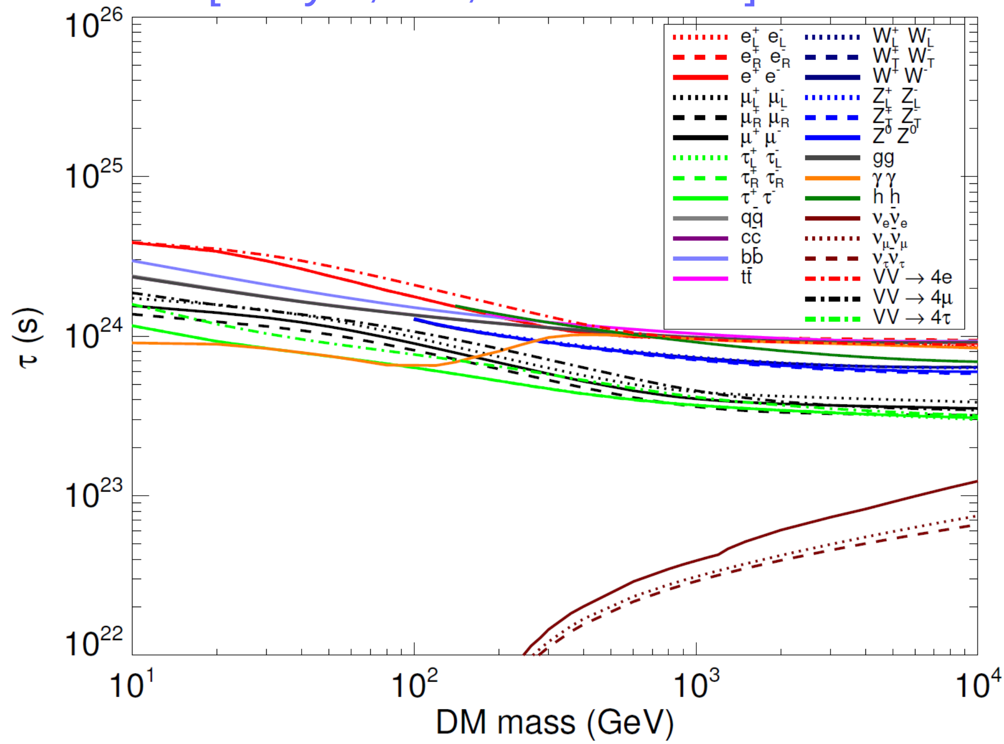
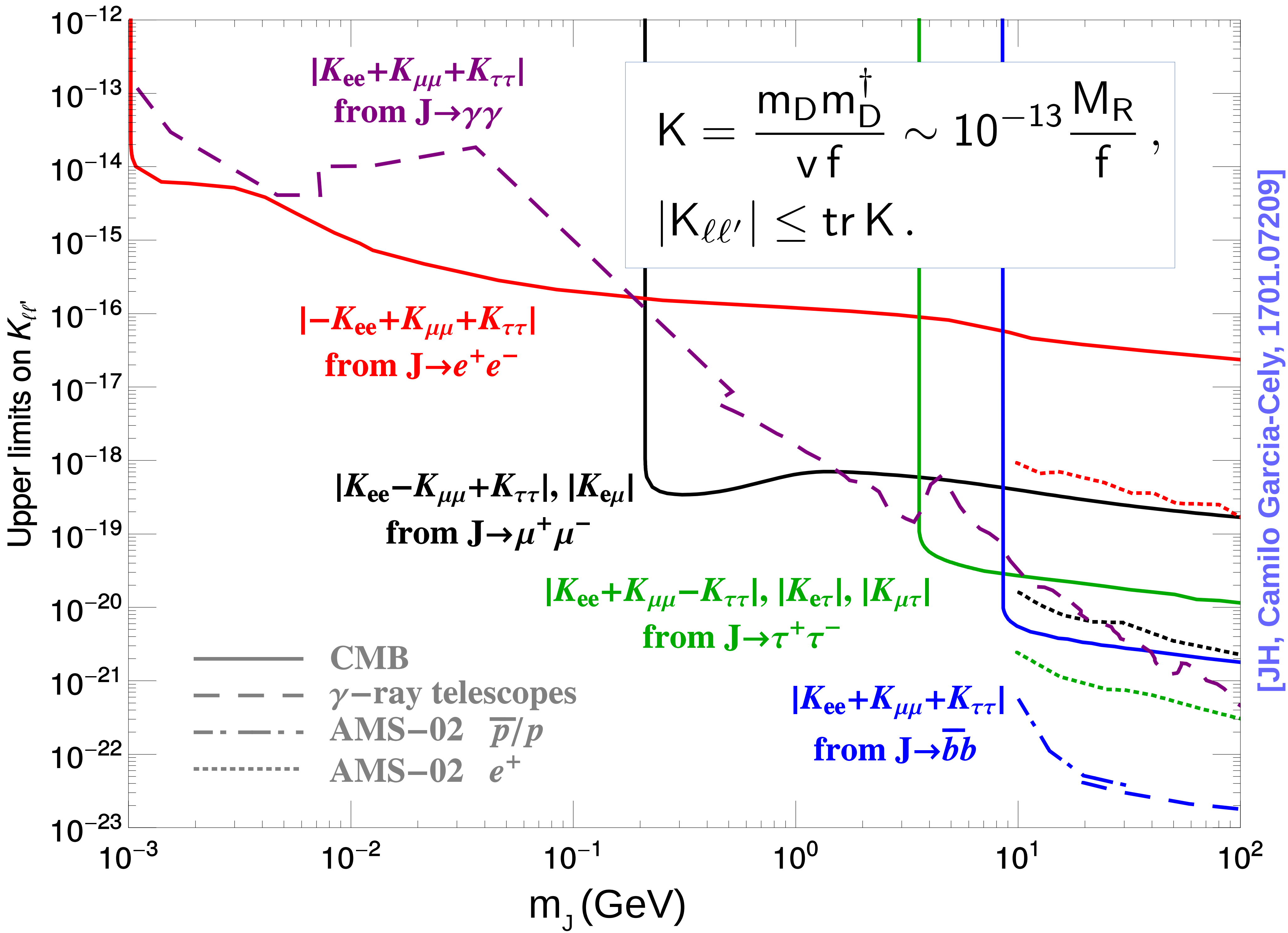
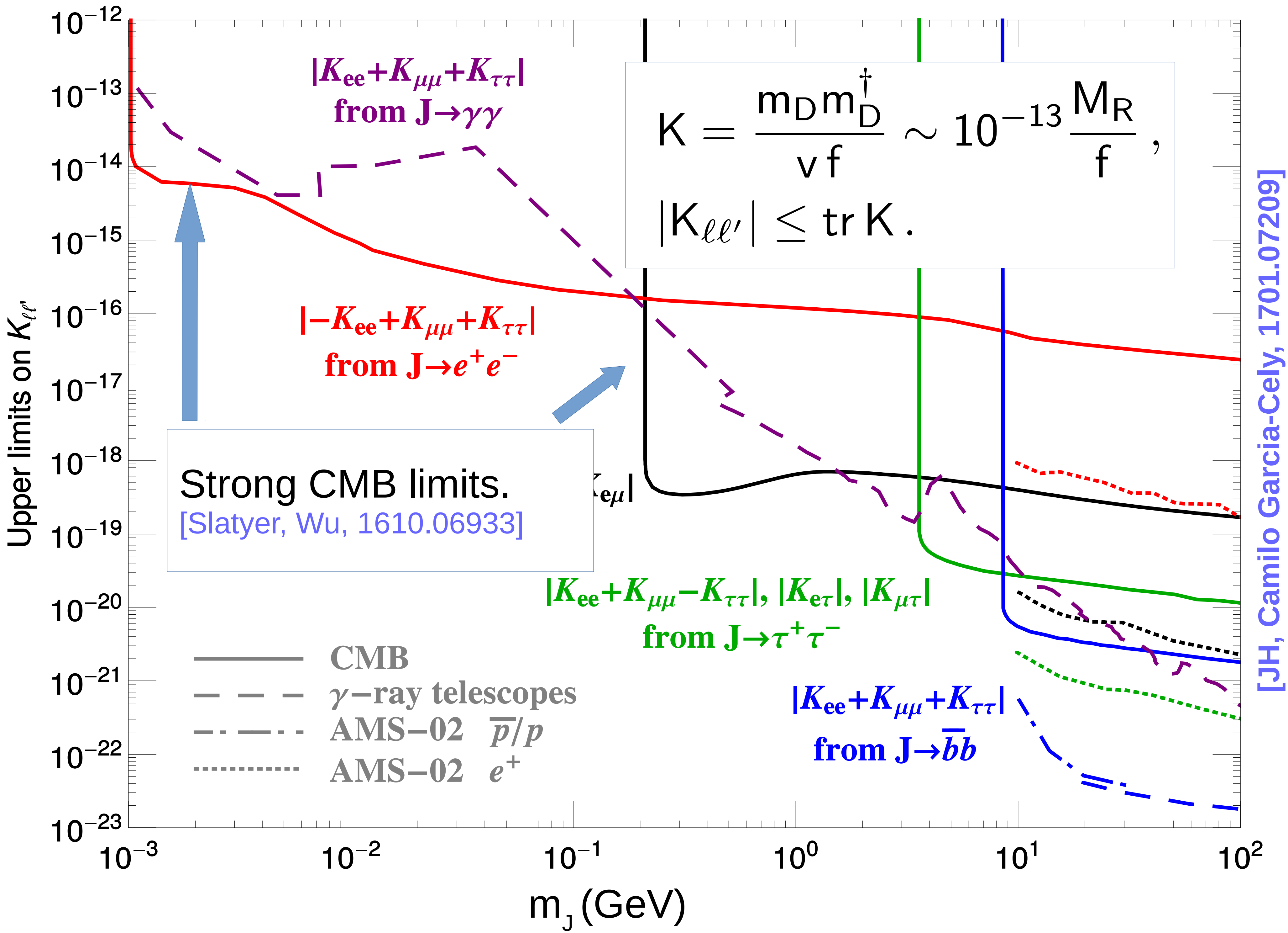




$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\, K$.
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|$, $|K_{e\mu}|$
from $J\to\mu^+\mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$, $|K_{e\tau}|$, $|K_{\mu\tau}|$
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]
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}



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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 $J\to\tau^+\tau^-$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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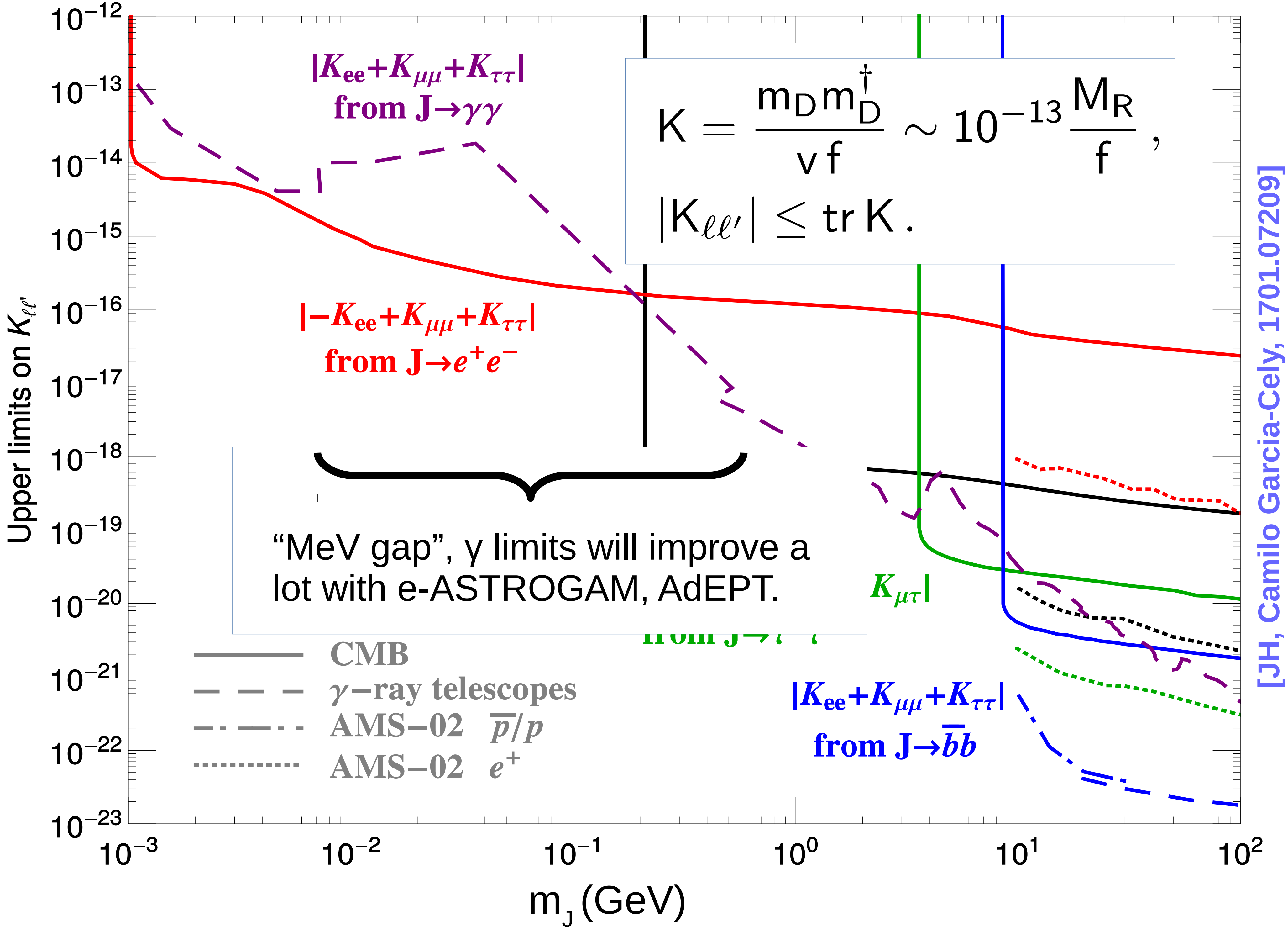

$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
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$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
"MeV gap", γ limits will improve a lot with e-ASTROGAM, AdEPT.
$K_{\mu\tau}|$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

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

Yes!

$J \to \nu\nu$

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

depends on

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

depends on

$m_D m_D^\dagger$.

Independent / Complementary!

Summary

- Reconstruct seesaw to go beyond 3x3.
- Measure couplings of N_R or majoron J!
- Seesaw parameters encoded in $J\bar{f}f$ couplings.
- Axion-like particle pheno + LFV $\ell_\alpha \to \ell_\beta J$.
- J as long-lived dark matter: $J \to \nu\nu, \gamma\gamma, \bar{\ell}\ell', \bar{q}q$.
- Future: Mu3e, Belle-II, Hyper-K, DUNE,….

Always look out for lines!

Backup

Majoron = DM

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

  [JH, Daniele Teresi, 1706.09909, 1709.07283]

Majoron ≠ DM

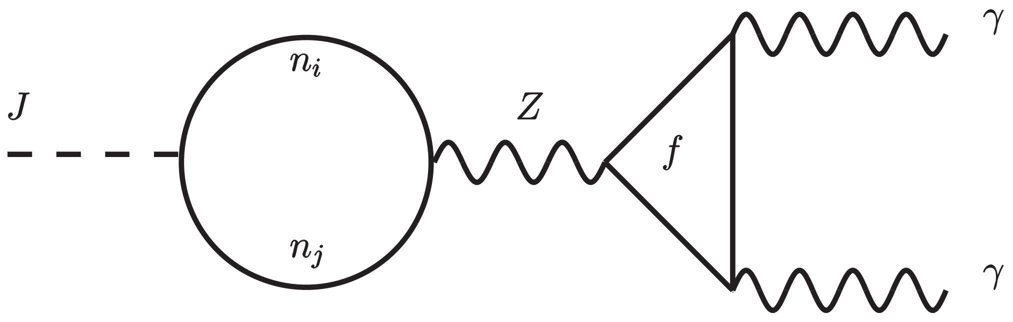
- Increase couplings to produce J in lab.
- Measure seesaw parameters.

  [JH, work in progress]

Two-loop couplings

- Full calculation non-trivial, only do:

  [JH, 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]

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]

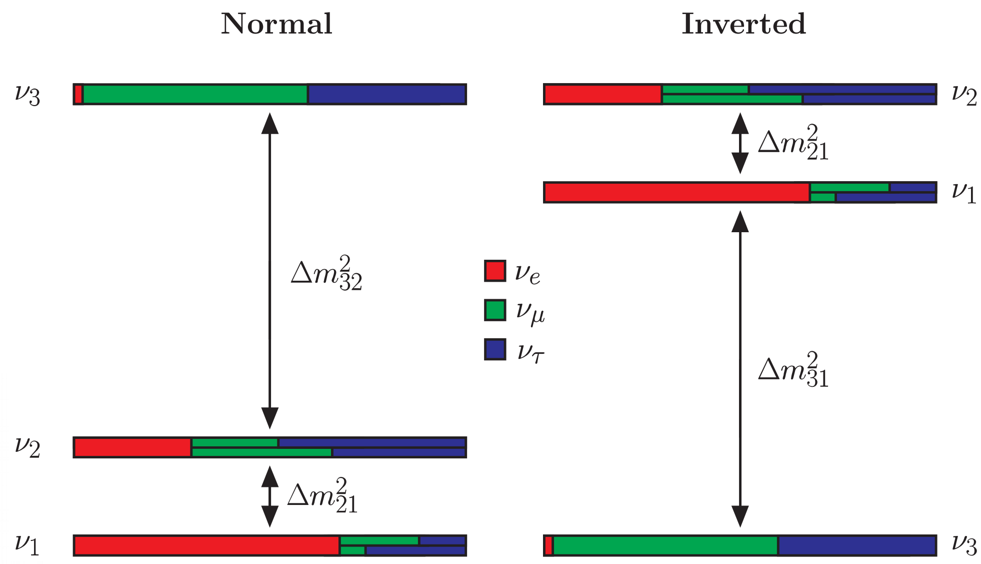
  - Anomalies, e.g. if $U(1)_{B-L} = U(1)_{PQ}$.

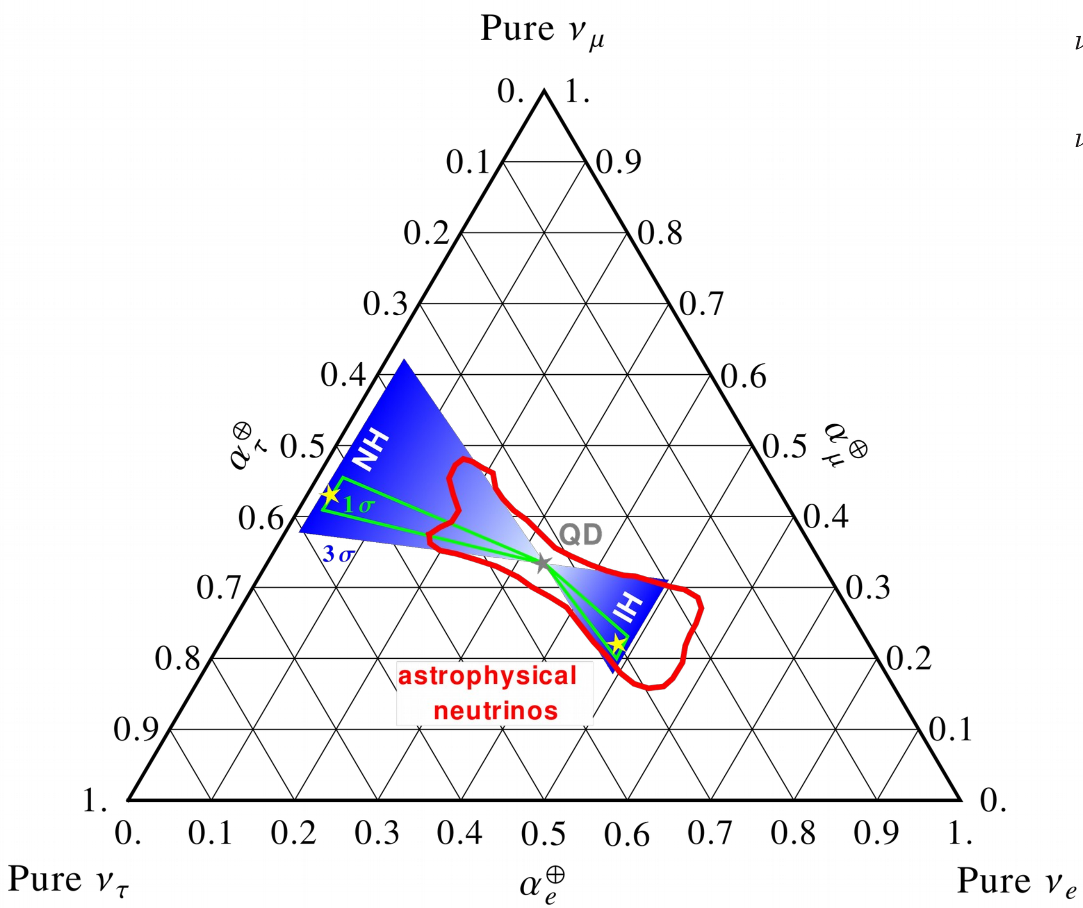
[Mohapatra, Senjanovic ‘83; Langacker, Peccei, Yanagida ‘86; SMASH ‘16]

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

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, Camilo Garcia-Cely, 1701.07209]