Majorons as cold light dark matter

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Fundamental .be Interactions

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Majoronic seesaw

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

B−L breaking scale

Heavy scalar (inflaton?)

Majoron

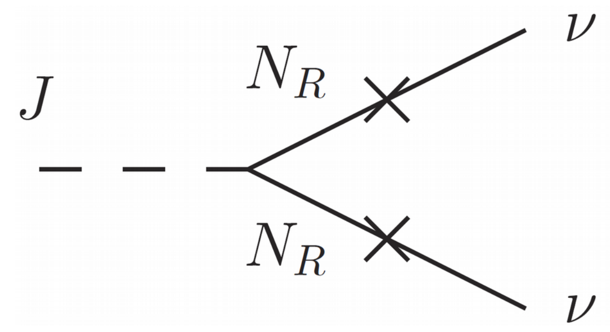
[Chikashige, Mohapatra, Peccei, '81; Schechter, Valle, '82]

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

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

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

Tree-level couplings



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

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

- Long lifetime → majoron dark matter!

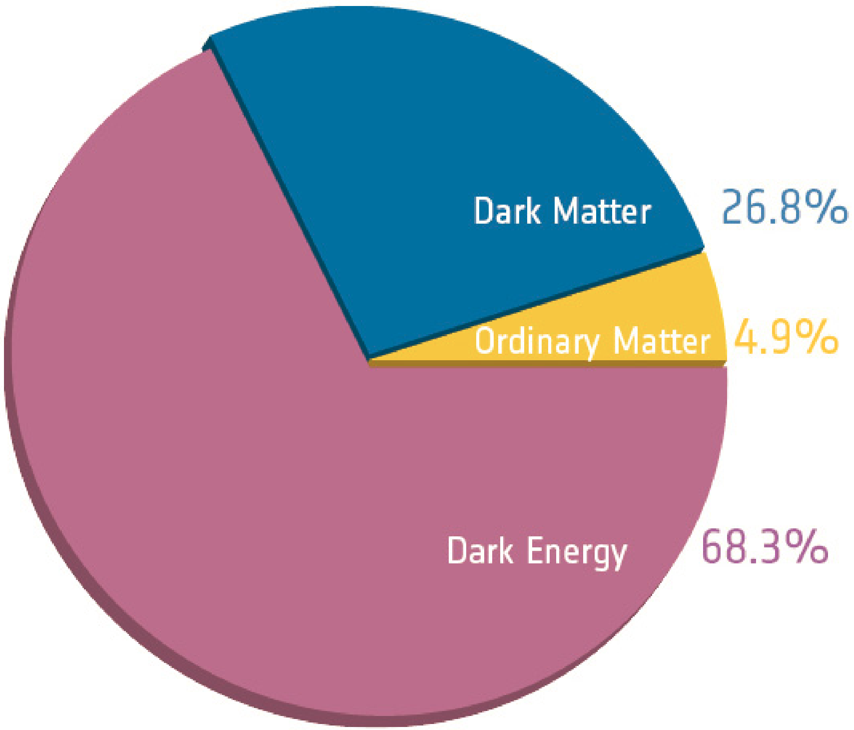
[Berezinsky, Valle '93; Lattanzi, Valle '07; Bazzocchi et al, '08; Queiroz, Sinha, '14]

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

- Signatures for MeV < m_J: J → νν, γγ, $f\bar{f}$.
- 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.



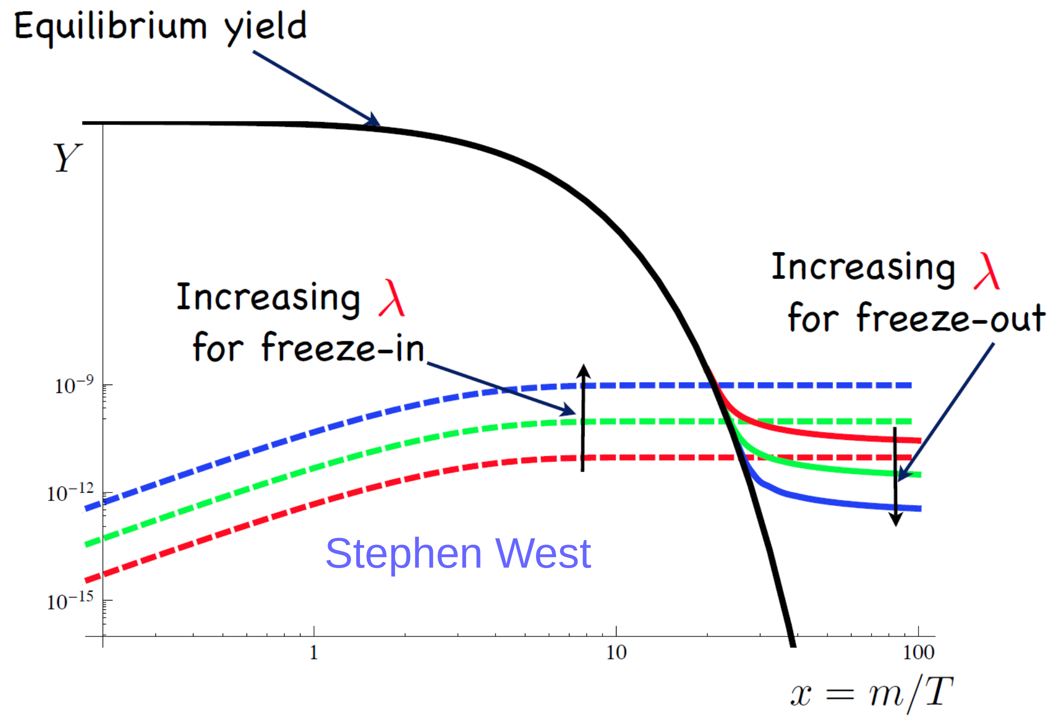
Dark matter abundance

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

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

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

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



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: $\tau \gtrsim 10 \times \tau_{\mathrm{Universe}}$.

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

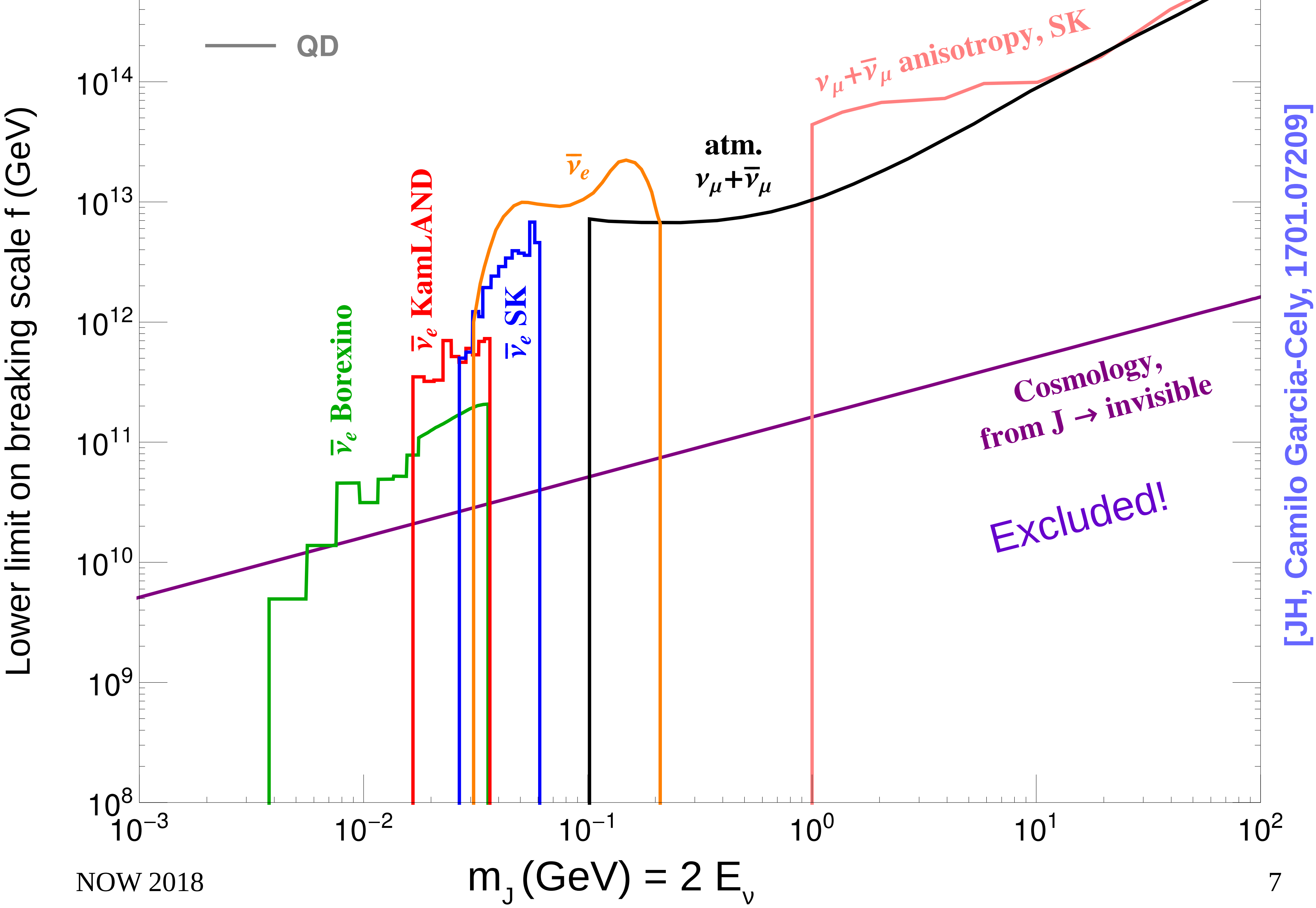
- Can we observe the **neutrino lines**?
  - m_J > 10 TeV: **No.** Dominant decay is J →ννh(h). ► no line!

    [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!**

(See also Carsten Rott's talk!)

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



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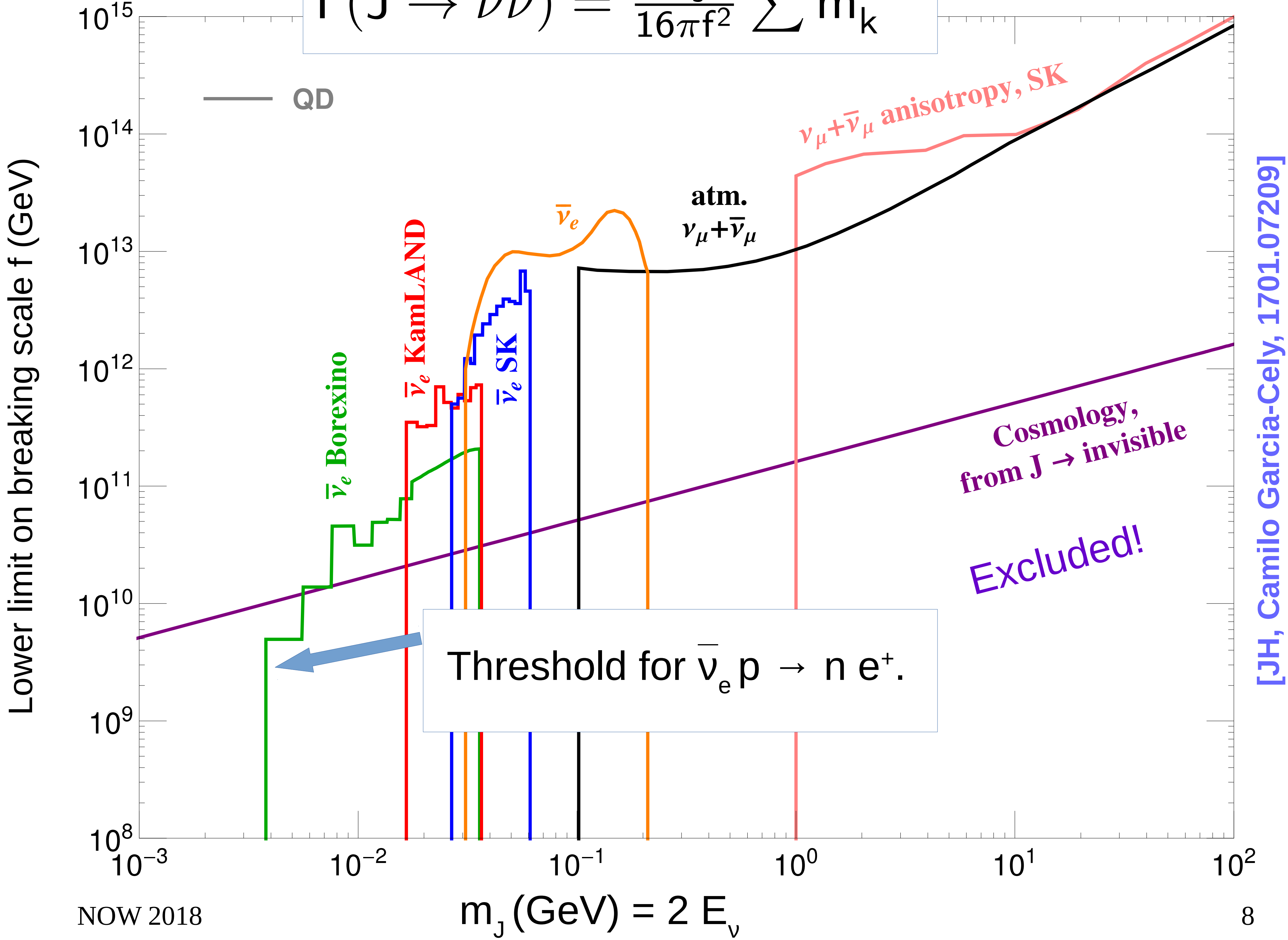

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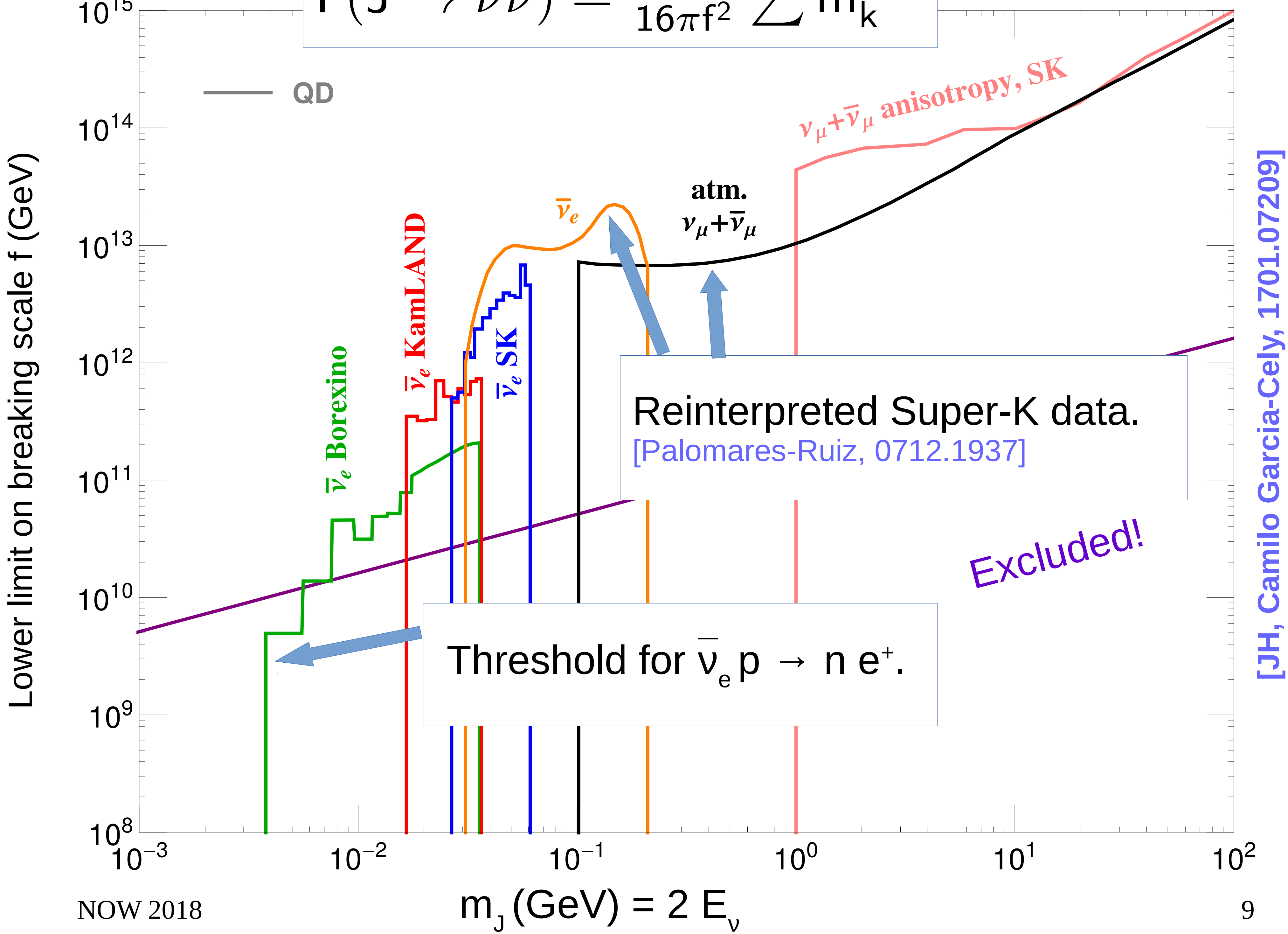
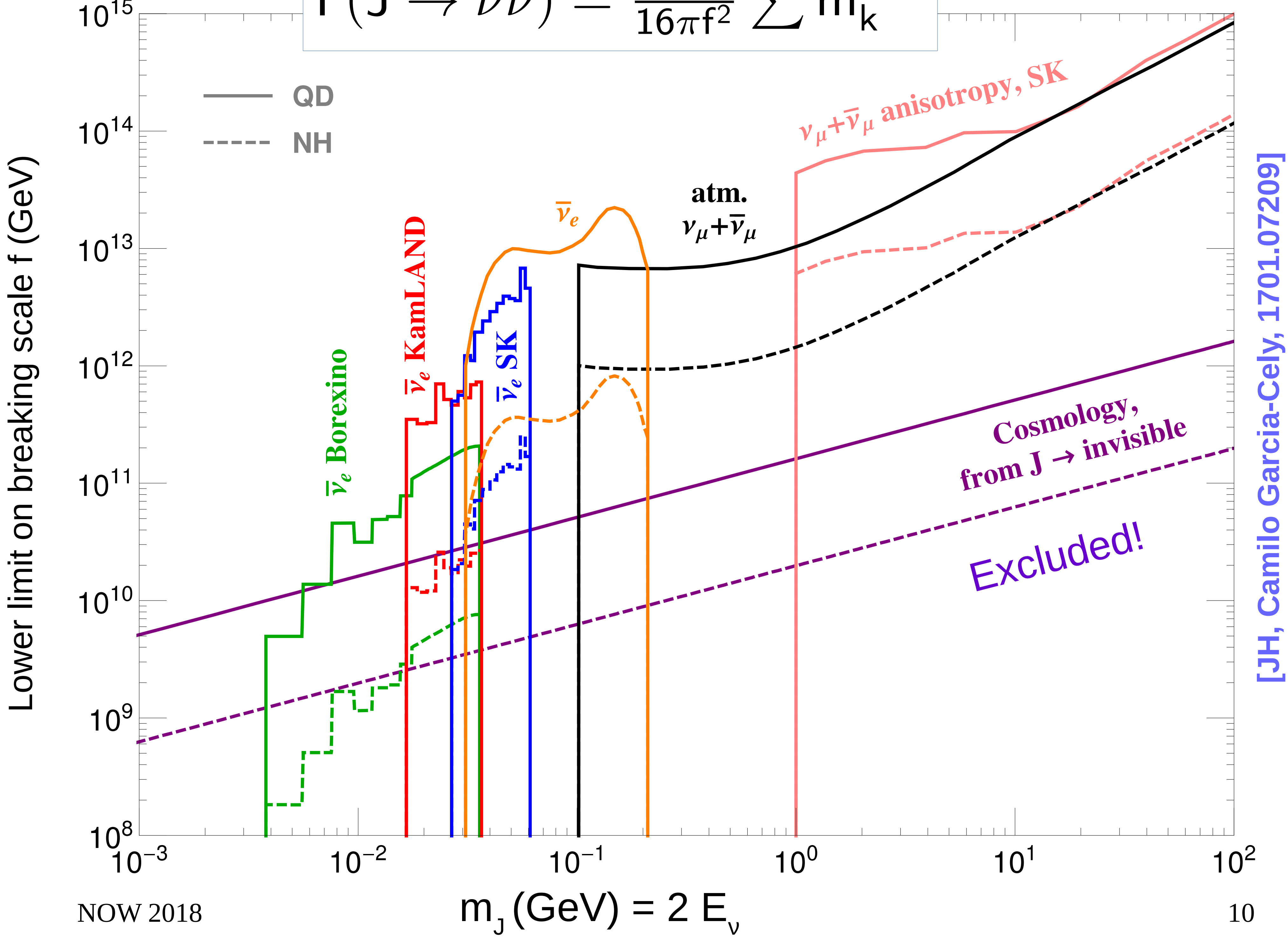


$$\Gamma(\mathrm{J} \to \nu\nu) = \frac{\mathrm{m_J}}{16\pi \mathrm{f}^2} \sum \mathrm{m_k^2}$$



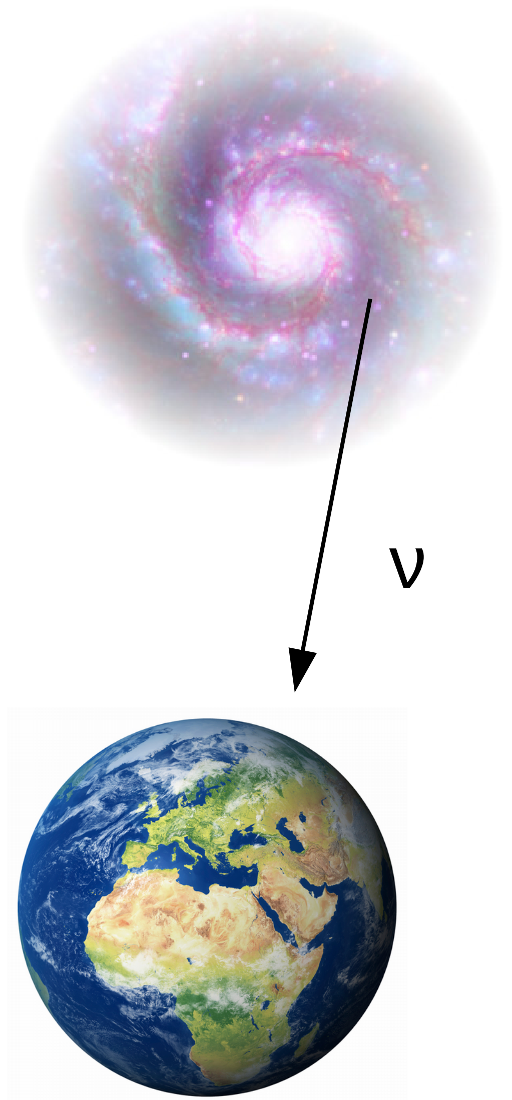
Look for neutrinos from light DM!

- 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.

(See also Josef Pradler's talk!)

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

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

- 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!

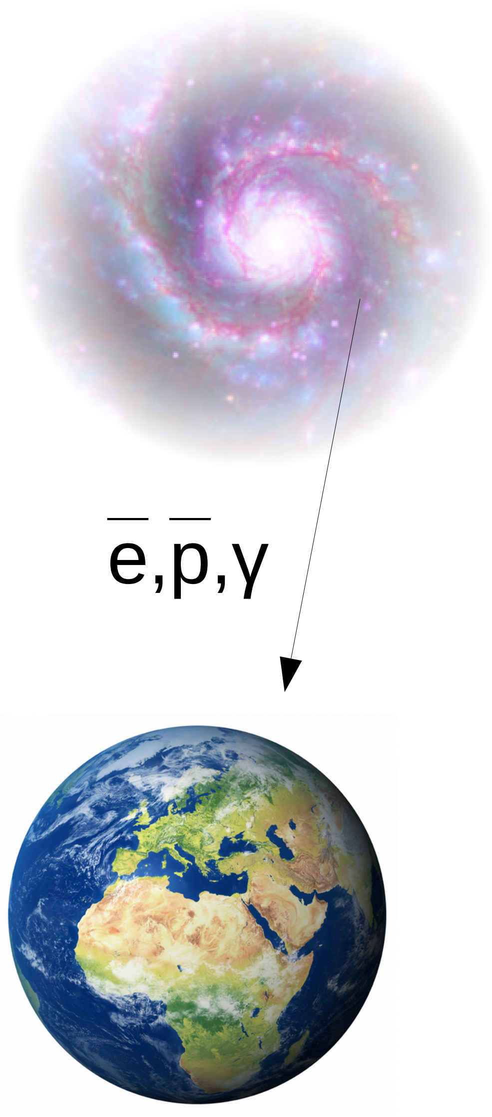
- One generation: $K \sim \frac{m_\nu M_R}{v\, f} \sim 10^{-13} M_R/f$.

[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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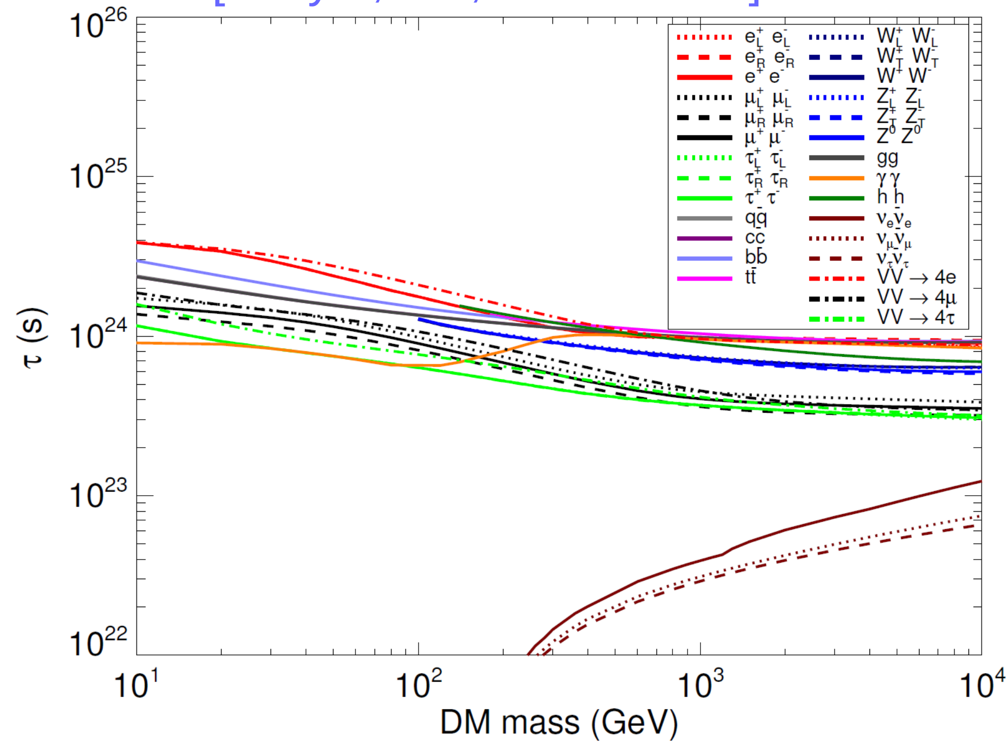

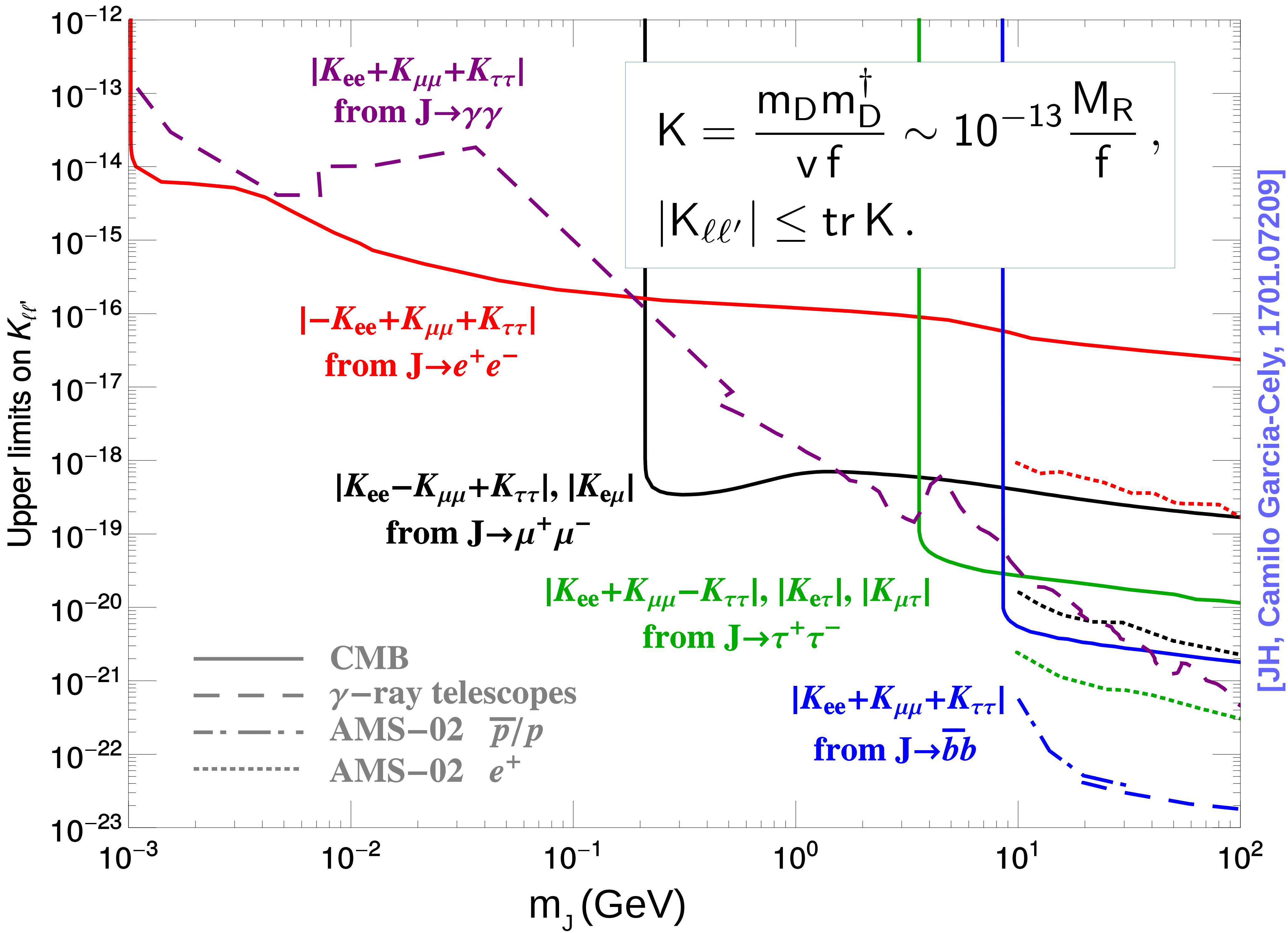

$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v f} \sim 10^{-13}\frac{M_R}{f}$,
$|K_{\ell\ell'}| \leq \mathrm{tr}\,K$.
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
$|K_{ee}-K_{\mu\mu}+K_{\tau\tau}|$, $|K_{e\mu}|$
from $J\to\mu^+\mu^-$
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|$,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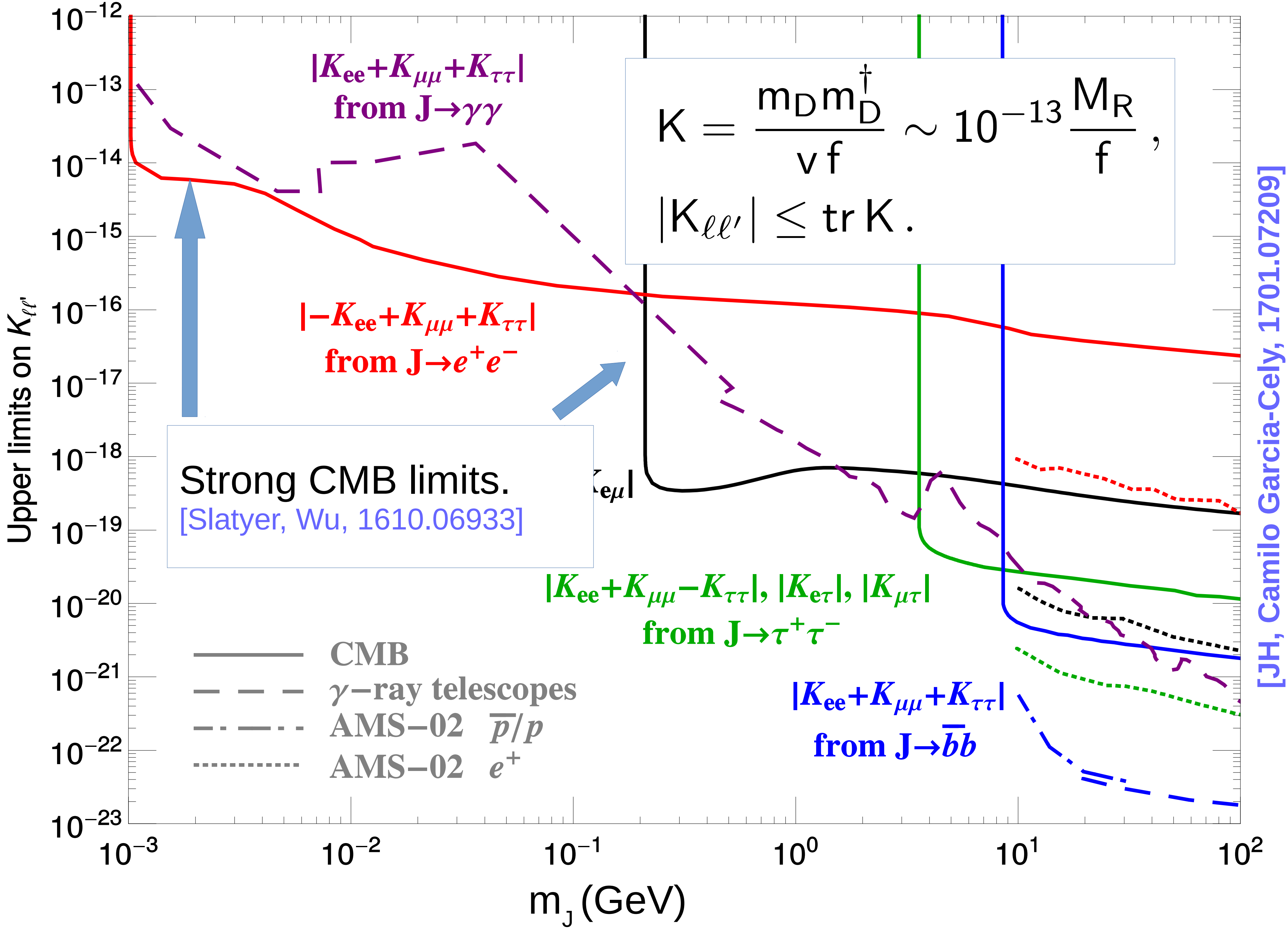
from $J\to\bar{b}b$
CMB
γ−ray telescopes
AMS−02 $\bar{p}/p$
AMS−02 e^+
Upper limits on $K_{\ell\ell'}$
m_J (GeV)
[JH, Camilo Garcia-Cely, 1701.07209]



$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$K = \frac{m_D m_D^\dagger}{v\,f} \sim 10^{-13}\frac{M_R}{f}\,,$
$|K_{\ell\ell'}| \leq \mathrm{tr}\,K\,.$
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
Strong CMB limits.
[Slatyer, Wu, 1610.06933]
$|K_{ee}+K_{\mu\mu}-K_{\tau\tau}|, |K_{e\tau}|, |K_{\mu\tau}|$
from $J\to\tau^+\tau^-$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
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[JH, Camilo Garcia-Cely, 1701.07209]
Upper limits on $K_{\ell\ell'}$
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10^{-20}
10^{-21}
10^{-22}
10^{-23}
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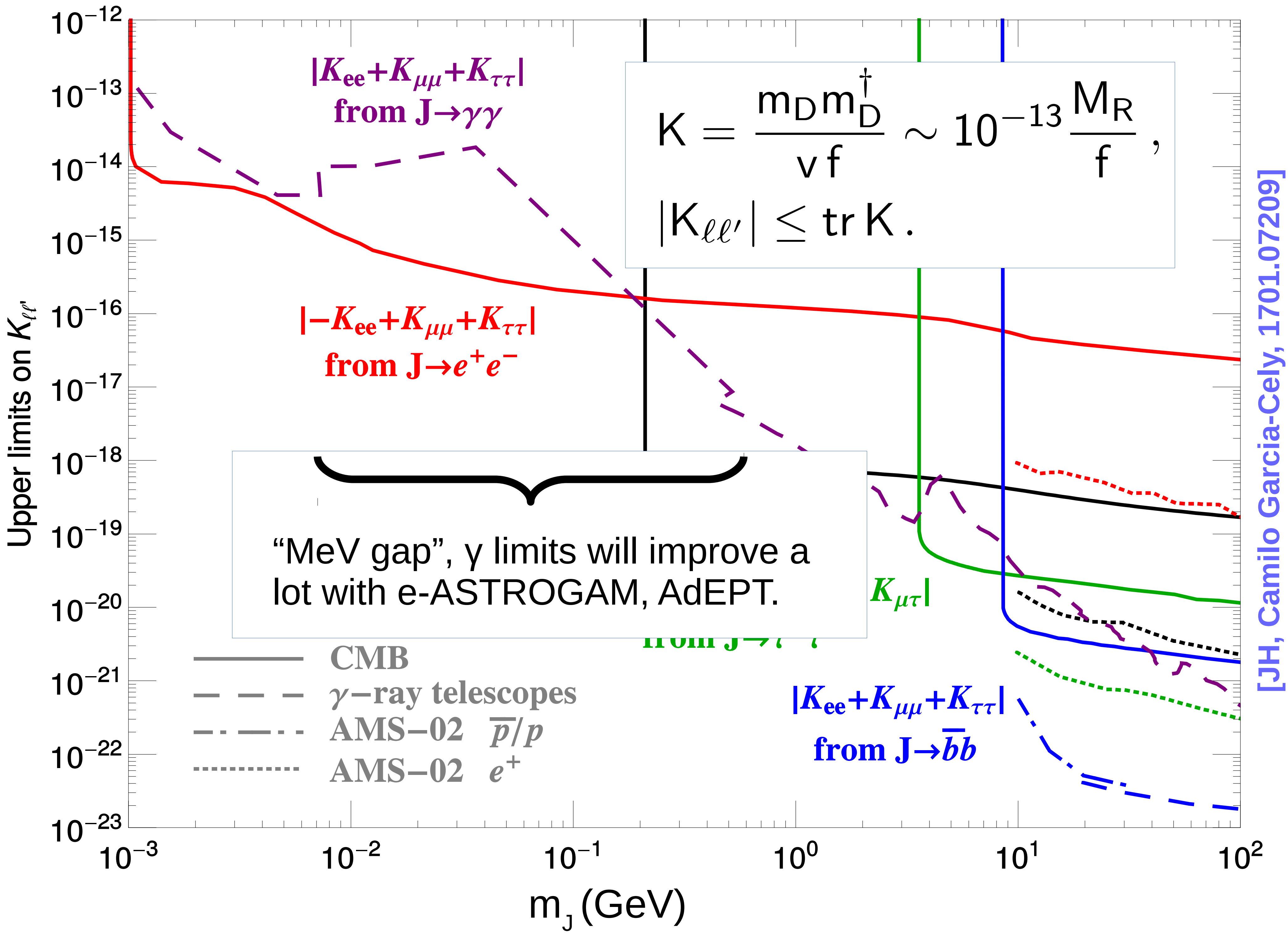
10^{0}
10^{1}
10^{2}



$$K = \frac{m_D m_D^\dagger}{v\,f} \sim 10^{-13}\,\frac{M_R}{f}\,,$$
$$|K_{\ell\ell'}| \leq \mathrm{tr}\,K\,.$$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\gamma\gamma$
$|-K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to e^+e^-$
“MeV gap”, γ limits will improve a lot with e-ASTROGAM, AdEPT.
$K_{\mu\tau}|$
$|K_{ee}+K_{\mu\mu}+K_{\tau\tau}|$
from $J\to\bar{b}b$
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10^{0}
10^{1}
10^{2}
[JH, Camilo Garcia-Cely, 1701.07209]

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

Yes!

J

$\nu\nu$ $\quad$ $\bar{\mathrm{f}}\mathrm{f}', \gamma\gamma$

depends on

$\mathrm{M}_\nu \simeq -\mathrm{m}_\mathrm{D} \mathrm{M}_\mathrm{R}^{-1} \mathrm{m}_\mathrm{D}^\mathrm{T}.$

depends on

$\mathrm{m}_\mathrm{D} \mathrm{m}_\mathrm{D}^\dagger.$

Independent / Complementary!

Going down to keV

(See also Jörn Kersten's talk!)

- Only signature of sub-MeV J: DM$\rightarrow\gamma\gamma$.
  [Bazzocchi, Lattanzi, Riemer-Sørensen, Valle, '08; Lattanzi, Riemer-Sørensen, Tórtola, Valle, '13; Queiroz, Sinha, '14]
- E.g. $E_\gamma = 3.55$ keV line. $m_J = 7$ keV?
  [Bulbul et al.; Boyarski et al. '14, …, recent review: Abazajian '17]
- For $m_J < O(10)$ keV: DM naively too *warm*, structure formation and Lyman-α constraints.
  [Merle, Schneider '15; Schneider '16]
  [Viel et al '05, Baur et al '15 &'17, Yèche et al., '17, Iršič et al '17]
- Depends on the *production mechanism*, not just the DM mass! Can be softened!
  [e.g. Merle, Totzauer, '15; König, Merle, Totzauer, '16]

HOT or NOT

- Free-streaming length λ depends on average DM momentum:

$$\left\langle \frac{p}{T} \right\rangle = \left\langle \frac{p}{T} \right\rangle_{\text{prod}} \left(\frac{g_*(T)}{g_*(T_{\text{prod}})} \right)^{1/3} .$$

- Lyman-α limits: $\left\langle \frac{p}{T} \right\rangle_{\text{prod}} \lesssim \frac{m_{\text{DM}}}{5.1\,\text{keV}} \left(\frac{g_*(T_{\text{prod}})}{106.75} \right)^{1/3} .$

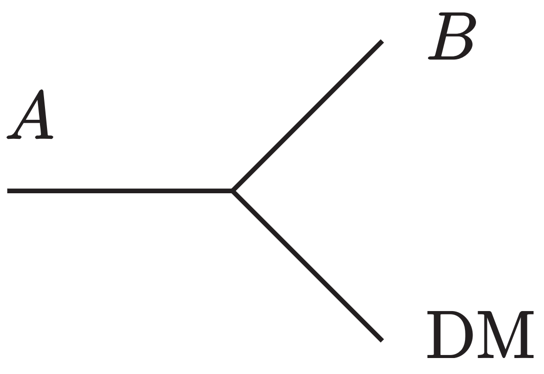
  - Thermal DM: <p/T> ~ 3.
  - Thermal A → DM DM: <p/T> ~ 2.5. [Shaposhnikov, Tkachev, ’06; Bezrukov, Gorbunov, ’14]
  - Freeze-out A → DM DM: <p/T> > 2.5. [Petraki, Kusenko, ’07; Merle, Totzauer, ’15]
  - Freeze-in A → DM DM: <p/T> ~ 1.

    [Merle, Niro, Schmidt ’13; König, Merle, Totzauer, ’16]

Cold keV majorons from decay

- Decay $A \to B\ DM$ of thermal A:

  (with $m_{DM} \ll m_A - m_B$)



- Phase space suppression gives *cold* light DM!

$$\left\langle \frac{p_{\rm DM}}{T} \right\rangle_{\rm prod} = \frac{5}{2}\left(1 - \frac{m_B^2}{m_A^2}\right)$$

[**JH,** Teresi, 1706.09909]

- Can go to cold keV DM via $m_A \sim m_B$.
- Natural in inverse seesaw majorons: $N_i \to N_j\ J$.

  [**JH,** Teresi, Boulebnane, Nguyen, 1709.07283]

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 $J \to \gamma\gamma$, $\bar{\ell}\ell'$, $\bar{q}q$.
- Cold keV majorons from inverse seesaw: $J \to \gamma\gamma$.

Always look out for lines!

Backup

Inverse seesaw majoron

- One example: majoronic seesaw plus S ~ -1:

$$N_L = (\nu_L, N_R^c, S_R^c)$$

$$\mathcal{L} \supset -\frac{1}{2}\overline{N}_L^c \begin{pmatrix} 0 & m_D & 0 \\ m_D & \lambda_1\sigma & M \\ 0 & M & \lambda_2\sigma^* \end{pmatrix} N_L + \text{h.c.}$$

- Masses:

$$m_1 \simeq \mu_2 \frac{m_D^2}{M^2}\,, \quad m_2 \simeq M - \frac{\mu_1}{2} - \frac{\mu_2}{2}\,, \quad m_3 \simeq M + \frac{\mu_1}{2} + \frac{\mu_2}{2}$$

- Couplings:

$$\mathcal{L} \supset -\frac{J}{2f}\overline{N_i} \begin{pmatrix} \mathrm{i}\gamma_5 m_1 & -\mathrm{i}\gamma_5\frac{\mu_2 m_D}{\sqrt{2}M} & -\frac{\mu_2 m_D}{\sqrt{2}M} \\ -\mathrm{i}\gamma_5\frac{\mu_2 m_D}{\sqrt{2}M} & -\mathrm{i}\gamma_5\frac{\mu_1-\mu_2}{2} & \frac{\mu_1+\mu_2}{2} \\ -\frac{\mu_2 m_D}{\sqrt{2}M} & \frac{\mu_1+\mu_2}{2} & \mathrm{i}\gamma_5\frac{\mu_1-\mu_2}{2} \end{pmatrix}_{ij} N_j\,.$$

[**JH,** Teresi, Boulebnane, Nguyen, 1709.07283, see also Gonzalez-Garcia & Valle ‘89]

Inverse seesaw majoron II

- Relevant processes: $\Gamma(N_3 \to N_2 J) \simeq \frac{(\sum_j \mu_j)^3}{8\pi f^2}\,,$

$$\Gamma(N_{2,3} \to N_1 J) \simeq \frac{\mu_2^2 m_D^2}{32\pi M f^2}\,, \qquad \Gamma(J \to N_1 N_1) \simeq \frac{m_1^2 m_J}{16\pi f^2}\,.$$

- Mass scales:

$$m_D \simeq 0.2\,\mathrm{GeV}\left(\frac{170\,\mathrm{Gyr}}{\tau_J}\right)^{1/2}\left(\frac{m_1}{0.1\,\mathrm{eV}}\right)^{-1/2}\left(\frac{\sum_j \mu_j}{\mathrm{TeV}}\right)^{3/2}\left(\frac{\mu_2}{\mathrm{TeV}}\right)^{-1/2},$$

$$M \simeq 6\times 10^5\,\mathrm{GeV}\left(\frac{170\,\mathrm{Gyr}}{\tau_J}\right)^{1/2}\left(\frac{m_1}{0.1\,\mathrm{eV}}\right)^{-1}\left(\frac{\sum_j \mu_j}{\mathrm{TeV}}\right)^{3/2},$$

$$\left\langle\frac{p}{T}\right\rangle_{\mathrm{prod}} \simeq 8\times 10^{-3}\left(\frac{170\,\mathrm{Gyr}}{\tau_J}\right)^{-1/2}\left(\frac{m_1}{0.1\,\mathrm{eV}}\right)\left(\frac{\sum_j \mu_j}{\mathrm{TeV}}\right)^{-1/2}.$$

[**JH,** Teresi, Boulebnane, Nguyen, 1709.07283]

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]

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 $U(1)_{B-L} = U(1)_{PQ}$.

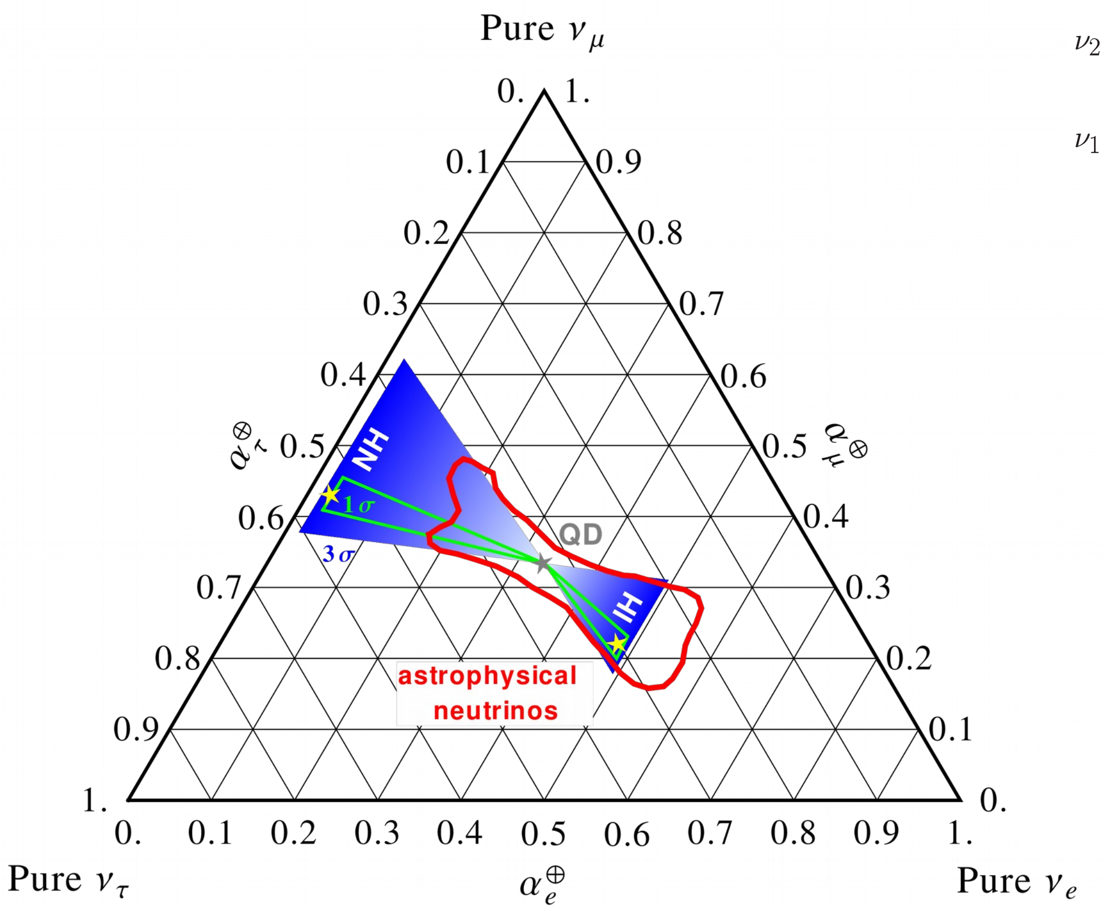
[Mohapatra, Senjanovic ‘83; Langacker, Peccei, Yanagida ‘86; SMASH ‘16]

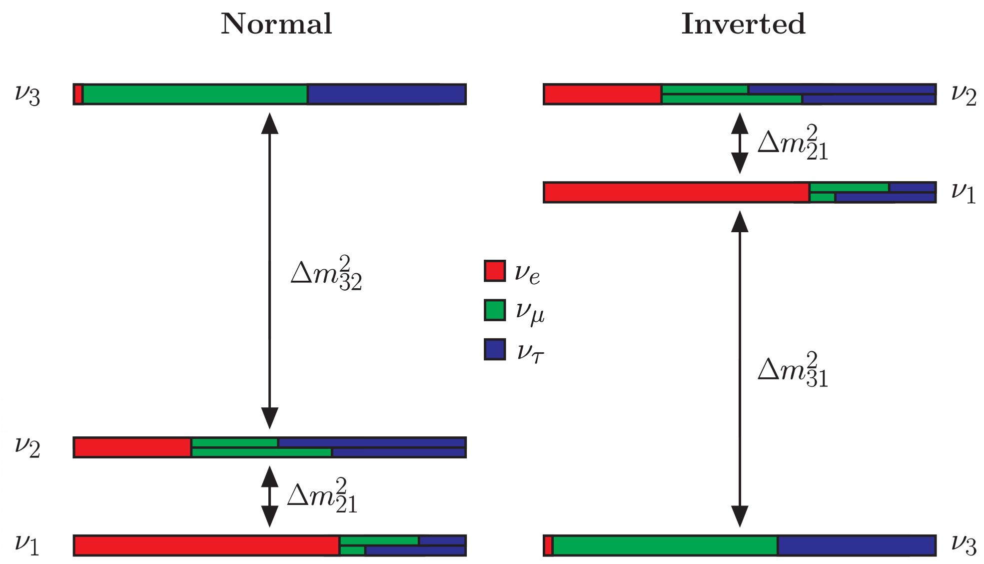
  - Explicit breaking, e.g. $\Delta V = \frac{1}{2} m_J^2 J^2$.

Stay ignorant here, just put m_J.

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]

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

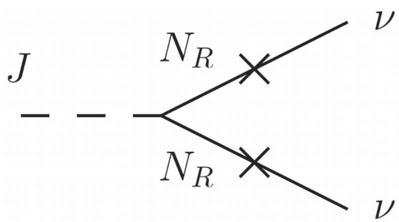
- Leaves 9 unknown parameters in seesaw.
- Here: hermitian $m_D m_D^\dagger$.

  [Davidson, Ibarra, hep-ph/0104076]

- One-to-one: $\boxed{\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}.}$
- Useful: majoron loop couplings depend on $m_D m_D^\dagger$.

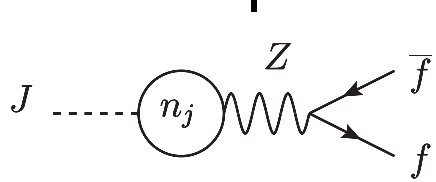
Majoron couplings

- Tree level coupling only to neutrinos:



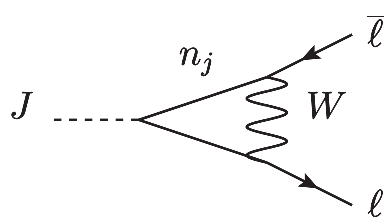
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 (m_D^* M_R^{-1} m_D^\dagger)_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k \gamma_5 m_k \nu_k$$

- 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!



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

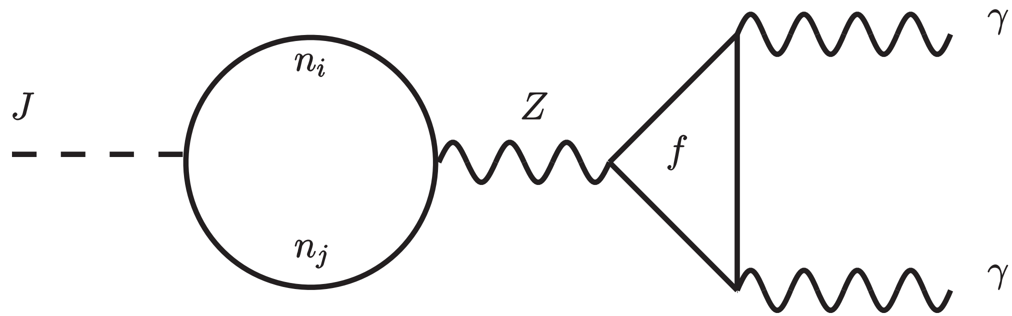
- Two loop: $\Gamma(J\to\gamma\gamma) \simeq \frac{\alpha^2\,\mathrm{tr}\left(m_D m_D^\dagger\right)^2}{4096\pi^7}\frac{m_J^3}{v^4 f^2}\left|\sum_f N_c^f T_3^f Q_f^2\, g\left(\frac{m_J^2}{4m_f^2}\right)\right|^2$

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

Two-loop couplings

- Full calculation highly non-trivial.

  [JH, in progress]



- J-Z mixing formally similar to triplet majoron:

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

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

- Gives the only DM signature for m_J < MeV.

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

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

[JH, Camilo Garcia-Cely, 1701.07209]

Properties

- Crucial observation: the two matrices are independent!

$$\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D m_D^\dagger\}.$$

[Davidson, Ibarra, hep-ph/0104076]

- $J\bar{\ell}\ell'$ 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:

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

$\ell \to \ell' J$ 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]

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

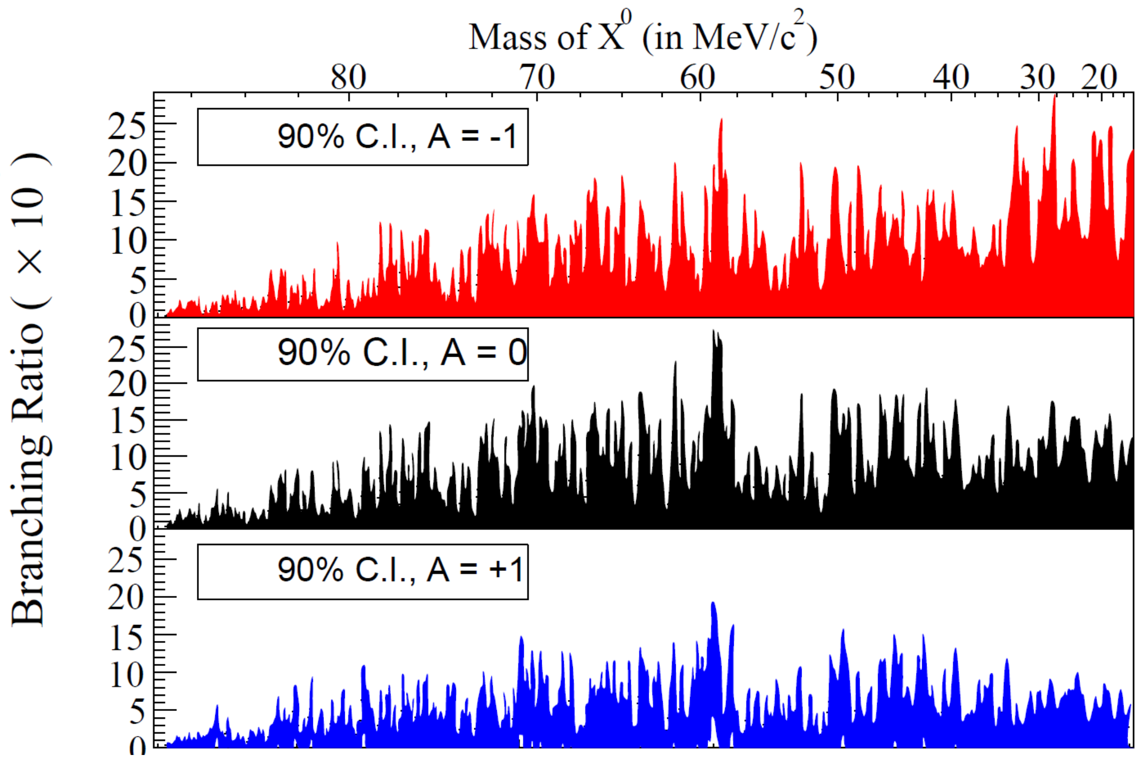
- If M_R= diag(M): $\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell' J)} \simeq 2\pi\alpha\frac{m_\ell^2}{M^2}\frac{f^2}{M^2}\begin{cases} \gg 1 \text{ for } M \ll f\,, \\ \ll 1 \text{ for } , M \sim f \gg m_\ell\,. \end{cases}$

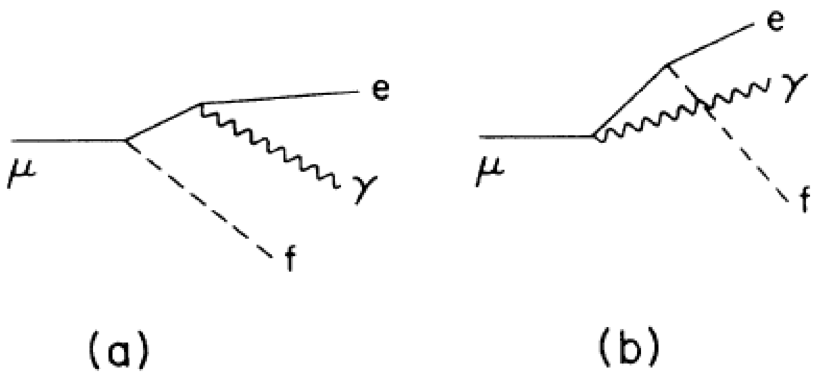
μ → e J with J → invisible

- 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

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





μ → e J with J → invisible

Can be improved significantly with Mu3e!

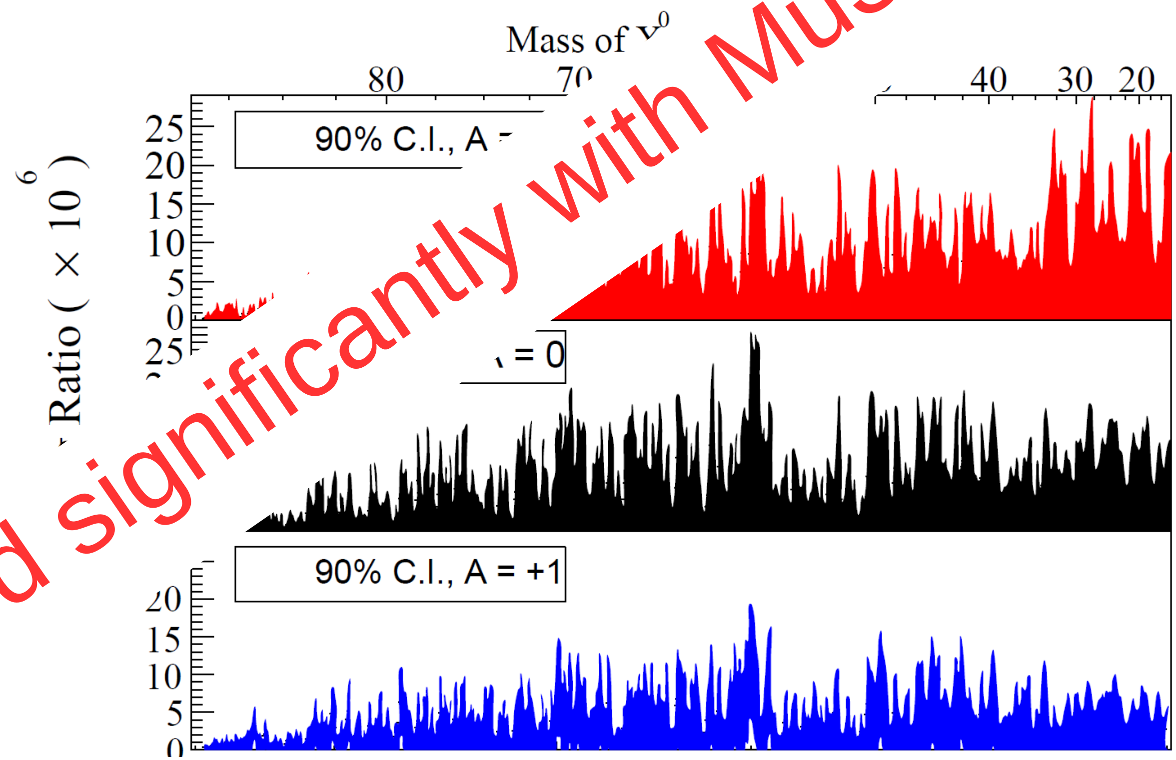
- TWIST, '15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

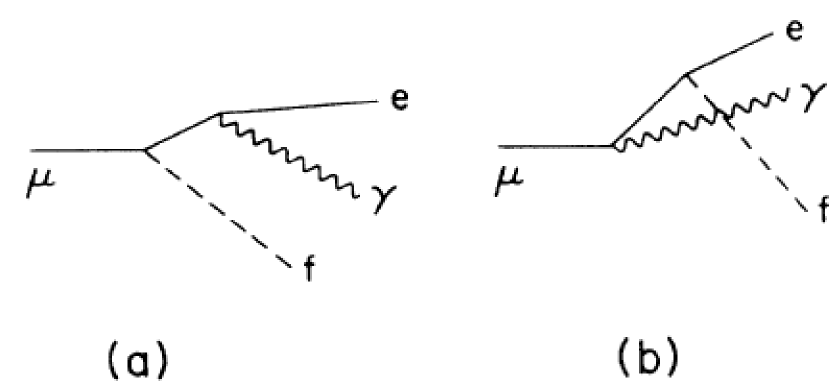
  [Heeck, Garcia-Cely, 1701.0720…]

- Bremsstrahlun… competitive… …
  [Goldman et …]

- Appr… …imit

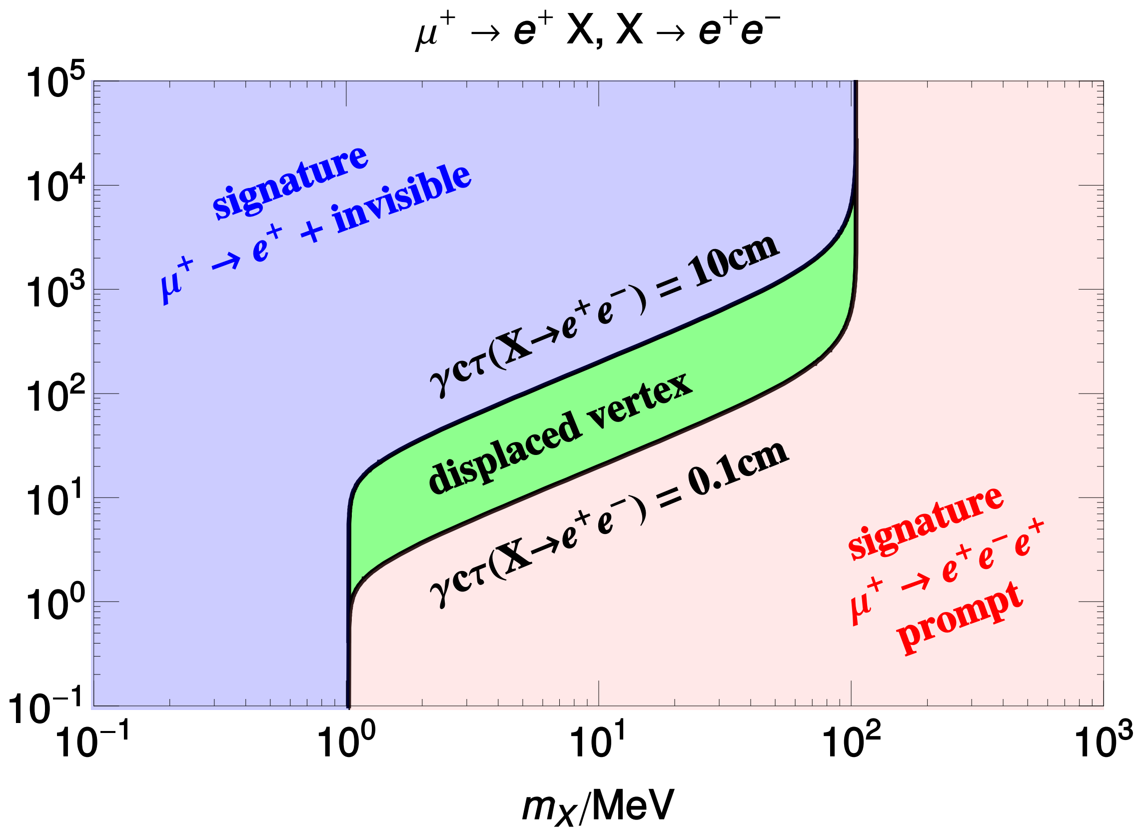
$$\frac{|(\ldots m_D^\dagger)_{\mu e}|}{v f} \lesssim 10^{-5}.$$





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

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



- Muon at rest:

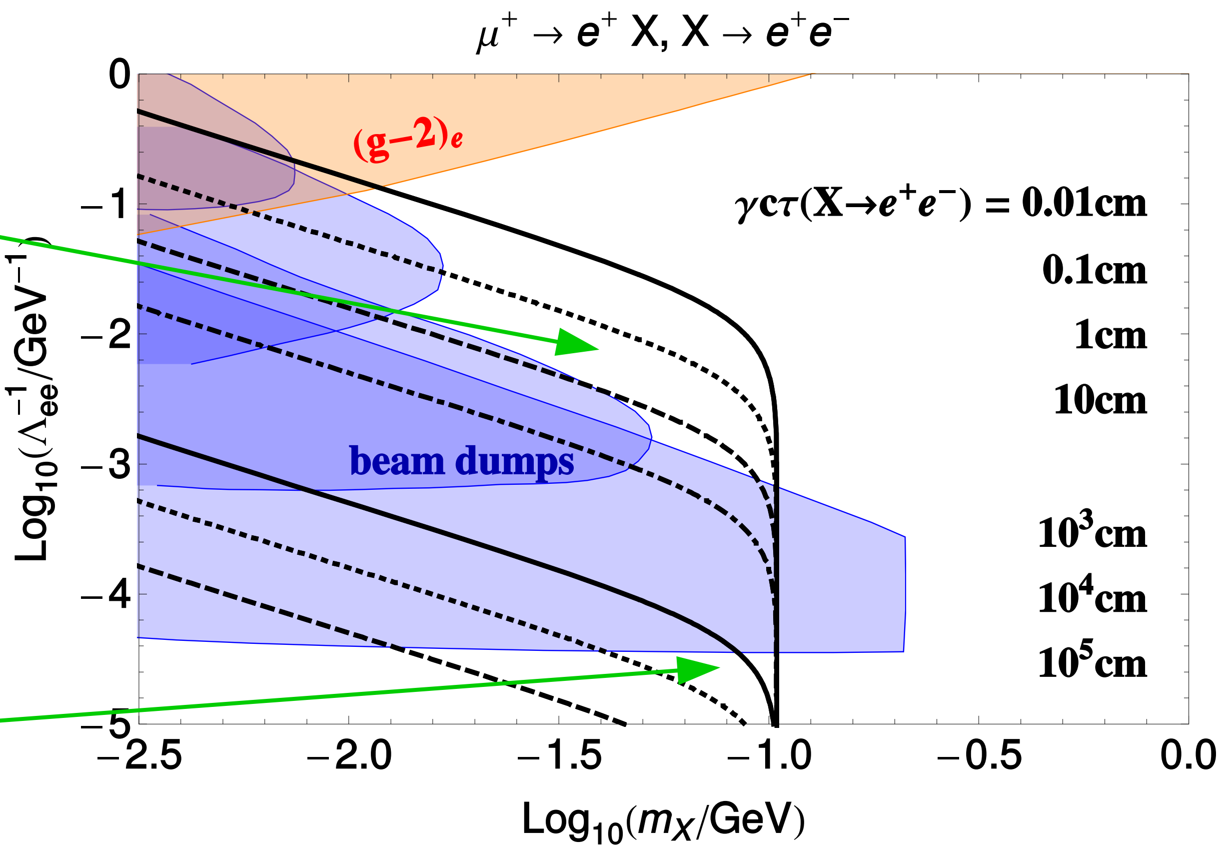
$$\gamma c \tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm} \left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

[Heeck, Rodejohann, 1710.02062]

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

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



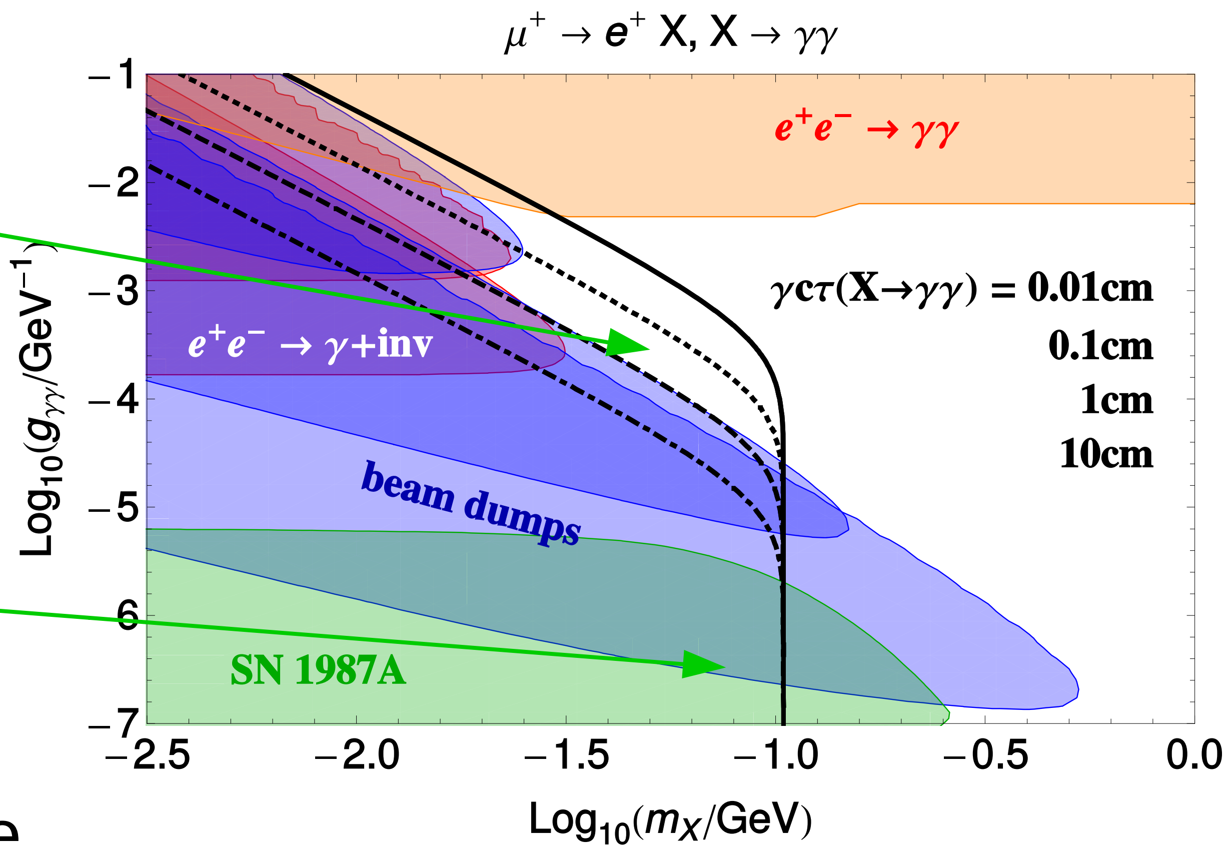
$$\mathrm{BR}(\mu \to eX)\mathrm{BR}(X \to ee)(1 - P(l_{\rm dec}))$$
$$\simeq \mathrm{BR}(\mu \to eX)\frac{l_{\rm dec}}{\gamma c\tau}\,.$$

Possible in Mu3e!

[Heeck, Rodejohann, 1710.02062]

$\mu \rightarrow e$ X with X$\rightarrow$ $\gamma\gamma$

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

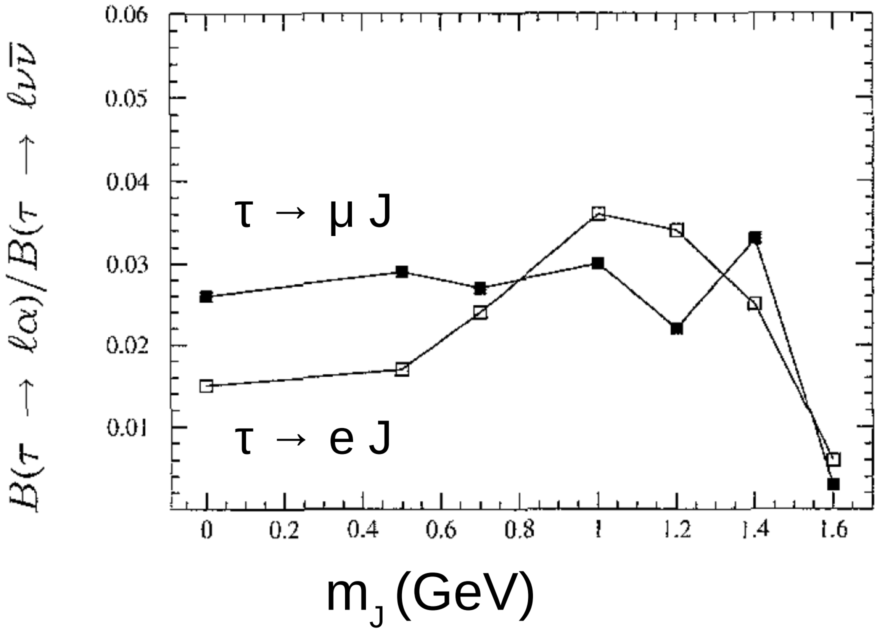


[Recent limits: Dolan et al, 1709.00009]

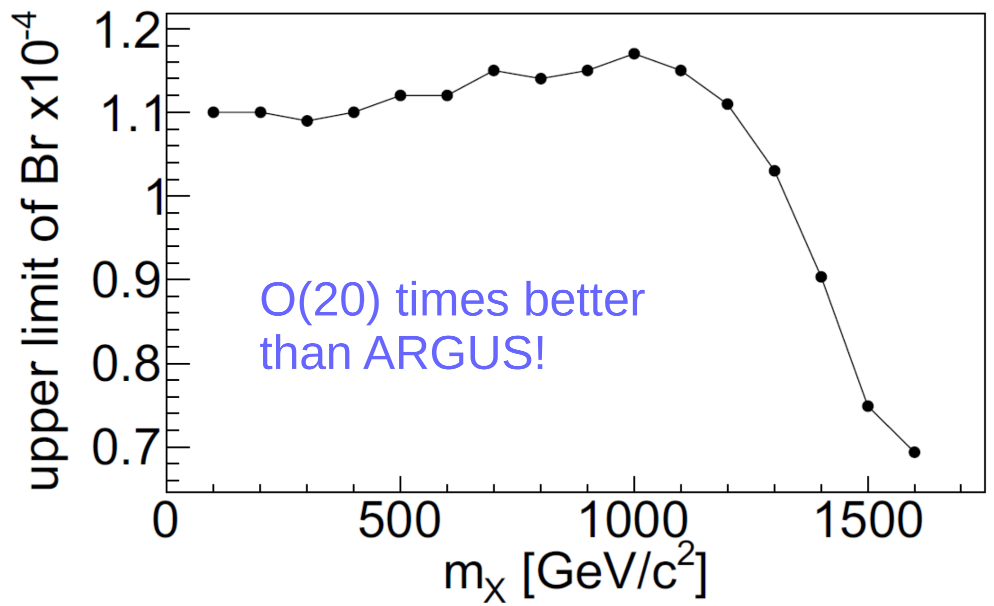
Muons difficult, taus easier.

τ → ℓ J with J→ 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]

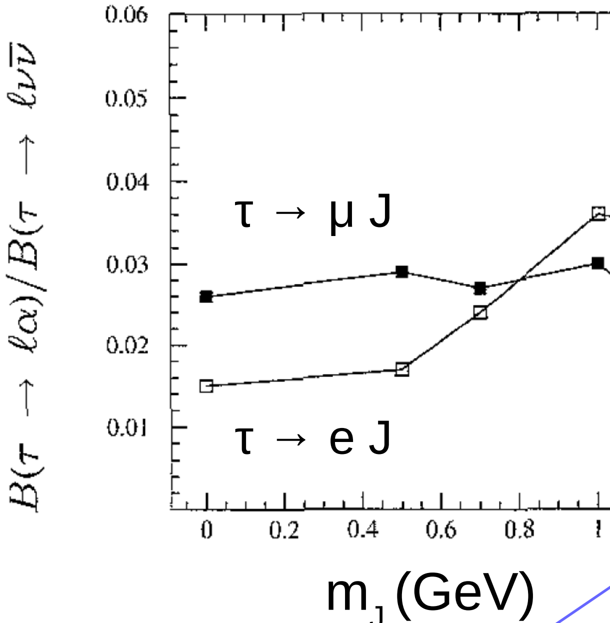
- Improvement with Belle-II.

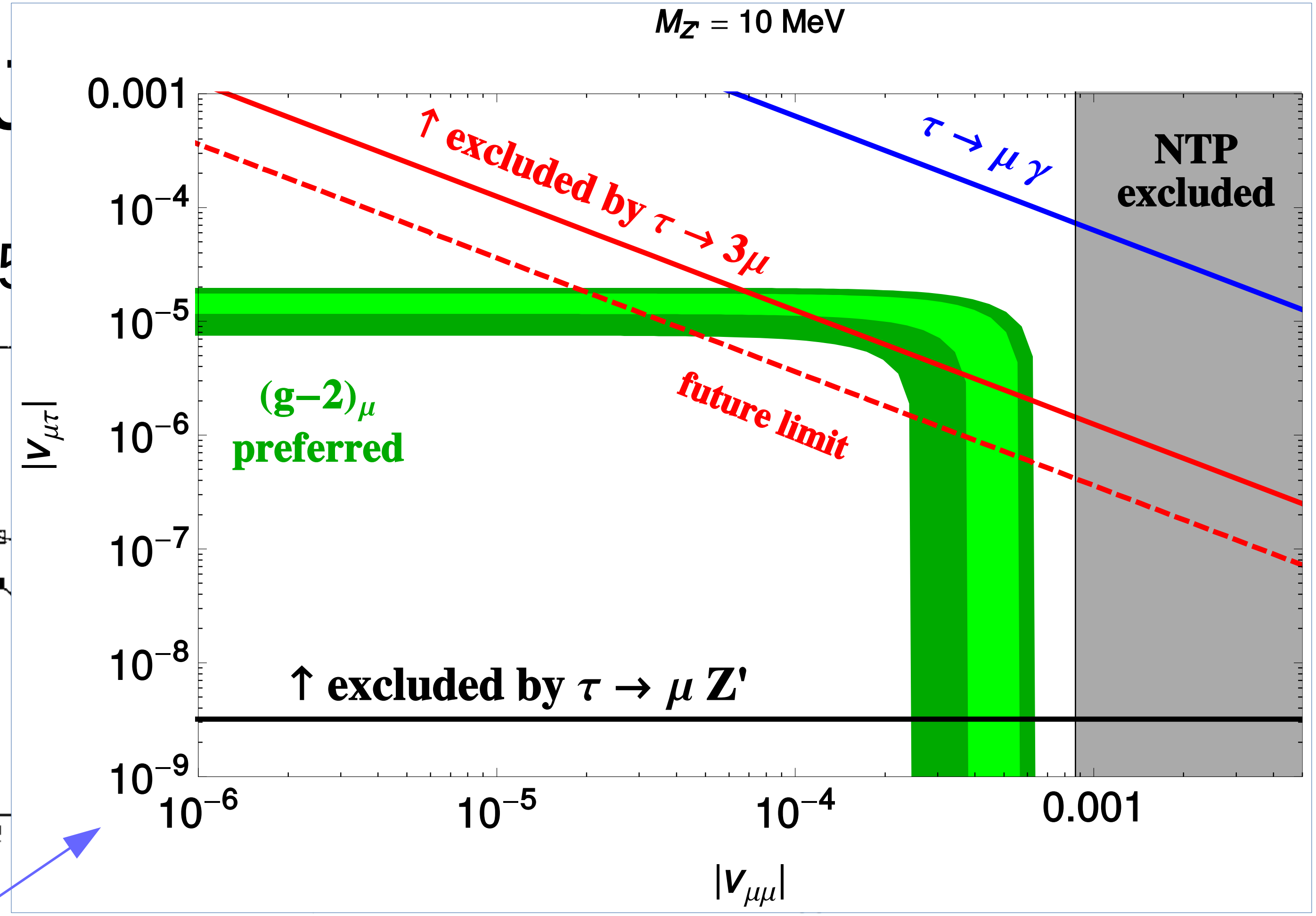
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6\times 10^{-3},$$

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

$\tau \to \ell J$ with J

- ARGUS, ‘95; 5e5





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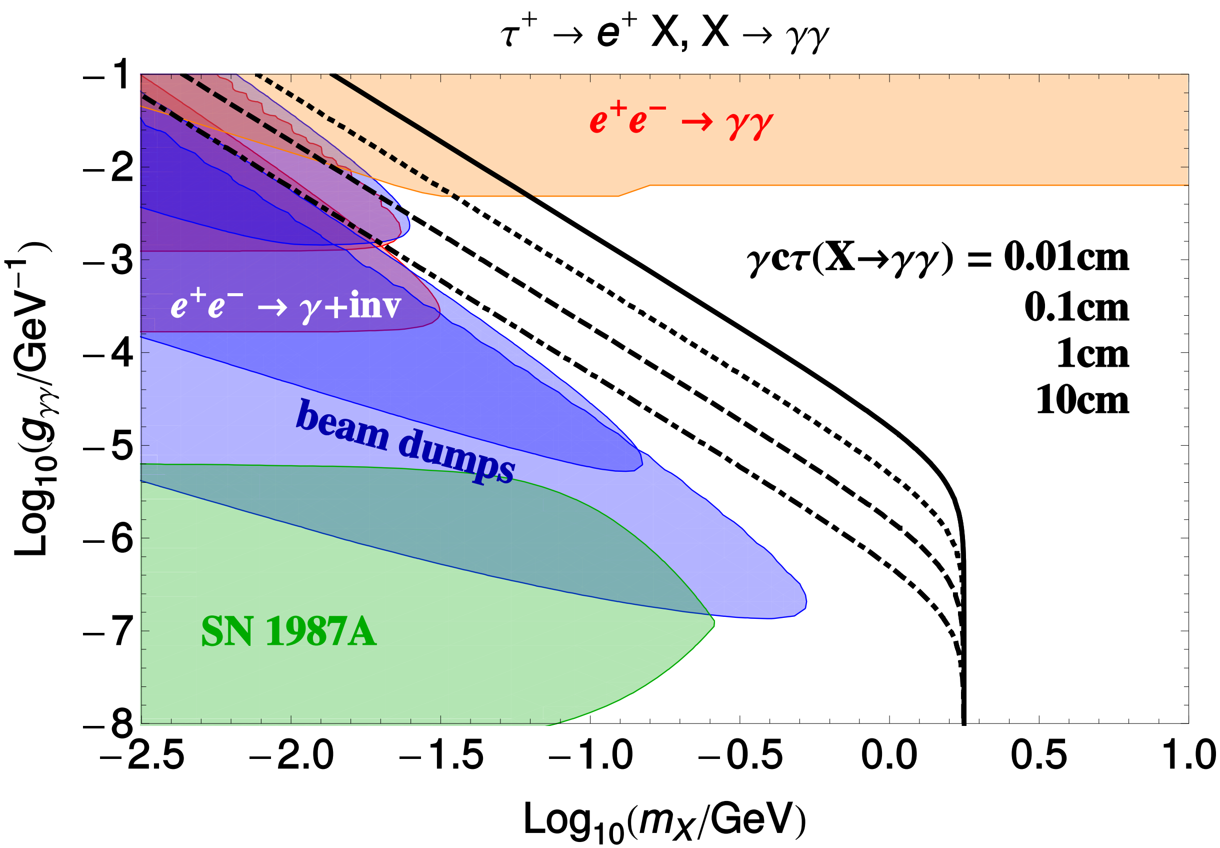
[Heeck, Rodejohann, 1710.02062]

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

- Tau at rest, higher X boost.
- Arbitrary decay lengths possible.
- Similar for $X \to ee, \mu\mu, \mu e$.
- Worthwhile in LHCb and Belle (II).



[Recent limits: Dolan et al, 1709.00009]

Muons difficult, taus easier...

Reconstruct seesaw?

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

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

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

Take from axion/ALP searches.