Neutrino interactions with the dark sector

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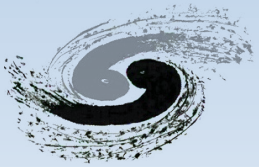


https://xunjiexu.github.io/

Talk at CERN Neutrino Platform Pheno Week, 15/03/2023, https://indico.cern.ch/event/1210319/

ν-osc $\rightarrow$ BSM: Do ν's really interact as the SM predicts?

New ν interactions?

- interactions of ν with SM particles
  - some extensively studied cases:
    $\nu\nu\ell\ell$, $\nu\nu qq$ (NSI), $W^{\pm}$ and Z vertices, ...
  - well constrained, typically at $10\% \sim 1\%$
- interactions of ν with dark particles
  - motivated by the neutrino portal
  - interesting scenarios:
    with ν_R/DM/dark mediators (Z', ϕ), ...
  - weak lab. constraints
  - cosmological consequences

Outline

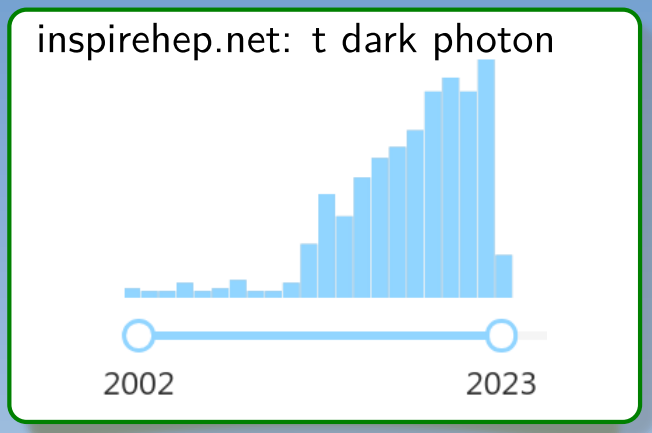
- ν interactions with dark photons/Z'
- ν interactions with dark matter
- ν self-interactions

Neutrino interactions with dark photons/Z'

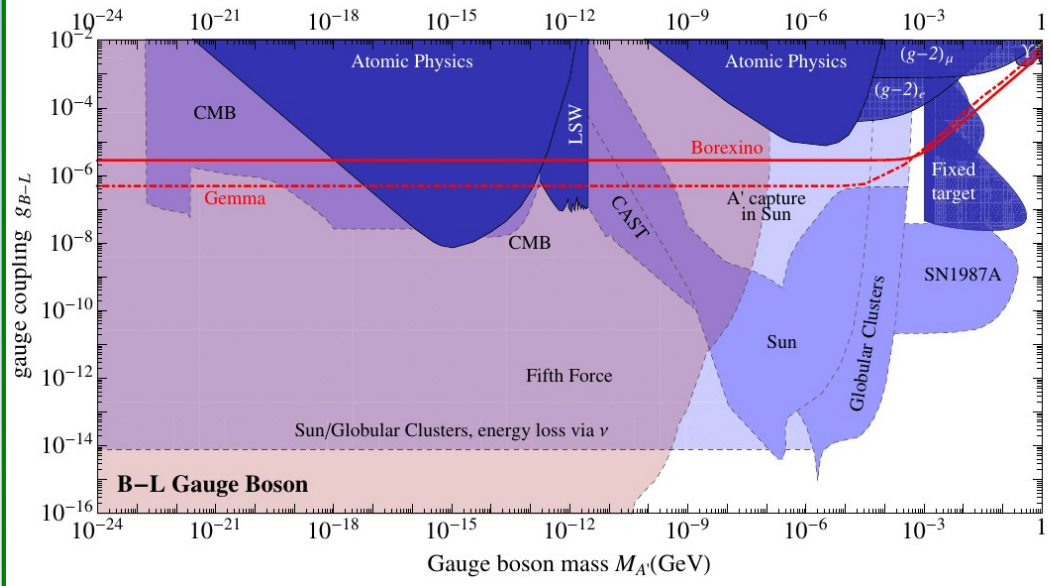
Dark gauge bosons

- rising interest
- intensity frontier, cosmology
- $\epsilon F^{\mu\nu} F'_{\mu\nu}$ vs. $g' Q$ (more model-dep.)

$B - L$, $L_\mu - L_\tau$, ...

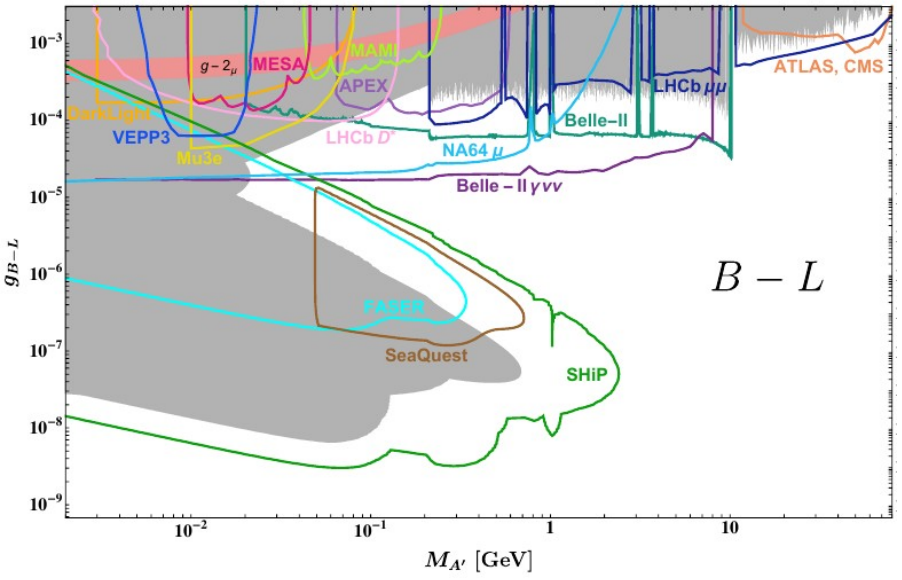


2012



Harnik, Kopp, Machado, 1202.6073

2018



Bauer *et al*, 1803.05466

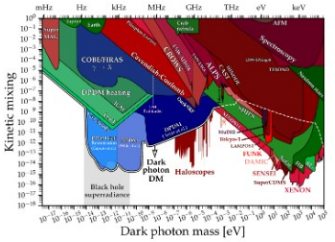
2023 → github/gitlab

Two github/gitlab projects compiling all kinds of bounds

[1] Ciaran O'Hare's Github
https://github.com/cajohare/AxionLimits

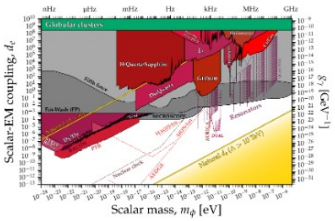
Dark photons

Data files
Plot (pdf, png)



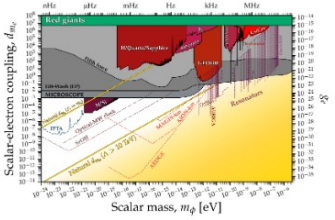
Scalar-photon coupling

Data files
Plot (pdf, png)

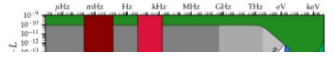


Scalar-electron coupling

Data files
Plot (pdf, png)



Vector B-L coupling

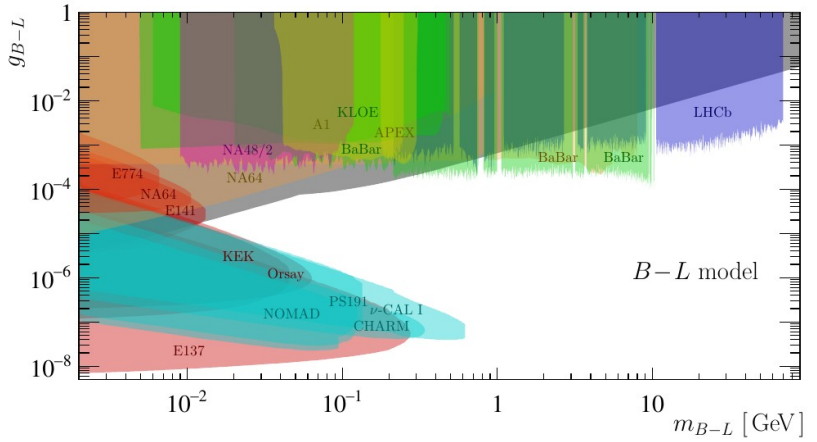


[2] Philip Ilten's Gitlab
https://gitlab.com/philten/darkcast

Philip Ilten › darkcast

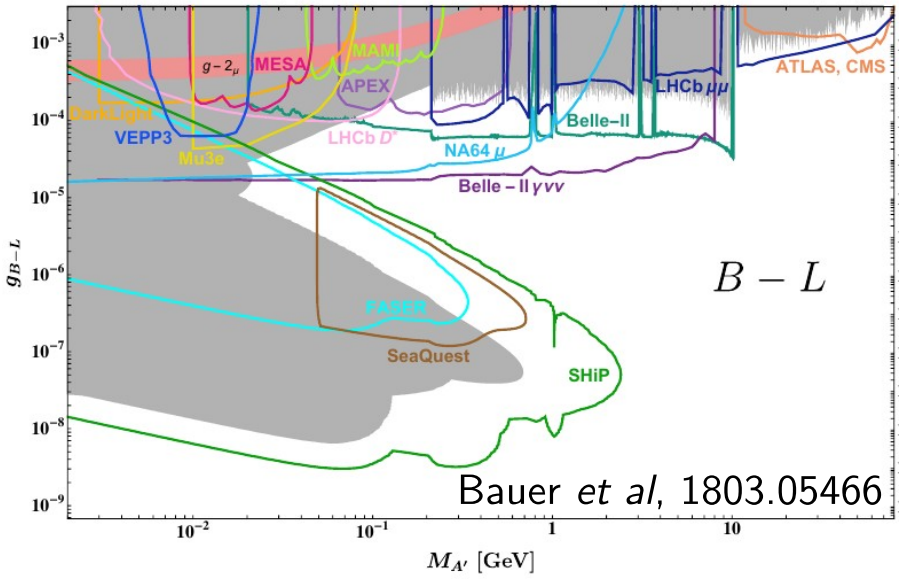
darkcast
Project ID: 5119210

88 Commits 2 Branches 4 Tags 3.6 MB Project Storage

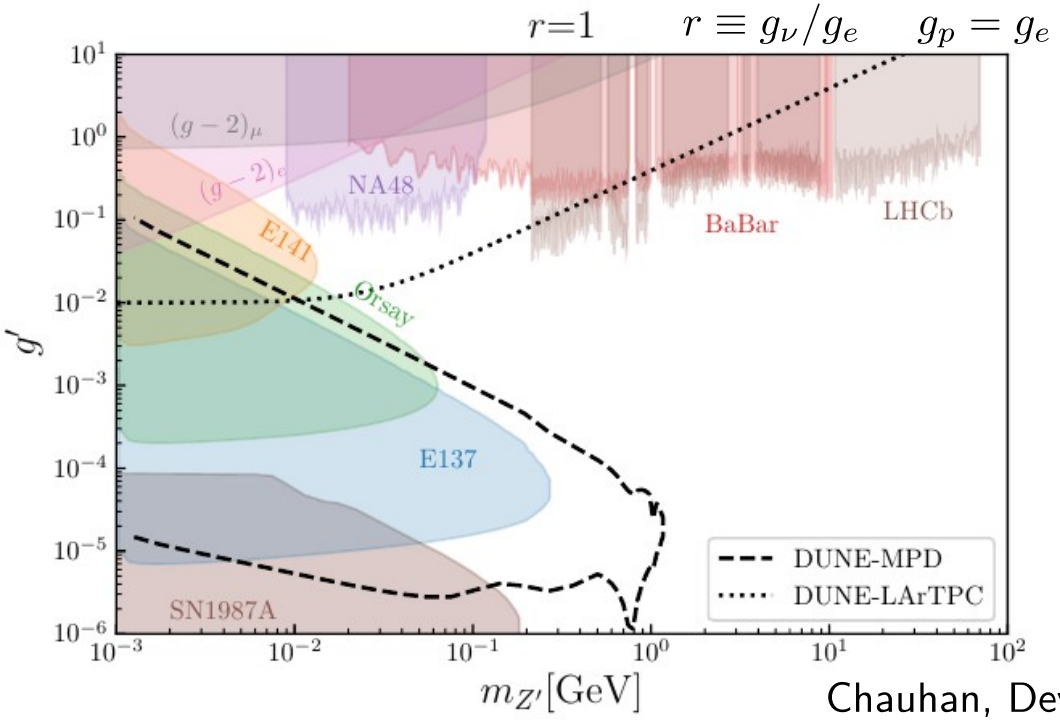


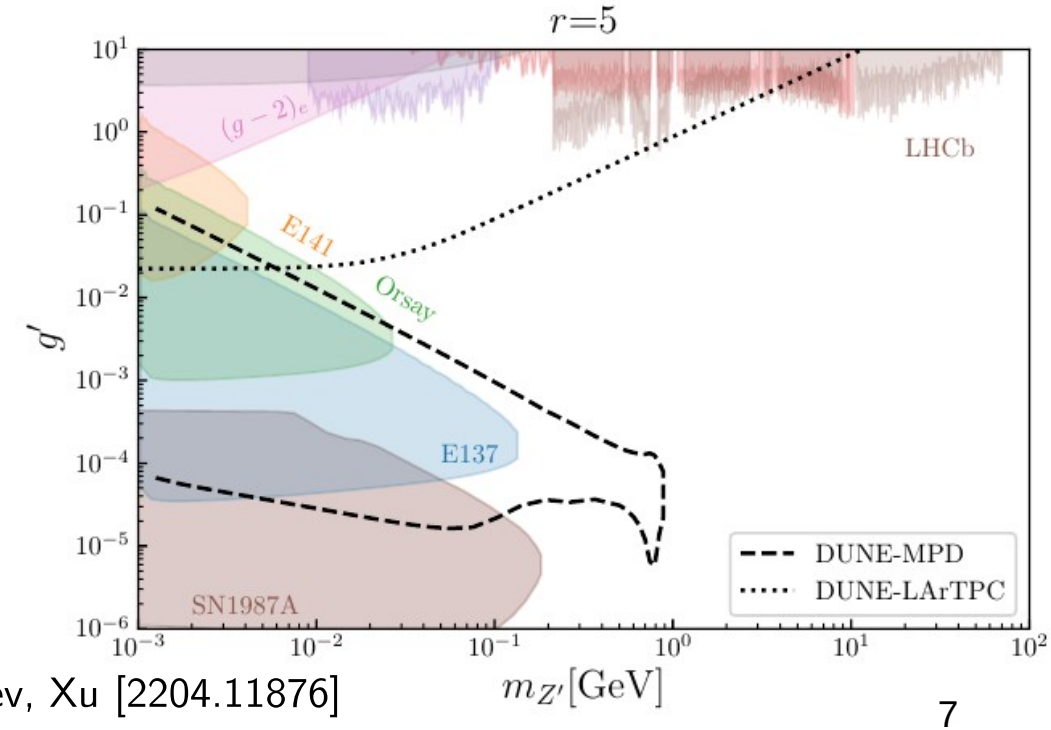
Bounds on $B - L$ gauge boson

- bounds rely on couplings to normal matter (g_e, g_q, ...). also depend on g_ν
- $g_{e,q} \downarrow \rightarrow Z'$ production $\downarrow$
- $g_\nu \uparrow \rightarrow$ Br. of Z' invisible decay $\uparrow$
- $g_\nu \gg g_{e,q}$ more hidden for most exp
  - but for DUNE, ...



Bauer *et al*, 1803.05466





Chauhan, Dev, Xu [2204.11876]

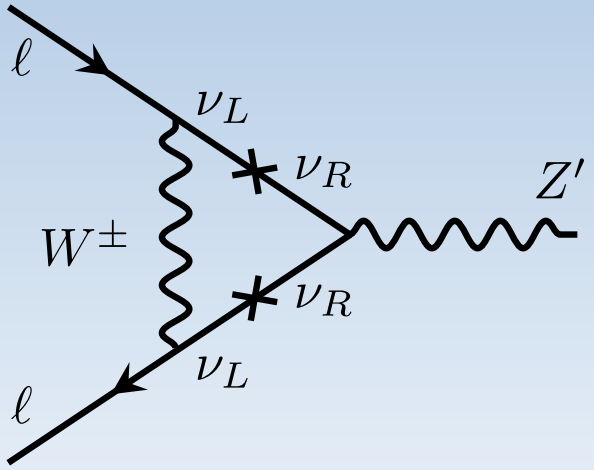
$g_\nu \gg g_e, g_p$, any models?

- yes, often arises from ν_L mixing with dark sector fermions (ν_R)
- see e.g.
  E. Ma, B. Batell, M. Lindner, Y. Farzan, J. Heeck, P. Ballett, M. Hostert, S. Pascoli ... *
- interesting example, the scotogenic model,
  - very economical extension to include: m_ν + DM
  - requires dark symmetry $\rightarrow$ DM stability
    $\downarrow$
    could be dark $U(1)$ in the ν_R sector (E. Ma)

* 1308.5313, 1007.0045, 1310.6582, 1607.07616, 1903.07589, ...

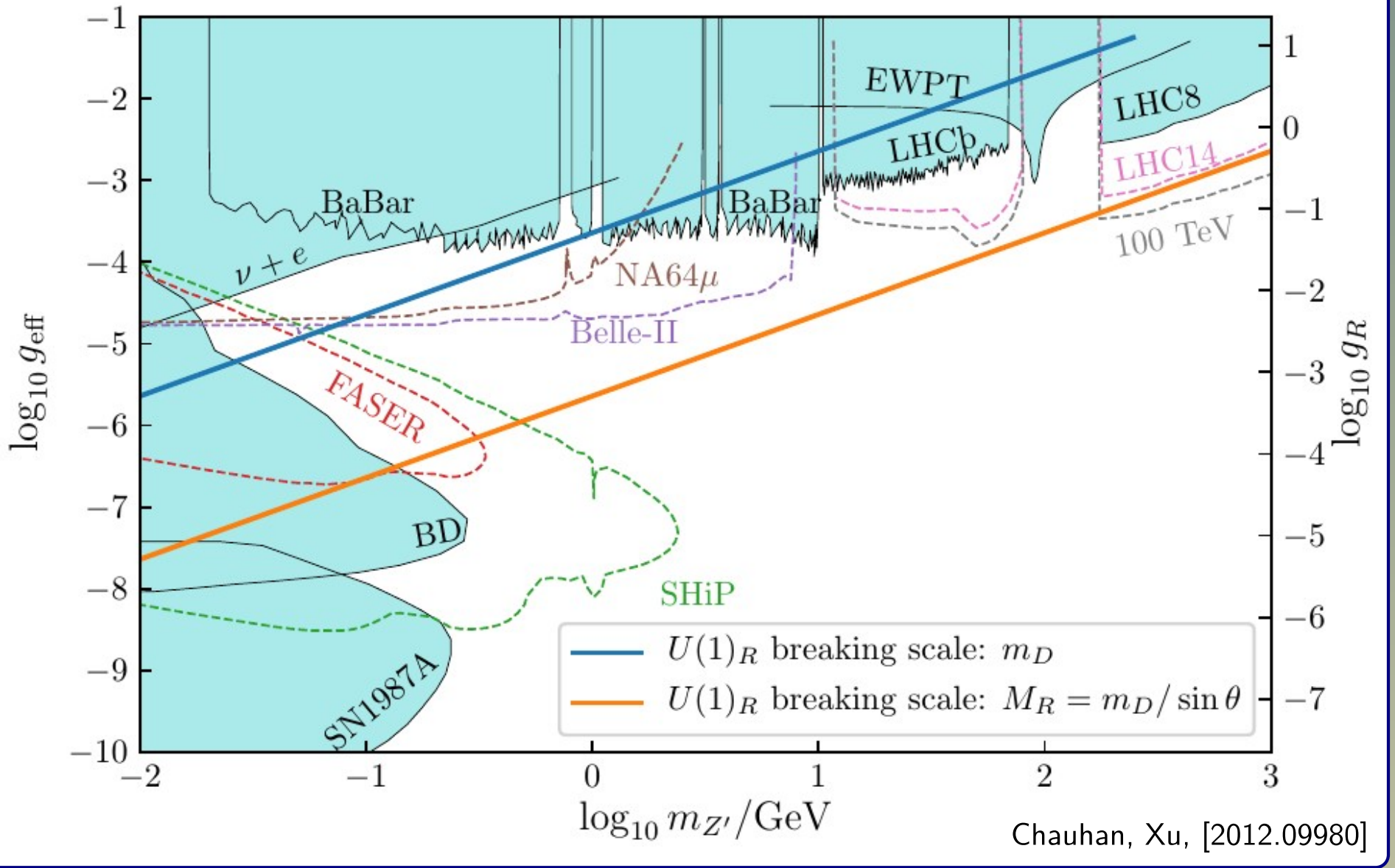
Dark U(1) in the ν_R sector

- Z' not directly coupled to SM, how can we probe it?
- as long as ν_R mixes with ν_L, always loop-induced coupling
- could be accessible to future experiments (SHiP, FASER, etc.)



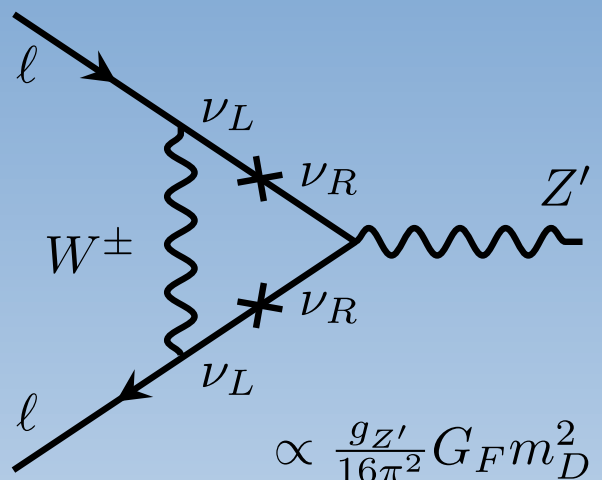
$$g_\ell \propto \frac{g_{Z'}}{16\pi^2} G_F m_D^2$$

ν_R-philic dark photon @ future experiments



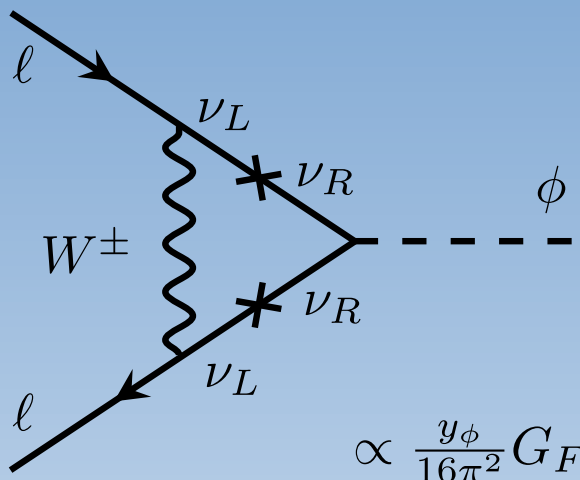
Chauhan, Xu, [2012.09980]

What if vector $\to$ scalar?



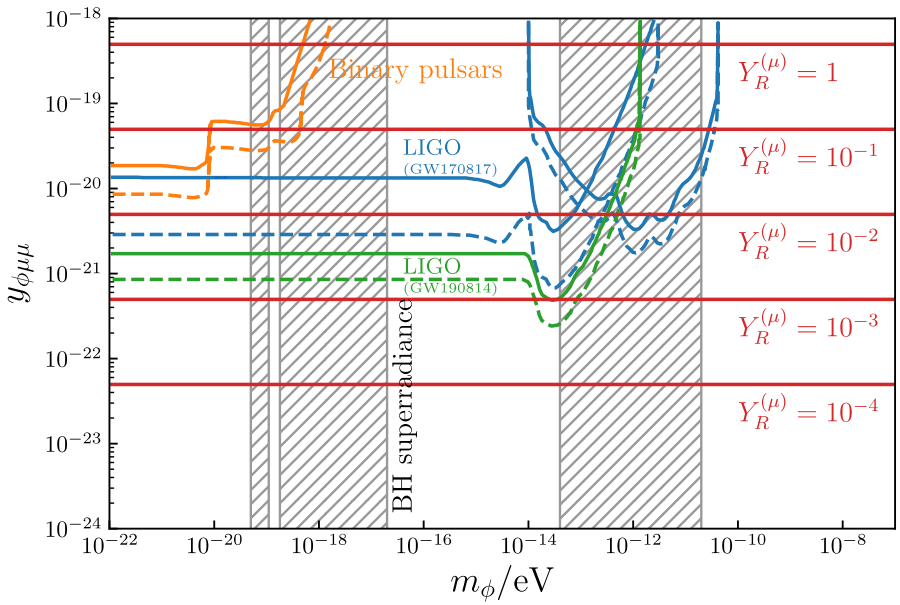
$\propto \frac{g_{Z'}}{16\pi^2} G_F m_D^2$

$\to$



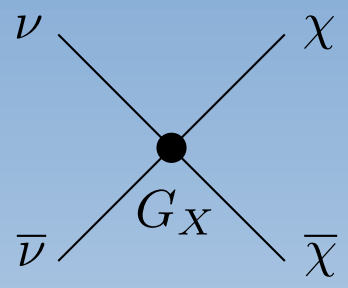
$\propto \frac{y_\phi}{16\pi^2} G_F m_\ell m_\nu$

- suppressed by m_ν
- First computed in Y. Chikashige, R. Mohapatra, R. Peccei (1981) for Majoron
  - Conclusion: too weak for exps.
- Today, might be accessible
  - torsion balance, LIGO, ...



Neutrino interactions with DM

ν-DM interactions



- Contact interaction always $\rightarrow$ DM χ thermalizes $\rightarrow$ freeze-out
- How large is G_X?
  - $\Omega_{\rm DM}h^2 = 0.12 \rightarrow G_X \sim G_F \times 10^2 {\rm GeV}/m_\chi$
- observational consequences from today's DM annihilation
  - monochromatic ν from $\chi\overline{\chi} \rightarrow \nu\overline{\nu}$, sounds great (IceCube, Super-K, ...)
    - but, in general, ☹ [Aisati, Garcia-Cely, *et al*]*
    - Interesting exception: PTOLEMY, keV ν [Hufnagel, Xu]*
  - 1-loop: $\chi\overline{\chi} \rightarrow \nu\overline{\nu} \rightarrow \ell\overline{\ell}$ [M. Blennow, E. Fernandez-Martinez, *et al*]*

* 1706.06600, 2110.09883, 1903.00006

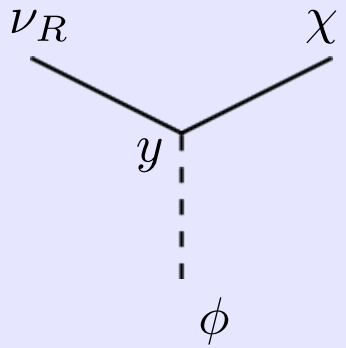
ν-DM interactions

model building: DM-ν_R is much easier than DM-ν_L; ($m_D \nu_L \nu_R$ + DM-ν_R) $\Rightarrow$ DM-ν_L

what if DM only couples to SM via ν_R?

Simplest example

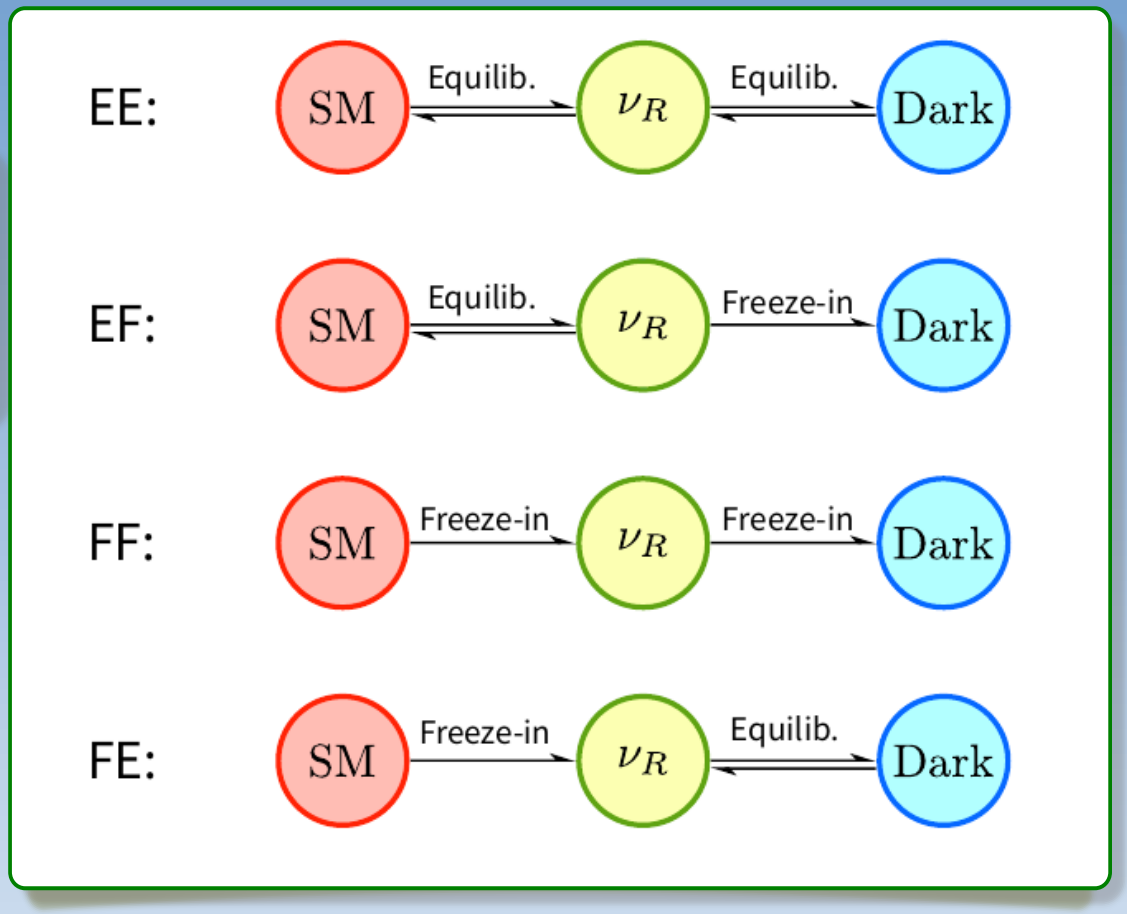
$$\mathcal{L} \supset y \chi \nu_R \phi + \text{h.c.}$$



- all singlets
- χ, ϕ may have dark charges

A lot of papers on this:
M. Pospelov, A. Ritz, A. Falkowski, M. Chianese, B. Dev,
M. Escudero, R. Coy, A. Gupta, T. Hambye, ...

If DM is connected to SM via ν_R,
then in the early universe ...
4 possibilities



Which one?
— depending on SM-ν_R
and ν_R-dark couplings

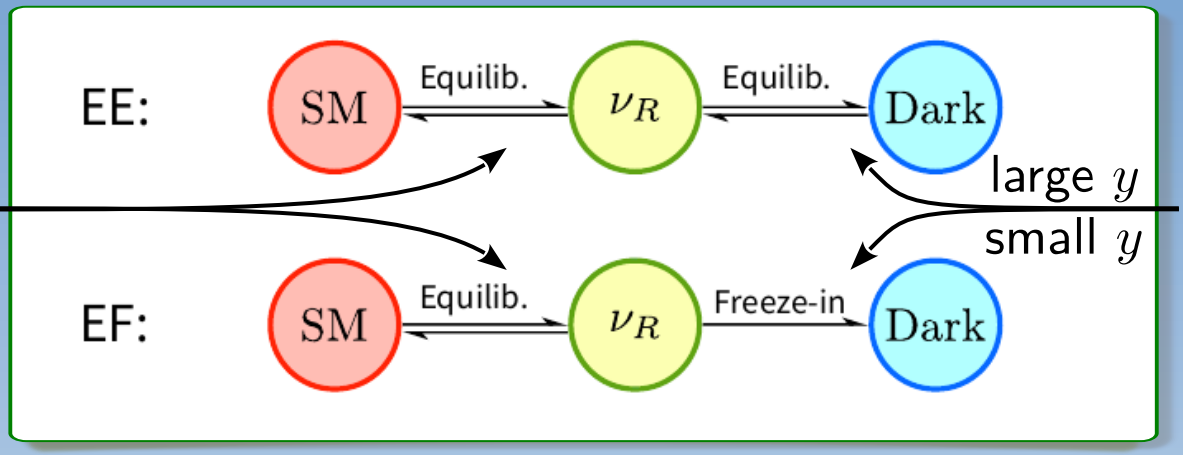
What if the SM-ν_R coupling is fixed by type-I seesaw?

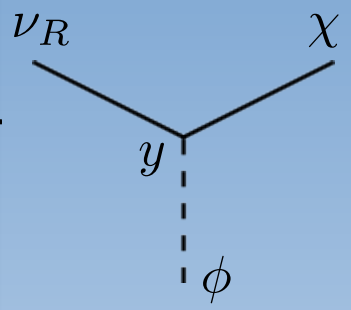
- short answer: EE or EF *
- but ... flavor structure (3 ν_R's)$\rightarrow$ one ν_R could be arbitrarily weakly coupled
  $\rightarrow$ FE/FF also possible †

* Barman, Dev, Ghoshal [2210.07739], Li, Xu [2212.09109]

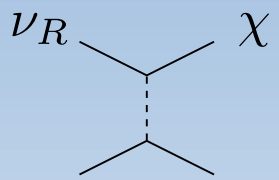
† R. Coy, A. Gupta, T. Hambye [2104.00042]

Type-I seesaw

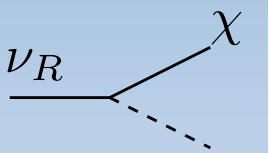


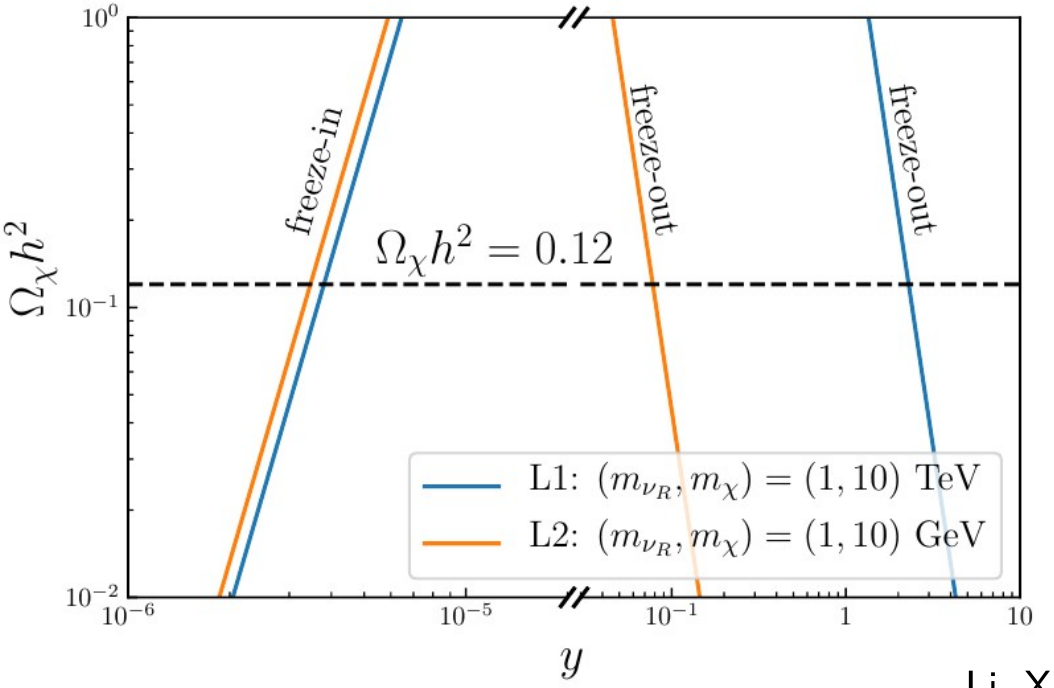


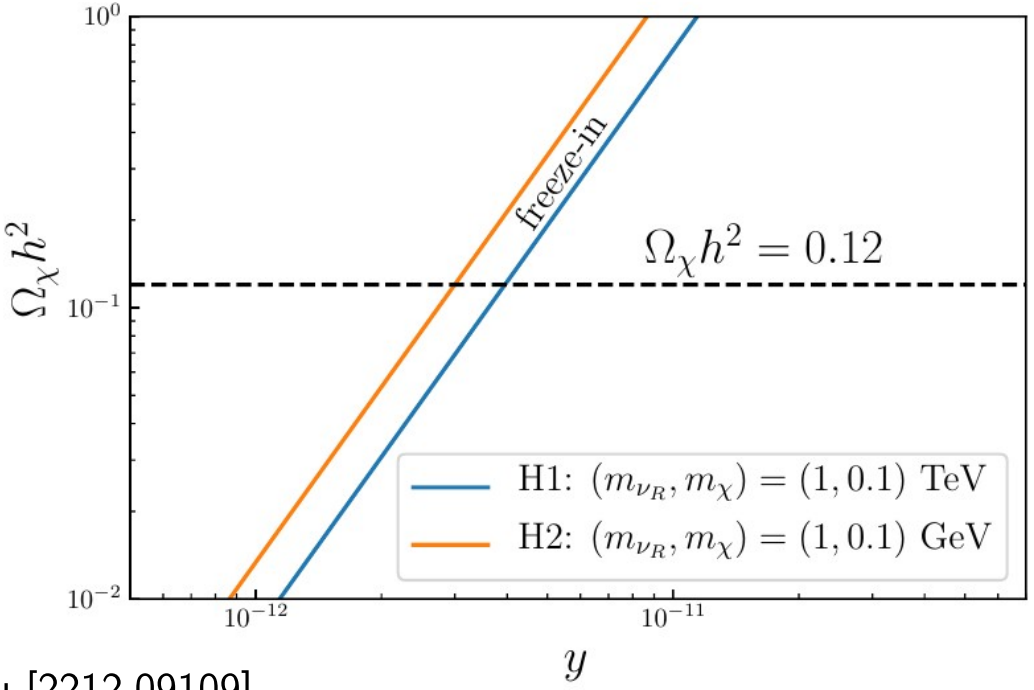
Light ν_R: scat. dominated



Heavy ν_R: decay dominated



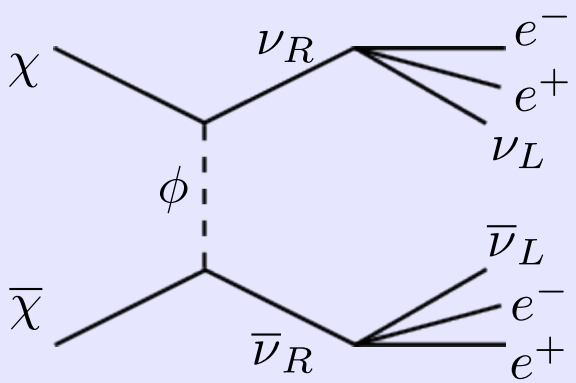




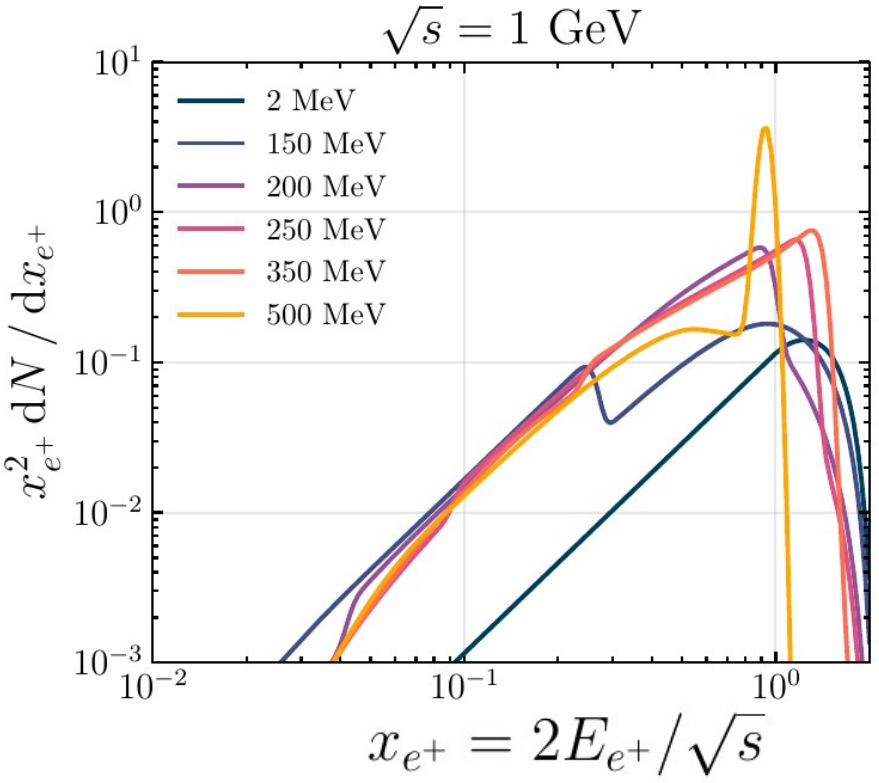
Li, Xu [2212.09109]

Observational consequences

Indirect detection



- $\chi\overline{\chi} \to$ high-E $e^+/\gamma/\nu$ rays.
- HESS, CTA, LHAASO, IceCube
- no longer monochromatic
- still, a bump at $E \sim m_\chi$

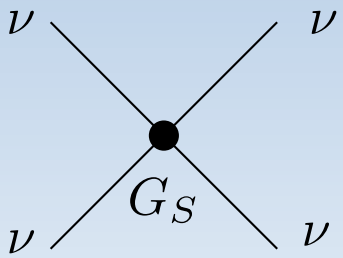


Morrison, Profumo, Shakya, [2211.05996]

$N_{\rm eff}$

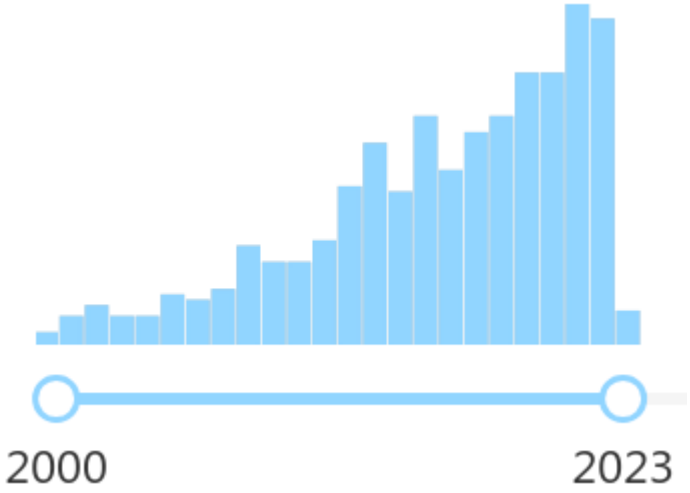
- $\chi\overline{\chi} \to \nu_L\overline{\nu}_L$ below MeV, or $\chi\overline{\chi} \to \nu_R\overline{\nu}_R$ for Dirac ν; casuing $\Delta N_{\rm eff}$
- In general, too small; but FE $\to$ large $\Delta N_{\rm eff}$ [Li, Xu, 2212.09109]

Neutrino self-interactions

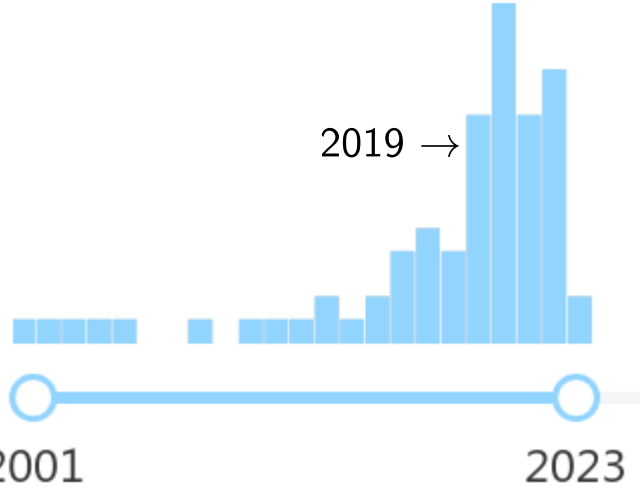


Rising interest, why?

fulltext: neutrino self-interactions

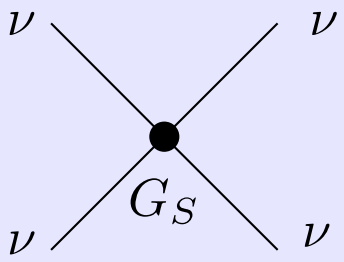


t neutrino* and t self-interact*



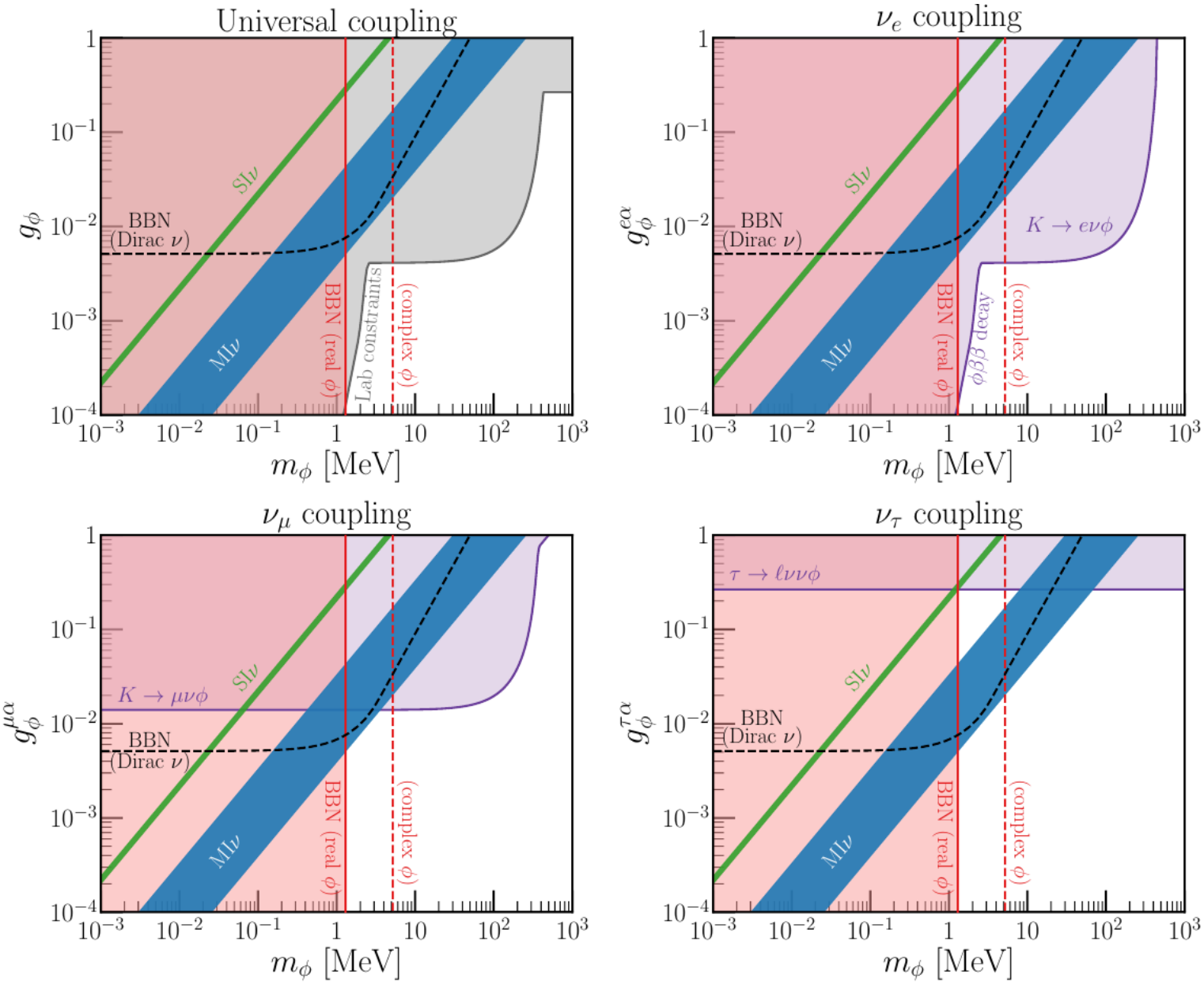
see also 4 talks tomorrow and Friday

- partially due to the cosmological H_0 tension*
- A question for particle physicists:
  how much do we know about ν self-int.?
  - Ans: not much, even $G_S = 10^{7\sim9} G_F$ cannot be ruled out!

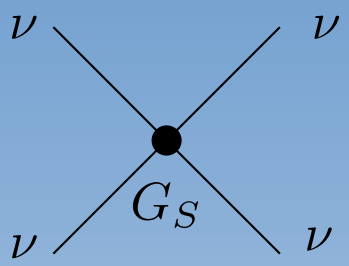


* Kreisch *et al* 1902.00534; Brinckmann *et al* 2012.11830; ... see Shouvik's talk on Friday

... even $G_S = 10^{7\sim9} G_F$ cannot be ruled out!



N. Blinov, K. Kelly, G. Krnjaic, S. McDermott, [1905.02727]

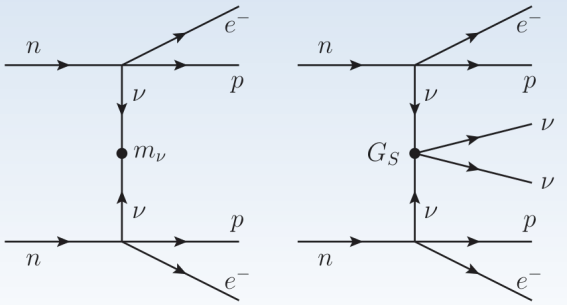


Why so difficult to probe/exclude ν self-interactions?

—hard to find circumstances where ν's meet each other

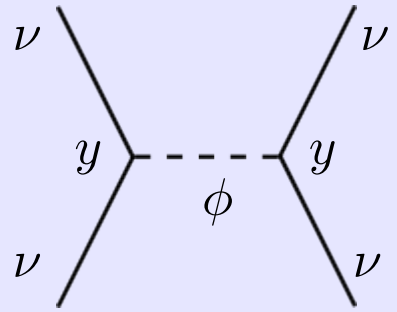
... still, some ways ...

- dense environment, such as supernovae:
  - Bustamante *et al* [2001.04994], Chang *et al* [2206.12426], Cerdeño *et al* [2301.00661] ...
    see Ivan's and Marina's talks tomorrow
- ν scattering CνB
  - A. Das *et al* [2204.11885], ...
    see Yuber's talk
- ν from particle decays:
  - Z and τ decay [Brdar, *et al* 2003.05339], ...
  - meson decay [Berryman, *et al* 1802.00009], ...
  - $0\nu\beta\beta$ [Deppisch *et al* 2004.11919], ...



A (somewhat crazy) consequence of ν self-interactions ...

Neutrino stars



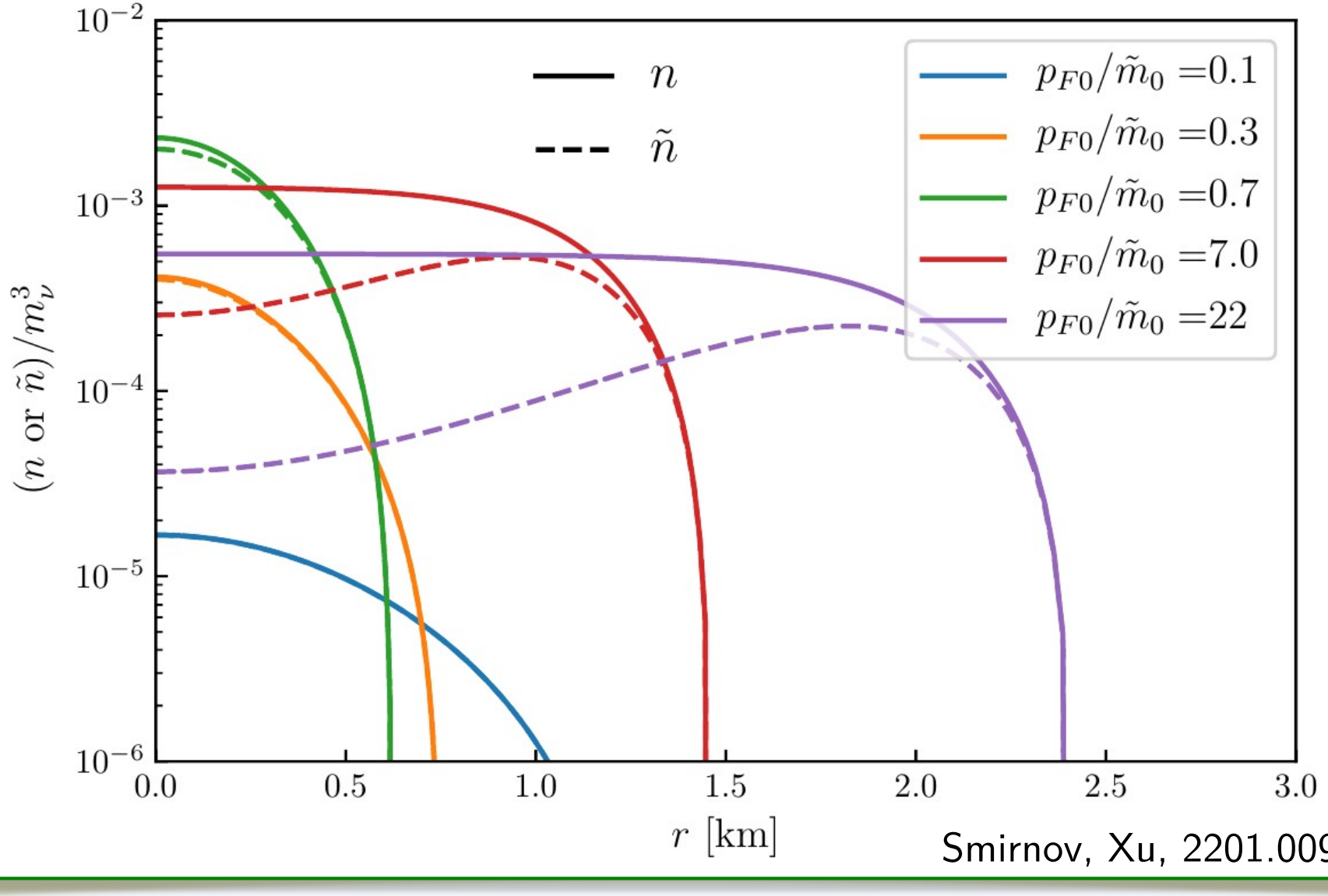
$\Rightarrow$ Yukawa potential

$$V \approx \frac{y^2}{4\pi r} e^{-m_\phi r}$$

- 2-ν bound states always possible if ... $\lambda \equiv \frac{y^2}{8\pi}\frac{m_\nu}{m_\phi} \gtrsim 0.84.$
- 2-$\nu \to$ 3-ν, 4-ν, 5-ν, ... N-ν
- evetually, you get a ν star, condition: $S_\phi \equiv y^2 \frac{m_\nu^2}{m_\phi^2} \gtrsim 70$
- with the minimal radius:

$$R_{\rm min} \approx 0.62{\rm km} \times \left(\frac{10^{-7}}{y}\right)\left(\frac{0.1\ {\rm eV}}{m_\nu}\right)$$

Smirnov, Xu, 2201.00939



Smirnov, Xu, 2201.00939

Summary

- ν-Z' interactions
  - $g_\nu \gg g_{e,q} \rightarrow$ large Br. of $Z' \rightarrow$ invisible
    $\rightarrow Z'$ more hidden from exp.
  - motivated by the ν_R portal
    loop-induced couplings, small but accessible by exp.
- ν-DM interactions
  - $\Omega_\chi h^2 = 0.12 \rightarrow G_X = ...$, or $y = ...$
  - observational consequences: ν signals from DM anni., $\Delta N_{\rm eff}$
- ν self-interactions
  - very strong ν self-int. still cannot be effectively ruled out
  - bounds from SN, ν-CνB scattering, $Z/K^\pm/0\nu\beta\beta$ decays, ...
  - ν's could form ν stars

Backup

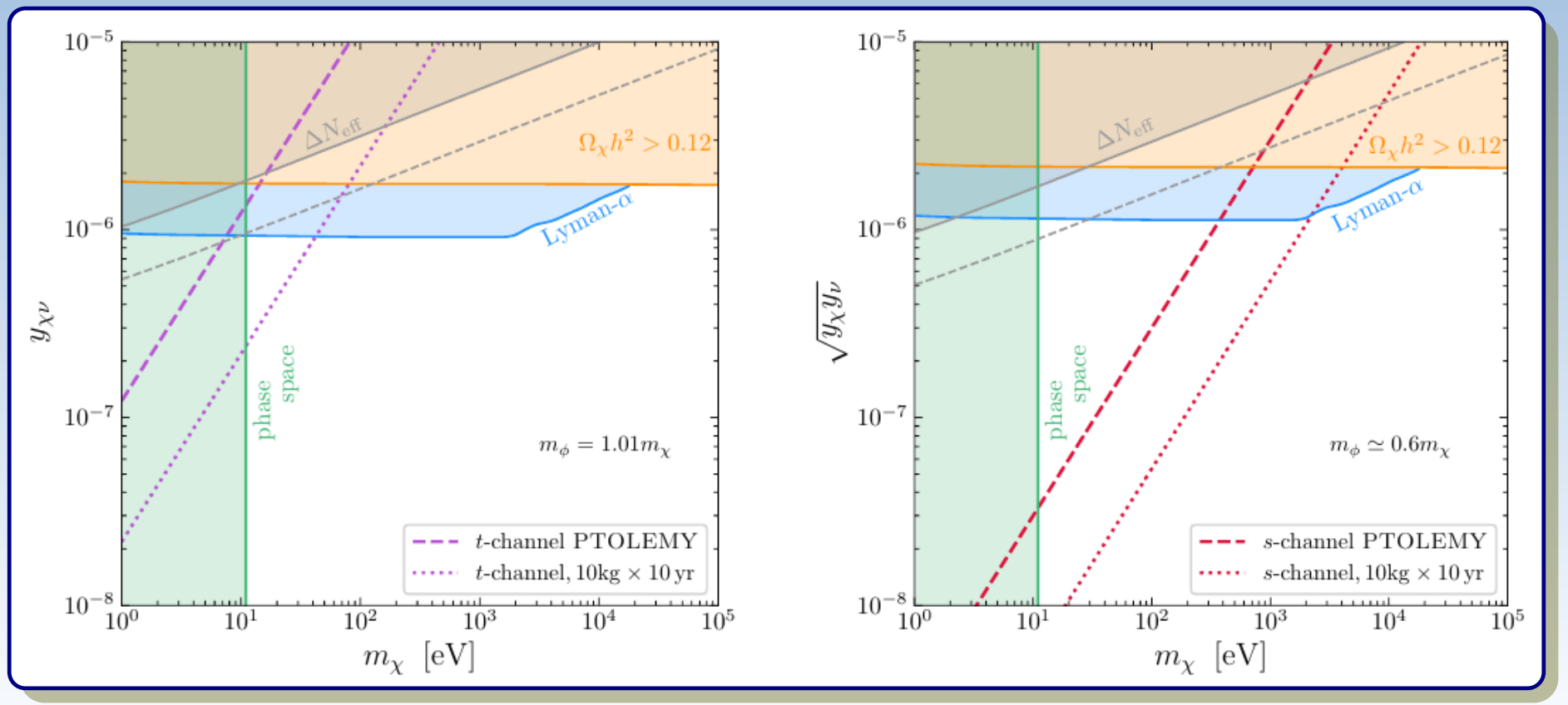
Neutrinos from Galactic DM annihilation

PTOLEMY:

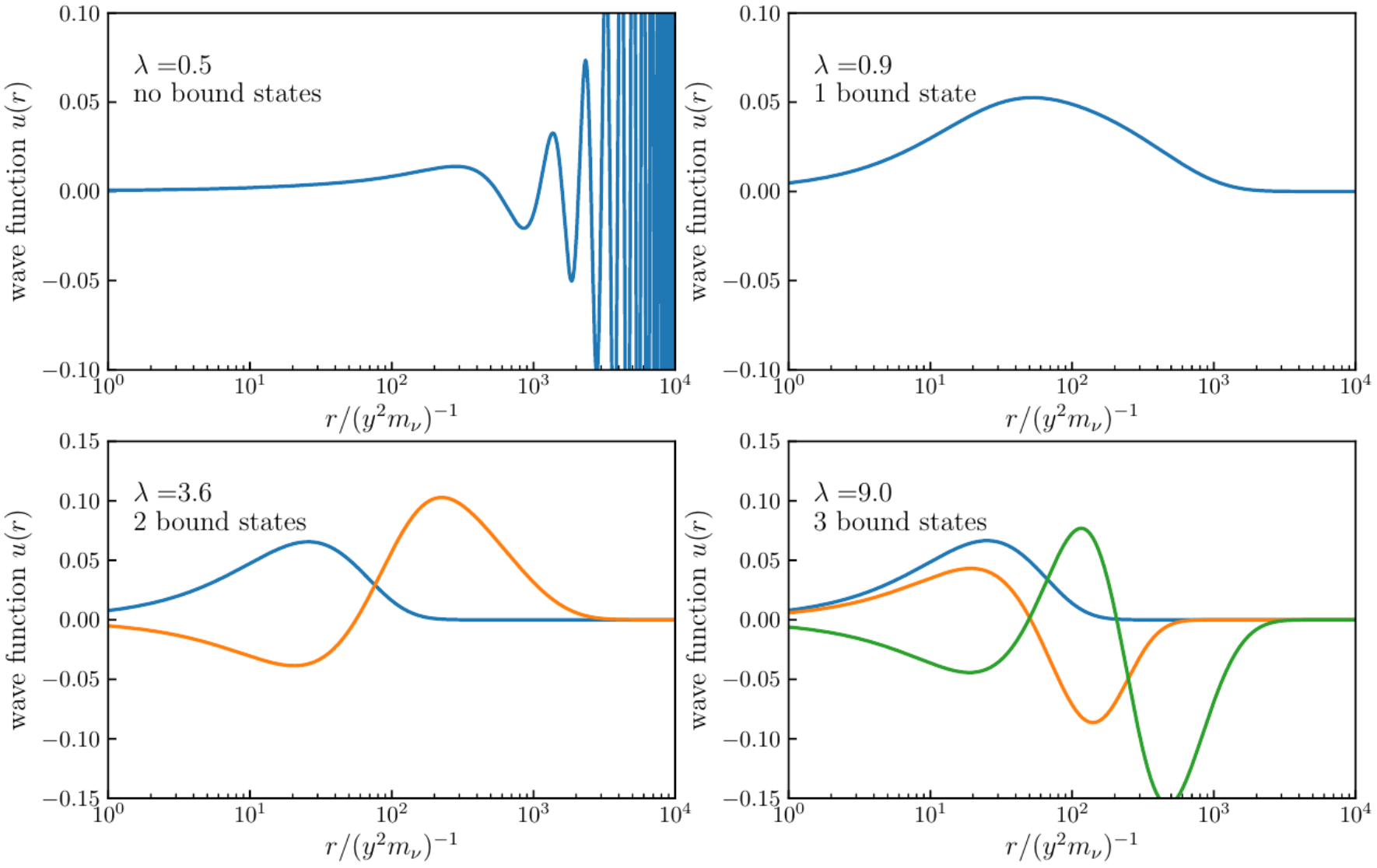
$$\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

zero threshold, but requires high energy resolution.
detection of ν from DM anni. less challenging than CνB

$$\Gamma_{\mathrm{cap}} = 1\,\mathrm{event/year} \times \left(\frac{M_{\mathrm{tritium}}}{100\,\mathrm{g}}\right) \times \left(\frac{\Phi_\nu}{2\times 10^{11}\,\mathrm{cm^{-2}s^{-1}}}\right)$$



2-neutrino bound states



known bounds on very light ν-philic ϕ

processes	flavor dependence	bounds	Ref.
$\pi^{\pm}$ decay	ν_e	$y < 1.3 \times 10^{-2}$	[25]
$K^{\pm}$ decay	ν_e, ν_μ	$y < 1.4 \times 10^{-2}$ (ν_e) or $< 3 \times 10^{-3}$ (ν_μ)	[25]
$\beta\beta$ decay	ν_e	$y < 3.4 \times 10^{-5}$	[26]
Z decay	all flavors	$y < 0.3$	[27]
BBN	all flavors	$y < 4.6 \times 10^{-6}$	[9]
CMB	all flavors	$y < 8.2 \times 10^{-7}$	[28]
SN1987A (energy loss)	all flavors	$y < 3 \times 10^{-7}$ or $2 \times 10^{-5} < y < 3 \times 10^{-4}$	[29]
SN1987A (deleptonization)	ν_e	$y < 2 \times 10^{-6}$	[30]

Phase transition