Dark forces from right-handed neutrinos

Xun-Jie XU

Service de Physique Théorique, Université Libre de Bruxelles

xunjie.xu@gmail.com

https://xunjiexu.github.io/

[1] X. Xu, JHEP 09, 105, (2020), [2007.01893]
[2] Garv Chauhan, X. Xu, [2012.xxxxx]

The SM and fundamental forces

1. Gravity

   graviton:

2. Electromagnetic force

   photon:

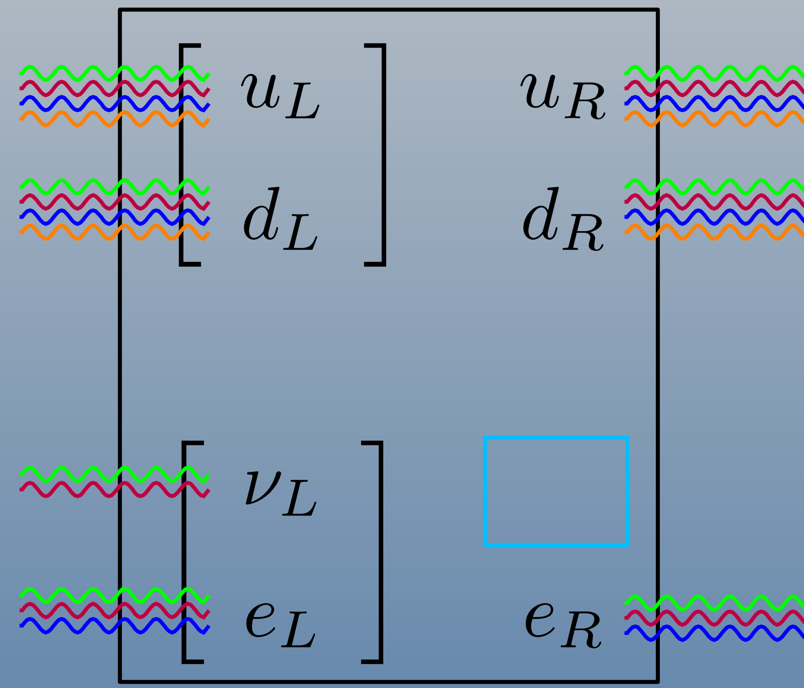
3. Weak force

   $W^{\pm}/Z$:

4. Strong force

   gluons:

5. ...



Fundamental long-range forces

Long-range forces in spin-2? Gravity

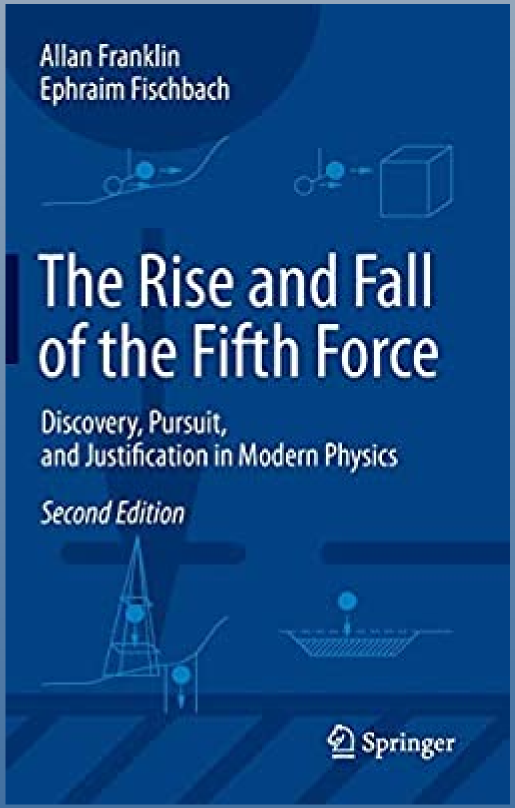
spin-1? Photon

spin-0?

Search for long-range Yukawa forces?

... not new ...

from 1980s to 1990s, already ...



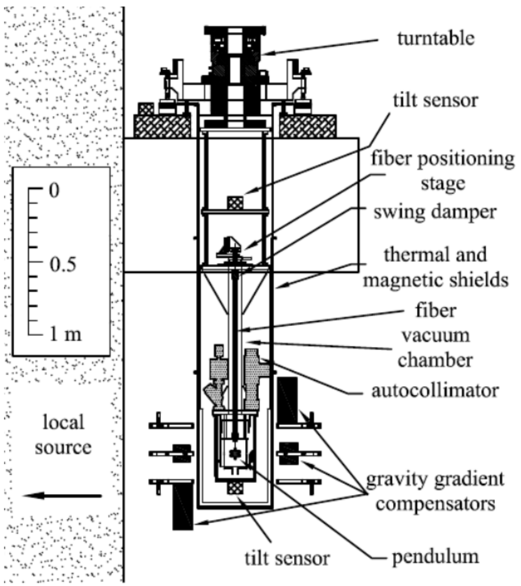
Progress still going on ...

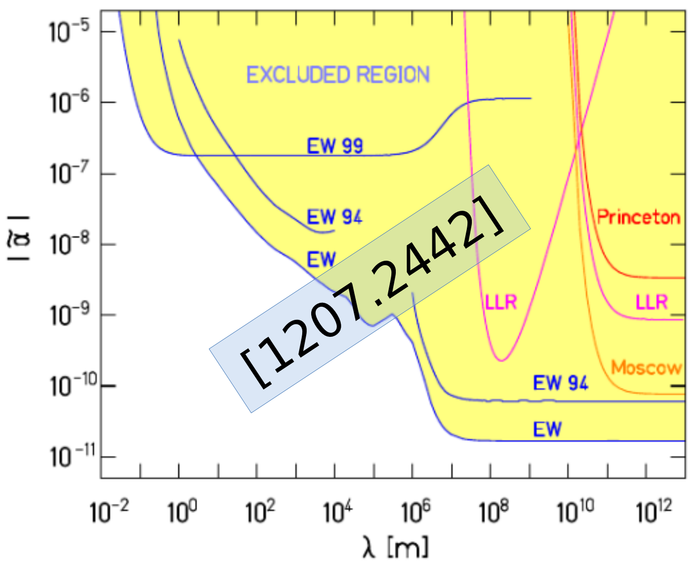
Torsion-balance tests of Equivalence Principle

Lunar Laser-Ranging (LLR) technology

Long-range forces in neutrino oscillation

And, of course, LIGO/VIRGO ...





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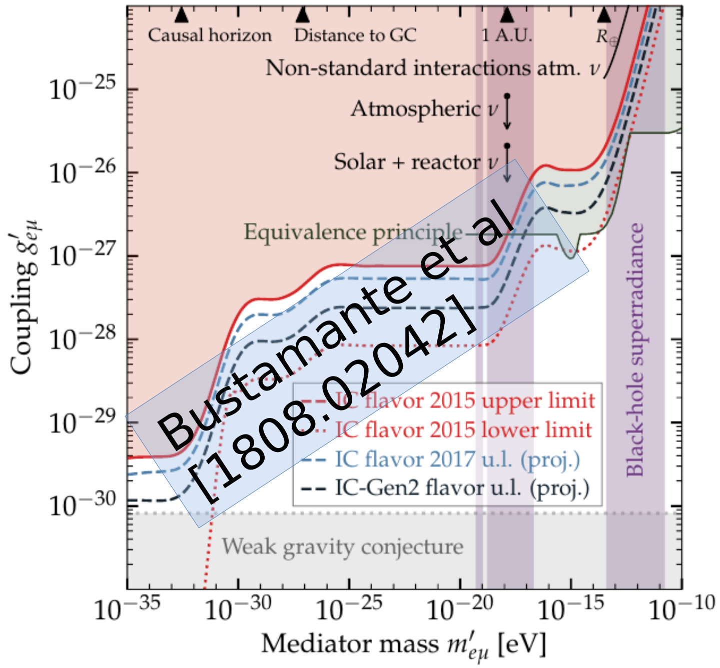

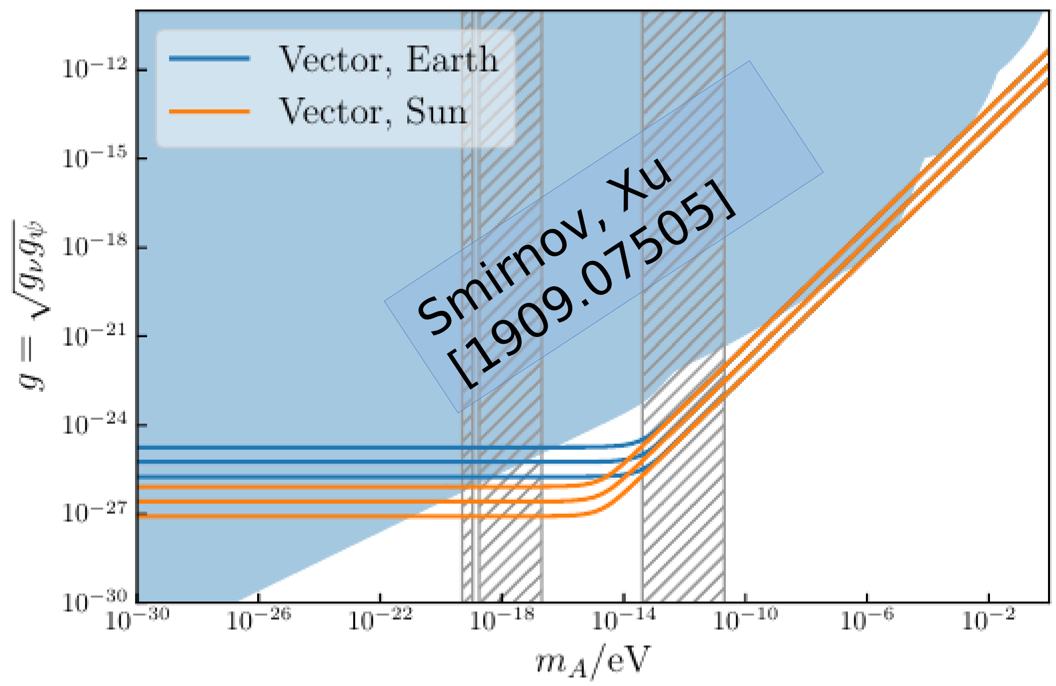

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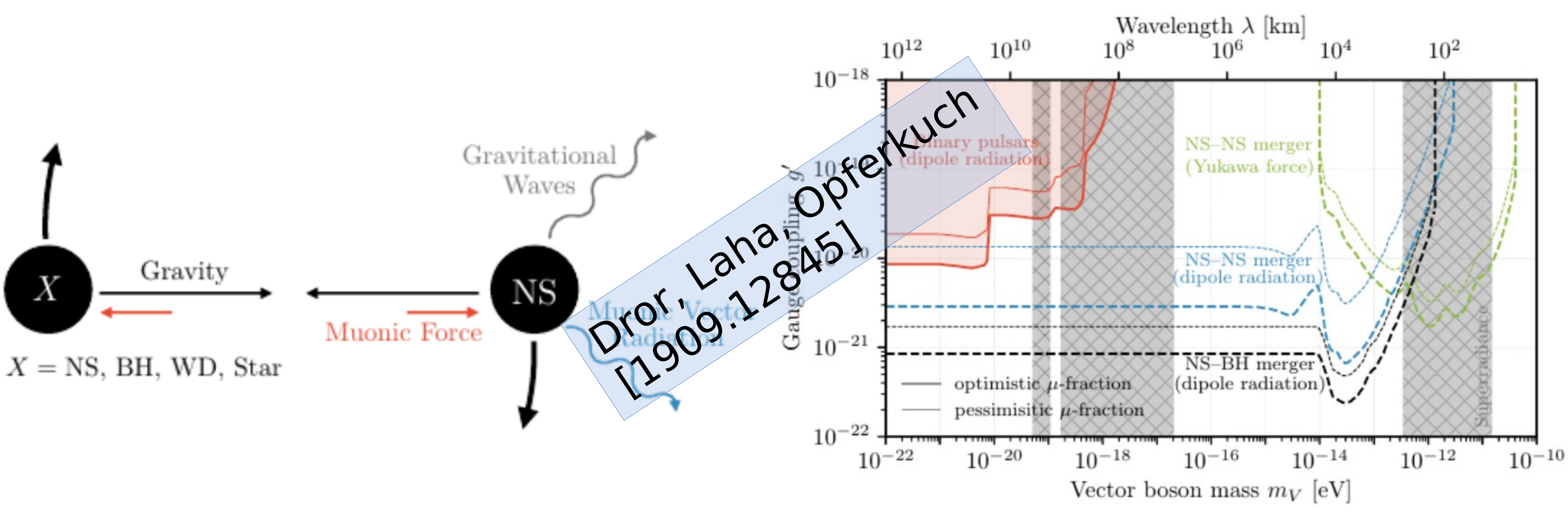


Dror, Laha, Opferkuch [1909.12845]

Experimental bounds:

$$\ldots, 10^{-10}, 10^{-15}, 10^{-20}, \ldots$$

How weak do you expect the new force to be?

How weak do you expect the new force to be?

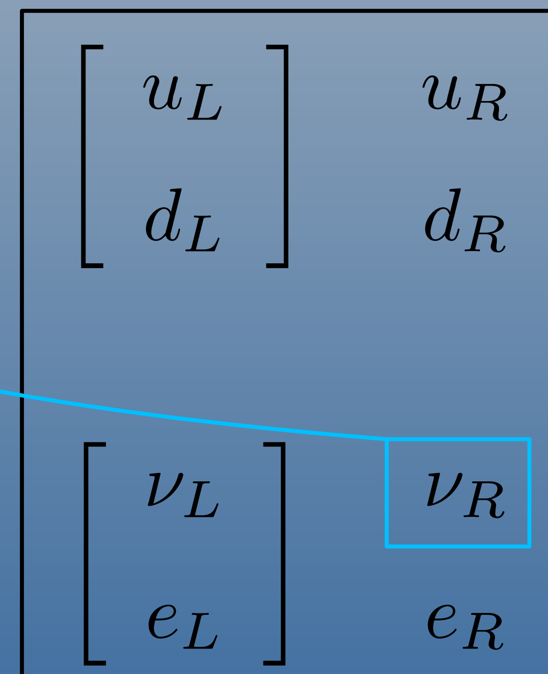
An answer from ν_R-philic scalar:

$$y_e \sim \frac{G_F m_e m_\nu}{16\pi^2} \sim \mathcal{O}\left(10^{-21}\right), y_\mu \sim \frac{G_F m_\mu m_\nu}{16\pi^2} \sim \mathcal{O}\left(10^{-19}\right)$$

Adding the missing piece of SM, we get a ν_R-portal:

$$\mathcal{L} \supset \nu_R \nu_R \phi$$

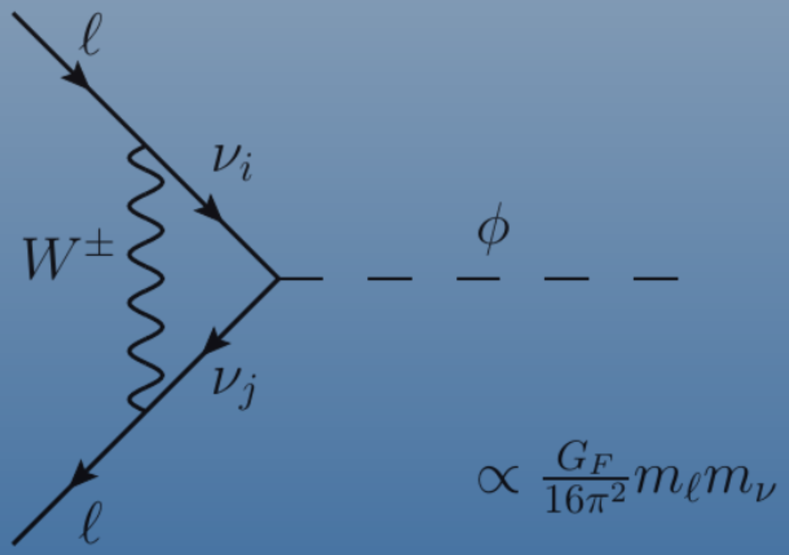
and hence a new dark force

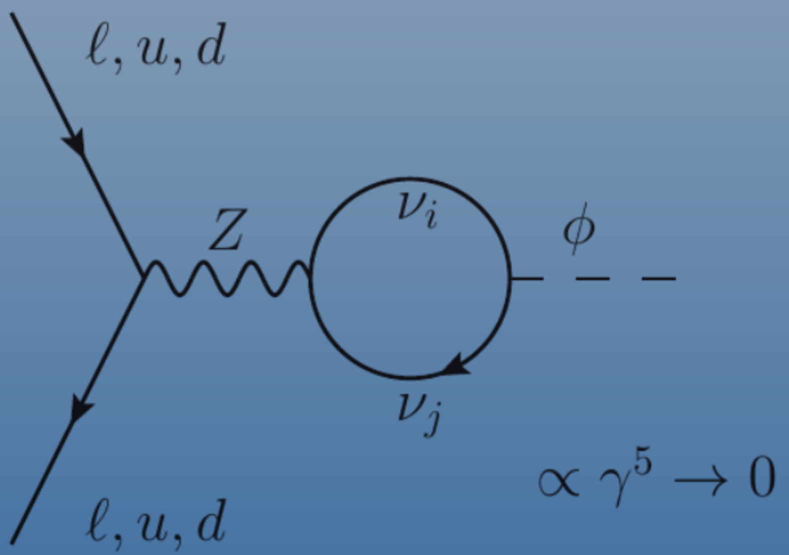


The new dark force from

$$\mathcal{L} \supset \nu_R \nu_R \phi$$

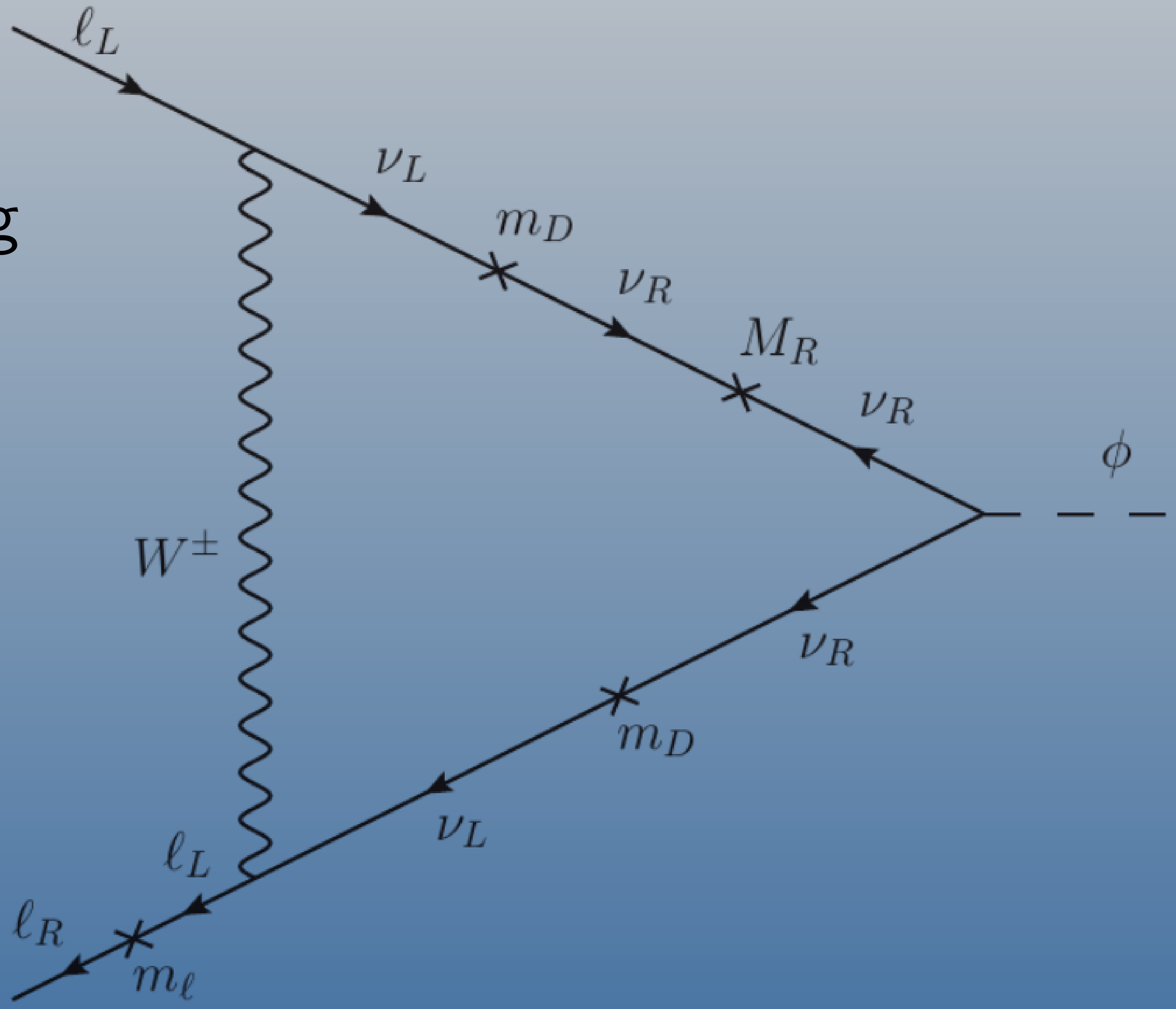
does not couple to normal matter directly.
But, ...





Why $\frac{G_F}{16\pi^2} m_\nu m_\ell$?

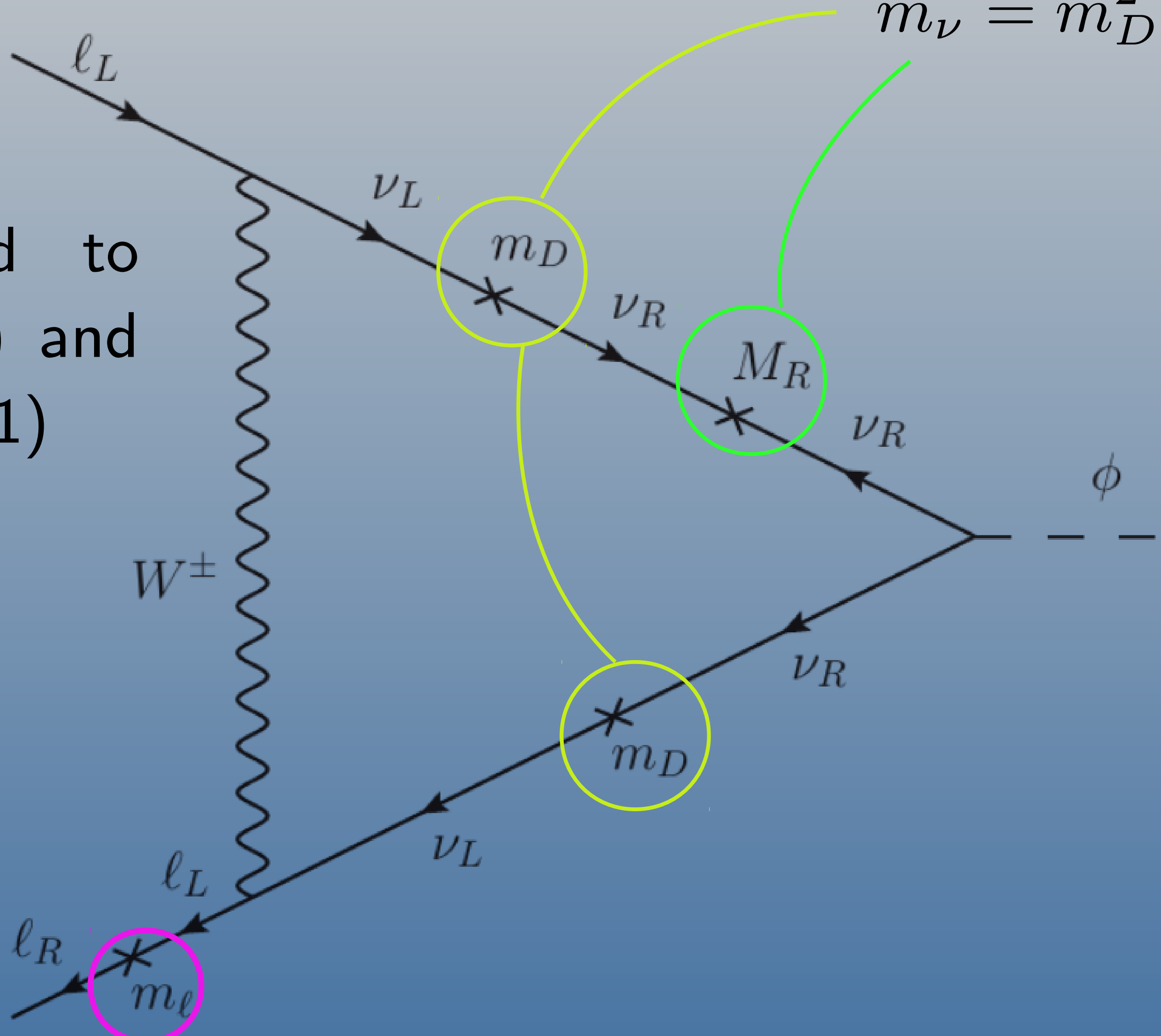
Because of chirality flipping



Why $\frac{G_F}{16\pi^2} m_\nu m_\ell$?

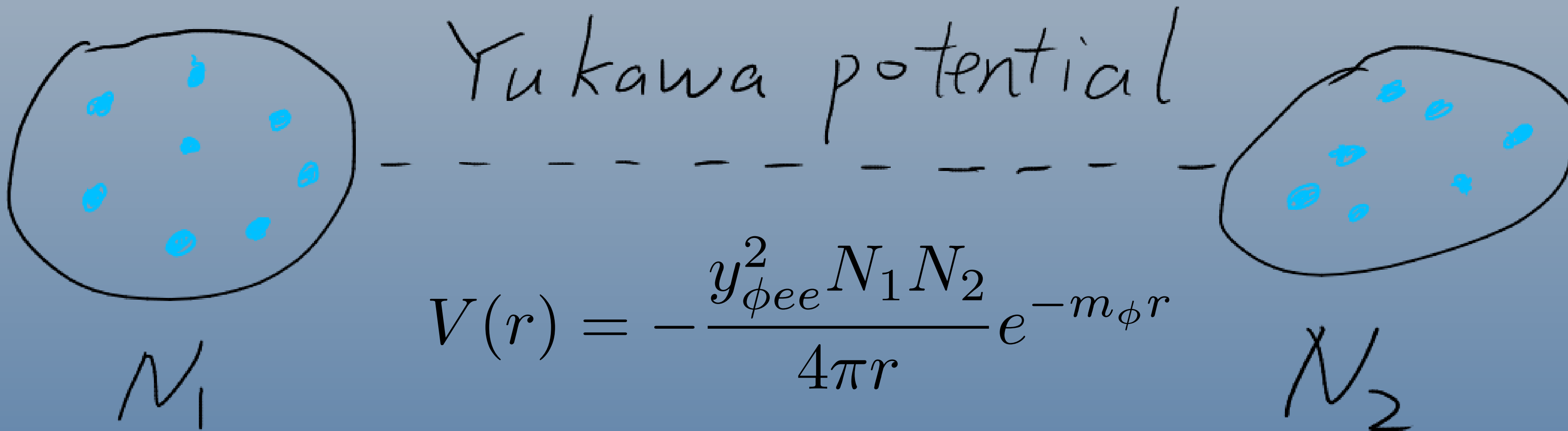
Seesaw formula:
$m_\nu = m_D^2/M_R$

Because we need to flip chirality ($\times$ 3) and lepton number ($\times$ 1)



$$\mathcal{L} = \frac{y_R}{2}\nu_R\nu_R\phi + m_D\nu_L\nu_R + \frac{M_R}{2}\nu_R\nu_R + m_\ell\ell_L\ell_R + \cdots$$

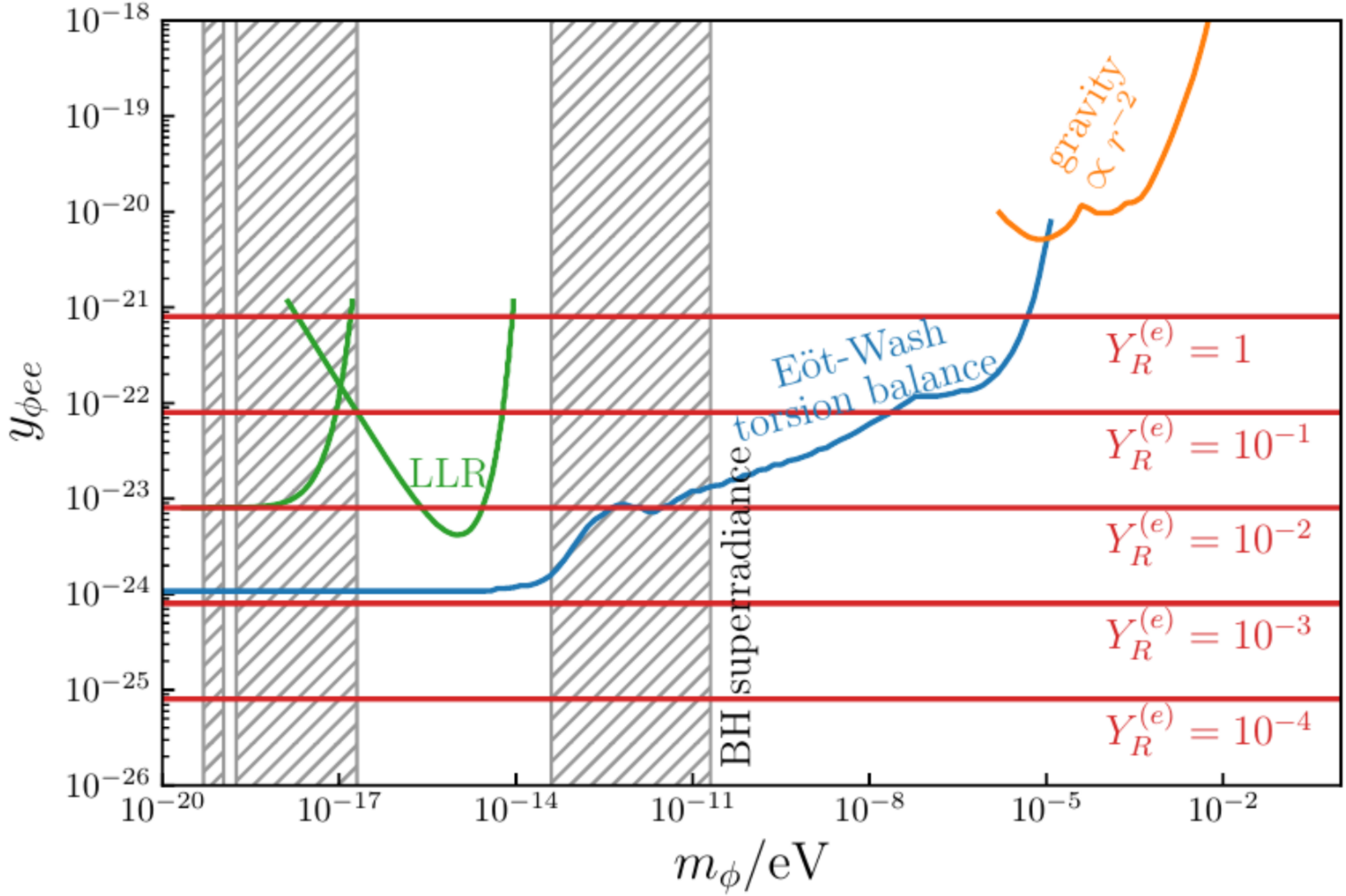
Now let's compare it to experiments



$$V(r) = -\frac{y_{\phi ee}^2 N_1 N_2}{4\pi r} e^{-m_\phi r}$$

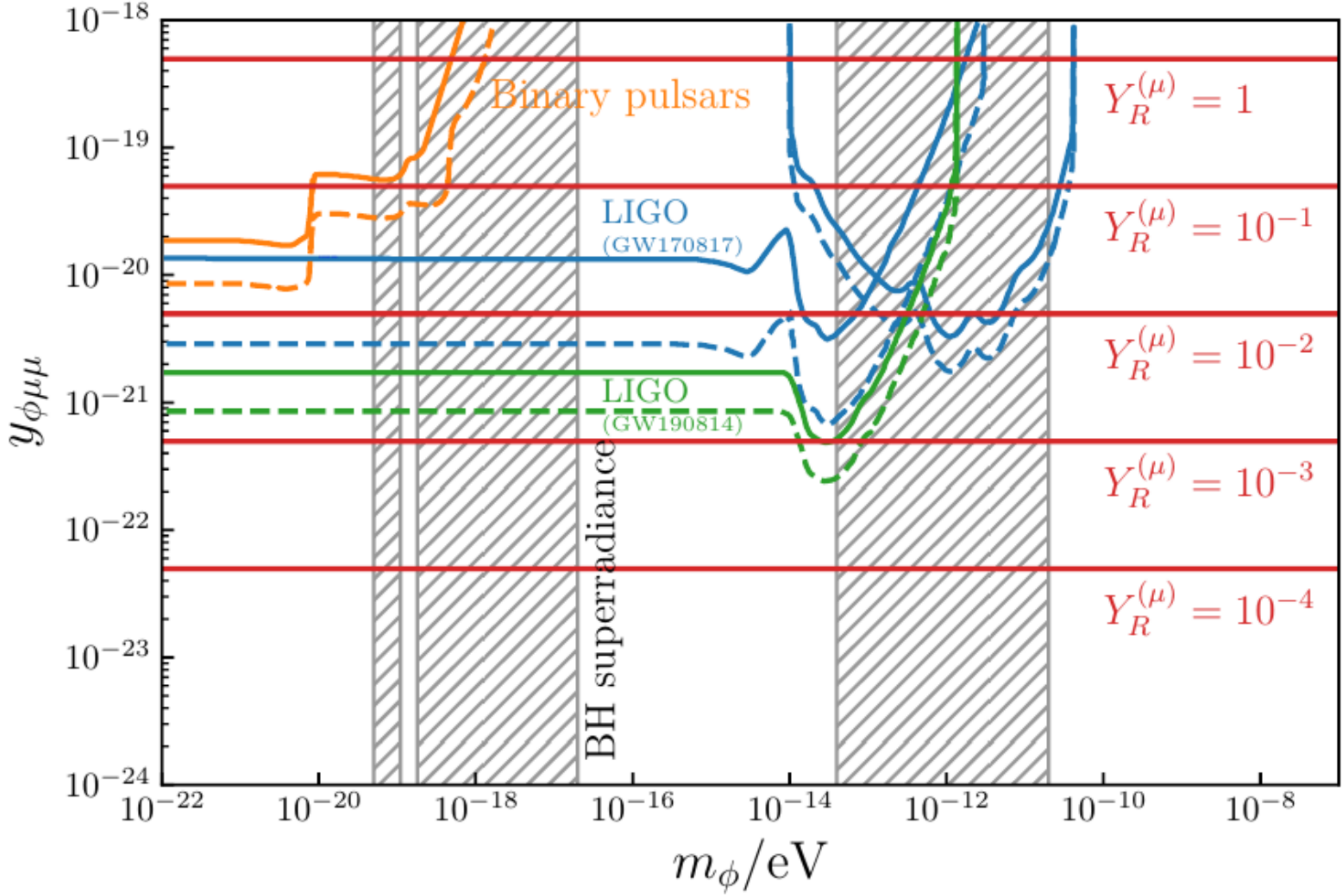
$$y_{\phi ee} = \frac{3 G_F m_e Y_R^{(e)} m_\nu^{(e)}}{16\sqrt{2}\pi^2} \approx 8.0 \times 10^{-22}\, Y_R^{(e)} \left(\frac{m_\nu^{(e)}}{0.01\ \text{eV}} \right)$$

In normal matter, ϕ only couples to electrons



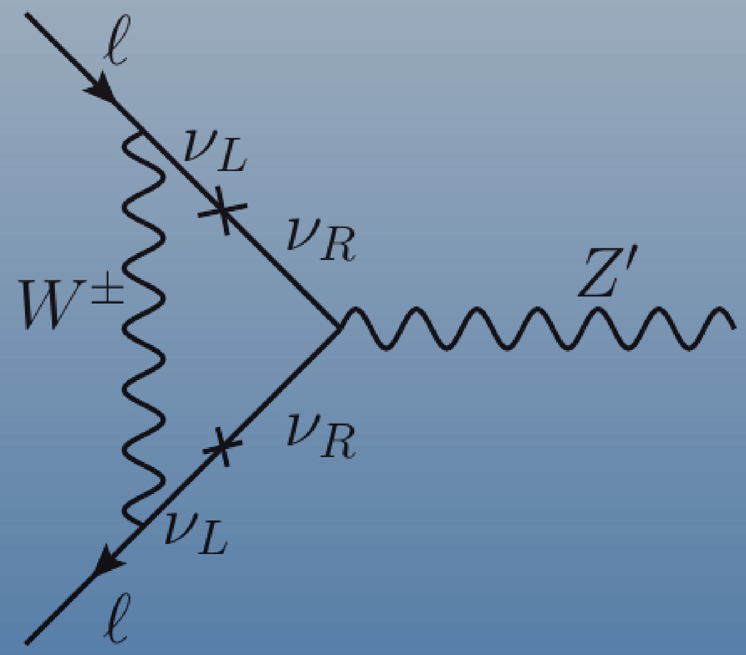
In neutron stars, we can probe the muonic force because

$$F^{(\mu)} \sim (m_\mu/m_e)^2 F^{(e)} \gg F^{(e)}$$



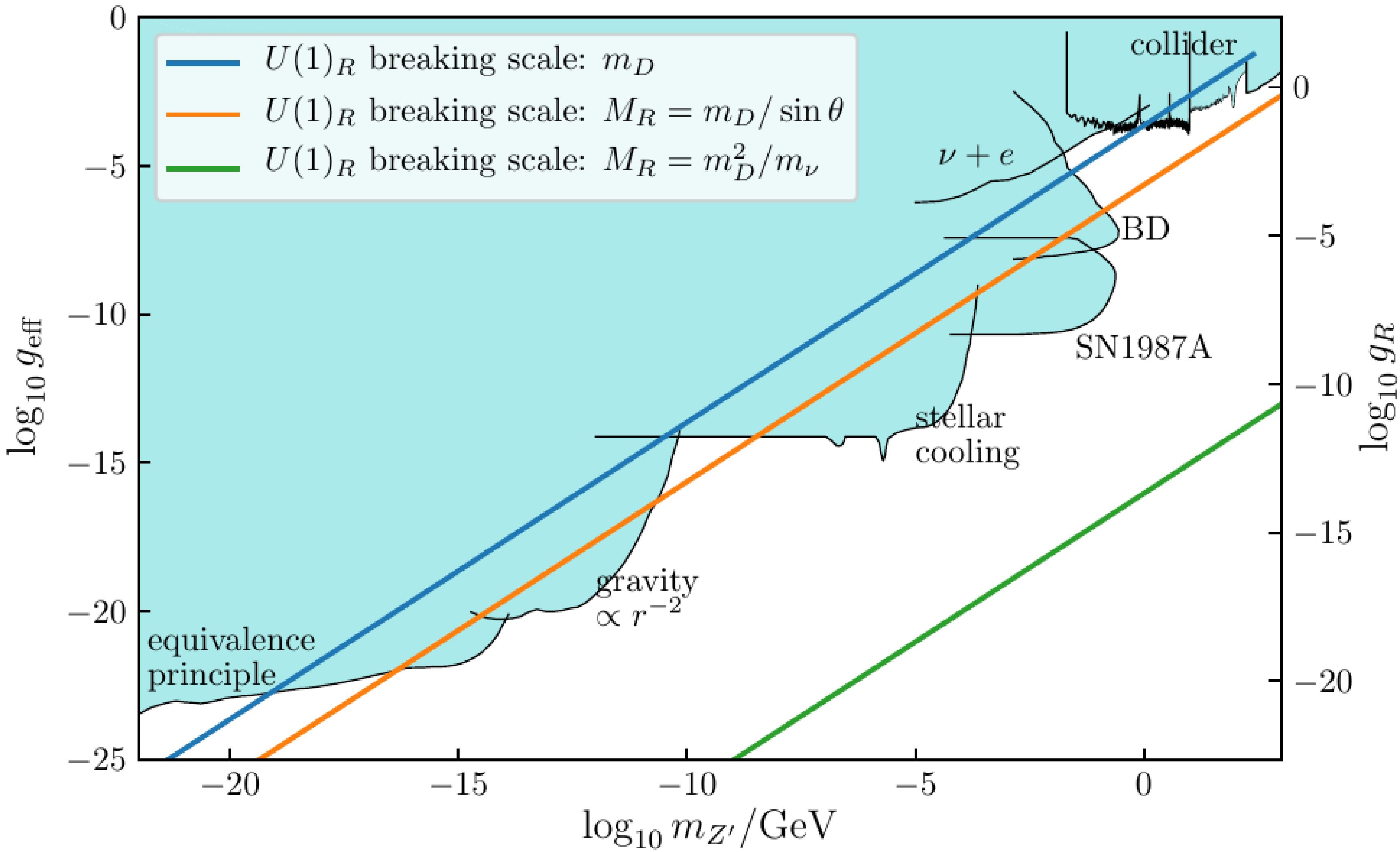
What if the dark force is mediated by a vector?

$$\mathcal{L} \supset \nu_R \nu_R \phi \rightarrow \mathcal{L} \supset \overline{\nu_R} \not{Z}' \nu_R$$



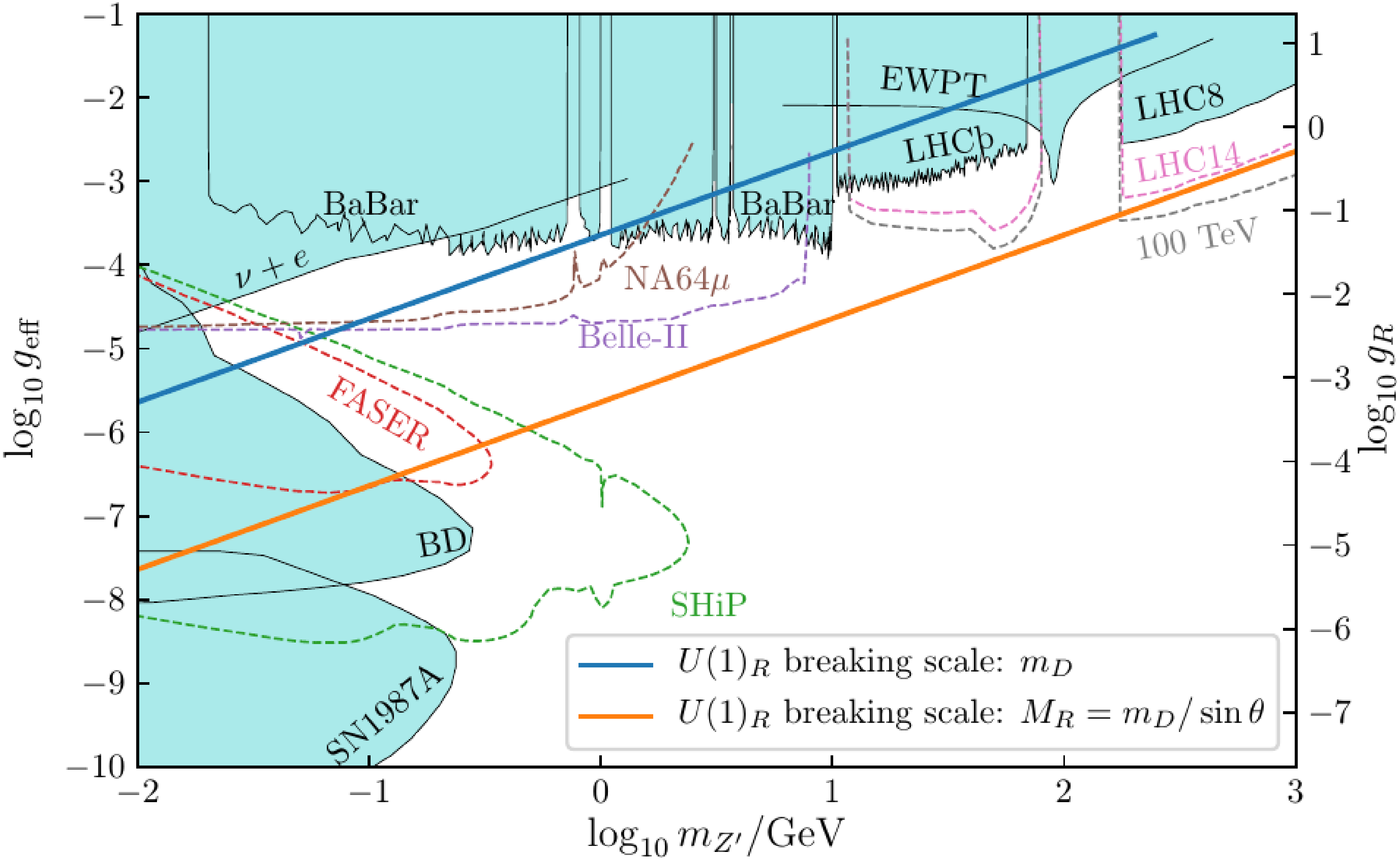
$$\propto \frac{G_F}{16\pi^2} m_D^2$$

Answer: coupling no longer suppresed by m_ν

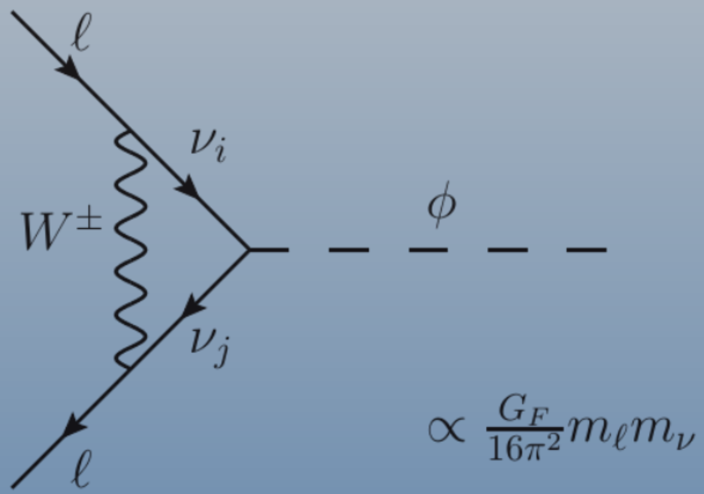


$U(1)_R$ breaking scale: m_D
$U(1)_R$ breaking scale: $M_R = m_D/\sin\theta$
$U(1)_R$ breaking scale: $M_R = m_D^2/m_\nu$
collider
$\nu + e$
BD
SN1987A
stellar cooling
gravity $\propto r^{-2}$
equivalence principle
$\log_{10} g_{\rm eff}$
$\log_{10} g_R$
$\log_{10} m_{Z'}/{\rm GeV}$
0
−5
−10
−15
−20
−25
0
−5
−10
−15
−20
−20
−15
−10
−5
0

ν_R-philic dark photon in future experiments

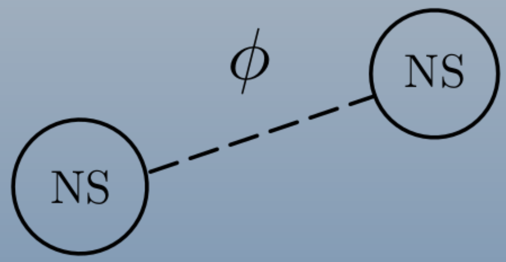


Summary



$$\ell = e: \; y \sim 10^{-21}$$

$$\ell = \mu: \; y \sim 10^{-19}$$



GW170817

$$y \sim [10^{-19}, \; 10^{-20}]$$

Note: in NS, $n_\mu \sim n_e$,
since $m_\mu \gg m_e$, μ-μ force $\gg$ e-e force

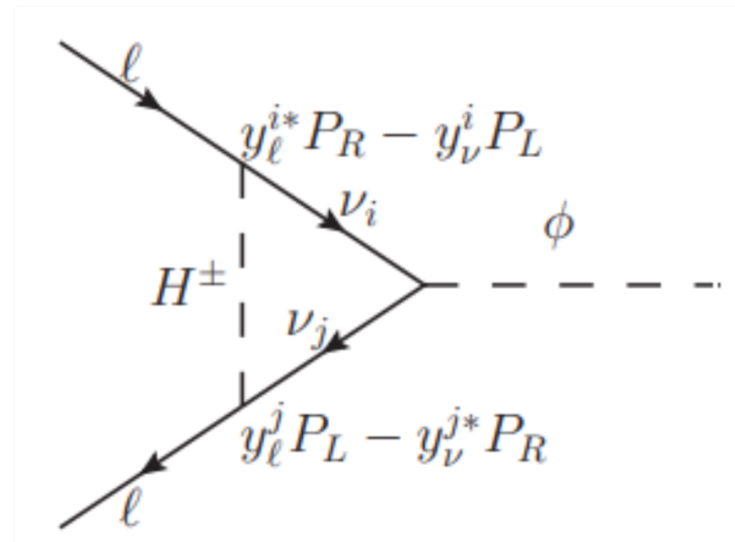
Backup

Unitarity gauge ?

R_ξ gauges ?

Feynman-'t Hooft gauge?

$$\Delta^W_{\mu\nu}(k) = -i\frac{g_{\mu\nu} - k_\mu k_\nu/m_W^2}{k^2 - m_W^2} - i\frac{k_\mu k_\nu/m_W^2}{k^2 - \xi m_W^2},$$



$k \to \infty$ vs $\xi \to \infty$

$$i\mathcal{M}_W = i\frac{m_\ell G^{ij}}{256\pi^2 m_W^2}\left[F_1(m_i,\ m_j) + F_2(m_i,\ m_j)\right]\overline{u(p_2)}u(p_1)$$

$$\begin{aligned}
F_1 = {} & 6\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{m_W^2}\right) - 2\frac{m_j^2 + 2m_W^2}{m_j^2 - m_W^2}\log\frac{m_j^2}{m_W^2} \\
& + \frac{5m_i^2 m_j^2 - 5m_i^2 m_W^2 - 5m_j^2 m_W^2 + 11m_W^4}{\left(m_i^2 - m_W^2\right)\left(m_j^2 - m_W^2\right)} \\
& - \frac{2\left(m_i^2 m_j^2 m_W^2 + m_i^2 m_j^4 - 2m_i^2 m_W^4 - 7m_j^4 m_W^2 + 2m_j^2 m_W^4 + 2m_j^6\right)\log\frac{m_i^2}{m_j^2}}{\left(m_i^2 - m_j^2\right)\left(m_j^2 - m_W^2\right)^2} \\
& - \frac{2m_W^4\left(17m_i^2 m_j^2 - 10m_i^2 m_W^2 + 5m_i^4 - 7m_j^2 m_W^2 + 2m_j^4 + 2m_W^4\right)\log\frac{m_i^2}{m_W^2}}{\left(m_i^2 - m_W^2\right)^2\left(m_j^2 - m_W^2\right)^2} \\
& - \frac{2m_i^2 m_j^2\left(2m_i^2 m_j^2 - 7m_i^2 m_W^2 - 4m_j^2 m_W^2\right)\log\frac{m_i^2}{m_W^2}}{\left(m_i^2 - m_W^2\right)^2\left(m_j^2 - m_W^2\right)^2},
\end{aligned}$$

$$\begin{aligned}
F_2 = {} & -6\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{\xi m_W^2}\right) + 2\frac{m_j^2}{m_j^2 - \xi m_W^2}\log\frac{m_j^2}{\xi m_W^2} \\
& - \frac{5m_i^2\left(m_j^2 - \xi m_W^2\right) + \xi m_W^2\left(7\xi m_W^2 - 5m_j^2\right)}{\left(m_i^2 - \xi m_W^2\right)\left(m_j^2 - \xi m_W^2\right)} \\
& + \frac{2m_j^2\left[m_i^2\left(m_j^2 - \xi m_W^2\right) - 3\xi m_j^2 m_W^2 + 2m_j^4\right]\log\frac{m_i^2}{m_j^2}}{\left(m_i^2 - m_j^2\right)\left(m_j^2 - \xi m_W^2\right)^2} \\
& - \frac{2\xi^2 m_j^2 m_W^4\left(2m_j^2 - 3\xi m_W^2\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2} \\
& + \frac{2\xi m_i^2 m_W^2\left(9\xi m_j^2 m_W^2 - 4m_j^4 - 4\xi^2 m_W^4\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2} \\
& + \frac{2m_i^4\left(2m_j^4 - 5\xi m_j^2 m_W^2 + 3\xi^2 m_W^4\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2}.
\end{aligned}$$

UV divergence ?

$$F_1 = \frac{6}{\epsilon} + \cdots\cdots$$

$$F_2 = -\frac{6}{\epsilon} + \cdots\cdots$$

Cancellation of ξ - dependence (in the limit of large ξ)

$$i\mathcal{M}_W = i\frac{m_\ell G^{ij}}{256\pi^2 m_W^2}\left[F_1(m_i,\ m_j) + F_2(m_i,\ m_j)\right]\overline{u(p_2)}u(p_1)$$

Each single diagram is gauge dependent!

$\xi \to \infty$

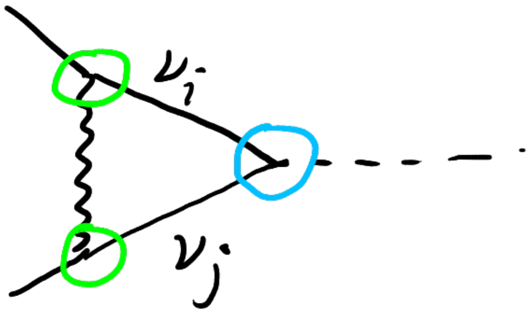
$F_2 \to 6\log\xi$

But,

$$\sum_{ij} G^{ij}\log\xi = 0$$

$$\begin{aligned}
F_2 = &-6\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{\xi m_W^2}\right) + 2\frac{m_j^2}{m_j^2 - \xi m_W^2}\log\frac{m_j^2}{\xi m_W^2} \\
&- \frac{5m_i^2\left(m_j^2 - \xi m_W^2\right) + \xi m_W^2\left(7\xi m_W^2 - 5m_j^2\right)}{\left(m_i^2 - \xi m_W^2\right)\left(m_j^2 - \xi m_W^2\right)} \\
&+ \frac{2m_j^2\left[m_i^2\left(m_j^2 - \xi m_W^2\right) - 3\xi m_j^2 m_W^2 + 2m_j^4\right]\log\frac{m_i^2}{m_j^2}}{\left(m_i^2 - m_j^2\right)\left(m_j^2 - \xi m_W^2\right)^2} \\
&- \frac{2\xi^2 m_j^2 m_W^4\left(2m_j^2 - 3\xi m_W^2\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2} \\
&+ \frac{2\xi m_i^2 m_W^2\left(9\xi m_j^2 m_W^2 - 4m_j^4 - 4\xi^2 m_W^4\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2} \\
&+ \frac{2m_i^4\left(2m_j^4 - 5\xi m_j^2 m_W^2 + 3\xi^2 m_W^4\right)\log\frac{m_i^2}{\xi m_W^2}}{\left(m_i^2 - \xi m_W^2\right)^2\left(m_j^2 - \xi m_W^2\right)^2}.
\end{aligned}$$

$G^{ij} = \circ \times \circ \times \circ$



$$G^{ij} \equiv g_W^{i*} g_W^{j} (m_j y_R^{ij} + m_i y_R^{ij*})$$

$\downarrow \; \sum_{ij} G^{ij}$

$[g_W^\dagger]\,[Y_R]\,[m \; \; m]\,[g_W]$

Chiral basis (orignial basis)

$$\mathcal{L} \supset \frac{g}{2c_W} Z_\mu \nu_L^\dagger \bar{\sigma}^\mu \nu_L + \left[\frac{g}{\sqrt{2}} W_\mu^- \ell_L^\dagger \bar{\sigma}^\mu \nu_L - y_\nu H^+ \ell_L \nu_R + y_\ell H^- \nu_L \ell_R + \frac{y_R}{2} \nu_R \nu_R \phi + \text{h.c.} \right],$$

$\Downarrow$

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_4 \end{pmatrix}, \; U^T \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} U = \begin{pmatrix} m_1 & \\ & m_4 \end{pmatrix}$$

mass basis

$$\mathcal{L} \supset g_Z^{ij} Z_\mu \nu_i^\dagger \bar{\sigma}^\mu \nu_j + \left[g_W^i W_\mu^- \ell_L^\dagger \bar{\sigma}^\mu \nu_i - y_\nu^i H^+ \ell_L \nu_i + y_\ell^i H^- \nu_i \ell_R + \frac{y_R^{ij}}{2} \nu_i \nu_j \phi + \text{h.c.} \right].$$

$\begin{pmatrix} 1 \\ 0 \end{pmatrix} \to U^T \begin{pmatrix} 1 \\ 0 \end{pmatrix} \equiv g_W$

$U^T \begin{pmatrix} 0 & \\ & 1 \end{pmatrix} U \equiv Y_R$

$g_W^\dagger Y_R = 0 \, !$

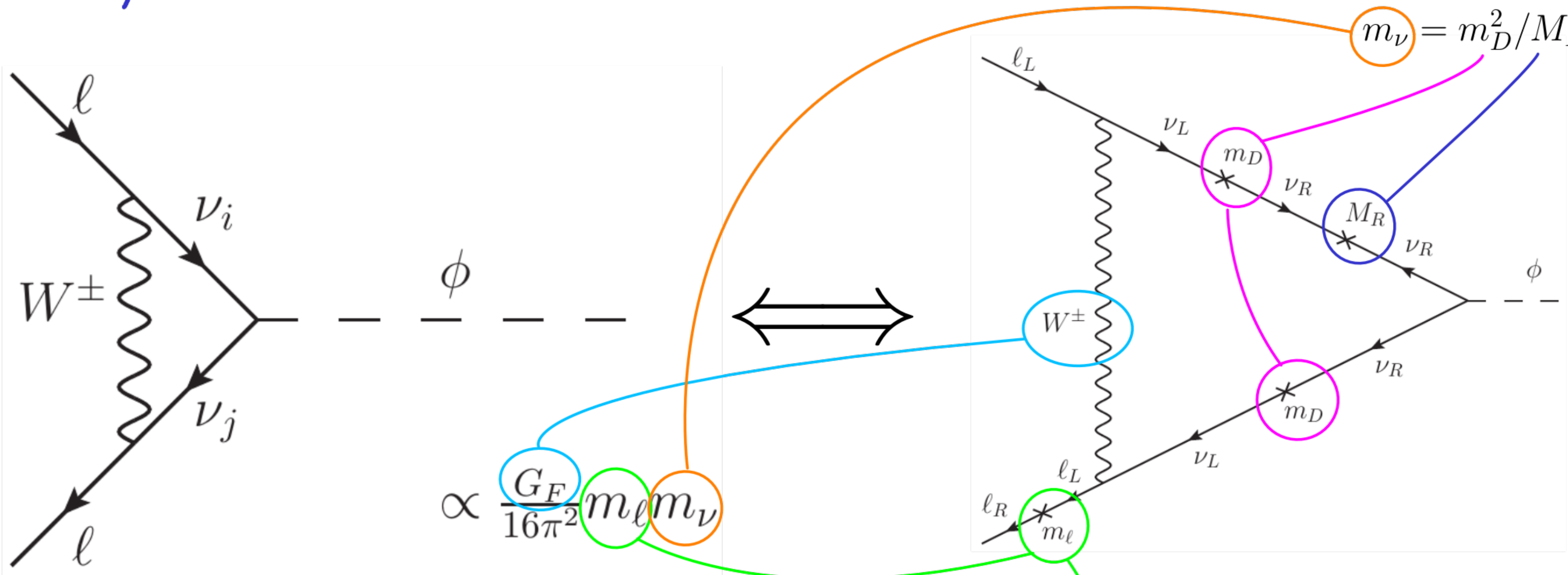
An implication of $\sum_{ij} G_{ij} = 0$

even if $\frac{1}{\epsilon}$ didn't cancel out in $F_1 + F_2$

it would disappear after $\sum_{ij}$

Why this result ?

Seesaw formula: $m_\nu = m_D^2/M_R$



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

$$\phi \overline{\psi}_\ell \psi_\ell = \phi \ell_L \ell_R + \text{h.c.}$$

$$\mathcal{L} = \frac{y_R}{2} \nu_R \nu_R \phi + m_D \nu_L \nu_R + \frac{M_R}{2} \nu_R \nu_R + m_\ell \ell_L \ell_R + \cdots$$