Neutrino forces and experimental probes

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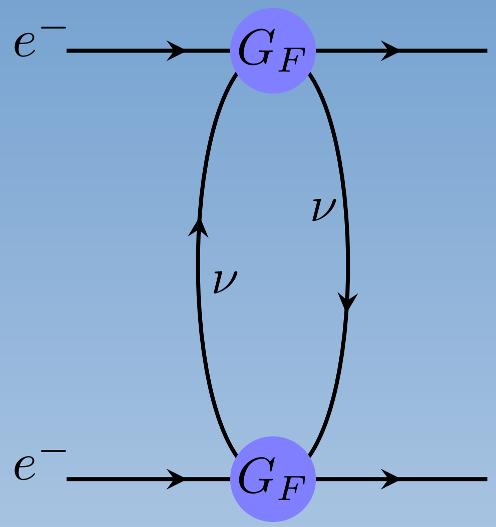
https://xunjiexu.github.io/

Talk at Rencontres de Moriond, 19/03/2023, https://moriond.in2p3.fr/2023/EW/

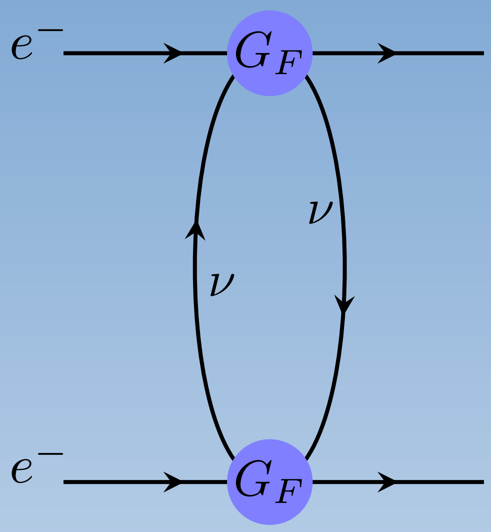
In collaboration with Rupert Coy, Mijo Ghosh, Yuval Grossman, Walter Tangarife, Bingrong Yu.

- exchange any $m = 0$ particles $\to$ long-range forces
  - graviton, photon
- what about ν?
  - has to be a pair



History

- 1930s: Bethe & Bacher, Gamow & Teller, ...
  - exchange ν pairs $\to$ long-range forces between nucleons
- 1960s: carefully computed by G. Feinberg and J. Sucher
- 1960s: Feynman Lectures, Feynman:"ν-forces=gravity?"
- 1990s: Fischbach:"ν-forces destroy neutron stars!"
  - disproved by Kiers & Tytgat, Smirnov & Vissani, ...



Effective potential:

$$V_{ee}(r) = \left(2\sin^2\theta_W + \frac{1}{2}\right)^2 \frac{G_F^2}{4\pi^3}\frac{1}{r^5}$$

- Why $1/r^5$?
  - dimensional analysis
- If $\nu \to$ scalar, $V \propto 1/r^3$
  - also dimensional analysis

Can we detect it?

Compare to gravity: $1/r^5$ vs $1/r$

- ν-force $>$ gravity if $r < 10^{-8}$ cm
- so either ... or ...

short-range probe ($r < 10^{-8}$ cm)

- atomic and nuclear spectroscopy
  Y. V. Stadnik, PRL'17
- atomic parity violation
  Ghosh, Grossman, Tangarife, PRD'19

long-range probe ($r > 10^{-8}$ cm)

- precision test of gravity:
  - $1/r^2$ law
  - weak equivalence principle

short-range probe ($r < 10^{-8}$ cm)

- atomic and nuclear spectroscopy
  Y. V. Stadnik, PRL'17
- atomic parity violation
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$\to$ how?
put $V(r) \propto G_F^2/r^5$ into

$$i\frac{\partial}{\partial t}\Psi = \left[-\frac{\nabla^2}{2m} + V(r)\right]\Psi$$

The problematic $1/r^5$

$$\int \left\langle \psi \left| \frac{1}{r^5} \right| \psi \right\rangle d^3r \to \text{divergent at } \int_0$$

In QM, $1/r^n$ with $n < 2$ (> 2) $\equiv$ regular (singular) potential; see backup slides

Is $1/r^5$ always valid down to arbitrarily small r?

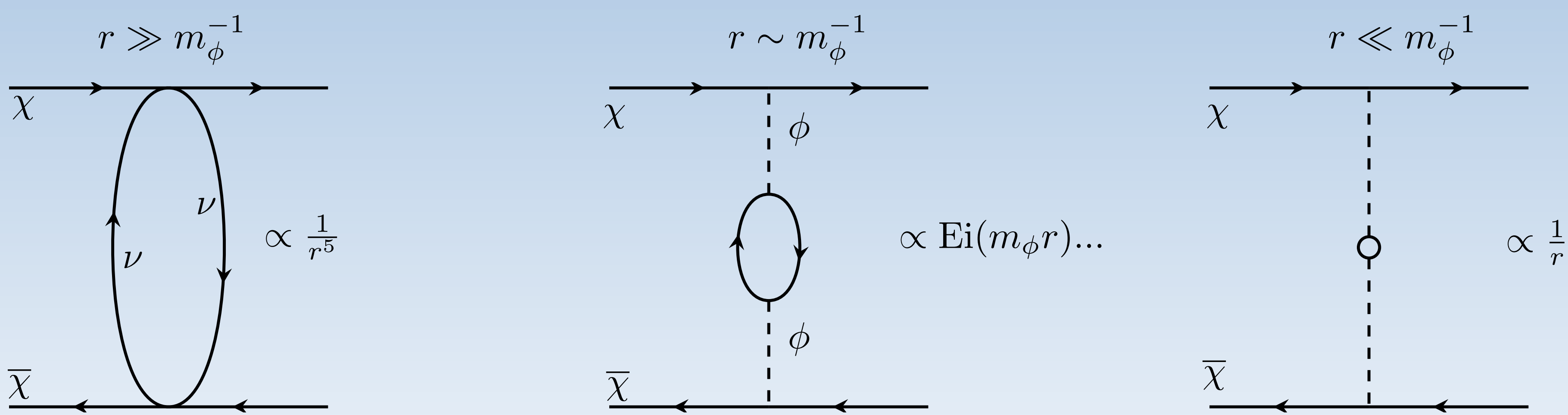
arXiv > hep-ph > arXiv:2112.03060v1

High Energy Physics - Phenomenology

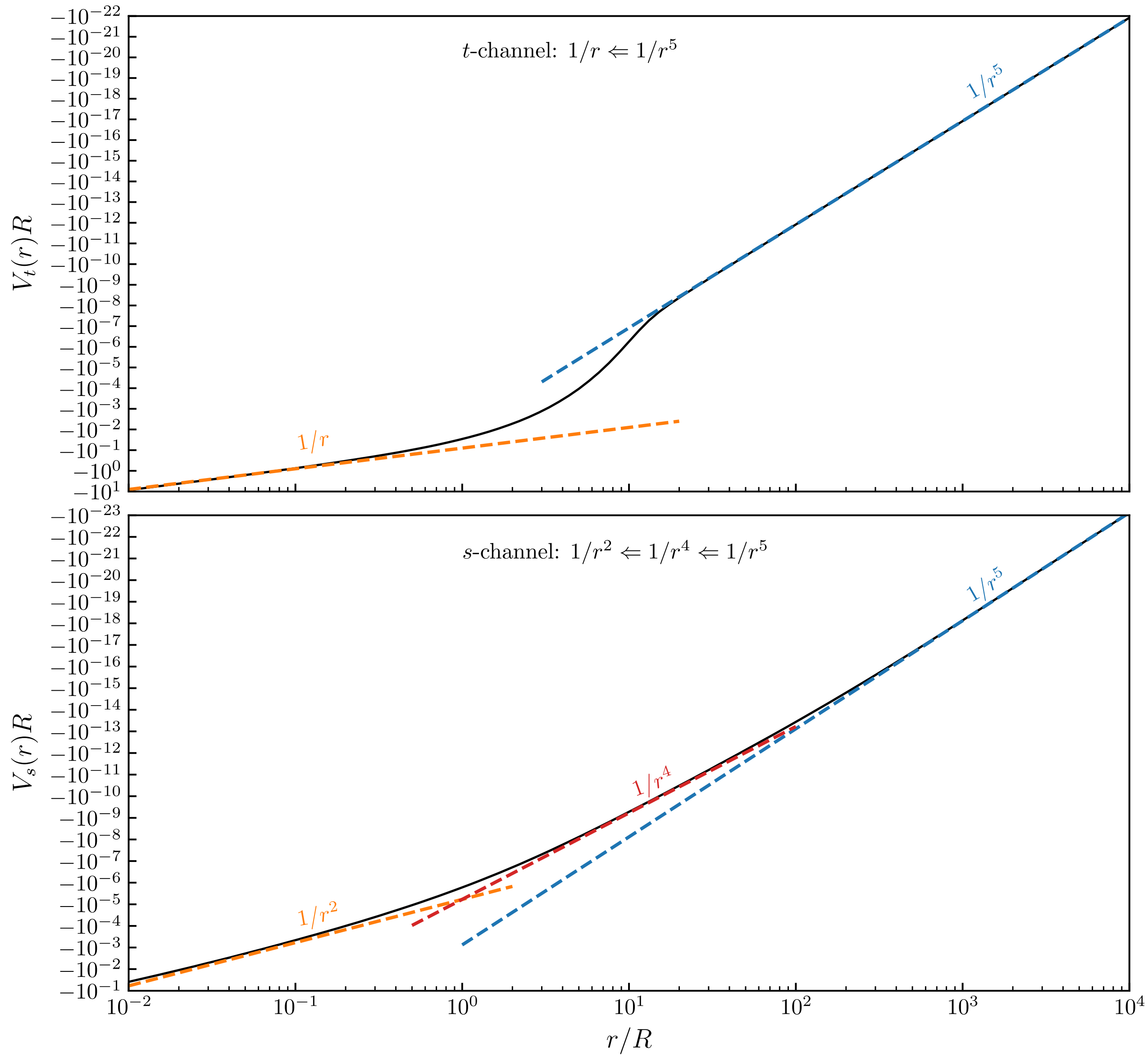
On the short-range behavior of neutrino forces: from $1/r^5$ to $1/r^4$, $1/r^2$, and $1/r$

Xun-jie Xu, Bingrong Yu

The exchange of a pair of neutrinos between two objects, seperated by a distance r, leads to a long-range effective potential proportional to $1/r^5$, assuming massless neutrinos and four-fermion contact interactions. In this paper, we investigate how this known form of neutrino-mediated potentials might be altered if the



Here is how it varies from $1/r^5$ to $1/r$ ...



PHYSICAL REVIEW LETTERS **120,** 223202 (2018)

Probing Long-Range Neutrino-Mediated Forces with Atomic and Nuclear Spectroscopy

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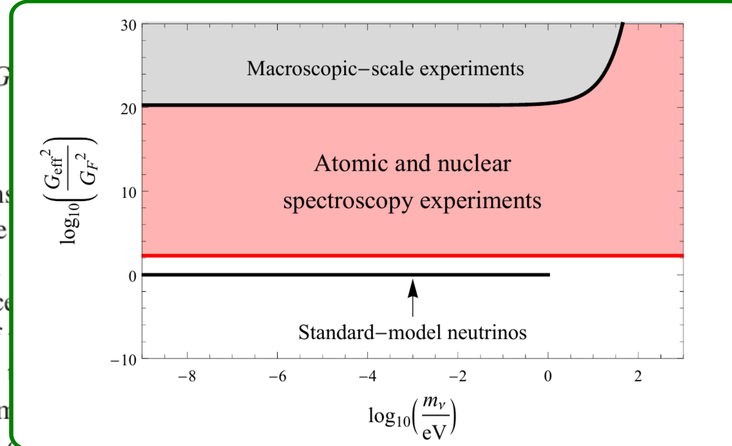
(Received 18 November 2017; published 1 June 2018)

The exchange of a pair of low-mass neutrinos between electrons, protons, and neutrons
"long-range" $1/r^5$ potential, which can be sought for in phenomena originating on the
subatomic length scales. We calculate the effects of neutrino-pair exchange on transition
energies in atoms and nuclei. In the case of atomic s-wave states, there is a large enhanc
induced energy shifts due to the lack of a centrifugal barrier and the highly singular nature of
mediated potential. We derive limits on neutrino-mediated forces from measurements of
binding energy and transition energies in positronium, muonium, hydrogen, and deuterium
isotope-shift measurements in calcium ions. Our limits improve on existing constraints
mediated forces from experiments that search for new macroscopic forces by 18 orders of magnitude.
Future spectroscopy experiments have the potential to probe long-range forces mediated by the exchange of
pairs of standard-model neutrinos and other weakly charged particles.



looks promising ... but ...

long-range probe ($r > 10^{-8}$ cm)

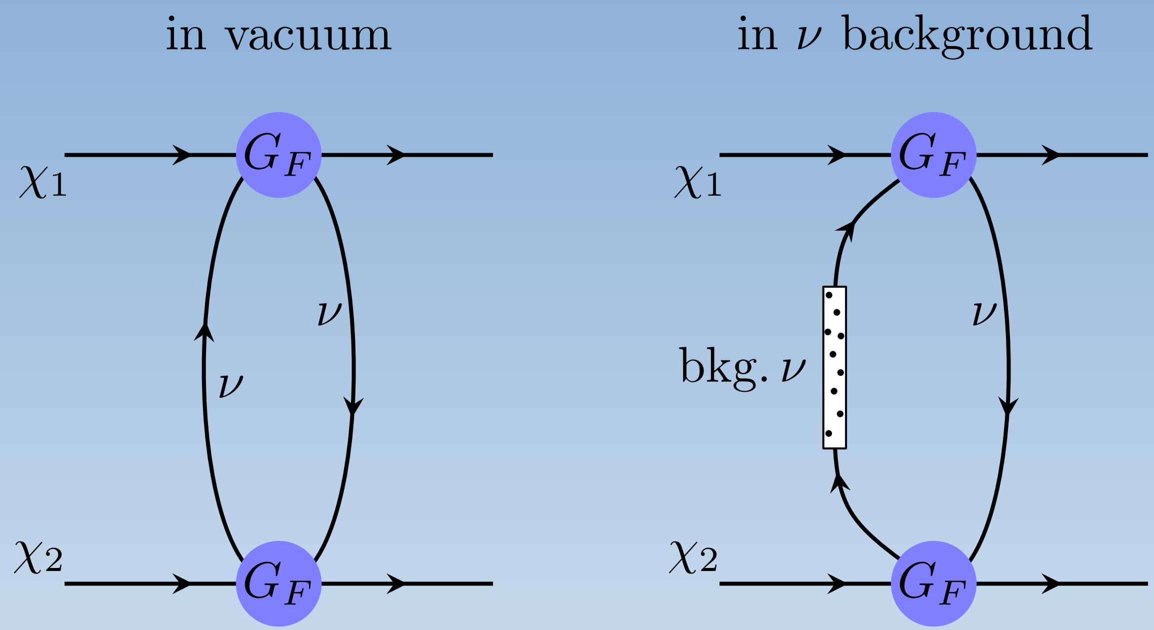
- precision test of gravity:
  - $1/r^2$ law
  - weak equivalence principle

looks impressive!
But how much do we need?
... think about $1/r$ vs $1/r^5$ ...

exp	$\delta V/V_{\text{gravity}}$	$\langle r \rangle$	Refs
Washington2007	3.2×10^{-16}	~ 6400 km	[45]
Washington1999	3.0×10^{-9}	~ 0.3 m	[46]
Irvine1985	0.7×10^{-4}	$2-5$ cm	[42]
Irvine1985	2.7×10^{-4}	$5-105$ cm	[42]
Wuhan2012	10^{-3}	~ 2 mm	[47]
Wuhan2020	3×10^{-2}	~ 0.1 mm	[44]
Washington2020	~ 1	52 μm	[43]
Future levitated optomechanics	$\sim 10^4$	1 μm	[48]

possible to make $1/r^5 \to 1/r$ at long ranges?

yes, if there is a backgound ... †



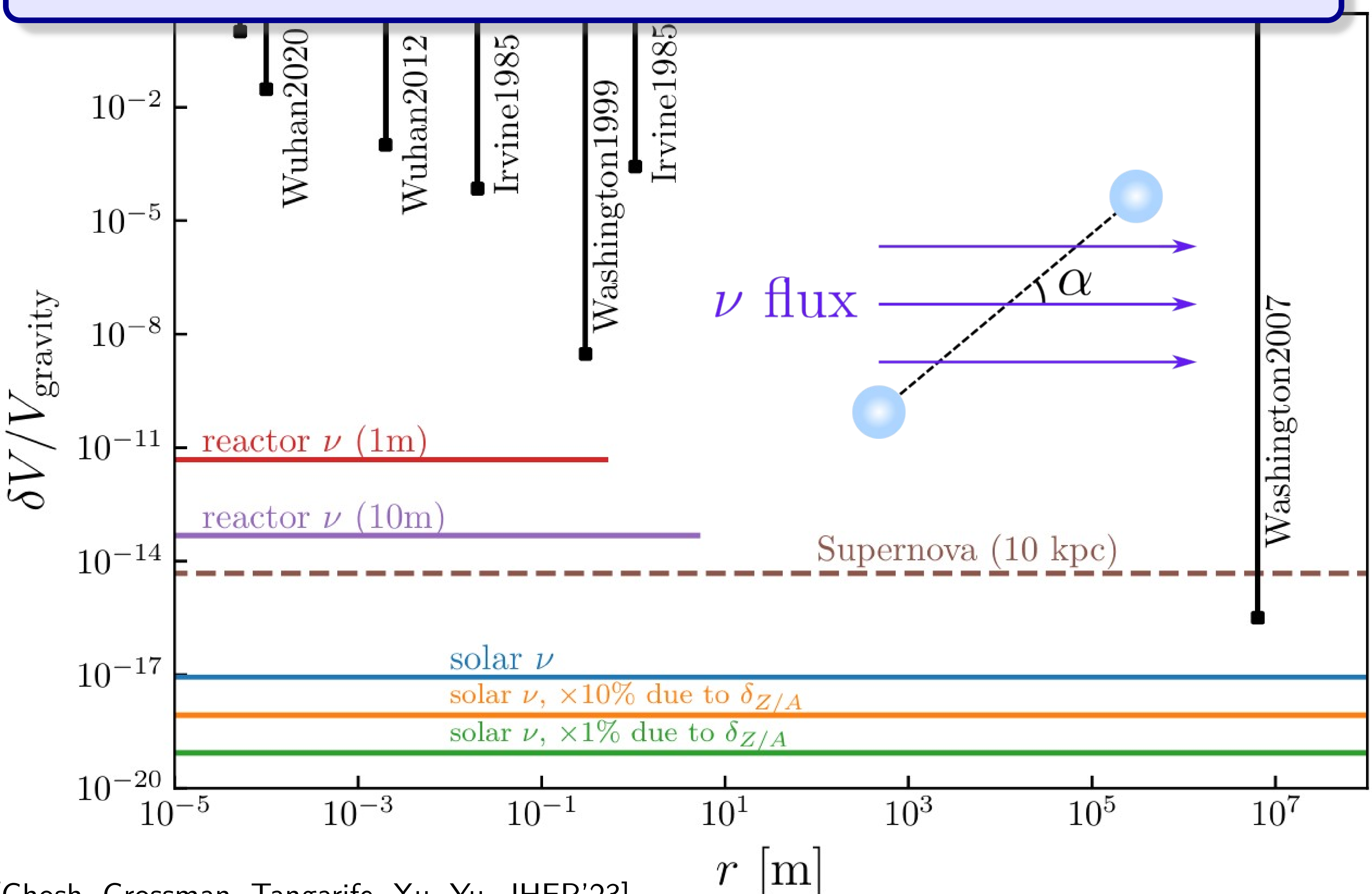
propagator in finite-T/n

$$S_\nu(k) = (\not{k} + m_\nu)\left\{\frac{i}{k^2 - m_\nu^2 + i\epsilon} - 2\pi\delta\left(k^2 - m_\nu^2\right)\left[\Theta\left(k^0\right) n_\nu\left(\mathbf{k}\right) + ...\right]\right\}$$

† Feynman used basically the same trick to make neutrino forces gravity-like $(1/r)$
see backup slides

Result

$$V_{\rm bkg}\left(r \gg E_\nu^{-1}, \alpha \ll 1\right) = -\frac{1}{\pi} G_F^2 \times \Phi_0 E_\nu \times \frac{1}{r} \times \left[1 + \mathcal{O}(\alpha^2)\right]$$



[Ghosh, Grossman, Tangarife, Xu, Yu, JHEP'23]

However …

However ...

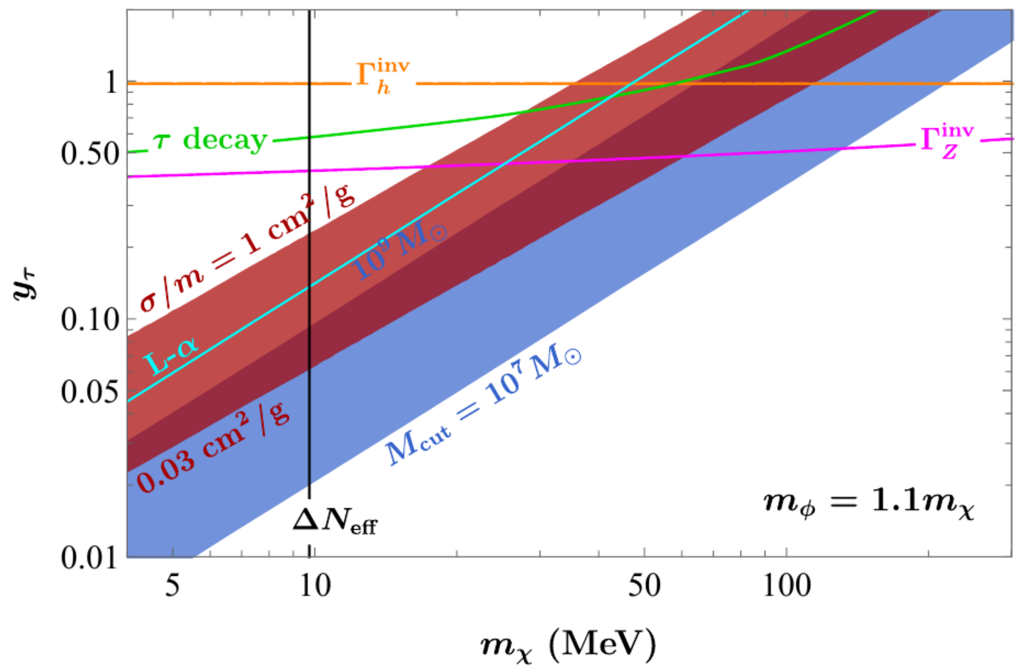
- arXiv-v1 (Sep. 15): only able to integrate it analytically at $\alpha = 0$ or 90°
  - both $\to V \propto 1/r$, exiciting!
- arXiv-v2 (Nov. 8): able to integrate it for $\forall\alpha$ (some approx.)

Result

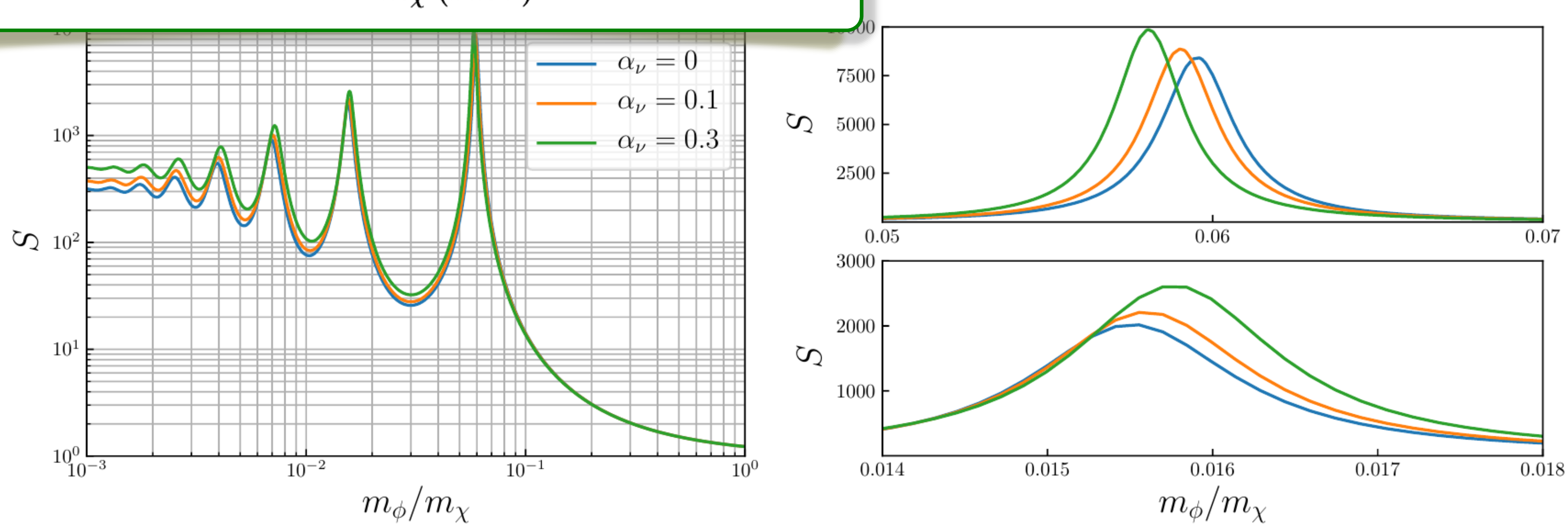
$$V \approx -\frac{1}{\pi} G_F^2 \Phi_0 E_\nu \frac{1}{r} \left\{ \cos^2\left(\frac{\alpha}{2}\right) \cos\left[(1-\cos\alpha) E_\nu r\right] + \sin^2\left(\frac{\alpha}{2}\right) \cos\left[(1+\cos\alpha) E_\nu r\right] \right\}$$

  - smearing effect at finite α, weaken conclusions before journal submission
- D. Blas, I. Esteban, ... [2212.03889] (Dec. 7):
  - also pointed smearing effect (we agree)
  - by including wavepacket (interesting, 2 ways $\to$ same smearing, but overkill)
- arXiv-v3 (JHEP-v2):
  - note added; our comment: $\Delta x \Delta p_x < \hbar/2$, yes, but $\Delta x \Delta p_y < \hbar/2$? no!

Application to Dark Matter



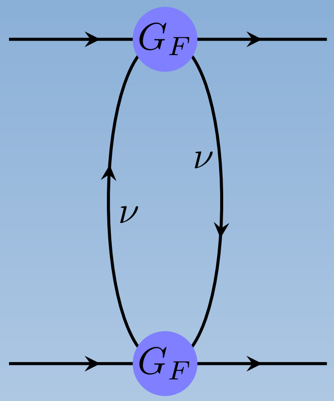
- ν-force $\rightarrow$ DM self-int.
  - N. Orlofsky, Yue Zhang, PRD'21
- the Sommerfeld enhancement
  - R. Coy, X. Xu, B. Yu, JHEP'22



Conclusion

Theory

- $1/r^5$
  - why? and what happens if $r \to 0$?
- very different in ν bkg.



Experimental probes

- parity violation at large scales
- atomic spectroscopy
- torsion balance experiments (with ν bkg.)

Can we detect neutrino forces? — No

Conclusion

Theory

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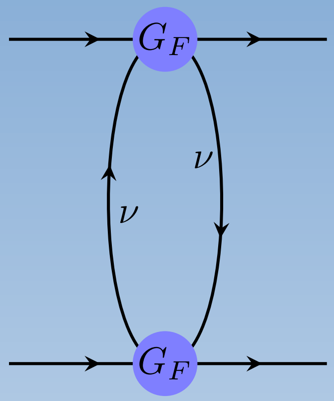


Experimental probes

- parity violation at large scales
- atomic spectroscopy
- torsion balance experiments (with ν bkg.)

Can we detect neutrino forces? — Future†, yes!

† atomic/muonic spectroscopy in ν bkg.; laser interferometer; BSM ν ...

Backup

How Feynman got $1/r$?

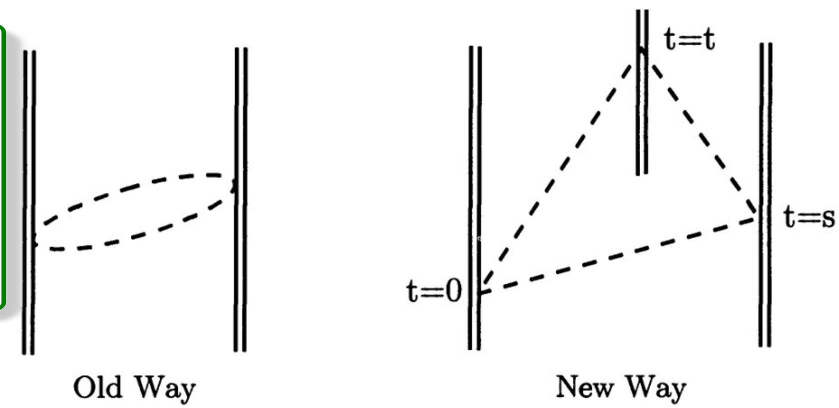
Feynman Lectures on Gravitation, Sec. 2

Two-body:

$$E = m_1 m_2 G'^2 \int \frac{i\,dt}{(t^2 - r^2 + i\epsilon)^2}. \qquad (2.4.1)$$

$$E = m_1 m_2 \frac{G'^2 \pi}{2} \frac{1}{r^3}, \qquad (2.4.2)$$

Figure 2.5



Three-body:

$$E = -G'^3 m_1 m_2 m_3 \pi^2 \frac{1}{(r_{12} + r_{23} + r_{13}) r_{12} r_{23} r_{13}}. \qquad (2.4.4)$$

Now "3" = the entire universe:

$$E = -\frac{G'^3 m_1 m_2 \pi^2}{r_{12}} \int \frac{4\pi \rho(R) R^2 dR}{2R^3}, \qquad (2.4.5)$$

Regular vs singular potential

$1/r^n$ with $n < 2$ (> 2) $\equiv$ regular (singular) potential

REVIEWS OF MODERN PHYSICS VOLUME 43, NUMBER 1 JANUARY 1971

Singular Potentials

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Why $1/r^n$ with $n > 2$ is problematic?

Landau and Lifshitz's argument:

when the particle is approaching the center of the potential, the kinetic energy $E_k = k^2/(2m_\chi)$ with $k \sim r^{-1}$ increases as $1/r^2$ while V decreases as $-1/r^m$. Therefore, the total energy would not be bounded from below and the particle would keep falling to infinitely small r, corresponding to infinitely high energy.