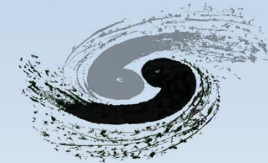


Neutrino forces and experimental probes

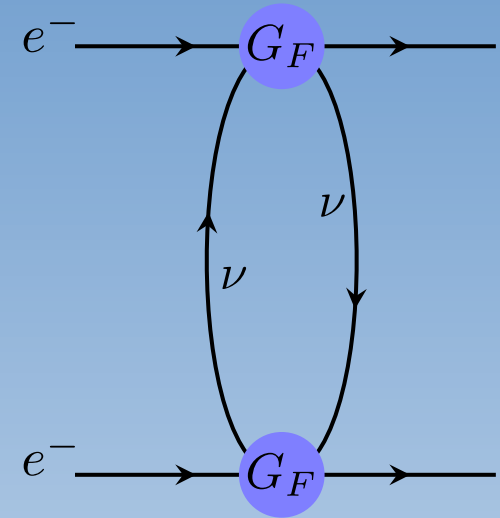
Xun-Jie Xu

Institute of High Energy Physics (IHEP)
Chinese Academy of Sciences (CAS)



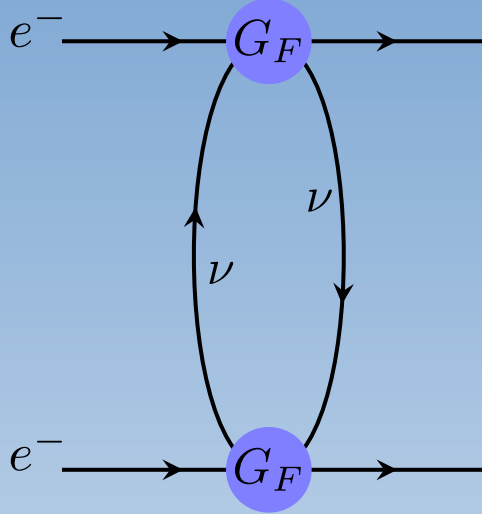
<https://xunjiexu.github.io/>

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



History

- 1930s: Bethe & Bacher, Gamow & Teller, ...
 - exchange ν pairs \rightarrow 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 $\nu \rightarrow$ scalar, $V \propto 1/r^3$
 - also dimensional analysis

Feynman's idea: neutrino forces = gravity. ... But how did Feynman get $1/r$?

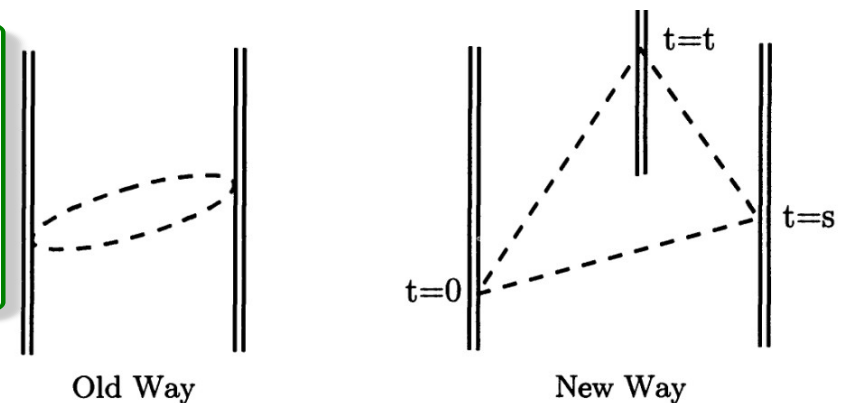
Feynman Lectures on Gravitation, Sec. 2

Two-body:

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

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

Figure 2.5



Three-body:

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

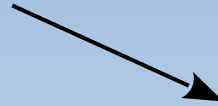
Now "3" = the entire universe:

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

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
Ghosh, Grossman, Tangarife, PRD'19

→ 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 $1/r^5$

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

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

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

REVIEWS OF MODERN PHYSICS

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Singular Potentials

WILLIAM M. FRANK AND DAVID J. LAND

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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.

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

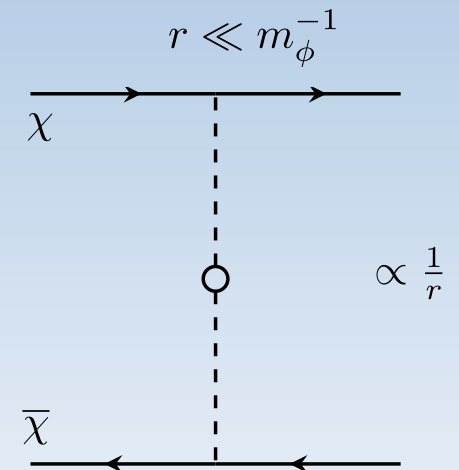
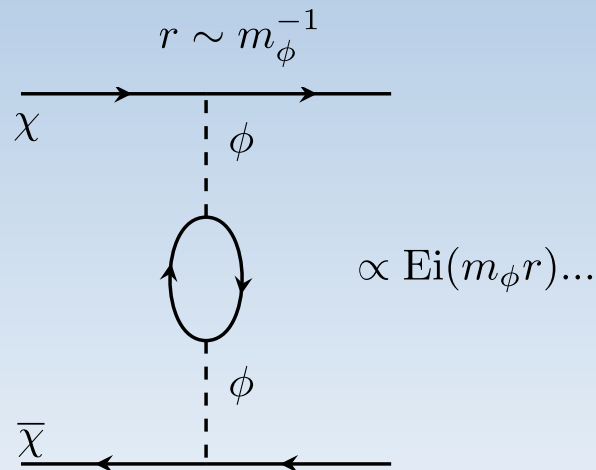
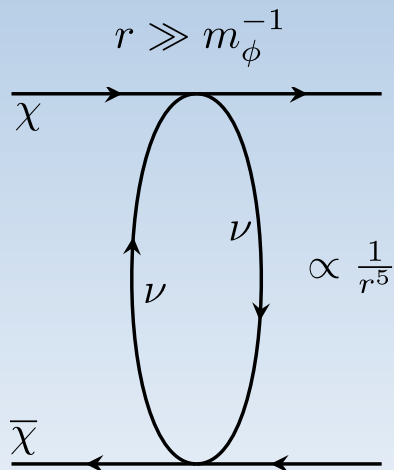
arXiv > hep-ph > arXiv:2112.03060v1

High Energy Physics - Phenomenology

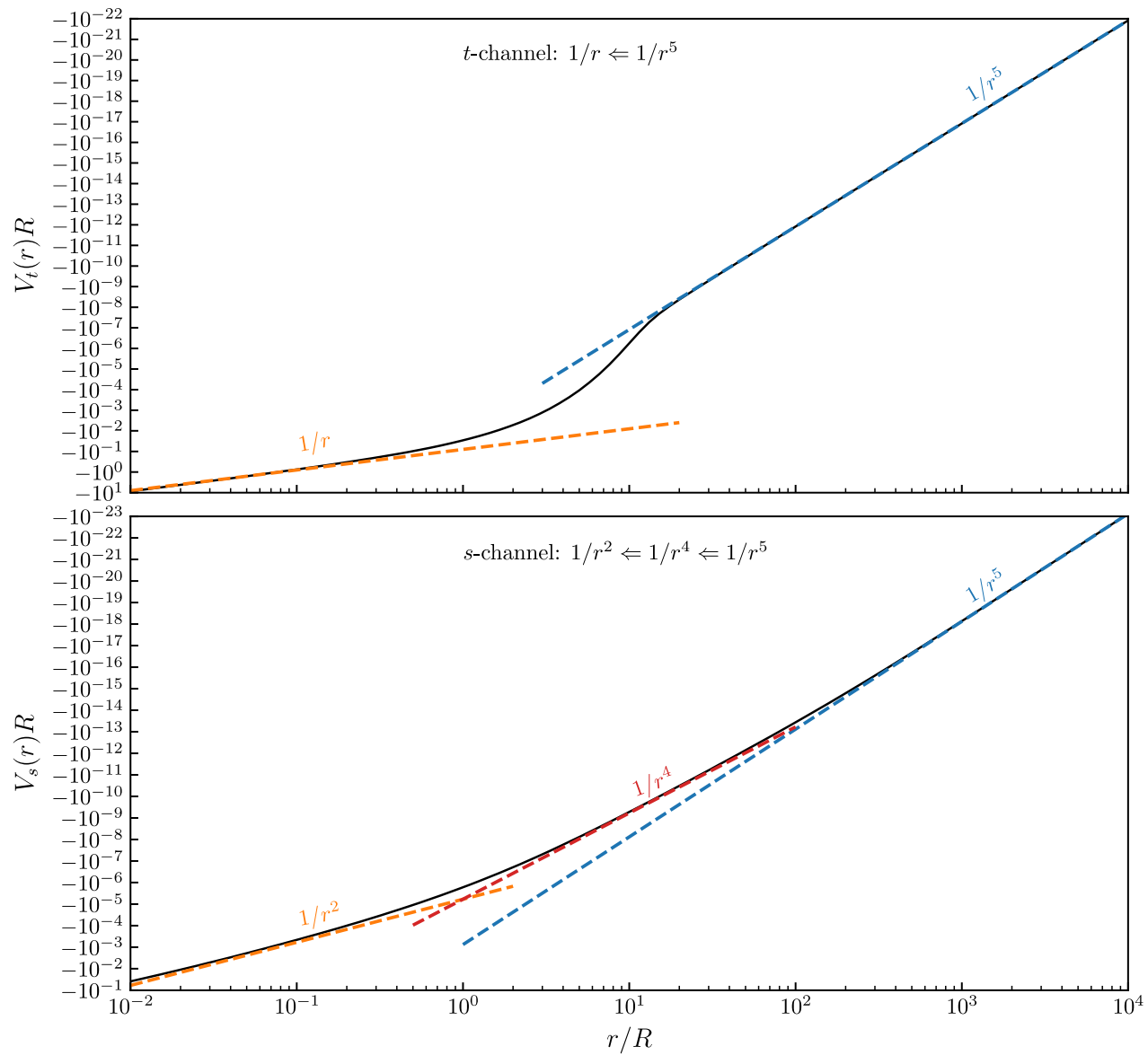
On the short-range behavior of neutrino forces: from $1/r^5$ to $1/r^4$, $1/r^2$, and $1/r$

Xun-jie Xu, Bingrong Yu

The exchange of a pair of neutrinos between two objects, separated 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 $1/r$...



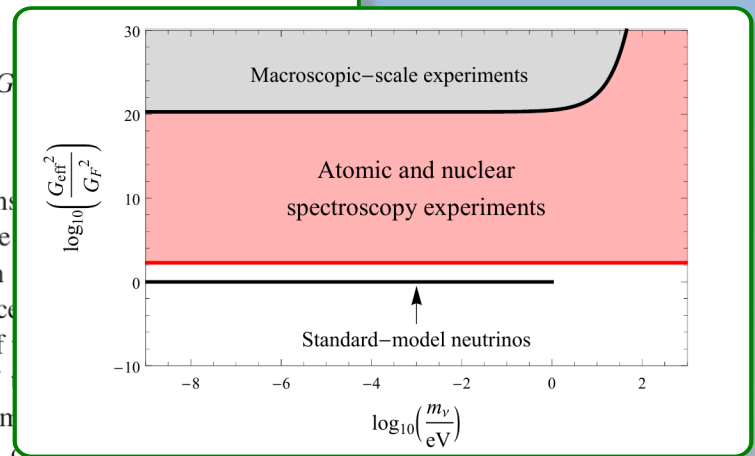
Probing Long-Range Neutrino-Mediated Forces with Atomic and Nuclear Spectroscopy

Yevgeny V. Stadnik

Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany

 (Received 18 November 2017; published 1 June 2018)

The exchange of a pair of low-mass neutrinos between electrons, protons, and neutrons induces a “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 enhancement of energy shifts induced by neutrino-mediated forces due to the lack of a centrifugal barrier and the highly singular nature of the $1/r^5$ mediated potential. We derive limits on neutrino-mediated forces from measurements of transition energies, binding energy and transition energies in positronium, muonium, hydrogen, and deuterium, and isotope-shift measurements in calcium ions. Our limits improve on existing constraints on neutrino-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.

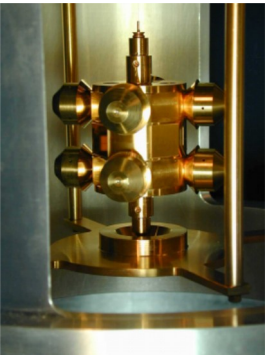


looks promising ... but ...

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

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

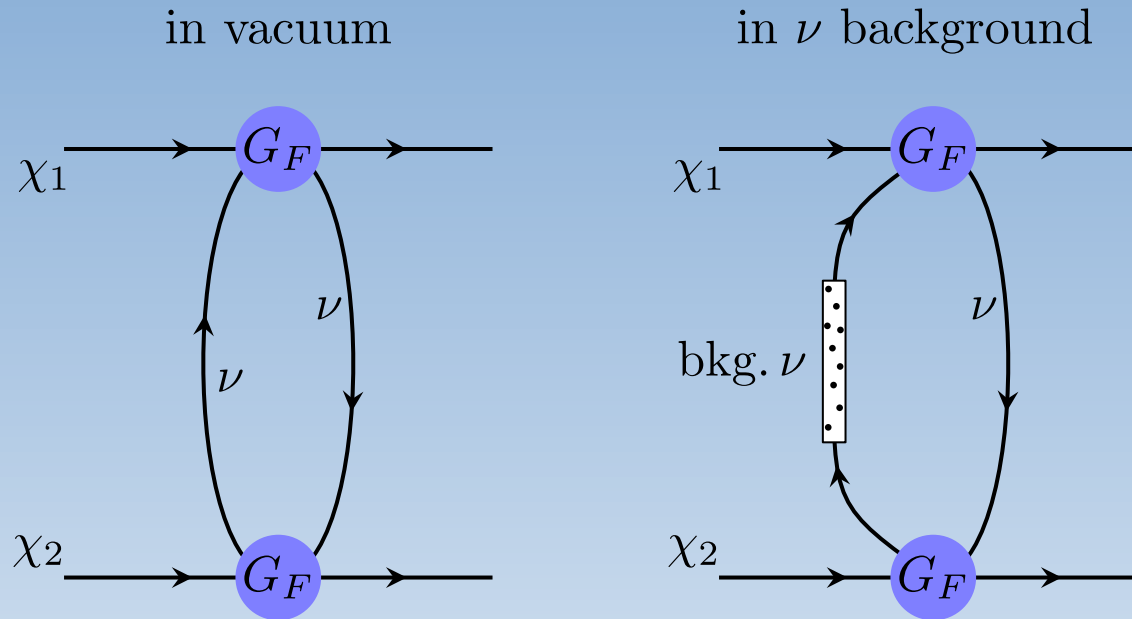
looks impressive!
 But how much do we need?
 ... think about $1/r$ vs $1/r^5$...



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 $1/r^5 \rightarrow 1/r$ at long ranges?

yes, if there is a background ... †



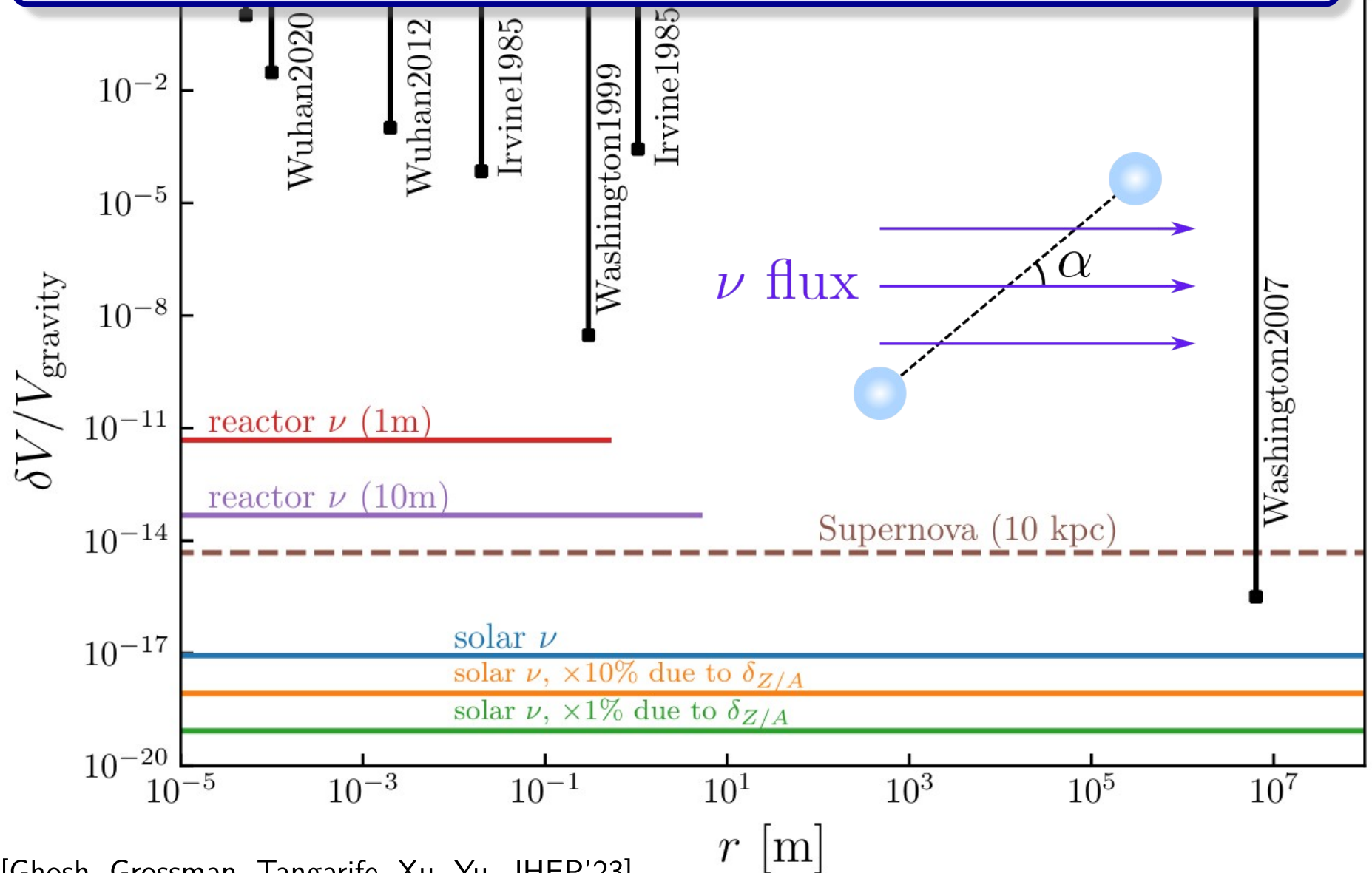
propagator in finite-T/n

$$S_\nu(k) = (k + m_\nu) \left\{ \frac{i}{k^2 - m_\nu^2 + i\epsilon} - 2\pi\delta(k^2 - m_\nu^2) [\Theta(k^0) n_\nu(\mathbf{k}) + \dots] \right\}$$

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

Result

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



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

However ...

However ... smearing effect at finite α ...

- ... only able to integrate it analytically at $\alpha = 0$ or 90°
 - both $\rightarrow V \propto 1/r$, exciting!
- for $\forall \alpha$, ... difficult ..., but eventually

Result

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

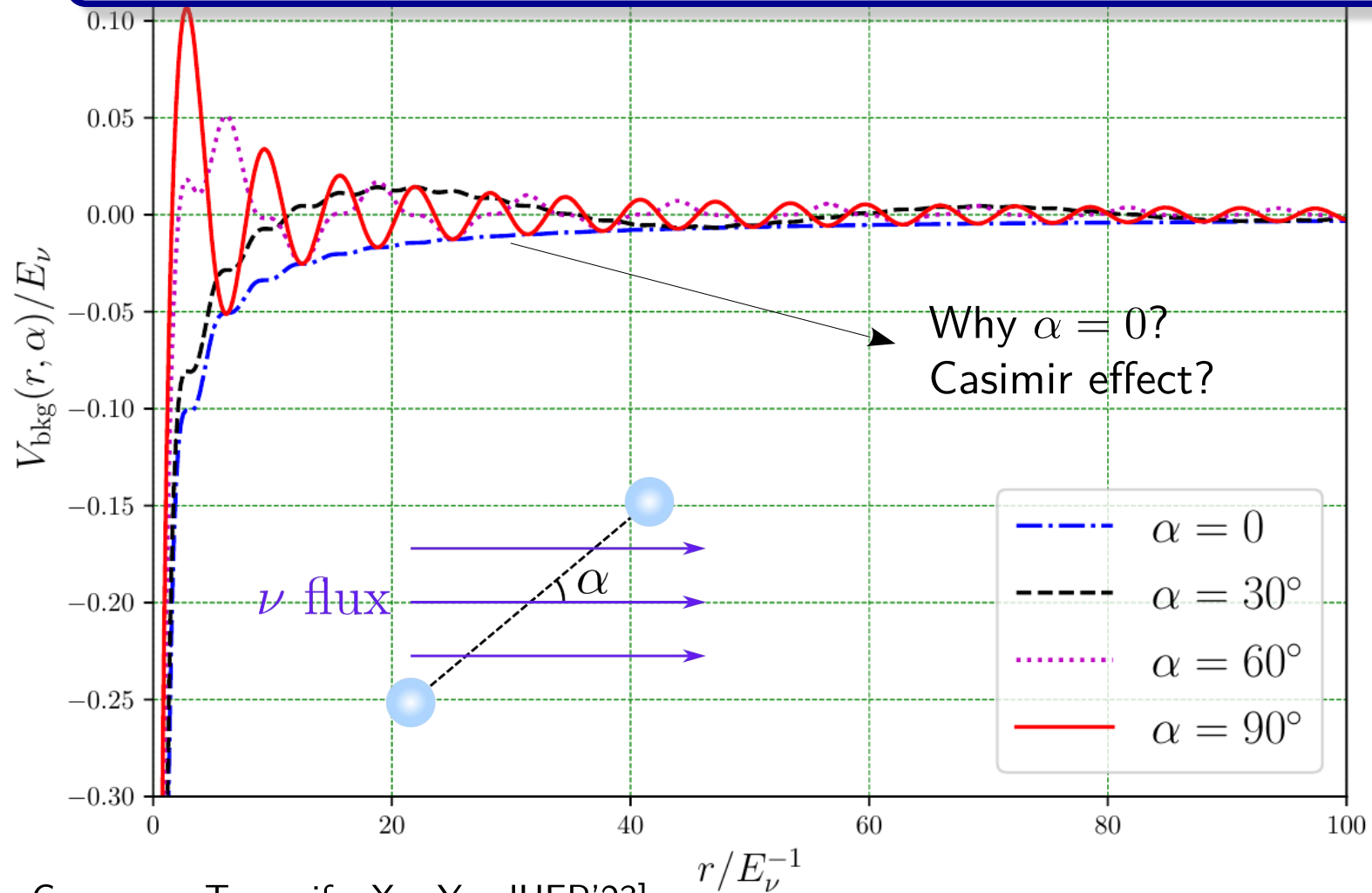
- unfortunately smearing effect at finite α !
- ... unless you design an exp with extremely suppressed α

condition to avoid smearing

$$\alpha^2 \lesssim \frac{\pi}{\delta_{E_\nu r}}$$

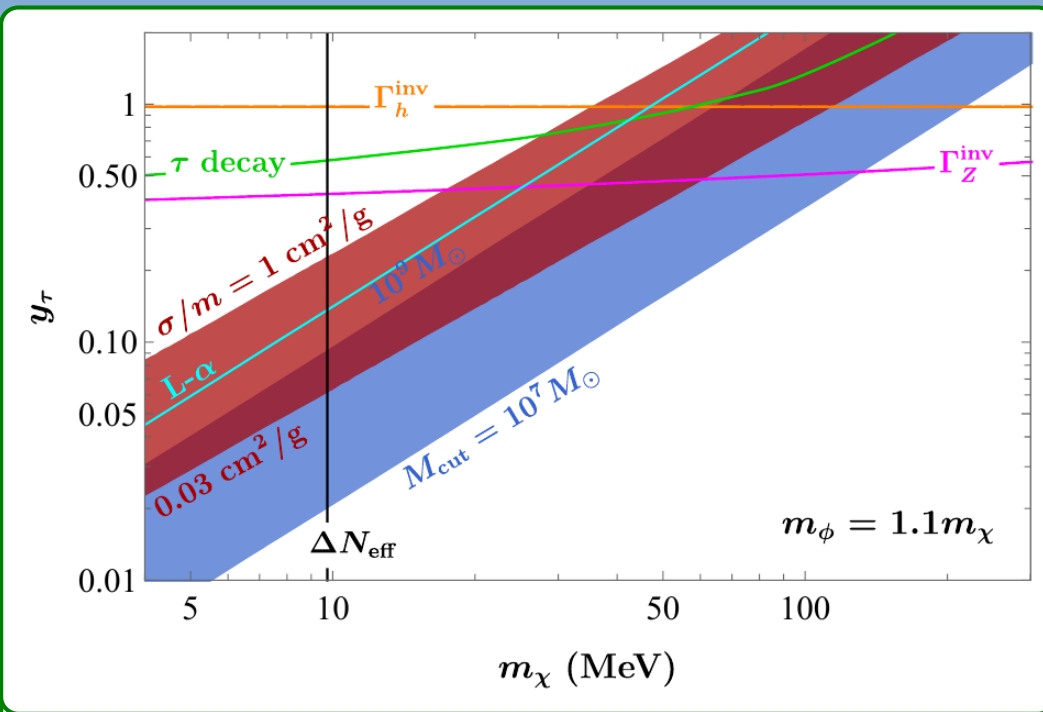
Result

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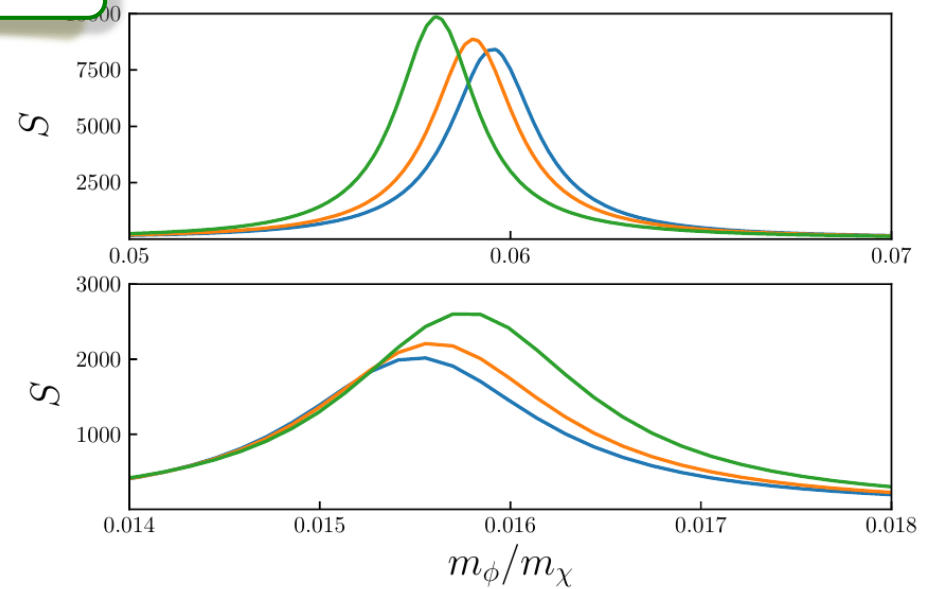
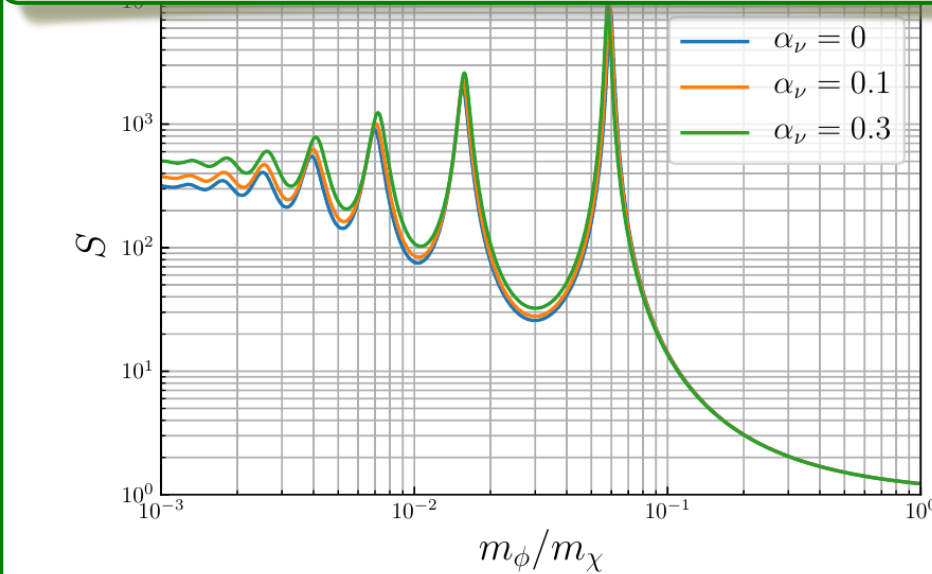


[Ghosh, Grossman, Tangarife, Xu, Yu, JHEP'23]

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



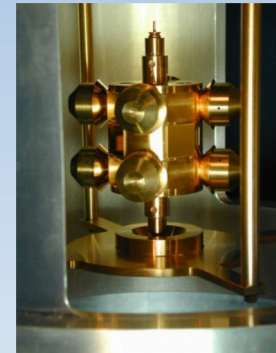
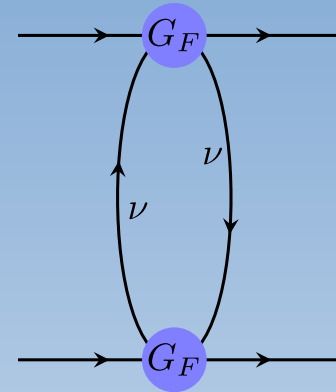
Conclusion

Theory

- $1/r^5$
 - why? and what happens if $r \rightarrow 0$?
- 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

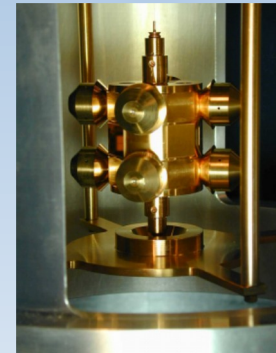
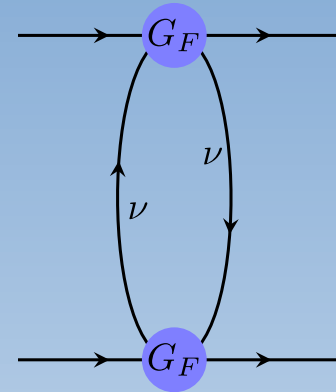
Conclusion

Theory

- $1/r^5$
 - why? and what happens if $r \rightarrow 0$?
- 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? — Future[†], yes!

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

Thanks