COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Rethinking Detection of Cosmic ν Background

Georgia Karagiorgi
Columbia University

"Table-Top Experiments with Skyscraper Reach" Workshop at MIT

August 9-11, 2017

Cosmic ν Background…

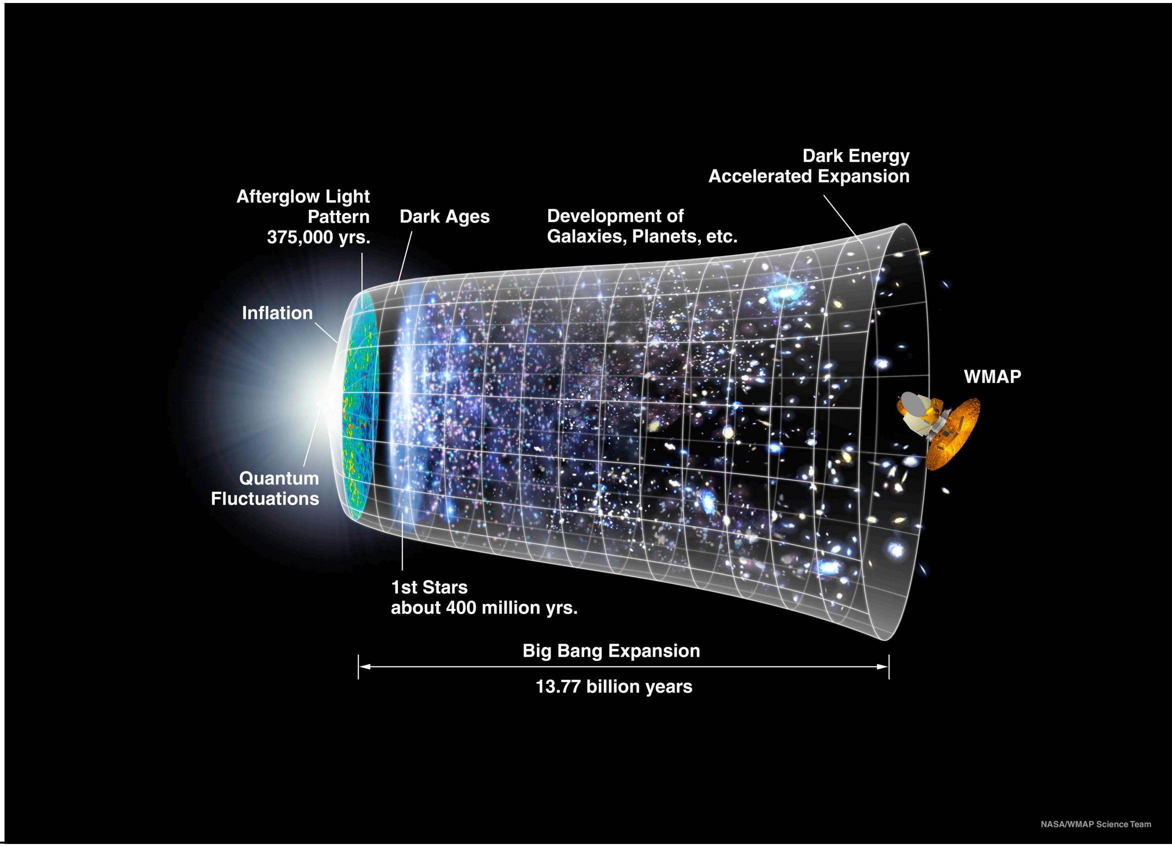
ν's are the second most abundant "standard" particles in our Universe.

~100 ν/cm^3

"Frozen in" as our universe cooled down to ~1 MeV (~1sec after Big Bang).

Only have indirect evidence of its existence.

Never been directly observed!



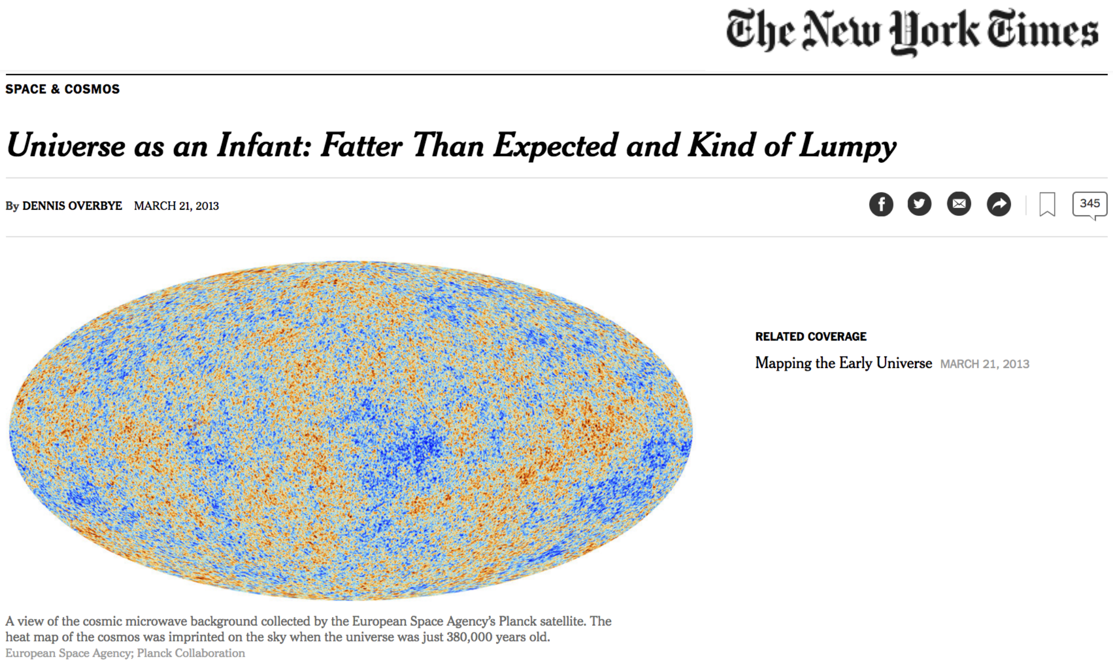
NASA/WMAP Science Team

…Analogue to CMB

What we have learned **from CMB measurements**:

- Composition of our Universe (baryonic, dark matter, dark energy)
- Physics of early Universe (inflation,…)
- Sum of neutrino masses, number of neutrino species
- …

One of the most significant discoveries of 20th century, and a triumphant validation of ΛCMD cosmological model!



The New York Times

SPACE & COSMOS

Universe as an Infant: Fatter Than Expected and Kind of Lumpy

By **DENNIS OVERBYE** MARCH 21, 2013

RELATED COVERAGE

Mapping the Early Universe MARCH 21, 2013

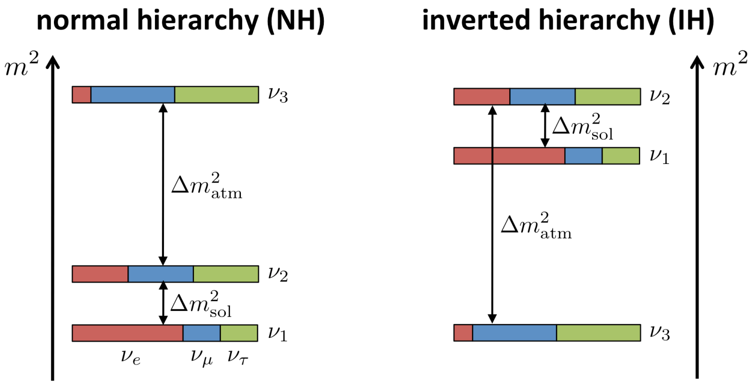
A view of the cosmic microwave background collected by the European Space Agency's Planck satellite. The heat map of the cosmos was imprinted on the sky when the universe was just 380,000 years old.

European Space Agency; Planck Collaboration

What we know about the CνB

- Fermi-Dirac distribution
- $T_\nu = (4/11)^{1/3}\, T_\gamma = 1.95$ K
- 56 $\nu(\bar{\nu})$/flavor/cm^3

  $\rho_\nu = (3)(7/8)(4/11)^{4/3}\, \rho_\gamma$
- $<p_\nu> = 0.5$ meV
- at least two neutrino species are non-relativistic (today)



Normal

$$m_2 \gtrsim \sqrt{\Delta m^2_{21}} \simeq 0.009\ eV \quad (\text{assuming } m_2 = 0)$$

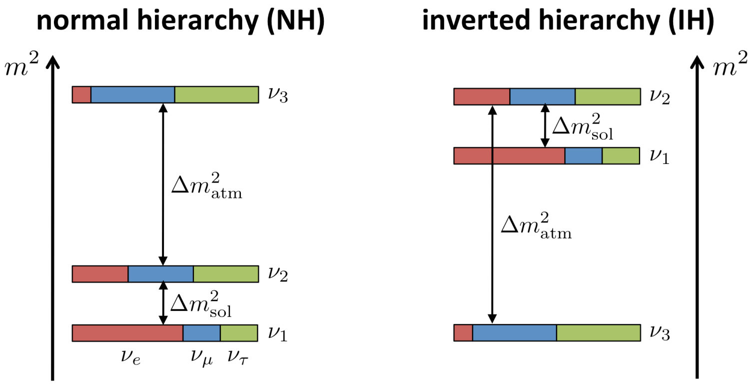
$$m_3 \gtrsim \sqrt{\Delta m^2_{32}} \simeq 0.05\ eV$$

Inverted

$$m_1 \simeq m_2 \gtrsim \sqrt{\Delta m^2_{32}} \simeq 0.05\ eV\ (\text{assuming } m_3 = 0)$$

What we don't know about the CνB

- absolute neutrino mass
- neutrino mass hierarchy
- *local* overdensity due to gravitational "clumping"
- additional neutrinos
- additional interactions
- Dirac or Majorana, and CP phase(s)
- [all your favorite question about neutrino properties!]



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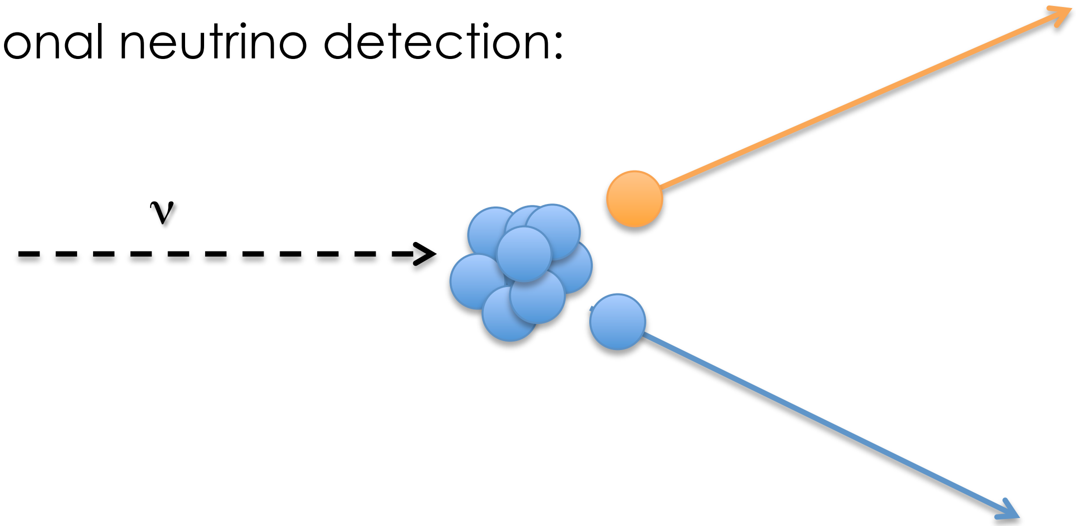
Why we have yet to detect it directly

Conventional neutrino detection:



Extremely low interaction probabilities.

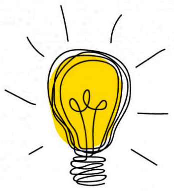
Interaction must be energetically allowed; usually requires some min. ν energy.

Final states must be "visible" in detector medium

- Final state energy loss processes (e.g. Cherenkov, ionization, scintillation) usually associated with some energy threshold
- Detector instrumentation for energy loss detection usually inefficient or has some energy threshold

Lots of IDEAs out there!

[A brief literature review]

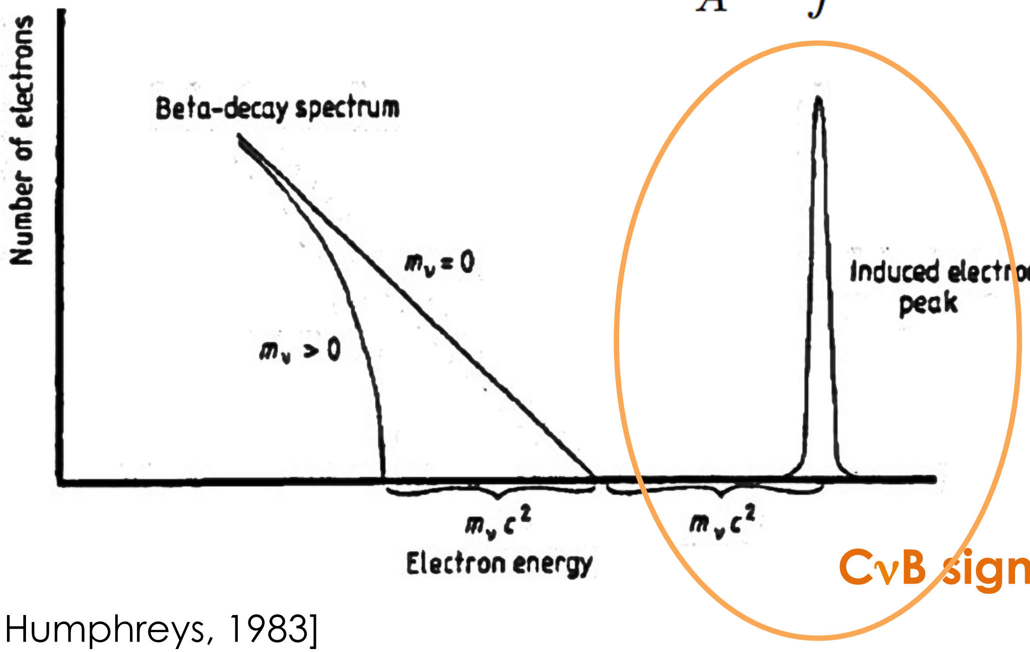


IDEA #1. Neutrino capture on beta-decaying nuclei

$$\nu_e + (A,Z) \rightarrow (A,Z+1) + e^-$$

No energy threshold for process (crucial for low-energy neutrinos)!

$$R_\nu = n_\nu \frac{N_A\ M_{\rm eff}}{A} \int \sigma_\nu v_\nu f(p_\nu) \frac{d^3 p_\nu}{2\pi^3}$$



CνB signal

Requires detector energy resolution σ << $2m_\nu$

(and a lot of beta-decaying nuclei!)

[Irvine, Humphreys, 1983]

IDEA #1. **Neutrino capture on beta-decaying nuclei**

E.g. **KATRIN** [e.g., Kaboth, Formaggio, Monreal, 2010]

- Tritium beta decay experiment
- Magnetic Adiabatic Collimation + Electrostatic Filter
- Measures beta spectrum using with sub-eV sensitivity to neutrino mass

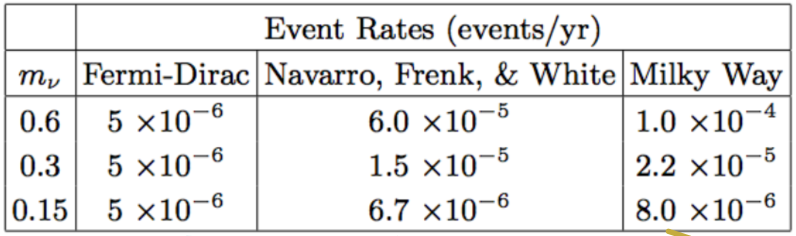
$$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \nu_e$$

IDEA #1. **Neutrino capture on beta-decaying nuclei**

E.g. **KATRIN** [e.g., Kaboth, Formaggio, Monreal, 2010]

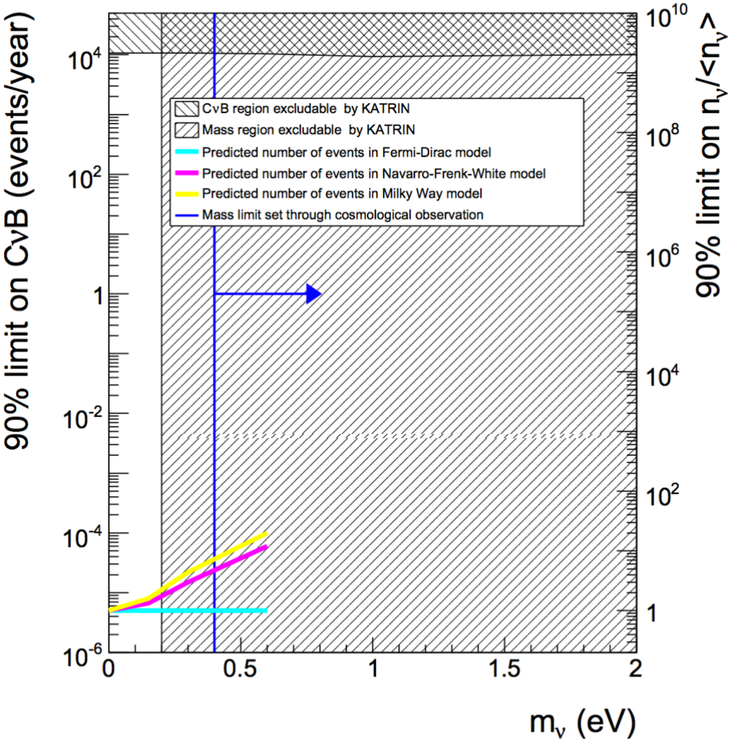
ν_e capture on ^{3}H:

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



	Event Rates (events/yr)		
m_ν	Fermi-Dirac	Navarro, Frenk, & White	Milky Way
0.6	5×10^{-6}	6.0×10^{-5}	1.0×10^{-4}
0.3	5×10^{-6}	1.5×10^{-5}	2.2×10^{-5}
0.15	5×10^{-6}	6.7×10^{-6}	8.0×10^{-6}

3 different local density scenarios

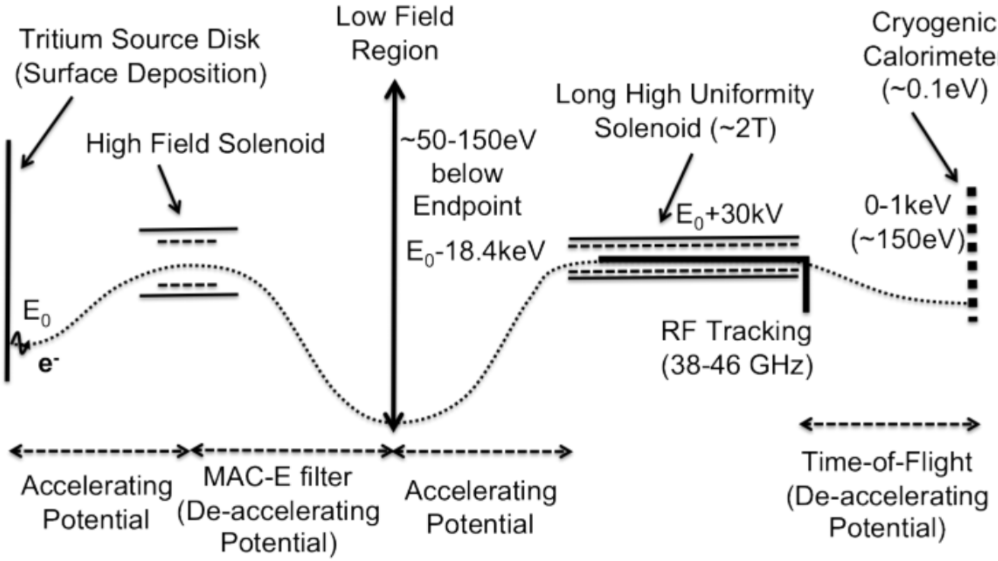


IDEA #1. **Neutrino capture on beta-decaying nuclei**

Also

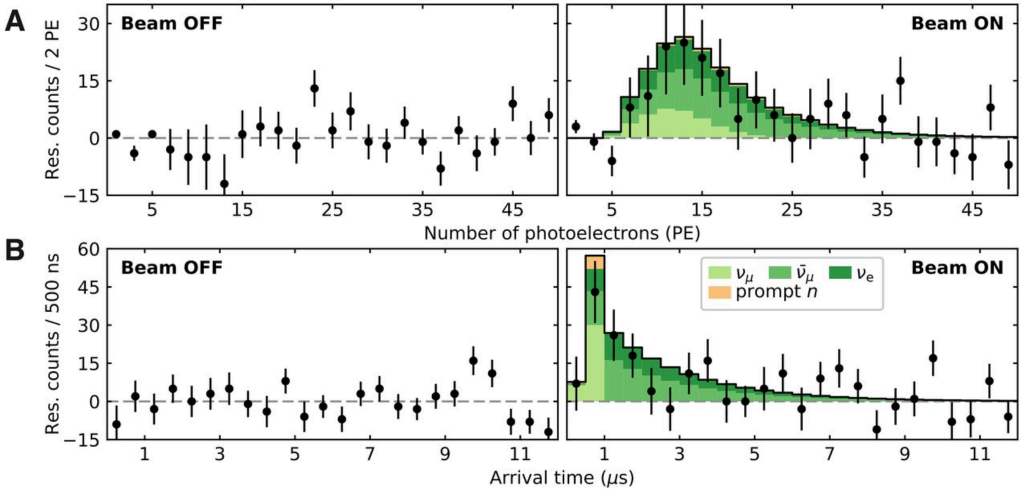
- **MARE** using ^{187}Re (much lower capture cross-section)
  [Andreotti *et al.*, 2007]

- and **PTOLEMY** using ^{3}H (as KATRIN) and variation on detection principle
  [Betts *et al.*, 2013]



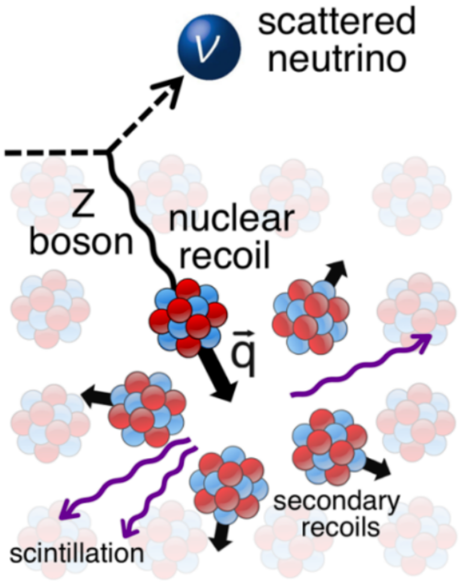
IDEA #2. **Mechanical force due to coherent elastic scattering off target**

Scattering process analogue to neutrino coherent scattering on nucleus:



[COHERENT Collab,
Science, Aug. 3, 2017]

A **well understood process**!
Announcement of
first ever observation
(using stopped-pion neutrinos)
just 1 week ago!

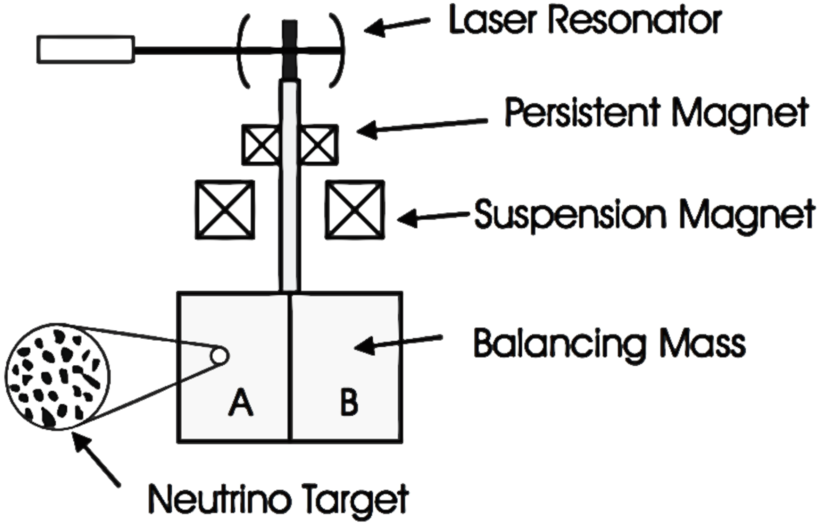


[see also next talk!]

IDEA #2. **Mechanical force due to coherent elastic scattering off target**

Cavendish-type torsion balance to detect neutrino wind induced acceleration

[Hagmann, 1999]



mass linear size < $\lambda_\nu \sim 0.23$ cm

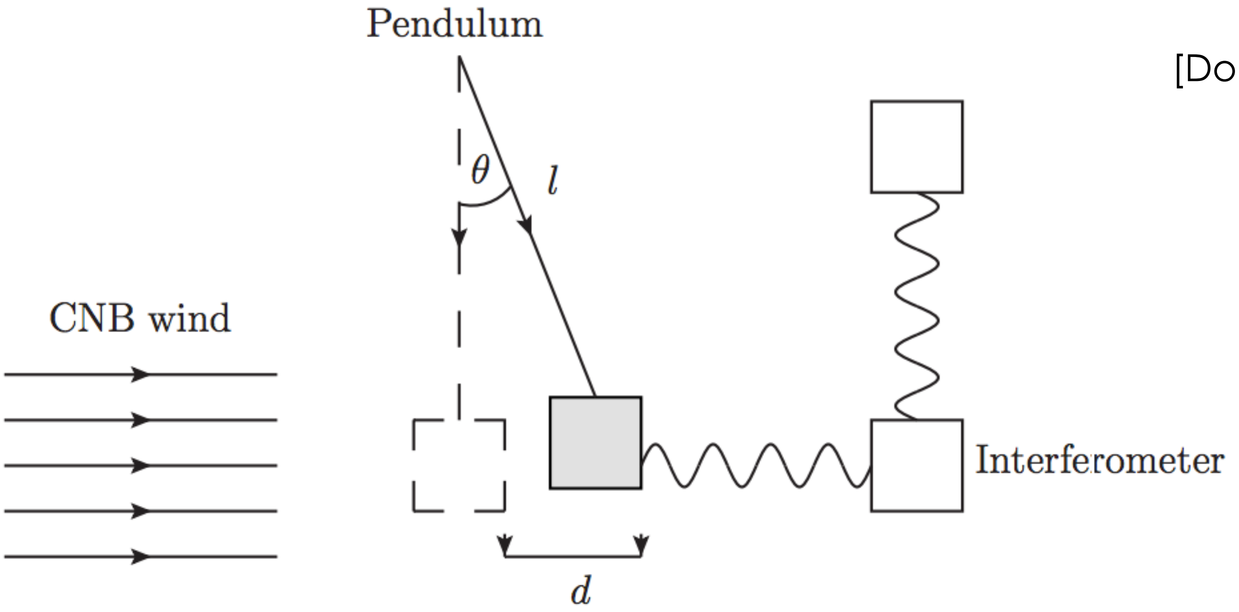
$$a_t \simeq \sum_{\nu,\bar{\nu}} \underbrace{n_\nu \, v_{\rm rel}}_{\rm flux} \frac{4\pi}{3} N_A^2 \, \rho_t \, r_t^3 \, \sigma_{\nu N} \; \underbrace{2\, m_\nu \, v_{\rm rel}}_{\rm mom.\ transfer}$$

$$\simeq 2 \times 10^{-28} \, \frac{\rm cm}{\rm s^2} \left(\frac{n_\nu}{\bar{n}_\nu}\right) \left(\frac{10^{-3}\, c}{v_{\rm rel}}\right) \left(\frac{\rho_t}{\rm g/cm^3}\right) \left(\frac{r_t}{\bar{\lambda}}\right)^3$$

and search for annual modulation due to Earth’s motion through CνB.

IDEA #2. **Mechanical force due to coherent elastic scattering off target**

A variation involving laser inferferometry



[Domcke, Spinrath, 2017]

Current technology: ~10^{-16} cm/s^2
Optimistic predictions for signal: ~10^{-27} cm/s^2

IDEA #3. **Absorption lines in extremely energetic neutrino spectra**

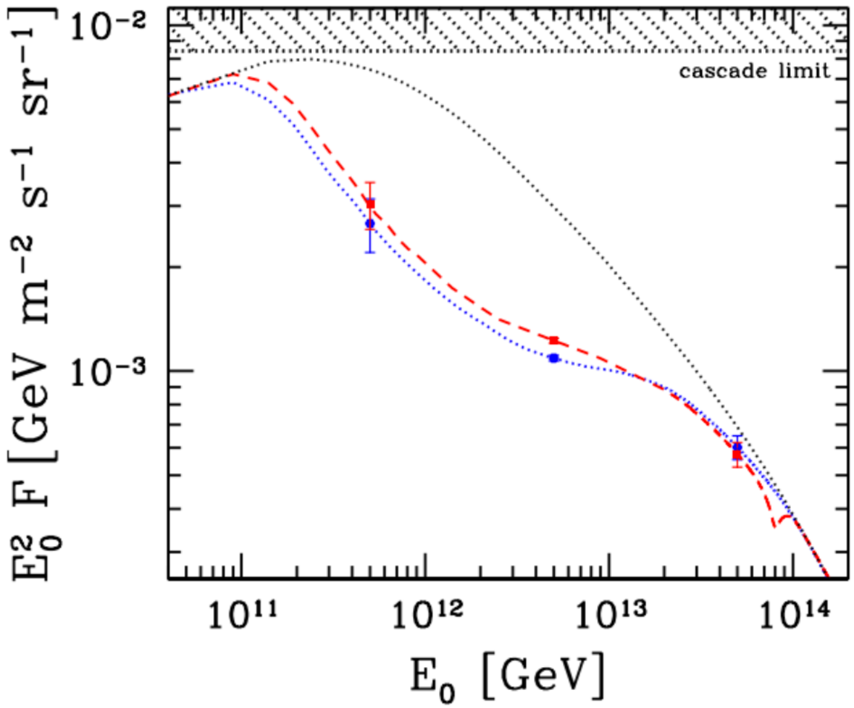
Extremely-energetic cosmic neutrinos **annihilating with relic** antineutrinos (or vice versa) into Z’s at resonant energies

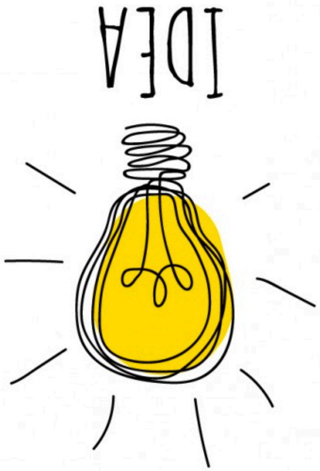
$$E_{0,i}^{\rm res} = \frac{m_Z^2}{2m_{\nu_{0,i}}} = 4.2 \times 10^{12} \left(\frac{\rm eV}{m_{\nu_i}}\right) {\rm GeV}$$

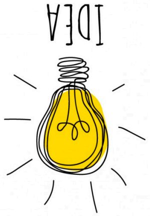
E.g. predicted ν spectrum from decaying super-heavy particles (10^{16} GeV), and projected **ANITA** and **LOFAR** sensitivity.

(*not quite direct, or “tabletop”)

[Ringwald, Schrempp, 2006]




IDEA

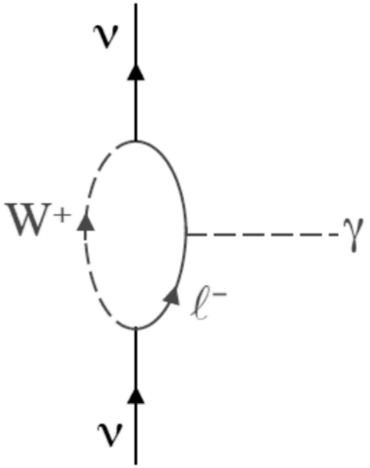


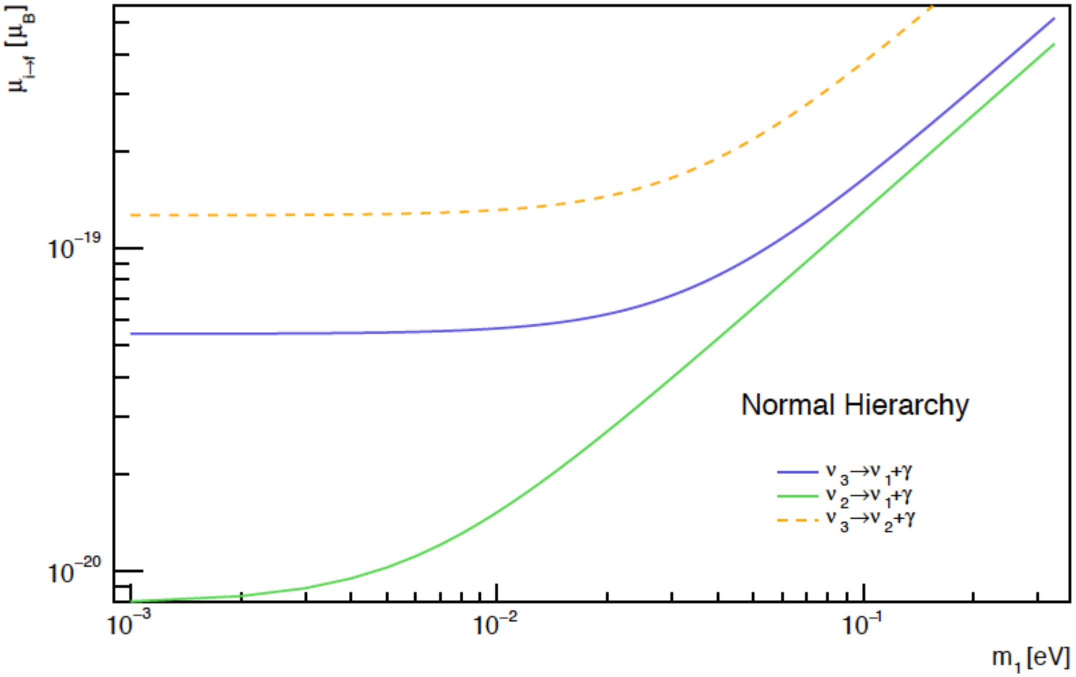
New idea: Exploit **(non-zero) neutrino magnetic moment**

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = \frac{3G_F m_e m_\nu}{4\pi^2\sqrt{2}}\mu_B$$

(νSM, Dirac, predicted)

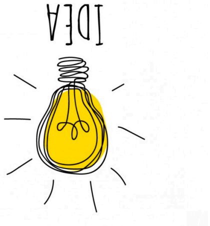
$$\mu_\nu \approx 3\times 10^{-19}\left(\frac{m_\nu}{1\mathrm{eV}}\right)\mu_B$$





[Marciano, Sanda;
Lee, Shrock;
Fujikawa, Shrock]

[See also Giunti & Studenikin 2015,
for a thorough review]



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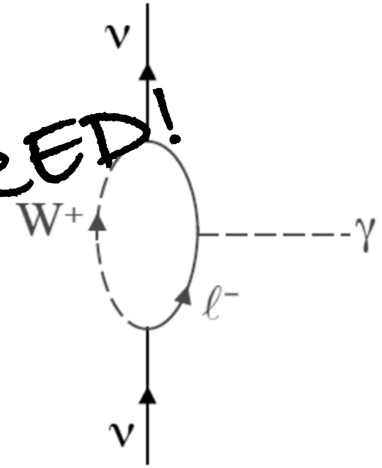
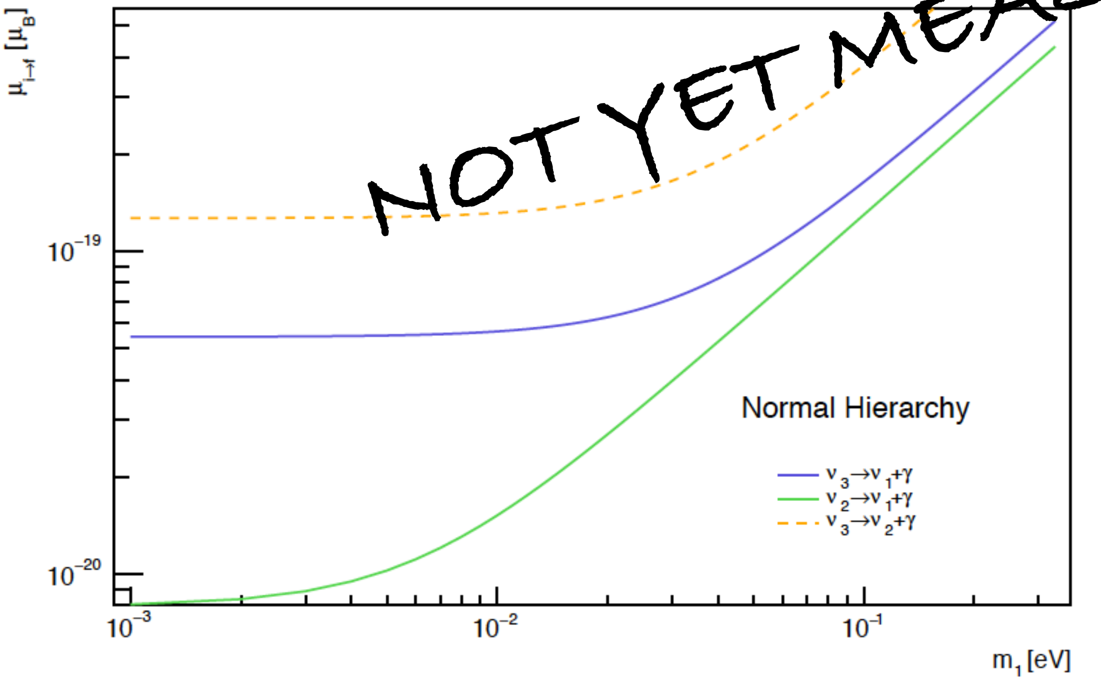


NOT YET MEASURED!



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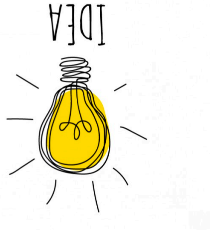
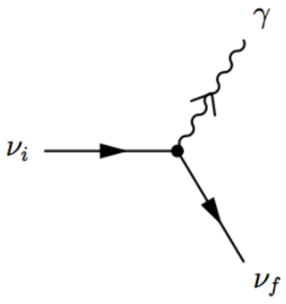


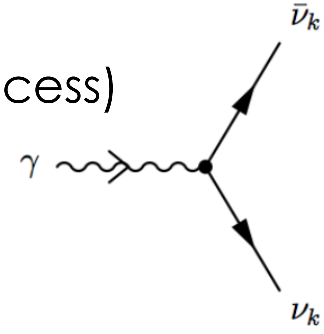
New idea: Exploit **(non-zero) neutrino magnetic moment**

Rich phenomenology!

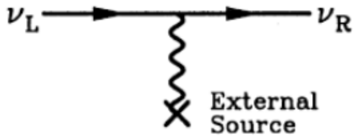
- Neutrino decay and neutrino cherenkov radiation



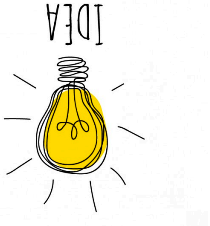
- Photon decay (plasma process)



- Neutrino-e/N scattering
- Spin precession



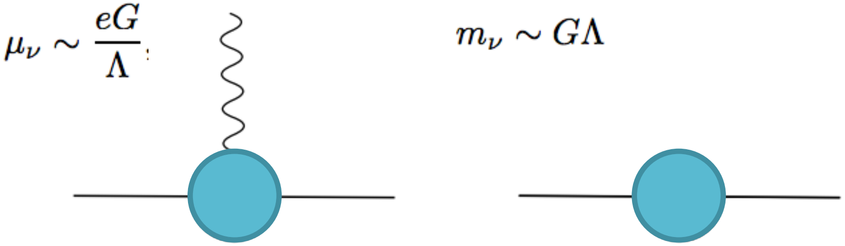
[Raffelt, 1999]



New idea: Exploit **(non-zero) neutrino magnetic moment**

Tiny effects, BUT, possible enhancement due to New Physics!

Generally difficult to reconcile smallness of neutrino mass with large μ_ν,



$$\mu_\nu \sim \frac{eG}{\Lambda}$$

$$m_\nu \sim G\Lambda$$

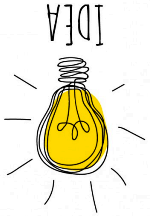
$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \ \mathrm{eV}$$

but **careful choice** of new physics allows for μ_ν as large as

$$\mu_\nu^{\mathrm{Dirac}} \lesssim 3\times 10^{-15}\mu_B\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \rightarrow \ \mu_\nu \lesssim 10^{-15}\mu_B \quad \text{for } \Lambda\text{~}1 \text{ TeV and } m_\nu < 0.3 \text{ eV}$$

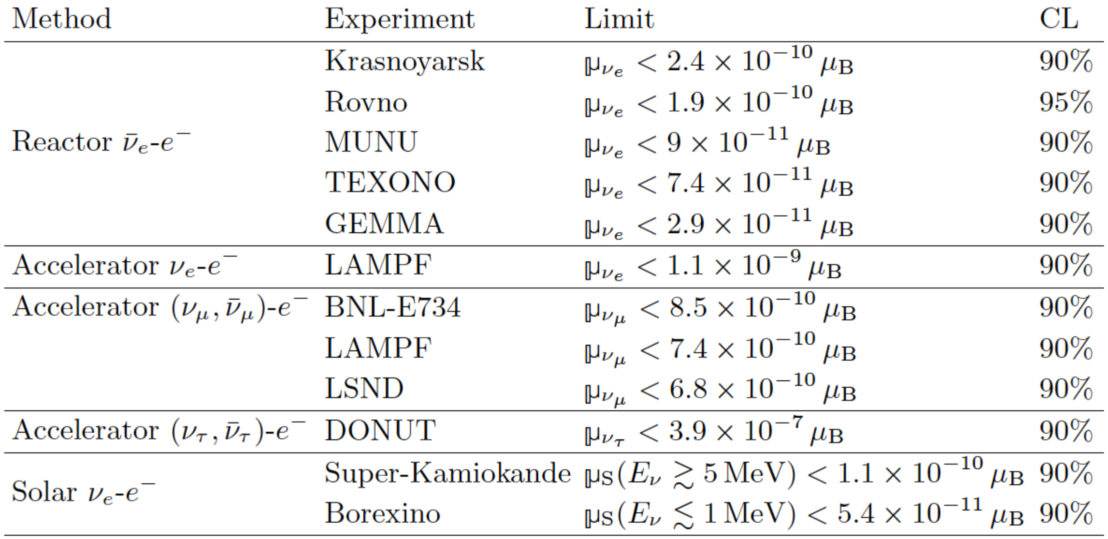
$$\mu_{\alpha\beta}^{\mathrm{Majorana}} \leq 4\times 10^{-9}\mu_B\left(\frac{[m_\nu]_{\alpha\beta}}{1\ \mathrm{eV}}\right)\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2\left|\frac{m_\tau^2}{m_\alpha^2 - m_\beta^2}\right|$$

[Bell, 2007]



New idea: Exploit **(non-zero) neutrino magnetic moment**

Experimental bounds:

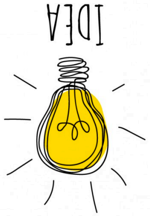


Method	Experiment	Limit	CL
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_B$	90%
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_B$	95%
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}\,\mu_B$	90%
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_B$	90%
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_B$	90%
Accelerator ν_e-e^-	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}\,\mu_B$	90%
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_B$	90%
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_B$	90%
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_B$	90%
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_B$	90%
Solar ν_e-e^-	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}\,\mu_B$	90%
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 5.4 \times 10^{-11}\,\mu_B$	90%

[Giunti & Studenikin, 2015]

Constraints generally from:

- Reactor neutrino experiments
- Solar neutrino experiments
- Also energy loss from stars



New idea: Exploit **(non-zero) neutrino magnetic moment**

Reactor neutrino measurements:

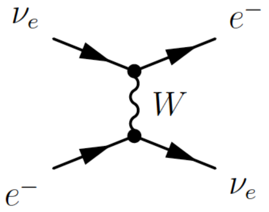
$$\frac{d\sigma}{dT} = \boxed{\frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T}{E_\nu}\right)^2 + (g_A^2-g_V^2)\frac{m_e T}{E_\nu^2}\right]}$$

SM

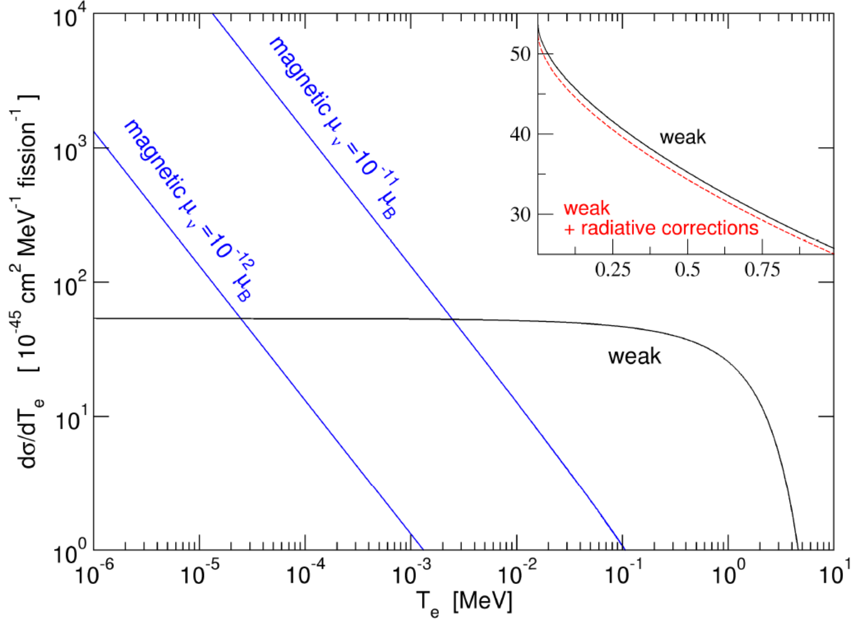
$$+ \boxed{\frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1}{T}-\frac{1}{E_\nu}\right]}$$

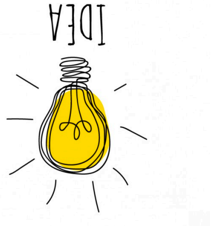
contribution from μ_ν dominates for

$$\frac{T}{m_e} < \frac{\pi^2\alpha^2}{(G_F m_e^2)^2}\mu_\nu^2$$

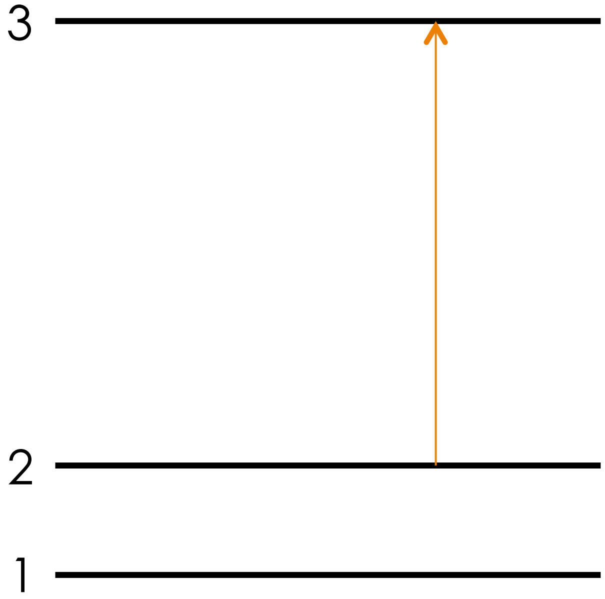


[Balantekin, Vassh, 2014]





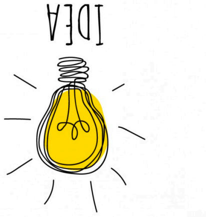
Photon absorption spectroscopy
through **(Non-zero) Neutrino Magnetic Moment**



Assuming $m_1 \sim 0$ and approx. $KE_2 \sim 0$.

$E_\gamma = E_{2\rightarrow3} \sim \Delta m^2_{32}/2m_2 \sim 0.14$ eV

$\lambda_{23} \sim 8850$ nm



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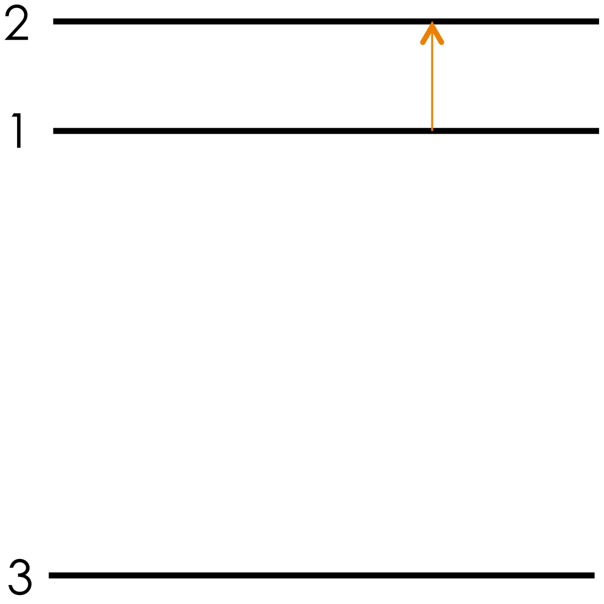
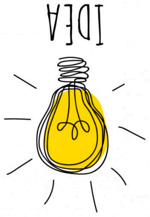


Assuming $m_3 \sim 0$ and approx. $KE_1 \sim 0$.

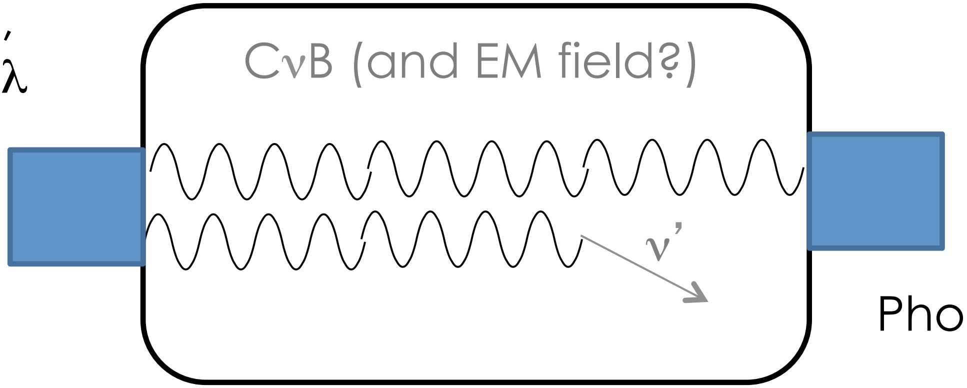
$E_\gamma = E_{1\rightarrow 2} \sim \Delta m^2_{12}/2m_1 \sim 0.77$ meV

$\lambda_{12} \sim 1610\ \mu m$

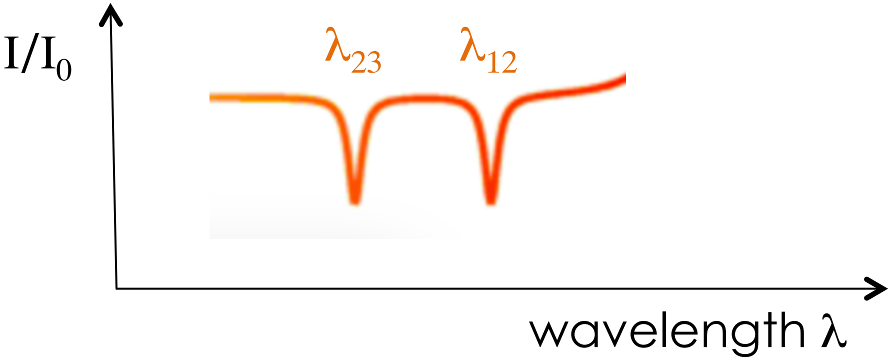


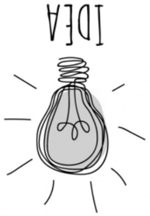
Photon absorption spectroscopy
through **(Non-zero) Neutrino Magnetic Moment**

Photon source I_0,
wide or tunable λ



Photon detector I





Some considerations

Extremely low rate would require intense photon source:

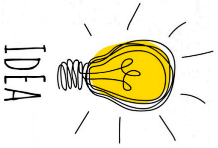
“tabletop” ✗ LIGO-style → would need O(10)’s of GW laser and tens of km!
high vacuum, cooling are an issue

“tabletop” ✓ Optical cavity-style with higher finesse → still worry about heating

Mono-energetic, tunable? Or wide-band?

Additional limitations:

- Detector energy resolution
- High vacuum and impurity levels

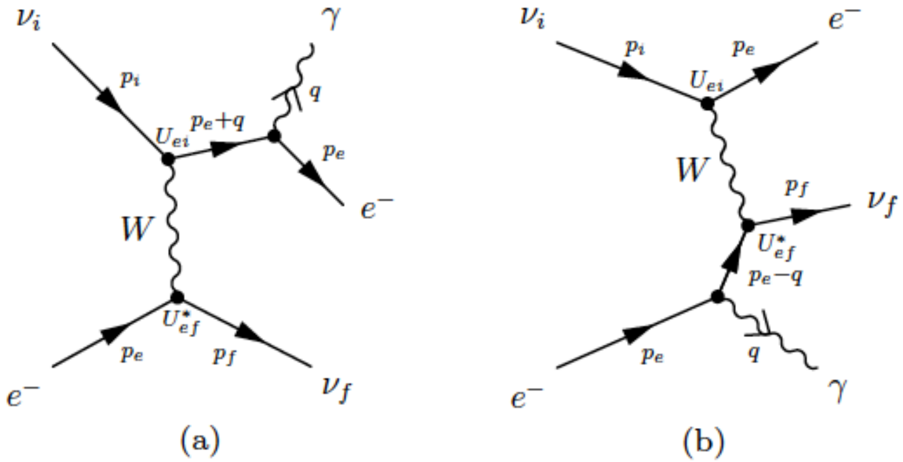


Further considerations, other avenues?

- Appearance-style, zero-background experiments are easier than disappearance ones!
  - Neutrino radiative decay instead?
  - Lifetime is estimated to be > age of Universe.
- Radiative decay in matter (instead of vacuum)?

$$\frac{\tau^{\mathrm{mat}}_{\nu_i\to\nu_f+\gamma}}{\gamma_i\tau^{\mathrm{rf}}_{\nu_i^{\mathrm{D}}\to\nu_f^{\mathrm{D}}+\gamma}} \simeq 1.1\times10^{-19}\left(\frac{|U_{\tau i}|^2|U_{\tau f}|^2}{|U_{ei}|^2|U_{ef}|^2}\right) \times\left(\frac{m_i}{\mathrm{eV}}\right)^4\left(\frac{N_{\mathrm{A}}\,\mathrm{cm}^{-3}}{N_e}\right)^2 .$$

(νSM, Dirac)



(a)

(b)

[Giunti & Studenikin 2015]

Closing in: Detection of Cosmic ν Background

An interesting challenge!

Potential for **table-top** solutions, to be explored.

Physics reach, should it be feasible to experimentally probe beyond current μ_ν bounds:

1. Detection of CνB
2. Measurement of neutrino magnetic moment
3. Majorana nature of neutrino
4. New physics and contributions to $\boldsymbol{\mu_\nu}$
5. Additional neutrino mass states?

[Exploring these ideas w/ M. Toups, Fermilab]