Physics with Beta Beams

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Outline

- Neutrino Physics: An Introduction
- Beta Beams
- Neutrino Physics with Beta Beams
  - CP violation and Θ_{13}
  - ν-nucleus interactions
  - ν magnetic moment

Neutrino Properties

- spin 1/2 fermions
- interact weakly
- 3 flavors couple to Z boson

$$\nu_e,\ \nu_\mu,\ \nu_\tau$$

- ν_e produced by beta beam, e.g.

$$\begin{aligned} {}^6\mathrm{He} &\to {}^6\mathrm{Li} + e^- + \bar{\nu}_e \\ {}^{18}\mathrm{Ne} &\to {}^{18}\mathrm{F} + e^+ + \nu_e \end{aligned}$$

- mass scale from direct searches

$$\begin{aligned} m_{\nu_e} &< 2.2\,\mathrm{eV} \\ m_{\nu_\mu} &< 170\,\mathrm{keV} \\ m_{\nu_\tau} &< 18\,\mathrm{MeV} \end{aligned}$$

$$\boxed{\text{but: mixing constrains all } m_\nu < 2.2\,\mathrm{eV}}$$

because we know some mass splittings

solar	$\delta m_{12}^2 \simeq m_2^2 - m_1^2 \simeq 7.0 \times 10^{-5}\,\mathrm{eV}^2$
atmos	$\delta m_{32}^2 \simeq m_3^2 - m_2^2 \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

MNS Matrix

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

3 mixing angles, CP violating phase

$$\begin{aligned} U_{e1} &= \cos\theta_{12}\cos\theta_{13} \\ U_{e2} &= \sin\theta_{12}\cos\theta_{13} \\ U_{e3} &= \sin\theta_{13}e^{-i\delta} \end{aligned}$$

Measured Parmeters

$\Theta_{12} \simeq 35^o$	solar neutrinos/ KamLAND
$\Theta_{23} \simeq 45^o$	atmospheric neutrinos
$\Theta_{13} < 7^o$	reactor neutrinos
δ	no information

Some Open Questions

- What is Θ_{13}? Is there CP violation?

  long baseline experiment

- Absolute mass scale?

  ^{3}H β decay, cosmology

- Majorana vs Dirac

  2β decay

- what is the magnetic moment?
- are neutrinos stable?

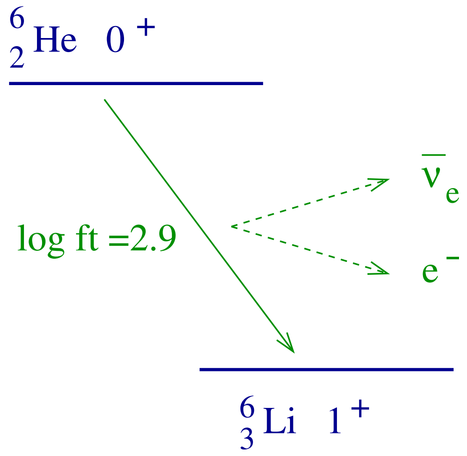
Important for Astrophysics

- How do neutrinos interact with nuclei?

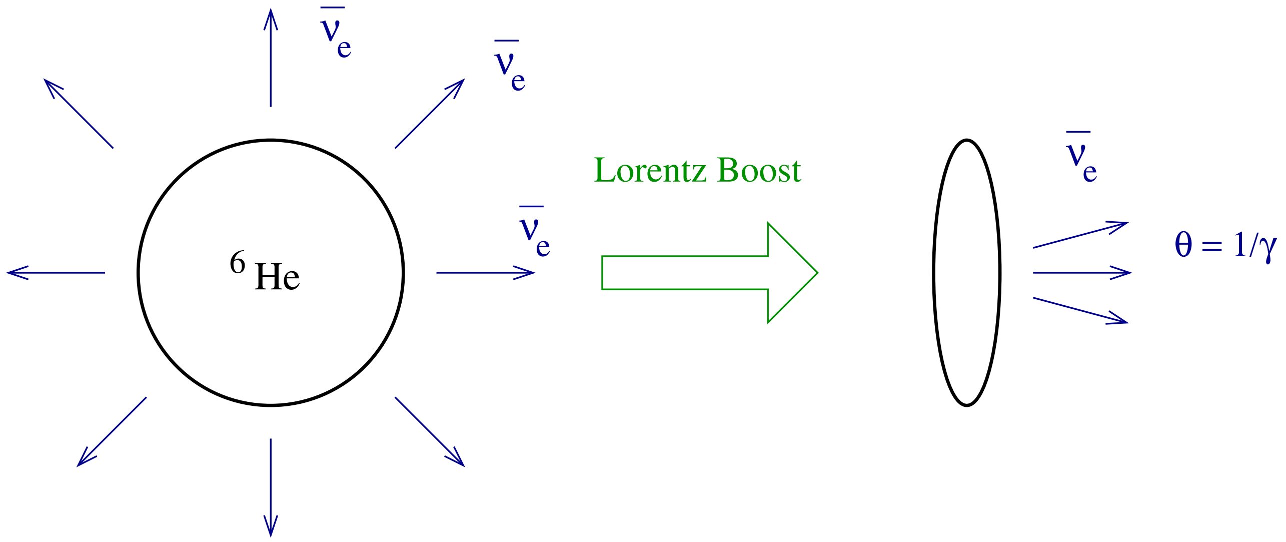
<u>**Beta Beams**</u>

first discussed by Zucchelli (2002)

Neutrinos, either $\nu_e, \bar{\nu}_e$, or both, come from beta decay of accelerated radioactive ions



$$\tau_{1/2} = 0.8065\,\mathrm{s}$$
$$Q_{\beta^-} = 3.507\,\mathrm{MeV}$$

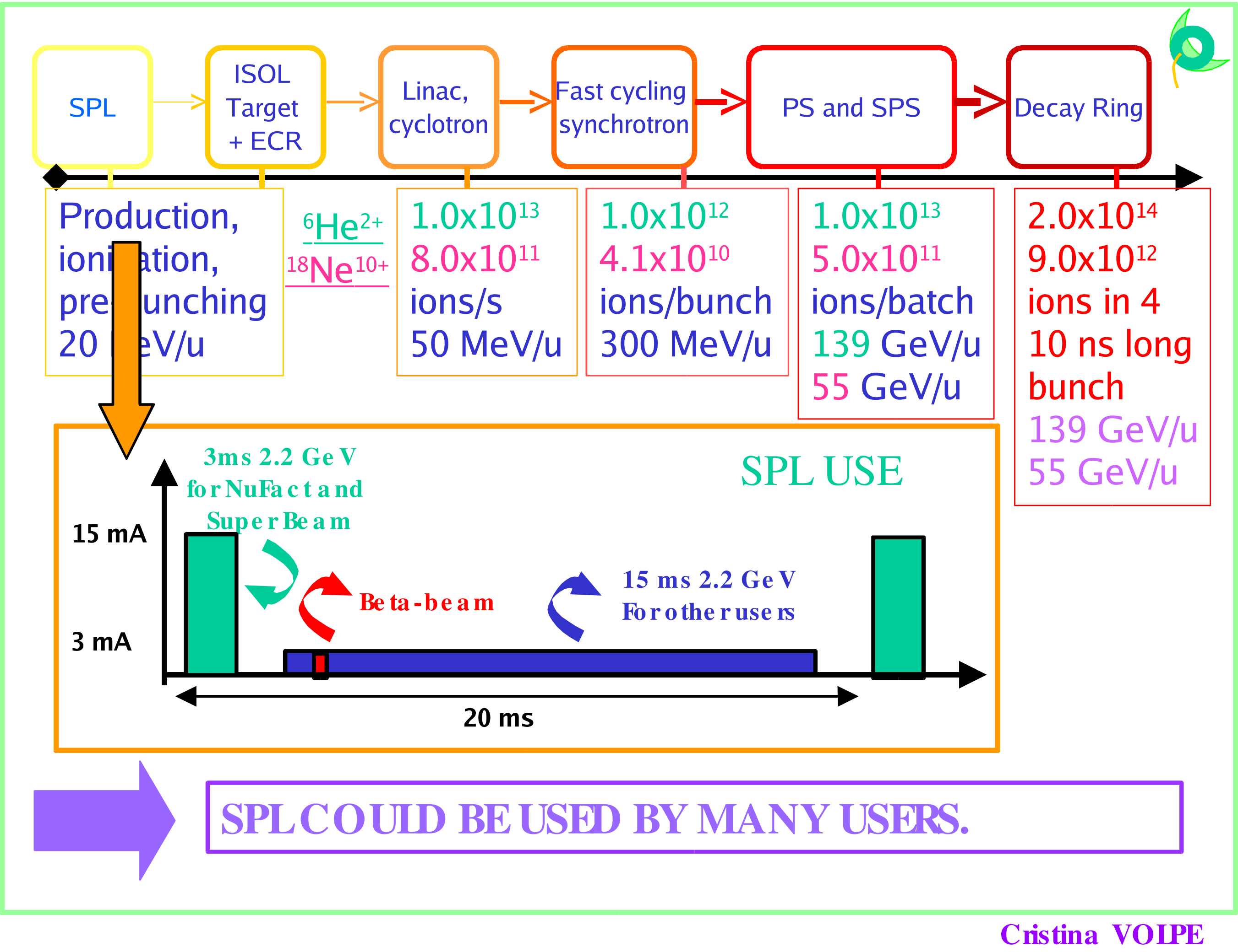


- pure ν_e or $\bar{\nu}_e$ beam
- well known flux
- highly collimated $\gamma \sim (55 - 140)$

Compare to conventional ν beam: $\pi \to \mu\bar{\nu}_\mu \quad \mu \to \nu_\mu e \bar{\nu}_e$

Neutrino factory: $\mu \to \nu_\mu e \bar{\nu}_e$

Example of how it could work at CERN



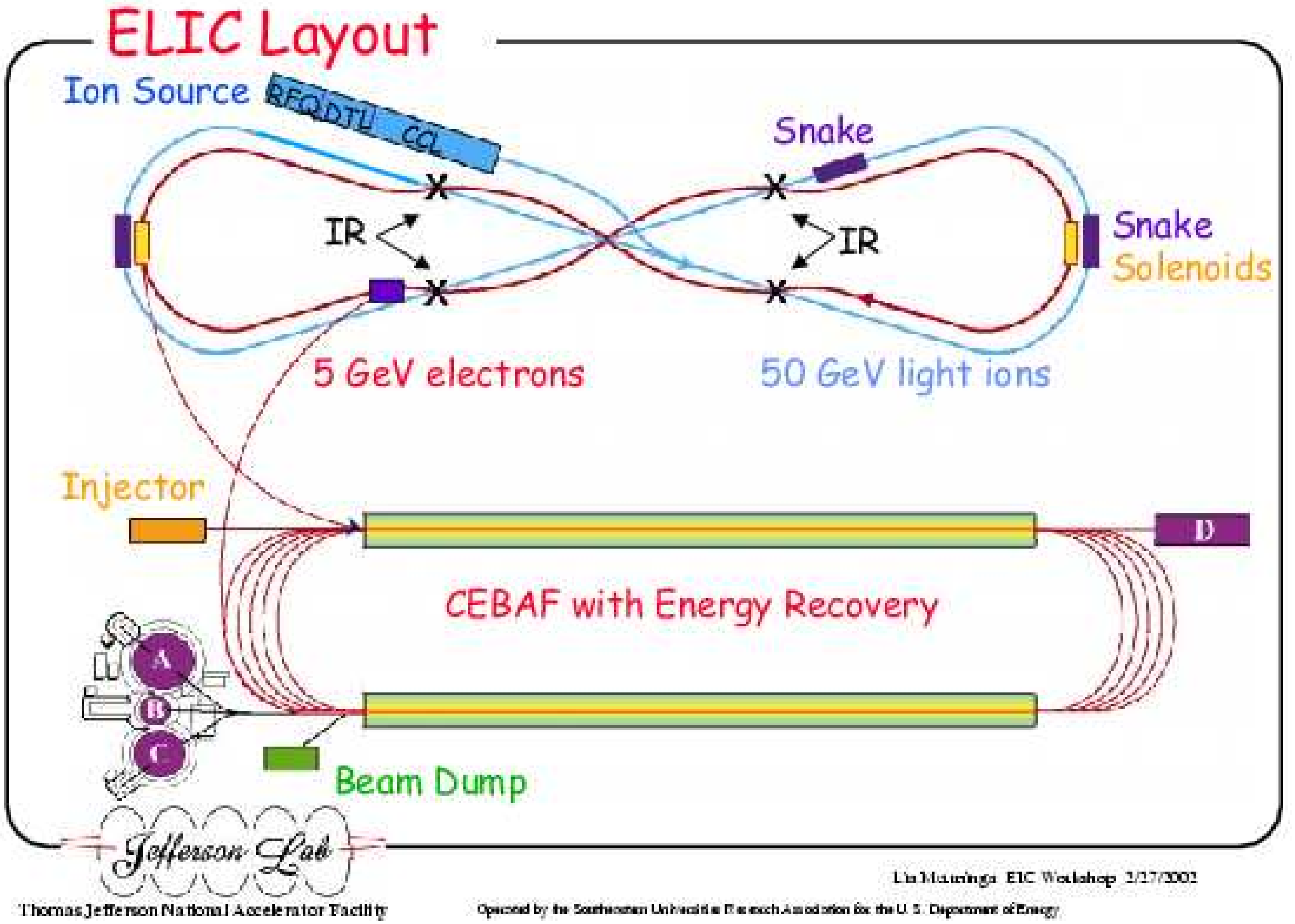
Design discussed in Lindroos (2003)

Slide from B. Flemming (2003)

Neutrino beam program at JLab:

•parasitic running of neutrino SB program off ELIC booster

•beta beams along arms of ELIC collider rings



Analogous idea to running AGS for a neutrino program while it is a feeder for RHIC and eRHIC

And at JLAB

Oscillations with Θ_{13}

Two flavor oscillations

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left[1.27\left(\frac{\delta m^2}{\mathrm{eV}^2}\right)\left(\frac{L}{\mathrm{km}^2}\right)\left(\frac{\mathrm{GeV}}{E}\right)\right]$$

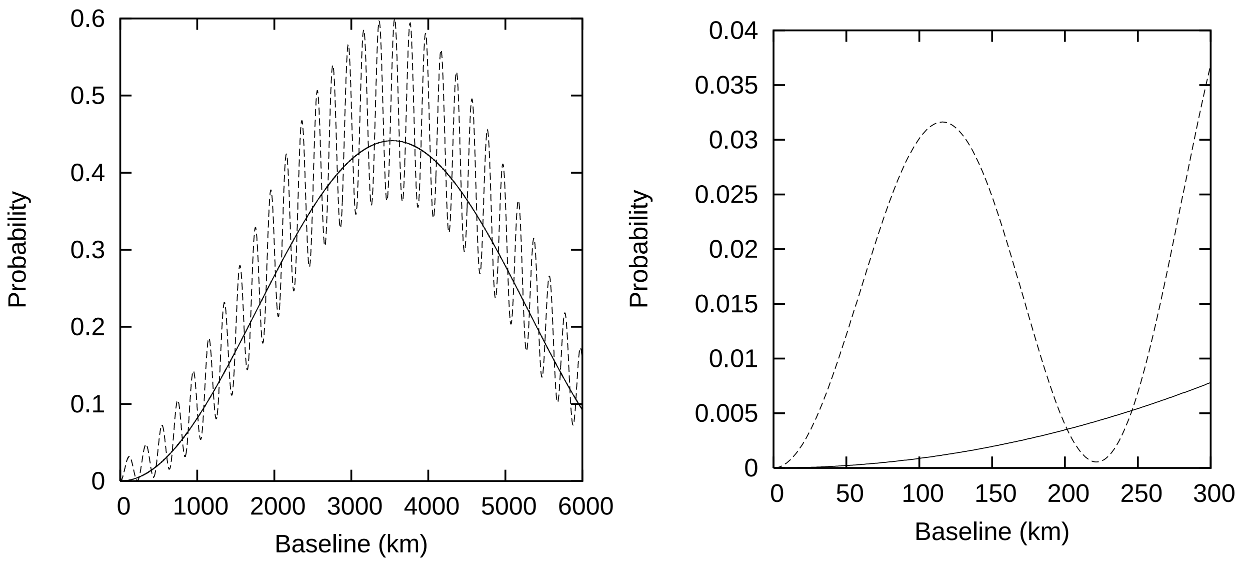
Use $\delta m^2_{32} = 2.5 \cdot 10^{-3}\mathrm{eV}^2$ (atmospheric)

$$E = \text{few hundred MeV} \quad \Rightarrow \quad \text{need } L \sim 100 \text{ km}$$

But: Really have more than two flavors, should use full expression with

$$\delta m^2_{31}, \delta m^2_{21}, \delta m^2_{23}, \Theta_{12}, \Theta_{23}, \Theta_{13}, \delta$$

Probability $\nu_e \to \nu_\mu$

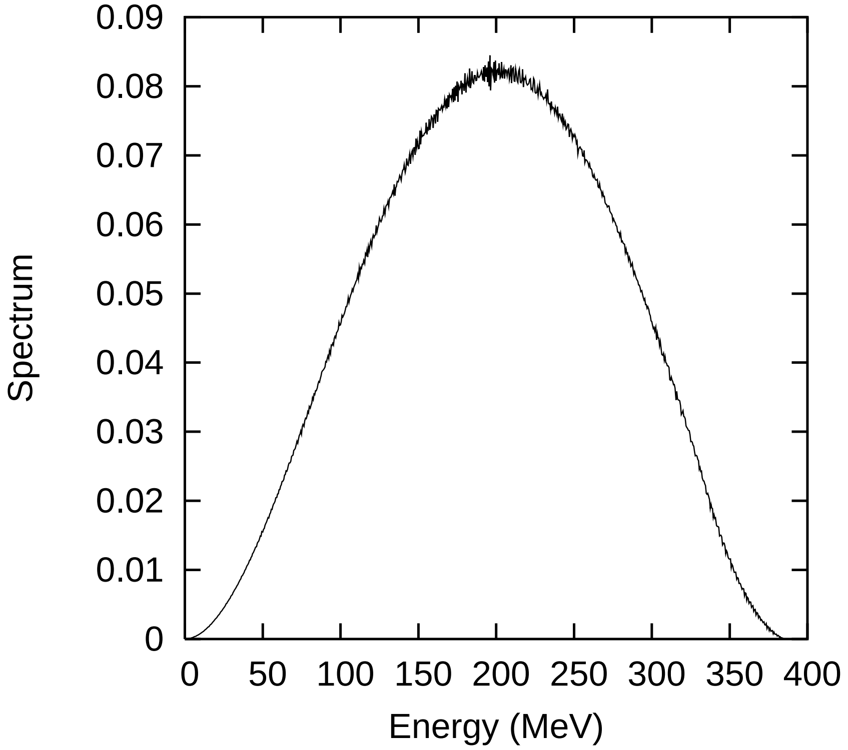


solar scale $\qquad\qquad$ δm^2_{31} scale

(solid: $E_\nu = 200$ MeV, $\Theta_{13} = 0^o$, $\delta = 0$)
(dashed: $E_\nu = 200$ MeV, $\Theta_{13} = 7^o$, $\delta = 0$)

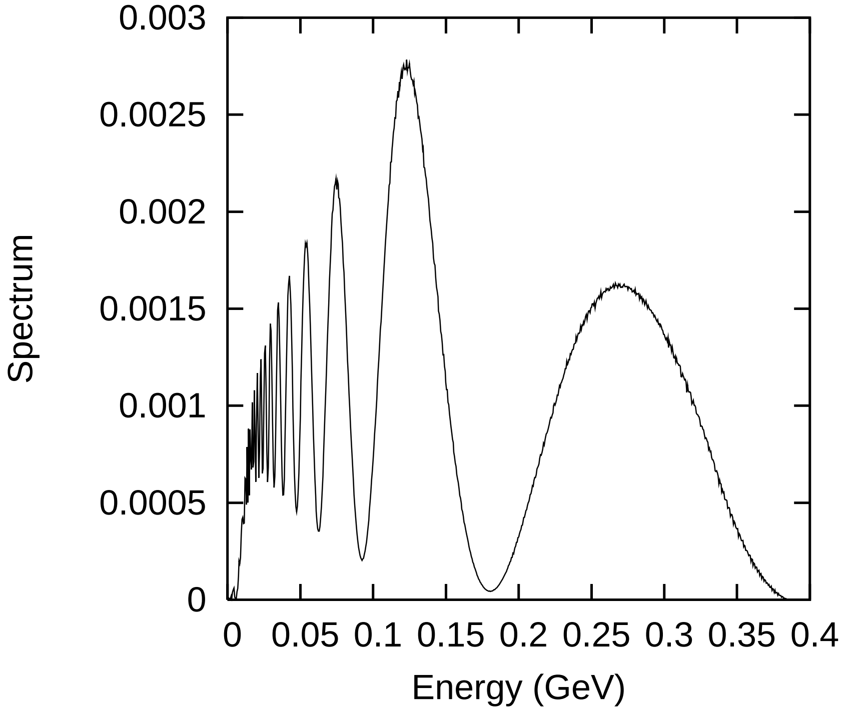
beta beam $\bar{\nu}_e$ spectrum

(angle 0.5^o, $\gamma = 55$)



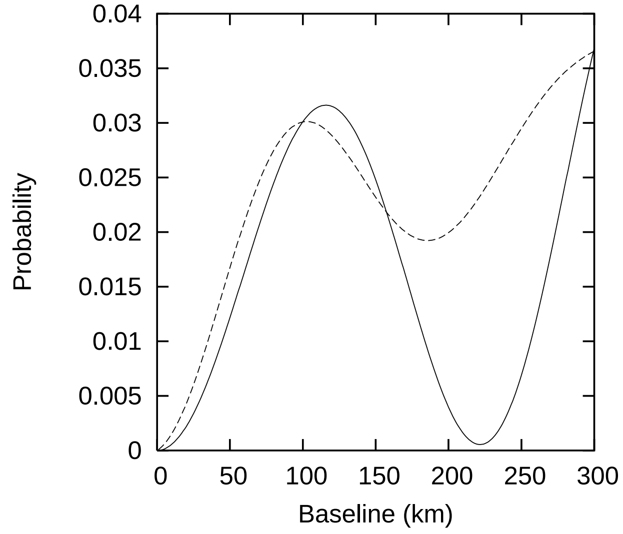
produced $\bar{\nu}_\mu$ spectrum at 200 km

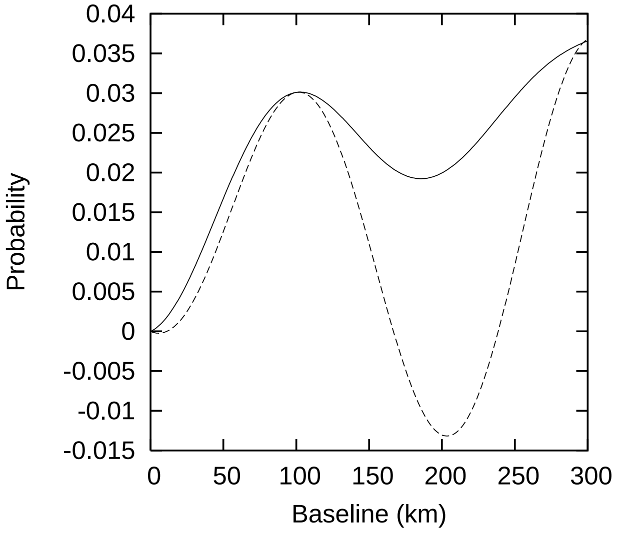
($\Theta_{13} = 7^o$, $\delta = 0$)



Oscillations with CP violation

$$\begin{array}{ccccc} \nu_e & \to \nu_\mu & \Leftrightarrow & \bar{\nu}_e & \to \bar{\nu}_\mu \\ \uparrow & & & \uparrow & \\ \beta^+ & \text{decay} & & \beta^- & \text{decay} \end{array}$$





solid: no CP violation
dashed: max CP violation

solid: $P(\nu_e \to \nu_\mu)$
dashed: $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
(max CP violation)

consider 440kT after 10 years, $\theta_{13} = 3^o$, $\delta = 90^o$

^{18}Ne : 66 oscillated (24 from CP odd term)

^{6}He : 32 oscillated (-47 from CP odd term)

(Mezzetto 2003)

T Violation

$$\begin{array}{ccccc} \beta \text{ beam} & & & \text{conventional beam} & \\ \downarrow & & & \downarrow & \\ \nu_e & \to \nu_\mu & \Leftrightarrow & \nu_\mu & \to \nu_e \end{array}$$

Neutrino-Nucleus Interactions

Why study?

- Understand Nuclear Structure
- Astrophysics

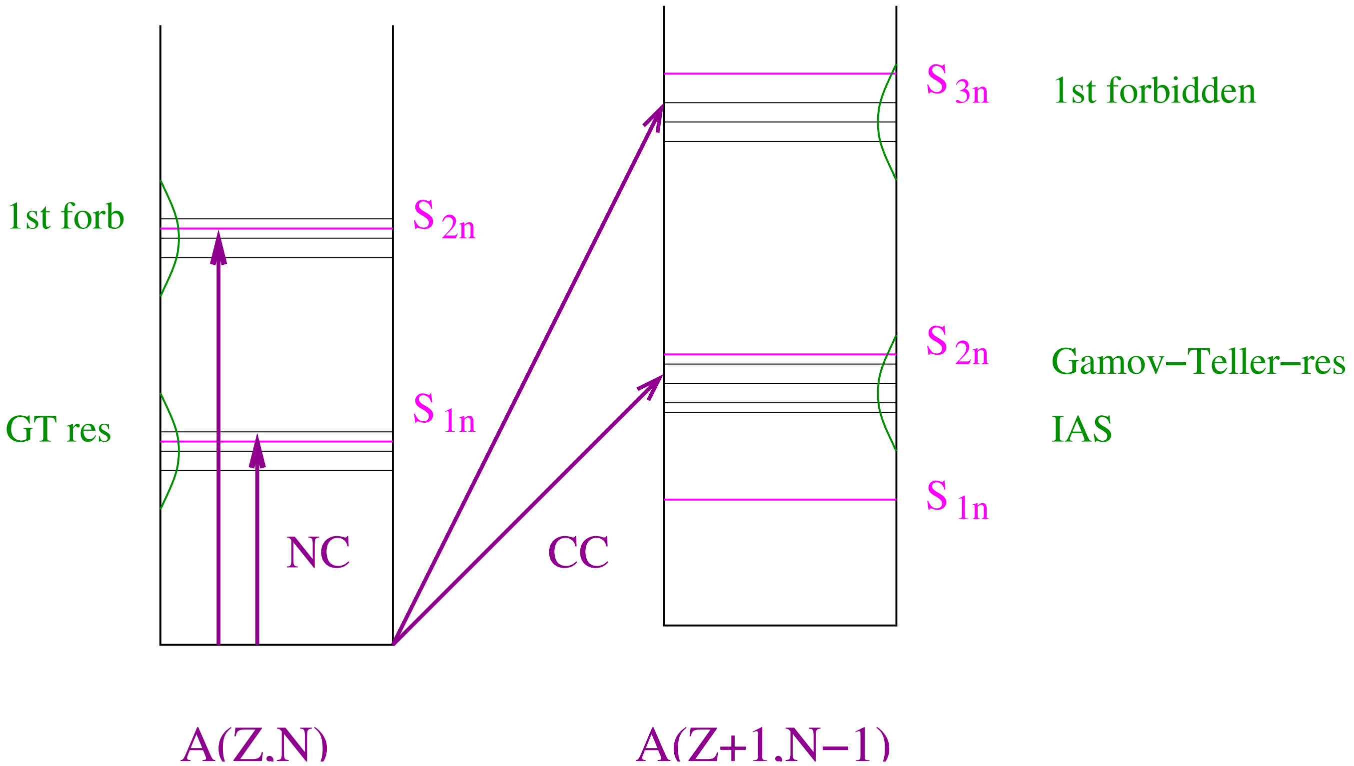
relevant energies 10s of MeV
  - Supernova Neutrino Dtection
  - Supernova Nucleosynthesis
  - Solar Neutrino Detection

Current situation

Only carbon meassured with $\sim (4-10)\%$ accuracy

$^{2}H, ^{56}Fe, ^{127}I$ reported with $\sim 40\%$ error

requires extrapolation to lower energy and heavier nuclei



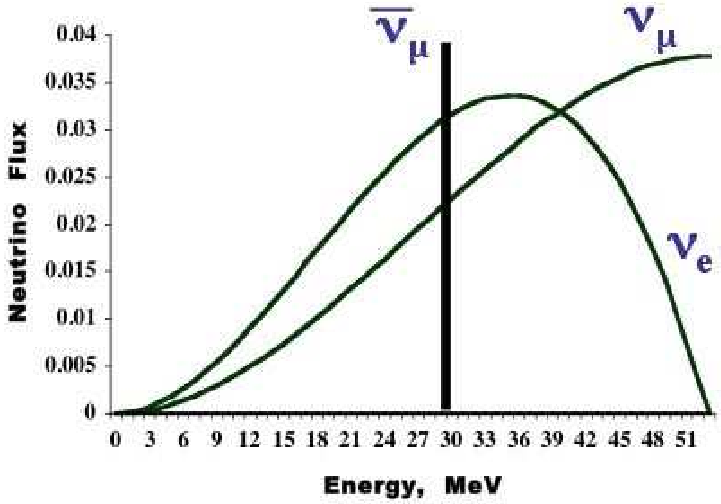
At $\sim$ 30 MeV states which are not well known make a significant contribution

Low Energy Neutrino Measurements

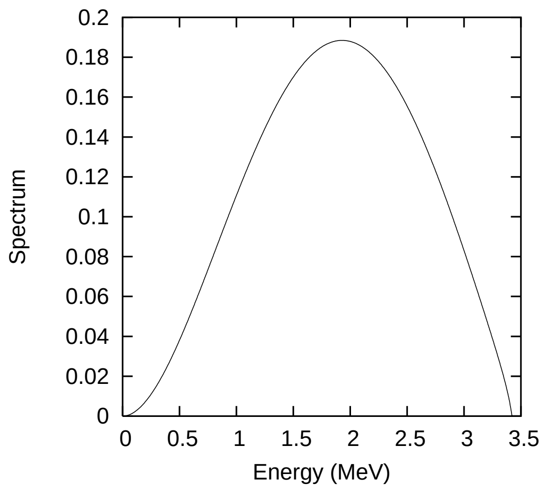
Cross sections $\sigma \sim 10^{-41}\text{cm}^2$

so for a $10^{15}\nu/s$ source need $\sim$ 10 ton detector to make 10% measurement.
e.g. ^{12}C $\sim$ 10 events per day

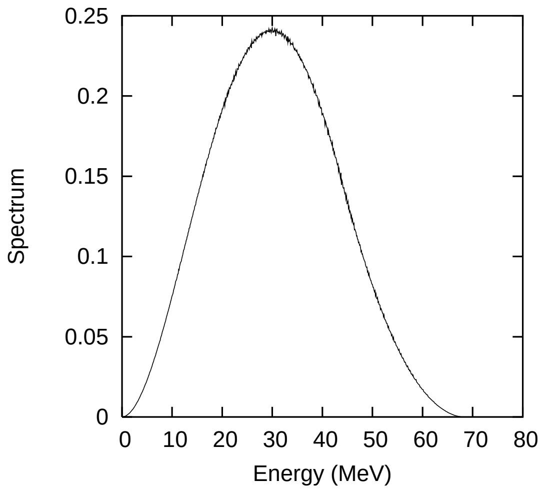
pion decay at rest
ν SNS at Oak Ridge
(proposed)



Low energy β-beam suggested by Volpe (2003)
e.g. ν_e from ^{18}Ne

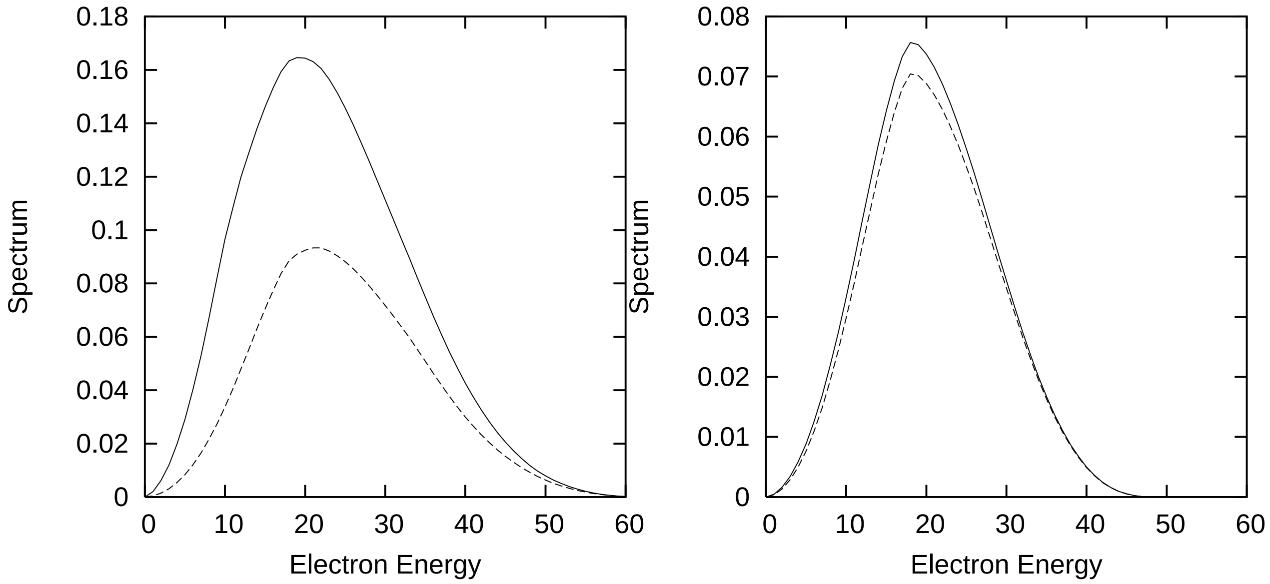


boosted
to
$\gamma = 10$
$\longrightarrow$



Example: $\nu_e + \mathrm{Pb} \to \mathrm{Bi} + e^-$

for ν_e from ^{18}Ne, $\gamma = 10$, look at electron spectrum



Electron spectrum using the total cross section and two neutron cross section.
Dashed lines show the contribution of higher multipoles (above $0^+, 1^+$) to electron spectrum

Neutrino Magnetic Moment

Neutrinos mix $\rightarrow$ Neutrinos have mass

$\searrow \quad \swarrow$

magnetic moment

How large?

Clue to physics beyond the standard model

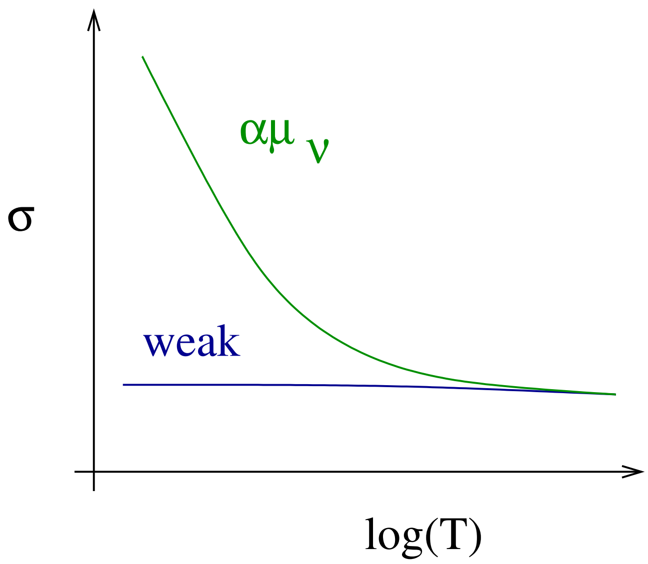
Current limits

$\mu_\nu < 1 \cdot 10^{-10} \mu_B$ reactor $\nu s, e.g. MUNU$

$\mu_\nu < 1.5 \cdot 10^{-10} \mu_B$ solar νs

$\mu_\nu < 1 \cdot 10^{-12} \mu_B$ supernova νs

Measure using ν-electron scattering

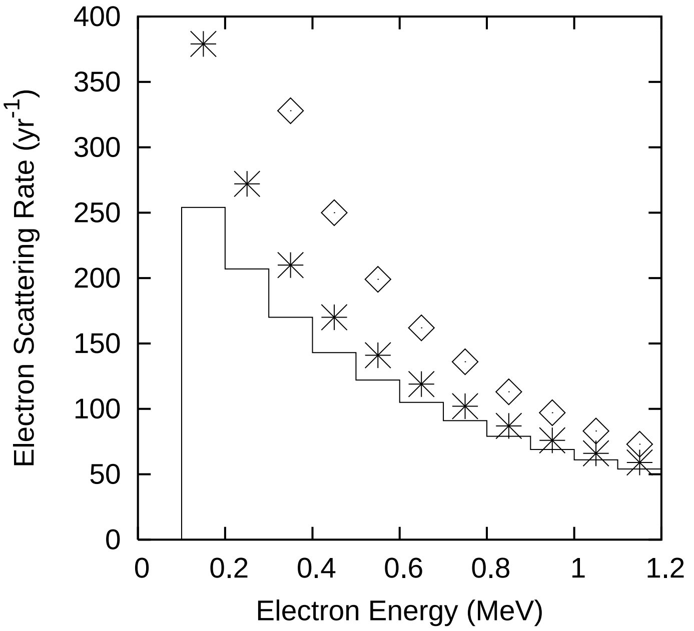


cross section increases at low electron recoil energy

Measuring the ν-magnetic moment

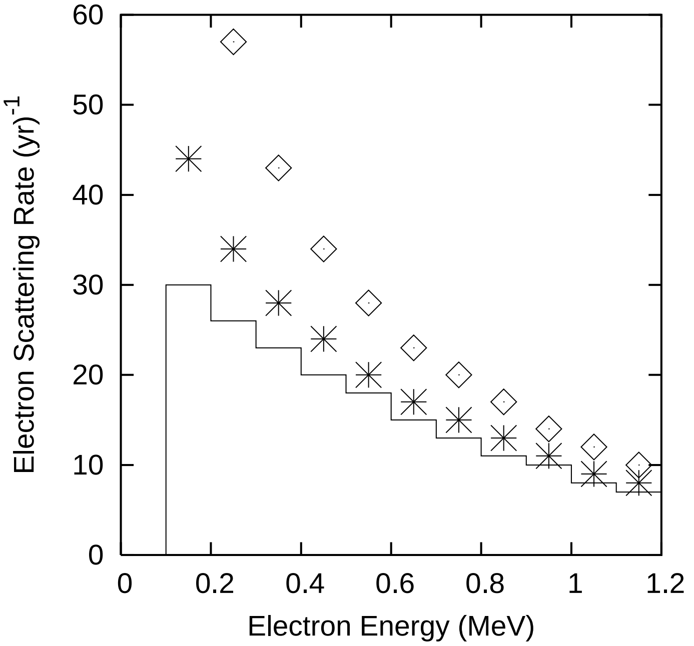
Need:
- large flux
- well understood ν spectrum
- detector sensitive to low energies

Traditional 2750MW reactor, $1m^3$ TPC detector at 18m



histogram $\mu_\nu = 0$
$\diamond$ $\mu_\nu = 10^{-10}$
$\star$ $\mu_\nu = 5 \times 10^{-11}$

ν_e from ^{6}He at rest, 4π TPC detector, r= 10m



PRO:
Well understood low energy ν_e spectrum
CON:
Need large flux

(need 10^{15} ions/s) McLaughlin & Volpe 2003

Summary

Many open questions in neutrino physics

Beta beams proposed to

high energy:	- measure Θ_{13}, CP violation
low energy:	- neutrino nucleus interactions
lowest energy:	- neutrino magnetic moment