Weak Interactions Discussion Group

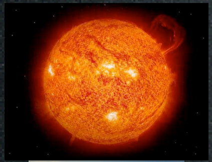
Marco Cirelli

β-beams?

discussion on
P.Zucchelli, Phys.Lett.B 532 (2002)

and M.Mezzetto, J.Phys.G:Nucl.Part.Phys.29 (2003)
C.Volpe, J.Phys.G30:L1-L6 (2004)
M.Lindroos et al., Proceedings of NuFact'03
J.Burguet-Castell et al., Nucl.Phys.B695 (2004)
F.Terranova et al., Eur.Phys.J.C38 (2004)
A.Donini et al., Nucl.Phys.B710 (2005)
A.Donini et al., Phys.Lett.B621 (2005)
J.Bernabeu et al., hep-ph/0505054
...

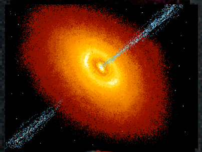
Sources of neutrinos



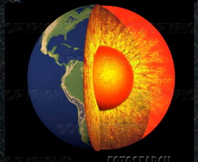
fusion in the Sun

cosmic rays on atmosphere

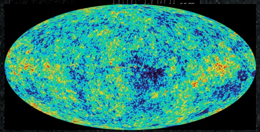
SuperNovae



astrophysical engines (active galaxies, stars)

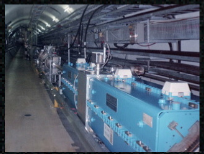


nuclear decays in Earth's interior



the Big Bang

fission in nuclear reactors

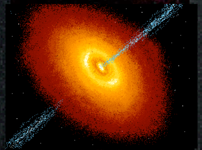
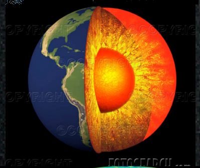
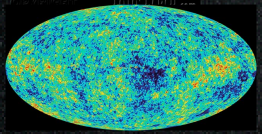
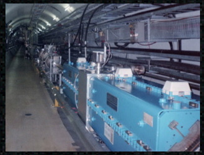


particle accelerators

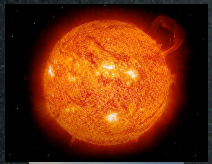
- SBL/LBL beams + SuperBeams
- ν -factories

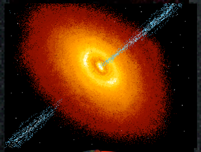
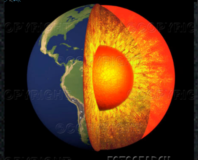
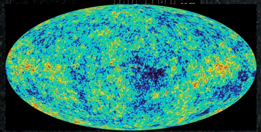
β-beams

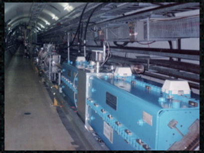
Sources of neutrinos

		pure flavor?	known spectrum? interesting Energy?	rates?
	solar			
	atmo			
	SN			
	astro			
	geo			
	cνb			
	reactor			
	beams+SuperB			
	ν -factories			
	β-beams			

Sources of neutrinos





	pure flavor?	known spectrum? interesting Energy?	rates?
solar	ν_e	quite, < few MeV	it's ok
atmo	$\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e$	quite, GeV	it's ok
SN	all	no, 10 MeV	unreliable
astro	$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu ?$	no, no	what flux?
geo	$\bar{\nu}_e$	no, < MeV	low
cνb	all	yes, useless	highest
reactor	$\bar{\nu}_e$	yes, MeV	diluted
beams+SuperB	$\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e$	yes, GeV	fairly high
ν -factories	$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu$	yes, tens GeV	fairly high
β-beams			

Sources of neutrinos

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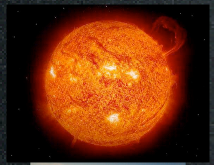	solar	ν_e	quite, < few MeV	it's ok
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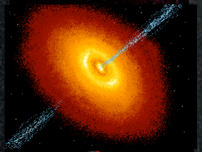
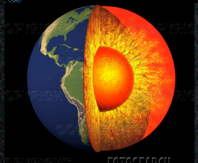
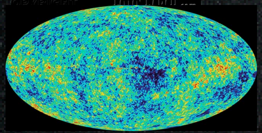
	astro	$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu$?	no, no	what flux?
	geo	$\bar{\nu}_e$	no, < MeV	low
	cνb	all	yes, useless	highest
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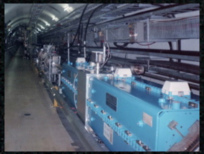
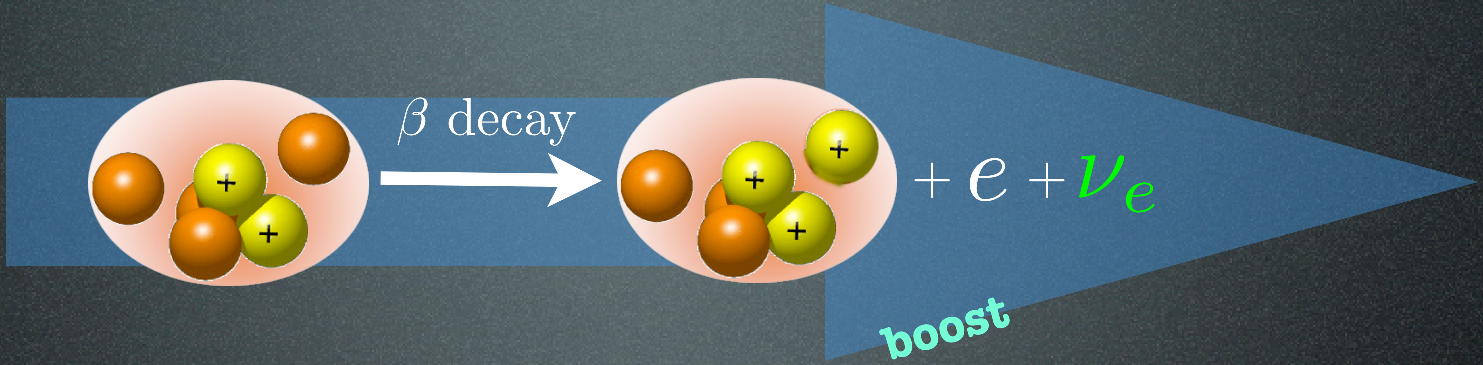
	beams+SuperB	$\overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e$	yes, GeV	fairly high
	ν -factories	$\overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu$	yes, tens GeV	fairly high
	β-beams	$\bar{\nu}_e, \nu_e$ ✓	**yes, GeV** ✓	**high** ✓

The β -beam idea



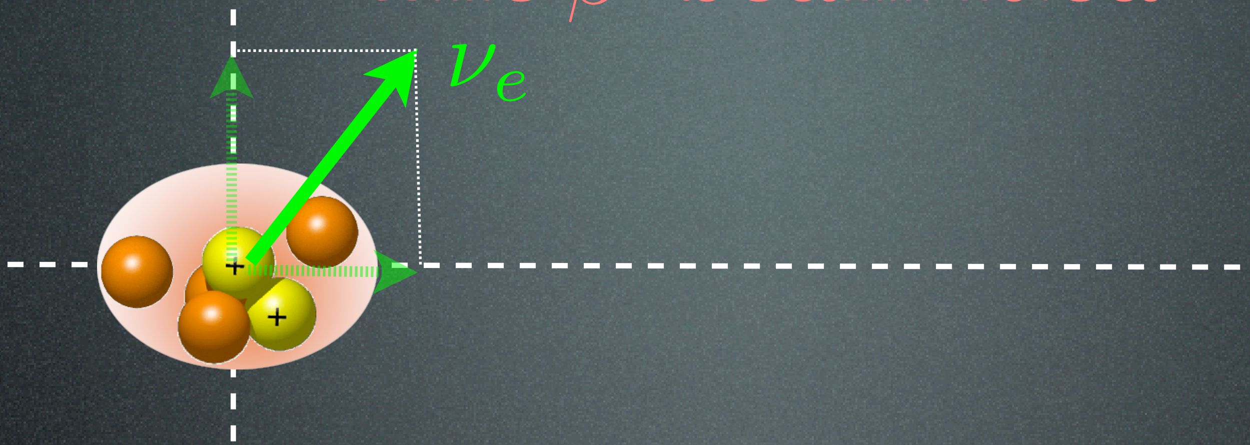
A β decaying nucleus (ion) which has:

- short half-life $(t_{1/2} \sim 1 \text{ sec})$
- easy production mechanism
- known energy/spectrum

is accelerated at high energies and
let decay in a straight section of an accumulation ring.

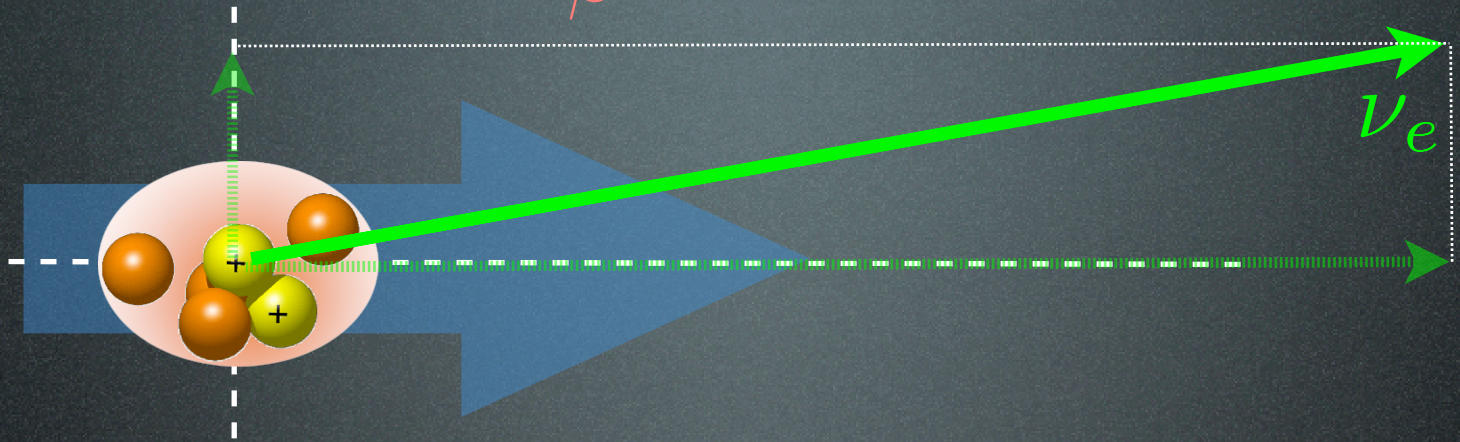
An intense beam of energetic neutrinos is produced.

The β -beam idea



rest frame $\left(E_\nu^\star, E_\nu^\star \sin\theta^\star, 0, E_\nu^\star \cos\theta^\star\right)$

The β -beam idea



rest frame $\left(E_\nu^\star, E_\nu^\star \sin\theta^\star, 0, E_\nu^\star \cos\theta^\star \right)$

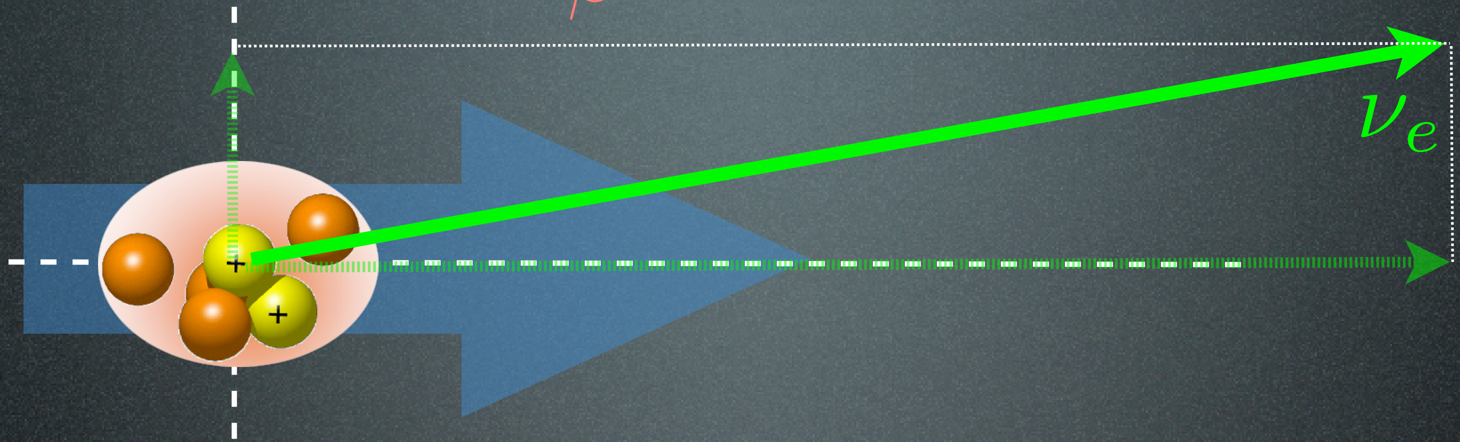
lab frame $\left(\gamma E_\nu^\star (1+\beta\cos\theta^\star), E_\nu^\star \sin\theta^\star, 0, \gamma E_\nu^\star (\beta + \cos\theta^\star) \right)$

$$= (E_\nu, E_\nu \sin\theta, 0, E_\nu \cos\theta)$$

$$\begin{cases} p_\perp & = p_\perp^\star \\ p_\parallel & = \gamma E_\nu^\star (\beta + \cos\theta^\star) \\ E_\nu & \simeq 2\gamma E_\nu^\star \end{cases}$$

$$\tan\theta = \frac{\sin\theta^\star}{\gamma(\beta+\cos\theta^\star)} \propto \frac{1}{\gamma} \ll 1$$

The β-beam idea



pure ✅

rest frame $\left(E_\nu^\star, E_\nu^\star \sin\theta^\star, 0, E_\nu^\star \cos\theta^\star \right)$

lab frame $\left(\gamma E_\nu^\star (1+\beta\cos\theta^\star), E_\nu^\star \sin\theta^\star, 0, \gamma E_\nu^\star(\beta + \cos\theta^\star) \right)$

$$= (E_\nu, E_\nu \sin\theta, 0, E_\nu \cos\theta)$$

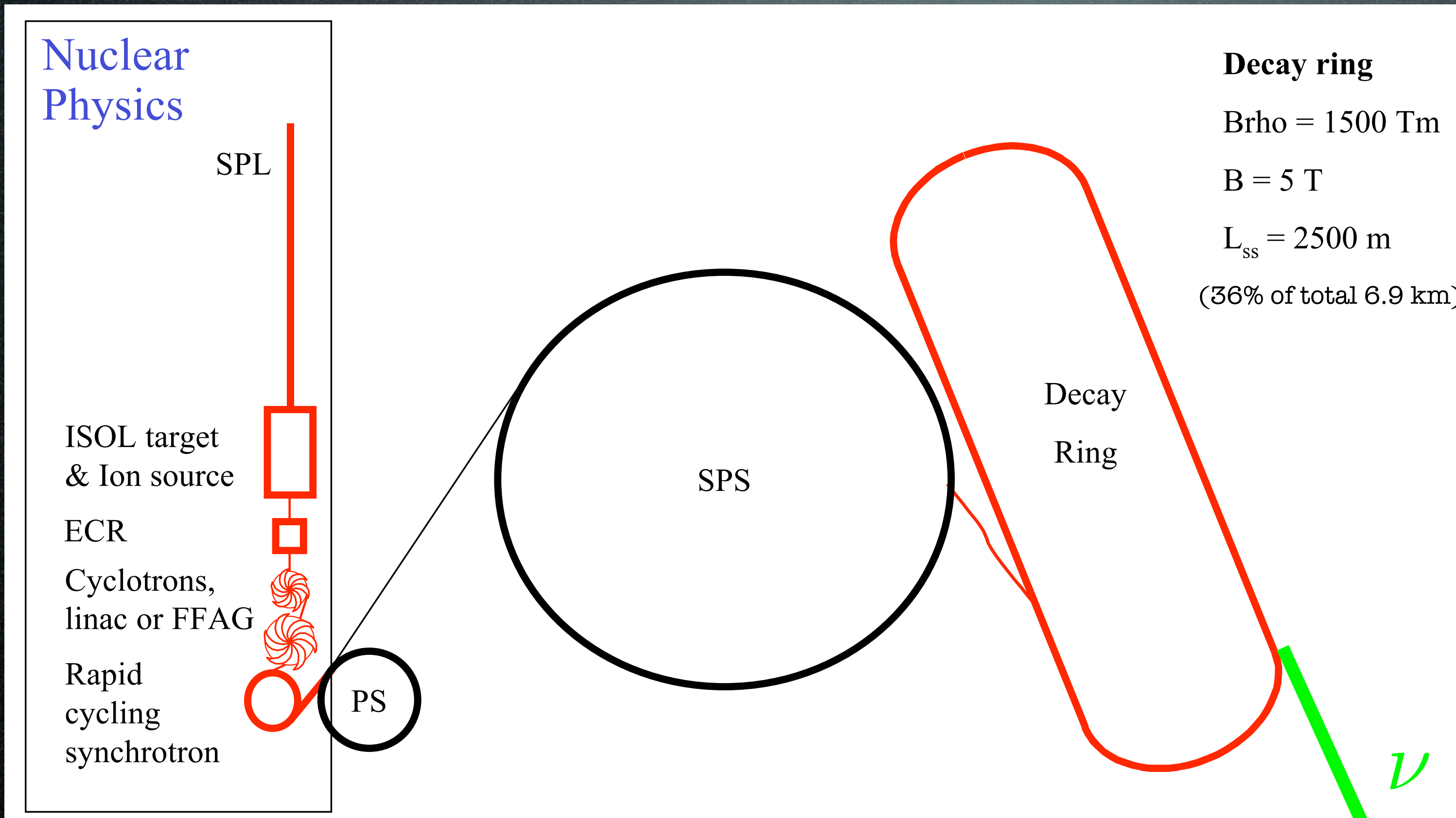
$$\begin{cases} p_\perp & = p_\perp^\star \\ p_\parallel & = \gamma E_\nu^\star(\beta + \cos\theta^\star) \\ E_\nu & \simeq 2\gamma E_\nu^\star \end{cases}$$

high energy ✅

$$\tan\theta = \frac{\sin\theta^\star}{\gamma(\beta + \cos\theta^\star)} \propto \frac{1}{\gamma} \ll 1$$

highly focussed ✅

The β-beam setup

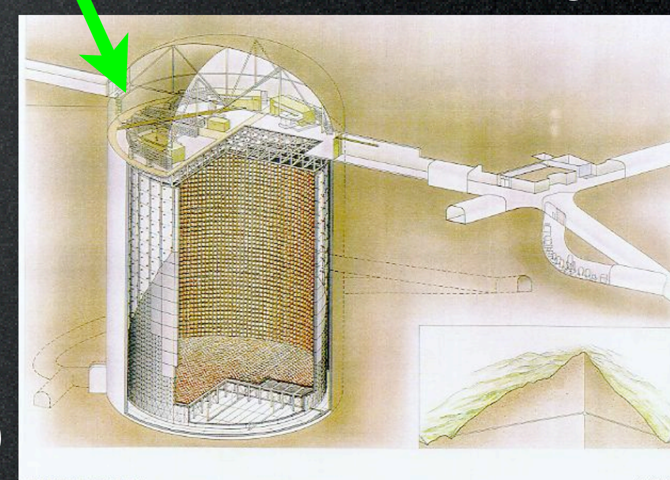


M.Lindroos

CERN

$L \simeq 130$ Km

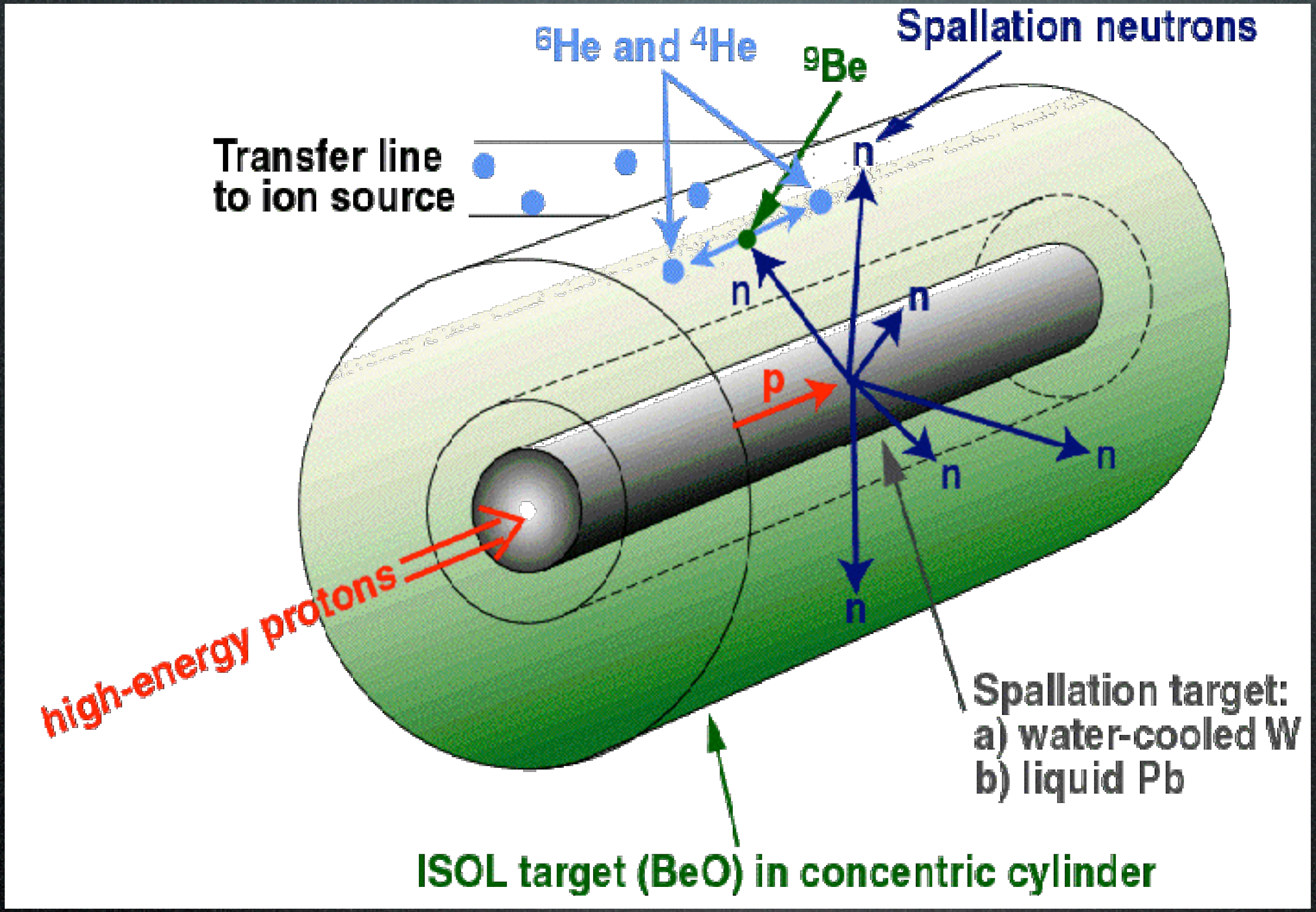
Frejus



Mton water Cerenkov (UNO)

The β-beam proposal

unstable nuclei production via spallation neutrons

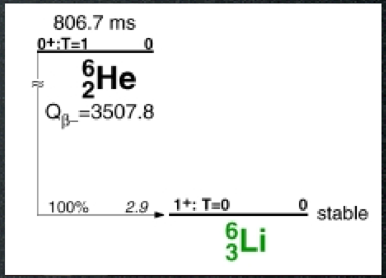


U.Koster via P.Zucchelli

$\sim 10^{13}$ nuclei/sec, in bunches every 8 sec

The β-beam proposal

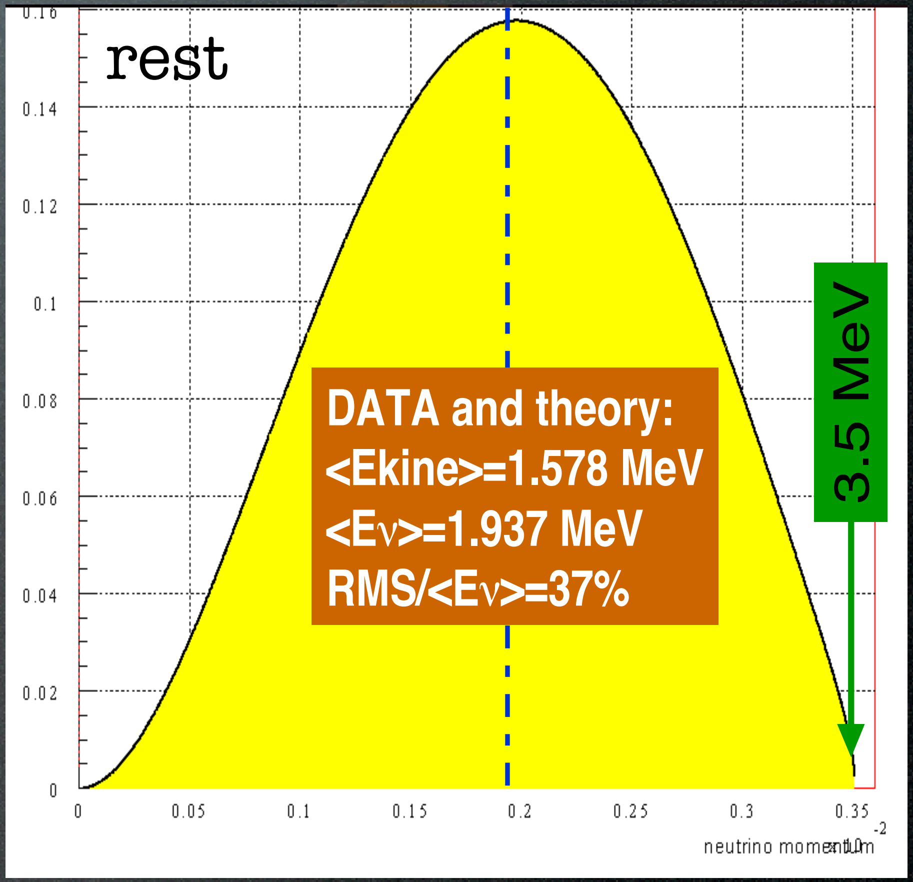
$\bar{\nu}_e$ source: $\quad {}^6\mathrm{He}^{++} \rightarrow {}^6\,\mathrm{Li}^{+++}\ e^-\ \bar{\nu}_e$



ν spectrum is known
from e spectrum

parent nucleus spinless:
isotropic emission

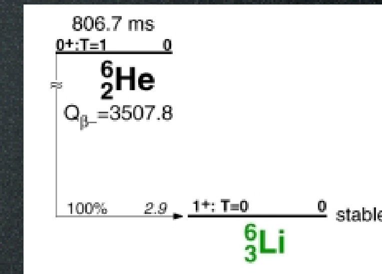
$5\ 10^{13}$ nuclei/sec



Rustand,Ruby (1955)
Ridley (1961)
via P.Zucchelli

The β-beam proposal

$\bar{\nu}_e$ source: $\quad {}^6\mathrm{He}^{++} \rightarrow {}^6\,\mathrm{Li}^{+++}\ e^- \ \bar{\nu}_e$



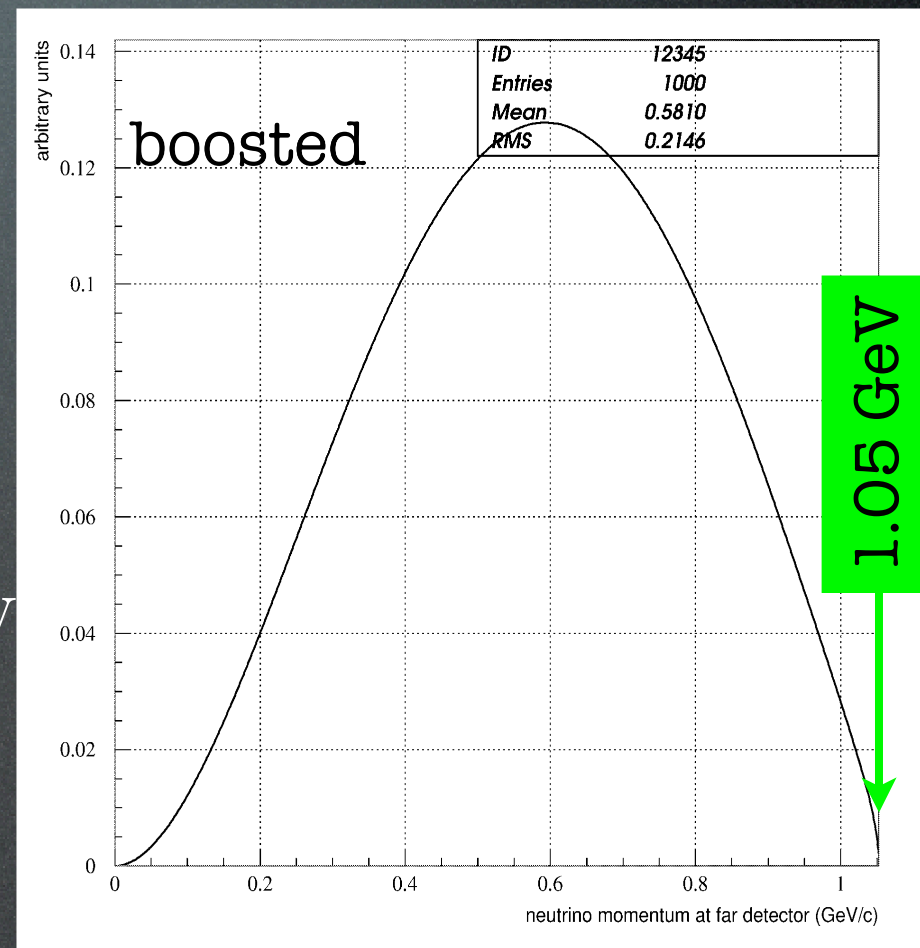
ν spectrum is known
from e spectrum

parent nucleus spinless:
isotropic emission

$5\ 10^{13}$ nuclei/sec

typical E_ν after boost ≈ 0.5 GeV
$(\gamma \approx 150)$

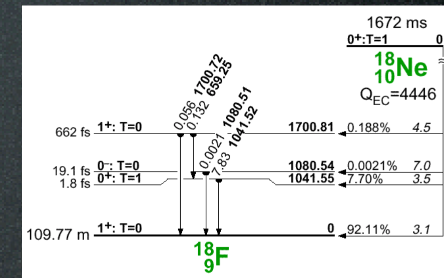
# of events at $L \simeq 130$ Km :
$\approx$ 70 /kton/year



P.Zucchelli

The β-beam proposal

ν_e source: $\quad {}^{18}\mathrm{Ne} \rightarrow {}^{18}\,\mathrm{F}\; e^+\; \nu_e$



ν spectrum is known
from e spectrum

parent nucleus spinless:
isotropic emission

$1\ 10^{12}$ nuclei/sec

typical E_ν after boost ≈ 0.9 GeV
$(\gamma \approx 250)$

# of events at $L \simeq 130$ Km :
$\approx$ 2 /kton/year

Nucleus	Z/A	$T_{\frac{1}{2}}$ (s)	Q_β	Q_β^{eff}	E_β	E_ν	E_{LAB}
$\overline{\nu}_e$ decay							
${}^6_2$He	3.0	0.807	3.5	3.5	1.57	1.94	582
${}^8_2$He	4.0	0.119	10.7	9.1	4.35	4.80	1079
${}^8_3$Li	2.7	0.838	16.0	13.0	6.24	6.72	2268
${}^9_3$Li	3.0	0.178	13.6	11.9	5.73	6.20	1860
${}^{16}_6$C	2.7	0.747	8.0	4.5	2.05	2.46	830
${}^{18}_7$N	2.6	0.624	13.9	8.0	5.33	2.67	933
${}^{25}_{10}$Ne	2.5	0.602	7.3	6.9	3.18	3.73	1344
${}^{26}_{11}$Na	2.4	1.072	9.3	7.2	3.34	3.81	1450
ν_e decay							
${}^8_5$B	1.6	0.77	17.0	13.9	6.55	7.37	4145
${}^{10}_6$C	1.7	19.3	2.6	1.9	0.81	1.08	585
${}^{18}_{10}$Ne	1.8	1.67	3.4	3.4	1.50	1.86	930
${}^{33}_{18}$Ar	1.8	0.173	10.6	8.2	3.97	4.19	2058
${}^{34}_{18}$Ar	1.9	0.845	5.0	5.0	2.29	2.67	1270
${}^{35}_{18}$Ar	1.9	1.775	4.9	4.9	2.27	2.65	1227
${}^{37}_{19}$K	1.9	1.226	5.1	5.1	2.35	2.72	1259
${}^{80}_{37}$Rb	2.2	34	4.7	4.5	2.04	2.48	1031

The β-beam proposal

feasibility: - unstable nuclei production at ISOLDE ok

- acceleration technology exists
- storage technology exists
- radiation issues under control

backgrounds: - none at production

(hadronic interactions of daughter nuclei in tunnel: negligible)

- atmospheric neutrinos at detection

use directionality
use timing of bunches

The β-beam proposal: variations

- a low energy β-beam: C.Volpe, J.Phys.G 30:L1-L6 (2004)

$$E_\nu \sim \text{few} \cdot 10 \text{ MeV}$$

study νN interactions at energies like SN

(energy deposition for explosion, stellar nucleosynthesis...)

- a high energy β-beam: J.Burguet-Castell et al.,Nucl.Phys.B695(2004) F.Terranova et al.,Eur.Phys.J.C38(2004)

$$E_\nu \sim \text{few GeV} \quad (\gamma \sim 1000) \quad L \sim \mathcal{O}(1000) \text{ km}$$

larger ν cross-sections

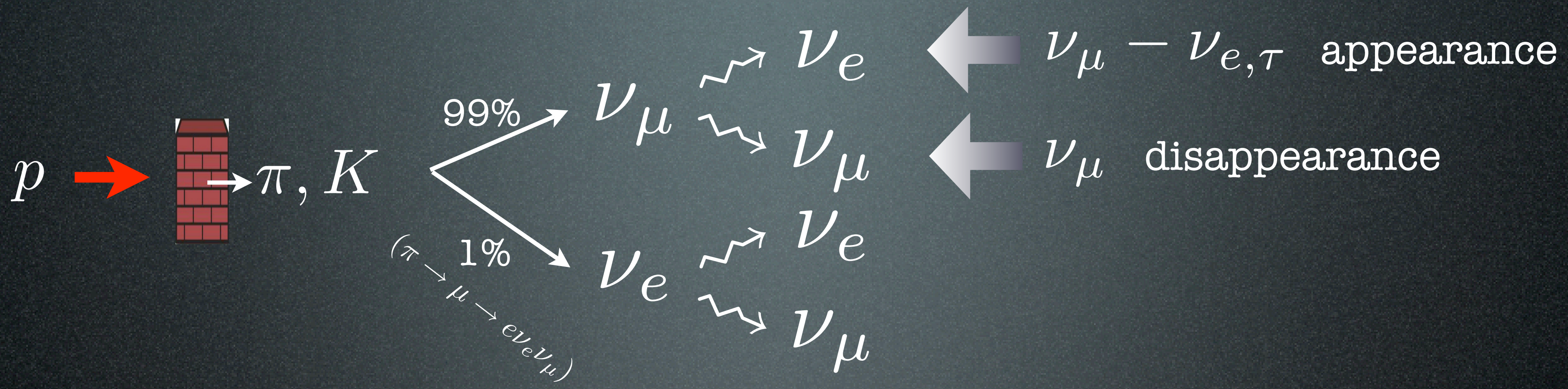
(you may use the rock as a target for high energy muons)

handle on matter effects

- a mono energetic β-beam: J.Bernabeu et al., hep-ph/0505054

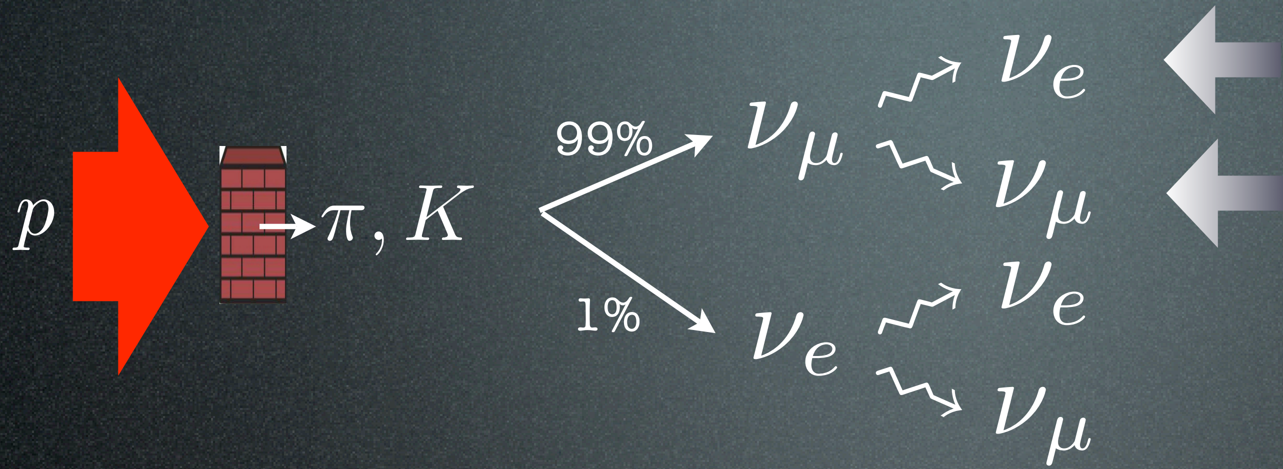
using electron-capture decaying nuclei (2 body)

Conventional Beams



$$E \sim \text{some GeV}$$
$$L \sim \text{few} \cdot 100 \text{ km}$$

Conventional Beams and SuperBeams

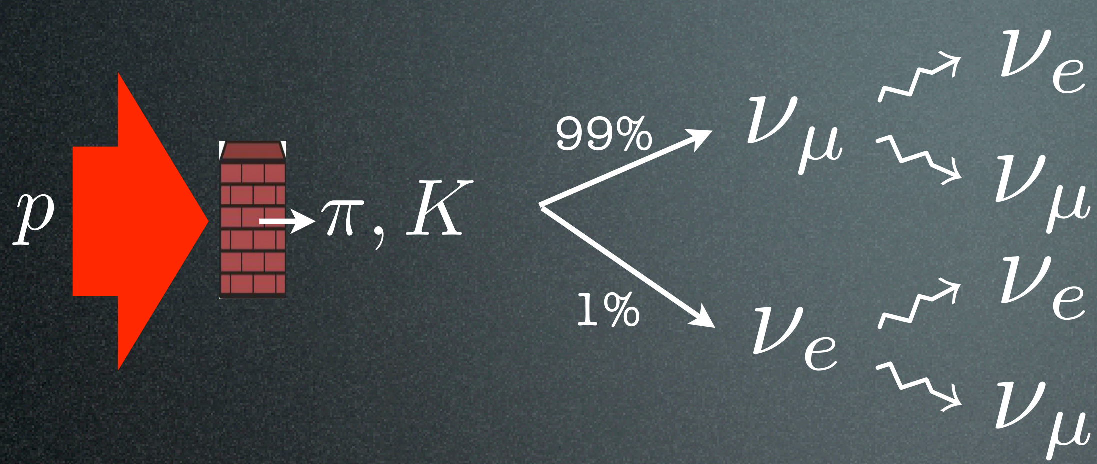


$\nu_\mu - \nu_{e,\tau}$ appearance

ν_μ disappearance

$$E \sim \text{some GeV}$$
$$L \sim \text{few} \cdot 100 \text{ km}$$

Conventional Beams and SuperBeams



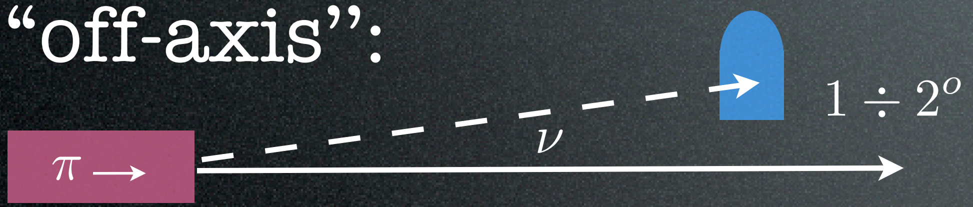
$\nu_\mu - \nu_{e,\tau}$ appearance

ν_μ disappearance

$E \sim$ some GeV

$L \sim$ few $\cdot$ 100 km

"off-axis":



ν_μ emitted isotropically from π

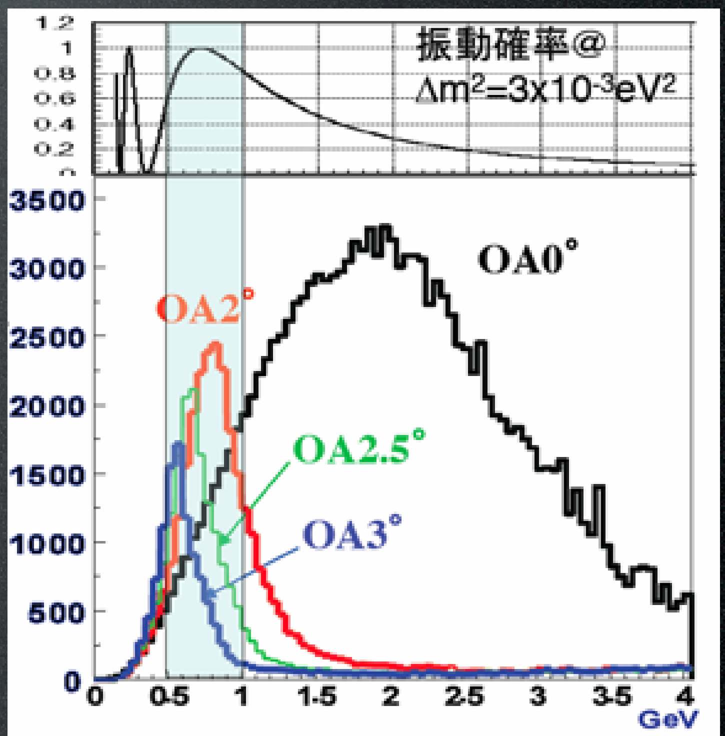
boosting to lab frame:

$$\tan\theta = \frac{E_\nu^\star \sin\theta^\star}{\gamma_\pi E_\nu^\star(\beta_\pi + \cos\theta^\star)} \approx \frac{E_\nu^\star \sin\theta^\star}{E_\nu}$$

$$E_\nu \approx \frac{E_\nu^\star \sin\theta^\star}{\tan\theta} \leq \frac{E_\nu^\star}{\tan\theta} \text{ ; so } \exists \text{ maximum } E_\nu(\theta)$$

a-more monochromatic beam

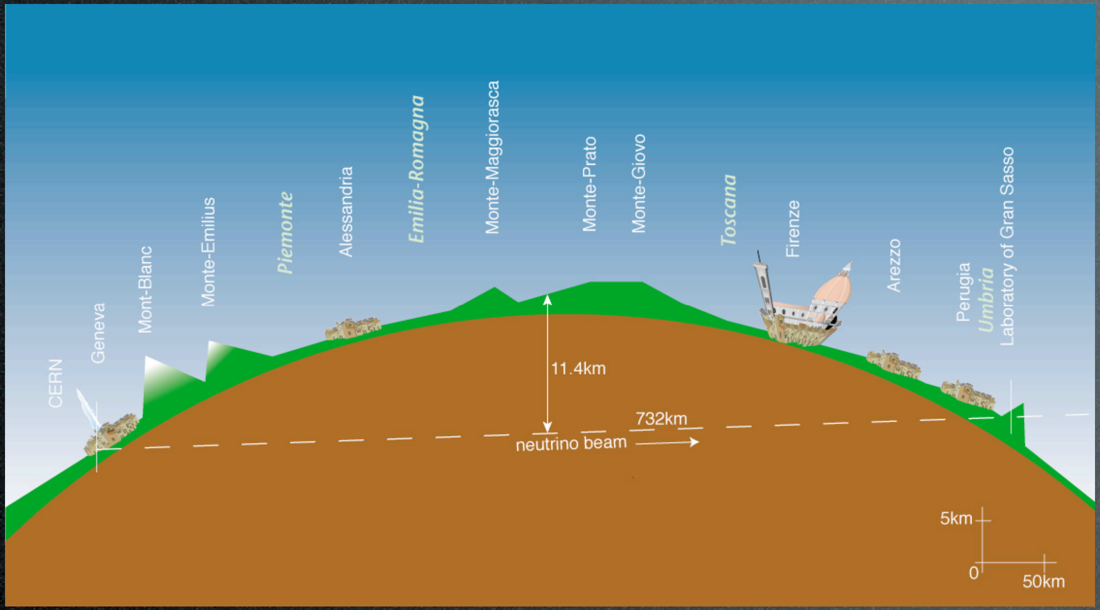
b-reduce ν_e contamination



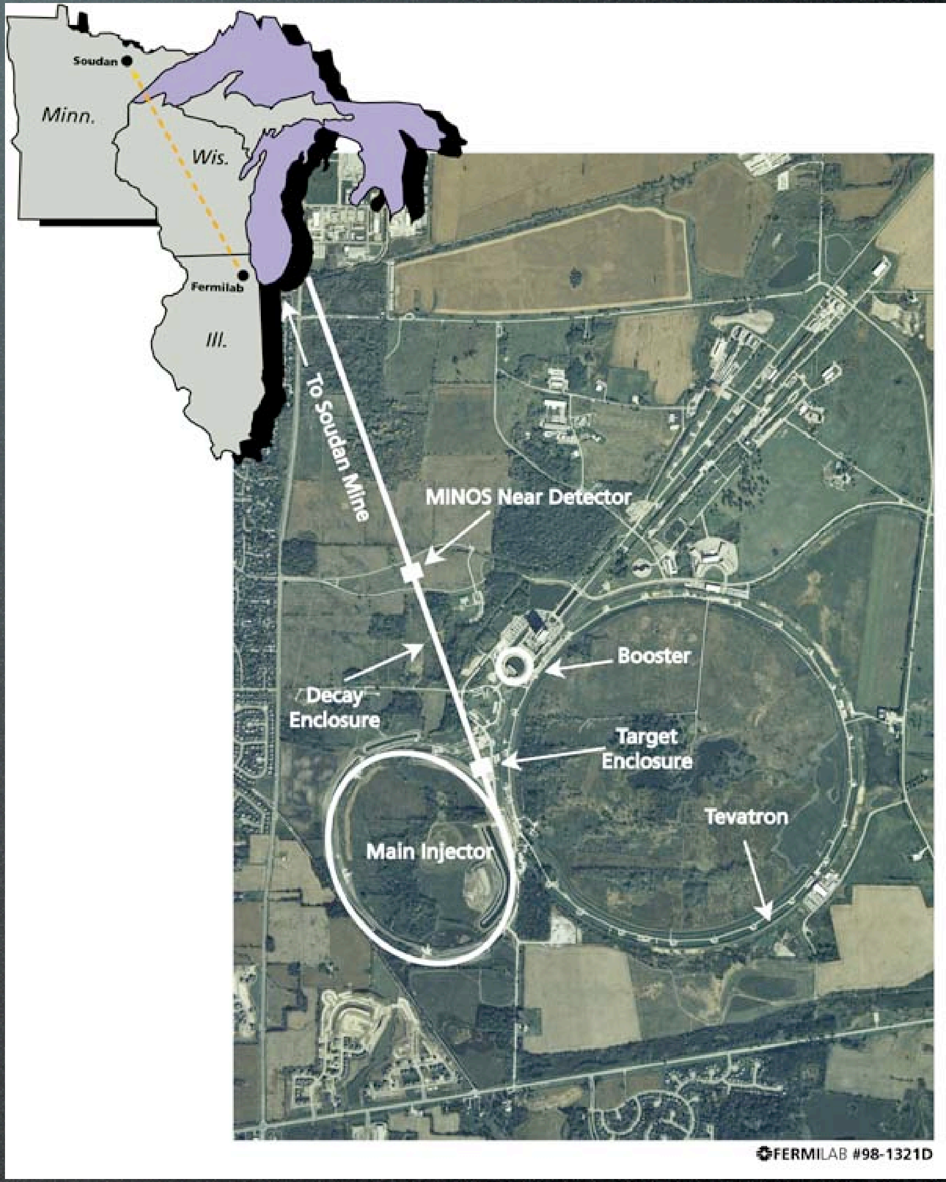
T.Kobayashi

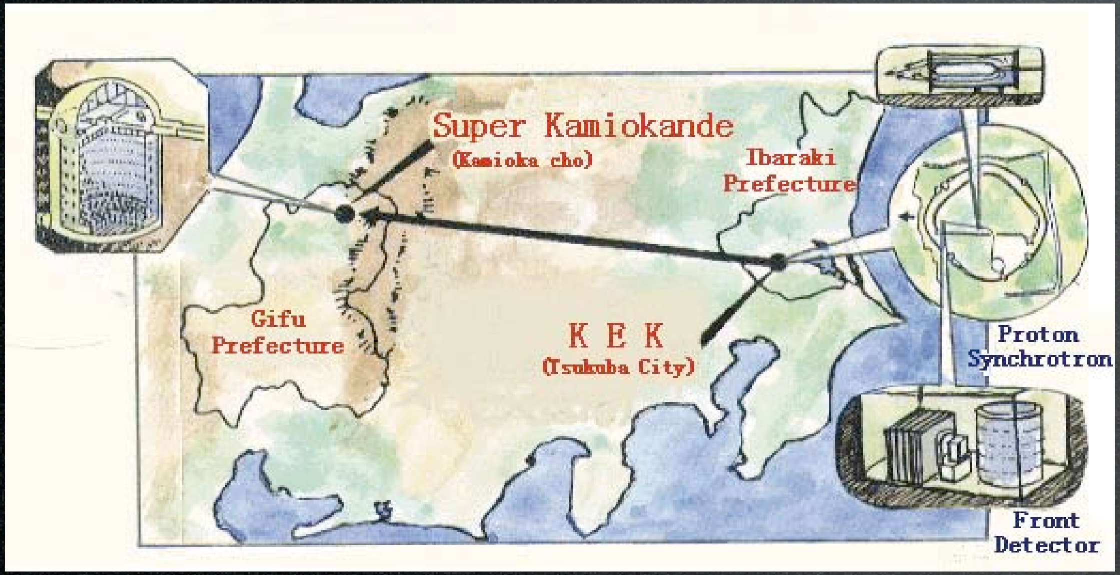
Conventional Beams and SuperBeams

CNGS



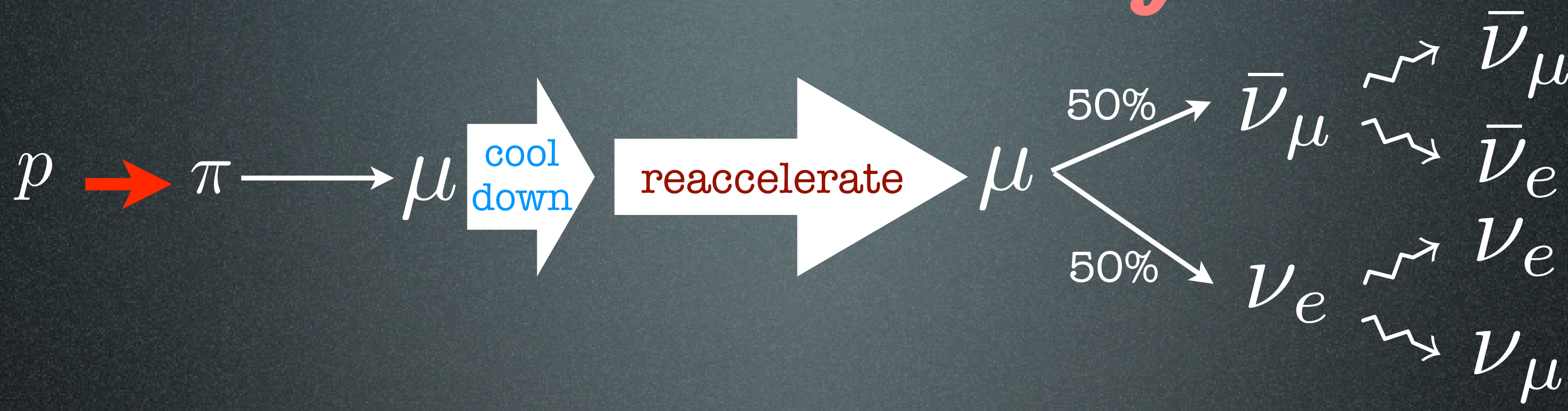
MINOS → NuMI

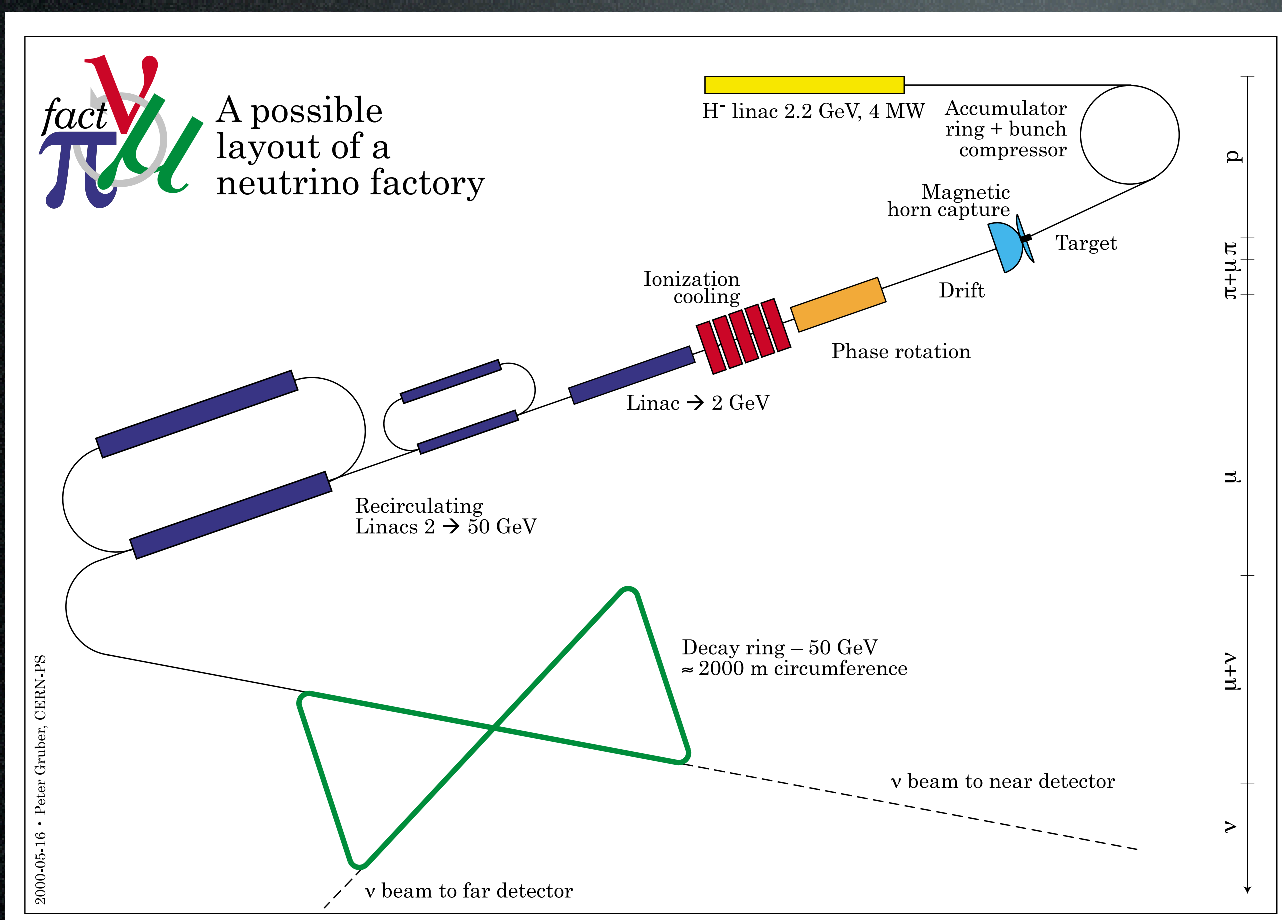




K2K → JPARK-SK

Neutrino factory





$$E \sim 50 \text{ GeV}$$

$$L \sim 3000 \text{ km}$$

Neutrino numerology:

what we know

(september 2005)

[neutrino mixings]

$$\Delta m^2_{\rm sun} = (7.2 \div 8.9)\ 10^{-5}\mathrm{eV}^2$$

$$|\Delta m^2_{\rm atm}| = (1.7 \div 3.3)\ 10^{-3}\mathrm{eV}^2$$

$$\theta_{\rm sun} = 30^o \rightarrow 38^o$$

$$\theta_{\rm atm} = 36^o \rightarrow 54^o$$

$$\theta_{13} < 10^o$$

$$m_0 <\sim 1\ \mathrm{eV}$$

Neutrino numerology: and we'd like to know

better $\Delta m^2_{\rm sun}$

better $|\Delta m^2_{\rm atm}|$

better $\theta_{\rm sun}$

$\theta_{\rm atm} \neq 45^o?$

θ_{13}

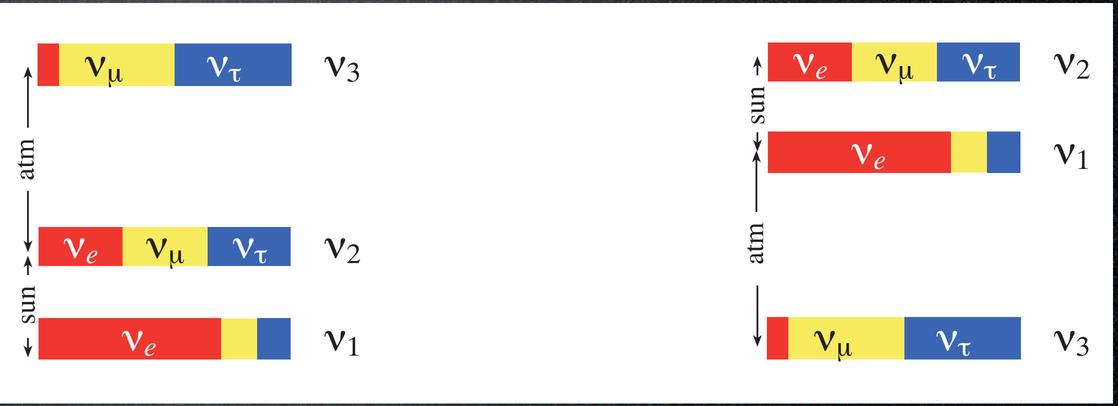
δ_{CP}

$\Delta m^2_{13} = \pm$

m_0

Majo/Dirac

$\alpha_{\rm Majo}, \beta_{\rm Majo}$



Neutrino numerology: and we'd like to know

better $\Delta m^2_{\rm sun}$

better $|\Delta m^2_{\rm atm}|$

better $\theta_{\rm sun}$

$\theta_{\rm atm} \neq 45^o?$

θ_{13}

δ_{CP}

$\Delta m^2_{13} = \pm$

(with oscillation experiments)

Neutrino numerology: and we'd like to know

	why	how
better $\Delta m^2_{\rm sun}$	check a lot of exotic, subdominant things	KamLand, D/N asy
better $\lvert\Delta m^2_{\rm atm}\rvert$	check a lot of exotic, subdominant things	LBL
better $\theta_{\rm sun}$	check a lot of exotic, subdominant things	low energy solar
$\theta_{\rm atm} \neq 45^o?$	related to a symmetry?	precision atmo
θ_{13}	the last missing; if zero, forget	LBL, ν fact
δ_{CP}	leptonic CP violation, leptogenesis...	LBL, ν fact
$\Delta m^2_{13} = \pm$	model building; access 0v2b	some LBL, ν fact

(with oscillation experiments)

Neutrino numerology: and we'd like to know

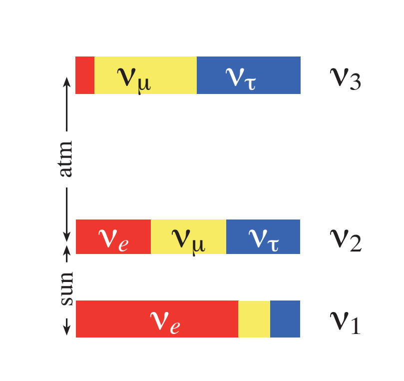
		why	how	
better	$\Delta m^2_{\rm sun}$	check a lot of exotic, subdominant things	KamLand, D/N asy	
better	$\lvert\Delta m^2_{\rm atm}\rvert$	check a lot of exotic, subdominant things	LBL	
better	$\theta_{\rm sun}$	check a lot of exotic, subdominant things	low energy solar	
	$\theta_{\rm atm} \neq 45^o$?	related to a symmetry?	precision atmo	
	θ_{13}	the last missing; if zero, forget	LBL, ν fact	β-beams
	δ_{CP}	leptonic CP violation, leptogenesis...	LBL, ν fact	β-beams
	$\Delta m^2_{13} = \pm$	model building; access 0v2b	some LBL, ν fact	β-beams

(with oscillation experiments)

Physics reach

oscillations

$$P(\nu_{f_1} \to \nu_{f_2}) = \sin^2 2\theta \cdot \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right)$$



ν_e oscillate in $\nu_{\mu,\tau}$

driven by $\Delta m^2_{\rm sun}, \theta_{\rm sun}$ at $L \approx 7000$ Km

$(E_\nu \sim 0.5$ GeV$)$

we'll look for subdominant oscillations $\nu_e \longleftrightarrow \nu_{\mu,\tau}$

driven by $\Delta m^2_{13}, \theta_{13}$ at $L \simeq 200$ Km

$(E_\nu \sim 0.5$ GeV$)$

Physics reach

e.g. full expression for $P(\nu_e \longrightarrow \nu_\mu)$ $\left(\begin{array}{c}\text{in powers of} \\ \alpha \ll 1,\ \theta_{13} \ll 1\end{array}\right)$

$$P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \quad \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$

$$\pm \sin\delta \cdot \sin 2\theta_{13}\ \alpha\ \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

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$$\hat{A} = \frac{2VE_\nu}{\Delta m^2_{31}}$$

$$V = \sqrt{2} G_F n_e$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E_\nu}$$

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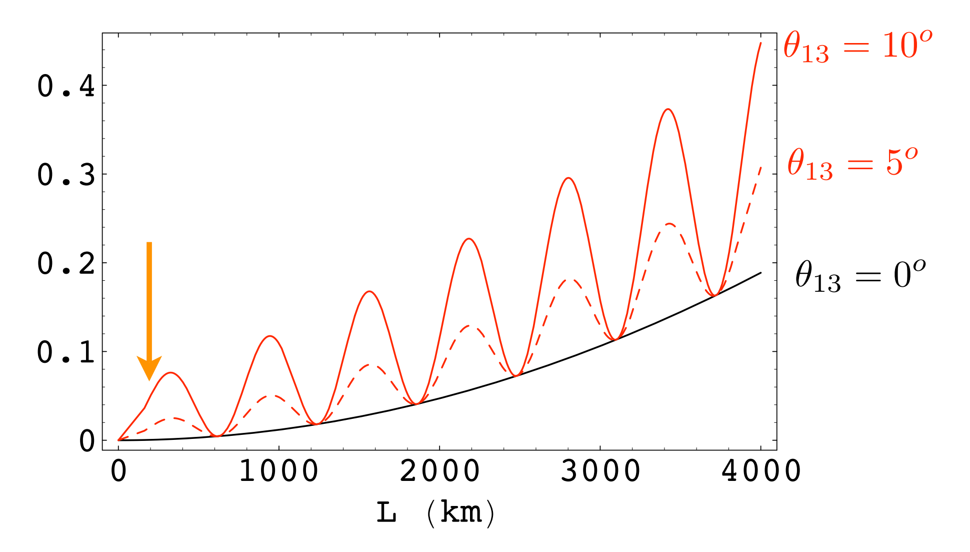

Physics reach

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ν

$\bar{\nu}$

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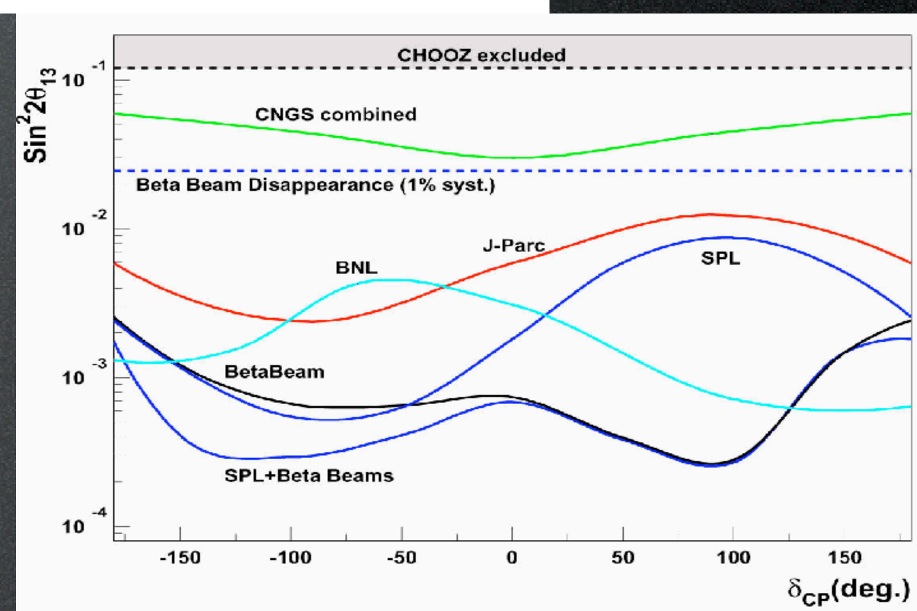

Bouchez,Lindroos,Mezzetto (2003)

Physics reach

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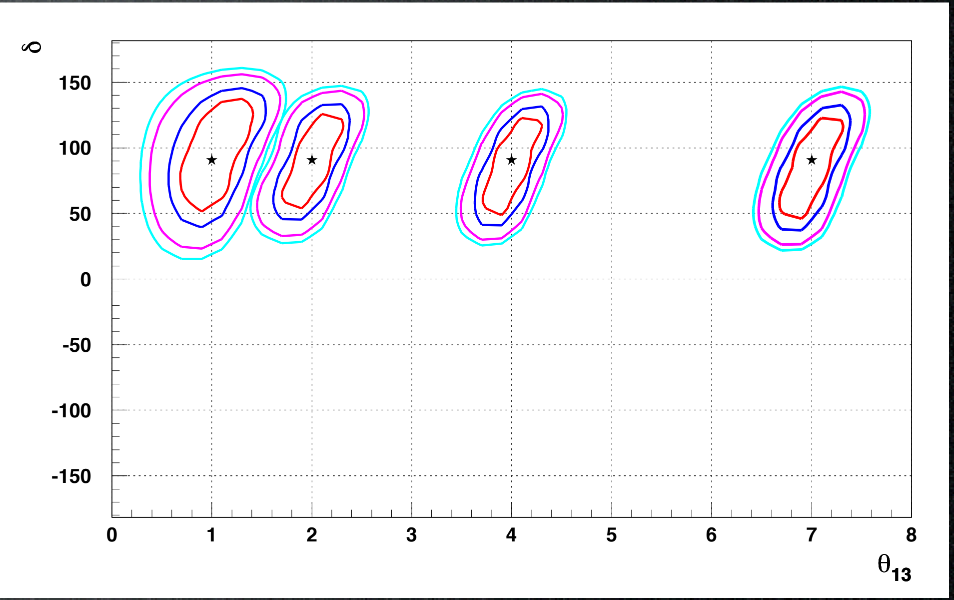

Bouchez,Lindroos,Mezzetto (2003)

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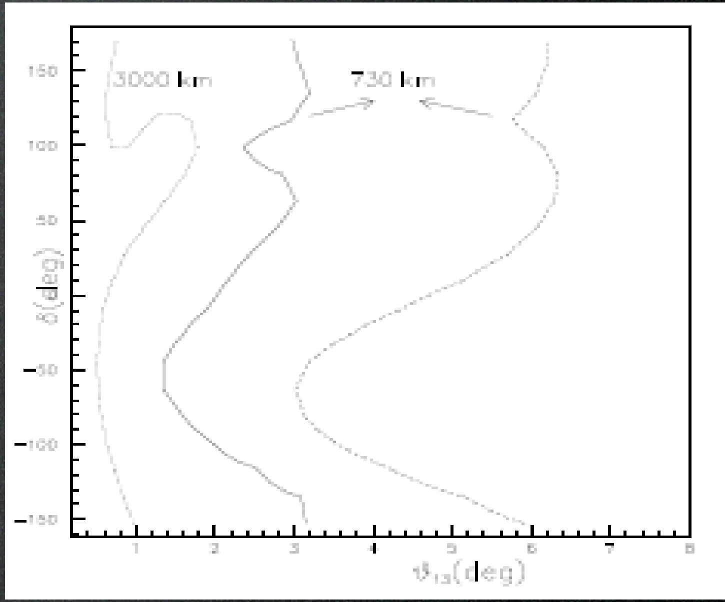
sign (Δm^2_{13}) requires matter effect

go to higher energy/
longer baseline



J.Burguet-Castell et al.,
Nucl.Phys.B695 (2004)

On Politics and Finance

- "if $\theta_{13} \simeq 0$, we'd better know it soon and cheap, go step by step"
- "a ν factory would be the most expensive hep project after the LHC, a superbeam is very expensive"
- "a β-beam is of interest also for the nuclear physics people"

Discussion...

1.?

2.energy tunability?

3.off-axis beta beam?

4.what exactly is of interest to nuclear?

Neutrino mixings

[back]

$$U \equiv U_{23} U_{13} U_{12}$$

$$\equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$