Neutrino Sources and Detectors

Neutrino Sources

Natural sources

- Relic and Supernovae
- Solar Neutrinos
- Atmospheric Neutrinos

Artificial sources

- Accelerator Neutrinos
- Reactor Neutrinos

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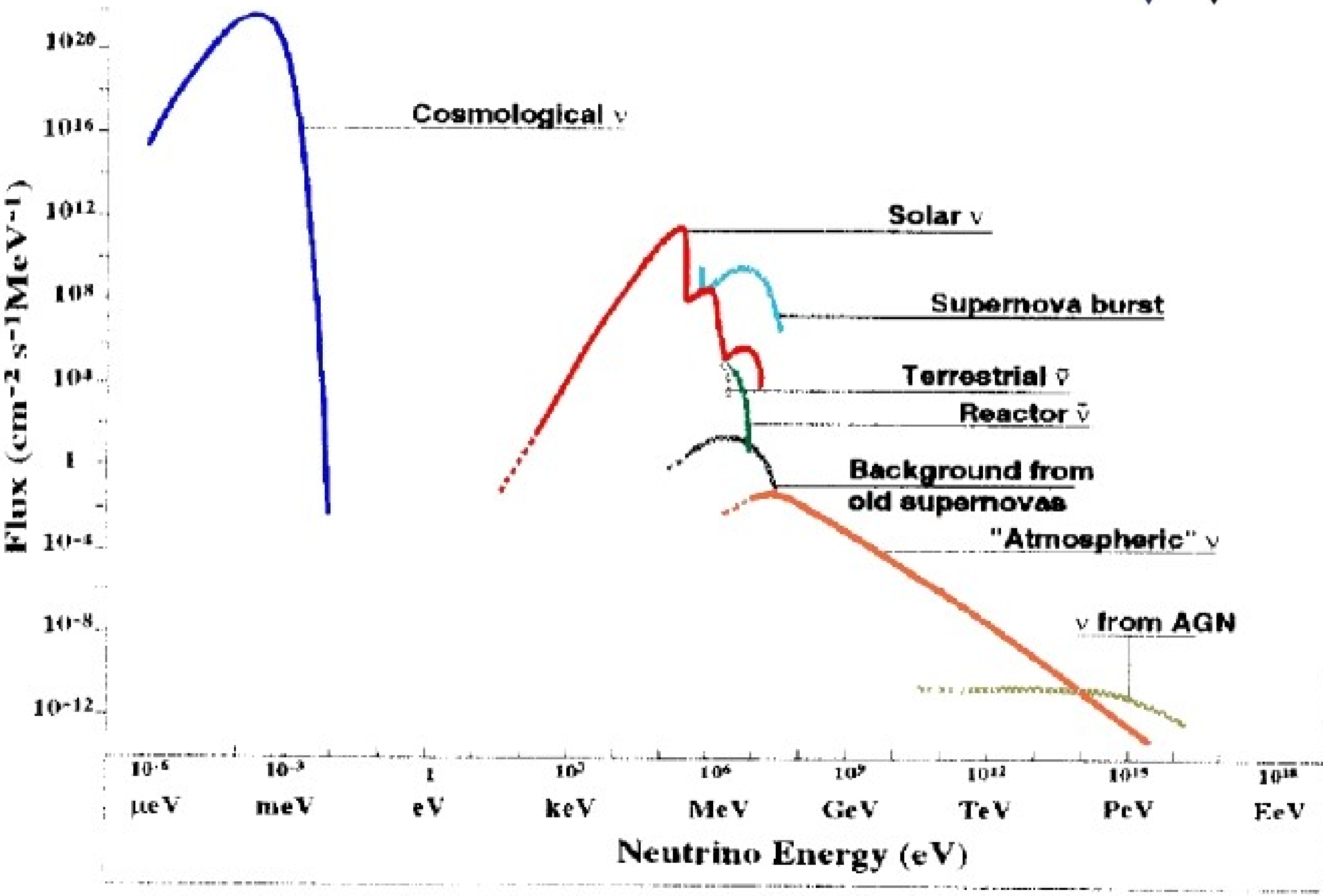
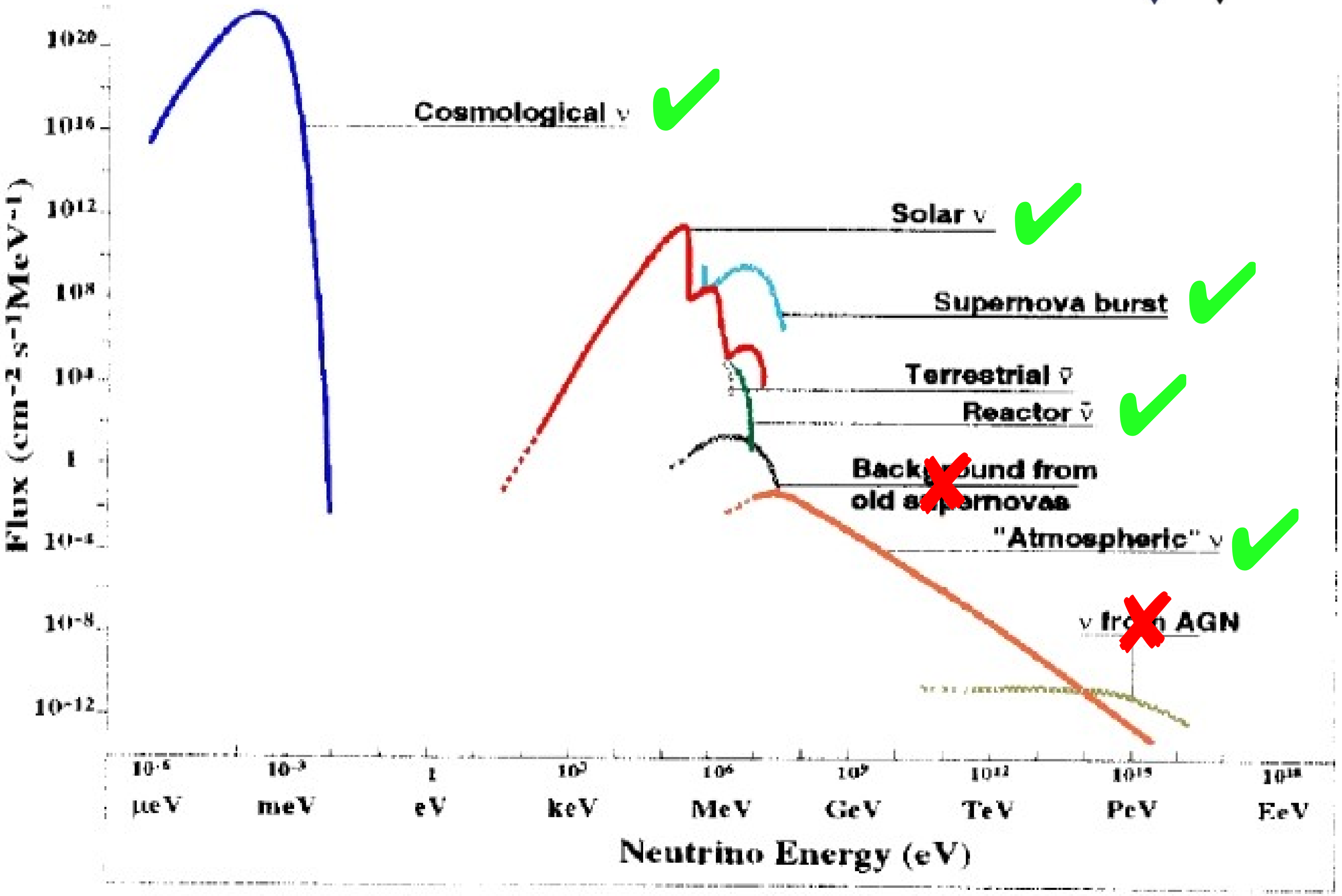


Cosmological ν
Solar ν
Supernova burst
Terrestrial ν̄
Reactor ν̄
Background from old supernovas
"Atmospheric" ν
ν from AGN
Flux (cm⁻² s⁻¹MeV⁻¹)
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino Energy (eV)


Cosmological ν
Solar ν
Supernova burst
Terrestrial ν̄
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Background from old supernovas
"Atmospheric" ν
ν from AGN
Flux (cm⁻² s⁻¹ MeV⁻¹)
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-6
10^-3
1
10^3
10^6
10^9
10^12
10^15
10^18
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
Neutrino Energy (eV)

Neutrinos and the Big Bang

The early universe

- Very soon after the BB, all elementary particles were in thermal equilibrium

$$e^{+} + e^{-} \leftarrow Z^{0} \rightarrow \nu + \overline{\nu}$$

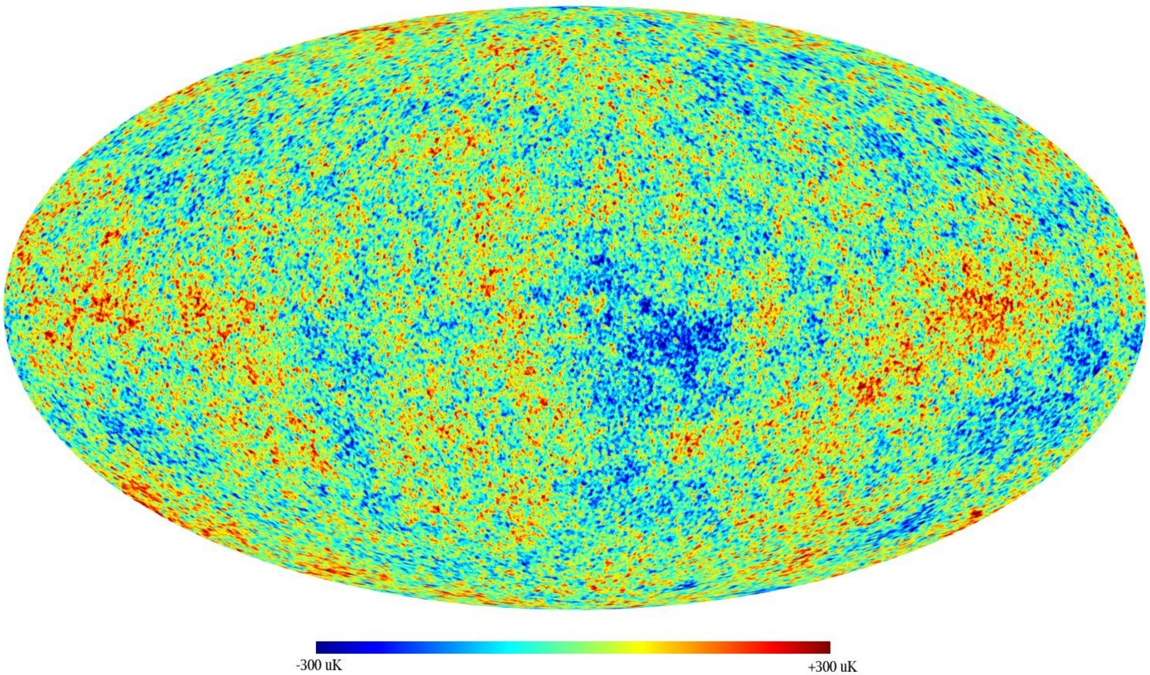
- As the universe expands and the temperature falls it becomes harder and harder for neutrinos to have enough energy to make 2 electron masses.

- Eventually, once the mean interaction time for the backwards reaction ($\nu + \nu \rightarrow e^{+} + e^{-}$) becomes longer than the age of the universe, the neutrinos effectively decouple from the other particles

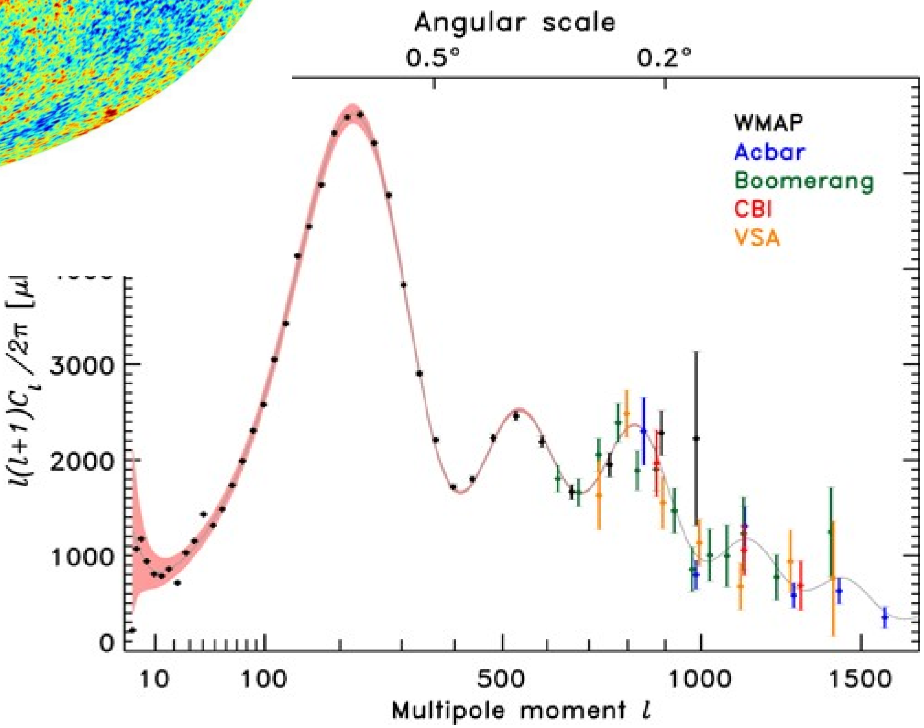
Thermal history

event	time	z	T	
Planck time graviton decoupling	10^{-43} s	10^{37}	10^{19} GeV (10^{31} K)	
GUT/Inflation/baryogenesis	10^{-35} s	10^{32}	10^{14} GeV (10^{26} K)	
EW unification	10^{-12} s	10^{21}	10^{3} GeV (10^{15} K)	
Quark-hadron transition	10^{-6} s	10^{18}	1 GeV (10^{12} K)	
Neutrino decoupling	1 s	10^{15}	1 MeV (10^{9} K)	← CνB
e^+e^- annihilation	1 s	10^{15}	1 MeV (10^{9} K)	
nucleosinthesis	1-100 s	10^{14}	0.1-1 MeV (10^{8}-10^{9} K)	
Matter-radiation equality	10^{3} years	10^{4}	1 eV (10^{31} K)	
recombination	10^{5} years	10^{3}	10^{-1} eV (10^{3} K)	
photon decoupling	10^{5} years	10^{3}	10^{-1} eV (10^{3} K)	← CMB

CMB



-300 uK
+300 uK



Angular scale
0.5°
0.2°
WMAP
Acbar
Boomerang
CBI
VSA
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l

Relic Neutrinos

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As the universe expanded and cooled, neutrinos decoupled from matter and were able to free stream.

Just like the cosmic microwave background, these relic neutrinos are still around acting as an echo of the big bang

- Decoupled < 1 s after the big bang (CMB decoupled 380,000 years!)
- Density : 340 ν/cm^{-3}
- Energy (now) : 10^{-4} eV (practically at rest)
- Could form about 10% of Cold Dark Matter

Detection

Relic neutrinos have too low an energy to be detectable by standard techniques (and the cross section is v. v. small)

Coherent Scattering

$$\lambda_{relic} \sim 0.1\, cm$$

Scattering coherently across many targets increases the cross section

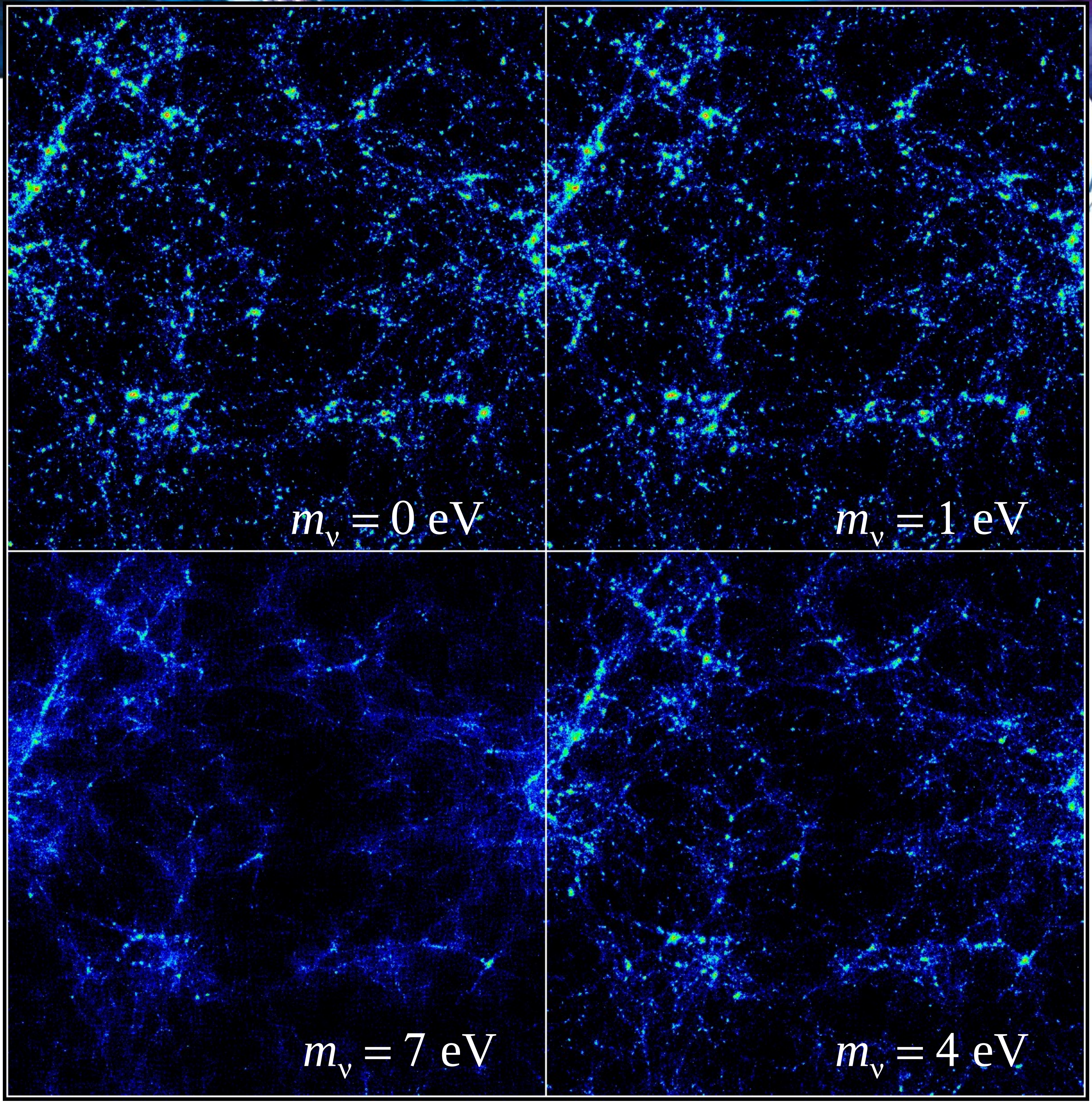
Try to detect neutrino wind using Cavendish torsion balances

Ultra high energy ν targets

$$\nu_{relic} \bar{\nu} \to Z^0$$

Interaction removes UHEν from flux

Absorption dips in the UHEν energy spectrum



$m_\nu = 0$ eV
$m_\nu = 1$ eV
$m_\nu = 7$ eV
$m_\nu = 4$ eV

How "clumpy" is the universe?

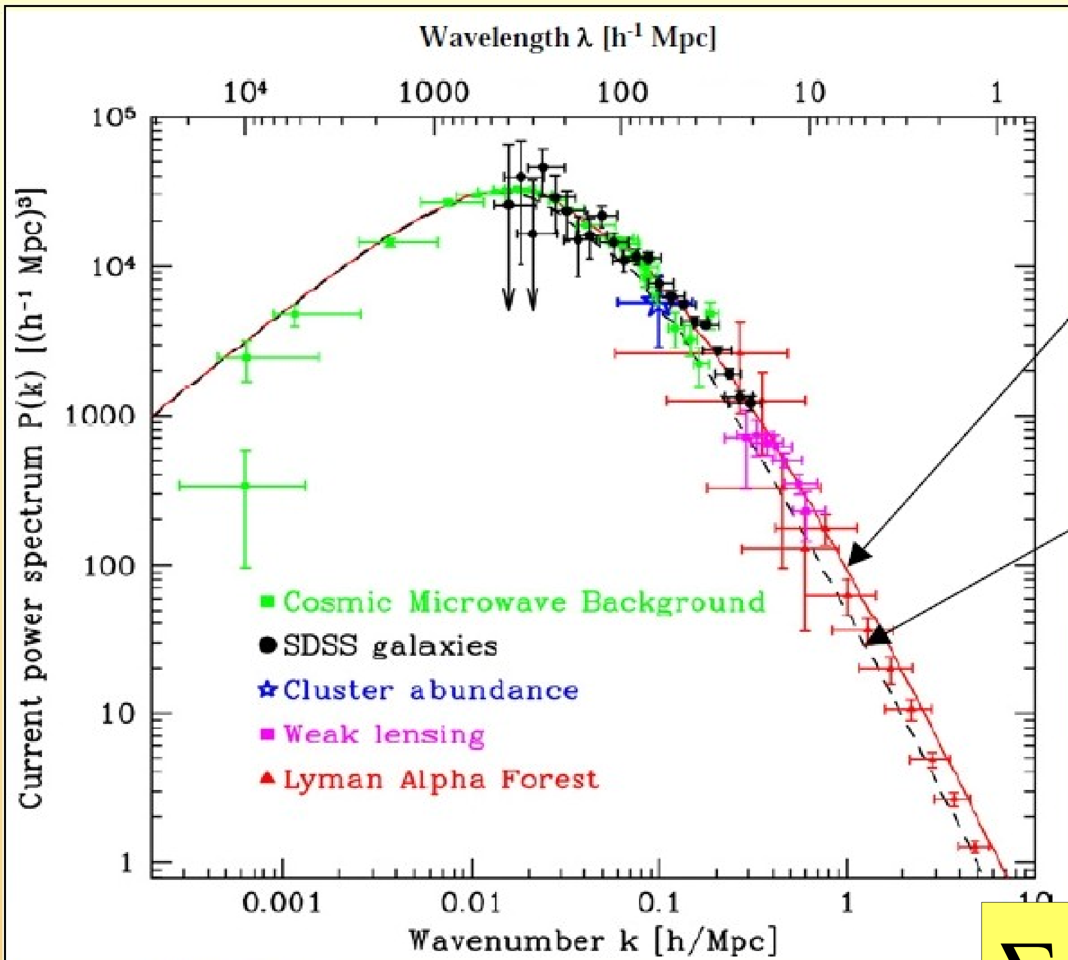


Figure from:
M. Tegmark, Physica Scripta. Vol. T121, 153–155, 2005

Solid line: standard cosmology, with neutrino mass = 0.

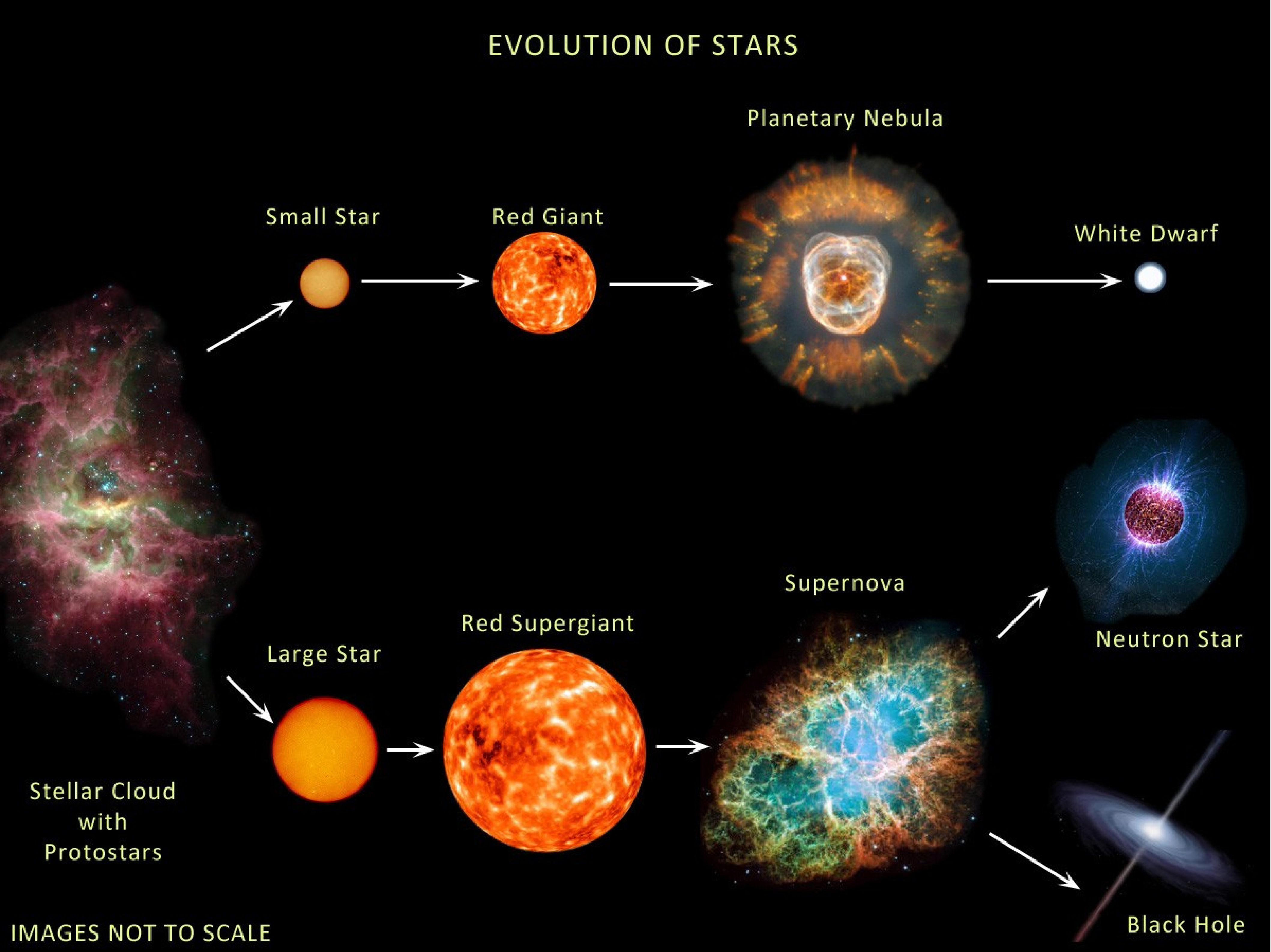
Dashed line: what would happen if the neutrino mass were 1 eV? (That would mean neutrinos made up 7% of the dark matter). As seen in the plot, this would suppress small-scale structure by a factor of 2.

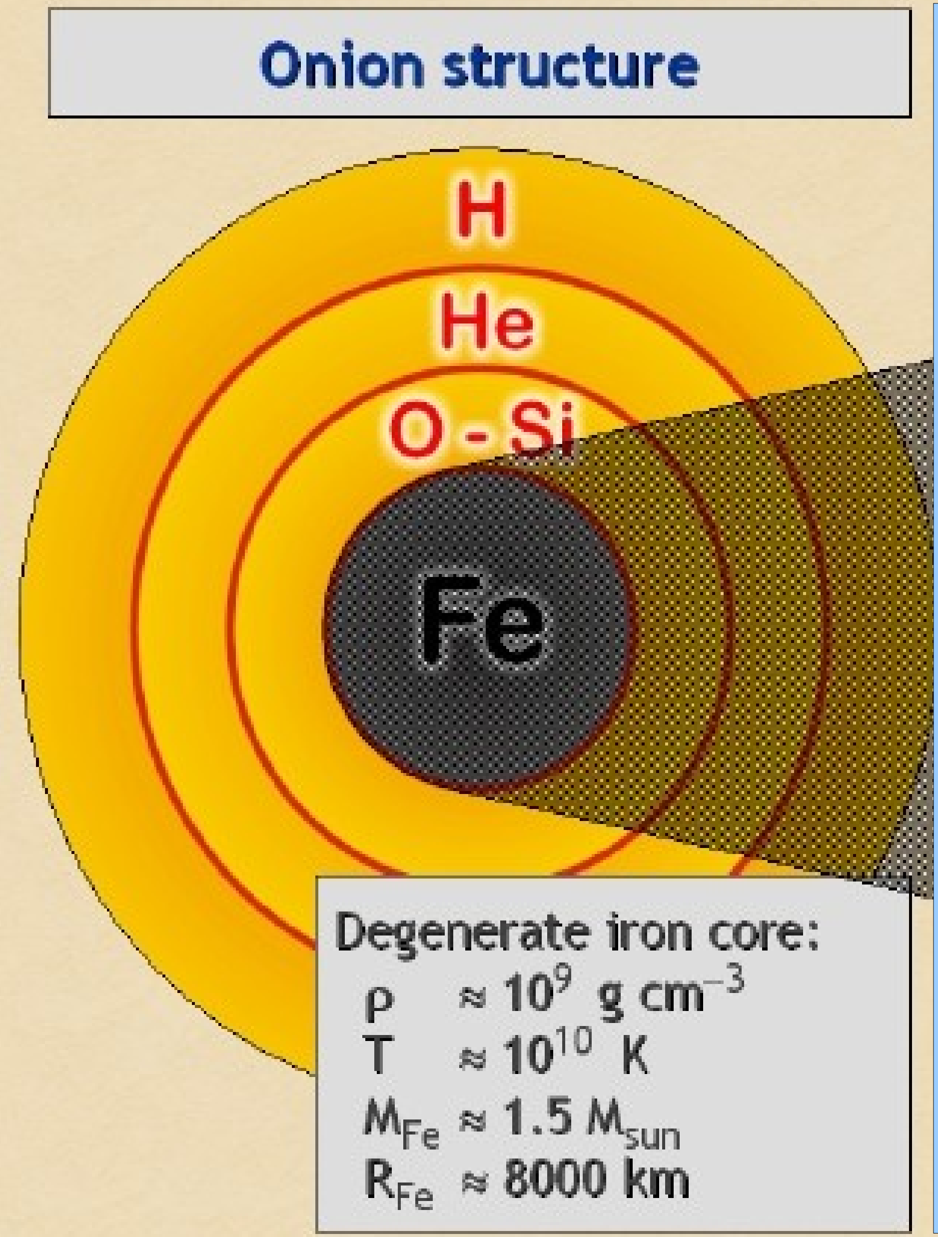
$\sum m_\nu < 0.28\text{-}0.81$ eV

Large scale structure

Small scale structure

Neutrinos and Supernovae


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Red Supergiant
Large Star
Neutron Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE



Once silicon is burnt & if $M_{Fe} > 1.3\ M_{solar}$, core begins to collapse. T rises

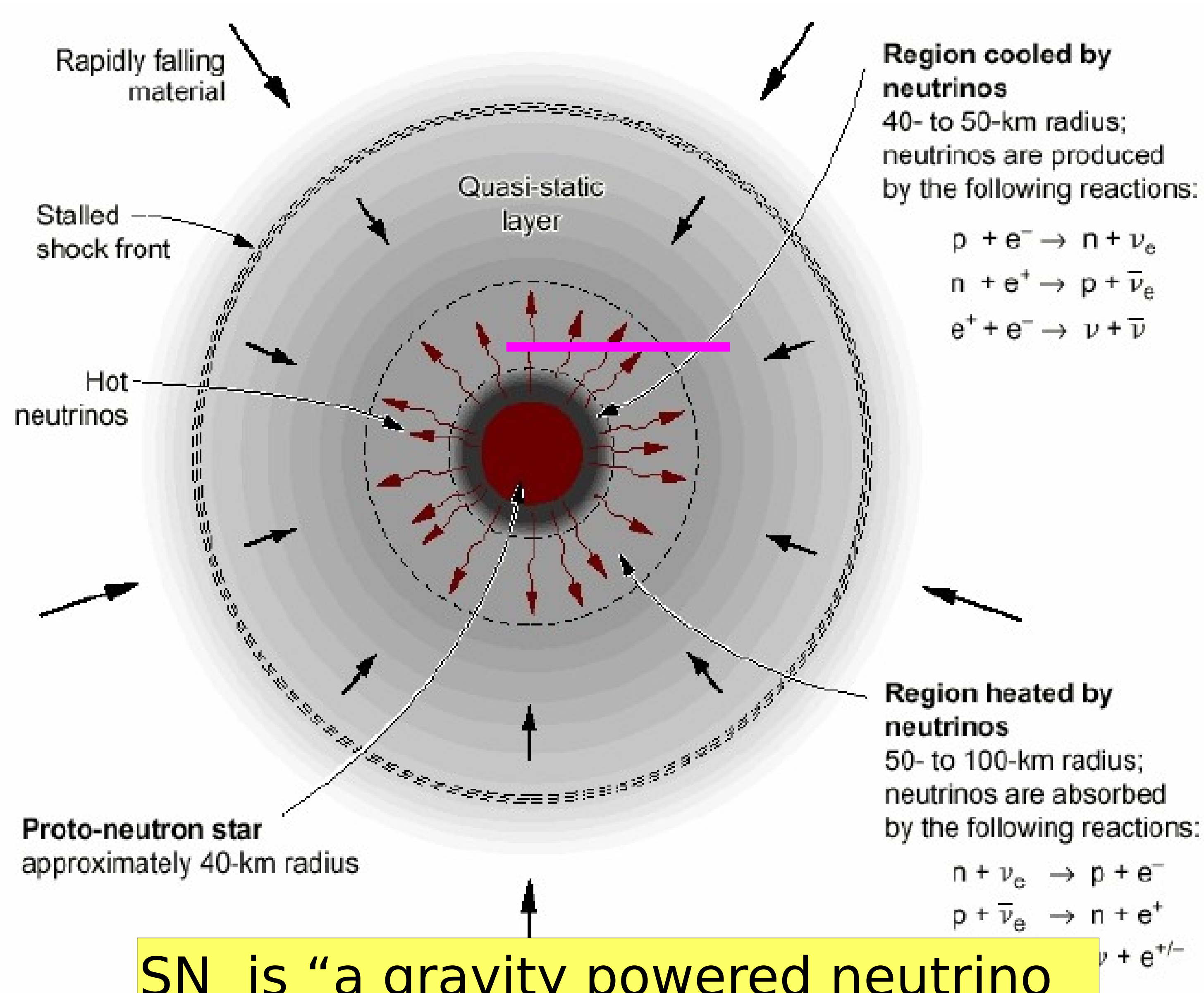
$$Fe^{56} + \gamma \rightarrow 13\,He^{4} + 4\,n$$

$$He^{4} + \gamma \rightarrow 2\,p + 2\,n$$

Core cools and goes into free fall. Collapse speed around 0.25c until stopped by neutron degeneracy

$$e^{-} + p \rightarrow n + \nu_{e}$$

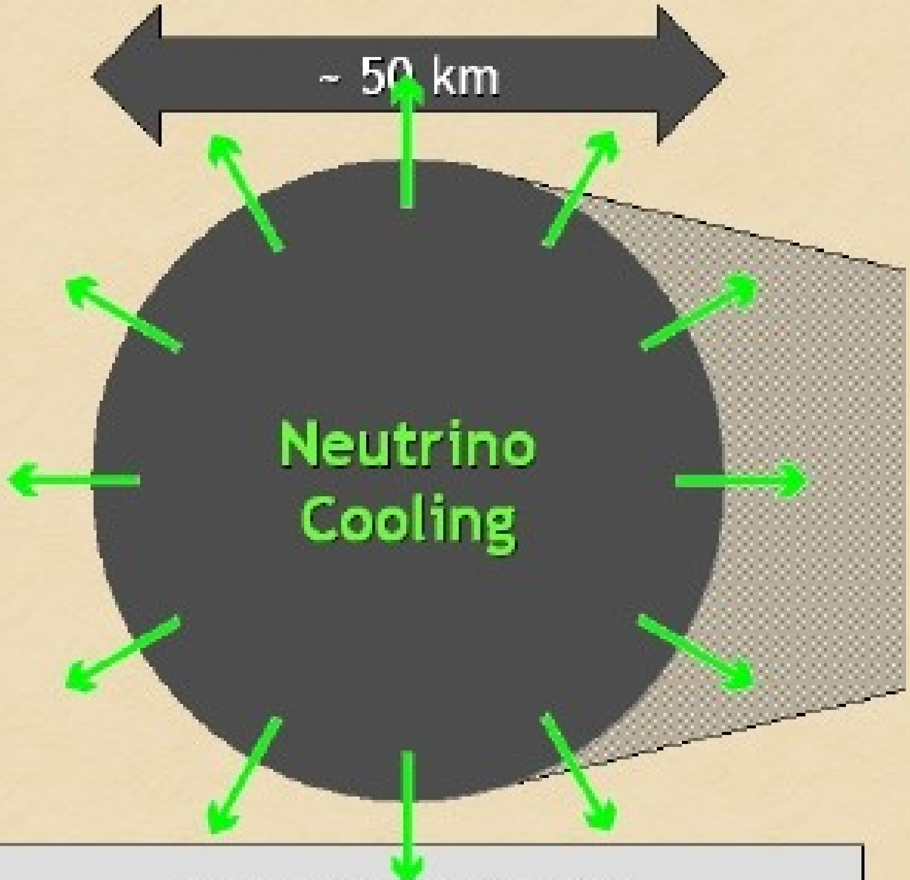
“deleptonisation”



SN is "a gravity powered neutrino explosion"

Newborn Neutron Star

Whole process happens in a few seconds



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

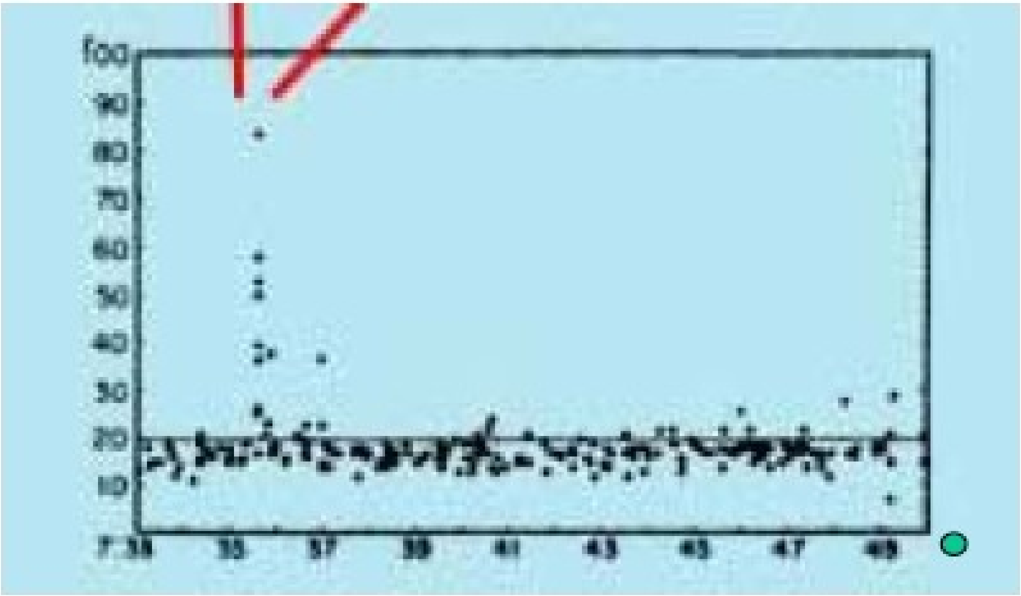
$\approx 3 \times 10^{19}\ L_{SUN}$

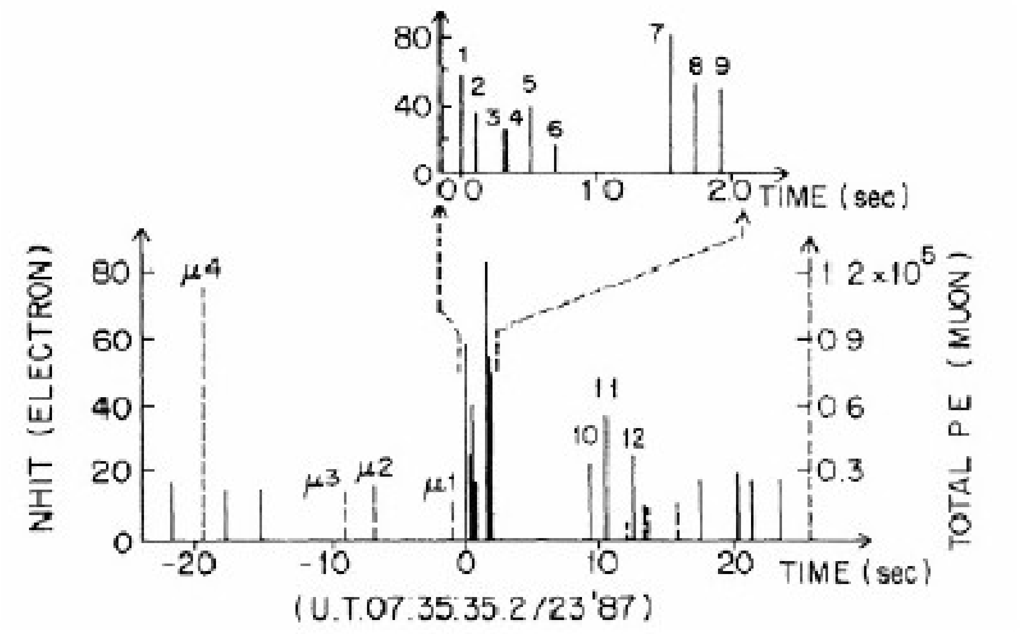
While it lasts, outshines the entire visible universe

SN 1987A

170,000 years ago, somewhere in the Large Magellanic Cloud
Staggeringly bright – amount of energy released in light was equal to 10^{16} suns (and that's 0.01% of released energy in visible light!)

4 hours earlier

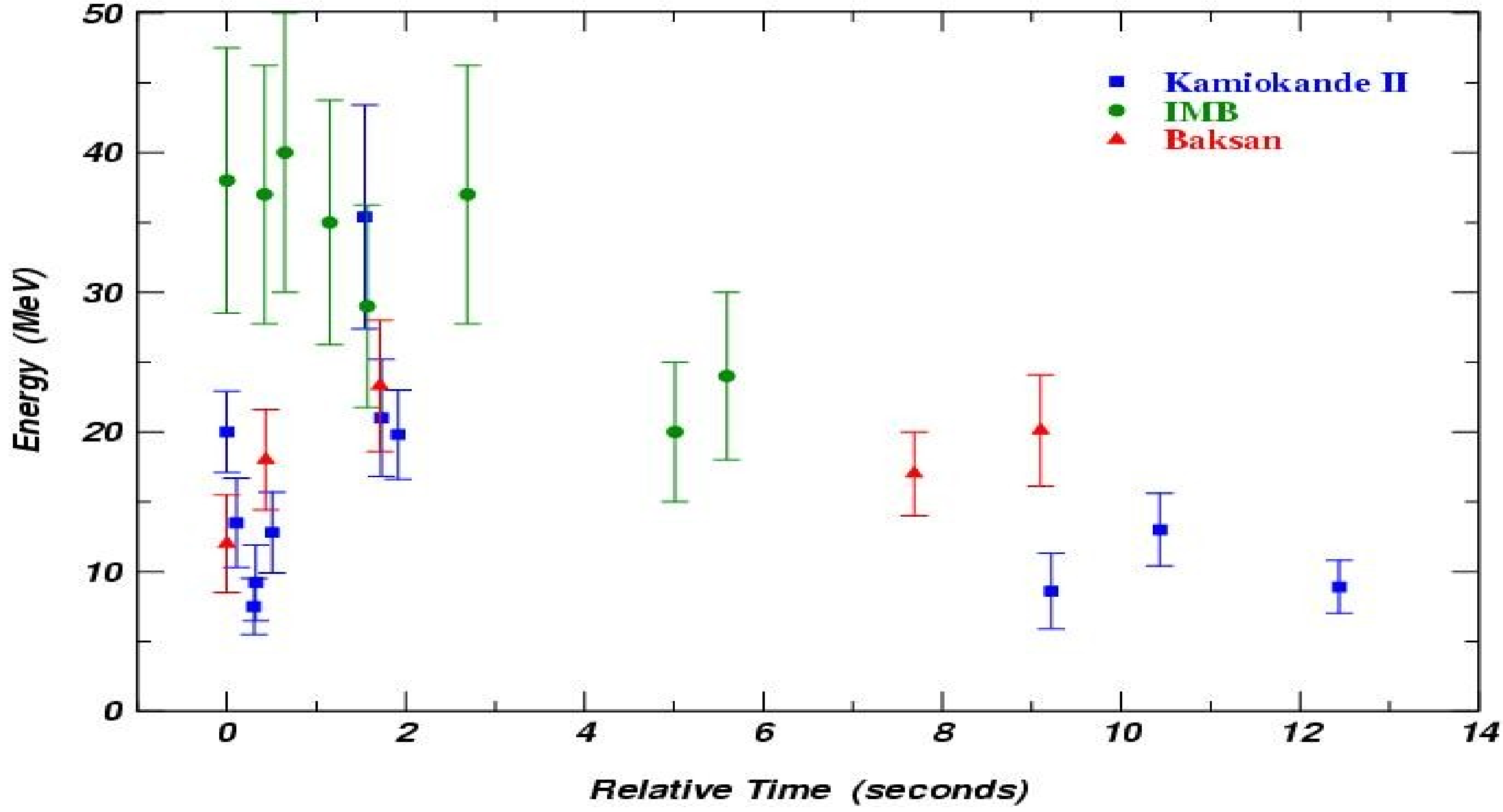




Kamiokande in Japan

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

4 hours earlier



$$\Delta t = \Delta t_0 + \frac{L m_\nu^2}{2c}\left(\frac{1}{E_2^2} - \frac{1}{E_1^2}\right) \rightarrow m_{\overline{\nu}_e} < 11\, eV$$

- Lifetime $\tau > 5\times10^{5}(m_\nu/GeV)\quad sec$

ν_e flux expected from models was measured

- Mass $m_{\overline{\nu}_e} < 11\,eV$

Difference between arrival time compared to models

- Magnetic moment $\mu(\overline{\nu}_e) < 8\times10^{-12}\mu_B$

Coupling to photons would flip helicity to RH and energy would be lost

- Electric charge $Q_\nu/Q_e < 1\times10^{-17}$

Charged ν would see an energy dependent delay due to travel through magnetic fields

SN1987A
Now

Neutrinos and other Astro things

Ultra-High Energy Neutrinos

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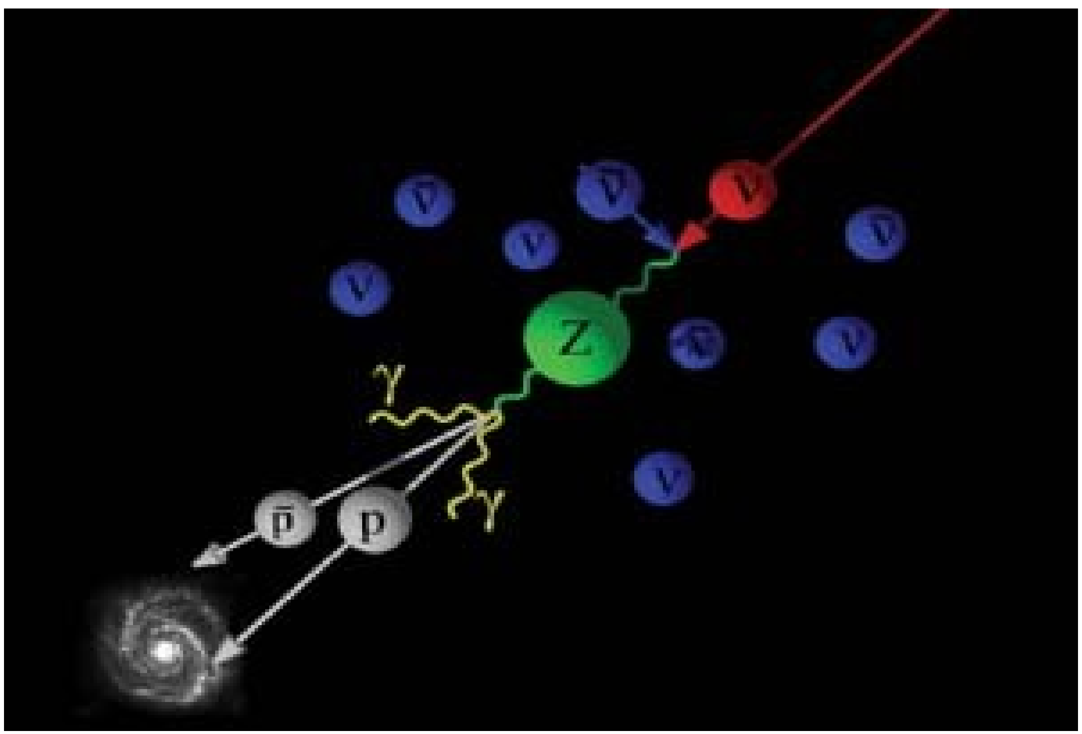
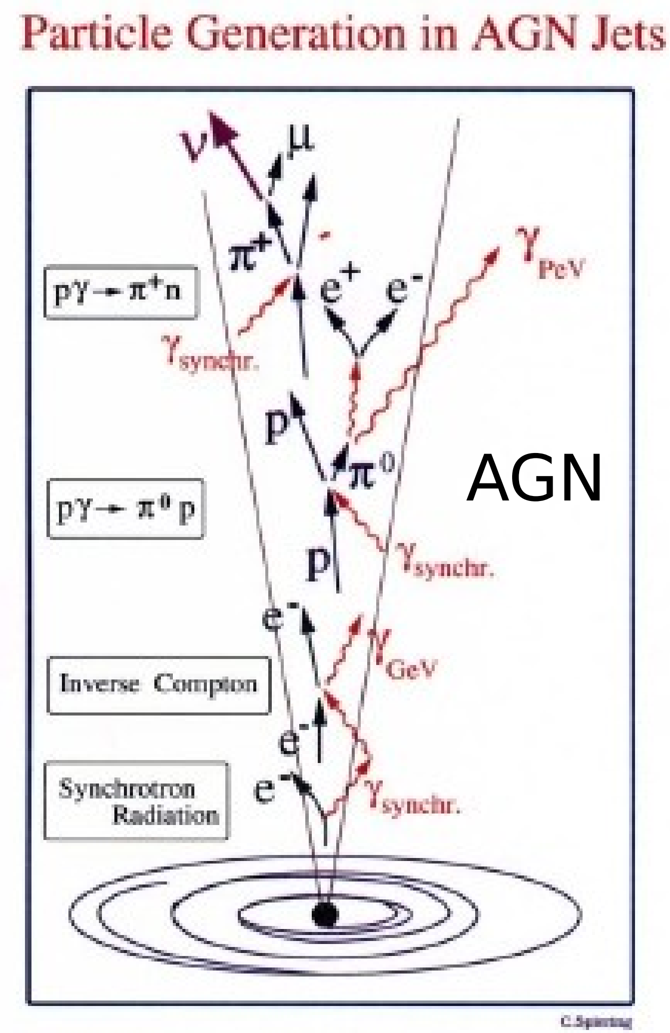
Neutrinos with energies > 10^5 GeV or so come from a whole range of cosmic accelerators

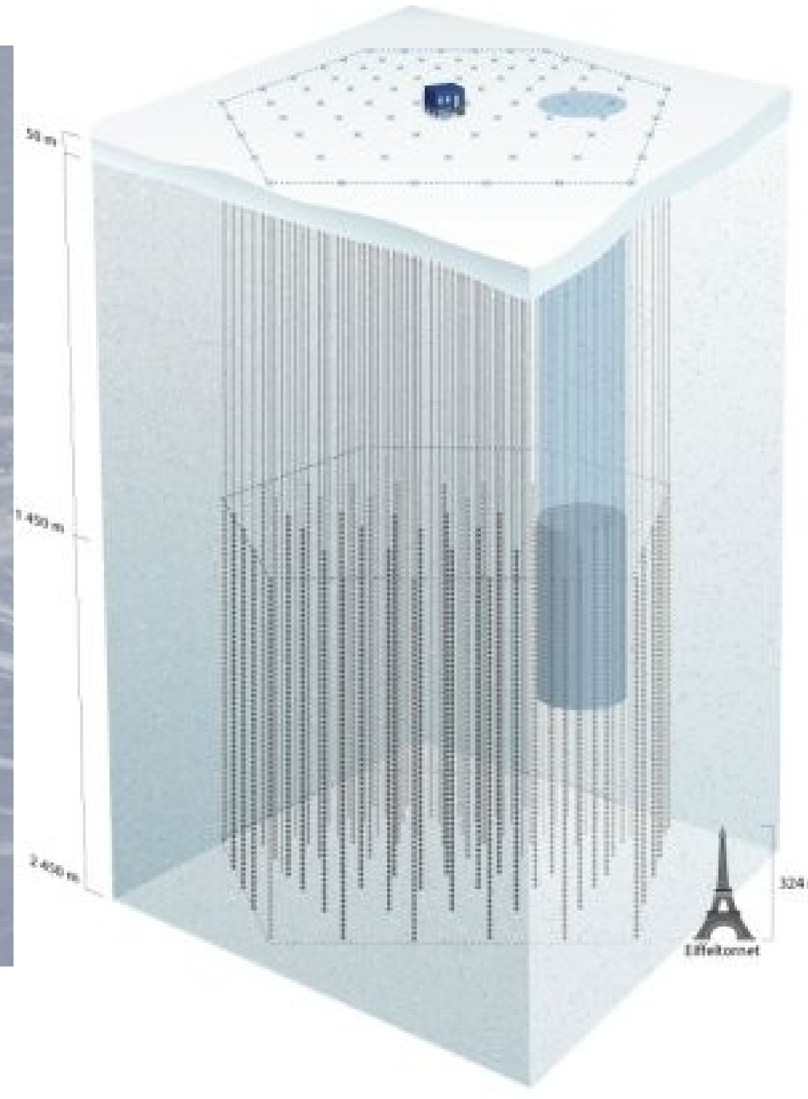


Z burst

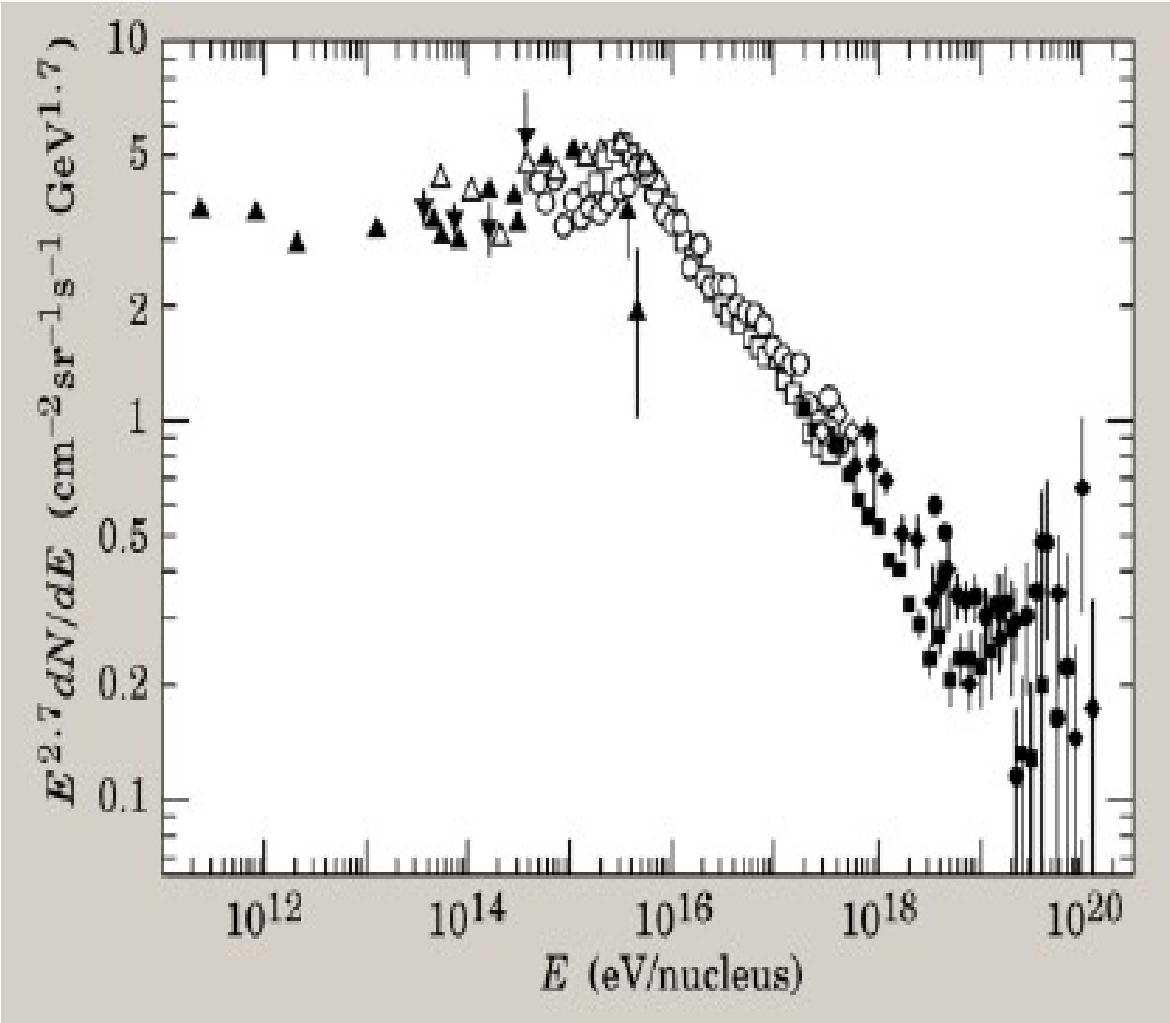


AGN

IceCube



Neutrino Astrophysics



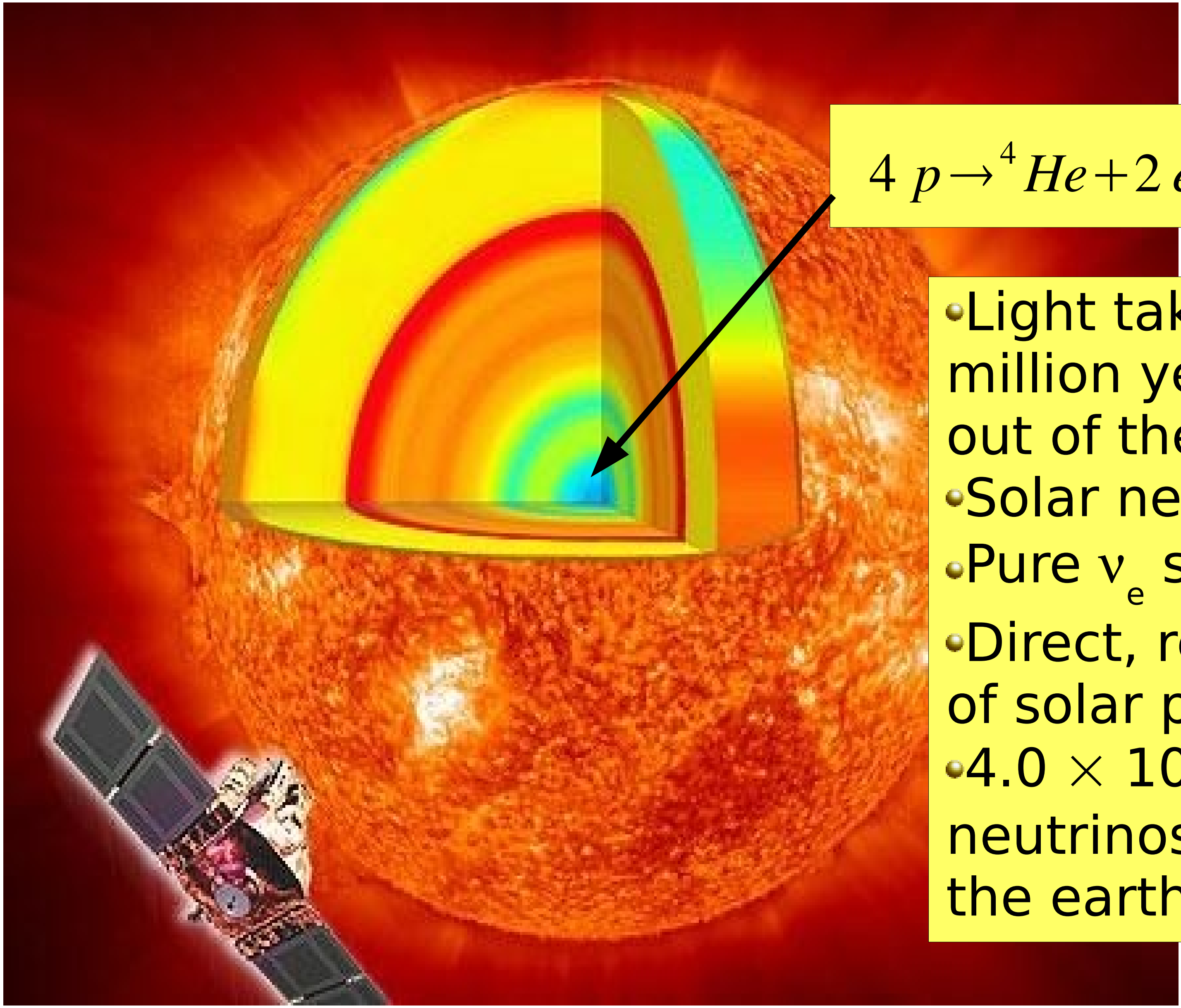
Intergalactic magnetic field cuts off high energy protons around 10^{20} eV (GZK)

Around 10^{12} eV, photons interact too much to be visible > 10 Mpc

Neutrinos – can see across the universe and point back to sources

Neutrinos and the Sun

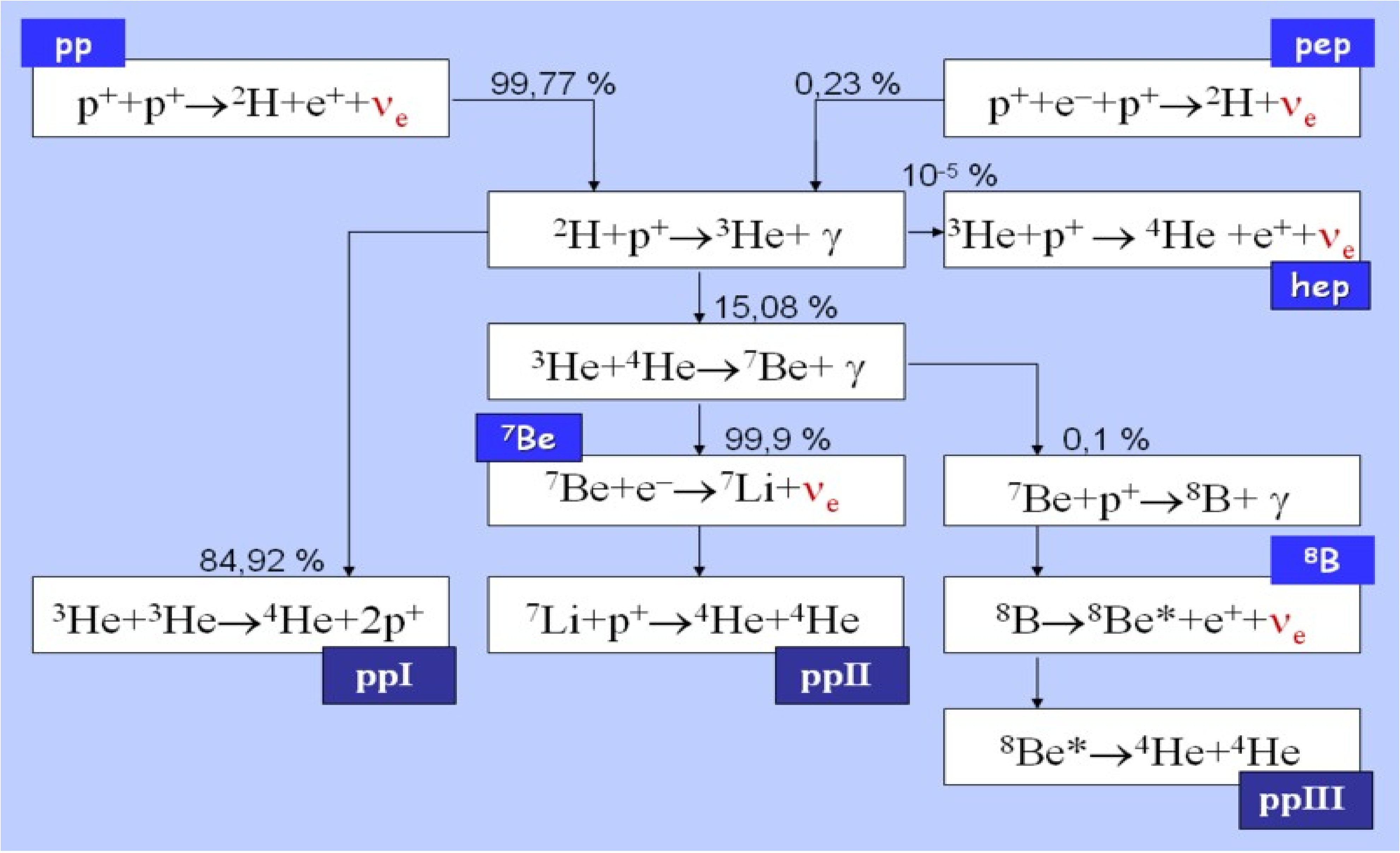
How the Sun burns



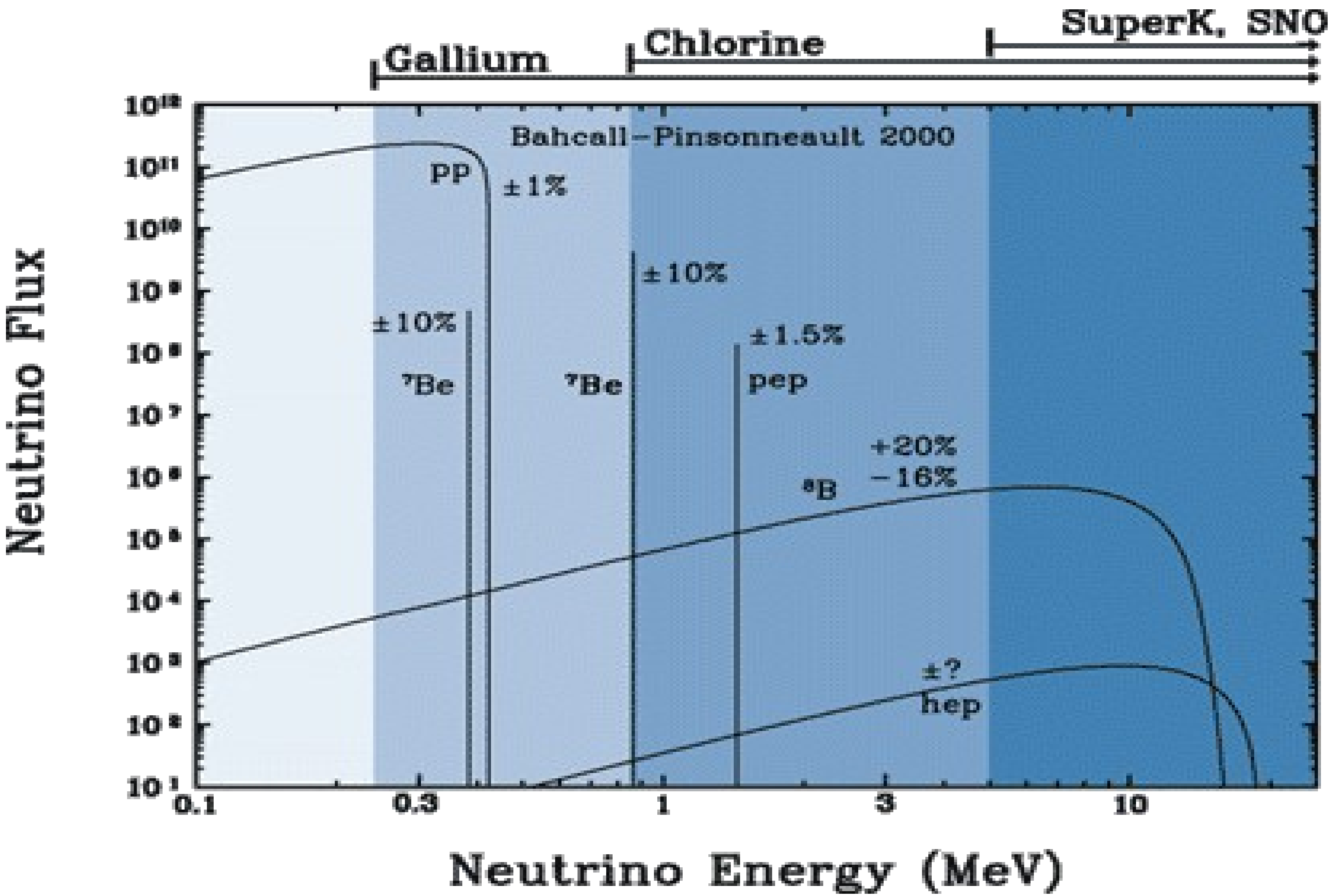
$$4\,p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + 25\,MeV$$

- Light takes about a million years to get out of the solar core
- Solar neutrinos take 2 s
- Pure ν_e source
- Direct, real-time probe of solar processes
- 4.0×10^{10} solar neutrinos / cm^2 / sec at the earth

The pp Cycle


pp
p⁺+p⁺→²H+e⁺+ν_e
99,77 %
0,23 %
pep
p⁺+e⁻+p⁺→²H+ν_e
10⁻⁵ %
²H+p⁺→³He+ γ
³He+p⁺ → ⁴He +e⁺+ν_e
hep
15,08 %
³He+⁴He→⁷Be+ γ
⁷Be
99,9 %
0,1 %
⁷Be+e⁻→⁷Li+ν_e
⁷Be+p⁺→⁸B+ γ
84,92 %
⁸B
³He+³He→⁴He+2p⁺
⁷Li+p⁺→⁴He+⁴He
⁸B→⁸Be*+e⁺+ν_e
ppI
ppII
⁸Be*→⁴He+⁴He
ppIII

Standard Solar Model



John Bahcall

1934-2005

Spent most of his career developing the Standard Solar Model

One of the first to use computers to model solar processes

Also a leading light in the Hubble Telescope

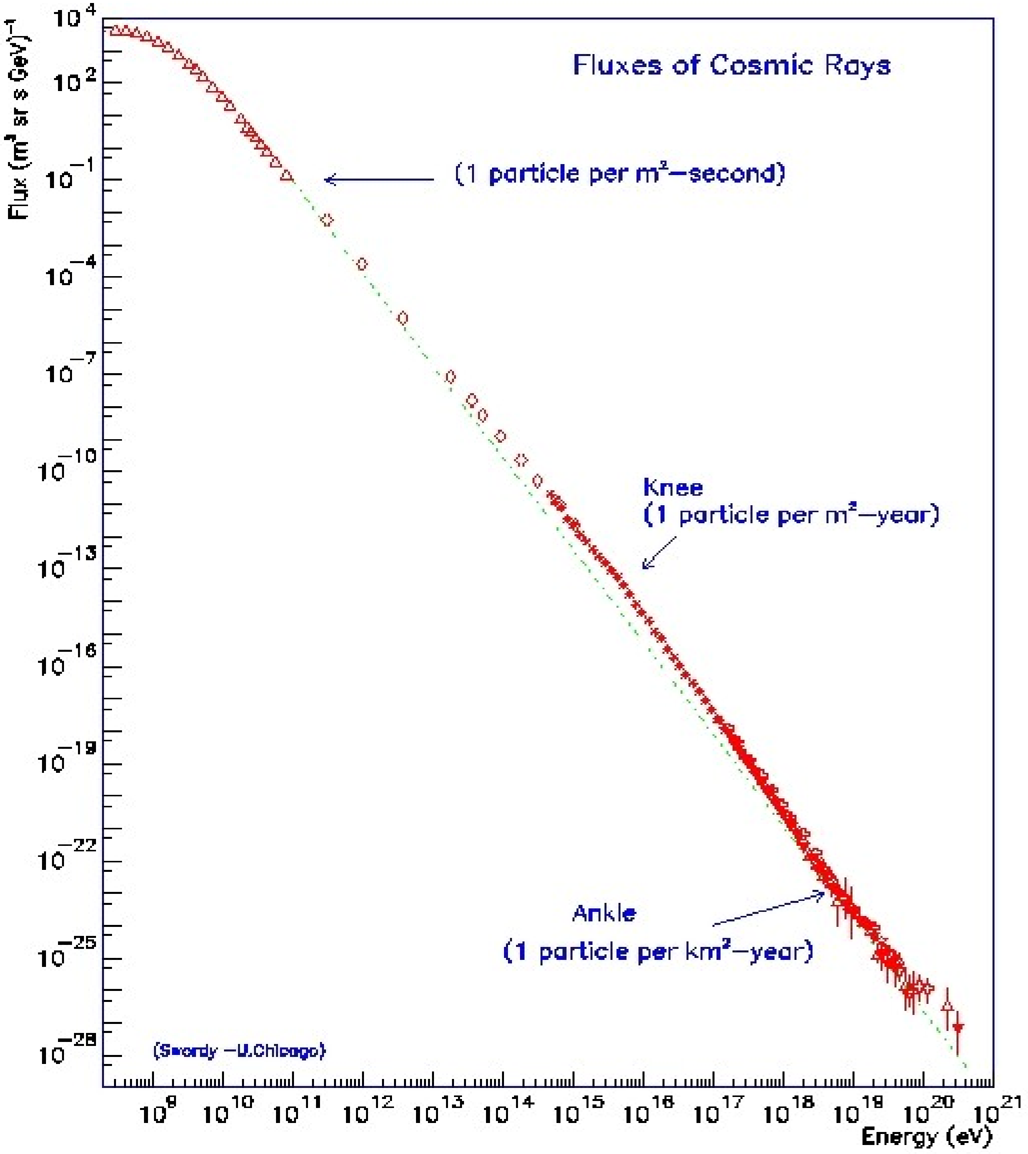
Neutrinos and Cosmic Rays

Atmospheric Neutrinos

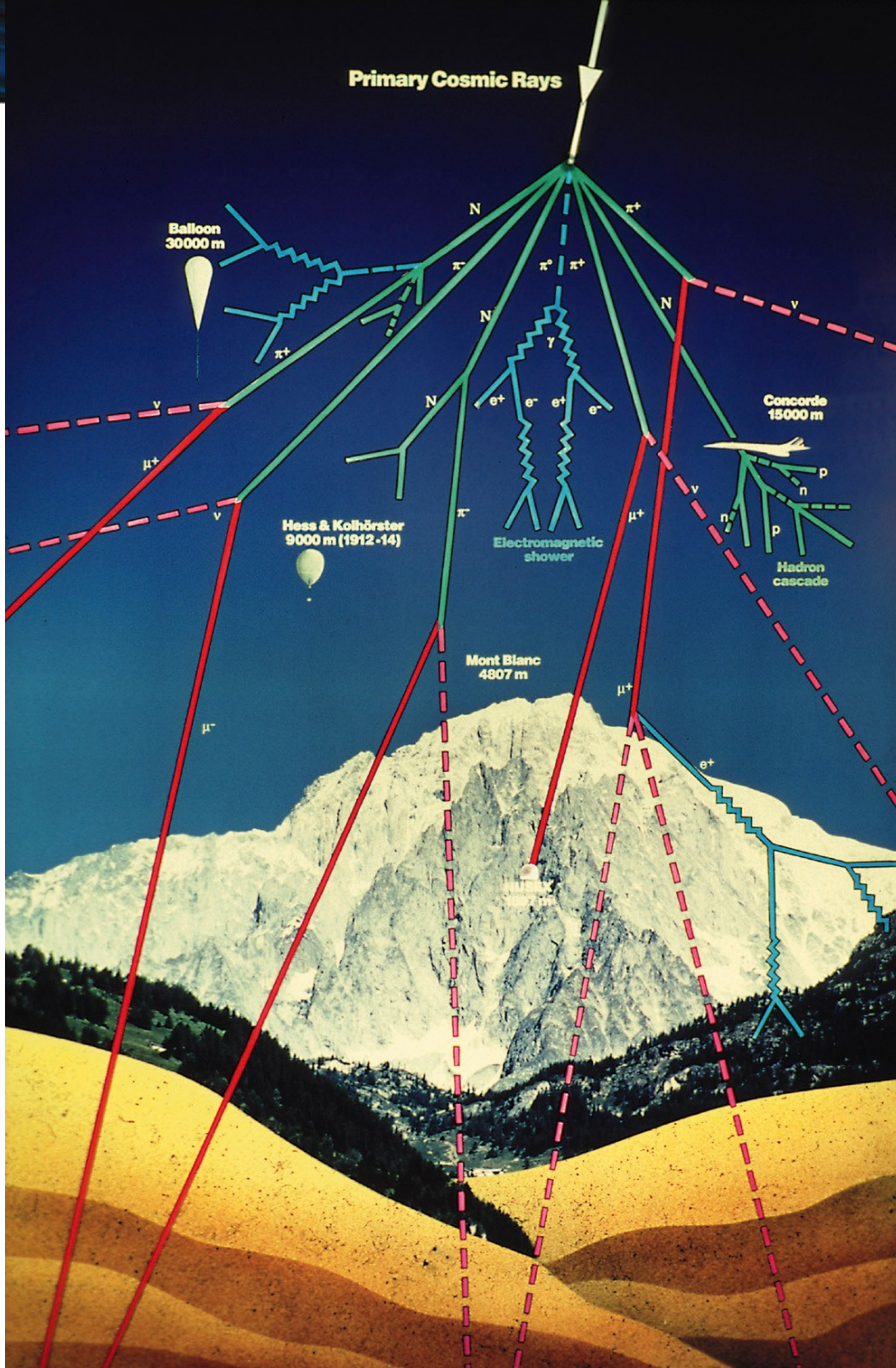
Primary cosmic rays coming from ????

- 87% protons
- 11% alphas
- rest – heavy nuclei

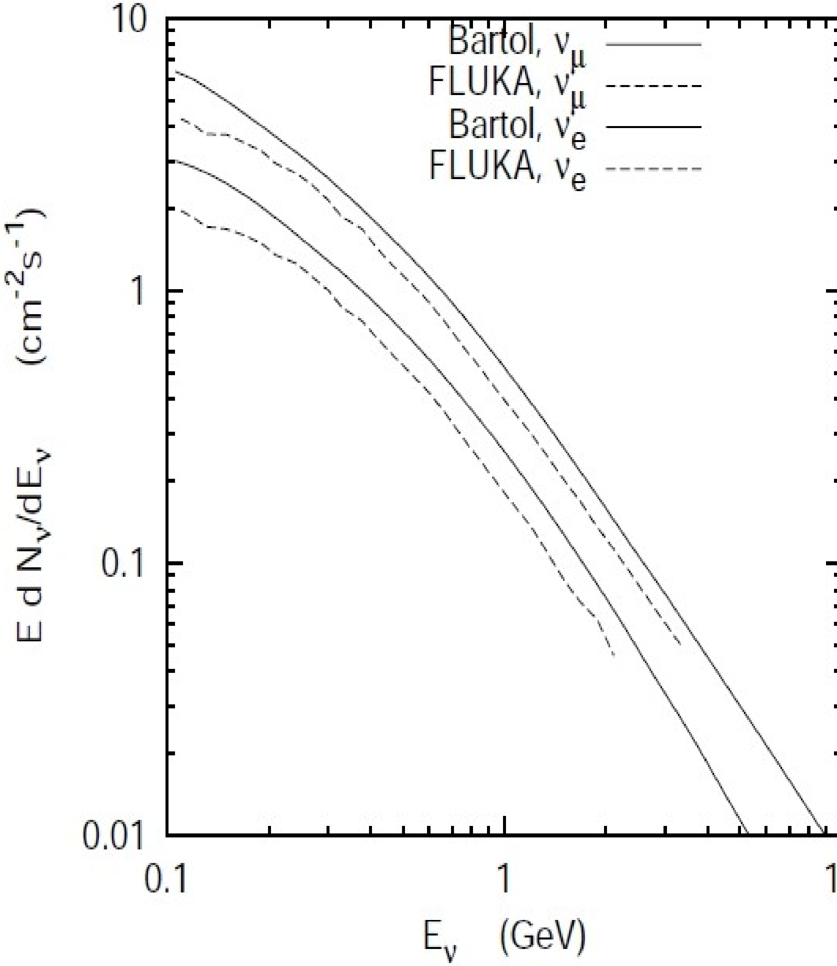
Energies up to and greater than 1 TeV



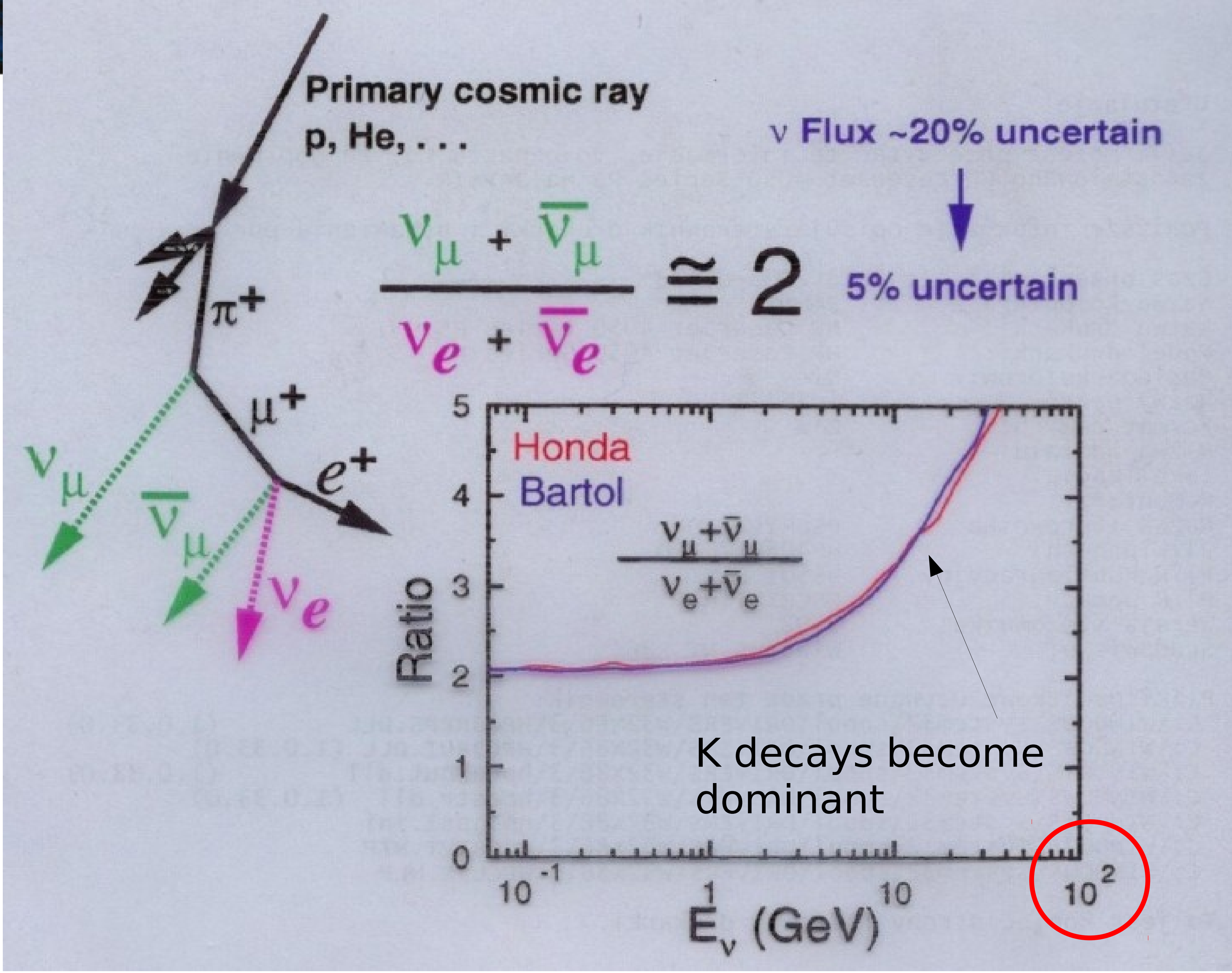
30 km



Primary Cosmic Rays
Balloon 30000 m
Concorde 15000 m
Hess & Kolhörster 9000 m (1912-14)
Electromagnetic shower
Hadron cascade
Mont Blanc 4807 m

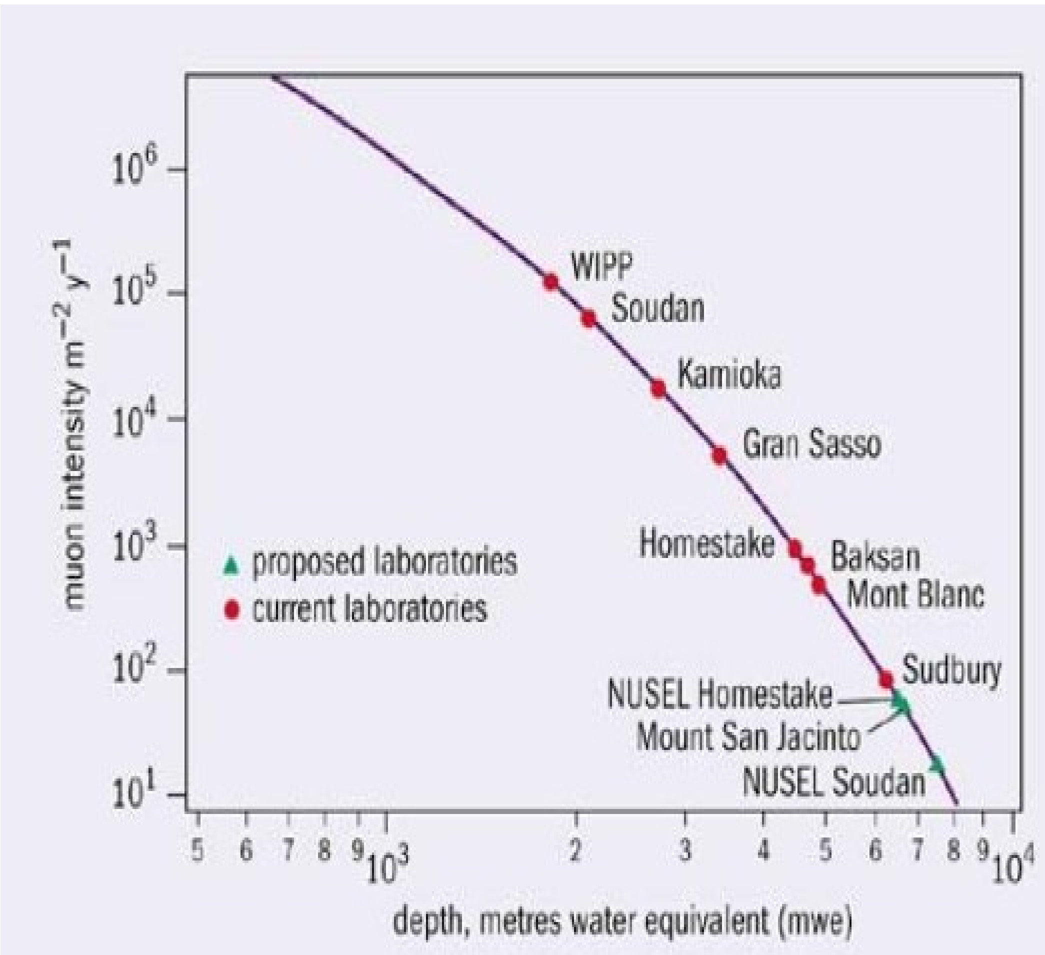


Bartol, ν_μ
FLUKA, ν_μ
Bartol, ν_e
FLUKA, ν_e
E d N_ν/dE_ν ($cm^{-2}s^{-1}$)
E_ν (GeV)
10
1
0.1
0.01
0.1
1
10



Primary cosmic ray
p, He, . . .
ν Flux ~20% uncertain
5% uncertain
$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2$
π+
μ+
e+
ν_μ
$\bar{\nu}_\mu$
ν_e
Honda
Bartol
$\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}$
Ratio
0
1
2
3
4
5
10^{-1}
1
10
10^2
E_ν (GeV)
K decays become dominant

Atm. Neutrino Experiments



To escape from cosmic ray muons detectors have to deep underground.

Roughly one order of magnitude suppression every 650 m.

Basic background is then interactions in the rock around the detector.

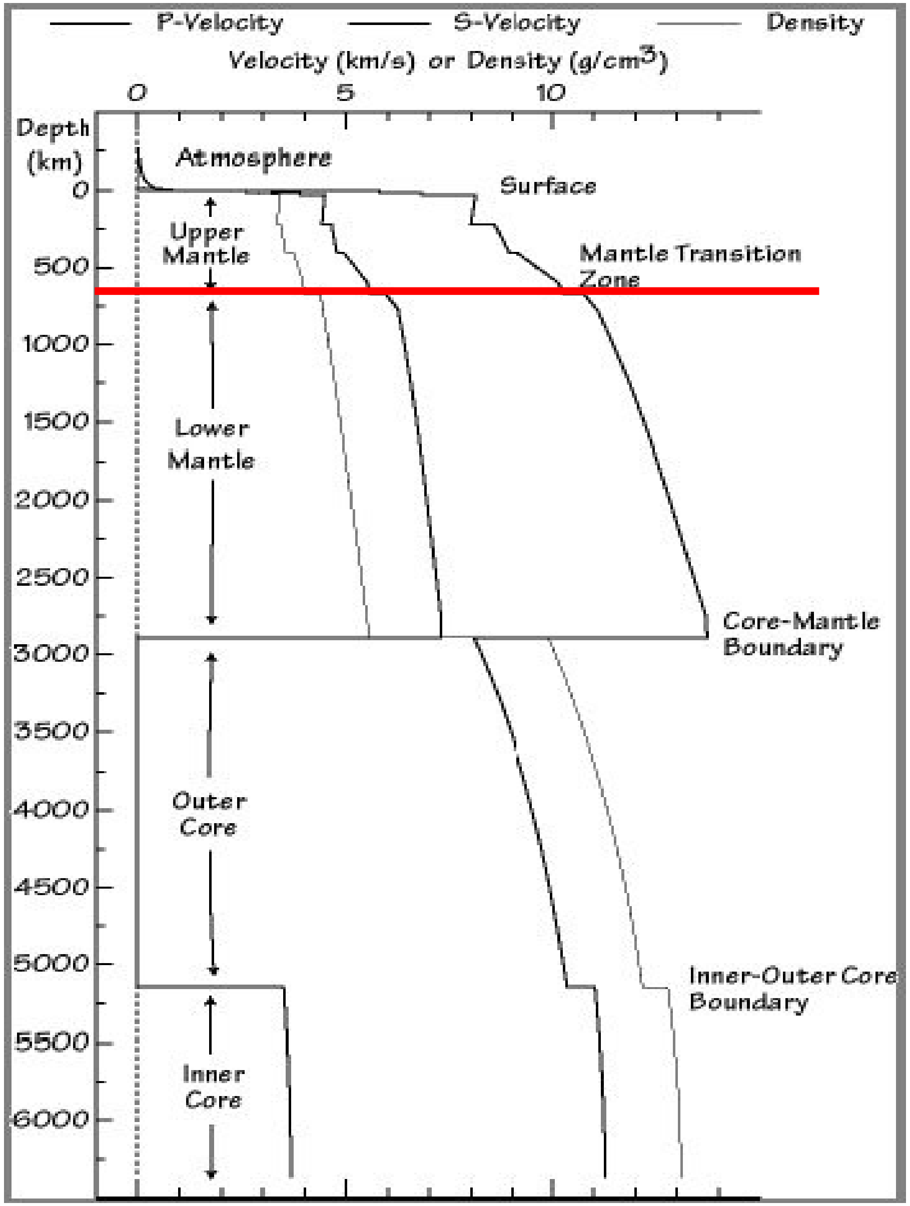
Neutrons are particularly dangerous.

Neutrinos and the Earth

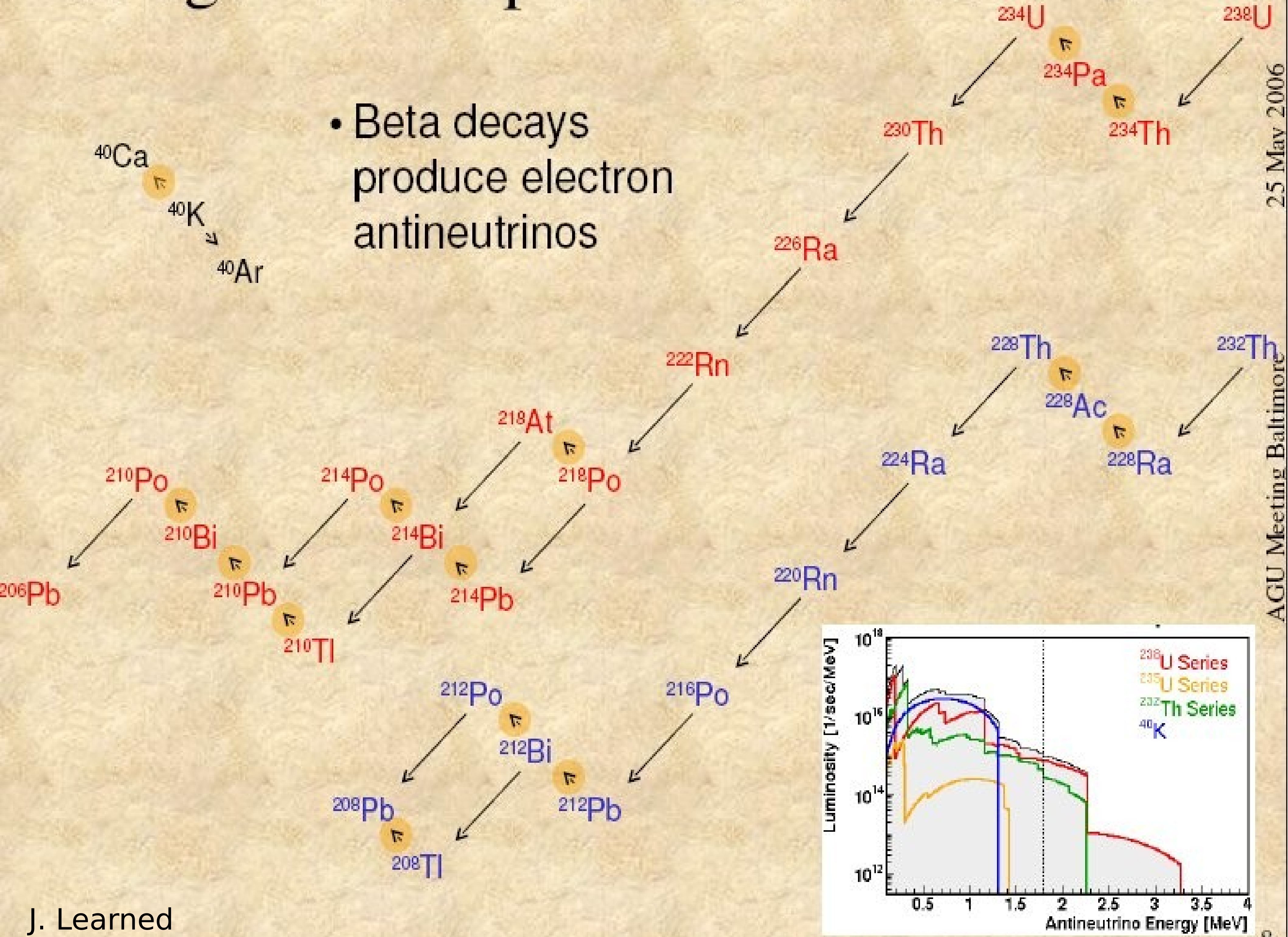
Geo-neutrinos

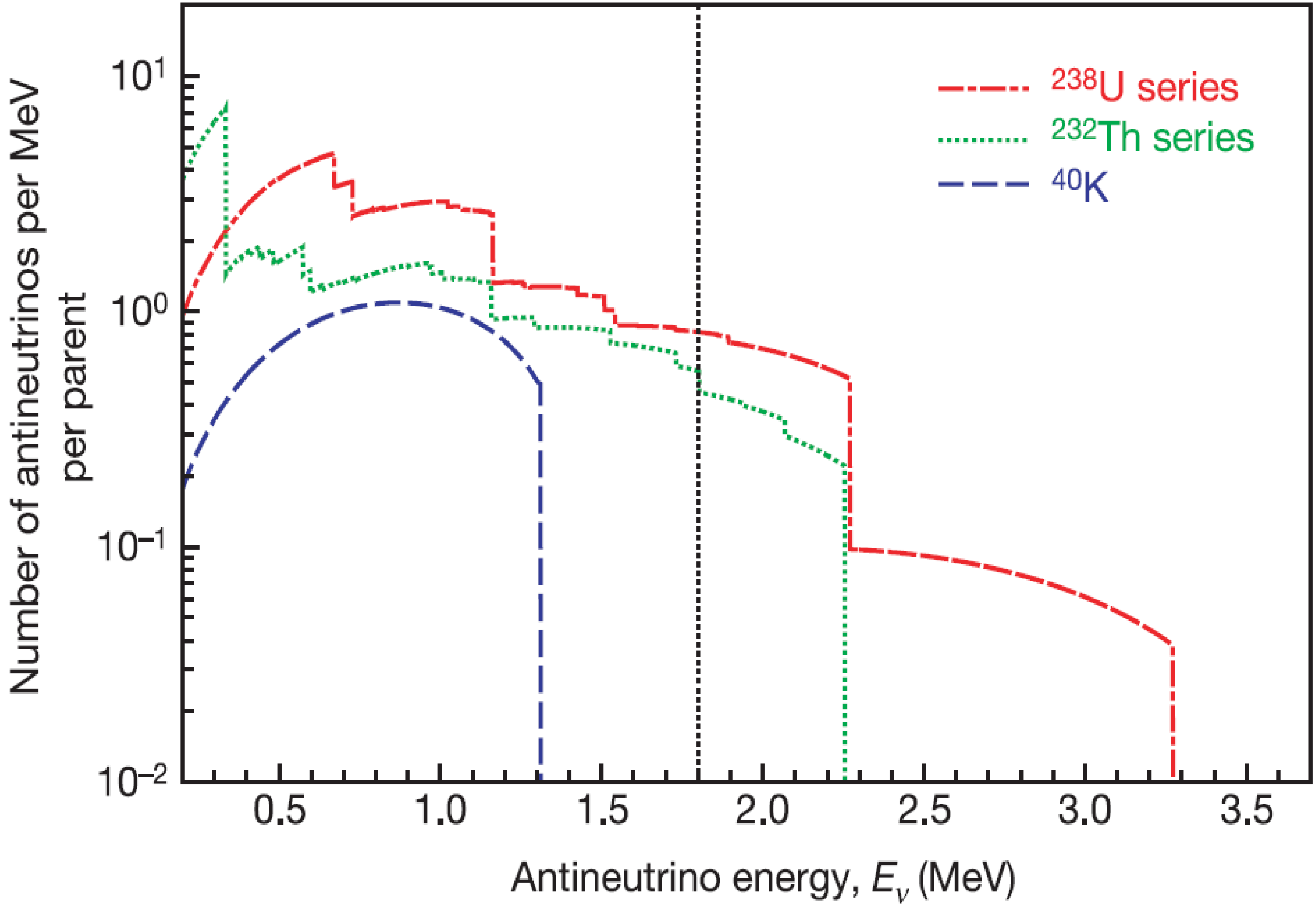
- Can only directly probe down to about 700 km

- Deep earth chemical composition
- Mass distribution
- Mechanism that powers the geo-dynamo
- Heat flow : 30-45 TW of which 19-31 TW are from radioactive decay



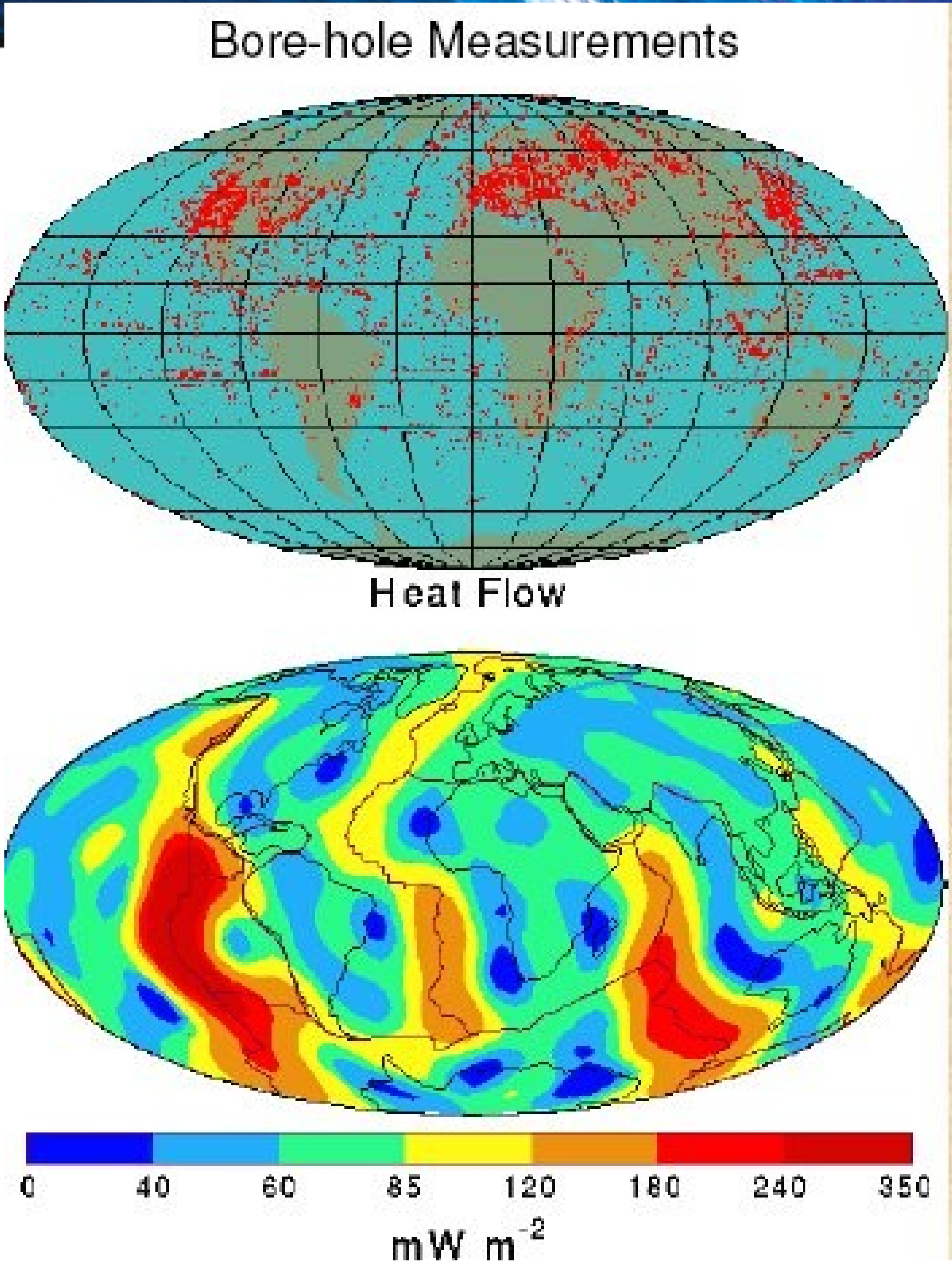
- Beta decays produce electron antineutrinos





$$\overline{\nu_e} + p \rightarrow n + e^{+} \qquad E_\nu > 1.8\, MeV$$

for scintillator detectors



- Conductive heat flow bore holes
- Deepest hole is only about 1/500th of Earth radius
- Total heat flow about 44 ± 1.0 TW according to models fit to this date
- Model predicts about 19 TW from radioactive decay

- KAMLanD detector in Japan measures 11 ± 8 TW (2013).

Summary

Neutrinos come from many natural sources over an energy range from 10^{-3} eV to more than 10^{18} eV

- Universe
- High energy astrophysical sources (fireballs, AGN,...)
- Supernovae
- Sun
- Cosmic ray interactions in the atmosphere
- Radioactive decay in the deep earth

Characterised by the low interaction cross section which makes them a pain to detect, but makes them the probe of choice for many sources, as they are not affected by stuff between the source and detector and can be used to point back to the source.

Neutrino Sources

Natural sources

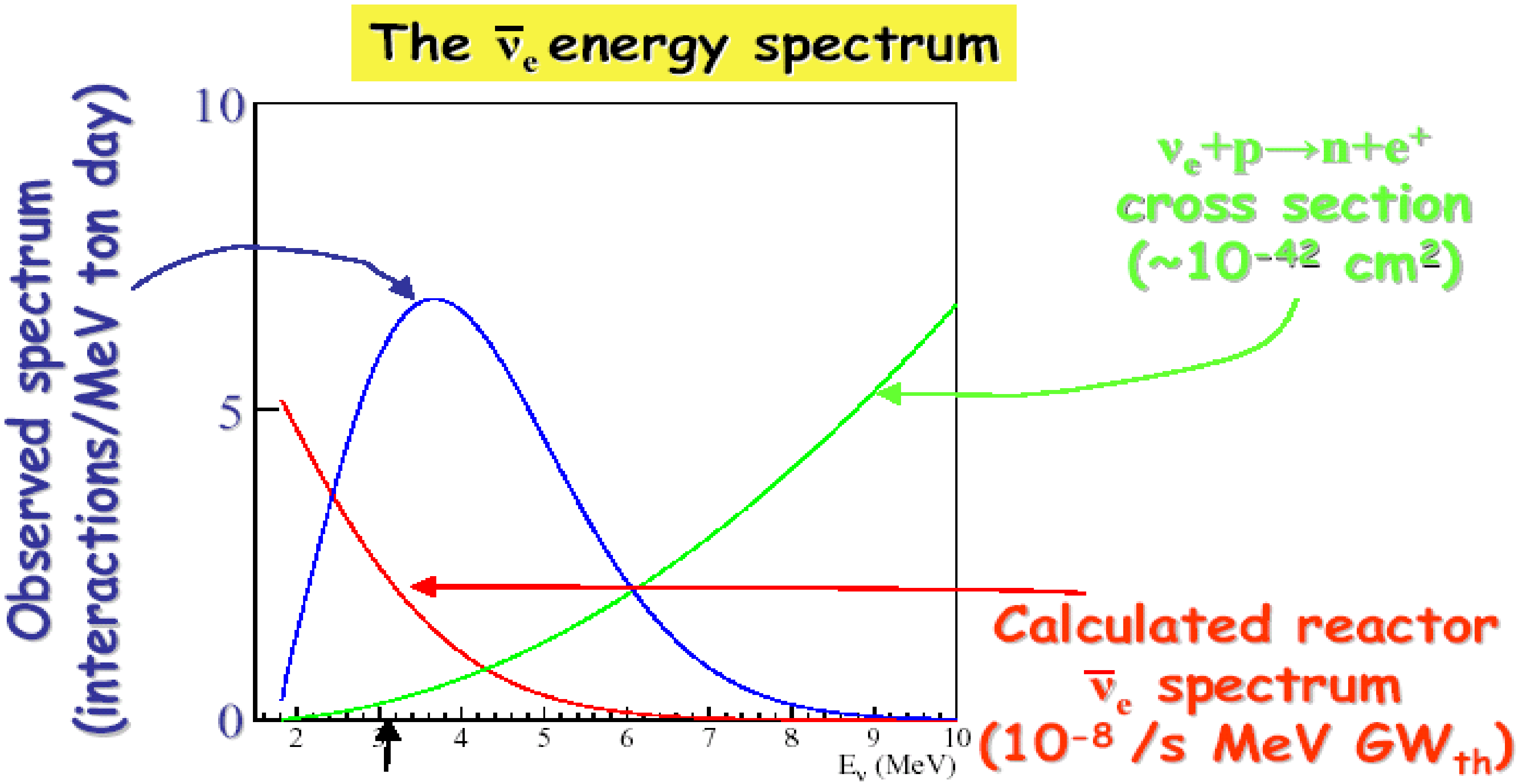
- Solar Neutrinos
- Atmospheric Neutrinos
- Supernova and Relics Neutrinos

Artificial sources

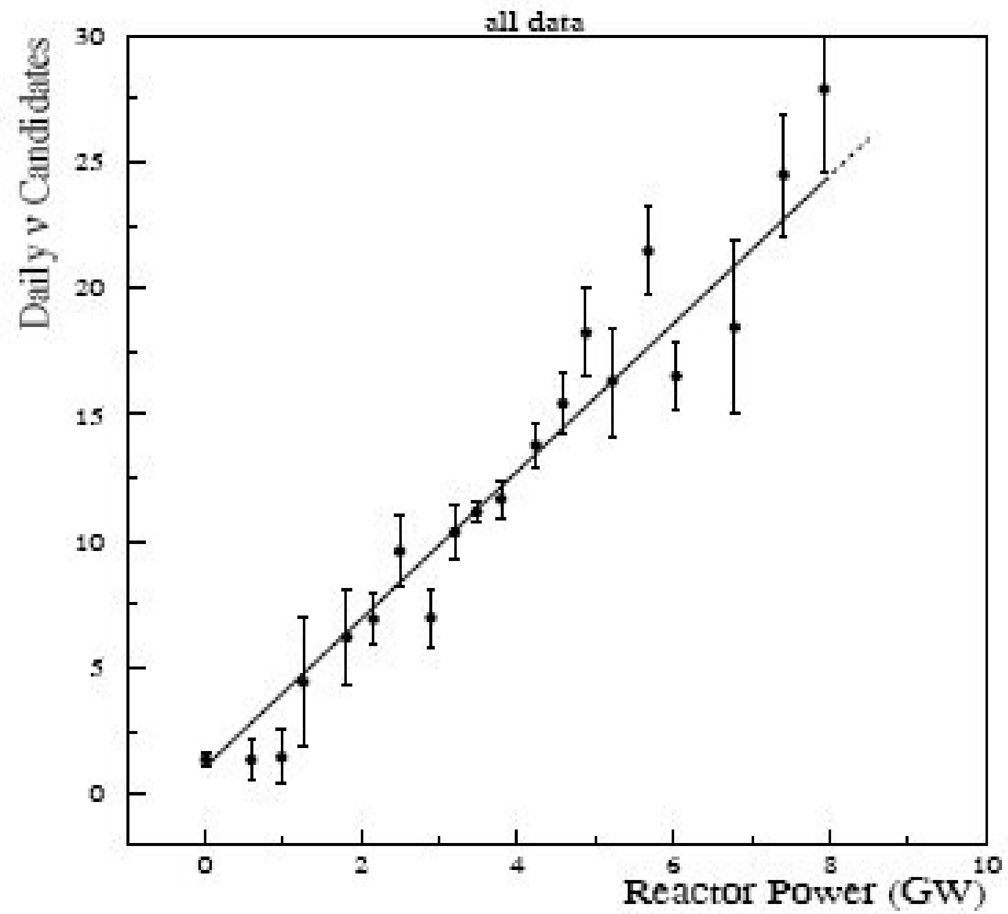
- Reactor Neutrinos
- Accelerator Neutrinos

Reactor Neutrinos

Nuclear reactors naturally produce electron anti-neutrinos through β decay with high fluxes (6×10^{20} ν/s)



Reactor Neutrinos



Advantages

- Absolute flux known to 1%
- 100% anti-ν_e source
- Event rate scales with reactor power (can turn reactor off and do background studies)

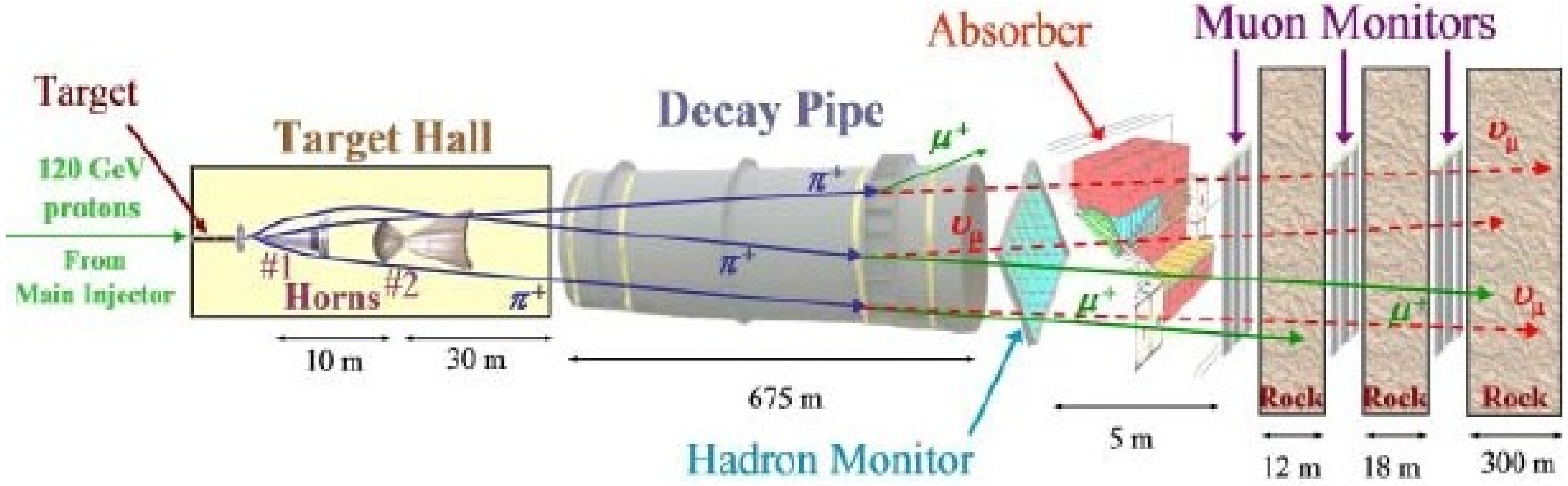
Disadvantages

- 100% anti-ν_e source
- Isotropic flux - event rate scales as $1/r^2$ from reactor

“..in an ordinary way I might say that I do not believe in neutrinos. Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos.”

Sir Arthur Eddington

How to make a neutrino beam



protons π/K μ,π,K,ν_e,ν_μ ν_μ,ν_e

- Each part of the beamline must be designed with many tradeoffs in mind
- Major uncertainty in beam is the production of π/K in p-target interactions
- Total flux uncertainties ~ 20%

Proton Beam

- Number of pions produced is roughly proportional to power of the proton beam (total number of protons on target (POT) times proton energy)
- The higher energy neutrino beam you want, the higher energy proton beam you need.

Source	p Energy (GeV)	p/year	Power (MW)	Neutrino Energy
KEK (Japan)	12	1.0E+20	0.01	1.4
FNAL Booster	8	5.0E+20	0.05	1
FNAL Main Injector	120	2.5E+20	0.25	3.0-17.0
CNGS (CERN)	400	4.5E+19	0.12	25
J-PARC (Japan)	40	1.1E+21	0.75	0.8

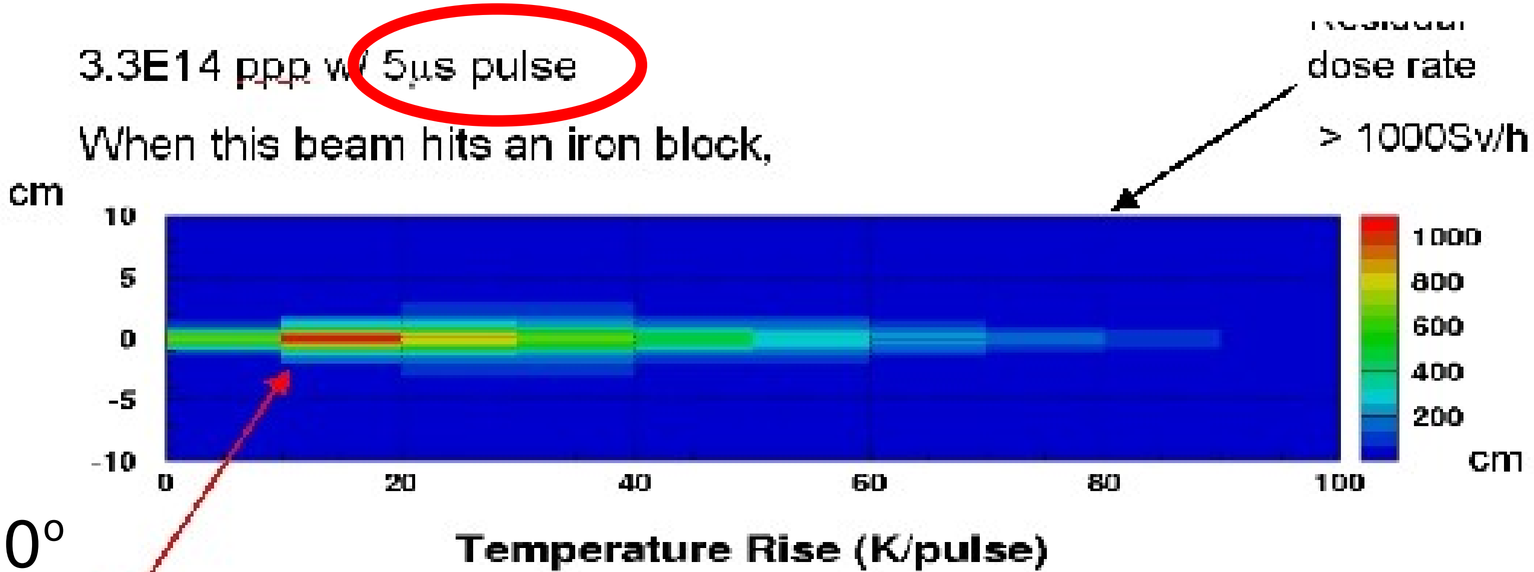
Targetry

Have to balance competing needs

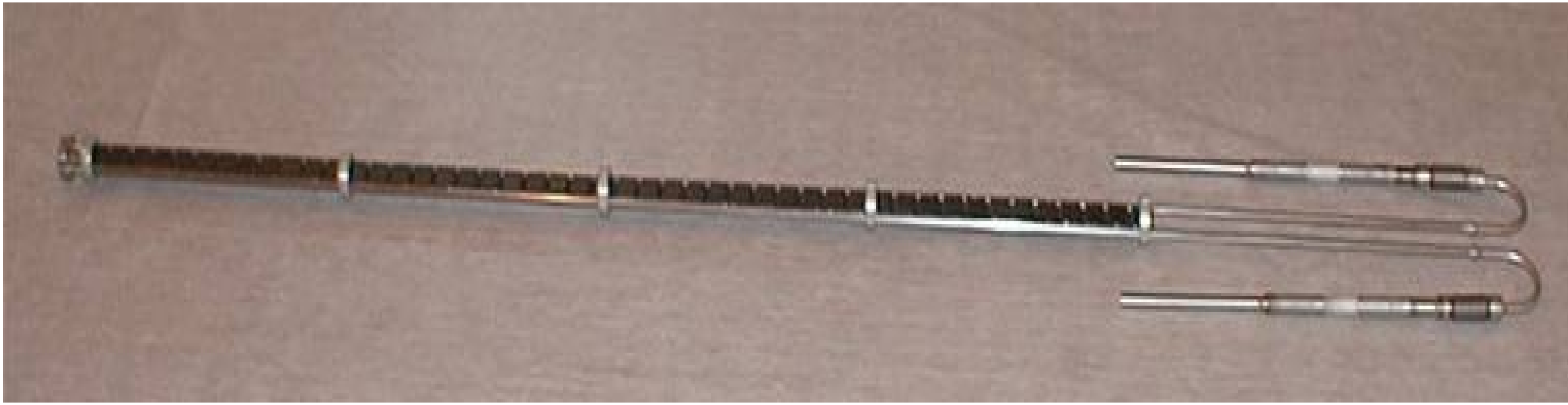
- The longer the target, the higher the probability that a proton will interact (good)
- But more secondary particles will scatter (bad)
- The more protons interact the hotter the target will get (bad)
- The wider the target the cooler it is but more material to scatter secondaries

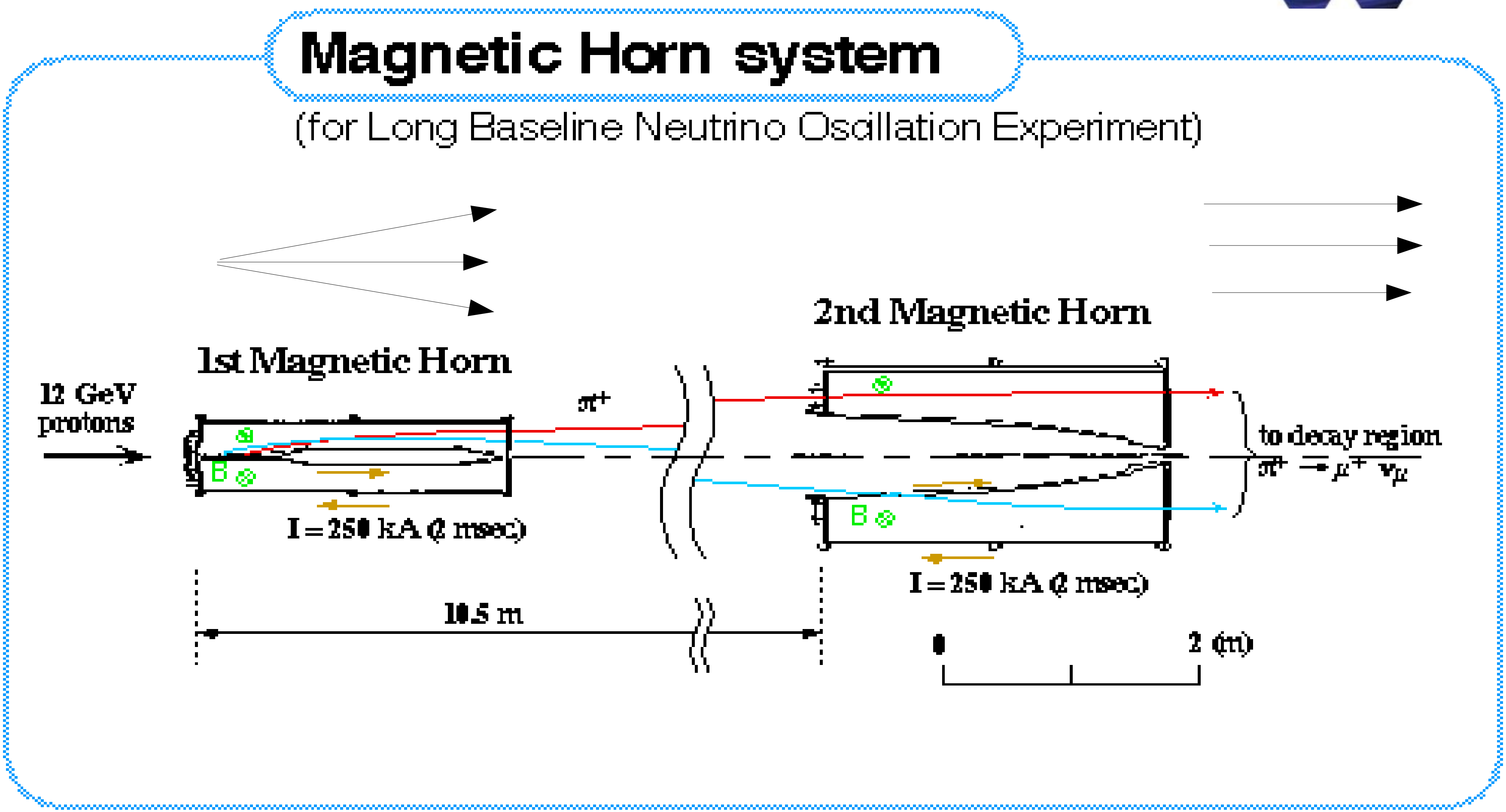
Low Z material (C, Be, Al) for heat properties
Usually around 50 cm to 1 m long
In small segments so that heating won't break the entire thing
Cooling systems needed (air, water, liquid helium)

Targetry



1100°

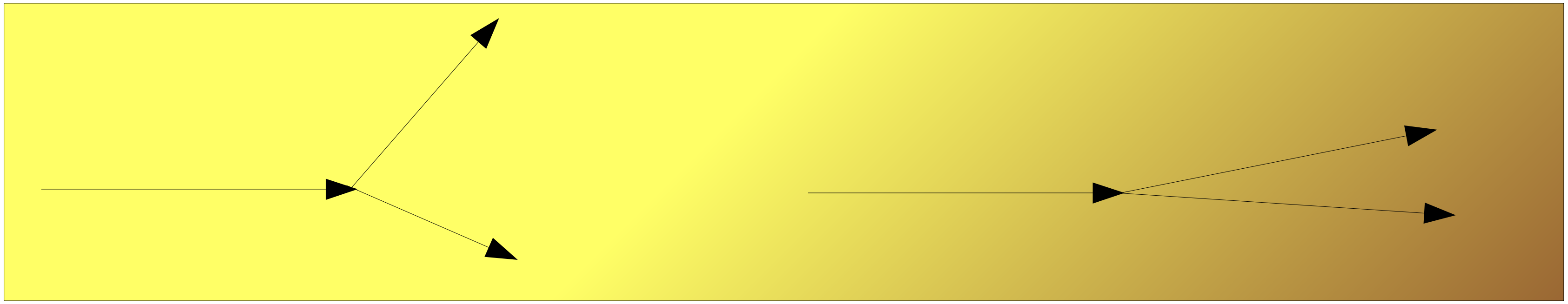




To give a 200 MeV transverse momentum kick to a pion requires a pulsed current of about 180 kA

Magnetic Horns

Decay Tunnel



Low Energy decays

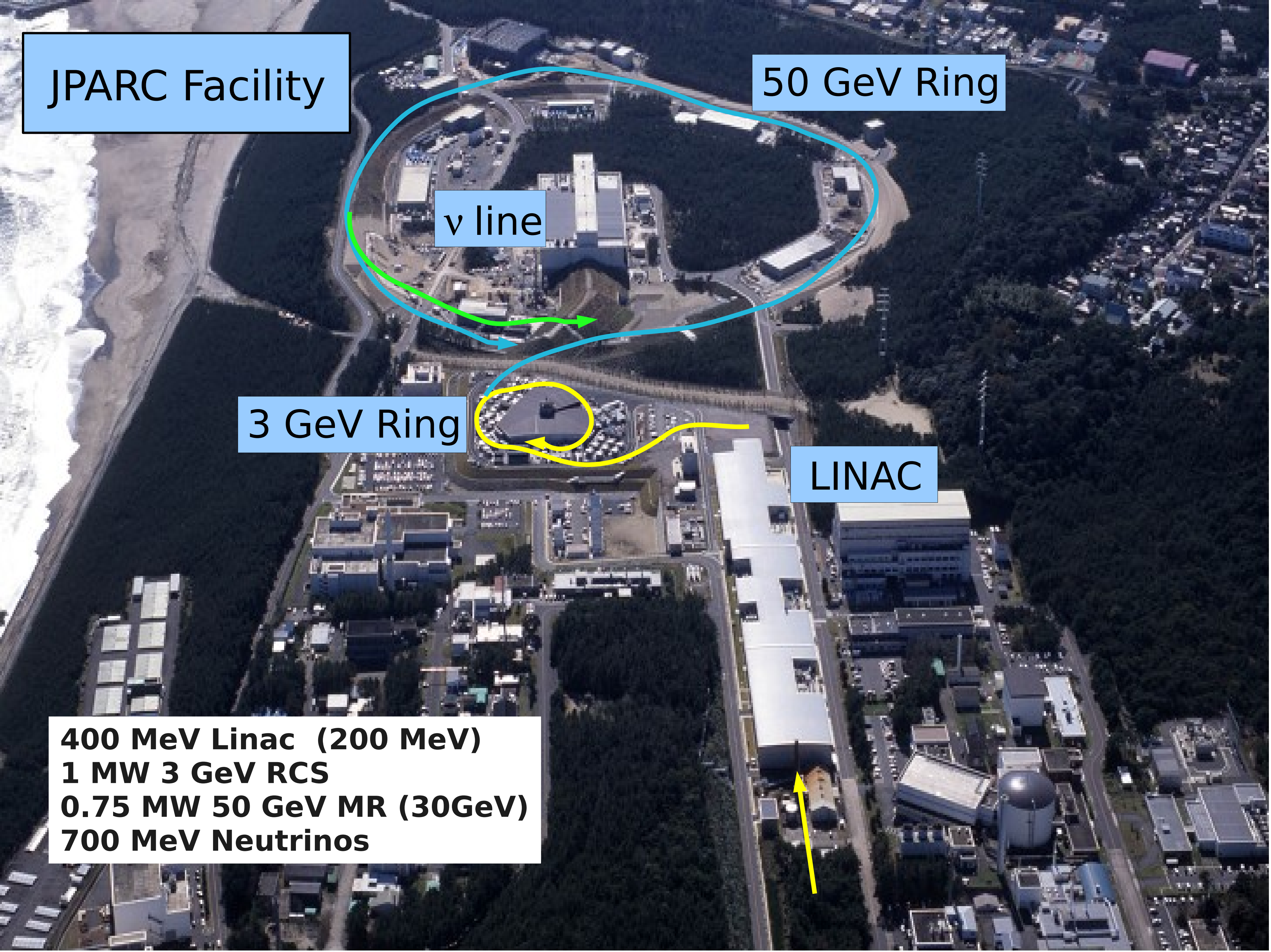
High Energy decays

$$P(\pi \rightarrow \nu\,\mu) = 1 - e^{-t/\gamma\tau} = 1 - e^{-L m_\pi / E_\pi \tau}$$

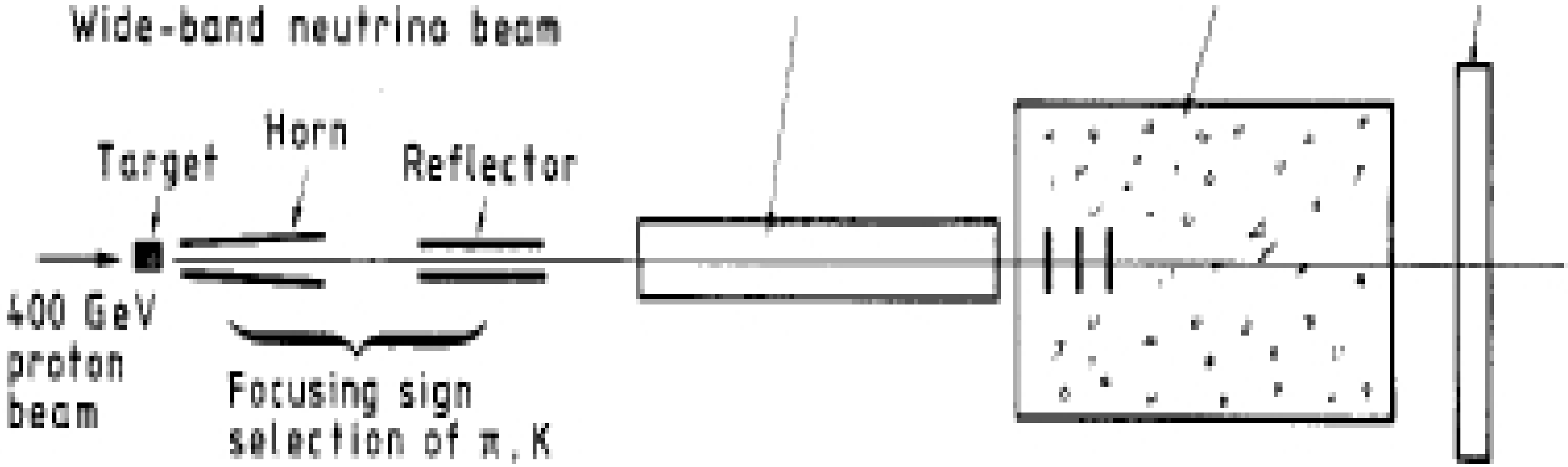
Shorter tunnel, less pion decays

Longer tunnel, more pion decays, but muons decay to ν_e as well

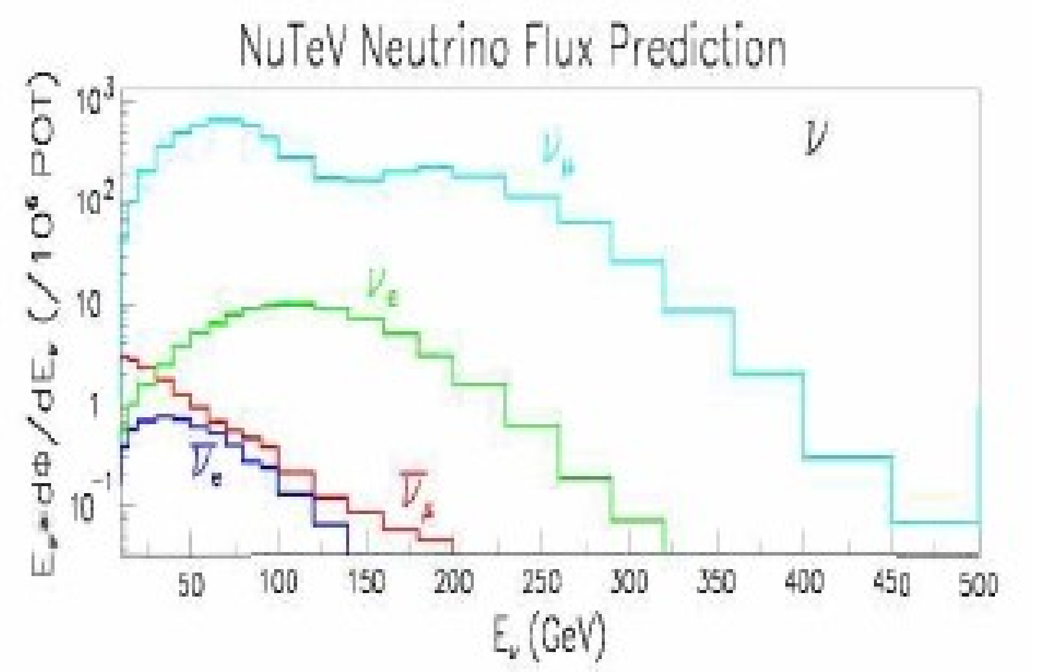
Vacuum? Then more material is needed to hold it. Air? Less material but interactions in decay pipe.


JPARC Facility
50 GeV Ring
ν line
3 GeV Ring
LINAC
400 MeV Linac (200 MeV)
1 MW 3 GeV RCS
0.75 MW 50 GeV MR (30GeV)
700 MeV Neutrinos

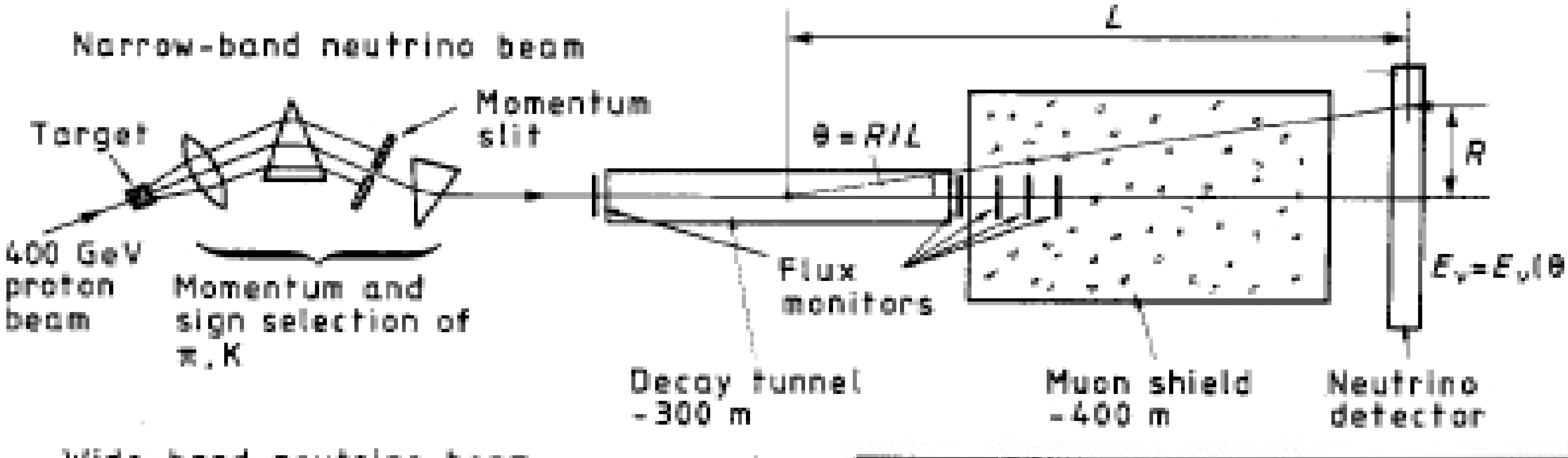
Wide band beams



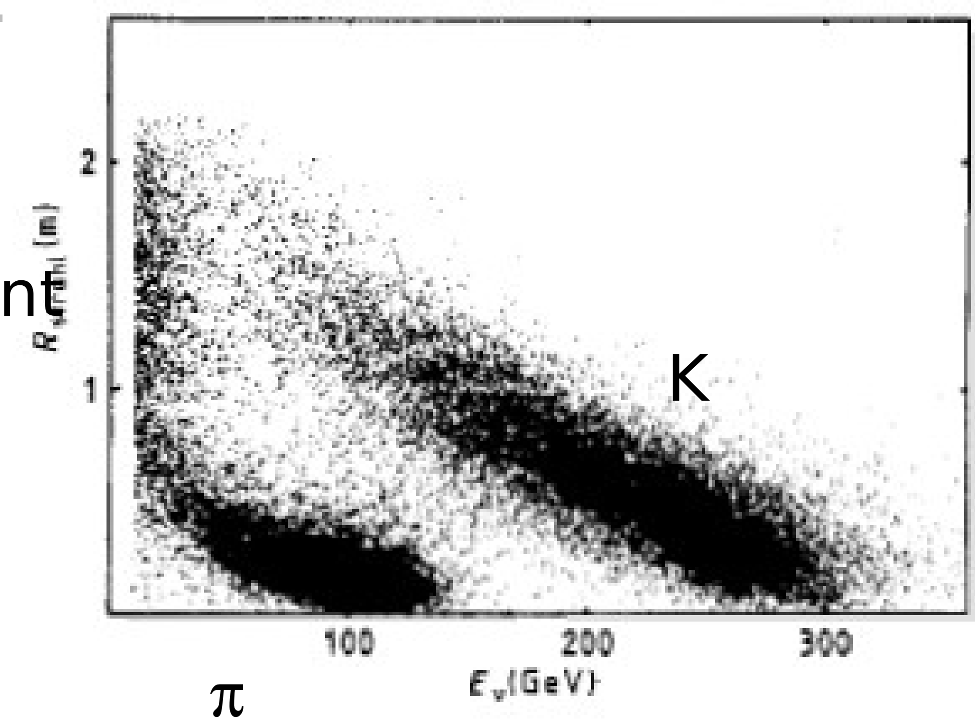
Large flux of neutrinos
Very hard to predict
(and measure) neutrino flux
Spectrum is a function
radius and decay point



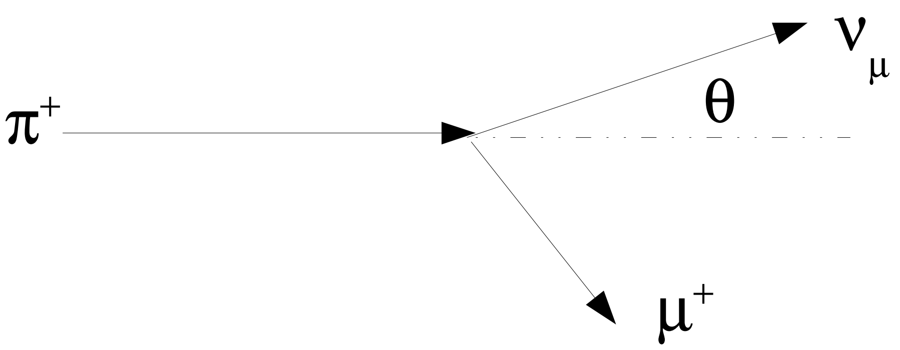
Narrow Band Beams



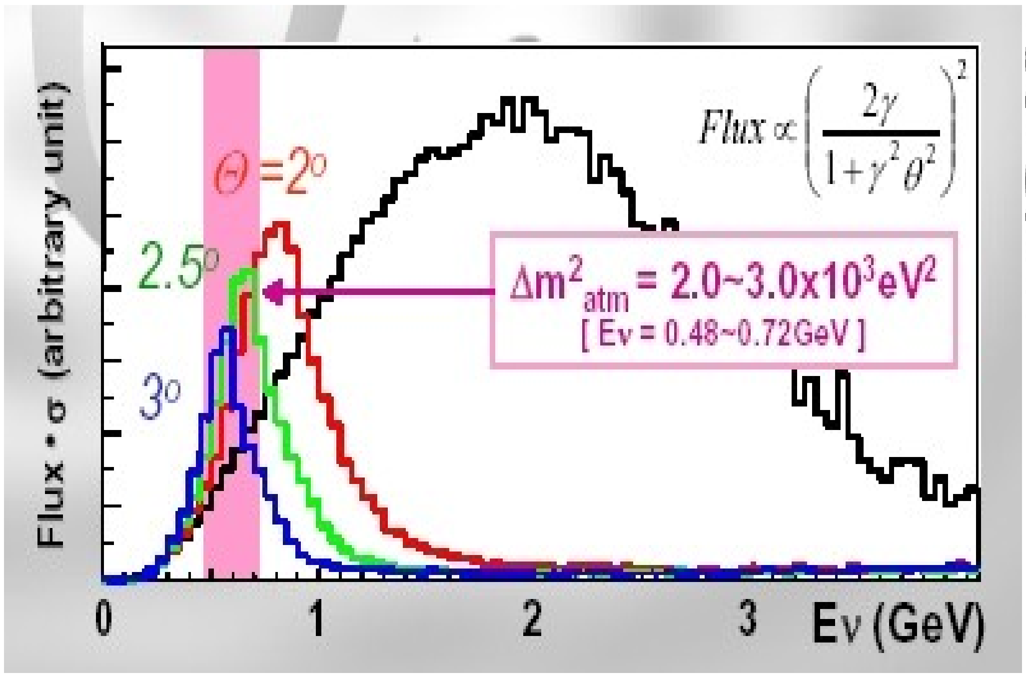
Flat flux (easy to predict)
Beam can be tuned to different energies
flux is 100 times lower than WBB

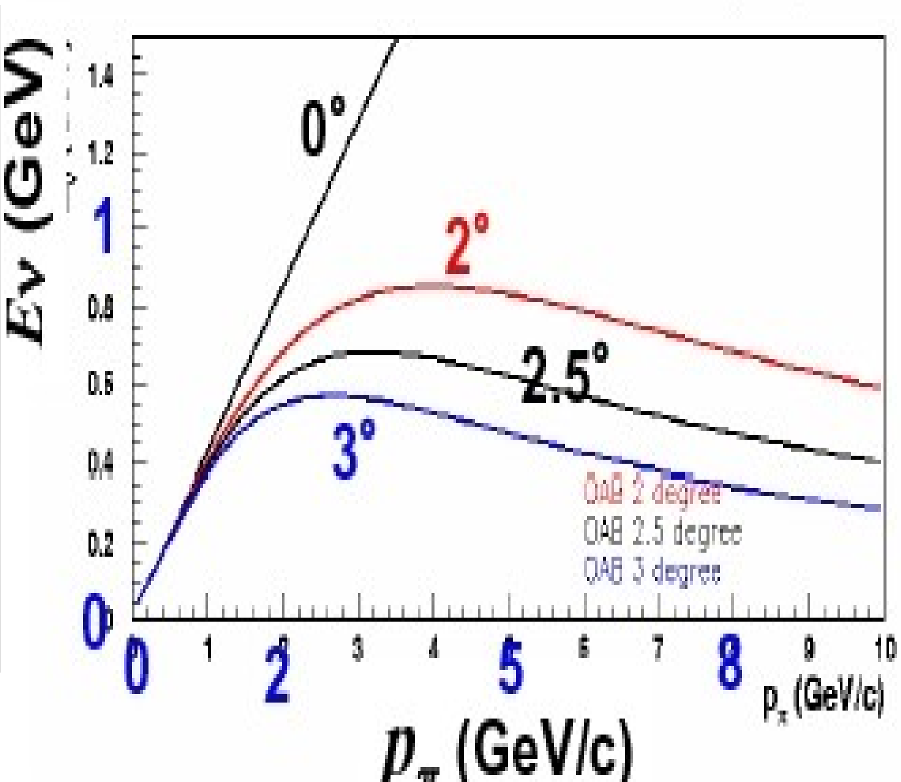


New idea : Off-axis beams

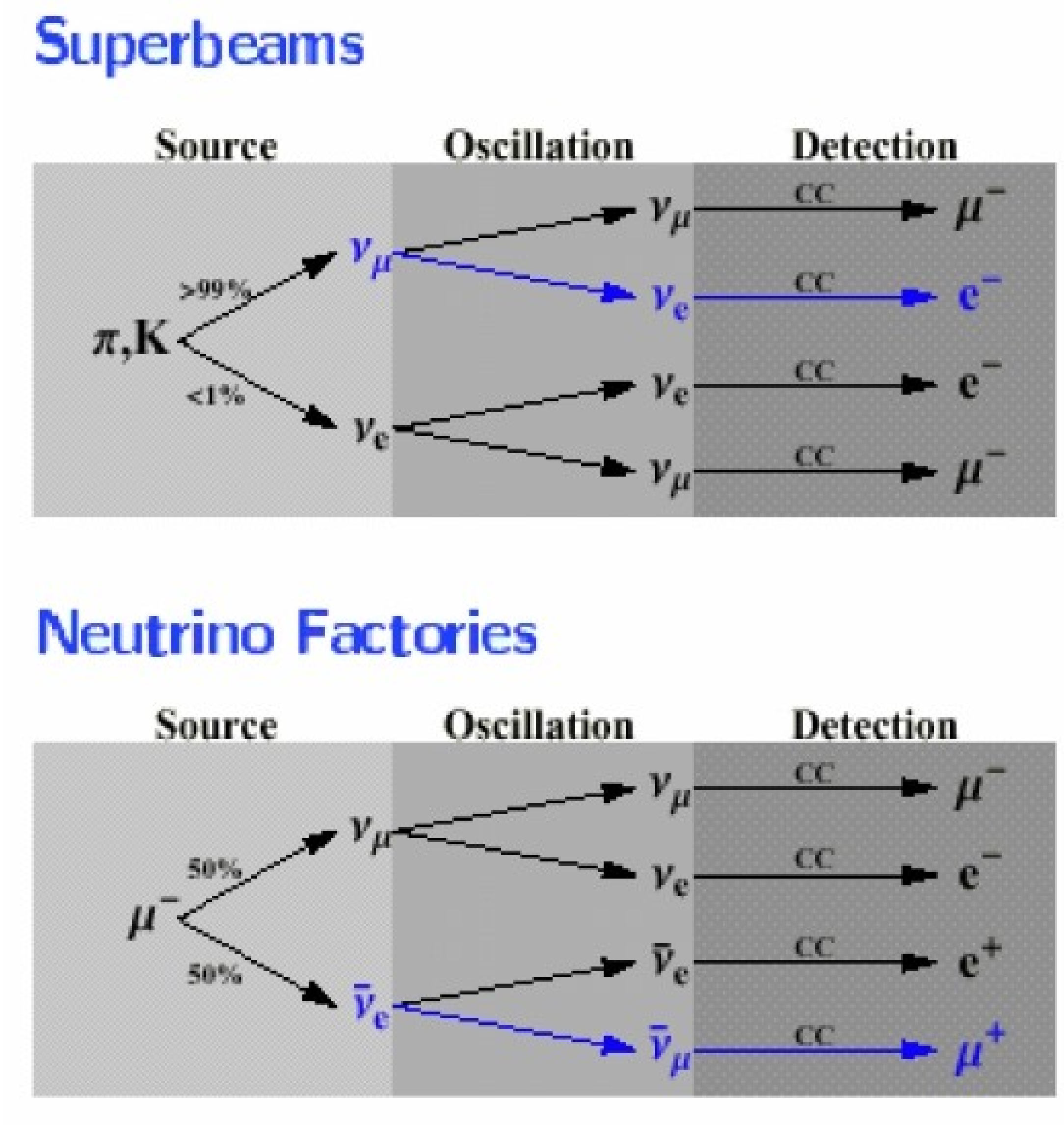


$$E_\nu = \frac{0.43\,E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = \frac{E_\pi}{m_\pi}$$





Future Neutrino Beams



Supersized, high power conventional proton beams

Extremely high intensity well-understood beams
A new type of accelerator