Neutrinos in Particle and Astroparticle Physics: An Overview

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Astroteilchenphysik in Deutschland:
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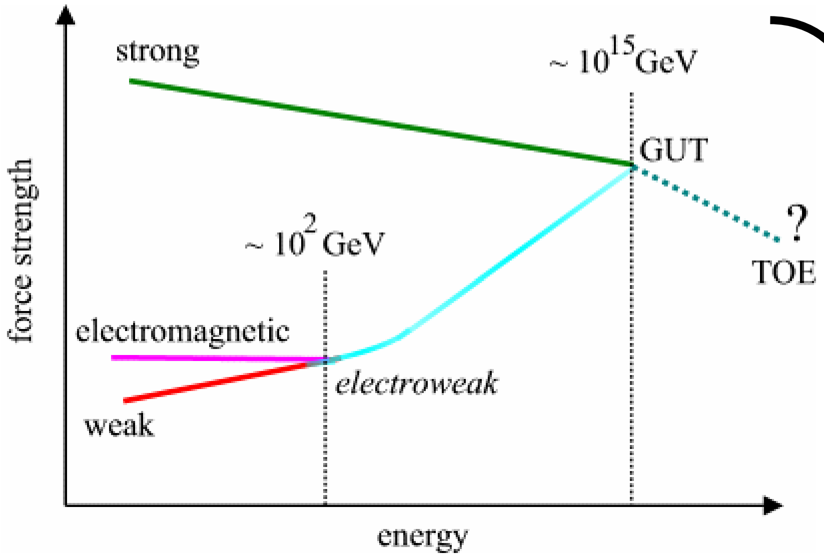
Motivation: Physics Beyond the SM

gauge bosons →



Higgs →

gauge hierarchy problem

$\delta m_H^2 \sim \Lambda^2$

quarks leptons →

3 generations, fermion rep.

many parameters (m_i ,mixings)

unification into GUTs

$m_\nu = (m^D)^T M_R^{-1} m_D$

experimental facts:

Dark Matter

Dark Energy

neutrino masses

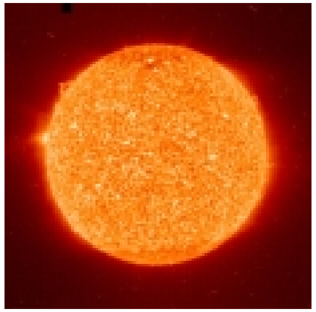
baryon asymetry: $m_\nu > 0$

SUSY ~TeV

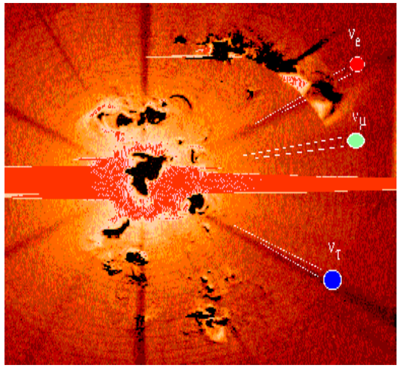
$\sim\Lambda_{GUT}$ +seesaw

astrophysics & cosmology

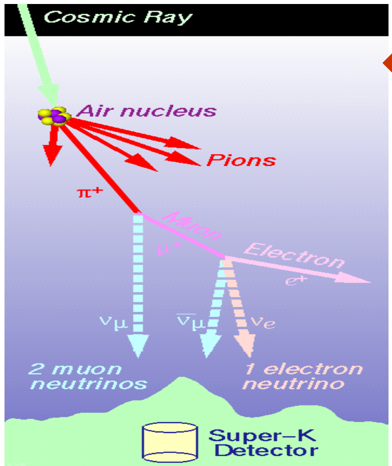
Motivation: Neutrino Sources



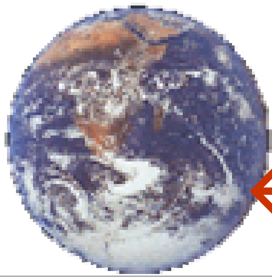
← **Sun**



← **Cosmology**

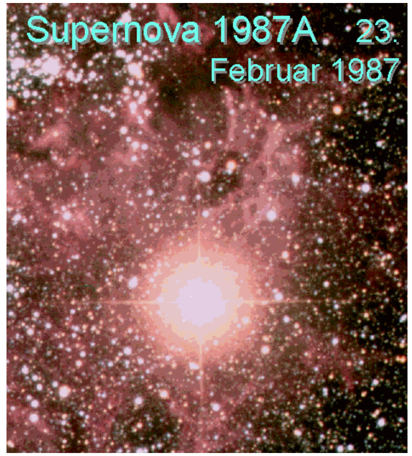


← **Atmosphere**



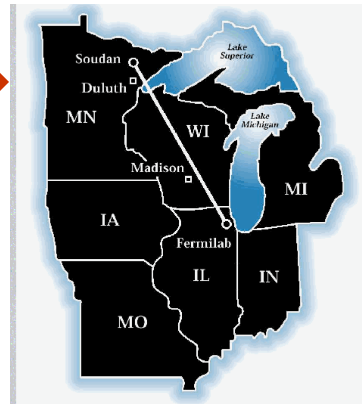
← **Earth**

Astronomy: →
Supernovae
GRBs
UHE ν's



Reactors →

Accelerators →



Four Methods of Mass Determination

- kinematical
- lepton number violation
  ←→ Majorana nature
- oscillations
- astrophysics & cosmology

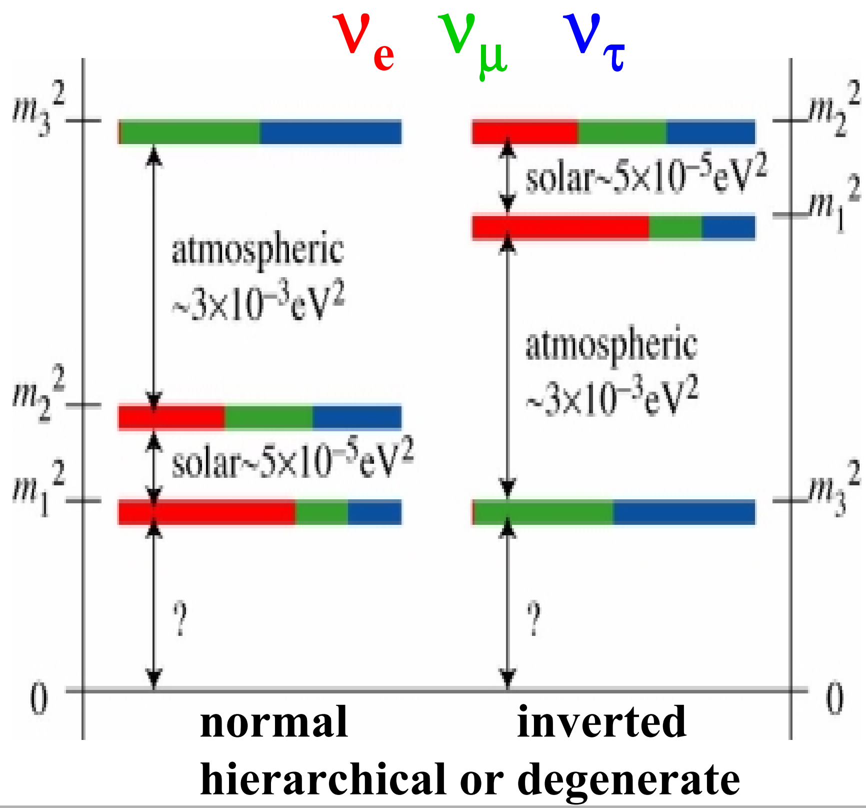
Parameters for 3 Light Neutrinos

mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

particle physics questions:

- ➔ Dirac or Majorana
- ➔ absolute mass scale: m_1
- ➔ mass ordering: sgn(Δm^2_{31})
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ LSND ←➔ sterile neutrino(s)
- ➔ L/E pattern of oscillations



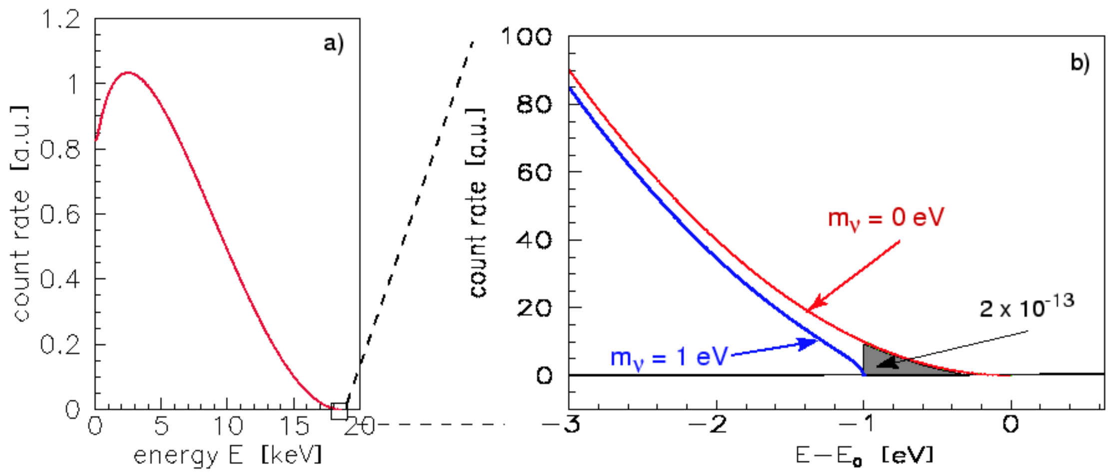
Kinematical Mass Determination

Relativistic kinematics:

$$E^2 = p^2 + m^2; \ \sum p_i^\mu = \sum p_f^\mu$$

Endpoint of decays:

Tritium $\longrightarrow He^3 + e^- + \overline{\nu}_e$



Bounds:

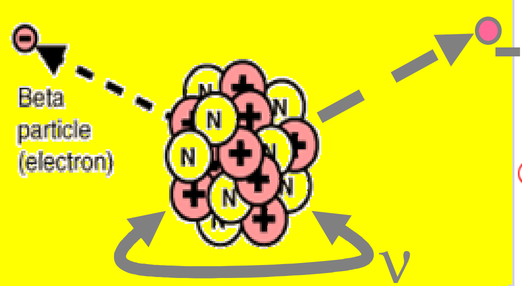
"Elektron-Neutrino":	$m < 2.2$ eV	(Mainz, Troitsk)
"Muon-Neutrino":	$m < 170$ keV	
"Tau-Neutrino":	$m < 15.5$ MeV	

Sensitivity $\Leftrightarrow$ **degenerate ν-spectrum**

$\Rightarrow$ **Oscillations:** $\Delta m_{ij}^2 \ll m_i^2 \Rightarrow$ $\sum m_i^2 |U_{ei}|^2 < (2.2 \text{ eV})^2$

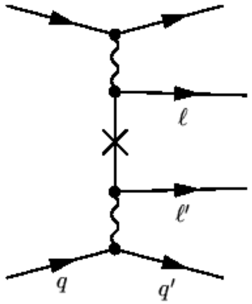
Future: KATRIN ➔ 0.25 eV ➔ ? ⇔ c.f. comological bounds

Neutrino-less Double β-Decay



Majorana ν ➔ 0ν2β decay

$\propto$

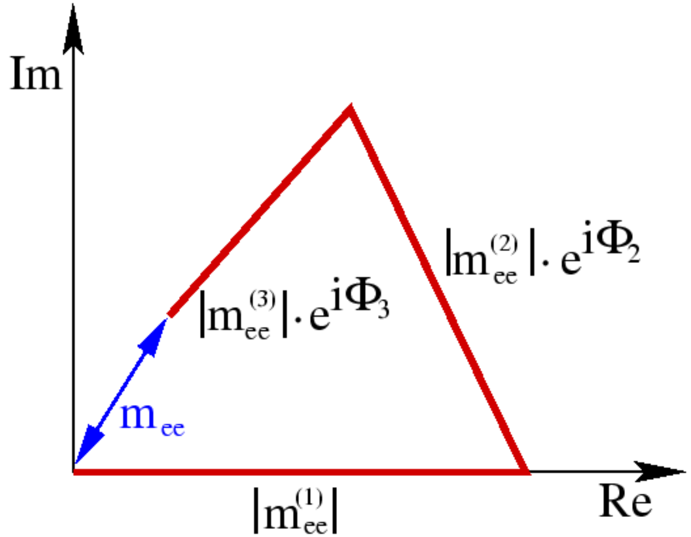


$\propto |\langle \mathbf{m_{ee}} \rangle| \;=\; |\sum \mathbf{m_i U_{ei}^2}|$ **$\leq$ 0.35 eV ?**

Heidelberg-Moscow experiment

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$
$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ free parameters: m_1 , sign(Δm^2_{31}) , CP-phases Φ_2, Φ_3

$m_1 \rightarrow$ small $\rightarrow m_{ee}$ =const. ~ $(\Delta m_{ij}^2)^{1/2}$ $\leftrightarrow$ sign(Δm^2_{31})

m_1 large $\rightarrow m_{ee} \sim m_1$

cosmological bound on m_1

claim ➔ ‚tension'

new experiments:
CUORICINO, GERDA ➔
CUORE, Majorana, …
aim: $(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV

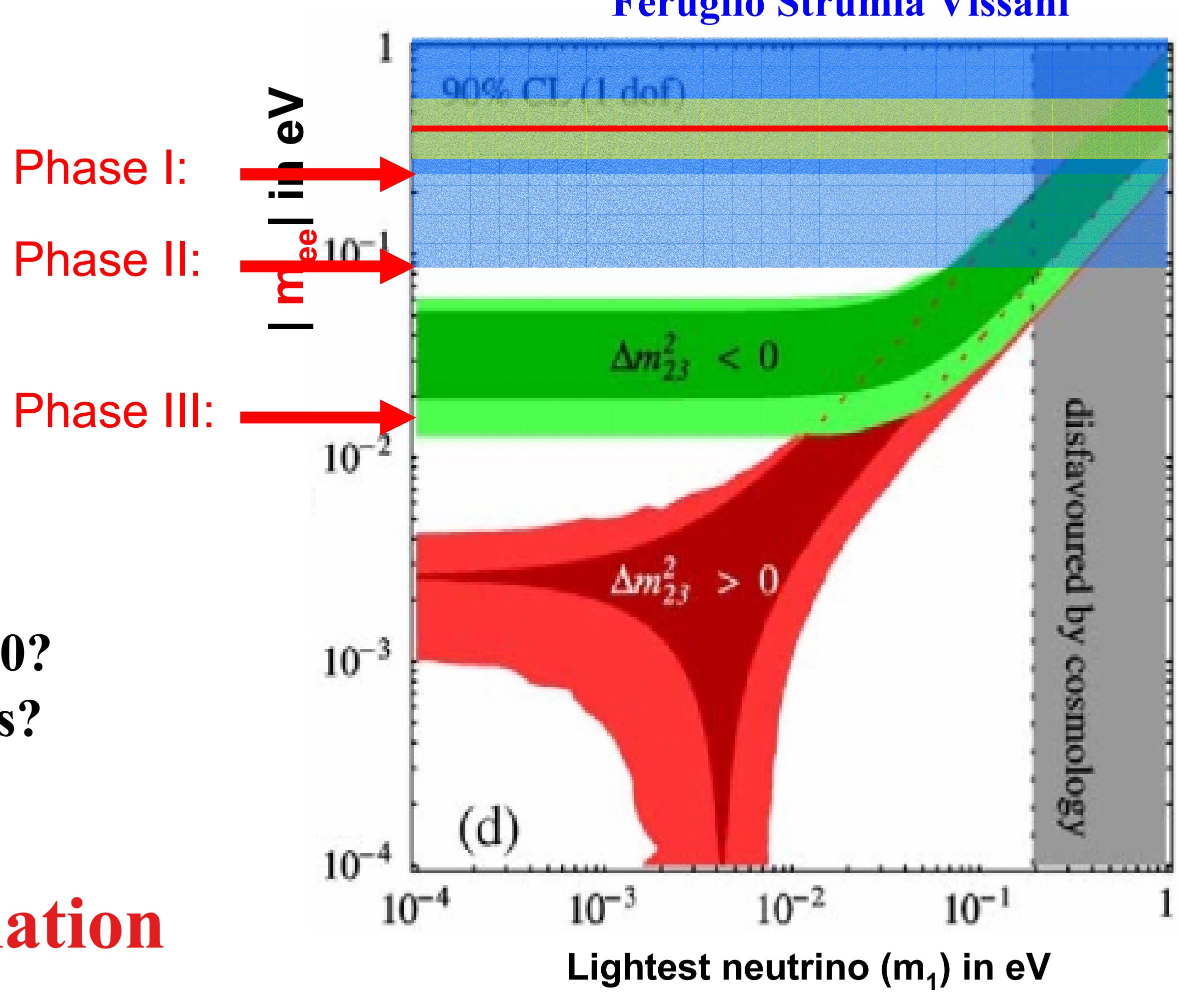
Cosmology: syst. errors ➔ X10?

$0\nu2\beta$ – nuclear matrix elements?

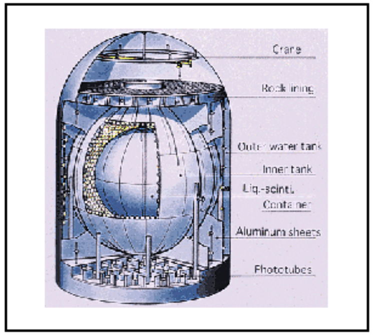
theory: LR, RPV-SUSY, ...

➔ lepton number violation

Feruglio Strumia Vissani



Neutrino Oscillation Signals

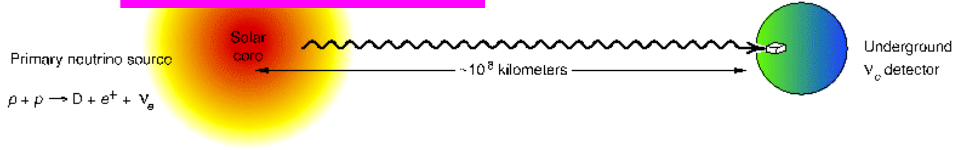


Reactors: KAMLAND

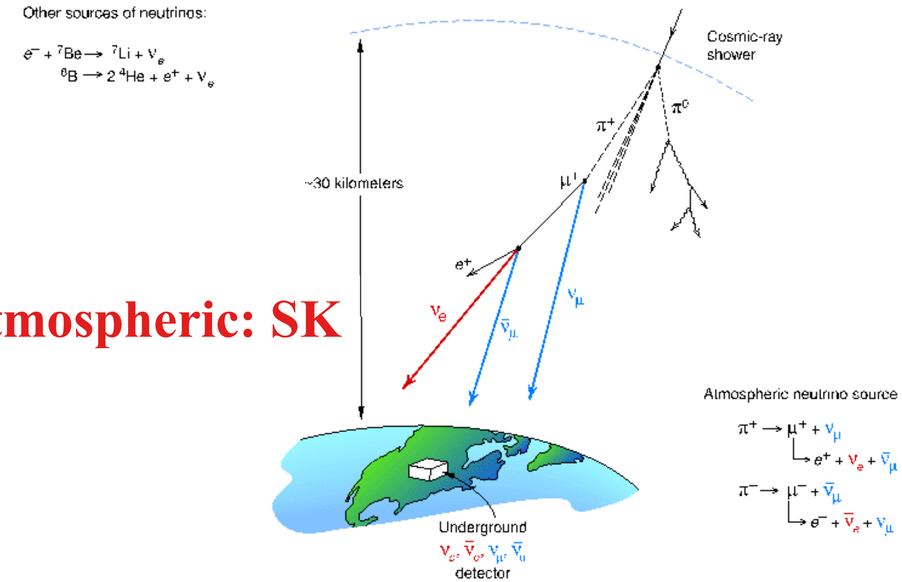
Beams: K2K, MINOS,
➔ ICARUS, OPERA

$\Delta m^2_{21} = (8.2 \pm 0.3) * 10^{-5}\ eV^2$
$\tan^2\theta_{12} = 0.39 \pm 0.05$
$\Delta m^2_{31} = (2.2 \pm 0.6) * 10^{-3}\ eV^2$
$\tan^2\theta_{23} = 1.0 \pm 0.3$
$\sin^2 2\theta_{13} < 0.16$

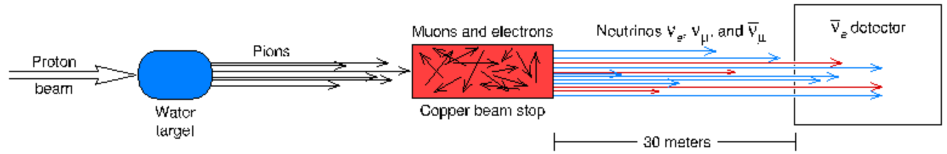
solar: GALLEX/GNO ➔ SK, SNO



atmospheric: SK



LSND? ➔ MiniBooNE

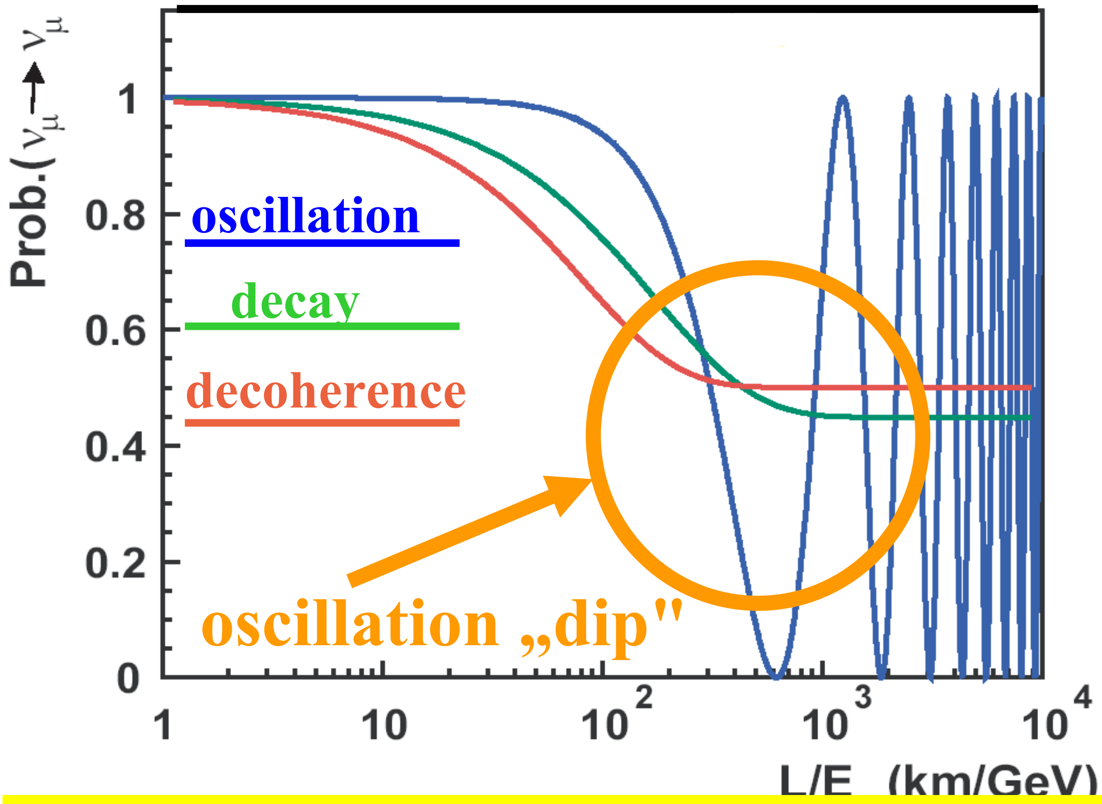


L/E Dependence

Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E}))$

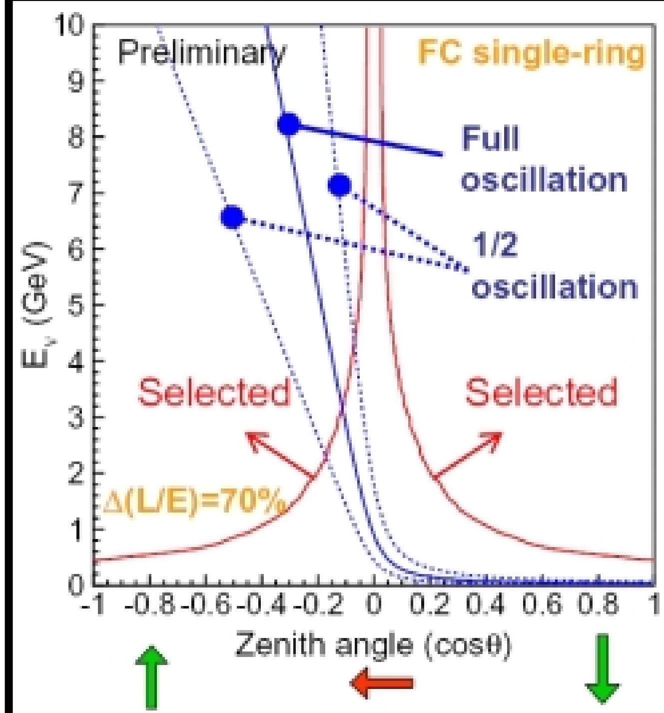


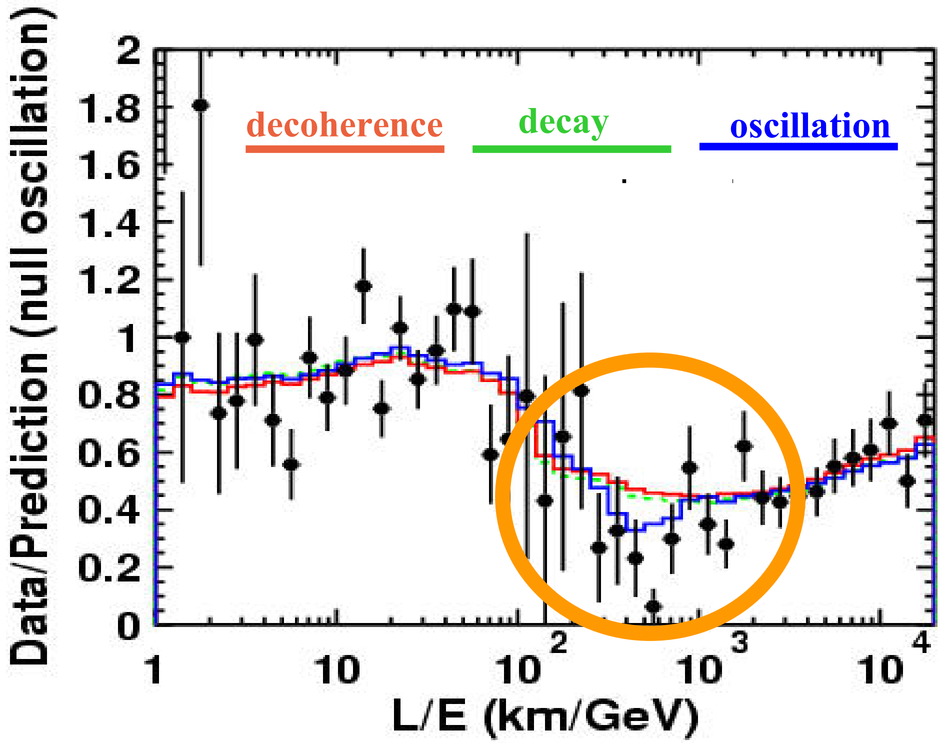
However: L/E dependence smeared out!

Bad L/E resolution:

- **horizontal events**
- **events with small E**

➔ cuts in E-cosθ plane





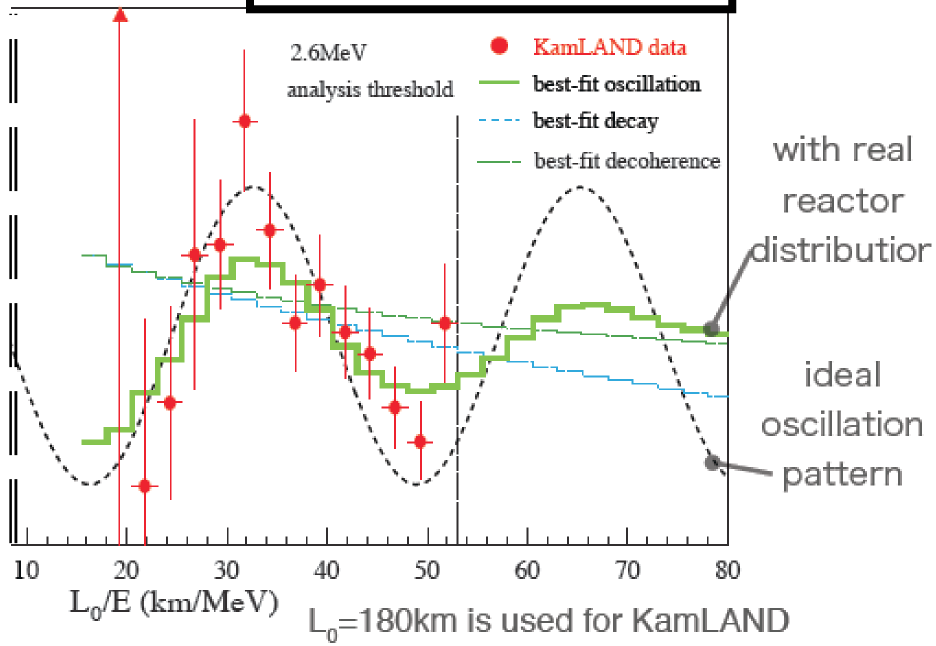
SK Result:

- 3,4σ for decay
- 3,8σ for de-coherence
- $\Delta m^2 = 2.4\ 10^{-3} eV^2$

←→long baseline exp.

SK II data
SK I similar

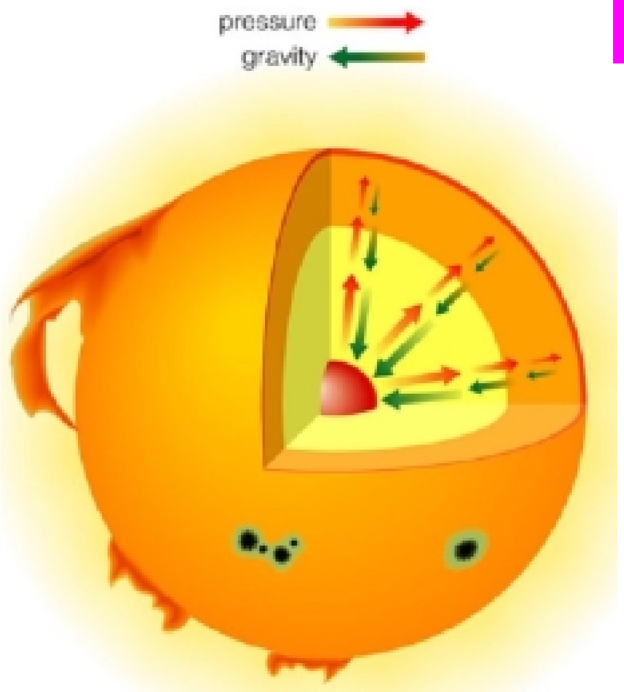
KamLAND L/E



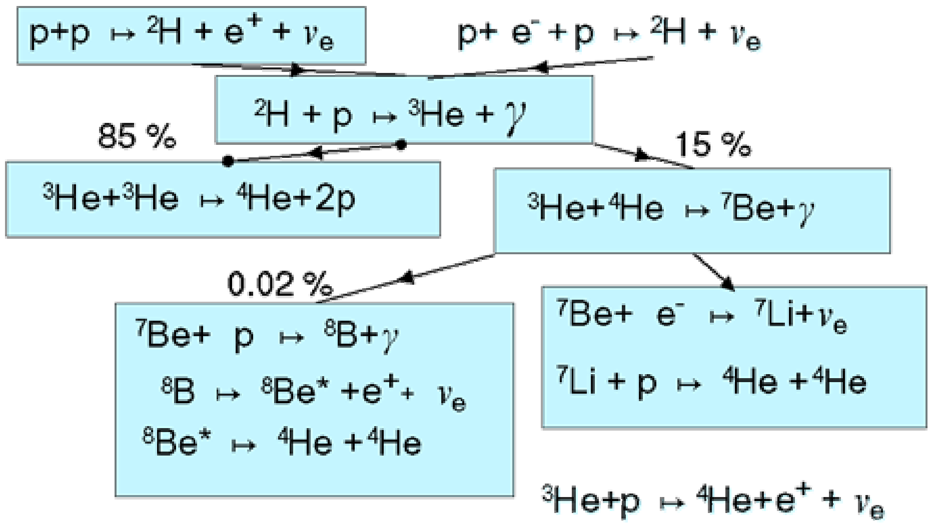
Solar Neutrinos: Learning About the Sun

Observables:

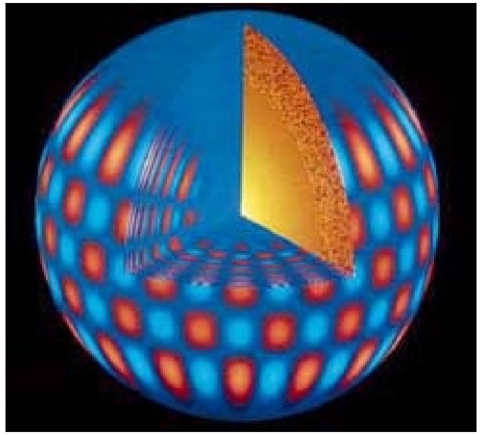
- **optical** (total energy, surface dynamics, sun-spots, historical records, B, ...)
- **neutrinos** (rates, spectrum, ...)



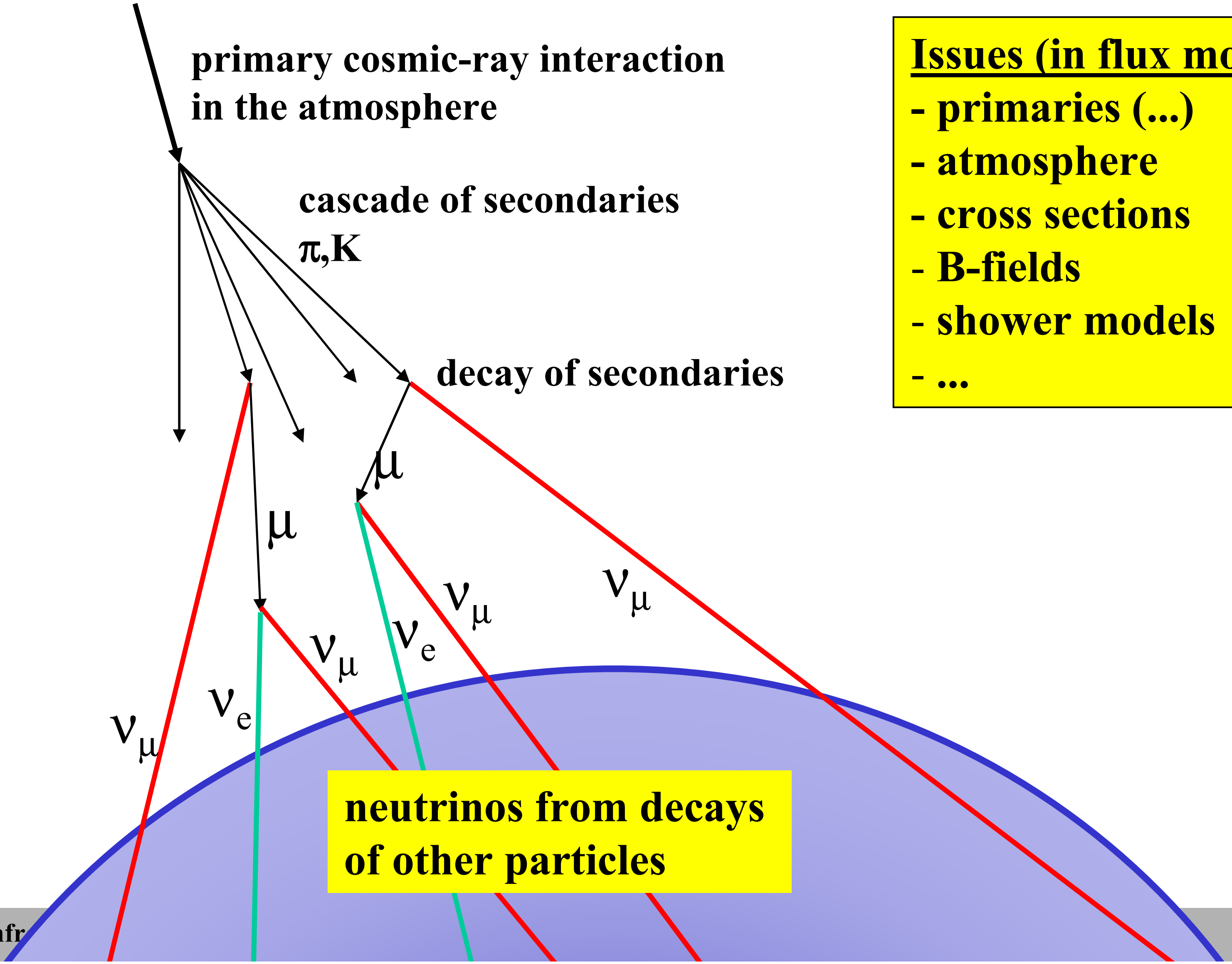
BOREXINO



Topics:
- **nuclear cross sections**
- **solar dynamics**
- **helio-seismology**
- **variability**
- **composition**



Learning from Atmospheric Neutrinos



Issues (in flux models):
- primaries (...)
- atmosphere
- cross sections
- B-fields
- shower models
- ...

The Future of Oscillation Physics

<u>Δm^2 and θ_{ij} regions</u> ➔ improved oscillation experiments
➔ controlled sources & detectors

➔ long baseline experiments with neutrino beams
➔ reactor experiments with identical near & far detector

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\theta_{12}}$$

x Majorana-CP-phases

S_{13} ➔ 3 flavour effects
➔ CP phase δ

matter effects

<u>Aims:</u> ➔ improved precision of the leading 2x2 oscillations
➔ detection of generic 3-neutrino effects: θ_{13}, CP violation

➔ precision neutrino physics

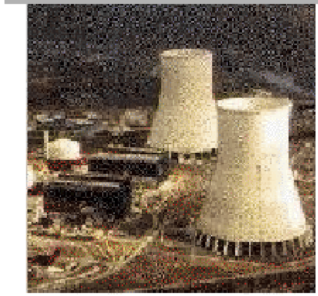
New Neutrino Beams

- **conventional beams, superbeams**
  ➔ MINOS, CNGS: OPERA ICARUS, T2K, NOνA, T2H,…
- **β-beams**
  ➔ pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \gtrsim 100$
- **neutrino factories**
  ➔ clean neutrino beams from decay of stored μ's

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\ & \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \cos\delta_{CP}\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

↳ **correlations & degeneracies**

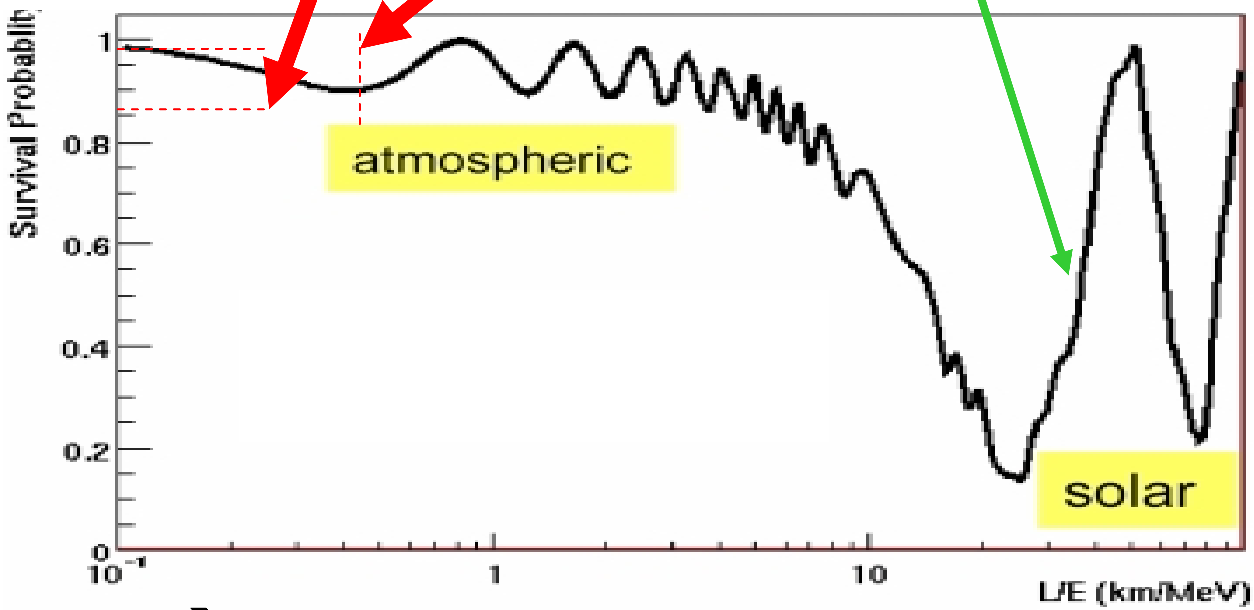
New Reactor Experiments



$\overline{\nu}_e \Rightarrow$ **near detector** (170m) $\overline{\nu}_e \Rightarrow$ **far detector** (1700m)

identical detectors ➔ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

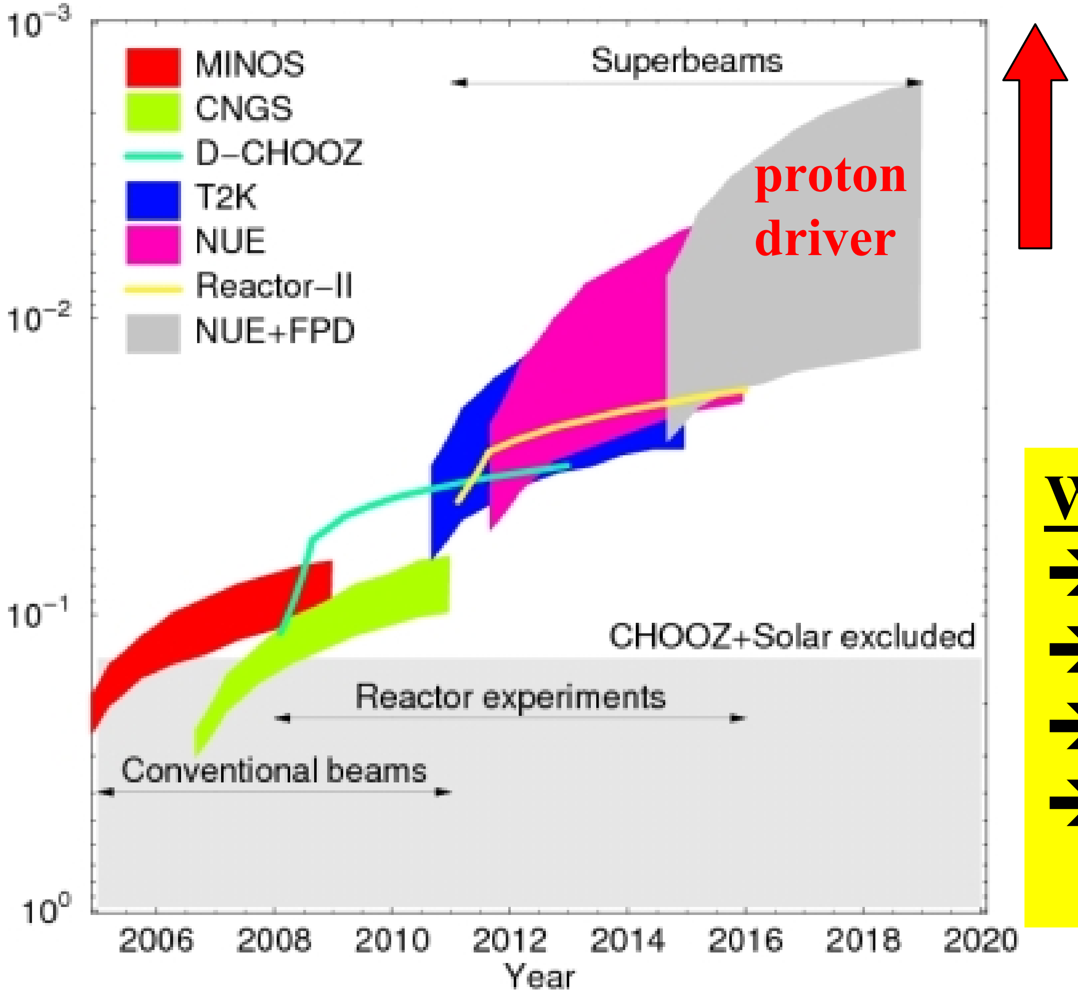


E=4MeV ➔ 2km 4km 40km 80km

- **➔ Double Chooz**
- **➔ KASKA**
- **➔ Braidwood**
- **➔ Angra, …**

no degeneracies
no correlations
no matter effects

Sensitivity Versus Time



$\sin^2 2\theta_{13}$ sensitivity versus time

- β-beam
- neutrino factory

What is precision good for?

➔ unique flavour information

➔ tests theories of flavour

➔ history: elimination of SMA

➔ find leptonic CP violation

⇐⇒ baryon asymmetry

The Value of Precision for θ_{13}

- **models for masses & mixings**
- **input: Known masses & mixings**
  ➔ **distribution of θ_{13} „predictions“**

- **θ_{13} often close to experimental bounds**
  ➔ **motivates new experiments**
  ➔ **θ_{13} controls 3-flavour effects like leptonic CP-violation**

for example: $\sin^2 2\theta_{13} < 0.01$ ➔

physics question: why is θ_{13} so small ?

→ **numerical coincidence**

→ **symmetry**

⇔ **precision!**

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
~~*SO(10)*~~		
Goh, Mohapatra, Ng [40]	0.18	0.13
~~*Orbifold SO(10)*~~		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
~~Blazek, Raby, Tobe [43]~~	~~0.05~~	~~0.01~~
Kitano, Mimura [44]	0.22	0.18
~~Albright, Barr [45]~~	~~0.014~~	~~$7.8 \cdot 10^{-4}$~~
~~Maekawa [46]~~	~~0.22~~	~~0.18~~
~~Ross, Velasco-Sevilla [47]~~	~~0.07~~	~~0.02~~
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
~~*SO(10) + texture*~~		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
~~Grimus, Lavoura [52, 53]~~	~~0~~	~~0~~
~~Grimus, Lavoura [52]~~	~~0.3~~	~~0.3~~
~~Babu, Ma, Valle [54]~~	~~0.14~~	~~0.08~~
~~Kuchimanchi, Mohapatra [55]~~	~~0.08 .. 0.4~~	~~0.03 .. 0.5~~
~~Ohlsson, Seidl [56]~~	~~0.07 .. 0.14~~	~~0.02 .. 0.08~~
King, Ross [57]	0.2	0.15
~~*Textures*~~		
~~Honda, Kaneko, Tanimoto [58]~~	~~0.08 .. 0.20~~	~~0.03 .. 0.15~~
Lebed, Martin [59]	0.1	0.04
~~Bando, Kaneko, Obara, Tanimoto [60]~~	~~0.01 .. 0.05~~	~~$4 \cdot 10^{-4}$ .. 0.01~~
Ibarra, Ross [61]	0.2	0.15
3 × 2 see-saw		
~~Appelquist, Piai, Shrock [62, 63]~~	~~0.05~~	~~0.01~~
~~Frampton, Glashow, Yanagida [64]~~	~~0.1~~	~~0.04~~
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
~~*Anarchy*~~		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
~~*Renormalization group enhancement*~~		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Further Implications of Precision

Precision allows to identify / exclude:

- special angles: $\theta_{13} = 0°$, $\theta_{23} = 45°$, ... ⇔ discrete f. symmetries?
- special relations: $\theta_{12} + \theta_C = 45°$? ⇔ quark-lepton relation?
- quantum corrections ⇔ renormalization group evolution

Provides also measurements or tests of:

- MSW effect (coherent forward scattering and matter profiles)
- cross sections
- 3 neutrino unitarity ⇔ sterile neutrinos with small mixings
- neutrino decay (admixture…)
- decoherence
- NSI
- MVN, ...

The Interplay of Topics

SM extensions: SUSY, …
flavour symmetries
unification
fundamental interactions
CPT & Lorentz inv.
extra dimensions
…

leptogenesis
supernovae
BBN
structure formation,
UHE neutrinos
dark matter & energy
...

<u>neutrino properties:</u>
masses, mixings,
CP-phases, ...

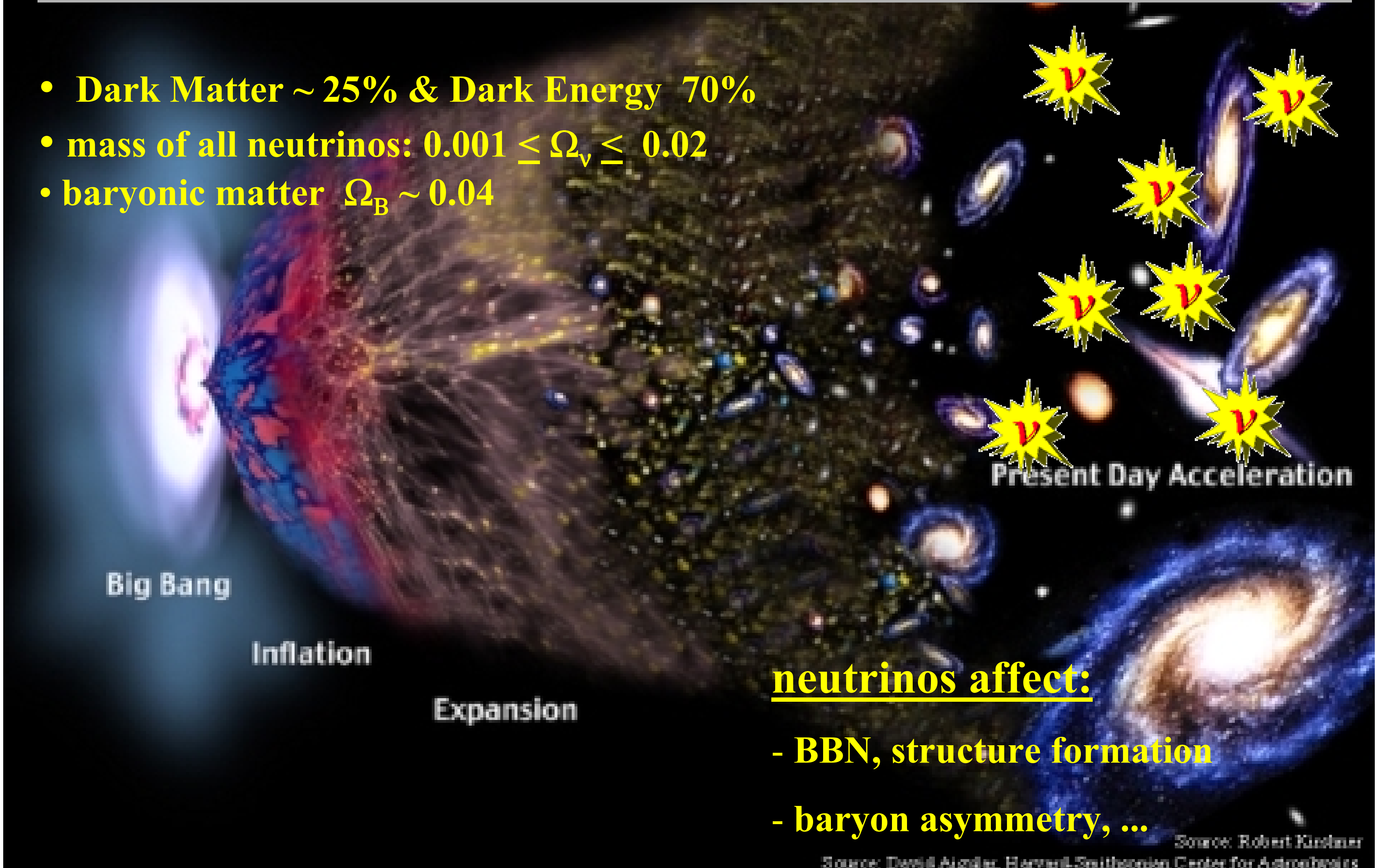
mass spectrum, mixings, CP-phases, lepton flavour violation, $0\nu2\beta$–decay, ...

➔ ν-parameters extremely valuable

➔ long term: most precise flavour info

Neutrinos & Cosmology

- Dark Matter ~ 25% & Dark Energy 70%
- mass of all neutrinos: $0.001 \leq \Omega_\nu \leq 0.02$
- baryonic matter $\Omega_B \sim 0.04$

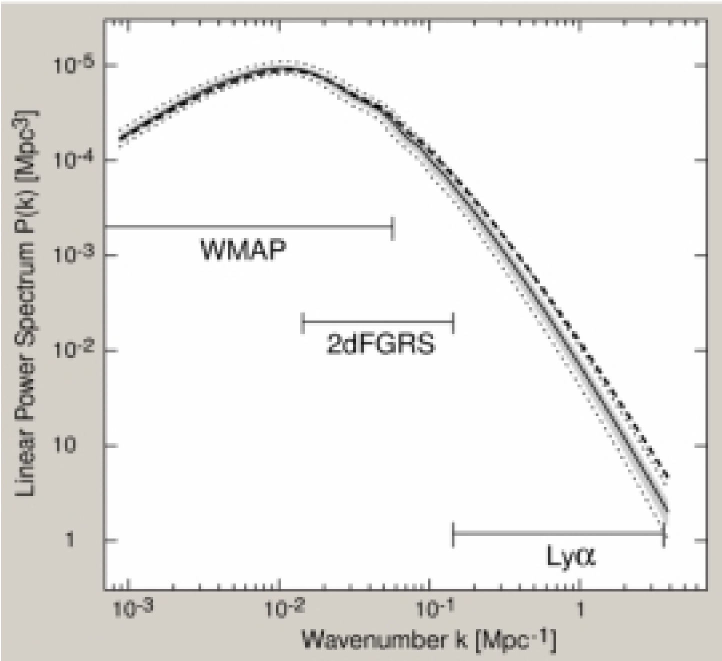


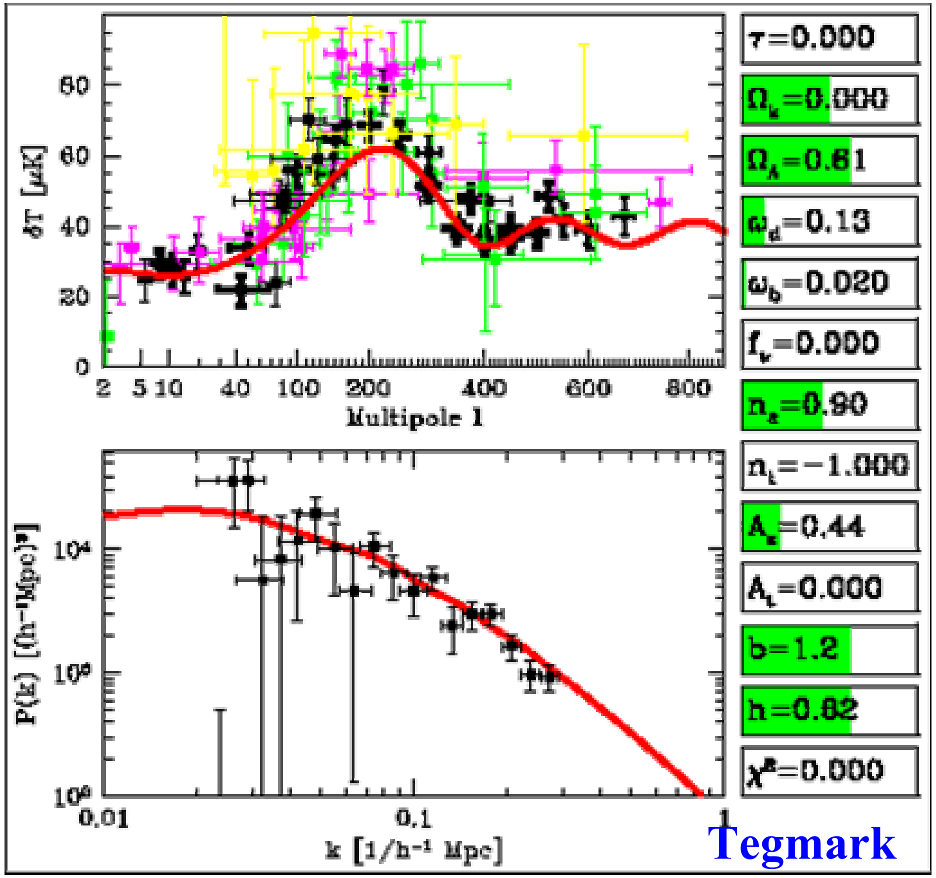
neutrinos affect:

- BBN, structure formation
- baryon asymmetry, ...

Cosmology and Neutrino Mass

• **ν's are hot dark matter ➔ smears structure formation on small scales**





•**WMAP+2dFGRS + Lyα**

➔ **mass bound: $\Sigma m_\nu < 0.7 \ldots 1.2$ eV**

• **3 degenerate neutrinos**

➔ **$m_\nu < 0.4$ eV future improvements: ~factor 5-10 ?**

$f_\nu = \Omega_\nu / \Omega_{matter}$

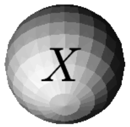
• **comparison with 0ν2β, LSND**

• **will be tested directly by KATRIN**

WMAP➔ PLANCK

Baryon Asymmetry & Neutrinos

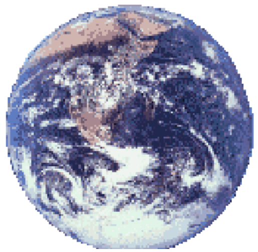
theory



↔ symmetry

particle **anti-particle**

observation



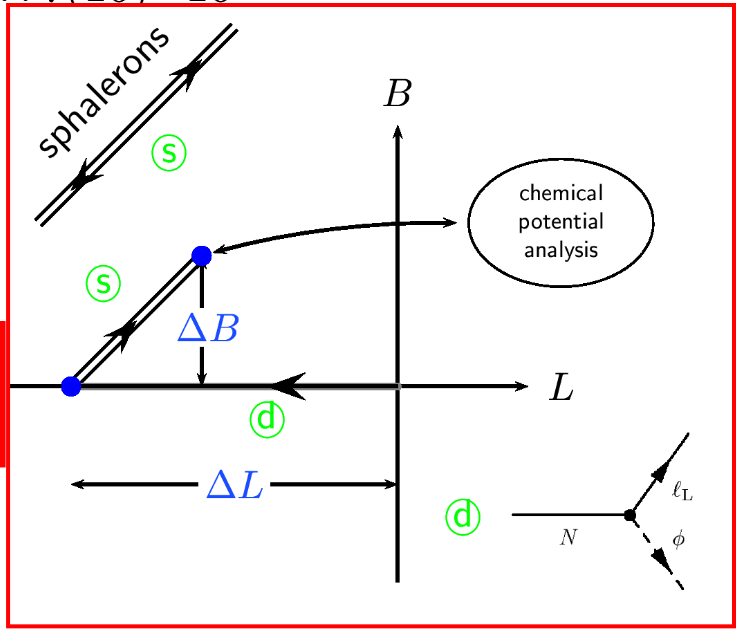
↔ baryon-asymmetry ?

matter **anti-matter**

measured baryon asymmetry: $\eta = \frac{n_B}{n_\gamma} = 4(3) \cdot 10^{-10} \ldots 7(10) \cdot 10^{-10}$

Necessary: Sakharov conditions:
- B-violating processes ↔ sphalerons
- C- and CP-violation ↔ contained in model
- departure from thermal equilibrium ↔ Γ < H

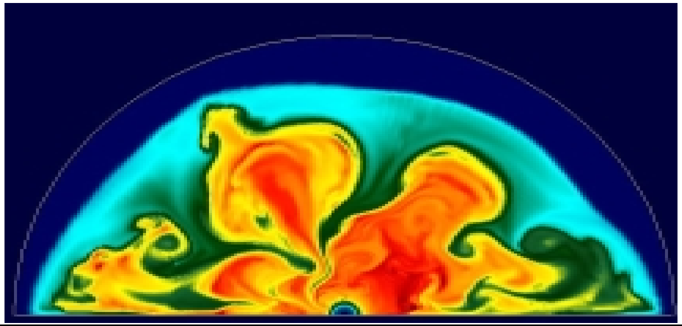
natural explanation of baryon asymmetry by **leptogenesis**

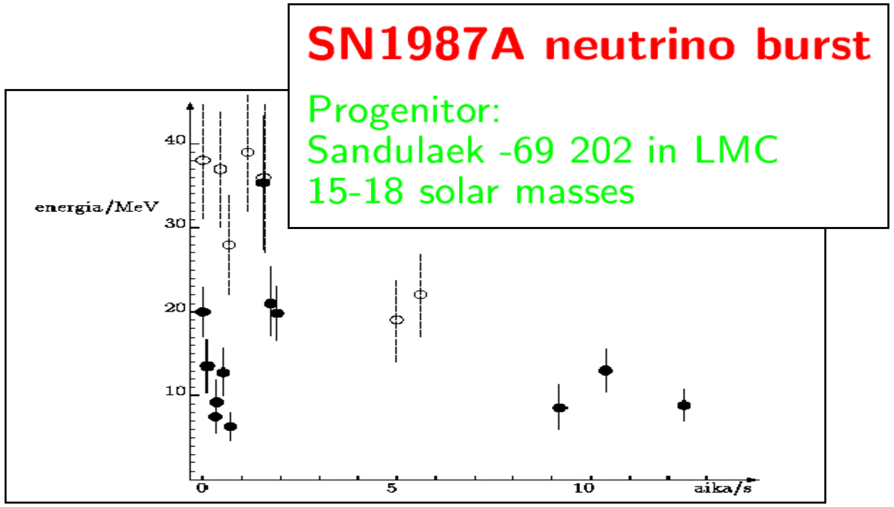


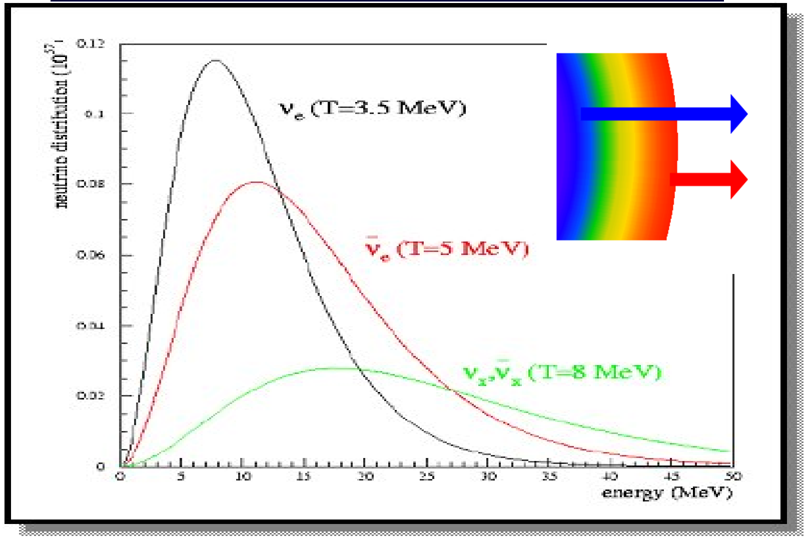
- **minimal leptogenesis works nicely**
- **different interesting variants ... a talk by itself**

Supernova Neutrinos

- Collaps of a typical star ➔ ~10^{57} ν's
- ~99% of the energy in ν's
- ν's essential for explosion
- 3d simulations do not explode
  (so far... 2d➔3d, ➔convection? ...)

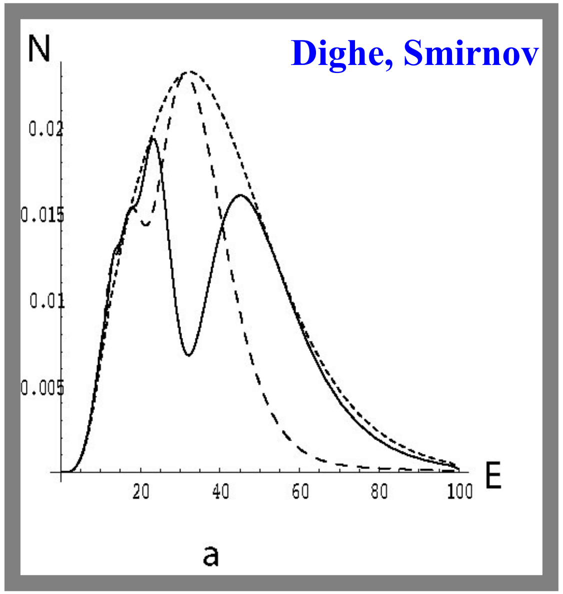






MSW: SN & Earth

Very sensitive to finite θ_{13} and sgn(Δm^2)

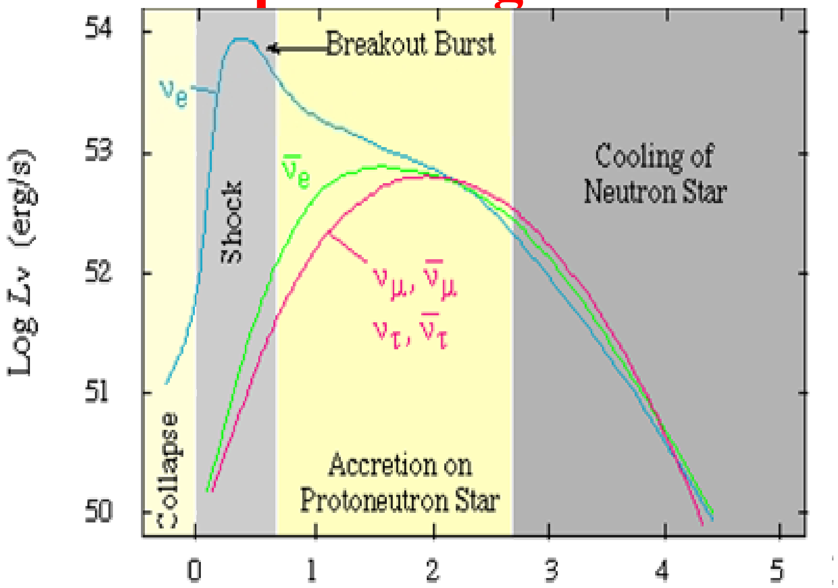


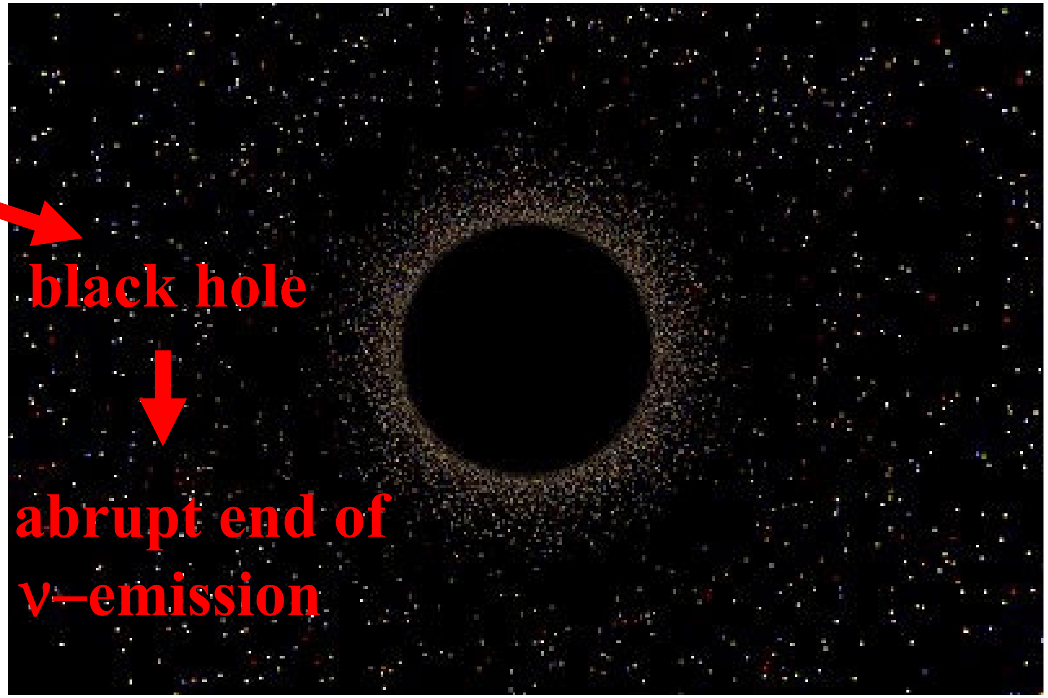
2 possibilities:

Supernova

neutron star or **black hole**

Keeps cooling...

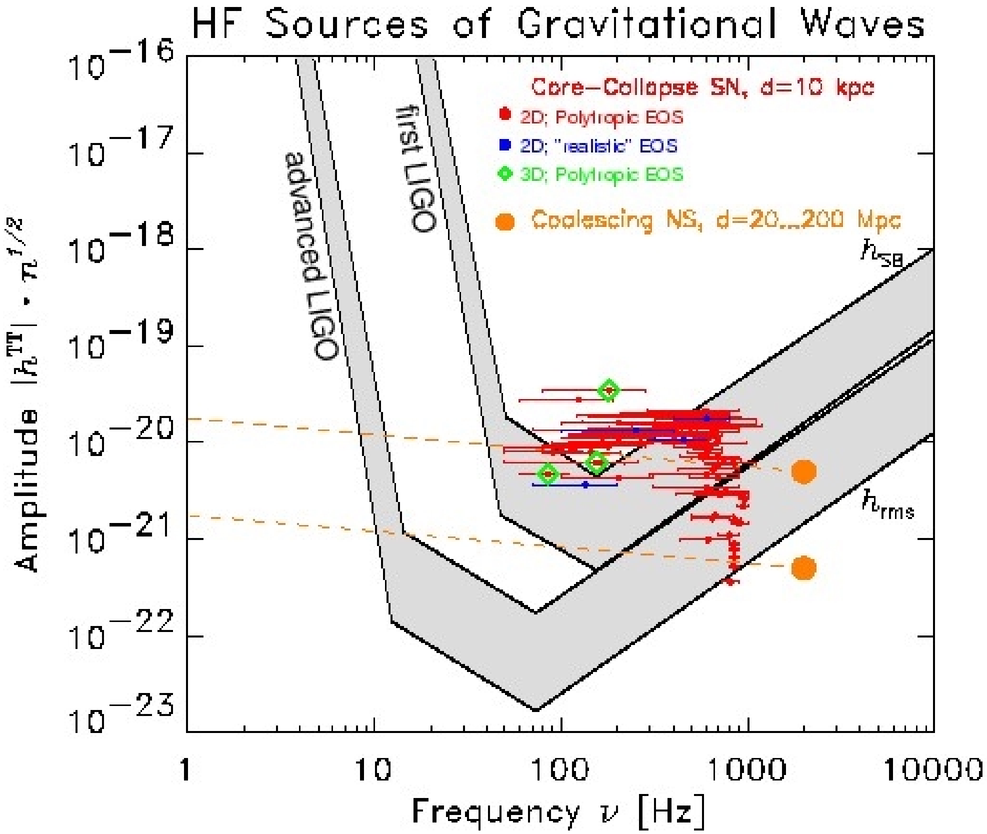


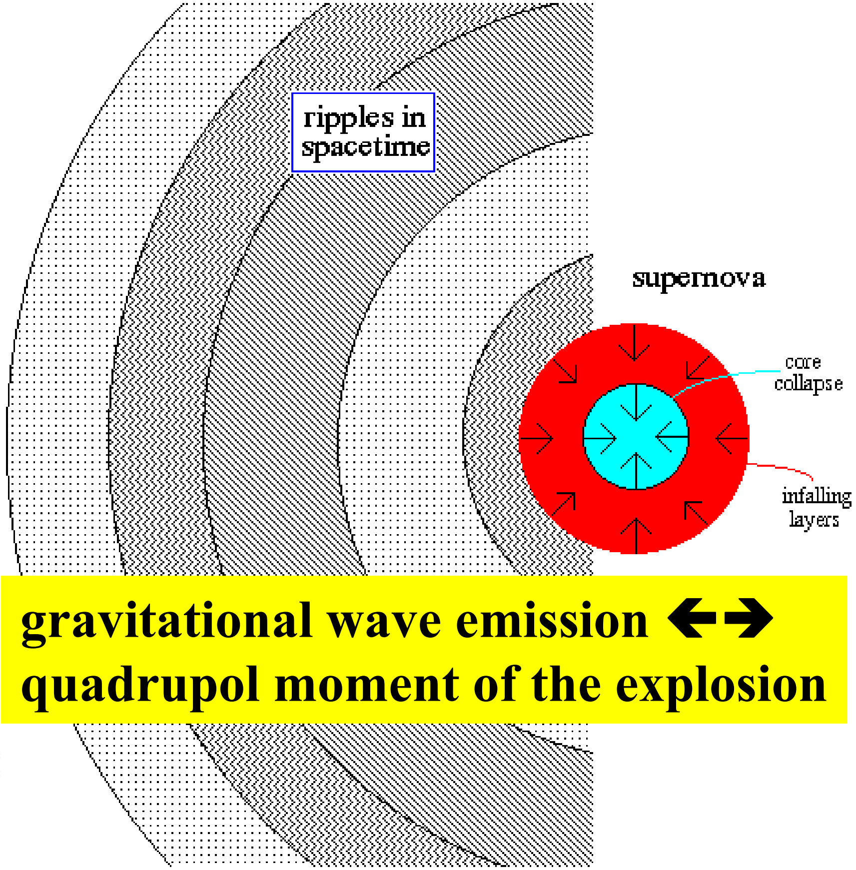


abrupt end of ν–emission

- **impressive signal of a black hole in neutrino light**
- **neutrino masses ←→ edge of ν-signal**

Supernovae & Gravitational Waves





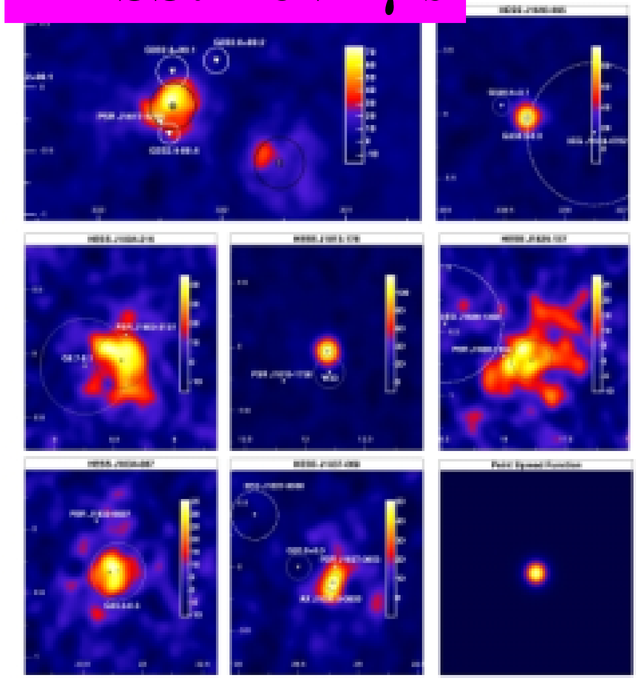
gravitational wave emission ←→ quadrupol moment of the explosion

Dimmelmeier, Font, Müller

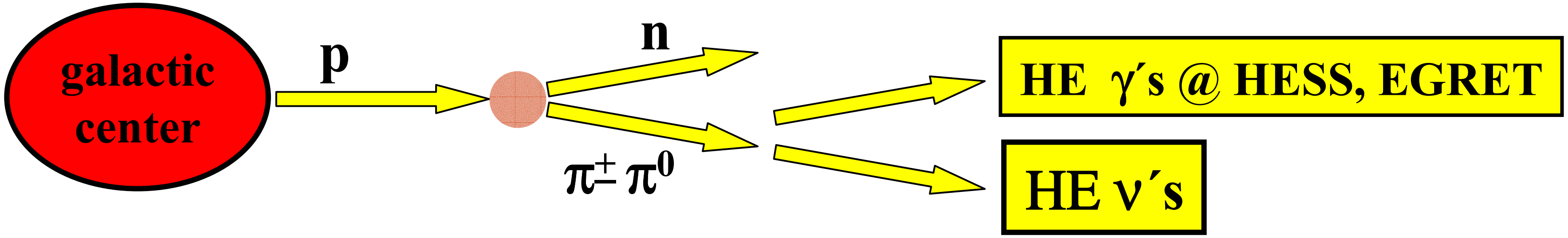
- ➔ additional information about galactic SN
- ➔ **global fits:** optical + neutrinos + gravitational waves
- ➔ neutrino properties + SN explosion dynamics
- ➔ SN1987A: strongest constraints on large extra dimensions

Neutrinos & TeV γ´s

HESS: TeV γ´s



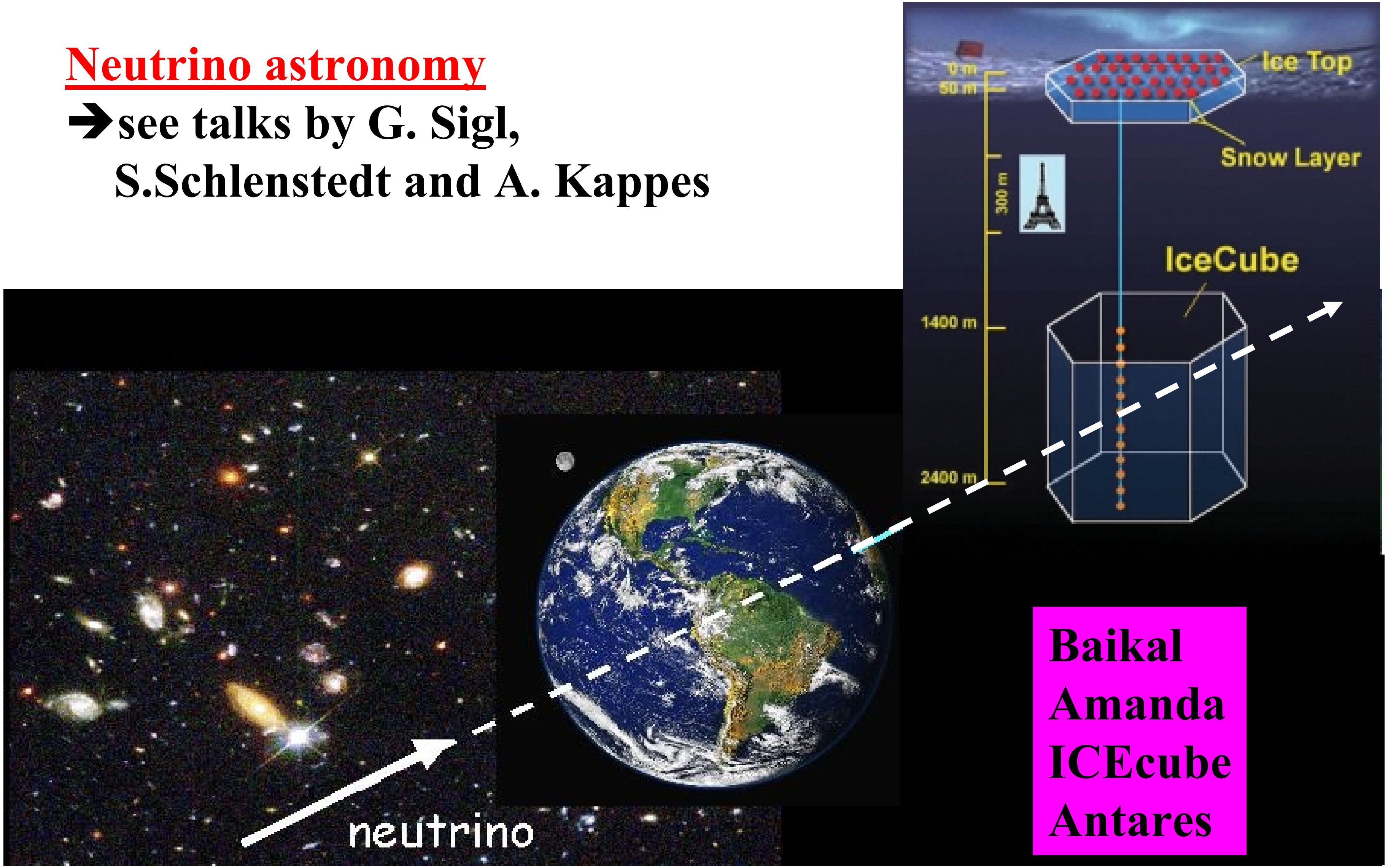
A plausible explanation:
- SN shock front acceleration
- γ´s from π^0 decay
  ➔ ν flux from GC
  ➔ ν signal @ km^3 detectors



Neutrino Telescopes

Neutrino astronomy

→see talks by G. Sigl, S.Schlenstedt and A. Kappes



- Baikal
- Amanda
- ICEcube
- Antares

Conclusions

Neutrinos probe new physics in many ways!