

Particles and the Cosmos

2019/2020

Sascha Caron, Jörg Hörandel

NM109
first semester, 6 ec

32 hrs lecture Wednesday 10:30 - 12:15 HG 00.086

32 hrs problem session Thursday 13:30 - 15:15 HG 02.052

Lectures:

Experimental methods (JRH)

04.09.2019 [1. Interactions with matter](#)

11.09.2019 [2. Detectors](#)

Standard model (SC)

18.09.2019 3. Particles, QED, Feynman rules

25.09.2019 4. Hadrons and QCD

02.10.2019 5. Hadrons and QCD

09.10.2019 6. Weak interactions, CP violation

16.10.2019 7. Higgs mechanism

Astroparticle physics (JRH)

06.11.2019 8. The birth of cosmic rays

13.11.2019 9. Cosmic rays in the Galaxy, in the heliosphere, and the Earth magnetic field

20.11.2019 10. Cosmic rays at the top of and in the atmosphere

27.11.2019 11. Cosmic rays underground - neutrino oscillations

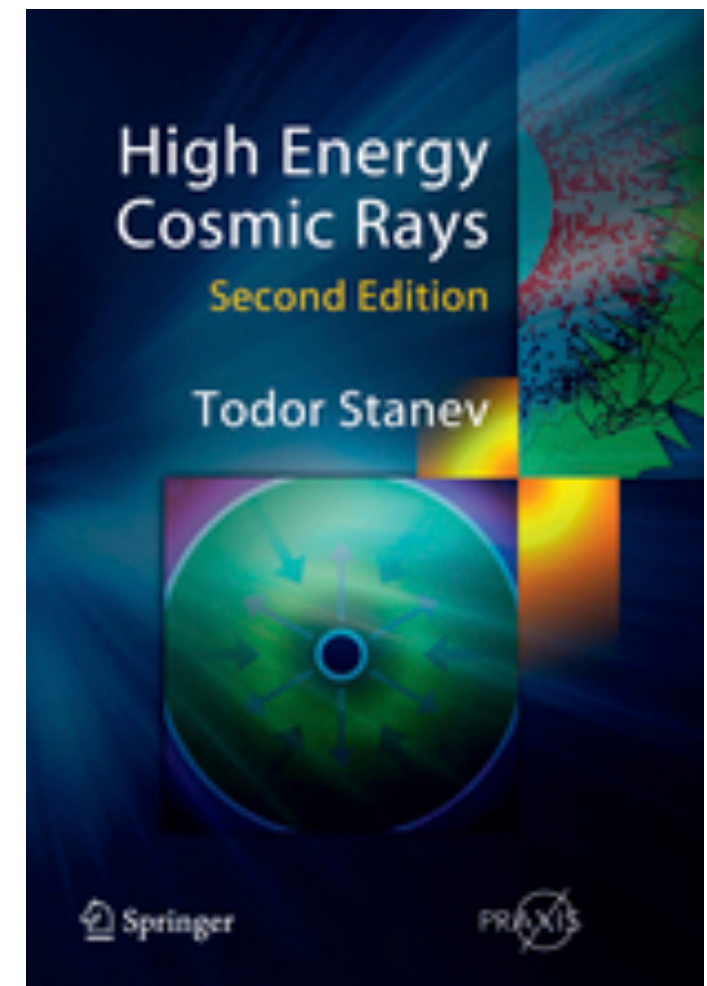
04.12.2019 12. Neutrino oscillations, Astroparticle Physics

Beyond the Standard Model, Dark Matter (SC)

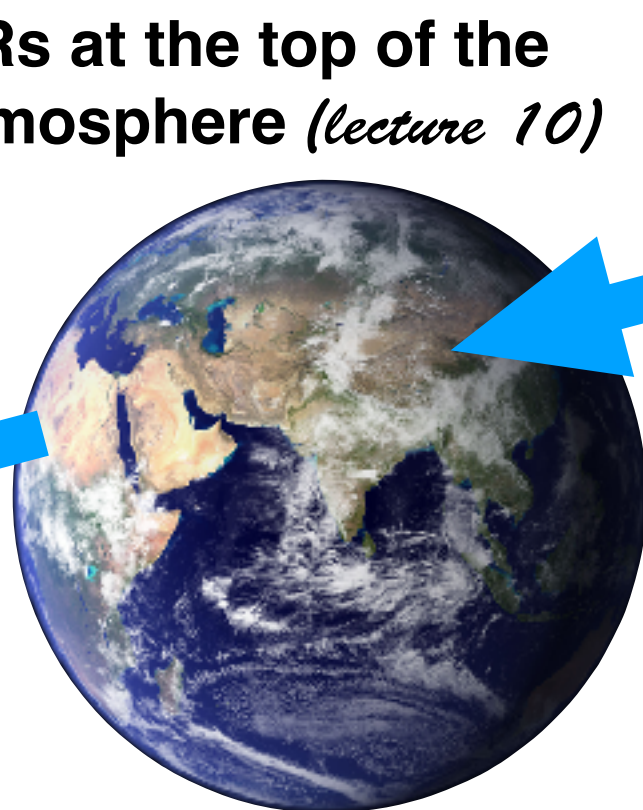
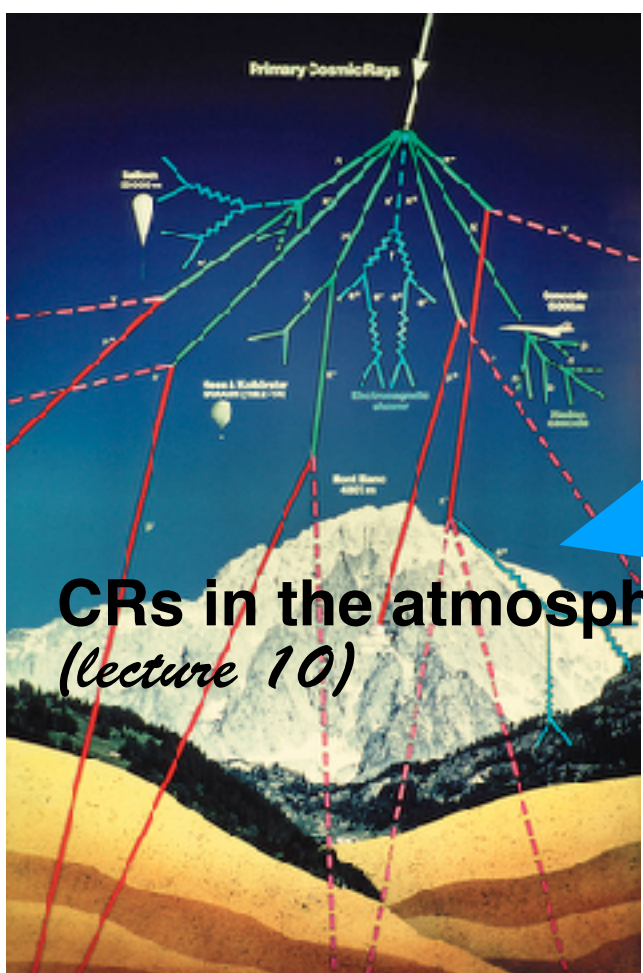
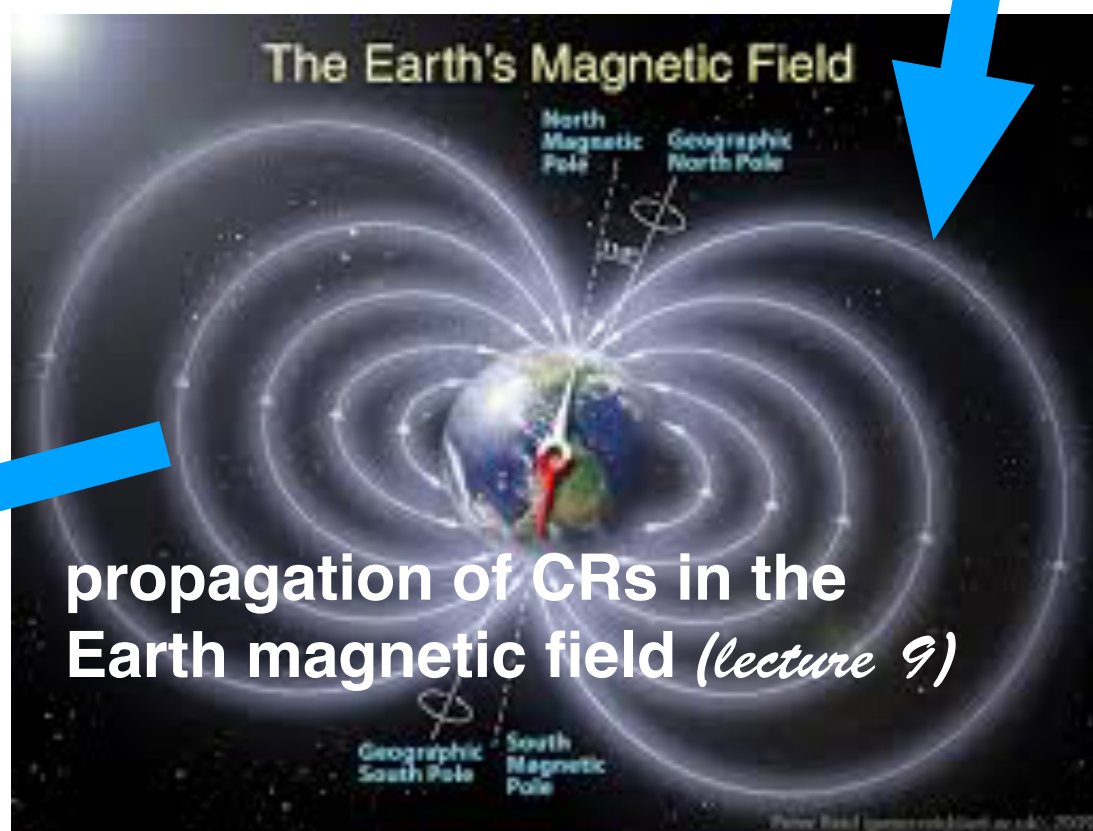
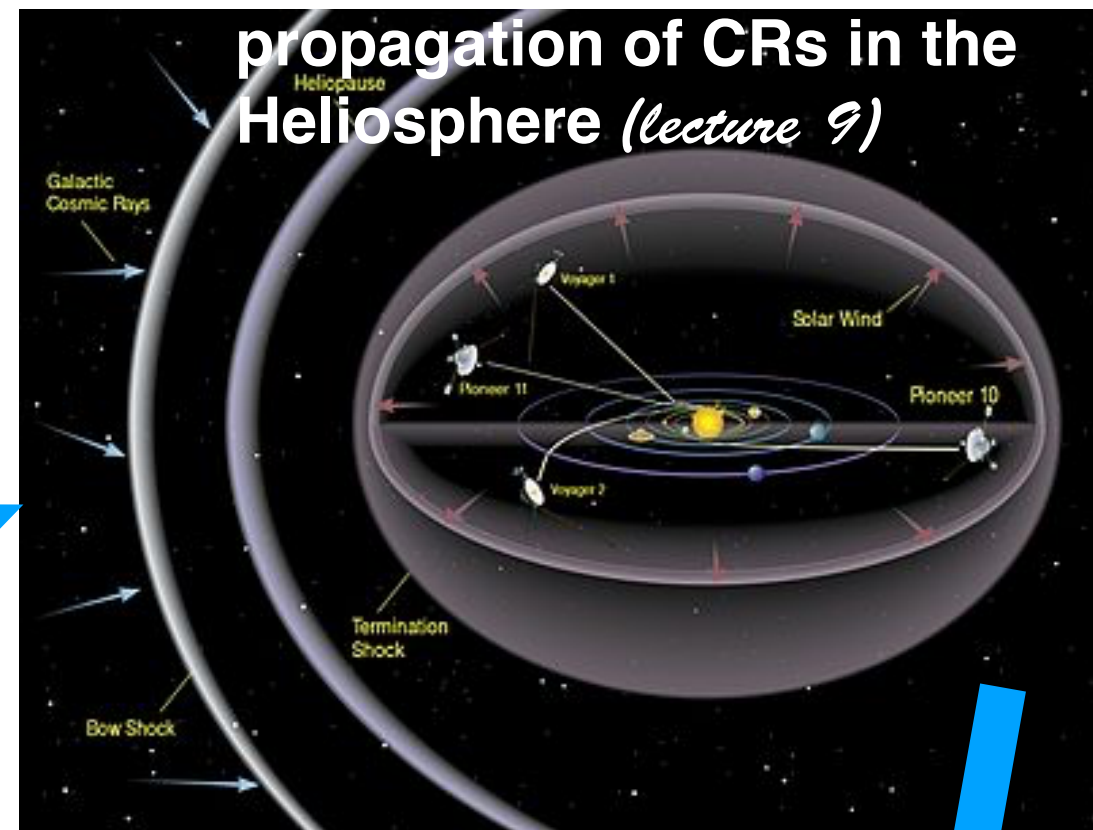
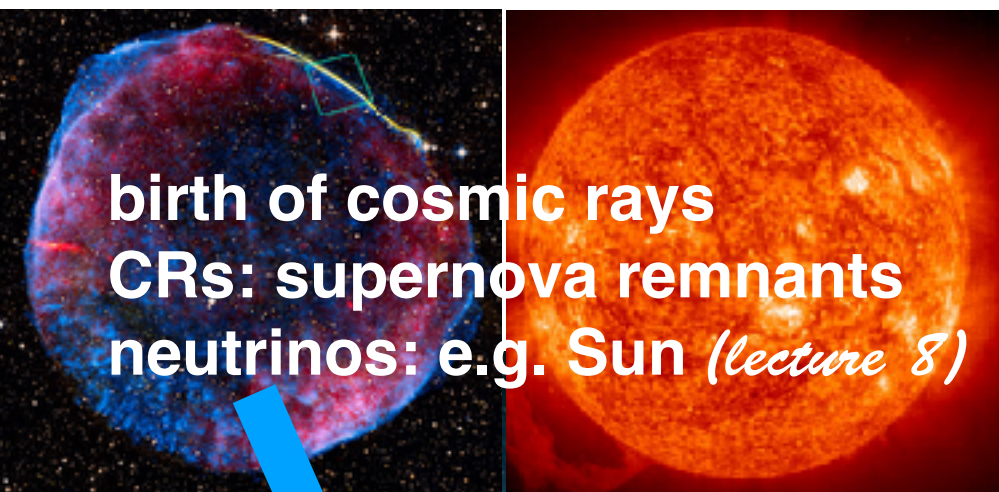
11.12.2019 13. Lambda CDM, Big-bang nucleosynthesis

18.12.2019 14. Dark matter - Beyond-the-standard-model reasons

for Astroparticle Physics



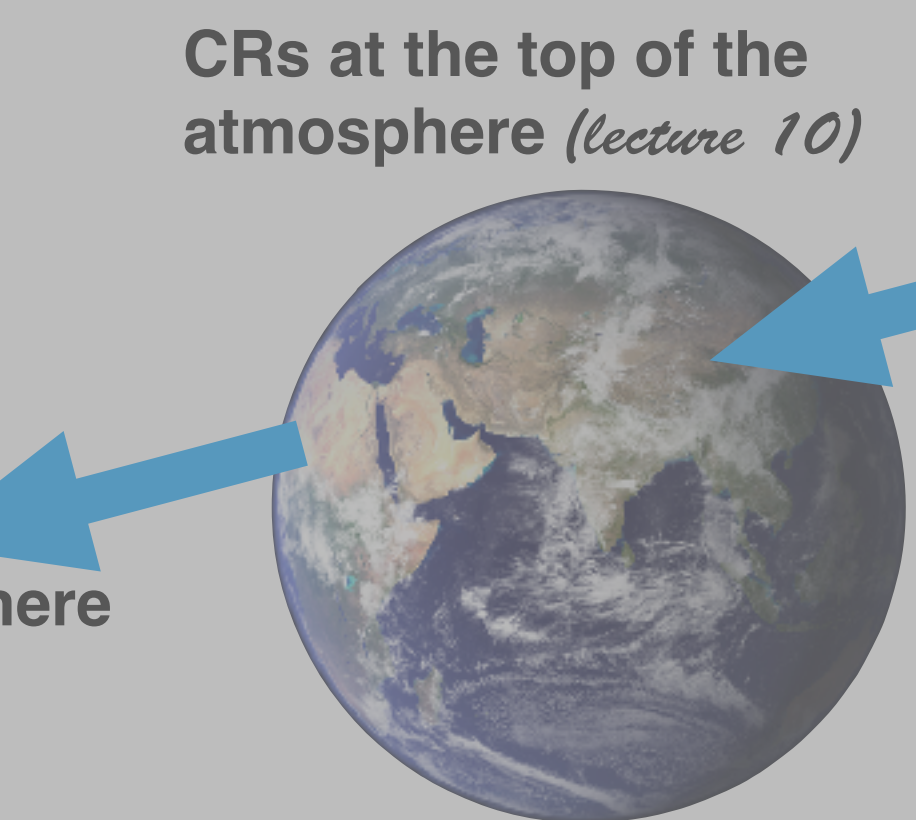
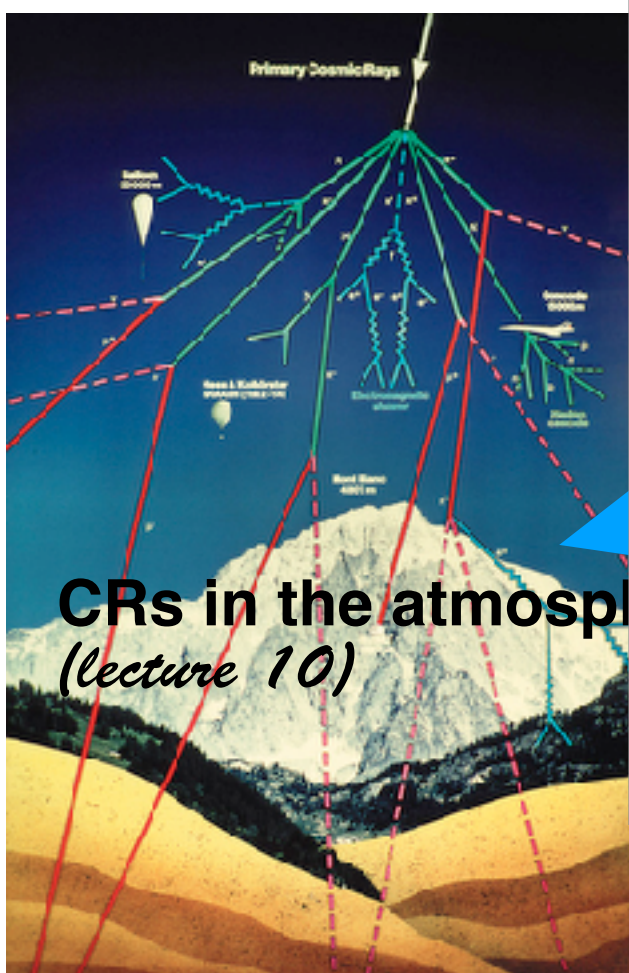
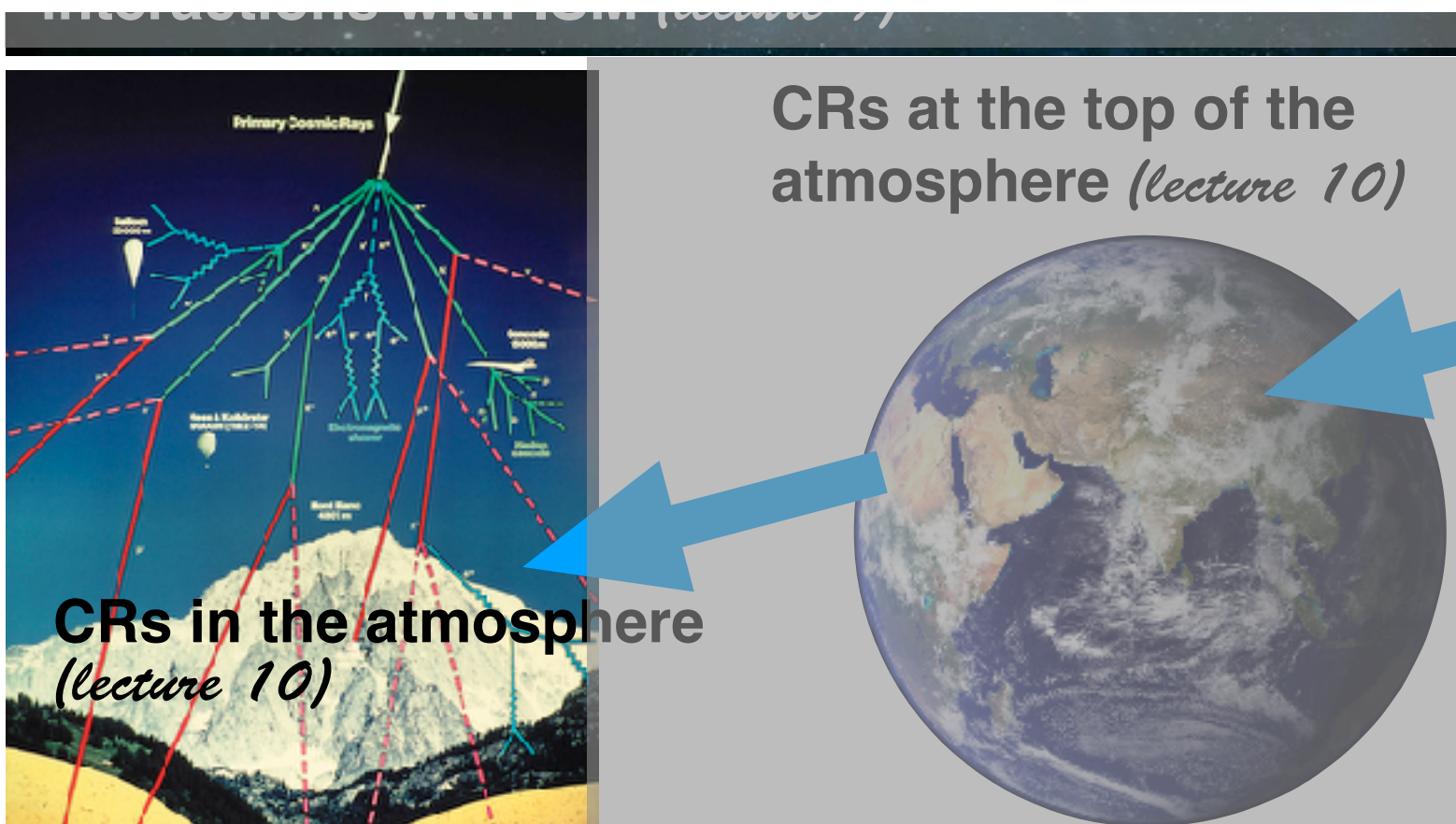
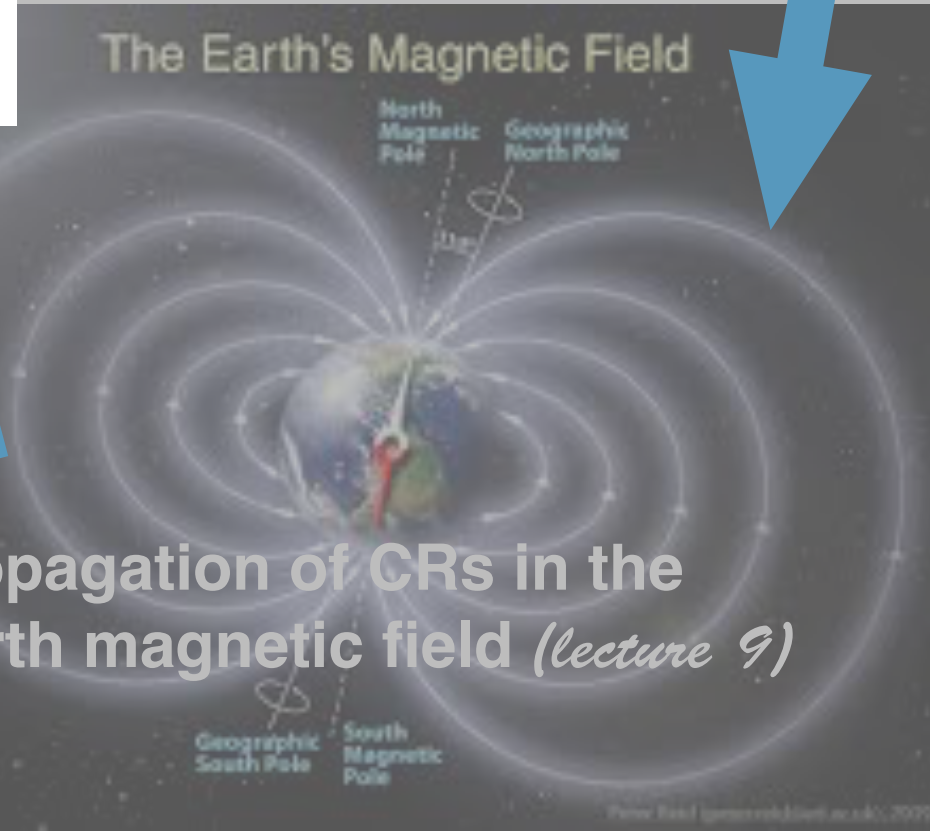
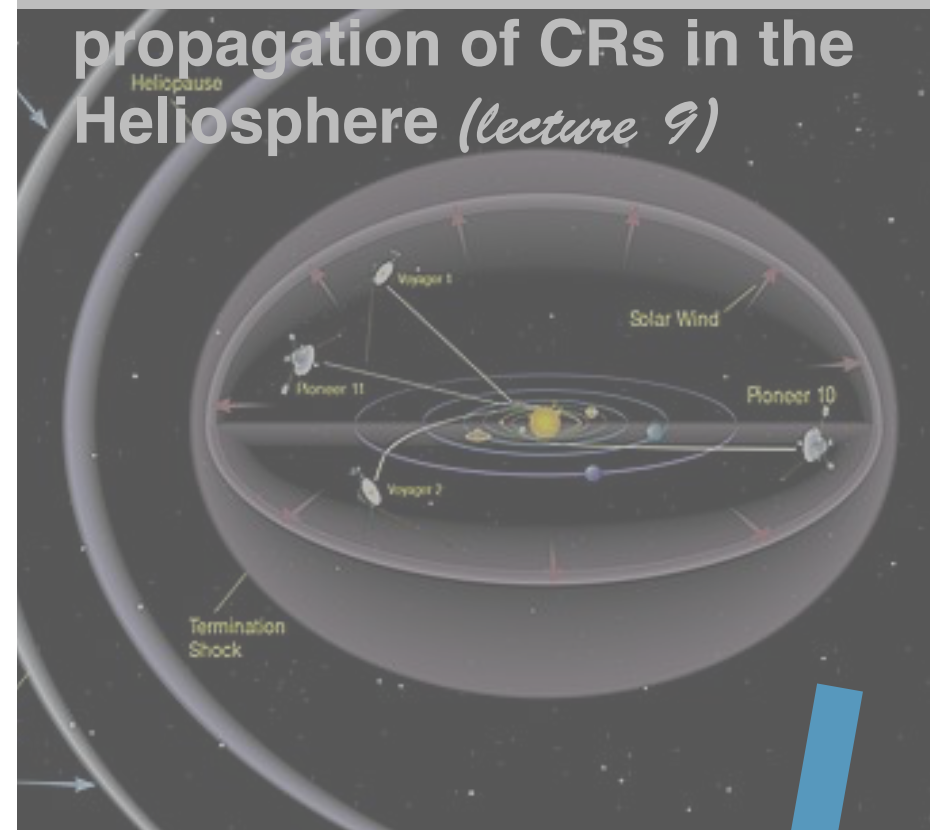
Jörg R. Hörandel
HG 02.721
<http://particle.astro.ru.nl>



CRs underground (lecture 11)
neutrino oscillations (lecture 11+12)

today: Stanev, chapter 7

7	Cosmic rays underground	137
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CRs underground (lecture 11)
neutrino oscillations (lecture 11+12)

Neutrino oscillations

Neutrino oscillations were first suggested as a possibility by Pontecorvo [224]. Oscillations imply that neutrinos have nonzero mass. The known neutrino flavor eigenstates can be represented as a linear combination of different ‘basic’ neutrino flavors. In the simple two-neutrino case this assumption can be expressed as:

$$\begin{aligned}\nu_\alpha &= \cos\theta \times \nu_1 + \sin\theta \times \nu_2 \\ \nu_\beta &= -\sin\theta \times \nu_1 + \cos\theta \times \nu_2,\end{aligned}\tag{7.23}$$

where θ is the mixing angle between ν_1 and ν_2 . A calculation of the wave functions for neutrino flavors α and β shows the development of a phase difference $\Delta\phi = \Delta m^2 t / (2E_\nu)$, where $\Delta m^2 = |m_\alpha^2 - m_\beta^2|$ is the absolute value of the difference in the squared masses of the two flavors. This phase difference defines the conversion (oscillation) probability of ν_α into ν_β

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2(2\theta) \sin^2\left(\pi \frac{L}{L_{osc}}\right),\tag{7.24}$$

which is proportional to the strength of the mixing in (7.23). The oscillation length L_{osc} is proportional to the neutrino energy E_ν and inversely proportional to the squared mass difference Δm^2 .

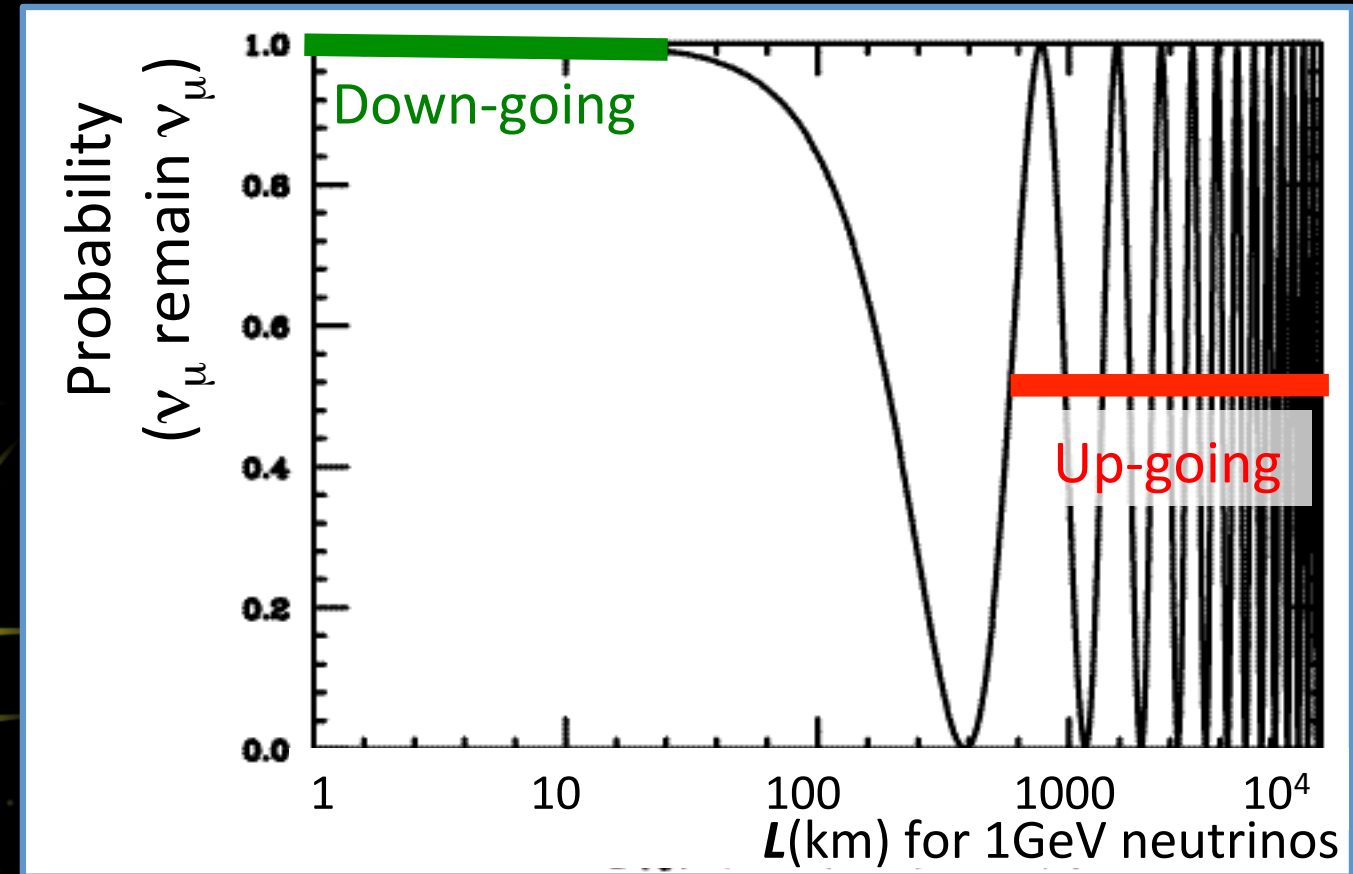
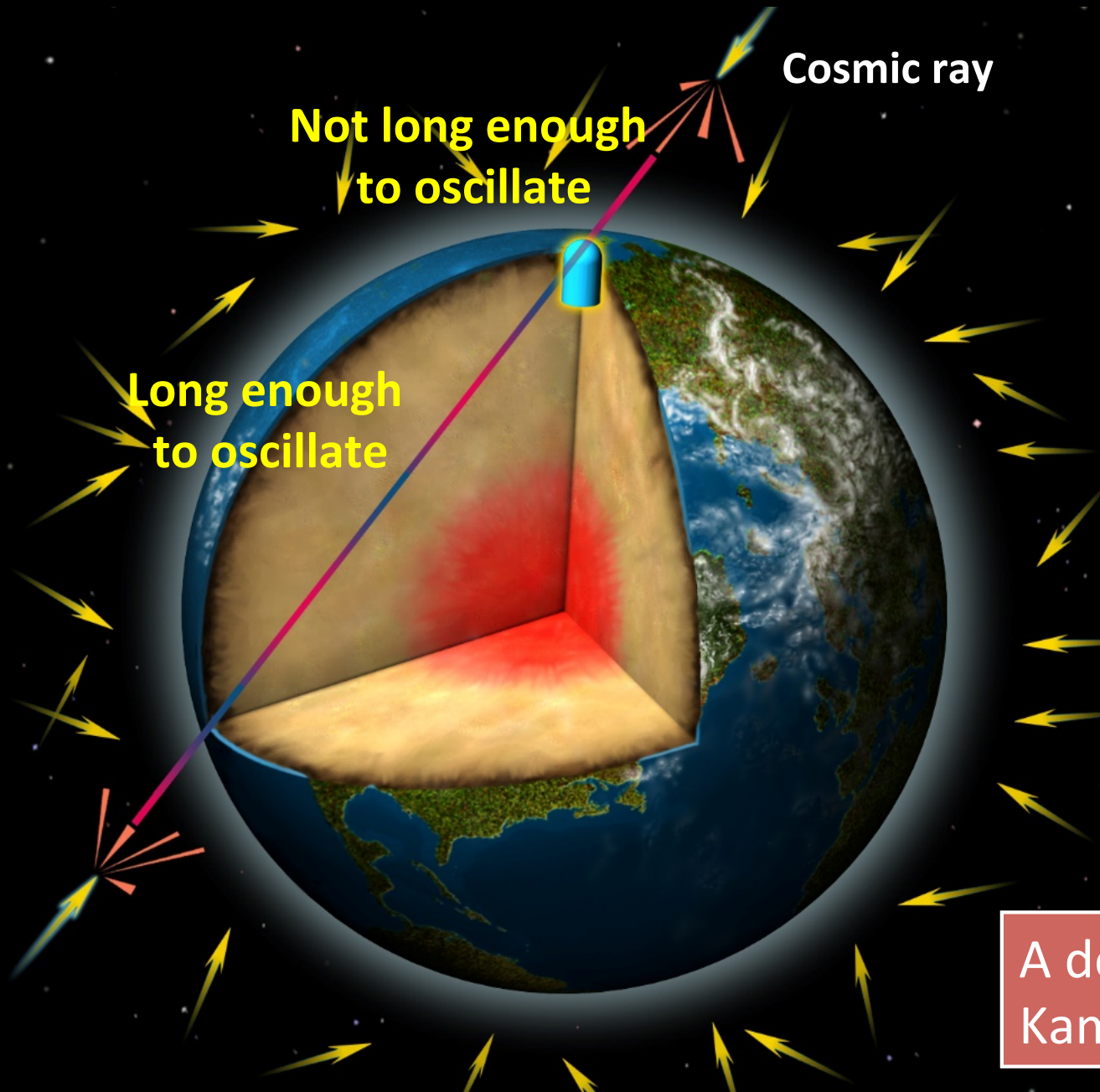
Neutrino oscillations

Expressed in units suitable for the energy of the atmospheric neutrinos and for the geometry of their detection the oscillation probability is

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m^2 (\text{eV}^2) L_{\text{km}}}{E_{\text{GeV}}} \right). \quad (7.25)$$

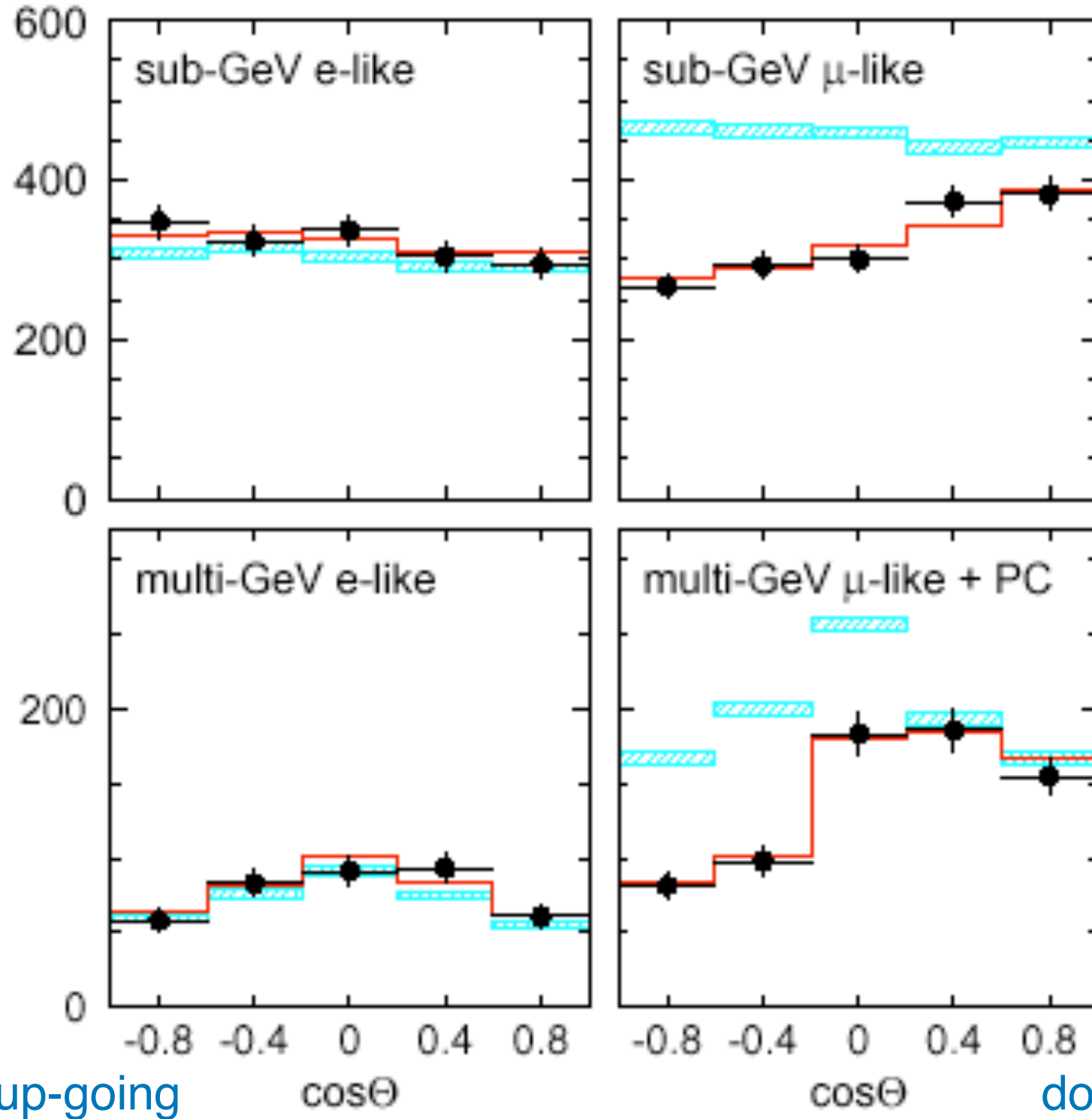
In neutrino oscillation studies the sensitivity to Δm^2 comes from the L/E ratio while the determination of the mixing strength is a matter of experimental statistics independently of Δm^2 .

What will happen if the ν_μ deficit is due to neutrino oscillations



A deficit of upward going ν_μ 's should be observed!
Kamiokande was too small. → Super-Kamiokande

Super Kamiokande



ν_e experimental results agree with expectations at all angles

ν_μ small angles ($l \sim 10\text{-}30$ km): agreement with expectations
 large angles ($l \sim 13000$ km): experimental data are a factor ~ 2 less than expectation

preferred explanation: neutrino oscillations $\nu_\mu \rightarrow \nu_\tau$

best fit values:

$$\sin 2\Theta = 1.0$$

$$\Delta m^2 = 3.5 \cdot 10^{-3} \text{ eV}^2$$

Angular distributions for e-like (left) and μ -like (right) events, for sub-GeV (top) and multi-GeV (bottom) samples. The bars show the MC no-oscillation prediction with statistical errors, and the line shows the oscillation prediction for the best-fit parameters, $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 3.5 \times 10^{-3} \text{ eV}^2$.

solar
neutrinos

Matter effects

The scenario of the previous section assumes that neutrinos are propagating in vacuum. In the presence of matter this scenario will be modified because different neutrino flavors have different interactions in matter [225]. Matter necessarily contains electrons and ν_e s can have charge current interactions on electrons while ν_μ and ν_τ can only have weaker neutral current interactions. The extra ν_e cross-section creates an effective potential V_{ν_e} which is different from the potential V_{ν_μ, ν_τ} . For ν_e the effective potential $V_{\nu_e} = \sqrt{2} G_F n_e$, where n_e is the electron density of the medium and G_F is the Fermi coupling constant. This potential can be considered as a contribution to the ν_e mass and changes the neutrino mixing and transition probability.

Matter effects

The mixing angle term $\sin^2 2\theta$ in (7.24) is replaced by its matter value

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{[(\varphi - \cos 2\theta)^2 + \sin^2 2\theta]^{1/2}} \quad (7.26)$$

and the oscillation length L_{osc} with

$$L_{osc}^m = \frac{L_{osc}}{[(\varphi - \cos 2\theta)^2 + \sin^2 2\theta]^{1/2}}, \quad (7.27)$$

where $\varphi = 2V_{\alpha\beta}E_\nu/\Delta m^2$ contains the difference in the effective potential of the two neutrinos in the medium. For neutrino species with identical effective potential one recovers the expressions for vacuum oscillations.

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2(2\theta) \sin^2 \left(\pi \frac{L}{L_{osc}} \right) \quad (7.24)$$

Matter effects

These new definitions have a very strong effect on the propagation of neutrinos in the Sun [226] – the MSW effect. The Sun contains an enormous range of electron densities and for a large range of neutrino energies the difference in the effective potential V_{ν_e, ν_μ} which is proportional to the electron density ρ_e could become equal to $\cos 2\theta$. Even a very small mixing angle instantaneously increases and causes quick resonant oscillations. On the exit from the Sun n_e decreases and for fixed E_ν the electron neutrino flux cannot recover after the resonant transition. Figure 7.17 shows the change of $\sin^2 2\theta_m$ as a function of the electron density for a choice of oscillation parameters. The MSW effect has become a favorite explanation of the solar neutrino puzzle.

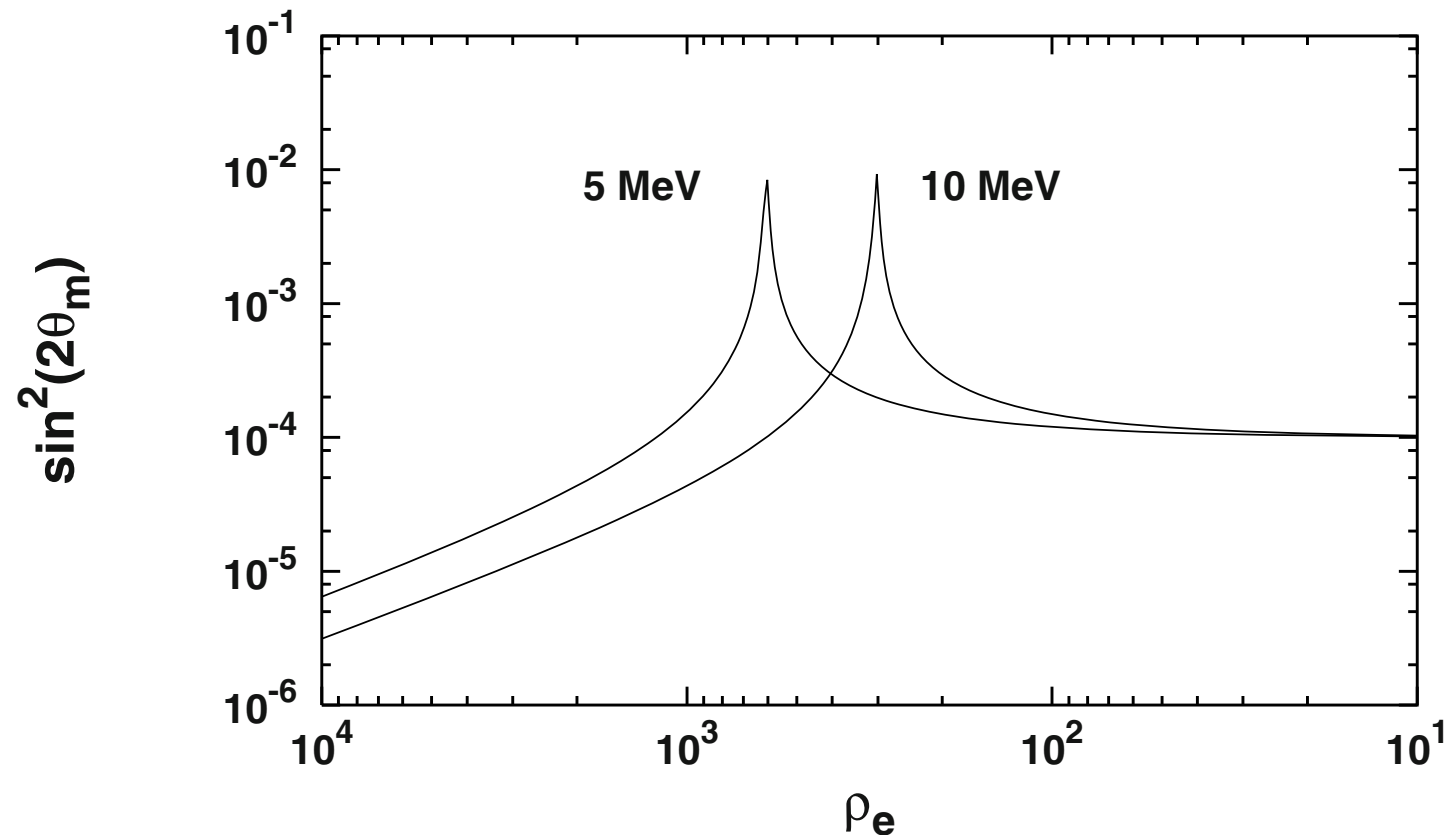


Fig. 7.17. Change of $\sin^2 2\theta_m$ with the electron density. $\Delta m^2 = 10^{-4} \text{ eV}^2$ and $\sin^2 2\theta = 10^{-4}$ for this example.

Sudbury Neutrino Observatory (SNO)

NEUTRINO

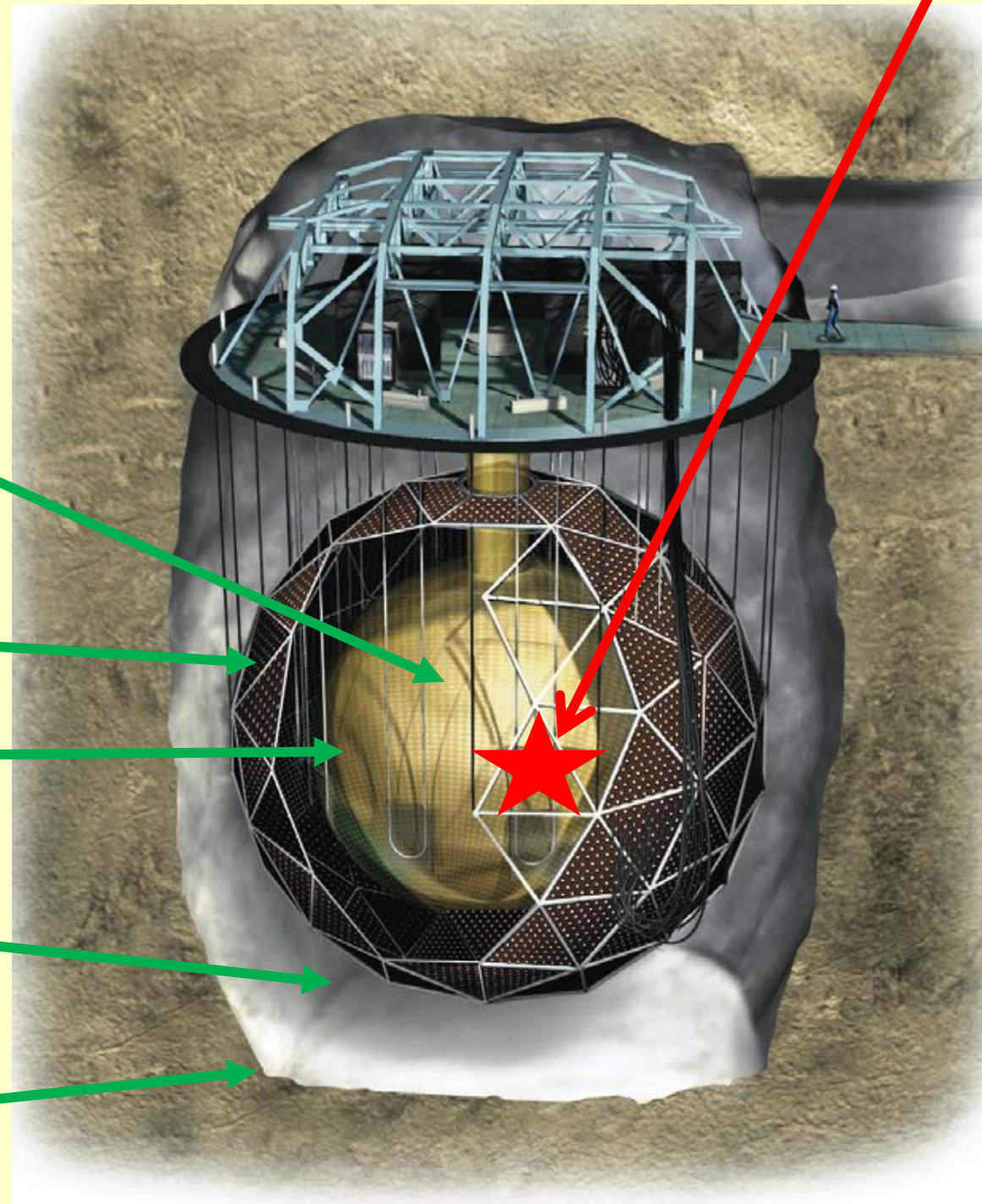
1000 tonnes of heavy water: D₂O
\$ 300 million on Loan for \$1.00

9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H₂O.

Urylon Liner and Radon Seal

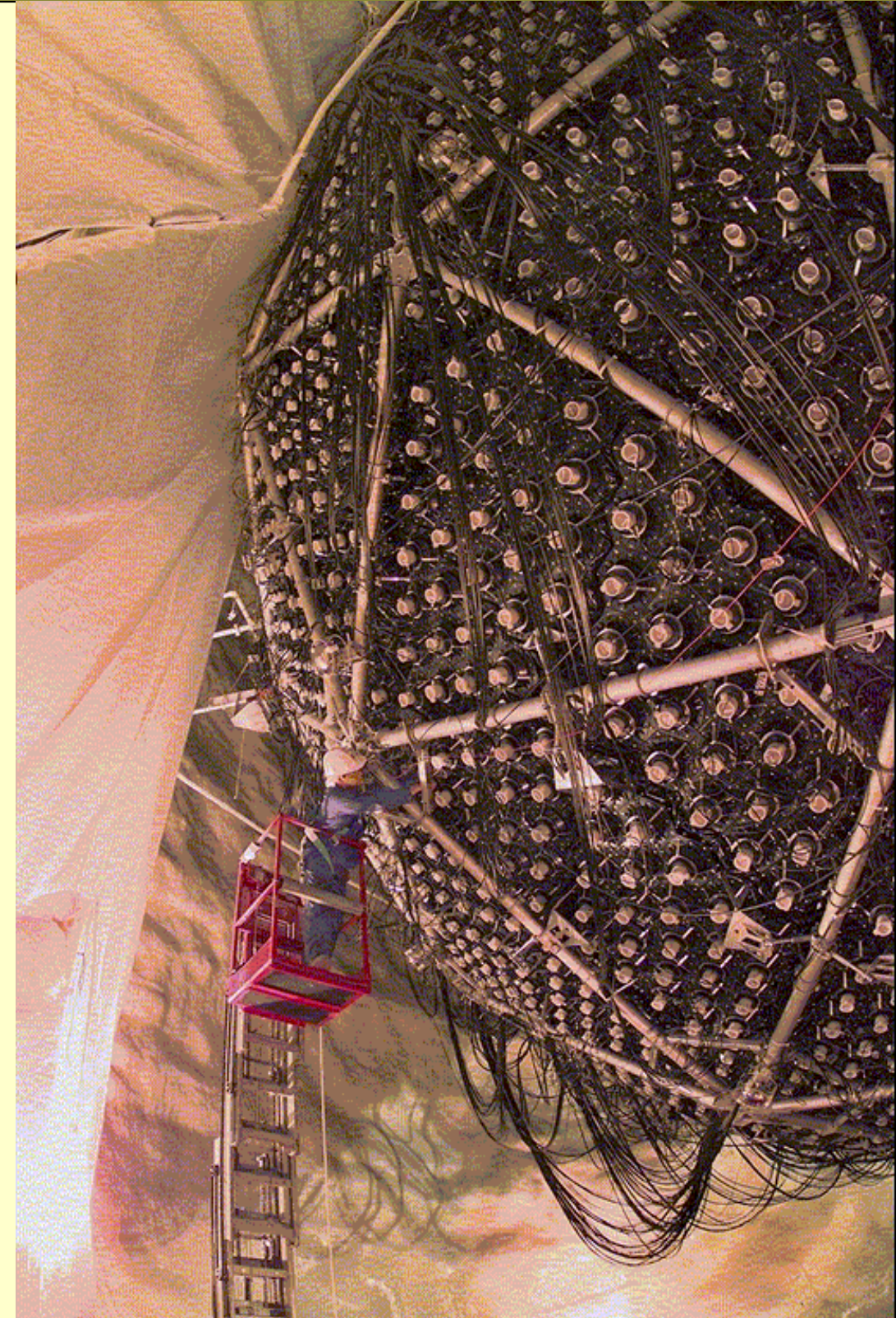
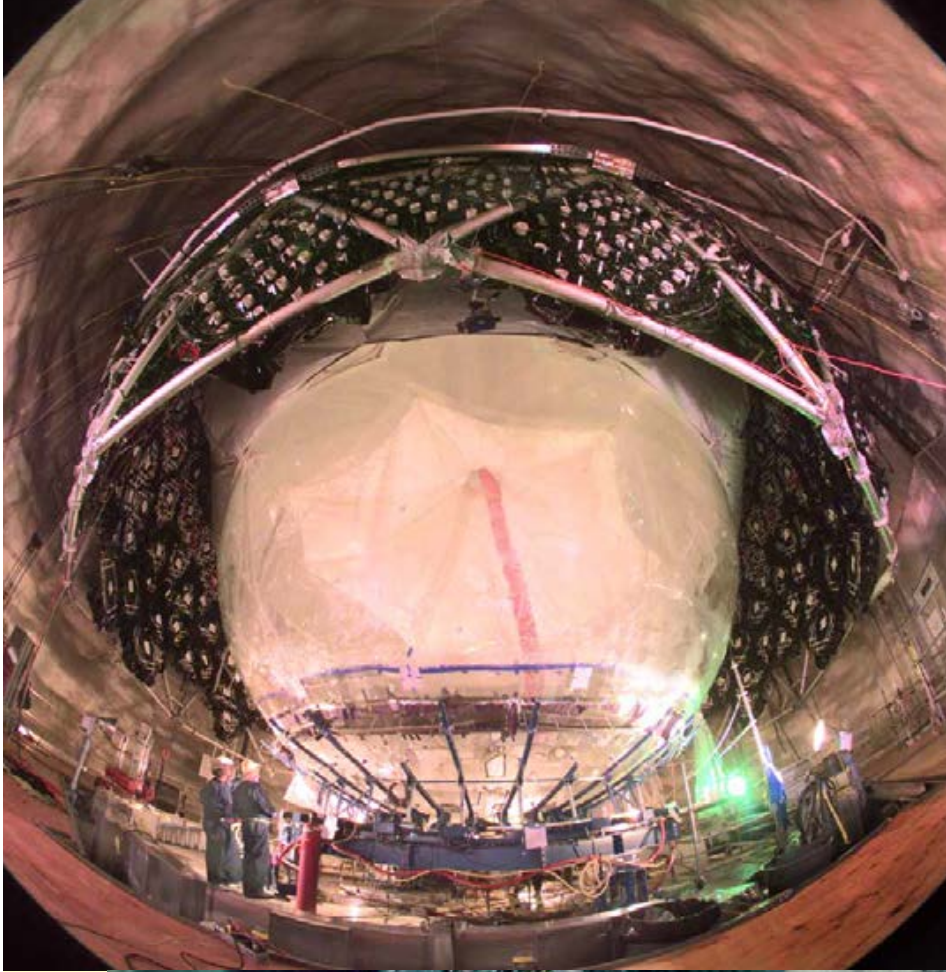


**34 m
or
~ Ten
Stories
High!**

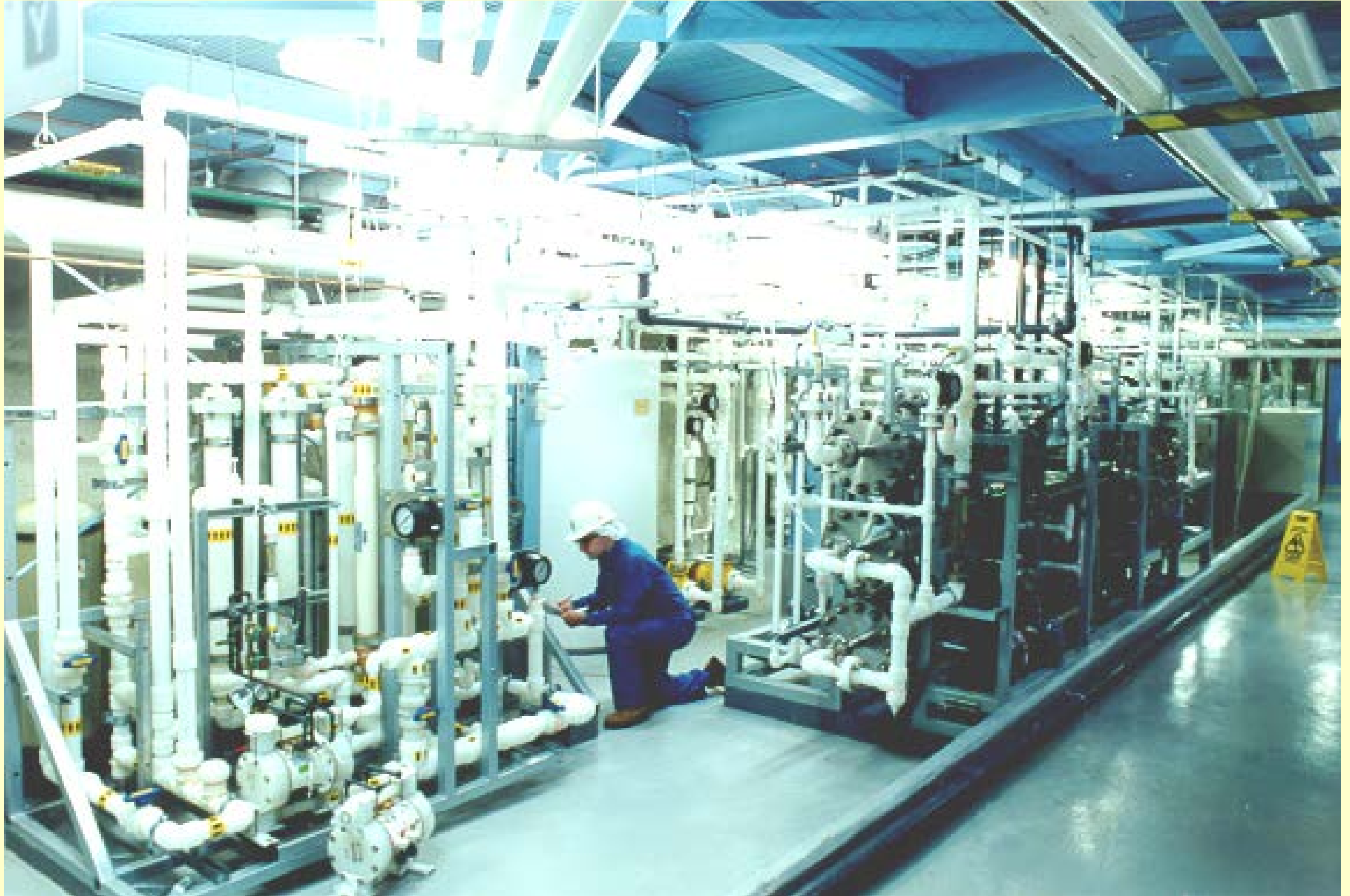
**2 km
below
the
ground**

SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000 showers during the course of the SNO project



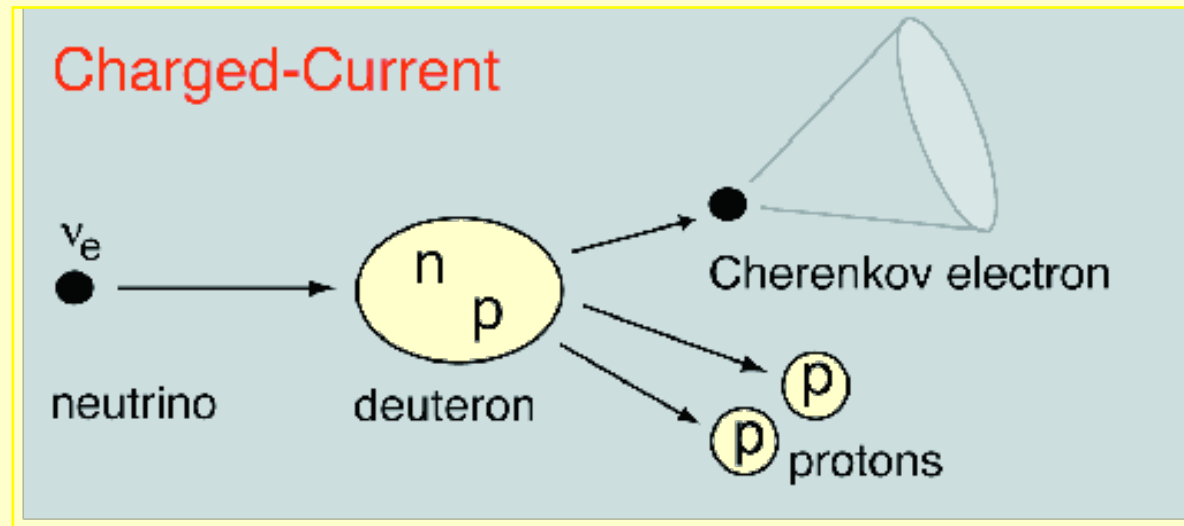
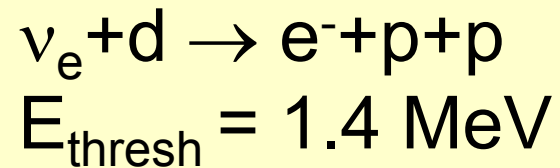
Water systems were developed to provide low radioactivity light water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!



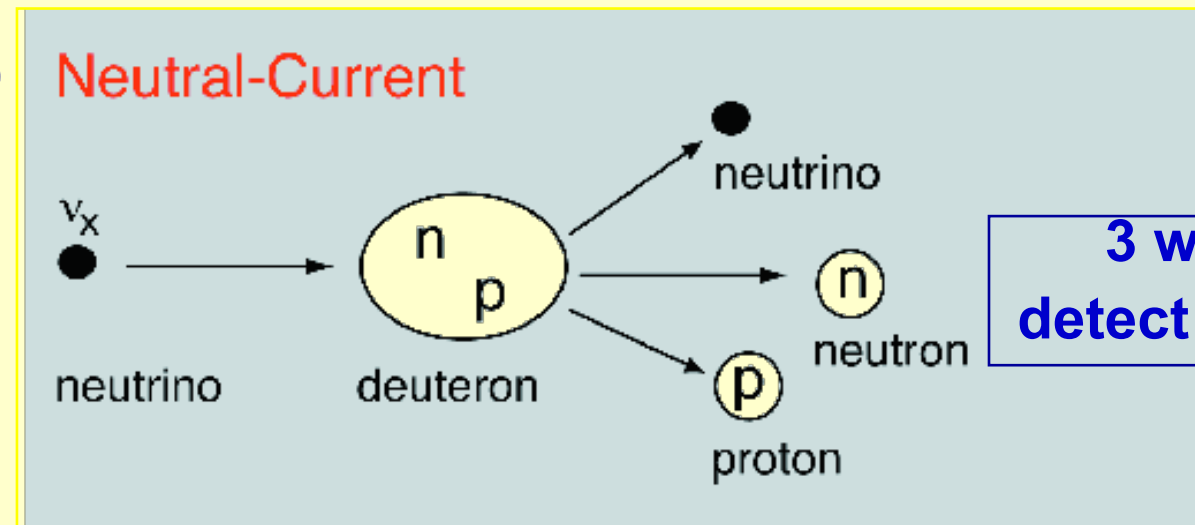
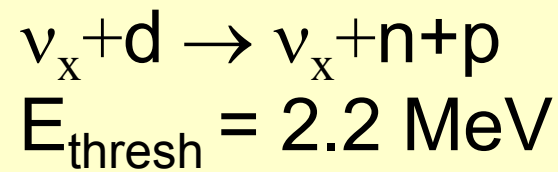
Unique Signatures in SNO (D₂O)

(1 in 6400 molecules in ordinary water are D₂O. We used >99.75% D₂O)

Electron Neutrinos (CC)

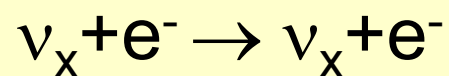


Equal Sensitivity All Types (NC)

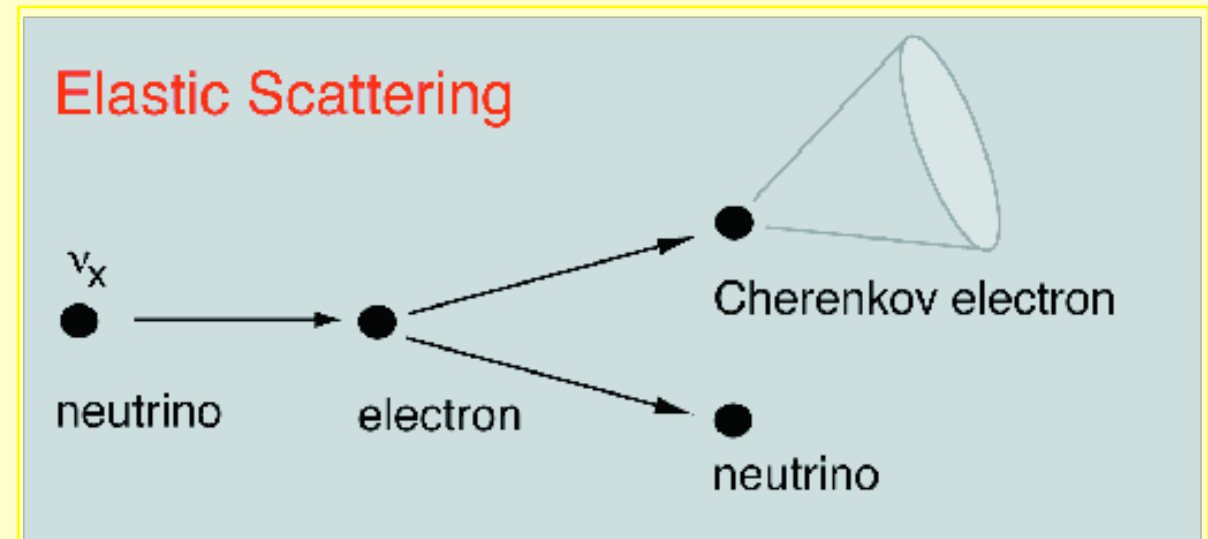


3 ways to detect neutrons

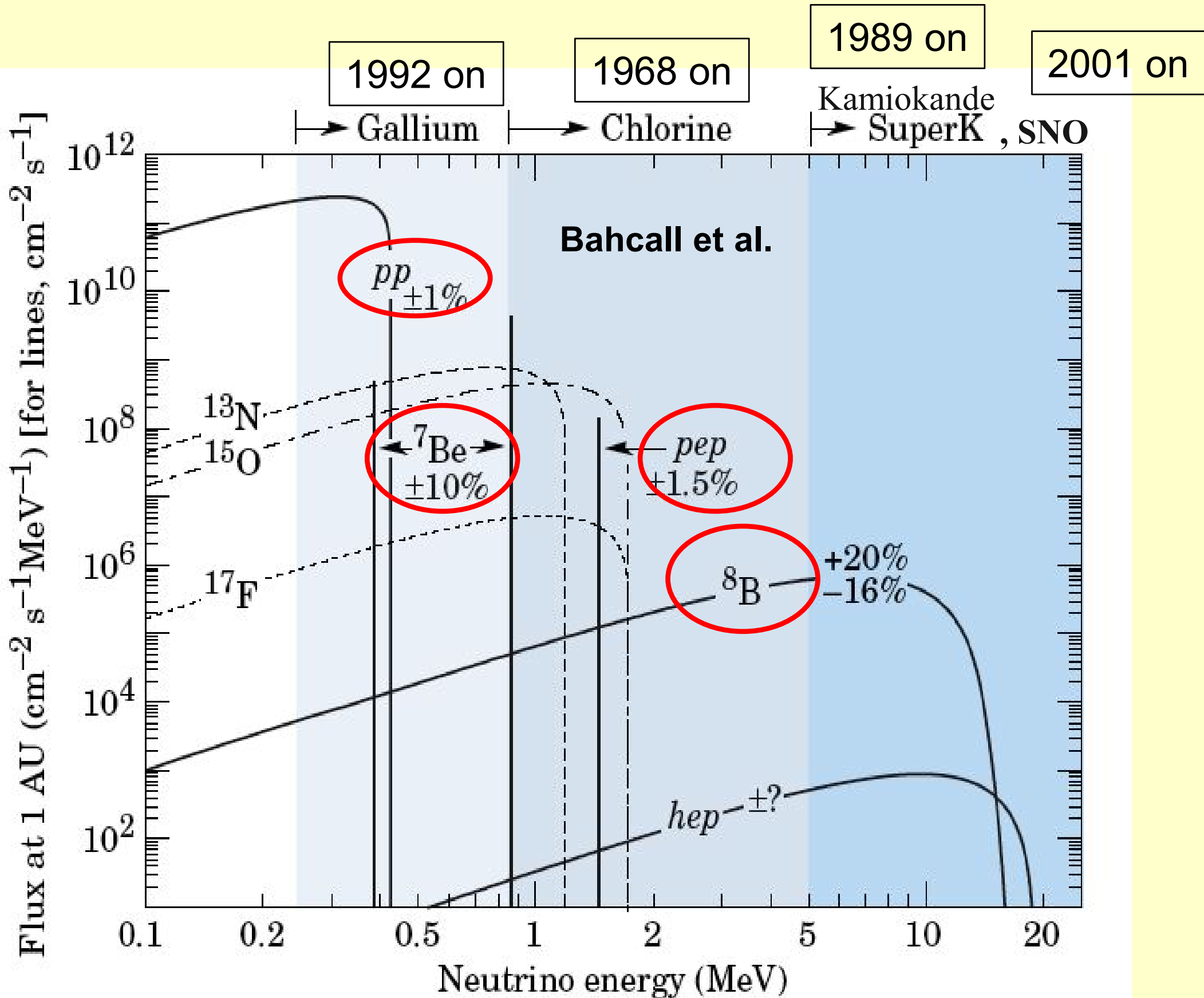
Elastic Scattering from Electrons



ν_x , but enhanced for ν_e x 6
10 times lower count rate
Points away from the Sun

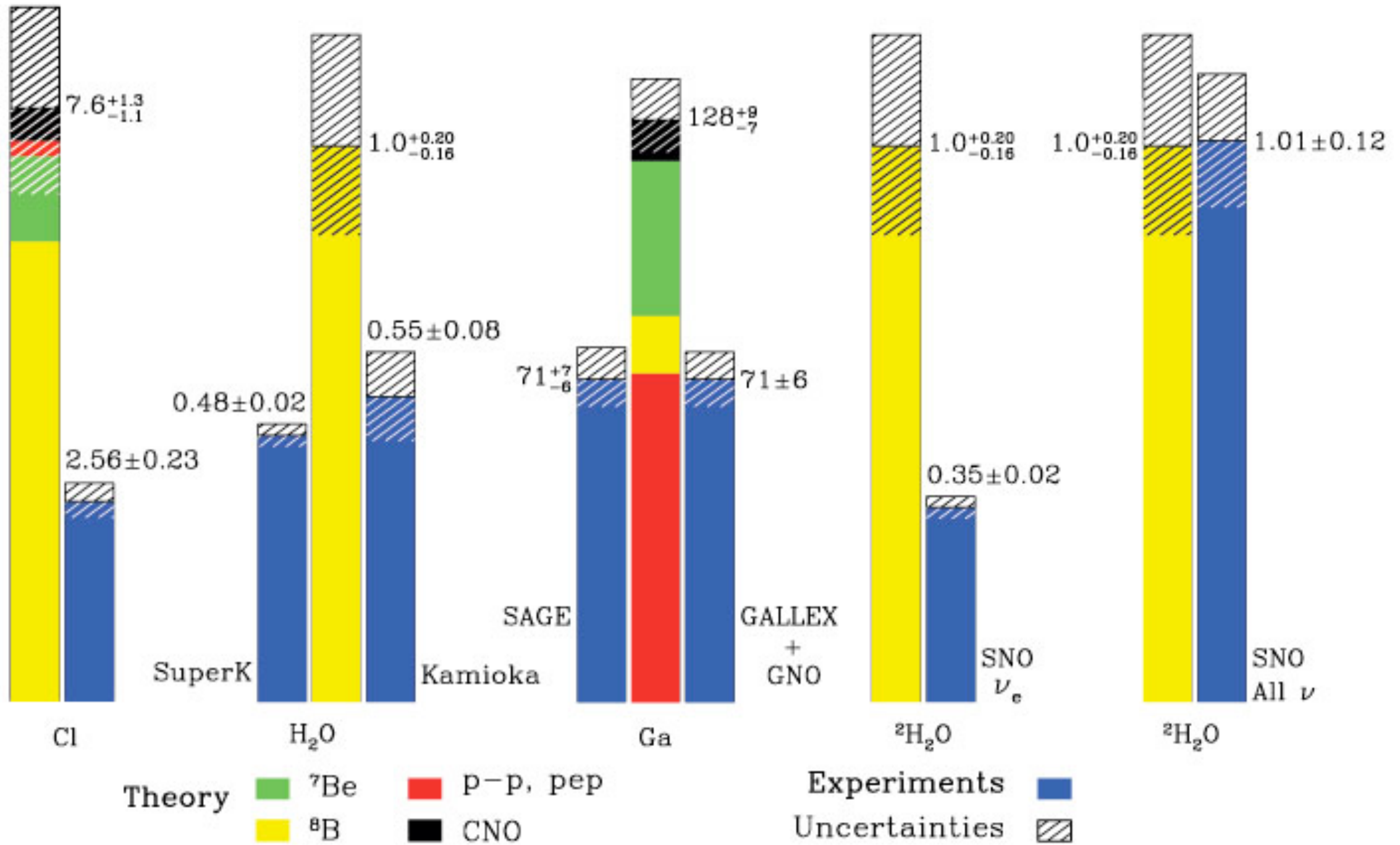


Including other solar neutrino measurements



Total Rates: Standard Model vs. Experiment

Bahcall-Pinsonneault 2000



Oscillation parameters

The situation with the solar neutrino data is more complicated. Radiochemical experiments give only the total rate of neutrinos above the threshold energy of the experiment. Super-K can measure the energy spectrum only of B neutrinos. All four data sets are fitted simultaneously. The oscillation theory is more complicated and includes more free parameters. There are at least three possibilities:

- **vacuum oscillations.** Because of the large distance to the Sun and the MeV energy of the solar neutrinos Δm^2 has to be small, less than 10^{-10} eV². Vacuum oscillations can manifest themselves on a yearly basis because of the small eccentricity of the Earth orbit around the Sun. A seasonal change as a function of the Earth–Sun distance has been observed but there is not a clear manifestation of vacuum oscillations. Several Δm^2 values between 10^{-11} and 10^{-10} eV² are allowed.
- **LMA MSW.** The MSW effect branches into a large mixing angle (LMA) solution and small mixing angle (SMA) solution. The LMA solution is allowed for $\sin^2 2\theta > 0.5$ and Δm^2 between 10^{-5} and 10^{-4} eV².
- **SMA SMW.** The small mixing angle solution is allowed for $\sin^2 2\theta$ between 2×10^{-3} and 10^{-2} and Δm^2 between 5×10^{-6} and 10^{-5} eV².

Oscillation parameters

Figure 7.20 shows schematically the allowed regions for atmospheric neutrino and MSW solar neutrino oscillations.

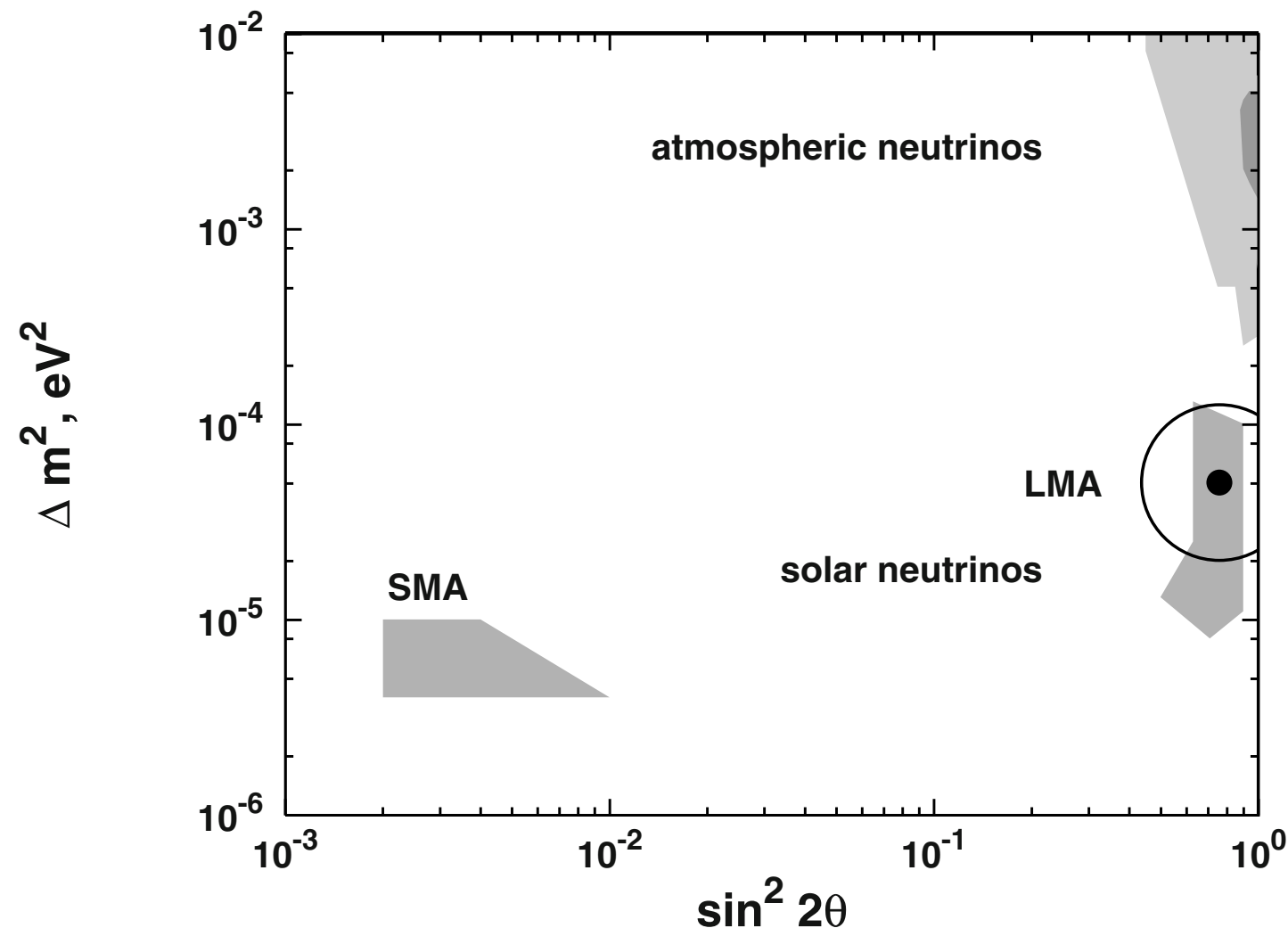


Fig. 7.20. Allowed parameter values for neutrino oscillations. Atmospheric neutrinos are all bunched in the upper right-hand part of the graph. Light shaded areas come from Soudan2 and MACRO, and the darker shading from Super-K. The SMA (lower left) and LMA solutions for MSW oscillations of solar neutrinos are also shown. The vacuum oscillations solution for solar neutrinos is not shown. The dot and the circle show the best fit of the new SNO data combined with the world data set.

MIXING OF THREE NEUTRINOS

$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$

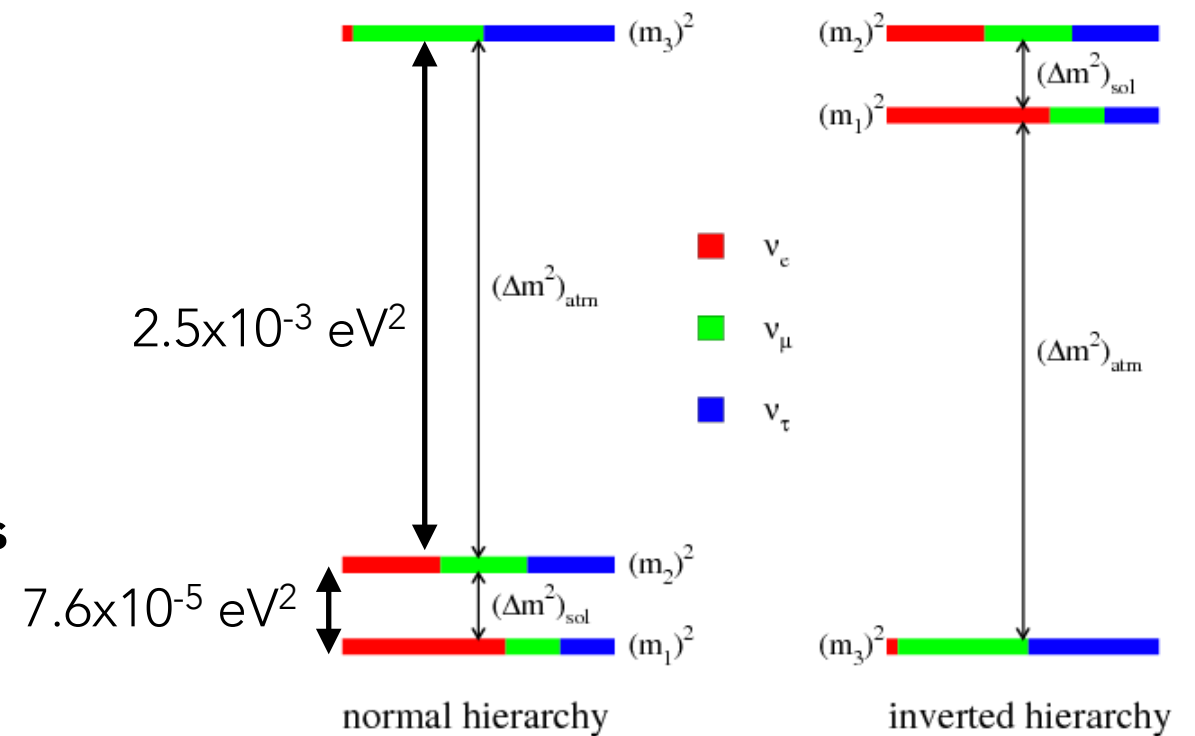
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{ij} = \sin \theta_{ij}$
 $c_{ij} = \cos \theta_{ij}$

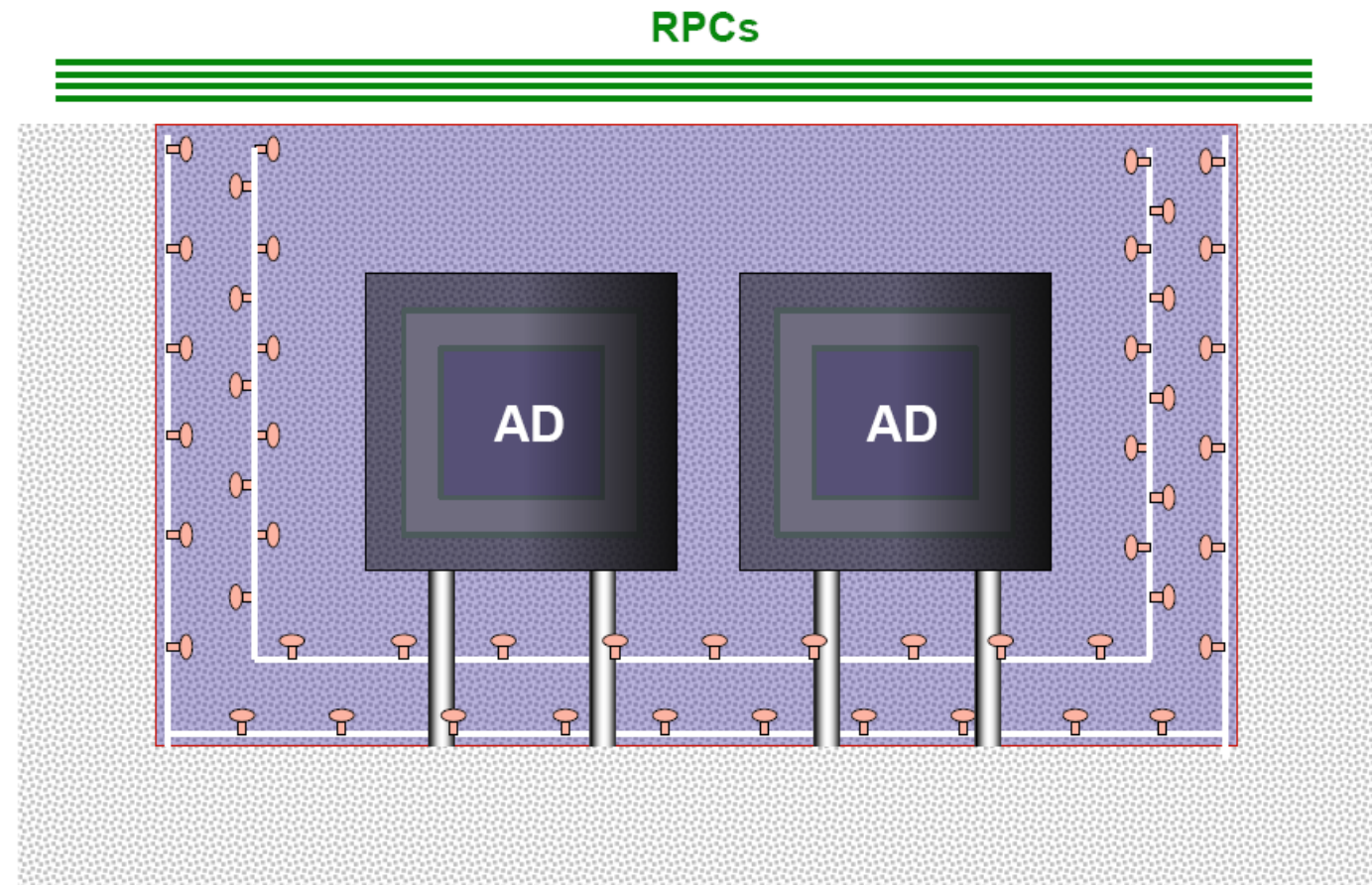
"standard" parametrization

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

- Three rotation angles ($\theta_{12}, \theta_{13}, \theta_{23}$)
 - θ_{12} : solar and reactor experiments
 - θ_{13} : reactor and long-baseline experiments
- One complex phase δ_{CP}
 - additional phases if neutrinos are "Majorana"
 - **CP-odd: changes sign for antineutrino oscillations**



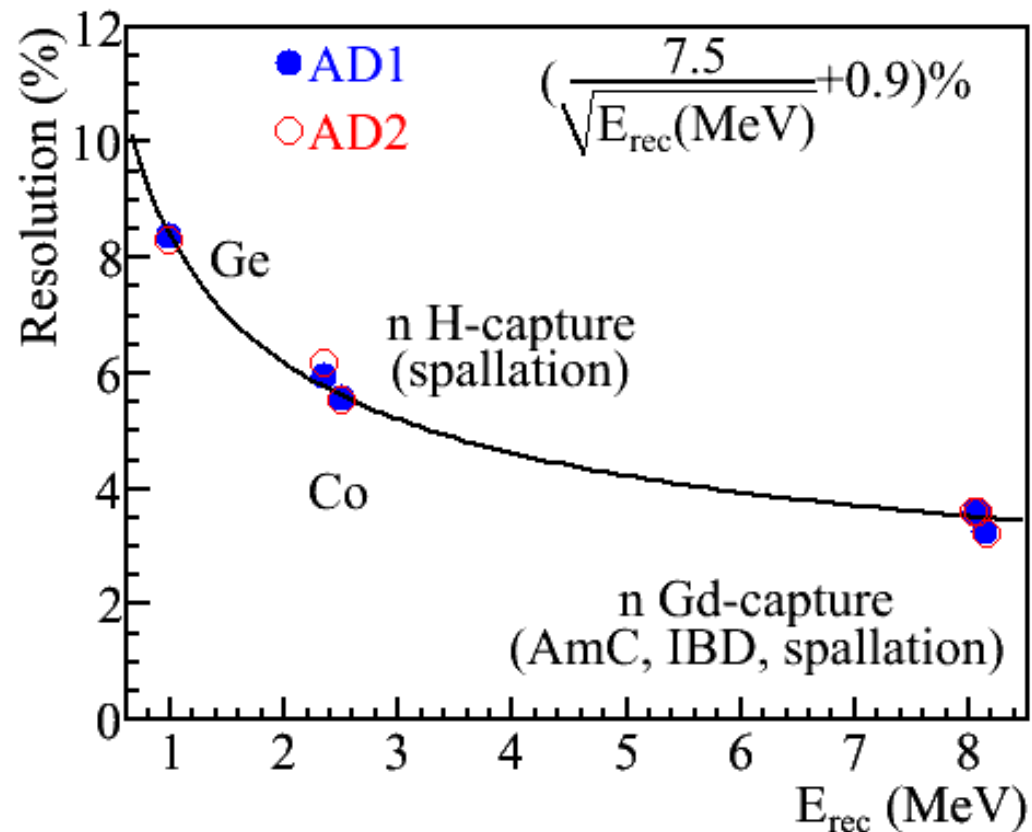
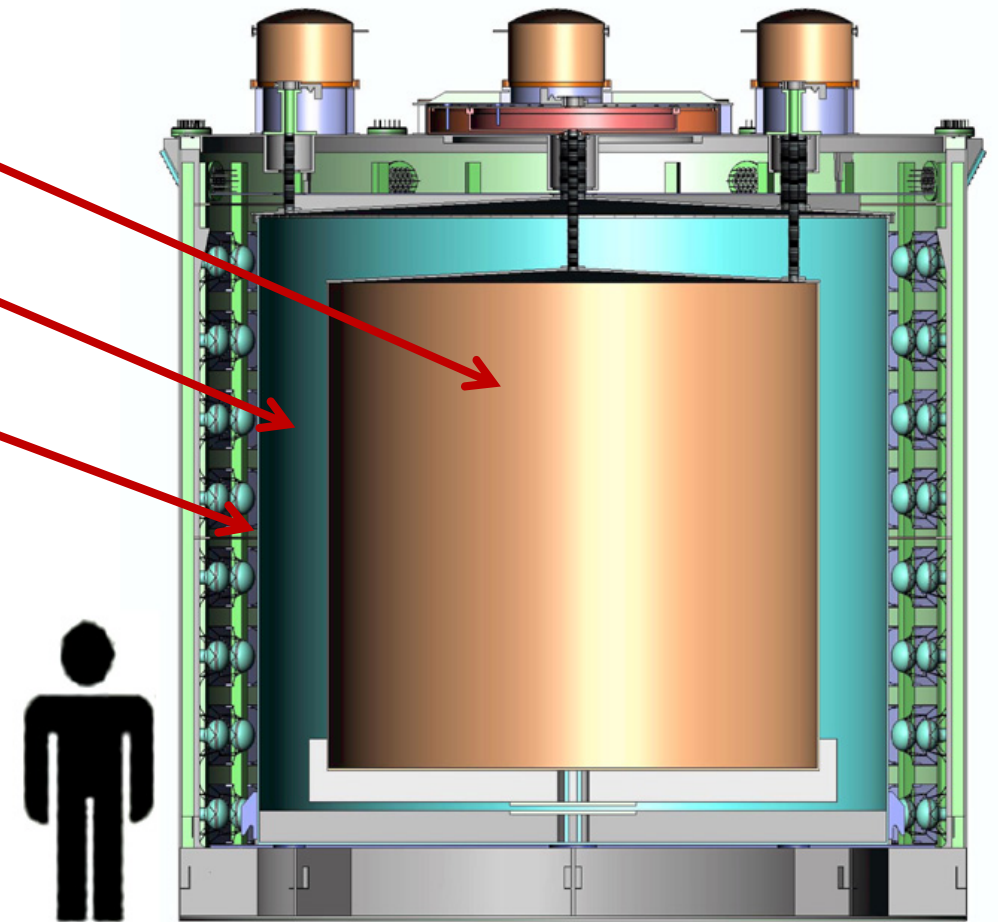
Daya Bay Experiment: Layout



- ◆ **Relative measurement to cancel **Corr. Syst. Err.****
 - ⇒ 2 near sites, 1 far site
- ◆ **Multiple AD modules at each site to reduce **Uncorr. Syst. Err.****
 - ⇒ Far: 4 modules, near: 2 modules
- ◆ **Multiple muon detectors to reduce **veto eff. uncertainties****
 - ⇒ Water Cherenkov: 2 layers
 - ⇒ RPC: 4 layers at the top + telescopes

Anti-neutrino Detector (AD)

- ◆ **Three zones modular structure:**
 - I. target: Gd-loaded scintillator
 - II. γ -catcher: normal scintillator
 - III. buffer shielding: oil
- ◆ **192 8" PMTs/module**
- ◆ **Two optical reflectors at the top and the bottom, Photocathode coverage increased from 5.6% to 12%**



Target: 20 t, 1.6m

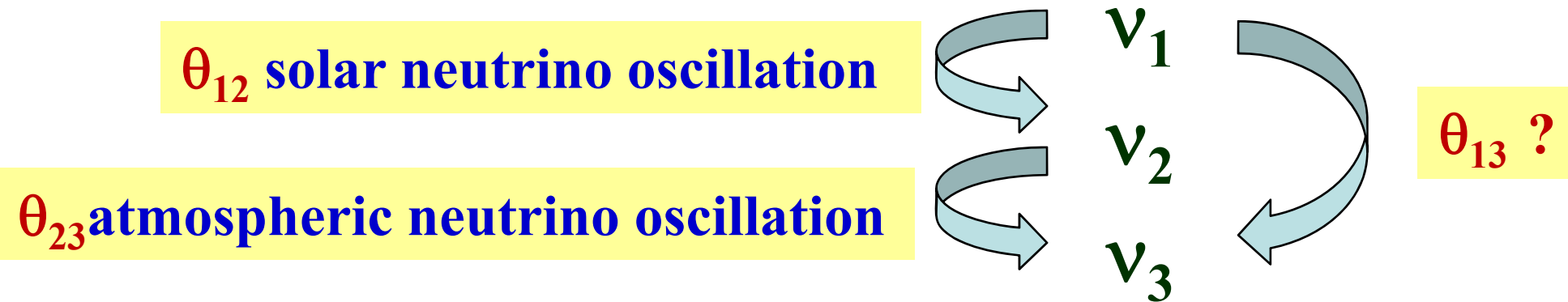
γ -catcher: 20t, 45cm

Buffer: 40t, 45cm

Total weight: ~110 t

Daya Bay: for a New Type of Oscillation

- ◆ Goal: search for a new oscillation mode θ_{13} ?



- ◆ Neutrino mixing matrix:

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

Unknown mixing parameters: θ_{13} , δ + 2 Majorana phases

Need sizable θ_{13} for the δ measurement

Observation of Electron Anti-neutrino Disappearance at Daya Bay

Summary

- ◆ Electron anti-neutrino disappearance is observed at Daya Bay,

$$R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)},$$

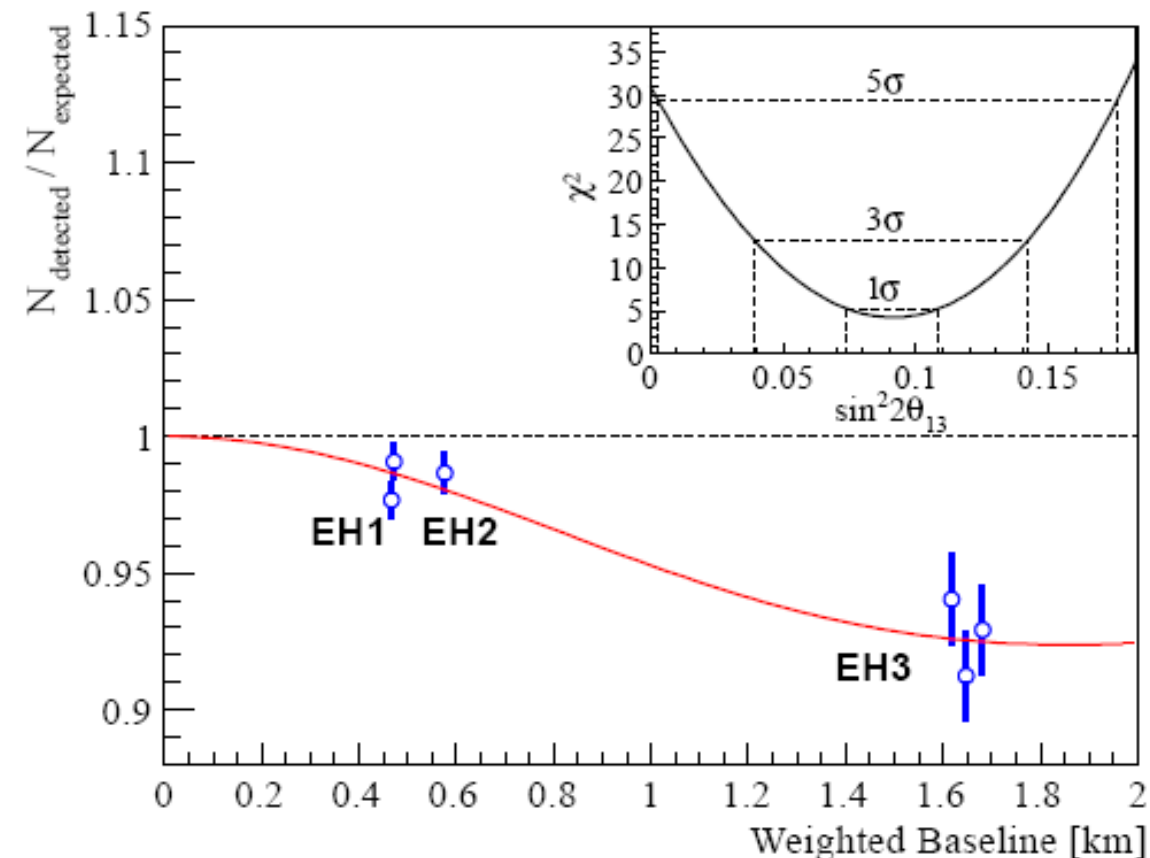
together with a spectral distortion

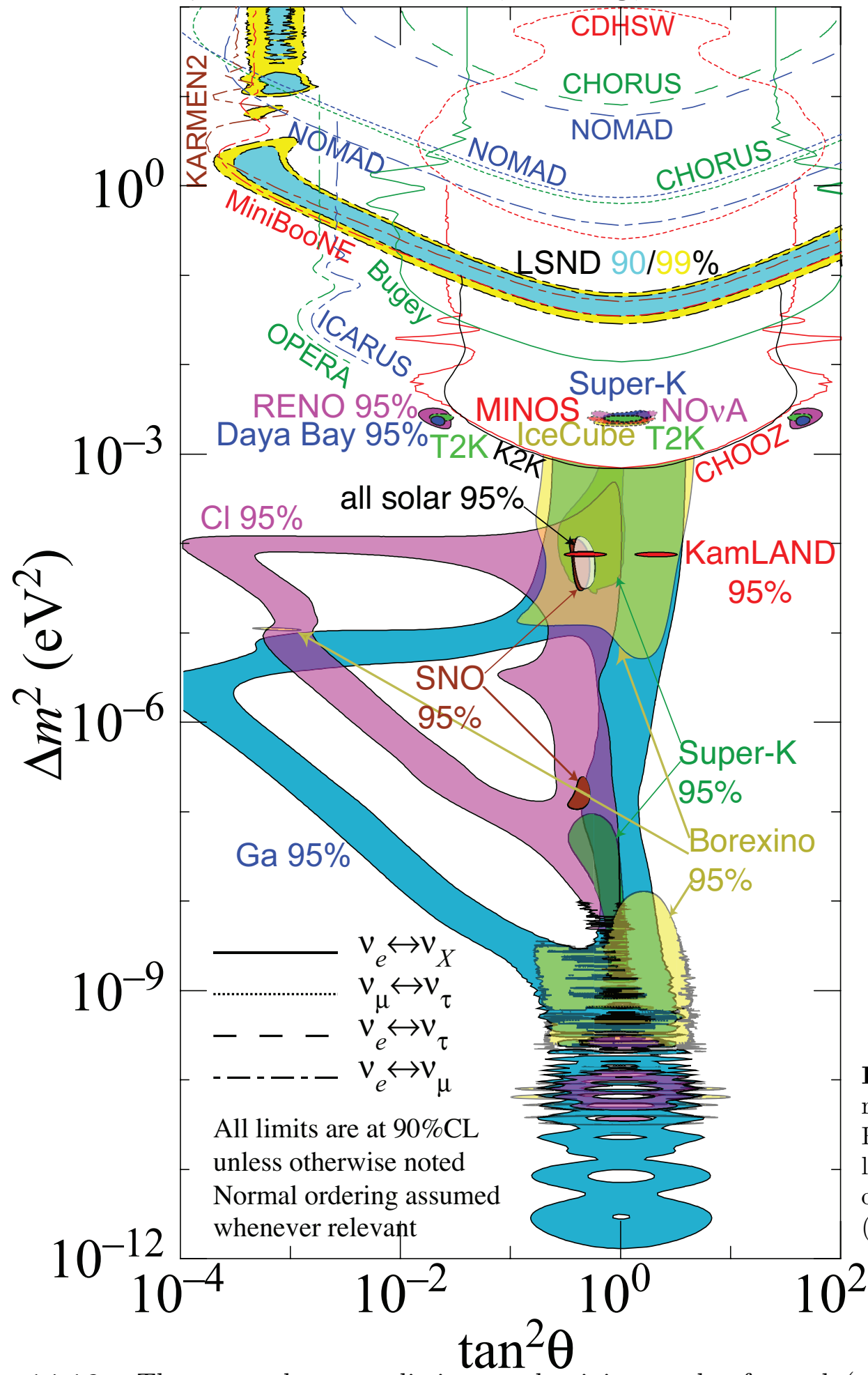
- ◆ A new type of neutrino oscillation is thus discovered

$$\text{Sin}^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

$$\chi^2/\text{NDF} = 4.26/4$$

5.2 σ for non-zero θ_{13}





14. Neutrino Masses, Mixing, and Oscillations

Updated November 2017 by K. Nakamura (Kavli IPMU (WPI), U. Tokyo, KEK), and S.T. Petcov (SISSA/INFN Trieste, Kavli IPMU (WPI), U. Tokyo, Bulgarian Academy of Sciences).

1. Introduction: Massive neutrinos and neutrino mixing
2. The three-neutrino mixing
3. Future progress
4. The nature of massive neutrinos
5. The seesaw mechanism and the baryon asymmetry of the Universe
6. Neutrino sources
 - 6.1 Standard solar model predictions of the solar neutrino fluxes
 - 6.2 Atmospheric neutrino fluxes
 - 6.3 Accelerator neutrino beams
 - 6.4 Reactor neutrino fluxes
7. Neutrino oscillations in vacuum
8. Matter effects in neutrino oscillations
 - 8.1 Effects of Earth matter on oscillations of neutrinos
 - 8.2 Oscillations (flavour conversion) of solar neutrinos
 - 8.2.1 Qualitative analysis
 - 8.2.2 The solar ν_e survival probability
 - 8.2.3 The day-night asymmetry
9. Neutrino oscillation experiments
 - 9.1 Solar neutrino experiments
 - 9.2 Atmospheric neutrino oscillation experiments
 - 9.3 Accelerator neutrino oscillation experiments
 - 9.4 Reactor neutrino oscillation experiments
10. Results of solar neutrino experiments and KamLAND
 - 10.1 Measurements of Δm_{21}^2 and θ_{12}
 - 10.2 Solar neutrino flux measurements and indications of matter effects
11. Measurements of $|\Delta m_{31(32)}^2|$ and θ_{23} , and related topics
 - 11.1 ν_μ disappearance data
 - 11.2 Octant of θ_{23}
 - 11.3 Comparison of ν_μ disappearance and $\bar{\nu}_\mu$ disappearance data
 - 11.4 ν_τ appearance data
12. Measurements of θ_{13}
13. $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance data and measurements of δ .
14. Search for oscillations involving light sterile neutrinos
15. Outlook

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

June 5, 2018 19:50

Figure 14.16: The squared-mass splittings and mixing angles favored (solid regions) or excluded (open regions) by existing neutrino oscillation measurements. Results are categorized by channels: ν_e disappearance (solid lines), $\nu_\mu \leftrightarrow \nu_\tau$ (dotted lines), $\nu_e \leftrightarrow \nu_\tau$ (dashed lines), and $\nu_e \leftrightarrow \nu_\mu$ (dashed-dotted lines). The normal mass ordering is assumed where relevant. The figure was contributed by H. Murayama (University of California, Berkeley, and Kavli IPMU, University of Tokyo, 2018).

June 5, 2018 19:50



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. McFarlane,
Queen's University
/SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

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2019/2020

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first semester, 6 ec

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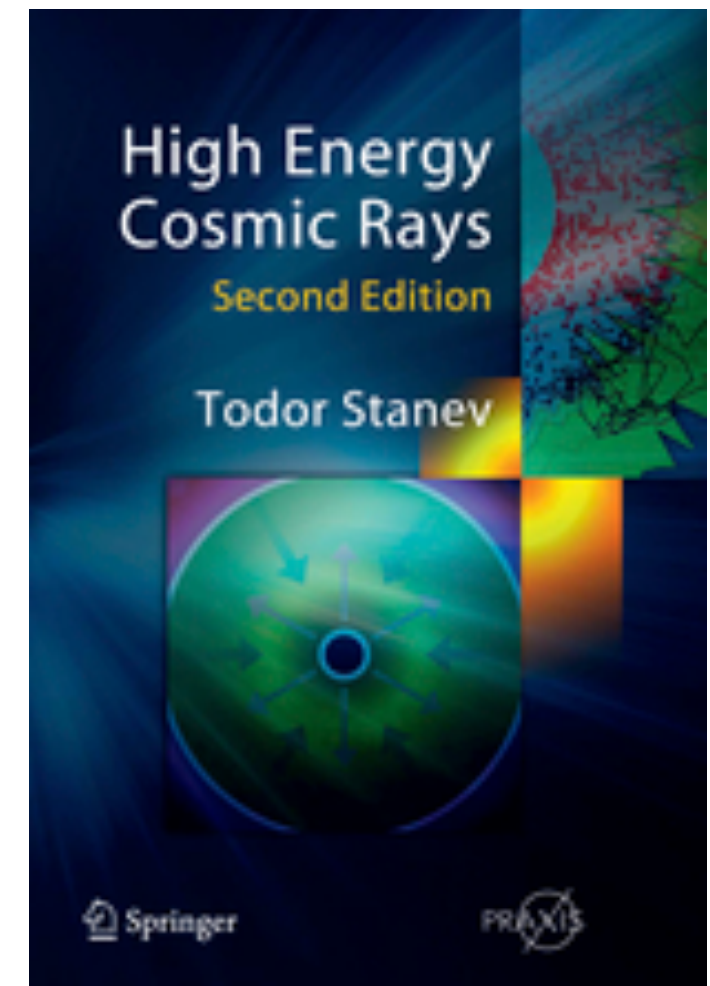
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Beyond the Standard Model, Dark Matter (SC)

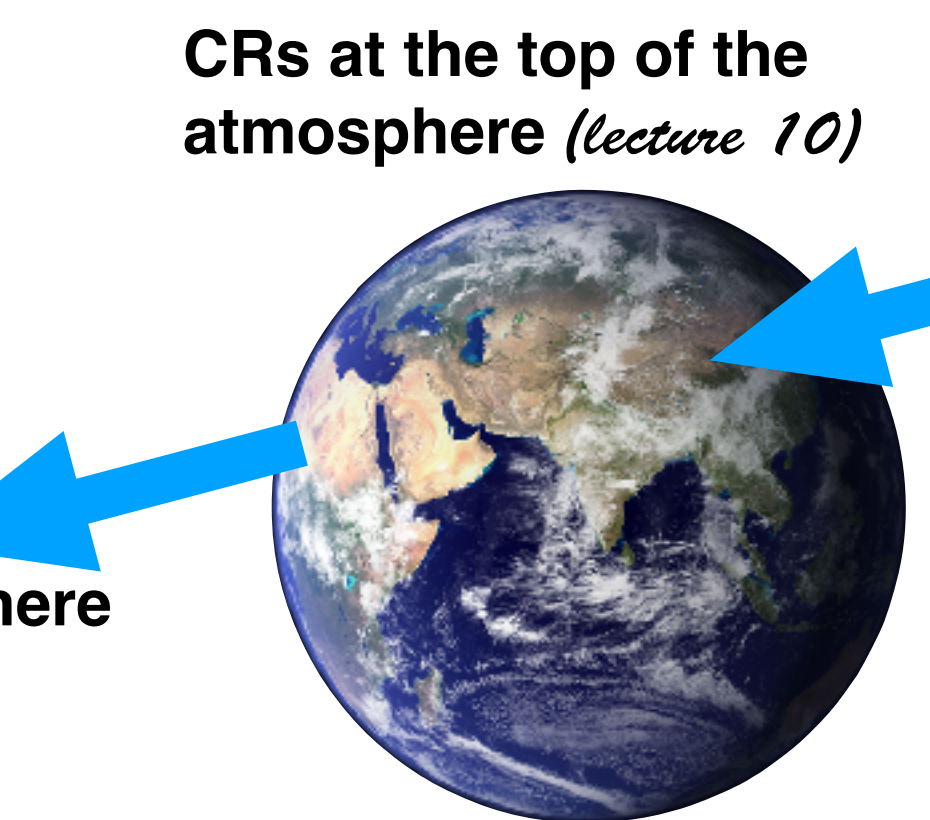
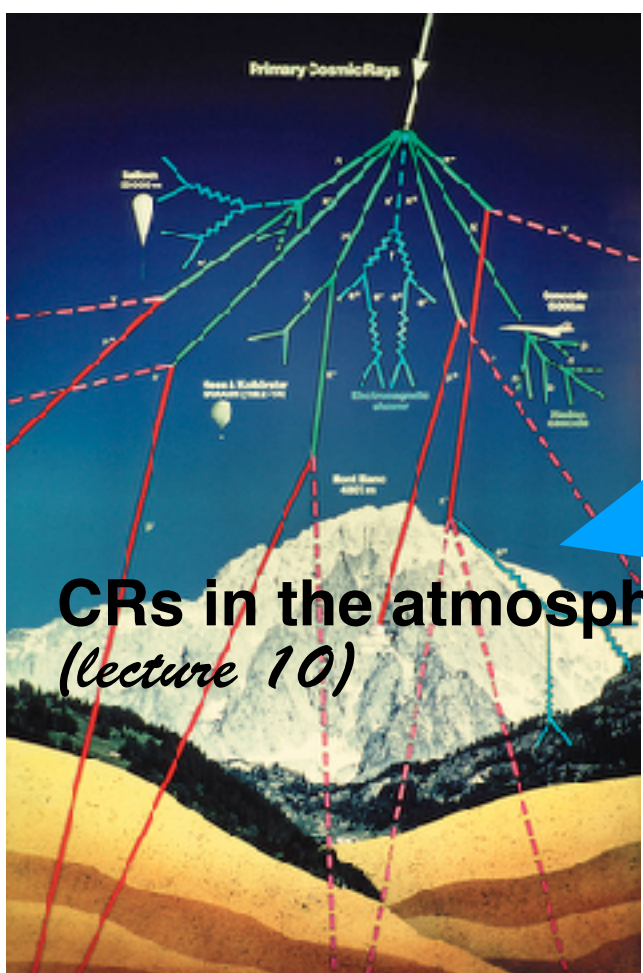
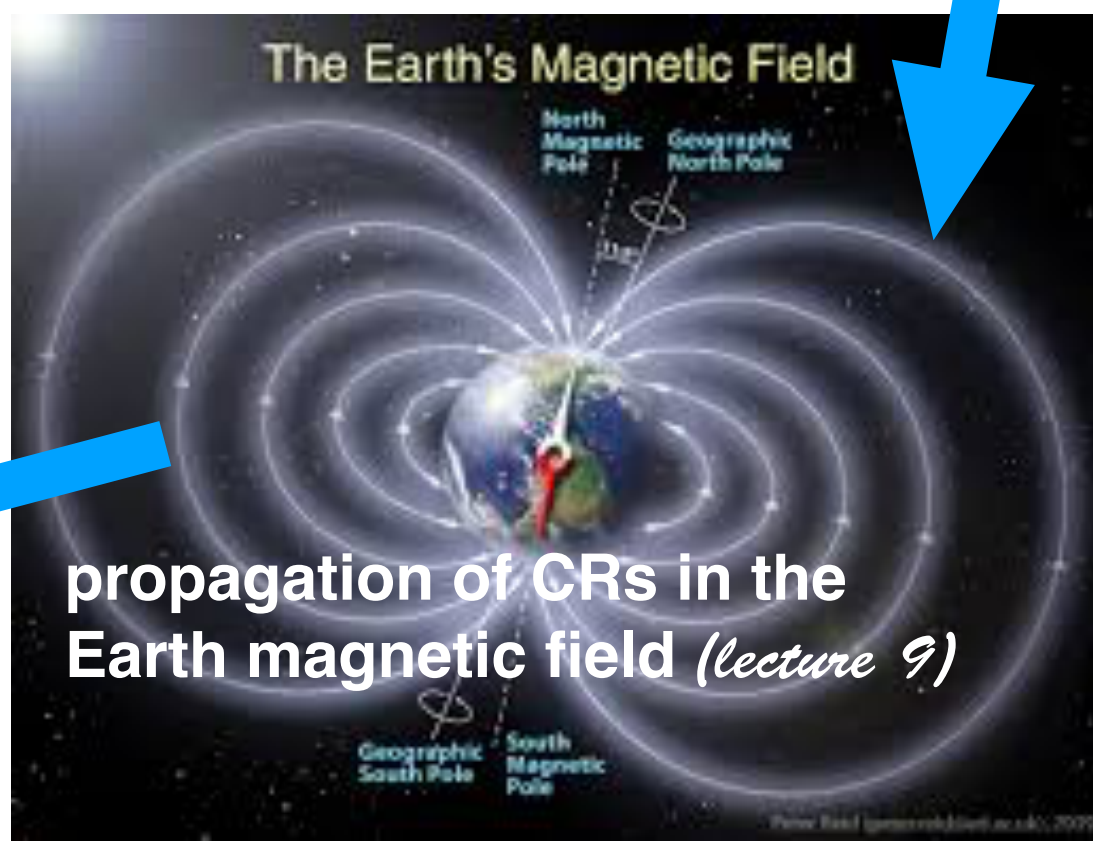
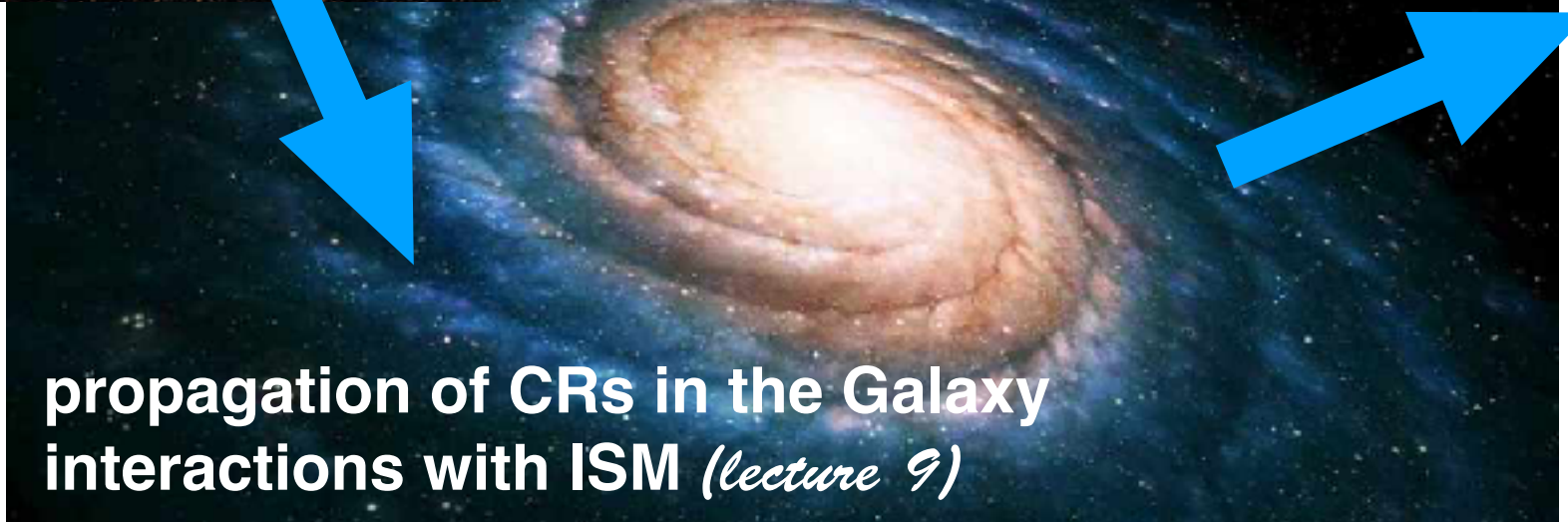
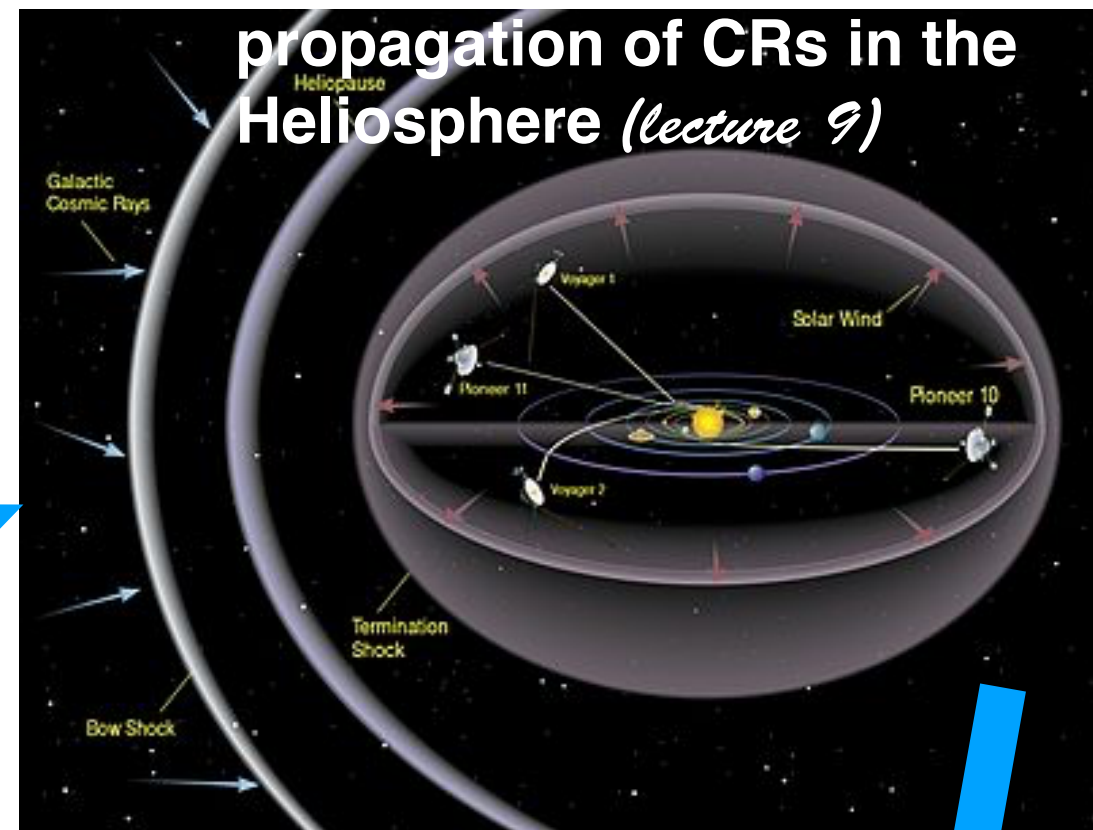
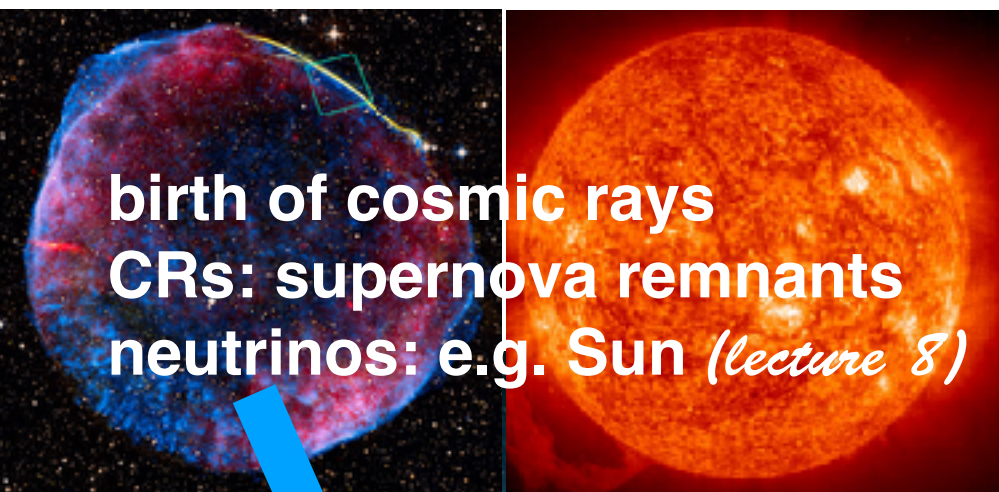
11.12.2019 13. Lambda CDM, Big-bang nucleosynthesis

18.12.2019 14. Dark matter - Beyond-the-standard-model reasons

for Astroparticle Physics

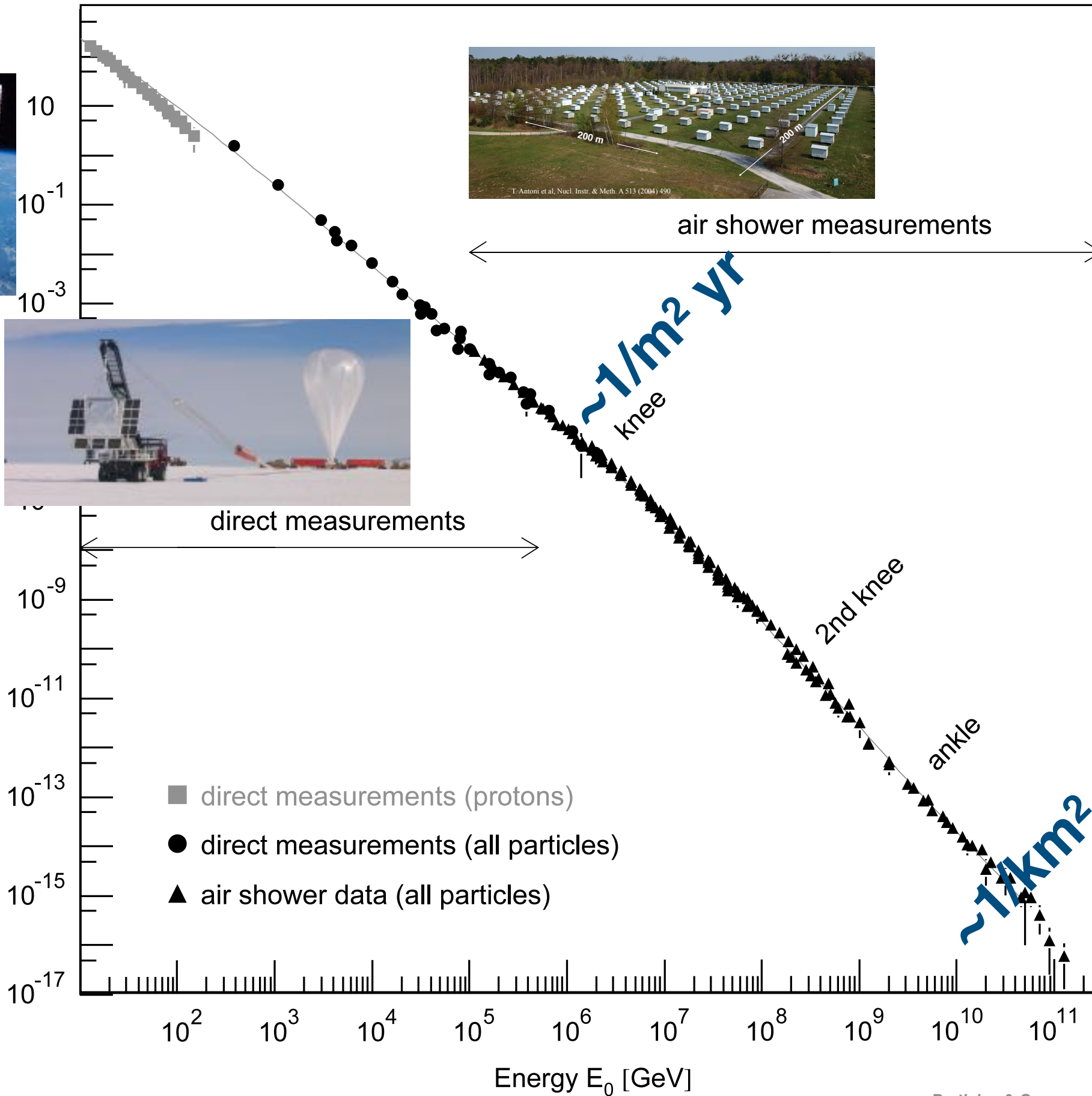


Jörg R. Hörandel
HG 02.721
<http://particle.astro.ru.nl>



CRs underground (lecture 11)
neutrino oscillations (lecture 11+12)

$\sim 1000/m^2 \text{ s}$



air shower measurements



direct measurements

$\sim 1/m^2 \text{ yr}$
knee

2nd knee

ankle

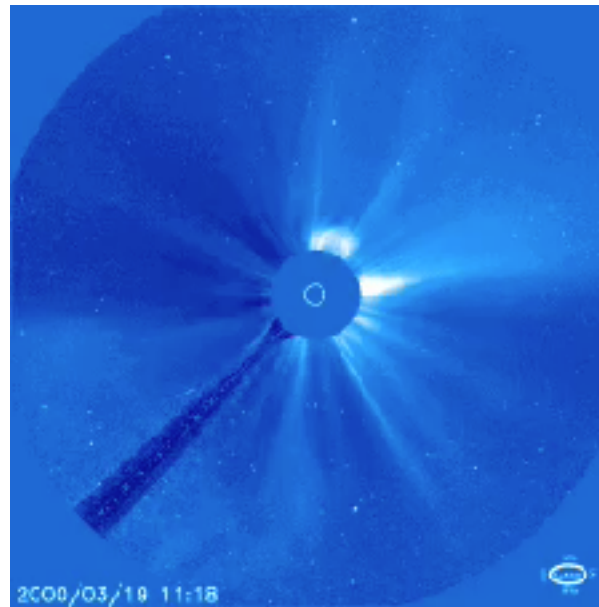
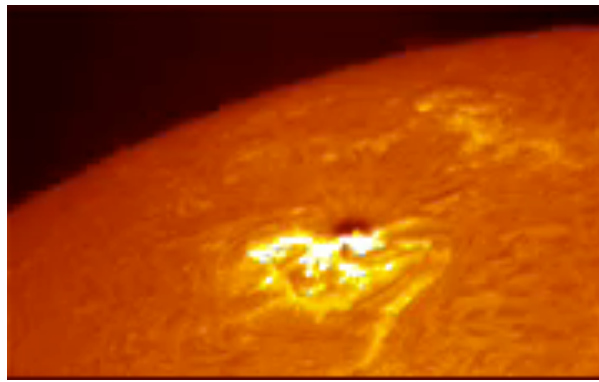
- direct measurements (protons)
- direct measurements (all particles)
- ▲ air shower data (all particles)

$\sim 1/km^2 \text{ century}$

energy spectrum of cosmic rays extends to extremely high energies:
 $10^{20} \text{ eV} \sim 16 \text{ J}$

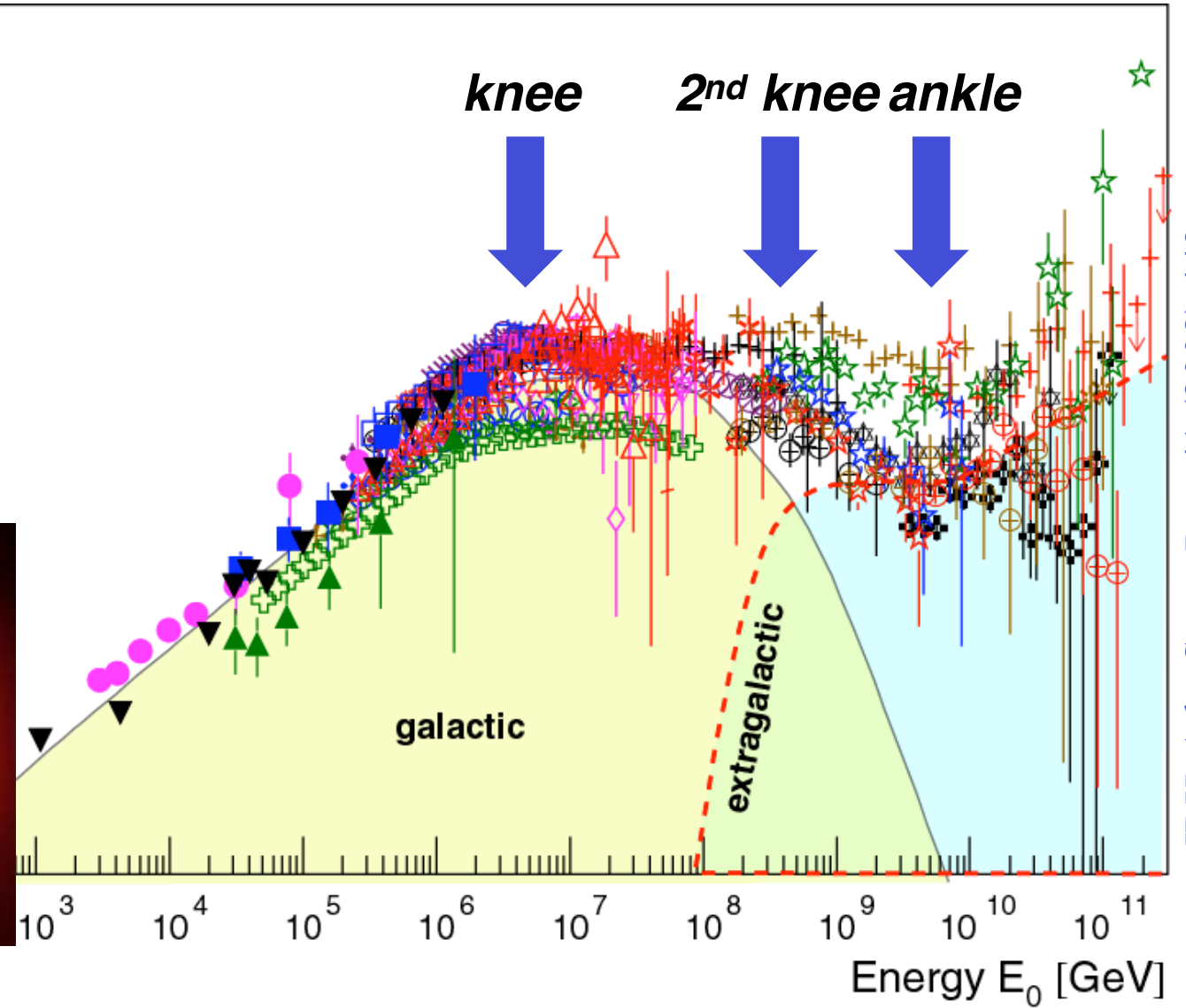
Cosmic rays

Solar flares

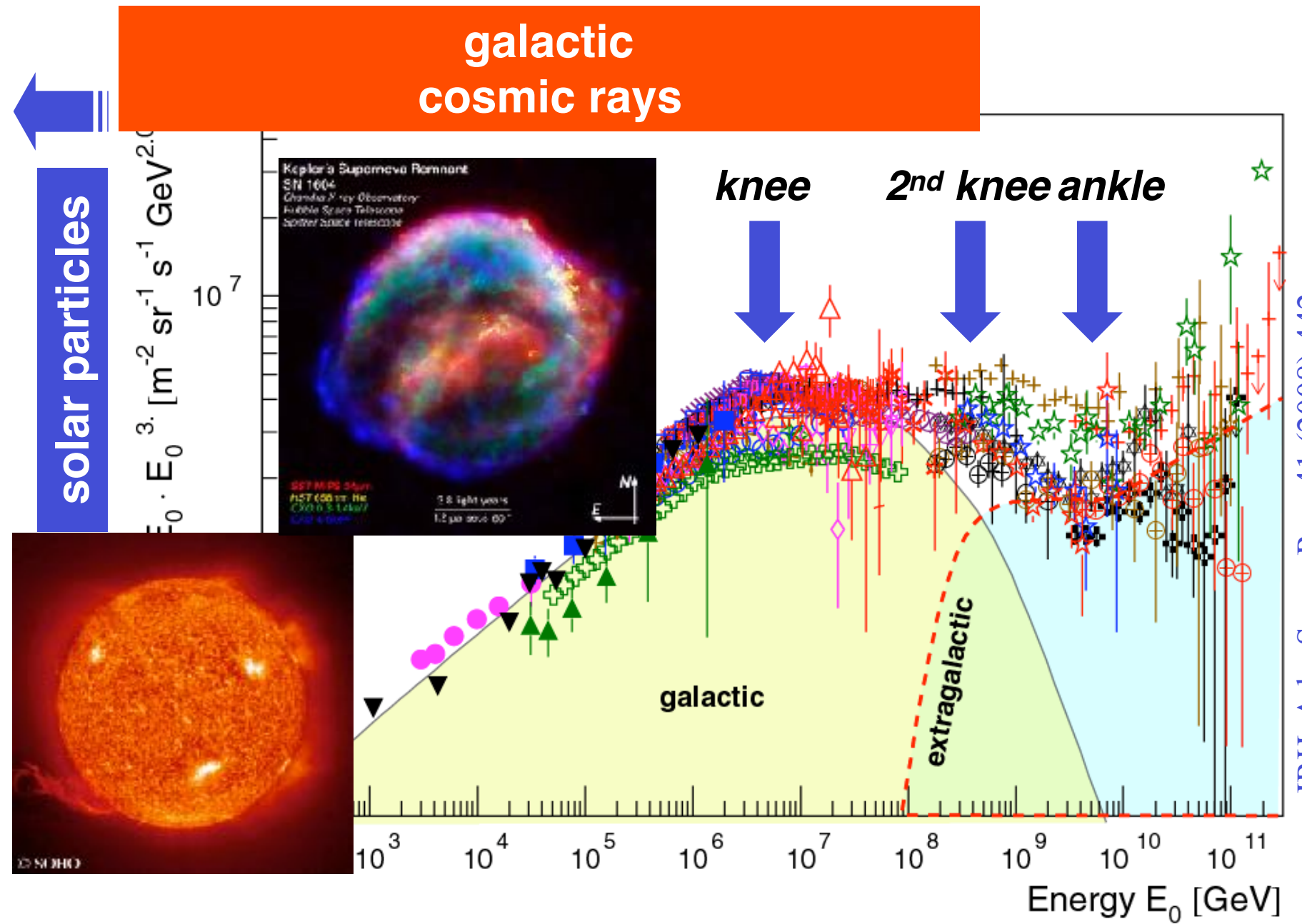


←
solar particles

$E_0 \cdot E_0^3 \cdot [\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{2.0}]$
 10^7



Cosmic rays



JRH, Adv. Space Res. 41 (2008) 442

Cosmic rays

Radius of particle in magnetic field

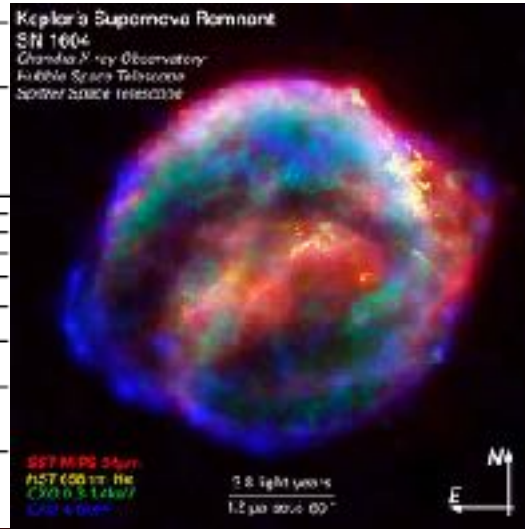
$$r = \frac{p}{ZeB} \quad r[\text{pc}] = 1.08 * \frac{E [\text{PeV}]}{B [\mu\text{G}]}$$



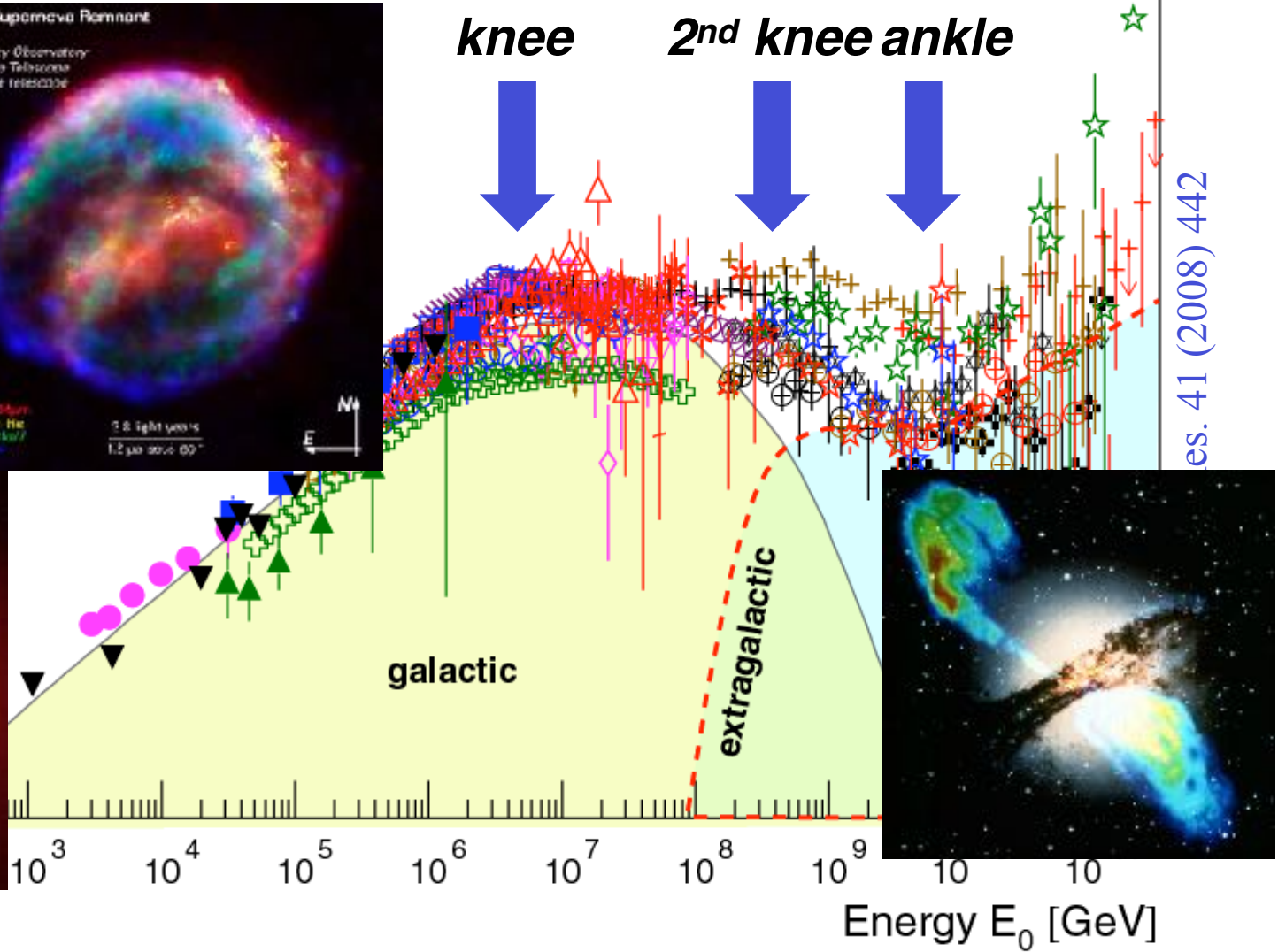
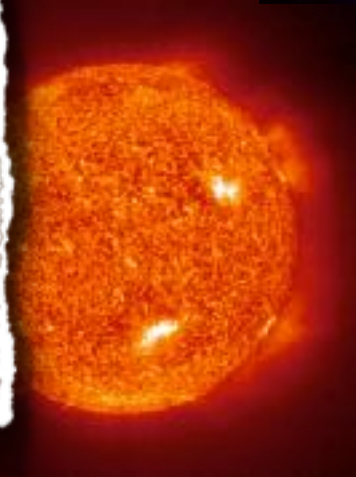
© N MRO

galactic cosmic rays extragalactic cosmic rays

$E_0 \cdot E_0^3 \cdot [\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{2.0}]$



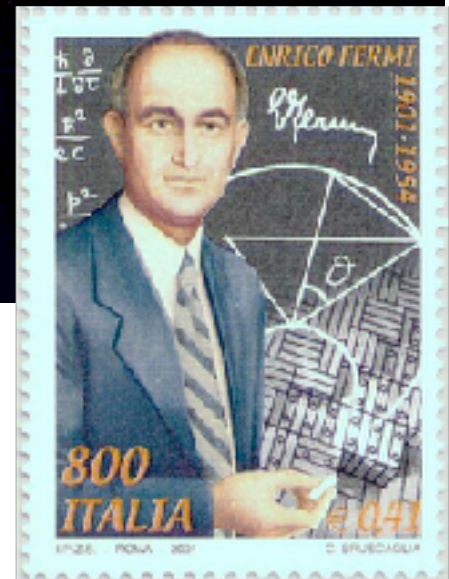
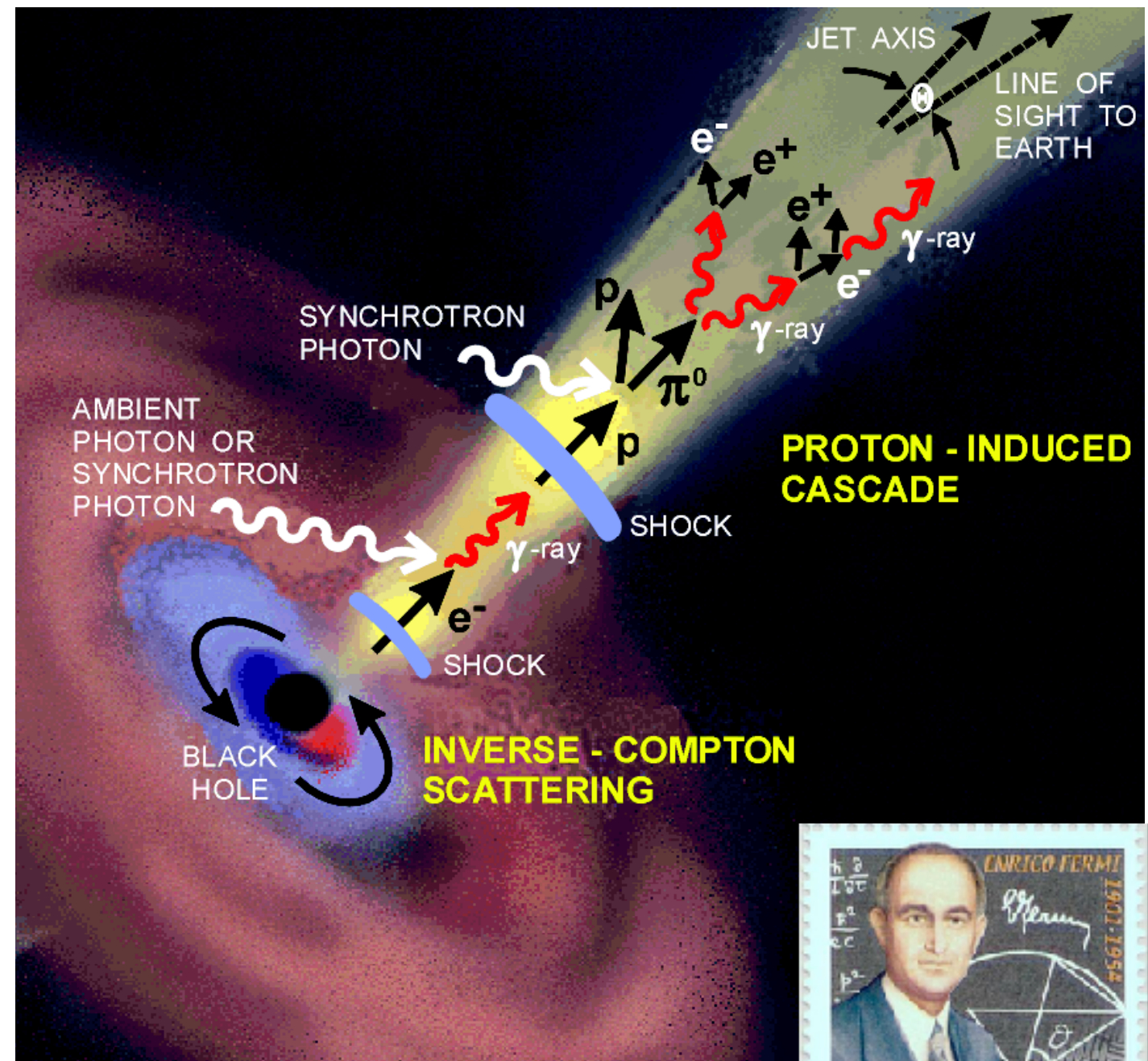
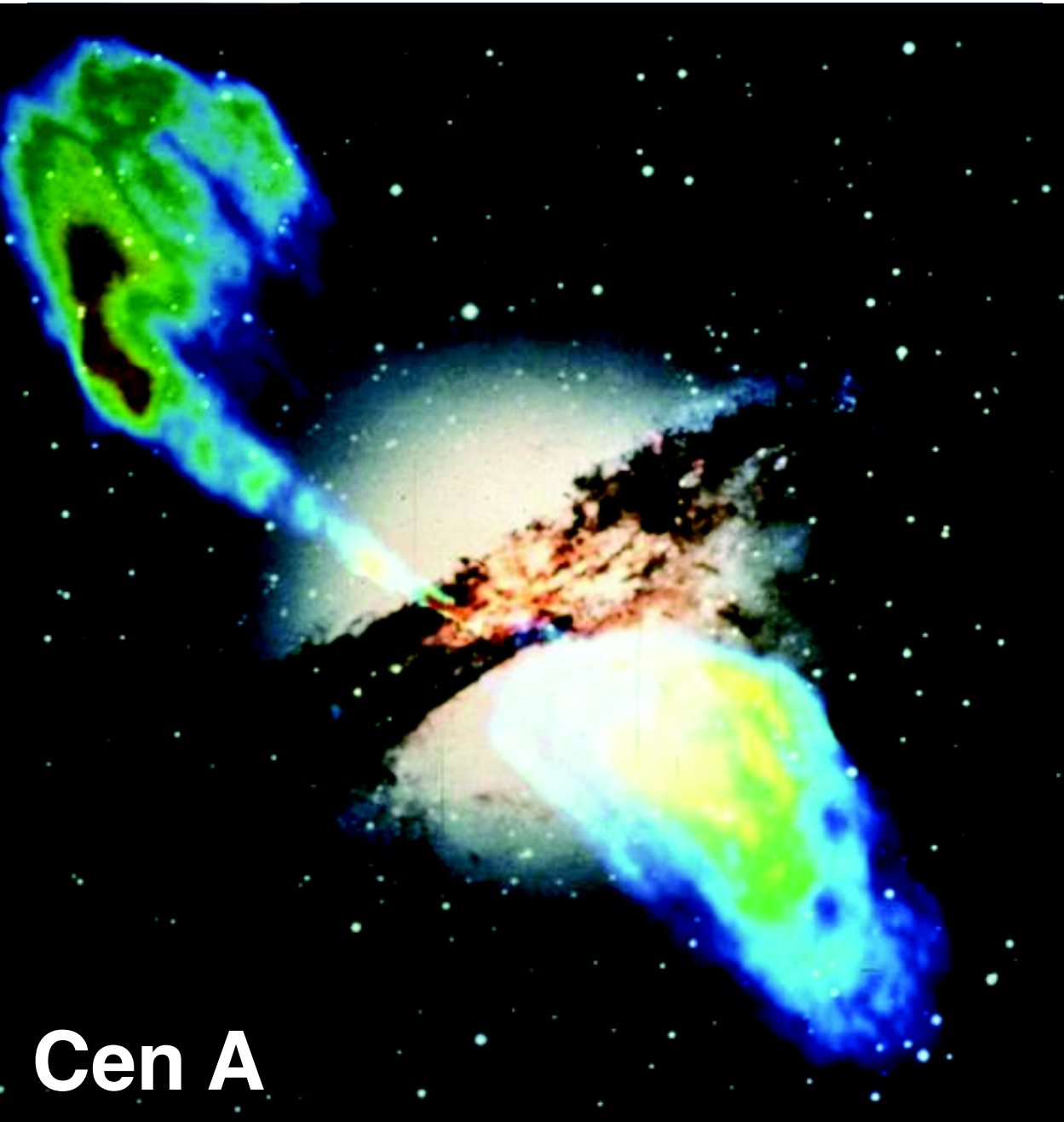
Kepler's Supernova Remnant
SN 1604
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope



es. 41 (2008) 442

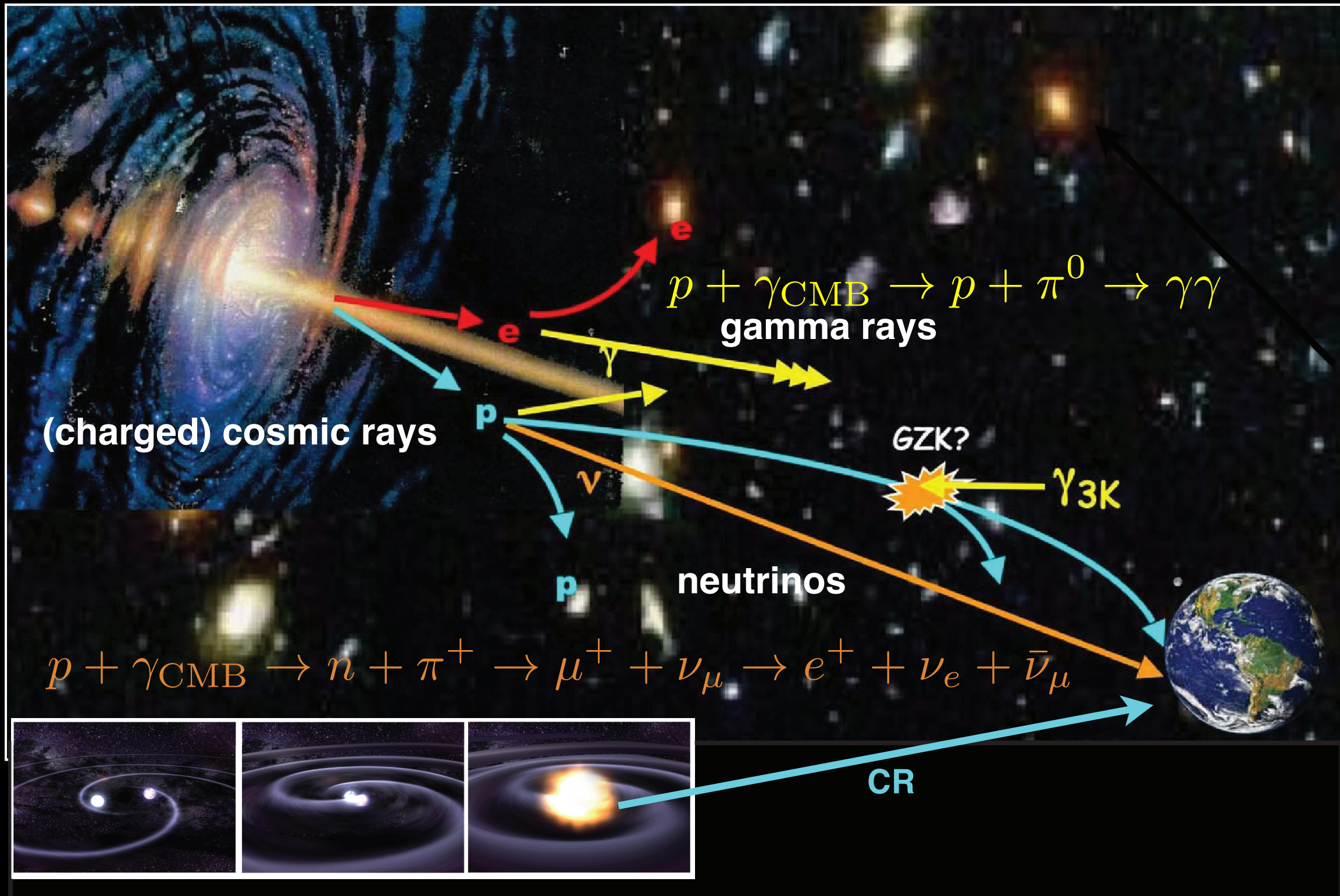
$r =$ 0.04 pc 3.6 pc 360 pc 36 kpc

Acceleration of cosmic rays in jets of AGN



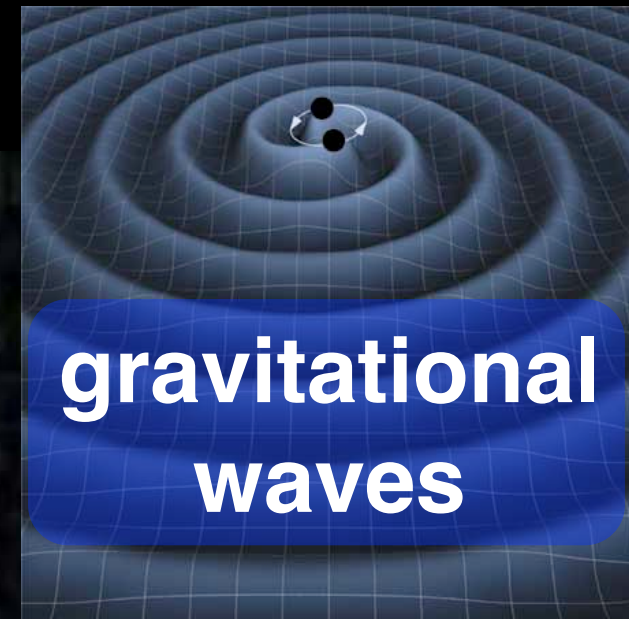
Origin of cosmic rays

multi messenger technique



Astroparticle Physics

messengers from the Universe



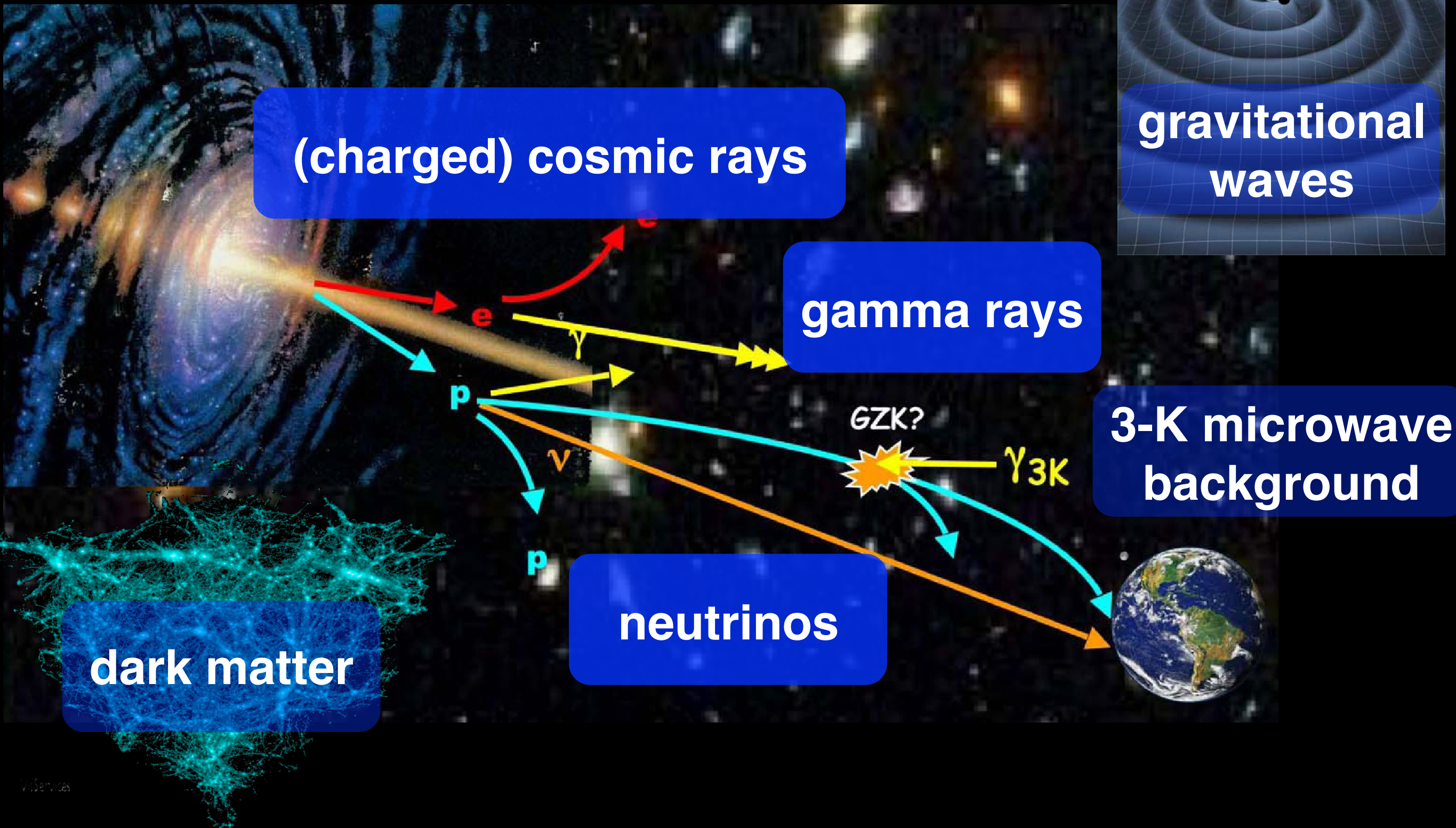
(charged) cosmic rays

gamma rays

3-K microwave background

neutrinos

dark matter



Astroparticle Physics

master course NM076B,

6 EC, 2nd semester, *starting January, 2020*

2 h lecture, 2 h student presentations

topics include:

1. Historical introduction, basic properties of cosmic rays
2. Hadronic interactions and accelerator data
3. Cascade equations
4. Electromagnetic cascades
5. Extensive air showers
6. Detectors for extensive air showers
7. High energy cosmic rays and the knee in the energy spectrum of cosmic rays
8. Radio detection of extensive air showers
9. Acceleration, astrophysical accelerators and beam dumps
10. Extragalactic propagation of cosmic rays
11. Ultra high energy cosmic rays
12. Astrophysical gamma rays and neutrinos
13. Neutrino astronomy
14. Gamma-ray astronomy

Shift at the Pierre Auger Observatory

2 weeks shift at the observatory in Malargue, Argentina
please contact me if you are interested

