Particles and the Cosmos

2020/2021

Sascha Caron, Jörg Hörandel

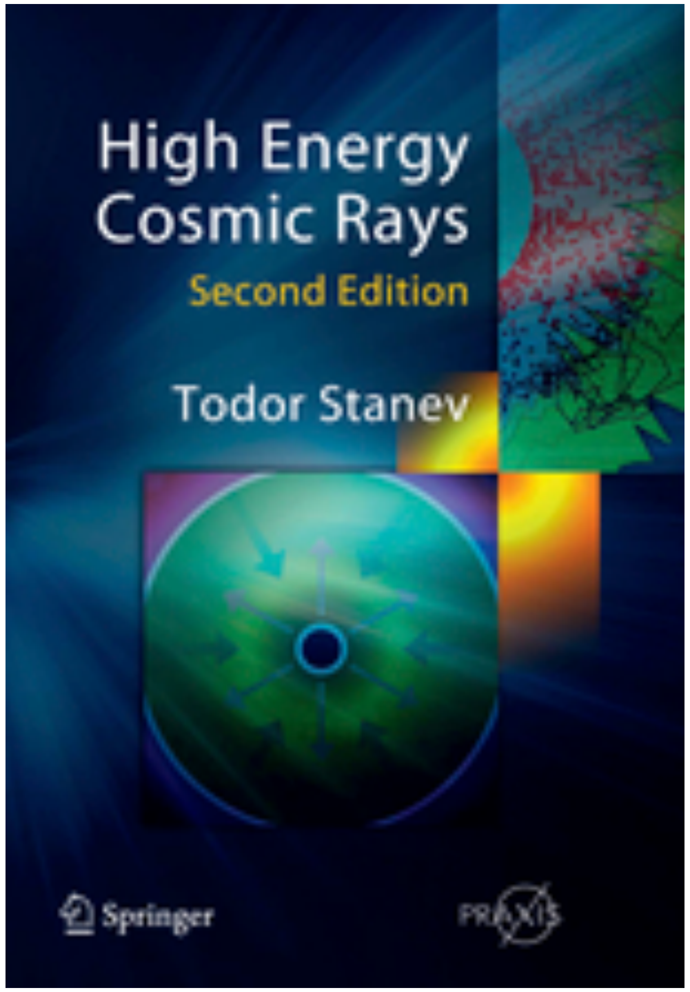
NM109
first semester, 6 ec

28 hrs lecture Tuesday 8:30 - 10:15
28 hrs problem session Wednesday 10:30 - 12:15

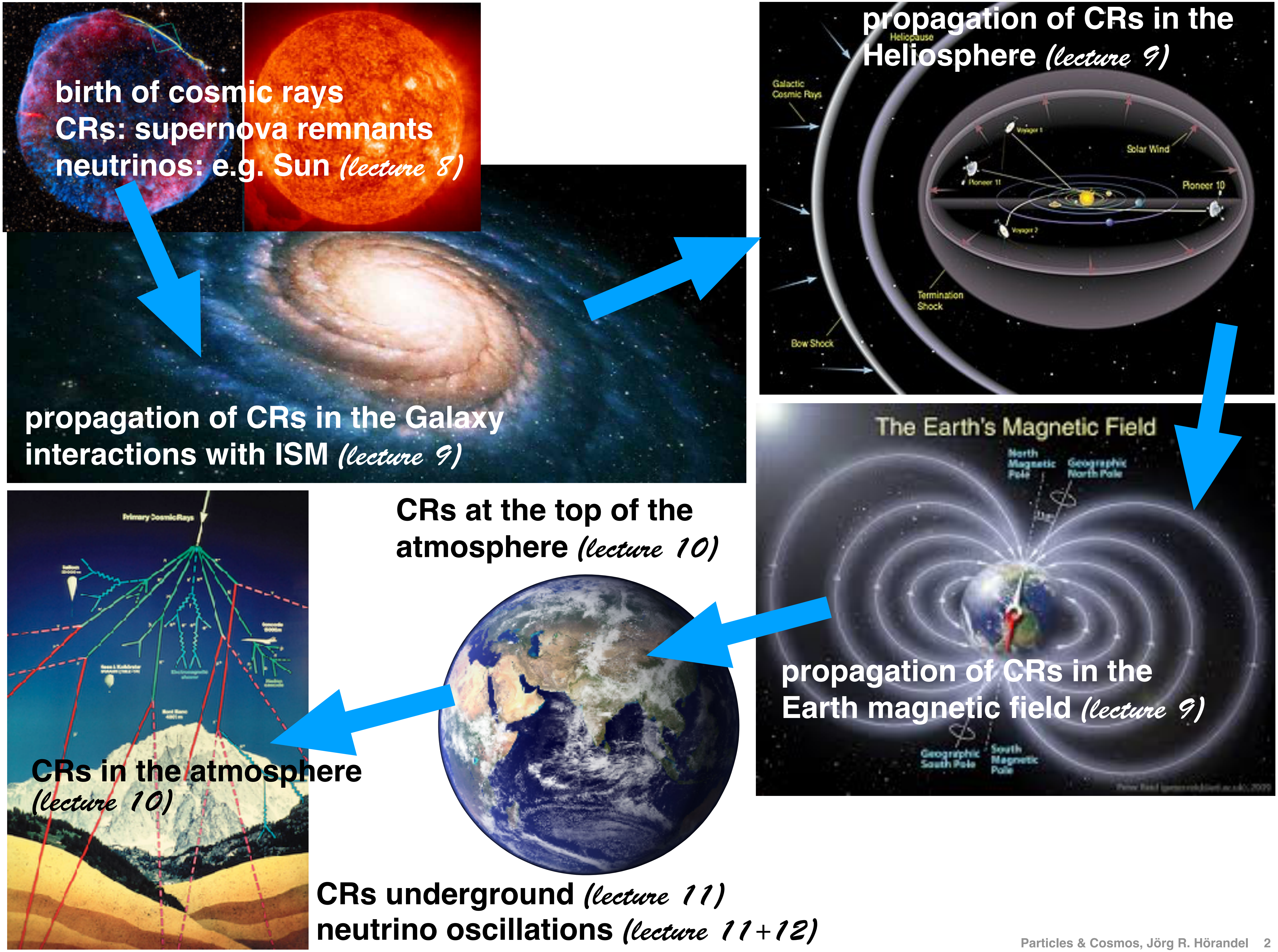
Lectures:

Experimental methods (JRH)
01.09.2020 1. Interactions with matter
08.09.2020 2. Detectors
Standard model (SC)
15.09.2020 3. Particles, QED, Feynman rules
22.09.2020 4. Hadrons and QCD
29.09.2020 5. Hadrons and QCD
06.10.2020 6. Weak interactions, CP violation
13.10.2020 7. Higgs mechanism
Astroparticle physics (JRH)
03.11.2020 8. The birth of cosmic rays
10.11.2020 9. Cosmic rays in the Galaxy, in the heliosphere, and the Earth magnetic field
17.11.2020 10. Cosmic rays at the top of and in the atmosphere
24.11.2020 11. Cosmic rays underground - neutrino oscillations
01.12.2020 12. Neutrino oscillations
Beyond the Standard Model, Dark Matter (SC)
08.12.2020 13. Lambda CDM, Big-bang nucleosynthesis
15.12.2020 14. Dark matter - Beyond-the-standard-model reasons

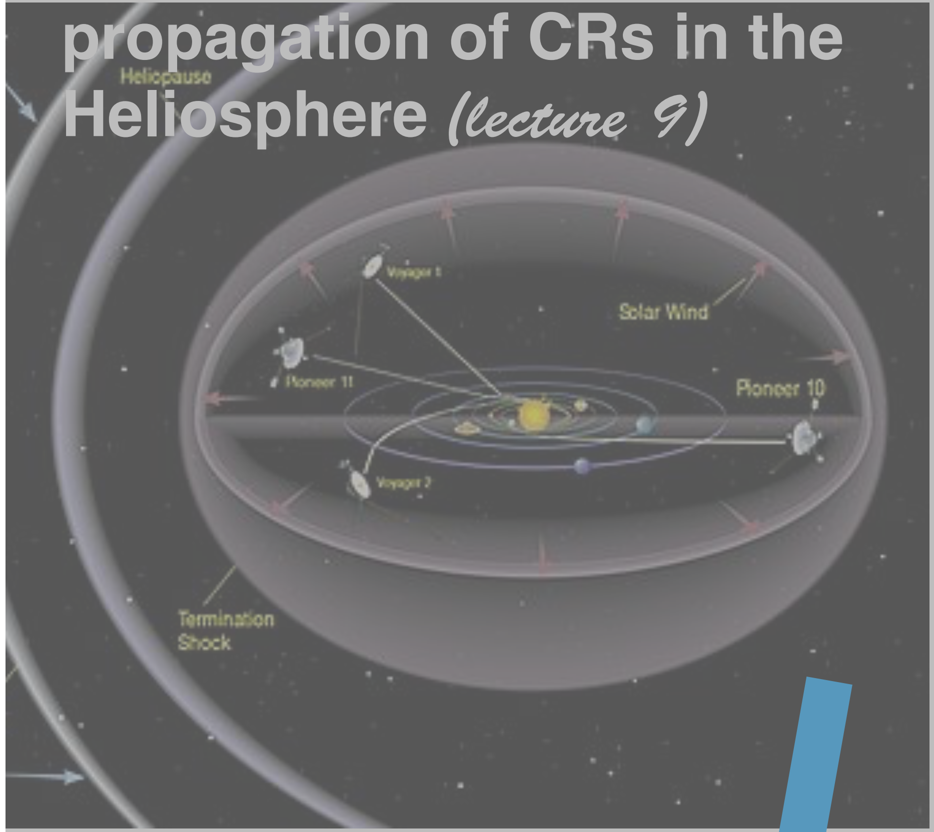
for Astroparticle Physics



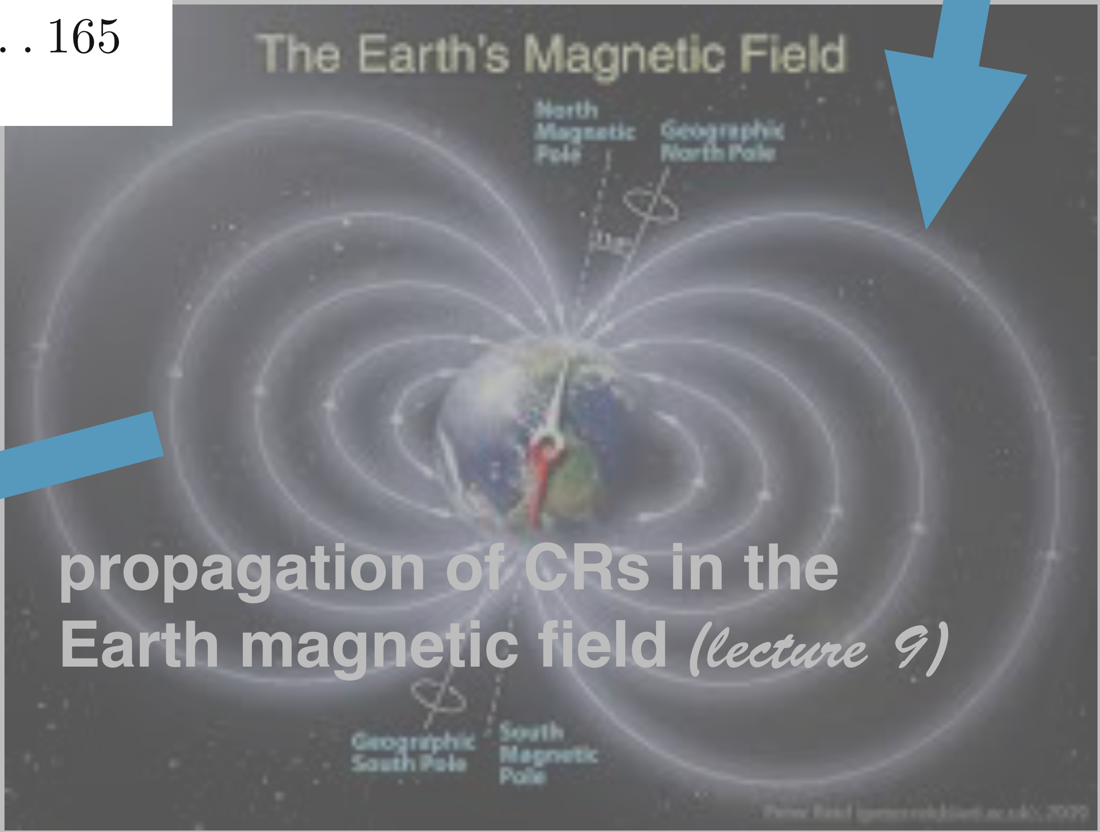
Jörg R. Hörandel
HG 02.728
http://particle.astro.ru.nl


birth of cosmic rays
CRs: supernova remnants
neutrinos: e.g. Sun (lecture 8)
propagation of CRs in the
Heliosphere (lecture 9)
Heliopause
Galactic
Cosmic Rays
Voyager 1
Solar Wind
Pioneer 11
Pioneer 10
Voyager 2
Termination
Shock
Bow Shock
propagation of CRs in the Galaxy
interactions with ISM (lecture 9)
The Earth's Magnetic Field
North
Magnetic
Pole
Geographic
North Pole
Primary Cosmic Rays
CRs at the top of the
atmosphere (lecture 10)
propagation of CRs in the
Earth magnetic field (lecture 9)
Geographic
South Pole
South
Magnetic
Pole
CRs in the atmosphere
(lecture 10)
CRs underground (lecture 11)
neutrino oscillations (lecture 11+12)

today:
Stanev, chapter 7

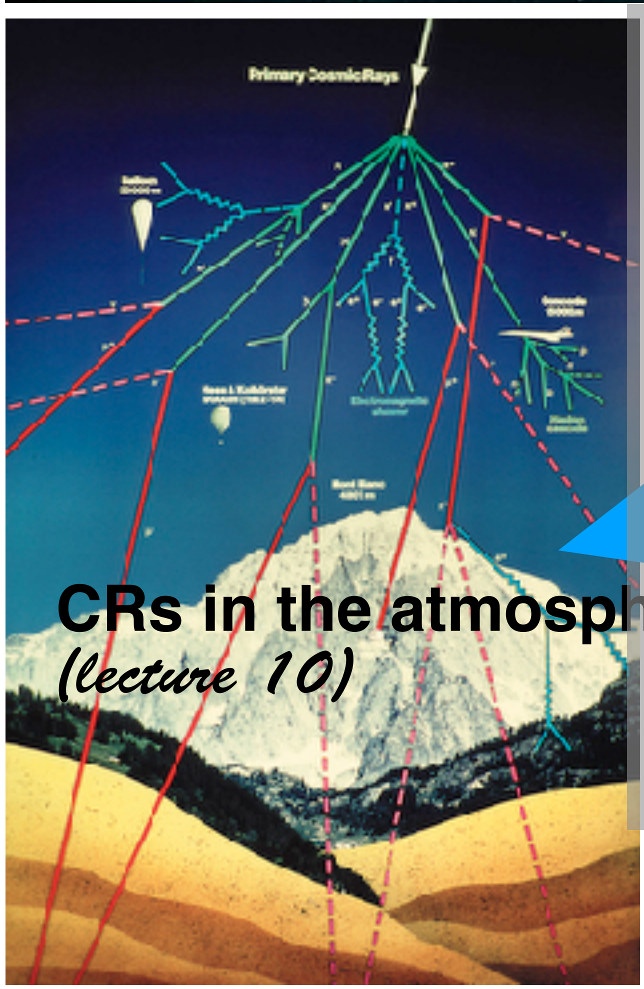


propagation of CRs in the Heliosphere *(lecture 9)*



propagation of CRs in the Earth magnetic field *(lecture 9)*

CRs at the top of the atmosphere *(lecture 10)*



CRs in the atmosphere *(lecture 10)*

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

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

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.

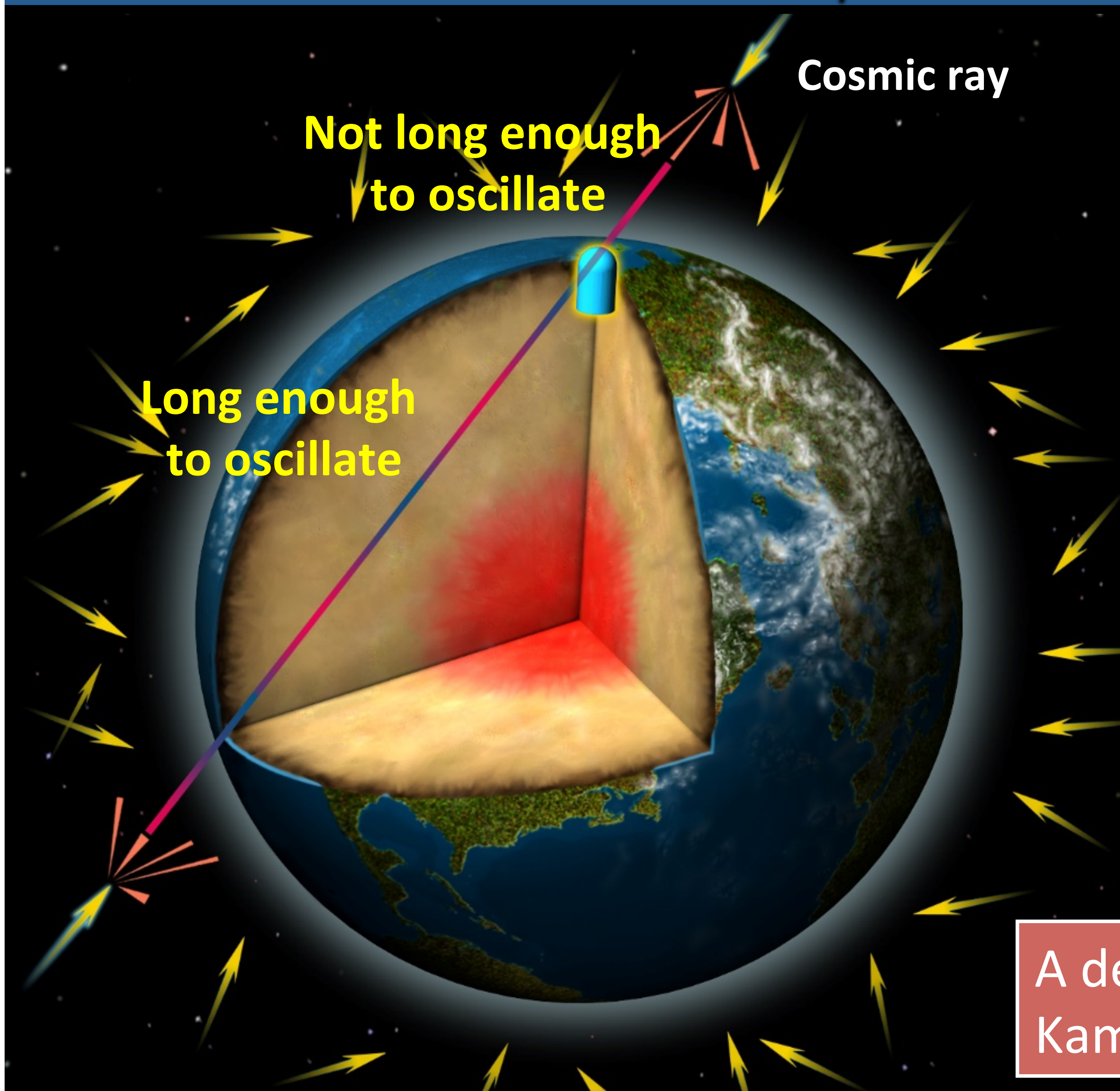
Neutrino oscillations

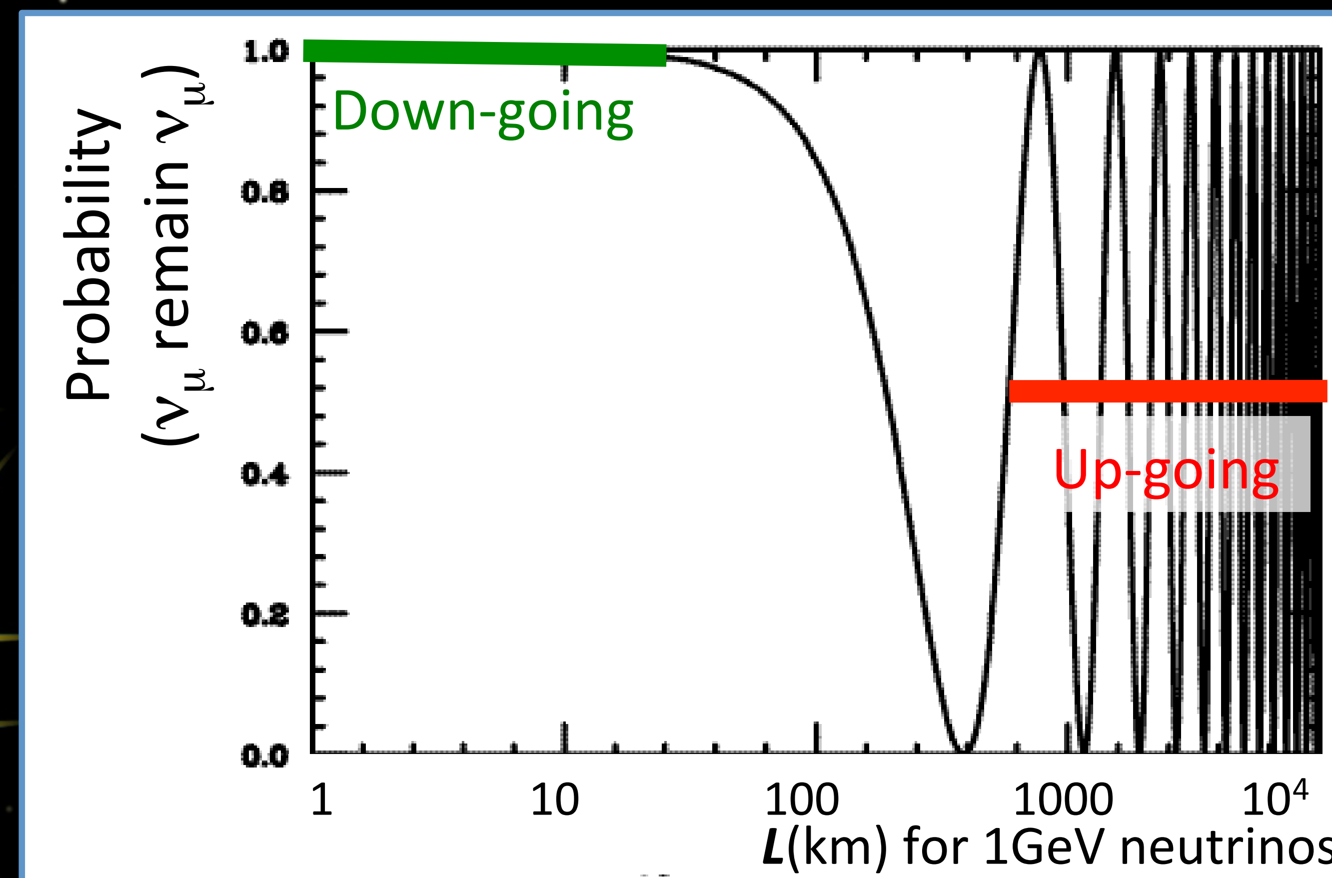
Expressed in units suitable for the energy of the atmospheric neutrinos and for the geometry of their detection the oscillation probability is

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

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.

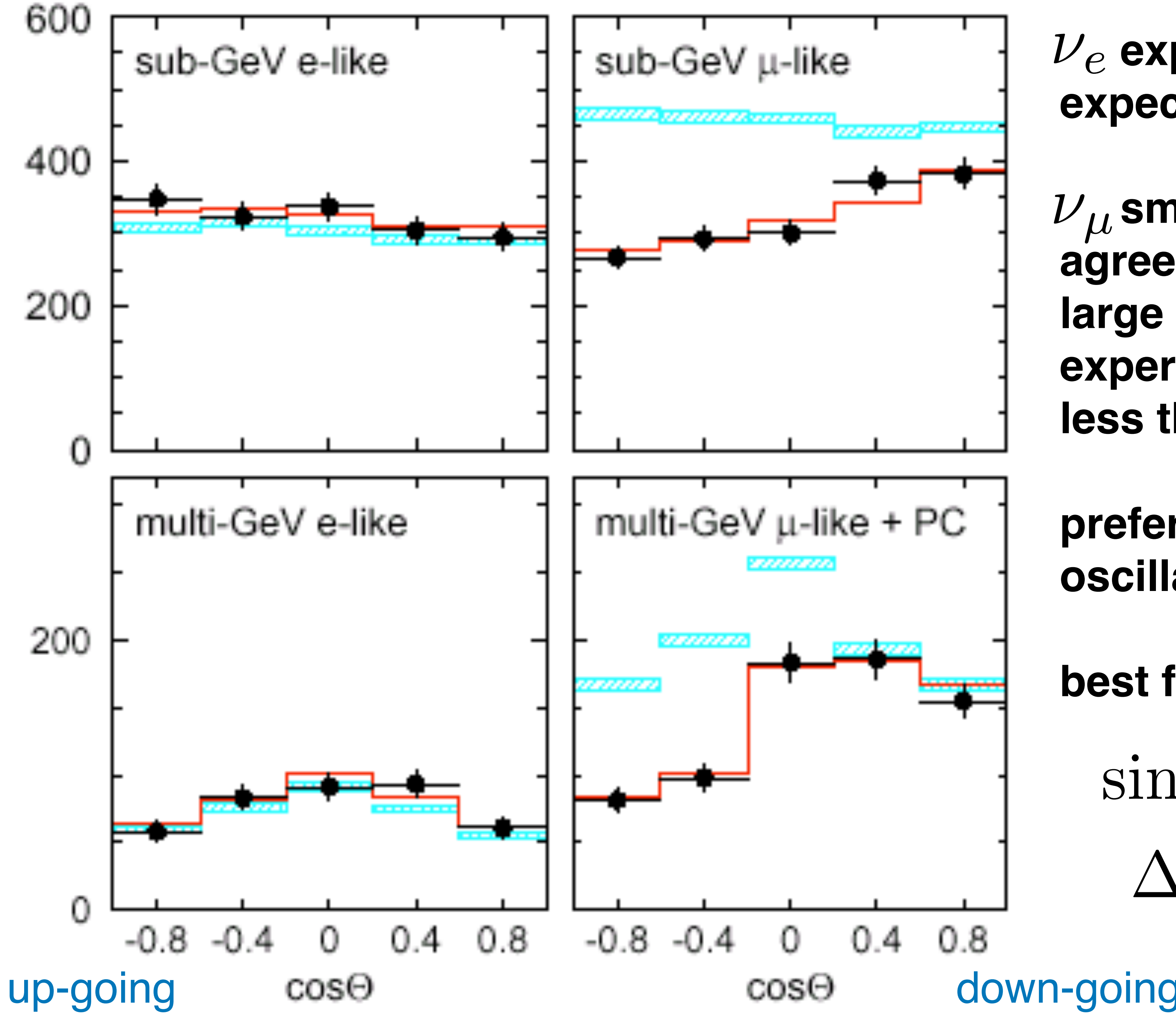
What will happen if the ν_μ deficit is due to neutrino oscillations





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

Super Kamiokande



Angular distributions for *e*-like (left) and m-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 2q = 1.0 and D*m*^{2} = 3.5 × 10^{-3} eV^2.

ν_e experimental results agree with expectations at all angles

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

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

best fit values:

$$\sin 2\Theta = 1.0$$

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

atmospheric neutrinos

The Nobel Prize in Physics 2002
Raymond Davis Jr., Masatoshi Koshiba, Riccardo Giacconi

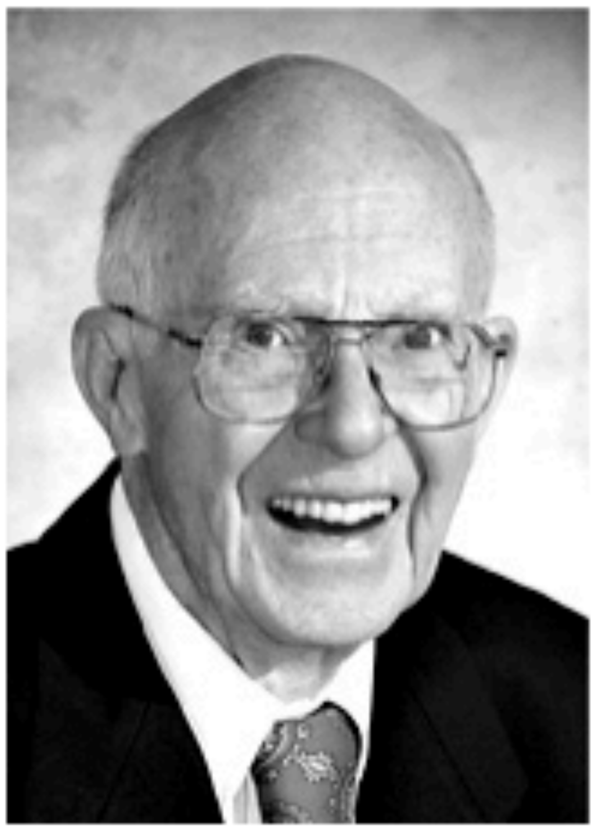
The Nobel Prize in Physics 2002

Nobel Prize Award Ceremony

Raymond Davis Jr.

Masatoshi Koshiba

Riccardo Giacconi



Raymond Davis Jr.

Masatoshi Koshiba

Riccardo Giacconi

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

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_es 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

$$\sin^2 2\theta_m = \frac{sin^2 2\theta}{[(\varphi - cos2\theta)^2 + sin^2 2\theta]^{1/2}} \tag{7.26}$$

and the oscillation length L_{osc} with

$$L_{osc}^m = \frac{L_{osc}}{[(\varphi - cos2\theta)^2 + sin^2 2\theta]^{1/2}} , \tag{7.27}$$

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.

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

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 φ 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.

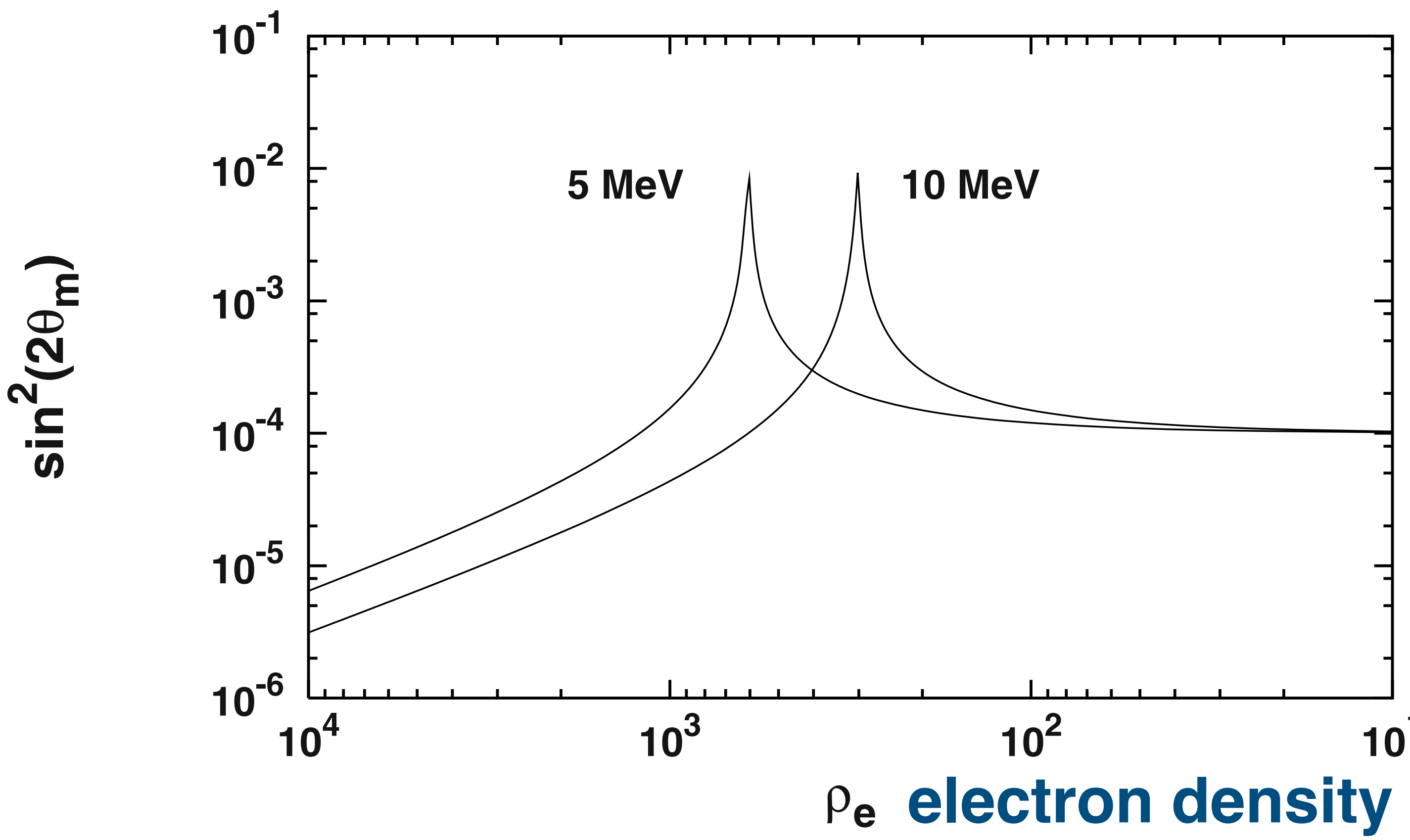


Fig. 7.17. Change of $\sin^2 2\theta_m$ with the electron density. $\Delta m^2 = 10^{-4}$ eV^2 and $\sin^2 2\theta = 10^{-4}$ for this example.

Sudbury Neutrino Observatory (SNO)

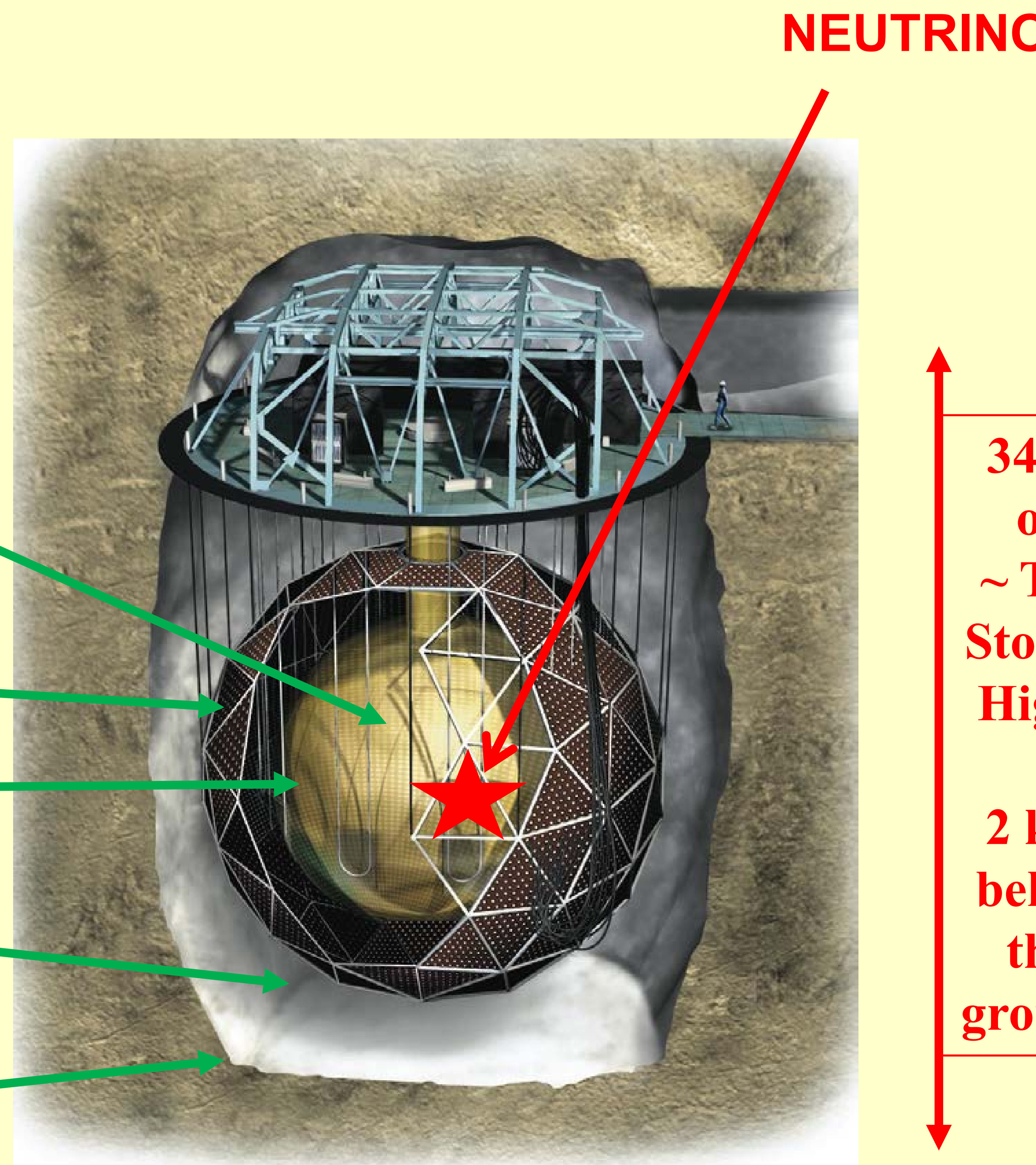
1000 tonnes of heavy water: D_2O
\$ 300 million on Loan for \$1.00

9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

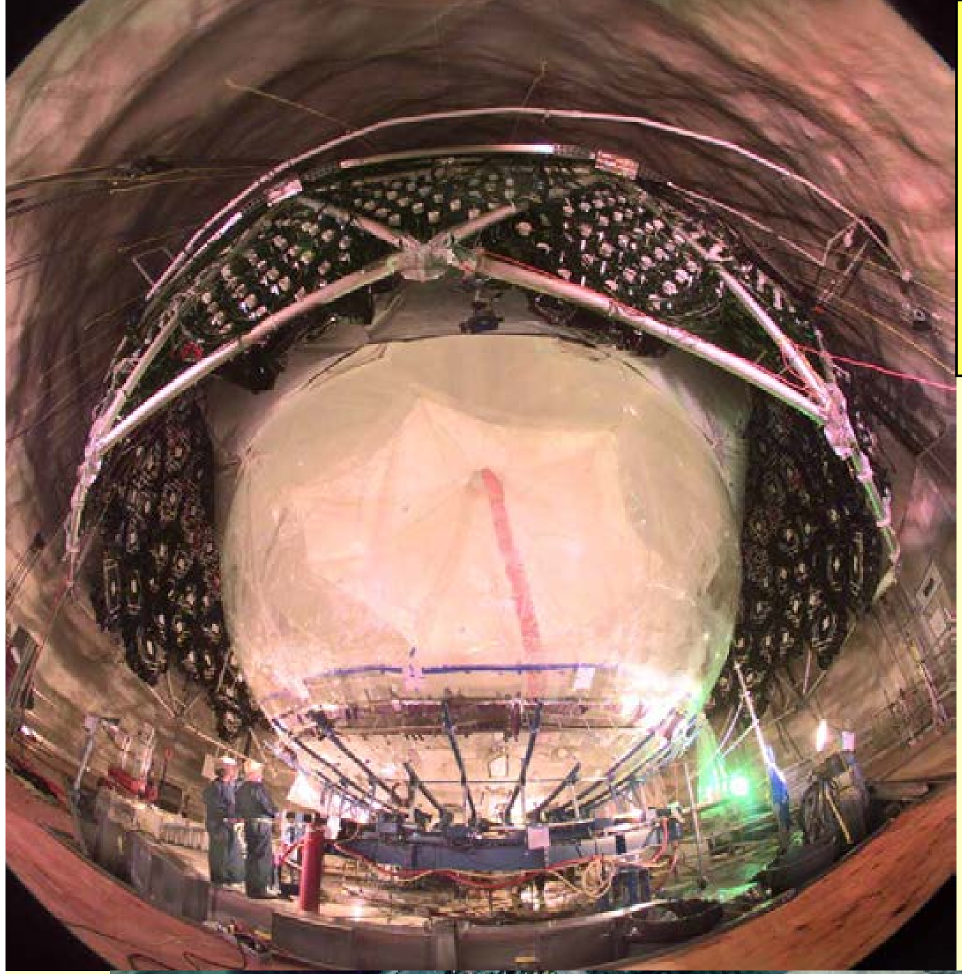
Urylon Liner and Radon Seal



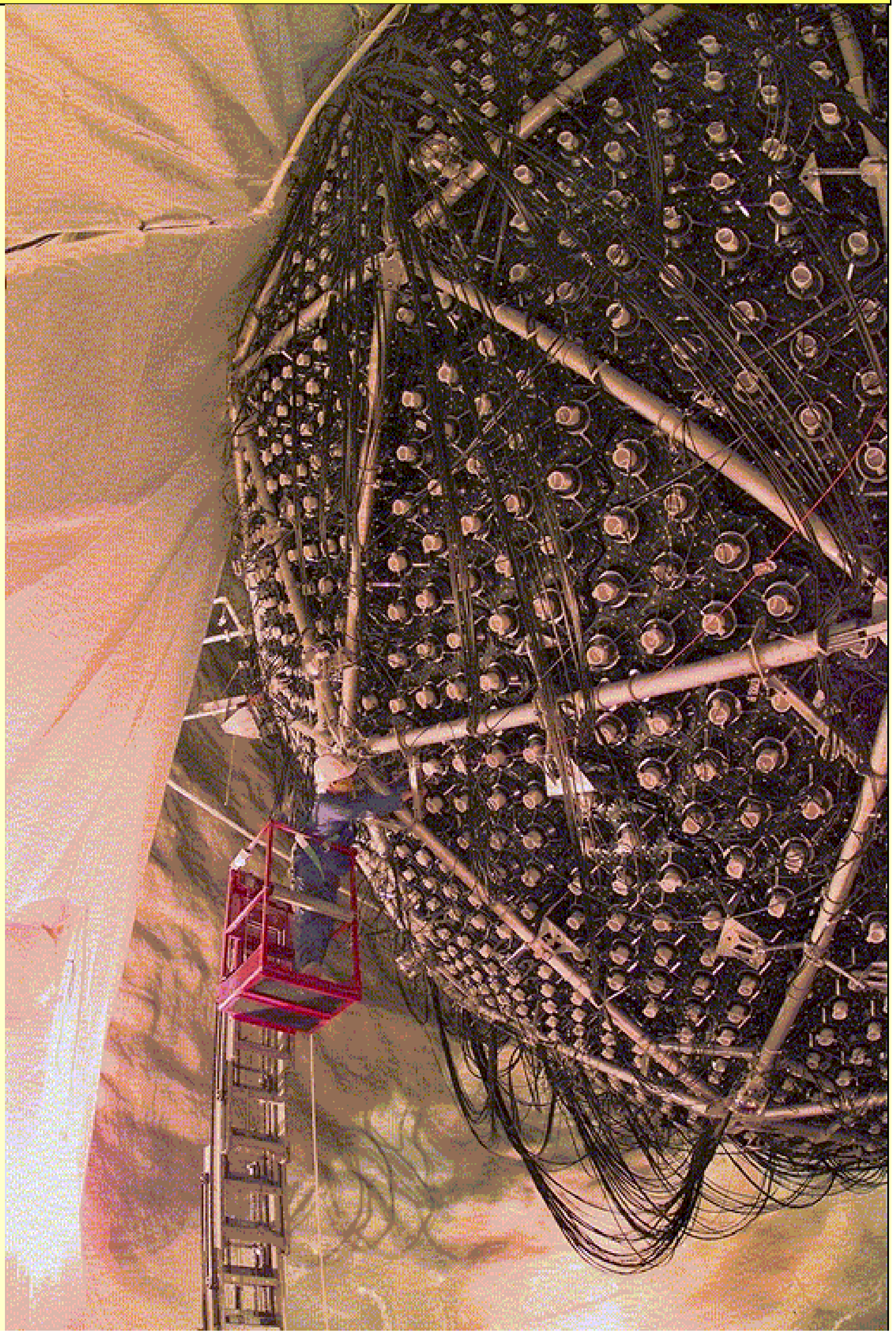
34 m or ~ Ten Stories High!

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!!

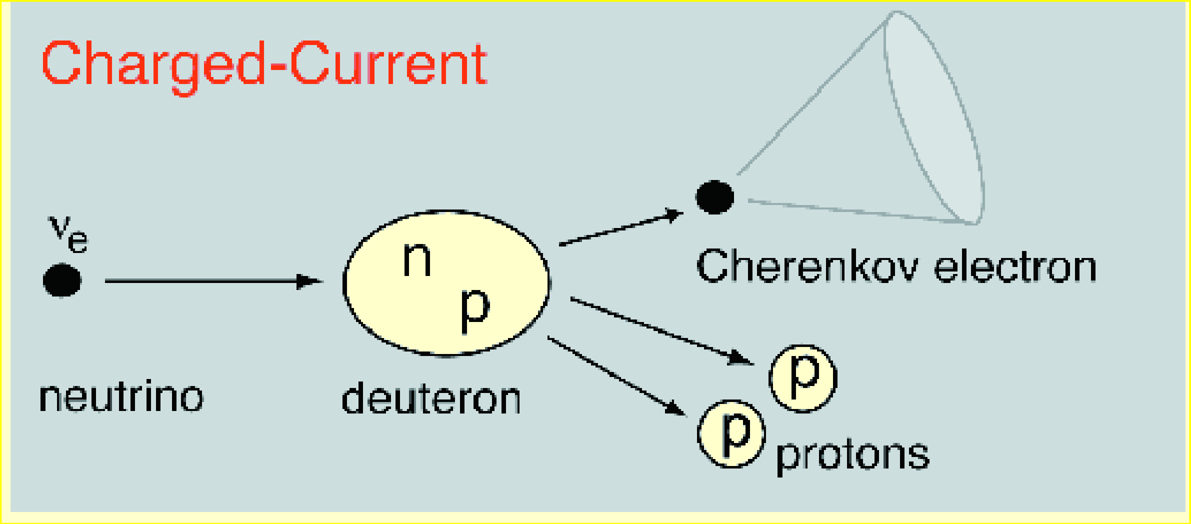
Unique Signatures in SNO (D_2O)

(1 in 6400 molecules in ordinary water are D_2O. We used >99.75% D_2O)

Electron Neutrinos (CC)

$\nu_e + d \rightarrow e^- + p + p$

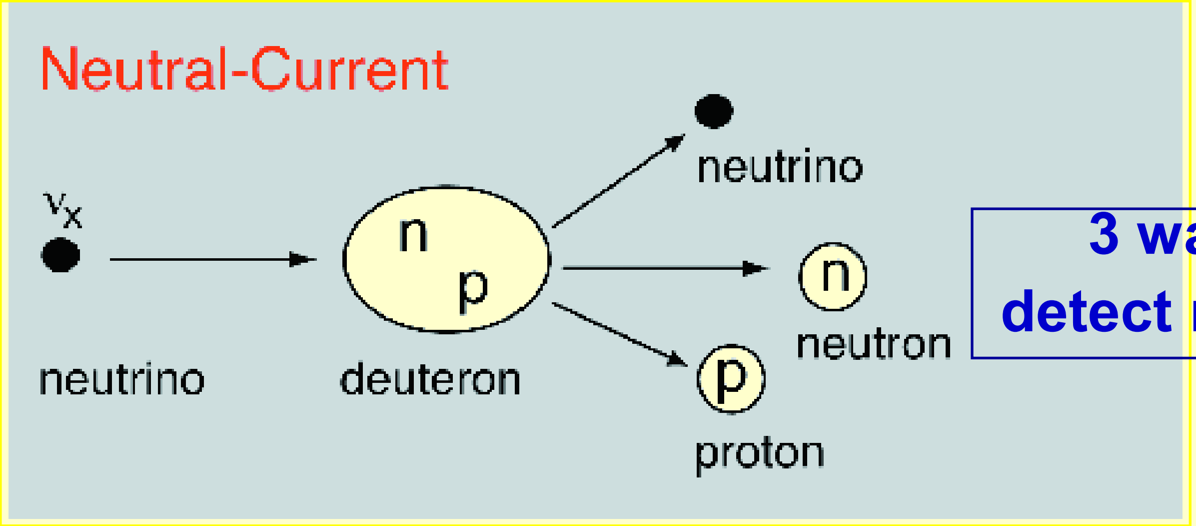
E_{thresh} = 1.4 MeV



Equal Sensitivity All Types (NC)

$\nu_x + d \rightarrow \nu_x + n + p$

E_{thresh} = 2.2 MeV



3 ways to detect neutrons

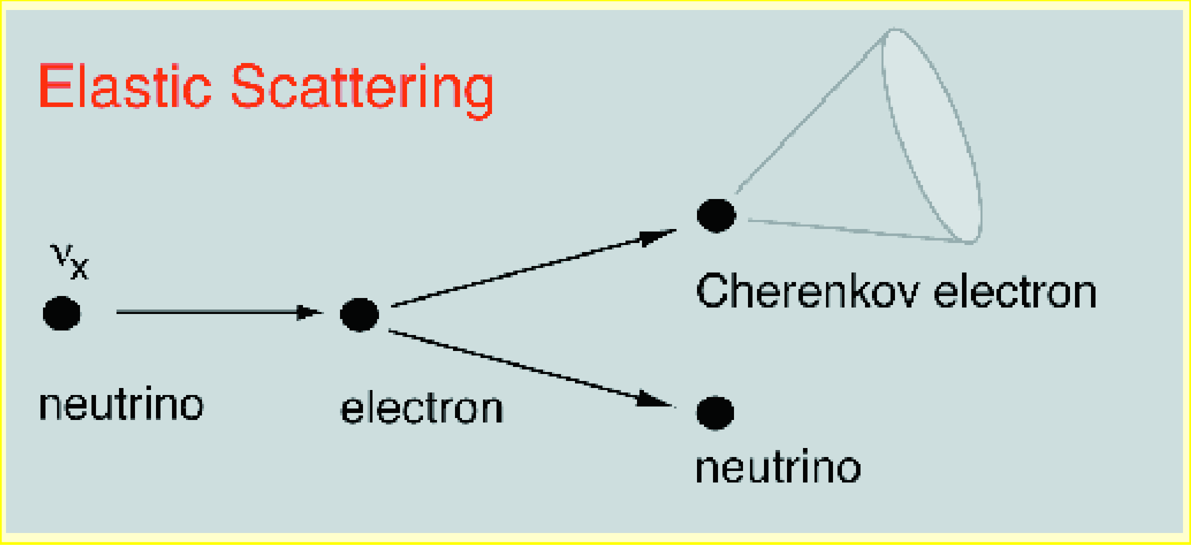
Elastic Scattering from Electrons

$\nu_x + e^- \rightarrow \nu_x + e^-$

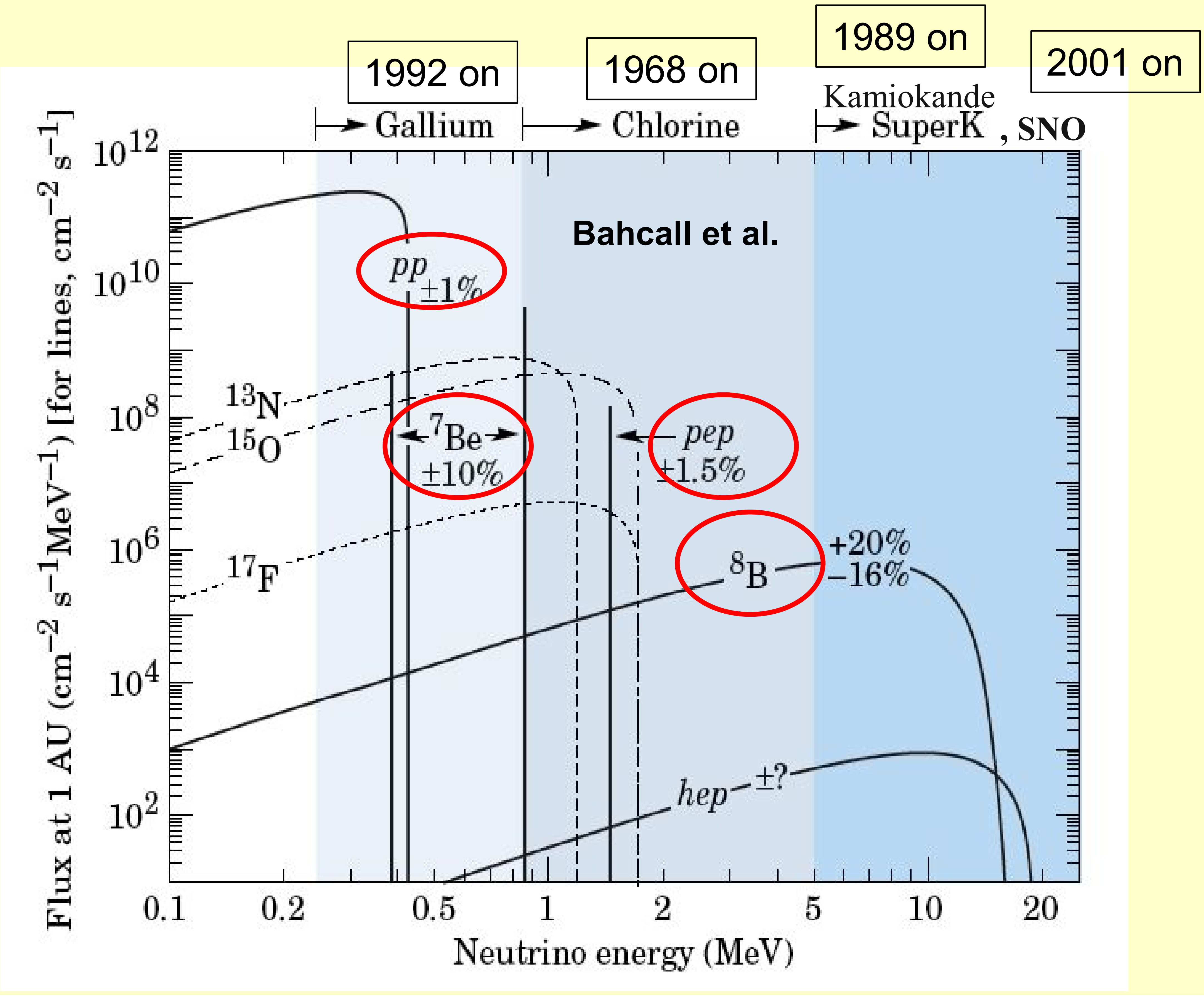
ν_x, but enhanced for ν_e x 6

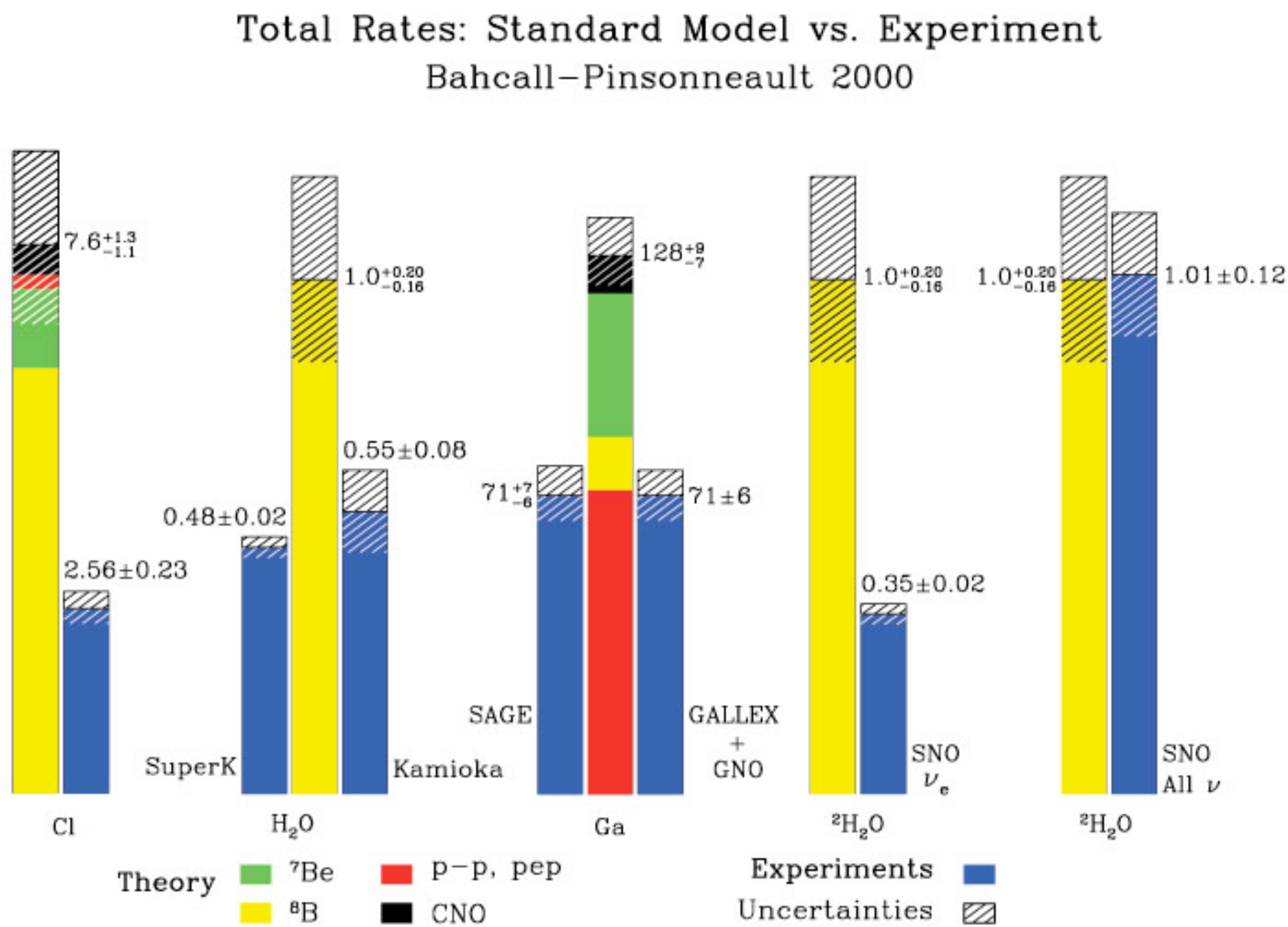
10 times lower count rate

Points away from the Sun



Including other solar neutrino measurements




Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
$7.6^{+1.3}_{-1.1}$
2.56±0.23
Cl
0.48±0.02
SuperK
$1.0^{+0.20}_{-0.16}$
0.55±0.08
Kamioka
H_2O
128^{+9}_{-7}
71^{+7}_{-6}
SAGE
71±6
GALLEX + GNO
Ga
$1.0^{+0.20}_{-0.16}$
0.35±0.02
SNO ν_e
^2H_2O
$1.0^{+0.20}_{-0.16}$
1.01±0.12
SNO All ν
^2H_2O
Theory
^{7}Be
^{8}B
p–p, pep
CNO
Experiments
Uncertainties

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} eV^2. 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} eV^2 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} eV^2.
- **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} eV^2.

Oscillation parameters

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

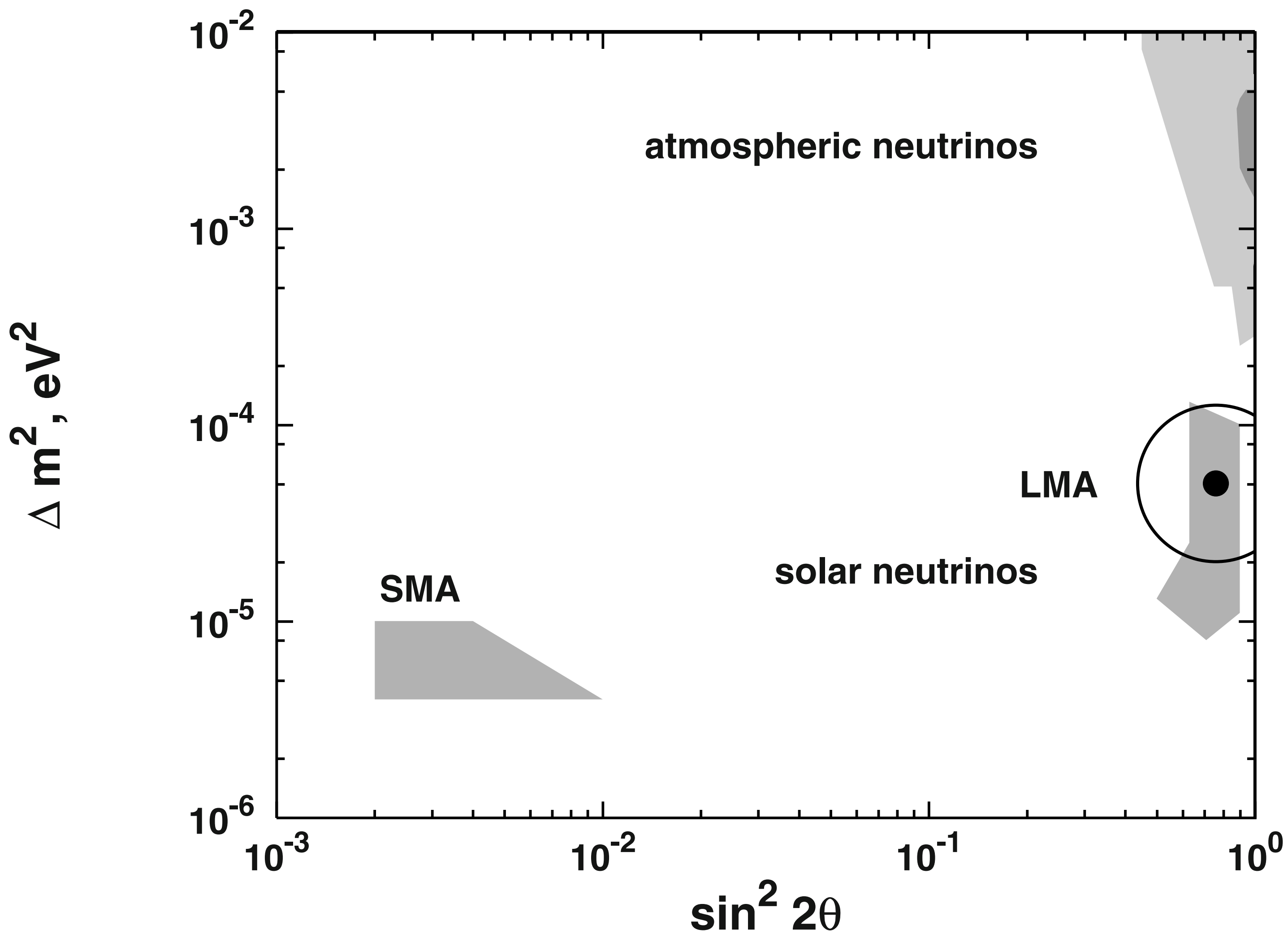
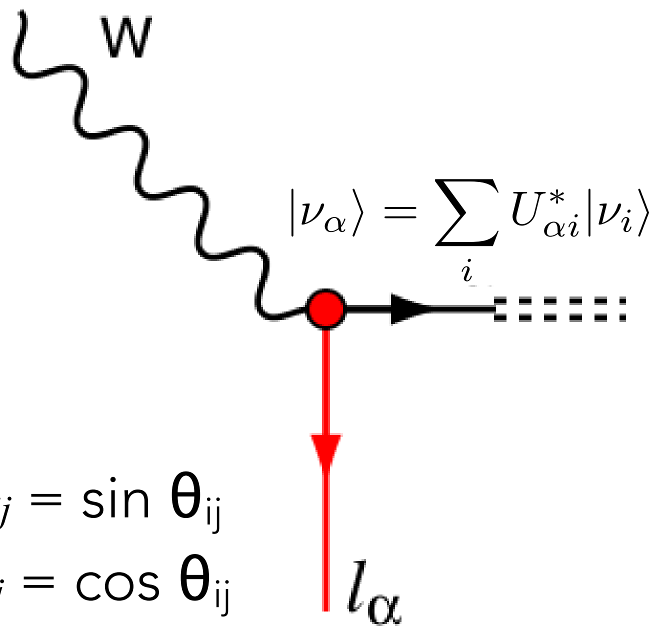


Fig. 7.20. Allowed parameter values for neutrino oscillations. Atmospheric neutrinos are all bunched in the upper right-hand part of the graph. Light shaded areas come from Soudan2 and MACRO, and the darker shading from Super-K. The SMA (lower left) and LMA solutions for MSW oscillations of solar neutrinos 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



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

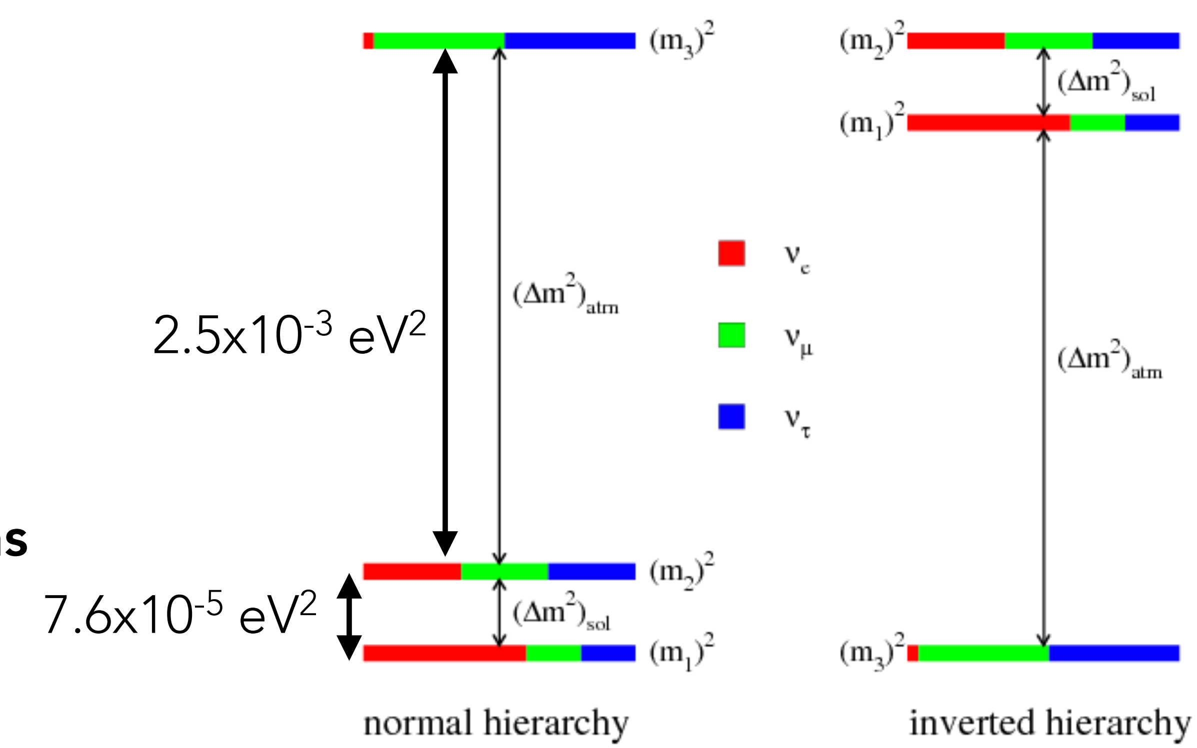
$s_{ij} = \sin \theta_{ij}$

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

"standard" parametrization

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

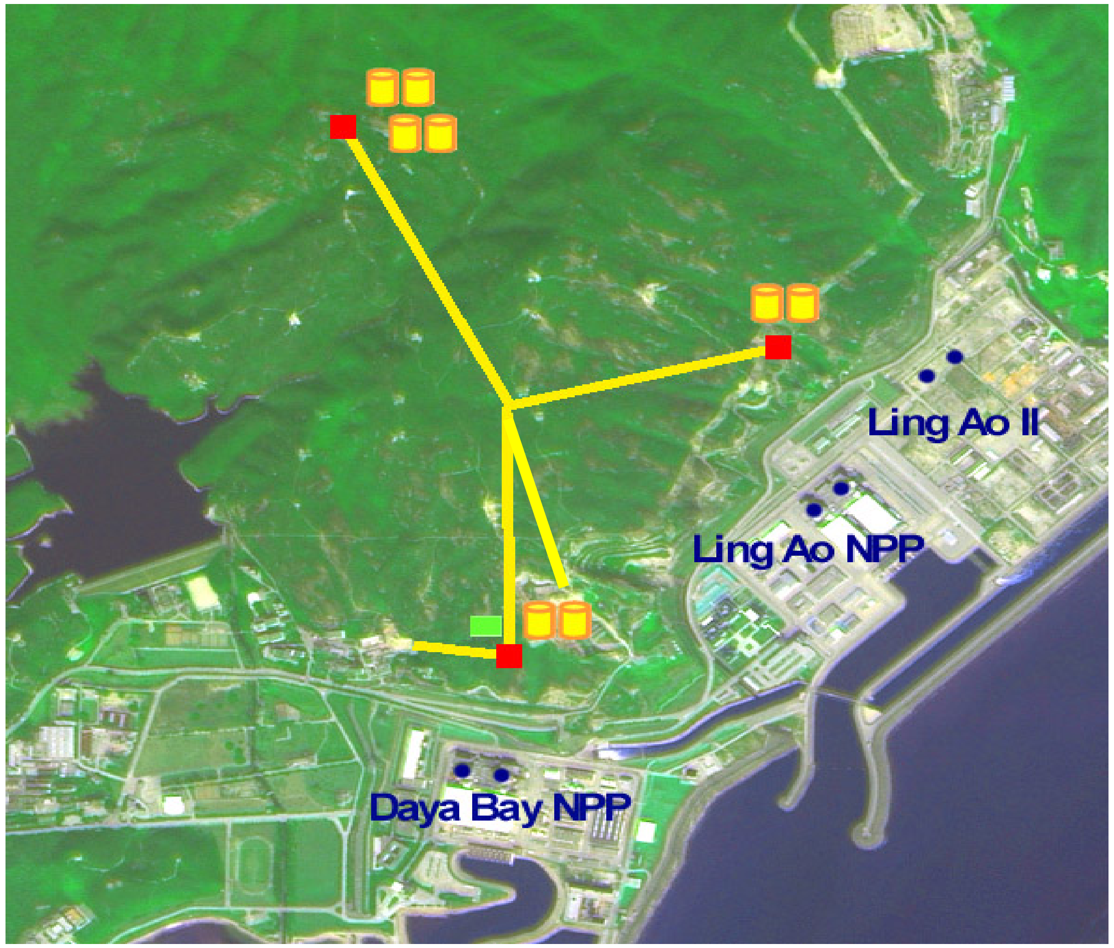
- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
  - θ_{12}: solar and reactor experiments
  - θ_{13}: reactor and long-baseline experiments
- One complex phase δ_{CP}
  - additional phases if neutrinos are "Majorana"
  - **CP-odd: changes sign for antineutrino oscillations**

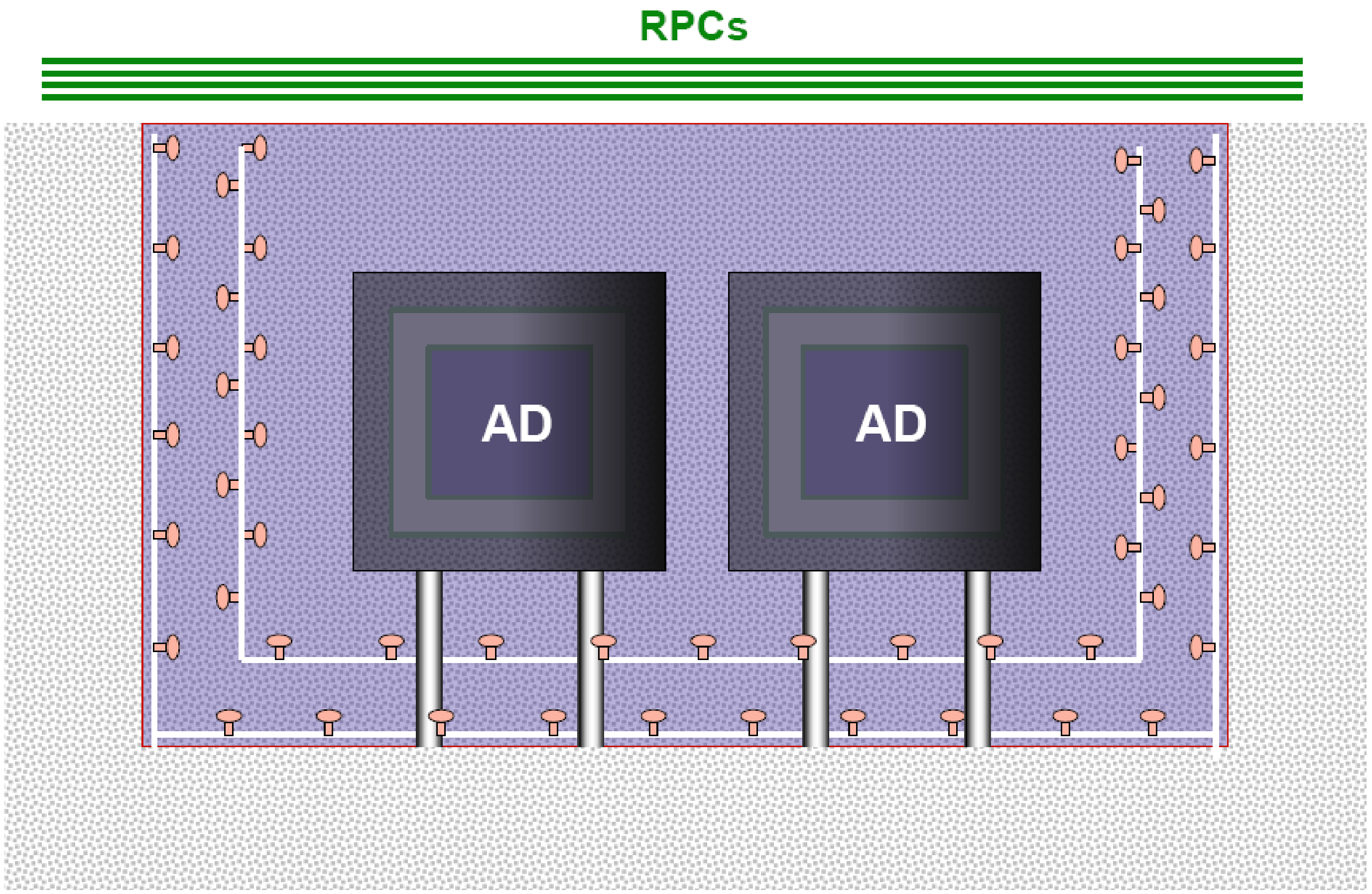


3

see Cabibbo-Kobayashi-Maskawa-Matrix (CKM-Matrix) for quarks

Daya Bay Experiment: Layout

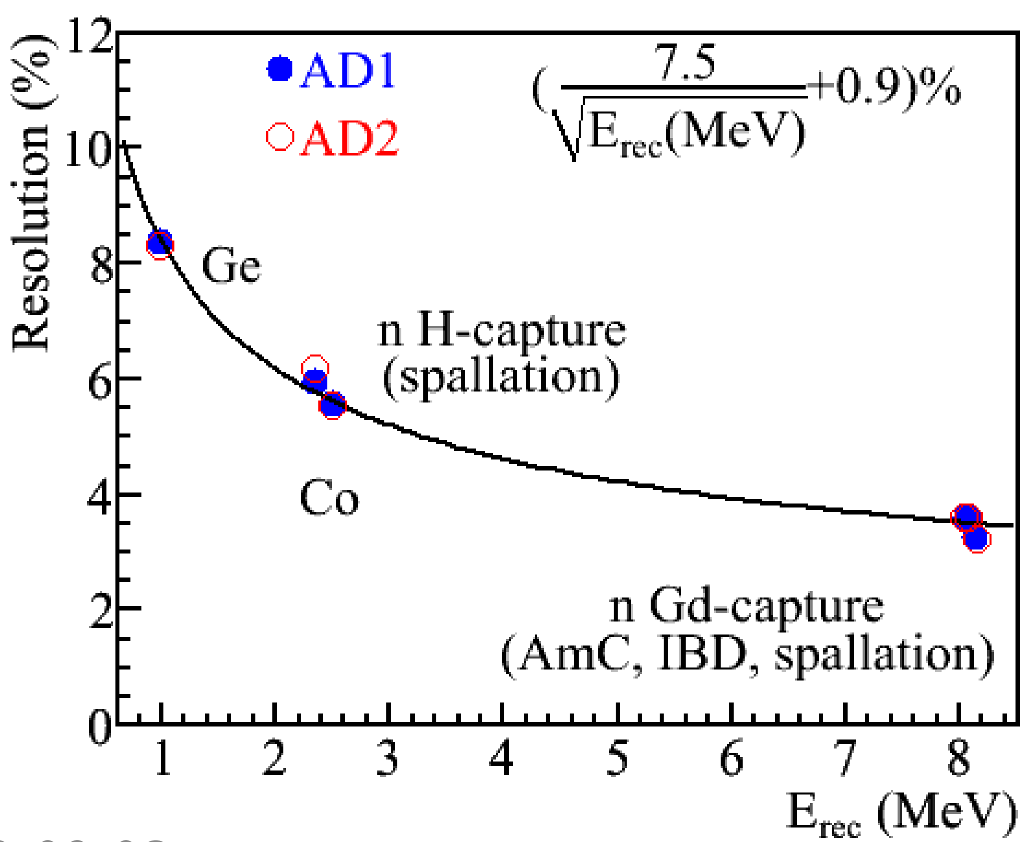


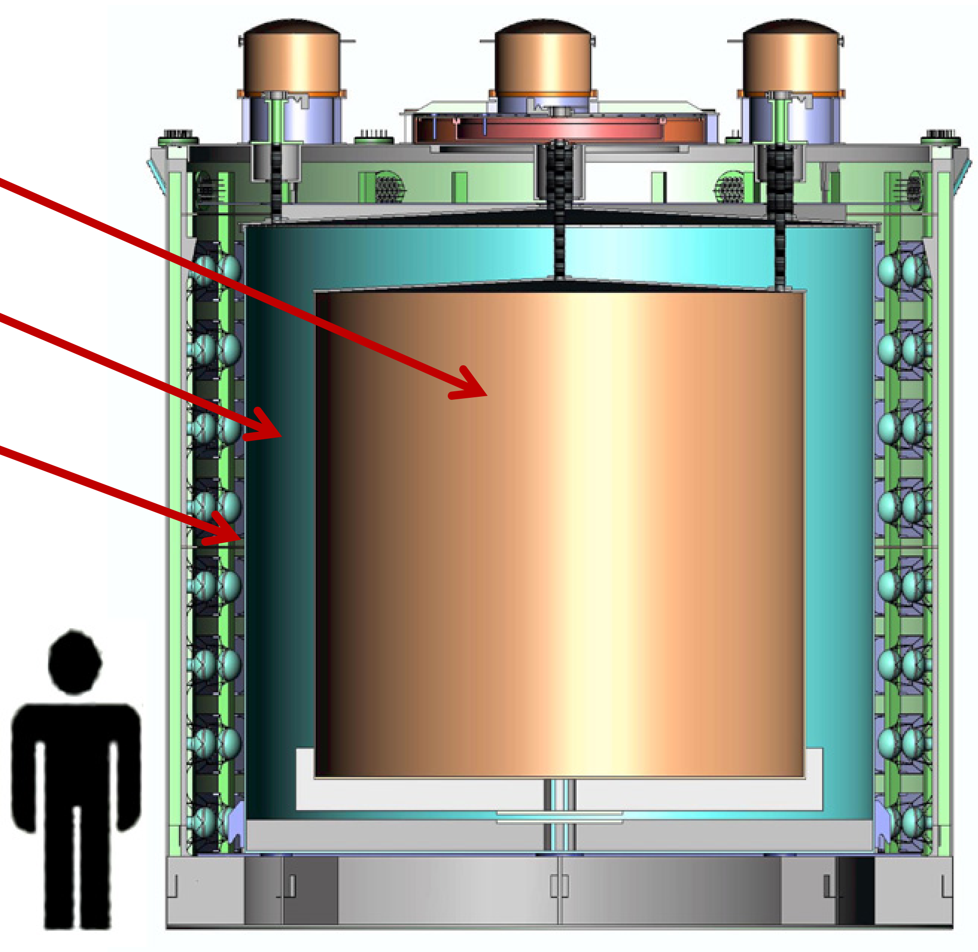


- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the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

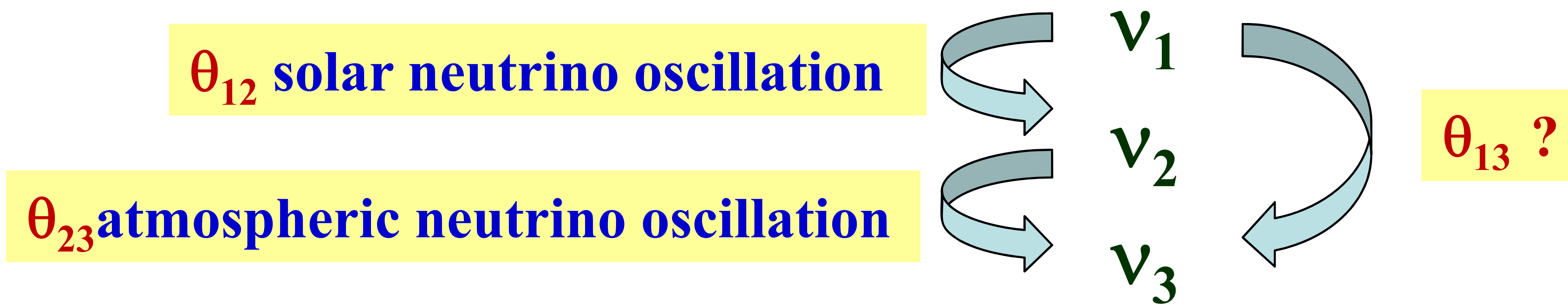




Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm
Total weight: ~110 t

Daya Bay: for a New Type of Oscillation

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



- **Neutrino mixing matrix:**

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

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,

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

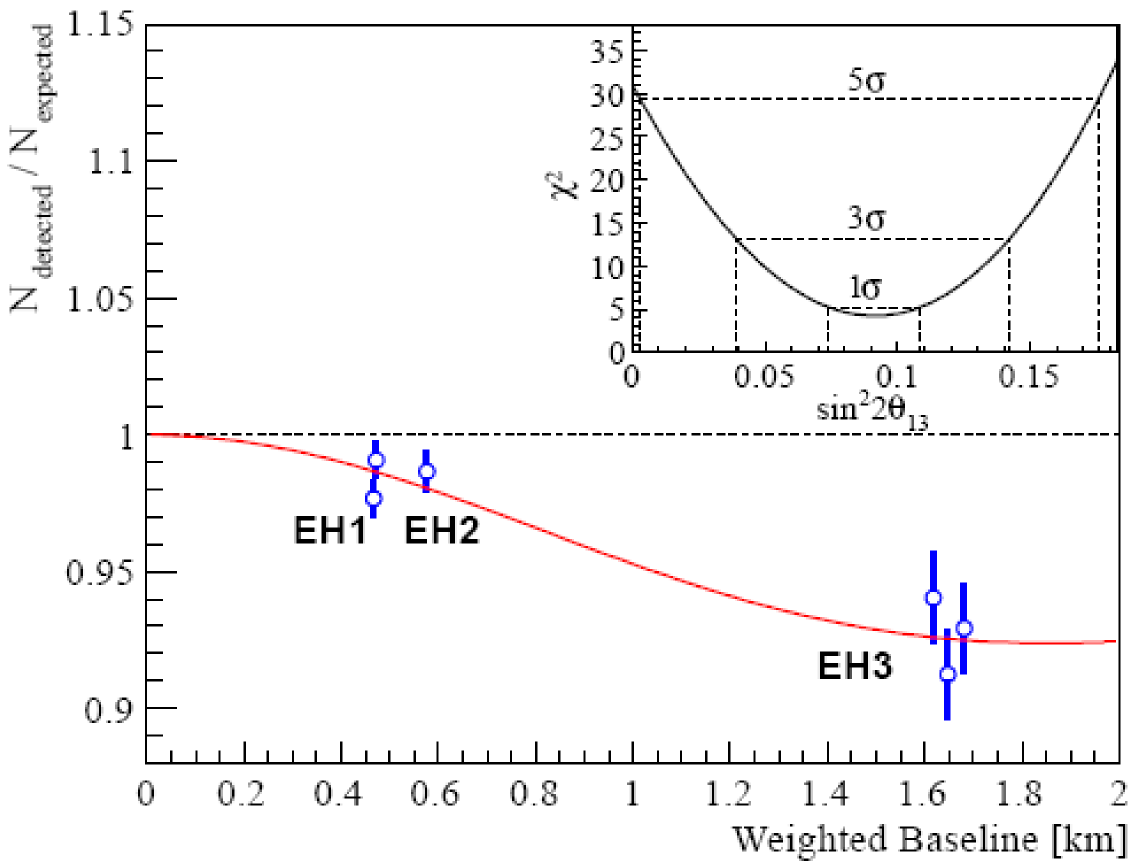
together with a spectral distortion

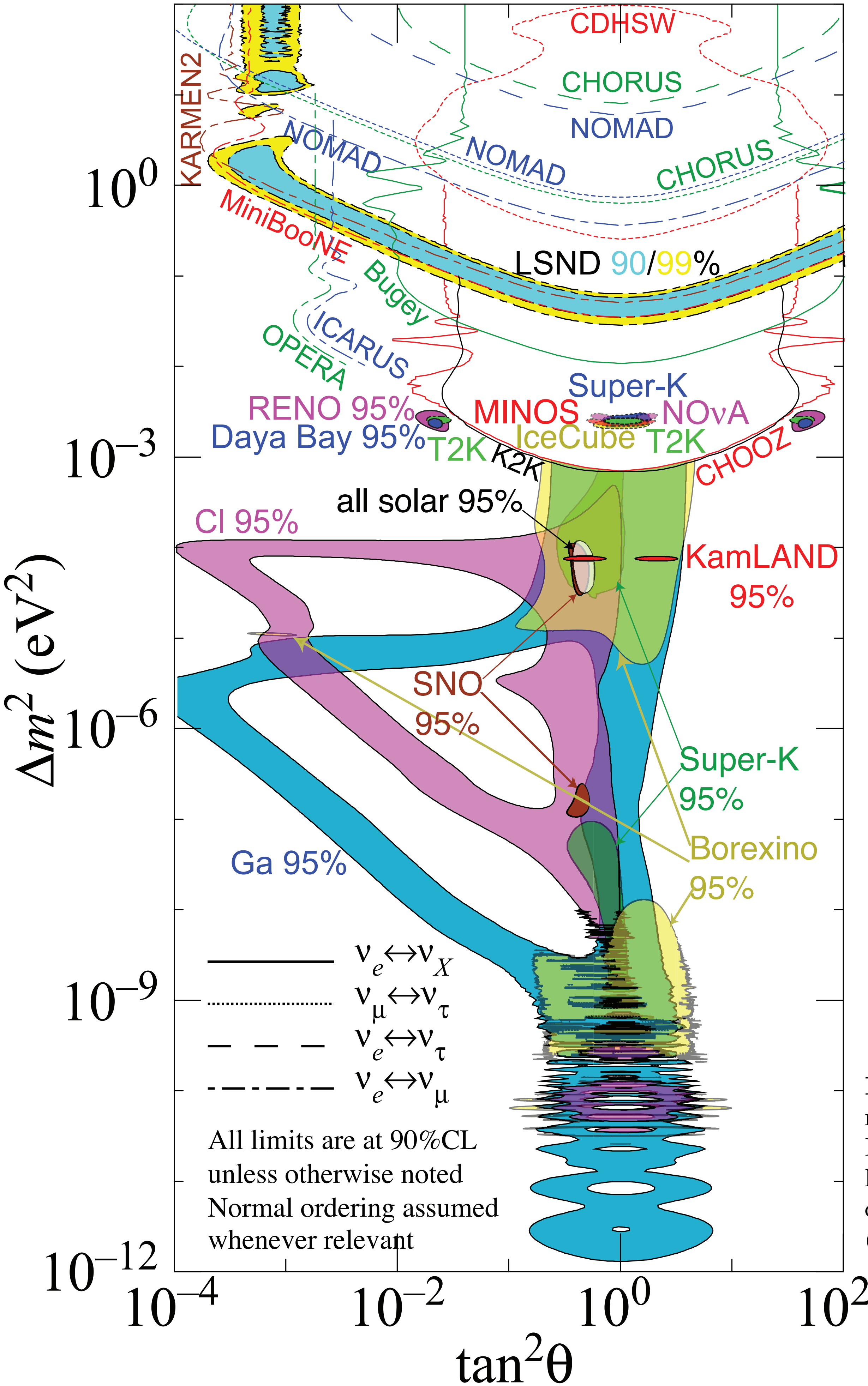
- A new type of neutrino oscillation is thus discovered

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

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

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).

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).

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

Share this: 1.6K

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"*

Particles and the Cosmos

2019/2020

Sascha Caron, Jörg Hörandel

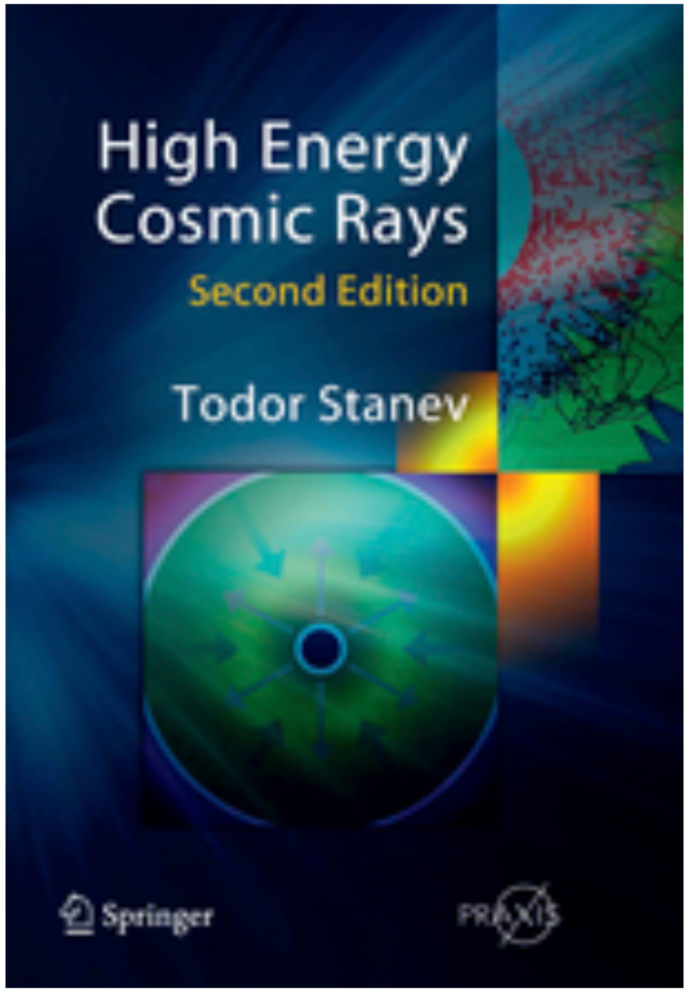
NM109
first semester, 6 ec

32 hrs lecture Wednesday 10:30 - 12:15 HG 00.086
32 hrs problem session Thursday 13:30 - 15:15 HG 02.052

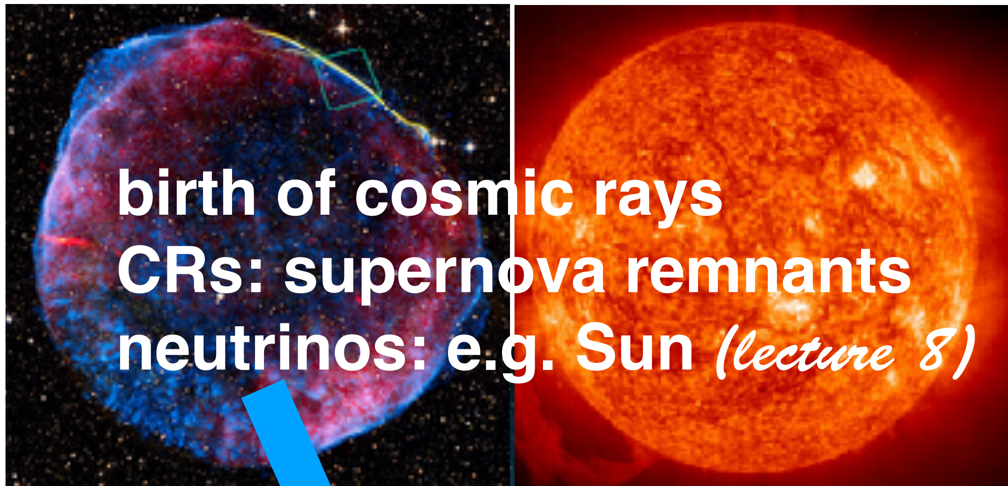
Lectures:

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

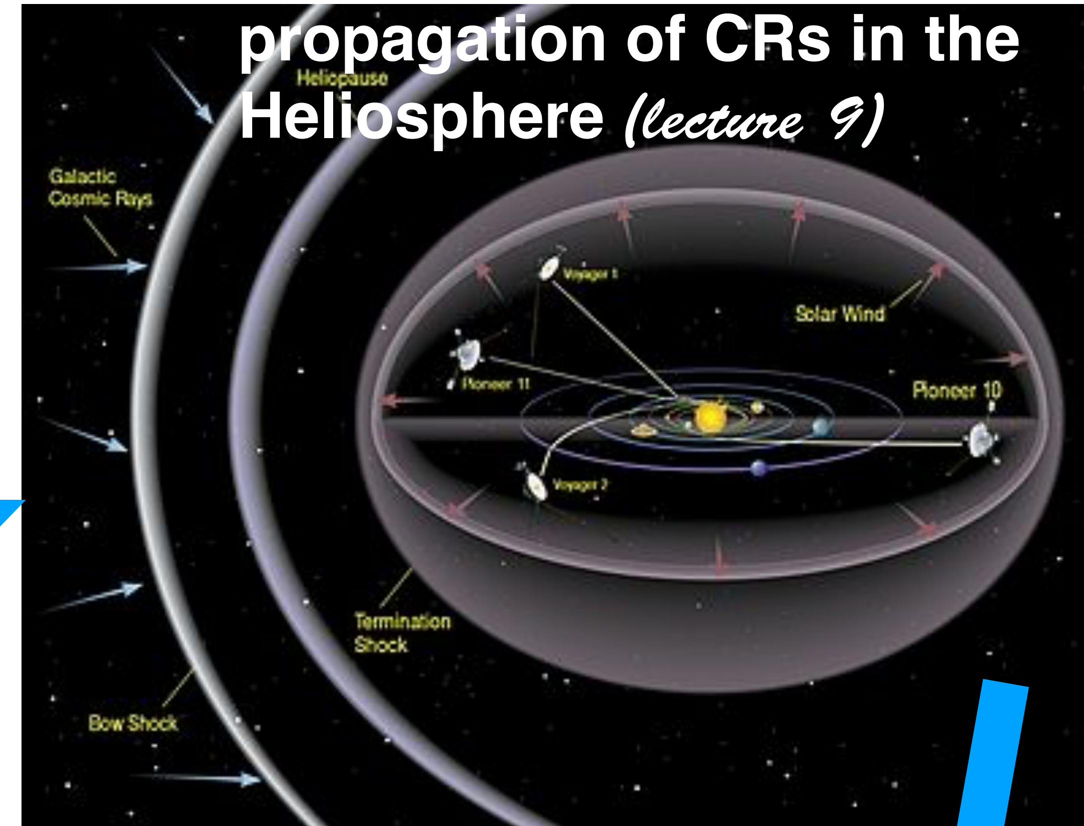


Jörg R. Hörandel
HG 02.721
http://particle.astro.ru.nl

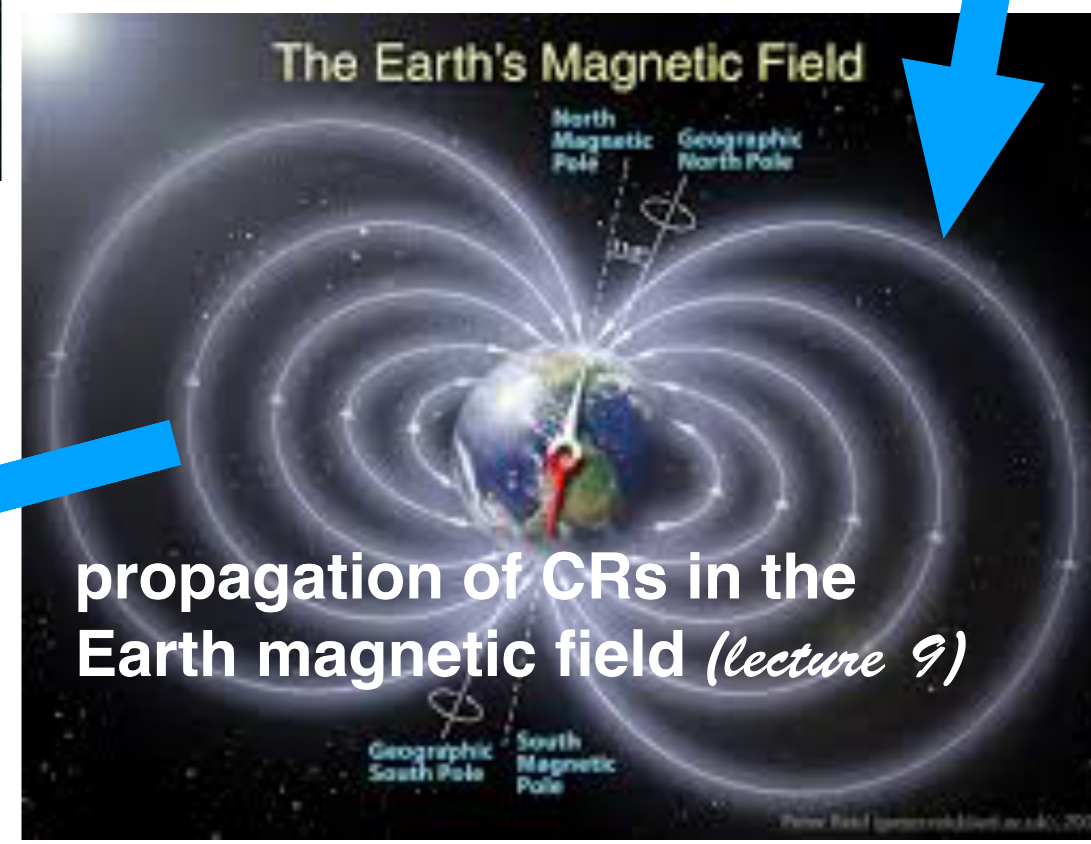


birth of cosmic rays
CRs: supernova remnants
neutrinos: e.g. Sun *(lecture 8)*

propagation of CRs in the Galaxy
interactions with ISM *(lecture 9)*

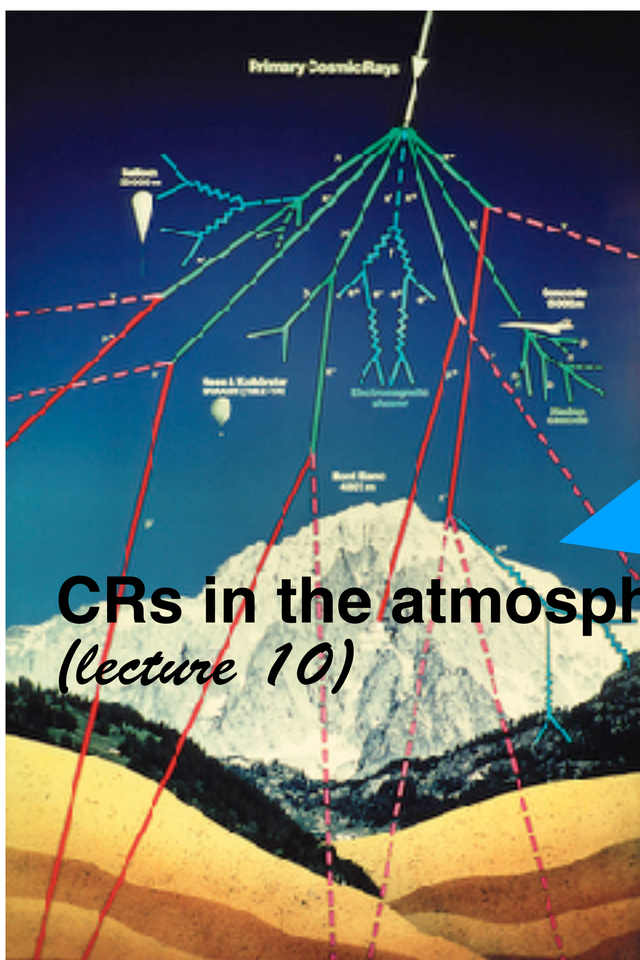


propagation of CRs in the Heliosphere *(lecture 9)*



propagation of CRs in the Earth magnetic field *(lecture 9)*

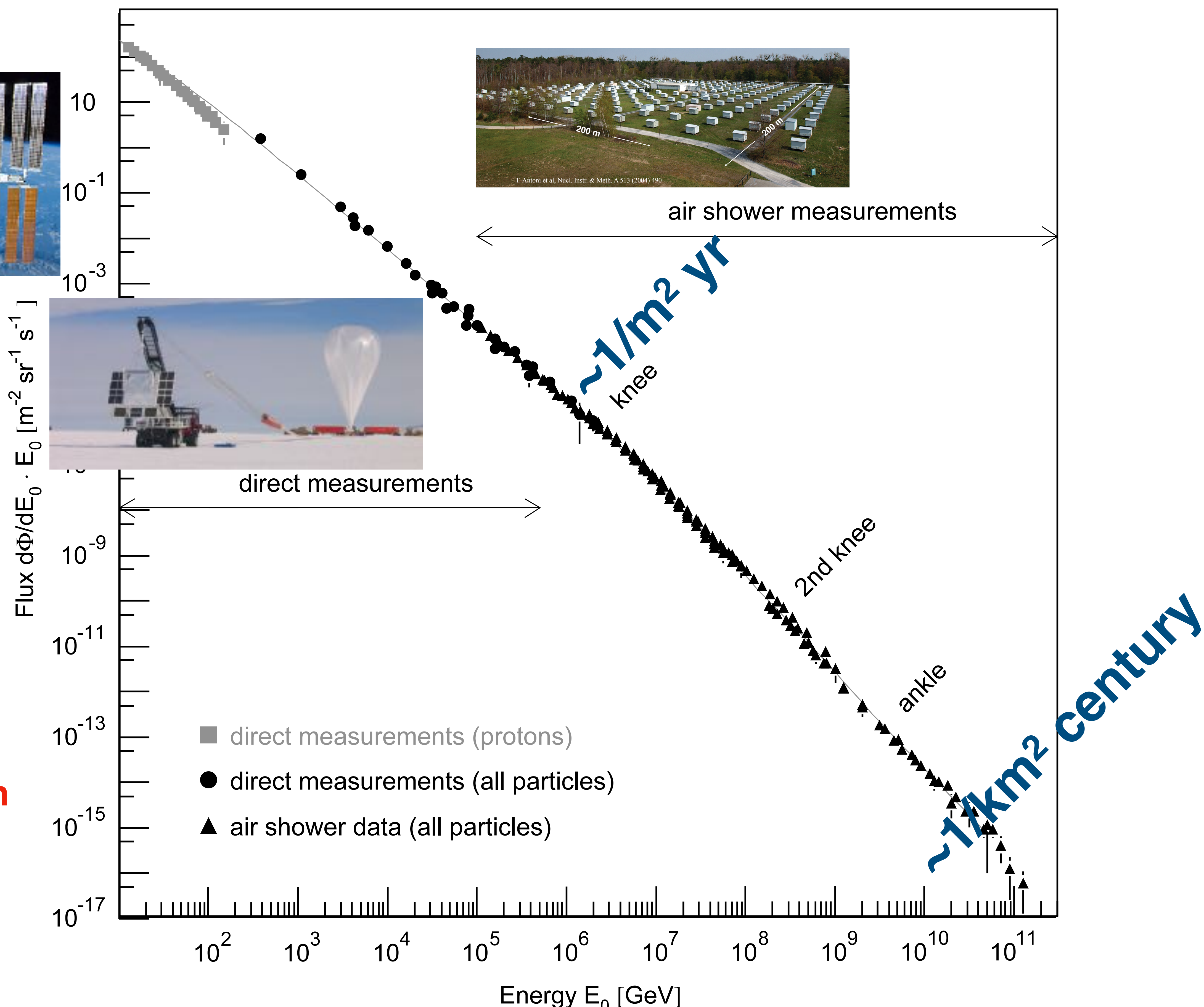
CRs at the top of the atmosphere *(lecture 10)*



CRs in the atmosphere *(lecture 10)*

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

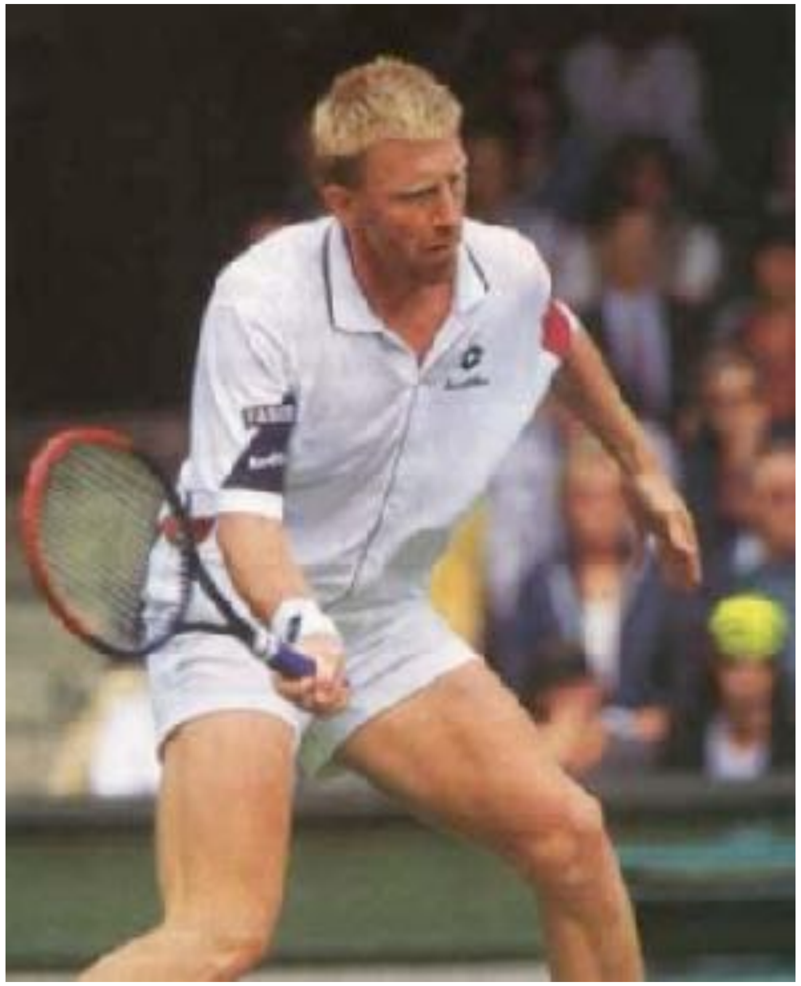
J. Blümer et al. / Progress in Particle and Nuclear Physics 63 (2009) 293–338



energy spectrum of cosmic rays extends to extremely high energies:
10^{20} eV ~16 J

Physics and origin of the highest-energy particles in the Universe

10^{20} eV = 16 J
macroscopic energy



tennisball (50 g) at 90 km/h = 16 J
Avogadro Number $N_A = 6*10^{23}$ mol^{-1}

The existence of such particles imposes immediate, yet to be answered questions:
- **What are the physics processes involved to produce these particles?**
- **Are they decay or annihilation products of Dark Matter?**

If they are accelerated in violent astrophysical environments:
- **How is Nature being able to accelerate particles to such energies?**
- **What are the sources of the particles? Do we understand the physics of the sources?**
- **Is the origin of those particles connected to the recently observed mergers of compact objects – the gravitational wave sources?**

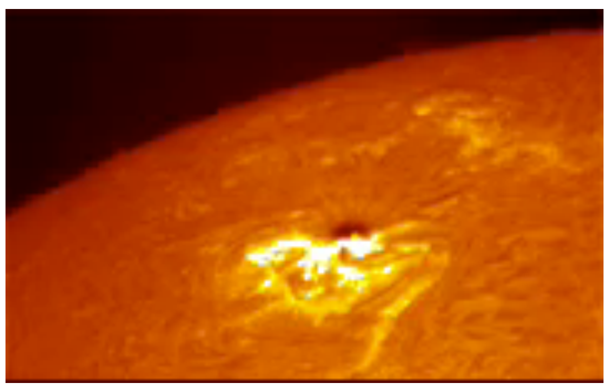
The highly-relativistic particles also provide the unique possibility to study (particle) physics at it extremes:
- **Is Lorentz invariance (still) valid under such conditions?**

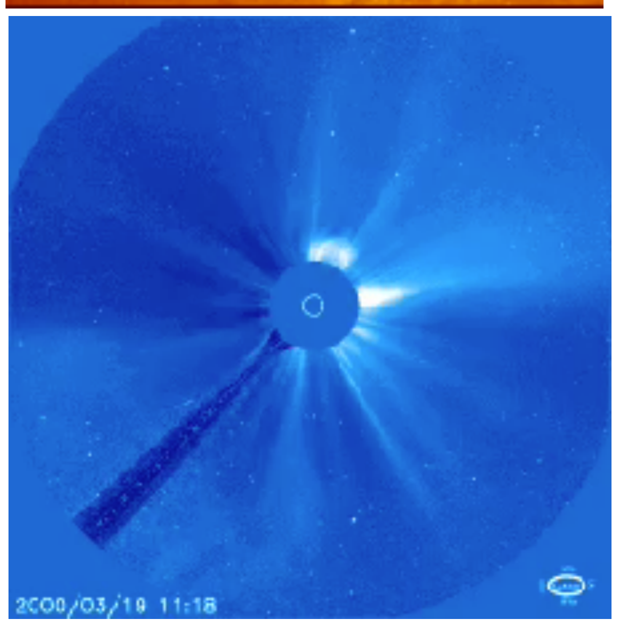
How do these particles interact?
- **Are their interactions described by the Standard Model of particle physics?**

When the energetic particles interact with the atmosphere of the Earth, hadronic interactions can be studied:
- **What is the proton interaction cross section at such energies?**

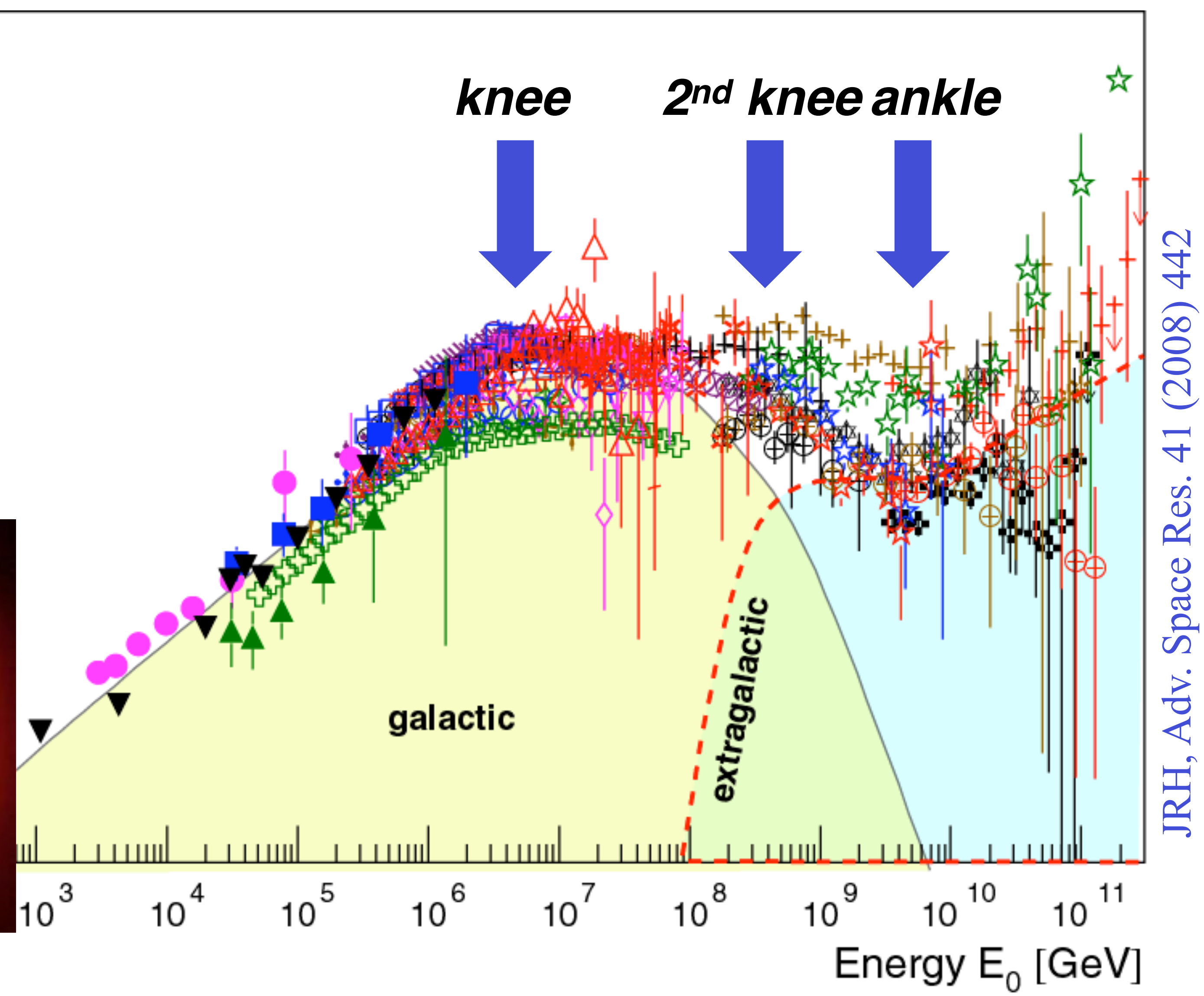
Cosmic rays

Solar flares

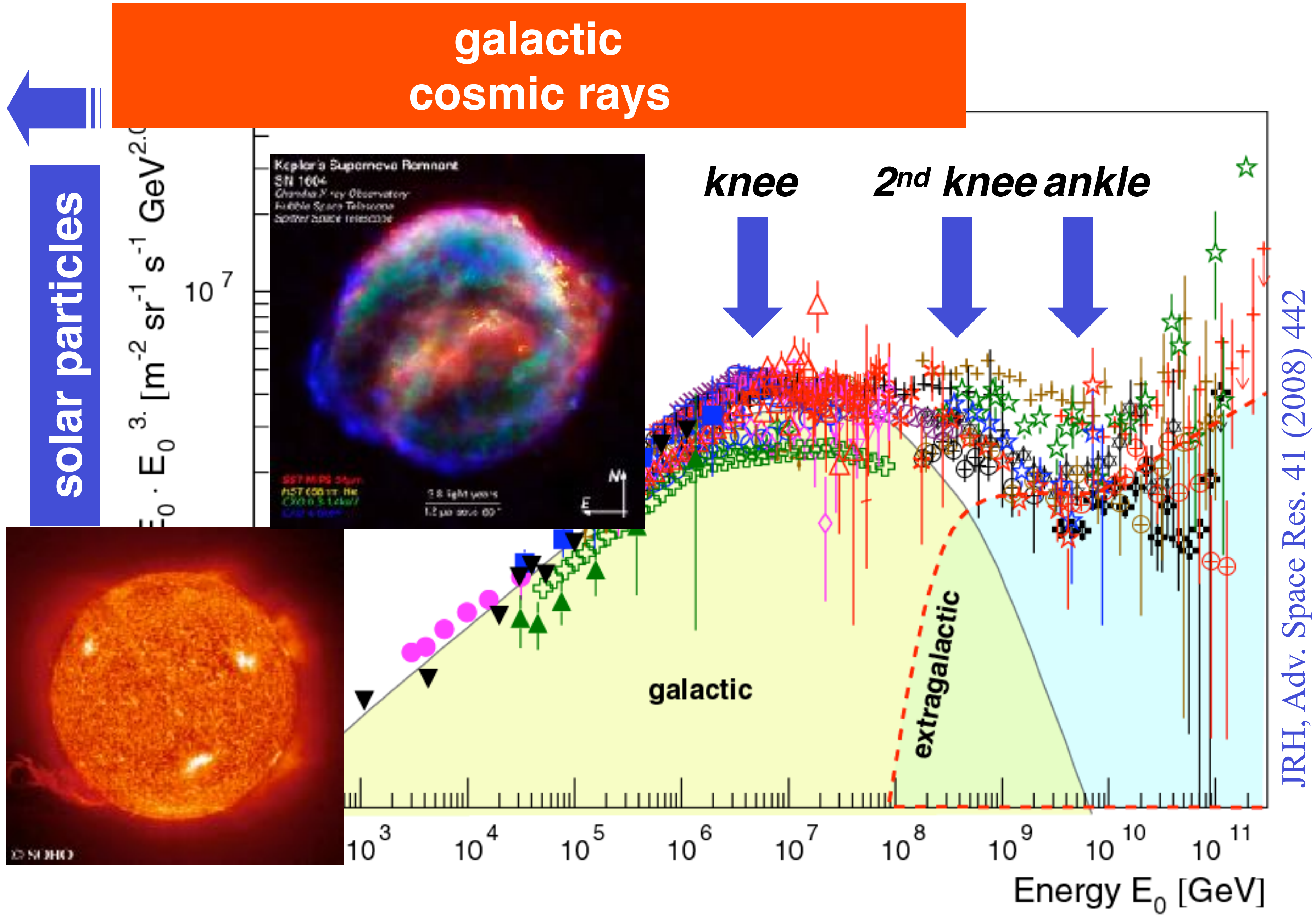




solar particles



Cosmic rays

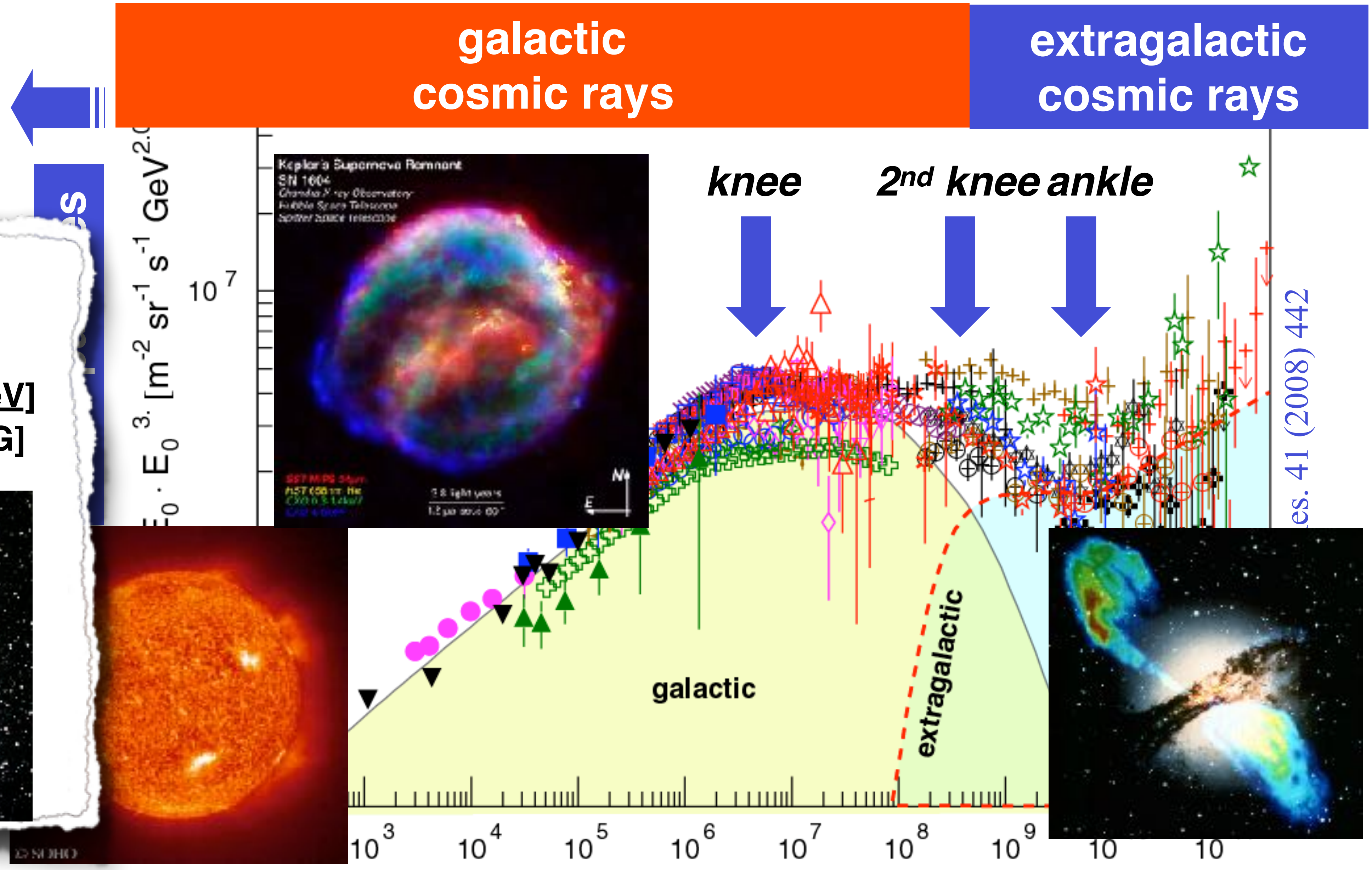

galactic
cosmic rays
solar particles
knee
2nd knee
ankle
galactic
extragalactic
Kepler's Supernova Remnant
SN 1604
10^7
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Energy E_0 [GeV]
JRH, Adv. Space Res. 41 (2008) 442

Cosmic rays

Radius of particle in magnetic field

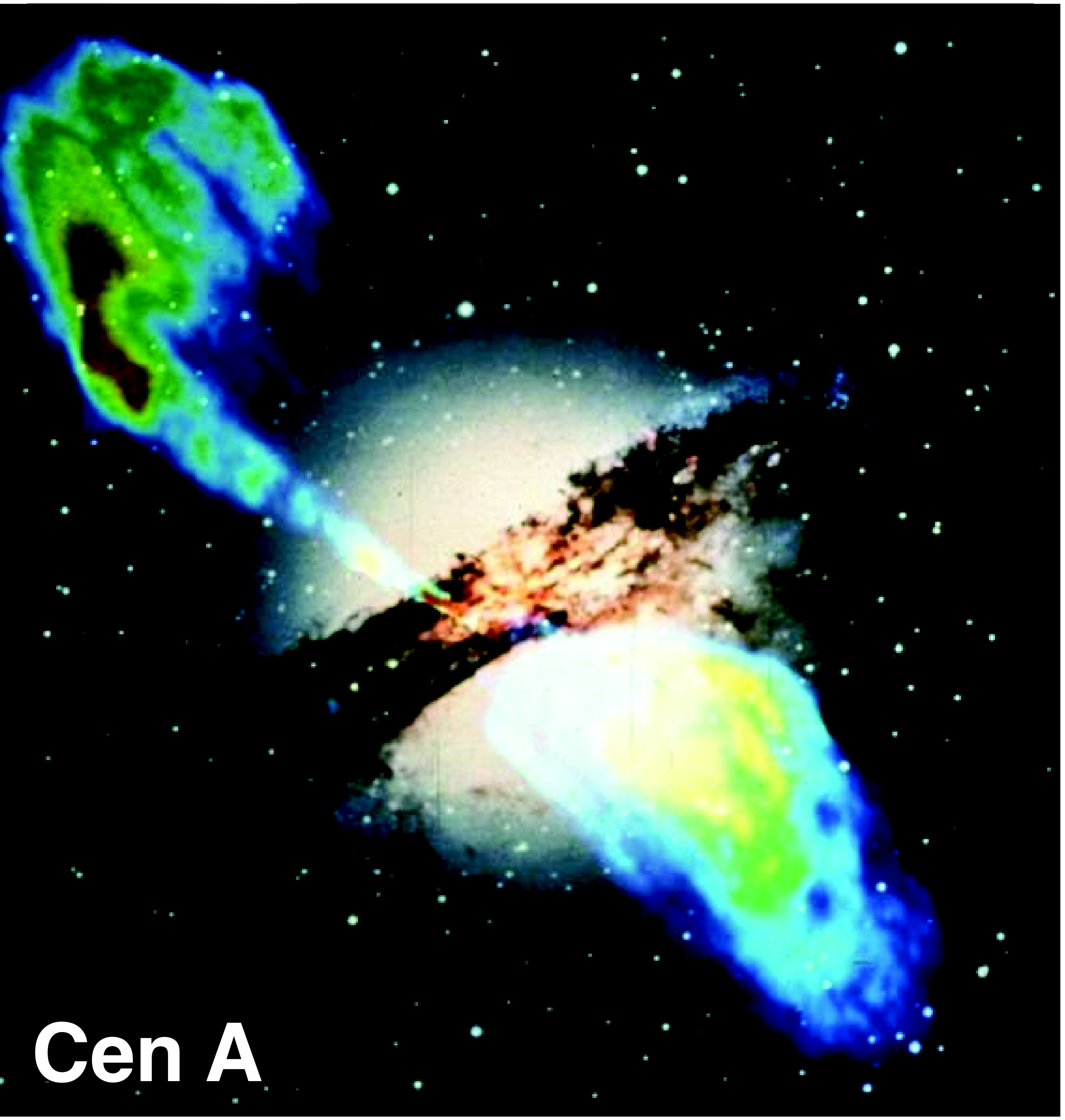
$$r = \frac{p}{ZeB}$$

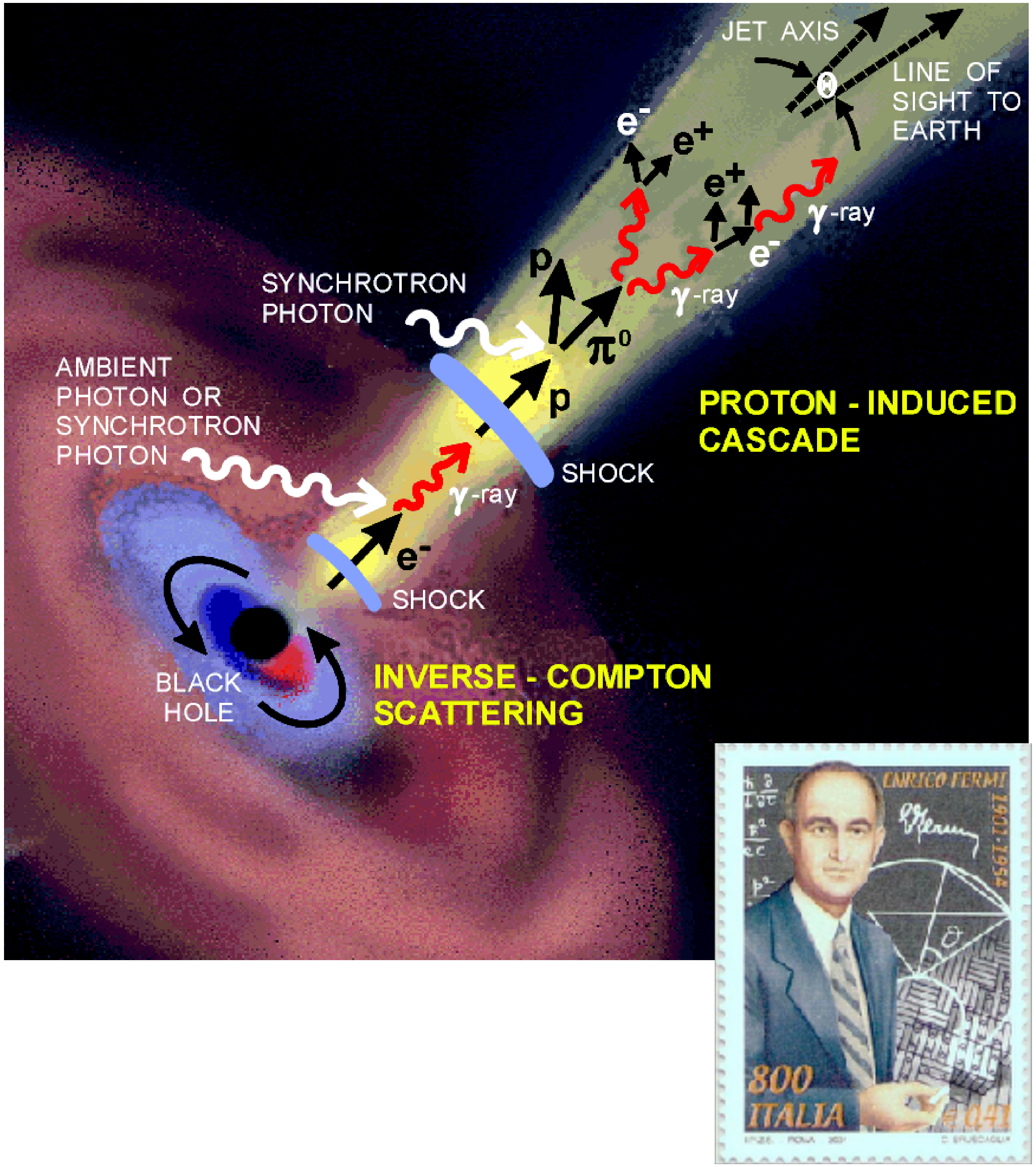
$$r[\mathrm{pc}] = 1.08 \cdot \frac{E\,[\mathrm{PeV}]}{B\,[\mu\mathrm{G}]}$$



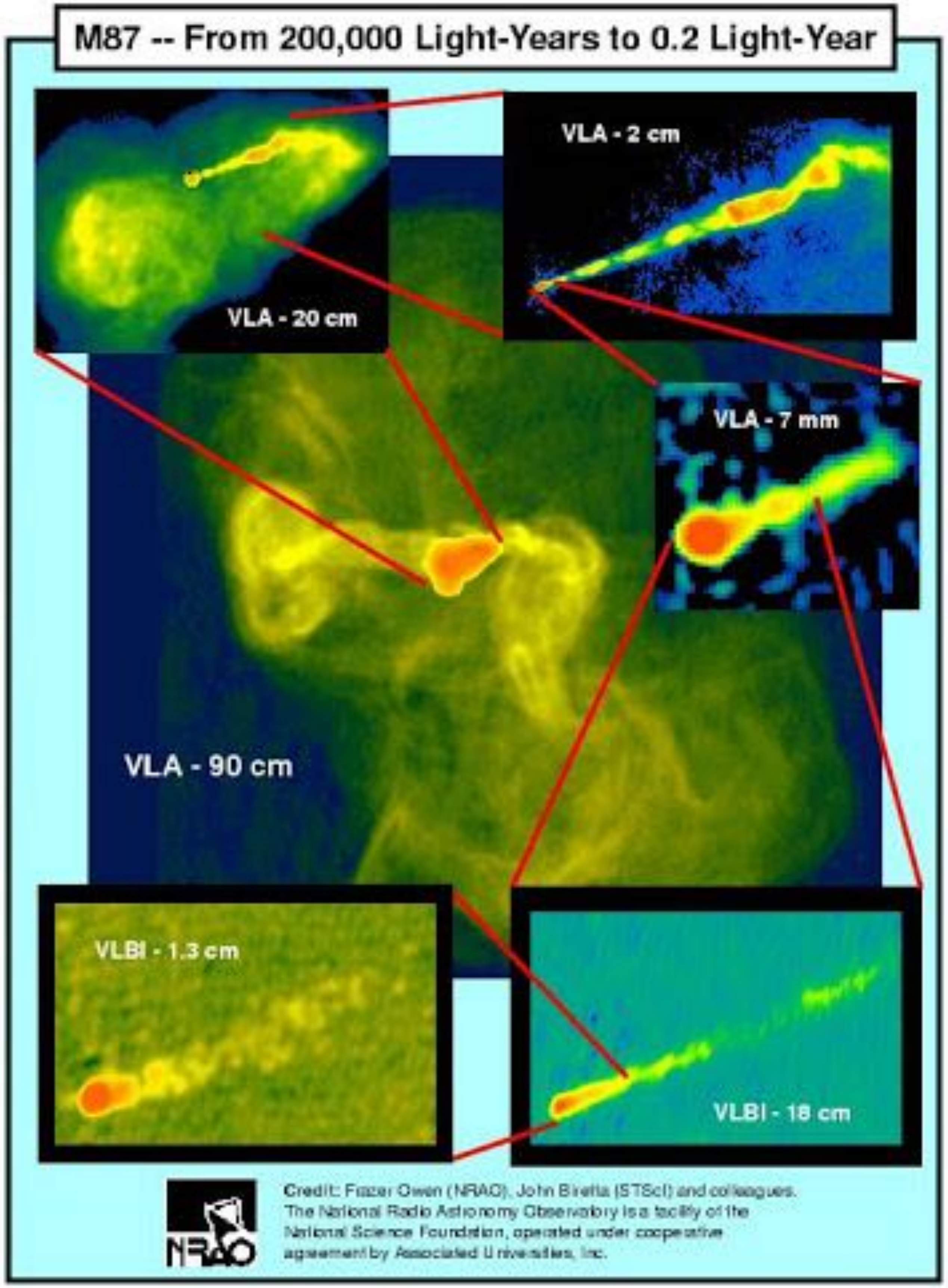
r= 0.04 pc 3.6 pc 360 pc 36 kpc

Acceleration of cosmic rays in jets of AGN

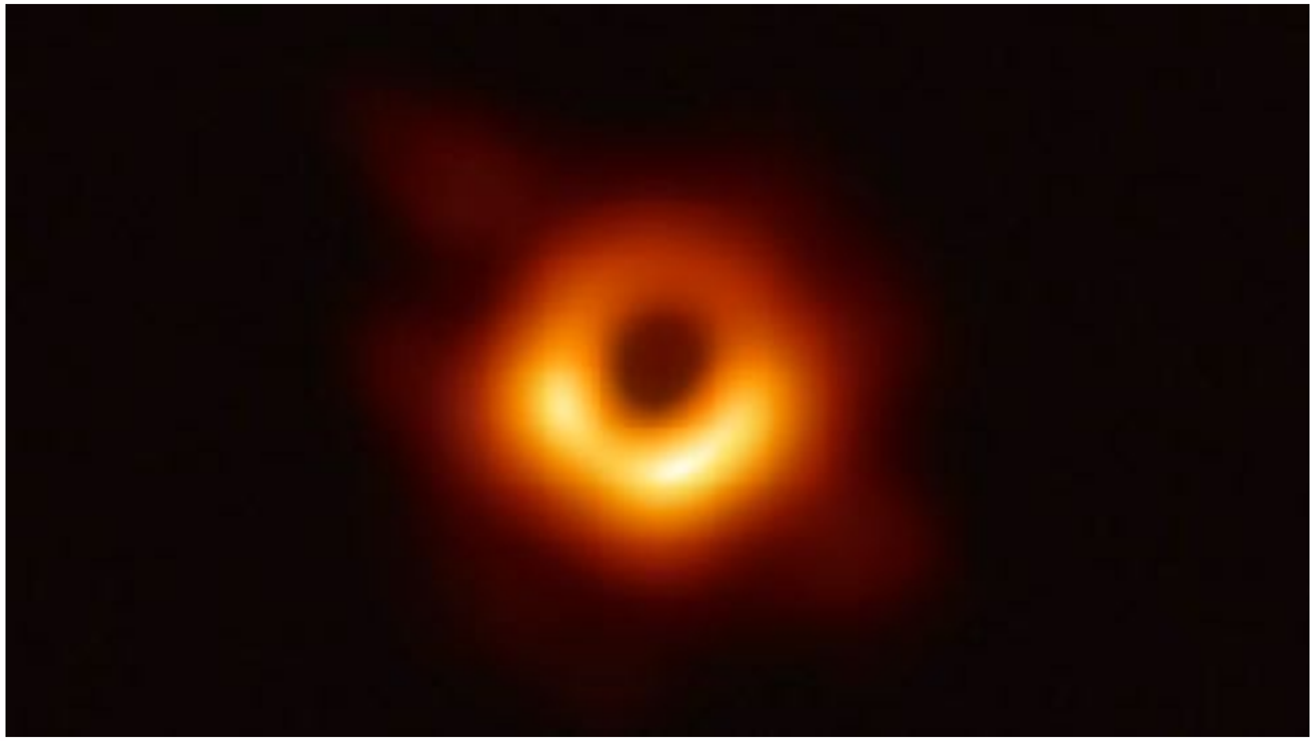




Active Galaxy M87

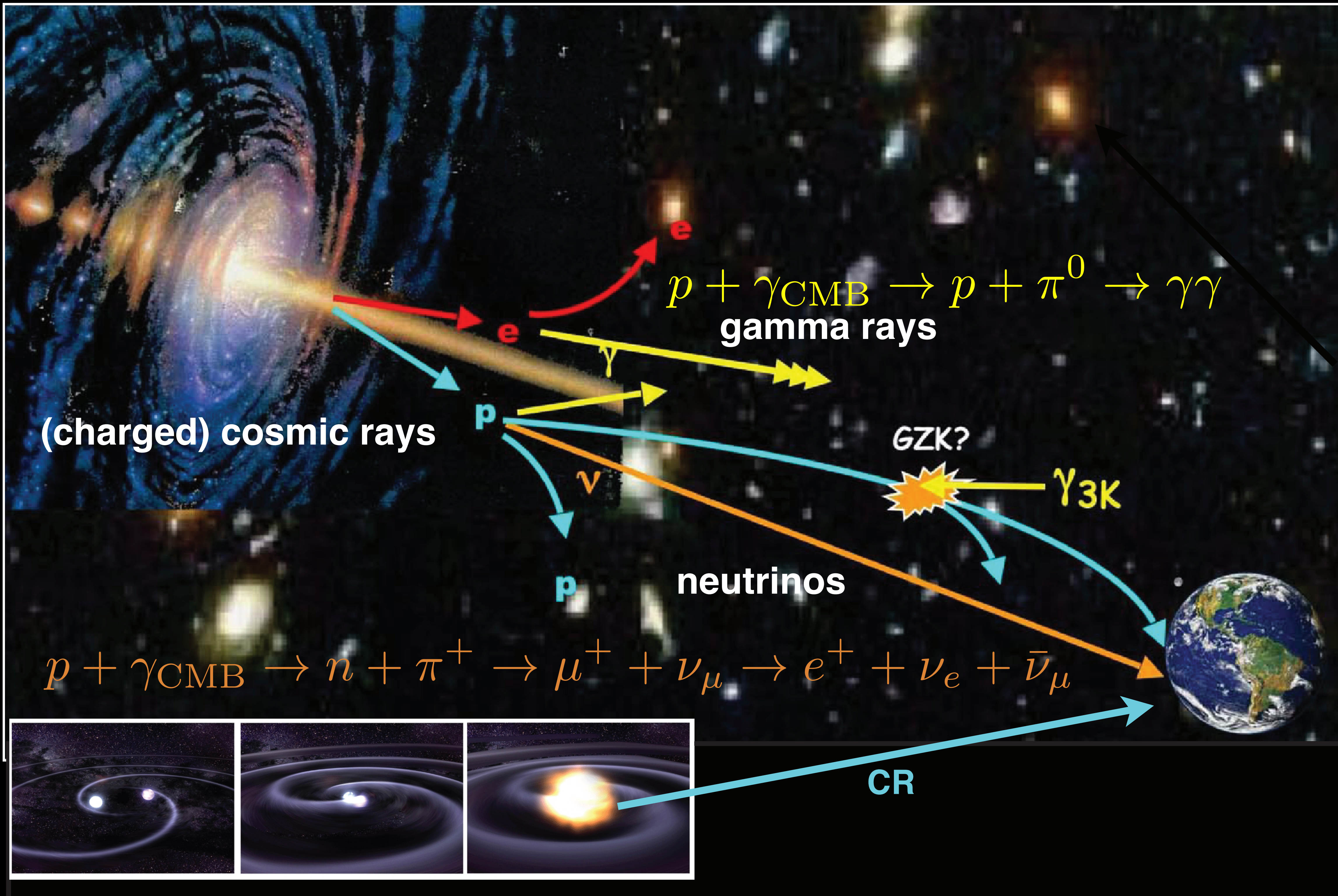


black hole in center



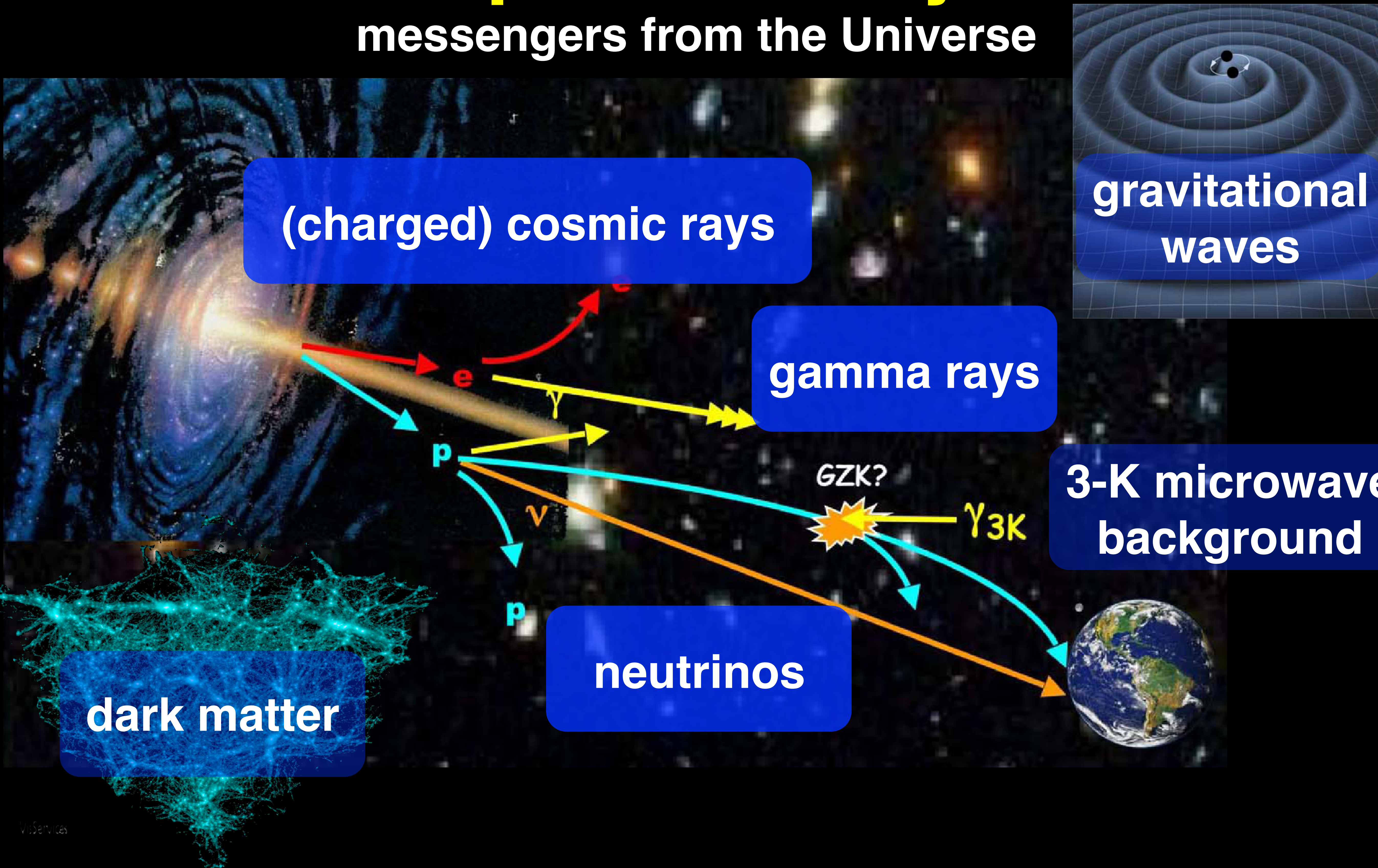
Event Horizon Telescope

Origin of cosmic rays
multi messenger technique

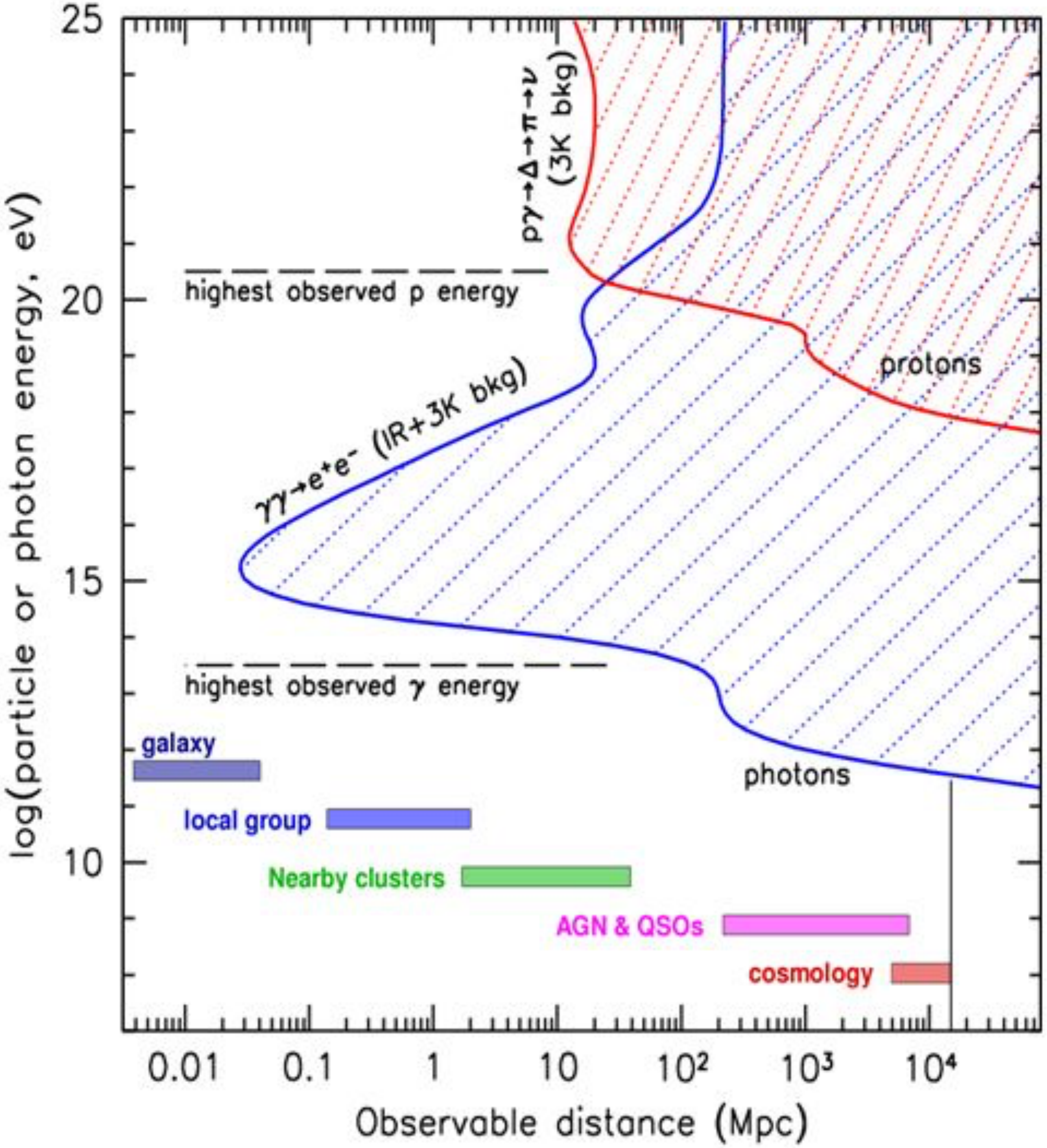


Astroparticle Physics

messengers from the Universe



Neutrinos as messengers



Study of the highest energy processes and particles throughout the universe requires PeV-ZeV neutrino detectors

To "**guarantee**"EeV neutrino detection, **design for the GZK neutrino flux**

Existence of extragalactic neutrinos inferred from CR spectrum, up to 10^{20} eV, and similarly, Galactic up to 10^{18} eV

Need gigaton (km^3) mass (volume) for TeV to PeV detection, and teraton at 10^{19} eV

Neutrino detection associated with EM sources will ID the UHECR sources

"EM Hidden" sources may exist, visible only in neutrinos.

Neutrino eyes see farther (z>1), and deeper (into compact objects), than gamma-photons, and straighter than UHECRs,with no absorption at (almost) any energy

Astroparticle Physics

master course NM076B,

6 EC, 2nd semester, *starting January, 2021*

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

http://particle.astro.ru.nl/goto.html?astropart2021

Shift at the Pierre Auger Observatory

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