Observing the Universe with the IceCube Observatory

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lectures outline

neutrino telescopes & the IceCube Observatory

observing the Universe

neutrino observations

cosmic ray observations

astrophysics & interdisciplinary sciences

outline

observing the Universe with IceCube

IceCube Observatory

event detection in Antarctica

cosmic ray acceleration mechanisms

neutrinos as probe into remote sources

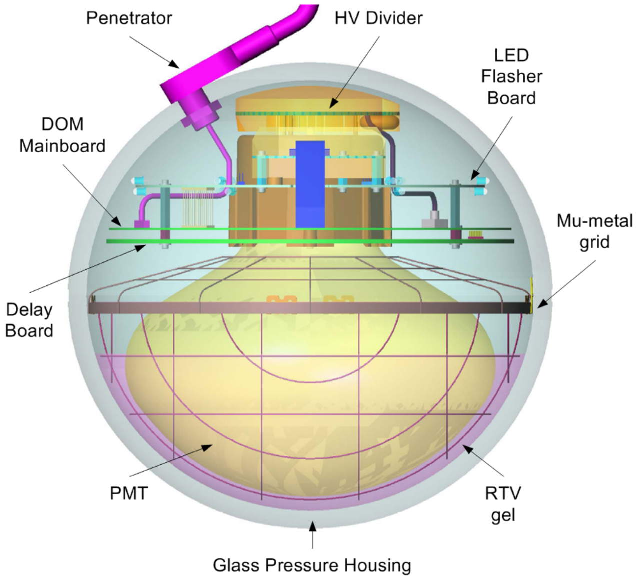
effective area

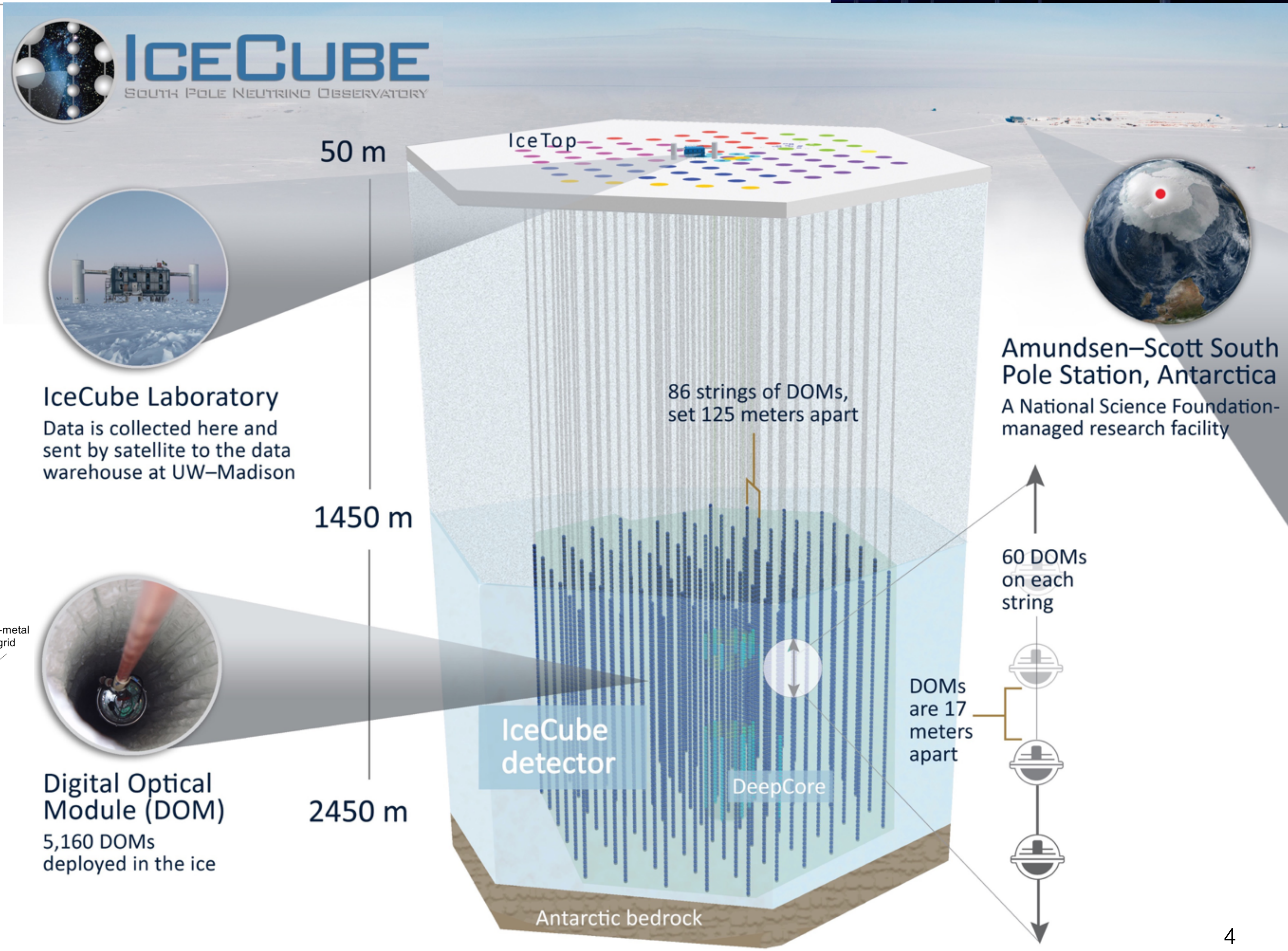
IceCube Observatory

the instrumentation

Digital Optical Module (DOM)

with 10” PMT
&
local DAQ electronics





IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

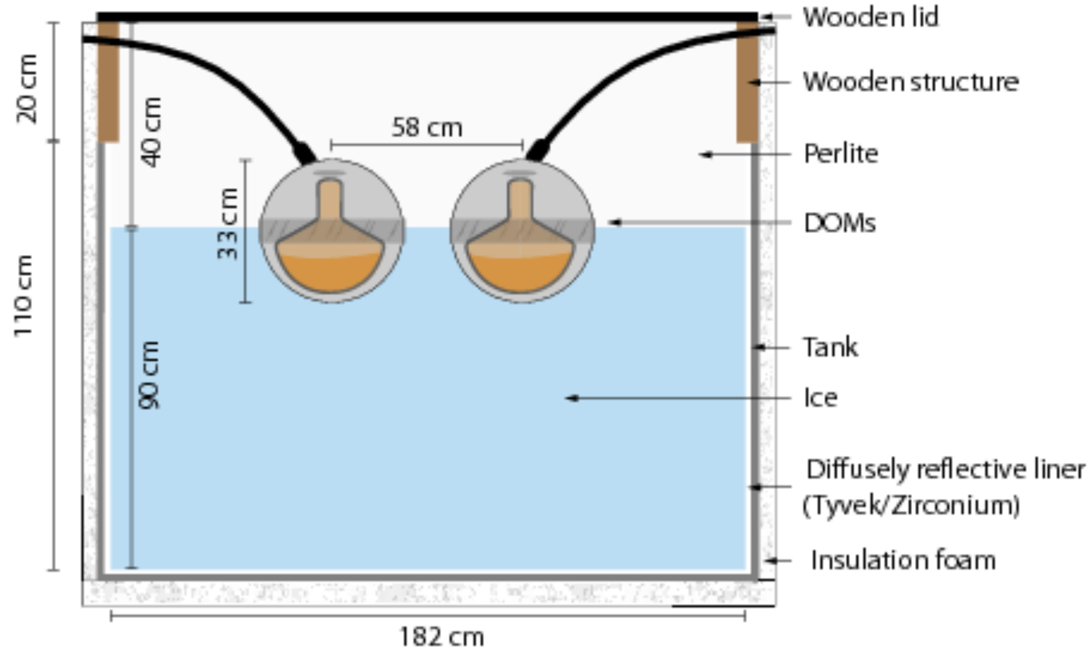
86 strings of DOMs, set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

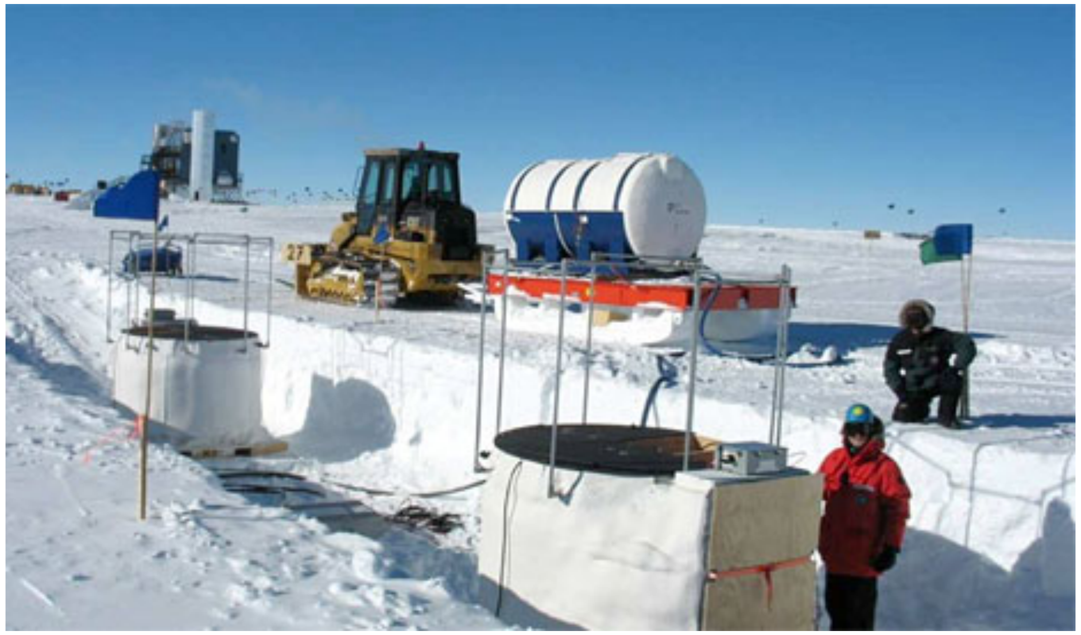
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

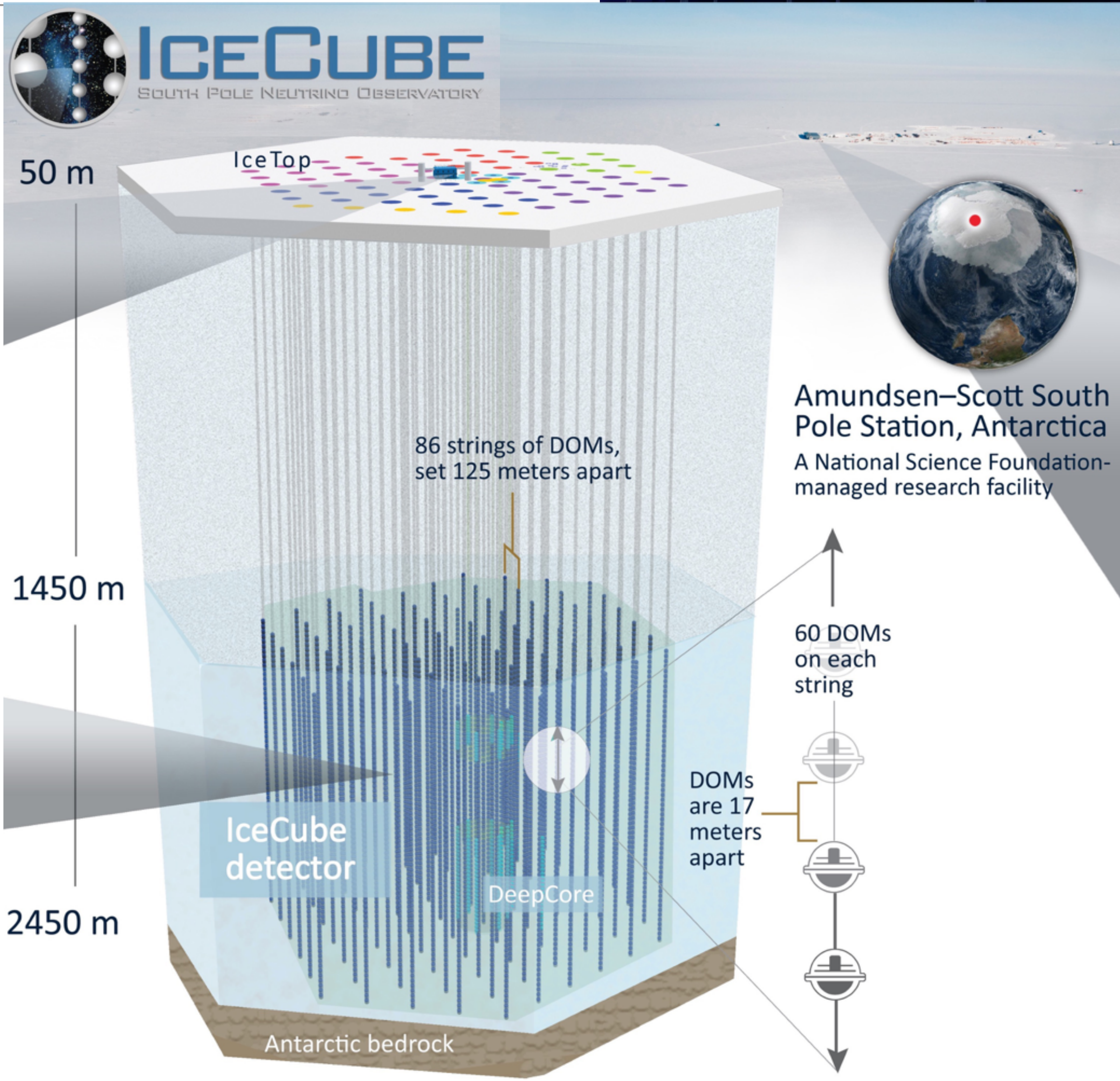
IceCube Observatory

the instrumentation



two tanks of one IceTop station

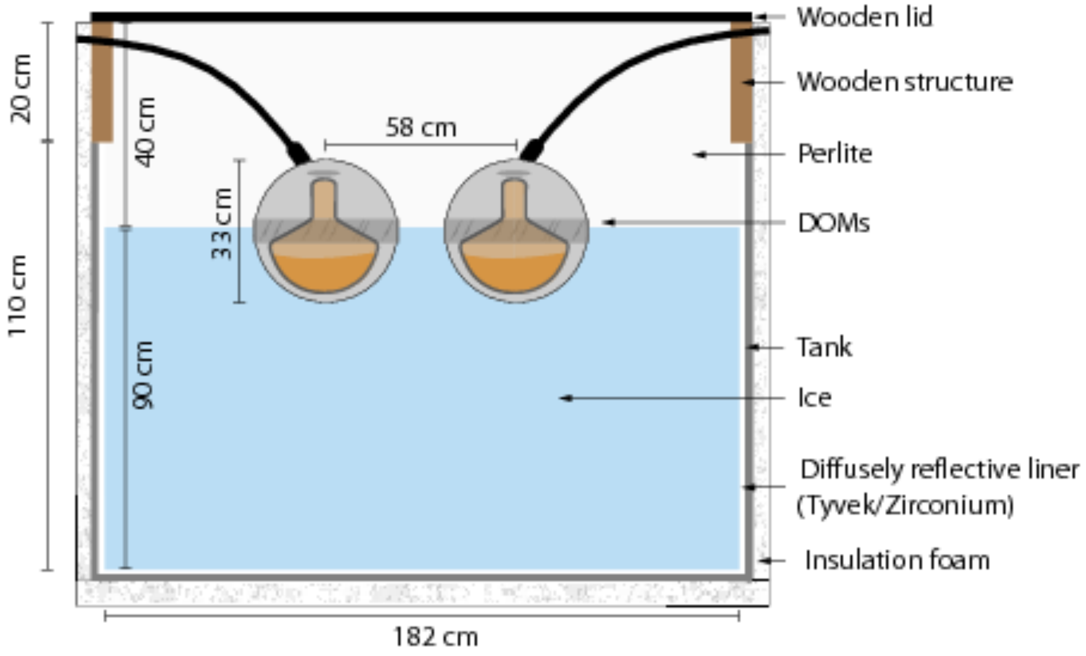




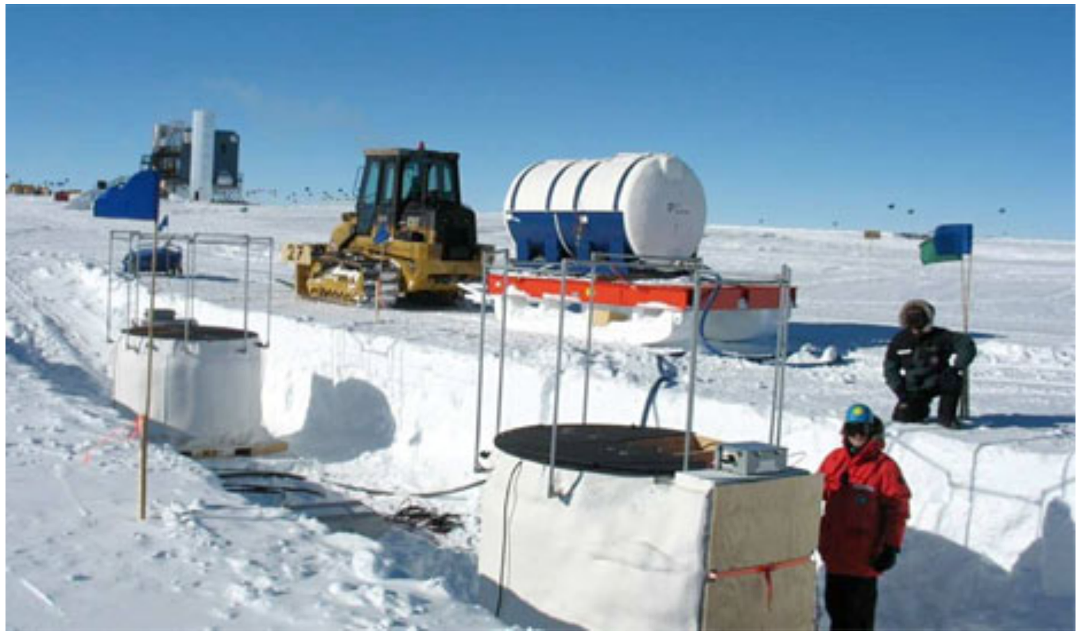
IceCube Observatory

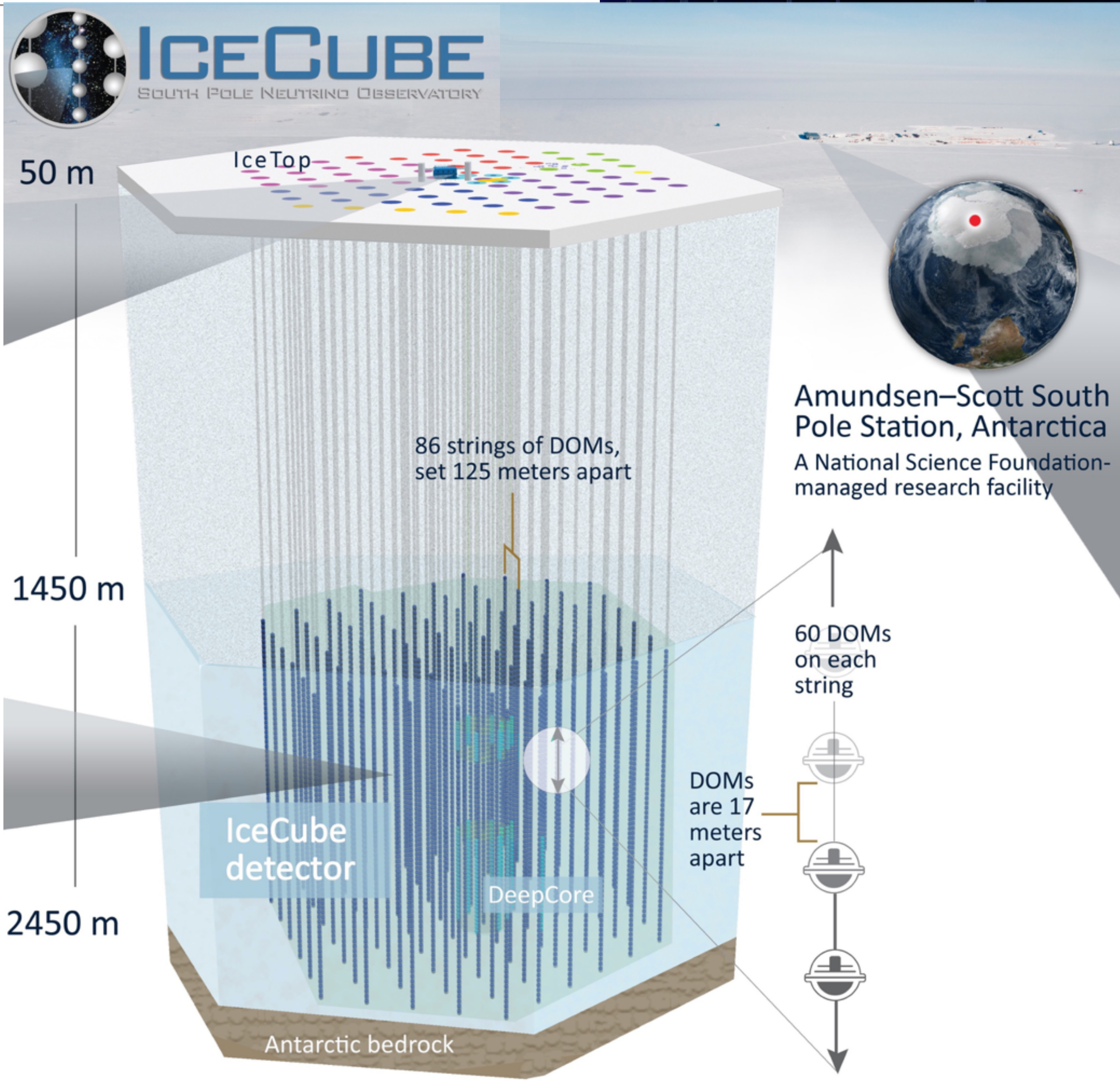
the instrumentation

KM^3 OBSERVATORY

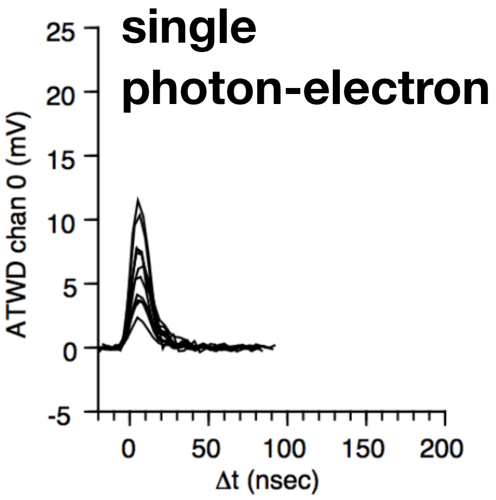


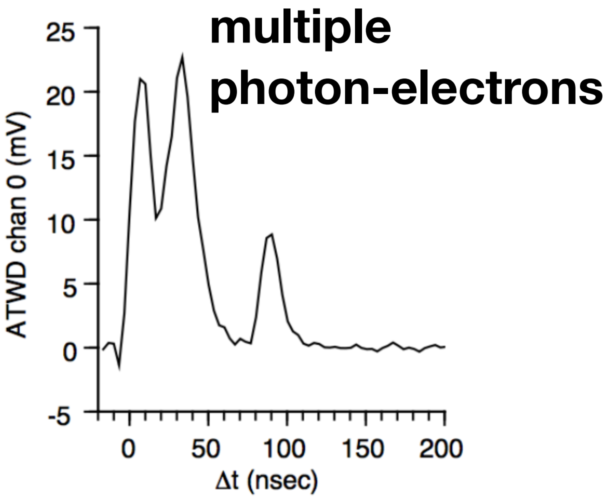
two tanks of one IceTop station

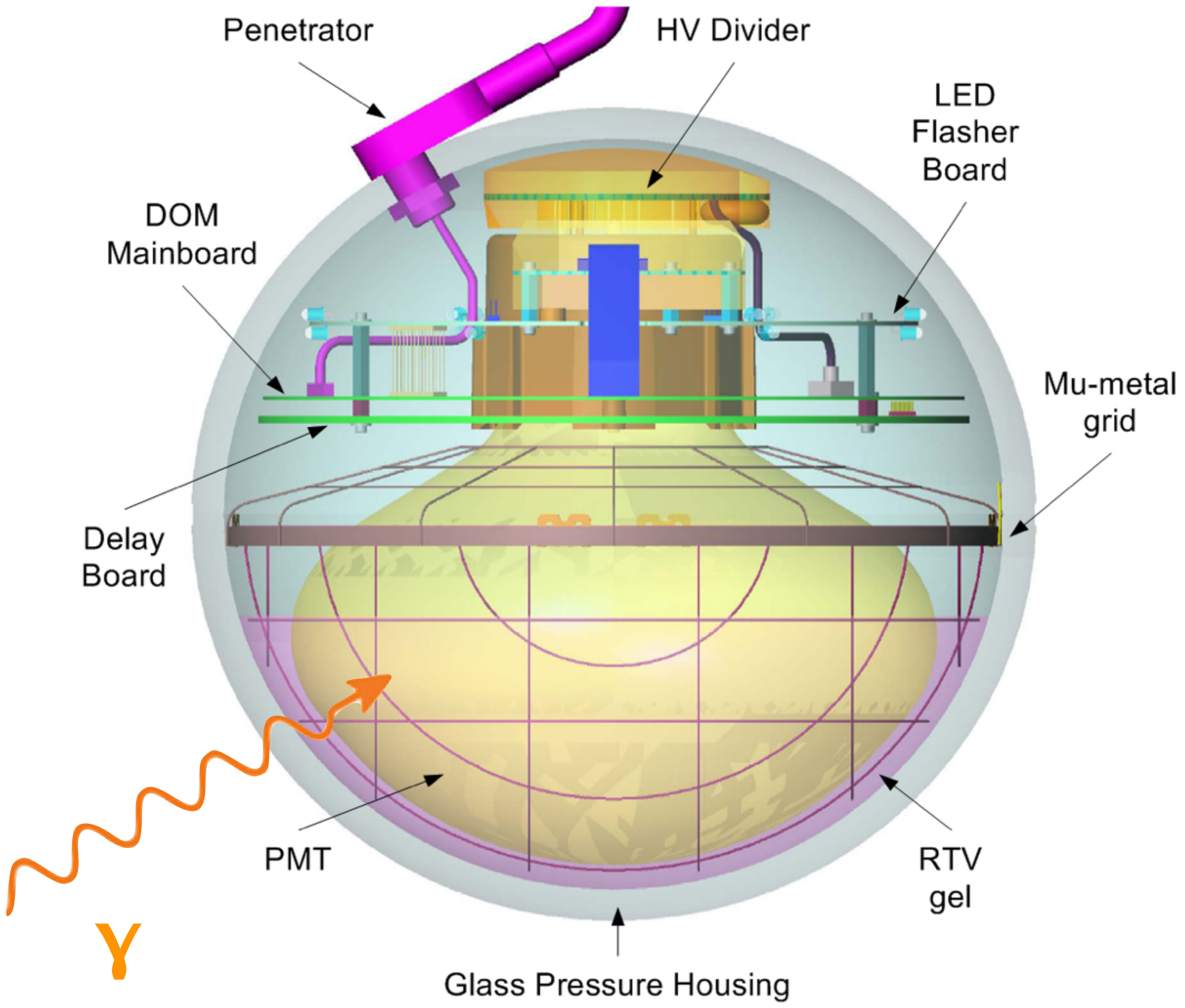




Digital Optical Module
the signal digitization

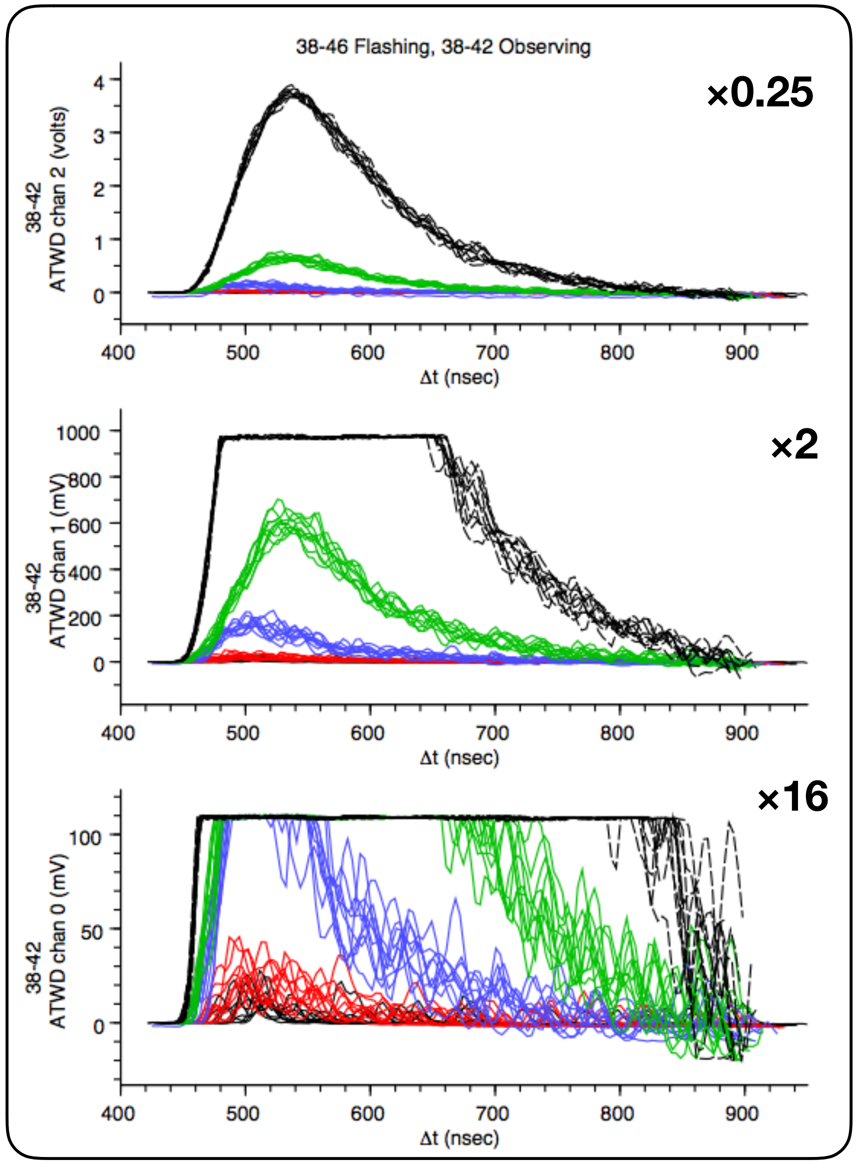






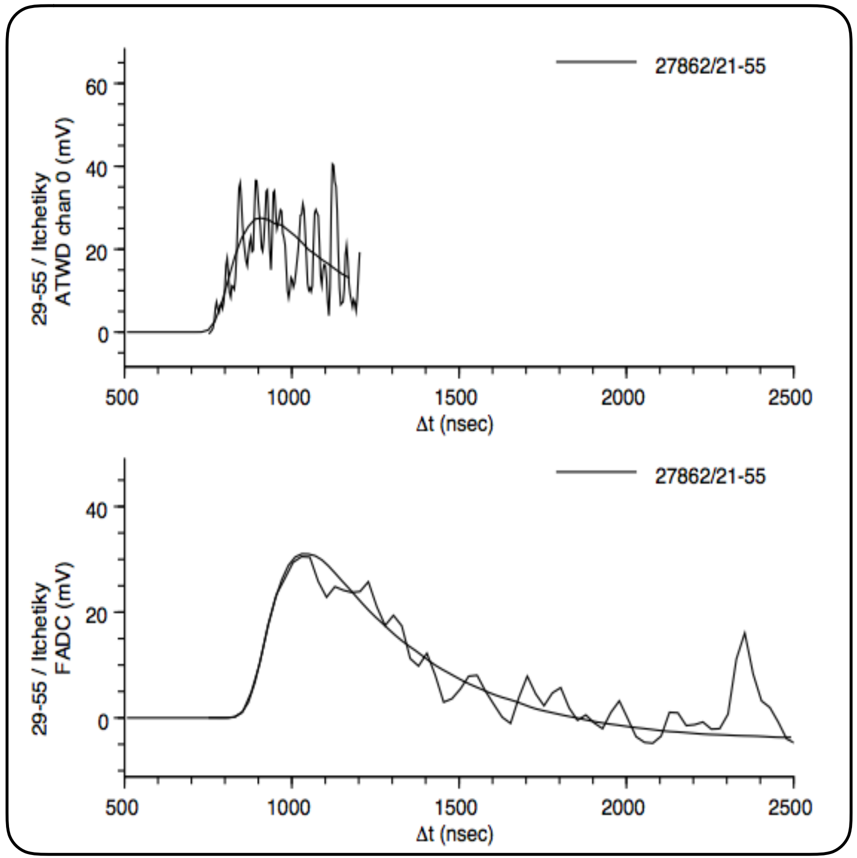
different gains

for wide dynamic range
in amplitude



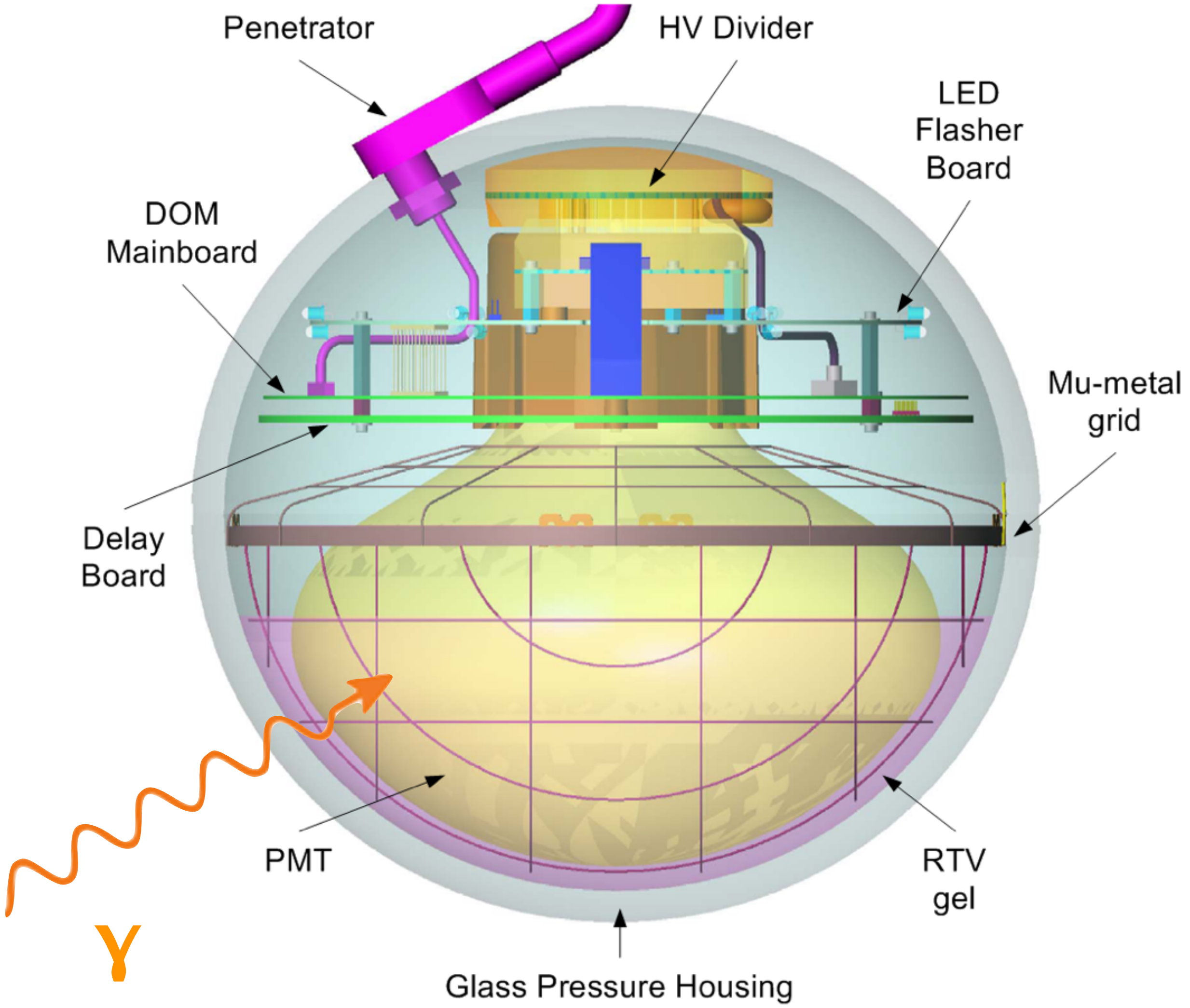
different time range

for long waveforms

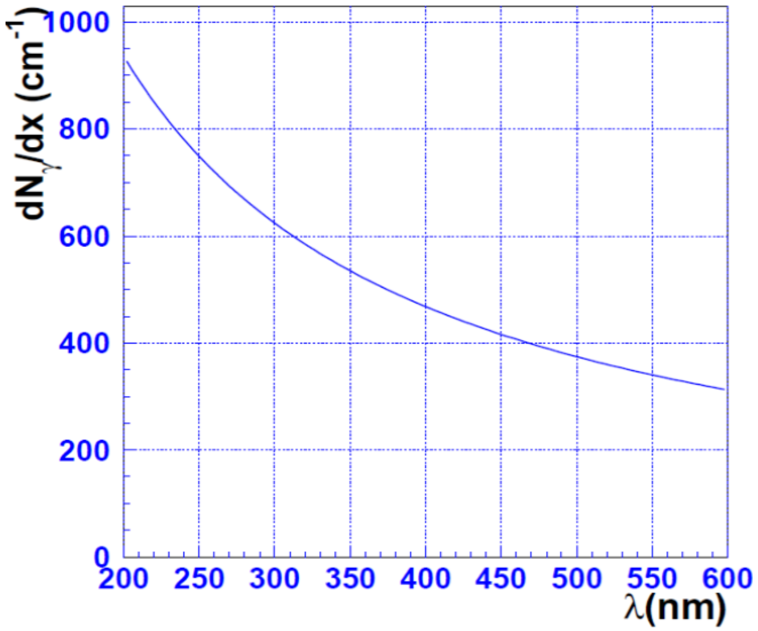


Digital Optical Module

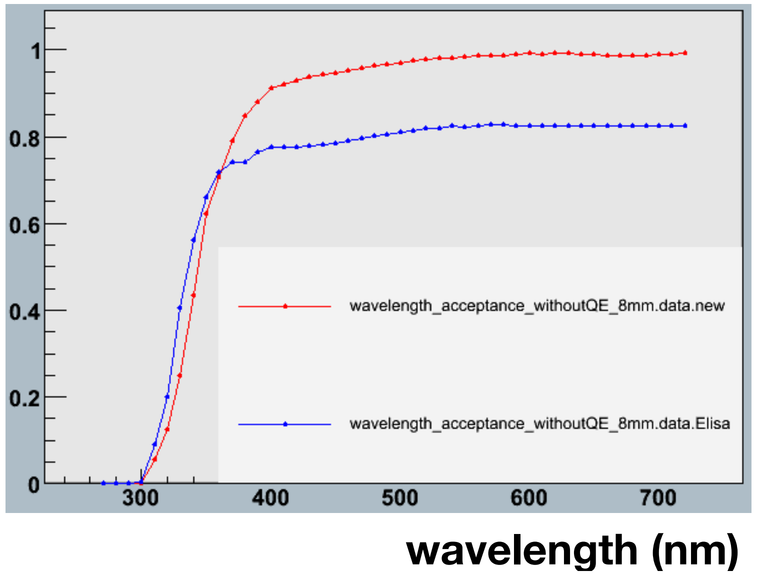
the photon sensitivity



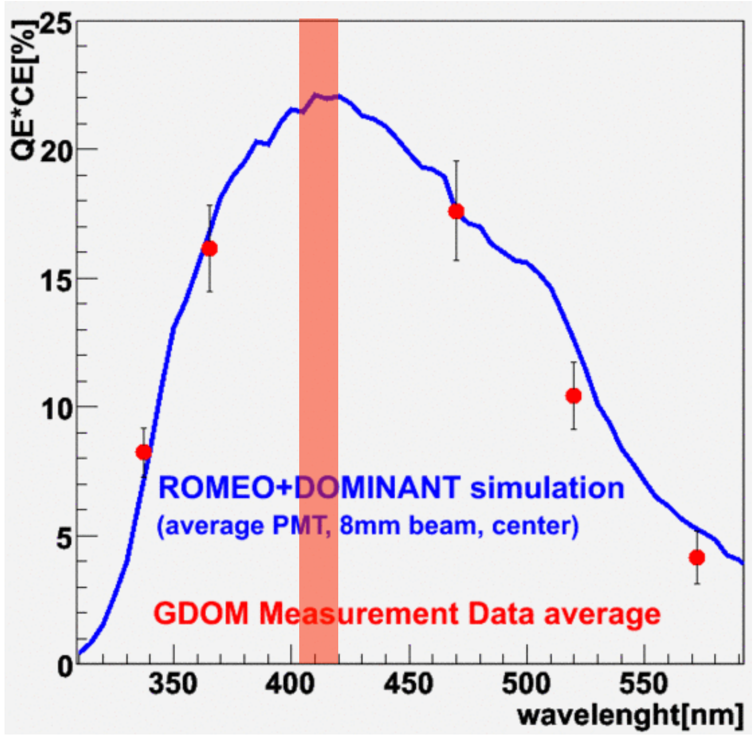
Cherenkov photon wavelength spectrum



glass/gel transmittance low wavelength cut-off

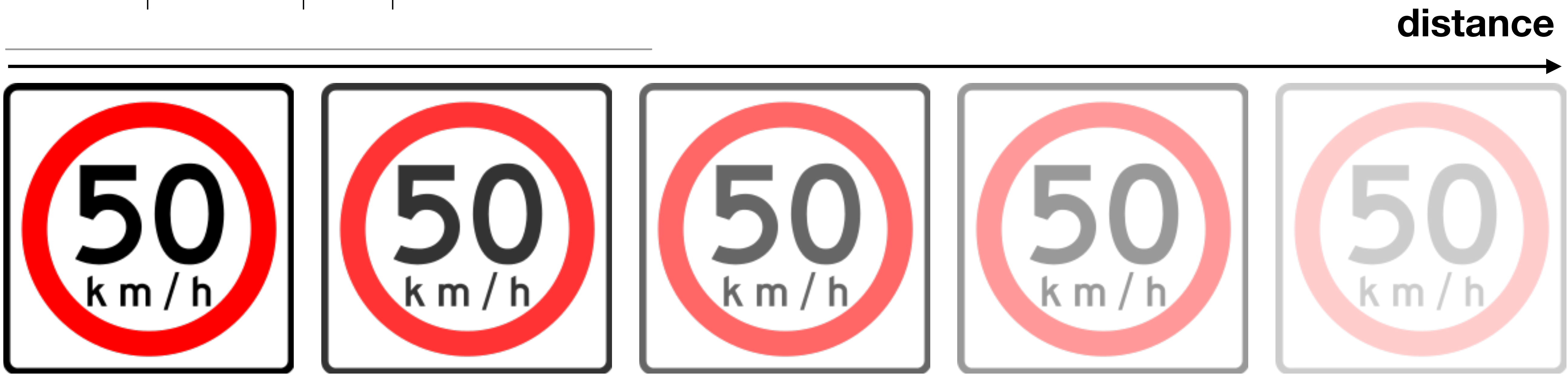


PMT Quantum Efficiency × Collection Efficiency



antarctic ice

ice optical properties



effect of light **absorption** as a function of distance

antarctic ice

ice optical properties

effect of light **scattering** as a function of distance

antarctic ice

ice optical properties

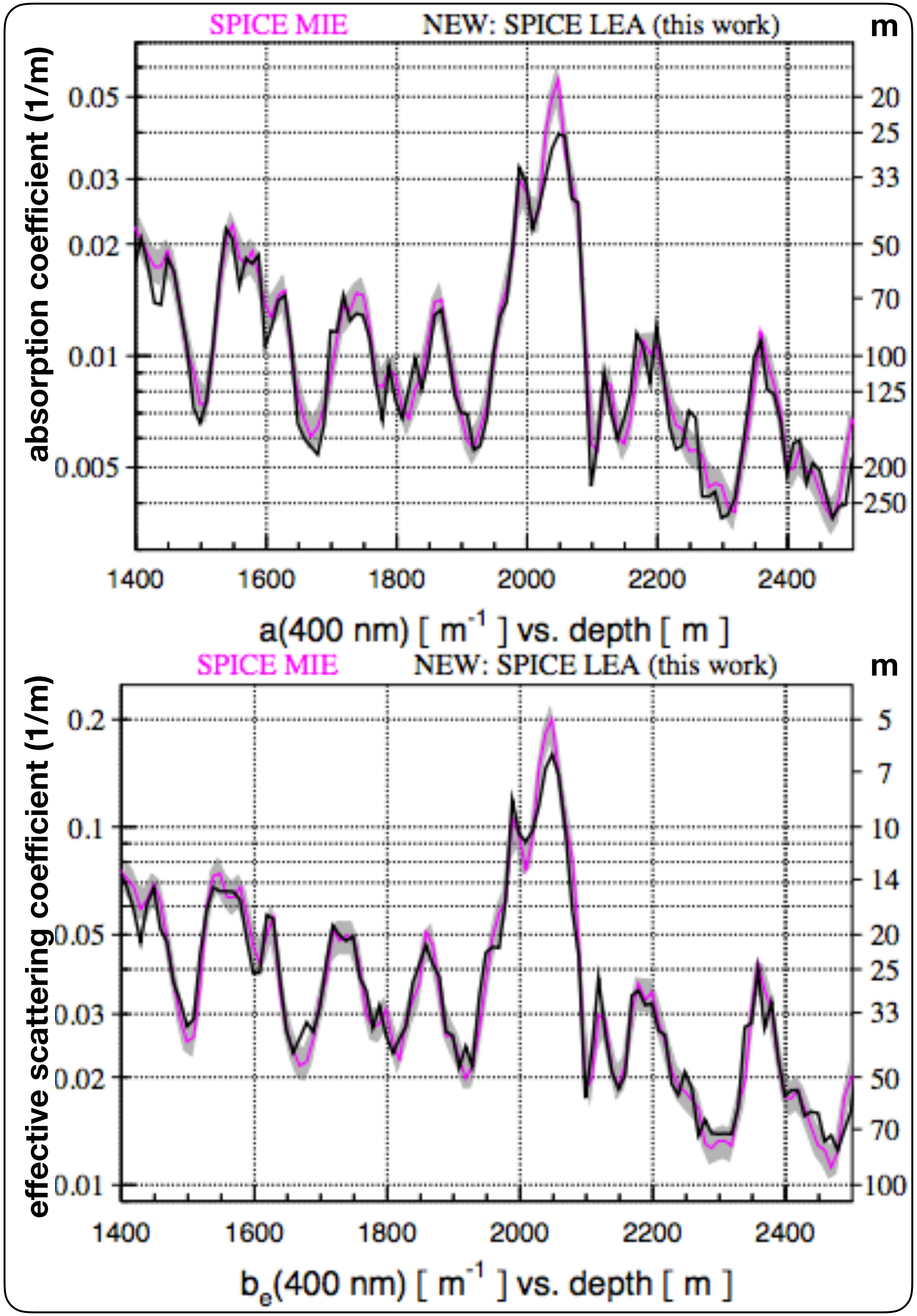
combined effect of light **absorption** and **scattering** as a function of distance

optical properties of antarctic ice important for estimating the **particle energy** (# Cherenkov photons) & the **particle direction** (photon arrival time)

antarctic ice

ice optical properties

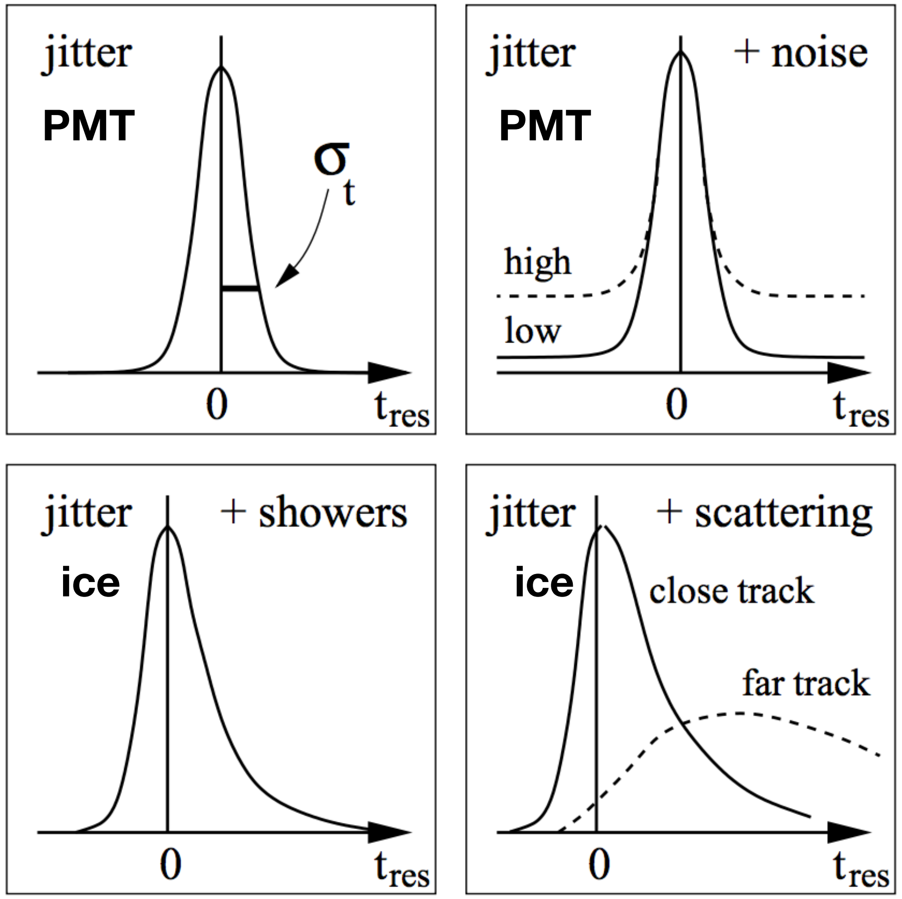
- depth dependency from **glaciological** history of Antarctica
- absorption & scattering about the same order of magnitude
- use on-site flasher LED to measure photon absorption and arrival times as a function of distance
- implement scattering models and account for wavelength dependence

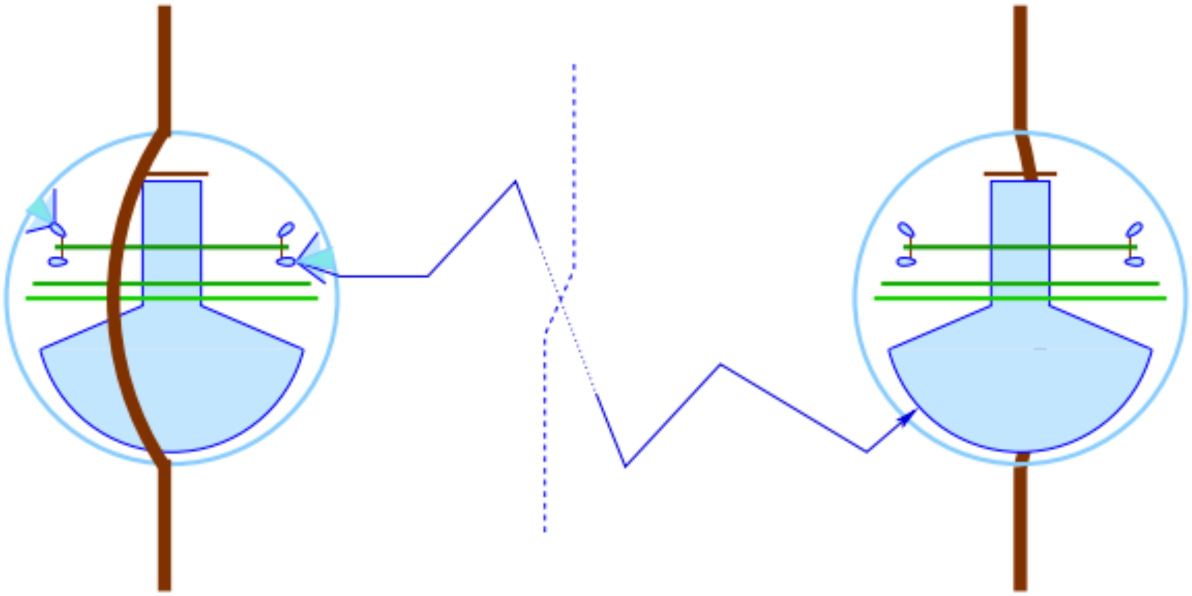


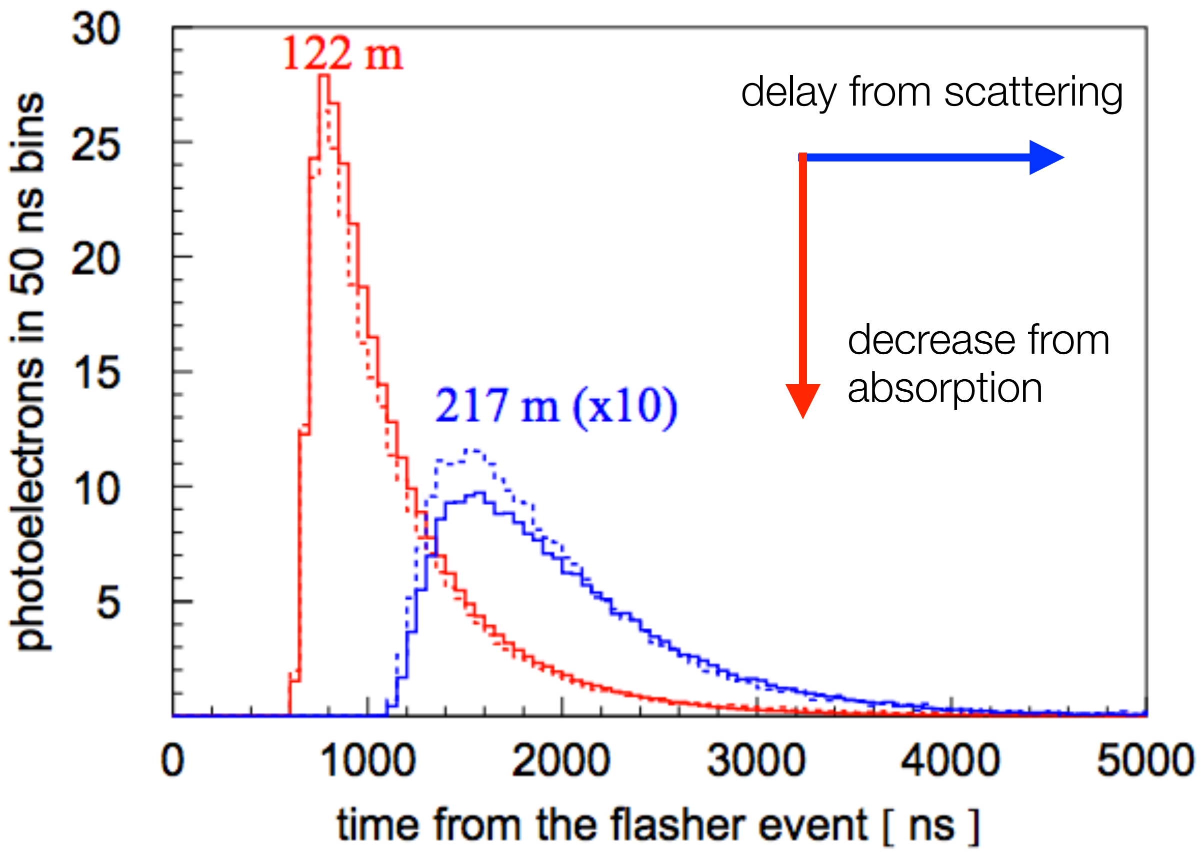
antarctic ice

ice optical properties

- ice optical properties essential for physics
- absorption affects charge ~ energy estimation
- scattering affects time ~ event direction

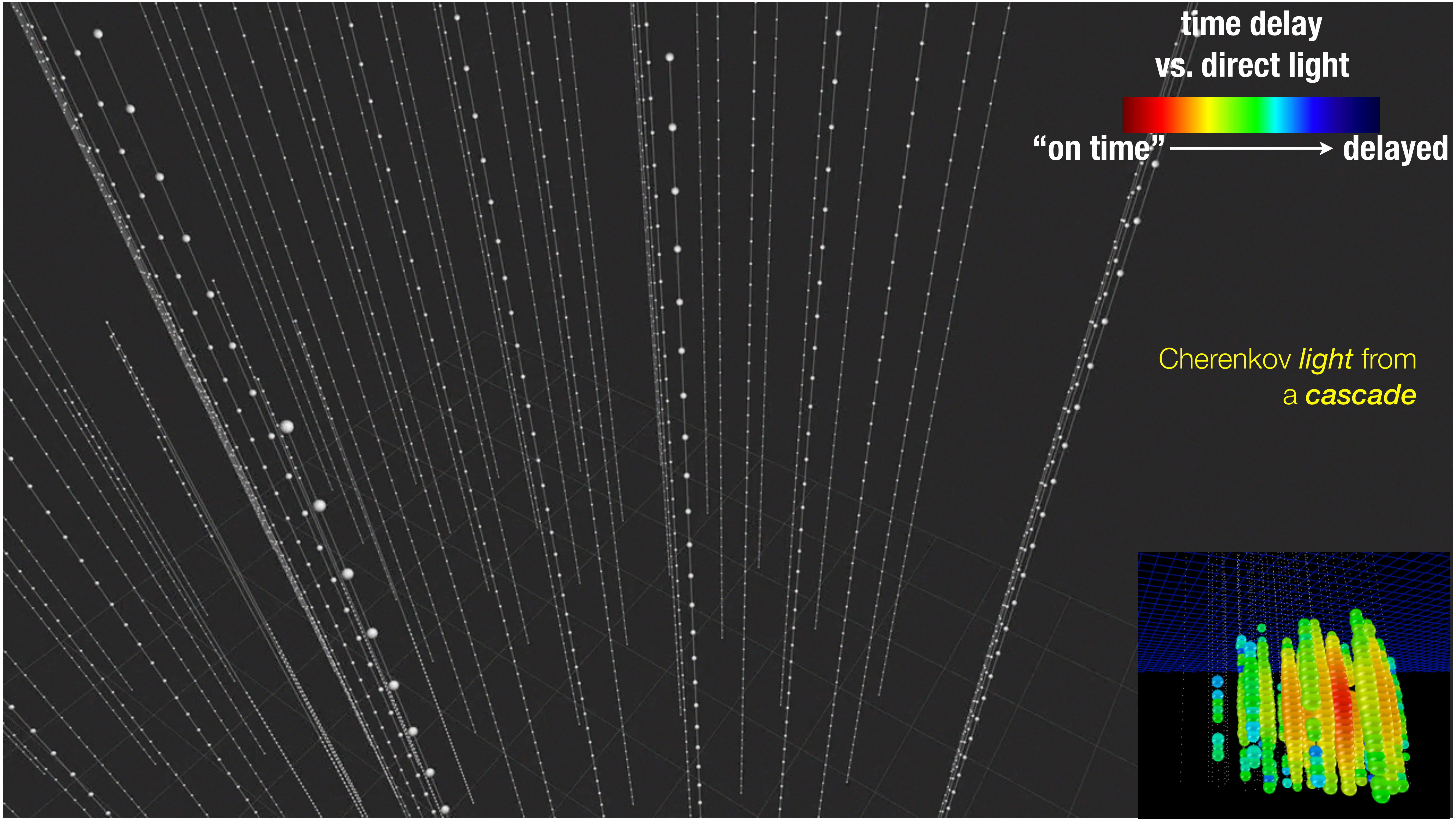






detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int



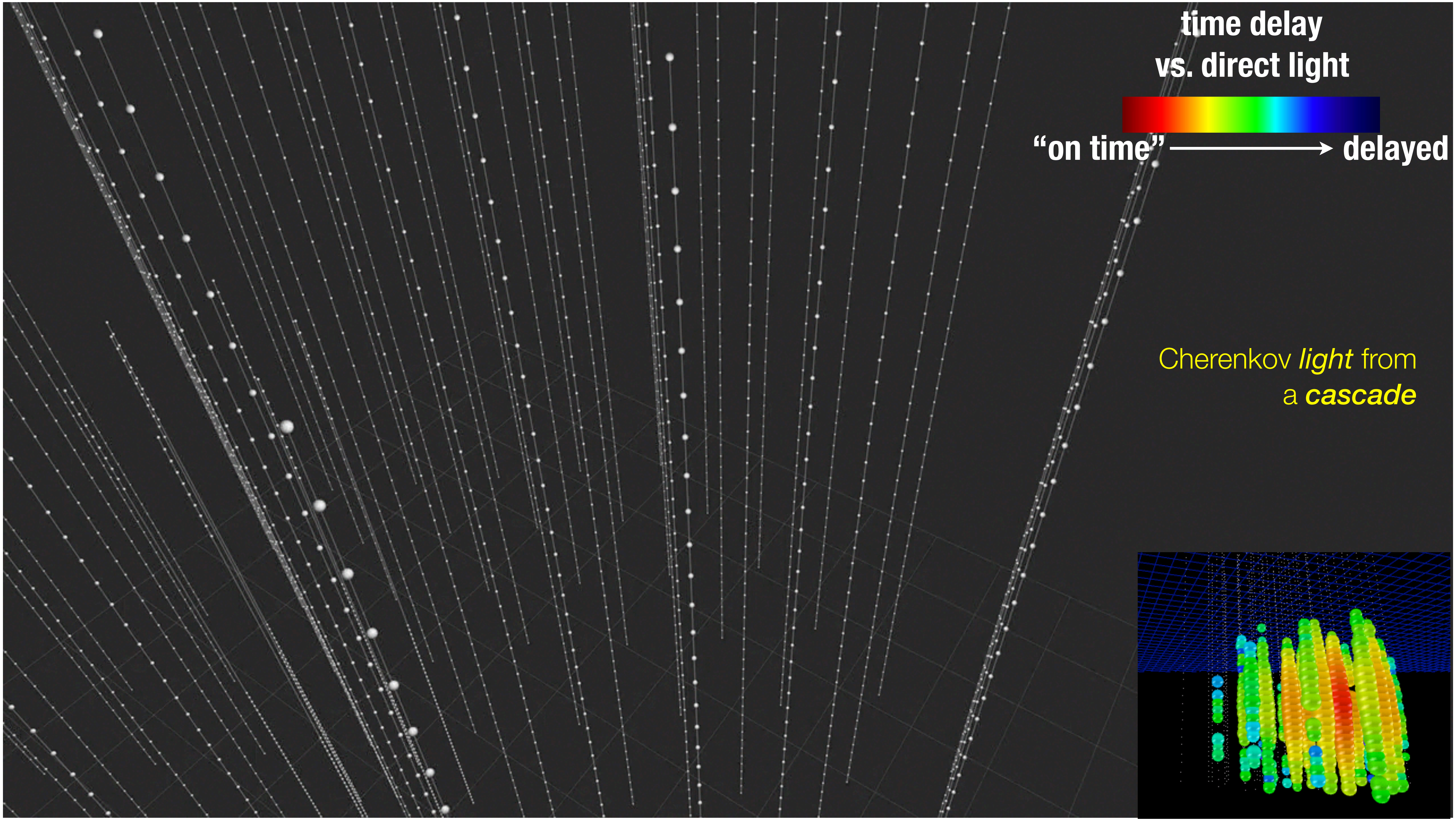
Cherenkov *light* from
a ***cascade***

Claudio Kopper - WIPAC

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int



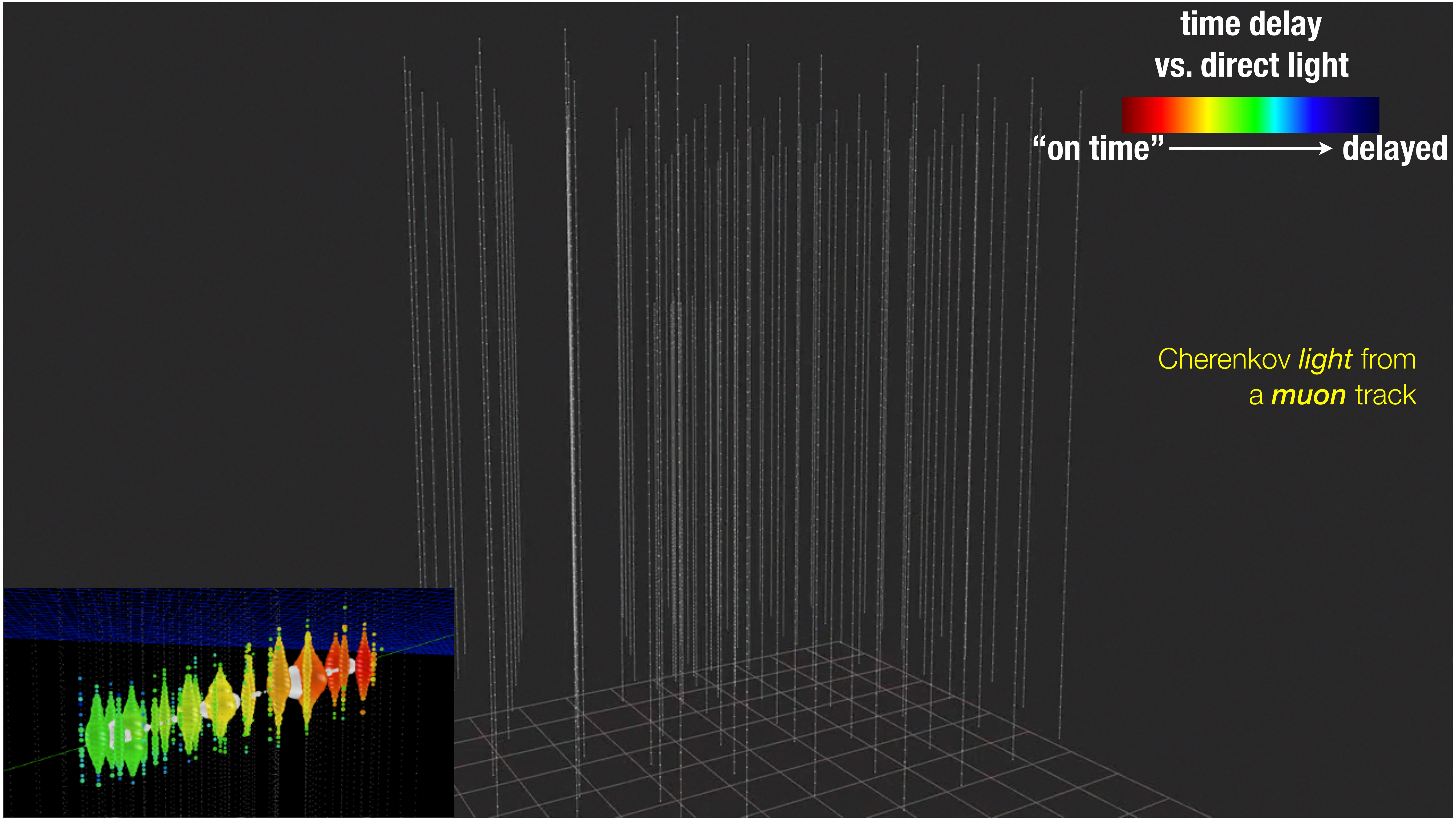
Cherenkov *light* from
a ***cascade***

Claudio Kopper - WIPAC

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

detection principle - *track*

ν_μ CC-int



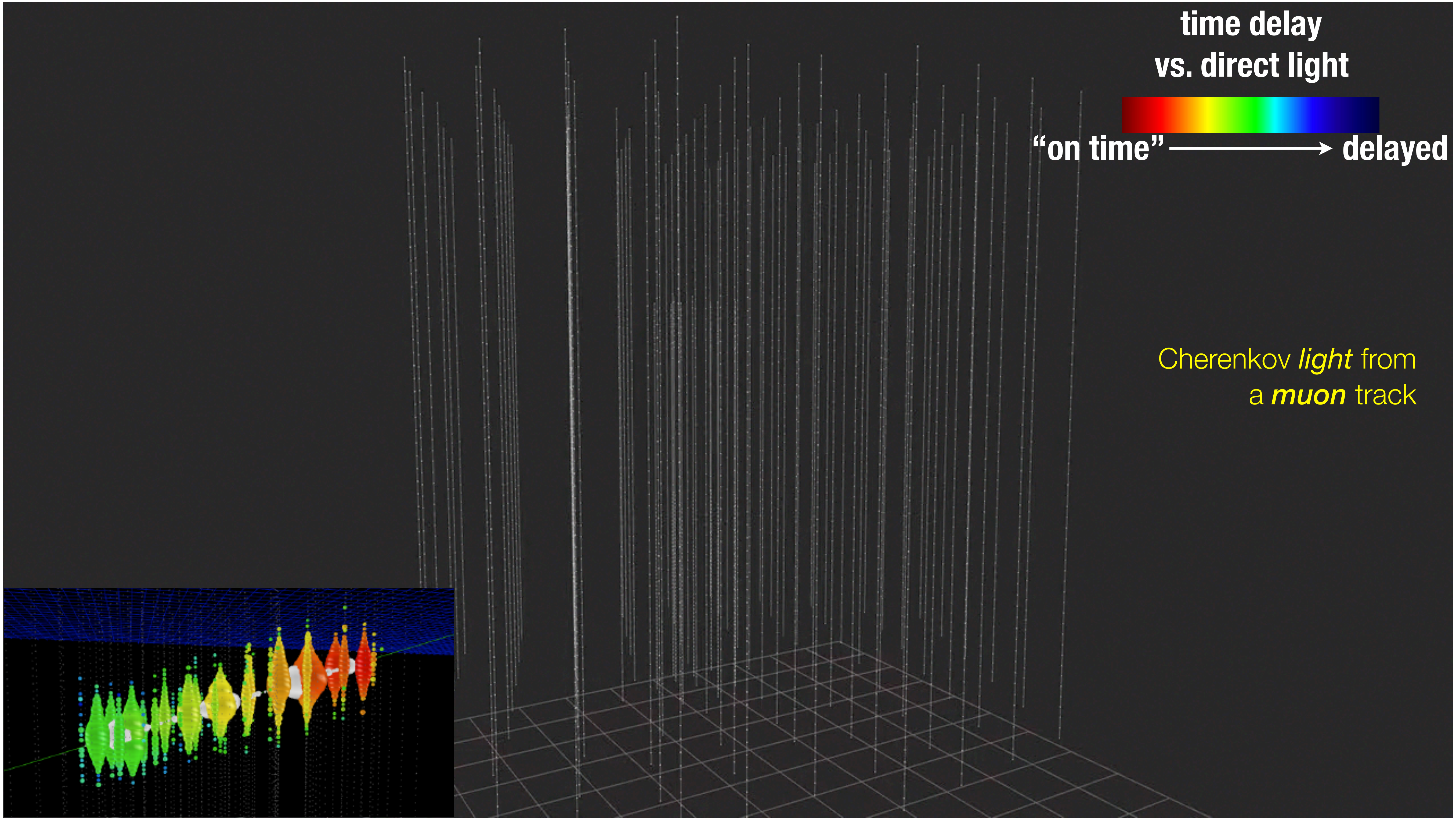
Cherenkov *light* from a ***muon*** track

Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution

detection principle - *track*

ν_μ CC-int



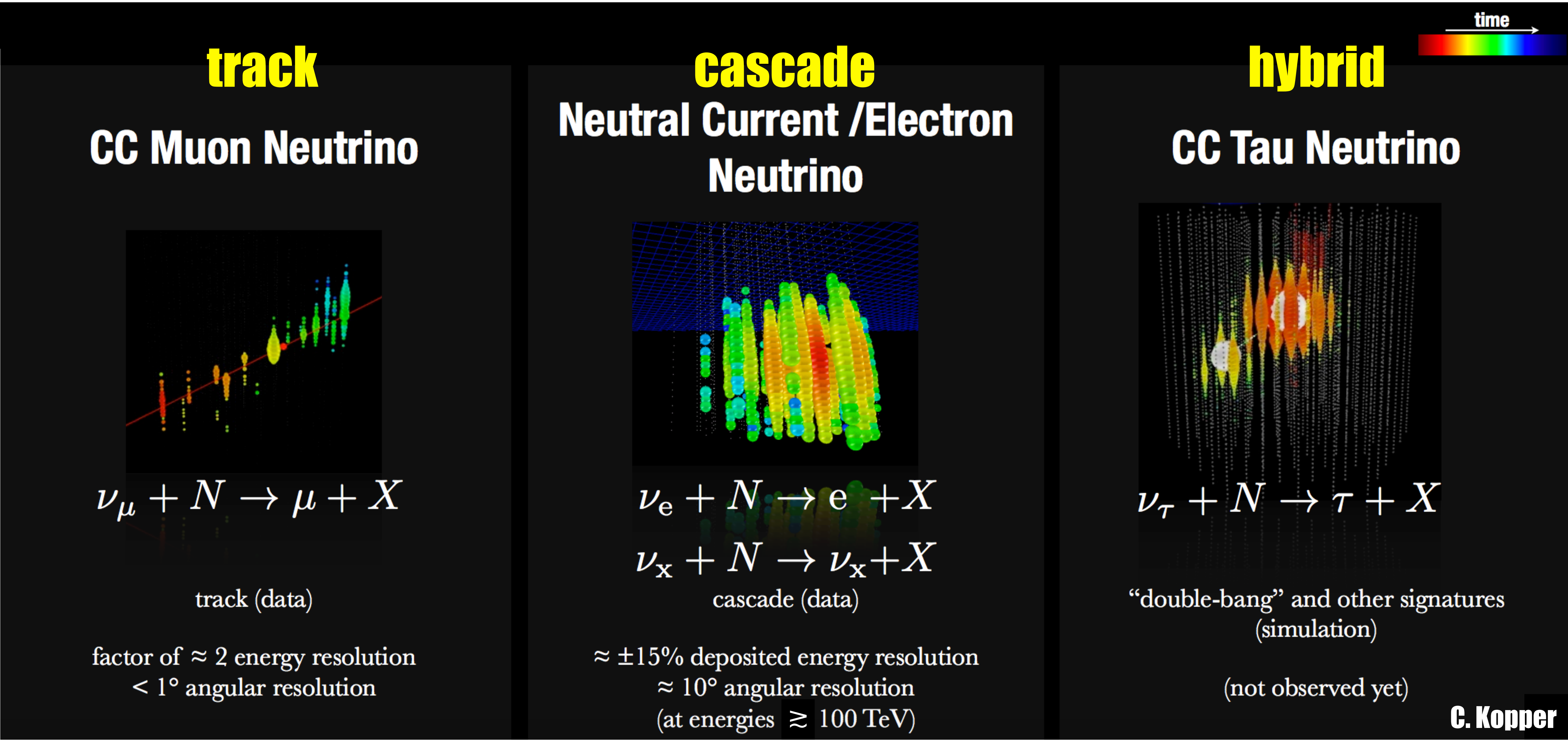
Cherenkov *light* from
a ***muon*** track

Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution

neutrino detection

event topologies



track

CC Muon Neutrino

$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

cascade

Neutral Current /Electron Neutrino

$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies $\gtrsim$ 100 TeV)

hybrid

CC Tau Neutrino

$$\nu_\tau + N \rightarrow \tau + X$$

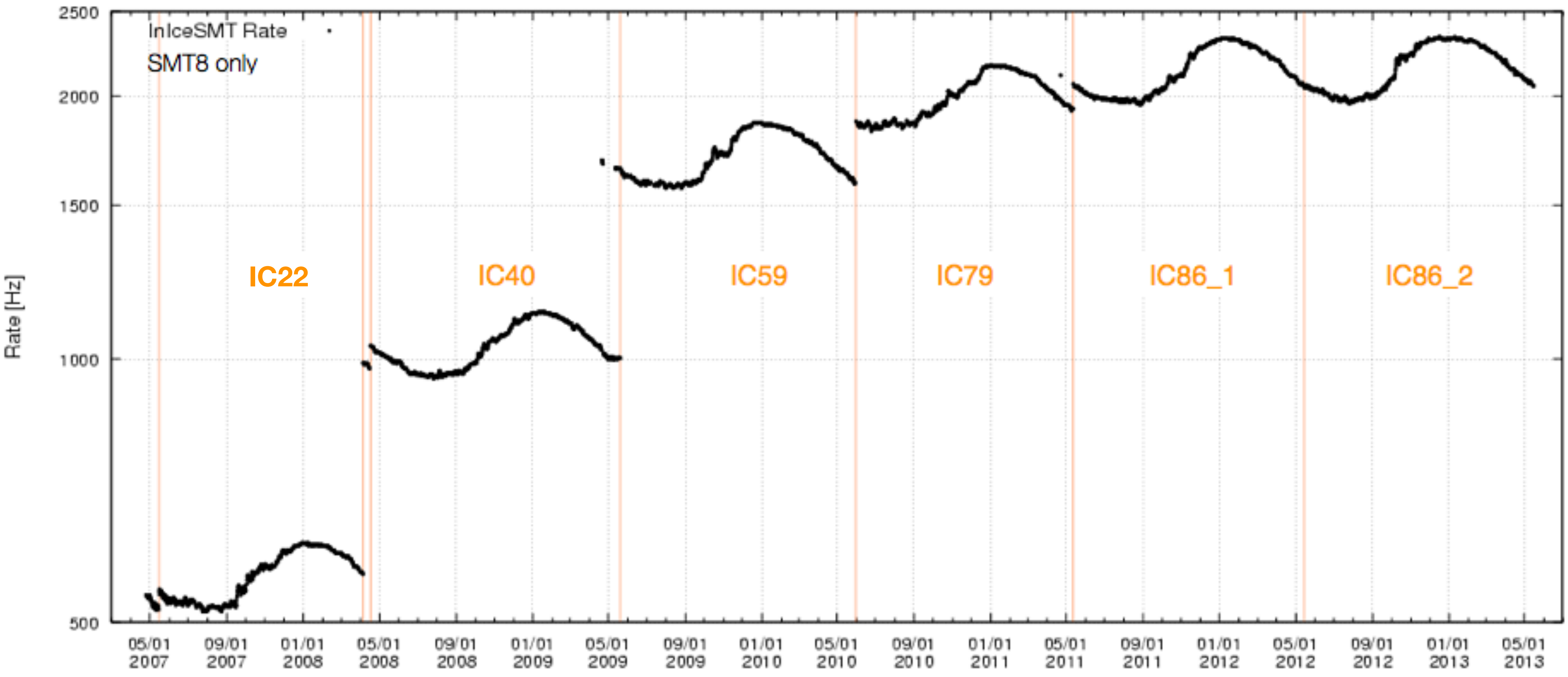
"double-bang" and other signatures
(simulation)

(not observed yet)

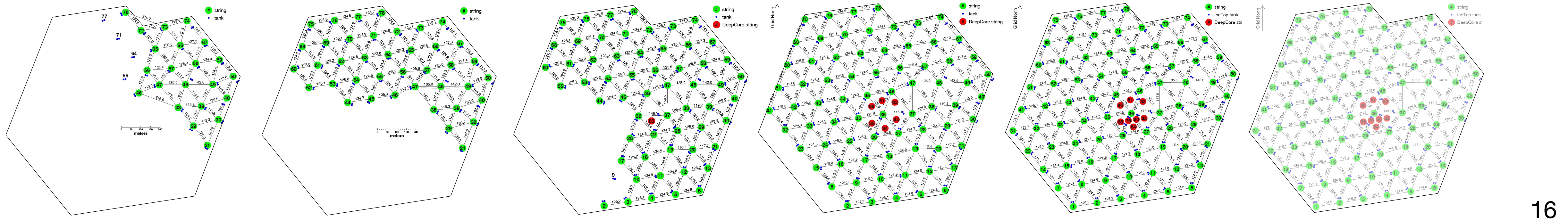
C. Kopper

event rate in IceCube

growing experiment

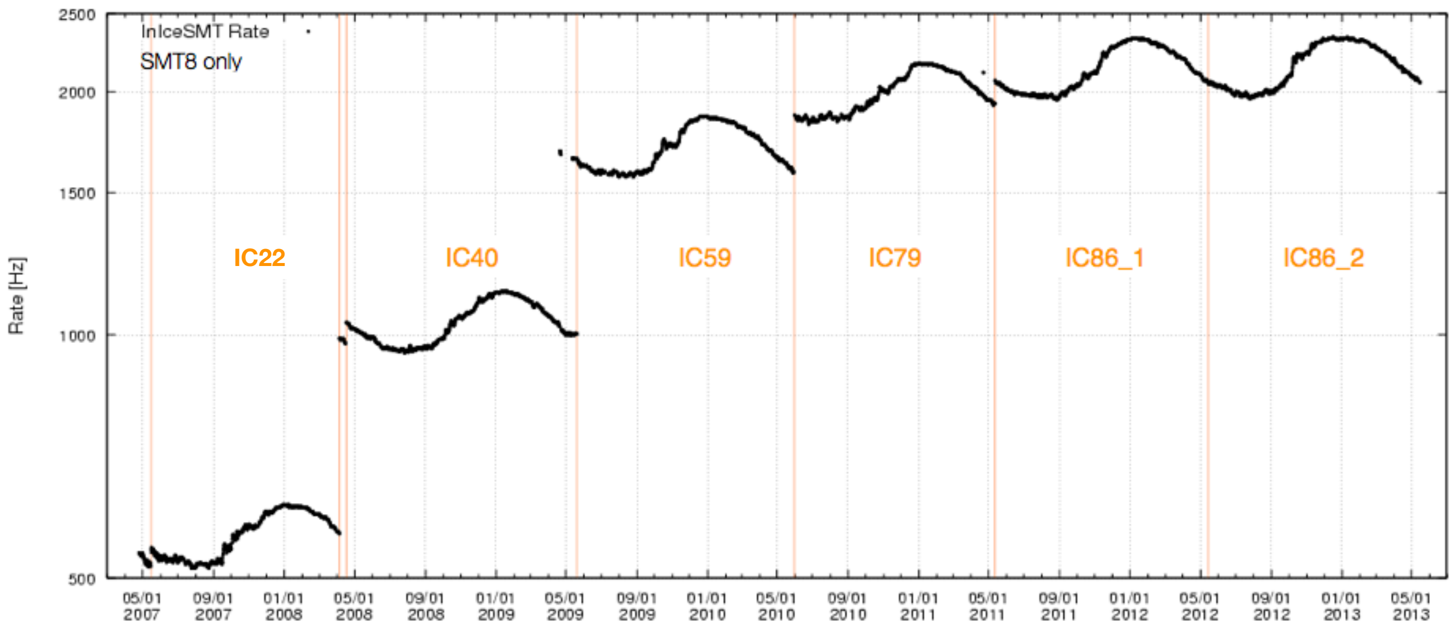


2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>

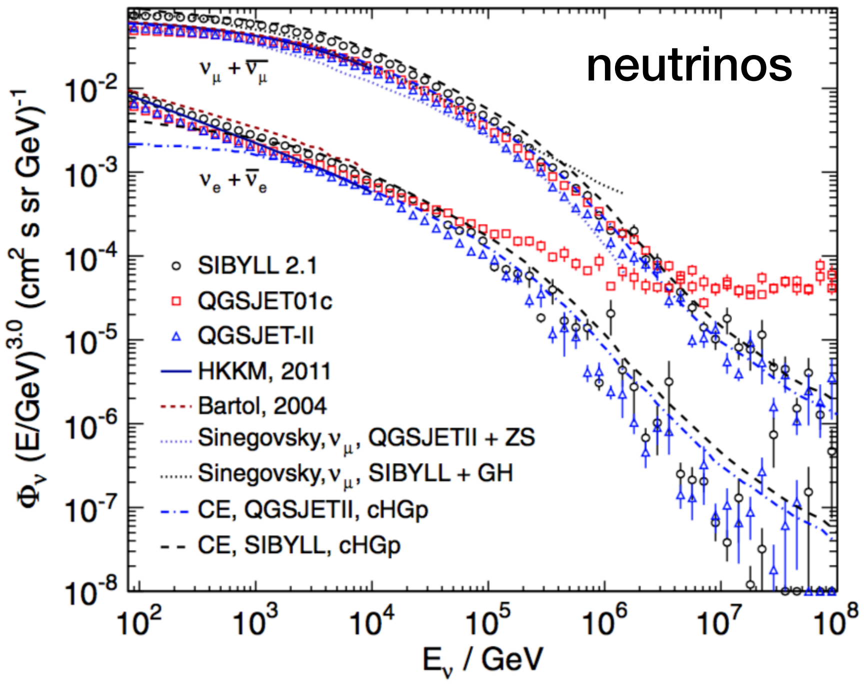


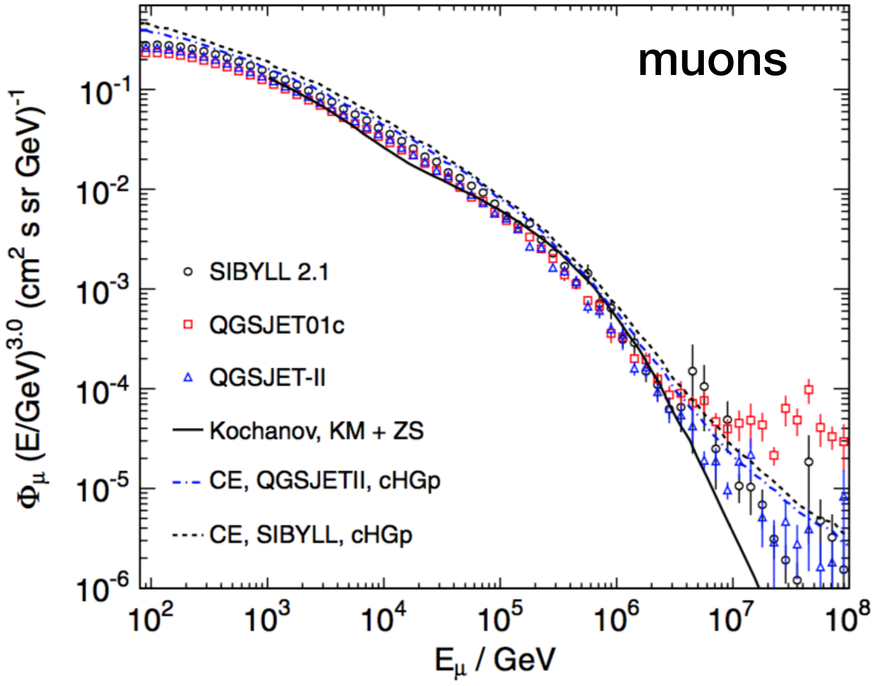
cosmic ray muons and neutrinos

- R_μ ~ 2200 Hz
- μ and ν produced in the atmosphere by cosmic rays
- atmospheric temperature seasonal variations



Fedynitch, Becker Tjus, PD, PRD 86, 114024

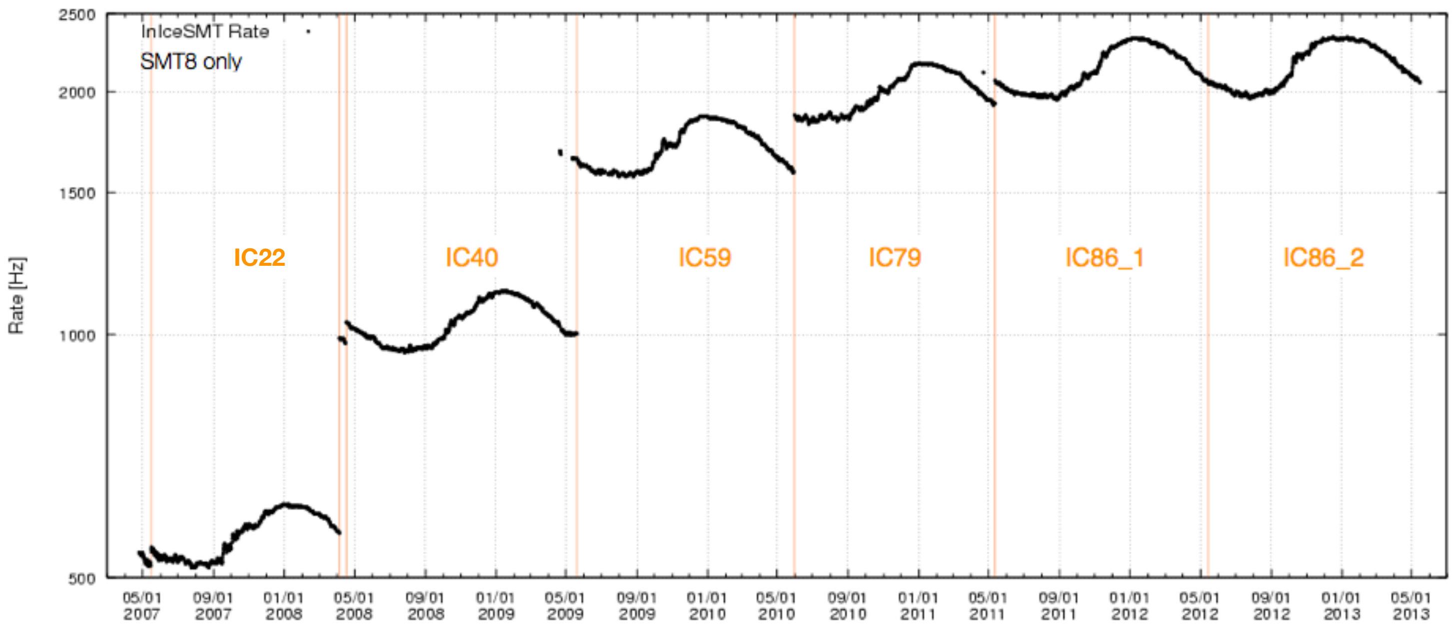




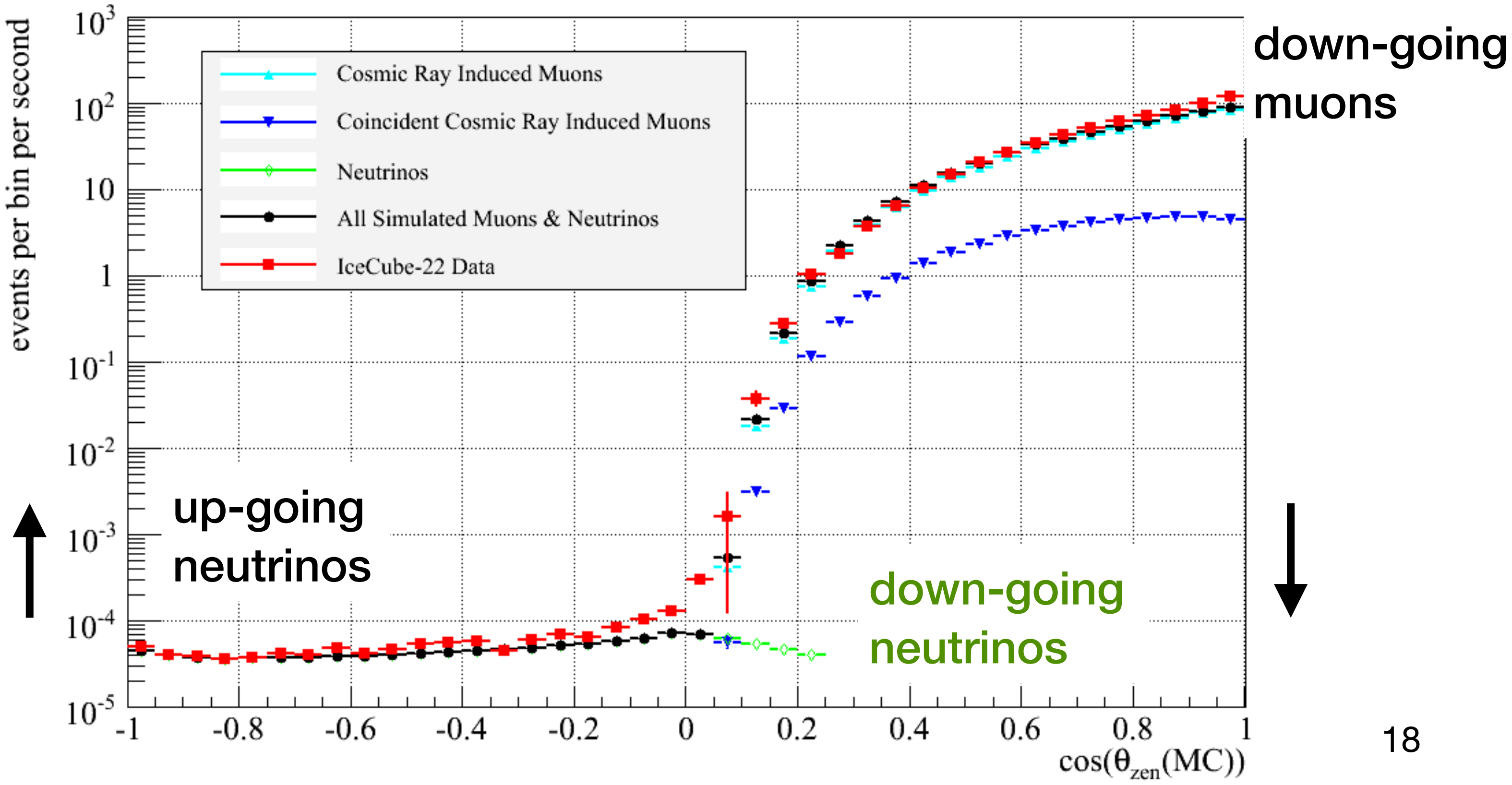
- ~ equal amount of μ and ν

cosmic ray muons and neutrinos

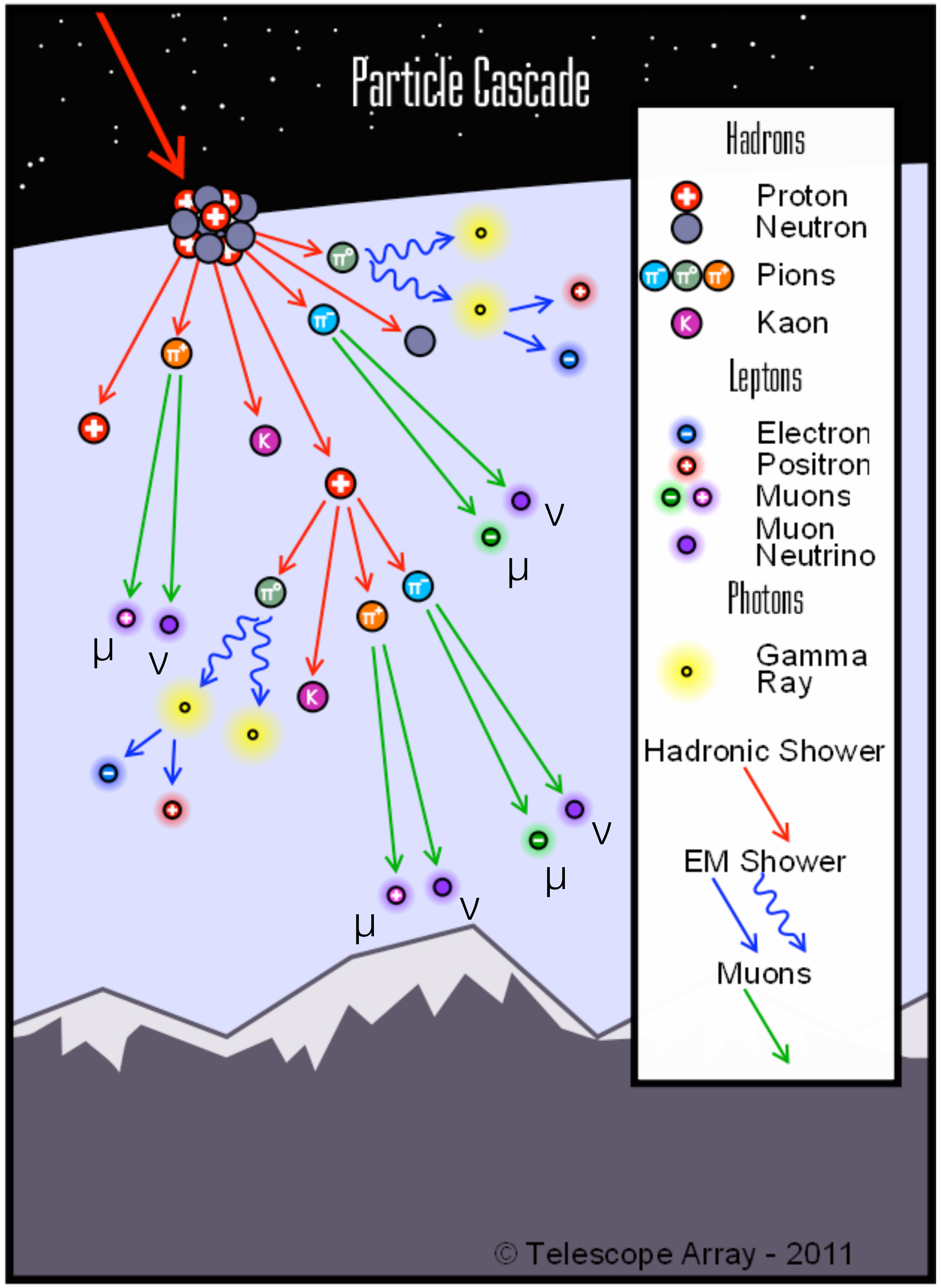
- R_{event} ~ 2200 Hz
- μ and ν produced in the atmosphere by **cosmic rays**
- atmospheric temperature seasonal variations



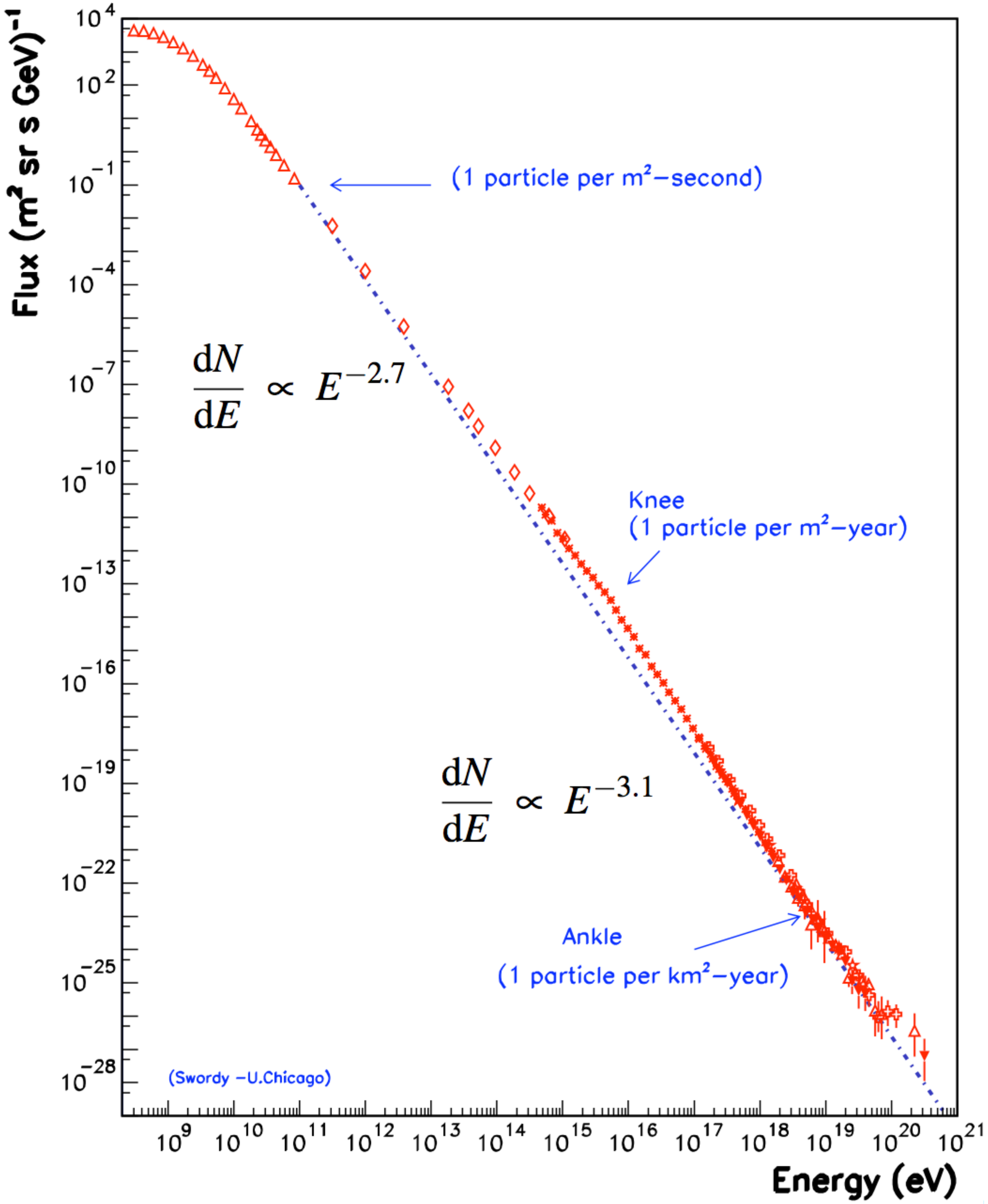
- ~1/10^6 TeV neutrinos interact in the ice and is detected and reconstructed in IceCube



cosmic ray muons and neutrinos



© Telescope Array - 2011

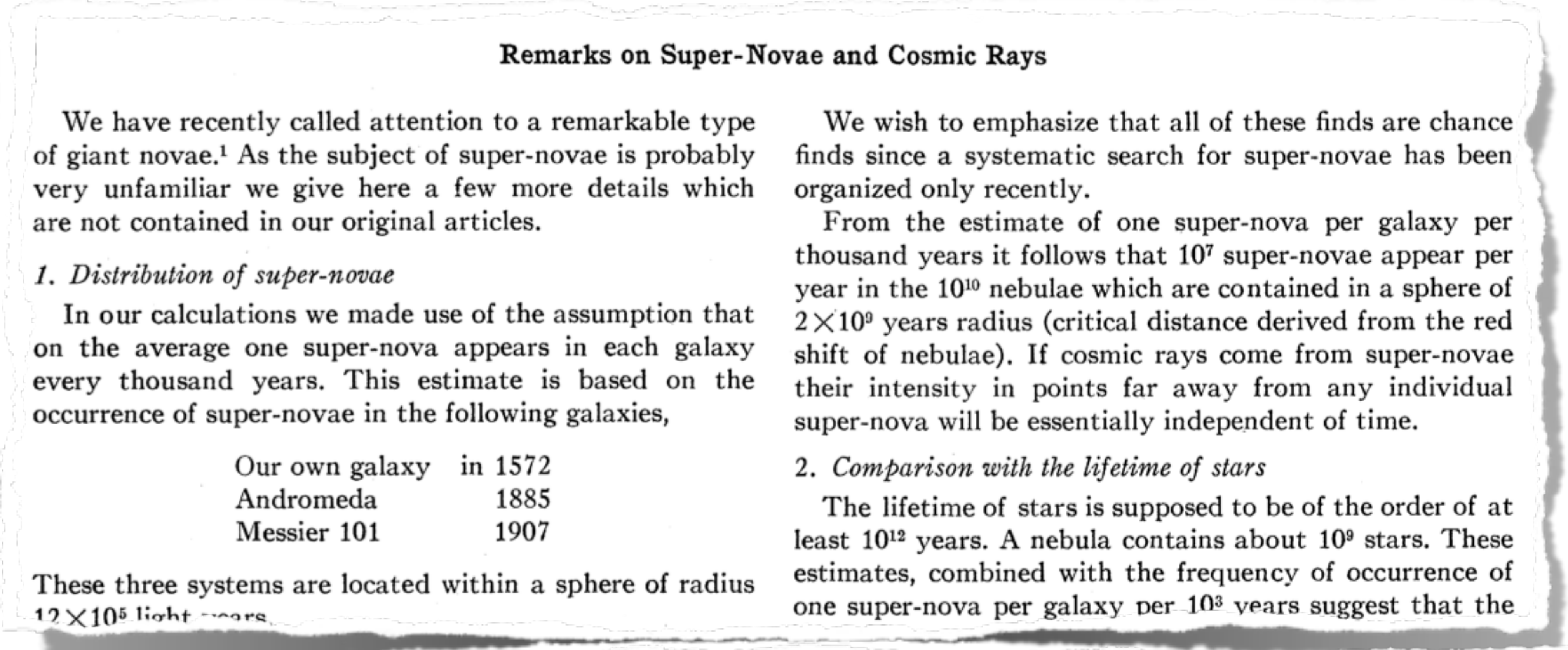


cosmic ray muons and neutrinos

WHERE DO COSMIC RAY COME FROM ?

cosmic ray acceleration mechanisms

where do cosmic ray come from ?



Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius 12×10^5 light-years.

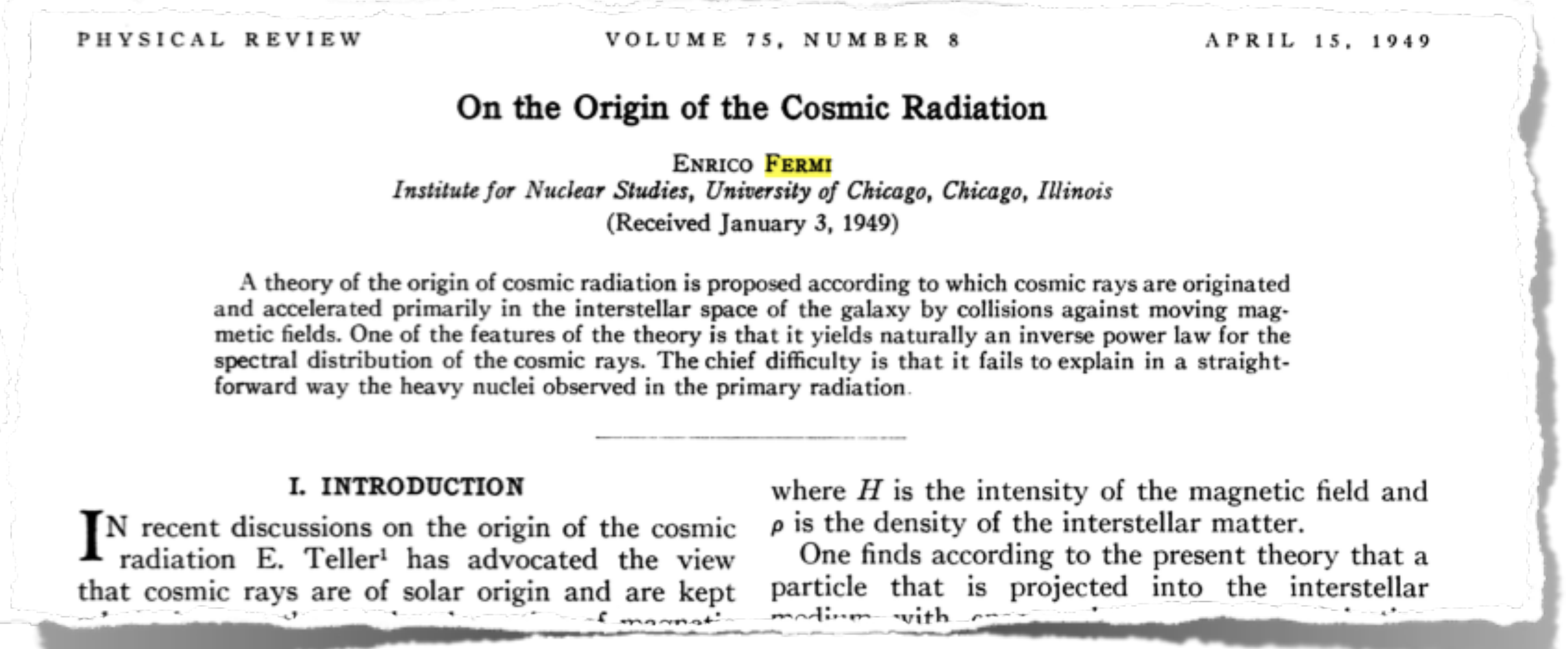
We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

From the estimate of one super-nova per galaxy per thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

2. Comparison with the lifetime of stars

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of one super-nova per galaxy per 10^3 years suggest that the

Baade & Zwicky 1934



PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

Enrico Fermi
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

In recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept

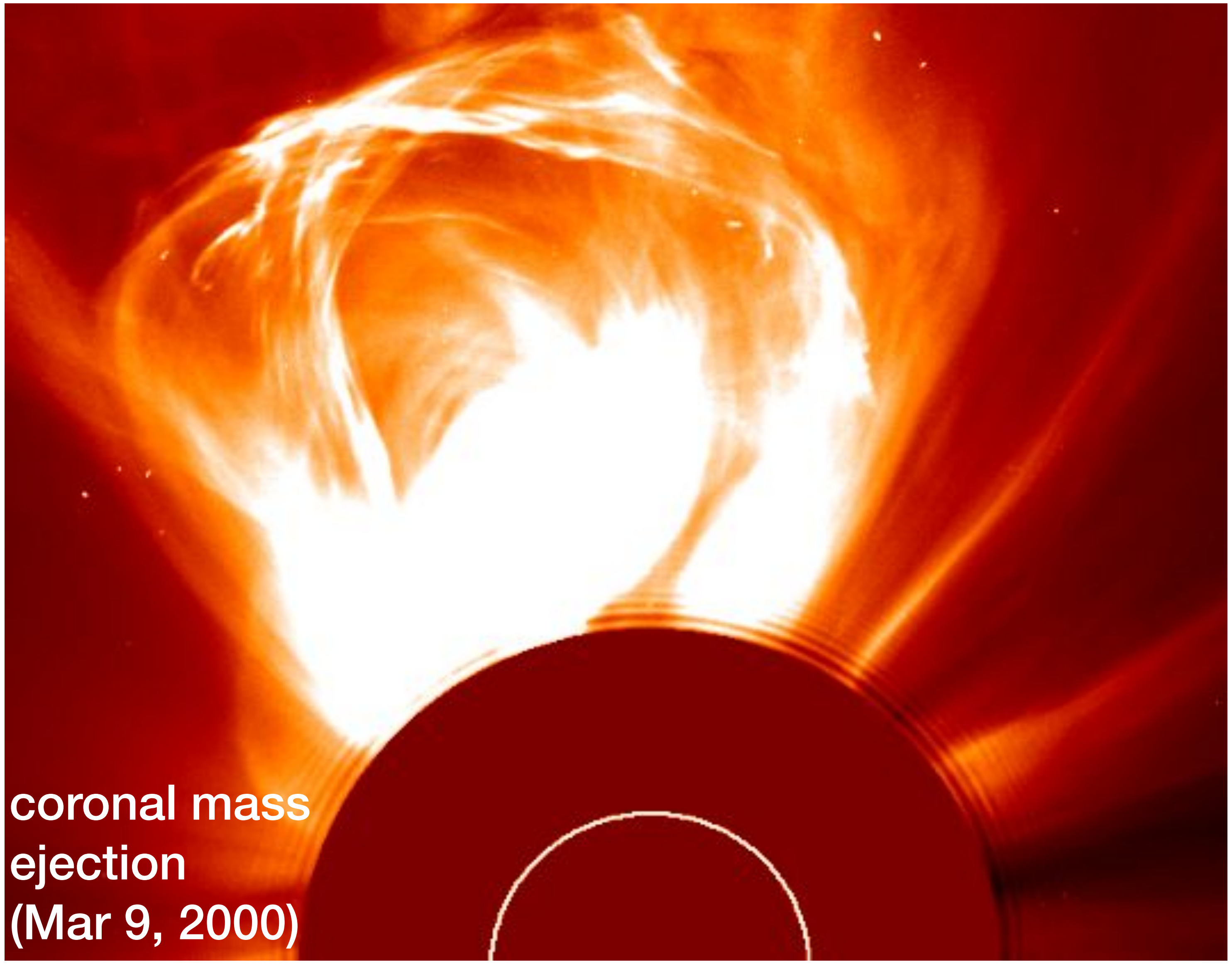
where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar

Fermi 1949

cosmic ray acceleration mechanisms

diffusive shock acceleration

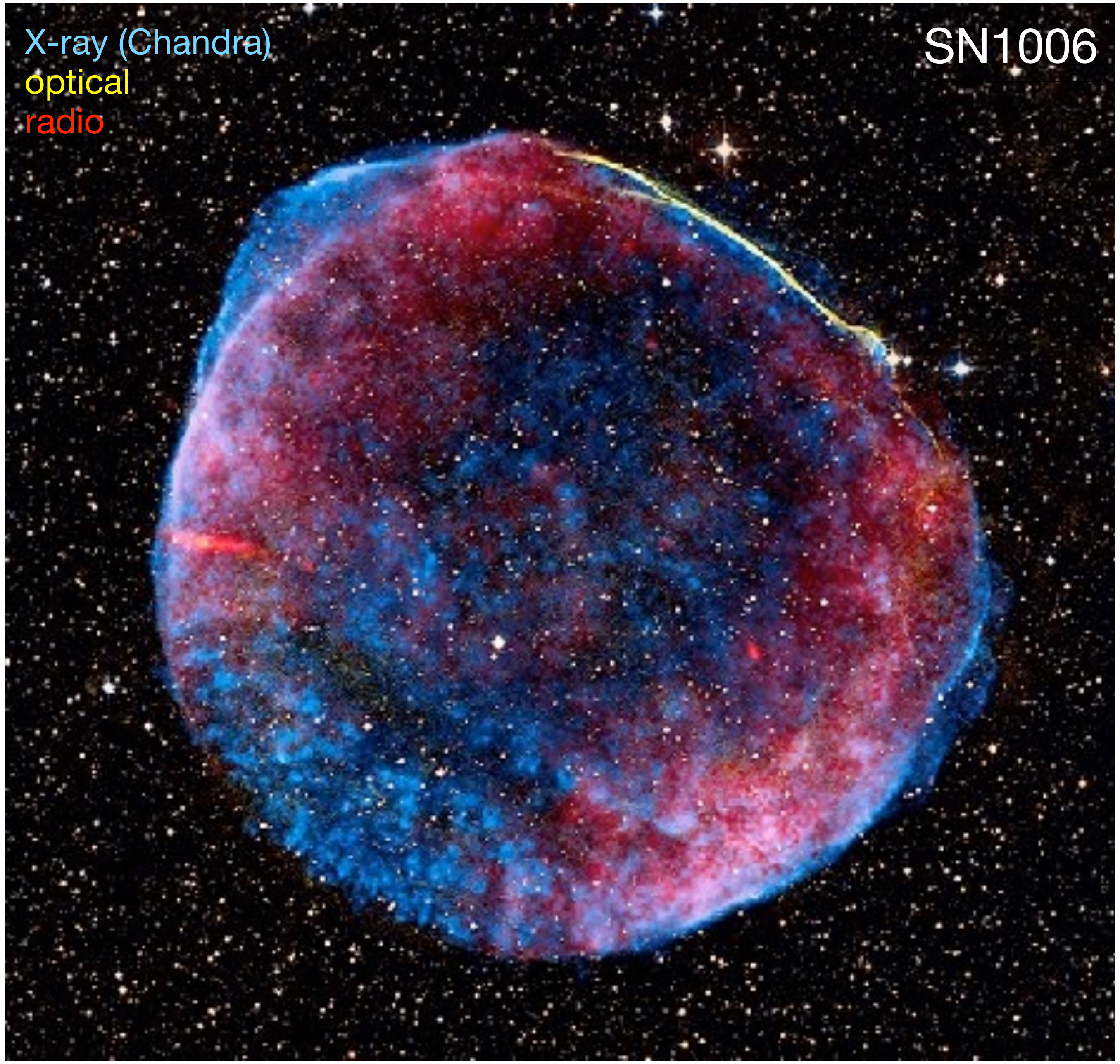


coronal mass ejection (Mar 9, 2000)

- particles accelerated in our solar system
- coronal mass ejections
- solar wind termination shock
- planetary bow shock
- **non thermal particle distributions**
- @ magnetized collisionless shocks

cosmic ray acceleration mechanisms

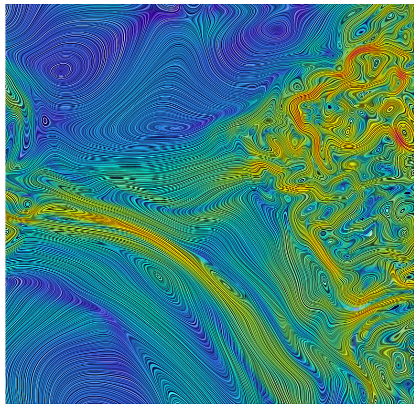
diffusive shock acceleration



- supernova explosion eject material into interstellar medium at *supersonic* speed
- **shocks** are produced with **strong magnetic** fields swiping across the interstellar medium
- **magnetic turbulence** & *supersonic* **magnetic clouds** accelerate thermal particles

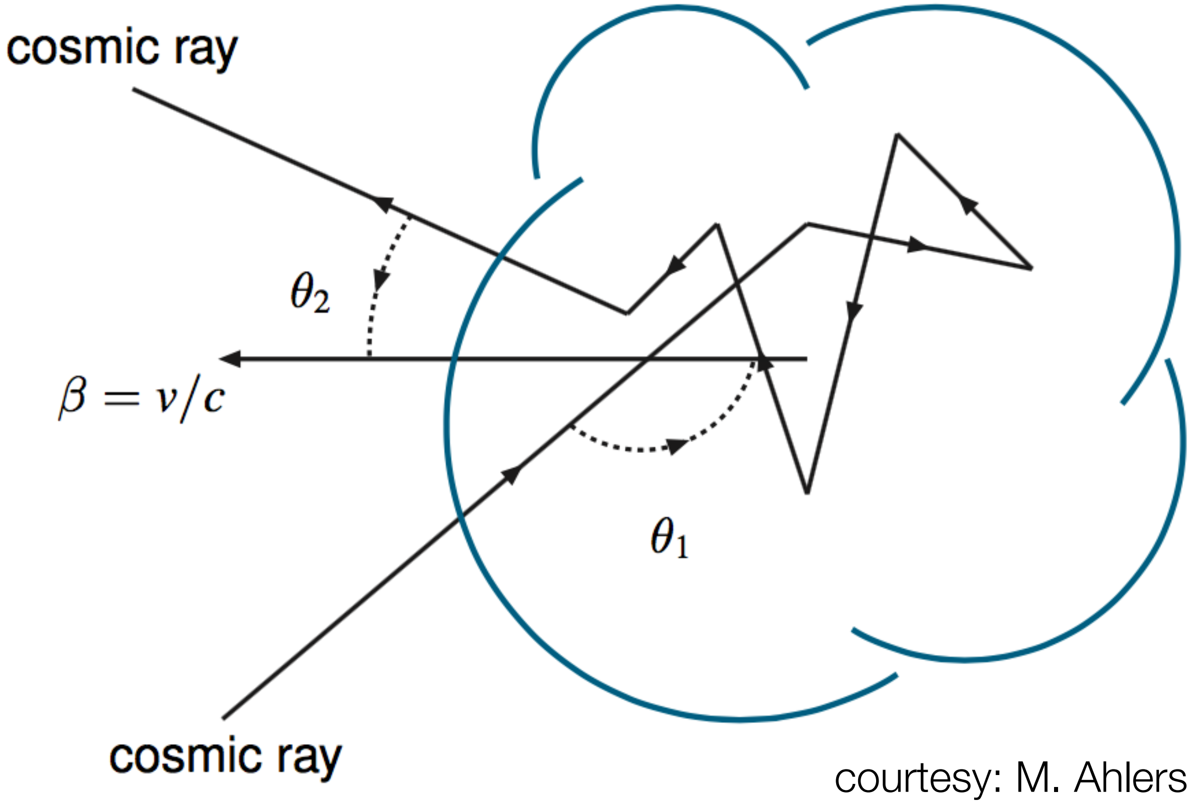
cosmic ray acceleration mechanisms

diffusive shock acceleration



magnetized turbulence
in astrophysical plasmas

particle scattering
in *magnetic cloud*

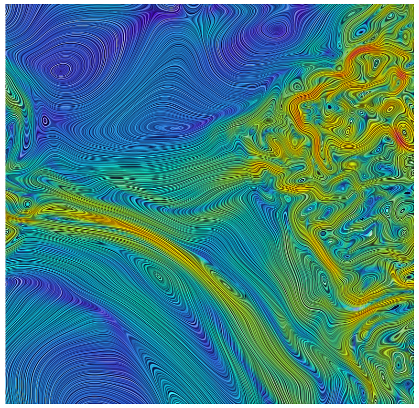


courtesy: M. Ahlers

- in astrophysical plasmas particle collisions are very rare $\lambda_{collision} \gg L_{cloud}$
- magnetic field interactions are **collisionless**
- particles with $r_{Larmor} \sim L_{cloud}$ effectively scatter conserving energy
- particle direction is *randomized* by the scattering process

cosmic ray acceleration mechanisms

diffusive shock acceleration



magnetized turbulence
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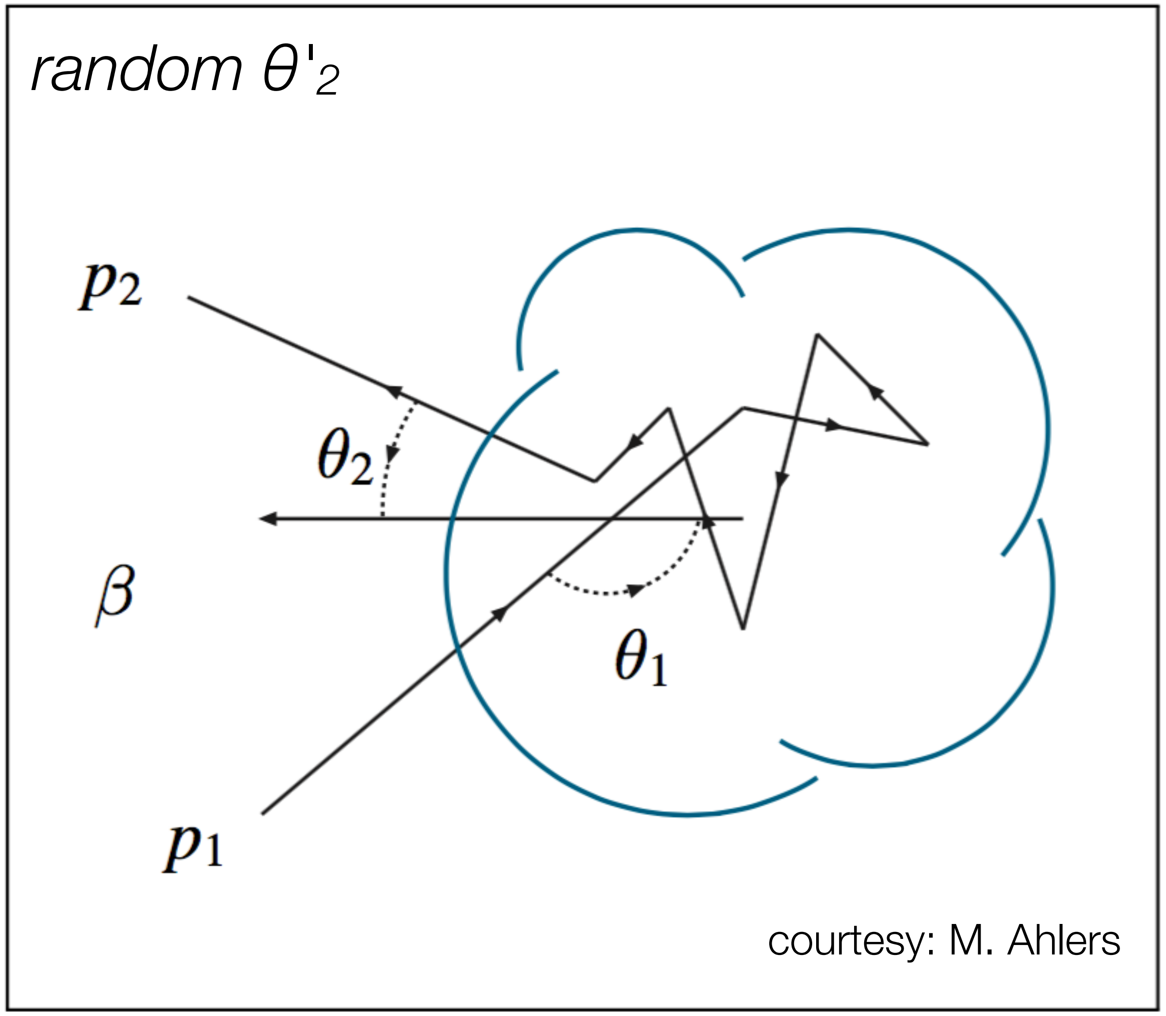


courtesy: M. Ahlers

- in the **cloud's reference frame** $(E_1' = E_2')$

$$E_1' = \gamma E_1 \left(1 - \beta \cos\theta_1\right)$$

- emitted in the **observer's reference** frame

$$E_2 = \gamma E_2' \left(1 + \beta \cos\theta_2'\right)$$

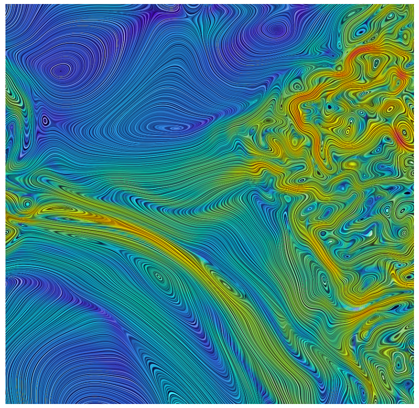
- energy gain per *scattering* process

$$\frac{\Delta E}{E_1} = \gamma^2 (1 + \beta\mu_2')(1 - \beta\mu_1) - 1$$

can be **positive** or **negative**

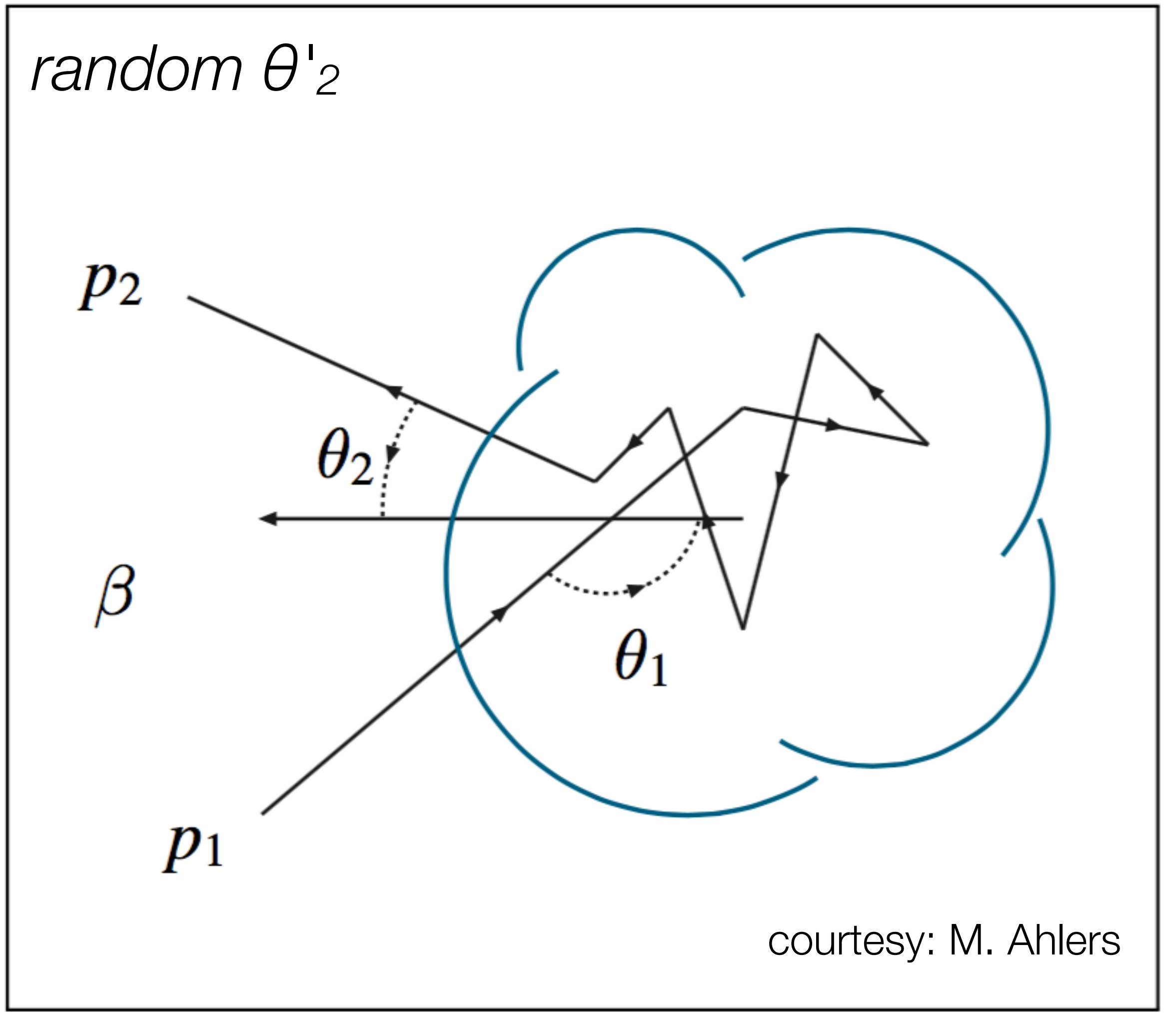
cosmic ray acceleration mechanisms

diffusive shock acceleration



magnetized turbulence
in astrophysical plasmas

particle scattering
in *magnetic cloud*



courtesy: M. Ahlers

- averaging over θ'$_2$ (flat in cosθ'$_2$)

$$\left\langle \frac{\Delta E}{E_1} \right\rangle_2 = \frac{\int_{-1}^{1} d\mu'_2 \frac{dn}{d\mu'_2} \frac{\Delta E}{E_1}}{\int_{-1}^{1} d\mu'_2 \frac{dn}{d\mu'_2}} = \gamma^2(1-\beta\mu_1) - 1$$

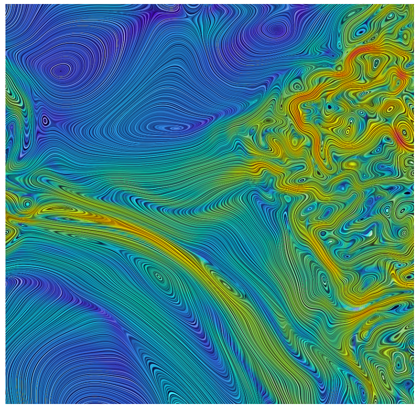
- averaging over θ$_1$ $\quad \frac{dn}{d\mu_1} \propto (v_{part} - v_{cloud}) \sim (1-\beta\mu_1)$

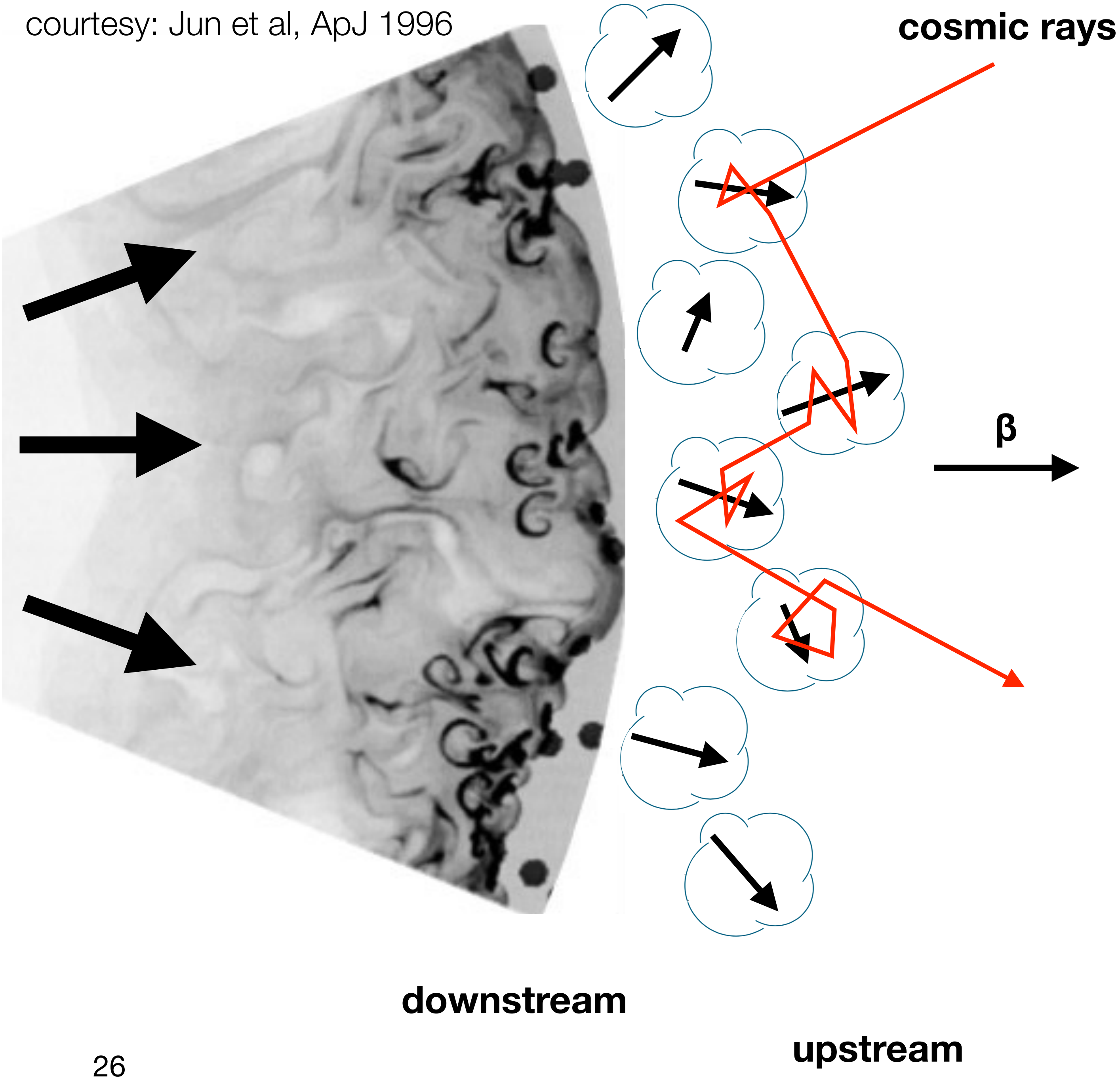
$$\left\langle \frac{\Delta E}{E_1} \right\rangle_{1,2} = \frac{\int_{-1}^{1} d\mu_1 \frac{dn}{d\mu_1} \left\langle \frac{\Delta E}{E_1} \right\rangle_2}{\int_{-1}^{1} d\mu_1 \frac{dn}{d\mu_1}} = \frac{4}{3}\beta^2$$

second order
Fermi acceleration

cosmic ray acceleration mechanisms

diffusive shock acceleration

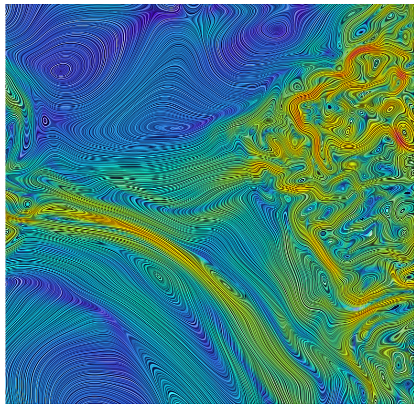


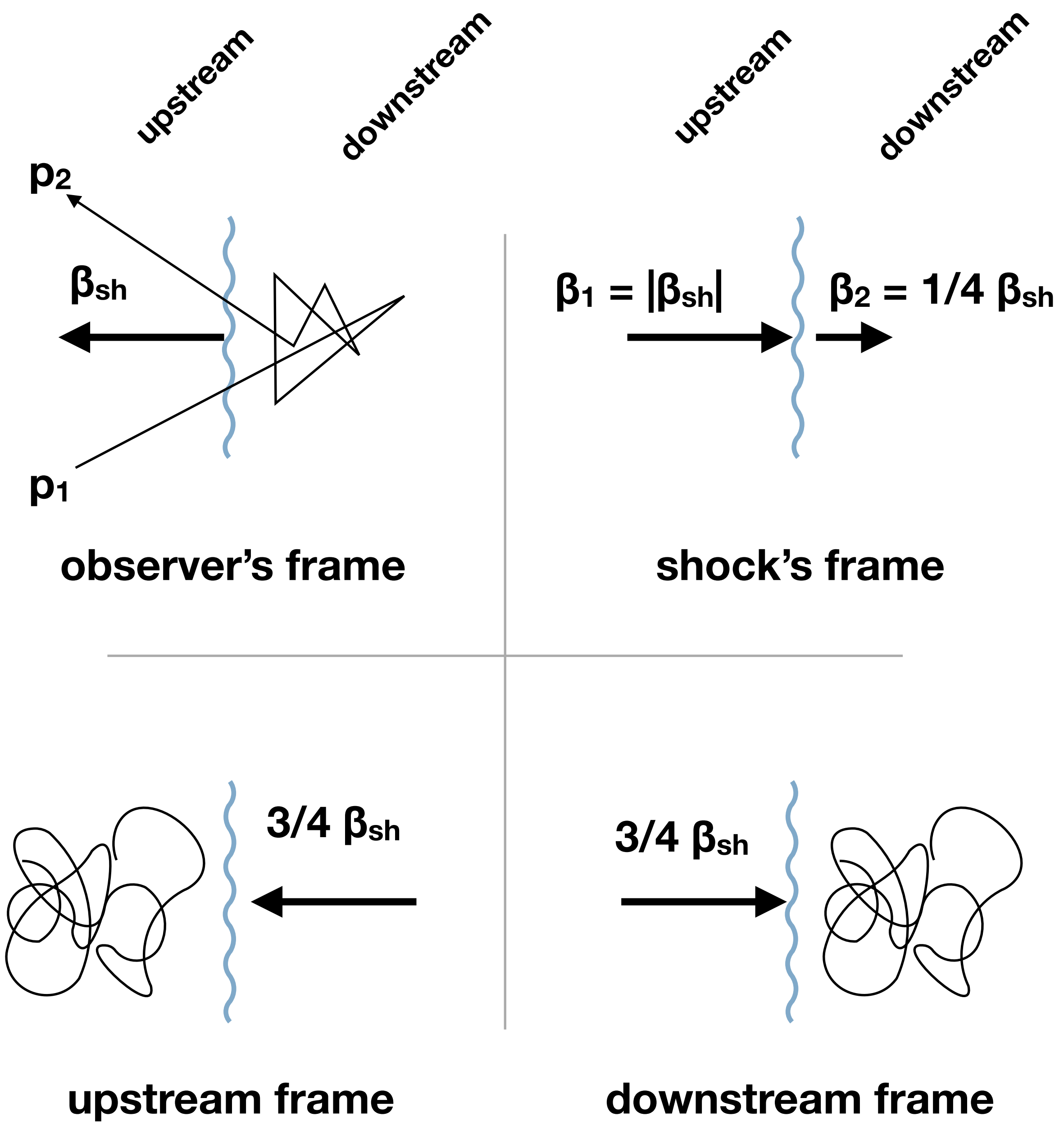

courtesy: Jun et al, ApJ 1996

- effects of magnetic turbulence from the shock dynamics
- astrophysical plasmas are turbulent
- cumulative effects of magnetic mirroring across magnetized shocks
- **balancing acceleration and escape probabilities**

cosmic ray acceleration mechanisms

diffusive shock acceleration





- when crossing the shock from either side, the particle sees plasma moving toward it at a velocity of

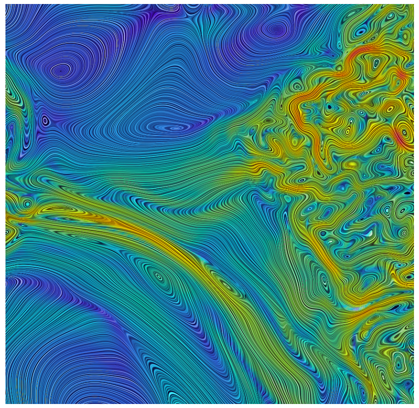
$$\beta = \beta_1 - \beta_2 = \frac{3}{4}\beta_{sh}$$

(non-relativistic shock)

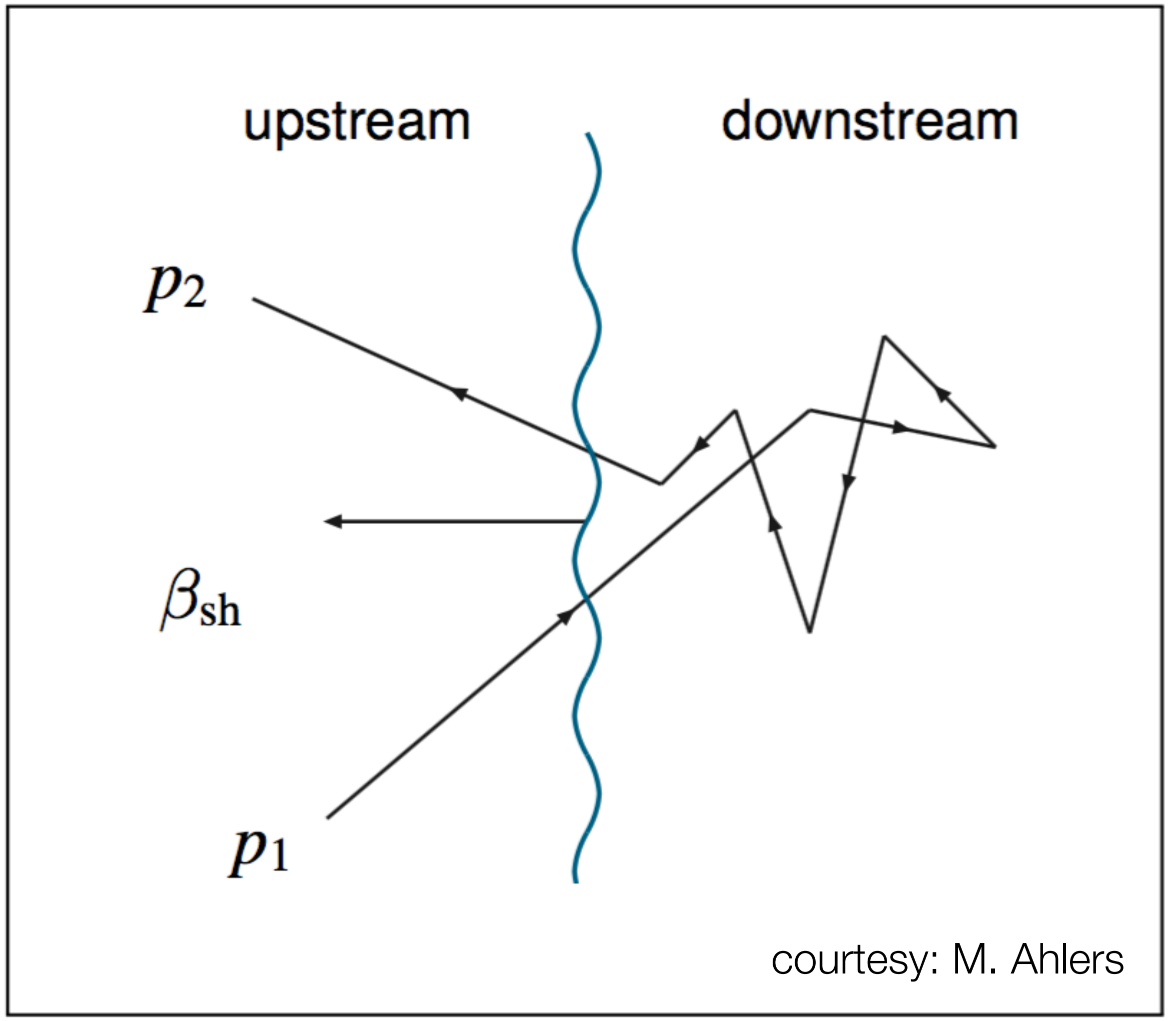
conservation of mass, energy & momentum

effect of plasma decompression at the two sides of the shocks on the particle momenta

cosmic ray acceleration mechanisms
diffusive shock acceleration



magnetized shock
in astrophysical plasmas



courtesy: M. Ahlers

- in the **cosmic ray reference** frame $(E'_1 = E'_2)$

$$E'_1 = \gamma E_1 \left(1 - \beta \cos\theta_1\right)$$

- emitted in the **observer's reference** frame

$$E_2 = \gamma E'_2 \left(1 + \beta \cos\theta'_2\right)$$

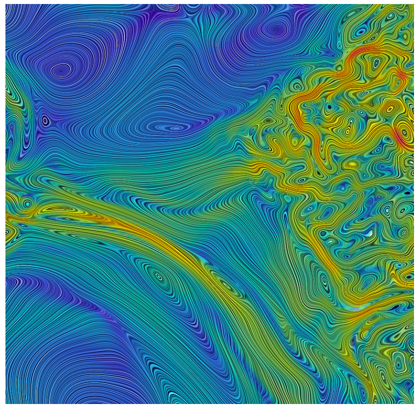
- energy gain per *scattering* process

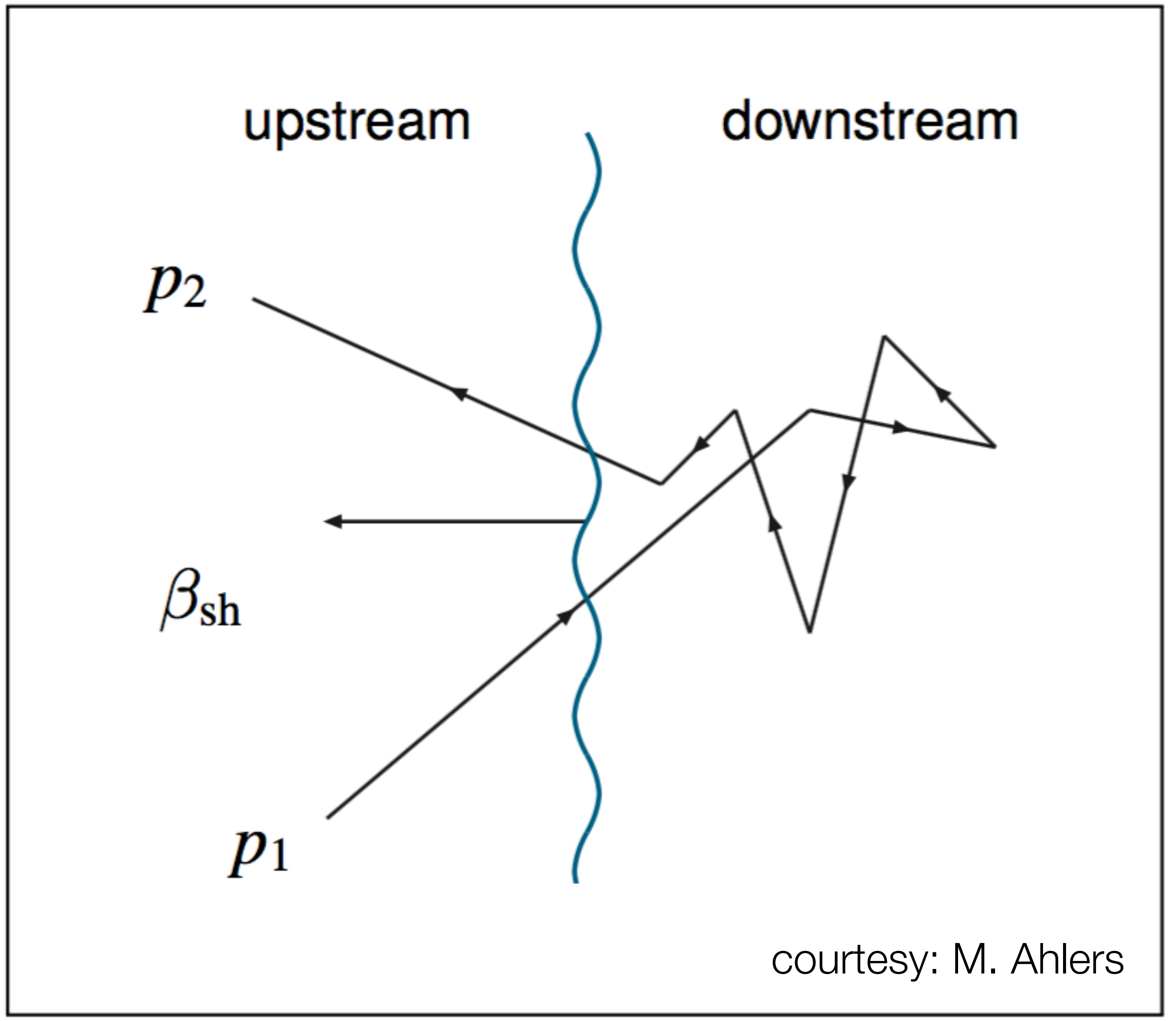
$$\frac{\Delta E}{E_1} = \gamma^2 (1 + \beta\mu'_2)(1 - \beta\mu_1) - 1$$

always **positive** $\mu_1 < 1 \quad \& \quad \mu'_2 > 0$

cosmic ray acceleration mechanisms

diffusive shock acceleration





courtesy: M. Ahlers

- averaging over θ'$_2$ $\quad \dfrac{dn}{d\mu'_2} \propto \mu'_2 (\mu'_2 > 0)$

$$\left\langle \frac{\Delta E}{E_1} \right\rangle_2 = \frac{\int_{-1}^{1} d\mu'_2 \frac{dn}{d\mu'_2} \frac{\Delta E}{E_1}}{\int_{-1}^{1} d\mu'_2 \frac{dn}{d\mu'_2}} = \gamma^2 (1 - \beta\mu_1 + \frac{2}{3}\beta - \frac{2}{3}\beta^2 \mu_1) - 1$$

- averaging over θ$_1$ $\quad \dfrac{dn}{d\mu_1} \propto \mu_1 (\mu_1 < 0)$

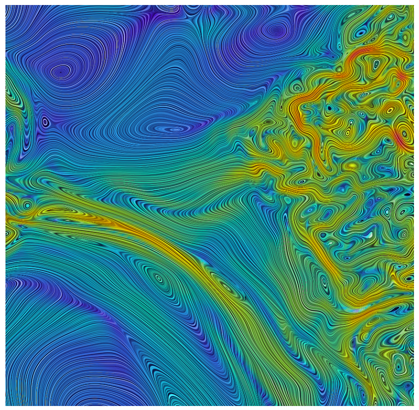
$$\left\langle \frac{\Delta E}{E_1} \right\rangle_{1,2} = \frac{\int_{-1}^{1} d\mu_1 \frac{dn}{d\mu_1} \left\langle \frac{\Delta E}{E_1} \right\rangle_2}{\int_{-1}^{1} d\mu_1 \frac{dn}{d\mu_1}} = \frac{4}{3}\beta$$

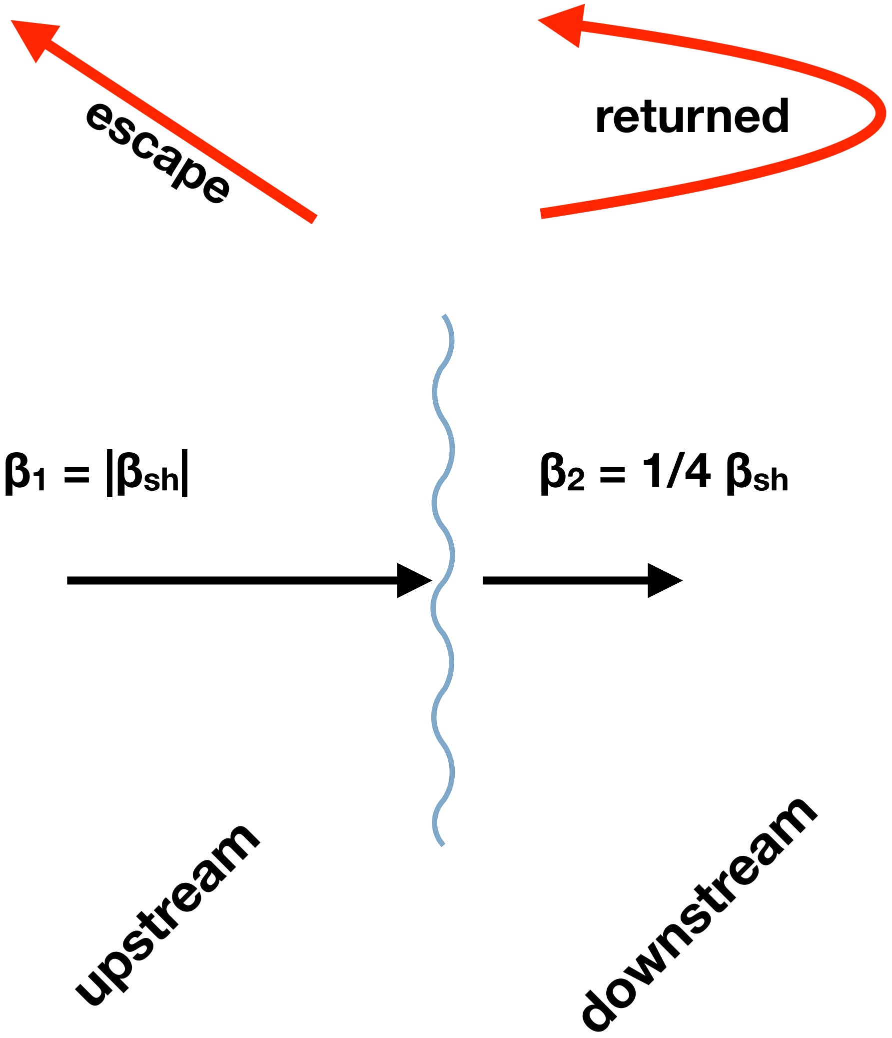
first order

Fermi acceleration

cosmic ray acceleration mechanisms

diffusive shock acceleration





shock's frame

Energy Spectrum

- **incoming flux**: rate of encounters for a plane shock is the projection of an isotropic flux onto the plane shock

$$\Phi_{in} = \int_0^1 d\mu \int_0^{2\pi} d\phi \frac{cn}{4\pi}\mu = \frac{cn}{4}$$

- **outgoing flux**: in the shock rest frame, there is an outflow of cosmic-rays upstream (removed from downstream region)

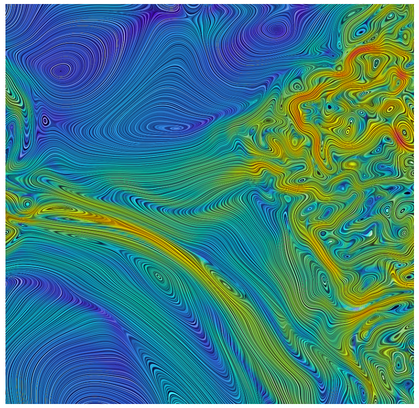
$$\Phi_{out} = n\beta_2 c$$

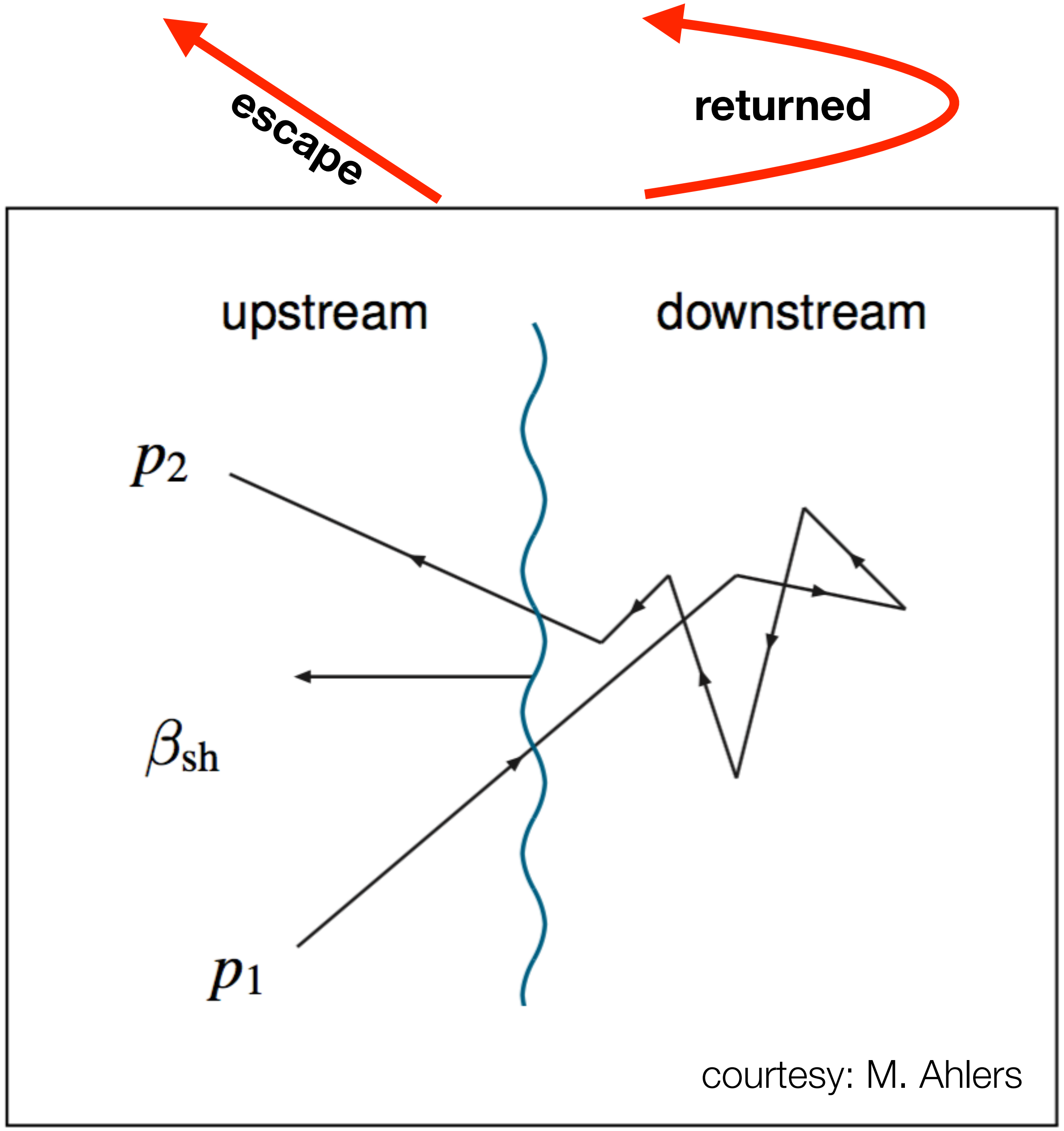
in shock's reference frame

- escape probability $P_{esc} = \frac{\Phi_{in}}{\Phi_{out}} = 4\beta_2$

cosmic ray acceleration mechanisms

diffusive shock acceleration





courtesy: M. Ahlers

Energy Spectrum

- energy gain / collision $\frac{\Delta E}{E} \equiv \xi = \frac{4}{3}\beta = \beta_{sh}$
- escape probability $P_{esc} = 4\beta_2 = \beta_{sh}$
- in a collision cycle (τ_{cycle}) $\frac{\Delta N}{\Delta E} = -\frac{P_{esc}}{\xi}\frac{N}{E}$
- energy spectrum $N(E)dE = N_0 \left(\frac{E}{E_0}\right)^{-1-\ln P_{esc}/\ln \xi} dE$

$$N(E)dE = N_0 \left(\frac{E}{E_0}\right)^{-2} dE$$

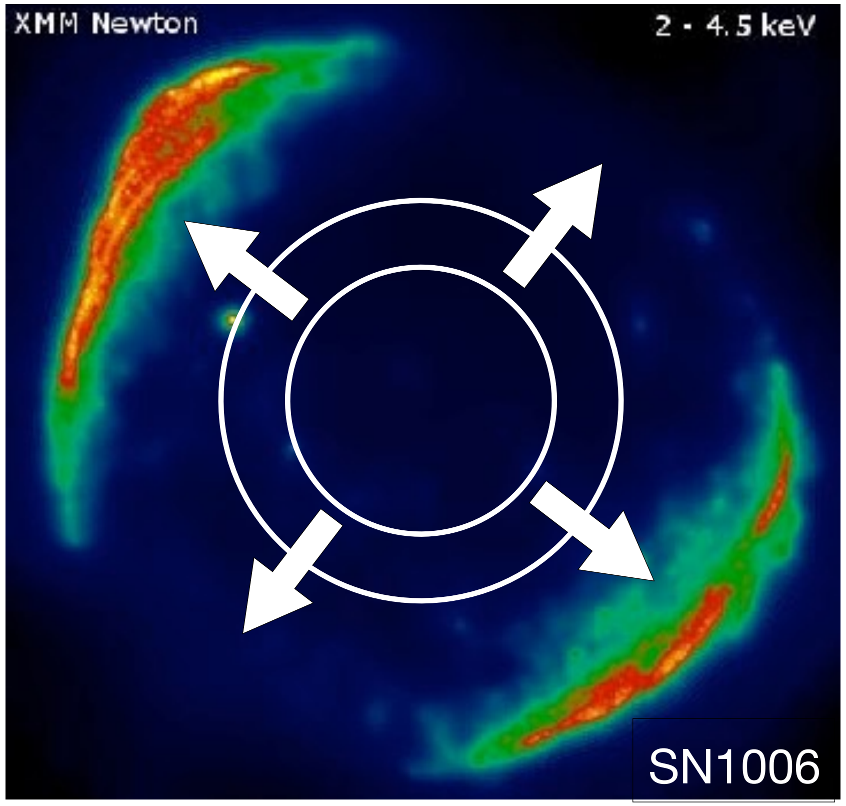
for non-relativistic shocks

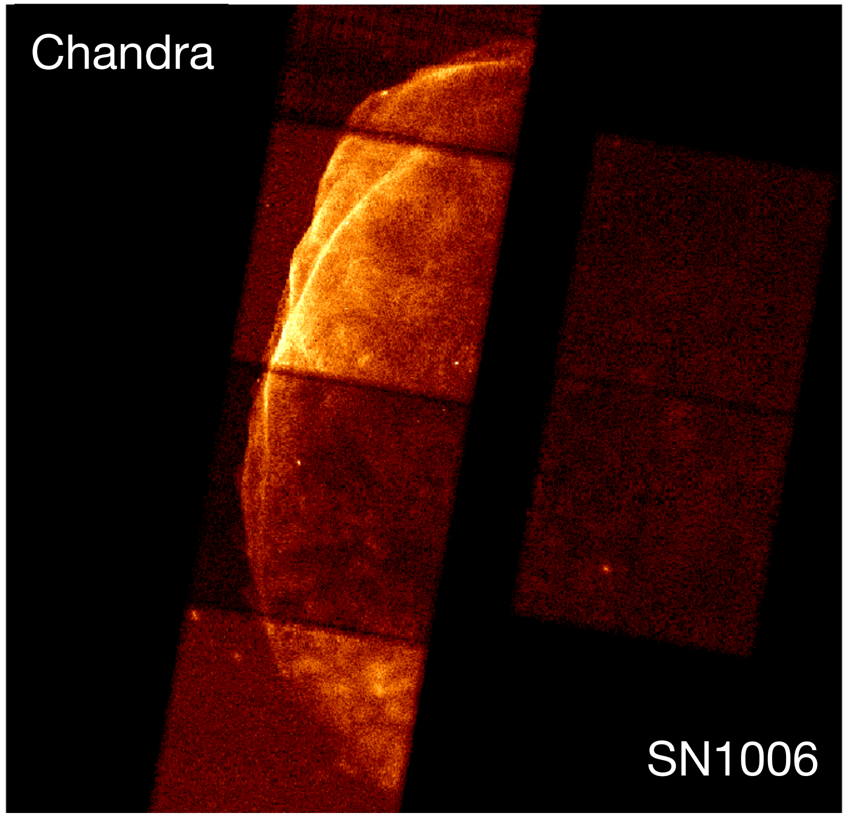
cosmic ray acceleration
in supernova remnants

- **efficient acceleration:** dynamical reaction of CR particle on magnetized plasmas
  - streaming instability induced by accelerated particles leads to **magnetic field amplification upstream**
  - in addition to magnetic field amplification by compression downstream

➡ non-linear diffusive shock acceleration

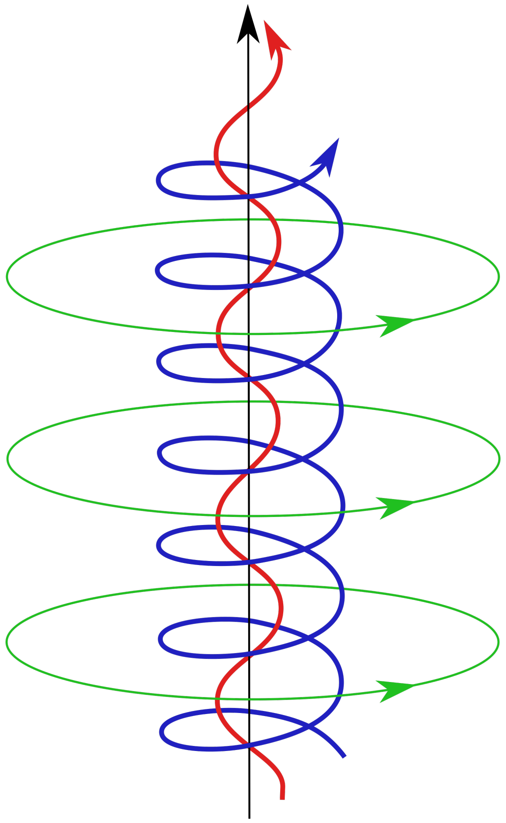
➡ predicts ∝ **E^{-2}** (or **concave spectra**)





cosmic ray acceleration sites

Hillas plot



$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v}\times\vec{B}}_{\text{Magnetic force}}$$

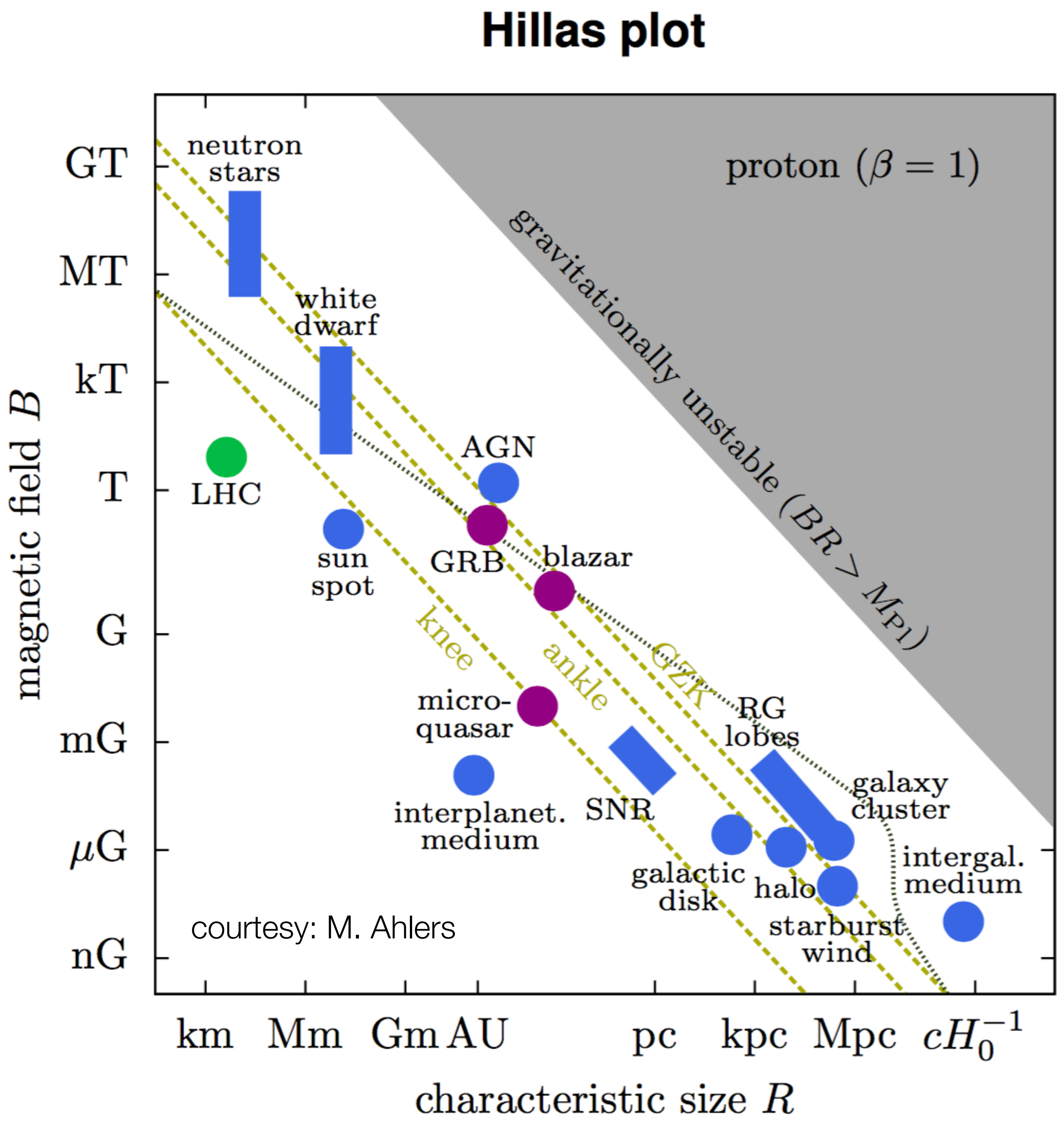
$$r_g = \frac{p_\perp}{|q|B}$$

- acceleration possible if particle confined in acceleration site

E

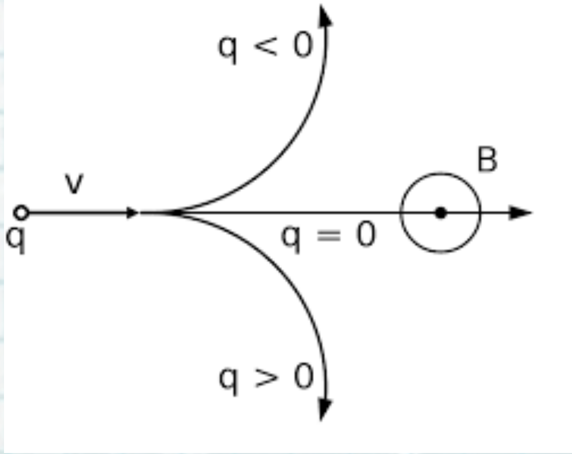
E_{max} ~ size × field strength

$$\boxed{E_{max} \sim 10^{18}\, Z\, \beta_{sh} \left(\frac{R_{size}}{kpc}\right) \left(\frac{B}{\mu G}\right)\ eV}$$



courtesy: M. Ahlers

Larmor radius



- magnetic (Lorentz) force $\vec{F} = q\left(\vec{v} \times \vec{B}\right)$ (perpendicular to velocity and B-field)
- Lorentz Force = centripetal force $$|q| v_\perp B = \frac{m v_\perp^2}{r_g}$$
- orbit radius (Larmor radius or gyro-radius) $$r_g = \frac{m v_\perp}{|q| B} \longrightarrow \boxed{r_g = \frac{p_\perp}{|q| B}}$$

$$\boxed{r_g \sim \frac{10^{-3}}{Z}\left(\frac{E}{TeV}\right)\left(\frac{\mu G}{B}\right)\ pc}$$

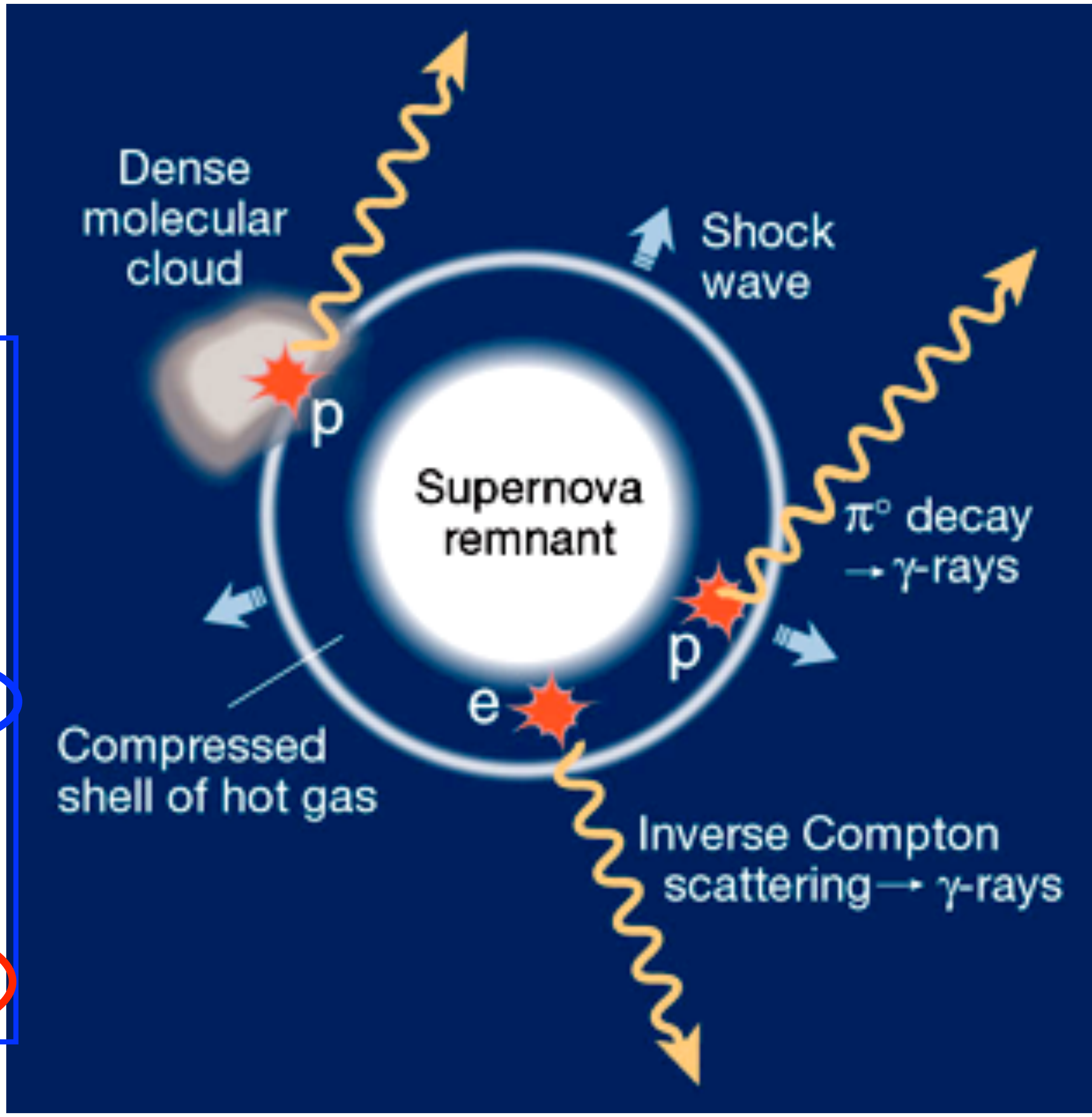
$$\boxed{r_g \sim \frac{200}{Z}\left(\frac{E}{TeV}\right)\left(\frac{\mu G}{B}\right)\ AU}$$

cosmic rays

reconstruct their history

$$\begin{tikzcd}[column sep=small]
p + N \to p(n) + & \pi^+ \arrow[d] & + \pi^- + & \pi^0 \arrow[d] \\
& \mu^+ + \nu_\mu \arrow[d] & & \gamma + \gamma \\
& e^+ + \nu_e + \bar{\nu}_\mu & &
\end{tikzcd}$$

hadronic emission



$$e^{\pm} + B \to e^{\pm} + \gamma_{synchrotron}$$

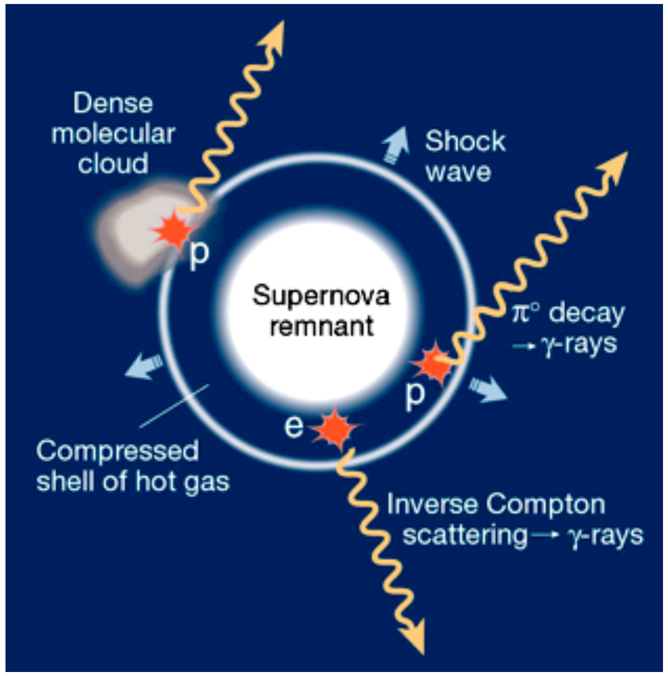
$$e^{\pm} + \gamma_{soft} \to e^{\pm} + \gamma_{Inverse\ Compton}$$

electromagnetic emission

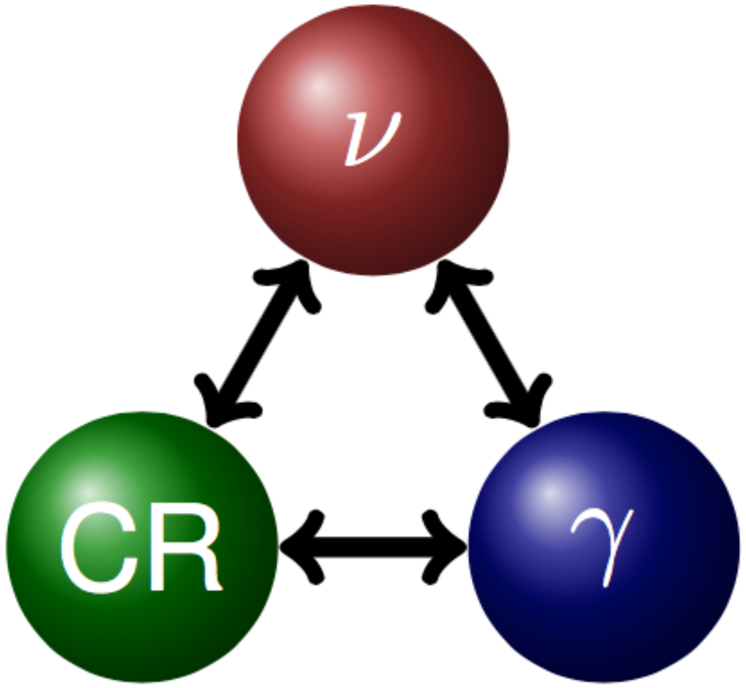
cosmic rays
at the sources

$$\begin{tikzcd}
p + N \rightarrow p(n) + & \pi^+ \arrow[d] & + \pi^- + & \pi^0 \arrow[d] \\
 & \mu^+ + \nu_\mu \arrow[dr] & & \gamma + \gamma \\
 & & e^+ + \nu_e + \bar{\nu}_\mu &
\end{tikzcd}$$

hadronic emission

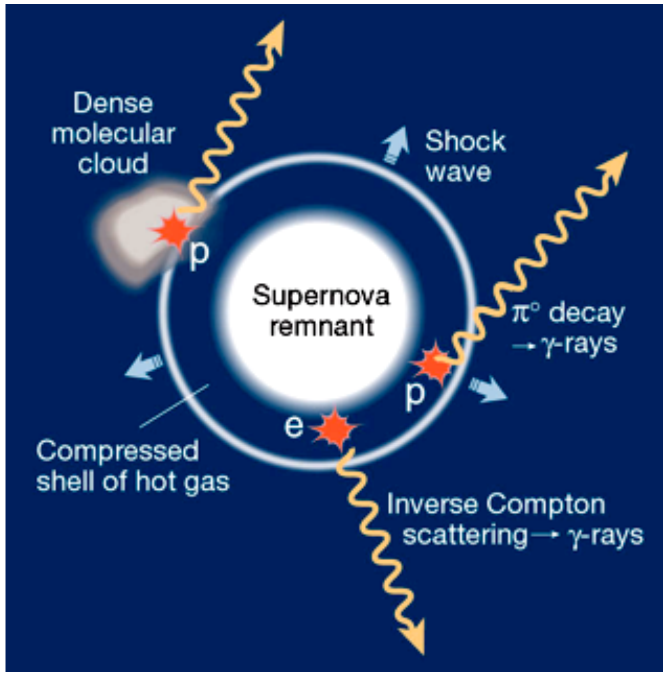


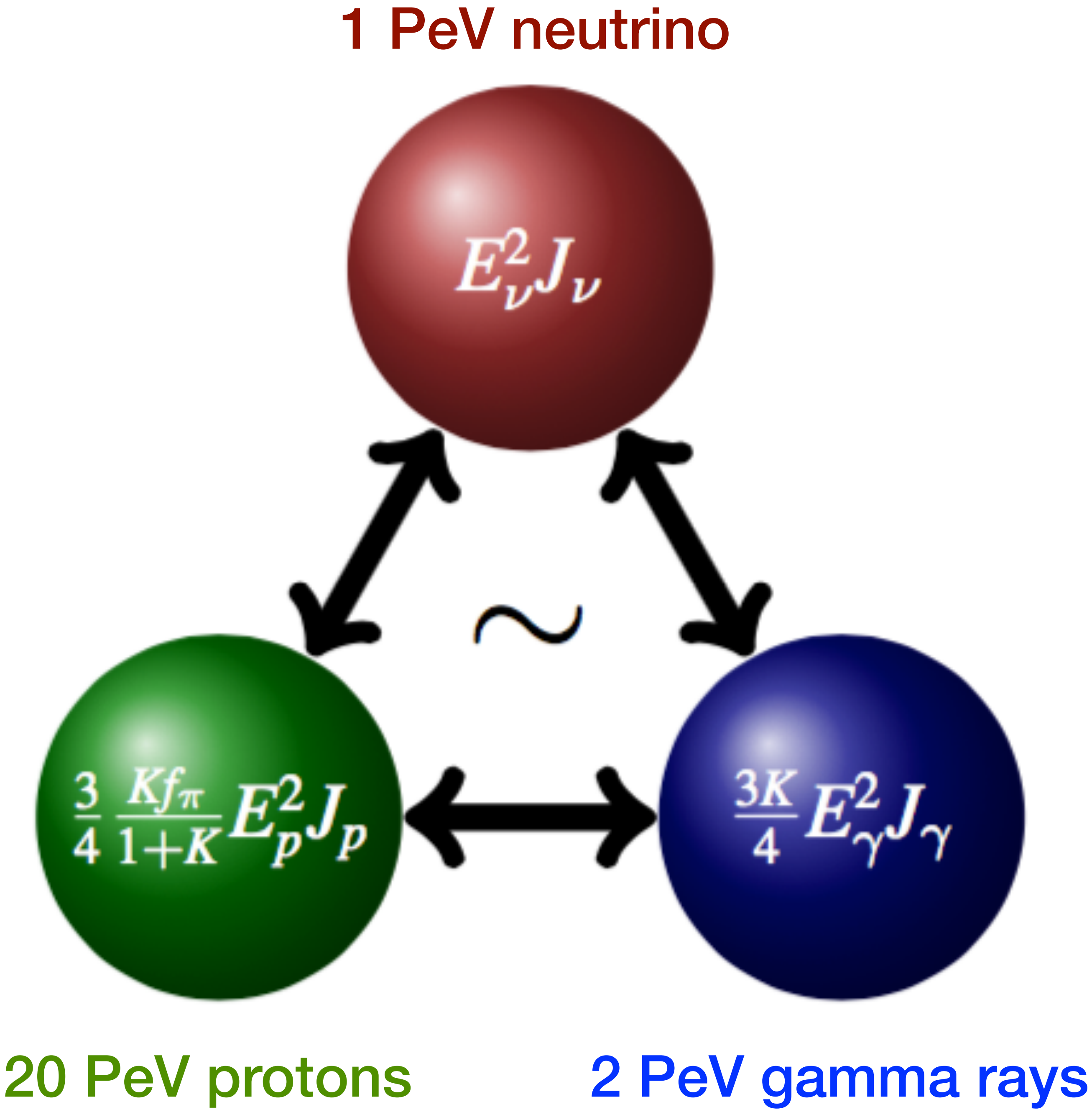
- inelasticity $E_\nu \sim E_\gamma/2 \sim \kappa E_p/4$
- relative multiplicity $K = N_{\pi^\pm}/N_{\pi^0}$
- pion fraction $f_\pi \sim 1 - e^{-\kappa\,\tau_{\text{optical depth}}}$



courtesy: M. Ahlers

cosmic rays
near the sources





courtesy: M. Ahlers

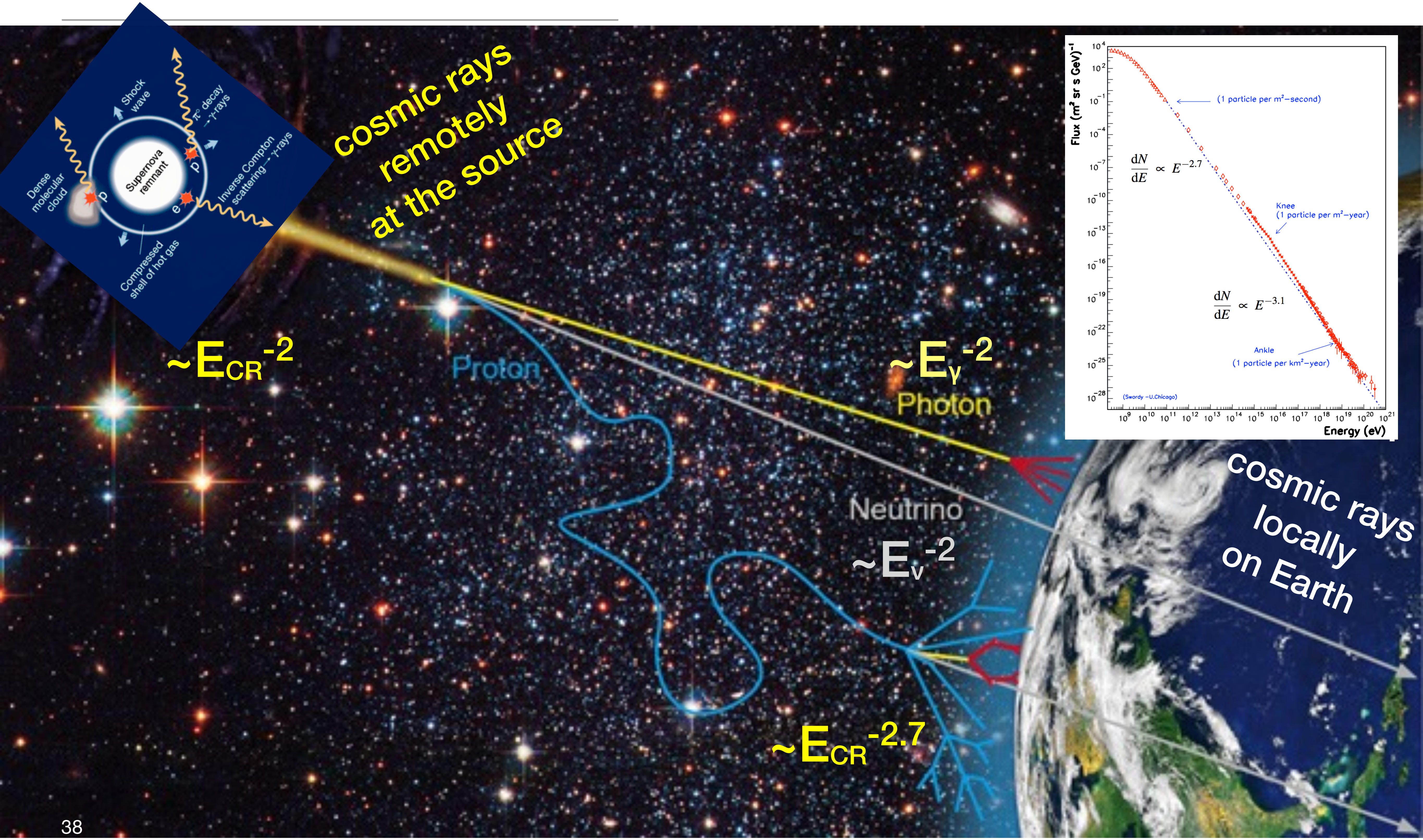
- pN (matter) or pγ (radiation) ?
- galactic or extra-galactic sources ?
- point sources or *diffuse* ?
- what mixture of hadronic/leptonic proc.'s ?

‣ ***find ν associated to γ rays***

‣ ***find ν associated to UHE cosmic rays***

cosmic rays

γ & ν carry the past history of cosmic rays



cosmic rays remotely at the source

$\sim E_{CR}^{-2}$

$\sim E_{\gamma}^{-2}$

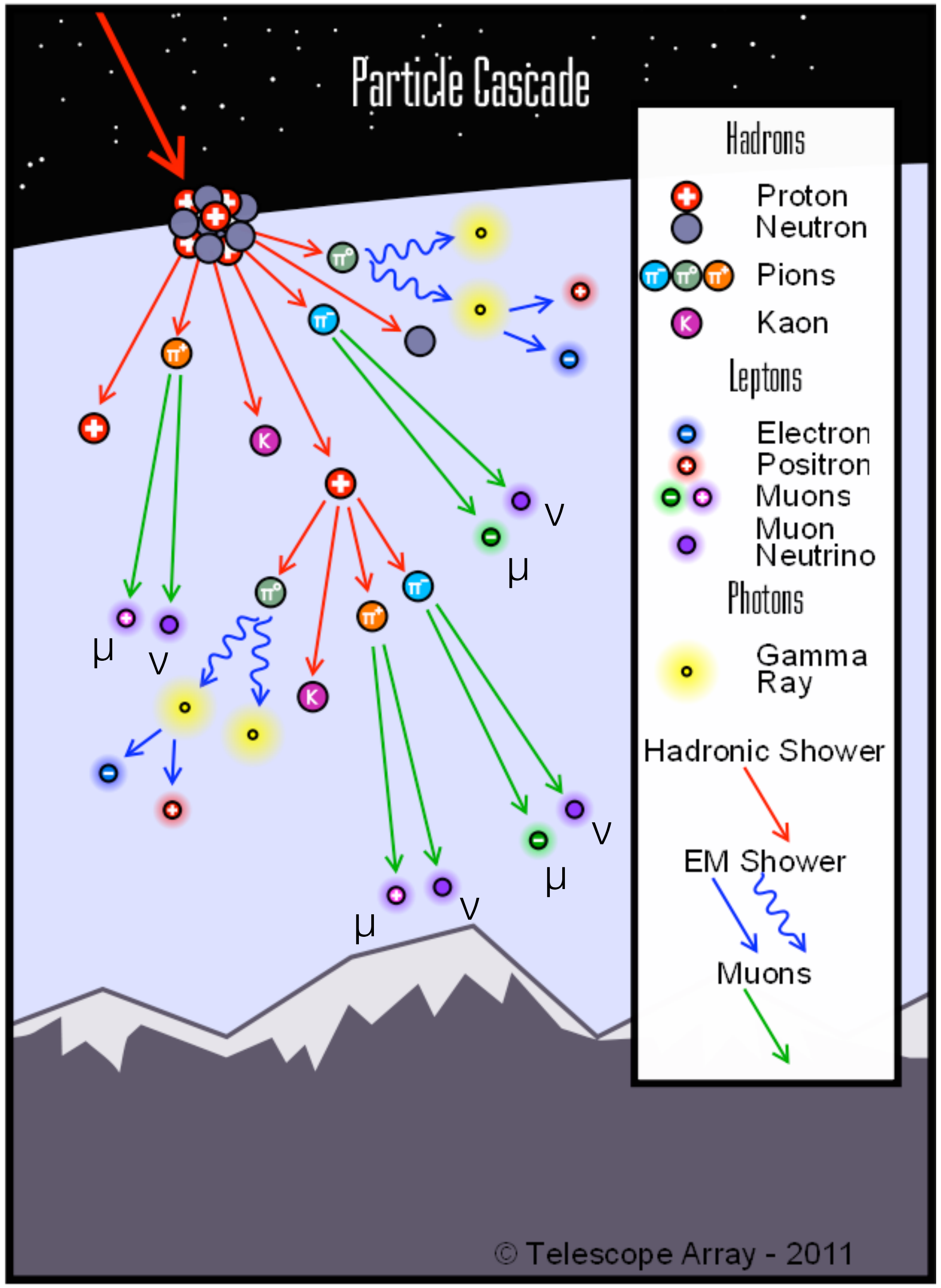
$\sim E_{\nu}^{-2}$

$\sim E_{CR}^{-2.7}$

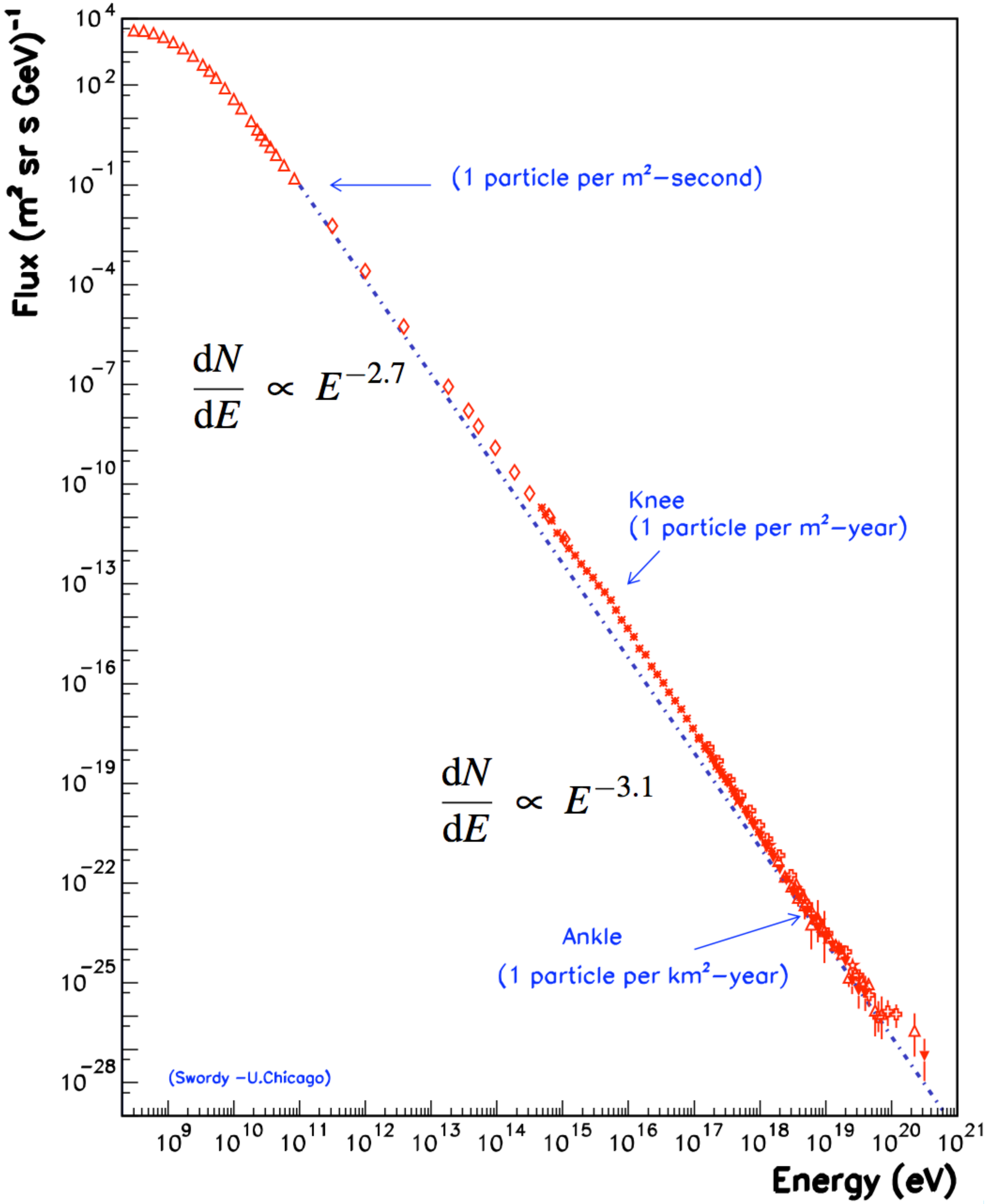
cosmic rays locally on Earth

cosmic rays

at Earth



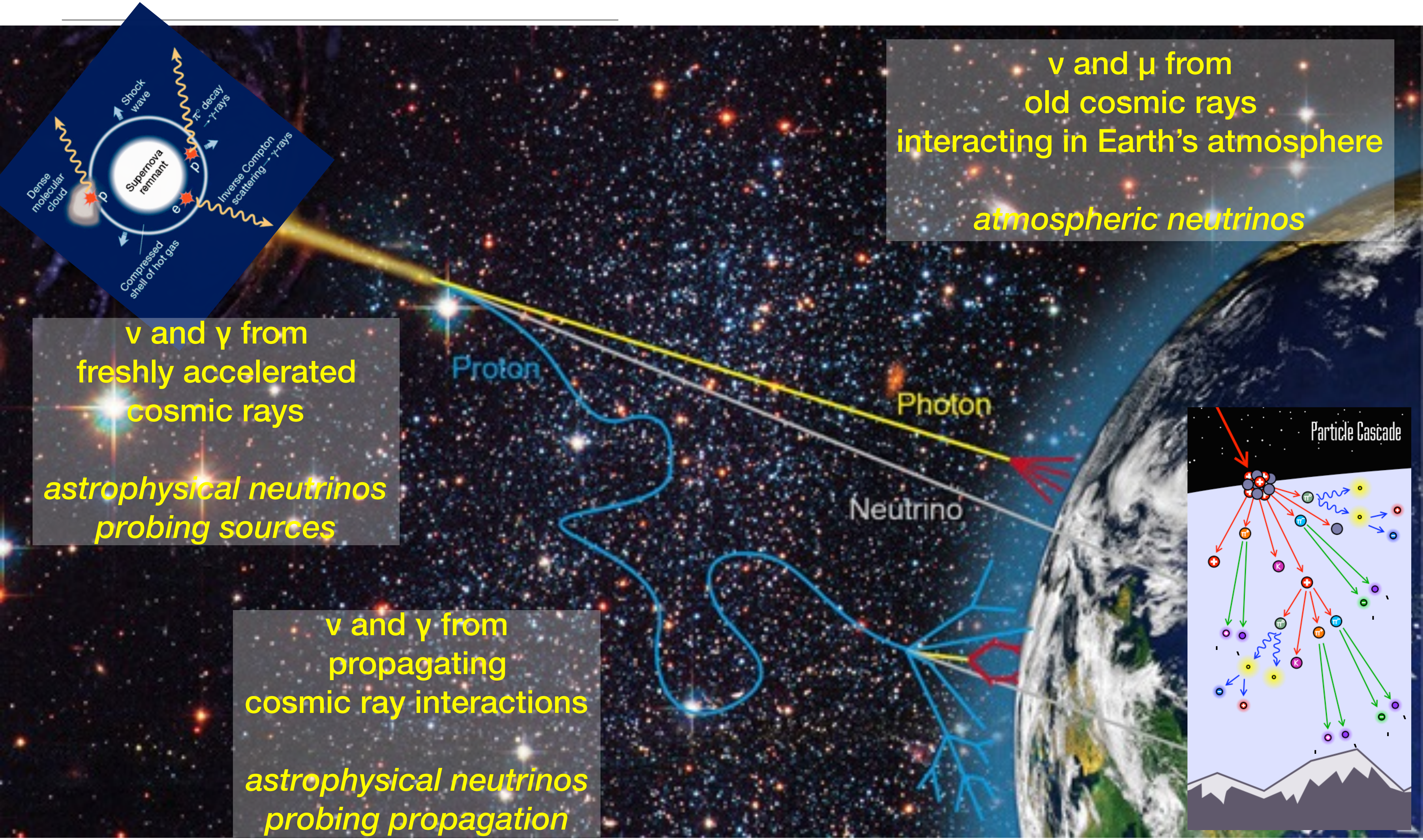
© Telescope Array - 2011



(Swordy – U.Chicago)

cosmic rays

reconstruct their history



ν and μ from
old cosmic rays
interacting in Earth's atmosphere

atmospheric neutrinos

ν and γ from
freshly accelerated
cosmic rays

astrophysical neutrinos
probing sources

ν and γ from
propagating
cosmic ray interactions

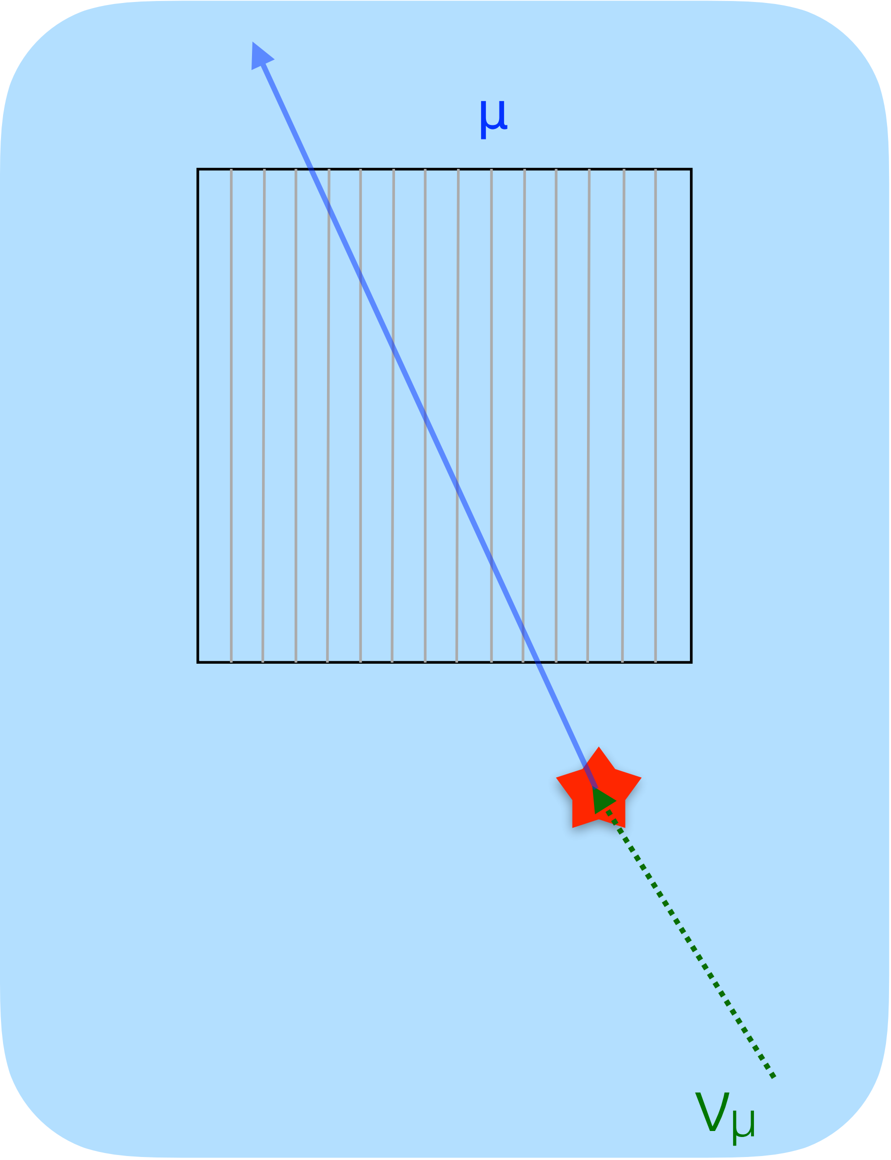
astrophysical neutrinos
probing propagation

neutrino telescopes

effective area

- neutrino telescopes have a well defined light sensitive instrumented volume …
- … however, they do NOT have a well defined detection volume
- neutrinos can interact outside the instrumented volumes and be indirectly detected

the **neutrino effective area** is the equivalent area for which all neutrinos of a given flux impinging on the Earth would be observed. Absorption effects of the Earth are considered as part of the detector and folded in the effected area



neutrino telescopes

effective area

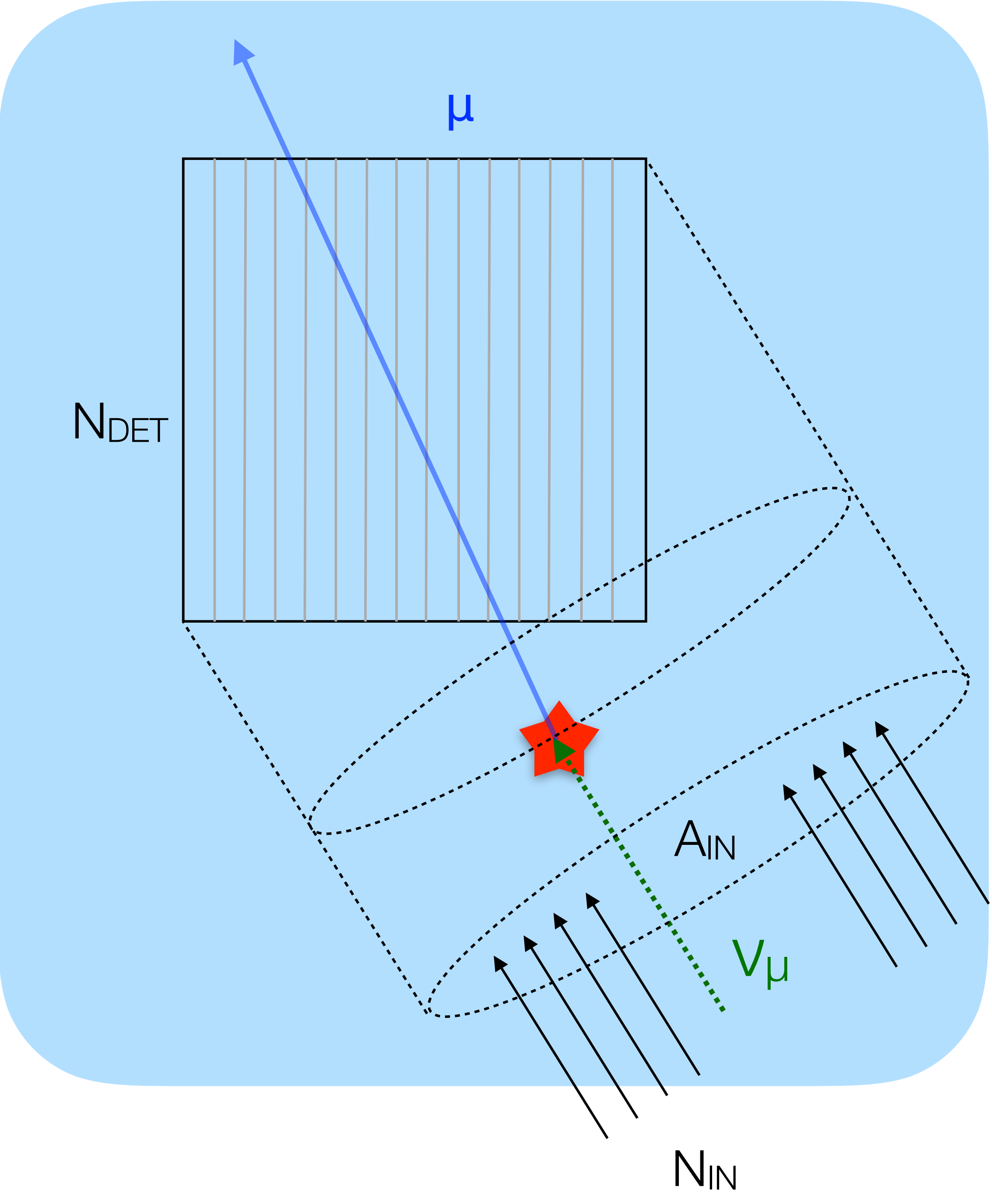
the **neutrino effective area** is the equivalent area for which all neutrinos of a given flux impinging on the Earth would be observed. Absorption effects of the Earth are considered as part of the detector and folded in the effected area

- empirical definition $A_{\mathrm{eff}}(E_\nu,\theta) = \dfrac{N_{\mathrm{DET}}(E_\nu,\theta)}{N_{\mathrm{IN}}(E_\nu,\theta)} \cdot A_{\mathrm{IN}}(E_\nu,\theta)$

$$A^{\nu}_{\mathrm{eff}}(E_\nu,\theta) = A_{\mathrm{IN}}(E_\nu,\theta) \cdot \frac{N_{\mathrm{A}}}{\mathrm{A}} \cdot \int_{E_\mu} \underbrace{\epsilon^{\mathrm{DET}}_{\mu}(E_\mu,\theta)}_{\text{instrumental detection efficiency}} \cdot \underbrace{\sigma_{\nu\mu}(E_\nu,E_\mu)}_{\text{neutrino interaction cross section}} \cdot \underbrace{R_\mu(E_\mu)}_{\text{muon range}} \cdot dE_\mu$$

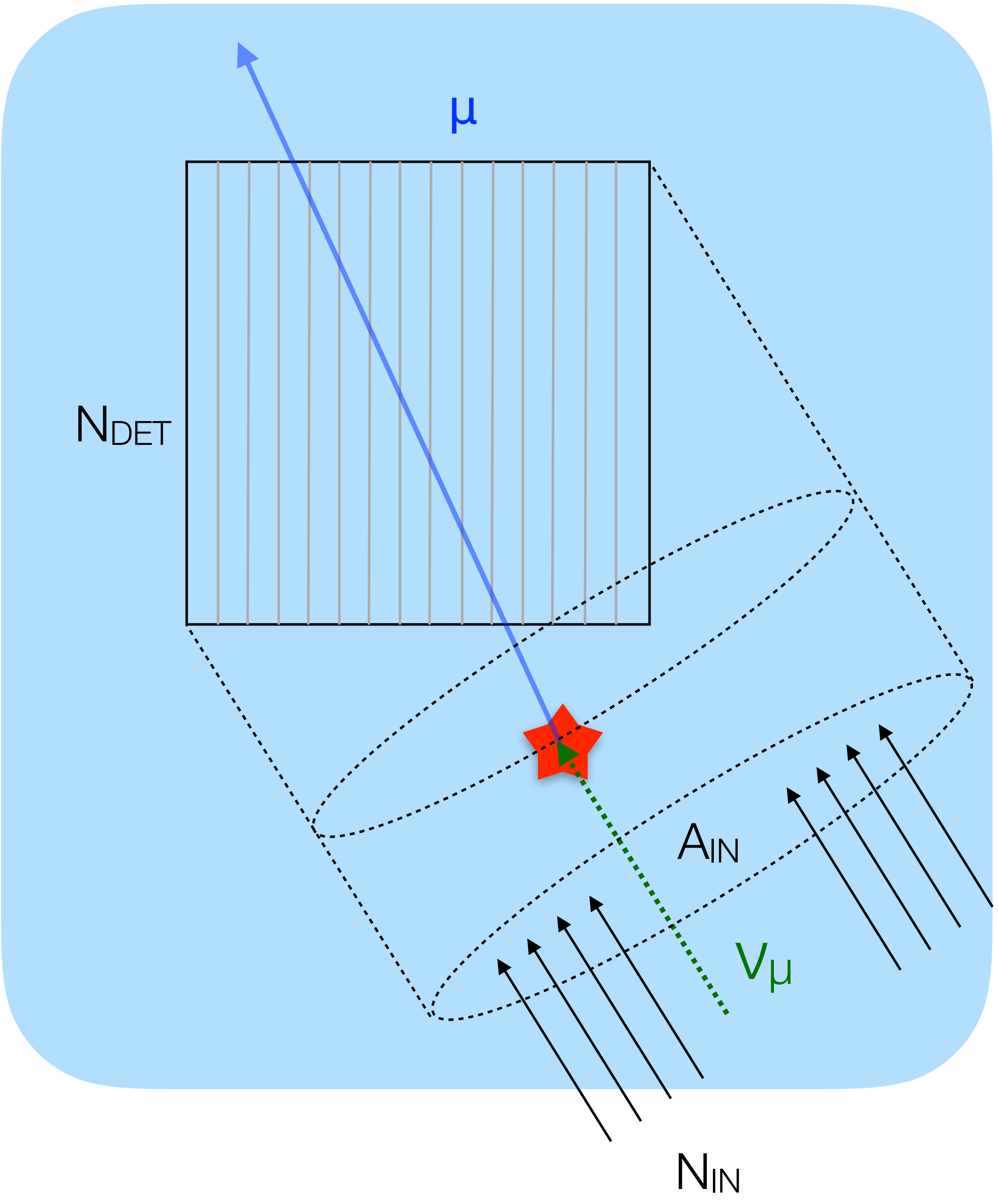
- number of events

$$n^{\mathrm{DET}}_{\nu} = T \cdot \int_{\Omega}\int_{E_\nu} A^{\nu}_{\mathrm{eff}}(E_\nu,\theta) \cdot \frac{d\Phi^{\nu}_{\mathrm{th}}(E_\nu,\Omega)}{d\Omega dE_\nu} \cdot d\Omega\, dE_\nu$$

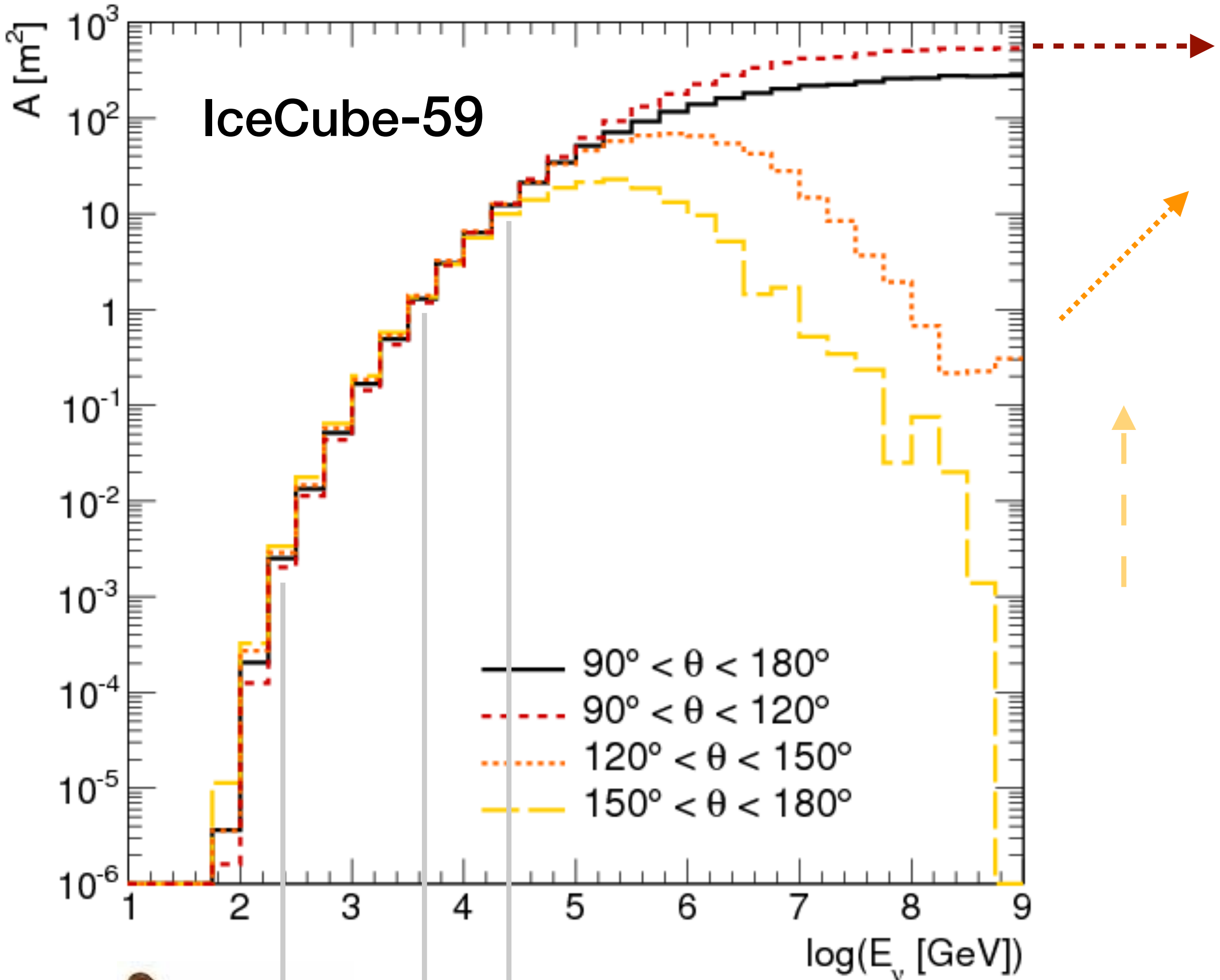


neutrino telescopes

effective area



Aartsen et al. Phys. Rev. D 89 (2014), 062007



neutrino absorption in the Earth

Galileo's telescope

AMS-02

Fermi-LAT

THANK YOU

NEXT:

- BACKGROUND REJECTION
- ATMOSPHERIC NEUTRINOS
- NEUTRINO ASTROPHYSICS