HIGH ENERGY ASTROPHYSICS

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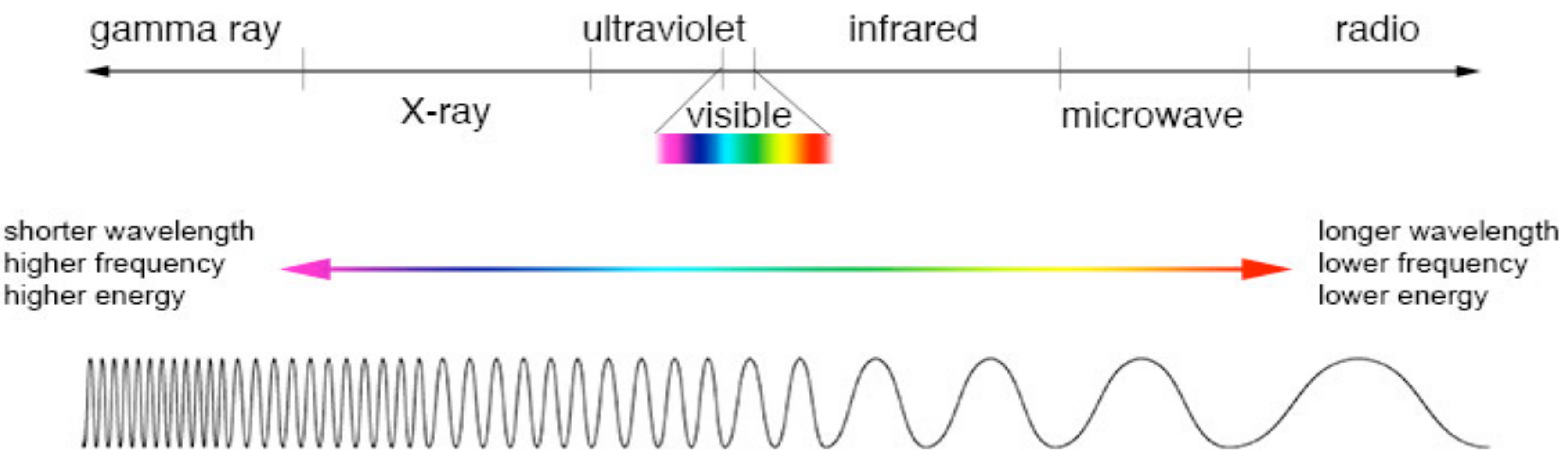
Reference: PHY418 Neil Spooner

Plans

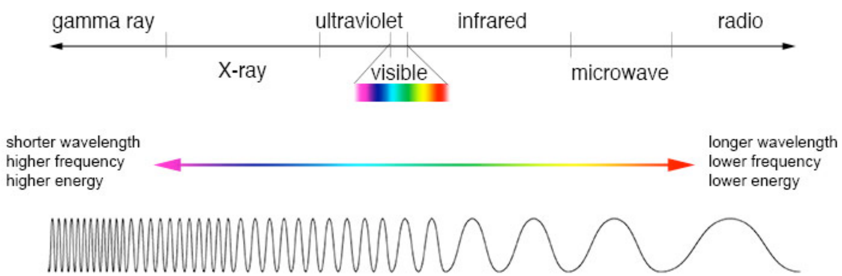
- ✓ Messengers of high energy astrophysics
  - Photons
  - Cosmic rays
  - Neutrinos
  - Gravitational waves
- ✓ Astrophysical sources
  - Supernova
  - Gamma-ray burst
  - Active Galactic Nuclei

→ address astrophysical questions.


gamma ray
ultraviolet
infrared
radio
X-ray
visible
microwave
shorter wavelength
higher frequency
higher energy
longer wavelength
lower frequency
lower energy

PHOTONS

Photons



- Modern astronomical telescopes and detectors span the observational range from tens of meters in the radio to hundreds of TeV for the highest energy gamma rays. The classification of different astronomical wavebands is generally driven by the technology used in the detectors.
- Radio (from ~ 10 MHz to ~ 100 GHz) very highest spatial resolution because coherent detection of the EM field allows interferometry.
- Millimeter, sub-millimeter and far-infrared (~ 0.3 mm to ~ 10 μm). Bolometers onboard satellites and high-altitude terrestrial sites.

Photons

- Infrared (10 μm to 1 μm) and optical (1 μm to 0.3 μm). Almost all of "traditional" astronomy. Most stars put out most of their energy in this range. Unsurprisingly the human eye is adapted to use these wavelengths!
- Ultraviolet (0.3 μm to ~ 3 nm). Satellite-borne instruments are needed because the atmosphere is opaque now; but we can still use essentially "ordinary" telescopes.
- X-rays (3 nm to ~ 3×10^{-12} m; 0.4 keV to ~ 100 keV). Satellite and rocket-borne instruments are needed. Special grating-incidence mirrors are used to focus X-rays.

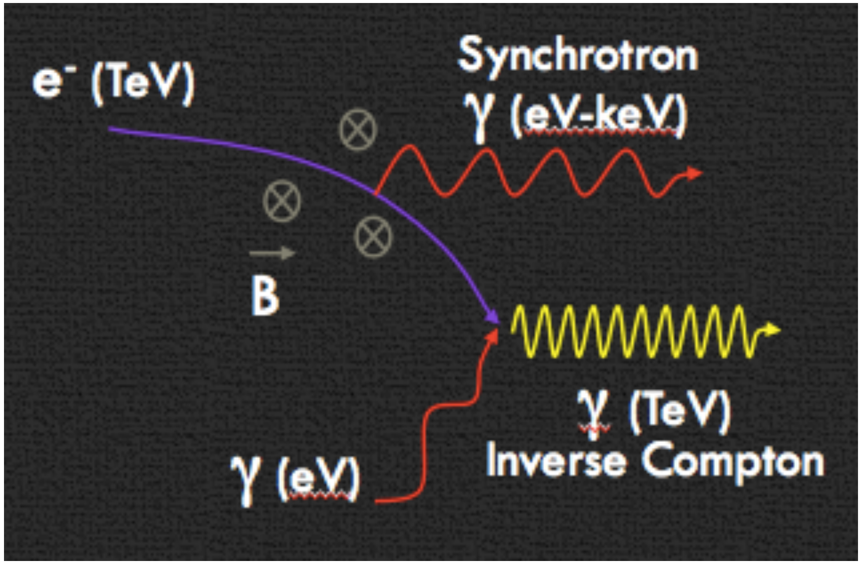
Photons

- Gamma-rays (~ 100 keV up to hundreds of GeV). Again telescopes are satellite-borne. Use similar detectors to particle physics experiments.
- Very high-energy photons and particles entering the Earth's atmosphere produce Cherenkov radiation. This is detected by very large "light bucket" telescopes which don't need finely-figured mirrors.

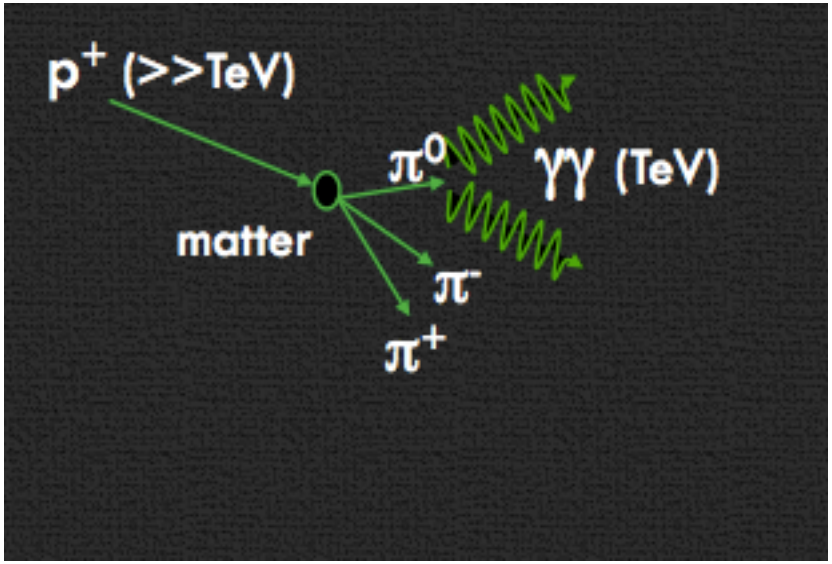
Gamma Rays

- 1, they always go with cosmic rays

Inverse Compton (electrons)

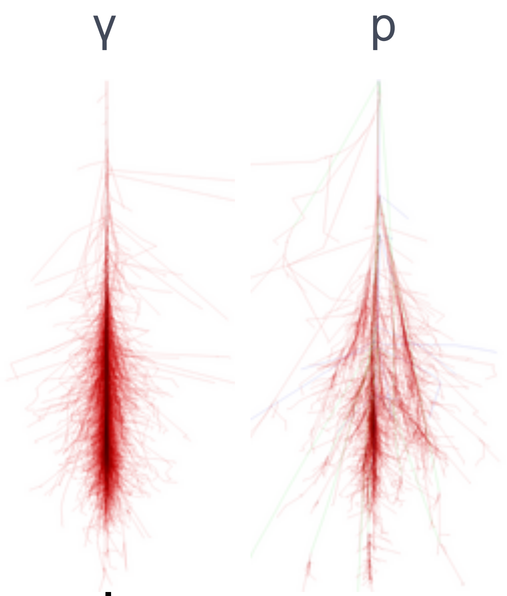


Pion-decay (protons)



- 2: gamma-rays can be easily absorbed/scattered,“remember” the interaction with ambient fields they crossed like with globular clouds, or the Extragalactic Background light
- 3. gamma-rays are not deflected by magnetic field

Photon-induced air showers

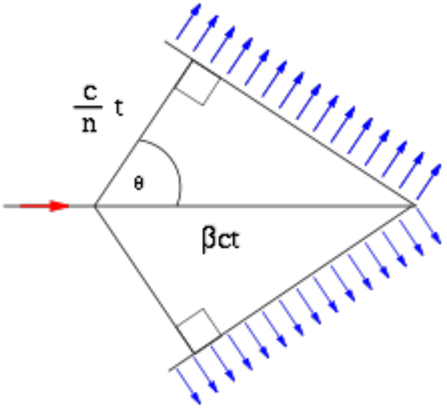


- Very-high-energy γ-rays are uncommon
  - space-based detectors are too small to get a decent rate
  - also, measurement quality degrades because larger showers leak out of back of calorimeter
- Therefore, as with charged cosmic rays, go for ground-based detectors and detect the shower produced in the atmosphere
  - very little of a photon shower reaches ground, so applicable techniques are nitrogen fluorescence and Cherenkov radiation
    - high-energy photon detectors tend to choose Cherenkov emission because of its high directionality (as photons point back to their source, direction reconstruction is important to identify optical counterparts of γ-ray sources)

Cherenkov radiation

- First observed by Pavel Cherenkov in 1934.
- When light passes through matter its velocity decreases.
  - Index of refraction (n) = (speed of light in vacuum)/(speed of light in medium)
  - speed of particle > speed of light in medium
  - an electromagnetic shock wave will be formed.
- very forward peaked: $\cos\theta = 1/n\beta$

~ 1° in air   blue light

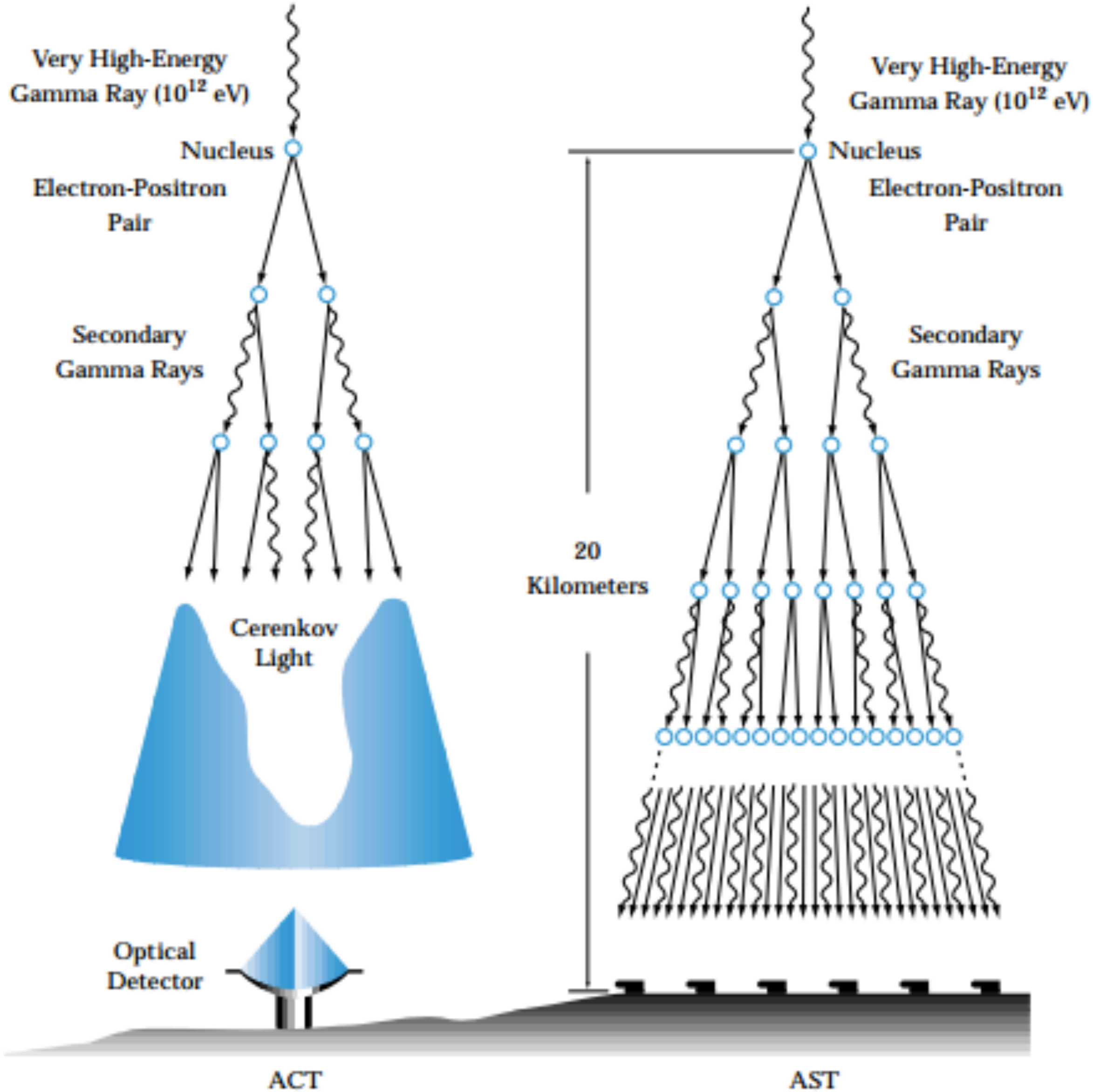


Cherenkov radiation

- Cherenkov emission per unit time is

$$I(\omega) = \frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}\omega \mathrm{d}t} = \frac{\omega e^2 \beta}{4\pi\epsilon_0 c}\left(1 - \frac{1}{n^2\beta^2}\right)$$

  - $I(\omega) \propto \omega$, hence Cherenkov light is blue (but note n also depends on ω, proportionality is not exact)
  - very little dependence on particle energy once $\beta \simeq 1$
  - but ***number of particles in shower*** depends on energy of incoming particle, so *total light yield* does provide a measure of the energy of the particle initiating the shower
- TeV-energy photon produces only ~100 Cherenkov photons per square metre
  - need large collecting areas (~100 m^2 typical)
  - but light pool is ~60000 m^2, so large effective area for low fluxes


Very High-Energy
Gamma Ray (10^{12} eV)
Nucleus
Electron-Positron
Pair
Secondary
Gamma Rays
Cerenkov
Light
Optical
Detector
ACT
Very High-Energy
Gamma Ray (10^{12} eV)
Nucleus
Electron-Positron
Pair
Secondary
Gamma Rays
20
Kilometers
AST

COMPLEMENTARITY OF TEV GAMMA-RAY DETECTORS

Imaging Air Cherenkov Telescopes

Energy Range .05-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution 0.05°
Energy Resolution ~15%
Aperture 0.003 sr
Duty Cycle 10%

High Resolution Energy Spectra
Precision Study of Known Sources
Source Location & Morphology
Deep Surveys of Limited Regions of Sky

Extensive Air Shower Arrays

Energy Range 0.1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Energy Resolution ~50%
Aperture > 2 sr
Duty Cycle > 90%

Unbiased Complete Sky Survey
Extended Sources
Transient Objects (GRB's)
Multi-Wavelength/Messenger Observations

High Altitude Water Cherenkov (HAWC) Observatory

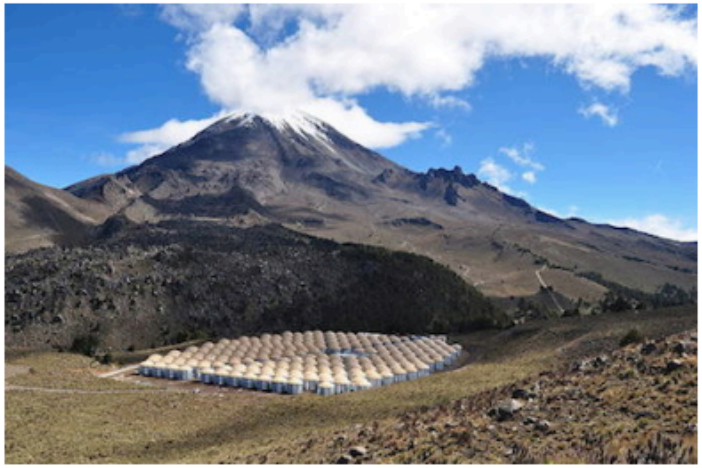
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

4100 m altitude near Sierra Negra Volcano, Puebla, Mexico

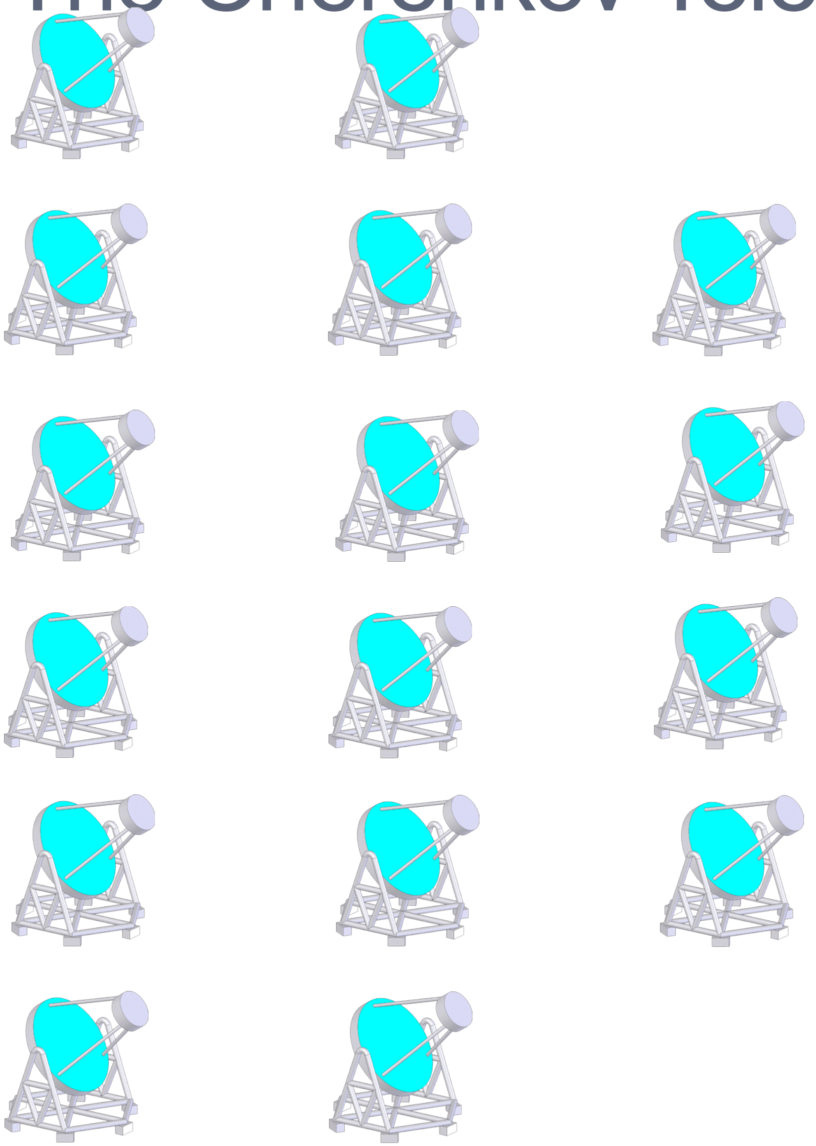
- 0.1 - 100 TeV
- 2pi sr Field of View
- 0.1 degree @ > 5 TeV

4 meters high
7.3 meters in diameter

300 tanks in total,
with 4 PMTs per tank

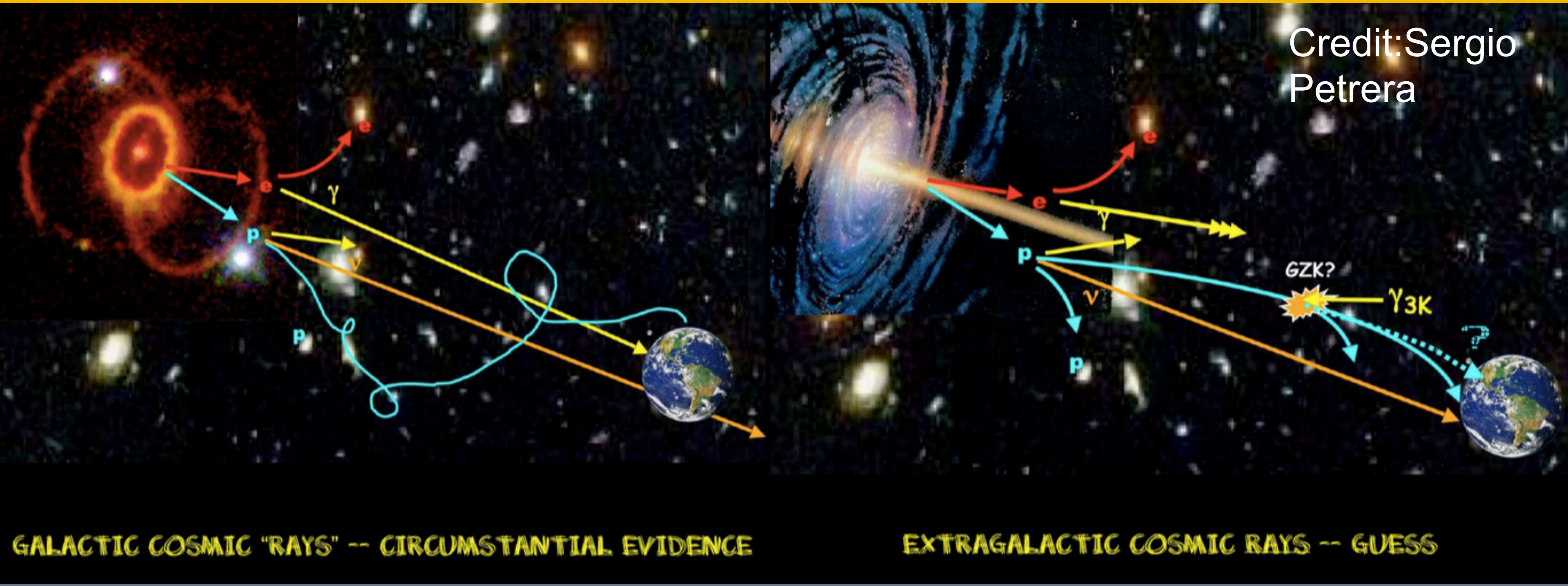


The Cherenkov Telescope Array facility



- aims to explore the sky in the 10 GeV to 100 TeV energy range
- builds on demonstrated technologies
- combines guaranteed science with significant discovery potential
- is a cornerstone towards a multi-messenger exploration of the nonthermal universe

- The atmosphere is not transparent to high-energy photons
- Detection techniques depend on energy
- Emission mechanisms include bremsstrahlung and synchrotron radiation plus inverse Compton scattering and π^0 decay
  - former dominate for lower energies (X-rays), latter two for high energies
- Sources include supernova remnants and pulsars (Galactic) and radio-loud AGN
  - most important ***transient*** sources are GRBs



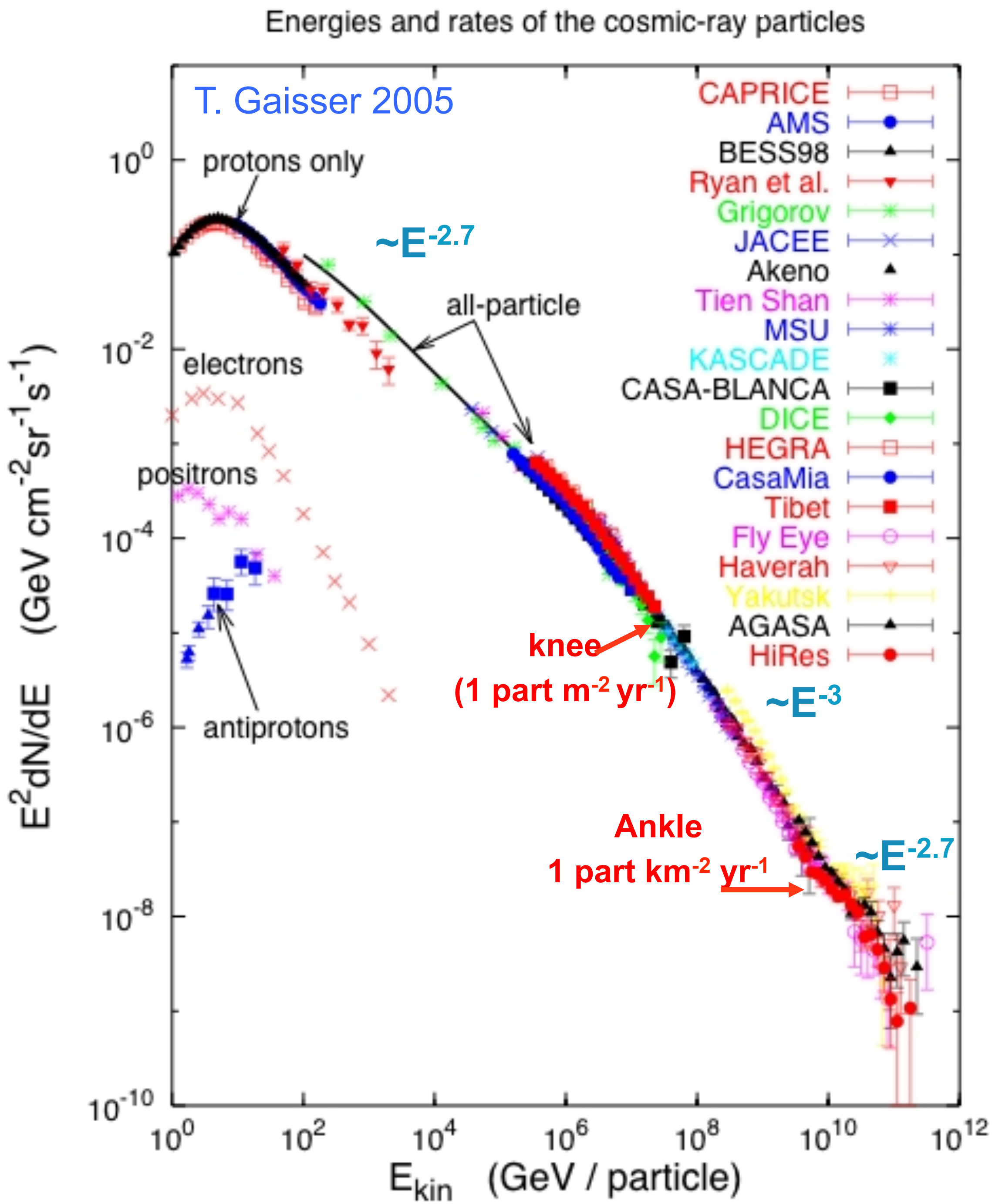
UHE COSMIC RAYS

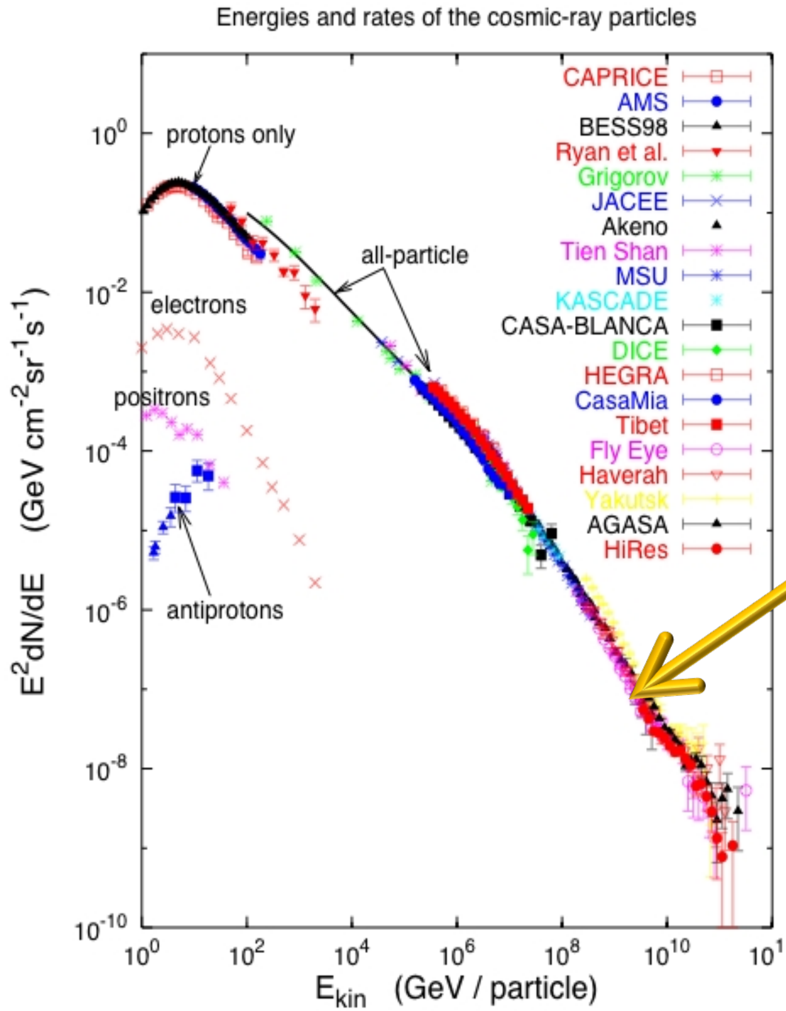
Cosmic rays

Isotropic

CR: 2% electrons, 98% hadrons.
Hadrons: 89% H, 10% He, 1% heavier elements.

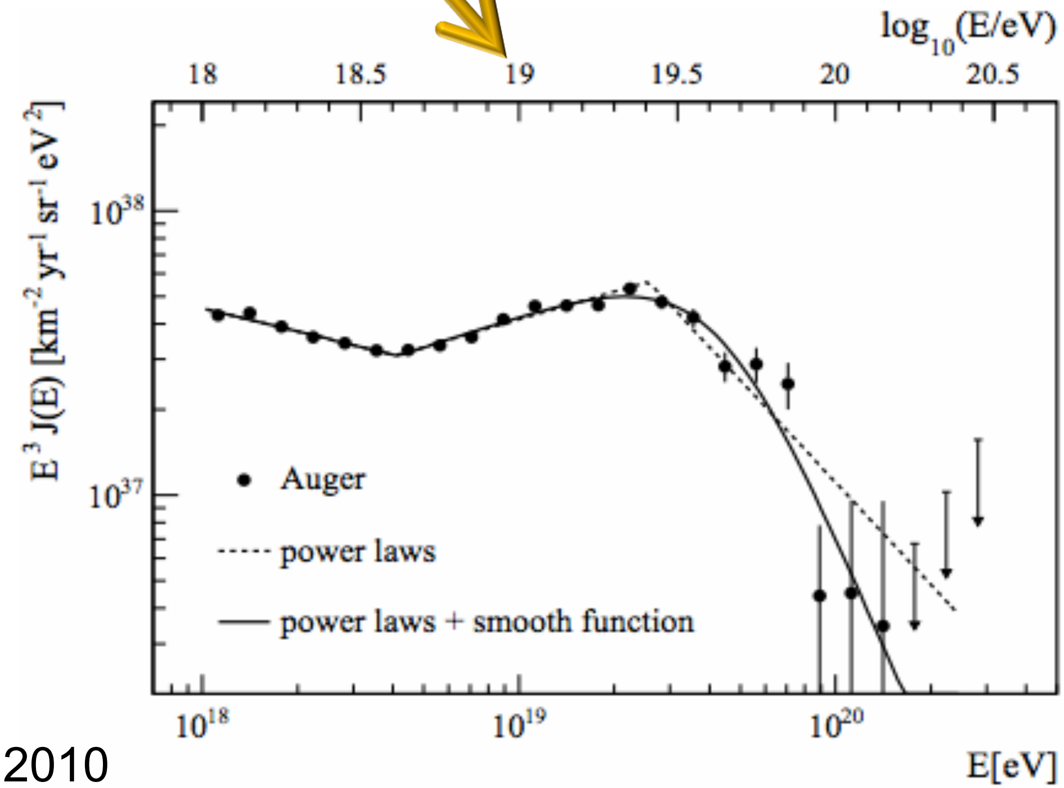
Energy spectrum is close to a power law with spectral index ~2.7
turn-over at low energies is due to solar magnetic field
two noticeable slope changes: "knee" at ~10^6 GeV and "ankle" at ~10^9 GeV possibly due to changeover of sources





Ultrahigh-Energy Cosmic Rays

Where are they from?



Pierre Auger Collaboration 2010

Cosmic Mysteries

- **No convincing acceleration process for explaining particle energy > 10^{20} eV**

  A handful of super-GZK events have been reported.

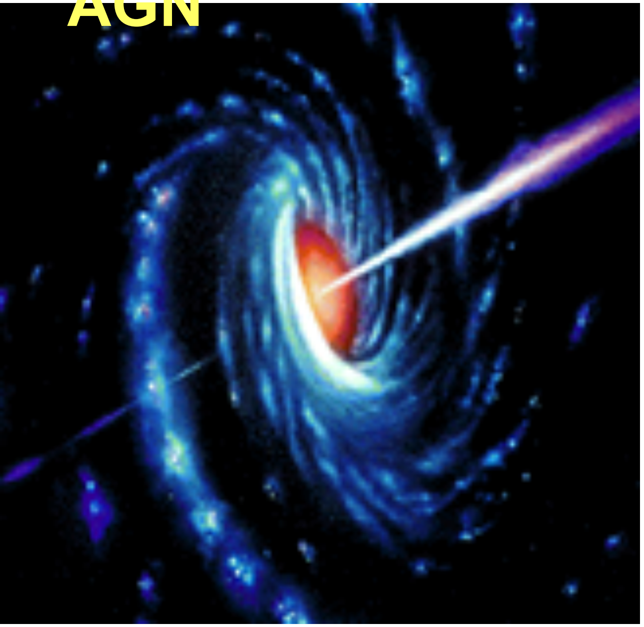
- **Sources of particles > 10^{20} eV must be closer than about 50 Mpc because of CMB**

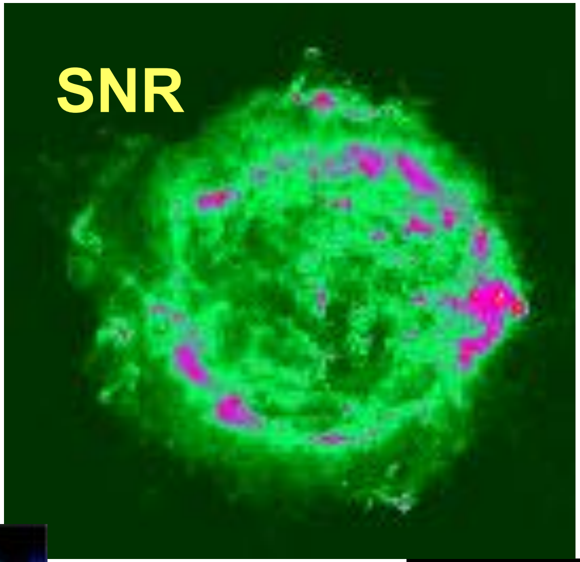
  No likely acceleration sites have been found nearby.

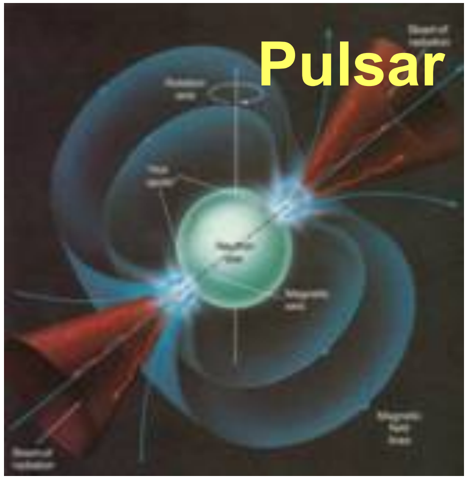
- **The highest energy cosmic rays should point back to possible sources**

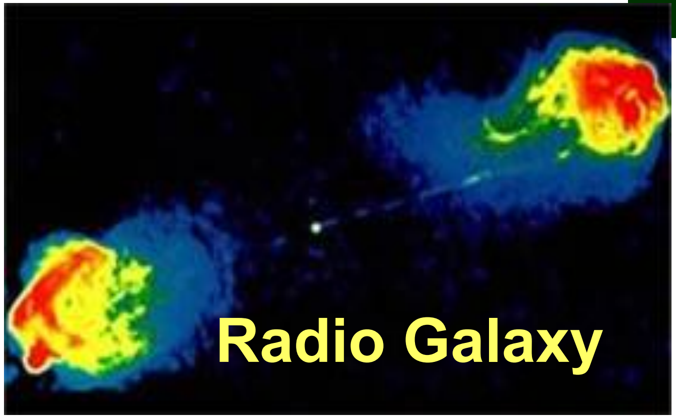
  Point sources or uniform on the sky?

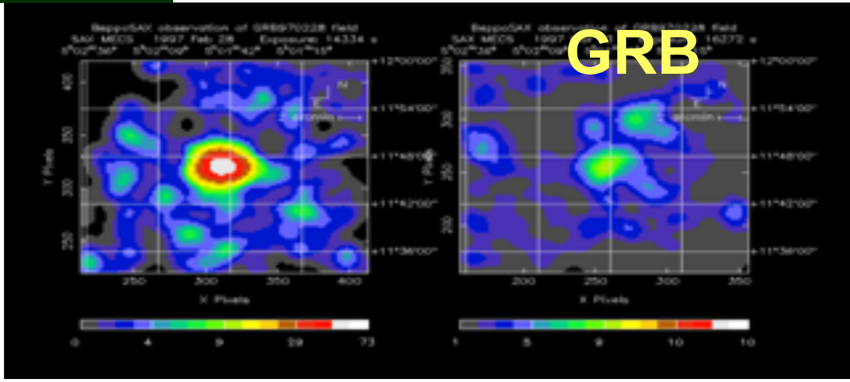
The Extreme Universe











Detection of cosmic rays

- Cosmic rays are strongly interacting
  - primary cosmic-ray shower high in the atmosphere
- Currently two approaches:
  - Detect CR primaries directly with balloon or satellites
    - **Only Up to 10^{14} eV**
  - Detect Extensive Air Showers (EAS)
    - **Higher energies, lower fluxes**
- Currently two techniques for EAS detection:
  - Surface detector array on the ground (Auger)
  - Fluorescence detector, both on the ground (Auger) or from the sky (JEM-EUSO)
- New techniques under development: Radio detection, MW detection

Detection of cosmic rays

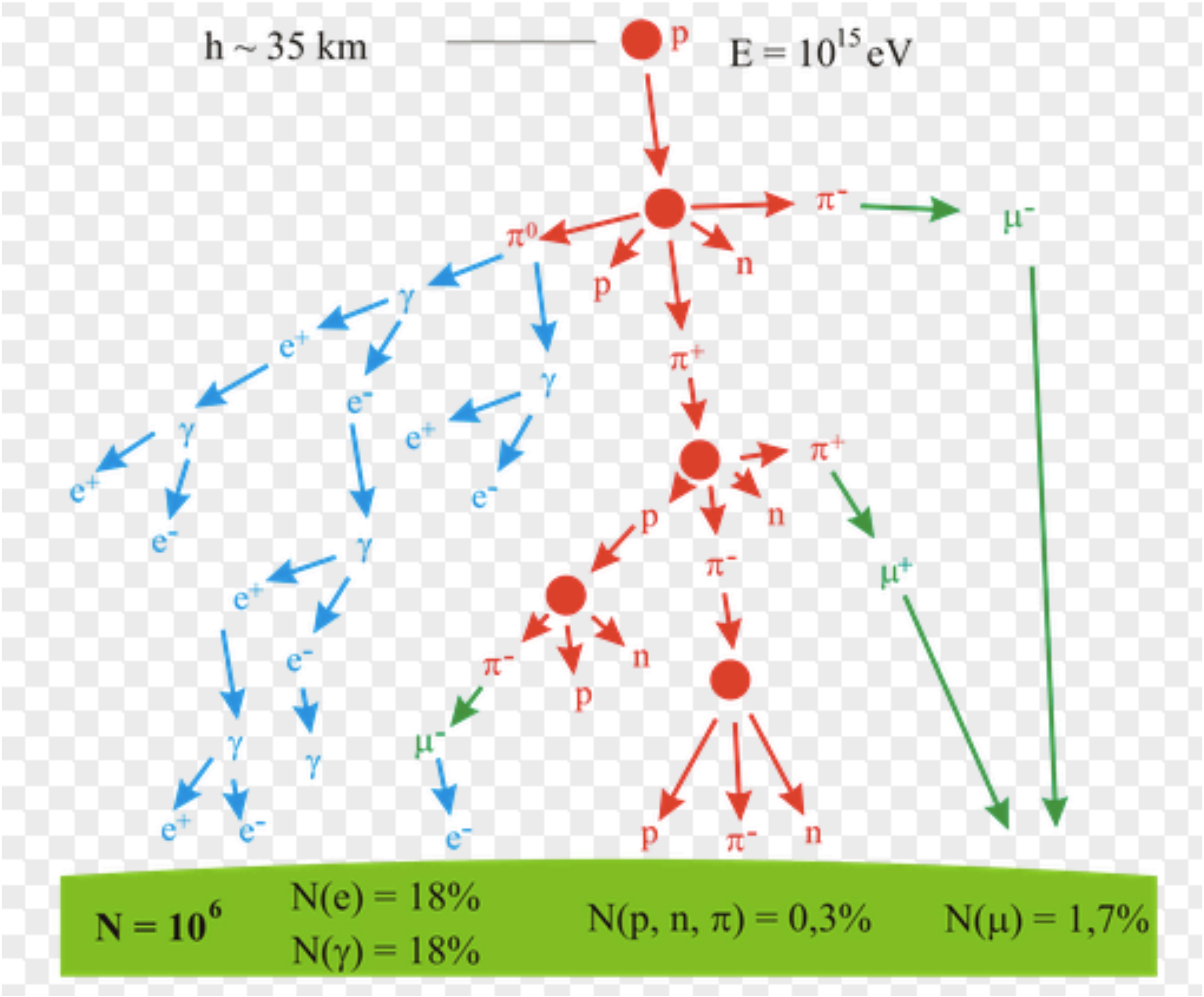
Nitrogen fluorescence: The passage of charged particles in an EAS through the atmosphere ionizes and excites N molecules. This excitations produces isotropical UV emission (properly luminescence)

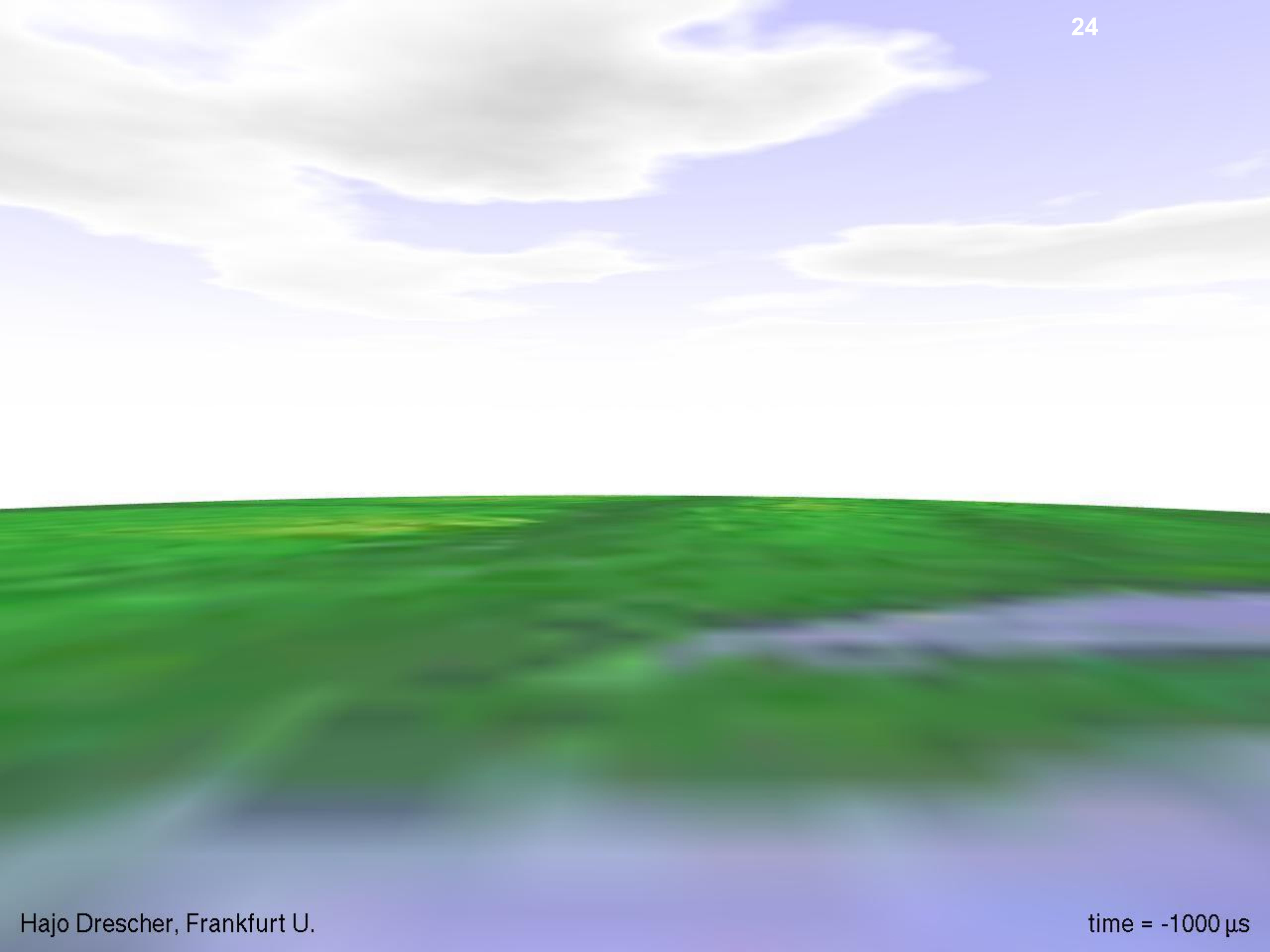
On average about 4 fluorescent photons m^{-1} per charged particle are emitted at wavelengths between about 300 nm to 400 nm. The intensity of the fluorescent radiation is proportional to the flux of charged particles and so, by measuring the flux of fluorescent radiation, the development of the shower through the atmosphere can be determined.

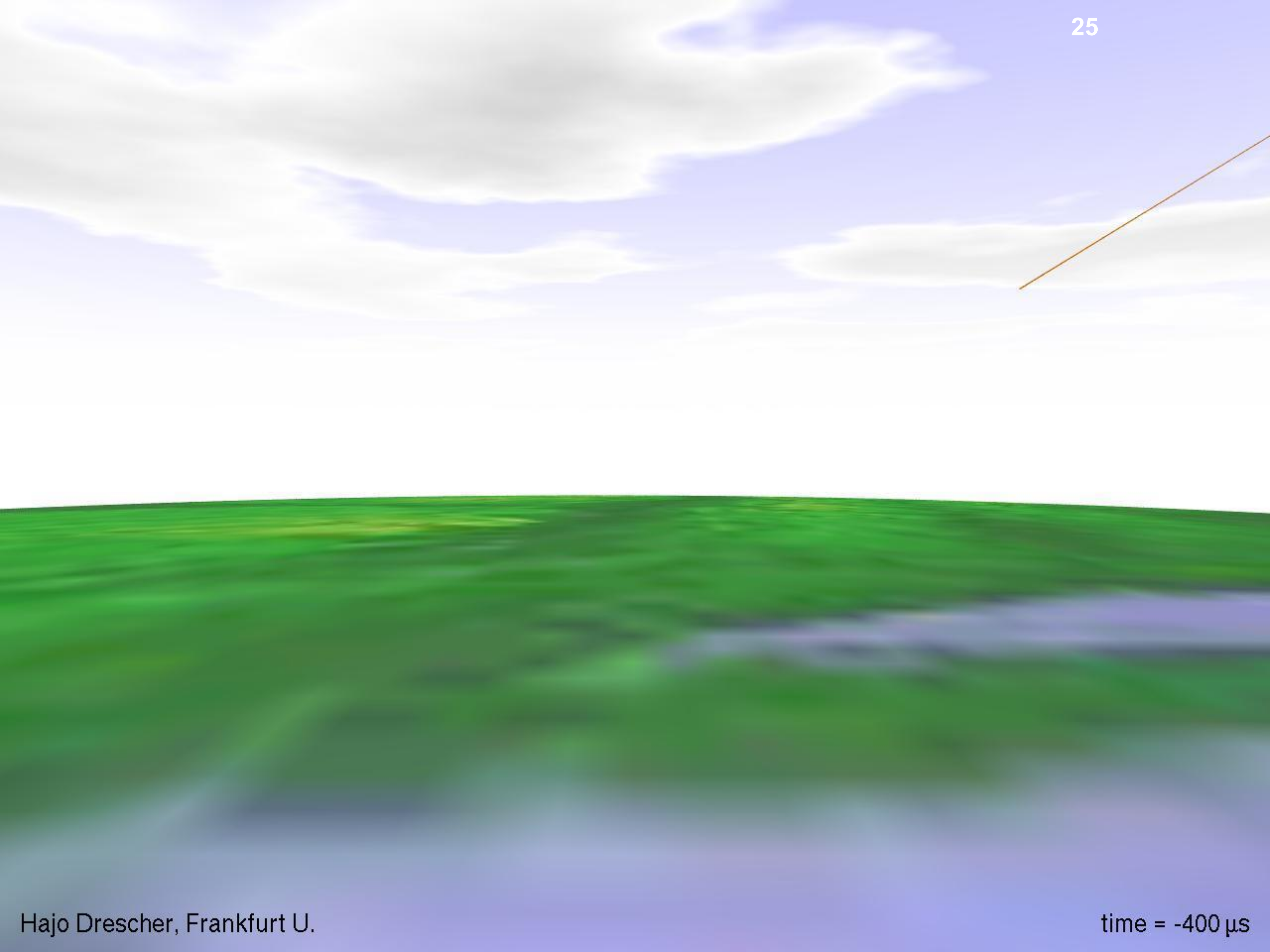
But isotropic light is very faint: require clear skies and very dark nights

poor duty cycle, but large effective area

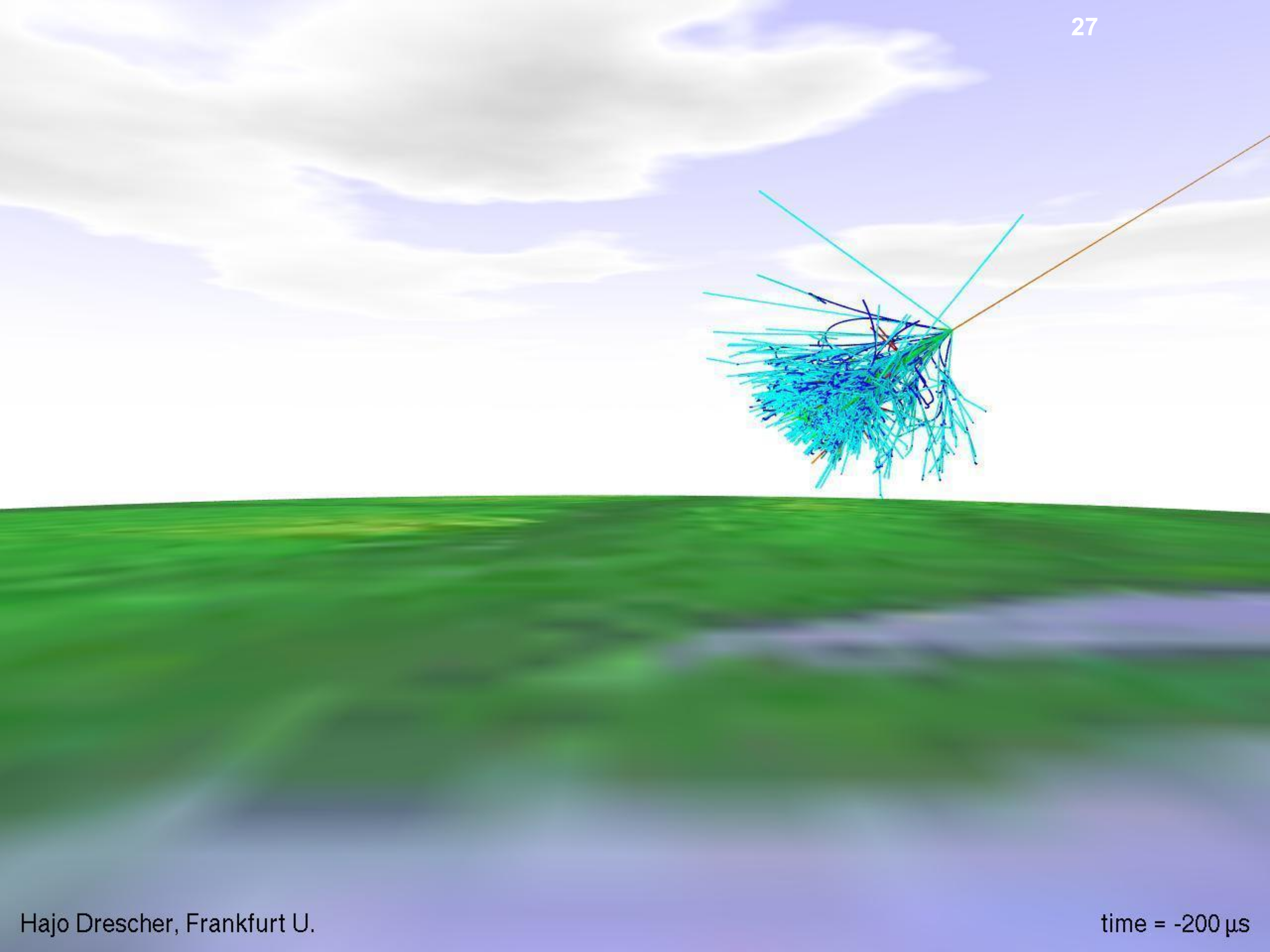
- Fly’s Eye, HiRes (High Resolution Fly’s Eye experiment), the Pierre Auger Observatory, and TA (Telescope Array), JEM-EUSO (Extreme Universe Space Observatory)

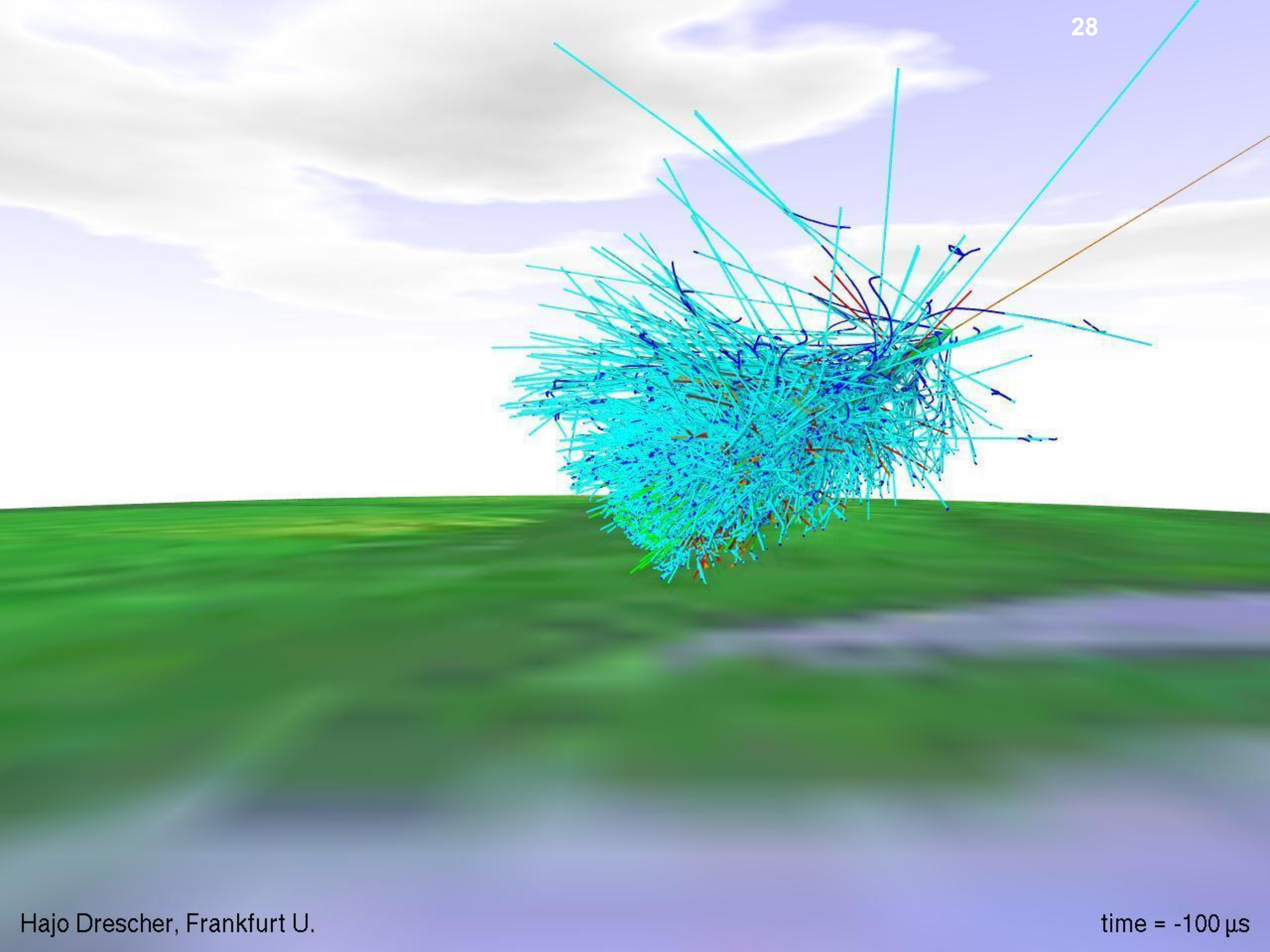

h ~ 35 km
p
E = 10^15 eV
π^-
μ^-
π^0
p
n
γ
e+
e-
π+
γ
e+
e-
π+
p
n
γ
e+
μ+
γ
π-
e-
e+
e-
π-
n
p
μ-
γ
γ
e+
e-
e-
p
π-
n
N = 10^6
N(e) = 18%
N(γ) = 18%
N(p, n, π) = 0,3%
N(μ) = 1,7%

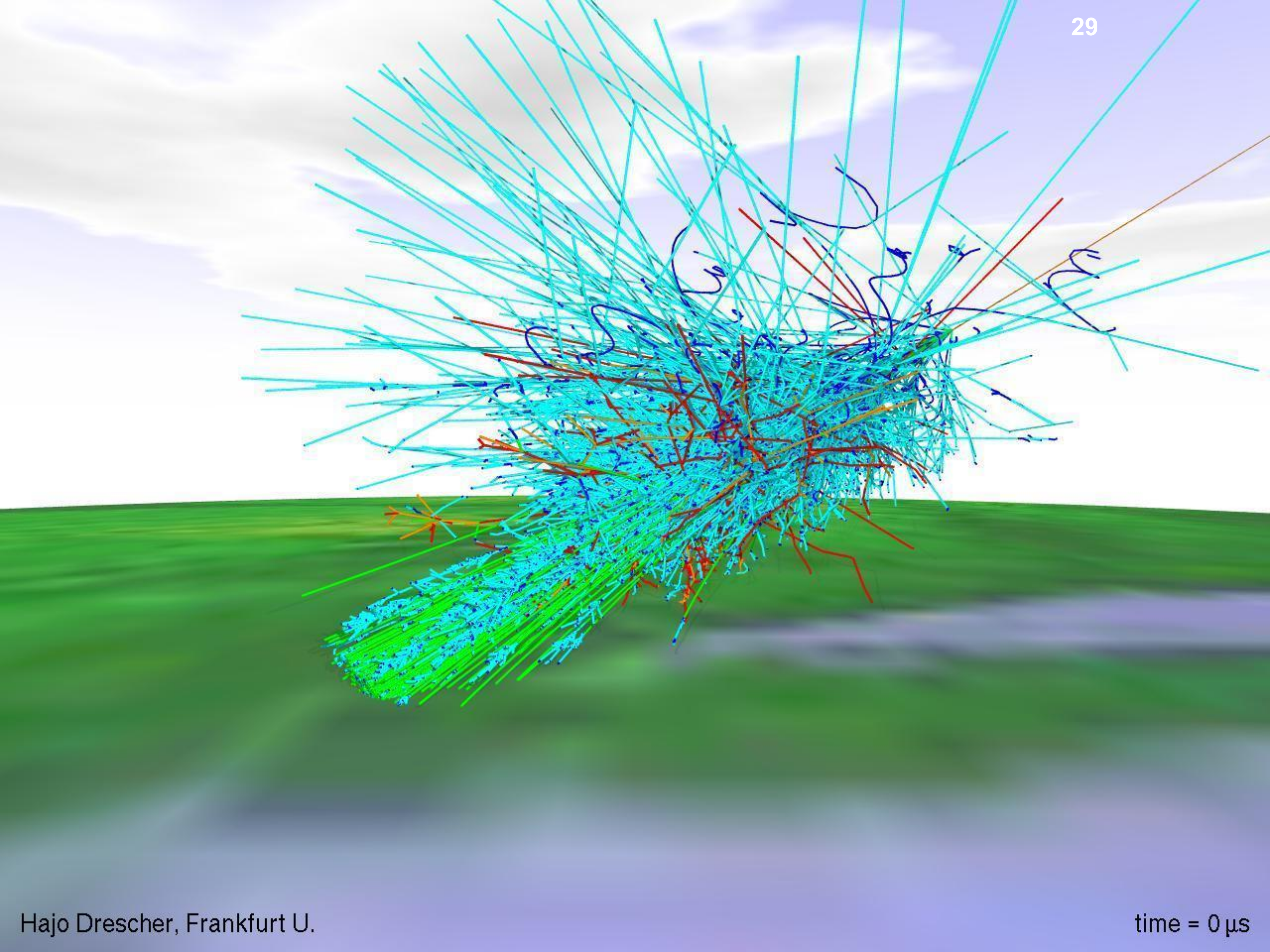

Hajo Drescher, Frankfurt U.
time = -1000 µs

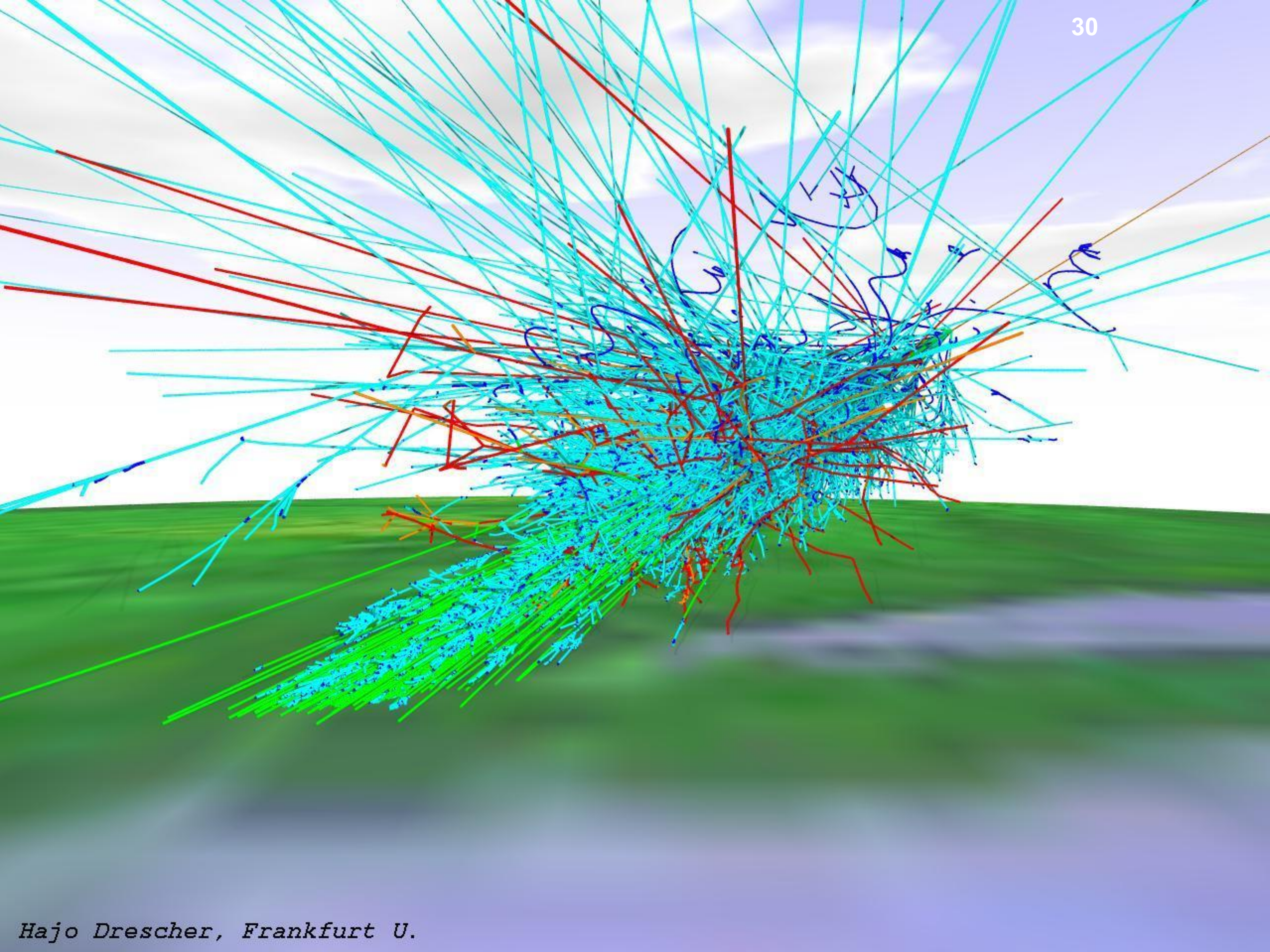

Hajo Drescher, Frankfurt U.
time = -400 µs


Hajo Drescher, Frankfurt U.
time = -300 μs

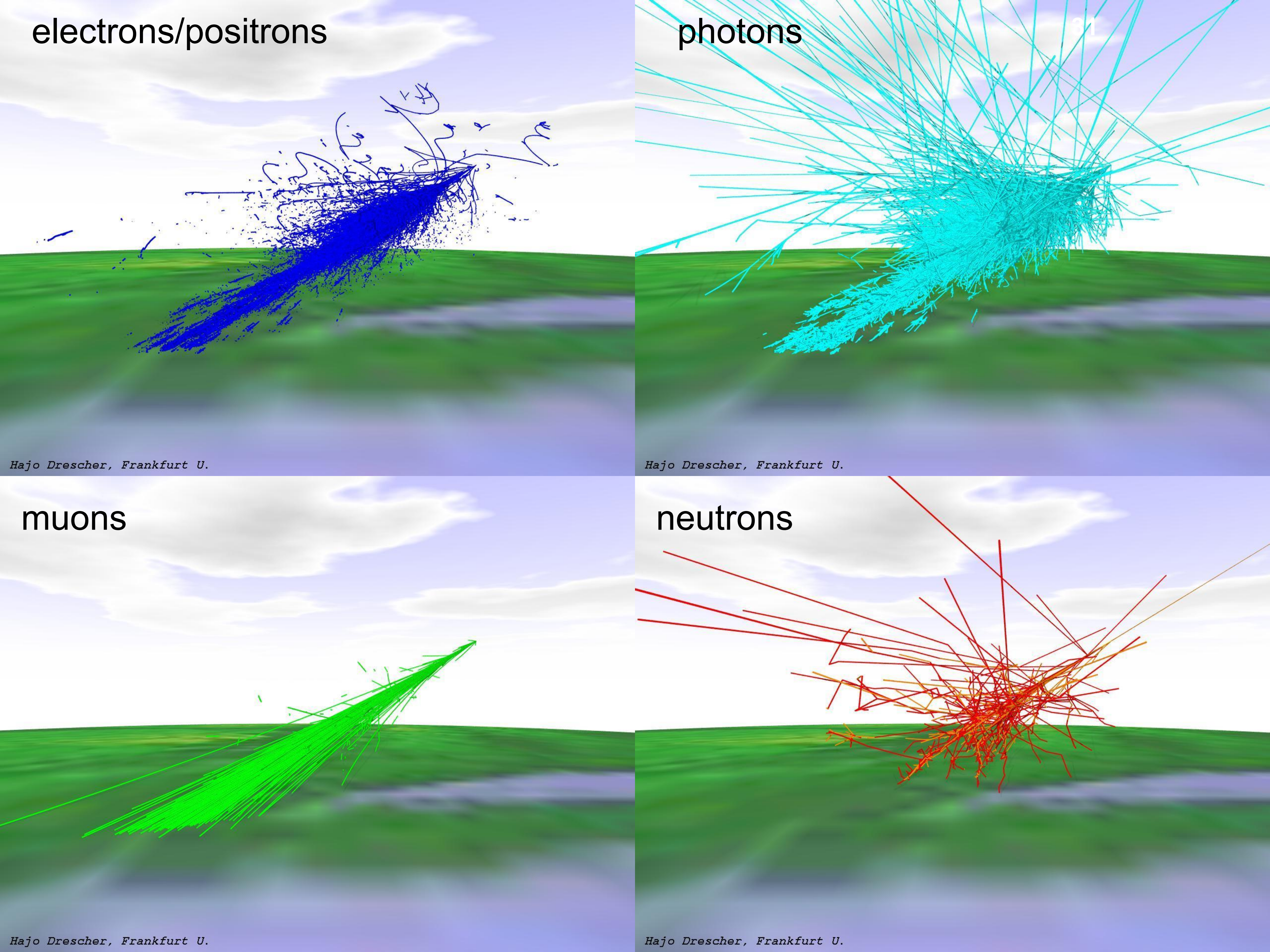

Hajo Drescher, Frankfurt U.
time = -200 μs

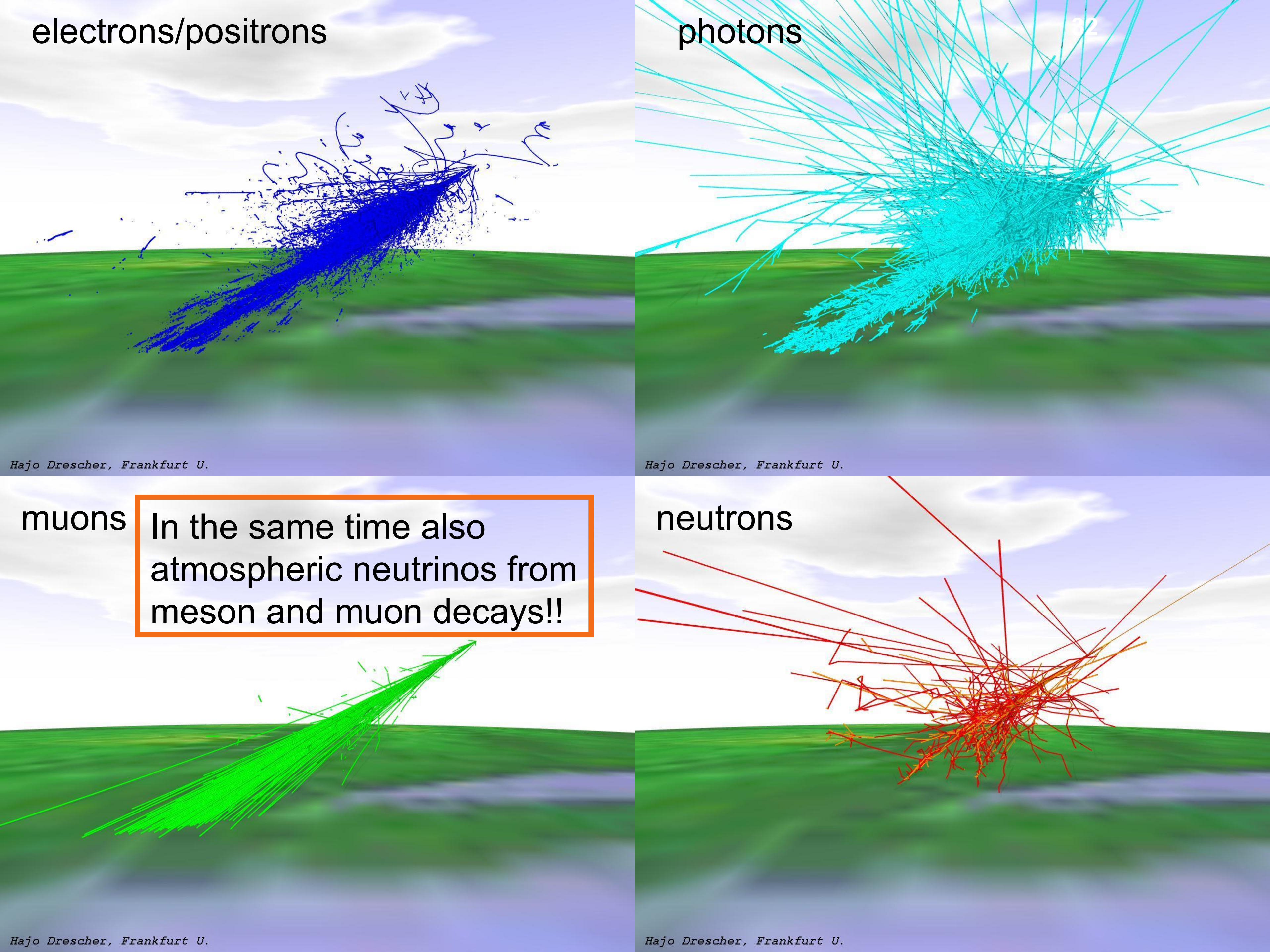

Hajo Drescher, Frankfurt U.
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 μs



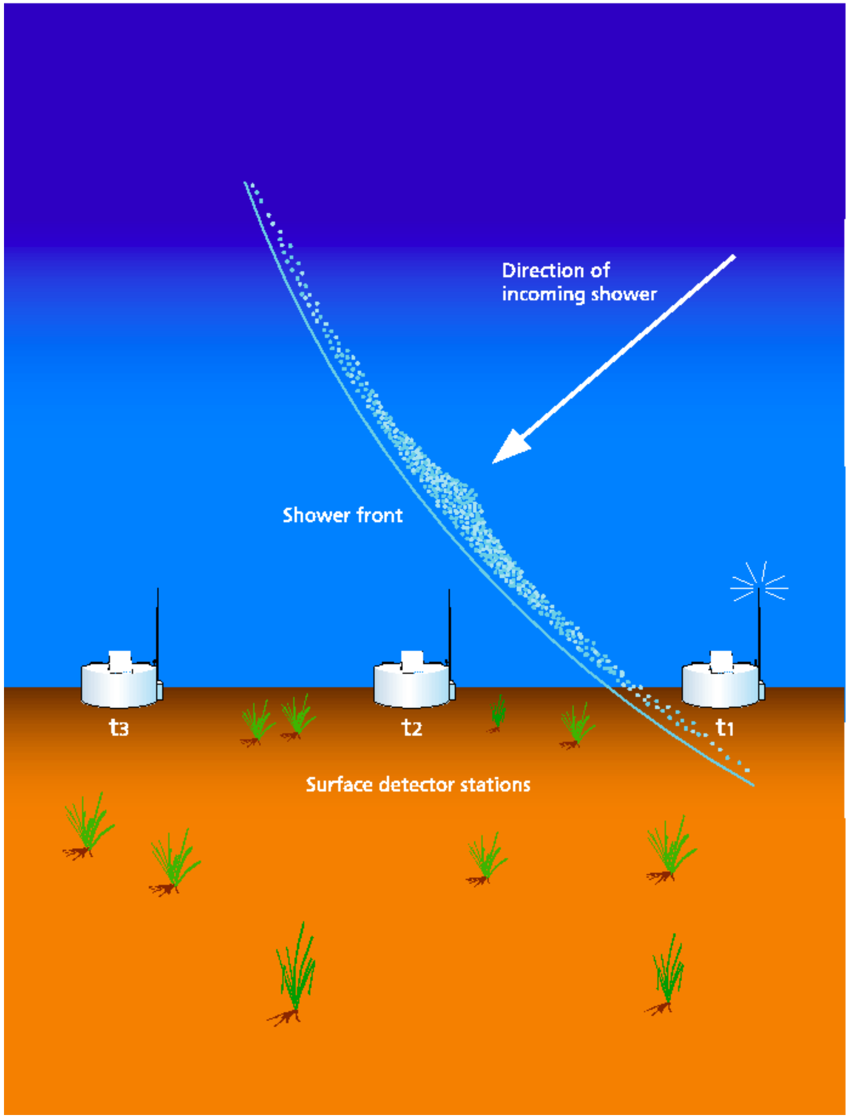
Hajo Drescher, Frankfurt U.


electrons/positrons
Hajo Drescher, Frankfurt U.
photons
Hajo Drescher, Frankfurt U.
muons
Hajo Drescher, Frankfurt U.
neutrons
Hajo Drescher, Frankfurt U.


electrons/positrons
Hajo Drescher, Frankfurt U.
photons
Hajo Drescher, Frankfurt U.
muons
In the same time also atmospheric neutrinos from meson and muon decays!!
Hajo Drescher, Frankfurt U.
neutrons
Hajo Drescher, Frankfurt U.

Pierre Auger Surface detector Array

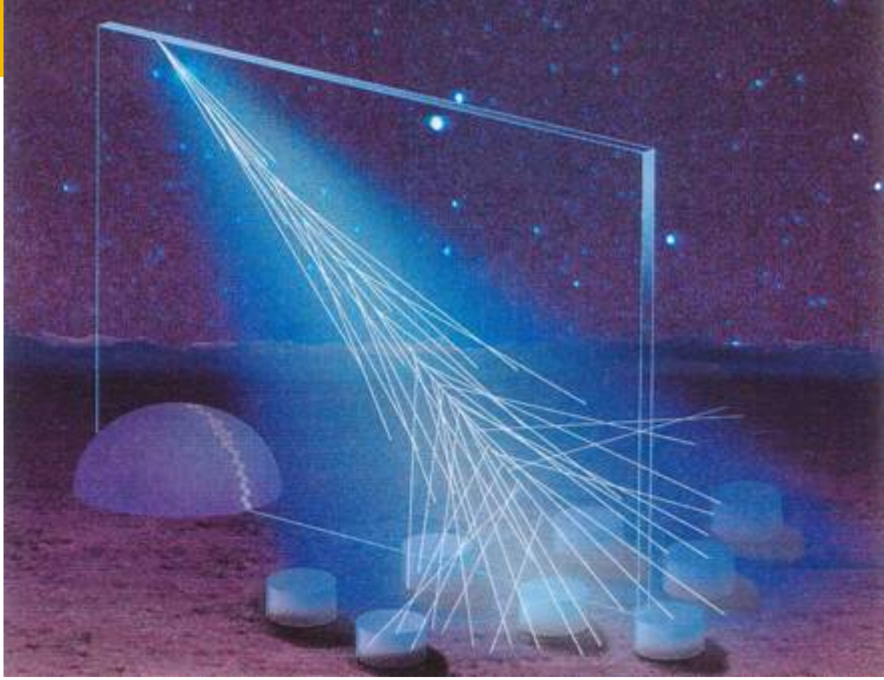
- Base of detector = $10m^2$
- 12 tons of very pure water as detection material
- 3 Photomultipliers detect cerenkov signals
- With GPS antenna high time correlation to different detectors
- Energy given in VEM (Vertical Equivalent Muon)

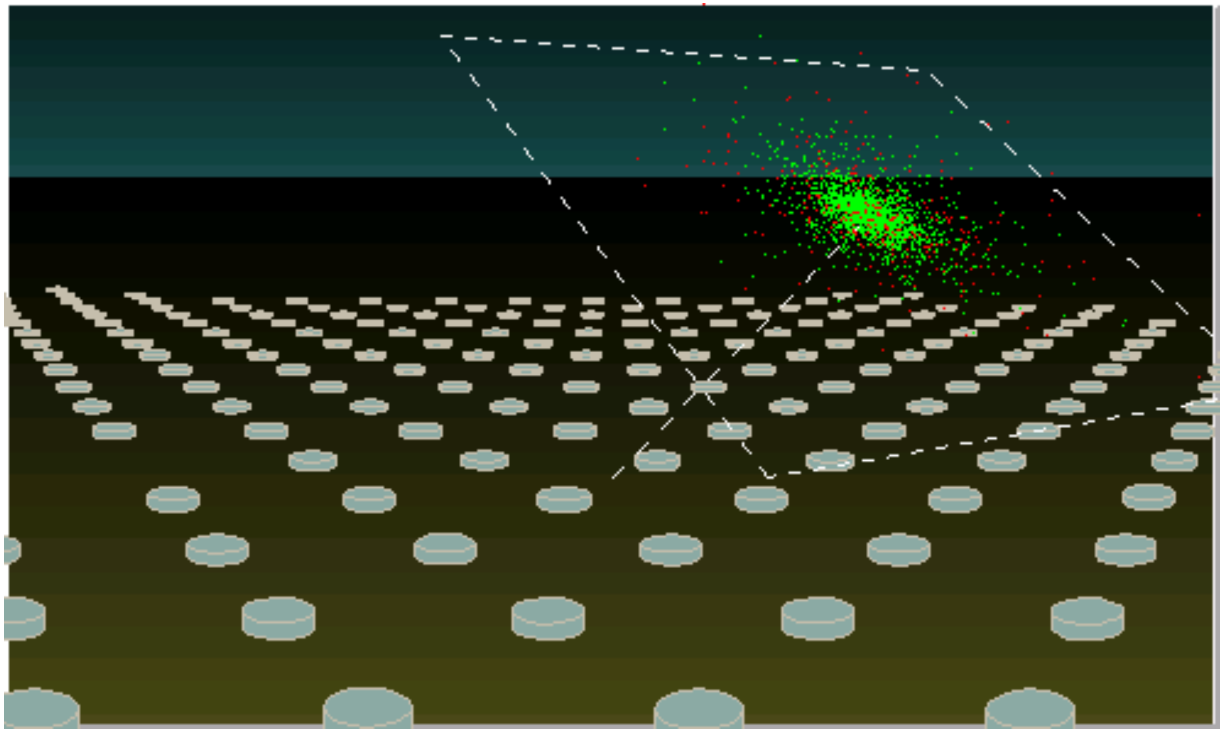


Extracting information from an EAS

- Tank timing
  - ➢ Arrival direction
- Number of particles in tanks
  - ➢ Total Energy
- Telescope image (digital camera like)
  - ➢ Arrival direction
- Light detected
  - ➢ Total Energy

Redundant measurement for cross-checks





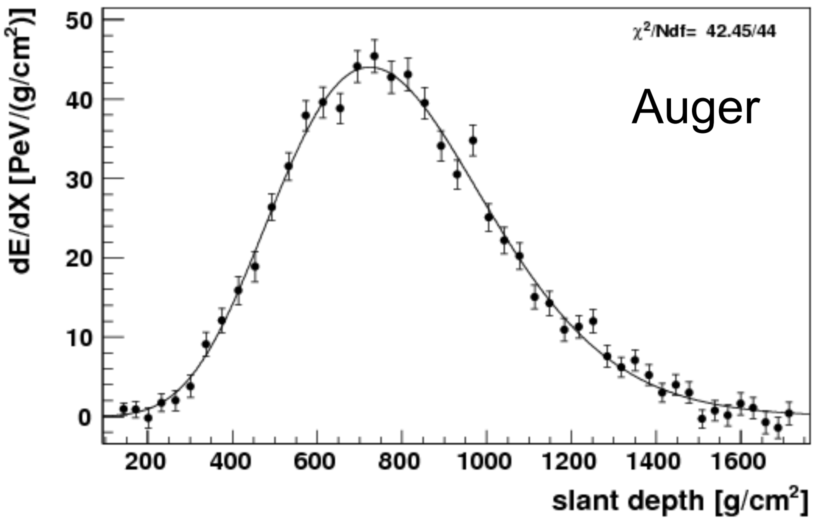
Animation of an event measured in Argentina

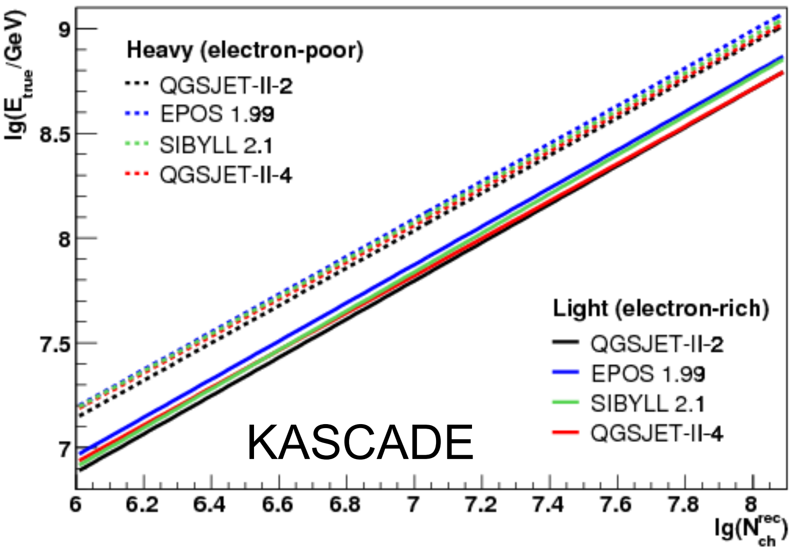
Fluorescence detector

- Charged particles in an air shower also interact with atmospheric nitrogen (excitation)
- Emitted ultraviolet light via a process called fluorescence
- Direction and energy of the cosmic particle can be determined

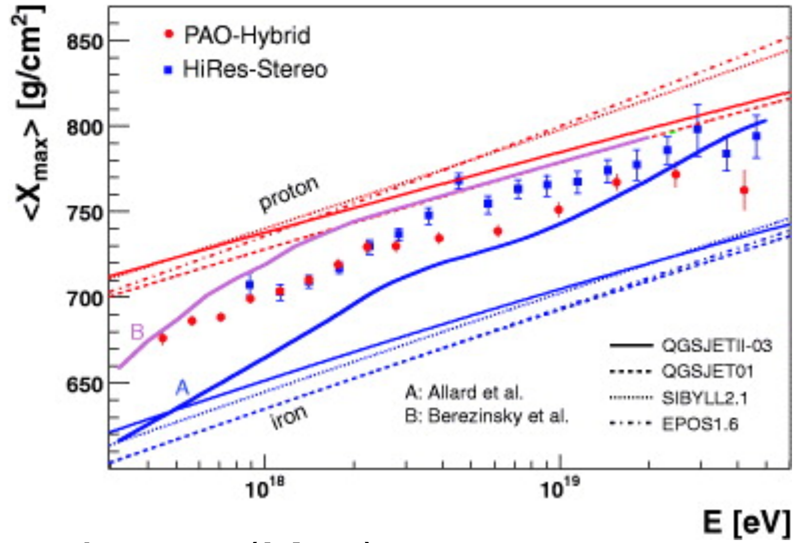
Energy measurement

- Fluorescence detectors measure light yield and longitudinal shower profile
  - a fit to this can be used to deduce energy of primary
- Ground arrays measure transverse shower profile at ground level
  - charged particle multiplicity or charged particle density at specified distance from shower axis can be used to deduce energy

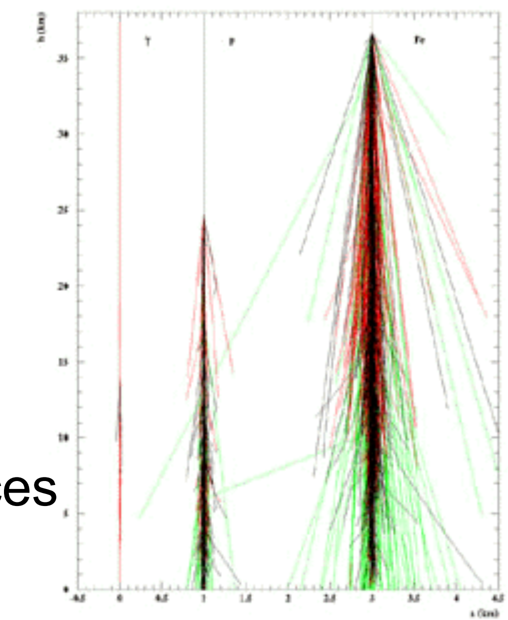




Particle identification



- Ground arrays cannot provide specific primary identification
  - "Heavy" and "light" primaries can be distinguished by the depth in the atmosphere at which they shower (X_{max})
  - Showers initiated by electrons/photons are narrower and contain only $e^{\pm}$ and γ
- At the highest energies there is some model dependence in this—no way to test models at these energies—and some disagreement between experiments
  - this is actually quite important as particle ID at highest energies has a bearing on possible sources



Surface Detector Array

Pros Duty cycle almost 100%

Cons Very strong dependence of nuclear interaction models (MonteCarlo simulations). Thus a big incertitude on the determination of the primary cosmic ray energy.

Fluorescence detection

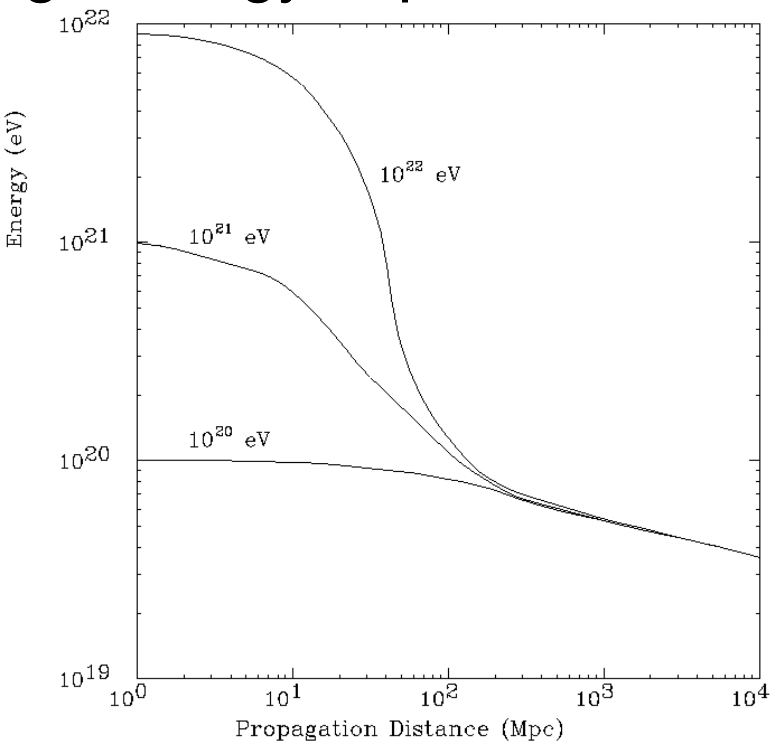
Pros Less model dependent
Cons Duty cycle of about 10-15% (clear moonless nights)

Greisen-Zatsepin-Kuzmin Cutoff

- At high energies, cosmic rays will unavoidably interact with CMB photons:

$$p+\gamma \rightarrow \Delta^{+} \rightarrow p+\pi^{0}(n+\pi^{+})$$

- Only occurs when proton has enough energy to produce pion, $E_p \sim 3\times10^{20}$ eV



- Reduce proton energy by 3%, owing to the production of pion mass
- Detection of particles above this energy requires "local" sources (or new physics).

*The **Universe is opaque** for protons with energy > 6*10^{19} eV*

"horizon" (p and nuclei) ≈100 Mpc (≈10^{20} eV)

Greisen-Zatsepin-Kuzmin Cutoff

- To start off, we should know the typical energy of CMB photon. The temperature of the CBM today is approximately 3 kelvin.

$$k_B T = 1.38\times10^{-23}\ [J/K]\times3[K] = 2.63\times10^{-10}\ \text{MeV}$$

$$(\mathbf{p}_p+\mathbf{p}_\gamma)^2=(\mathbf{p}_n+\mathbf{p}_\pi)^2$$

$$(\mathbf{p}_n+\mathbf{p}_\pi)^2=-(M_n+M_\pi)^2c^2 \quad \text{center of mass frame}$$

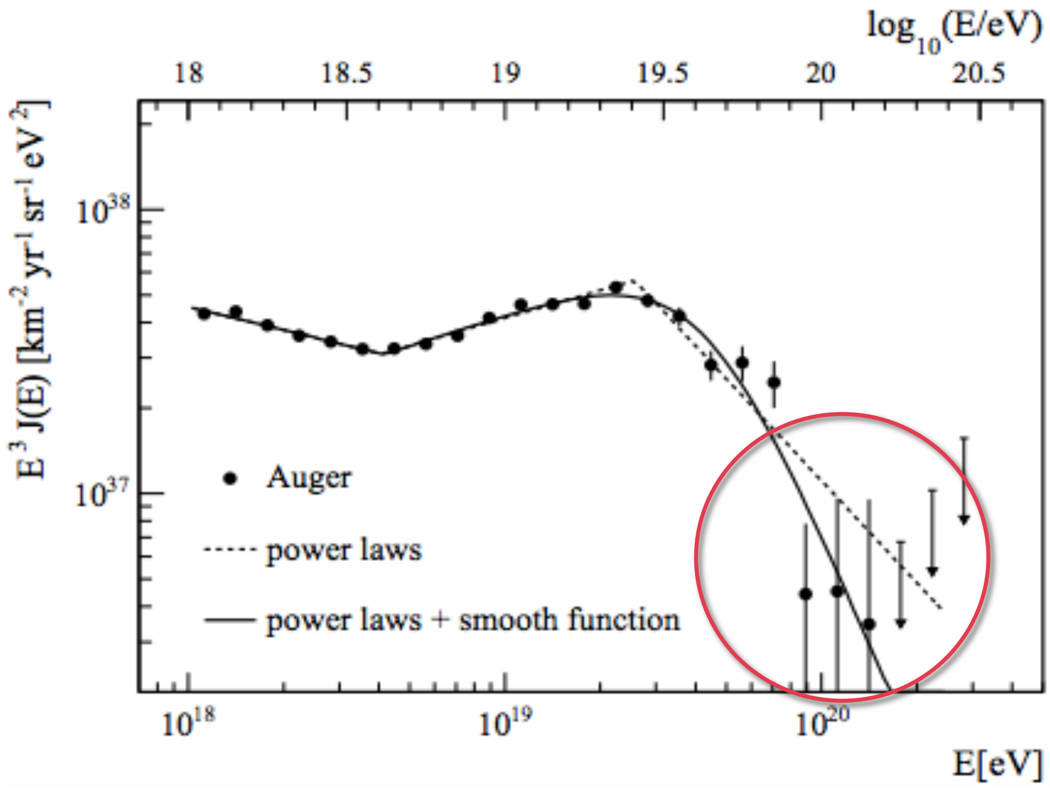
$$(\mathbf{p}_p+\mathbf{p}_\gamma)^2=\mathbf{p}_p^2+2\mathbf{p}_p\mathbf{p}_\gamma+\mathbf{p}_\gamma^2$$

$$-M_p^2c^2+2\mathbf{p}_p\mathbf{p}_\gamma=-(M_n+M_\pi)^2c^2$$

$$E_p=\frac{(M_nc^2+M_\pi c^2)^2-(M_pc^2)^2}{4E_\gamma}$$

Greisen-Zatsepin-Kuzmin Cutoff

- Therefore, M_n=939.6 MeV/c^2, and M_p=938.3 MeV/c^2, M_π=139.6 MeV/c^2,
- E_p=3×10^{20} eV



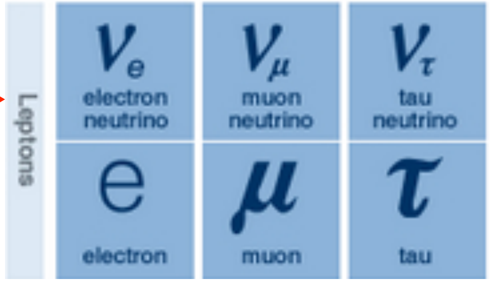
NEUTRINOS

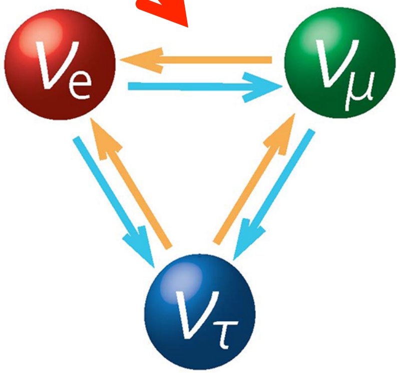
$\sum m_\nu < 0.23eV$

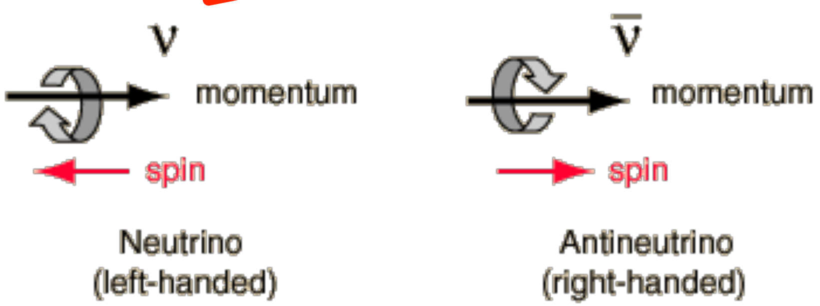
What we know

- Neutral charge, small mass
- Weak interaction
- At least three flavor ν_e, ν_μ, ν_τ
- Left-handed helicity
- Oscillation

involving the exchange of Z and W boson







Neutrino mass and hierarchy

At least two of the three masses are not zero

NH:

$$m_2 \geq \sqrt{\Delta m_{21}^2} \approx 8.6 \times 10^{-3} eV$$

$$m_3 \geq \sqrt{\Delta m_{31}^2} \approx 4.8 \times 10^{-2} eV$$

$m_1 < m_2 < m_3$

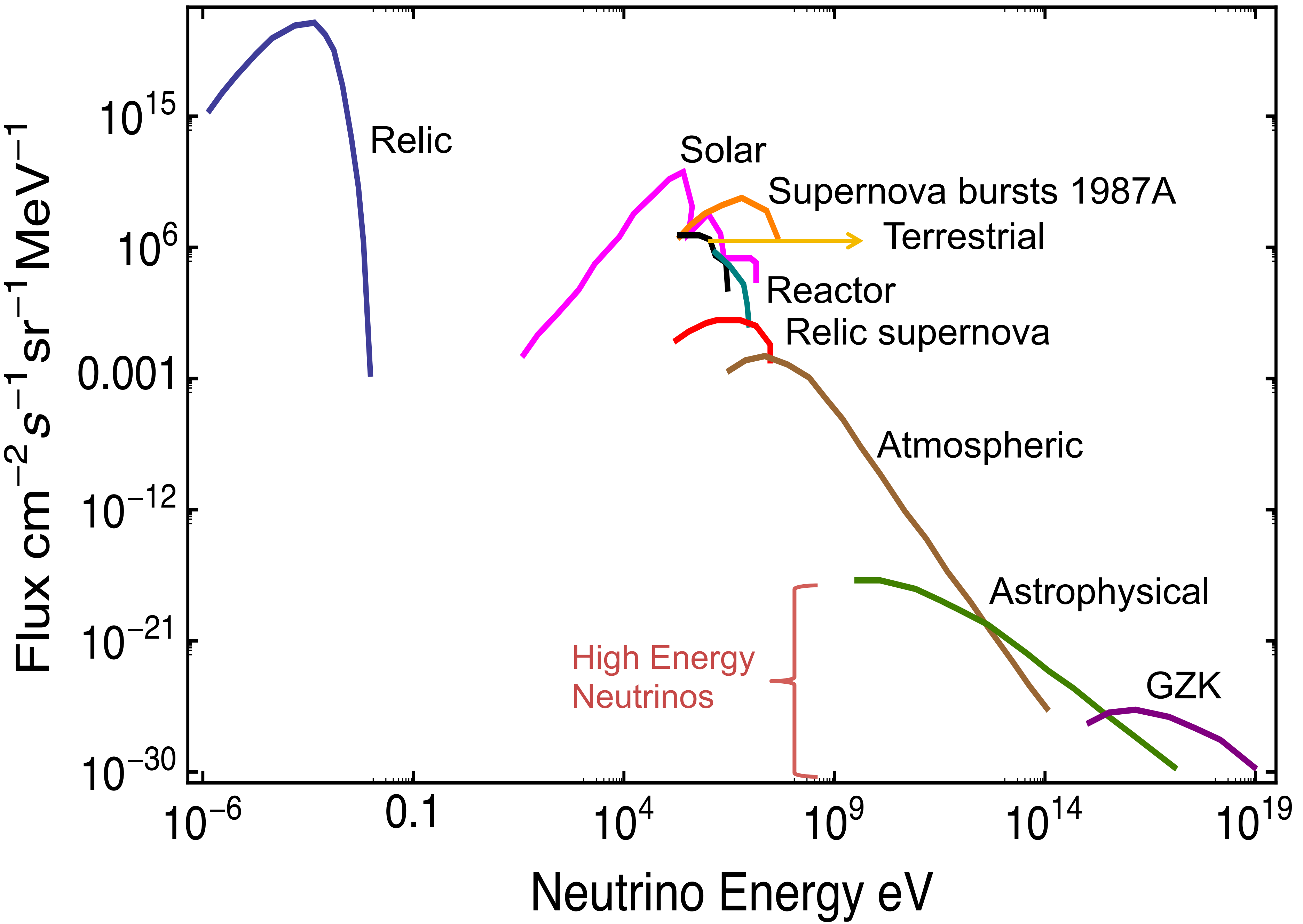
IH:

$$m_1 \sim m_2 \geq 4.8 \times 10^{-2} eV$$

$m_3 < m_1 < m_2$

Degenerate

$$m_1 \approx m_2 \approx m_3$$

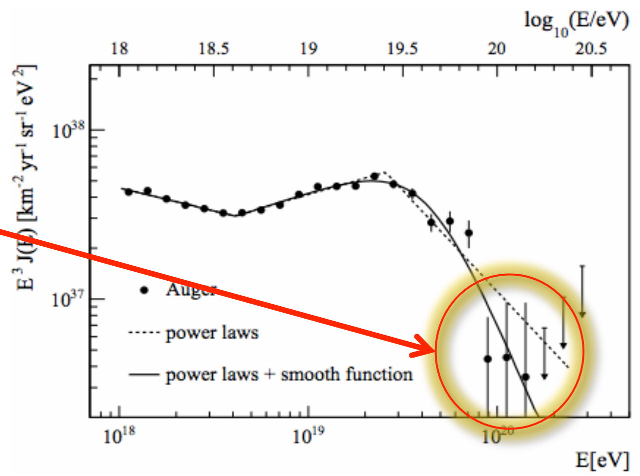


Flux cm^{-2}s^{-1}sr^{-1}MeV^{-1}
10^{15}
10^{6}
0.001
10^{-12}
10^{-21}
10^{-30}
10^{-6}
0.1
10^{4}
10^{9}
10^{14}
10^{19}
Neutrino Energy eV
Relic
Solar
Supernova bursts 1987A
Terrestrial
Reactor
Relic supernova
Atmospheric
Astrophysical
GZK
High Energy
Neutrinos

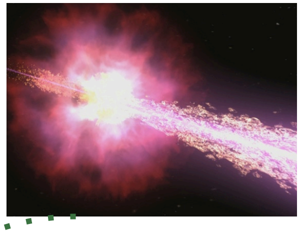
High Energy Neutrinos

- Neutrinos penetrate the whole Universe, point back to the source
- Particle acceleration mechanisms in astrophysical sources
- Neutrinos are produced at the sources of the cosmic rays
- Expected from dark matter annihilation
- Guaranteed GZK neutrino flux

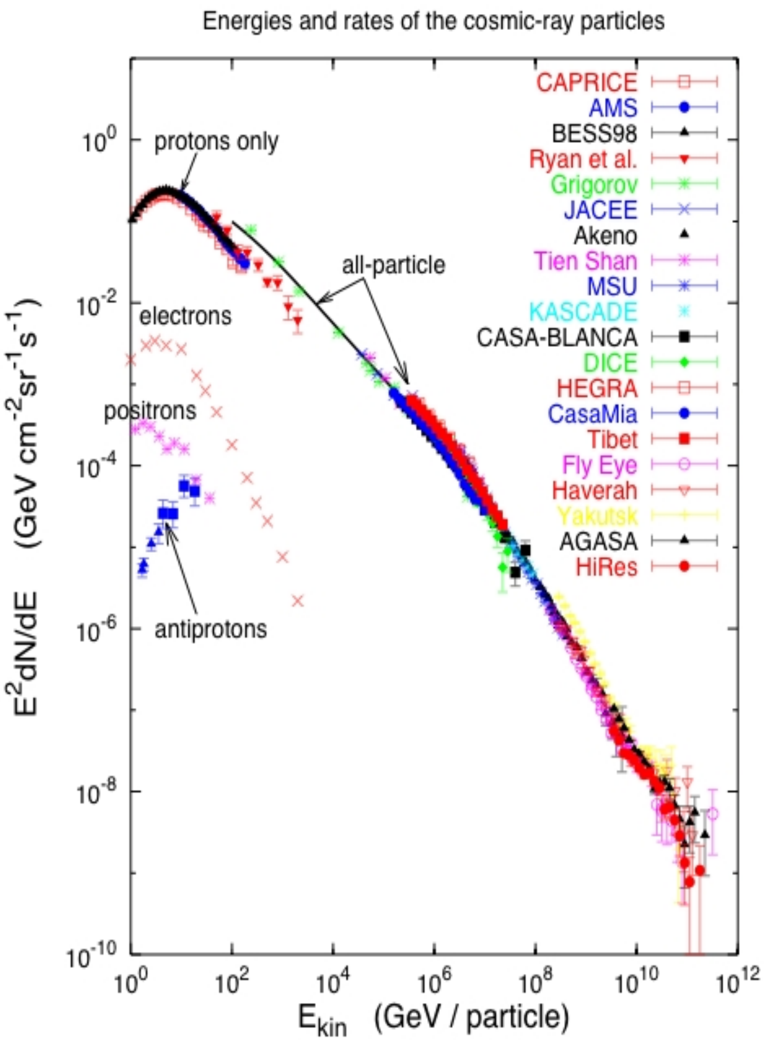
Where are they?



High Energy Neutrinos



Accelerators



p

CR-ν-γ

$$p+\gamma/p \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$

$$p+\gamma/p \rightarrow \pi^{0} \rightarrow \gamma+\gamma$$

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at source

↓

$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at earth

Flavor composition at the source

(Idealized – **energy independent**)

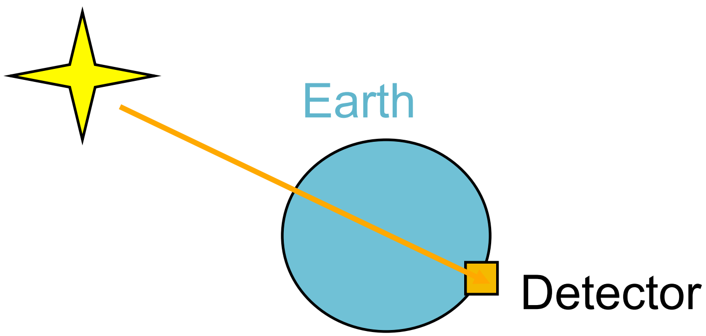
- Astrophysical neutrino sources produce certain flavor ratios of neutrinos (ν_e:ν_μ:ν_τ):
- Pion beam source (1:2:0)
  Standard in generic models
- Muon damped source (0:1:0)
  at high E: Muons lose energy before they decay
- Muon beam source (1:1:0)
  Cooled muons pile up at lower energies (also: heavy flavor decays)
- Neutron beam source (1:0:0)
  Neutron decays from pγ
  (also possible: photo-dissociation of heavy nuclei)

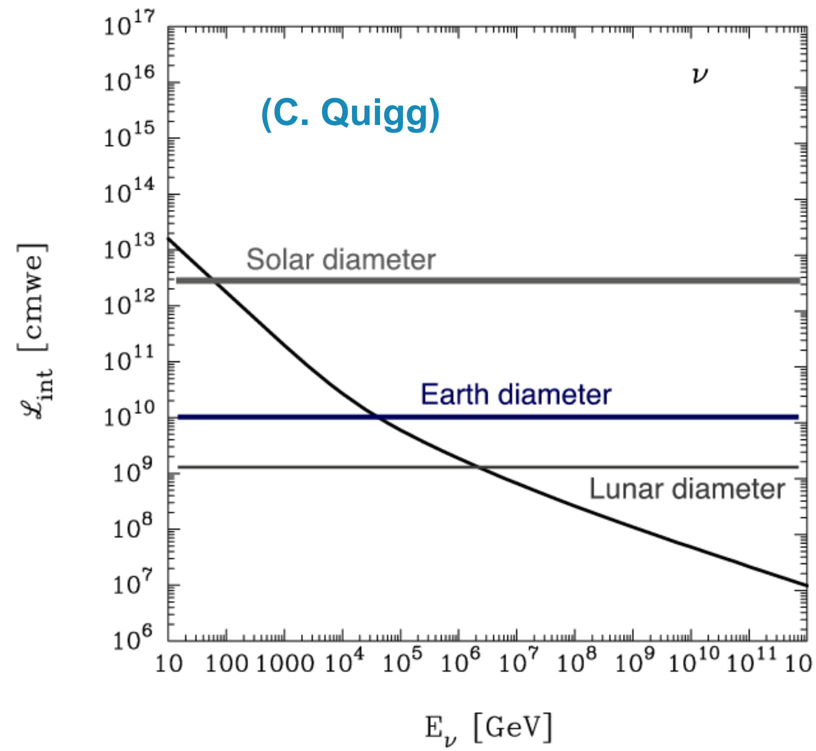
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

➢ At the source: Use ratio ν_e/ν_μ (nus+antinus added)

Earth attenuation

- High energy neutrinos interact in the Earth:

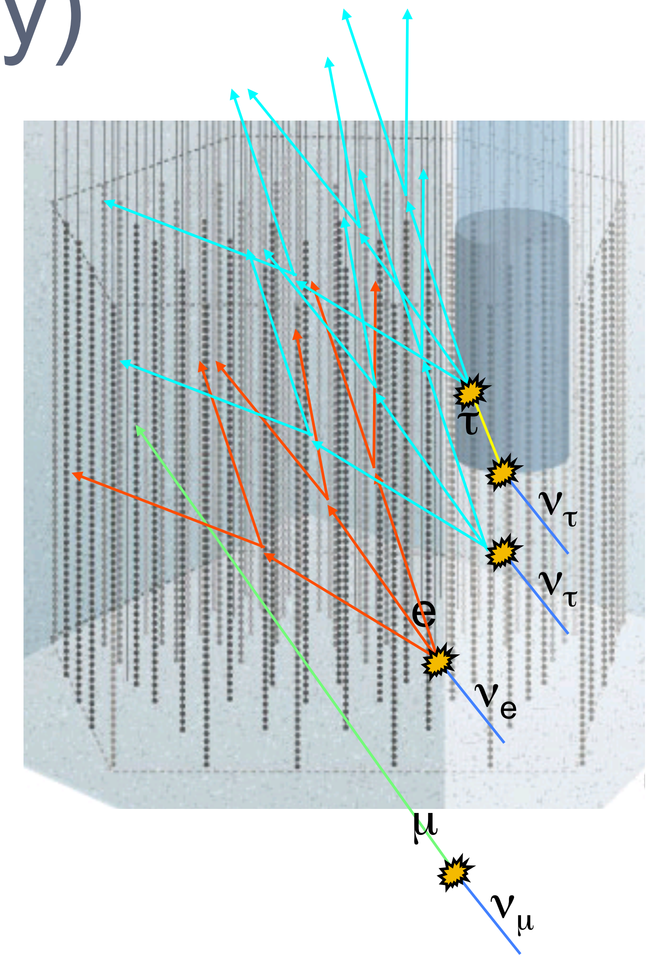




- However: Tau neutrino regeneration through ν_τ ⇨ τ ⇨ (17%) $\mu + \nu_\mu + \nu_\tau$

Neutrino detection (theory)

- Muon tracks from ν_μ
  Effective area dominated! (interactions do not have do be within detector)
- Electromagnetic showers (cascades) from ν_e
  Effective volume dominated!
- ν_τ: Effective volume dominated
  - Low energies (< few PeV) typically hadronic shower (ν_τ track not separable)
  - Higher Energies:
    ν_τ track separable
    - Double-bang events
    - Lollipop events
- Glashow resonace for electron antineutrinos at 6.3 PeV
- NC showers



(Learned, Pakvasa, 1995; Beacom et al, hep-ph/0307025; many others)

Waxman-Bahcall bound

- We know the spectrum of high-energy cosmic rays, and pγ interactions with ambient radiation—e.g. CMB photons — must occur and also produce pions, mainly via the Δ resonance, therefore we can calculate the expected neutrino flux from this source this is the Waxman-Bahcall bound
- assuming they are produced in cosmic accelerators together with
- the cosmic rays observed on Earth.

Waxman-Bahcall bound

- An energy spectrum $\propto E^{-2}$
- The sources of the high-energy protons are optically thin to photo-pion production and proton-nucleon interactions.
- The flux of cosmic rays observed on Earth is not affected by magnetic fields throughout the Universe.

Waxman-Bahcall bound

The energy production rate per volume of primordial cosmic ray protons can be expressed with production rate per volume $d\dot{n}/dE$

$$\dot{\varepsilon}_p = \int_{E_{\min}}^{E_{\max}} E_p \frac{d\dot{n}_p}{dE_p} dE_p$$

$$\frac{d\dot{n}_p}{dE_p} = AE_p^{-2} \Rightarrow \dot{\varepsilon}_p = A \ln(E_{\max}/E_{\min})$$

$$E_p^2 \left(\frac{d\dot{n}_p}{dE_p}\right) = \frac{\dot{\varepsilon}_p}{\ln(E_{\max}/E_{\min})}$$

Waxman-Bahcall bound

Now suppose that each proton loses some fraction η of its energy in pion production before it escapes from the source

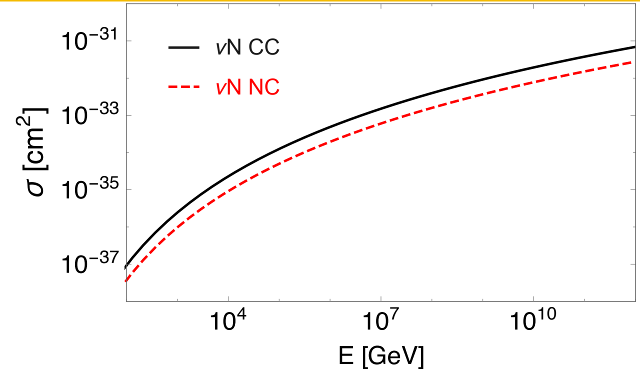
- roughly ¼ of that goes into neutrinos
- resulting neutrino energy density is

$$\dot{\varepsilon}_\nu = \frac{1}{4}\eta\dot{\varepsilon}_p$$

$$E_\nu^2 \frac{d\dot{n}_\nu}{dE_\nu} \ln(E_{\max}/E_{\min}) \cong \frac{1}{4}\eta\xi t_H E_p^2 \frac{d\dot{n}_p}{dE_p} \ln(E_{\max}/E_{\min})$$

$$E_\nu^2 \Phi_\nu = \frac{c}{4\pi}\frac{1}{4}\eta\xi t_H E_p^2 \left(\frac{d\dot{n}_p}{dE_p}\right) < 1.5\times10^{-8}\xi GeV/cm^2/s/sr$$

Neutrino Detection



Detection Techinique:

1) **Radiochemical Technique**

$$ {}_{N}^{A}Z + \nu_e \rightarrow {}_{N-1}^{A}(Z+1) + e^- $$

Unstable, and decays with a reasonably short halflife looking for the radioactive decay of the daughter nucleus.

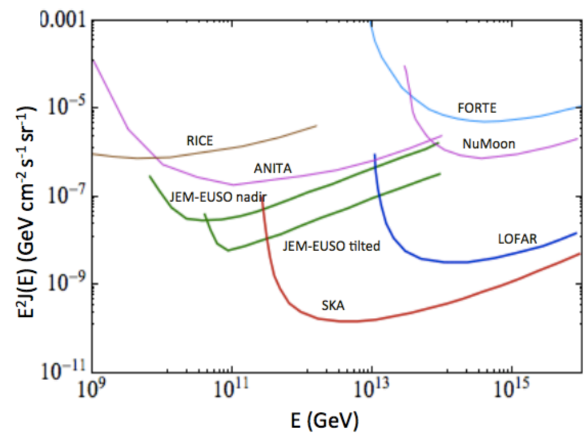
2) **Water Cherenkov Technique**

Super-Kamiokande

3) **Scintillation detectors**

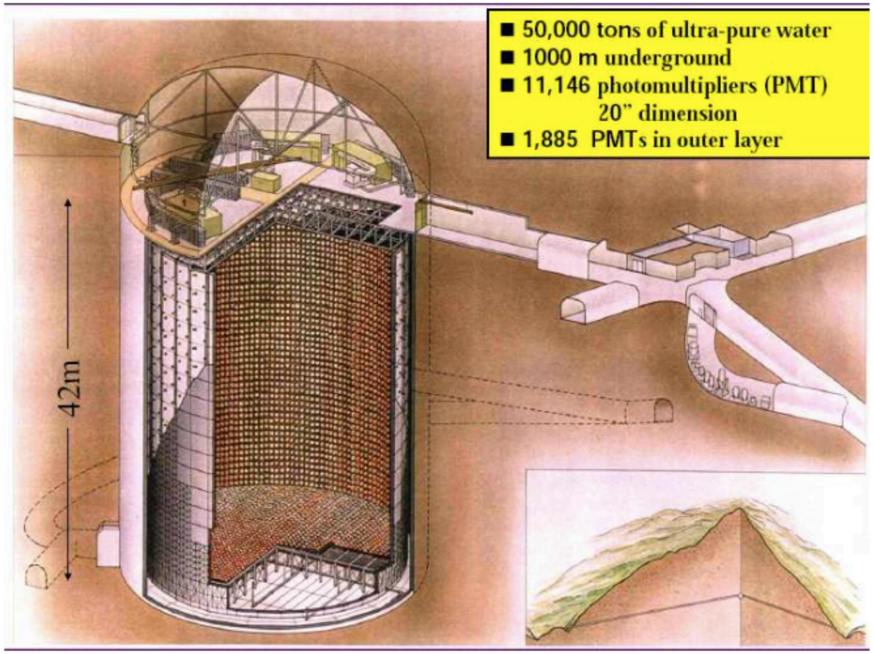
KAMLAND

4) **UHE neutrino detector**



Super-Kamiokande in Gifu, Japan

- **Total mass is 50kton and the fiducial mass is 22.5 kton.**
- **Inner detector: 11,146 20inch PMT**
- **Outer detector: 1,885 8inch PMT**



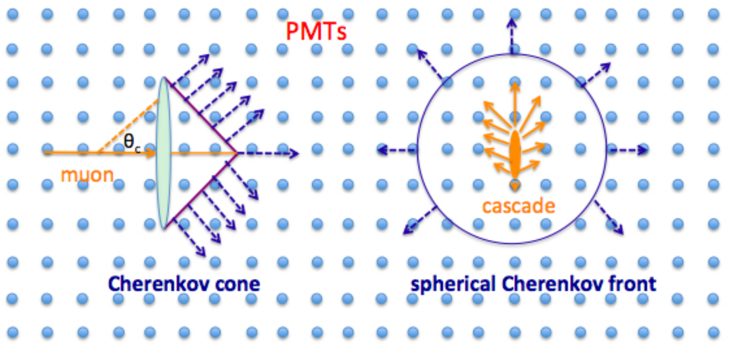
Super-Kamiokande in Gifu, Japan

Designed to observe the Cherenkov photons emitted from the secondary charged particles produced in neutrino interactions in water. Neutrinos observed in the Cherenkov detector interact in two ways: charged-current (CC) interaction, $v_l + N \rightarrow l + X$, (l presents the lepton flavor), the leading lepton would be detected; neutral-current (NC) interaction, e.g. the elastic scattering of neutrinos on electrons.

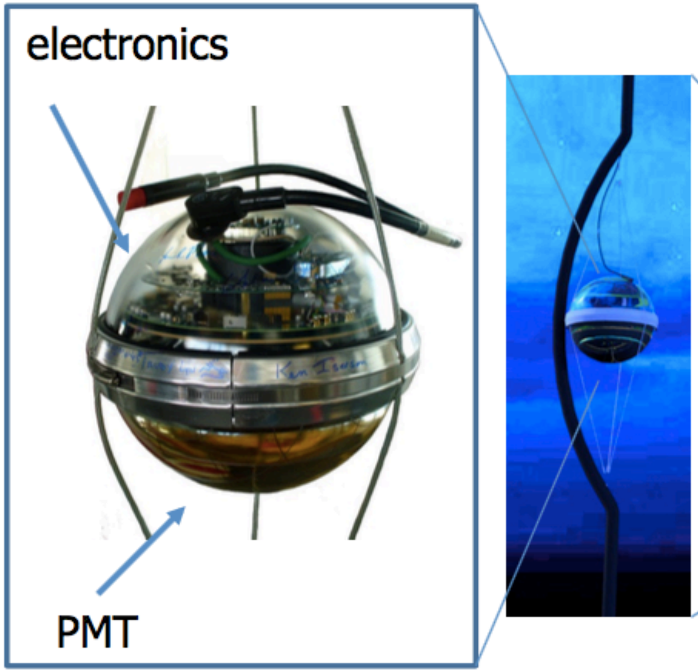
High-energy neutrino detection

- Neutrino interacts by either W exchange or Z exchange
  - W exchange produces charged lepton, which you detect
  - Z exchange at sufficiently high momentum transfer may cause hadronic shower (break-up of struck nucleon) which you also detect
- Detection is normally by Cherenkov radiation in water (ANTARES) or ice (IceCube)
  - for ultra-high-energy neutrinos use natural bodies of water/ice to get large effective volumes
    - Lake Baikal, Mediterranean Sea (ANTARES), South Pole (IceCube)
- Muons will leave track, electrons will shower
  - fairly good direction resolution (tenths of a degree) for ν_μ, but poor for ν_e; ν_τ OK if τ decay is seen (“double bang” event)

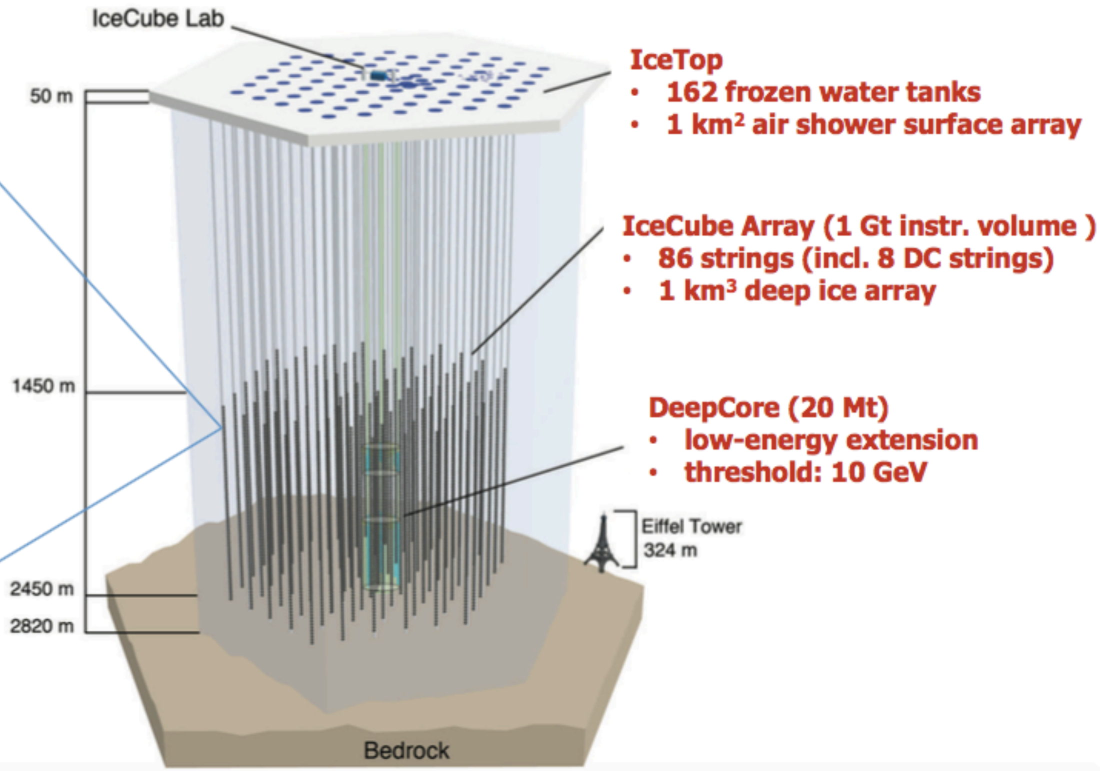
IceCube (AMANDA)

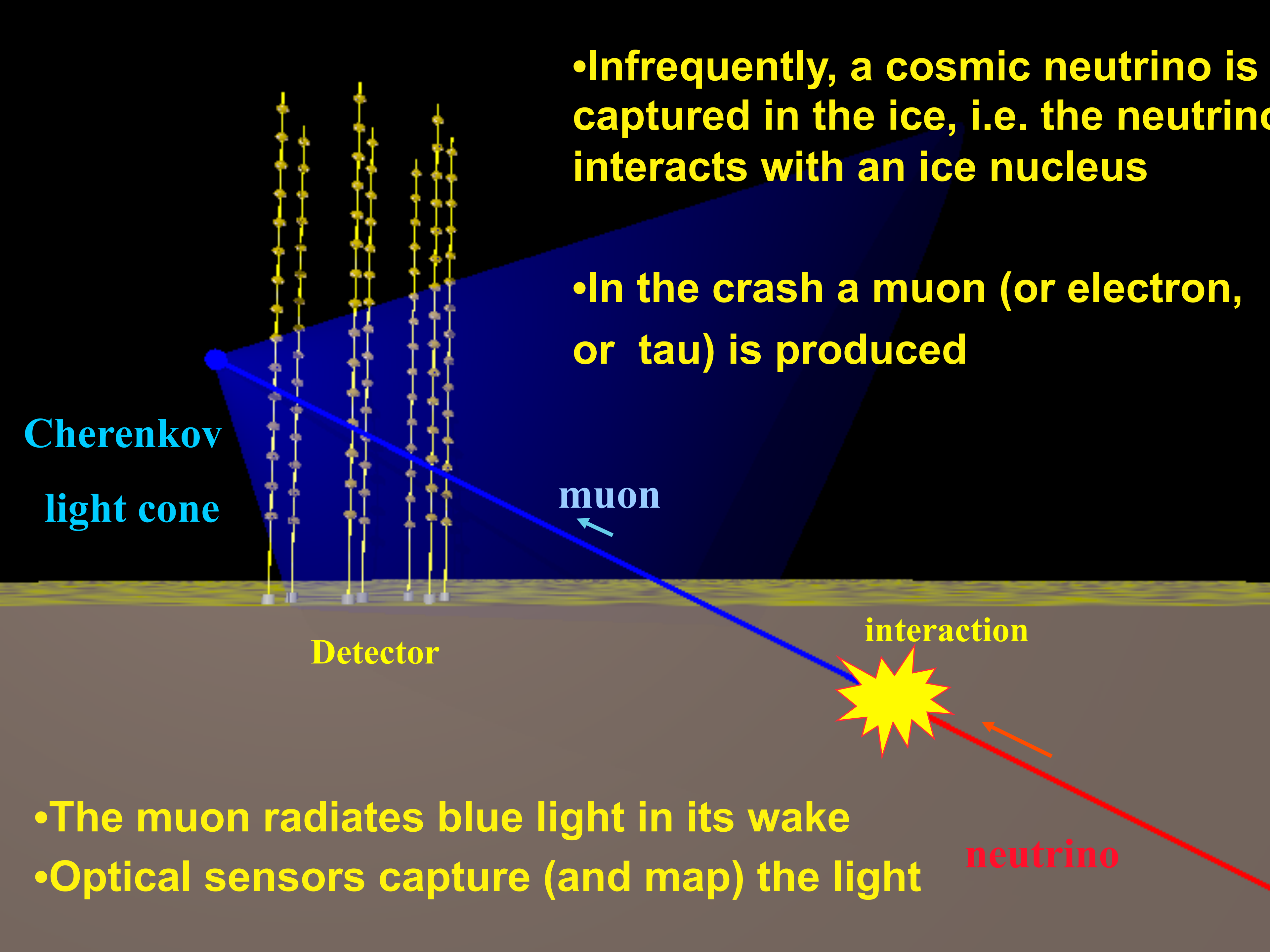


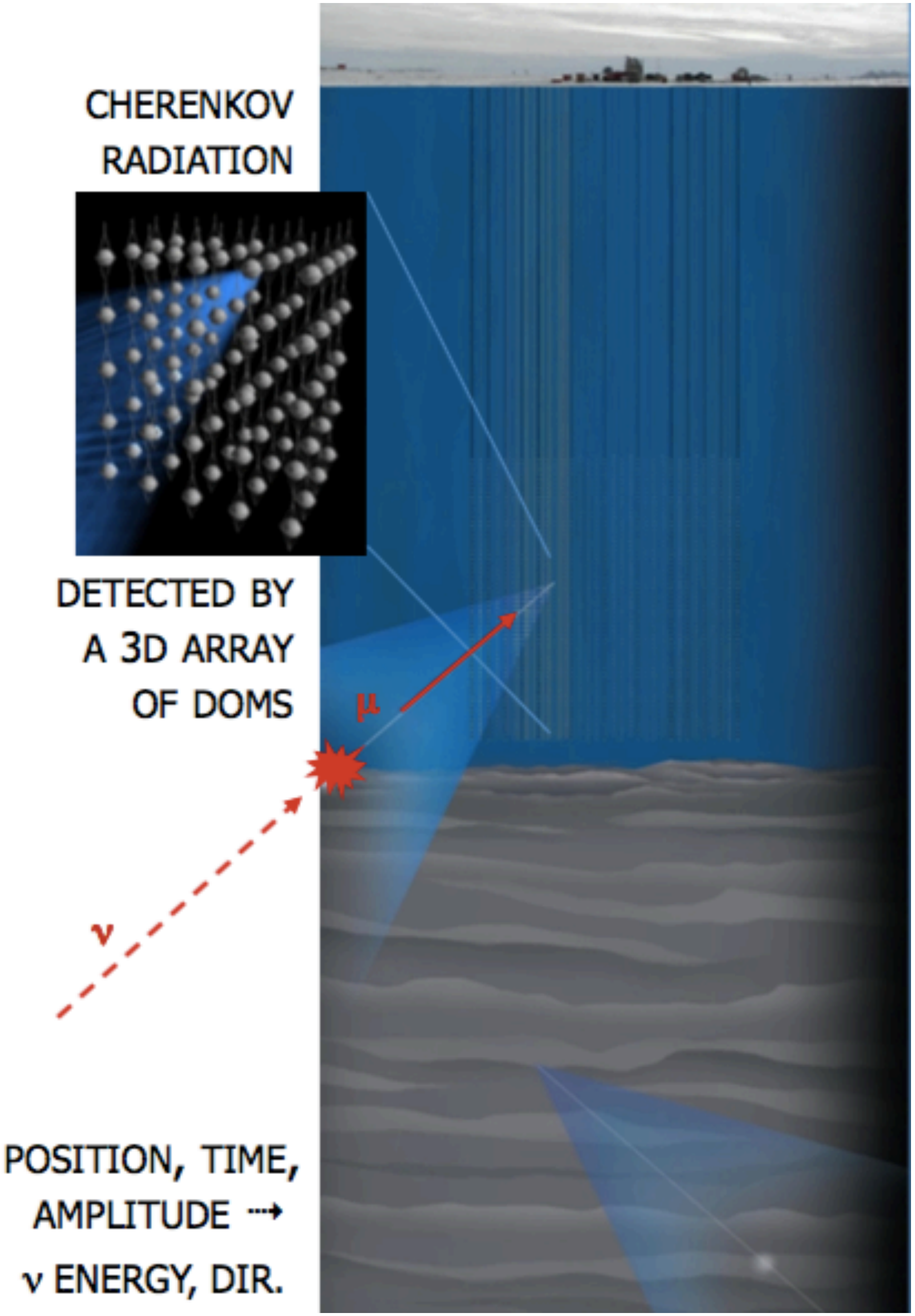
- 5160 Digital Optical Modules in deep ice
- 86 strings
- ~ 125 m between strings
- 60 DOMs per string, 17 m between DOMs

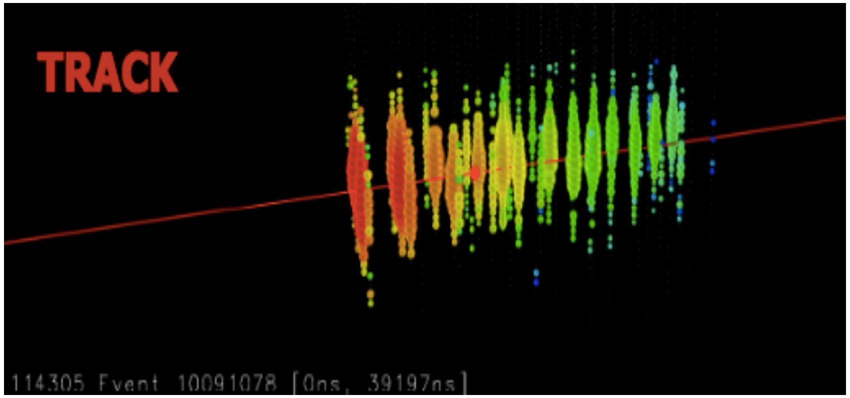


DIGITAL OPTICAL MODULE

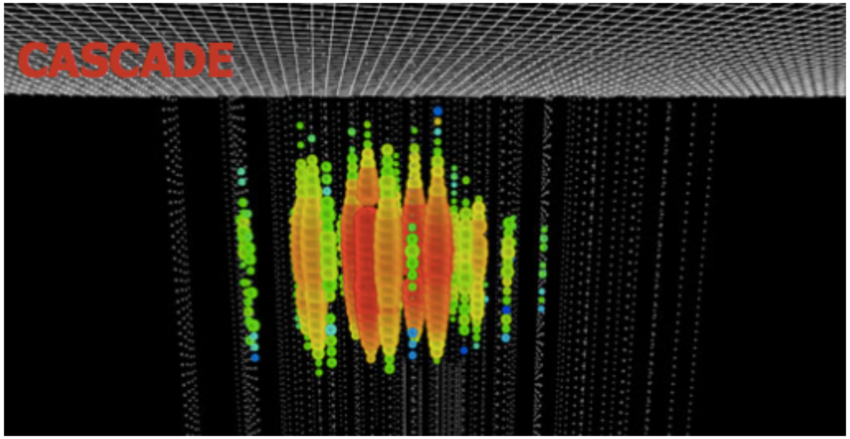



•Infrequently, a cosmic neutrino is
captured in the ice, i.e. the neutrin
interacts with an ice nucleus
•In the crash a muon (or electron,
or tau) is produced
Cherenkov
light cone
muon
Detector
interaction
neutrino
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light



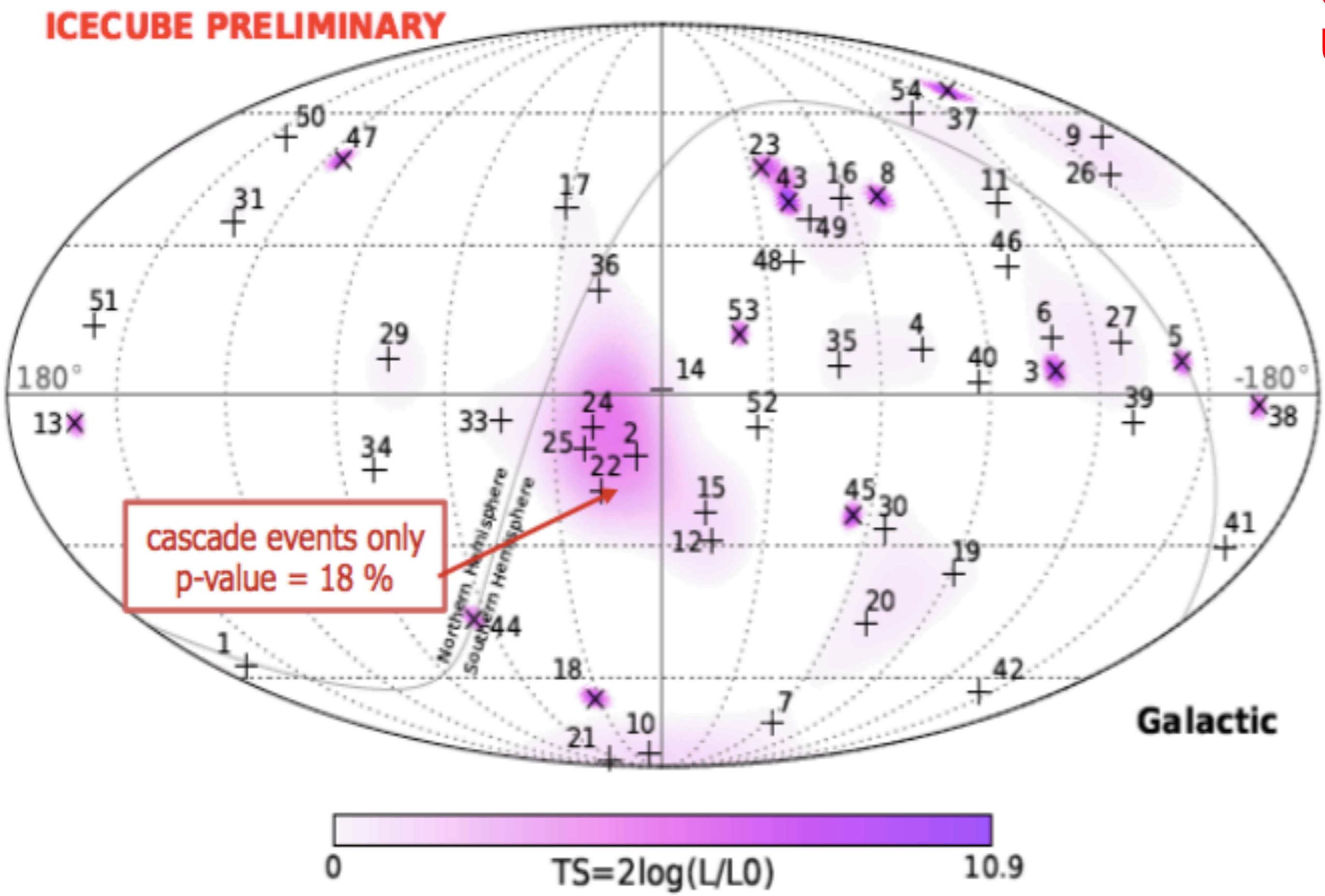


no direct E_ν measurement
angular resolution ~ 0.2--1°



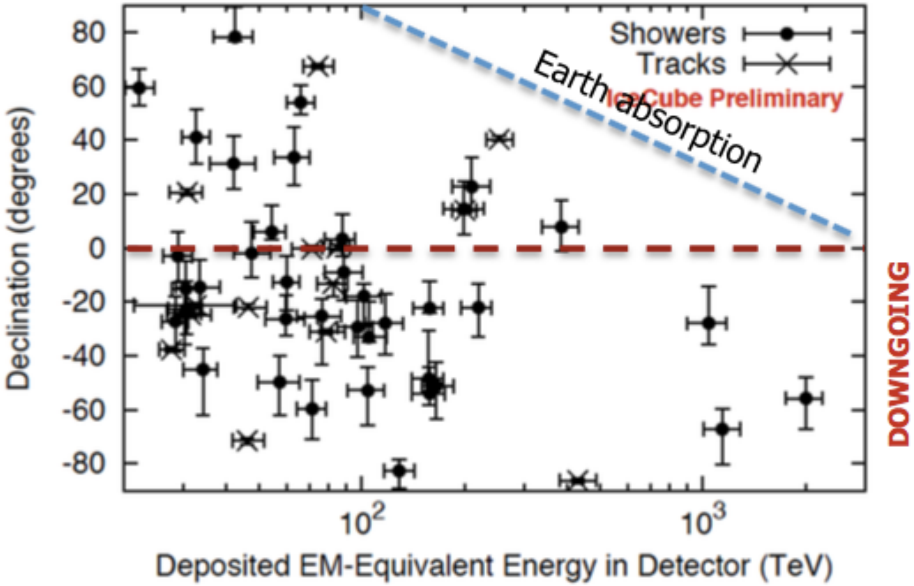
good E_ν measurement, resolution ~ 15%
decent pointing ang. resolution ~ 10--15°

OLGA BONTER
UPPSALA

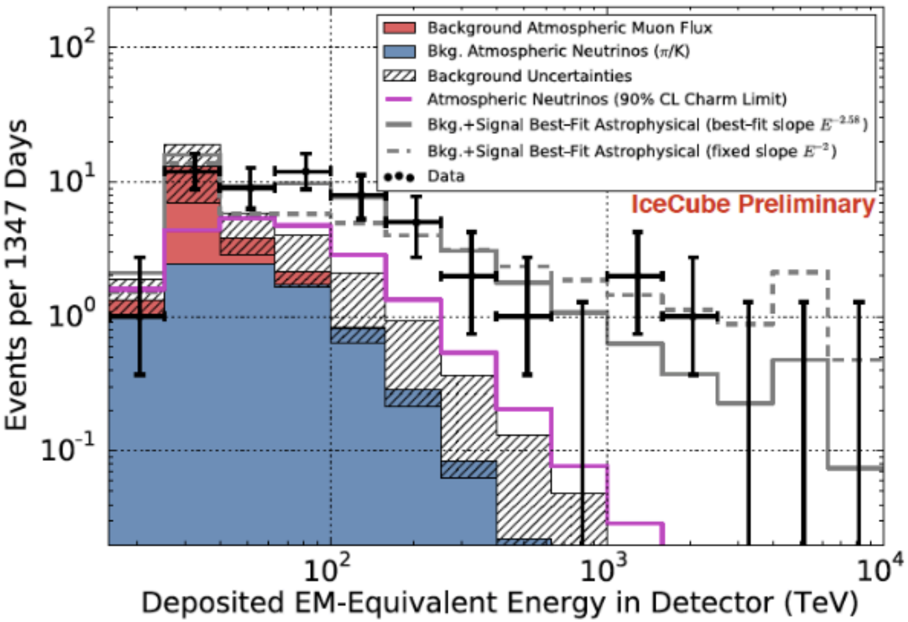


no significant correlations – spatial or temporal

- too few events to identify sources



4 yrs: 54 events mostly ν_e CC and NC cascades



FUTURE – ICECUBE-GEN2

- capitalize on the success – enhance the sensitivity of the existing detector

LOW ENERGIES

- dense in-fill subarray
- inside DeepCore

exploit the large flux of atm. ν's
for

- precise measurement of ν osc. param.
- determination of the ν mass ordering

also
– indirect searches for WIMP DM
at low energies

HIGH ENERGIES

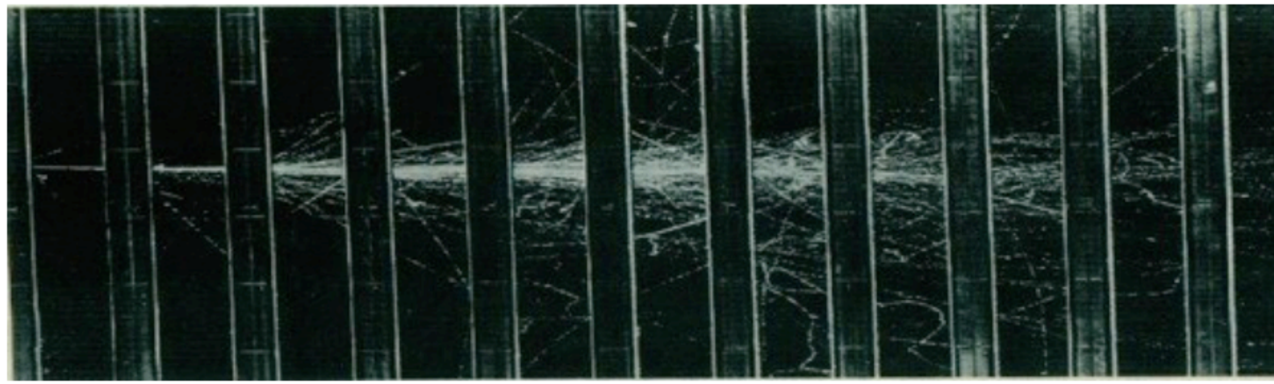
- widely spaced additional strings
- a large-area surface veto array

explore the unknown universe

- characterize the flux of the high-energy astrophysical ν's
- spectrum
- flavor composition
- identify cosmic sources

Askaryan Radio Array at the South Pole

$e^{\pm} or \gamma$



In dense material, $R_{Moliere}$~ 10cm:

When electron-gamma showers in matter, there will be 20% more electrons than positrons.

Compton scattering: $\gamma + e^-_{(at\ rest)} \rightarrow \gamma + e^-$

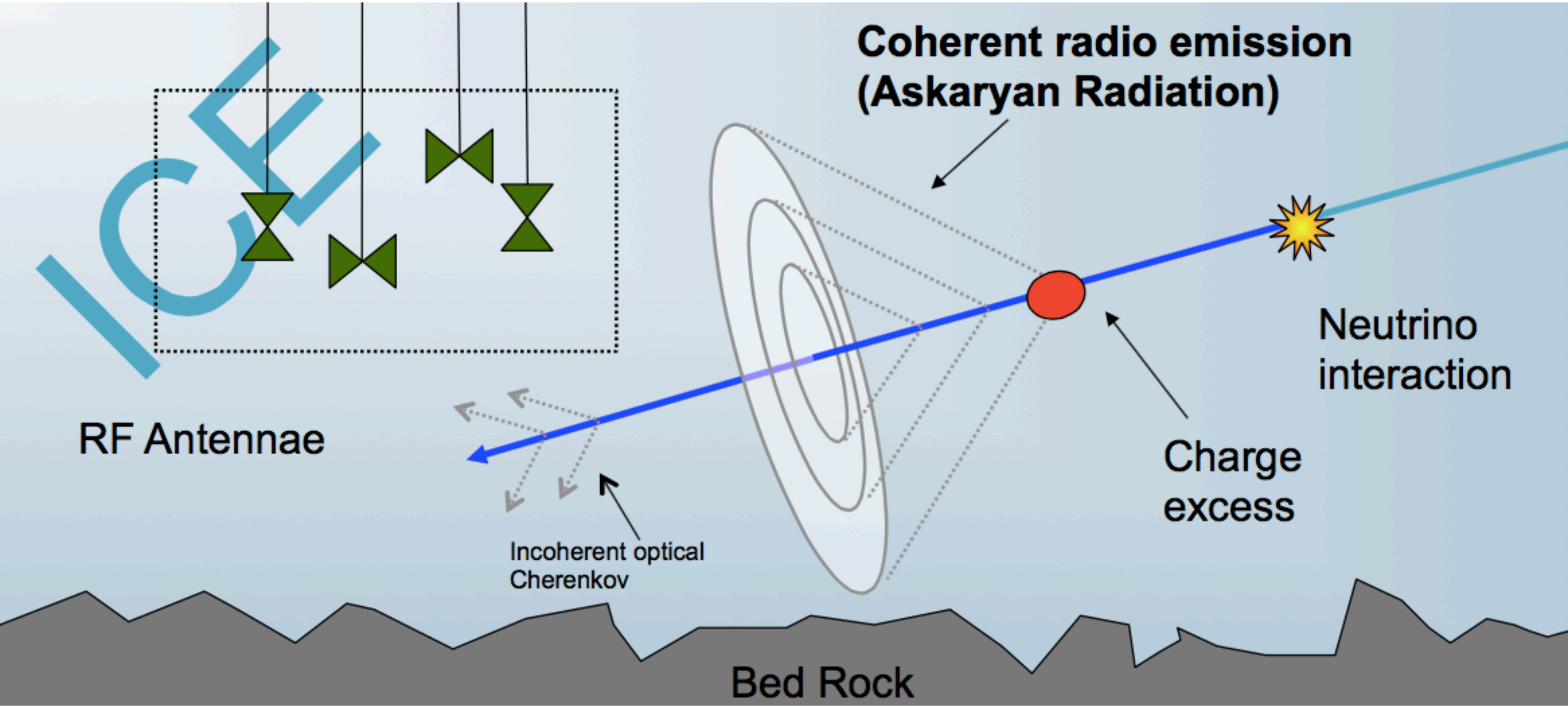
Positron annihilation: $e^+ + e^-_{(at\ rest)} \rightarrow \gamma + \gamma$

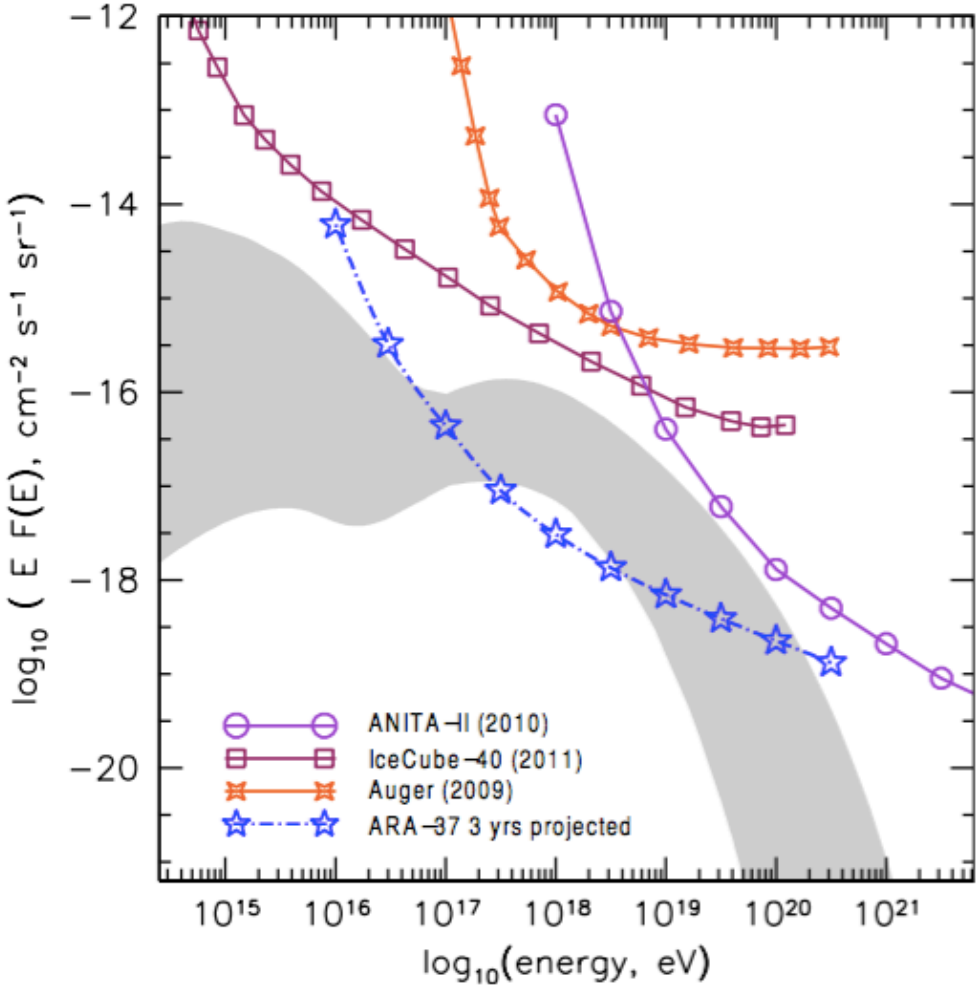
No radiation if exactly same amount of + and - charges

Coherent for $\lambda > R$

Askaryan Radio Array

Excess charge moving faster than speed of light will emit Cherenkov radiation.
In ice the peak frequency of radiation ~ 2 GHz (λ~15 cm).
The radiation is coherent ($\lambda_{rad} \geq$ lateral shower size) and power ~ E^2



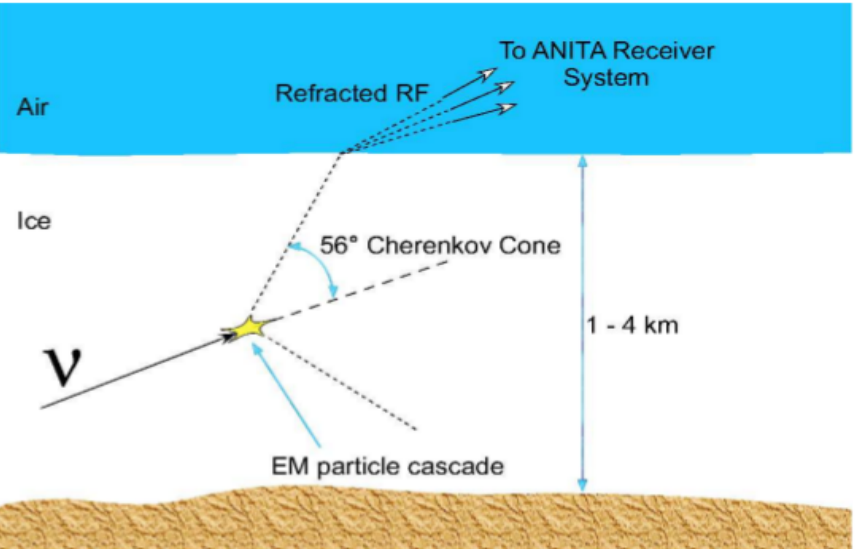


Prototype station has operated for 2 years

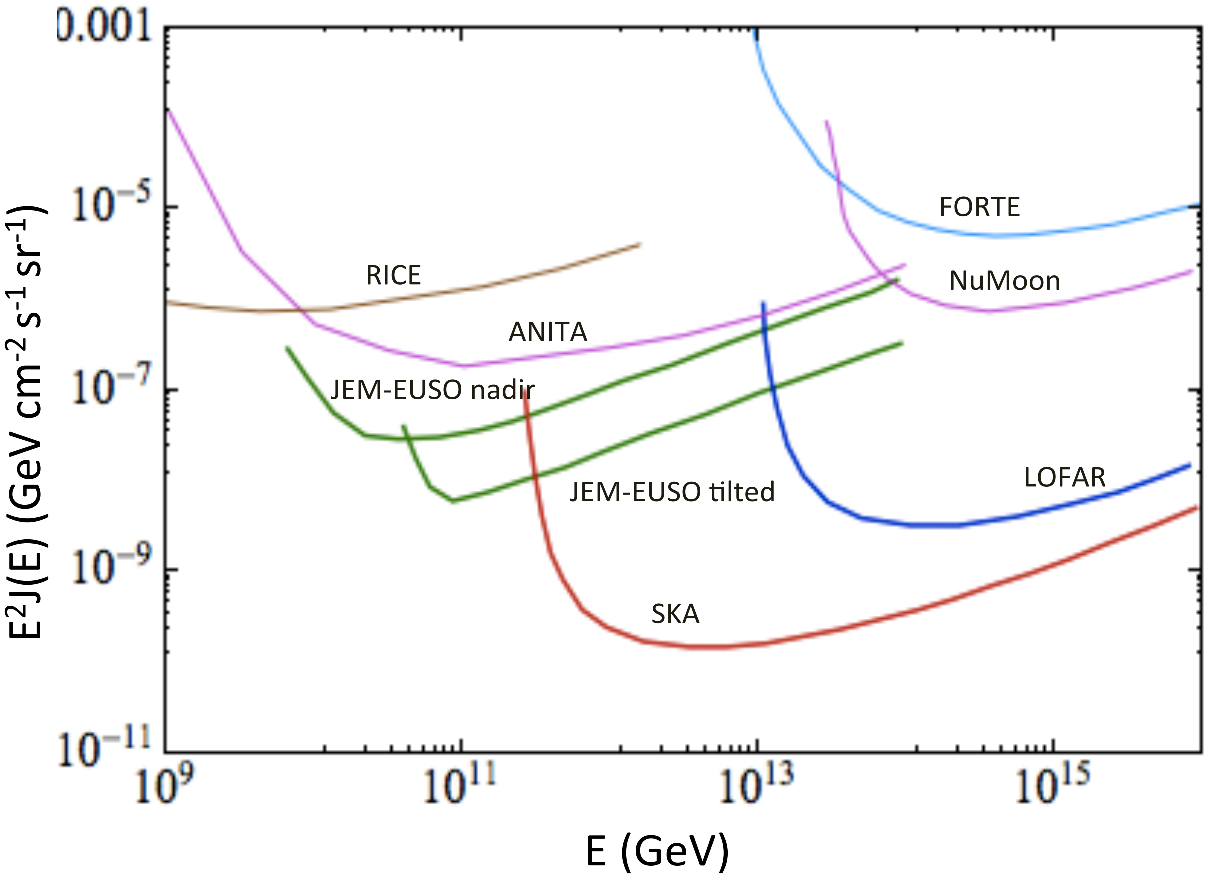
First 3 stations installed this past (austral) summer

Full ARA array improves sensitivity in peak flux region by 2 orders of magnitude

ARA could make the first measurements of GZK neutrinos



JEM-EUSO : space mission
NuMoon: lunar regolith
FORTE: ice of Greenland
ANITA, RICE: polar cap in Antarctica
LOFAR, SKA



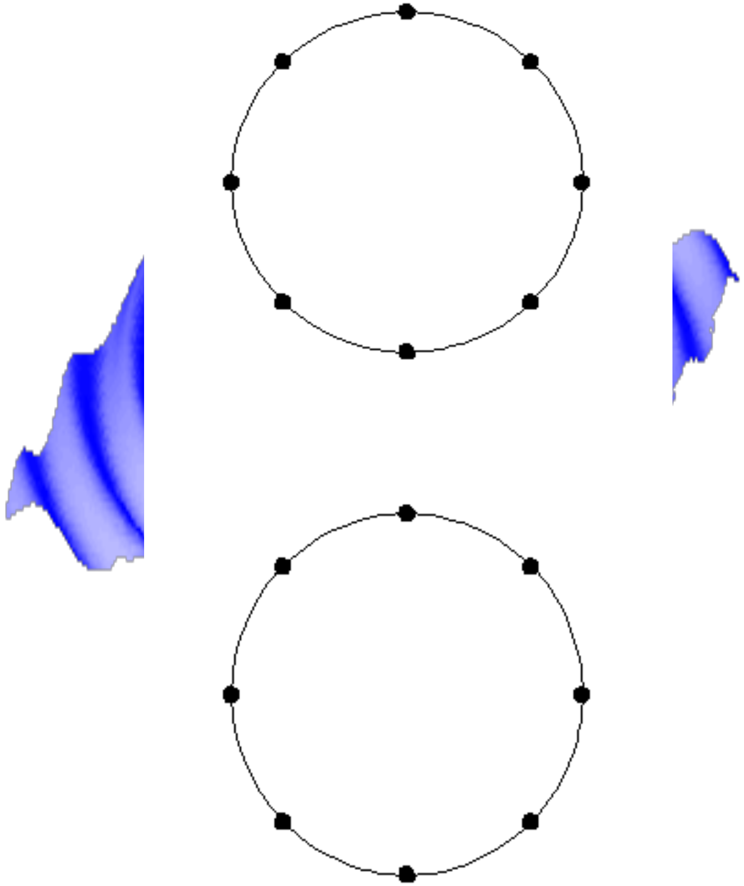
- High-energy astrophysical neutrinos are produced by $\pi^{\pm}$ decay
  - the pions come from CR proton interactions
- As neutrinos interact extremely weakly, very large detectors are required
  - natural bodies of water/ice instrumented with PMTs to detect Cherenkov radiation from produced leptons or hadronic showers
- The main background is atmospheric neutrinos also produced by CR interactions
  - penetrating CR muons also contribute
- There is a signal (from IceCube) but as yet no identified point sources

GRAVITATIONAL WAVE

What are Gravitational Waves?

- "Ripples in spacetime" – any rapidly moving mass generates fluctuations in spacetime curvature.
- These fluctuations propagate at the speed of light away from the source. These are gravitational waves!
- When a gravitational wave passes through, space is stretched and squeezed alternately. The effect is opposite in perpendicular directions.

Animation by William Folkner, LISA project, JPL



Electromagnetic vs Gravitational-waves

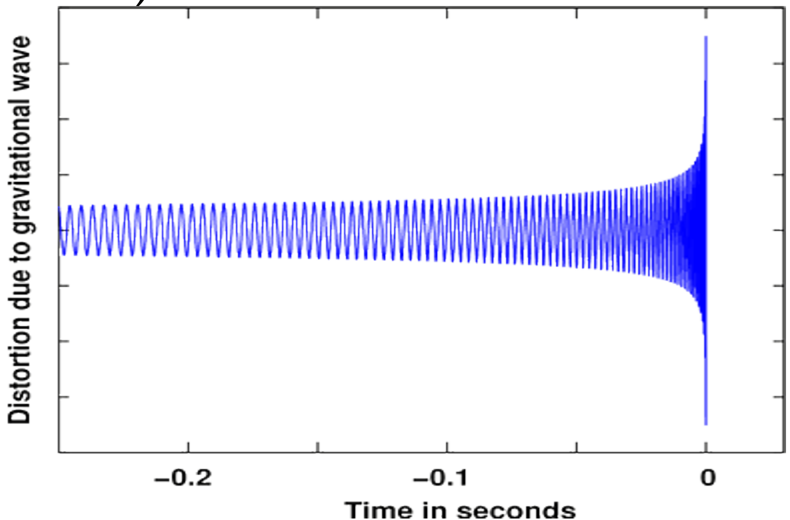
- EM waves are produced by accelerated charges, whereas GWs are produced by accelerated "masses".
- EM waves propogate through space-time, GWs are oscillations of space-time itself.
- Typical frequencies of EM waves range from (10^7 Hz – 10^{20} Hz) whereas GW frequencies range from ~ (10^{-9} Hz – 10^4 Hz). They are more like sound waves.

Sources of GWs

- **Inspiral sources**: Binary black holes, Binary Neutron stars (pulsars), Binary white-dwarfs or combination of these.

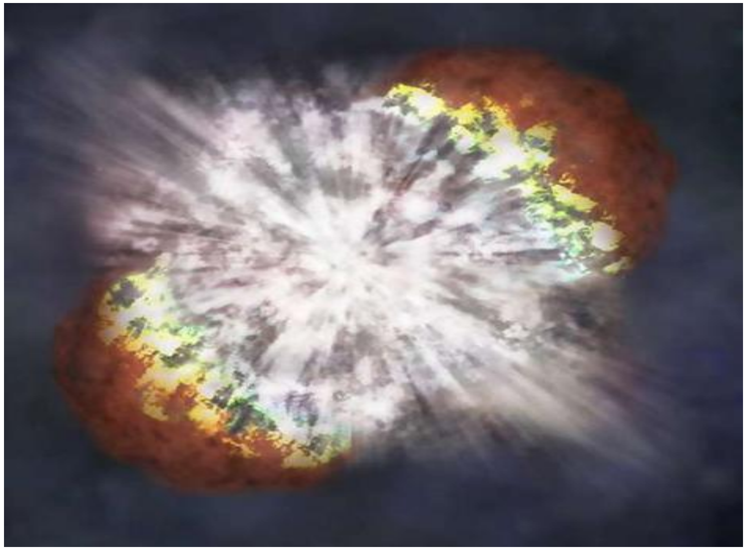
  As two stars orbit around each other, they steadily lose energy and angular momentum in the form of GWs.

  This makes the orbital separation to shrink slowly and they merge after some time (this time depends on their masses and orbital separation that we observe)

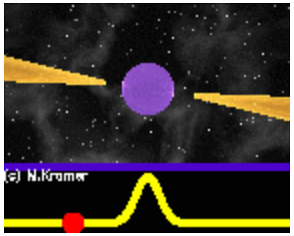


Sources of GWs

- **Exploding stars: Core collapse Supernovae**



- **Pulsars (rotating Neutron stars)**



- **Stochastic sources: Jumble of signals from lot of sources**

Detection of Gravitational-waves

- Ground based detectors:

  LIGO (U.S.A), VIRGO (Italy), GEO (Germany), TAMA (Japan), AURIGA (Australia)

- (Proposed) Space-based detectors:

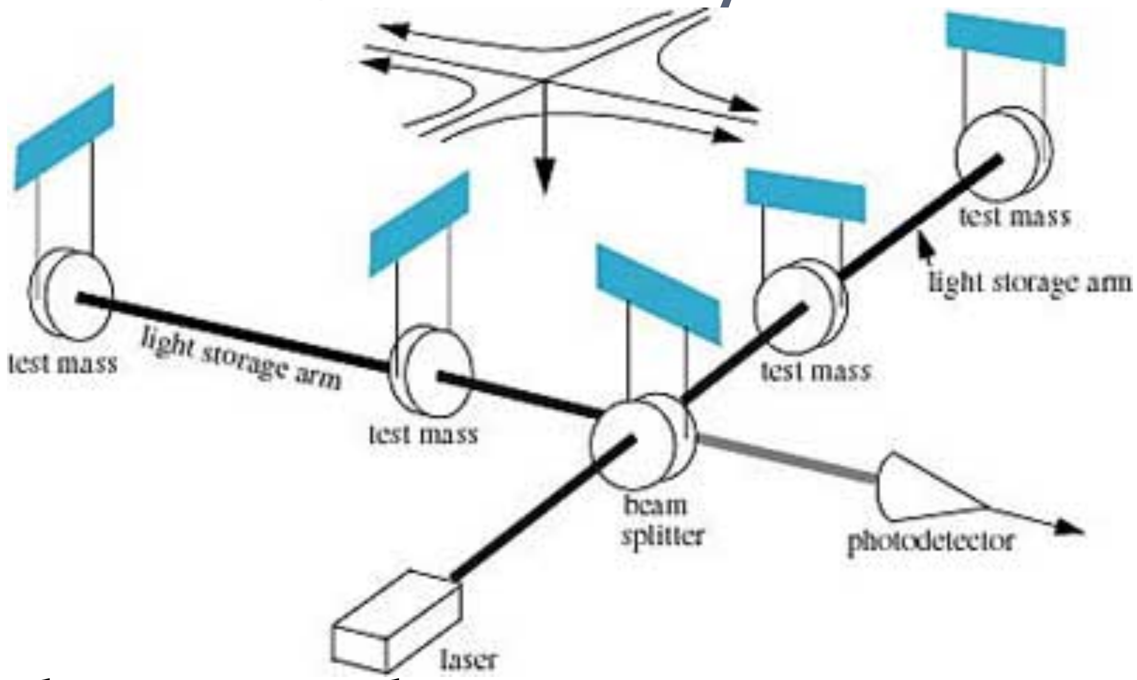
  LISA (NASA-ESA)

- Livingston, Louisiana Hanford, Washington

LIGO
Laser Interferometer Gravitational-Wave Observatory

*L*aser *I*nterferometer *G*ravitaional wave *O*bservatory

- LIGO



- Length of each arm, L = 4 km,
- frequency range , f = 10 Hz – 10^4 Hz
- $\Delta L \sim 10^{-18}$ meters, size of proton ~ 10^{-15} meters

Gravitational Waves

- Gravitational waves are one of the most interesting predictions of general relativity, and provide an unprecedented probe of extreme gravity environments in the Universe.
- There are many potential sources of gravitational waves for our detectors, ranging from binary star systems to supermassive black hole mergers to cosmic string cusps.
- We are on the verge of making our first direct gravitational wave detection. This should happen within 5-10 years, probably using Advanced LIGO.
- Once gravitational wave detections become routine, we stand to learn a great deal about systems that are inaccessible to electromagnetic telescopes.

Unkowns?

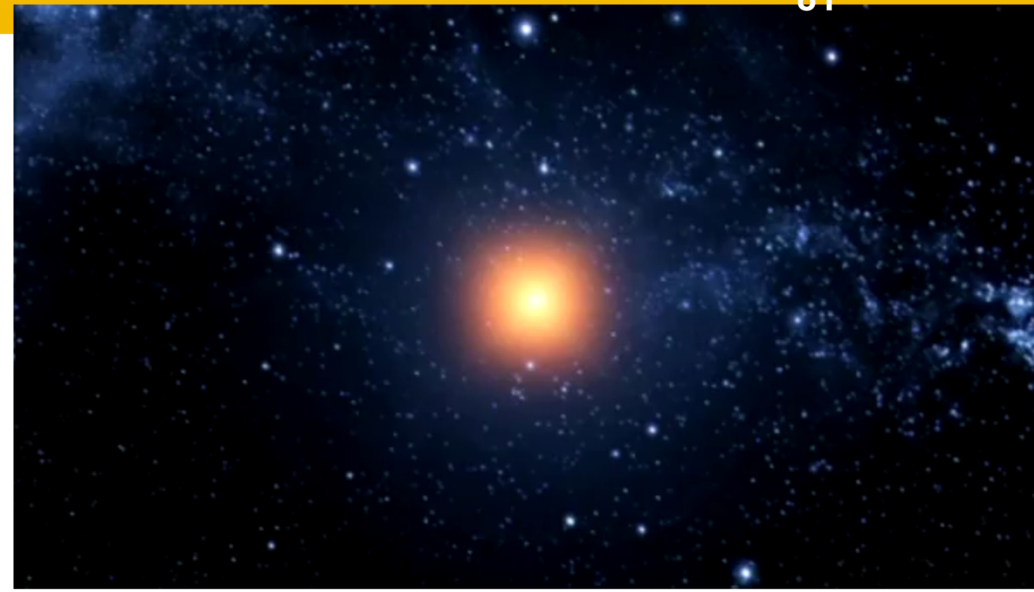
- ✓ The absolute scale of ν mass?
- ✓ The hierarchy, normal or inverted?
- ✓ If there are additional ν species?
- ✓ Dirac or Majorana?
- ✓ The three CP-violating phases?
- ✓ If νs have new interactions?

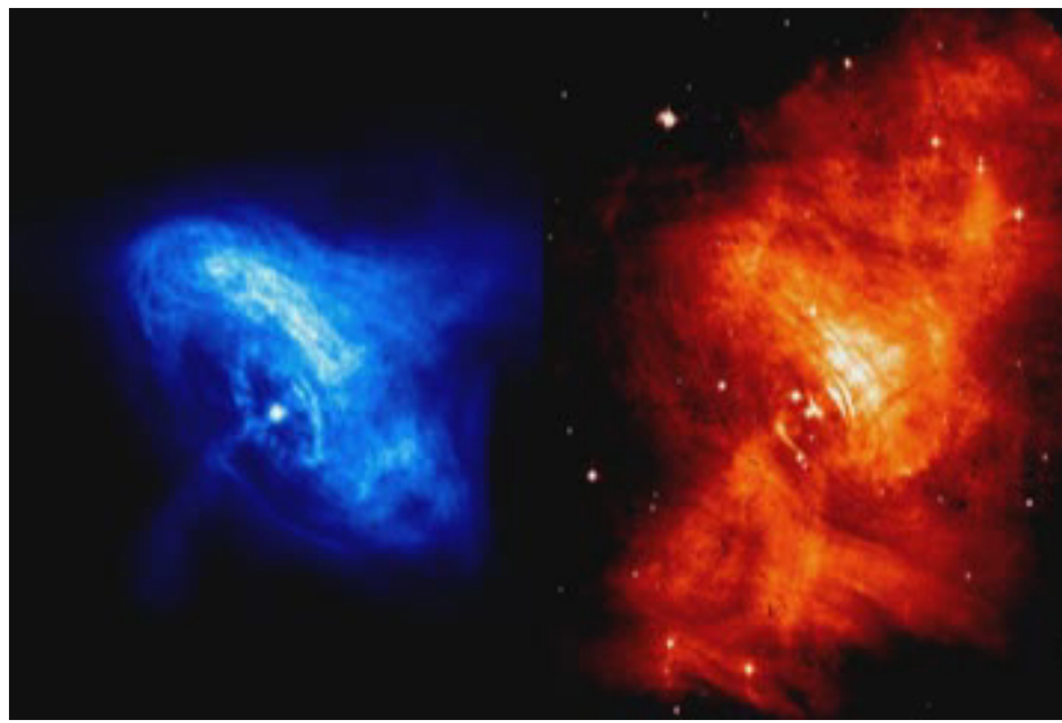
SUPERNOVAE

Core collapse supernovae (type II, Ib, Ic, not Ia)

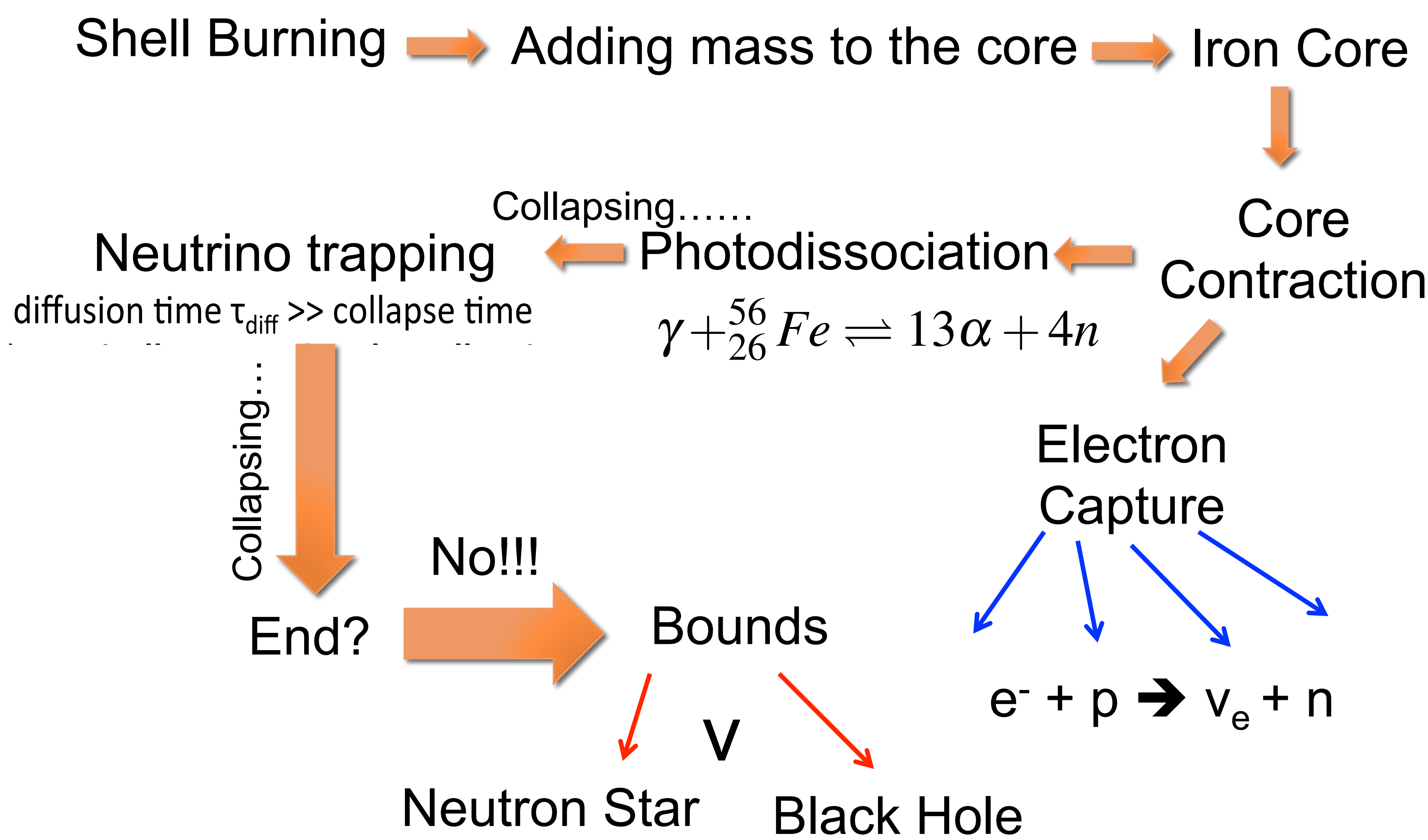
Stellar explosions

- Big stars may explode expelling 99% in neutrinos
- However two remains:
  - Expanding shell of shocked material (supernova remnant)
  - Dense object at the center (BH or pulsar)
- Place where CR are accelerated!





Supernova


Shell Burning
Adding mass to the core
Iron Core
Core Contraction
Collapsing……
Photodissociation
$\gamma + ^{56}_{26}Fe \rightleftharpoons 13\alpha + 4n$
Neutrino trapping
diffusion time τ_{diff} >> collapse time
Collapsing…
Electron Capture
$e^- + p \rightarrow \nu_e + n$
End?
No!!!
Bounds
V
Neutron Star
Black Hole

Classification of supernovae

No hydrogen			Early hydrogen	Hydrogen always present		
Si II	No Si II			Light curve		Narrow lines
	He	No He		Plateau	Linear	
Ia	**Ib**	**Ic**	**IIb**	**II-P**	**II-L**	**IIn**

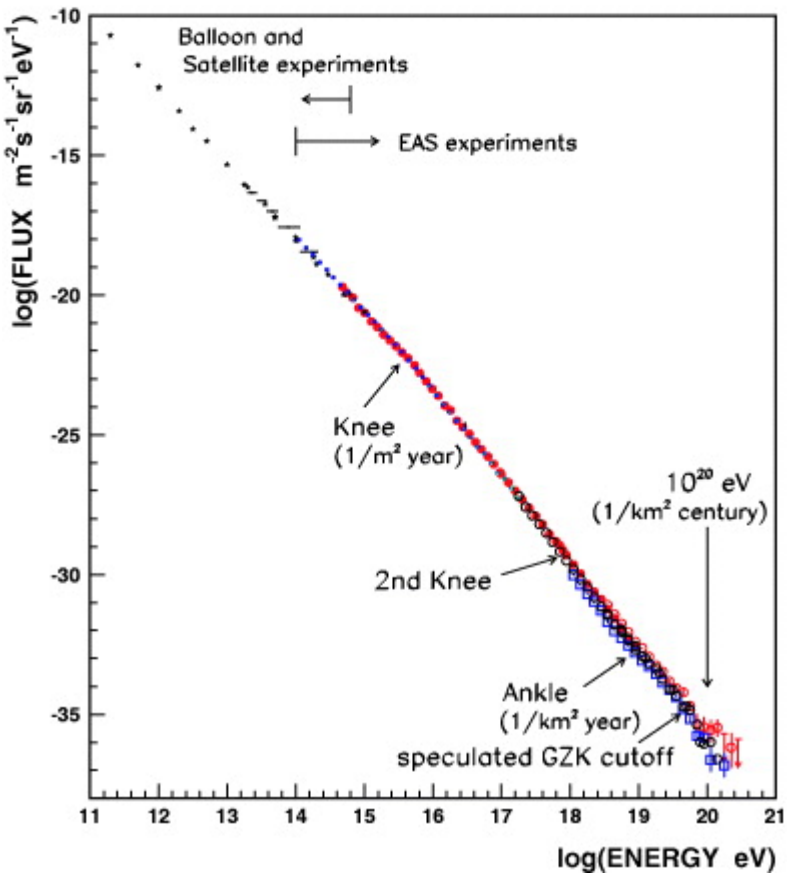
thermo-nuclear

massive star core collapse

All types of supernovae form supernova remnants (expanding shells of gas), but only CCSNe form compact objects (neutron stars/black holes)

Supernovae and supernova remnants

- Galactic SNRs are believed to be the source of cosmic rays up to the "knee" at ~10^{16} eV
- Rate of supernovae in Galaxy adequate to supply required energy if they are ~10% efficient in converting explosion energy to CRs
  - this is quite high but consistent with simulations of diffusive shock acceleration



Neutrino Emission

- Neutrino radiation is the most efficient mechanism of energy emission
- Rule of thumb: the most weakly coupled particle is the best cooling channel (least absorbed)
- Neutrinos are the most weakly coupled
- →most energy must be emitted in ν: star becomes colder by neutrino cooling

Neutrino Emission

- Luminosity ~ total energy budget
  – Energy emitted is of gravitational nature:
- $L_v \sim GM_f/R_f - GM_i/R_i \sim 3*10^{53}$ ergs (Rf ~ 10 Km)
- • Duration of neutrino burst ~ diffusion time
- – Time ~ (size^2)/(mean free path) ~ 10 s

Neutrino Emission

- Important deviation from flavor-democracy: different energy spectra
- $E_e < E_{anti\text{-}e} < E_x$ x=μ,τ,anti-μ, anti-τ
- Explanation:
- – Rule of thumb:the most strongly coupled particle decouples at lower density, where matter is colder --> colder spectrum
- ν_x have neutral current only: $\nu_x + n,p \rightarrow \nu_x + n,p$
- ν_e and anti-ν_e couple via neutral current and charged current : $\nu_e + n \rightarrow e^- + p$
- There are more n than p → ν_e more strongly coupled than anti-ve

Neutrino Emission

- A supernova is the only place in the modern universe with thermal neutrinos
- – Other places are not dense enough (m.f.p. ~ 1 light year of lead)
- – All other neutrino emitters are powered by different physics (fusion, fission, etc.)
- • Overwhelming luminosity:
- – $3*10^{53}$ ergs/10 s ~ 10^{18} L_{sun}
- – Optical SN luminosity is minor (10^{-2} L_{ν}), a SN is essentially a neutrino event

Diffuse supernova neutrino background

- Diffuse supernova neutrino flux (DSNF) in a detector:
-

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{\max}} R(z) F_{\bar{e}} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

Supernova Rate

Neutrino flux from single source

Diffuse supernova neutrino background

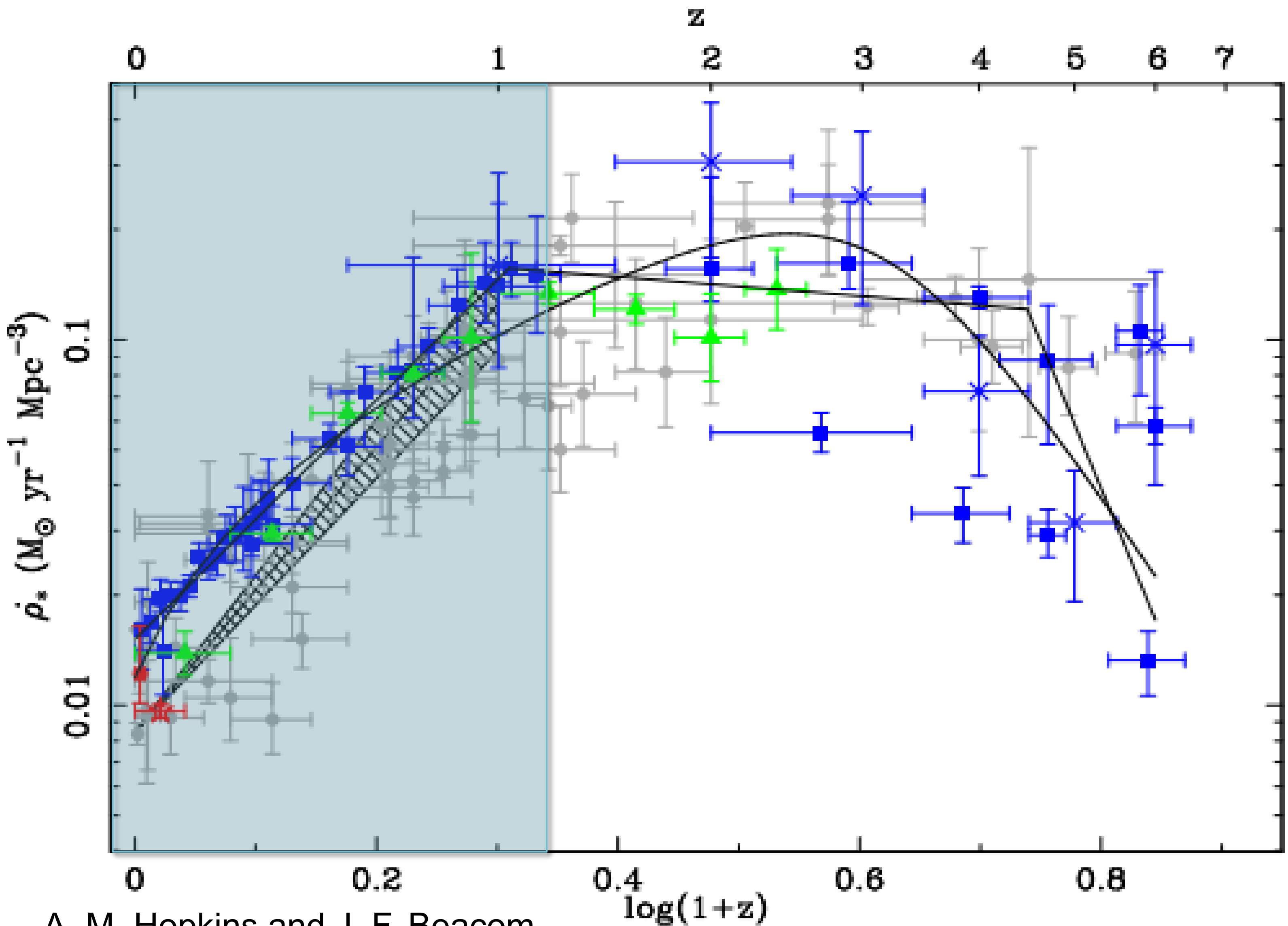
- The neutrino spectrum of each species w obtained by Monte Carlo simulation by Keil et. al (2003, Astrophys. J. 590, 971)

$$F_w^0 = \frac{dN_w}{dE} \cong \frac{(1+\alpha_w)^{1+\alpha_w} L_w}{\Gamma(1+\alpha_w) E_{0w}^2} \left(\frac{E}{E_{0w}}\right)^{\alpha_w} e^{-(1+\alpha_w)E/E_{0w}}$$

- After oscillation,

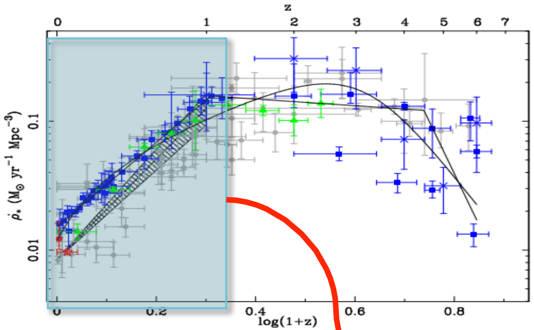
$$F_{\bar{e}} = \bar{p} F_{\bar{e}}^0 + (1-\bar{p}) F_x^0 \qquad x=\mu,\ \tau$$

Star Formation Rate

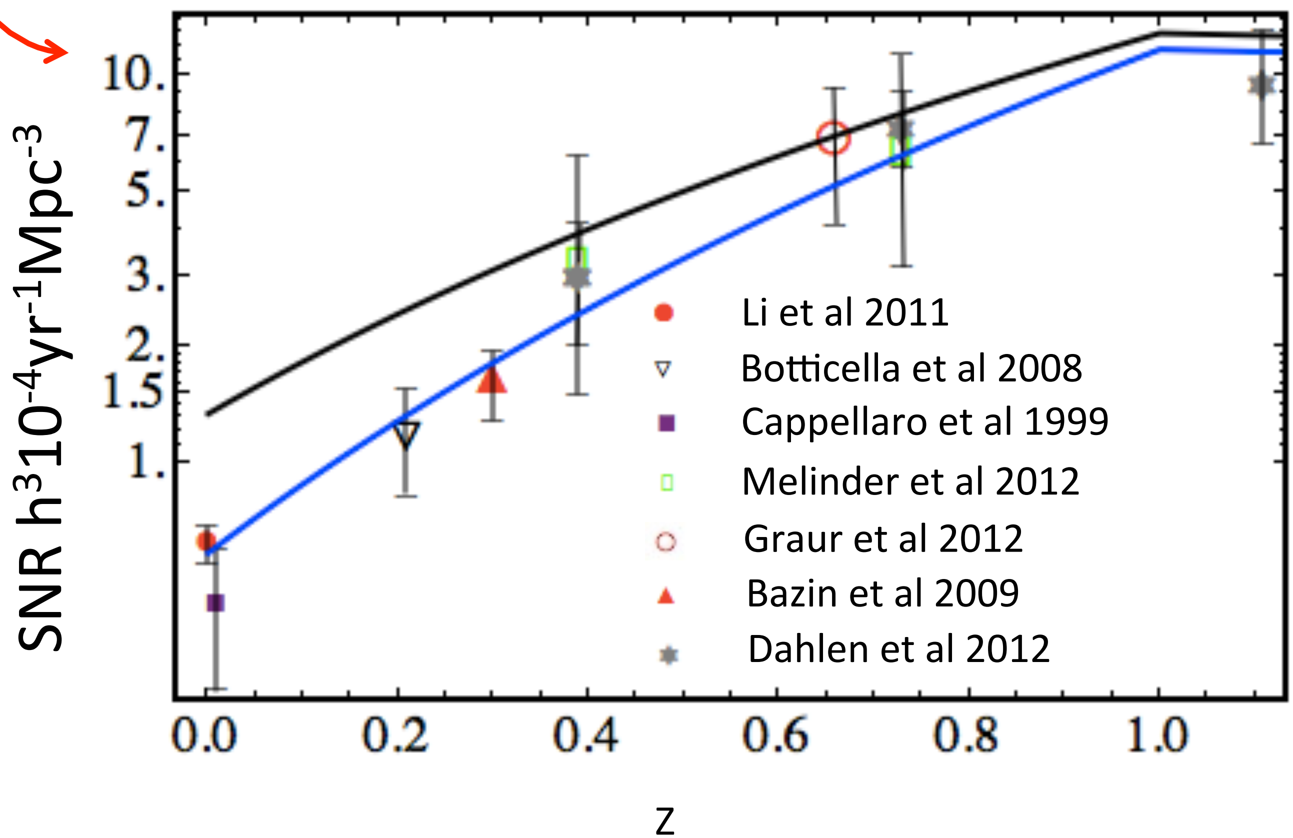


A. M. Hopkins and J. F. Beacom, Astrophys. J. 651, 142 (2006)

Cosmological supernova rate



A. M. Hopkins and J. F. Beacom, Astrophys. J. 651, 142 (2006)



Diffuse supernova neutrino background

Normal Hierarchy

$\Phi/cm^{-2}s^{-1}$	E>19.3 MeV	E>17.3 MeV	E>11.3 MeV
99% C.L.	0.07-0.37	0.11-0.55	0.52-2.37

The predicted flux of electron antineutrino in a detector above 11.3, 17.3, 19.3 Mev, in the interval of 99% C.L.

Up to 30MeV

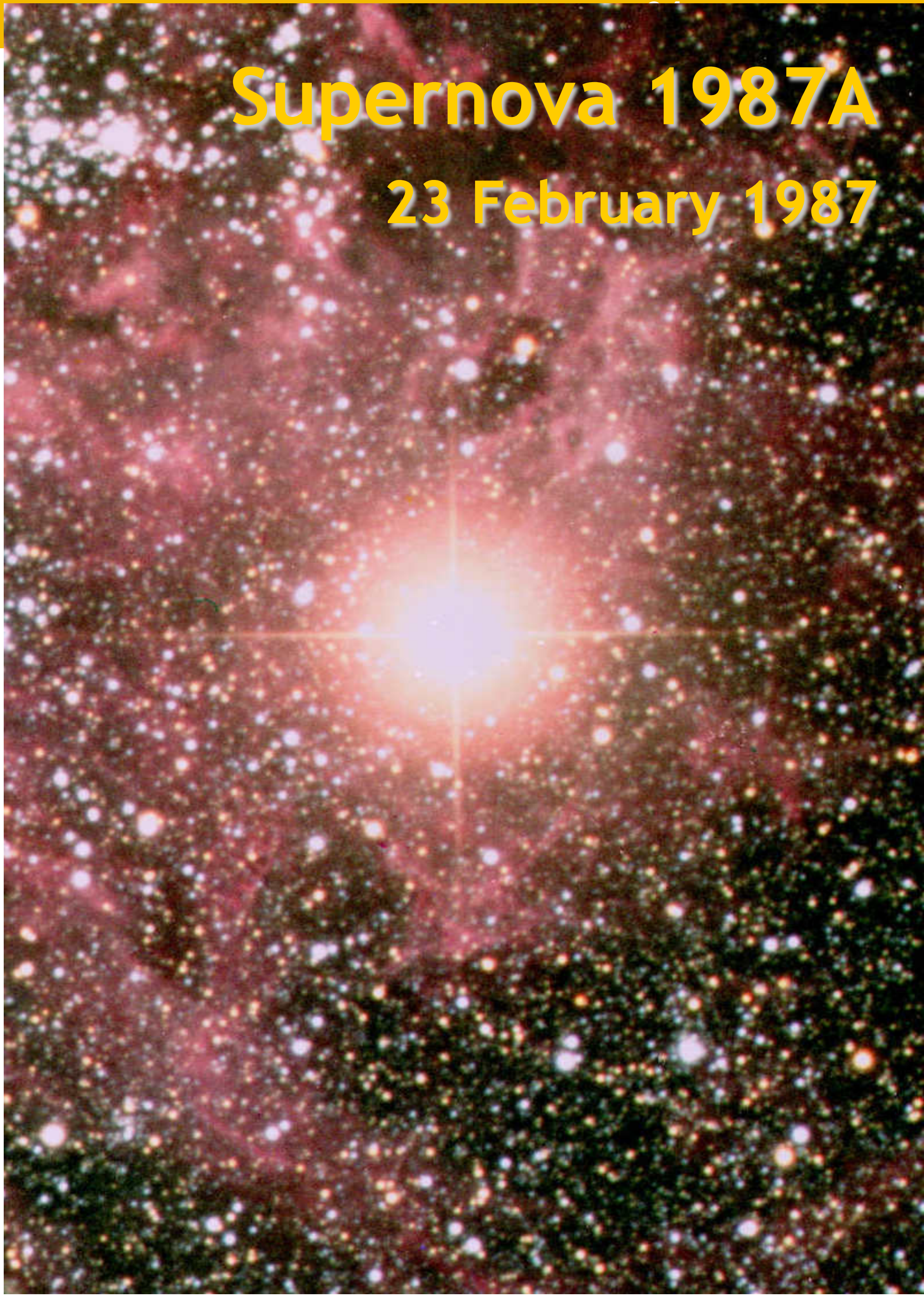
	Best Fit	68% C.L.	90% C.L.	99% C.L.	Atm. Bg
NH	18.8	14.9-23.7	11.1-30.1	7.28-40.5	12
IH	14.8	11.8-19.9	8.60-21.3	5.88-31.3	12

The predicted event rate for a 1Mton water Cherenkov detector above 17.3 MeV, in the point of maximum likelihood and in the intervals of 68, 90, 99% C.L

SN1987A

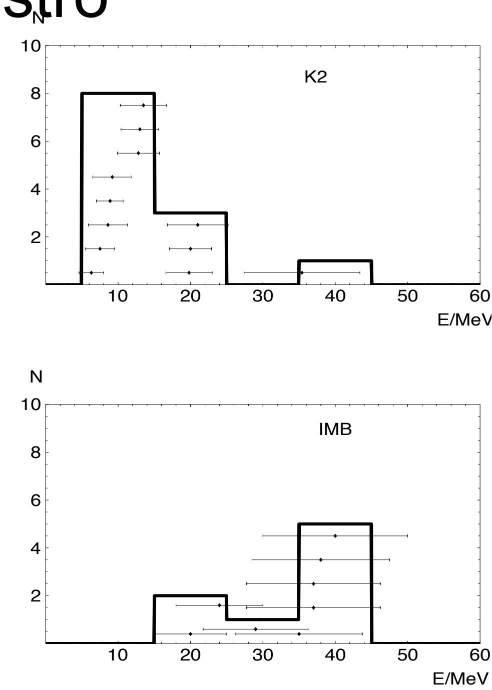
February 23rd 1987: the closest SN of the modern era: Sanduleak-69 202 (Blue SuperGiant) in the Magellanic Cloud (51.4kpc) exploded, thus becoming **SN1987A**

Several hours earlier, at the neutrino detector Kamiokande, an unmistakable flash was received...



Neutrino come first

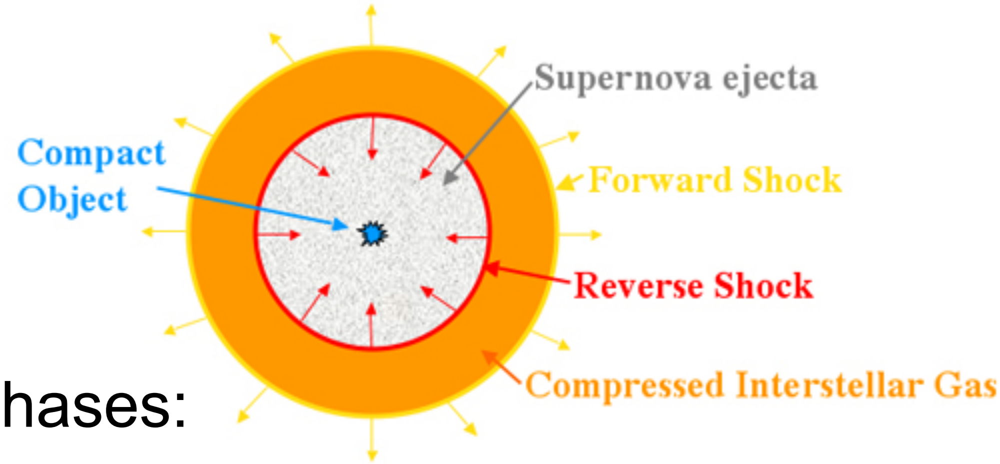
- Neutrinos escape a SN in ~10 s after collapse
- The explosion happens after few hours from collapse
- – Several hours is the time it takes for the shockwave to break though the surface of the star.
- Neutrino detector can give early alert to the astro community



The last SN seen in the galaxy was in the 1600's. Isn't a galactic SN overdue by now ?

- No reason to worry:
- – Statistics is statistics
- – We most likely have missed some
- Obscuration
- Before no telescopes available in suitable observation points (southern emisphere...)
- No neutrino detectors available until ~ 30 years ago

Evolution of supernova remnants

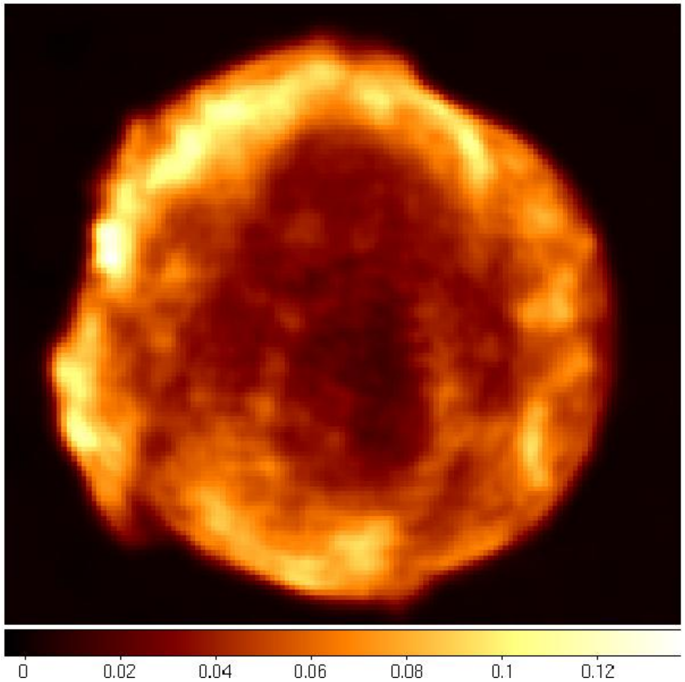


- Supernova blast wave is highly supersonic
  - forward shock develops at its leading edge
- Three main evolutionary phases:
  - free expansion (ejecta-dominated)
    - forward shock has swept up relatively little ambient gas, expansion velocity nearly constant (does decelerate slightly)
  - Sedov or Sedov-Taylor phase
    - mass of swept-up material becomes comparable to ejecta mass
    - forward shock decelerates, reverse shock generated
  - radiative phase
    - shock slows to ~200 km/s, significant energy loss through emission lines
- Particle acceleration probably only in first two phases

Observational evidence

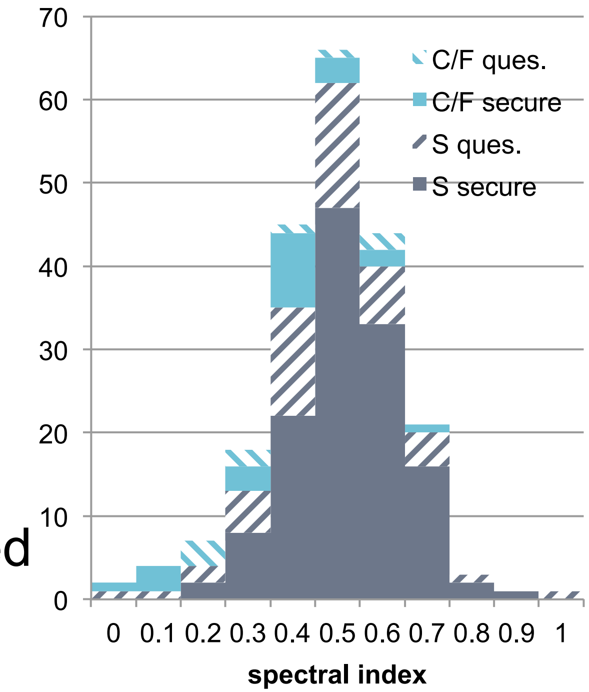
- Historical supernovae
  - naked-eye observations for SNe 1604 (Kepler's), 1572 (Tycho's), 1181, 1054, 1006 (also 393, 386, 185?)
    - two young remnants not seen as SNe (Cas A, ~1680, G1.9+0.3, ~1870)
- Radio
  - most SNRs are observed at radio wavelengths
  - 294 in standard catalogue (Green), only 20 have insufficient data for radio flux
    - 80% shell-type, 12% composite, 3% filled-centre (remainder unclassified)
  - ~40% also observed in X-rays, ~30% in optical
    - lack of detectable optical emission is partly due to location of massive stars close to Galactic plane, where there is a lot of dust absorption

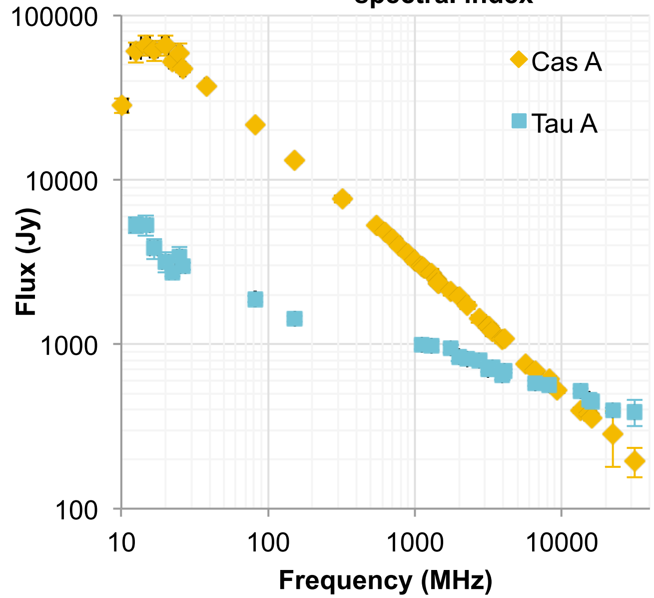
Tycho at 1.5 GHz



Observational evidence

- Radio emission is synchrotron
  - spectral index ~0.5 (electron index ~2)
    - younger objects have steeper spectra
    - filled-centre/composite objects flatter spectra
  - polarised, though less than would be expected
    - indicates disorder in magnetic field
    - this would be expected in diffusive shock acceleration since turbulent magnetic fields are key to this mechanism
  - steeper spectrum in younger objects may be a consequence of CR-modified shock
    - electrons "see" only the subshock with reduced *r*; their index is $(r + 2)/(r - 1)$



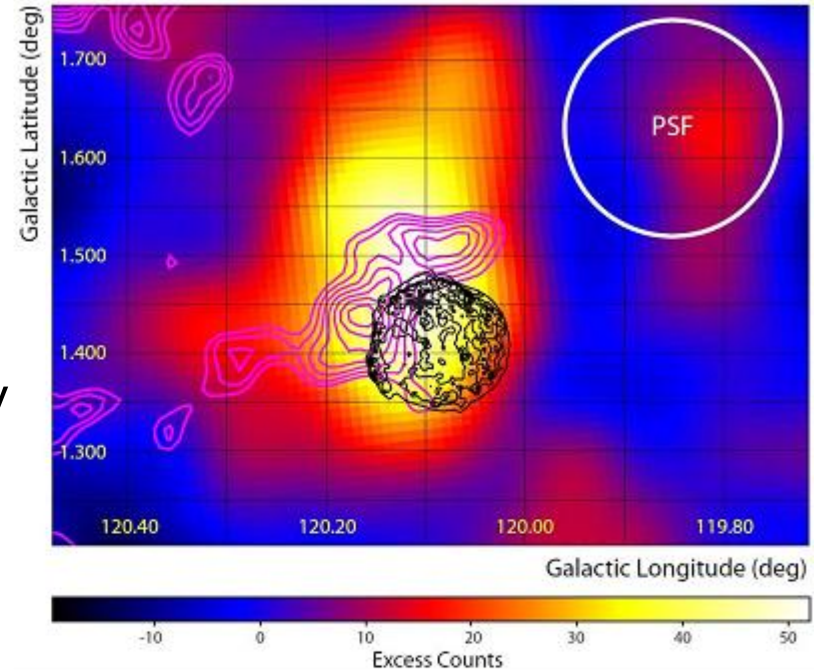


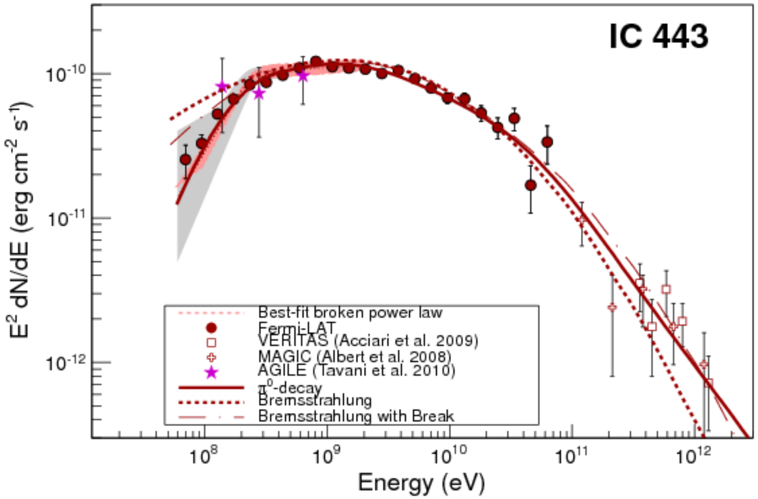
X-ray emission

- *Thermal* X-ray emission from shock-heated ejecta quite common in shell-type SNRs, but not relevant to particle acceleration as such
- However, some shell SNRs also have a featureless power-law X-ray spectrum
  - this is synchrotron radiation—wrong spectral index for IC, not accompanied by line emission as bremsstrahlung would be
  - implies a local population of very high energy electrons
- X-rays come from a thin outer rim
  - electrons accelerated locally
  - may imply amplification of magnetic field up to ~200 μG
    - if mechanism is synchrotron energy loss depleting electron population
    - but thin rims also seen in radio, so this mechanism may be wrong

GeV and TeV emission

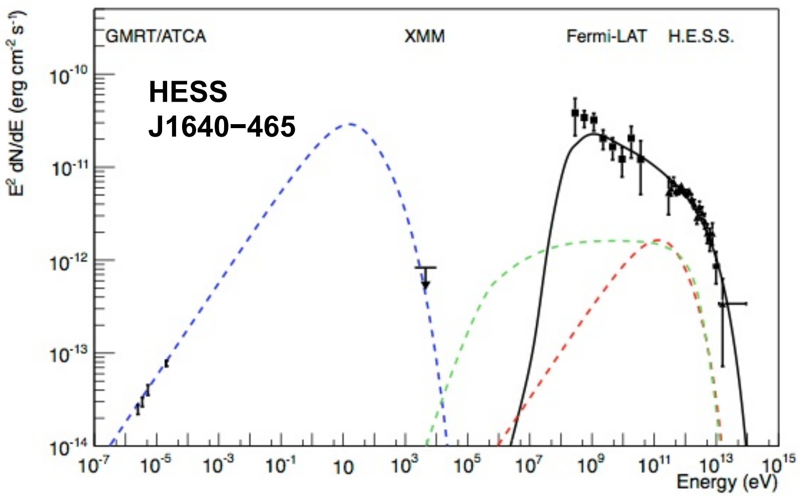
- Most shell SNRs do not emit high-energy photons
- Exceptions:
  - young objects such as Tycho
    - hard spectra, bright in TeV range
  - SNRs interacting with molecular clouds
    - softer spectra, more luminous in GeV

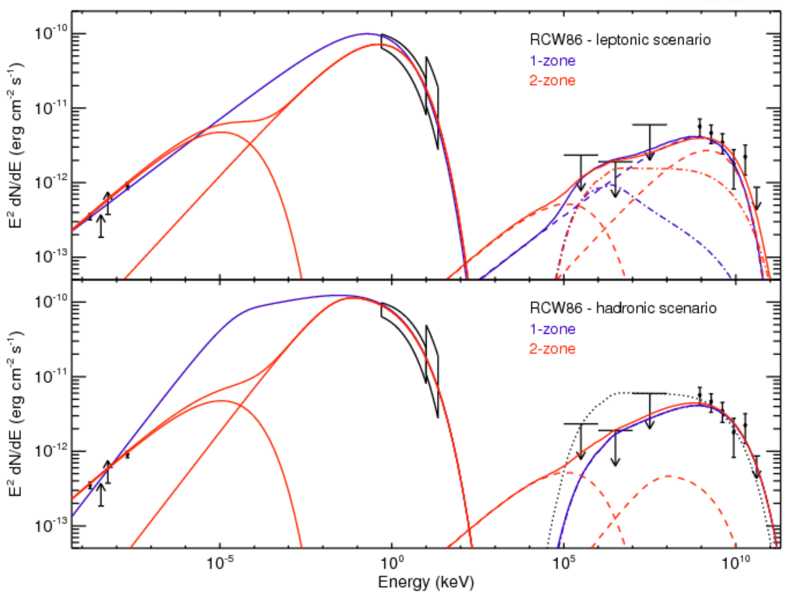




Both Tycho and IC 443 have high-energy spectra best fitted by π^0 decay. However, other young SNRs such as RXJ1713−3946 have IC spectra

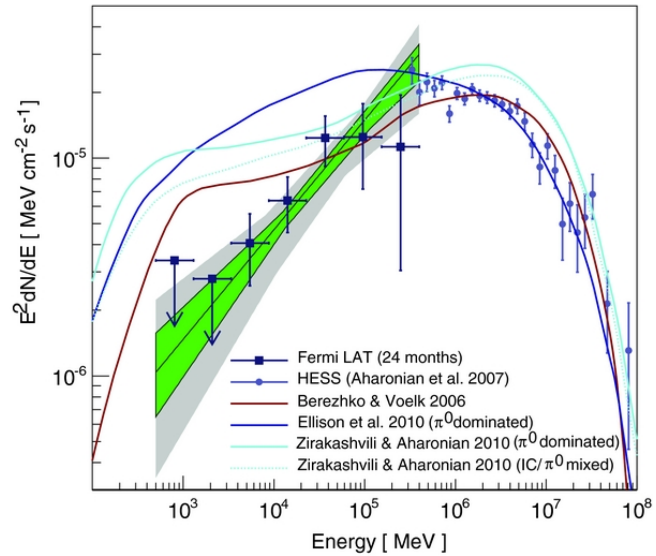
GeV and TeV emission

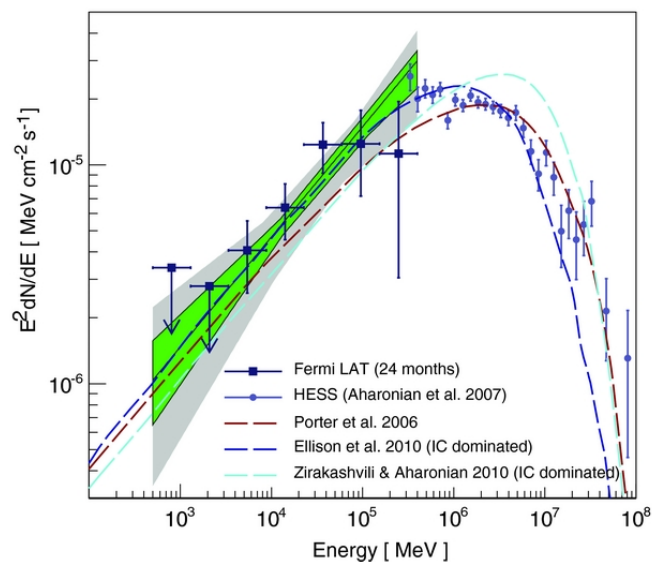




Observations at GeV energies are essential to distinguish IC and π^0 hypotheses.

Note that IC-dominated spectra don't necessarily mean that remnants do not accelerate cosmic rays!



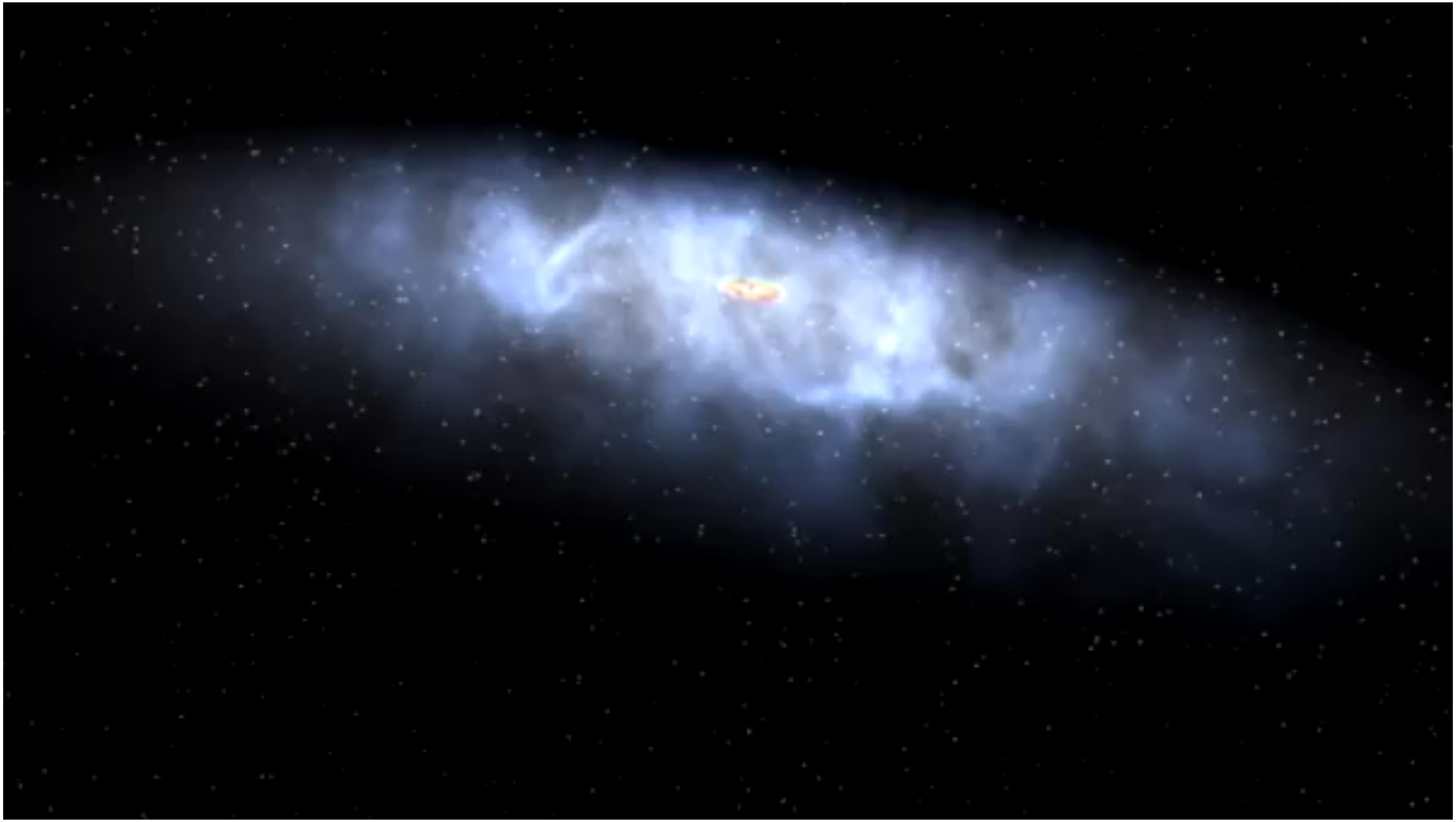


Conclusion: SNRs

- Supernovae occur about once every 40 years on average (±50%) and release about 10^{44} J of energy each
  - this is sufficient to account for cosmic rays up to the knee if SNRs are about 10% efficient in converting this energy into cosmic rays
- The supernova blast wave is highly supersonic and will produce a forward shock
  - subsequently also a reverse shock as the forward shock is decelerated by the ambient interstellar medium
  - the shock is seen in young SNRs as a sharp edge in synchrotron emission
- SNRs do accelerate particles
  - synchrotron emission seen in radio, and in young SNRs also in X-rays
  - GeV and TeV γ-rays emitted by young and interacting SNRs
- Properties are broadly consistent with diffusive shock acceleration
  - right synchrotron spectral index and combination of shock and B-field

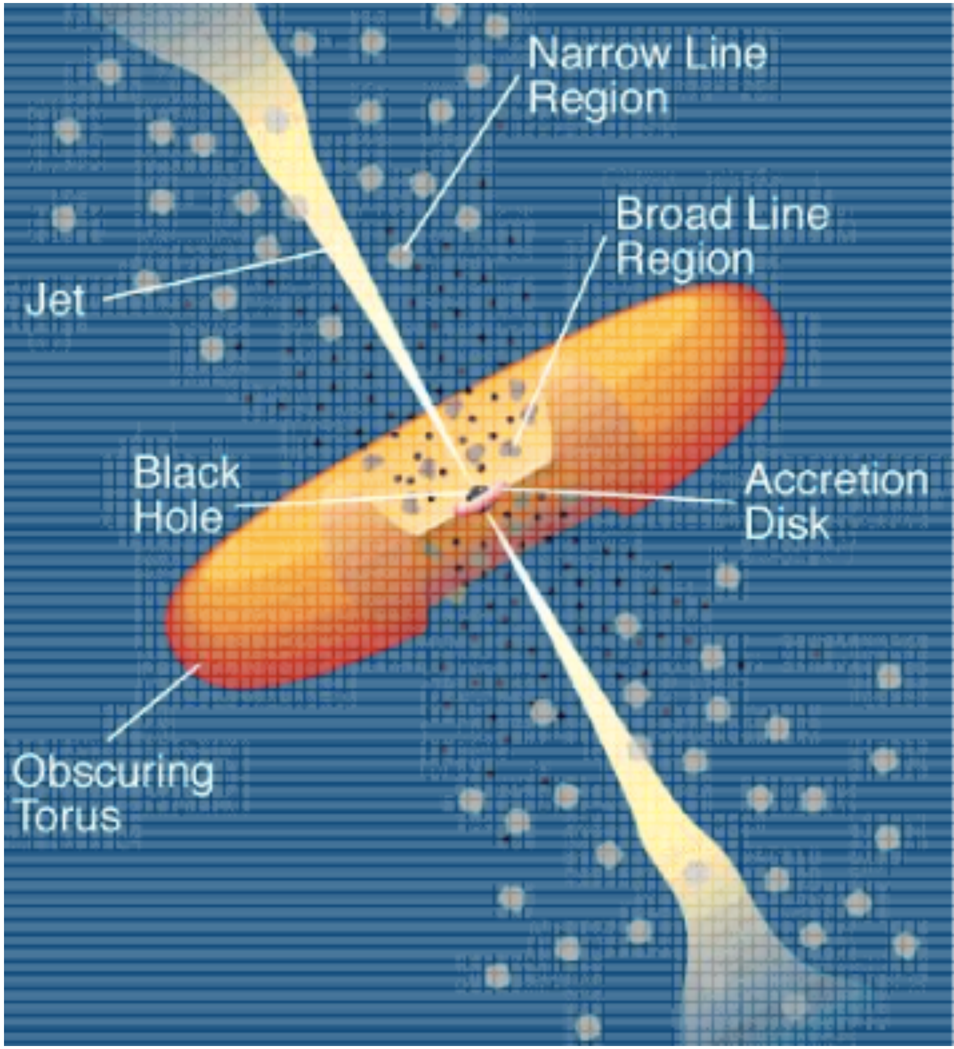
ACTIVE GALACTIC NUCLEI

Active Galactic Nuclei

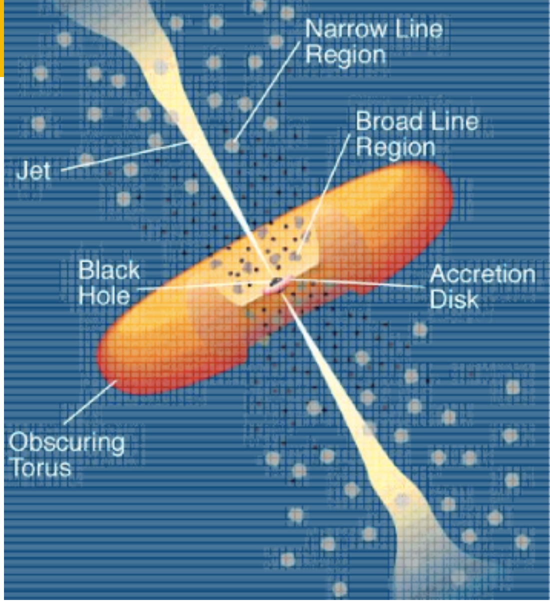


Active Galactic Nuclei

- Supermassive BH
- accretion disk
- jets – extend for tens of kpc
- Outside the jets, winds of high and low velocity gas are forming, referred to as broad line and narrow line region



AGN Unified Scenario



- Supermassive black hole
- Thin accretion disk – emission peaks in UV optically thick
- Disk corona – produces X-ray/hard X-ray emission optically thin
- Dusty torus – essentially outer part of accretion disk, optically thick, produces IR emission
- High-velocity clouds – located near BH, produce broad optical emission lines, electron density above 10^7 cm^{-3} (due to lack of forbidden lines), ionized by disk/corona
- Low-velocity clouds – located near/outside of torus, produce narrow optical emission lines which are collisionally excited, have a range of ionization levels, filling factor is small ~ 10^{-3}, material seems to be mainly outflowing
- Relativistic jets and radio lobes – extend parsecs to 100s kpc, detected up to X-rays, contain highly energetic particles

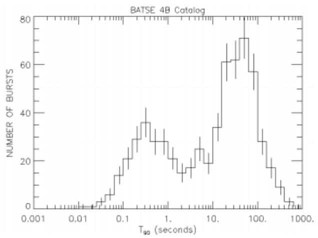
Black Hole Mass

- High luminosity and rapid variability suggest accretion onto black holes
- Estimate mass of black hole:
  - $M = L\Delta t/\eta c^2$
  - Δt = lifetime – estimate from size and expansion rate of radio lobes ~ 10^8 years
  - $\eta \sim 0.1$, $L \sim 10^{45}$ erg/s
  - $M \sim 3\times10^{40}$ gm ~ $10^7 M_\odot$

GAMMA RAY BURST

What are Gamma Ray Bursts?

- Are short flashes of γ-rays for a short time, with fluxes of ~ 0.1 – 100 ph/cm^2/s/keV



- Most powerful explosions in space:
  - visible across the universe
  - most luminous sources across the electromagnetic spectrum
  - afterglow lasts for days.

- GRB Duration (T90) from 10^{-3} to 10^{3} s, with two morphological classes
  - *Long GRBs*: collapse of massive stars to Black Holes, T90 > 2s.
  - *Short GRBs:* merging of binary compact objects, T90 < 2s

- Rate is ~10^{-7}/yr/galaxy

T. Piran, Phys. Rep. 314, 575 (1999).
P. Meszaros, Ann. Rev. Astron. Astrophys. 40, 137 (2002).
Kouveliotou et al. 1993

Why GRBs?

Long-duration (> 2 s) GRBs are the most luminous objects in the gamma-ray sky

$L_\gamma \sim 10^{51}\ \mathrm{erg/s}$

Non-thermal

Isotropic-equivalent

→ **particle acceleration**

→ GRBs as sources of UHECRs: Waxman 1995; Vietri 1995

Energy injection rate in UHECRs

Baryon loading>1

$$\dot{E}_{\rm CR} \sim 10^{51}\ \frac{\rm erg}{\rm GRB} \cdot \frac{20\,{\rm GRB}}{{\rm Gpc^3\,yr}} \eta_{\rm bol}\eta_p \sim 2\times 10^{43} \eta_{\rm bol}\eta_p\ \frac{\rm erg}{{\rm Mpc^3\,yr}}$$

Local true GRB rate

Bolometric factor<1

Energies in UHECRs

Energy injection rate in UHECRs from data

$$\dot{E}_{\rm UHECR} \approx 10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$$

Need baryon-loading factor > ~ 50

How many GRBs within the GZK volume (100 Mpc)?

- Depends on the Inter-Galactic Magnetic Field (IGMF)

$$\Delta t_{\rm CR} \sim 3.2 \times 10^4\, Z^2 \left(\frac{B_{\rm IG}}{1\,{\rm nG}}\right)^2 \left(\frac{E_{\rm CR}}{60\,{\rm EeV}}\right)^{-2} \left(\frac{\lambda_{\rm IG}}{1\,{\rm Mpc}}\right)^{3/2} {\rm yr}$$

- $$N_{\rm GRB} \sim \frac{20\,{\rm GRB}}{{\rm Gpc^3 yr}} \cdot V_{\rm GZK} \Delta t_{\rm CR} \sim 3 \times 10^3$$

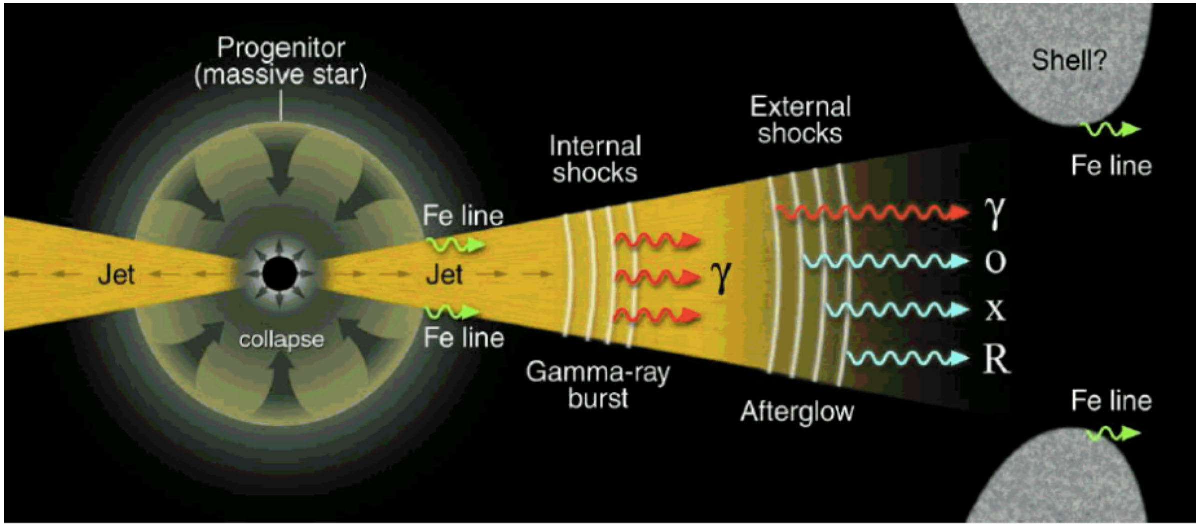
A fraction (~1/200) of these GRBs have their jets pointing to us

beaming angle correction

GRB fireball model

- Emission is separated into 2 components:
  - the prompt outburst phase due to internal shocks in the relativistic blast-wave
    - Acceleration of **electrons** in internal shocks in jets produces **keV- MeV γ-rays** (through synchrotron): Prompt emission
    - Acceleration of **protons** in the same shocks produces **neutrinos** in interactions with GRB photons

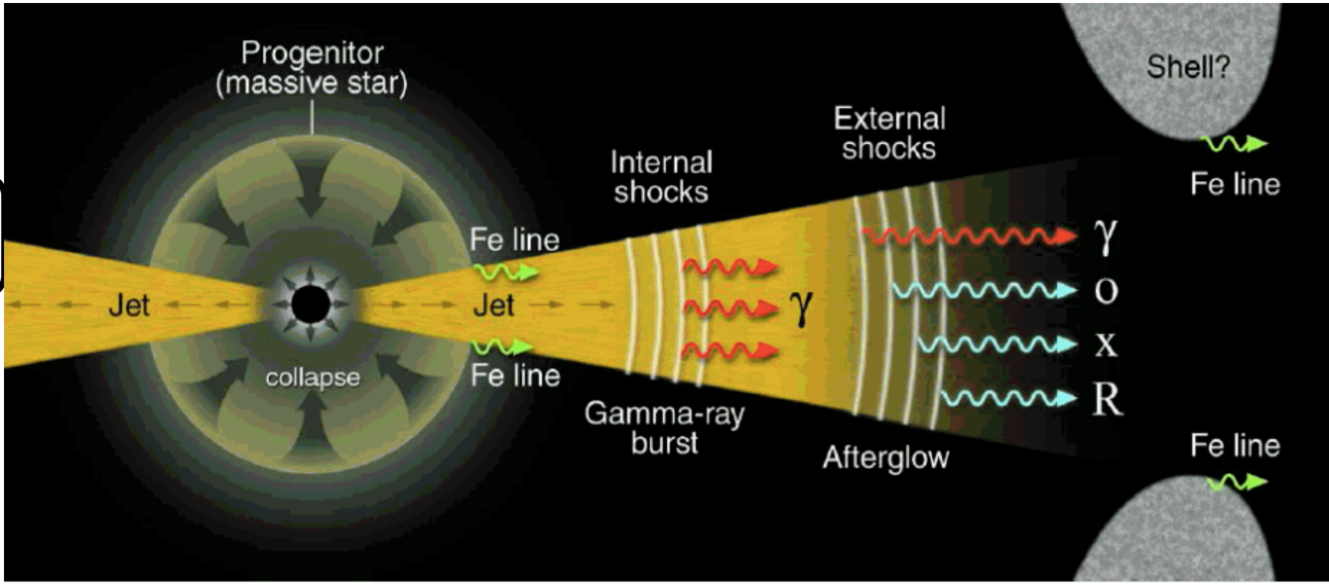
$$p\gamma_{GRB} \rightarrow n\pi^{+} \rightarrow \nu's$$



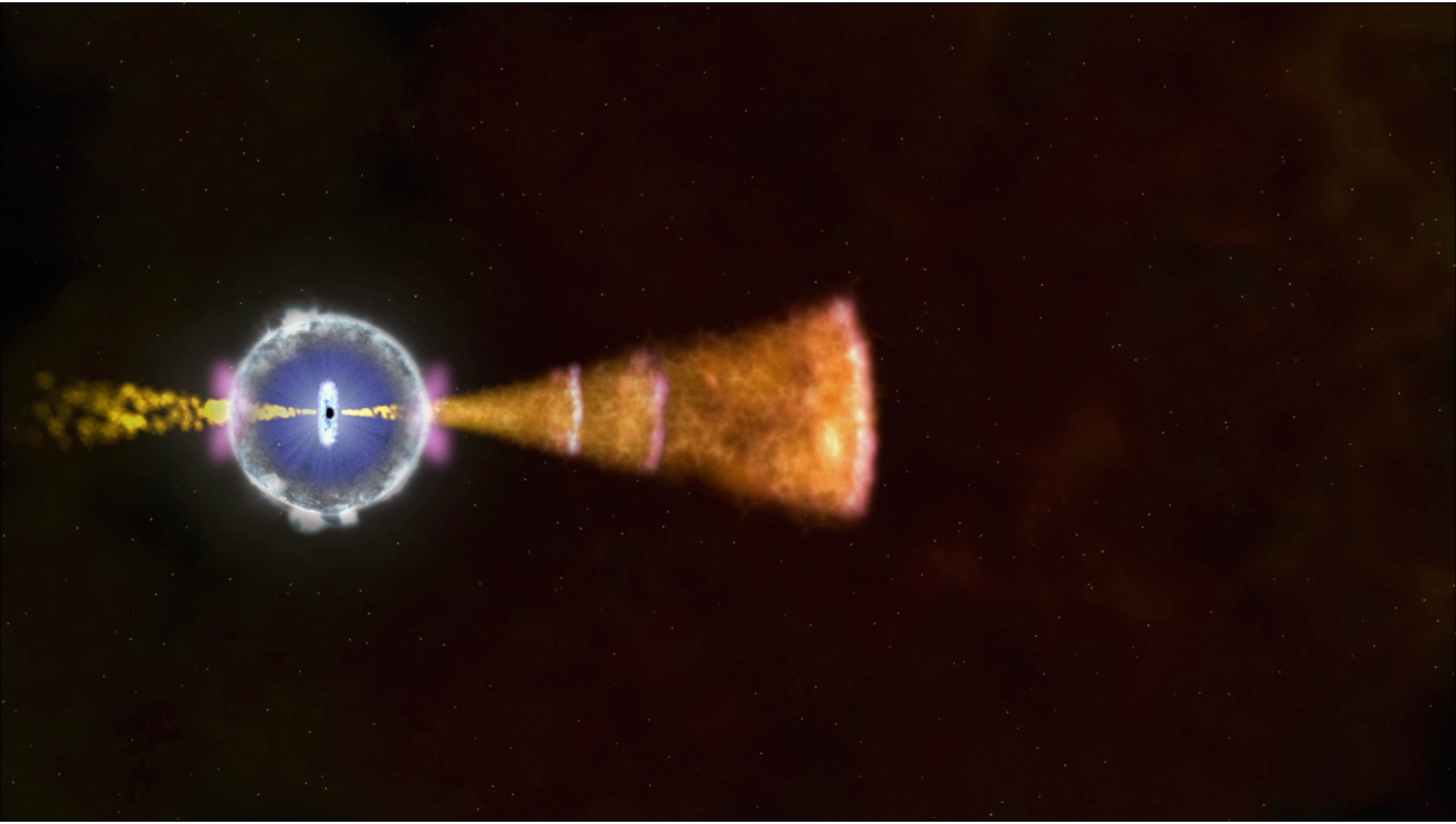
GRB fireball model

the afterglow (strong X-ray, optical and radio emission) arises from the cooling fireball and its interaction with the surrounding medium.

$p\gamma_{GRB} \rightarrow n\pi^{+} \rightarrow \nu$´s



Jets



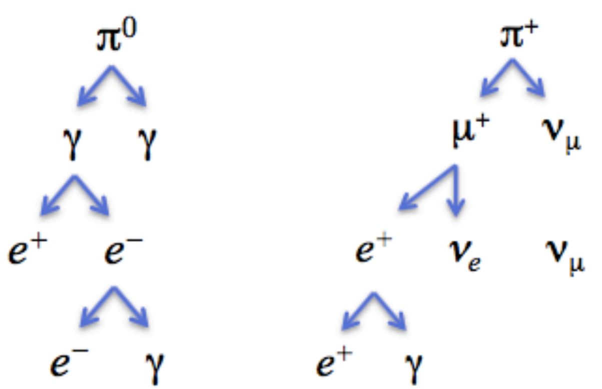
Neutrinos from GRBs

Interaction channels for cosmic rays in the vicinity

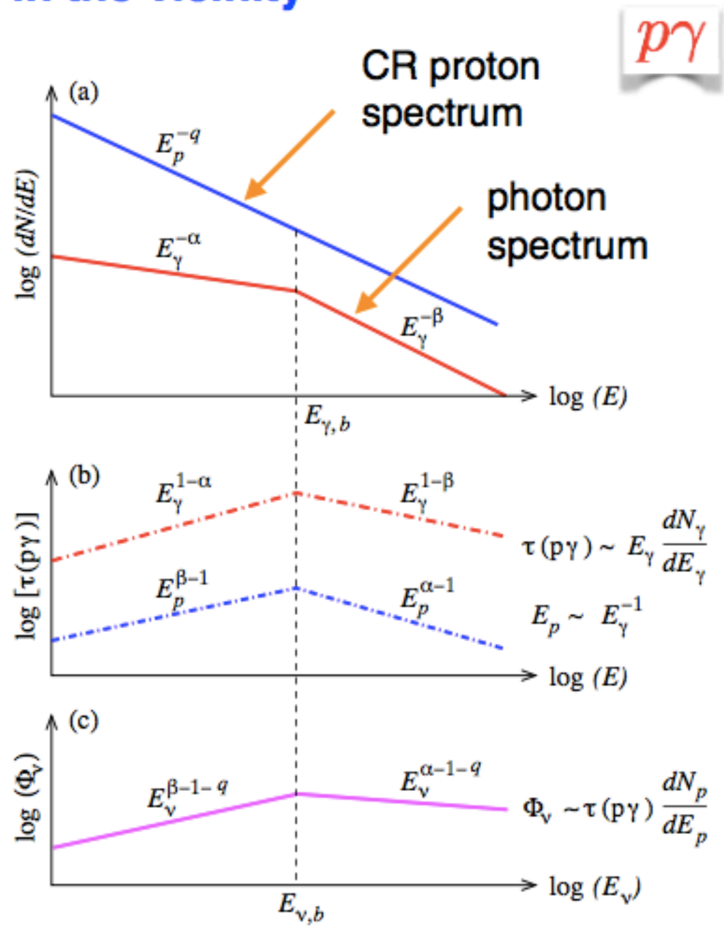
$$p\gamma \rightarrow \pi^0\,,\ \pi^+\,,\ \pi^-\,,\ K^+\,,\ K^-\,,\ etc.$$

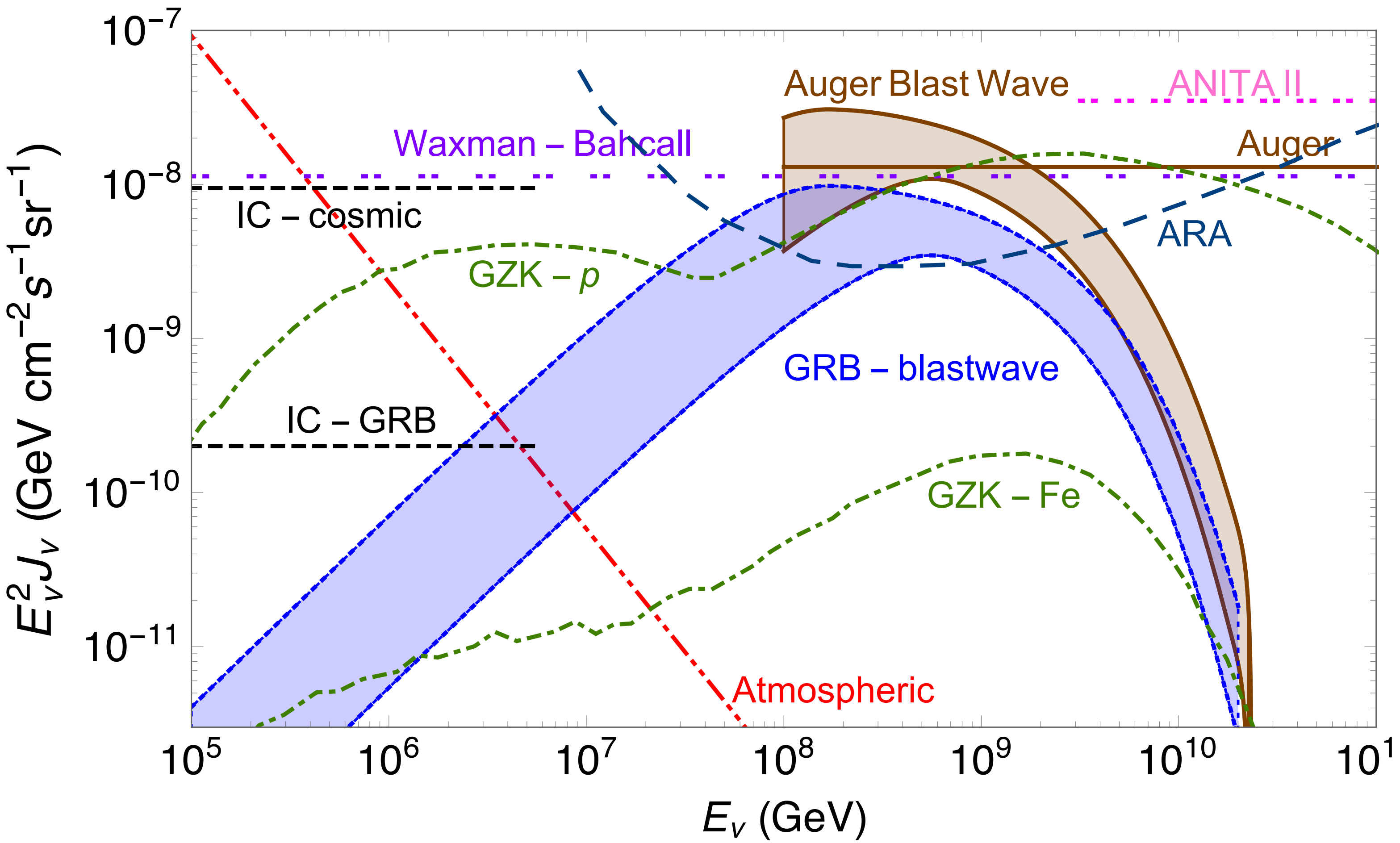
$$pp \rightarrow \pi^0\,,\ \pi^+\,,\ \pi^-\,,\ K^+\,,\ K^-\,,\ etc.$$

Pion decay chain



Energy for each neutrino flavor
~ 5% of CR energy




$E_\nu^2 J_\nu$ (GeV cm^{-2}s^{-1}sr^{-1})
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
E_ν (GeV)
Auger Blast Wave
ANITA II
Waxman – Bahcall
Auger
IC – cosmic
ARA
GZK – p
GRB – blastwave
IC – GRB
GZK – Fe
Atmospheric