Multi-messenger Astronomy – Cosmic Rays, Neutrinos & γ-rays

The Variable Universe – Lecture 10
Fall Semester 2022

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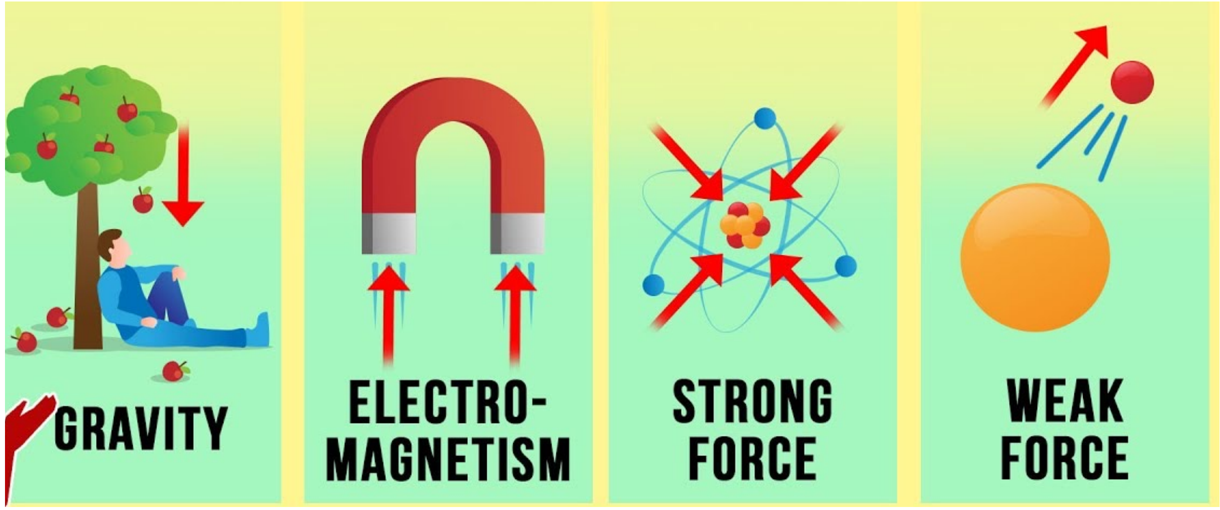
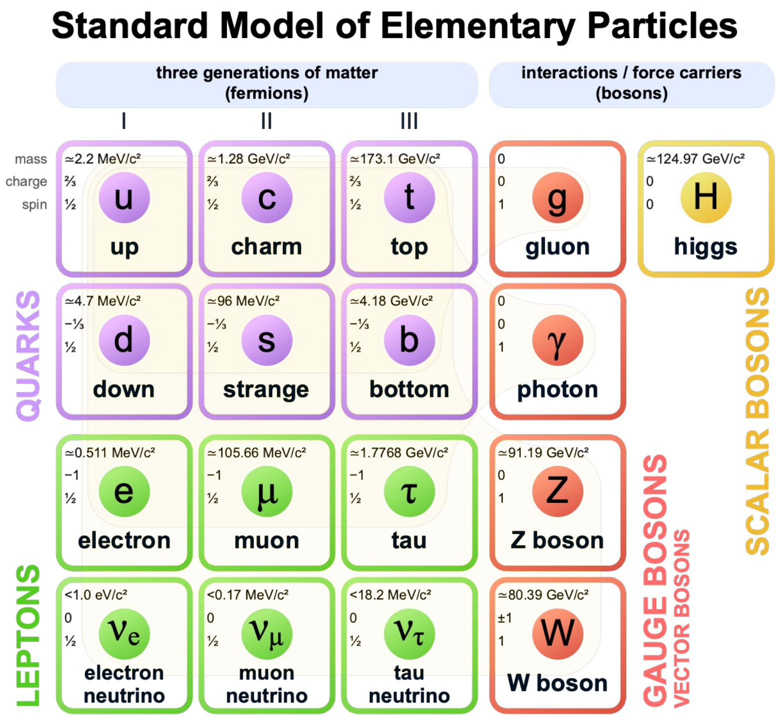
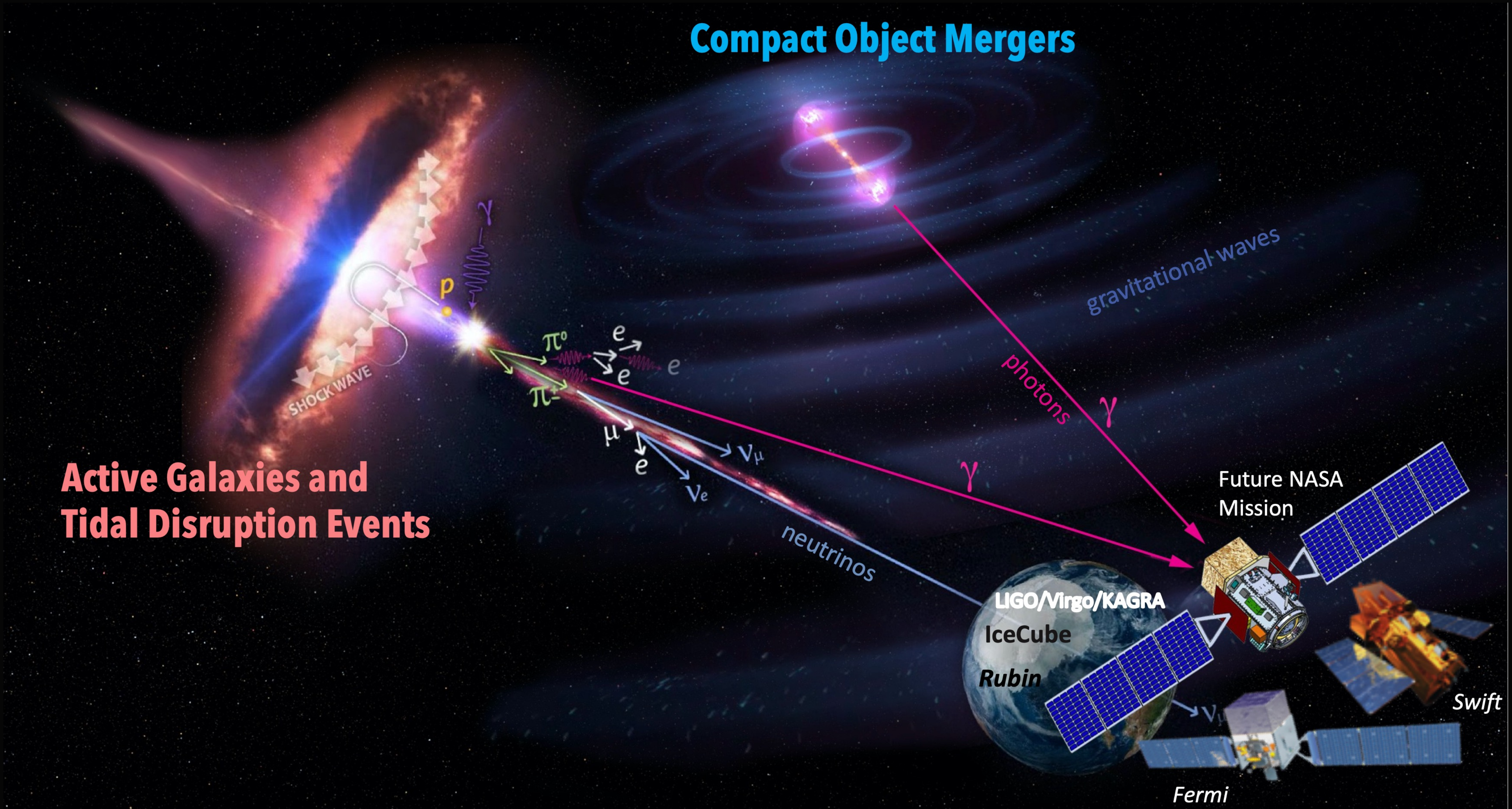
What is multi-messenger astronomy?

Multi-messenger astrophysics



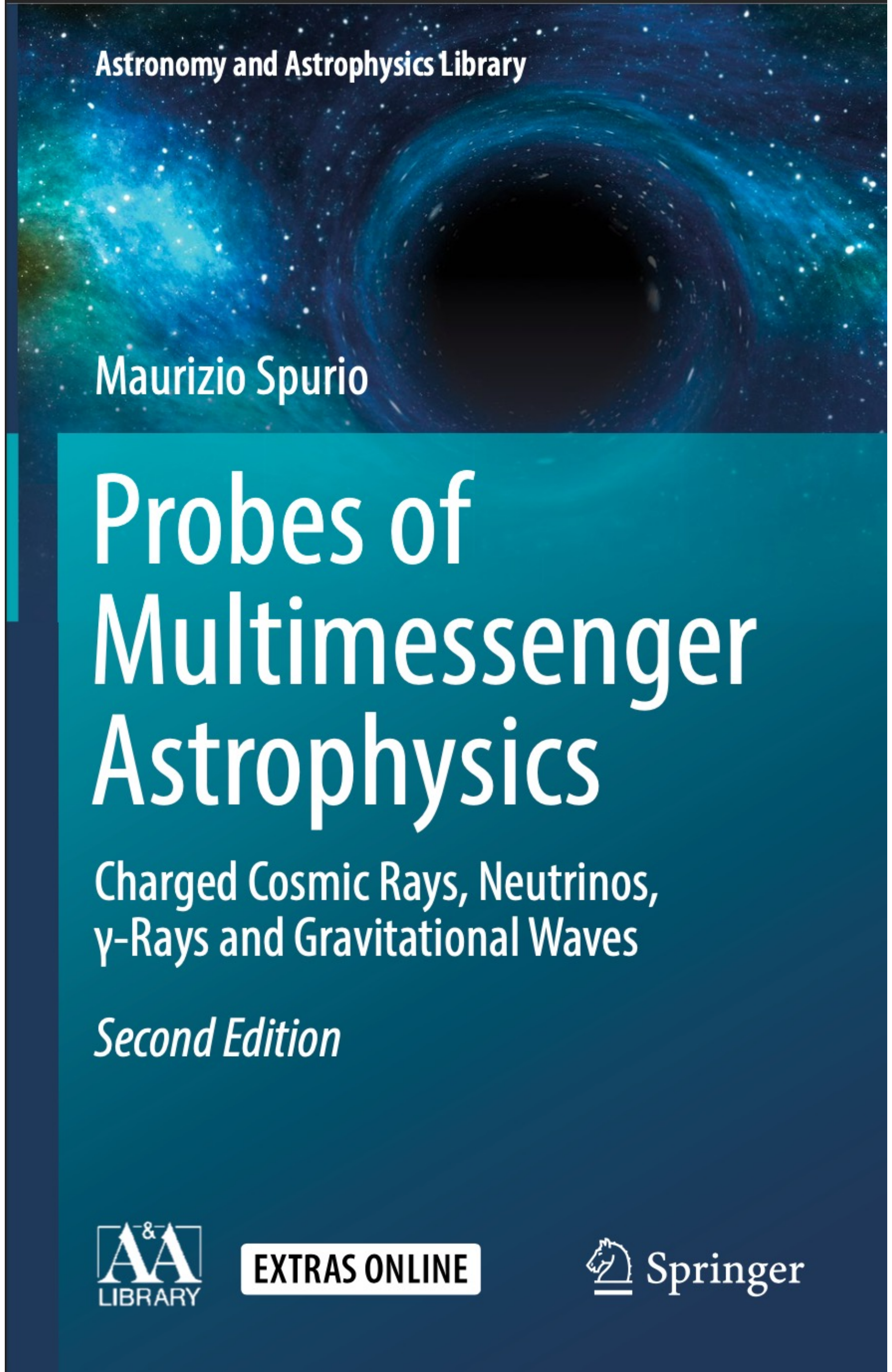
- Direct information mediated by multiple fundamental forces: gravity, electroweak force, EM
- Strong force not measured directly
- EM: full spectrum from Gamma rays to radio
- Gravity: gravitational waves
- Electroweak force: particle decays informed by standard model of particle physics
- What is a major conceptual difference between EW and the others?




Compact Object Mergers
gravitational waves
photons
γ
γ
p
SHOCK WAVE
π°
π±
e
e
e
μ
e
ν_μ
ν_e
neutrinos
Active Galaxies and
Tidal Disruption Events
Future NASA
Mission
LIGO/Virgo/KAGRA
IceCube
Rubin
Swift
Fermi

Multi-messenger astronomy connects observational windows mediated by different forces

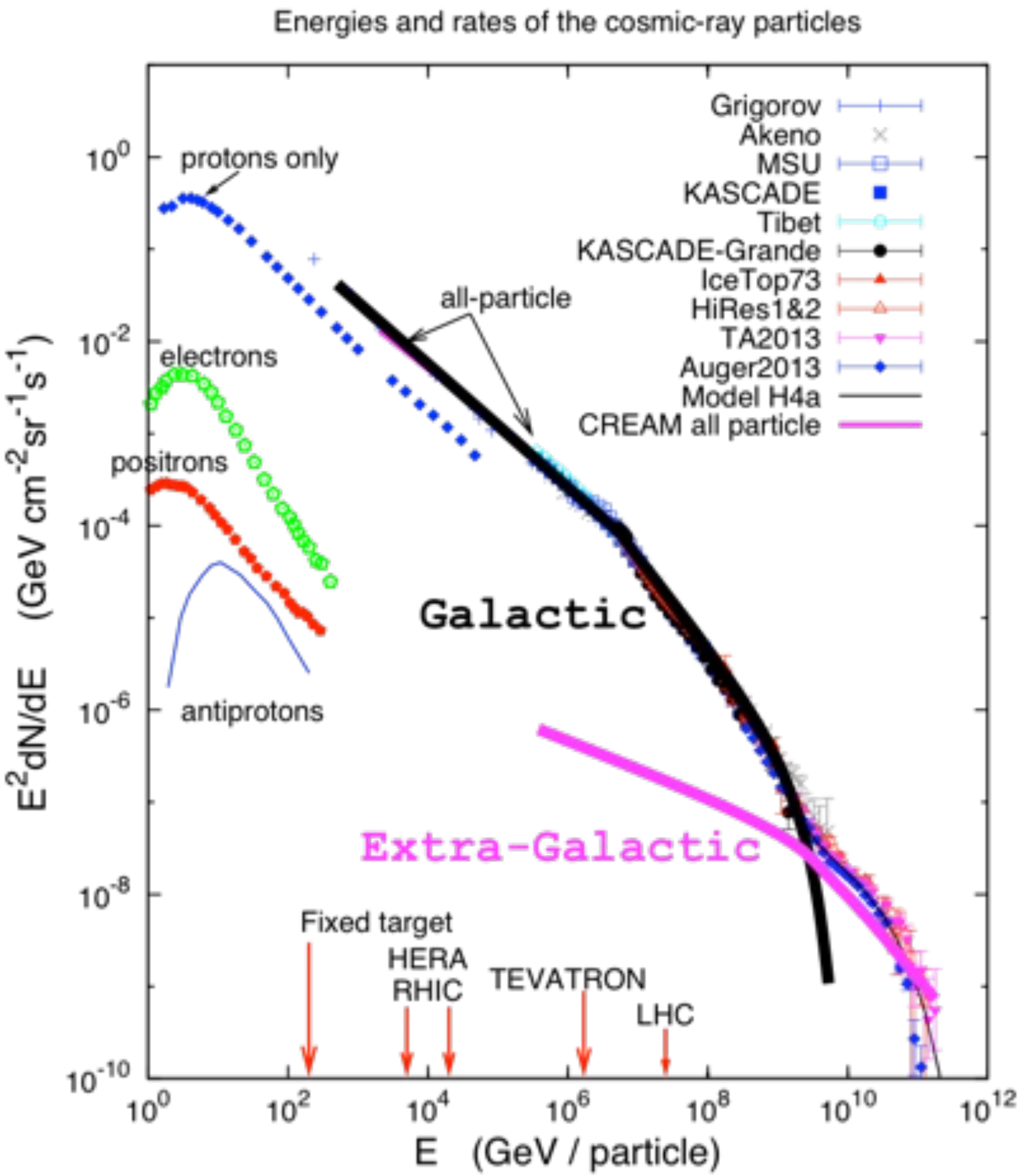
Particles, cosmic rays, electromagnetic radiation, and gravitational waves



Cosmic Rays and Cerenkov light from particle decays

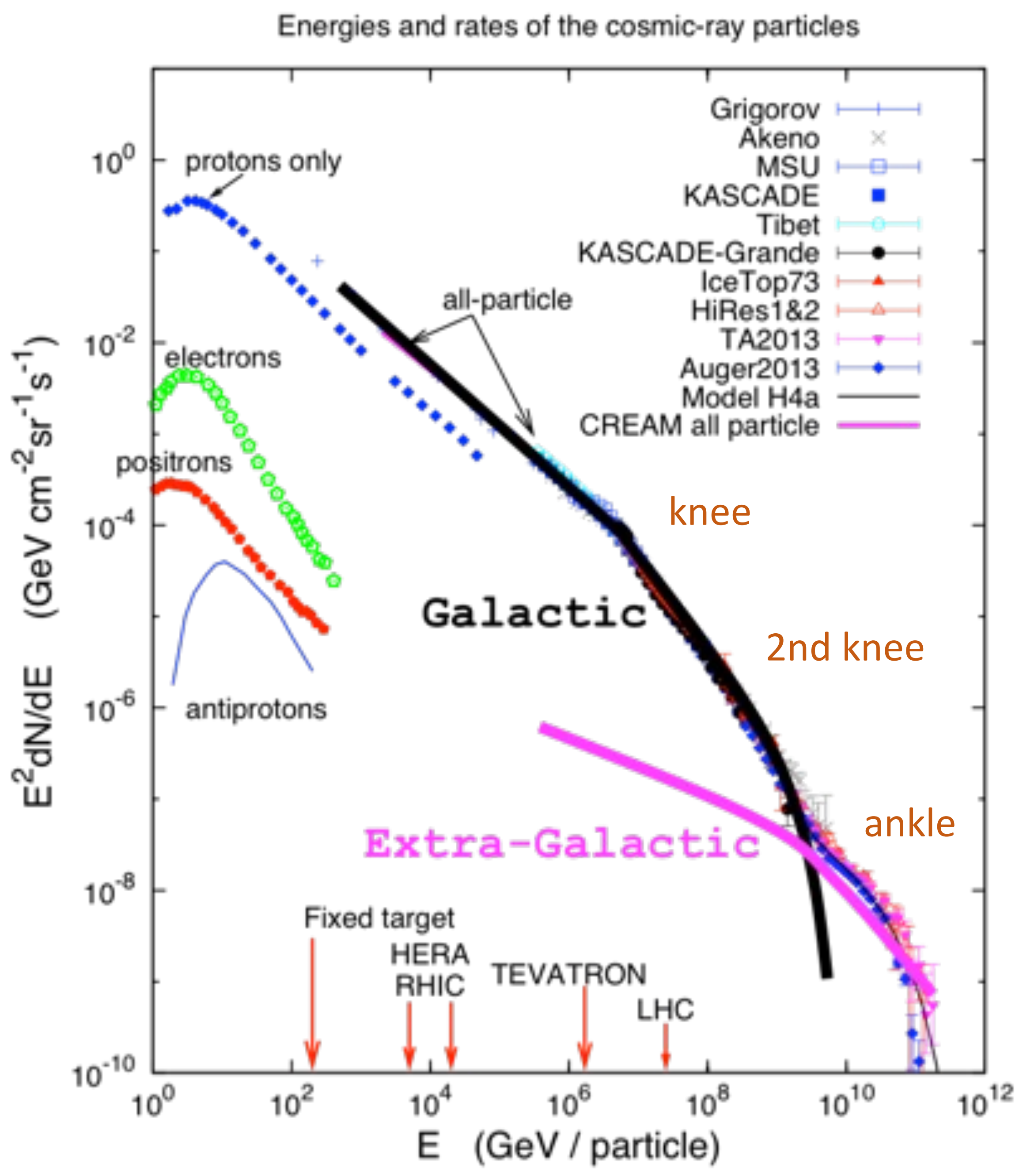
The Cosmic Ray Energy Spectrum

- Discovery by Hess in 1912
- Anderson 1932: Antimatter (e^+) in CRs
- Pions, muons, et al. in 1940s discovered in CRs
- Neutral CRs: γ-rays, neutrinos
- Charged CRs are ionized nuclei:
  - Protons (90%)
  - α particles (9%)
  - Heavier nuclei (1%)
- Incidence on Earth: 1000 $m^{-2}s^{-1}$
- Most CRs are relativisitic
- Energies up to 10^{20} eV (20 J), ~10^{11} m_p



Cosmic Ray origins

- Solar system (rare): coincide with violent phenomena on Sun, highly variable
- Majority of CRs exhibit anti-correlation with Solar activity: Sun's magnetized winds clear out CRs from Solar system
- Galactic CRs likely accelerated by Supernovae
- Highest energy CRs have Larmor radii > R_MW for typical Galactic fields: likely of extragalactic origin
- Where do they come from? What accelerates CRs?



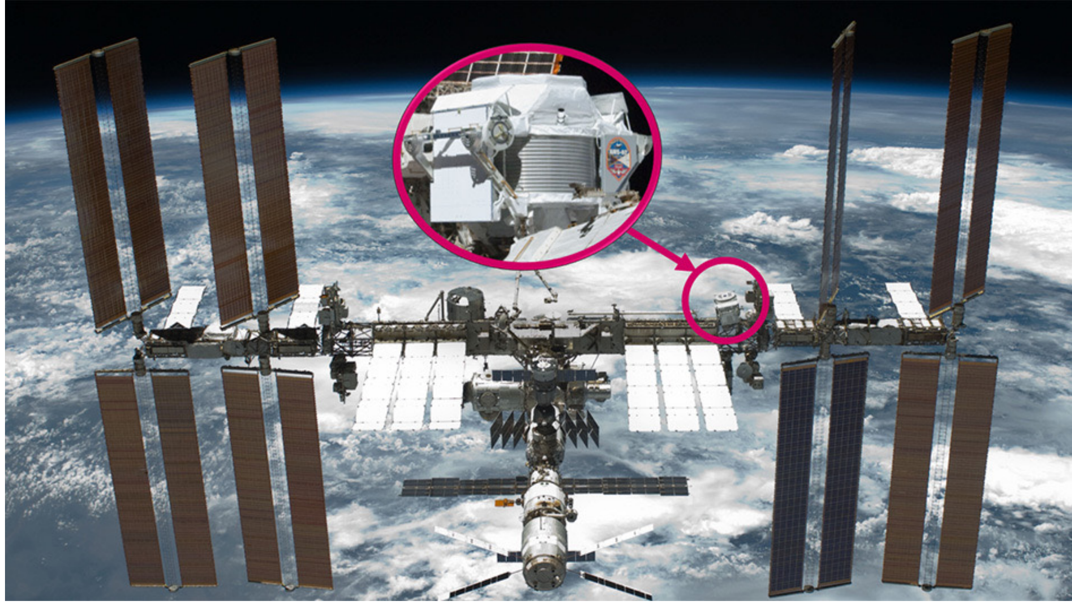
Astrophysical particle accelerators

- Cosmic Rays have E >> thermal (radiation/Bremsstrahlung)
- Repeated collisionless shock acceleration

$$\Delta E = \alpha E \rightarrow E = E_0(1+\alpha)^N$$

- Repeated accelerations: number of cycles $n = \frac{\ln(E/E_0)}{\ln(1+\alpha)}$
- $\frac{\mathrm{d}N(E)}{dE} \propto E^{-(1+s)}$; s $\sim$ 1.1 in shock-waves.
- Power law spectrum: $\phi(E) \propto E^{-\alpha}$
- Shock-wave acceleration capable of accelerating to 100*Z TeV (Z: proton number)
- Higher-energy CRs require different acceleration mechanisms

Alpha Magnetic Spectrometer @ ISS



- $2bn CERN experiment in space
- Last *Endeavor* flight after 2003 Columbia disaster
- Direct detection of cosmic rays to understand CRs, dark matter, primordial antimatter, exotic matter forms
- 25,000 events per second
- 213 bn events recorded: CR e-, e+, p, ~p, nuclei from He to Fe, He isotropic composition
- Also time-resolved spectra of e-, e+, p, He nuclei
- First measurement of energy spectrum up to iron!
- Percent precision challenges origin, acceleration & propagation paradigm
- Energy spectra of Fe, He, C, and O CRs belong to same group; different from Ne, Mg, Si ([Aguilar et al. 2021](#))

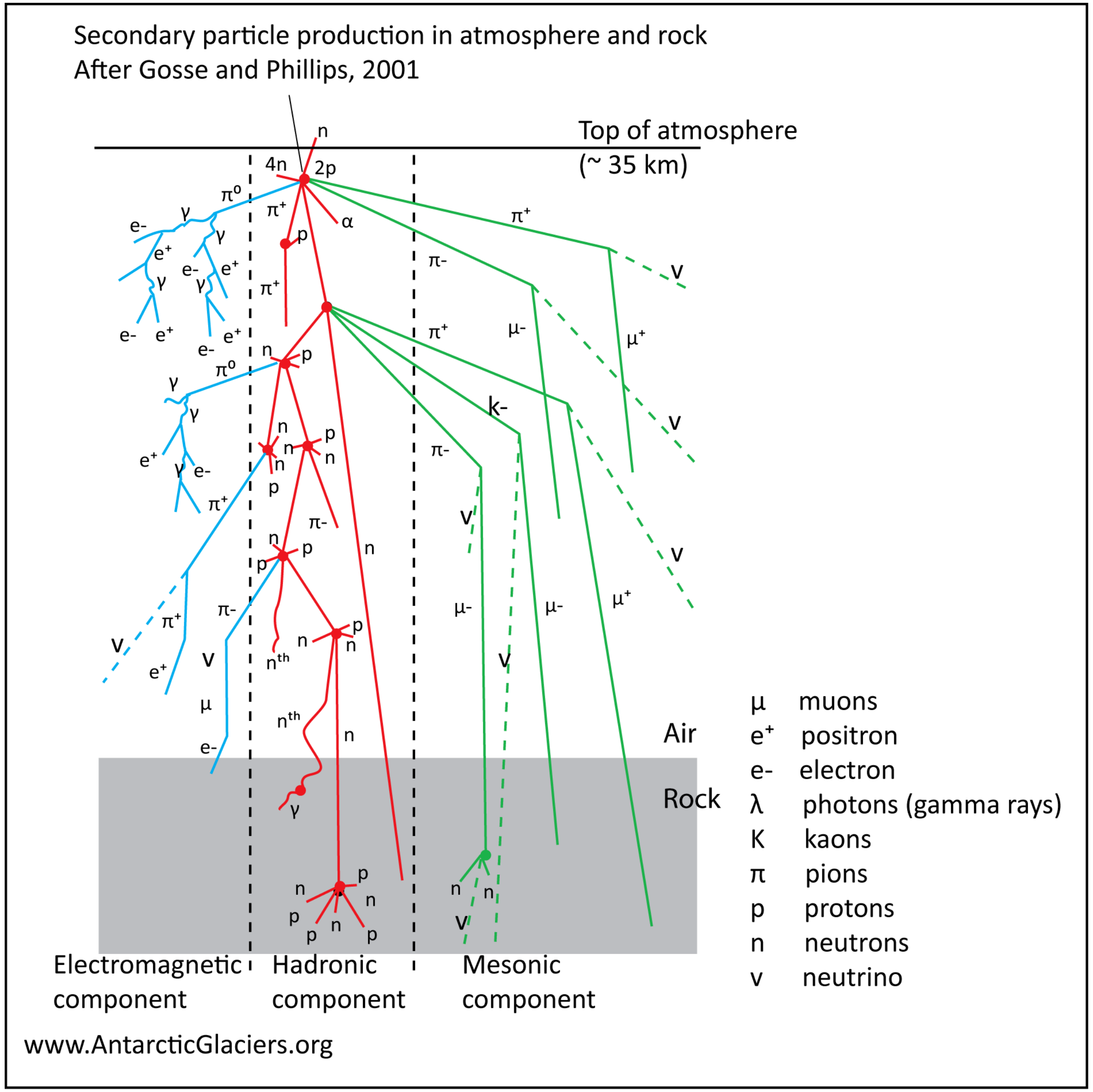
Dr Mercedes Paniccia (Université de Genève)
BSP 626, 11:00, Monday December 12, 2022
https://indico.cern.ch/event/1204609/

… but we like telescopes, so…

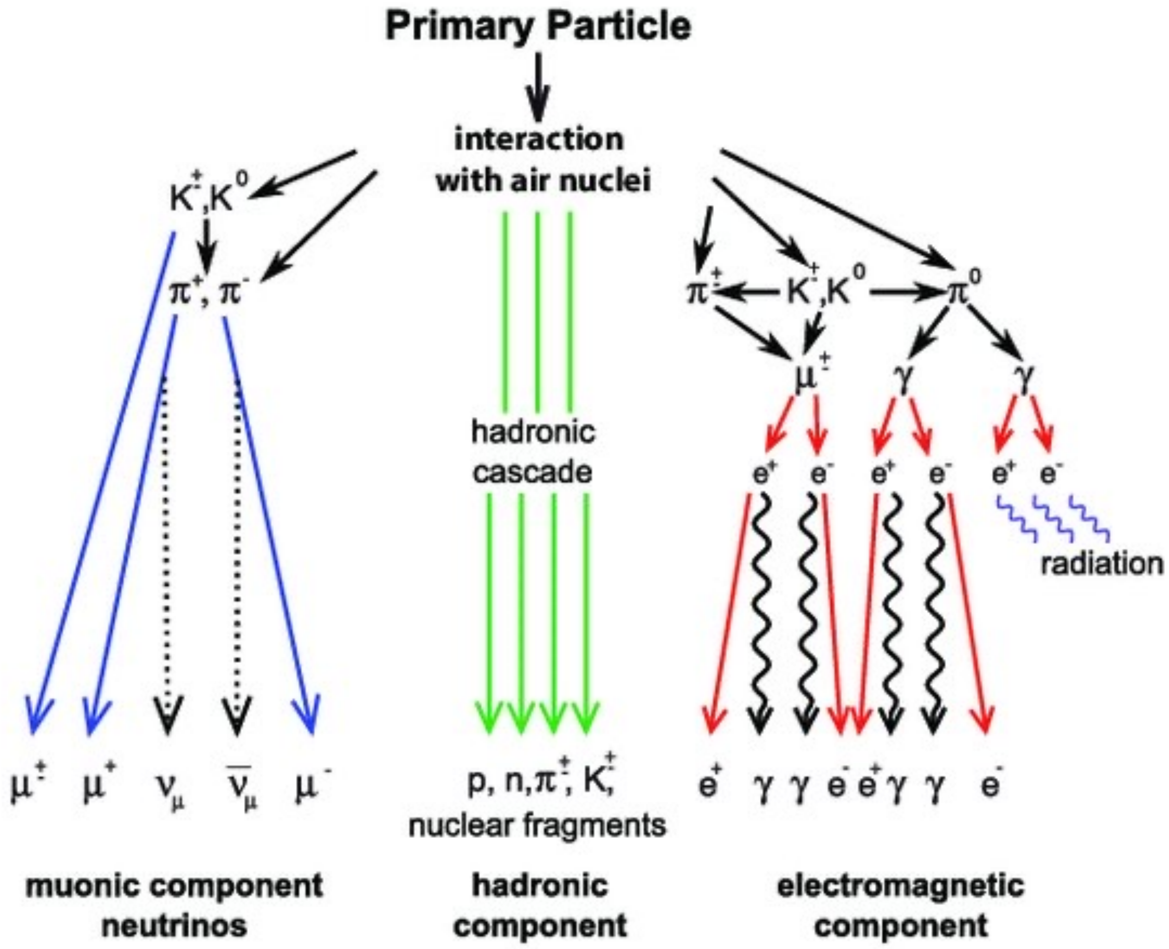
How can we detect cosmic rays with telescopes?

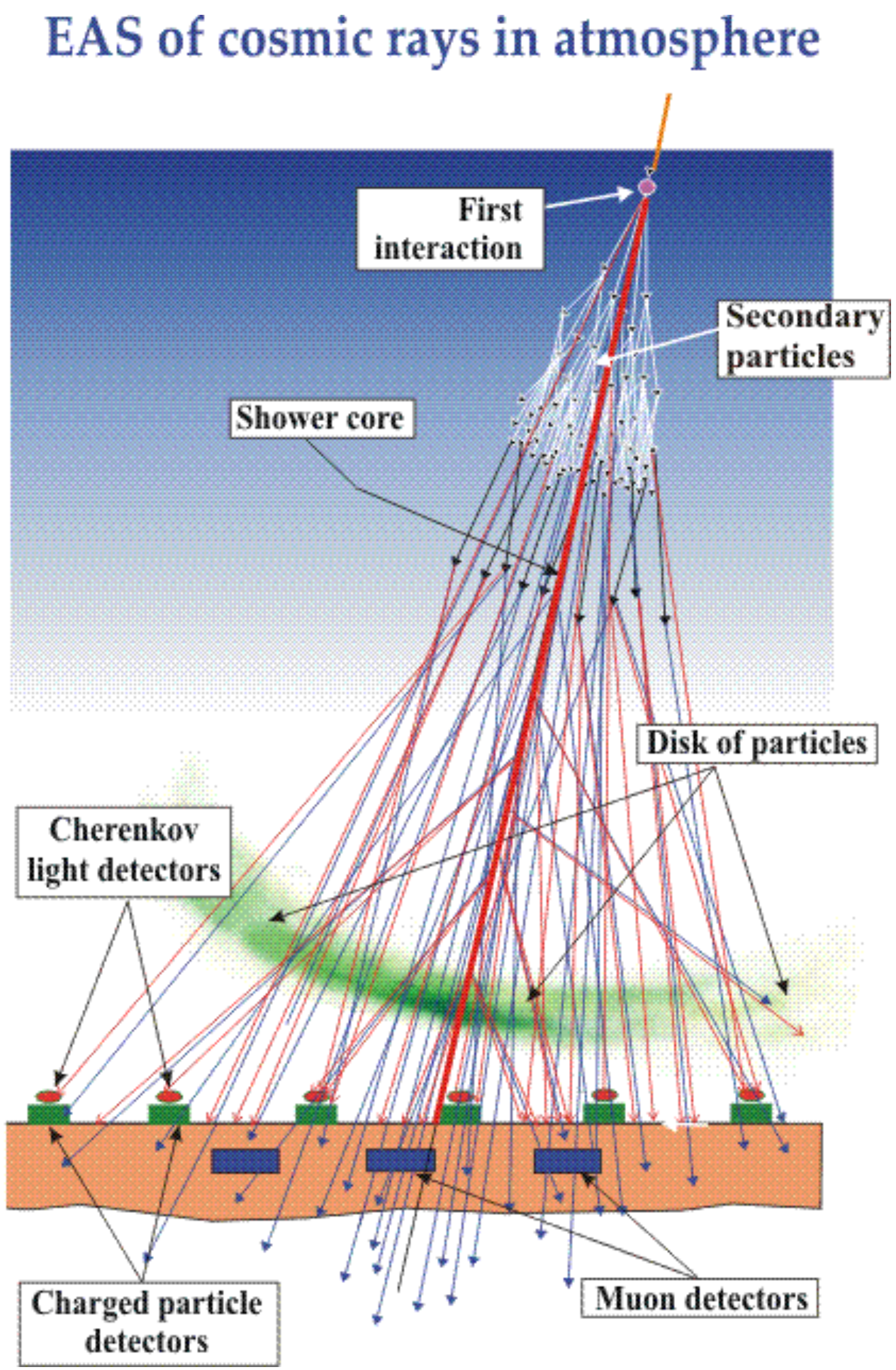
Connections to gamma ray astronomy & neutrino astronomy

- CRs in hit particles in Earth's atmosphere like in accelerators
- High-energy events studied indirectly via particle cascades
- Observables:
  - Relative nuclei abundance: compared to possible sources
  - Energy distribution (spectra): can be characteristic of acceleration
  - Arrival directions: can source be identified?

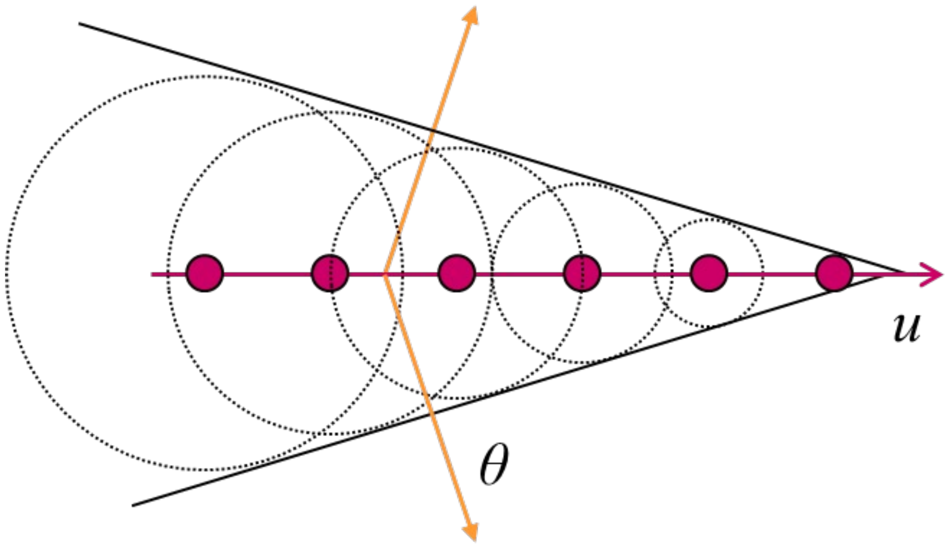


Extensive air showers

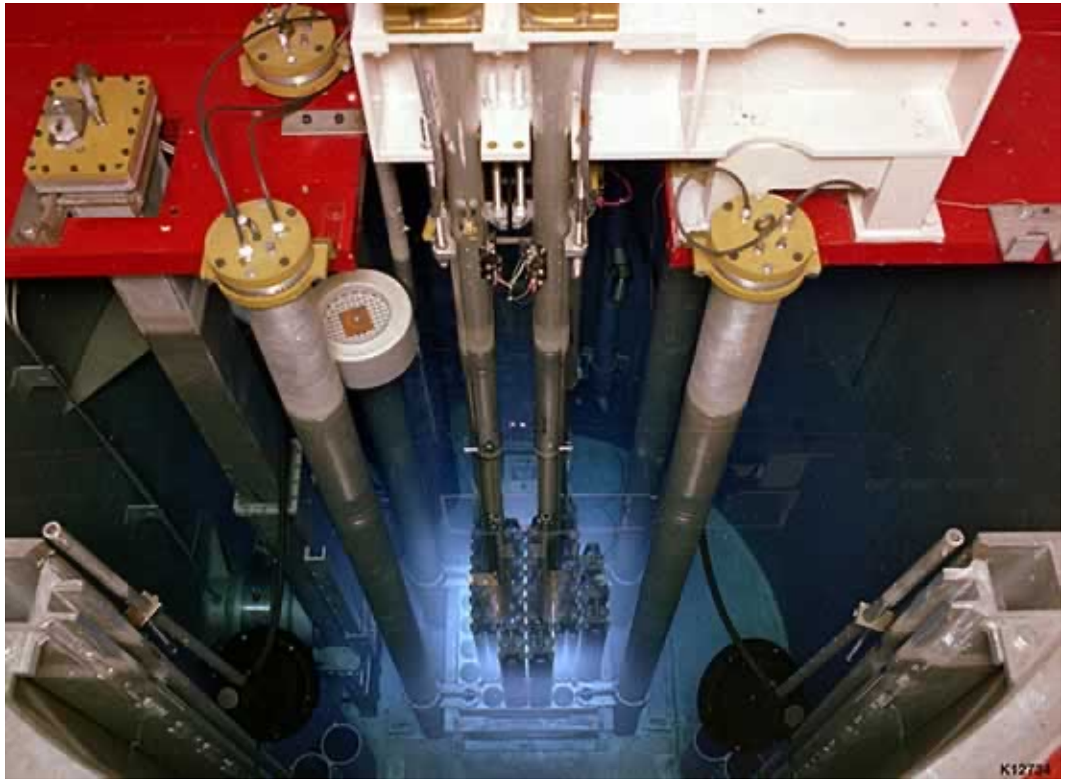


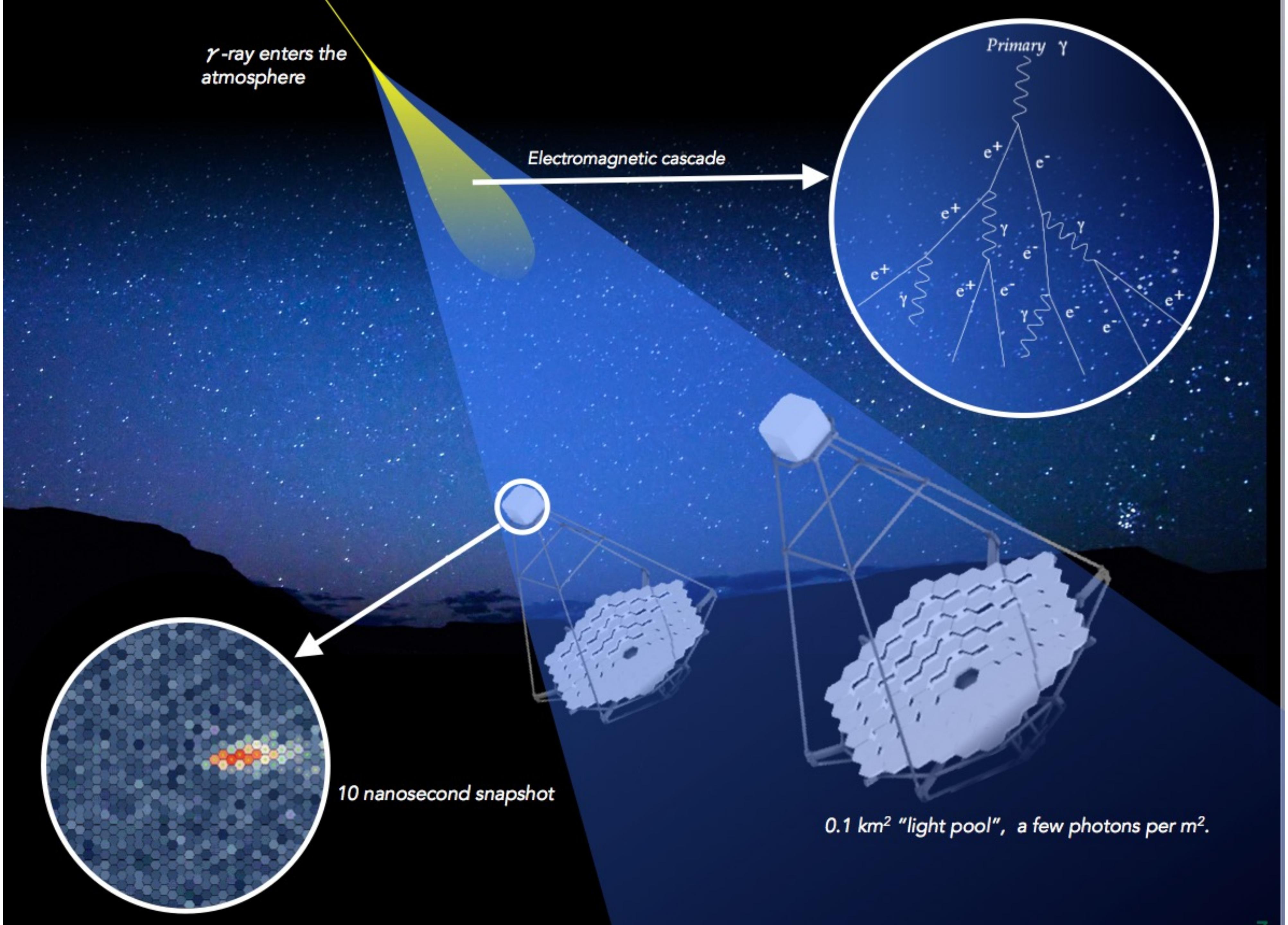


Cerenkov radiation $n = c/v$



- Cerenkov radiation analogous to Sonic boom
- Particle moving at speed exceeding c in medium
- Classical: moving charged particles emit EM waves
- QM: excitation of molecules in polarizable medium re-emit light spherically
- Cone opening angle depends on refraction index of atmosphere n(h)
- $\theta_C = \cos^{-1}\left(\frac{1}{n}\right) \approx 1.3°$ @ standard T&P
- Water: n=1.33: $\theta_C \leq 41.2°$



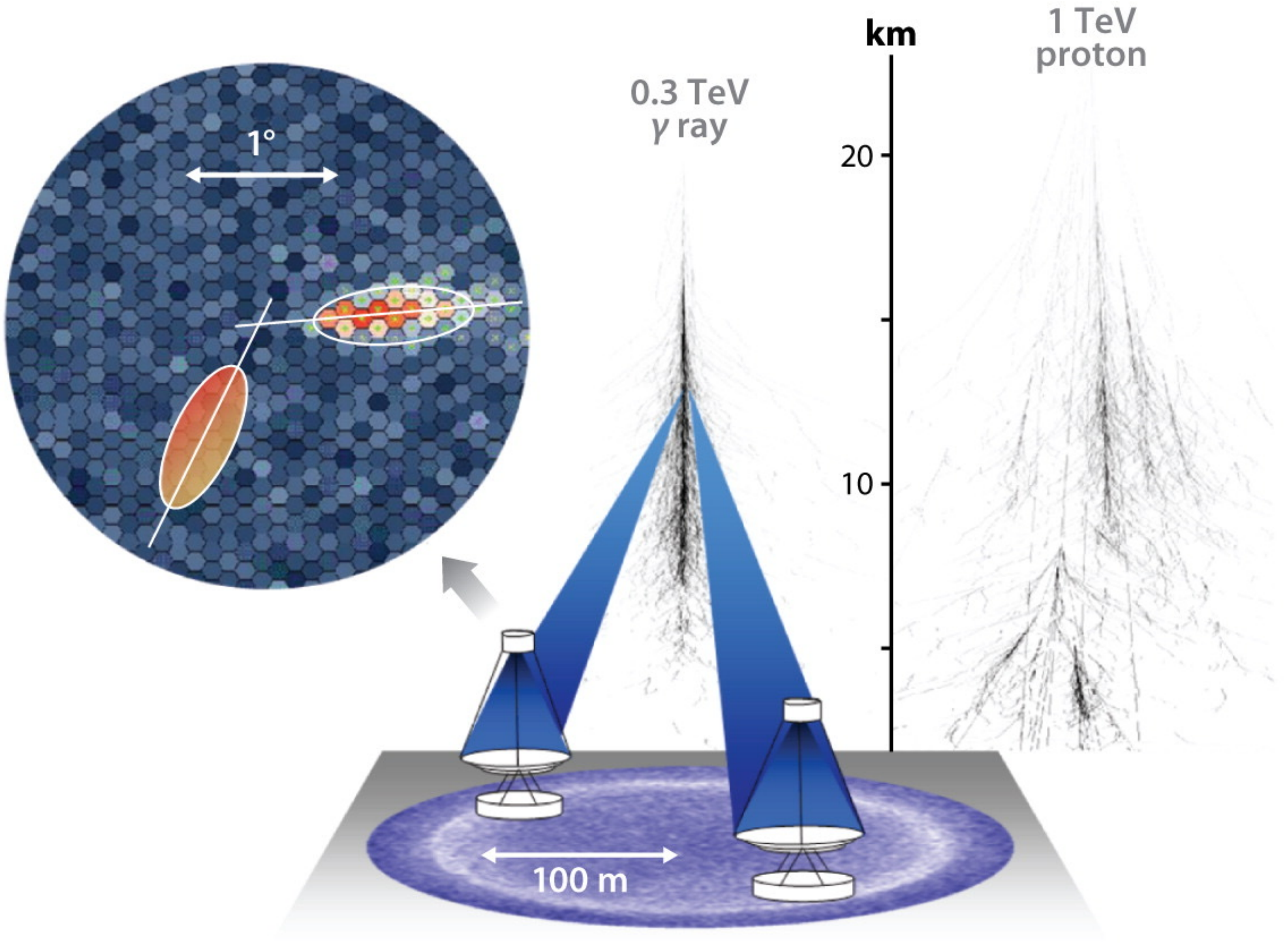


γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
10 nanosecond snapshot
0.1 km² "light pool", a few photons per m².

Stereoscopic TeV astronomy

Hinton & Hofmann (2009)

- Multiple telescopes pinpoint location of shower
- Time resolution!

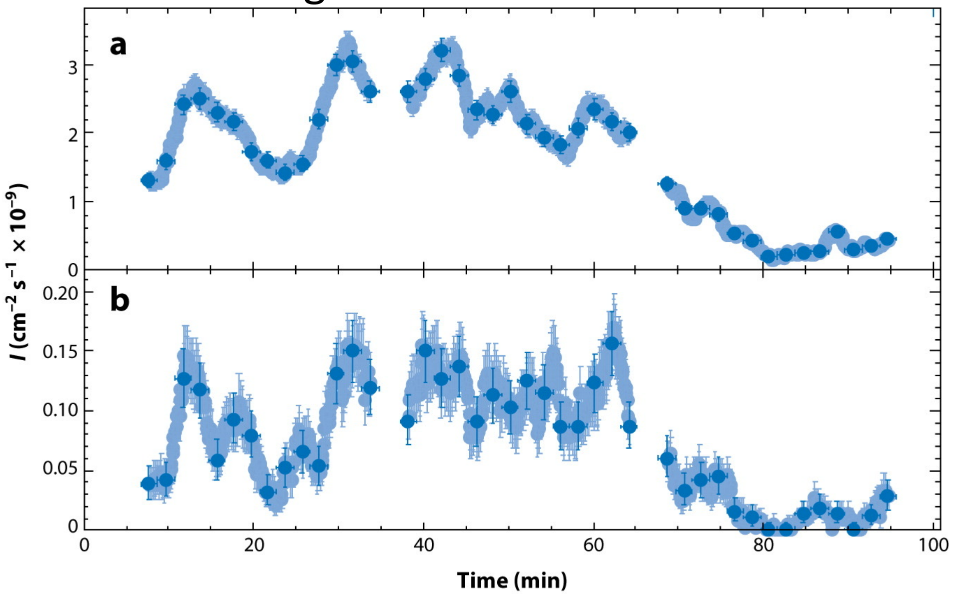


TeV astronomy

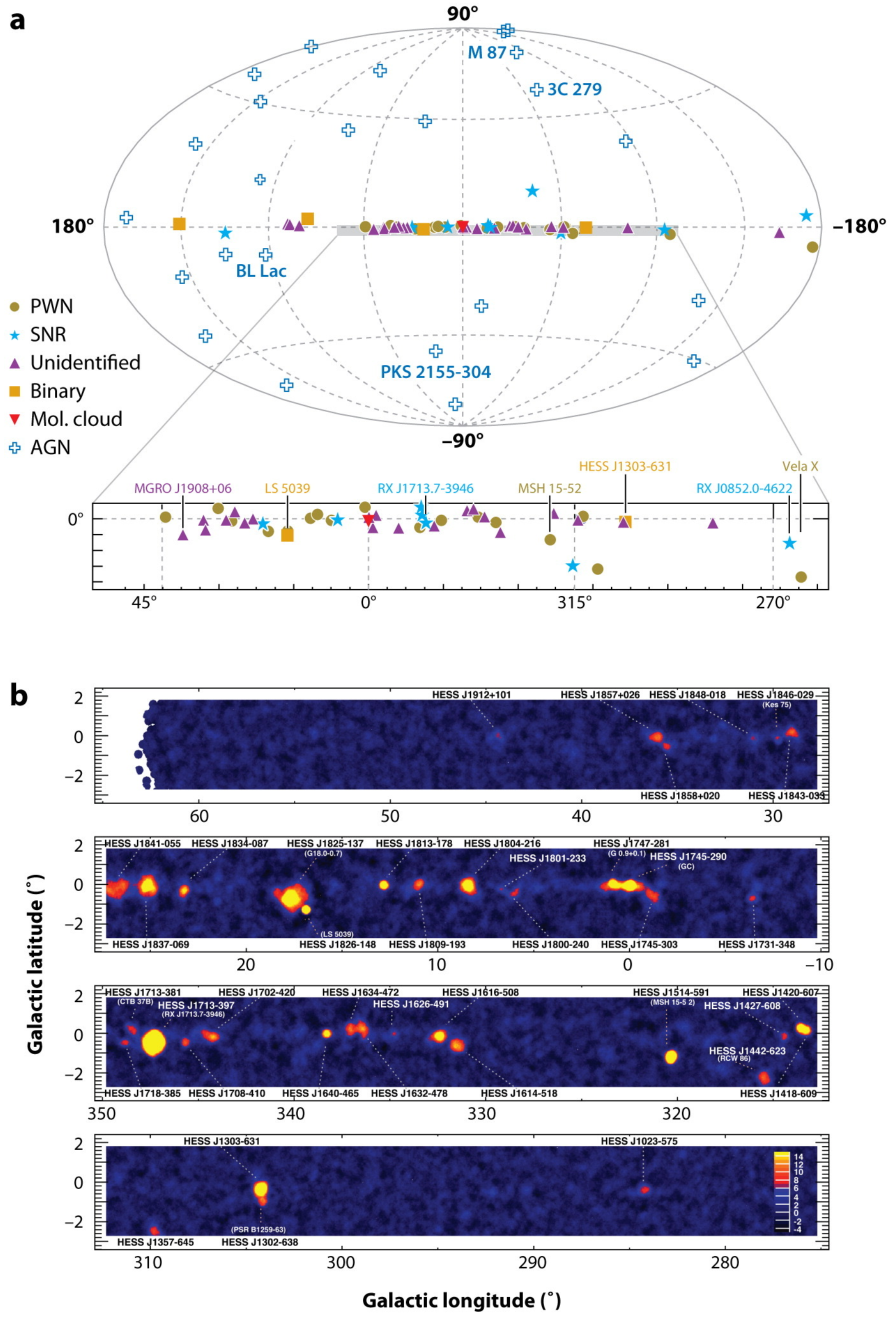
Hinton & Hofmann (2009)

- Probes the very most violent phenomena in the observable Universe

800 GeV “light curve”!



Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65



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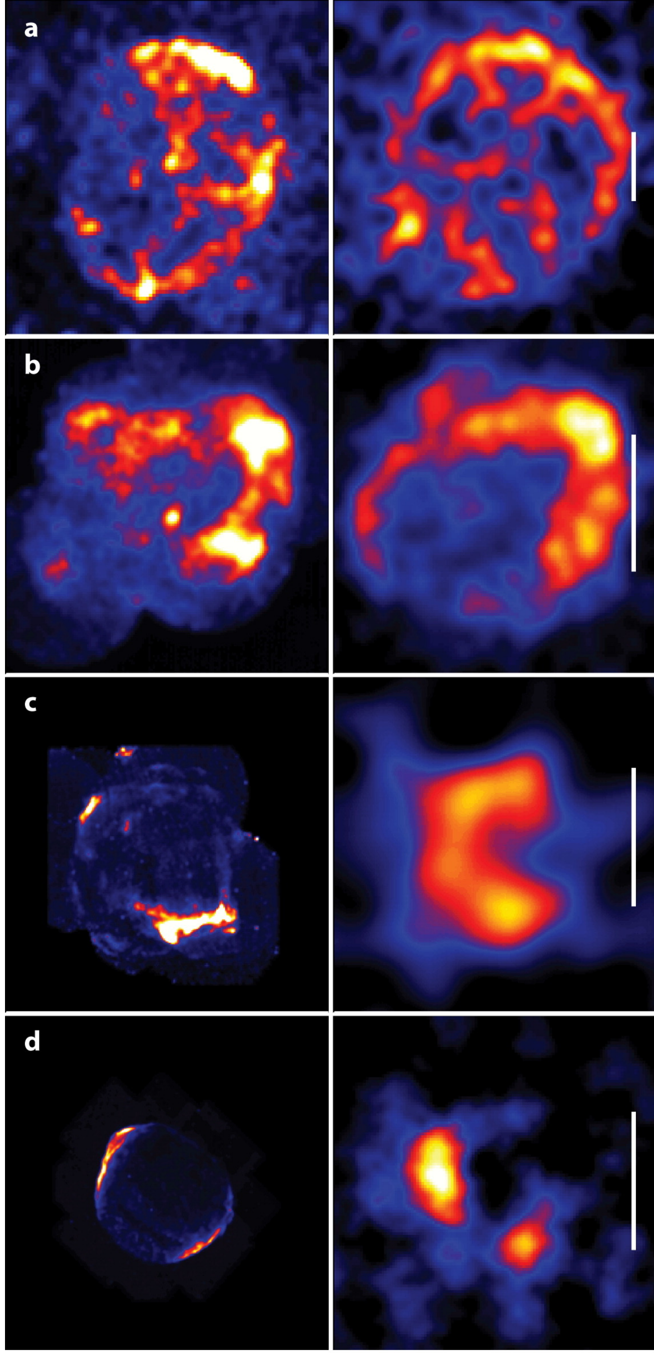


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

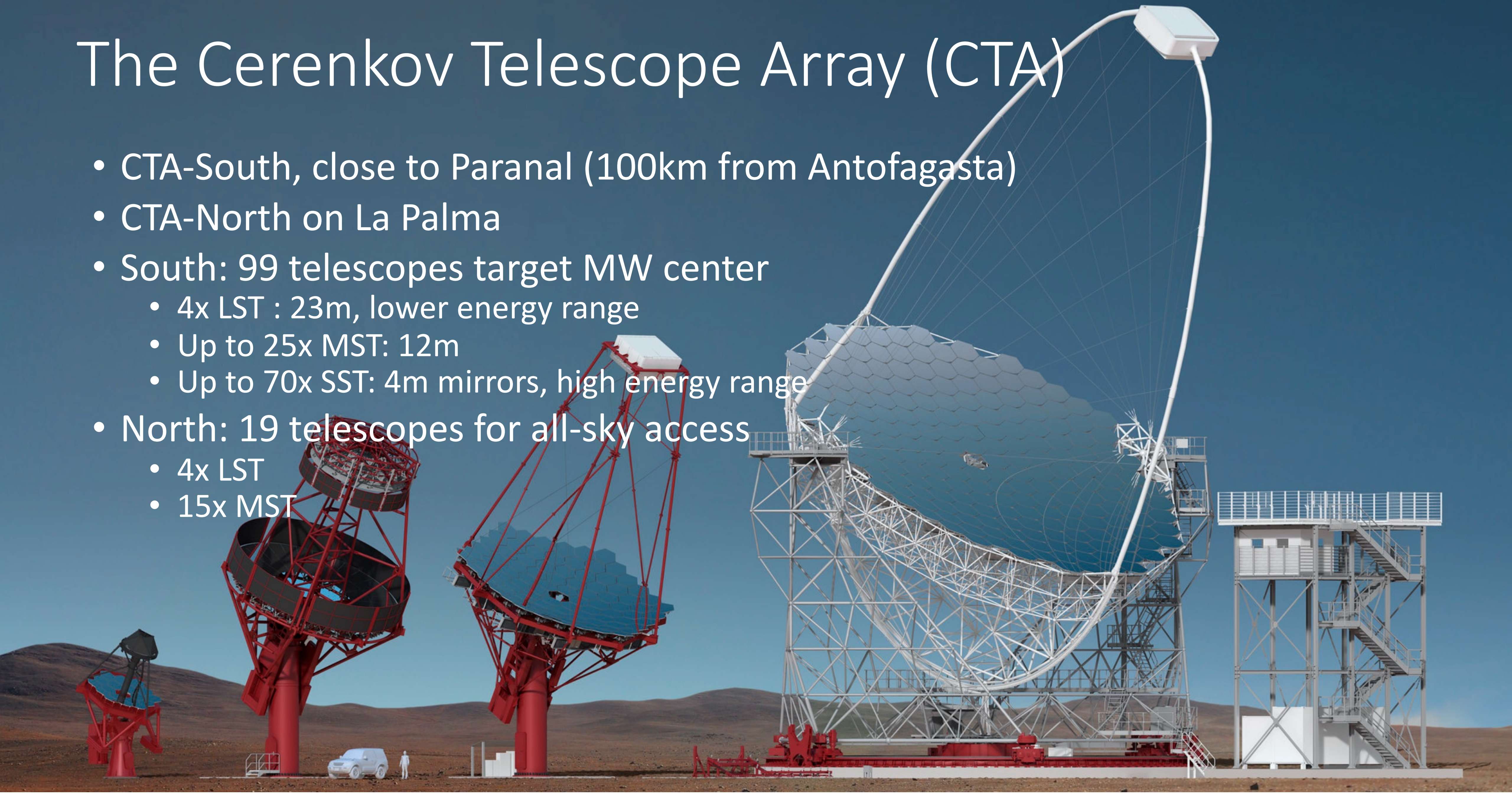
Imaging Cerenkov telescopes

- Large area mirrors + segmented photomultiplier camera
- Can only operate on moon-less & clear nights (10% duty cycle)
- What to do with these the rest of the time?

The Cerenkov Telescope Array

The Cerenkov Telescope Array (CTA)

- CTA-South, close to Paranal (100km from Antofagasta)
- CTA-North on La Palma
- South: 99 telescopes target MW center
  - 4x LST : 23m, lower energy range
  - Up to 25x MST: 12m
  - Up to 70x SST: 4m mirrors, high energy range
- North: 19 telescopes for all-sky access
  - 4x LST
  - 15x MST



The CTA in numbers: from black holes to cosmic voids

- 300 Million EUR buys you:
- Nanosecond time resolution
- 1 arcmin resolution at highest energies
- Single photons can be detected
- Energy range 20 GeV to 300 TeV
- 100x speed gain relative to previous TeV telescopes
- Time-domain machine! Two orders of magnitude collecting area increase = 1000x more sensitive in one hour than Fermi-LAT at 30GeV
- Two sites, full sky, sub-array capabilities

CTA synergies

- Complementary for WIMP Dark Matter detection using colliders & direct detection experiments in 200 GeV to 20 TeV range
- Surveys of: quarter-sky extragalactic, full-plane Galactic + LMC
- Key Science Projects:
  - Transients
  - PeV accelerators in MW
  - AGN
  - Star-forming systems
  - Perseus galaxy cluster
- Detections involve optical light: can be used for very different purposes

Transients and the CTA

[CTA science book (2017)]

- Unprecedented sensitivity allows for short-timescale variability search
- Wide FoV crucial for detecting transients
- Gamma Ray Bursts*: stellar collapses or mergers involving neutron stars or black holes
- Galactic transients*: flares from pulsar winds, magnetars, jets, etc.
- X-ray, optical, radio transients*: tidal disruption events, fast radio bursts, SN shock breakouts, etc.
- High-energy neutrino transients*: e.g. clarify origin of cosmic HE neutrinos
- Gravitational wave transients*: with or without EM emission
- Very high energy (VHE) transients: CTA real-time alerts; e.g. GRBs at onset

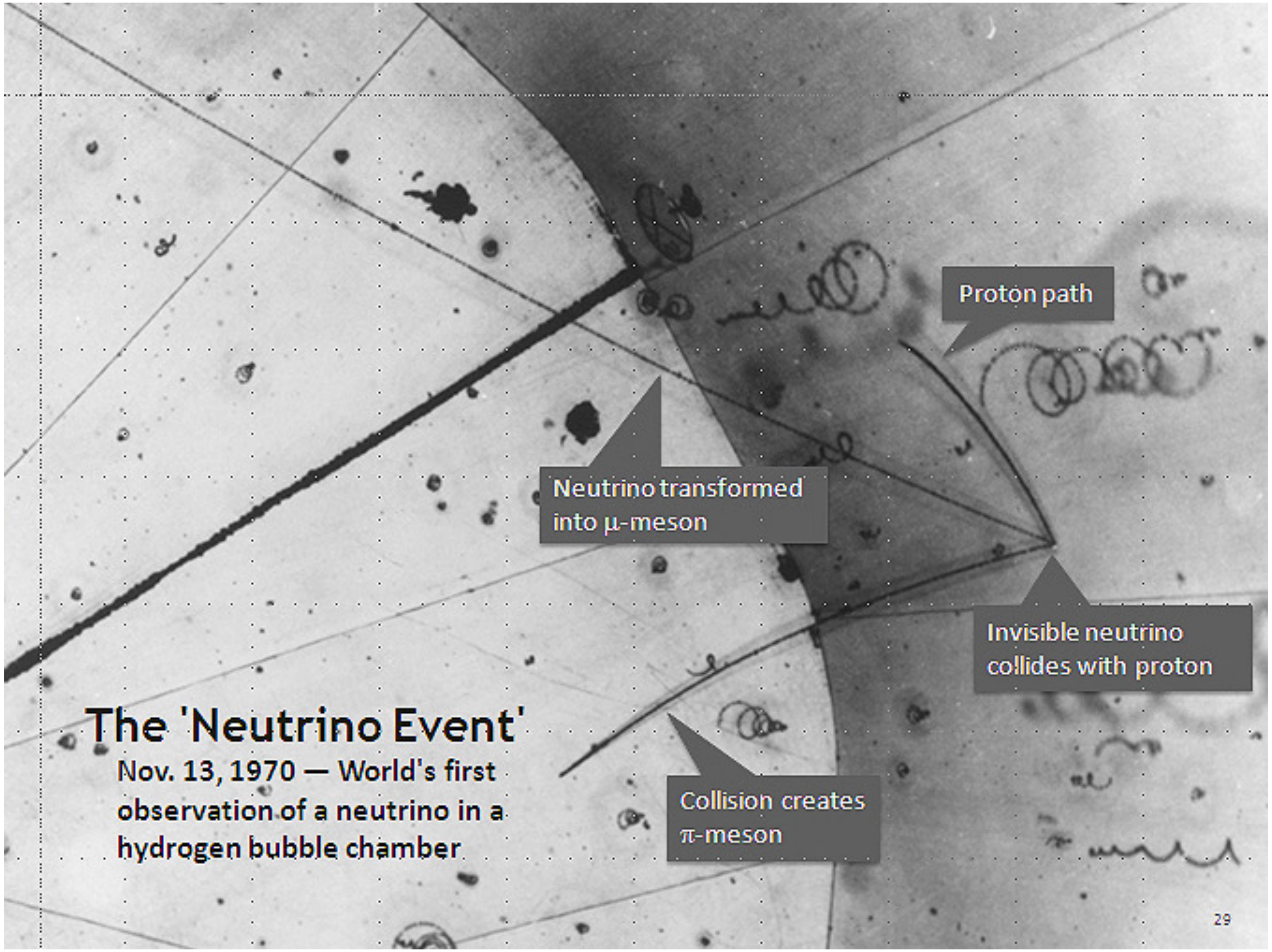
*: based on alerts from external facilities

Optical measurements with CTA

Dravins et al. (2013)

- 10,000 m^2 collecting area spread over a few square kilometers
- Possible use as an optical intensity interferometer
- Intensity is very insensitive to atmospheric conditions
- Telescope optics fairly unimportant
- Correlation of intensities can be done in computer similar to radio interferometry
- Simplifies a lot the interferometer
- Allows for much larger baselines
- At 350nm, CTA resolution ca $30\mu as$: 100x better than GRAVITY (3mas)!

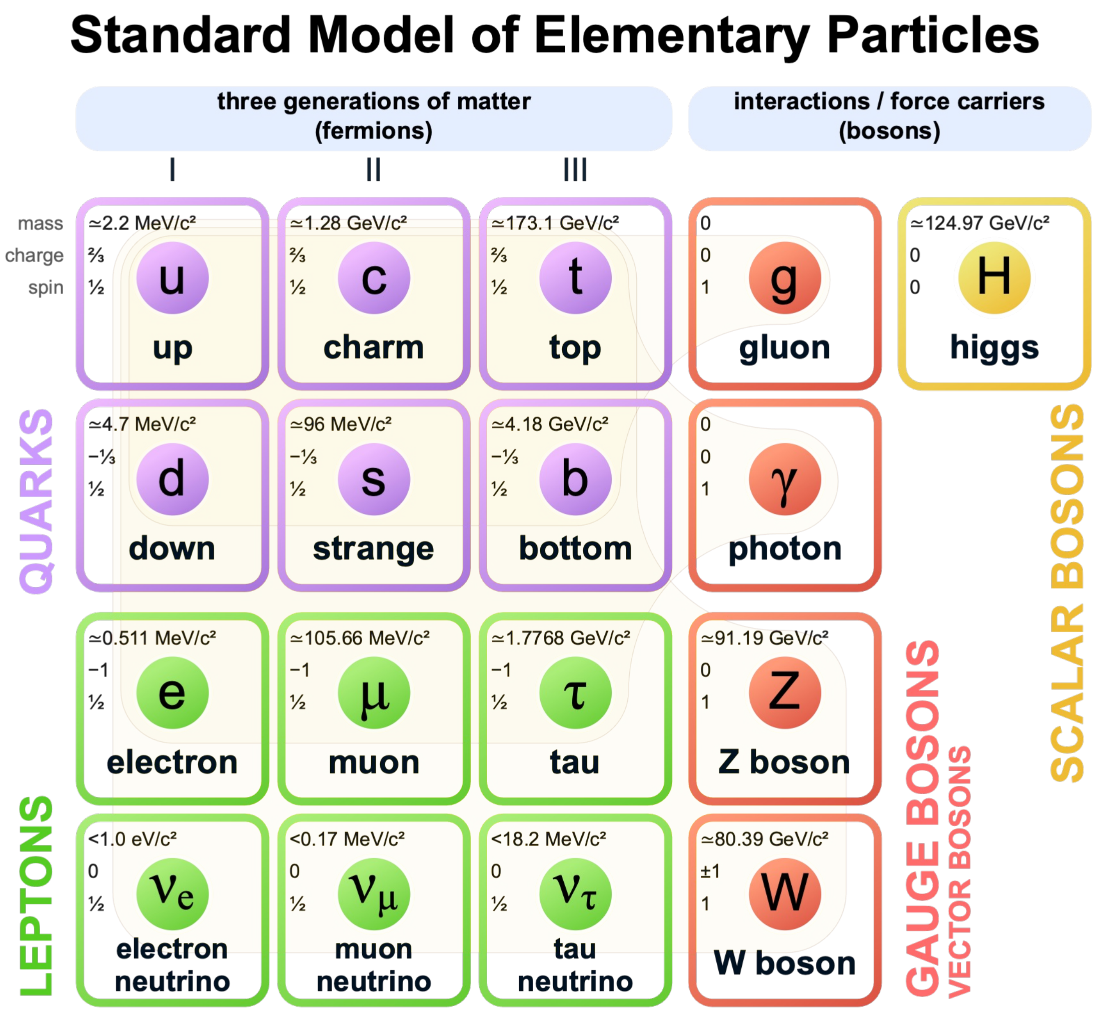
Neutrinos



Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
Collision creates π-meson
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
29

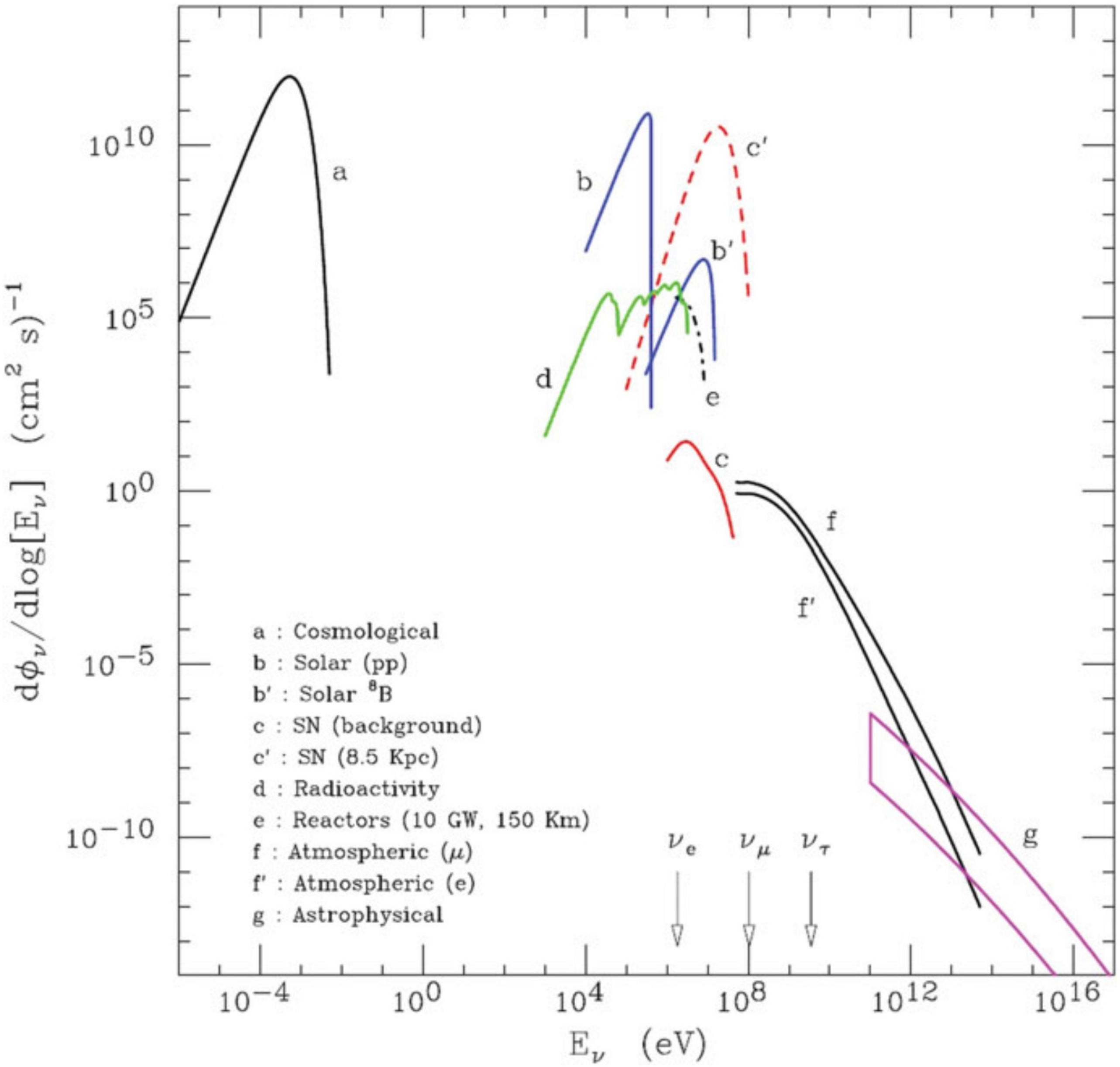
Neutrinos

- Pauli: neutrinos required to maintain momentum conservation in beta decay: $n^0 \rightarrow p^+ + e^- + \overline{\nu}_e$
- Neutrinos are fermions (spin ½)
- Interact only via electroweak force & gravity
- First detected in 1956 by Fred Reines and George Cowan

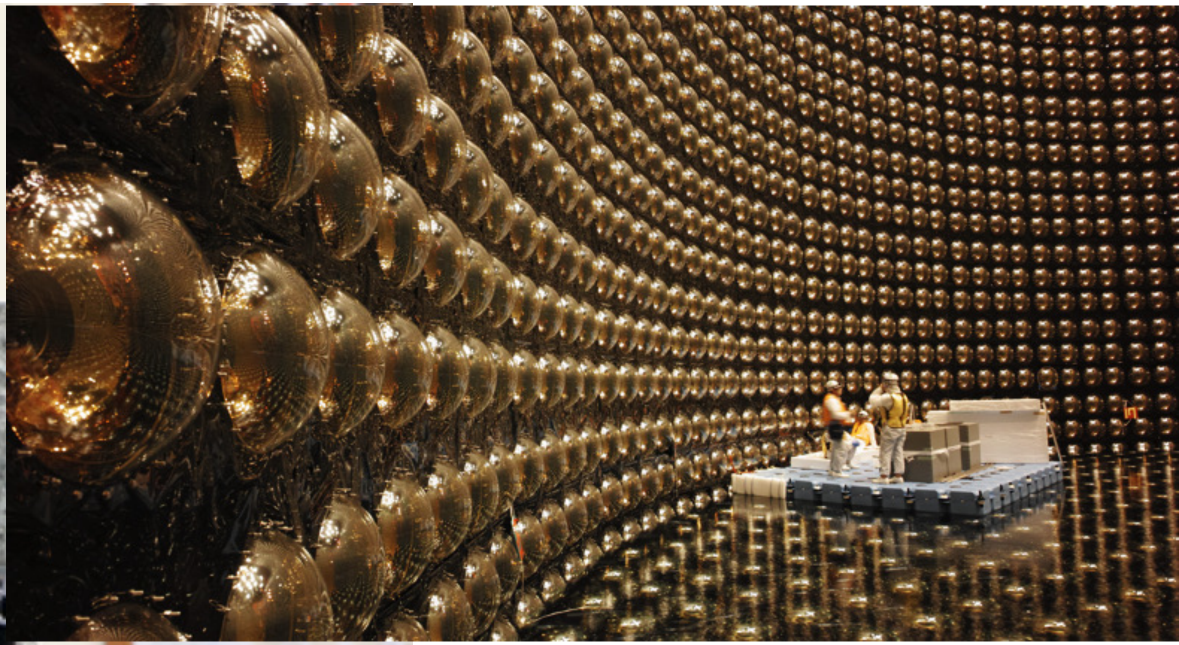


Astrophysical & cosmological neutrino sources

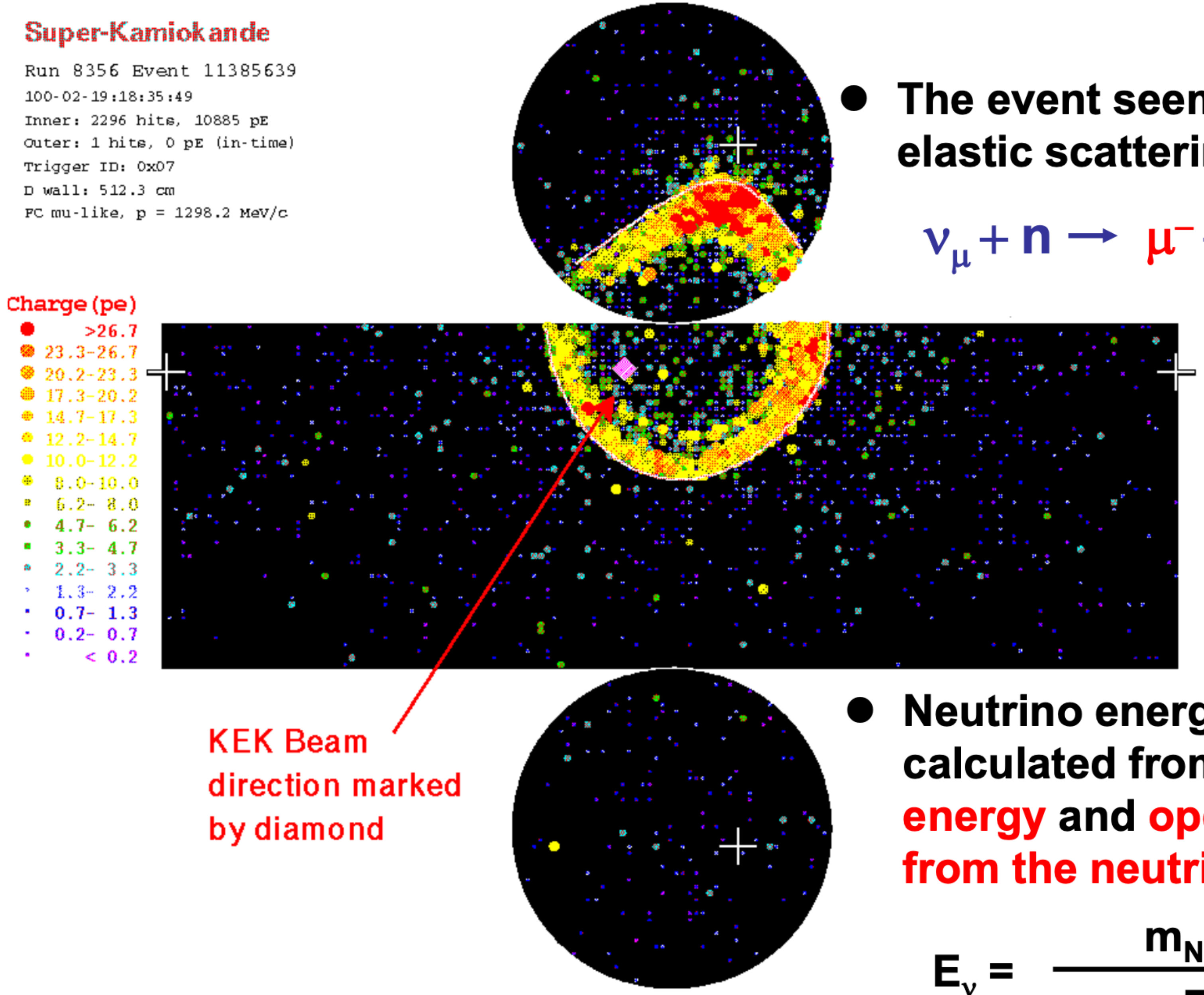
- Fusion in Sun and stars
- Atmospheric decay of cosmic rays
- Supernova remnants
- Supernova explosions
- Other particle accelerators
- Cosmic Neutrino Background $C\nu B$



From KamiokaNDE to Hyper-Kamiokande



A typical K2K neutrino event in Super-Kamiokande



- The event seems to be quasi-elastic scattering interaction;

$$\nu_\mu + n \rightarrow \mu^- + p$$

- Neutrino energy can be calculated from muon energy and opening angle from the neutrino direction.

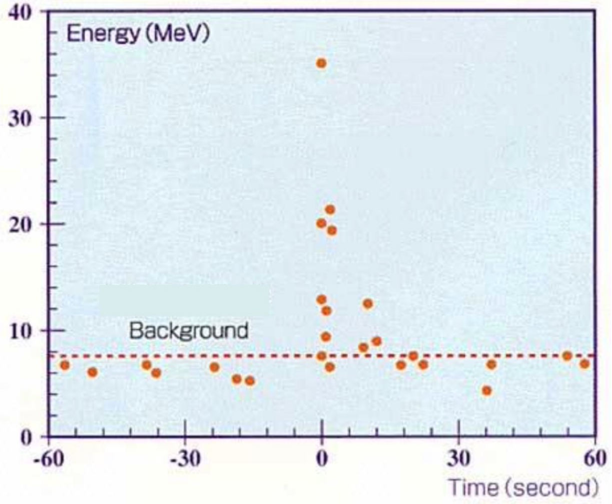
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_{\mu\text{-}\nu}}$$

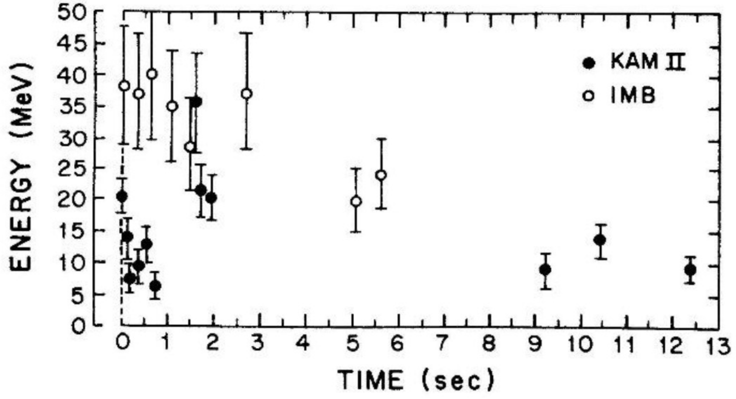
SN1987A – the Multimessenger era is born

Neutrino burst from 1987A as a fundamental success of theoretical physics

Podsiadlowski (2017)

- Kamiokande started observations of Solar neutrinos in early January 1987
- February 25, 1987: SN1987A in the LMC
- Kamiokande: 11 neutrino events in 13 s
- IMB group found another 8 neutrinos 20-40 MeV in 6s
- Kamiokande + IMB both on Northern Hemisphere: neutrinos had to pass through Earth
- Electron scattering: $\nu + e \rightarrow \nu' + e'$ (dominant for Solar ν)
- Antineutrino absorption: $\bar{\nu_e} + p \rightarrow n + e^+$ (dominant in stellar collapses)





The SN1987A neutrino burst

- Neutrinos arrived ~3h before SN became optically visible = shock travel time to progenitor surface
- Assuming 3 light neutrino species: $E_\nu = 2.5 \pm 1.5 \times 10^{46}\ J$, close to expected binding energy of neutron star (10% of rest mass 1.4 Msol)
- Neutrino emission over 12s, much longer than collapse time (<1s)
- Two timescales: initial collapse (~20 ms, 1% of energy) and thermal cooling of proto-neutron star (order of seconds, most of the rest)
- Proof that neutron star was initially formed; still not found observationally! (Alp et al. 2021)

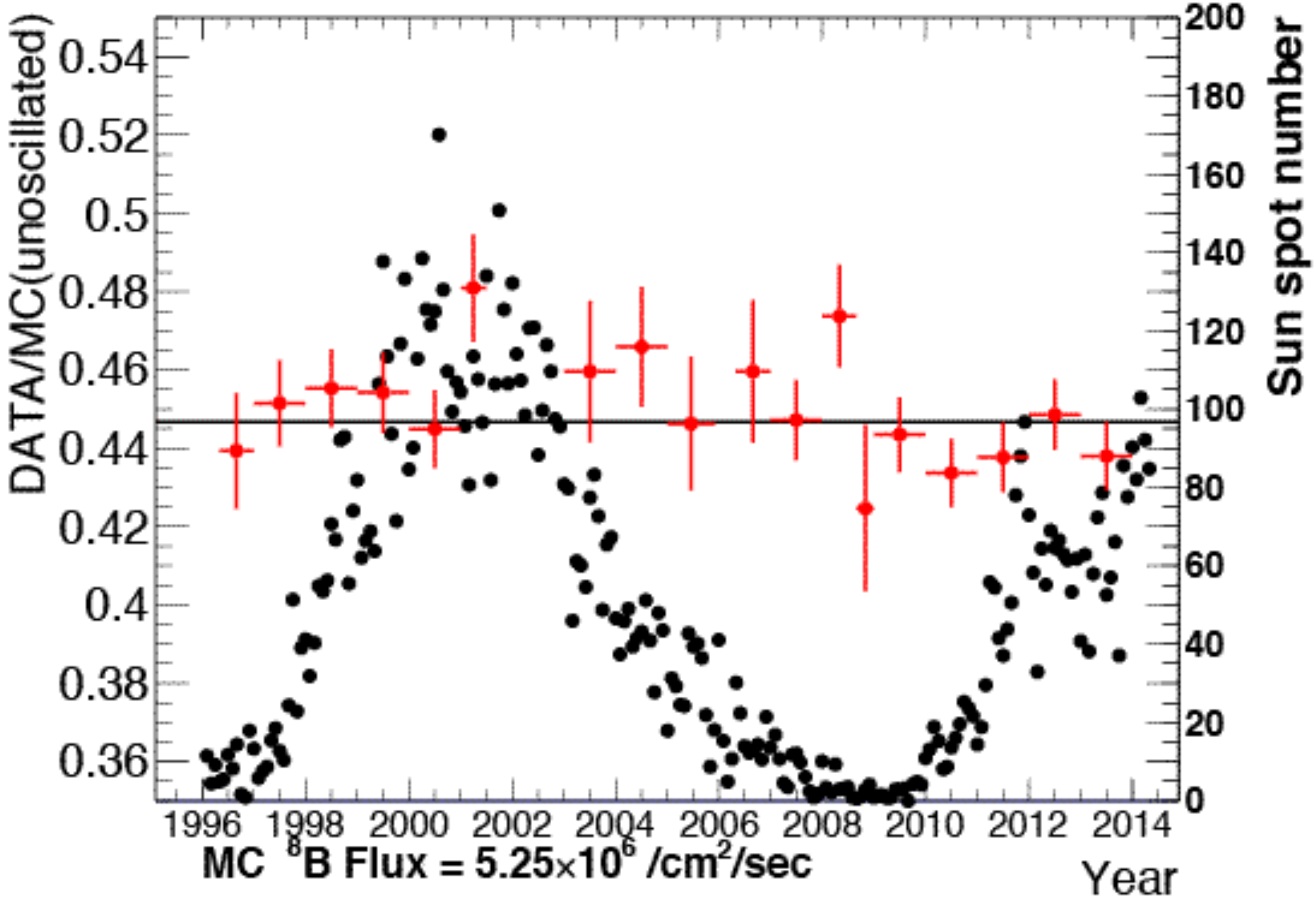
Arnett et al. (1989)

Table 3 Measured properties of neutrino events observed in water Cherenkov detectors[a]

Event	Event time (s)	Electron energy (MeV)	Electron angle (degrees)
Kamiokande II:			
1	0.0	20.0 ± 2.9	18 ± 18
2	0.107	13.5 ± 3.2	40 ± 27
3	0.303	7.5 ± 2.0	108 ± 32
4	0.324	9.2 ± 2.7	70 ± 30
5	0.507	12.8 ± 2.9	135 ± 23
6	0.686	6.3 ± 1.7	68 ± 77
7	1.541	35.4 ± 8.0	32 ± 16
8	1.728	21.0 ± 4.2	30 ± 18
9	1.915	19.8 ± 3.2	38 ± 22
10	9.219	8.6 ± 2.7	122 ± 30
11	10.433	13.0 ± 2.6	49 ± 26
12	12.439	8.9 ± 1.9	91 ± 39
IMB:			
1	0.0	38 ± 7	80 ± 10
2	0.41	37 ± 7	44 ± 15
3	0.65	28 ± 6	56 ± 20
4	1.14	39 ± 7	65 ± 20
5	1.56	36 ± 9	33 ± 15
6	2.68	36 ± 6	52 ± 10
7	5.01	19 ± 5	42 ± 20
8	5.58	22 ± 5	104 ± 20

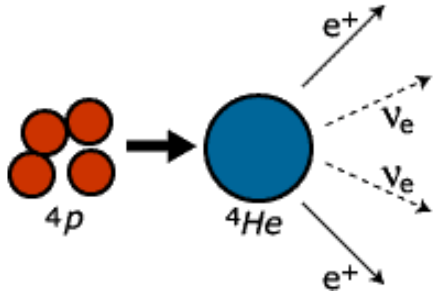
[a] The first events were detected on February 23, 1987, at about 7 hr 36 m UT. The angle in the last column is relative to the direction of the LMC. The errors are estimated 1σ uncertainties.

Solar Neutrinos independent of Solar activity

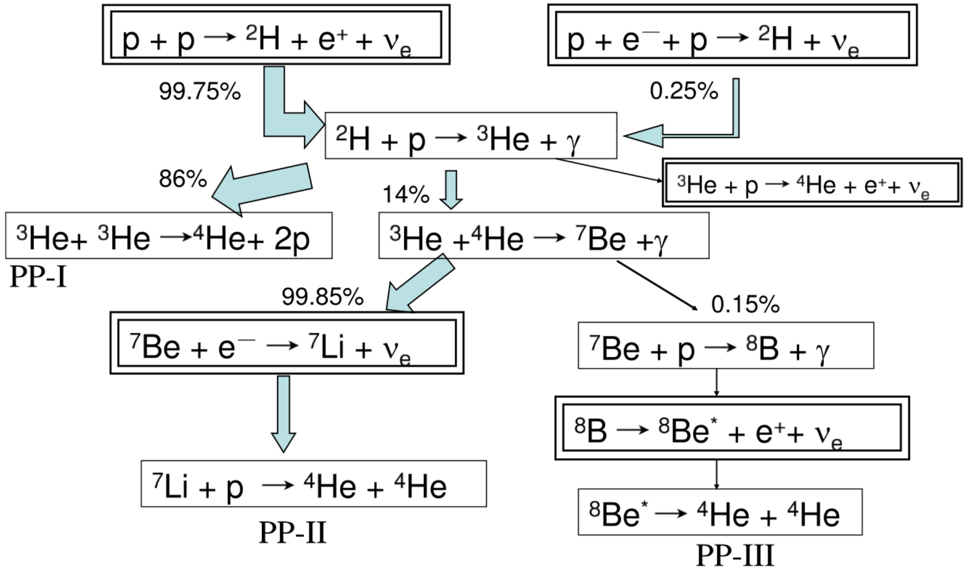


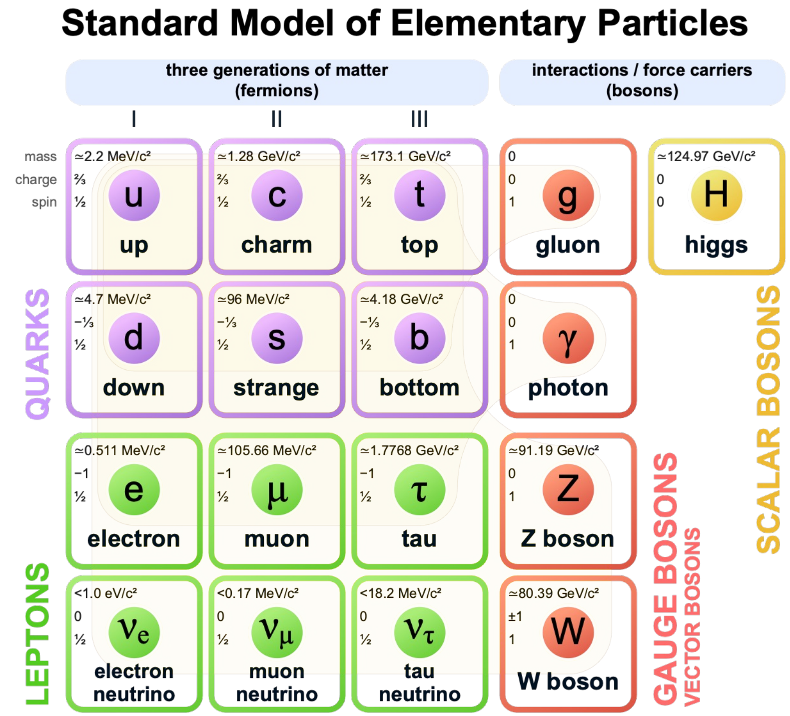
The Solar Neutrino Problem

Solar neutrinos



- Sun's energy source (pp-chain): 4p -> ^{4}He + 2e$^+$ + 2ν_e
- Neutrinos known to exist in three flavors: ν_e, ν_μ, ν_τ
- 1968: Raymond Davis Jr & John N. Bahcall detected only 1/3 expected neutrinos in Homestead underground tank
- Expectations miscalculated? Experiment wrong? Neutrino physics?
- 1969: Bruno Pontecorvo & Vladimir Gribov predicted flavor oscillations, but not initially taken very seriously
- Kamiokande: more neutrinos than Davis, 50% expected
- Sudbury Neutrino Observatory: 1/3 are ν_e, sum of all neutrino flavors is 100% of expected
- KamLAND: confirmed flavor oscillations by observing nuclear reactor neutrinos





Neutrino oscillations

- Solved the Solar neutrino problem
- Irrefutable evidence for thermonuclear fusion in Solar core
- Extremely sensitive test of core temperature: 1% error : 30% change in neutrino flux (Tunnel effect)
- Imply that neutrinos have mass!
- Standard Model assumes neutrinos are mass-less and resolution is not simple (and beyond the scope here)

Two Neutrino Nobel Prizes

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."

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."

The Nobel Prize in Physics 2002

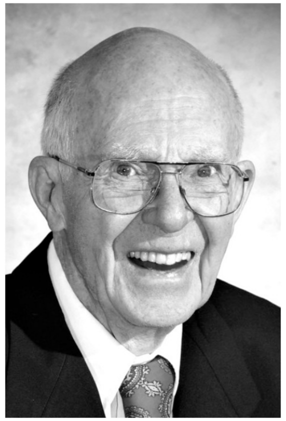


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

Photo from the Nobel Foundation archive.

Masatoshi Koshiba

Prize share: 1/4

Photo from the Nobel Foundation archive.

Riccardo Giacconi

Prize share: 1/2

The Nobel Prize in Physics 2015

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

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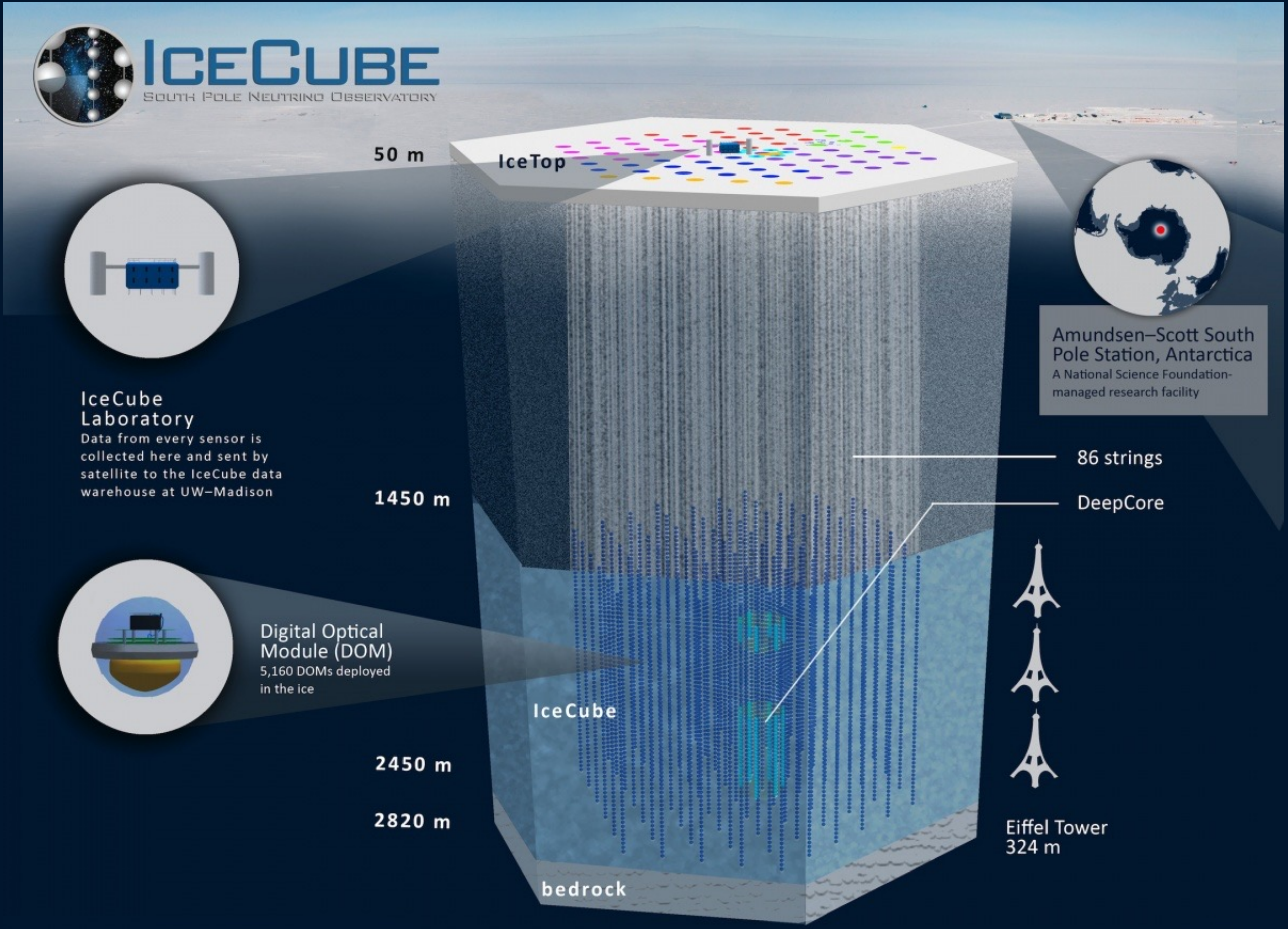
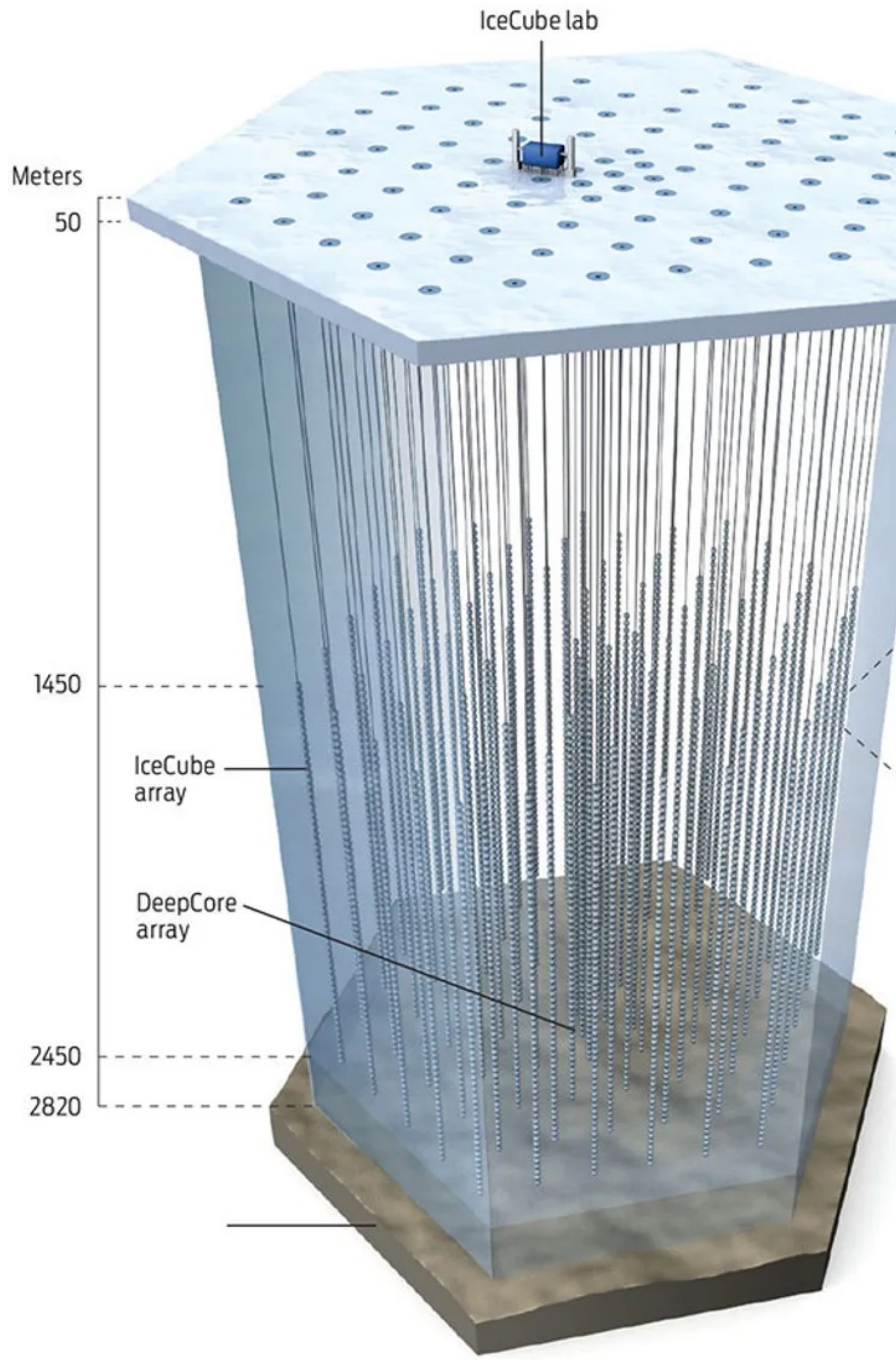
Arthur B. McDonald

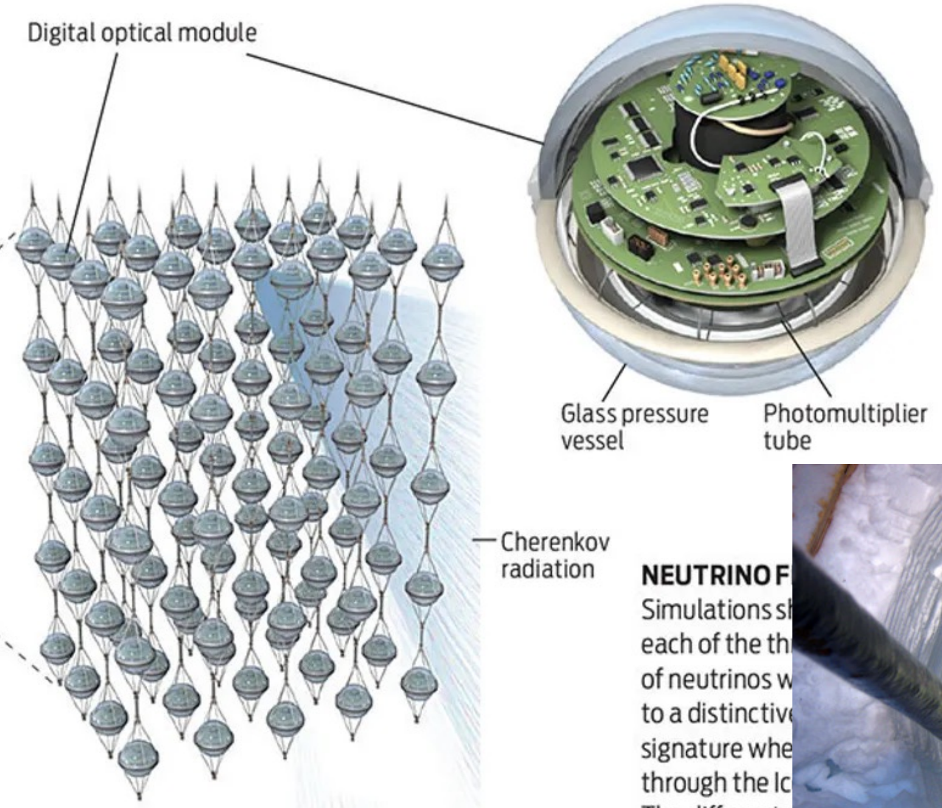
Prize share: 1/2

IceCube – the world's largest Neutrino detector


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data from every sensor is collected here and sent by satellite to the IceCube data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube
2450 m
2820 m
bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
86 strings
DeepCore
Eiffel Tower
324 m



ELECTRONIC PEARLS: The digital optical modules used to sense the passage of neutrinos through the ice are encased in spherical pressure vessels made of borosilicate glass. They are attached to their suspending cables at 17-meter vertical intervals, from 1450 to 2450 meters' depth. After a string has been deployed and tested, the surrounding water (left over from drilling the hole) freezes the detectors in place.



NEUTRINO F
Simulations sh
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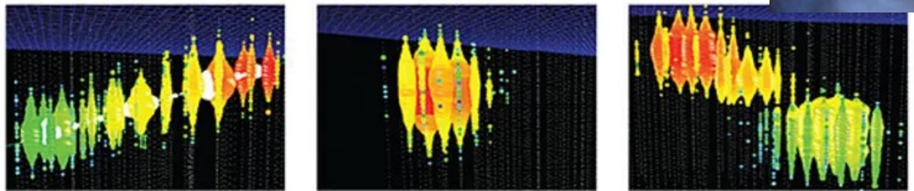
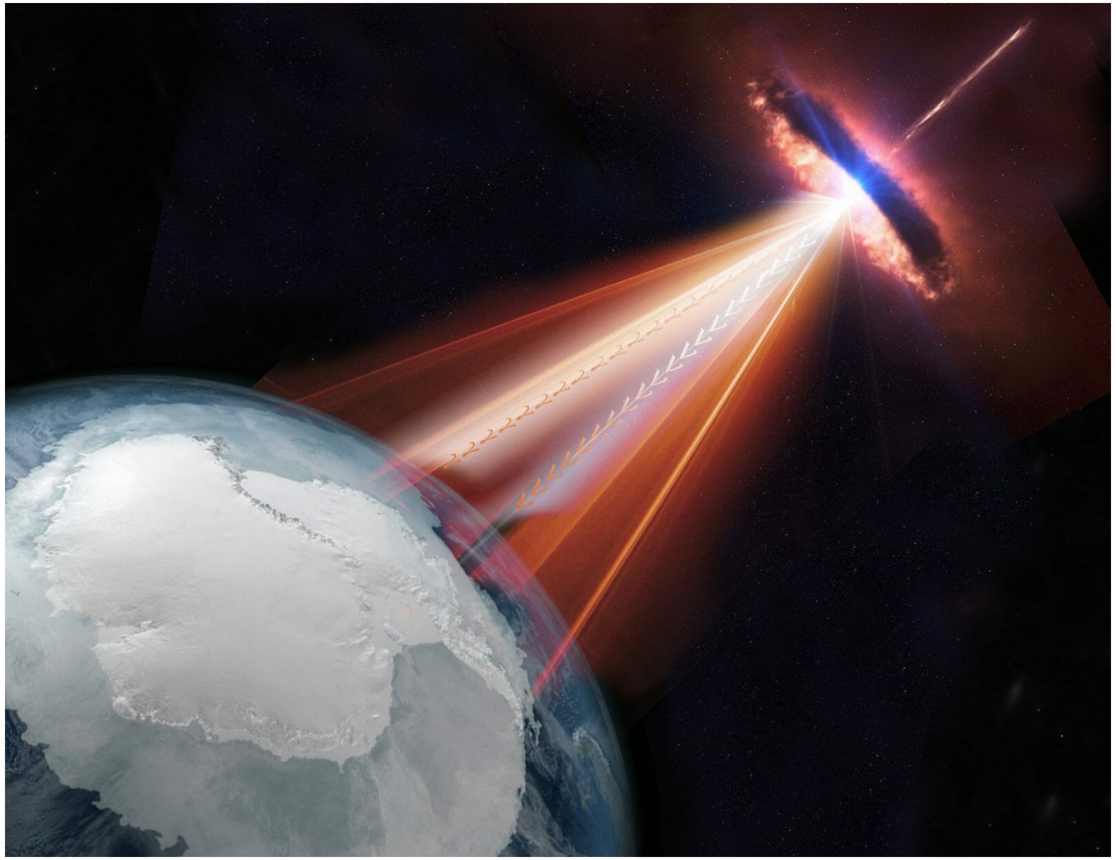


IceCube neutrino alerts

IceCube Collaboration (2013)

- In 2013, IceCube reported VHE neutrinos up to 1 PeV (1000 TeV) of extraterrestrial origin without identifying source
- Just like Fermi-LAT, ZTF, etc. IceCube notifies community about neutrino events to enable multi-messenger studies
- Goal: study highest-energy phenomena using Neutrinos, cosmic rays, gamma rays, x-rays, and the broadest EM spectrum
- Most detected neutrinos come from cosmic rays interacting with atmosphere (< 100 TeV)
- At higher energies, astrophysical origins more likely & easier to identify

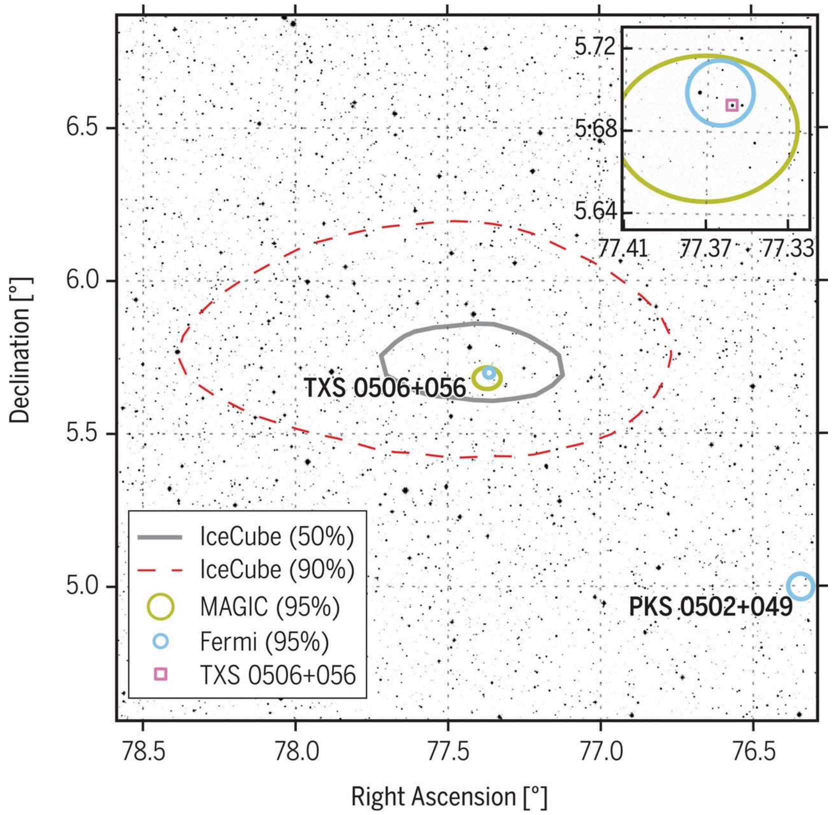


A neutrino from Blazar TXS 0506+056

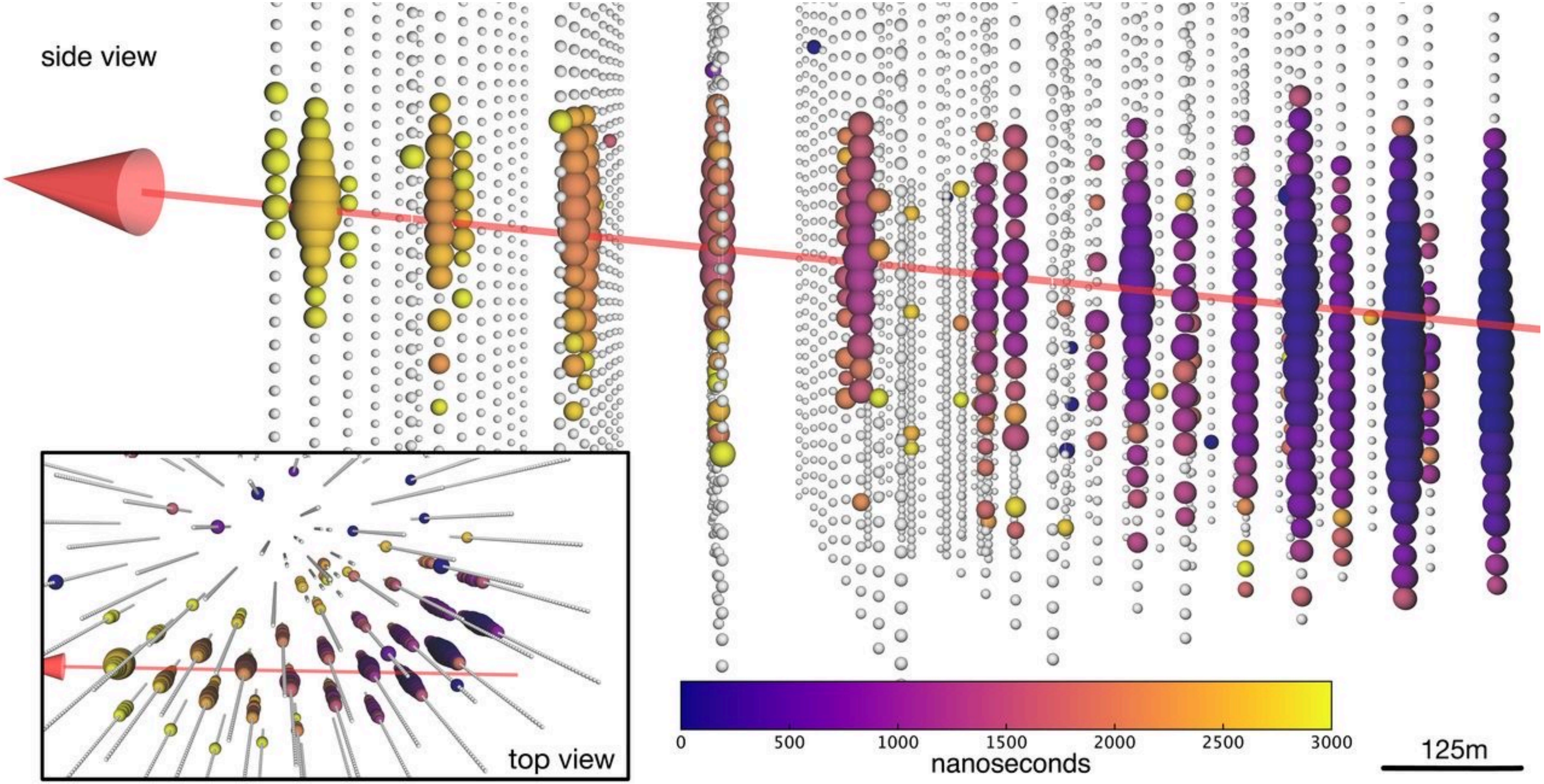
Gamma-ray flare prompted multi-wavelength campaign; IceCube collaboration found neutrinos over previous several years

BL Lacertae object TXS0506+056 (Blazar)

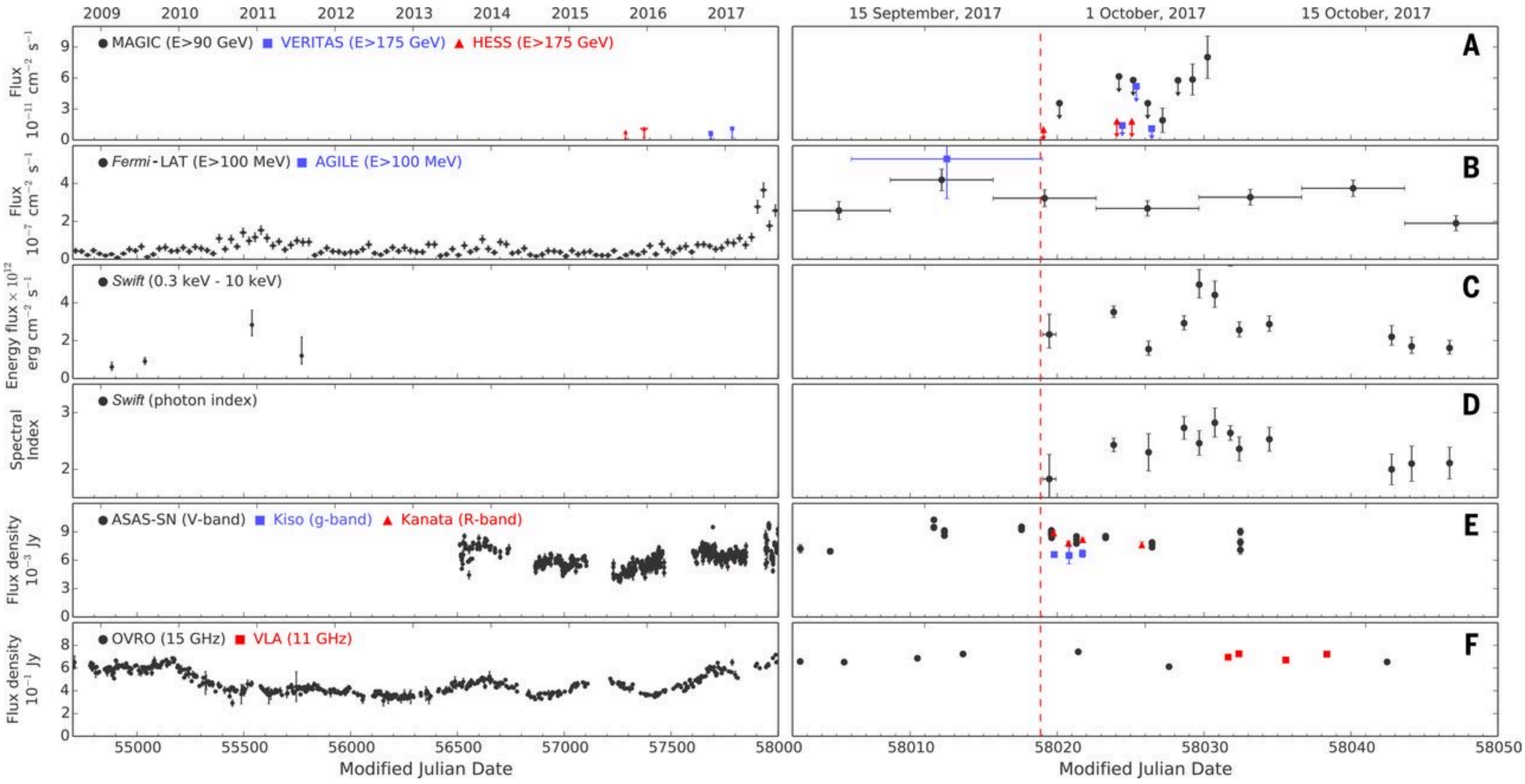
- BL Lacs: highly variable AGN with strong optical polarization
- Compared to Quasars, BL Lac spectra rather featureless with non-thermal emission across entire EM spectrum
- Blazars: intense extragalactic radio, optical, x-ray, & even γ-ray sources characterized by relativistic plasma jets oriented close to line of sight
- Among most powerful objects in the Universe
- This one at z=0.3365 (2 Gyr lookback time)
- Likely source of high-energy cosmic rays that decay to high-energy neutrinos
- 22 September 2017: IceCube detected a muon track induced by a ~290 TeV neutrino
- 28 Sep 2017: Fermi reported blazar in flaring state in GeV range; MAGIC found gamma-ray flux reaching up to 400 GeV
- Locations all coincide at 3 sigma + muon-neutrino luminosity ~ x-ray luminosity



290 TeV ν_μ: 56.5% likelihood of astrophysical origin

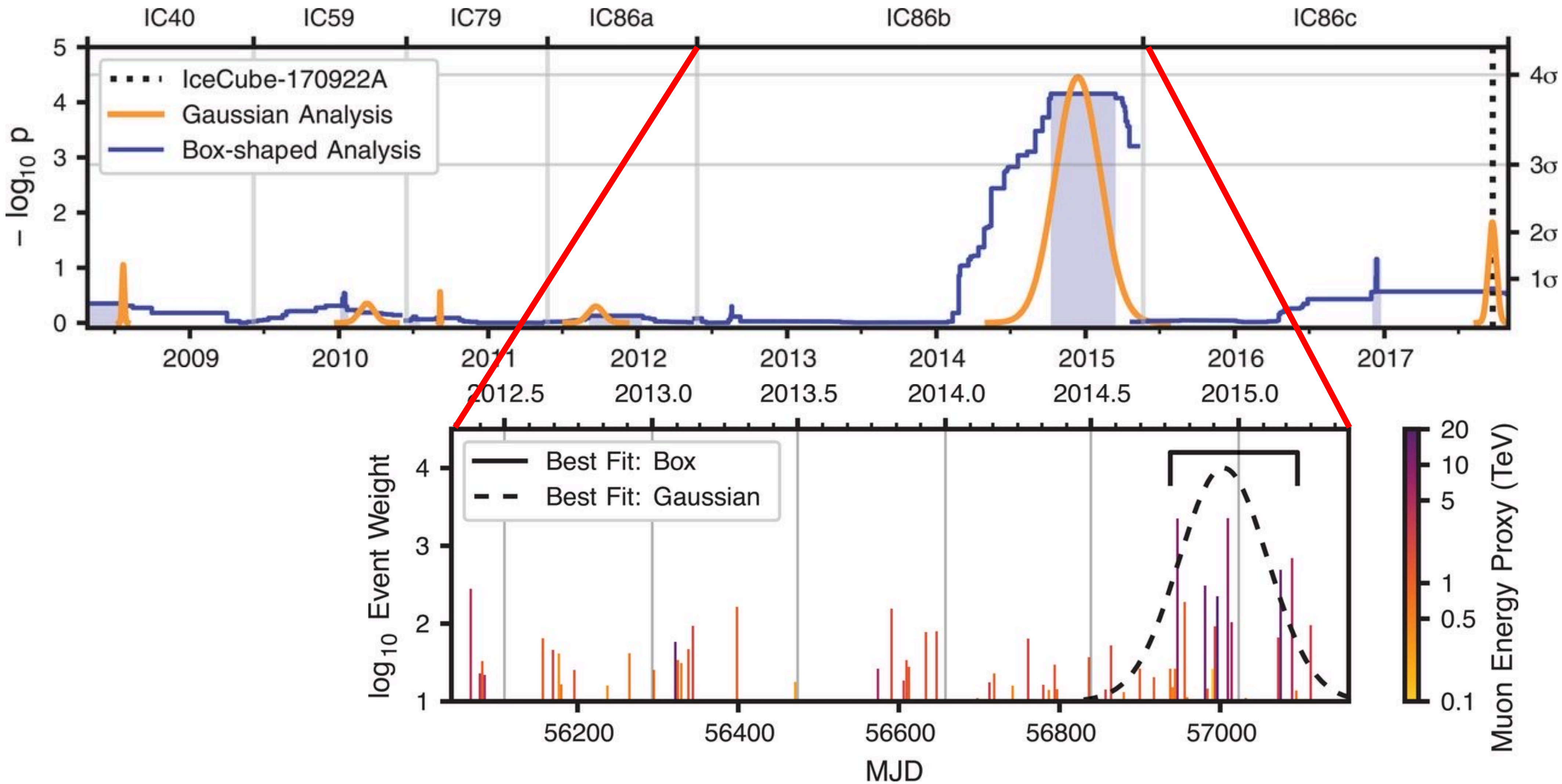


Blazar was in excited state at this time



Precovering 13 neutrinos from the blazar

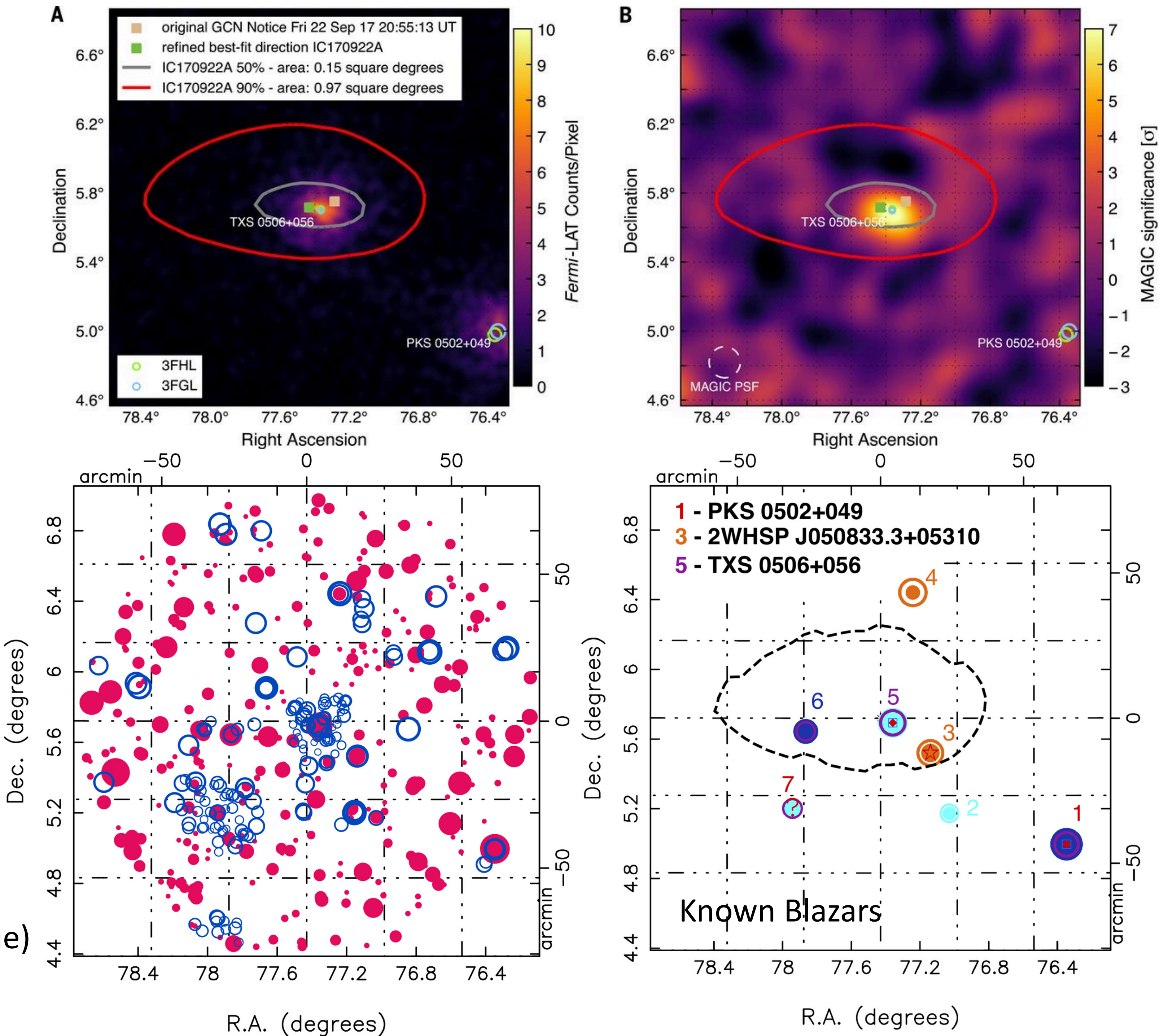
IceCube Collaboration (2018)   Padovani et al. (2018)



Pinpointing the source

[Padovani et al. (2018)](#)

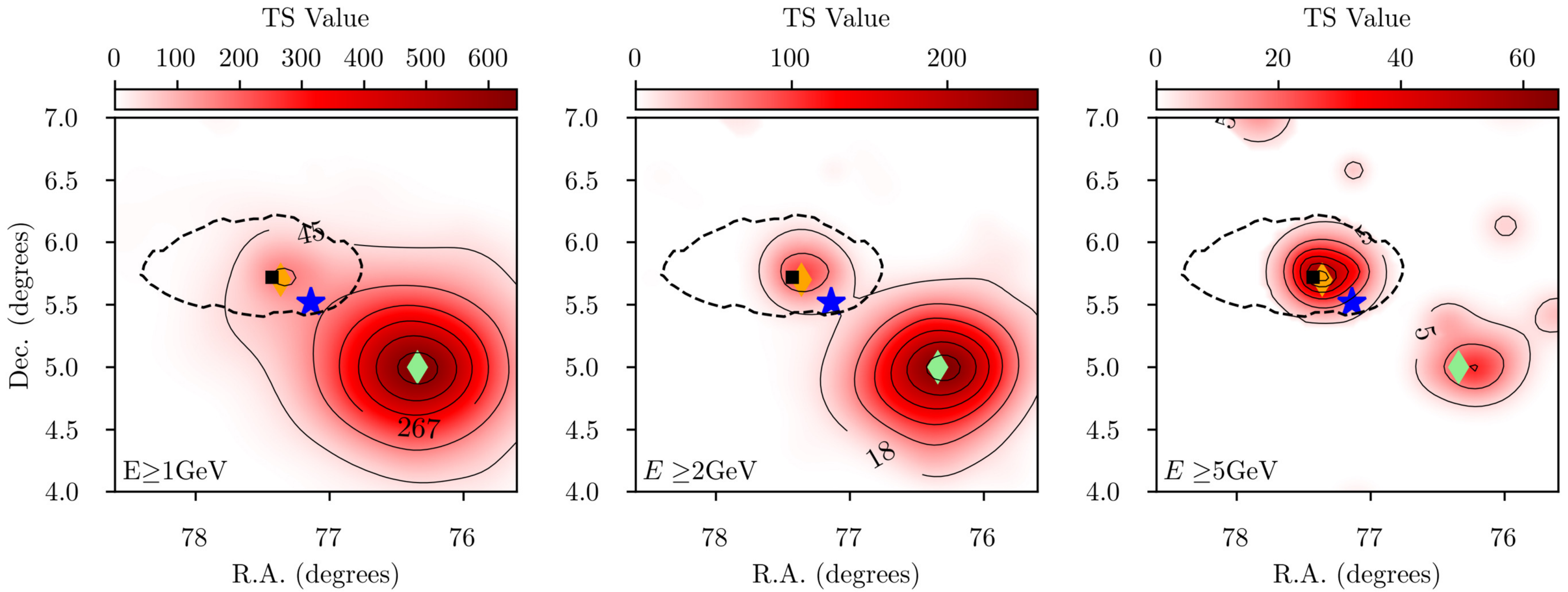
- 637 radio & x-ray sources within 80’
- 7 non-thermal sources w/ radio & x-ray emission
- 4 blazars: flux ratio X-ray/radio
- TXS & PKS compete for dominance
- TXS is higher-energy gamma-ray source
- TXS in high state during neutrino flare



Radio (red) & x-ray (blue)

High energy gamma rays key to localization

Padovani et al. (2018)

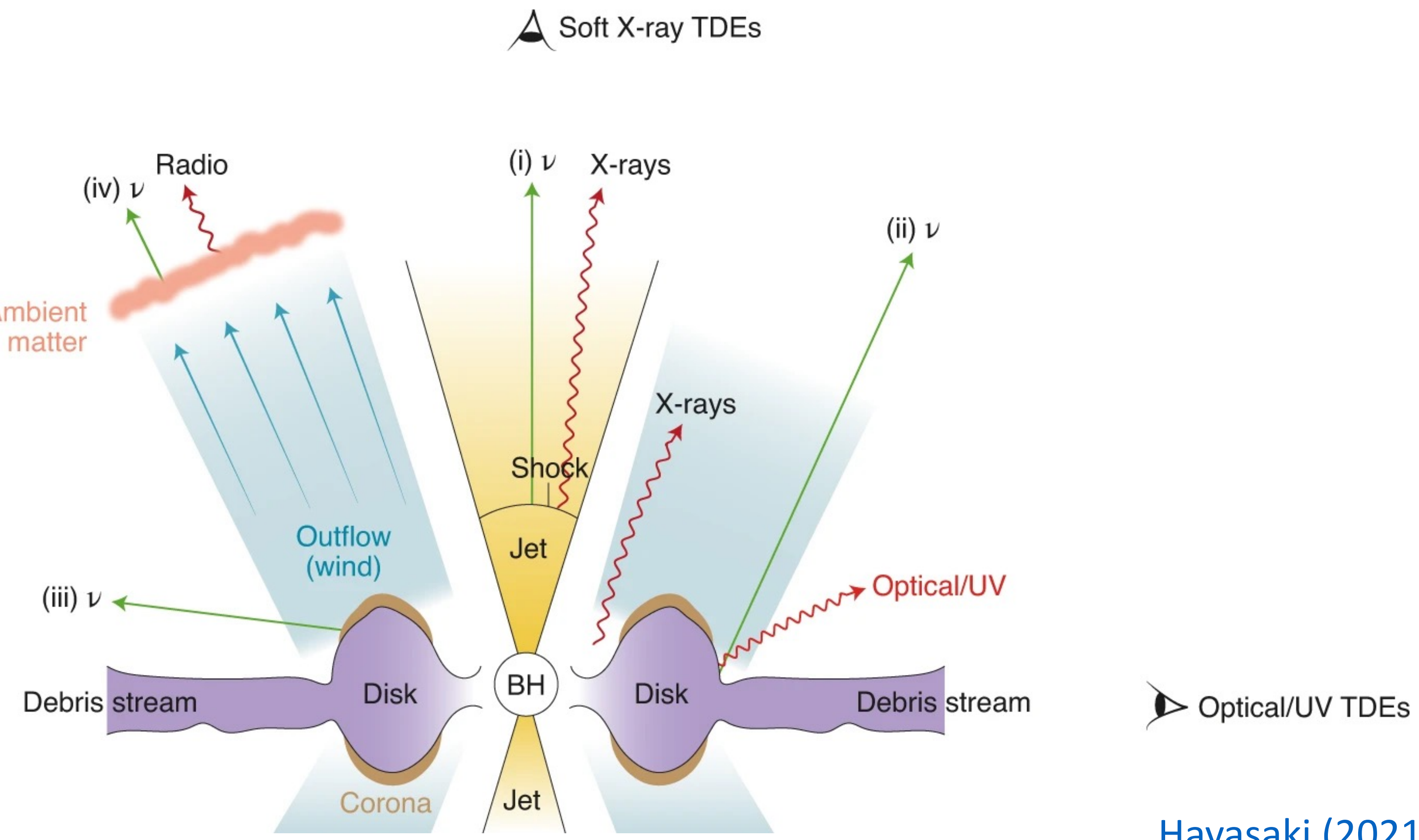


Blazar Summary

- Evidence points to neutrino detection from a BL Lac object (Blazar) accompanied by typical blazar flares (timescales & energies)
- Detailed spatio-temporal analysis makes credible argument that blazar exhibited previous neutrino flare and that other nearby sources less likely source
- Archival information very useful for time-domain astronomy!!
- Other searches for blazar neutrinos were less "fruitful" (e.g. Luo & Zhang 2020, ANTARES collaboration 2015)
- VanVelzen et al. (2021): accretion flares could be the course of VHE astrophysical neutrinos (e.g. from TDEs)

Next exercise: neutrinos from a tidal disruption event

Stein et al. (2021)



Hayasaki (2021)

Course Summary

- Multi-messenger astronomy: using all the forces!
- Cosmic ”Rays”: the first astroparticles, still a challenge & time-domain is just starting
- Cerenkov telescopes: Detecting particle events using optical light on ns timescales. CTA will hugely improve capabilities
- CTA: spatial & temporal resolution; off-duty use as intensity interferometers?
- Neutrino “telescopes” buried under Earth’s surface have detected tens of neutrinos from extragalactic sources!
- Solar neutrino flux informed that neutrinos have mass & oscillate in lepton flavor
- SN1987A: neutrinos preceded the light! Powerful evidence for NS creation
- TXS0506: Antarctic neutrinos from a SMBH > 2 bn ly away

Upcoming Saas Fee Courses

- Formal lectures, interactive hands-on sessions (observational and simulation data).
- Several-hour-long afternoon break for winter sports or participant interactions
- 2023:
  - https://www.astro.unige.ch/saasfee2023/
  - Deadline 15 Jan 2023
- 2024:
  - From stars to planets in the space-based photometry eras
  - Vincent Bourrier, Patrick Eggenberger, Gael Buldgen, and Svetlana Berdyugina