Windows on the Cosmos

Three types of "information carriers" about what's out there arrive on Earth:

- Electromagnetic Radiation
  - Visible light, UV, IR => telescopes (Earth/Space)
  - Radio waves => Antennae ("Dishes")
  - X-rays, Gamma rays => Detectors (often Space/Balloon)
- Material Objects
  - Comets, asteroids, chunks of planetary material
  - Nuclei (mostly H and He)
  - elementary particles (known and unknown)
- Gravity Waves !!!

Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation

Top: 3D view of Black Holes and Orbital Trajectory

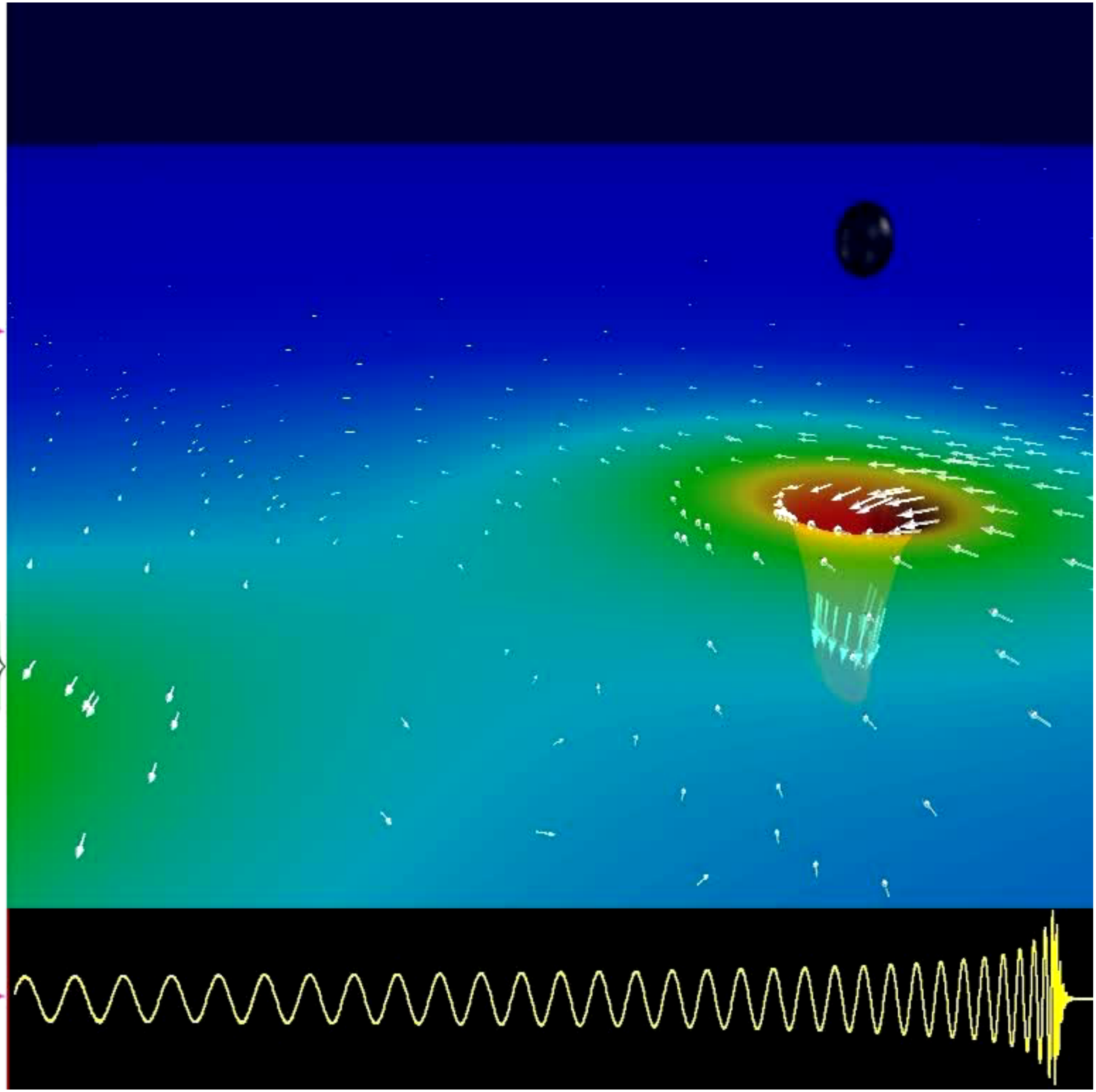
Middle: Spacetime curvature:

Depth: Curvature of space

Colors: Rate of flow of time

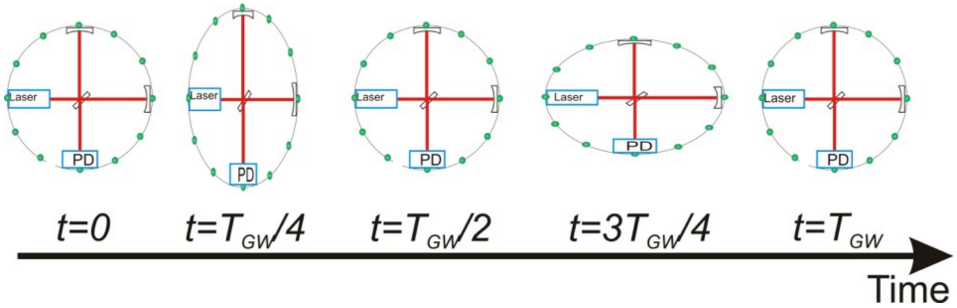
Arrows: Velocity of flow of space

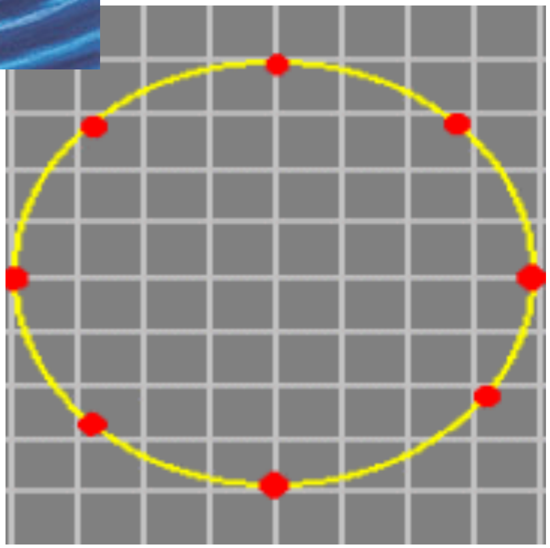
Bottom: Waveform
(red line shows current time)



Gravitational Waves

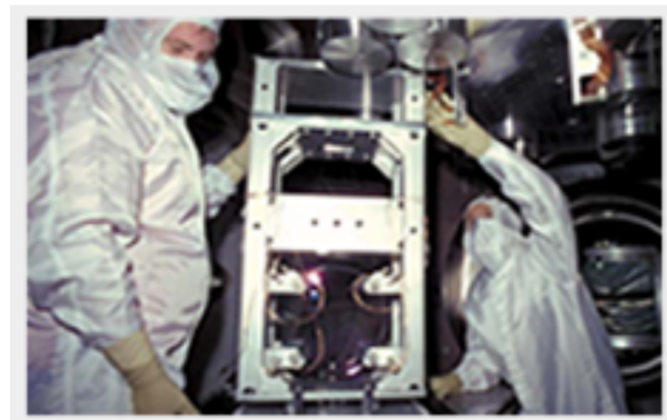
- An astrophysical source of gravitational waves from a violent event somewhere in the universe
- Gravitational waves interact very weakly with matter - even densest systems are transparent to gravitational waves



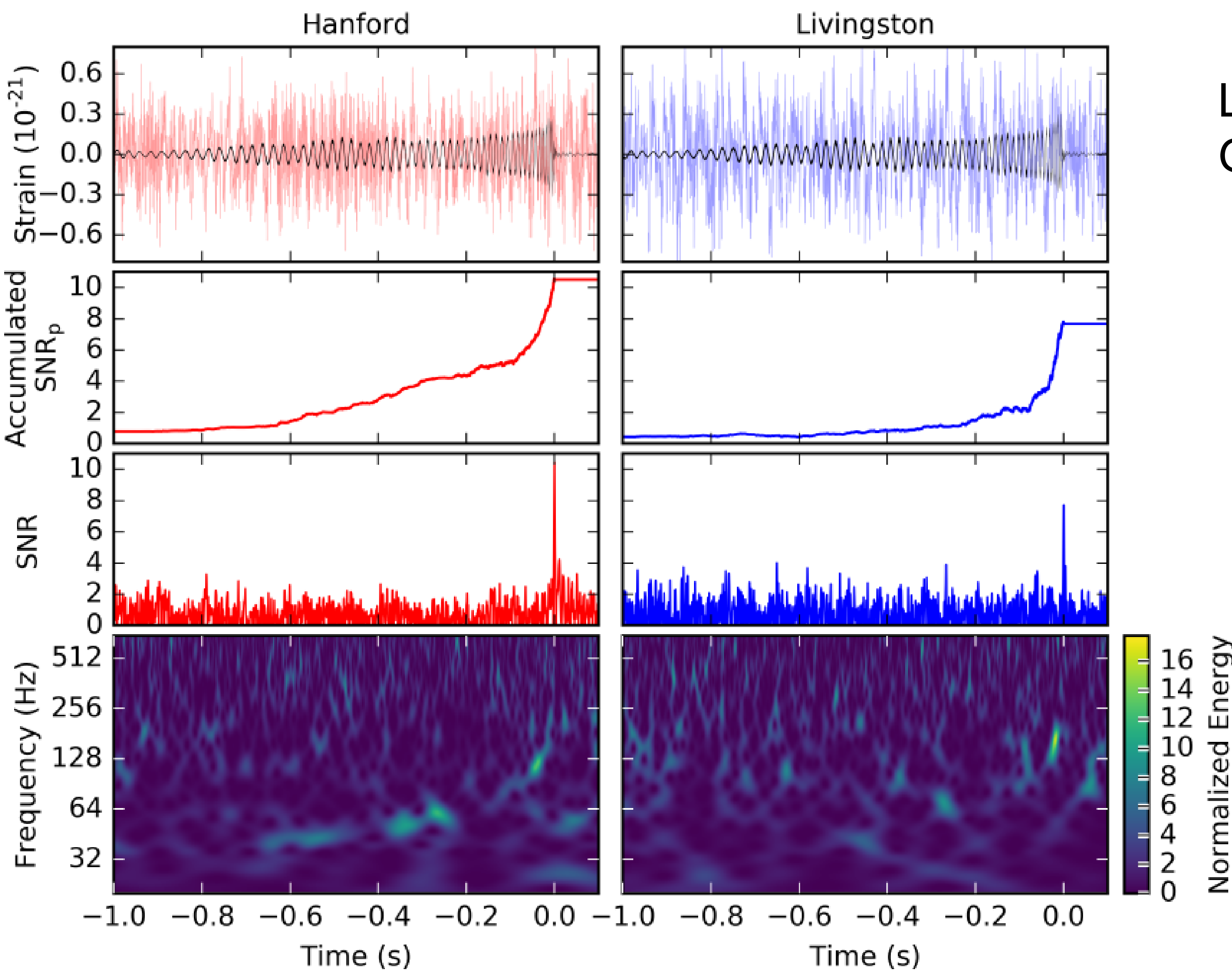


Gravitational Waves

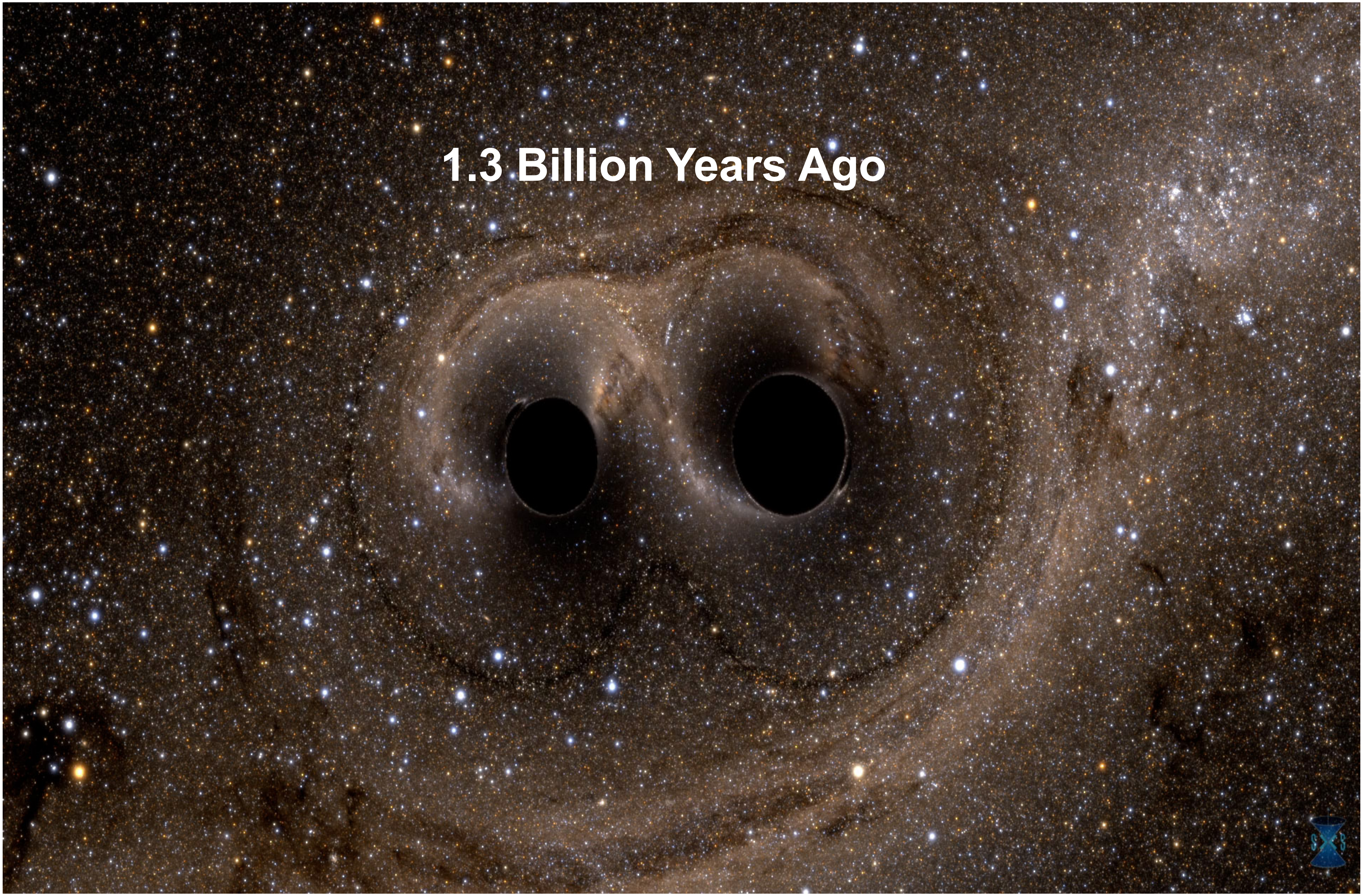
- Sources
  - Merging Neutron Stars/Black Holes
  - Supernovae - Black-hole collapses?
  - Rippels in Space-Time left over from Big Bang
- Detection Principle
  - Measure changes in distance between mirrors suspended miles apart (2 perpendicular directions)
  - Use laser interferometry to detect
- Example: LIGO -
  2 independent telescopes



Gravitational Waves



LIGO-G1601319


1.3 Billion Years Ago

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

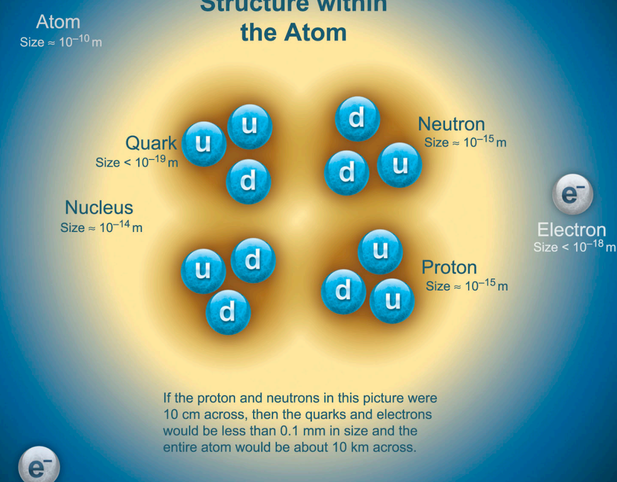
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

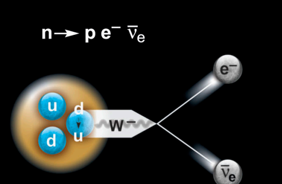
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

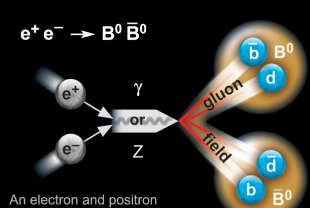
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

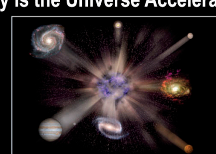


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

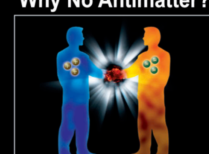
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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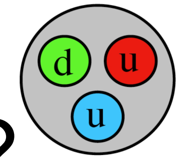
Hadronic Particle Zoo

- what can one build from quarks?

P


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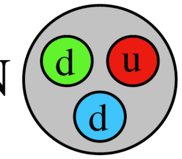


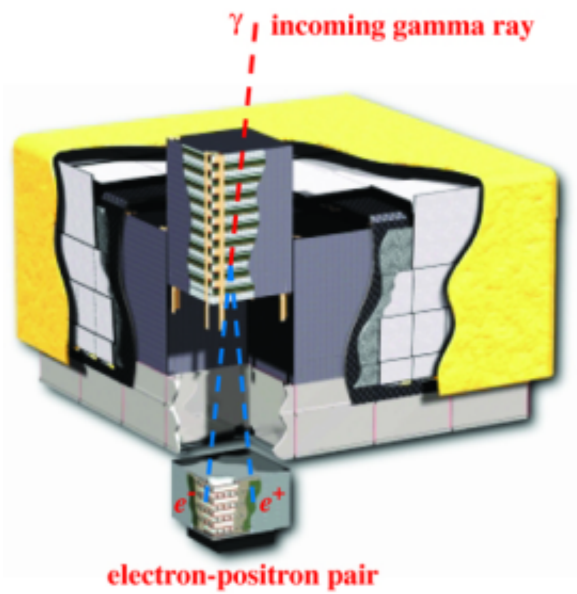
HADRONS

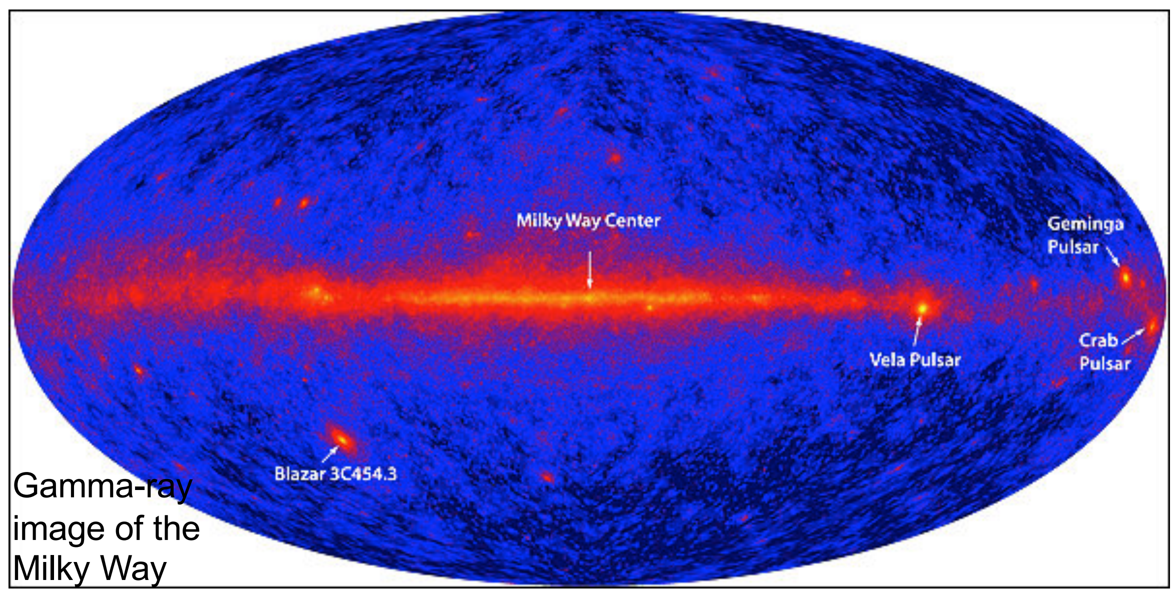
Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ^+_c	Λ^-_c	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^-$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^+$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	Ω^+	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B^0_s	$\bar{B}^0_s$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D^+_s	D^-_s	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-20}

*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

High Energy Photons (γ' s)

- Sources
  - Accretion on BH
  - γ-ray bursts ("GRBs")
  - matter/antimatter annihilation
- Detection Principle: EM showers
- Example: Fermi (formerly known as "GLAST")





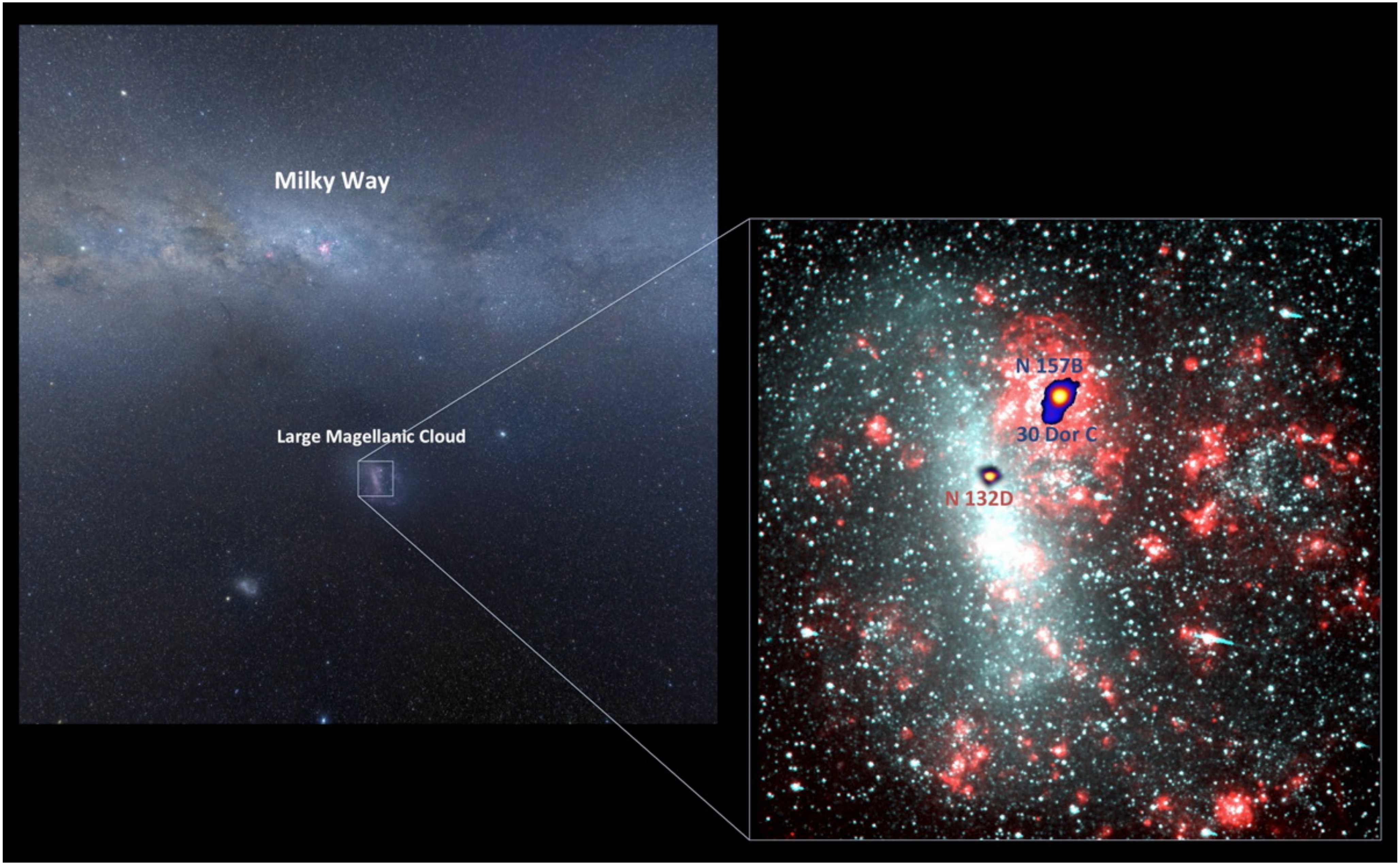
Gamma-ray image of the Milky Way

Observation of 100 GeV-100 TeV photons

http://www.mpi-hd.mpg.de/hfm/HESS/

- Detect bright flashes of Cerenkov light in the dark night sky of Namibia from Compton recoil electrons in the upper atmosphere
  - $\gamma e \rightarrow \gamma e$
  - Electro-magnetic shower does not penetrate to ground (unlike nuclear shower from protons)

Example: γ rays from the Large Magellanic Cloud



Cosmic Ray Spectrum

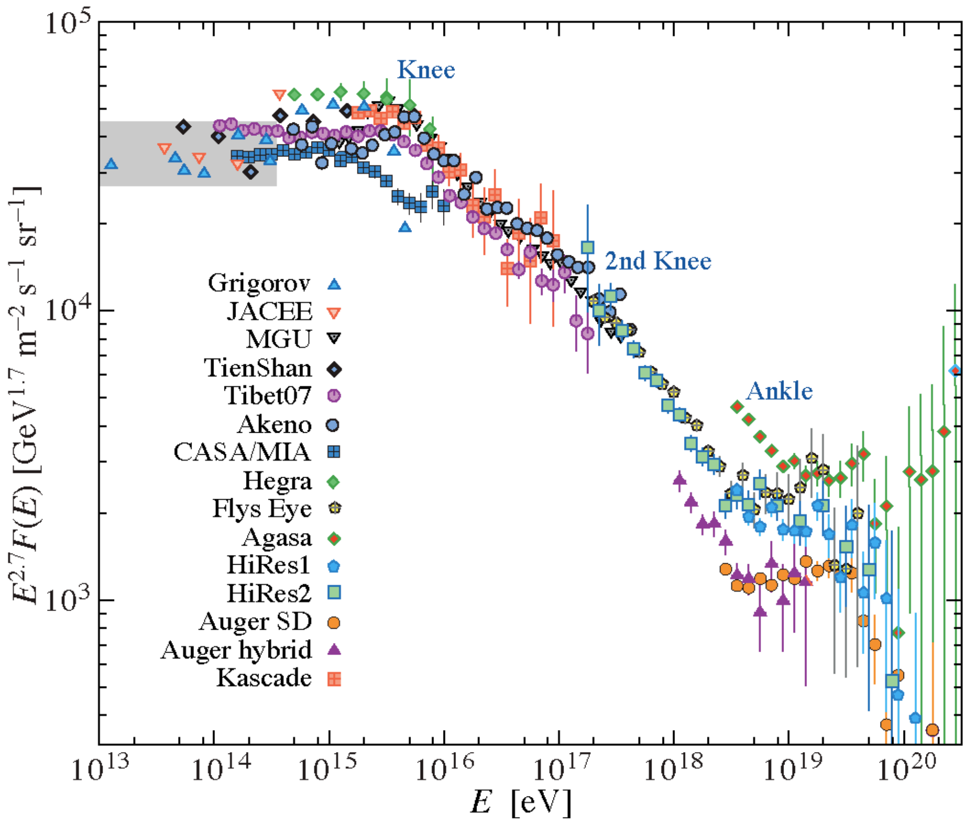


Figure 24.9: The all-particle spectrum from air shower measurements. The shaded area shows the range of the direct cosmic ray spectrum measurements.

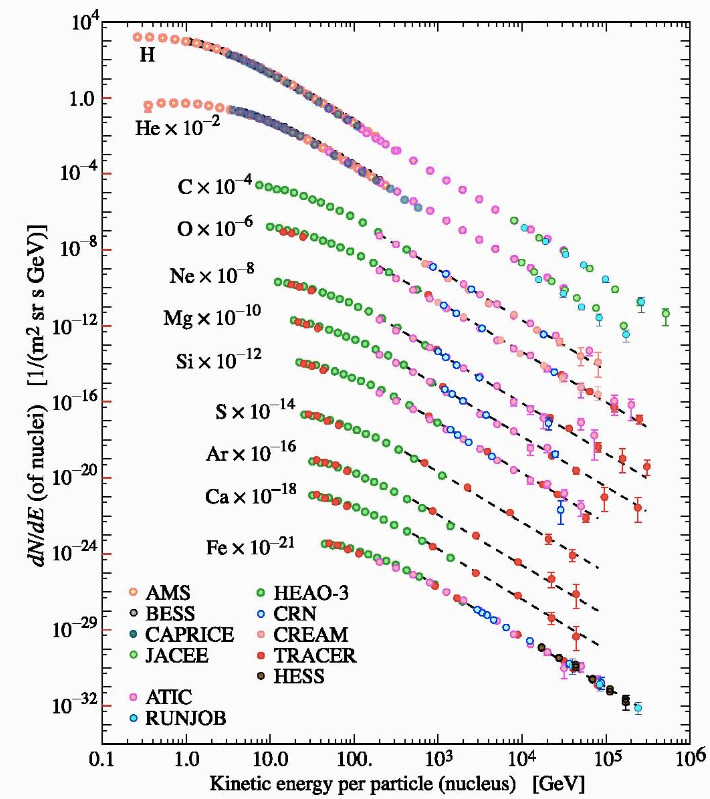
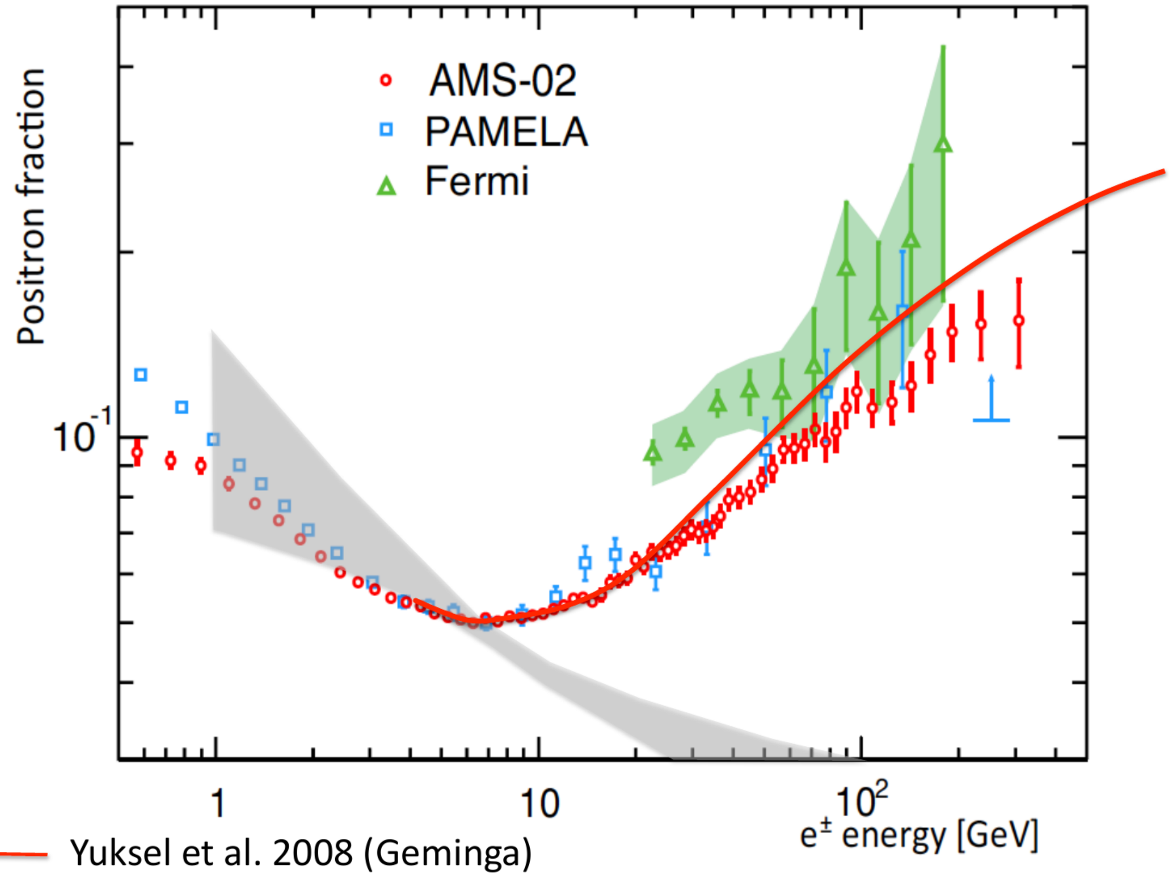


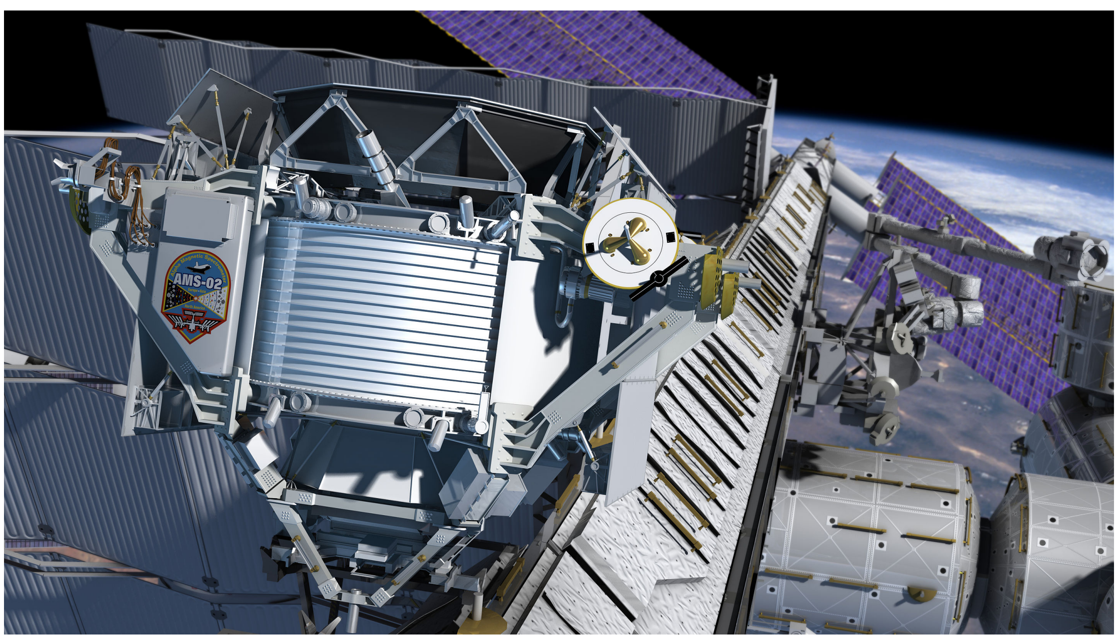
Figure 24.1: Major components of the primary cosmic radiation from Refs. [1–12]. The figure was created by P. Boyle and D. Muller.

Charged Cosmic Rays are Isotropic

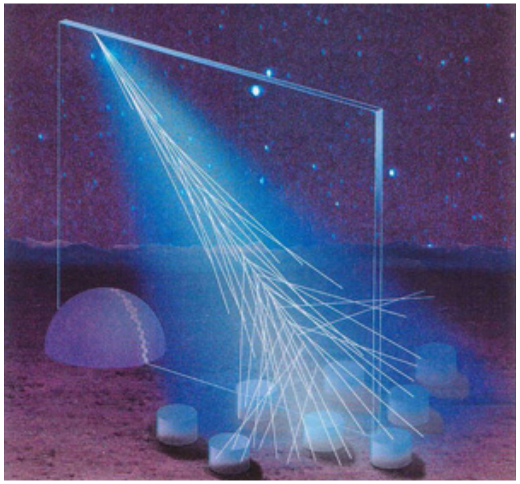
- Intergalactic Magnetic Field ≈ 10^{-12} T
  - $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$
  - Radius of relativisitic proton orbit
    - $r = pc/(eBc)$
  - Angular deviation after path length *L:*
    - $\theta = (eBcL)/(pc)$.
    - 1 Tesla = 1 Vs/m^2,   c=0.3 Gm/s
    - $\theta = \geq 1$ *rad* for $L \geq 10^6$ Light-yrz and $pc < 0.3\ 10^{19}$ *eV.*
- *Only the highest energy charged cosmic rays can point to Local Sources*

Electrons and Positrons

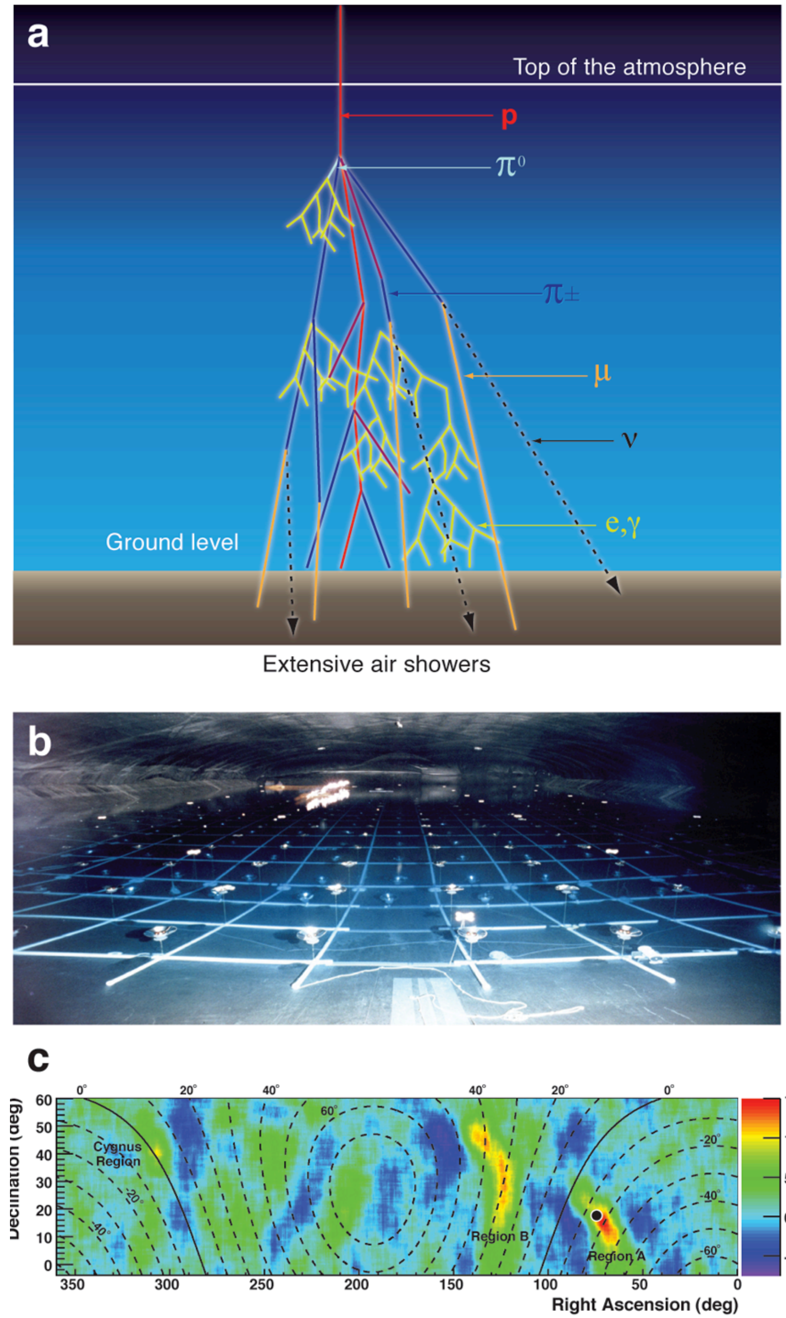




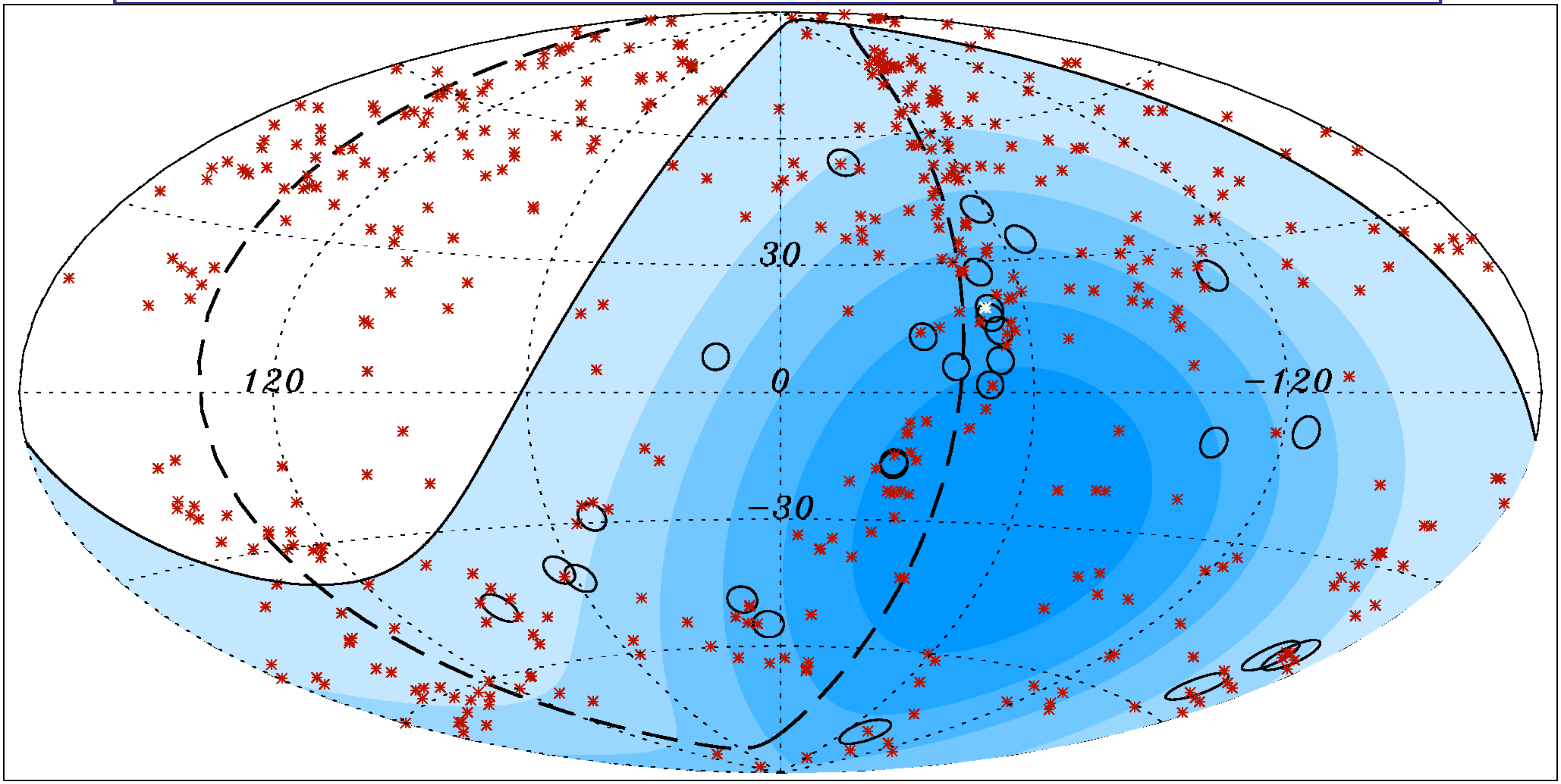
Protons + Nuclei



- Sources
  - Shockwaves from Collapses/Collisions
  - AGNs
  - "Afterburners" - magnetic shock acceleration
- Detection Principles:
  - Balloons, satellites
  - "Cosmic rays" - muons from air showers
  - Scintillation, Cherenkov light
- Example: Auger, Milagro
- Super-high energy: up to $>10^{20}$ eV (10^7 LHCs)!
- Magnetic fields - hard to point back



Where do UHE CR come from?

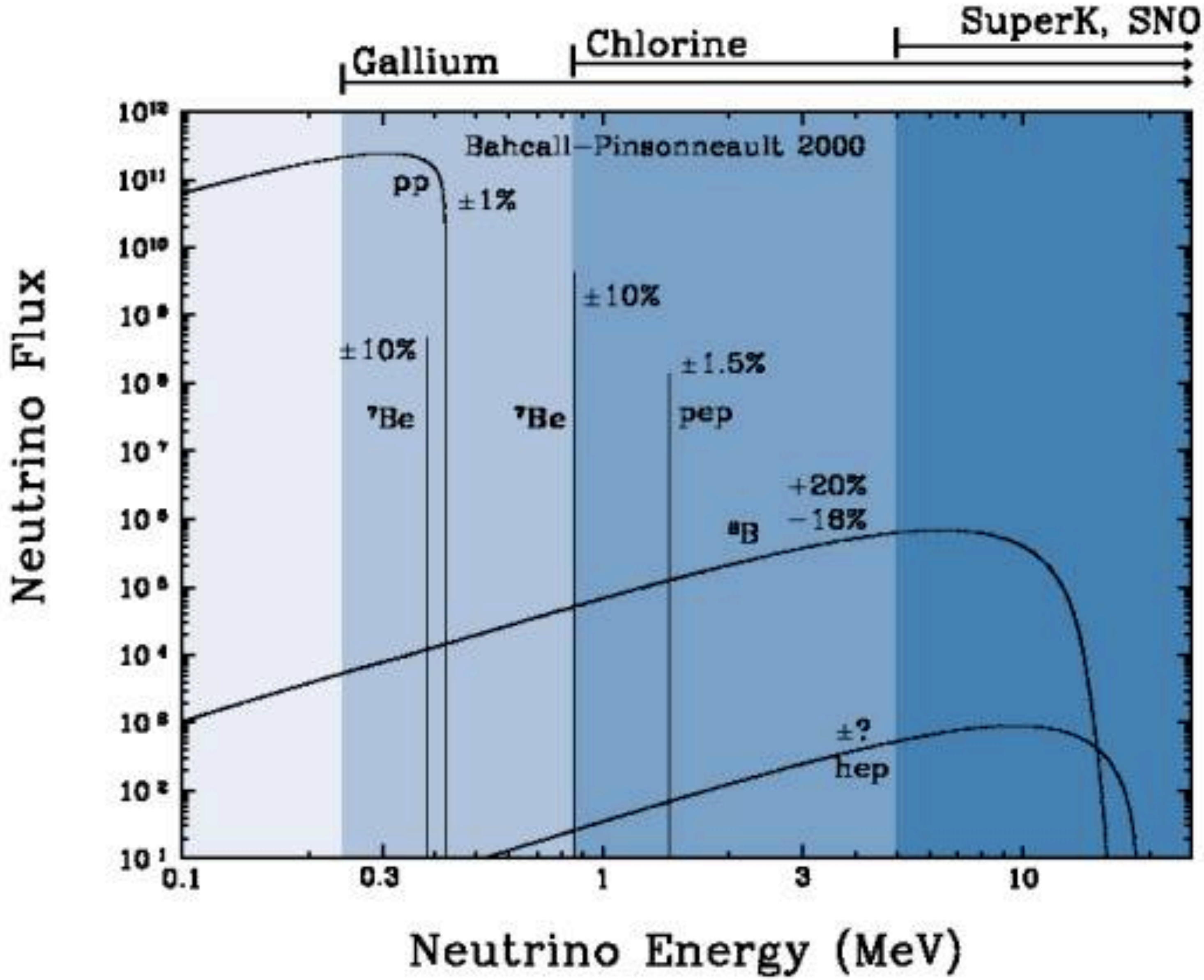


The celestial sphere showing directions of the 27 highest energy cosmic rays detected by Auger (>57 EeV), circles of radius 3.1° .
The 472 AGN within 75 megaparsecs are shown as red *'s.

Neutrinos

- Sources
  - Sun => Famous “Solar Neutrino Problem” (not enough seen)
  - Supernovae (remember 1987A)
  - Big Bang Relics (too low energy to be detectable)
  - Decay from violent cosmic ray interactions ($pp \rightarrow \pi \rightarrow \mu$)
- Detection Principles
  - ν hits e^-, nucleus -> recoil, or converts to electron, muon
  - recoil moves through water/ice faster than c/n -> shock wave (light equivalent to supersonic boom) -> Cherenkov radiation
  - Light collected and measured by gigantic phototubes
- Examples: Superkamiokande, Ice Cube

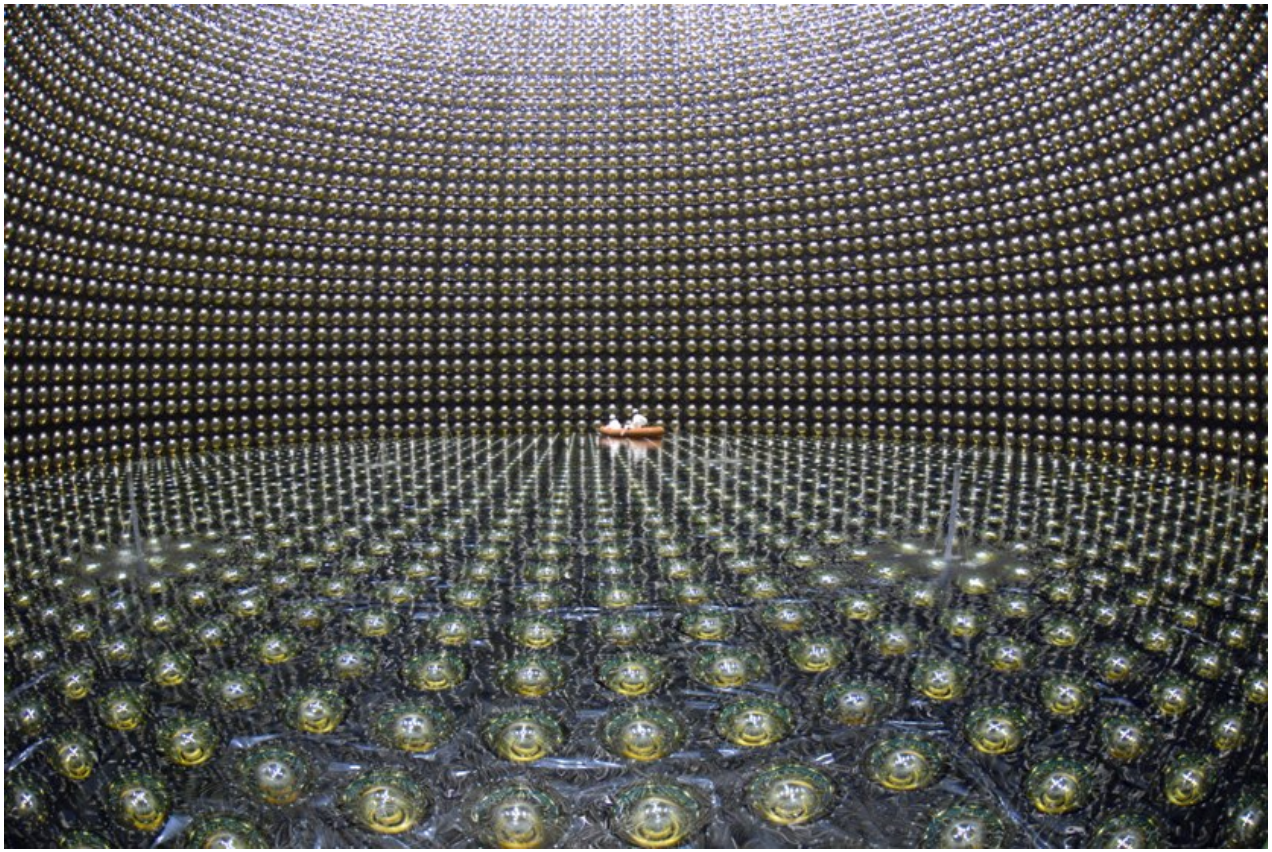
Solar Neutrinos, and their detection



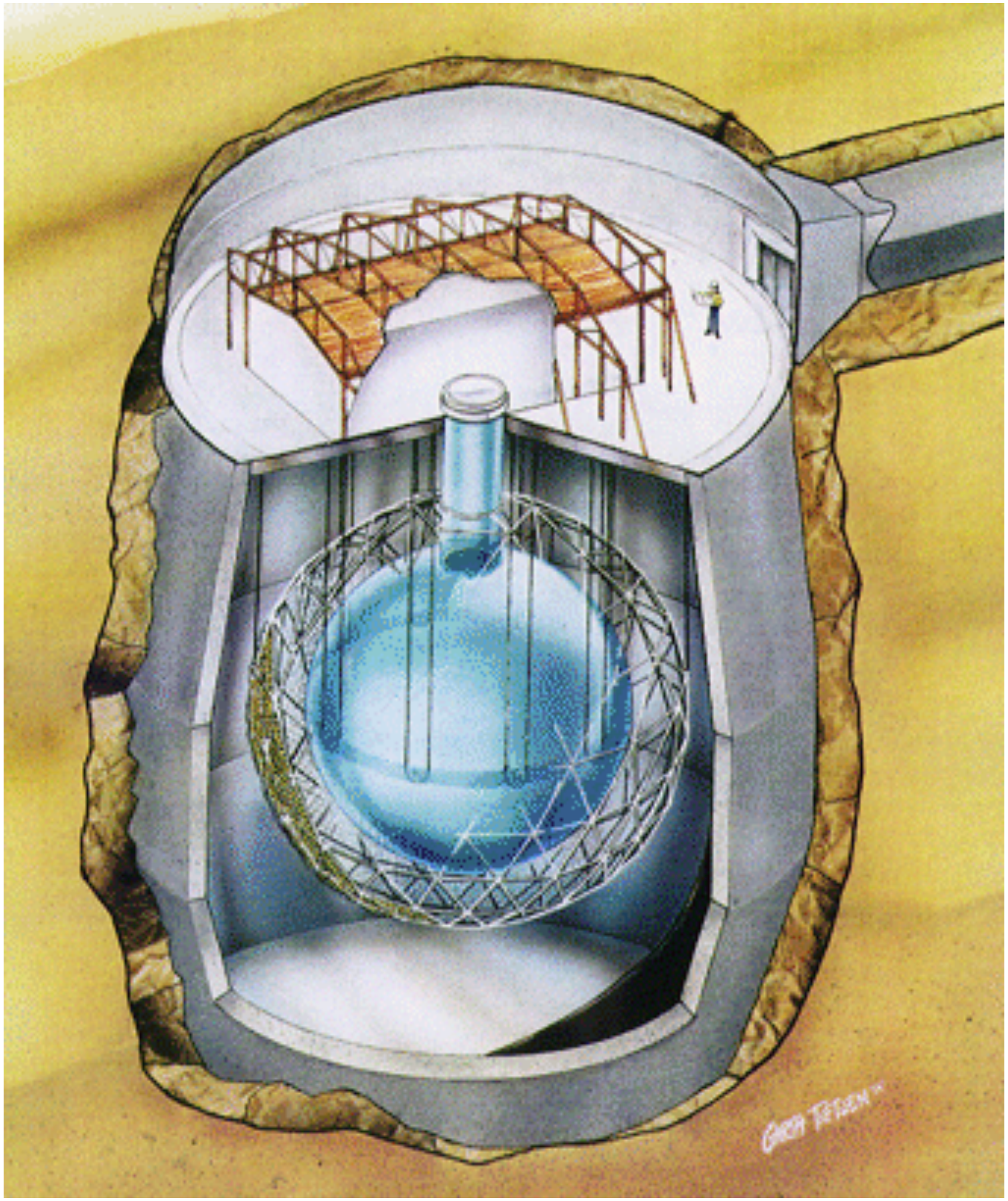
Kamiokande

Originally a proton decay experiment

- 50,000 Ton H_20+10,000 PMT

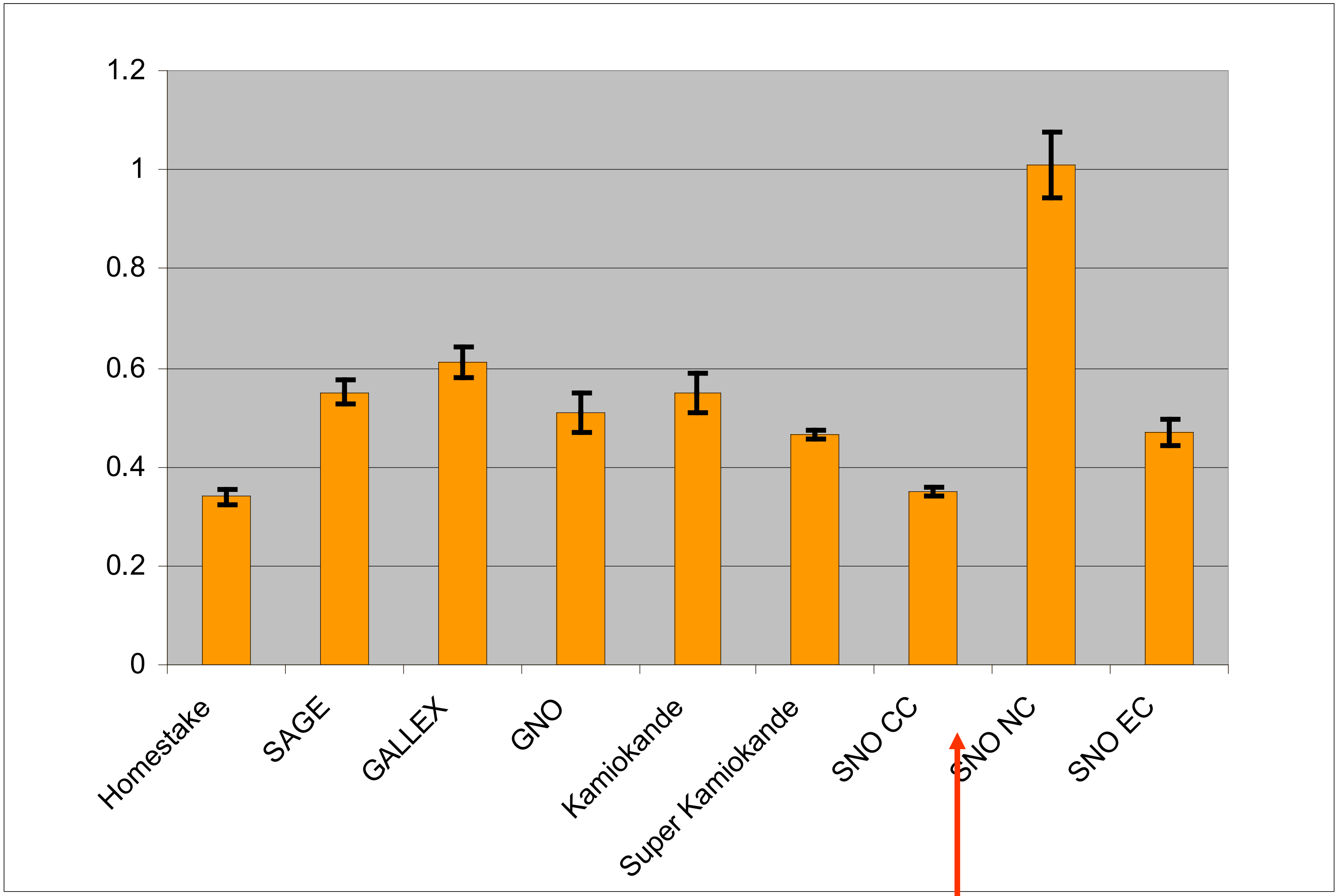


Sudbury Neutrino Observatory



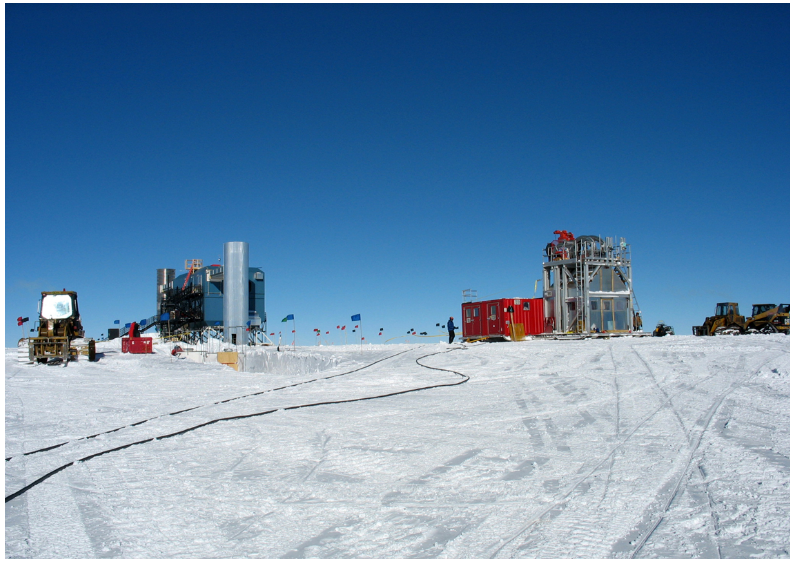
Canadian D_2O reserve for “CANDU” heavy water nuclear fission reactors.

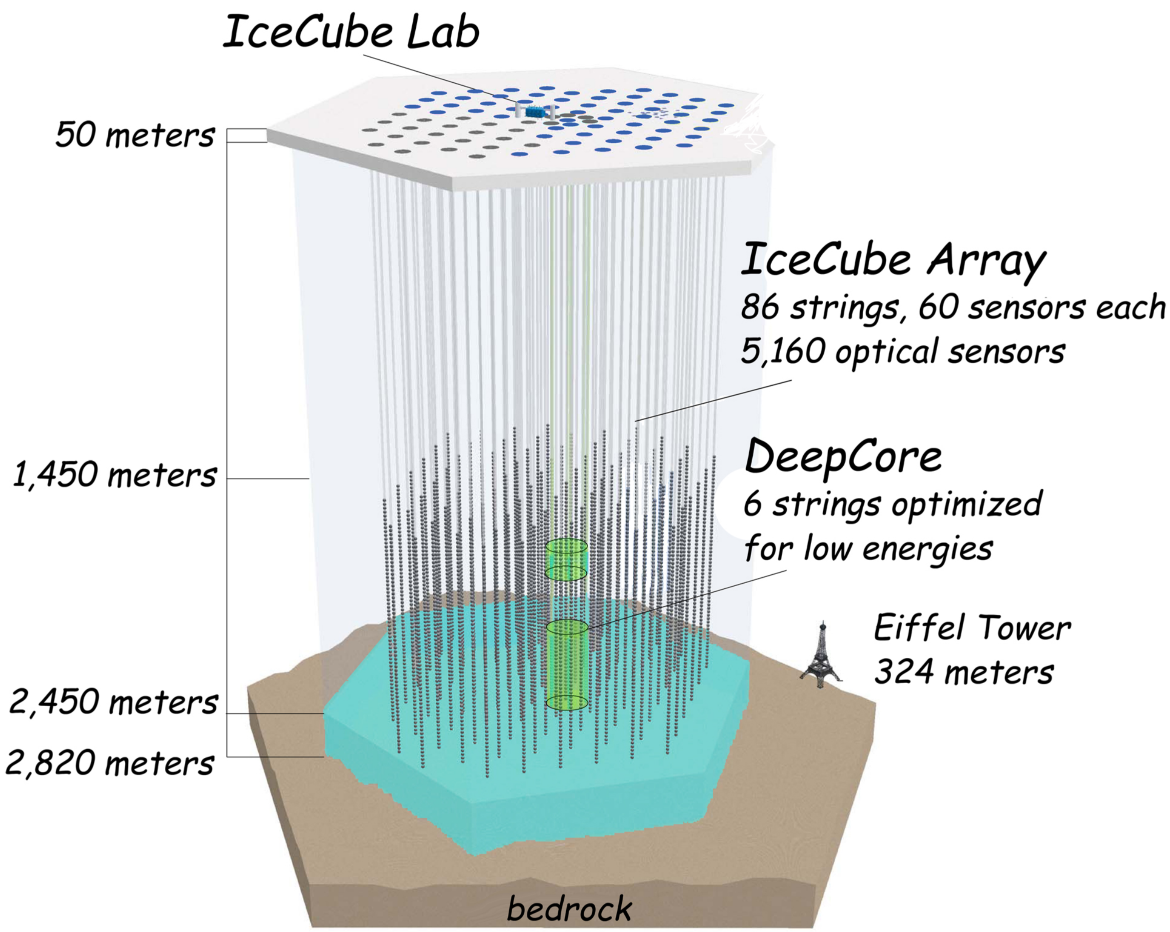
With SNO results:



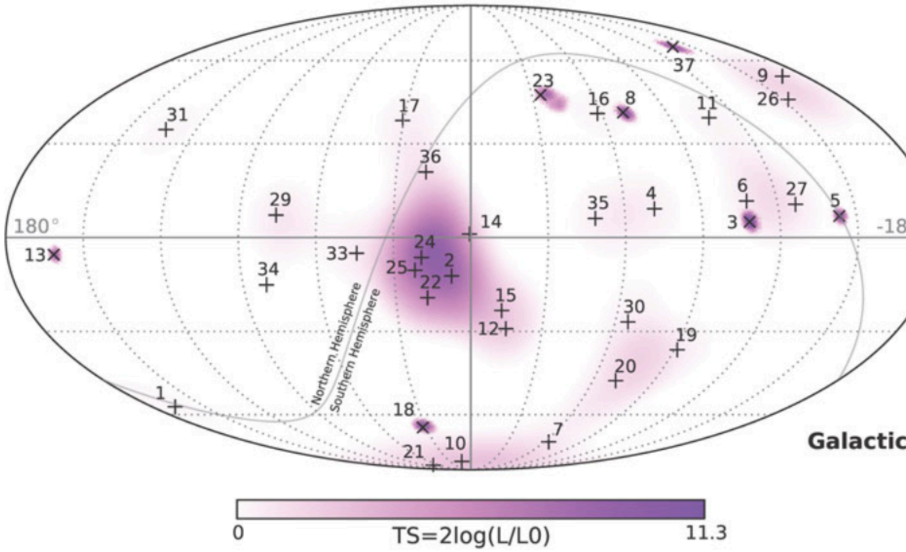
Puzzle solved …

Ice Cube



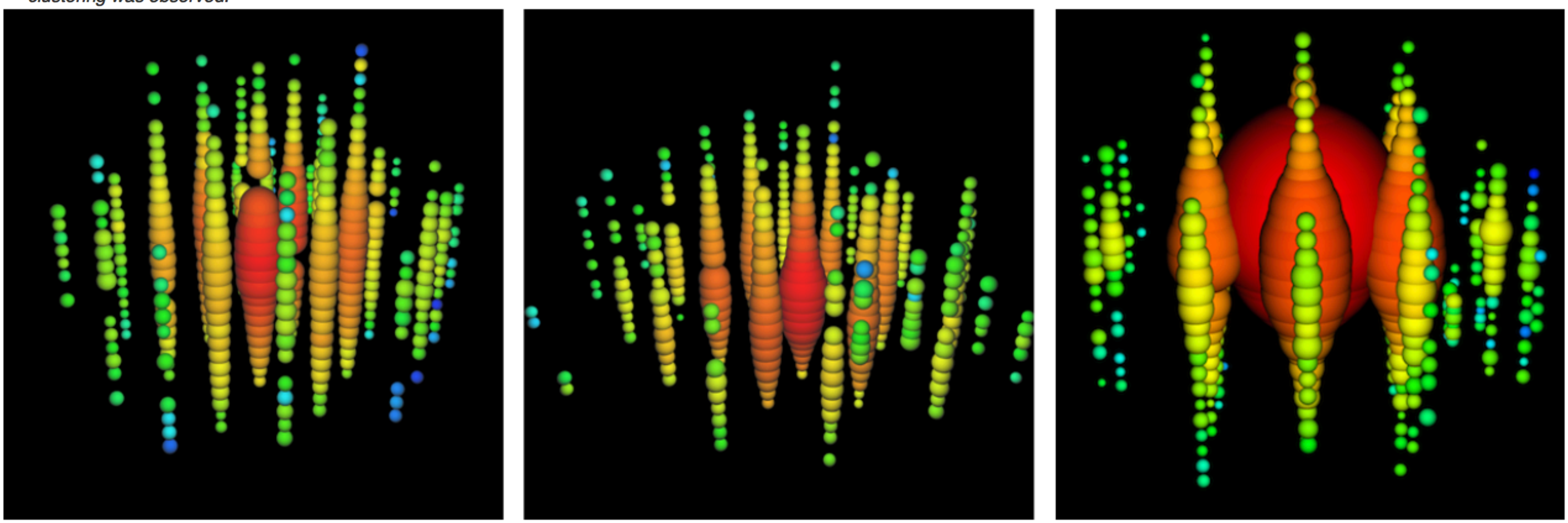

IceCube Lab
50 meters
1,450 meters
2,450 meters
2,820 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
bedrock

Ice Cube



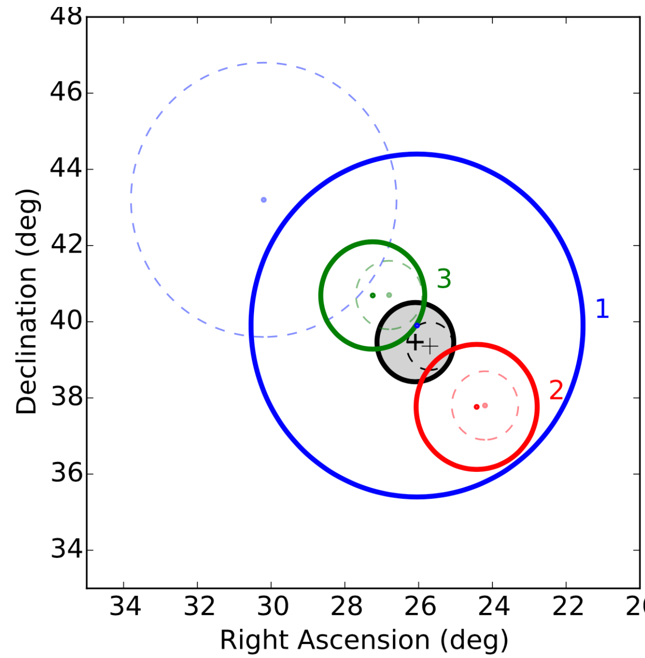
Arrival directions of the 37 very high energy events found in IceCube after analyzing three years of data (2010–2013). The grey line denotes the equatorial plane. The color map shows the test statistic (TS) for the point-source clustering test at each location. No significant clustering was observed.

Highest Recorded Temperature	+9.9°F (-12.3°C) December 25, 2011
Lowest Recorded Temperature	-117.0°F (-82.8°C) June 23, 1982
Average Annual Temperature	-57.1°F (-49.5°C)
Peak Wind	48 kts (55 mph) from 330 degrees on August 24, 1989
Average Wind	10.7 kts (12.3 mph) from 020 degrees

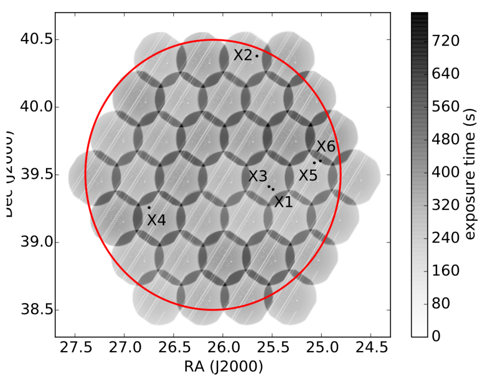


IceCube has detected the highest energy neutrinos ever recorded, with energies reaching above 2 PeV. From left to right, Bert, Ernie and Big Bird, with energies of 1.0, 1.1 and 2.2 PeV.

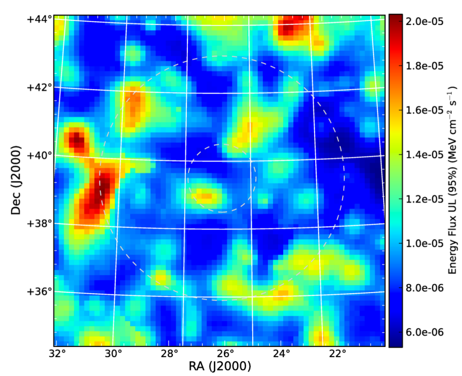
New ICECUBE detection:
3 neutrinos in 100 s from
roughly the same spot



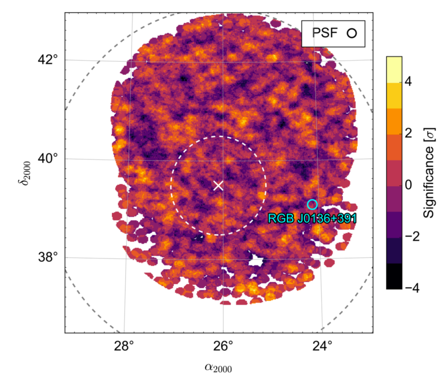
Can other detectors identify a source?



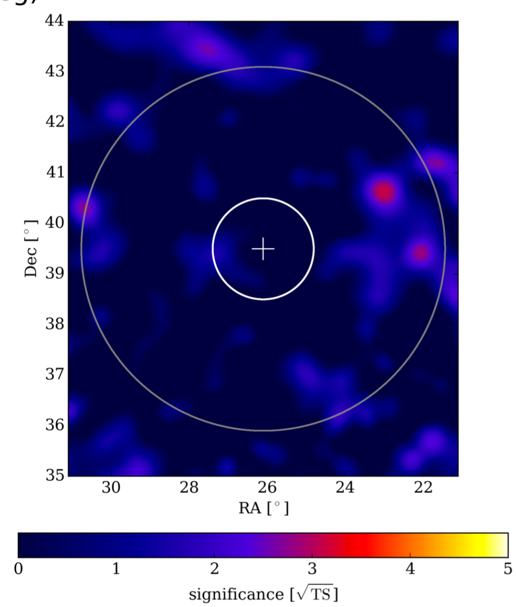
SWIFT x-ray satellite



FERMI γ-ray satellite



VERITAS UHE γ-ray array

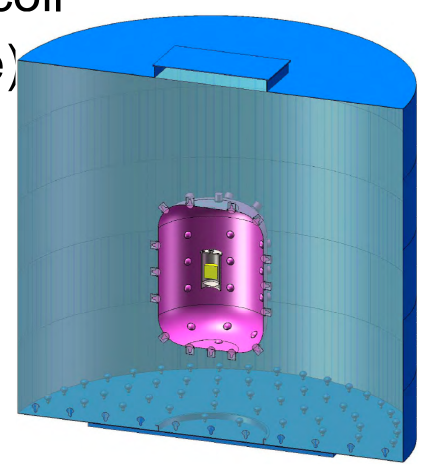


HAWC UHE γ-ray
Cherenkov array

…but, alas, no significant signal yet…

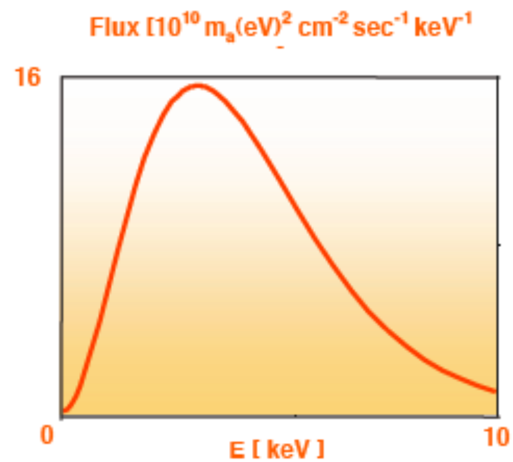
Particles: What else?

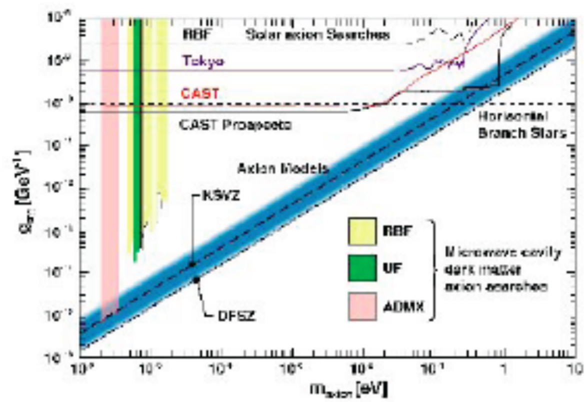
- WIMPs/Neutralinos?
  - Predicted by supersymmetric extensions of the Standard Model of Particle Physics
  - LHC at CERN is hunting actively for specimen produced in pp collisions
  - Could explain dark matter (see later); maybe passing through all the time
- Detection Principles
  - Go deep underground to shield other cosmic rays
  - Scatter off atomic nuclei (through weak interaction) -> recoil
  - Bubble chambers, acoustic detectors (phonon vs. charge), calorimeters (Lar / LXe Scintillator),
  - Look for “WIMP wind”! (annual modulation)
  - also indirect detection through annihilation products
  - create at LHC

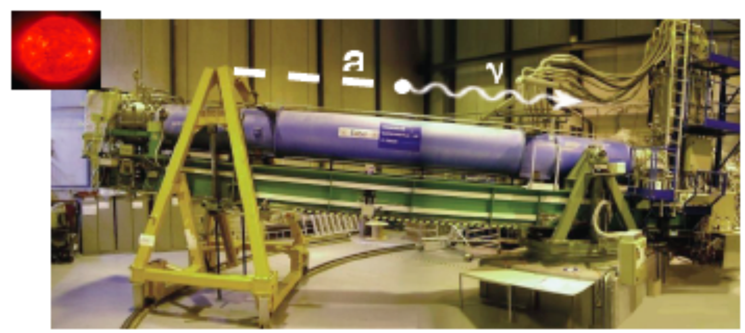


Particles: What else? cont'd

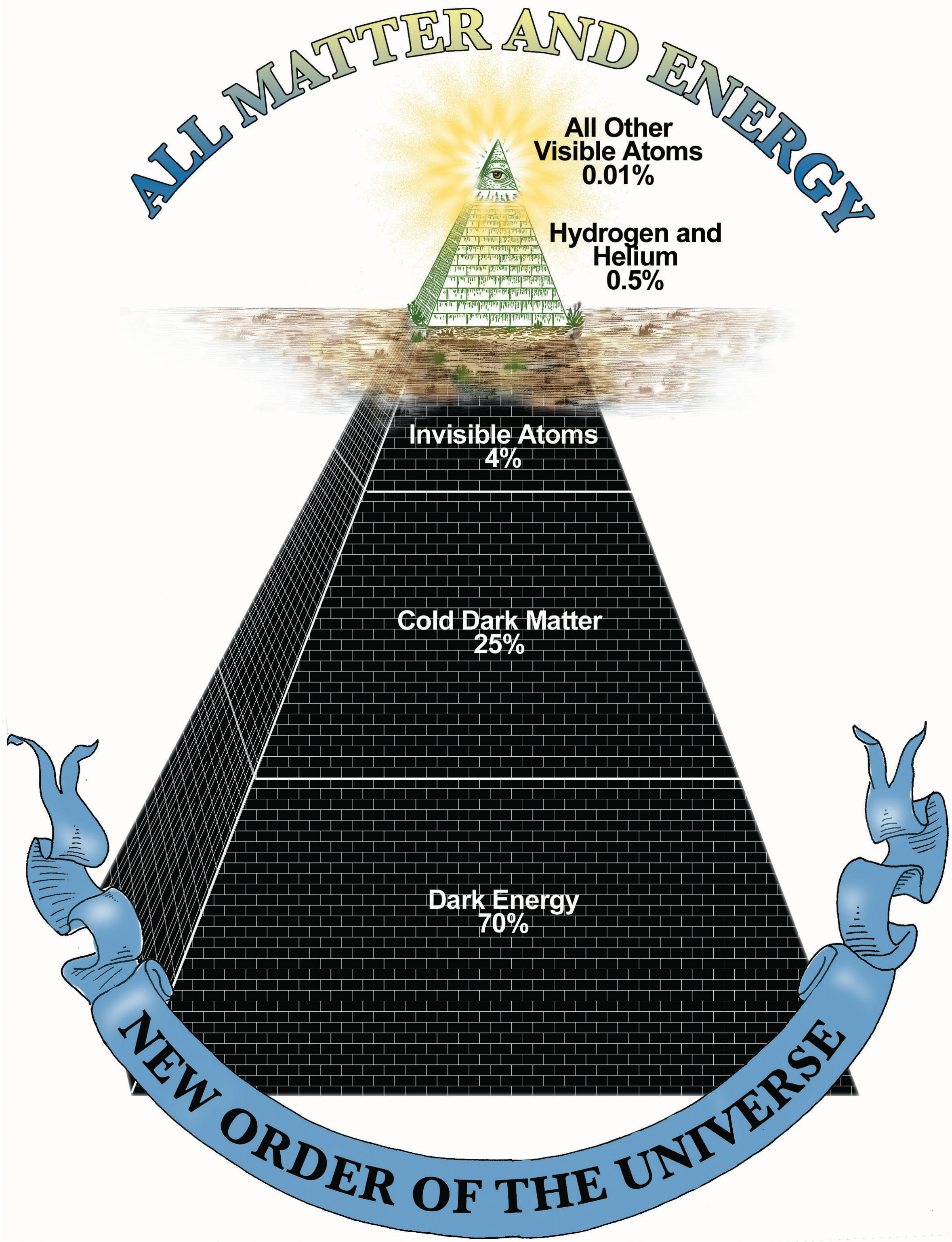
- And Axions?
  - Predicted by some models to explain "strong CP problem"
  - Interact mostly with photons (EM fields)
  - searches going on, but so far no success
- Or heavy photons?
- Or super-heavy neutrinos?
- Or Planckions?







And what about "dark energy"?
And what about the "inflaton"?



ALL MATTER AND ENERGY
All Other
Visible Atoms
0.01%
Hydrogen and
Helium
0.5%
Invisible Atoms
4%
Cold Dark Matter
25%
Dark Energy
70%
NEW ORDER OF THE UNIVERSE