Multimessenger Astroparticle Physics

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7. More Experimental Results. The Final Exam.

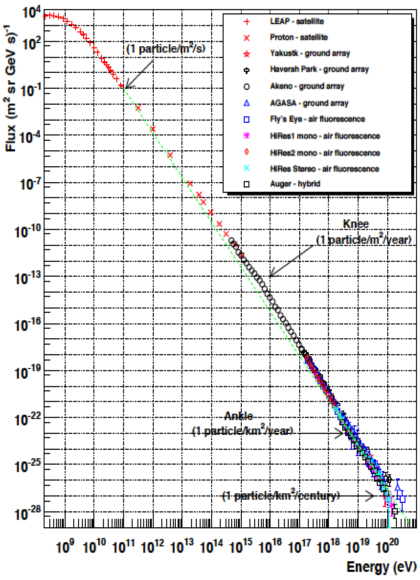
CHARGED COSMIC RAYS

Composition, energy dependence

- Charged CR arrive to the Solar System after deflection from the galactic B (~1 μG) and possibly by extragalactic B
- Close to the Earth they start interacting with B up to O (1G). Fluxes of charged particles at energies <1-2 GeV, can thus be influenced, e.g., by the solar cycle.
- Cosmic rays are basically protons (~90 %) and heavier nuclei. The e- flux at the top of the atmosphere is small (a few per mil) but extremely interesting as it may indicate unknown astrophysical or DM sources
- e+ fluxes are even smaller (about 4 orders of magnitude) and so far compatible with secondary production by hadronic interactions of primary CR with the interstellar medium. Up to now there is no evidence for the existence of heavier anti-nuclei (in particular anti-deuterium and anti-helium)

Energy spectrum

- At E~1 GeV, 1000s of particles/m^2/s) while strong cutoff at E ~ $10^{19.5}$ eV. At the highest, E ~ 10^{11} GeV, < 1 particle/km2/century.
- At the end of the known spectrum CR have energies >> the highest beam energies attained in any human-made accelerator and their interactions on the top of the Earth atmosphere have cm energies ~ few hundred TeV
- Low fluxes at VHE energies: one can study the energies up to the ~ 1 PeV with satellites, while above rely on ground-based detectors.



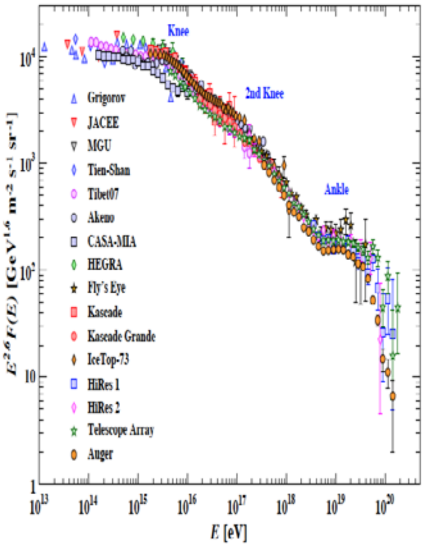
Energy spectrum

- Above a few GeV the CR flux follows a power law,

  I (E) ≅ k E^{-p}

  p between 2.7 and 3.3.
- Below a few GeV, flux modulated by the solar activity and in particular by solar B
  - Effects variable in time
- The small changes in p can be visualized multiplying the flux by some power of the energy. Anthropomorphic representation: 2 clear features corresponding to changes in the spectral index
  - The knee around E ~ 5 PeV, associated to the transition from galactic to EG cosmic rays; it corresponds to a steepening from p~2.7 to p~3.1
    - Second knee at E~ 400 PeV?
  - The ankle around E~ 5 EeV and its nature is still controversial
- From ~10 GeV to >> 100 TeV

$$\frac{dN}{dE} \simeq 1.8 \times 10^4 E^{-2.7} \frac{\text{nucleons}}{\text{m}^2\,\text{s}\,\text{sr}\,\text{GeV}}$$

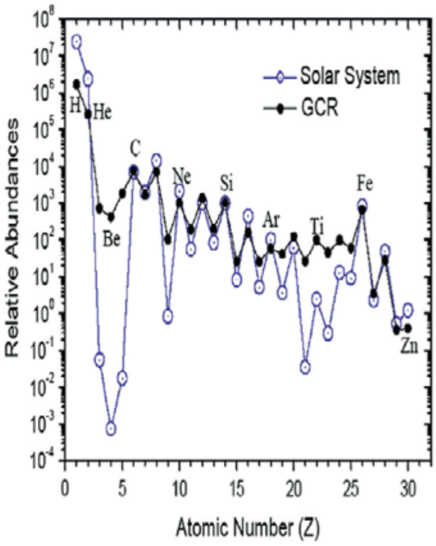


Composition

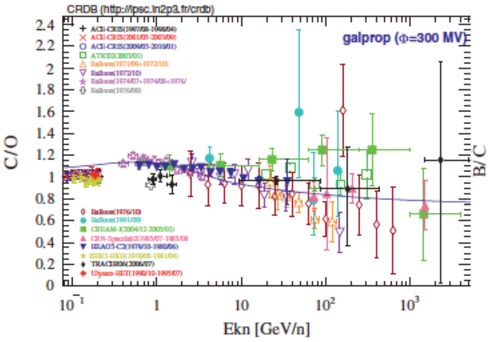
- Not a well-defined problem: it depends on where experiments are performed. One could try a schematic separation between “primary" cosmic rays as produced by astrophysical sources and “secondaries”, i.e., produced in interactions of the primaries with ISM or with nuclei in the atmosphere.
- Li, Be and Bo, for example, are very rare products in stellar nucleosynthesis, and thus are secondary particles, as well as antiprotons and positrons-if some antimatter is primary is a question of primary interest
- The interaction with the Earth's atmosphere is particularly important since it changes drastically the composition of cosmic rays. In the cases in which the flux of cosmic rays has to be measured at ground one needs nontrivial unfolding operations to understand the primary composition
- What one observes is a cascade shower generated by a particle interacting with the atmosphere, and the unfolding of the fundamental properties (nature and energy of the showering particle) requires the knowledge of the physics of the interaction at energies never studied at accelerators: experimental data are thus less clear
- Accessing the composition of cosmic rays can be done, in the region below a few TeV, at the top or above the Earth atmosphere by detectors placed in balloons or satellites able, for example, of combining the momentum measurement with the information from Cherenkov detectors, or transition radiation detectors.

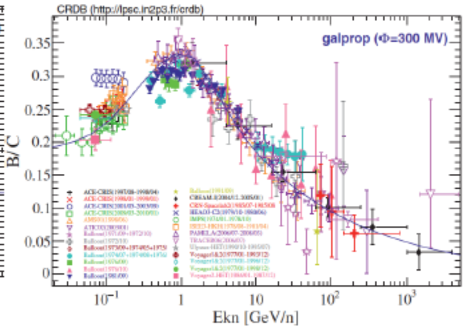
Composition

- Nucleons with even number of nucleons are more stable, having higher binding energy because of pairing effects.
- On top of this, primary CR are produced in stellar end-products, being the “valley" elements mainly secondaries produced in the interaction of the primaries with the ISM (“spallation").
- Direct composition measurements are not possible above a few hundred GeV. For EAS detectors, effective at higher energies, being able to distinguish between a shower generated by a proton or by a heavier particle is difficult
  - the muonic contents of the air shower;
  - depth of the maximum of the shower, X_{max}
- Experimental evidence that the chemical composition of cosmic rays changes after the knee with an increasing fraction of heavy nuclei at higher energy, at least up to about 1 EeV



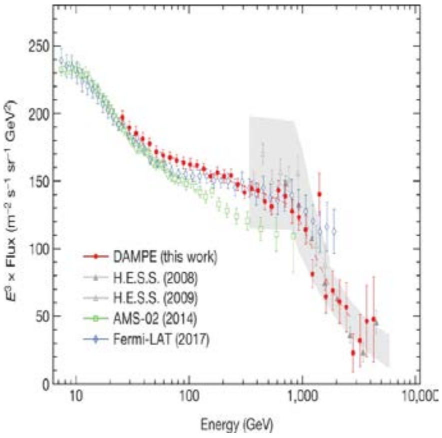
Primaries and secondaries





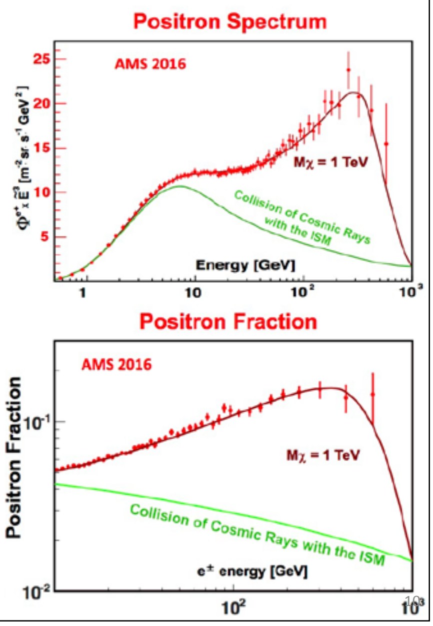
Electrons and Positrons

- HE e+ and e- have short propagation distances (~100 pc) as they lose energy through synchrotron and IC while propagating through the Galaxy.
- Their spectra are therefore dominated by local e accelerators or by the decay/ interactions of heavier particles nearby. Positrons in particular could be the signature of the decay of DM particles.
- The experimental data on the flux of e- plus e+ suggested in a recent past the possible evidence a bump-like structure (ATIC balloon experiment results) at energies between 250 and 700 GeV.
- These early results were not confirmed by later and more accurate instruments like the Fermi LAT, AMS-02, DAMPE

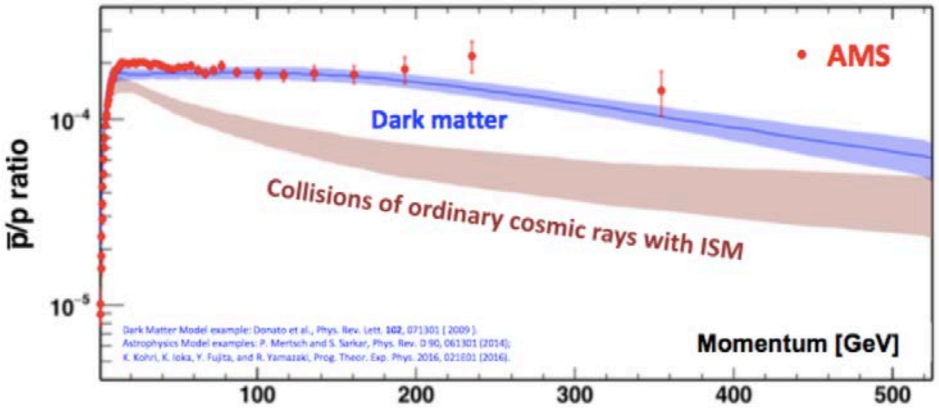


Positrons

- Excess in the HE e+ fraction with respect to standard sources (pulsars) and interactions of CR with the ISM, first observed by PAMELA and thus called the PAMELA effect, was clearly confirmed by AMS-02
- In a matter-dominated Universe, one would expect this ratio to decrease with E, unless specific sources of positrons are present nearby.
  - If these sources are heavy particles decaying into final states involving e+, one could expect the ratio to increase, and then steeply drop after reaching half of the mass of the particle.
  - If an astrophysical source of HE positrons is present, a smooth spectrum is expected instead.
- The present data is compatible with an hypothetical DM particle with a mass of ~1 TeV, but there is not a definite answer yet. The most recent data on the abundance of high-energy pulsars nearby might justify an astrophysical explanation of this excess but not the results in antiproton



Antiprotons



Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).
Astrophysics Model examples: P. Mertsch and S. Sarkar, Phys. Rev. D 90, 061301 (2014);
K. Kohri, K. Ioka, Y. Fujita, and R. Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016).

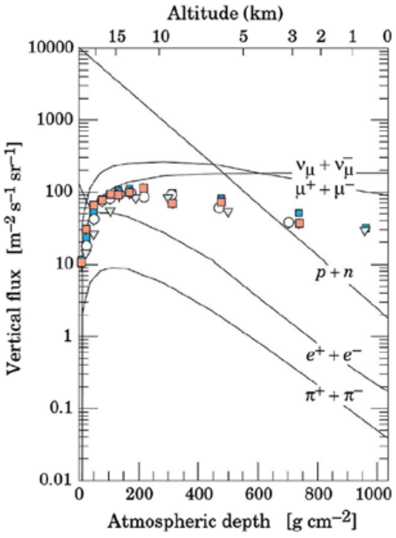
Muons

Astrophysical muons can hardly reach the Earth's atmosphere due to their lifetime ($\tau \sim 2\,\mu$s); this lifetime is however large enough, that secondary muons produced in the atmosphere can reach the Earth's surface, offering a wonderful example of time dilation: the space crossed in average by such particles is $L \simeq c\gamma\tau$, and already for $\gamma \sim 50$ (i.e., an energy of about 5 GeV) they can travel 20, 30 km, which roughly corresponds to the atmospheric depth. Muons lose some 2 GeV by ionization when crossing the atmosphere.

Charged particles at sea level are mostly muons (see Fig. 10.36), with a mean energy of about 4 GeV.

The flux of muons from above 1 GeV at sea level is about 60 $\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. A horizontal detector sees roughly one muon per square centimeter per minute. The zenith angular distribution for muons of $E \sim 3$ GeV is $\propto \cos^2\theta$, being steeper at lower energies and flatter at higher energies: low energy muons at large angles decay before reaching the surface. The ratio between μ^+ and μ^- is due to the fact that there are more π^+ than π^- in the proton-initiated showers; there are about 30 % more μ^+ than μ^- at momenta above 1 GeV/c.

A fortiori, among known particles only muons and neutrinos reach significant depths underground. The muon flux reaches $10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ under 1 km of water equivalent (corresponding to about 400 m of average rock) and becomes about $10^{-8}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 10 km of water equivalent.



UHECR

Ultra-High-Energy Cosmic Rays (UHECR) are messengers from the extreme Universe and a unique opportunity to study particle physics at energies well above those reachable at the LHC. However, their limited flux and their indirect detection have not yet allowed to answer to the basic, and always present, questions: Where are they coming from? What is their nature? How do they interact?

The energy spectrum of the UHECR is nowadays well measured up to 10^{20}eV (see Fig. 10.37). The strong GZK-like suppression at the highest energies may be interpreted assuming different CR composition and sources scenarios. Indeed, both pure proton and mixed composition scenarios are able to describe the observed features. In the case of a pure proton scenario, the ankle would be described by the opening, at that energy, of the pair production channel in the interaction of the incoming protons with the CMB photons ($p\,\gamma_{CMB} \rightarrow p\,e^{+}e^{-}$) (this is called the "dip model"), while the suppression at the highest energies would be described in terms of the predicted GZK effect. In the case of mixed composition scenarios such features may be described playing with different sources distributions and injection spectra, assuming that the maximum energy that each nucleus may attain, scales with its atomic number Z.

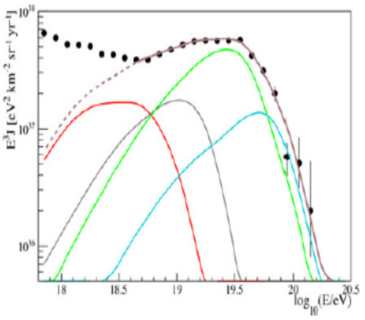
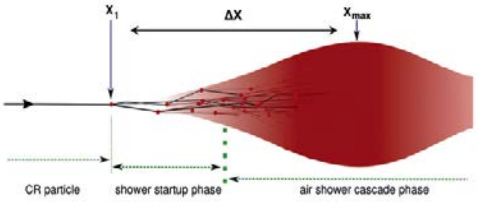


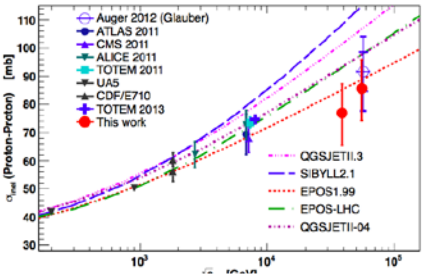
Fig. 10.37 UHECR Energy spectrum measured by the Pierre Auger Observatory (closed circles); the spectrum has been multiplied by E^3. Superposed is a fit to the sum of different components at the top of the atmosphere. The partial spectra are grouped as according to the mass number as follows: Hydrogen (red), Helium-like (grey), Carbon, Nitrogen,Oxygen (green), Aluminum-like (cyan), Iron-like (blue), total (brown). Image credit: Pierre Auger Collaboration

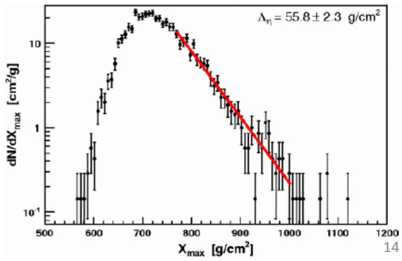
UHECR: Composition

The depth of the maximum number of particles in the shower, X_{max}, schematically represented in Fig. 10.38), is sensitive to the cross-section of the primary cosmic ray interaction in the air. Thus it can be used either to measure the cross-section, if the composition is known, or, once the cross section for a nucleus grows with its atomic number, to determine the composition, if the nuclei-air interaction cross-sections at these energies are assumed to be described correctly by the model extrapolations of the cross-sections measured at lower energies in the accelerators. Indeed, X_{max} may be defined as the sum of the depth of the first interaction X_1 and a shower development length $\varDelta X$ (see Fig. 10.38):

$$X_{max} = X_1 + \varDelta X\,.$$

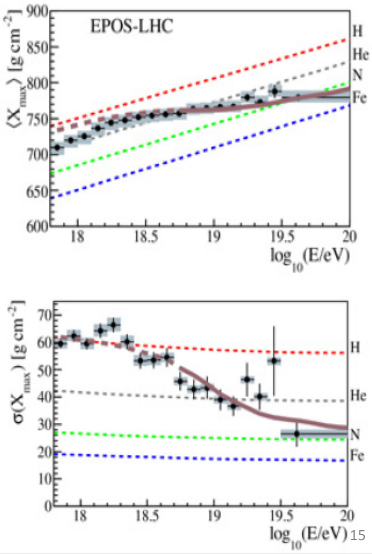






UHECR: Composition

The study of the first two momenta of the X_{max} ($\langle X_{\rm max}\rangle$ itself and the RMS of $\langle X_{\rm max}\rangle$) distributions is nowadays the main tool to constrain hadronic interactions models and hopefully access the cosmic ray composition. The mean and the RMS of the X_{max} distributions measured by the Pierre Auger collaboration as a function of the energy are shown in Fig. 10.42 and compared to the prediction for pure p, He, N and Fe. A fit to extract the fractions of each of these components as a function of the energy was then performed assuming several different hadronic interaction models. The results indicate evidence of a change of the cosmic ray composition from light elements (with a large fraction of protons) at lower energies to heavier elements (He or N depending on the hadronic model) but basically a null abundance of Fe at least until $10^{19.4}$ eV. However, none of the present simulations models is able to reproduce well the observed data. Combining the $X_{\rm max}$ results with variables related with the muonic contents of these extreme high energy EAS the tension between the measurements and the model predictions becomes even more evident.



UHECR: Sources

When integrating over all energies, say, above a few GeV, the arrival direction of charged cosmic rays is basically isotropic—a fact which can find explanation in the effect of the galactic magnetic field smearing the directions–the Compton-Getting effect, a dipole anisotropy of about 0.6% resulting from the proper motion of Earth in the rest frame of cosmic ray sources, has to be subtracted. However, Milagro, IceCube, HAWC, ARGO and the Tibet air shower array have observed additional small large-scale anisotropies (at the level of 10^{-3}), and small small-scale anisotropies (at the level of about 10^{-4}–10^{-5}) in an energy range from a few tens of GeV to a few hundreds of TeV (see Fig. 10.43). Its origin is still under debate; the disentangling of its probable multiple causes is not easy. There is no simple correlation of anisotropies with known astrophysical objects.

At extremely high energies, instead, statistically significant anisotropies have been found – and their interpretation is straightforward.

To accelerate particles up to the ultra-high-energy region above the EeV, 10^{18} eV, one needs conditions that are present in astrophysical objects such as the surroundings of SMBHs in AGN, or transient high-energy events such as the ones generating gamma ray bursts. Galactic objects are not likely to be acceleration sites for particles of such energy, and coherently we do not observe a concentration of UHECRs in the galactic plane; in addition, the galactic magnetic field cannot confine UHECRs above 10^{18} eV within our galaxy.

UHECR Sources

- Due to the GZK horizon and to EG B (1 nG - 1 fG), the number of sources is relatively small => some anisotropy could be found studying the arrival directions of UHECR
- Indication for intermediate-scale anisotropy, correlated to nearby AGN reported by Auger
- In ~30 000 CR with E>8 EeV recorded in 12 years, corresponding to a total exposure of 76,800 km2 sr yr, Auger has seen at > 5.2σ a dipole anisotropy of about 6.5%
- After correcting for B, the direction is consistent with the flux-weighted dipole from nearby AGN

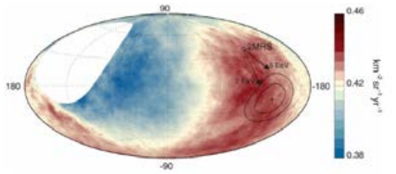
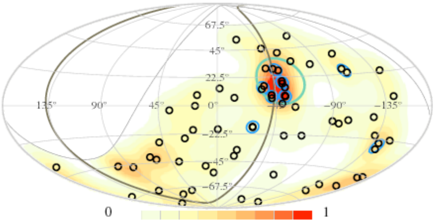
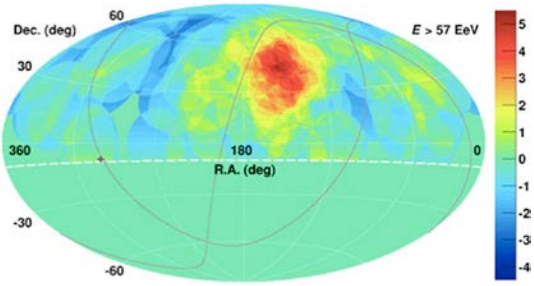


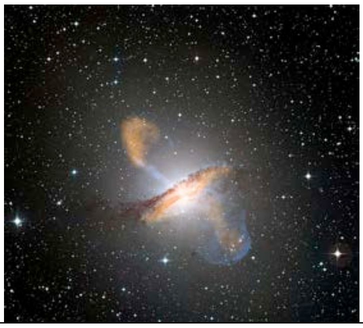
Fig. 10.44 Sky map in galactic coordinates showing the cosmic-ray flux for $E > 8$ EeV. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected due to the galactic magnetic field on particles with $E/Z = 5$ and 2 EeV. Image credit: Pierre Auger collaboration

UHECR individual sources?

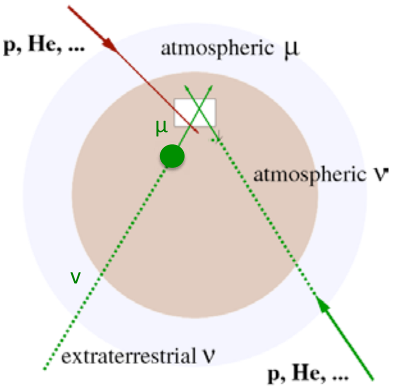
- In 2007 the Pierre Auger collaboration claimed with a signicance >3σ a hot spot near the Centaurus A AGN, at a distance of about 4 Mpc. Cen A is also a VHE gamma-ray emitter.
- However, the data collected after 2007 have not increased the signicance of the detection.
- The Telescope Array Project observes at energies above 57 EeV a hot spot, with best circle radius 25 degrees, near the region of the Ursa Major constellation.

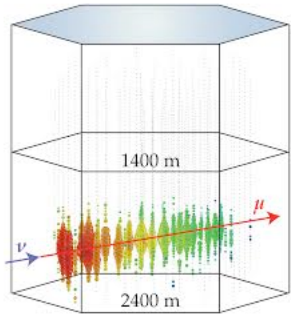






TXS 0506 +056: The IceCube neutrino



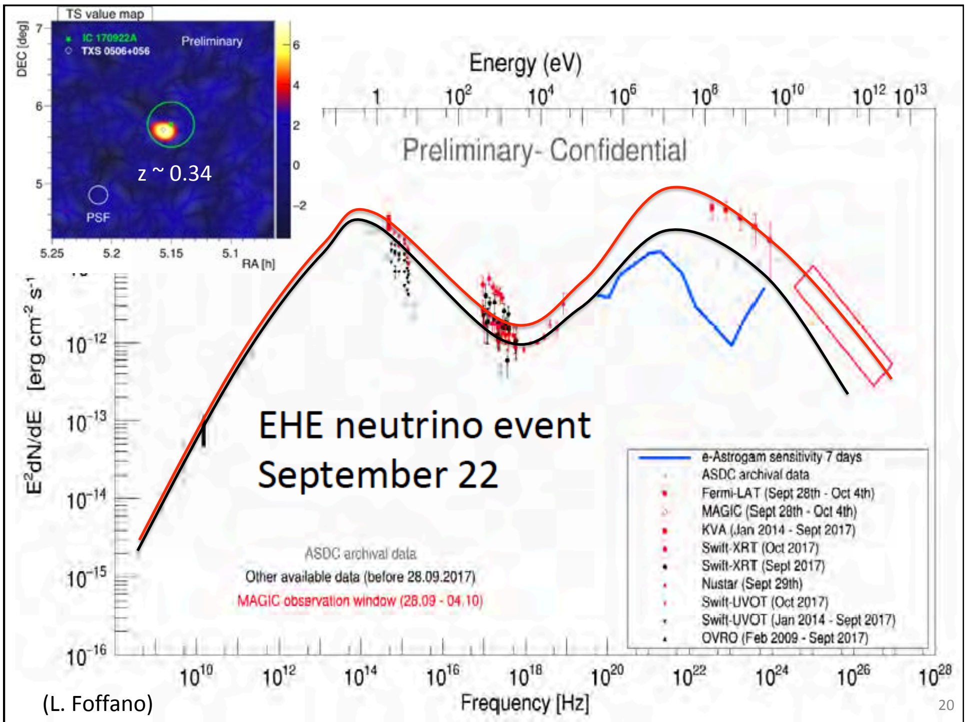


EXP

$E_{\mu,seen}$ ~ 20 TeV
E_ν ~ 300 TeV
E_p ~ 6 PeV – 10 PeV

TH

E_p ~ 10 PeV – 20 PeV



EHE neutrino event
September 22

(L. Foffano)

IceCube: Ep ~ 10 PeV

- Background probability extremely low

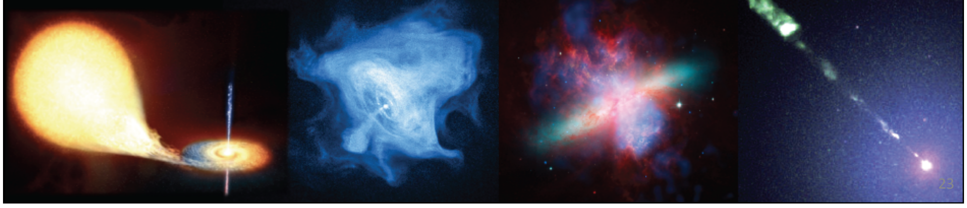
- Independent informations:
  - Neutrino flux (column density, cutoff energy for protons)
  - Gamma SED (column density, shape of the proton yield)
  - MW SED quiet/in flare: e/p ratio
  - Degradation of energy between gamma and neutrino: column density

GAMMA RAYS

TeV Impact

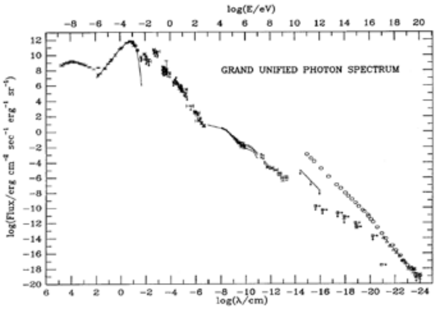
Highlights from **HESS, MAGIC, VERITAS & MILAGRO**

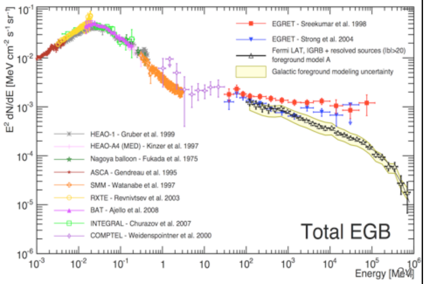
- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars:* Science 322, 1221 (2008), Science 334, 69 (2011)
- *Supernova Remnants:* Nature 432, 75 (2004)
- *The Galactic Centre:* Nature 439, 695 (2006)
- *Surveys:* Science 307, 1839 (2005), PRL 95, 251103 (2005)
- *Starbursts:* Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN:* Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL:* Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark Matter:* PRL 96, 221102 (2006), PRL 106, 161301 (2011)
- *Lorentz Invariance:* PRL 101, 170402 (2008)
- *Cosmic Ray Electrons:* PRL 101, 261104 (2009)



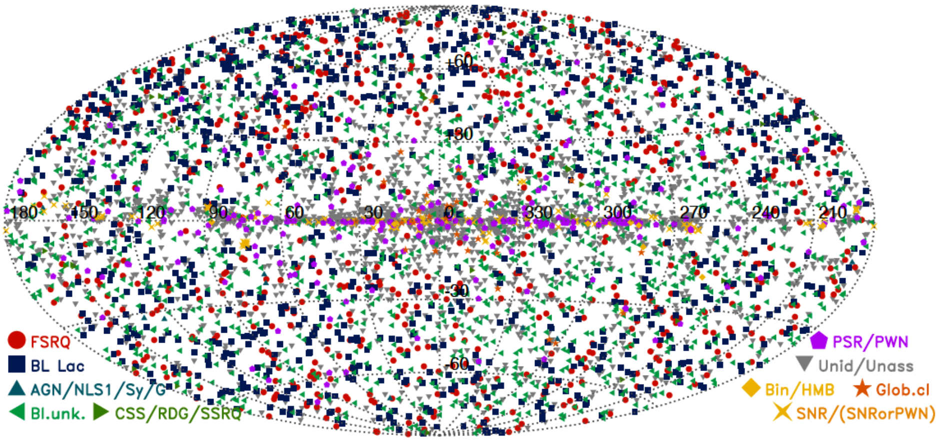
Diffuse spectrum

- The experimental data on the diffuse photon radiation span some 30 energy decades. A bump is visible corresponding to the CMB
- The general behavior can be approximated by an energy dependence as a power law ~E$^{-2.4}$
- A cutoff at energies ~1 TeV might be explained by the absorption of higher energy photons by background photons near visible populating the intergalactic medium through creation of e+e- pairs



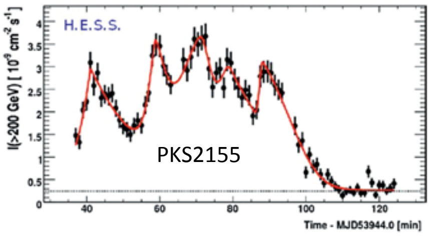


Sources of gamma radiation (and CR?)
Fermi 8-year catalog: ~5500 sources



Transient Phenomena

- Short timescale variability observed inseveral astrophysical objects, both galactic and extragalactic, in particular binary systems, and AGN.
  - For binary systems the variability is quasiperiodical and can be related to the orbital motion
  - for AGN it is in general related to some cataclysmic events; this is the phenomenon of flares
    - T << Rs/c => Evidence of acceleration in jets
    - Limits on LIV
  - Flares observed from Crab Nebula have, as today, no universally accepted interpretation.



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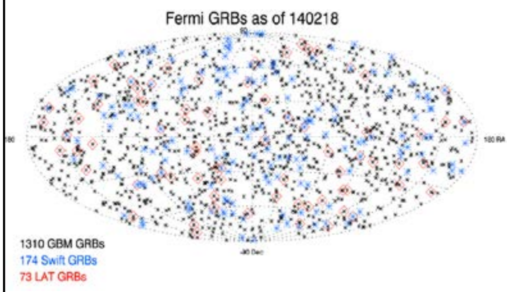
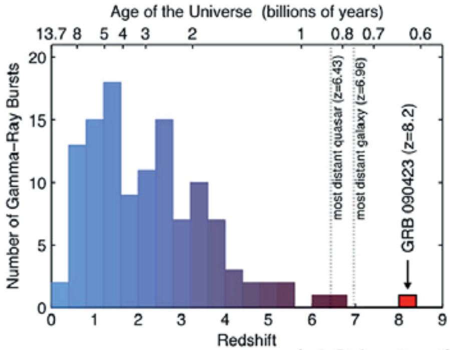
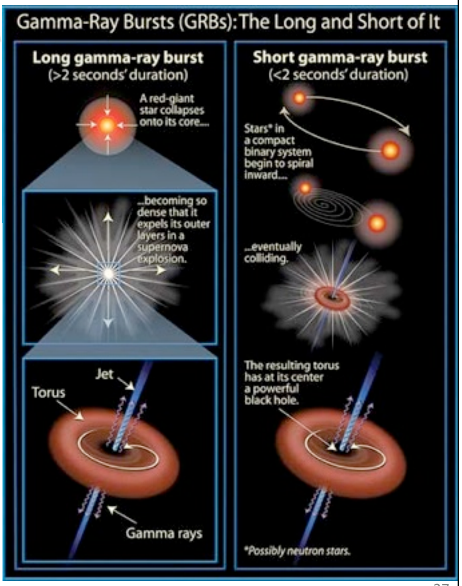
GRBs





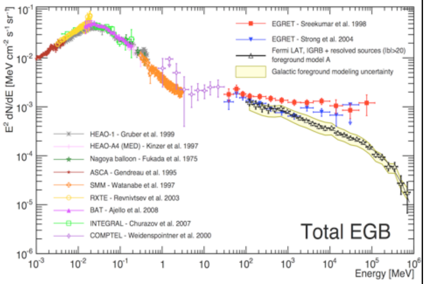
Credit: Edo Berger (Harvard/CfA)

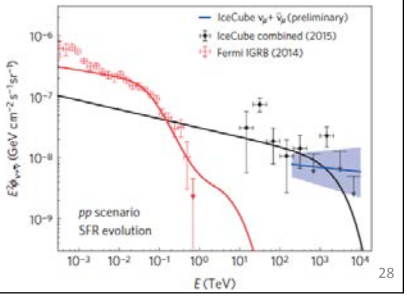


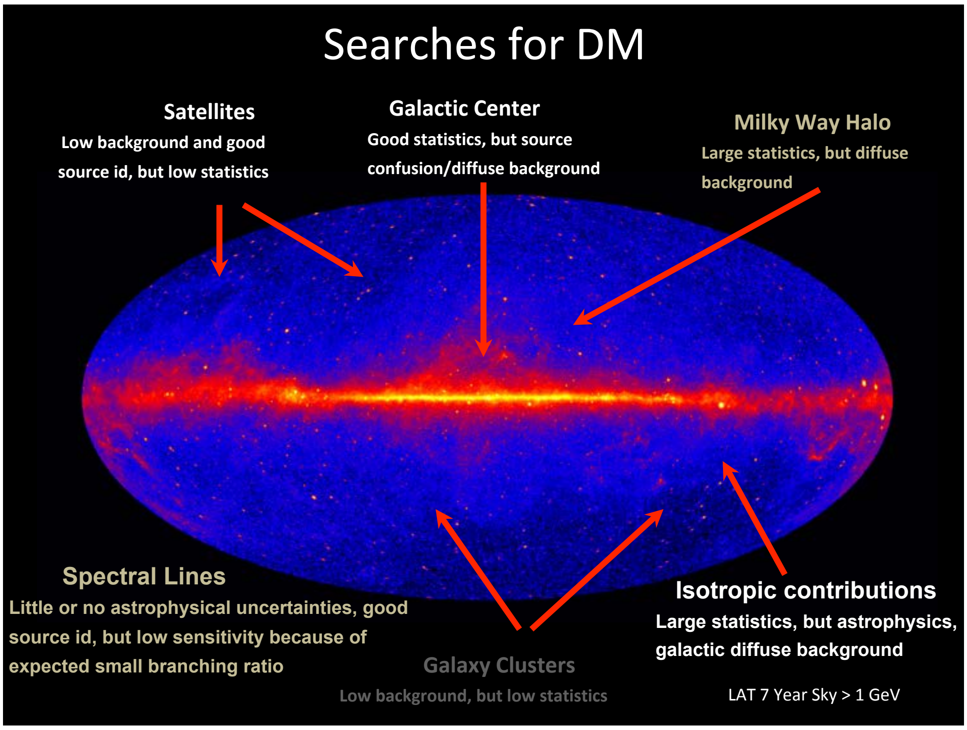
Gamma rays and CR accelerators

- Evidence of CR acceleration in SNRs
  - Several sources
  - A couple of PeVatrons (one in the GC, the other is Crab Nebula)
- Evidence of > PeVatron in a blazar
- The diffuse neutrino flux can be related to the diffuse photon flux

$$\boxed{\frac{dN_\gamma}{dE_\gamma} \propto \frac{dN_{p,e}}{dE_{p,e}}}$$







Searches for DM

Satellites
Low background and good source id, but low statistics

Galactic Center
Good statistics, but source confusion/diffuse background

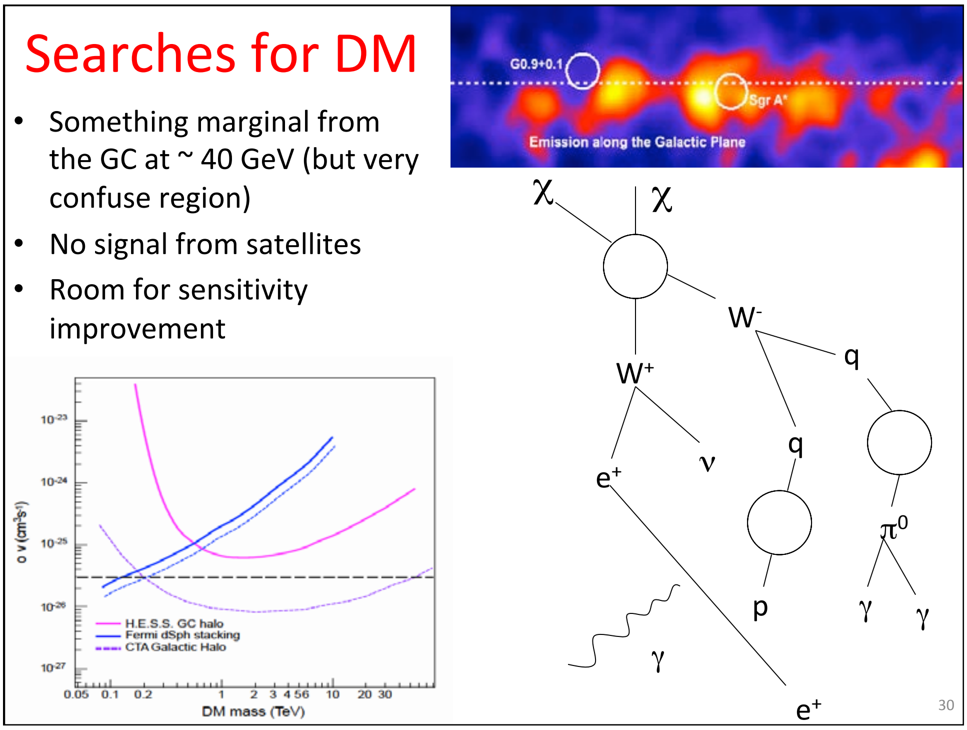
Milky Way Halo
Large statistics, but diffuse background

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters
Low background, but low statistics

Isotropic contributions
Large statistics, but astrophysics, galactic diffuse background

LAT 7 Year Sky > 1 GeV



Searches for DM

- Something marginal from the GC at ~ 40 GeV (but very confuse region)
- No signal from satellites
- Room for sensitivity improvement

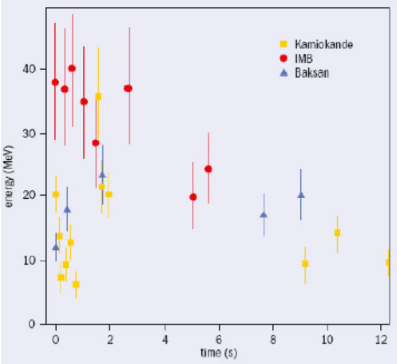
NEUTRINOS

Astrophysical neutrinos

- Experimental data on astrophysical neutrinos are scarce: their small cross section makes the detection difficult. We discussed in Chap. 4 the problems of neutrino detectors
- Up to now we detected astrophysical ν from
  - the Sun
  - the center of the Earth
  - the supernova SN1987A
  - one EHE neutrino from the blazar TXS 0506 +056
  - diffuse VHE astrophysical νs that we are can’t locate the origin of
- The (low-energy) ν from the Sun (and shortly from the Earth) are discussed in Chap. 9 and will be the subject of a Seminar; hereafter we review briefly the ν produced in SN1987A and the VHE IceCube data

SN1987A in the Large Magellanic Cloud

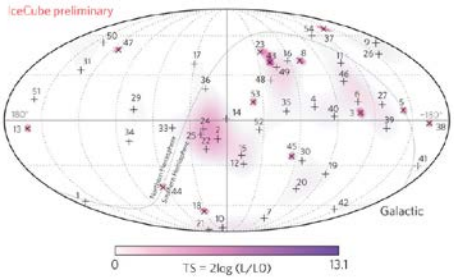
- On Feb 23, 1987, a SN was observed in the LMC, a satellite of the Milky Way (about ~1% of the mass of our Galaxy), about 50 kpc away
  - Also the first SN since 1604 visible with naked eye
  - Collapse of the star Sanduleak-69202, of mass ~20 M_S
- ~3h before optical detection, a bunch of neutrinos was observed on Earth.
- Three water Cherenkov detectors: Kamiokande, IMB, and the Baksan, observed 12, 8, and 5 neutrino interaction events, respectively, over a 13 s interval
- Within the limited statistics achieved by these 1st-generation detectors, number of events and burst duration consistent with standard estimates of the energy release and cooling time of a SN. Energy of neutrinos inferred from the energy of the recoil electrons ~10 MeV range, consistent with the origin from a collapse of a star of that mass
- No (V)HE gamma rays



- Fundamental properties of neutrinos:
  - ν arrival time distribution => $m_\nu < 10$ eV
  - No spread: $\mu < 10^{-12}\, \mu_B$
  - Optical delay: $|v-c|/c < 2\ 10^{-9}$

Diffuse VHE astrophysical neutrinos

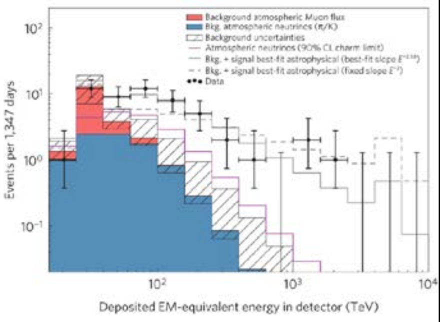
- IceCube reported for the 1st time in 2013 the detection of astrophysical νs; now the evidence is much stronger and ~1 astrophysical neutrino/month collected
- The experimental problem is linked to the relatively large background from atmospheric muons, which are recorded, even at a depth of 1450 m, at a rate of about 3000 per second. Two methods are used to identify genuine ν events:
  - Use the Earth as a filter remove the huge background of CR muons. i.e., look only to events from the bottom
  - Identify νs interacting inside the detector: divide the instrumented volume of ice into an outer veto shield and a 500 megaton inner fiducial volume. Total absorption calorimeter, and one can have an energy estimate.



- Physics result:
  - No clustering

Diffuse VHE astrophysical neutrinos

- Energy and zenith angle dependence is consistent with expectations for a flux of neutrinos produced by cosmic accelerators - a purely atmospheric component is excluded at more than 7 sigma.
- The cosmic neutrino flux dominates the atmospheric background above an energy ~30 TeV

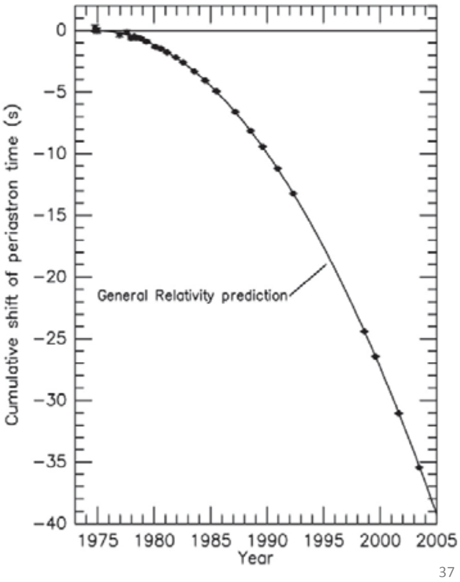


$$\Phi_\nu \simeq (0.9 \pm 0.3) \times 10^{-18} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.13\pm0.13} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$$

GRAVITATIONAL RADIATION

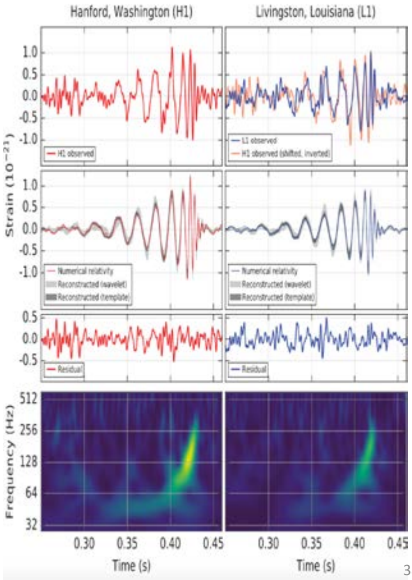
Gravitational waves

- The graviton, a massless spin 2 particle (condition required by the fact that gravity is attractive), is the proposed mediator of any FT of gravity. Einstein had sentenced that it was “impossible to detect" experimentally. However, evidence of gravitational radiation have been demonstrated
- In 1974, Hulse and Taylor (Nobel prize) observed that the orbital T of the binary pulsar PSR 1913+16 was decreasing in agreement with the prediction of Einstein GR (about 40 s in 30 years). Such system is composed by two NS ~1.4 solar masses; the period is ~7.75 h and the maximum and minimum separation are 4.8 and 1.1 solar radii
- The gravitational waves’ direct observation is out of the reach of the present GW detectors; however, they have been found from the study of dT/dt



First direct evidence

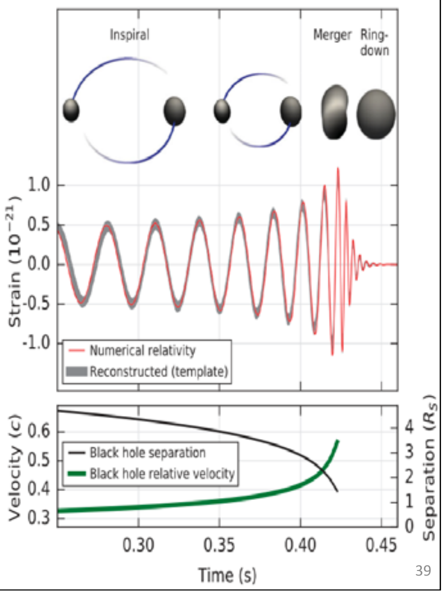
- On September 14th, 2015, the two LIGO detectors observed simultaneously a large and clear GW signal that matches the prediction of GR for the coalescence of a BH-BH system
- The observed amplitudes (strain), are ~10^{-21} and the frequencies are in the range 35 Hz to 250 Hz. The masses of initial BHs were estimated to be ~ 36±5 and 29±4 M_S and the final BH 62±4 M_S . The distance was ~400 Mpc.



The mechanism

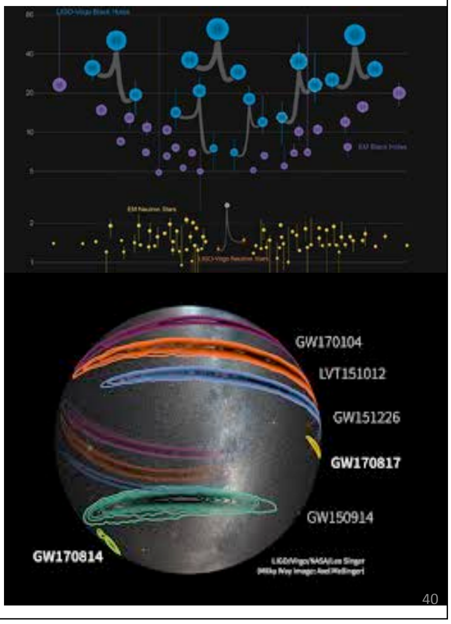
3 phases are well identified:

1. Inspiral : the approach of the 2 BH; frequency and amplitude increase slowly;
2. Merger : the merging of the two BHs; frequency and amplitude increase rapidly;
3. Ringdown : the newly formed BH is distorted and rings down to its final state by emitting radiation and the amplitude decays exponentially as time goes by. After this stage, there is only a single, quiet BH



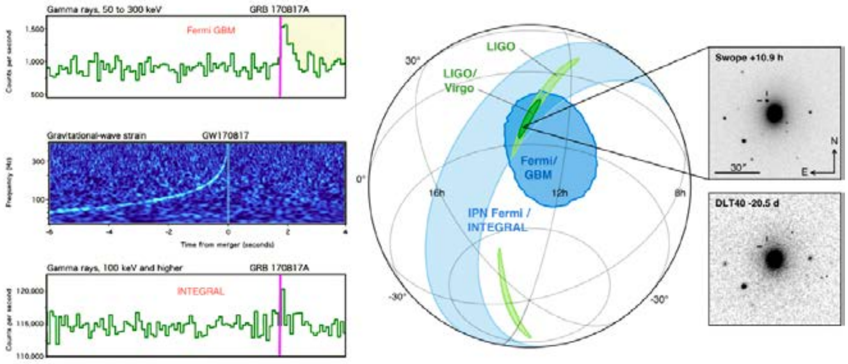
Many events

- Four more events were observed by LIGO respectively in December 2015, January 2017 (2), August 2017, again interpreted as the coalescence of binary black hole system
  - Two seen by VIRGO (improved localization)
  - See the masses
- And a special one: GW170817



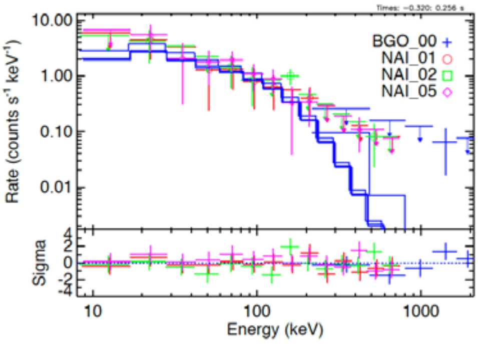
GW170817: proof of MM astrophysics

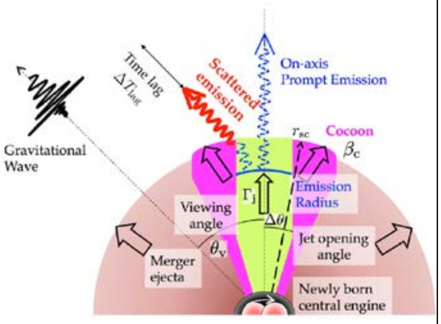
- 100 s starting from a ~24 Hz for ~3000 cycles, increasing in amplitude and frequency to a few hundred Hz
- GRB 170817A, a sGRB, detected by Fermi GBM 1.74±0.05 s after the merger time at ~80 keV and lasting a few s; confirmed by INTEGRAL
- Optical localization at ~40 Mpc; non-pointing axis (~30 degrees)
- Two NS of ~1.4 M_S, generating a sGRB; released energy >0.025 M_{Sun}



GW170817: the gamma-ray counterpart

- Seen by Fermi GBM, INTEGRAL, Chandra
- Extends to ~300 keV





Many things we learned from GW

- Speed of GW/Speed of light
- Coalescence rate of NS, BH
- NS-NS systems are progenitors of sGRB
- More stellar mass BHs than we thought
- …

ABOUT THE EXAM…

Some **scientific** articles you might choose for the final exam
(of course you can propose your own, and I'll answer you if it's OK for me)

1. Acceleration of petaelectronvolt protons in the Galactic Centre. By HESS Collaboration (F. Aharonian et al.). Nature 531 (2016) 476.

2. Search for Spectral Irregularities due to Photon–AxionLike-Particle Oscillations with the Fermi Large Area Telescope. By Fermi-LAT Collaboration (M. Ajello et al.). Phys. Rev. Lett. 116 (2016) no.16, 161101.

3. Detection of the Characteristic Pion-Decay Signature in Supernova Remnants. By Fermi-LAT Collaboration (M. Ackermann et al.). Science 339 (2013) 807.

4. Searches for Dark Matter annihilation signatures in the Segue 1 satellite galaxy with the MAGIC telescope. By MAGIC Collaboration (J. Aleksic et al.). JCAP 1106 (2011) 035.

5. Search for a Dark Matter annihilation signal from the Galactic Center halo with H.E.S.S. By HESS Collaboration (A. Abramowski et al.). Phys. Rev. Lett. 106 (2011) 161301.

6. Very-High-Energy Gamma Rays from a Distant Quasar: How Transparent Is the Universe? By MAGIC Collaboration (E. Aliu et al.). Science 320 (2008) 1752.

7. Evidence for a new light spin-zero boson from cosmological gamma-ray propagation? By Alessandro De Angelis, Marco Roncadelli, Oriana Mansutti. Phys. Rev. D76 (2007) 121301.

8. The energy spectrum of cosmic-ray electrons at TeV energies. By HESS Collaboration (F. Aharonian et al.). Phys. Rev. Lett. 101 (2008) 261104.

9. High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV with the Alpha Magnetic Spectrometer on the International Space Station. By AMS Collaboration (L. Accardo et al.). Phys. Rev. Lett. 113 (2014) 121101.

10. Probing Quantum Gravity using Photons from a flare of the active galactic nucleus Markarian 501 Observed by the MAGIC telescope. By MAGIC and Other Contributors (J. Albert et al.). Phys. Lett. B668 (2008) 253.

11. Observation of Gravitational Waves from a Binary Black Hole Merger. By LIGO and Virgo Collaborations (B. Abbott et al.). Phys. Rev. Lett. 116 (2016) 061102.