Multi-Messenger Astronomy

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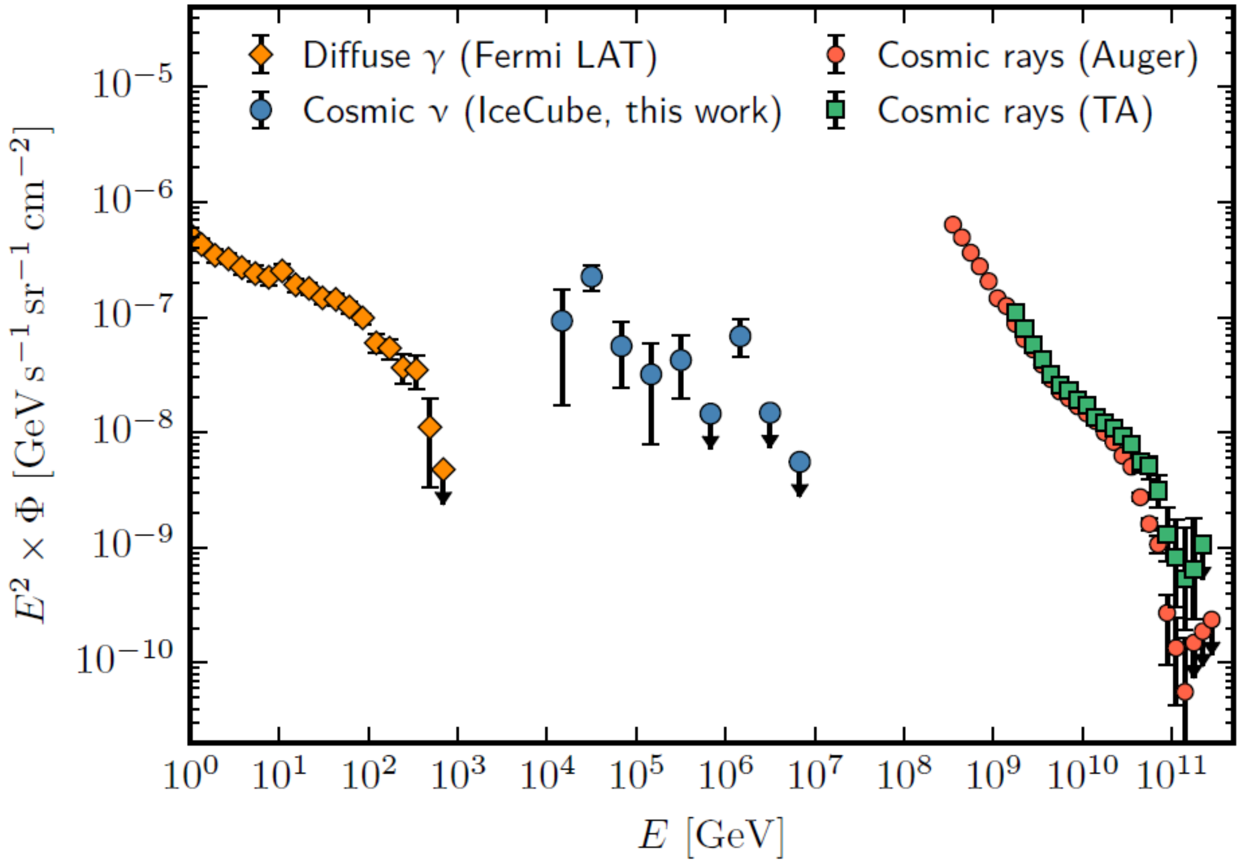
VRIJE UNIVERSITEIT BRUSSEL   FWO VLAANDEREN   ODYSSEUS Topwetenschap in Vlaanderen   iihe BRUXELLES BRUSSEL

Overview

Observed spectra

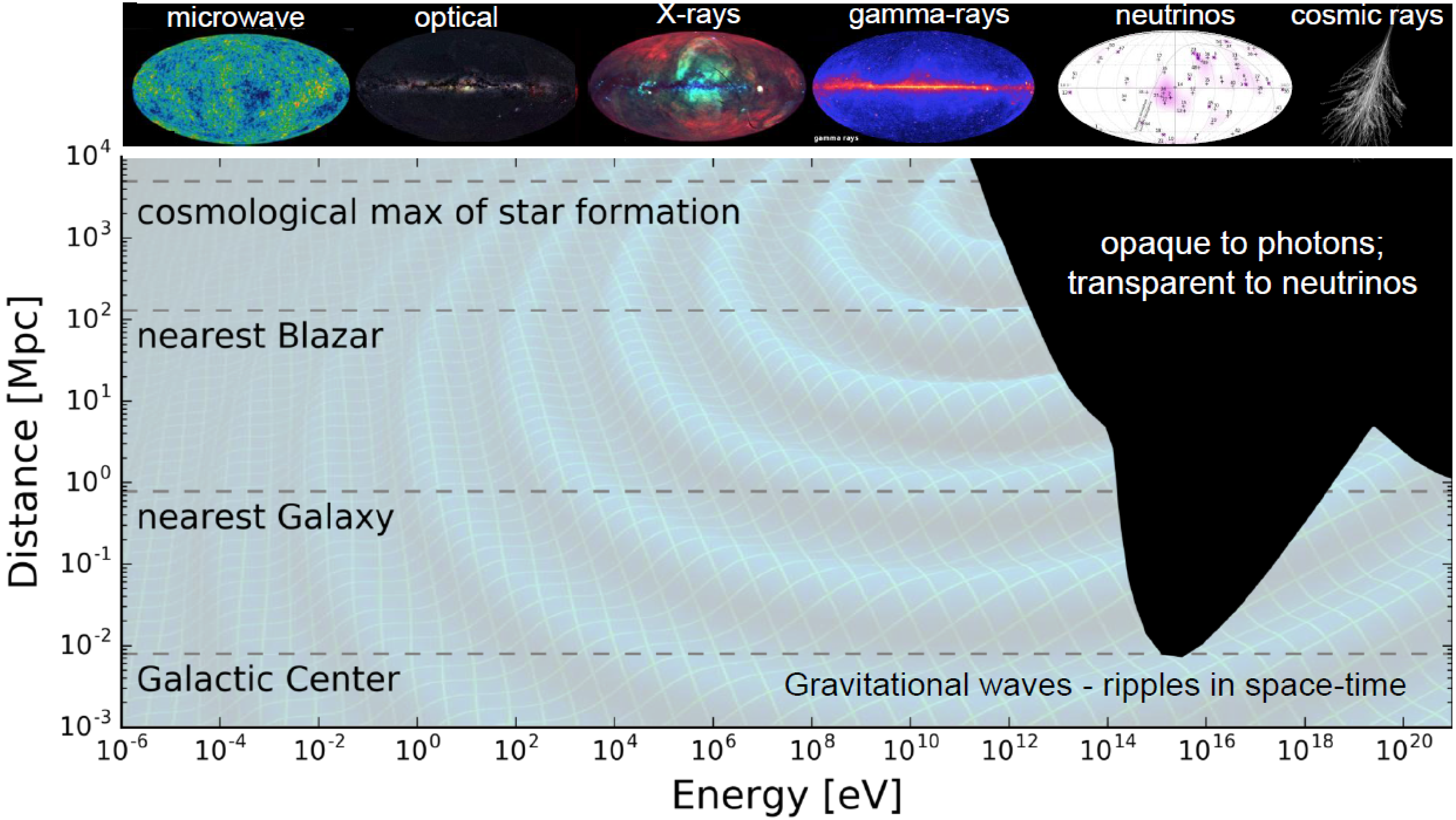


[Lars Mohrmann, PhD 2015, Humboldt University Berlin]

Common astrophysical sources ?

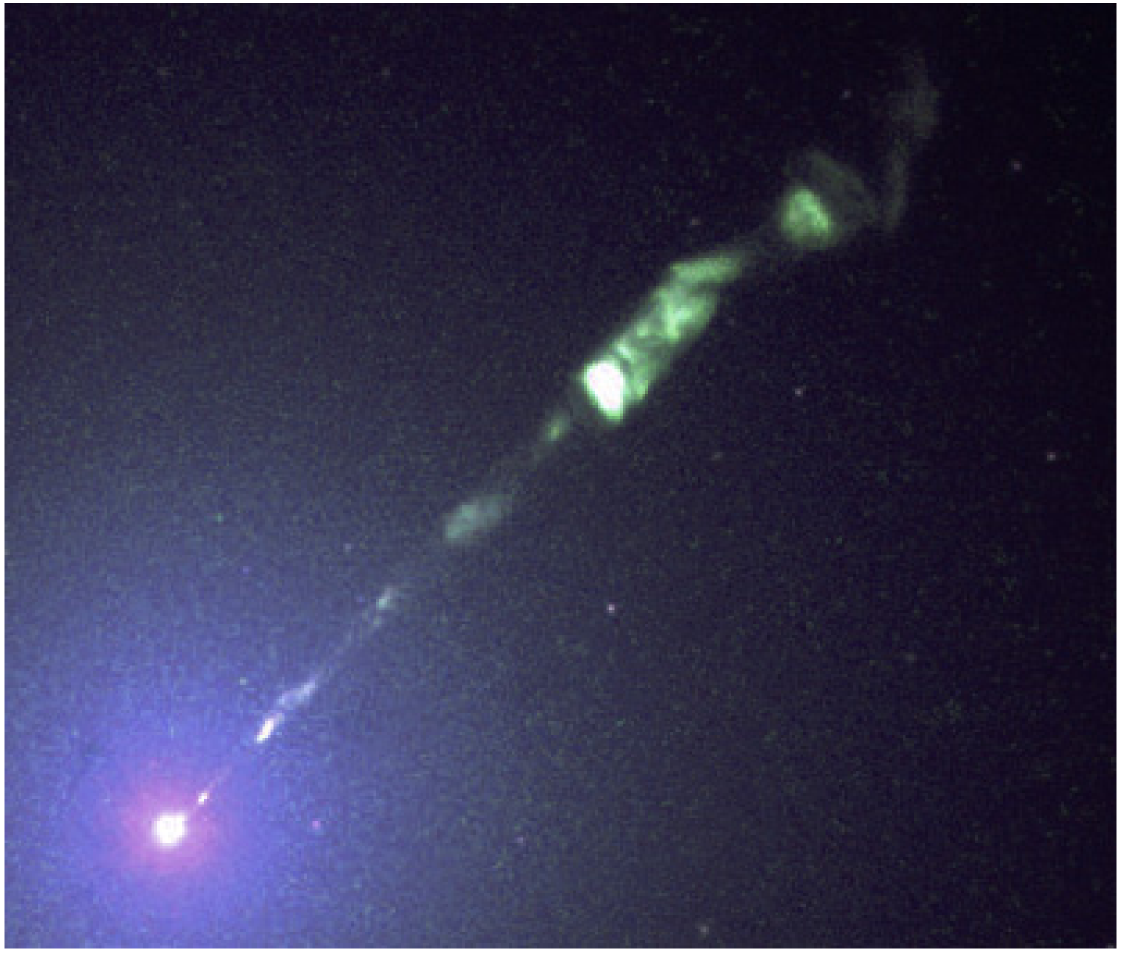
$N + \gamma \rightarrow \Delta \rightarrow \pi + N$ **(CR)** $\qquad \pi^0 \rightarrow \gamma\gamma$ **(Fermi)** $\qquad \pi^\pm \rightarrow \nu, \bar{\nu}$ **(IceCube)**

Beware of the observable Universe: $\gamma + \gamma_{EBL} \rightarrow e^+e^-$ $N + \gamma_{CMB} \rightarrow \Delta$



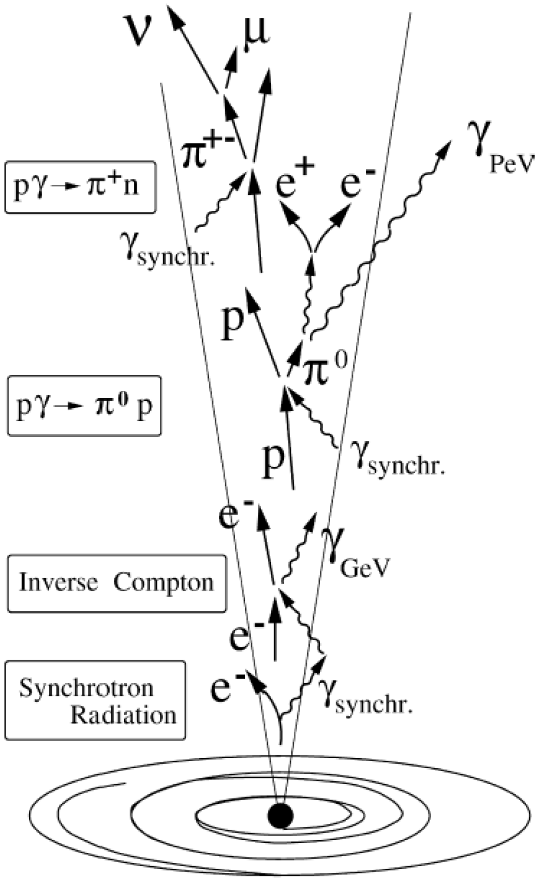
Credit Marek Kowalski

AGN and GRBs as possible sources



M87: Credit NASA

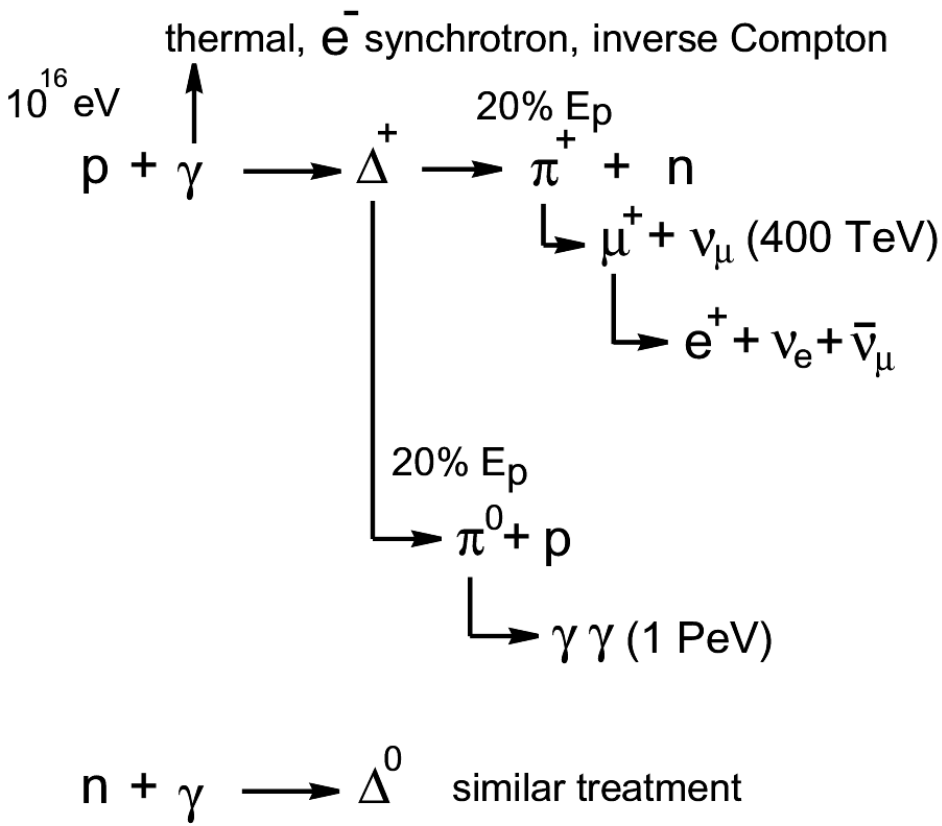
Processes in the jet



Credit C. Spiering

The CR-Neutrino connection

Neutrino production mechanism



- **Δ prod. threshold : $E_\gamma \geq 10$ eV (UV photons)**

- **Waxmann-Bahcall** [PRL 78 (1997) 2292]

  High-E p diffuse out of the shocks

  Observed CR $\rightarrow$ lower limit on p flux

  Fraction of p used for ν production ?

- **M. Ahlers et al.** [APP 35 (2011) 87]

  Protons trapped, neutrons escape

  CR observations provide the n flux

  Direct relation CR $\leftrightarrow$ ν flux

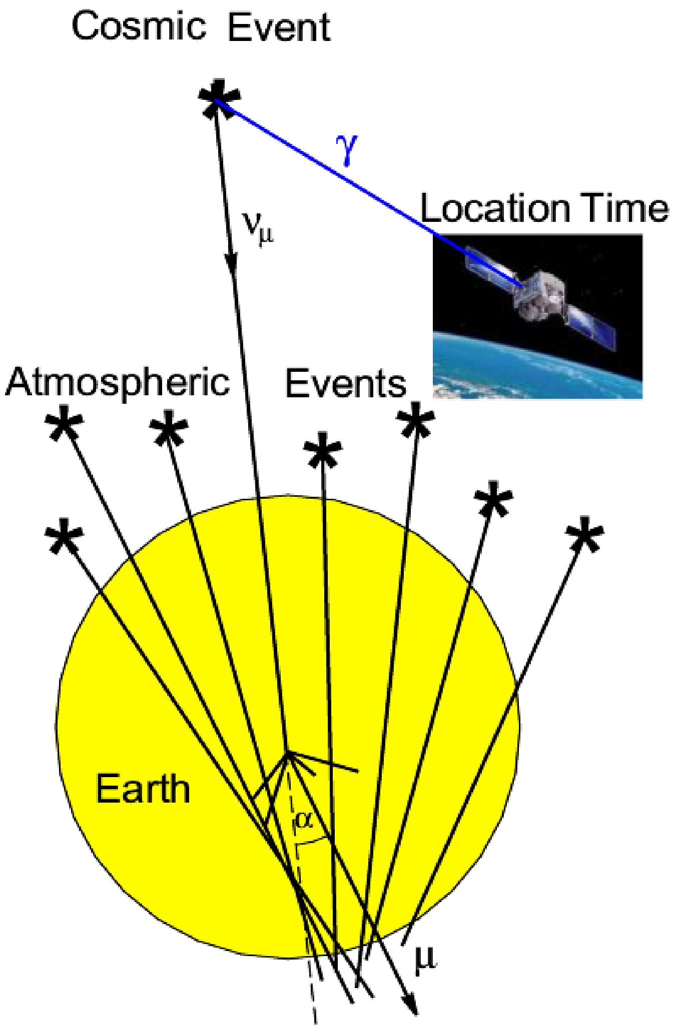
- **Generic broken powerlaw ν spectrum**

$$\Phi_\nu(E) \sim \begin{cases} E^{-1}\epsilon_b^{-1} & (E < \epsilon_b) \\ E^{-2} & (\epsilon_b \leq E \leq 10\epsilon_b) \\ E^{-4}(10\epsilon_b)^2 & (E > 10\epsilon_b) \end{cases}$$

with $\epsilon_b \approx 1$ PeV [JCAP 0903 (2009) 020]

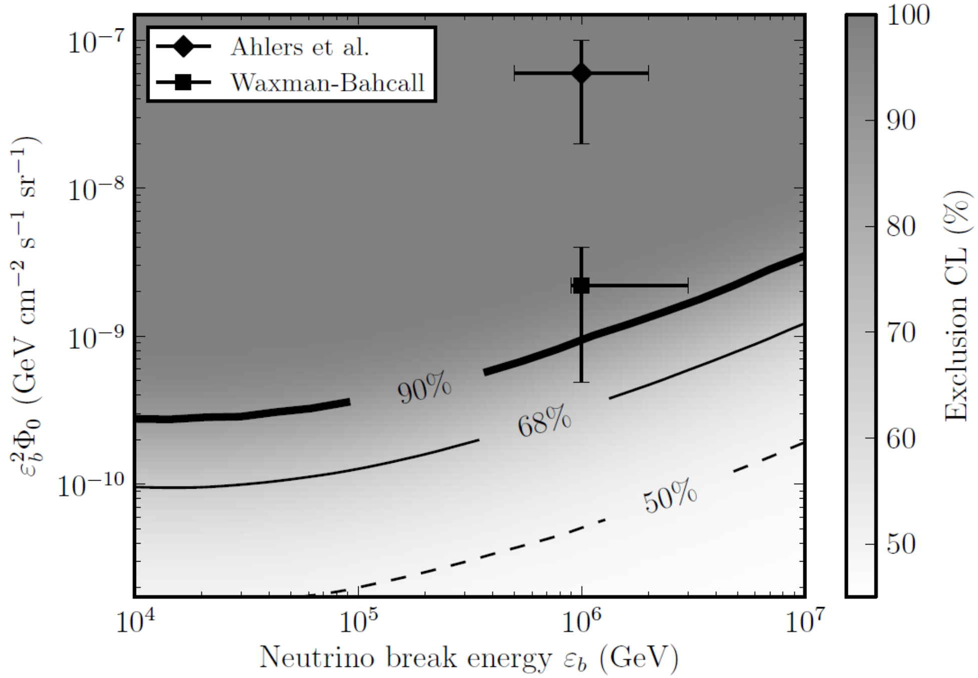
The CR-Neutrino connection

Multi-Messenger observations



IceCube GRB prompt ν flux limit

[ApJ Let. 805 (2015) L5]



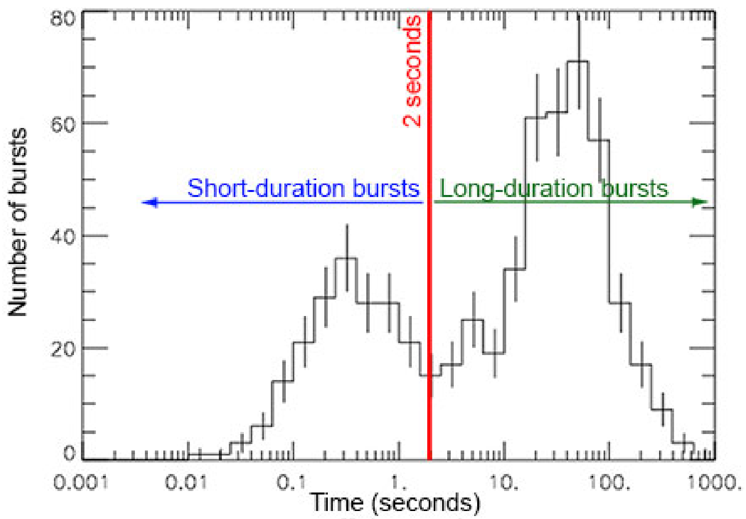
GRBs not the (only) UHECR sources

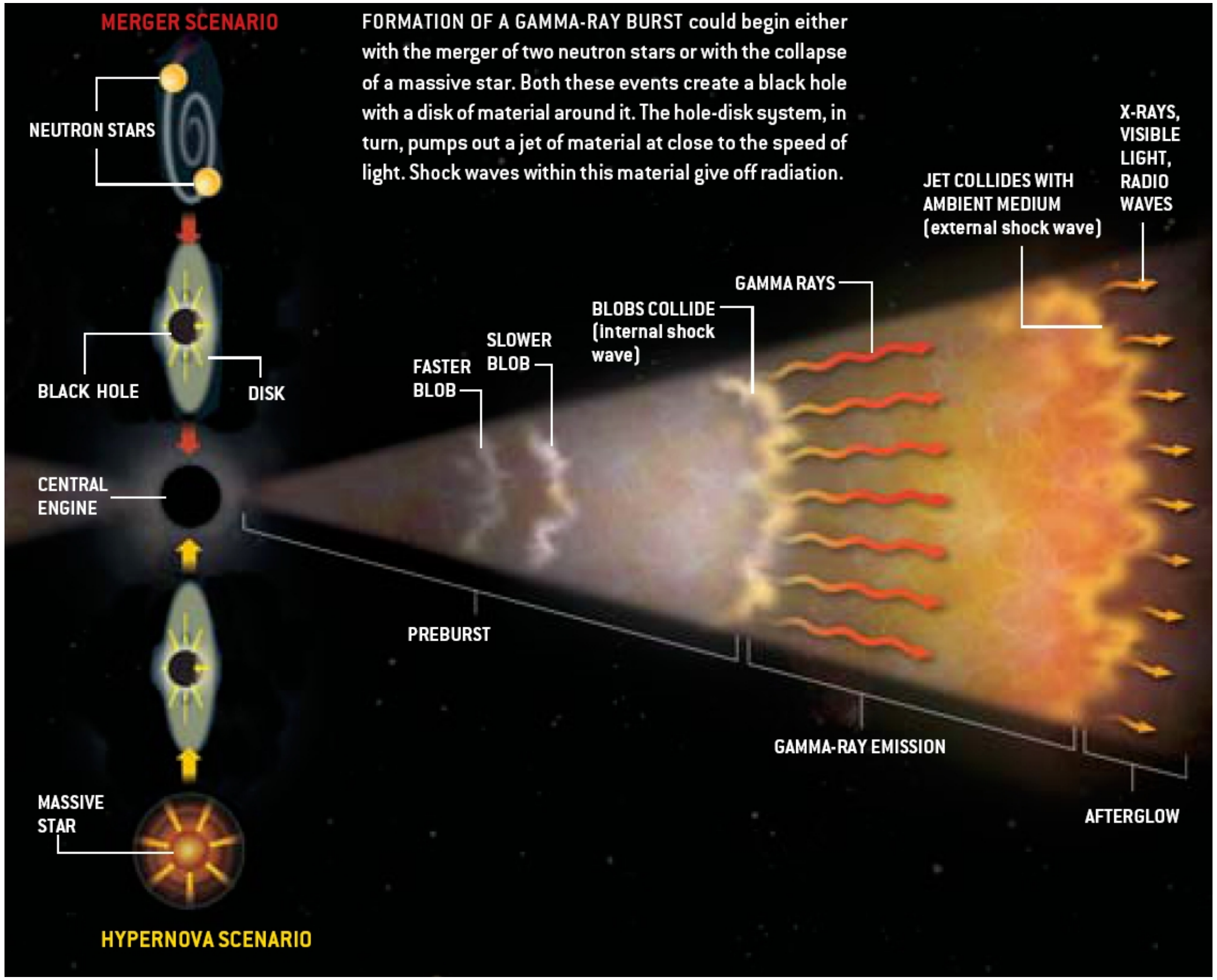
Or : ν prod./E lower than expected

Or : ν prod. outside prompt phase

Observed bi-modal duration distr.

Possible GRB scenarios



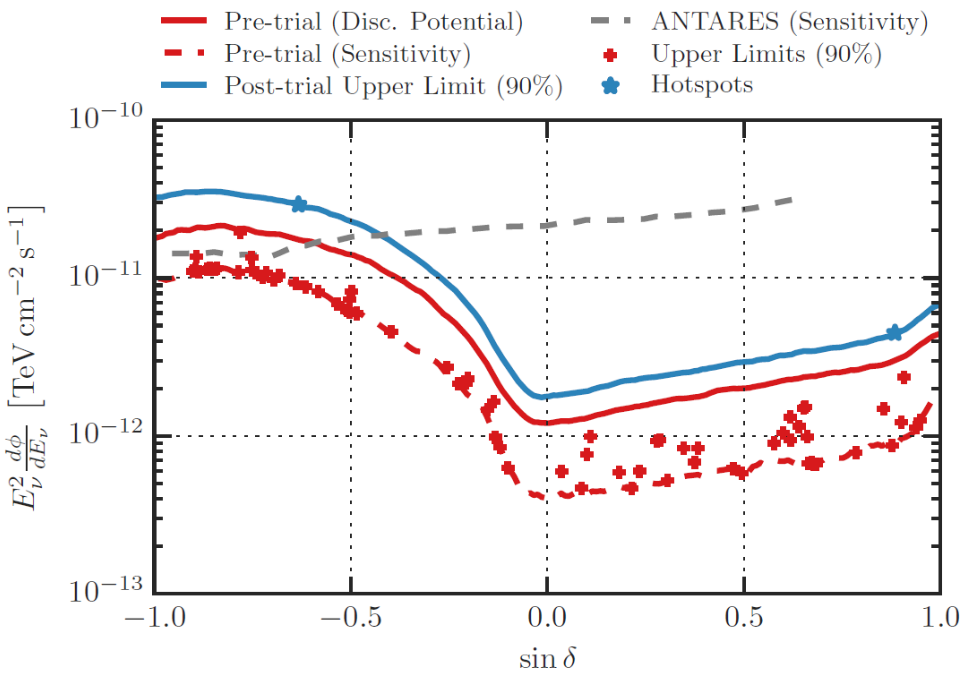


Multi-Messenger studies may provide insight in the various processes

IceCube search for neutrino point sources

All sky and bright AGN

[ApJ 835 (2017) 151]



- No point sources observed
- AGN source density

  $\rightarrow$ not the (only) UHECR sources

Cosmic ν and Fermi 2LAC Blazars

[ApJ 835 (2017) 45]

Various ν vs. γ flux models

Population	weighting scheme equal	γ	γ (extrapol.)
all 2LAC blazars	19% – 27%	7%	10%
FSRQs	5% – 17%	5%	7%
LSPs	6% – 15%	5%	7%
ISP/HSPs	9% – 15%	5%	7%
LSP-BL Lacs	3% – 13%	6%	9%

- Small contribution to cosmic ν flux

  Blazars not the cosmic ν sources

The Gamma-Neutrino connection

- Fermi EGB observations

  $\sim$85% of diffuse γ's from Blazars

- IceCube observations

  Cosmic ν's NOT from Blazars

- Take EGB NON-Blazar component

  $\rightarrow$ Prediction for ν flux

$*$ ν flux underestimated

Fermi and IceCube data tension

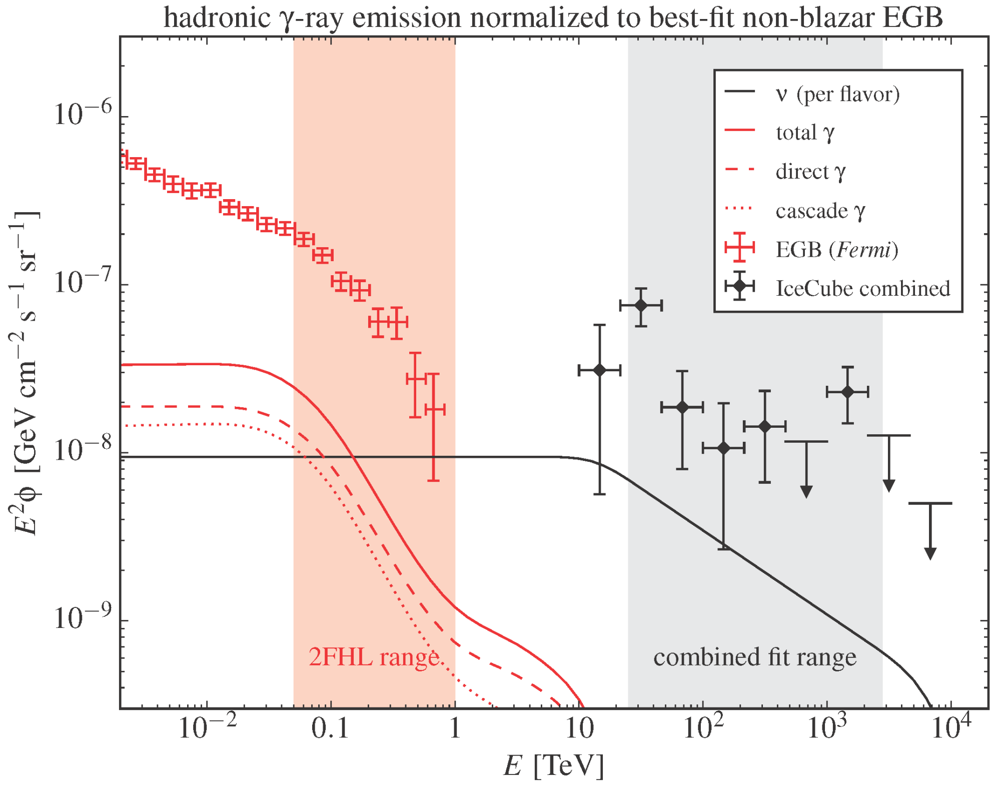
- Cosmic ν's from obscured sources ?

  [PRD 94 (2016) 103007]

- Dust may provide a "CR beam dump"

  $\rightarrow$ Neutrino factory

$*$ Accelerator must be present



[arXiv:1511.00688]

(2FHL: 2nd Fermi Hard Source List)

How to find obscured accelerators?

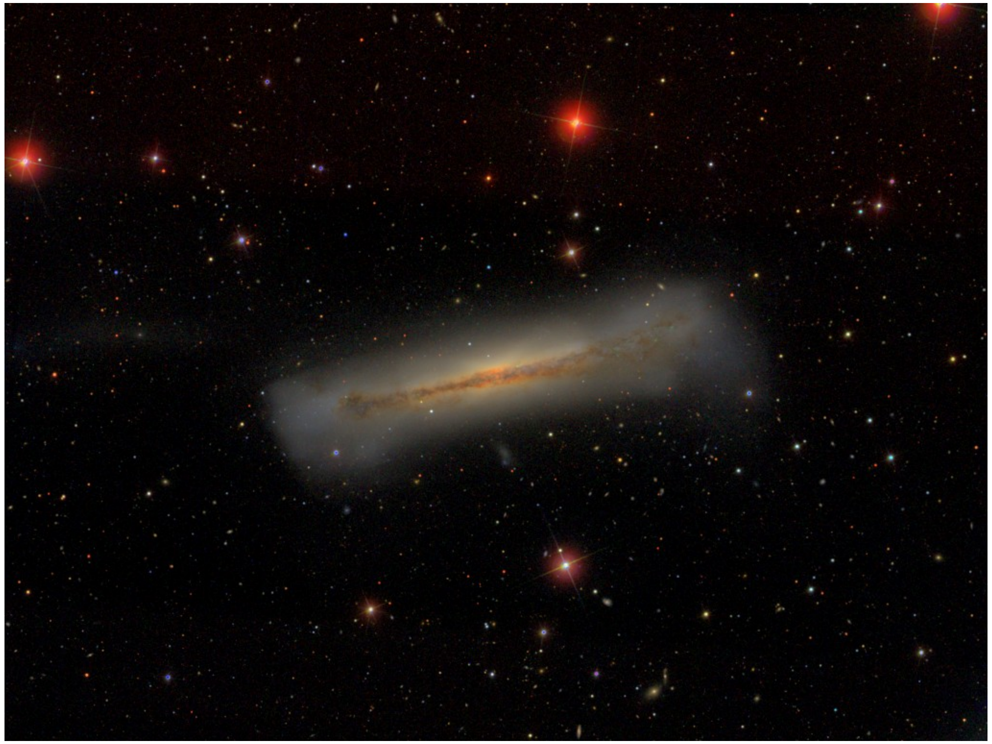
- Strong radio PS (flat spectrum)
  Possible pointing relativistic jet
- Weak X-ray and γ-ray
  Might indicate obscuration
- Strong infrared
  Indicates dusty environment

Promising ν sources

(numerous enough)

- Ultra Luminous IR Galaxies (ULIRGs)
- Starburst Galaxies with an AGN
- Interacting Galaxies

The "Hamburger" galaxy NGC 3628

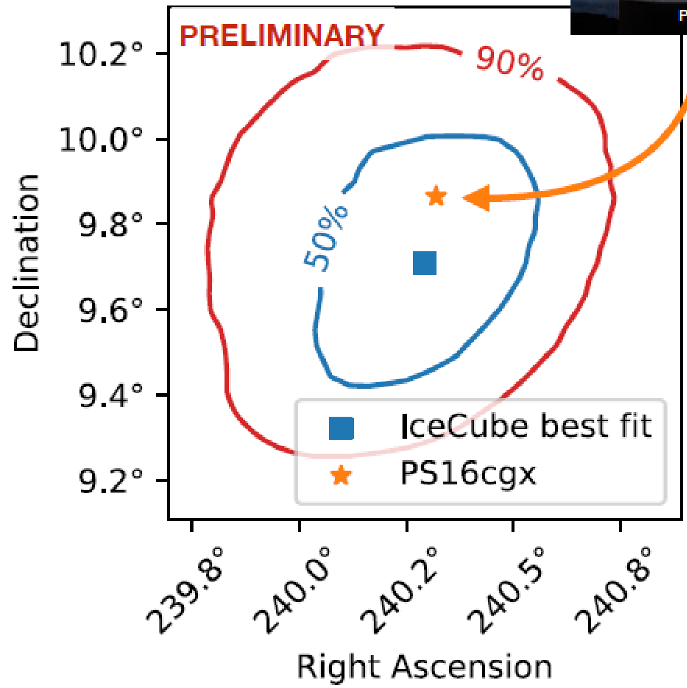


[NASA Extragalactic Database]

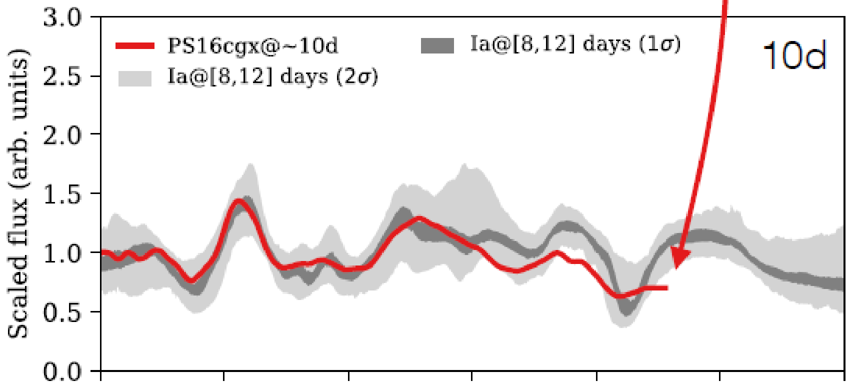
Follow-up on Transient alerts

PanStarrs follow up of IceCube alert on 2016-04-27 and found a young supernova at z=0.3:

Light curve consistent with explosion days before neutrino alert



Optical spectroscopy 10, 20 days post-peak



Features atypical for SNIa, but not sufficient to exclude

Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

Credit M. Kowalski SuGAR2018

nature physics

ARTICLES

PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1*], F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]

individual objects are too low to make an unambiguous source association. Here, we report that a major outburst of the blazar PKS B1424-418 occurred in temporal and positional coincidence with a third petaelectronvolt-energy neutrino event (HESE-35) detected by IceCube. On the basis of an analysis of the full sample of γ-ray blazars in the HESE-35 field, we

There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ~5% for a chance coincidence. Our model reproduces the

Credit M. Ahlers SuGAR2018

IceCube: Track with $E_{dep} \sim 20$TeV and $\sim 1^\circ$ error observed $\rightarrow$ EHE alert

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

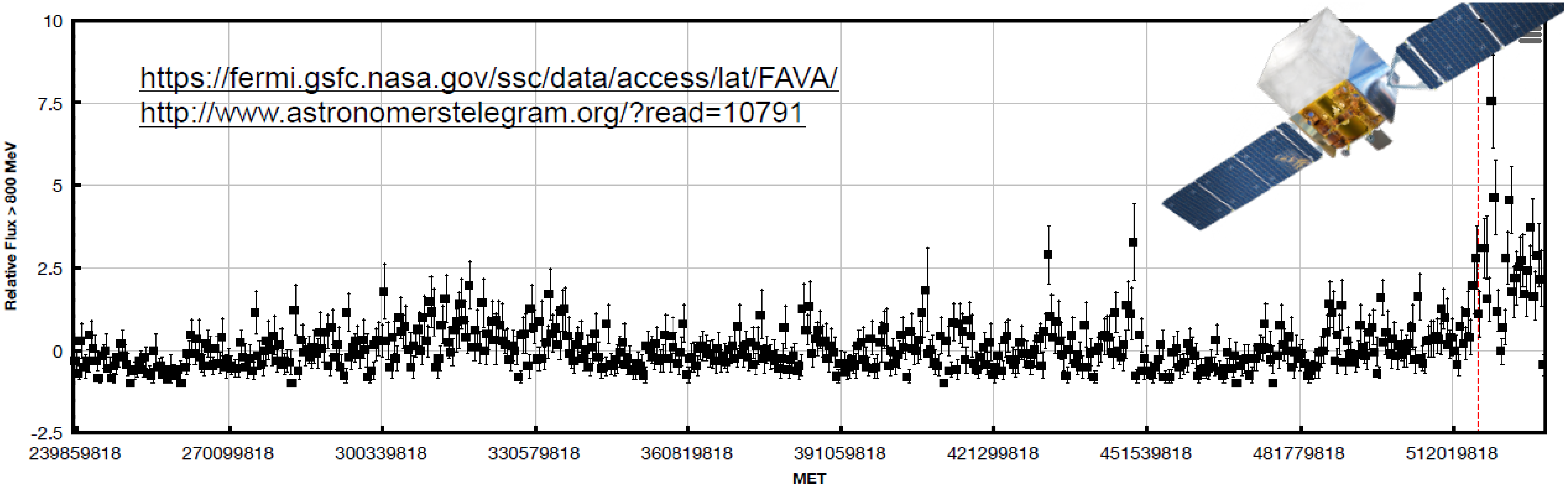
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Follow-up on Transient alerts

Fermi lightcurve for IC170922A

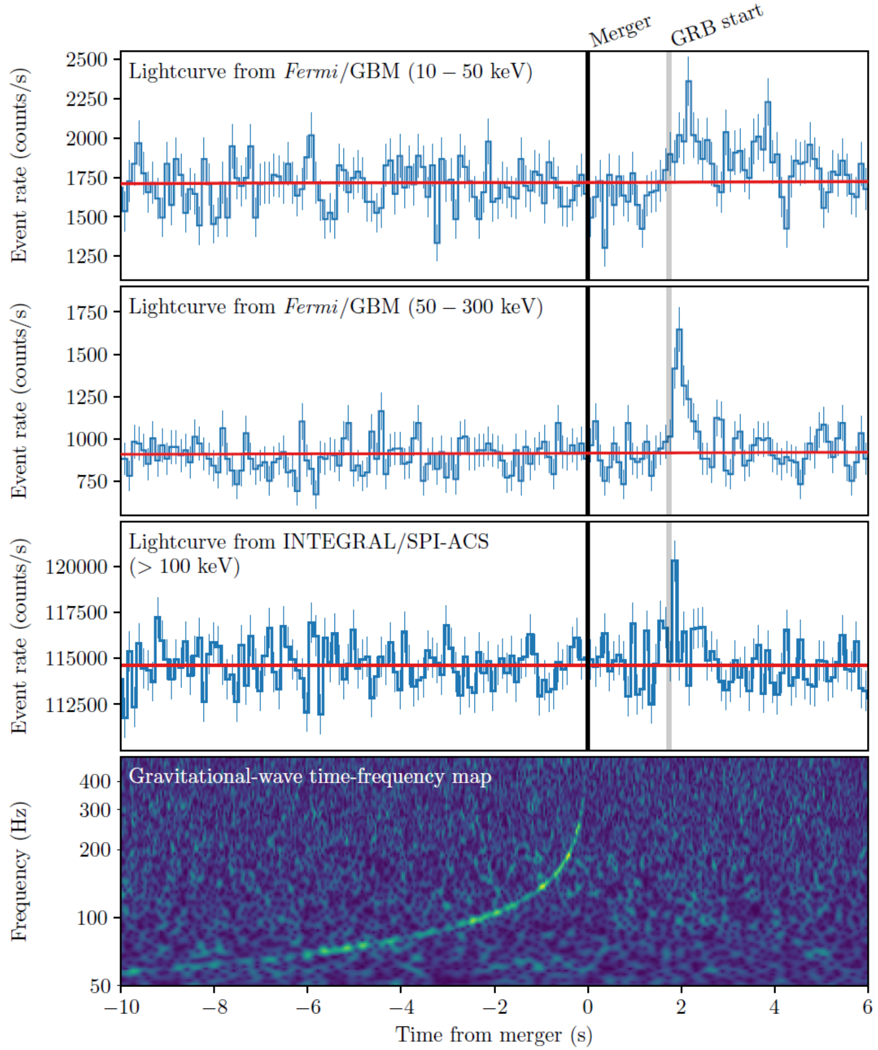


Credit M. Kowalski SuGAR2018

Many more observatories involved and analysis is ongoing

The GW-Gamma connection

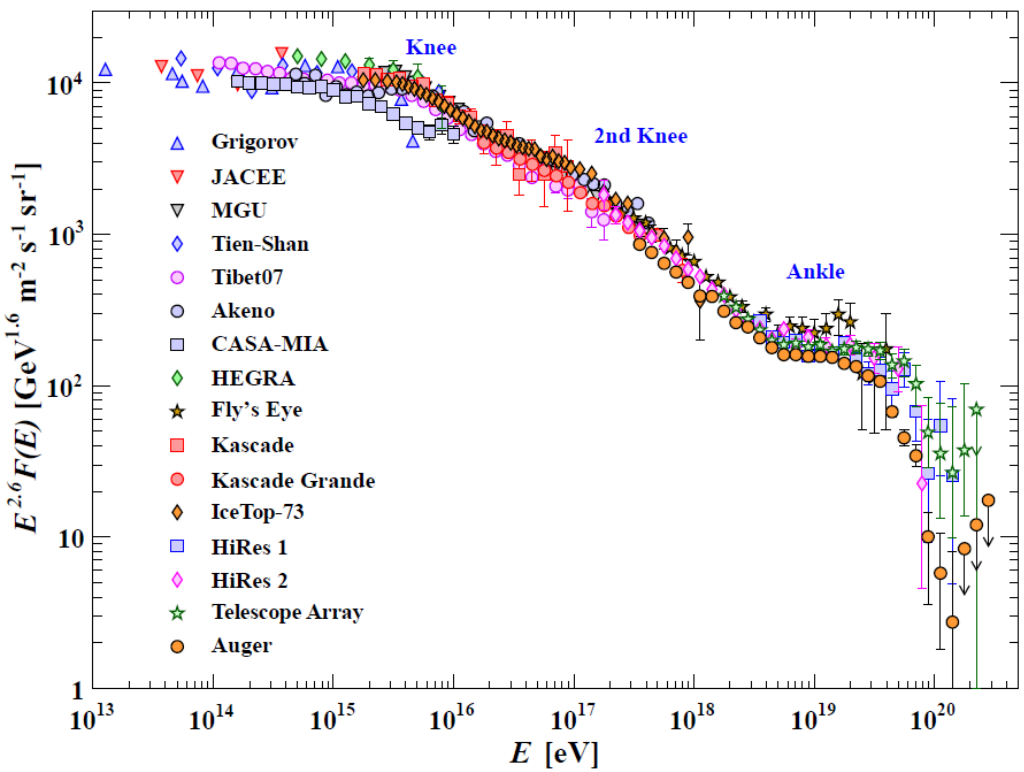
- GW170817: a NS-NS merger
- Weak, short GRB was observed
  - Location coincidence
  - GRB ∼1.7 sec. after the GW
  - Confirmed sGRB progenitor scenario
  - No neutrino counterpart was found
- GW gives good T_{start} for ν searches
  - Would be nice for long GRBs
- Observation of GW counterparts
  - Exploration of source evolution
  - Independent proof of GR ?
  - Discover new phenomena ?



[ApJ Let. 848 (2017) L13]

Do we observe the GZK cut-off ?

The $E^{2.6}$ scaled Cosmic Ray flux



Credit PDG 2014

- Supernova blast waves

  Gyroradius $r = \frac{p}{ZeB} \quad (\vec{p} \perp \vec{B})$

  $\rightarrow \left(\frac{p}{1 \text{ eV}}\right) = 0.03 \cdot Z \left(\frac{B}{1\ \mu\text{G}}\right) \left(\frac{r}{1 \text{ m}}\right)$

  Shock wave : extra factor $(\Gamma\beta)_{shock}$

- Accelerator of size R

  $r > R \rightarrow$ particles escape $\rightarrow E_{max}$

  Typical : $B \approx \mu$G $\quad R \approx$ pc

  $\rightarrow$ Protons : $E_{max} \approx 10^{15}$ eV

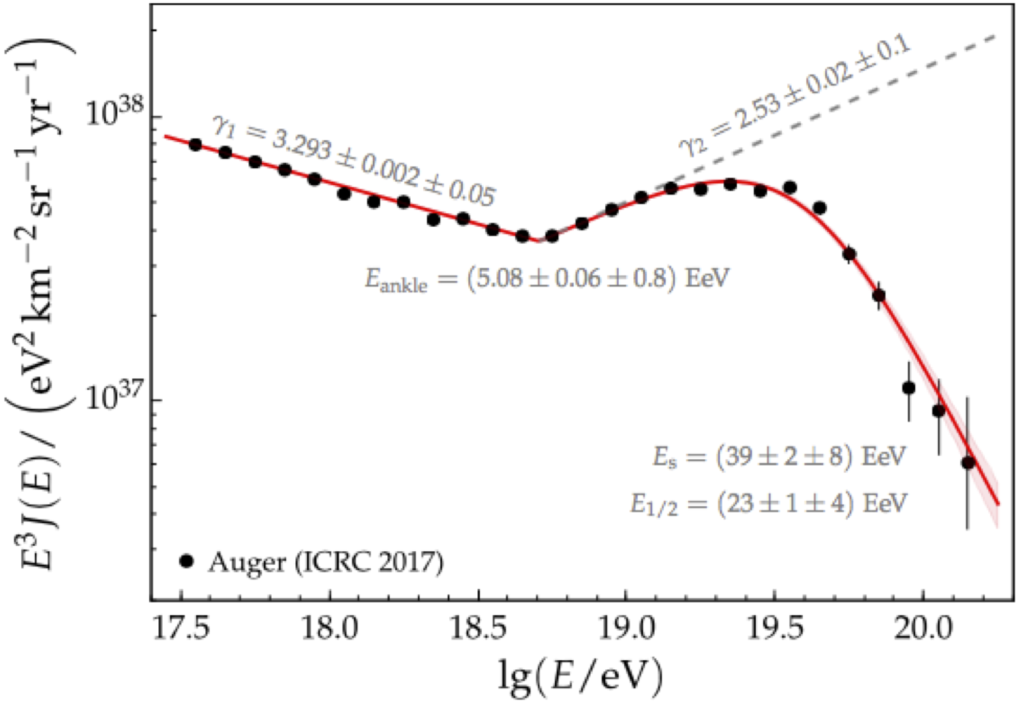
$*$ At a certain $r \rightarrow E_Z = ZE_{proton}$

Structure around the Knee

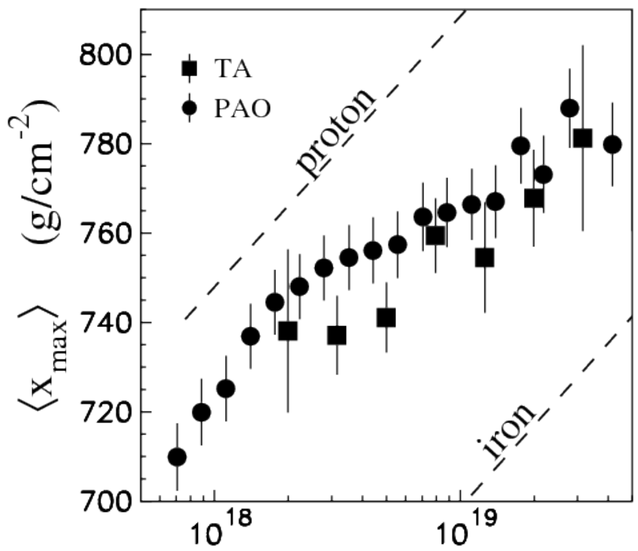
- Supernovae run out of steam
- Convolution of various nuclei

Do we observe the GZK cut-off ?

Region around the Ankle



Composition studies



- **Large flux drop around $10^{19.5}$ eV**

  Accelerators run out of steam ?

  Convolution of various nuclei ?

  GZK effect ? $(p + \gamma_{CMB} \rightarrow \Delta^+)$

- **Composition becomes heavier ?**

∗ **Can we identify a GZK component ?**

  Multi-messenger may provide answer

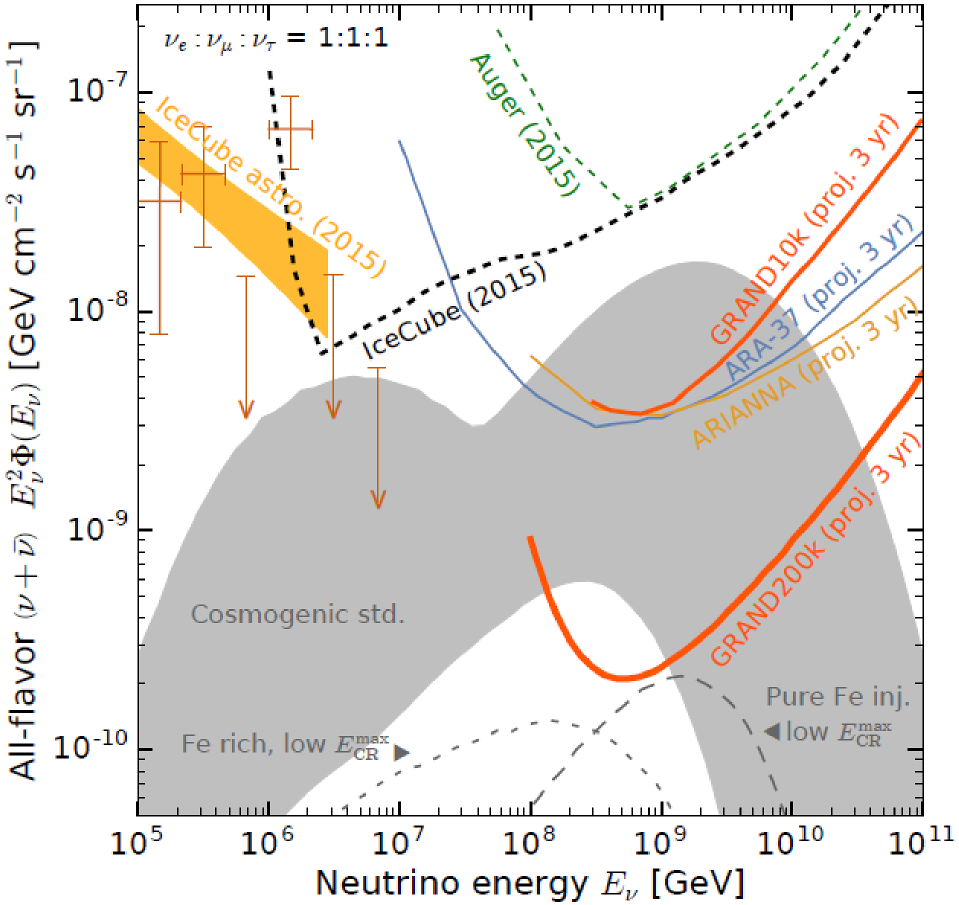
  GZK ν's from Δ decay chain

Radio detection of UHE ν interactions

- **Long (km-scale) attenuation length**
  Cover large (>100 km^2) area
- **Detect events $> 10^{17}$ eV**
- **GZK ν : Proof of GZK effect**
  or : Insight in UHECR composition
- $p + \gamma \rightarrow \Delta \rightarrow \nu \quad (E_\nu \approx 4\%\ E_p)$
  $p + \gamma_{EBL}$ **: Low-E bump**
  $p + \gamma_{CMB}$ **: High-E bump**
- **Iron: lower E/A and dissociation**
  $\rightarrow$ Higher E threshold and lower flux
  Radar reflections from shower plasma
  New idea for $E < 10^{17}$ eV
  Fill IceCube-Radio E gap

The GZK neutrino landscape

[arXiv:1708.05128]



Summary and Outlook

All disciplines within Astroparticle physics have come to maturity

Cosmic Rays : Auger, Telescope Array, IceTop, AMS, LOFAR

Gamma Rays : Integral, Fermi, Swift, HESS, Magic, Veritas, HAWC

Neutrinos : IceCube, Antares, ARA

Gravitational Waves : Ligo, Virgo

* Observatories in Optical, IR, X-ray and Radio in addition

- All experiments deliver high-quality data with significant impact

  Discovery of Cosmic Neutrinos → Birth of Neutrino Astronomy

  Discovery of Gravitational Waves → Another new window on the Universe

- Details about various (sub)processes become more and more clear

  BUT... All experiments have their characteristic limitations

  Overall picture can only be unraveled by combining the various data

- Various detector upgrades c.q. new initiatives are in the pipeline

  Auger-Prime, CTA, IceCube-Gen2, KM3Net, GVD, GRAND, ET, LISA

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Summary and Outlook

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Community consensus: Multi-Messenger is the way forward (SuGAR2018)

Rapid communication, follow-up campaigns and data exchange are needed

Currently : GCN, ATel, AMON, various MoU's

Creation of a Multi-Messenger consortium would be very instrumental

Same attitude was felt at the recent APPEC meeting

Let's combine forces and join a common enterprise !