Multimessenger astrophysics with neutrino telescopes: opening a new window on our Universe

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University of Bonn, Experimental Particle Physics Seminar
Bonn, 26-10-2023

SFB1491

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In origin were cosmic rays

Cosmic rays

Cosmic rays were discovered at the very beginning of the XX century.
V. Hess was awarded the Nobel prize in 1936!

Note how physics was very adventurous at the time!

- Flux and composition extensively measured in the following decades.
- More than 10^2 years later, we are still wondering about where the sources are. But *we have some ideas...*

Can it be so hard?

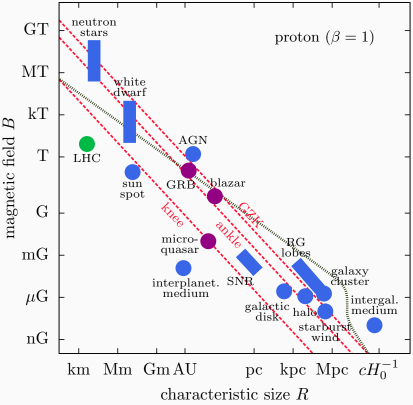
Cosmic rays cannot be traced back to their sources: they are **charged particles** and **magnetic fields are everywhere in the Universe** (galactic, inter-galactic, etc.)

However, we can look at their **energy** (GeV-EeV) and figure out their gyroradius $R = \frac{E}{qBc}$

Large Hadron Collider

$B \sim 8\,\mathrm{T}$, $R \sim 4.25\,\mathrm{km} \rightarrow E \sim 7\,\mathrm{TeV}$

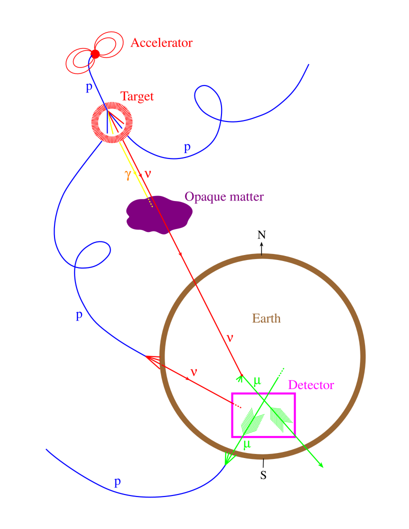
Hillas criterion: what characteristic size and magnetic field strengths are required to confine cosmic rays?



Knee $\sim$ 10 PeV, ankle $\sim$ 5 EeV, GZK $\sim$ 50 EeV

Something must come out...

What are possible CR interaction processes?



Proto-hadronic / hadro-nuclear:

$$p + p/N \rightarrow (\text{had.}) \rightarrow \pi^{0,\pm}$$

Photo-hadronic (resonant):

$$p + \gamma \rightarrow \Delta^{+}(1232) \rightarrow \pi^{0,\pm}$$

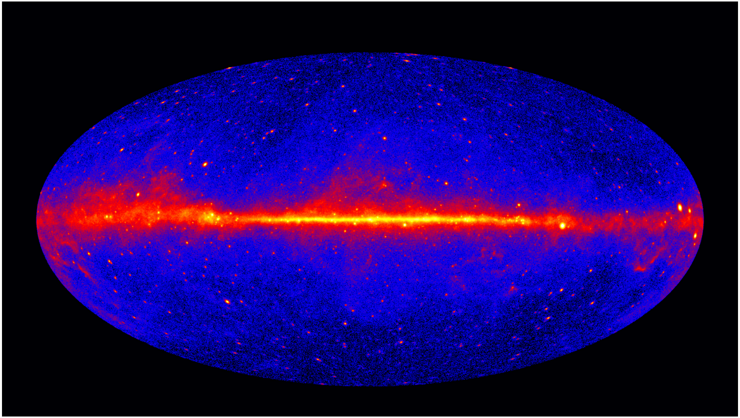
$$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu} \quad \pi^{0} \rightarrow \gamma\gamma$$

$$\mu^{\pm} \rightarrow e^{\pm}\ \nu_e\ \nu_{\mu}$$

The gamma sky

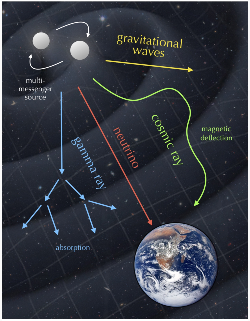
Historically, gamma-ray astronomy predated neutrino astronomy.

The Fermi-LAT sky...

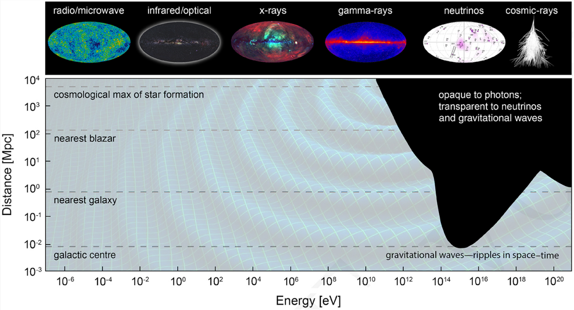


However, purely leptonic processes can generate gamma radiation: synchrotron, inverse-Compton, **synchrotron-self-compton (SSC)**.

Neutrino probe **dense environments** and cross undeflected the great **cosmic distances**.



Credits: Niels Bohr Institute

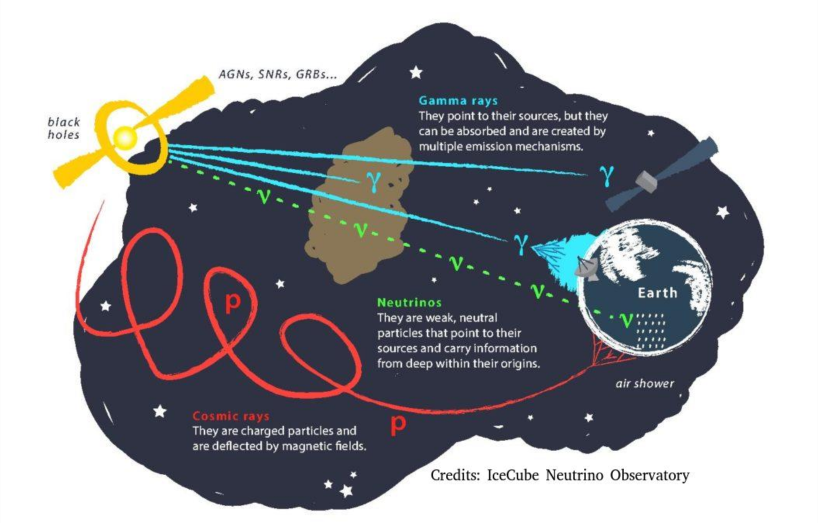


Credits: I. Bartos, M. Kowalski

High-energy neutrinos are also unequivocal signature of **hadronic particle acceleration**.

Compared to **gravitational waves** they also provide nice pointing.

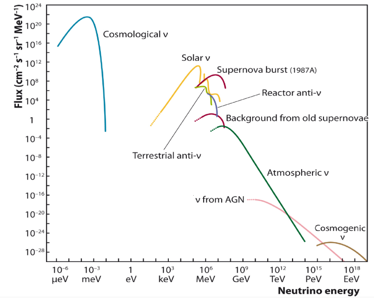
Going multimessenger

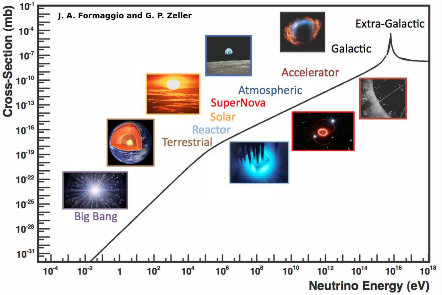


Taking neutrinos from physics to astronomy

The neutrino universe

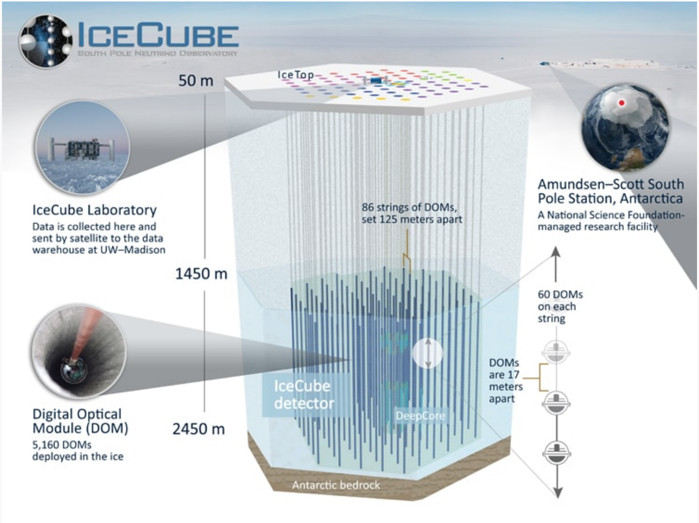
A variety of natural and artificial sources produce neutrinos across many order of magnitude in energy.





As energy gets higher, the flux becomes very small and required experiment size reaches the cubic-kilometre volume.

The IceCube Neutrino Observatory



A closer look at the detectors

Currently operating neutrino telescopes are IceCube (Antarctica), KM3NeT (Mediterranean), GVD (lake Baikal).

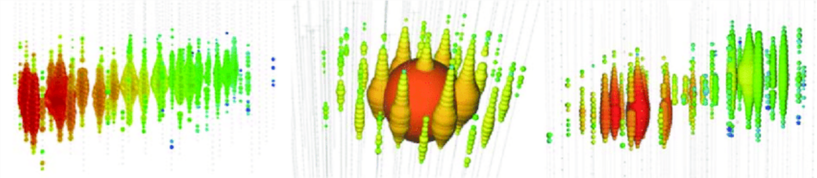
Their design is similar.

One or more PMTs enclosed in a pressure-resistant glass sphere and fitted with readout electronics.

Digital optical modules of IceCube and KM3NeT

Tracks, cascades and the (rare) double bangs

The typical event signatures in neutrino telescopes...



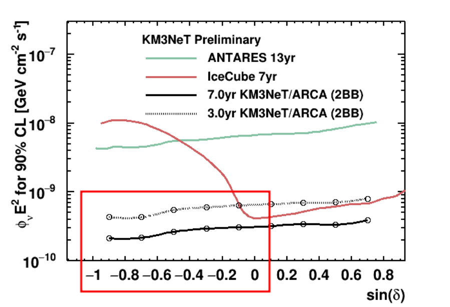
Tracks (ν_μ CC): 0.1-1.0 deg angular resolution (ideal for point sources).

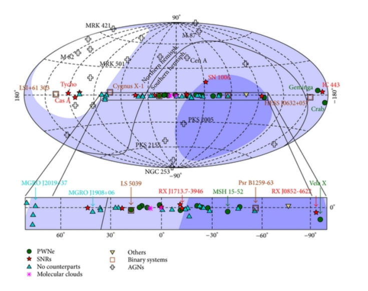
Cascades (ν_e CC, ν NC): very good energy resolution but $\sim$ 20-30 deg angular resolution (suitable for extended sources).

Double bangs (ν_τ): too rare to do astronomy!

First come **atmospheric muons**, then **atmospheric neutrinos**.

Atmospheric muons are an overwhelming background for downgoing events.

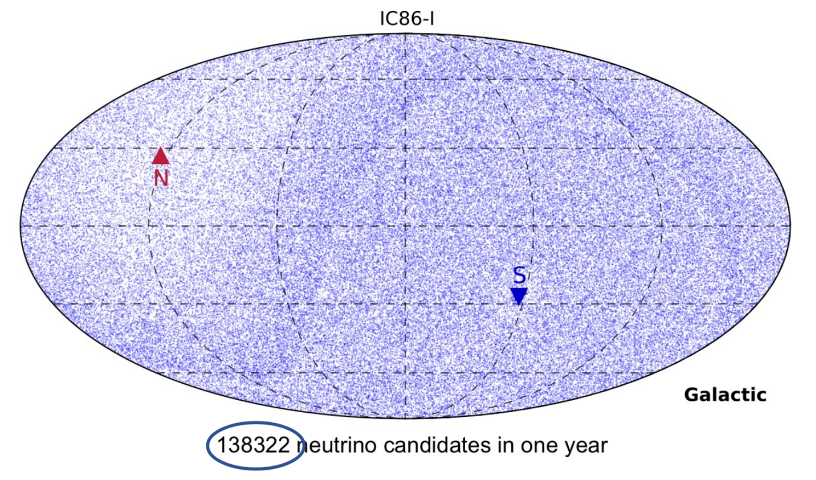




Detectors in **Antartica** and in **Northern-hemisphere** complement each other.

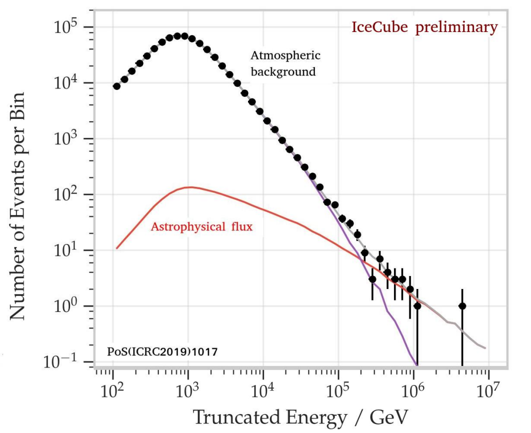
A signal in a haystack

One year of data yields $\sim$ 140000 atmospheric background events with $\sim$ 200 cosmic neutrinos are hidden within.



Looking at a different dimension

If we look at events in energy...



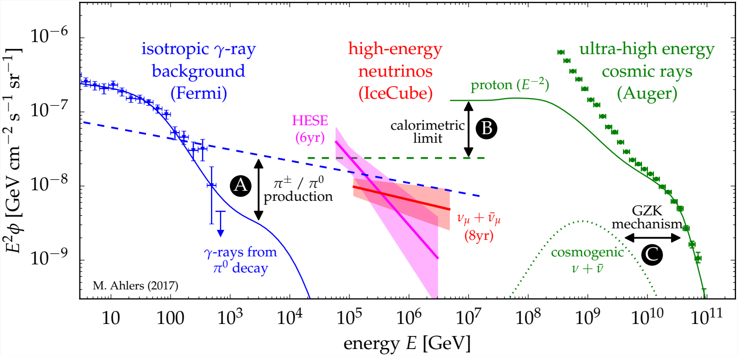
Astrophysical neutrinos emerge at the highest energy. But sources may emit where the atmospheric background is still predominant.

Back to a multimessenger perspective

We hoped that **neutrinos** could answer the question of **cosmic-ray origin**.

But... the **astrophysical flux is small** and **sources are hard to resolve**.

This may be a new puzzle altogether.



Hunting for neutrino sources

The swiss knife of neutrino astronomy

The **unbinned likelihood** is a very popular analysis tool:

$$\mathcal{L}(n_\mathrm{s}, \gamma) = \prod_{\mathrm{i}=0}^{\mathrm{N}} \left[\frac{n_\mathrm{s}}{\mathrm{N}} \mathcal{S}(\nu_\mathrm{i}, \gamma) + \left(1 - \frac{n_\mathrm{s}}{\mathrm{N}}\right) \mathcal{B}(\nu_\mathrm{i}) \right]$$

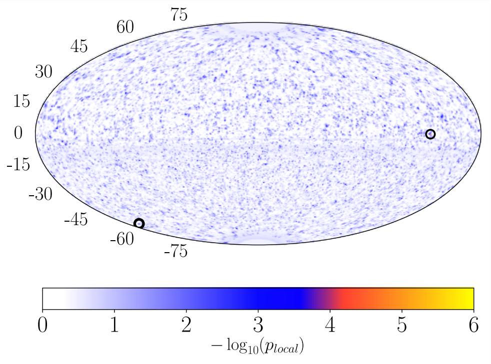
i runs over the neutrino events, n_s is the number of signal events, $\mathcal{S}$ and $\mathcal{B}$ are the signal and background PDFs, γ is the spectral index.

Maximising the ratio $\mathcal{L}(n_\mathrm{s}, \gamma)/\mathcal{L}(n_{\mathrm{s}=0})$ allows to estimate the best-fit parameters of n_s and γ at a given position in the sky.

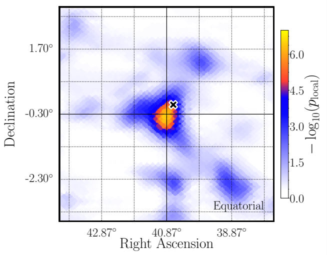
The signal PDF $\mathcal{S}$ may incorporate a **space** term, an **energy** term and a **time** term.

Searching for event clustering

10-year search for hotspots in IceCube data.



M. G. Aartsen et al. Physical Review Letters 124, 051103 (2020)



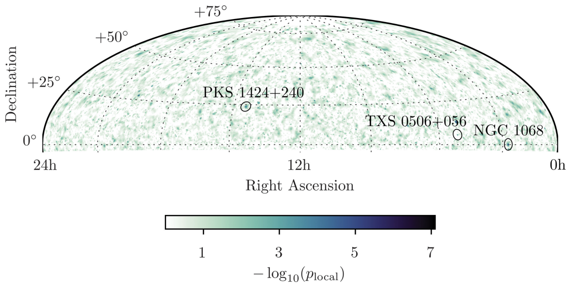
AGN / Seyfert **NGC 1068**.

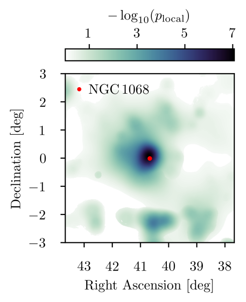
Significance at 2.9 σ in 2020.

First evidence from a steady point source

Simulating atmospheric muons is challenging.

Restricting the search to the Northern Sky allows to take them out of the picture and use **Monte Carlo** to accurately model the signal PDF.



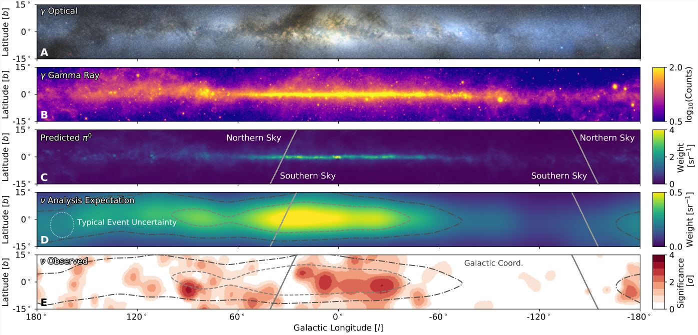


IceCube Coll., Science 378, 6619, 538-543 (2022)

NGC 1068 observed at 4.1 σ in 2022!

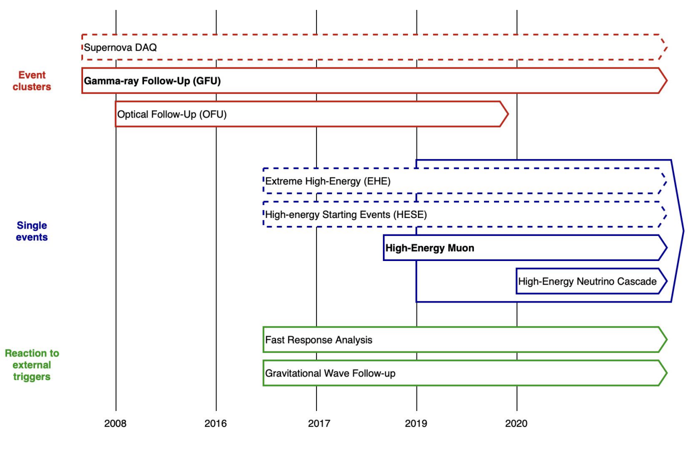
Finally, our Galaxy in neutrinos

An improved analysis of **cascade events** brought a 4.5 σ observation of neutrino emission from the galactic plane (Science 29 Jun 2023, Vol 380, Issue 6652)



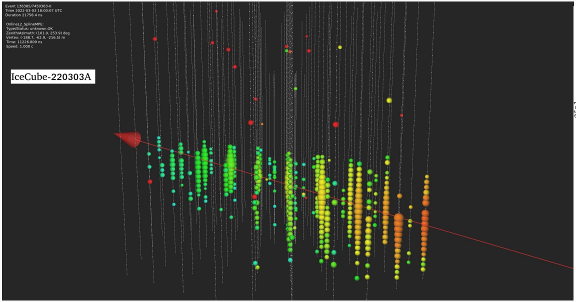
The realtime domain

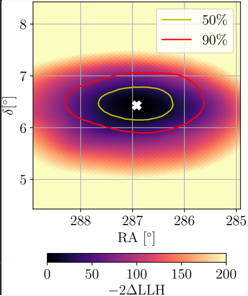
What we call targets of opportunity!



IceCube ASTROTRACK alerts

Individual events with **moderate or high probability of being astrophysical** are promptly published using global alert networks.

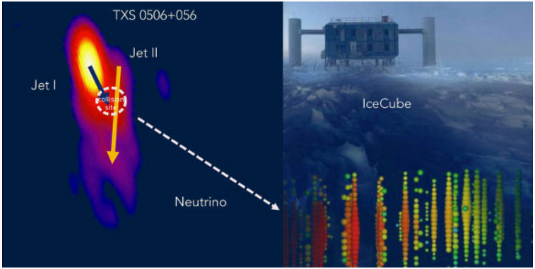




Uncertainty regions can go from around 1 sq. deg to tens of sq. deg

The first blazar connection

A 290 TeV neutrino **IC170922A** in coincidence with **flaring blazar TXS 0506+056** + **neutrino flare** in archival data when blazar was quiescent (*Science*, 2018 Vol 361, Issue 6398)

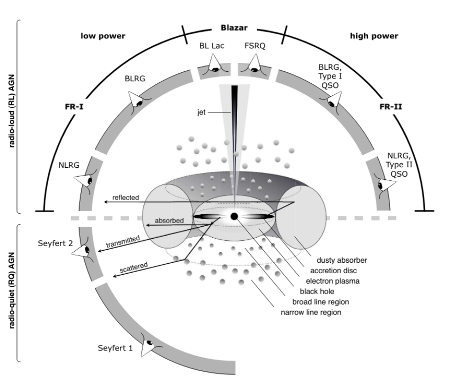


Evidence is still inconclusive about **how much** blazars contribute do the diffuse flux (or to neutrino alerts! But also about **how** blazars make neutrinos.

In general, attribution of **significance** to coincidences of transient events is a bit delicate.

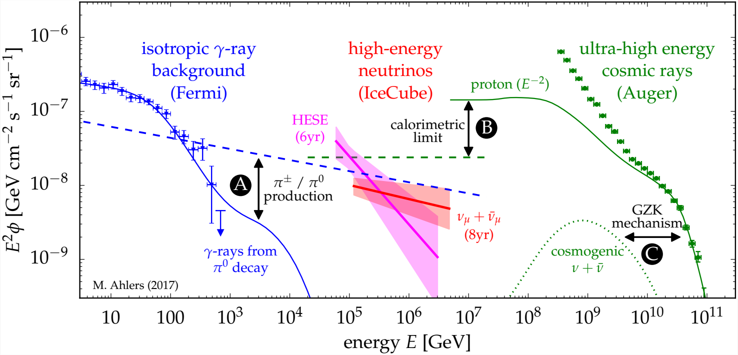
Neutrinos from AGN? Seyferts? Blazars?

Blazar jets, **AGN cores** or **AGN coronae** have all been proposed as acceleration environments and sources of neutrinos.



Is something dense enough to produce neutrinos able to let high-energy gamma rays out? Should we look at the **jet** or the **core**?

Far from the gamma-ray road

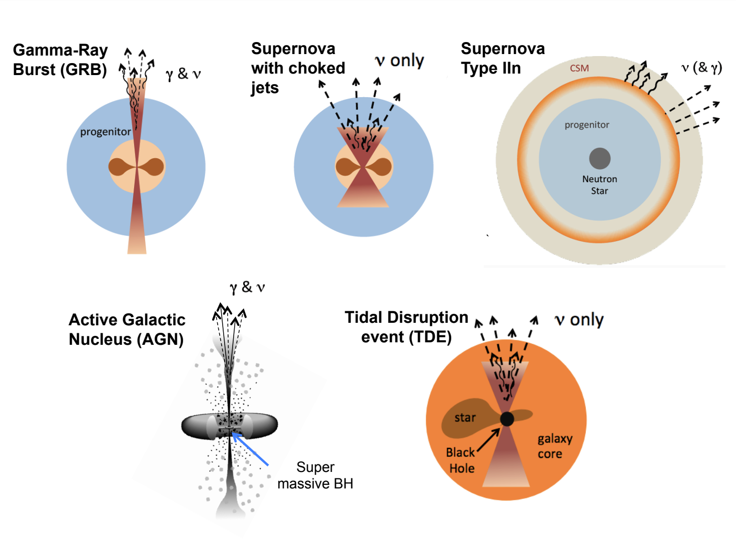


Highest energy neutrinos are consistent with gamma-ray and UHECR flux.

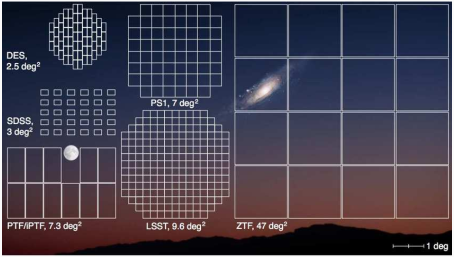
Intermediate energy neutrinos appear to be in excess.

There *could* (should? must?) be sources which are transparent to neutrinos but suppressed in gamma rays.

The atlas of (hypothetical) neutrino sources

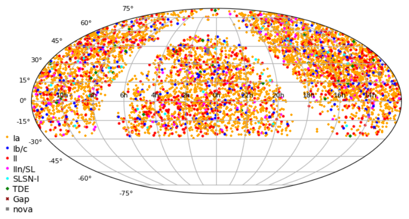


A prolific era of optical transients



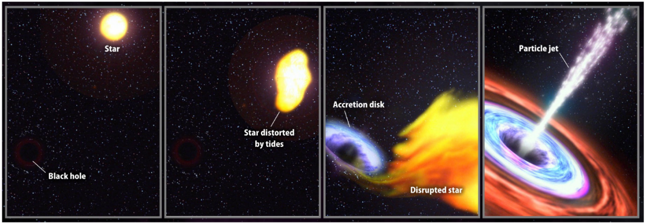
Wide field surveys such as the **Zwicky Transient Facility** are continuously observing the sky.

Unprecedented amount of high-quality data from optical transients. Example: ZTF Bright Transient Survey



AT2019dsg and the TDE-neutrino dilemma

The high energy neutrino IceCube-191001A was found in coincidence with **tidal disruption event AT2019dsg** → Stein et. al, Nature Astronomy 5, 510–518 (2021)



Credit: NASA

Two more tentative associations (AT2019fdr and AT2019aalc).

Phenomenological interpretation is challenging *and* follow-up studies by IceCube have questioned the spatial association.

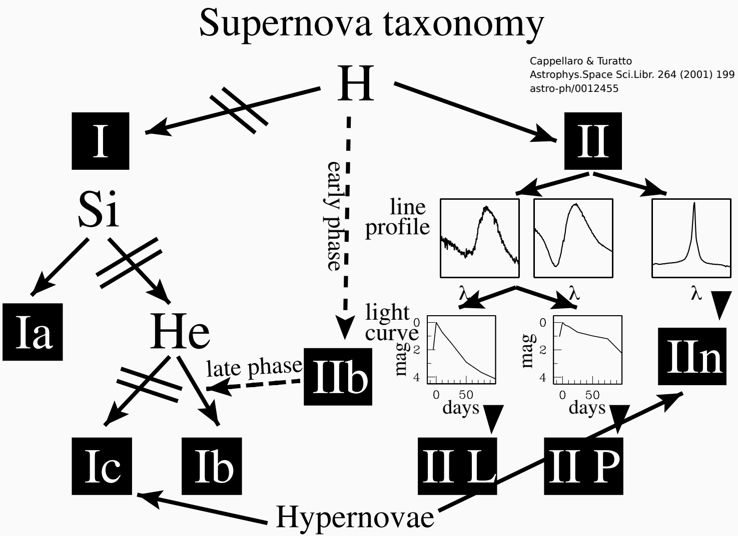
Going back at the origins

The term **super-nova** was coined by Baade and Zwicky postulating a connection with cosmic rays in 1934 (two years after the discovery of the neutron!)

With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. [...] We therefore feel justified in advancing tentatively the hypothesis that cosmic rays are produced in the super nova process.

Baade & Zwicky, PNAS May 1, 1934 20 (5) 259-263.

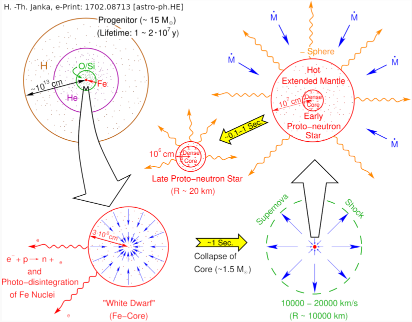
See also Burrows, PNAS February 3, 2015 112 (5) 1241-1242


Supernova taxonomy
Cappellaro & Turatto
Astrophys.Space Sci.Libr. 264 (2001) 199
astro-ph/0012455
H
I
II
Si
early phase
line profile
λ
λ
λ
Ia
He
light curve
mag
0
2
4
0
50
days
IIn
late phase
IIb
Ic
Ib
II L
II P
Hypernovae

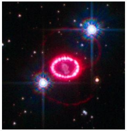
… and by astrophysicists

Thermonuclear supernovae (Type Ia): white dwarf accreting its mass beyond the Chandrasekar limit, fueling C-O fusion ($\rightarrow$ Si) and producing a thermonuclear explosion.

Core-collapse supernovae (Type Ibc, II): the Fe core of the star collapses into a proton-neutron star. Stellar material is expelled by the shockwave propagating outwards.

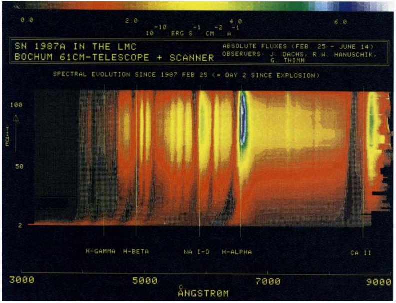


The spectacular SN 1987A

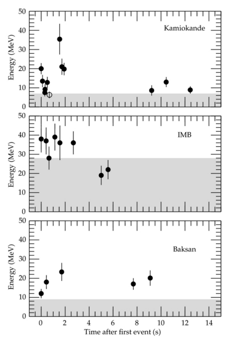


SN 1987A went off February the 23rd, 1987 from a blue supergiant in the Large Magellanic Cloud.
First and only detection of neutrinos from a CCSN: 24 events across three detectors.

Spectroscopy w/ Bochum 61cm telescope at La Silla.



Low energy neutrinos!



Hanuschik, R. W., Thimm, G., & Dachs, J. SN 1987A: spectroscopy of a once-in-a-lifetime event. The Messenger, vol. 51, p. 7-9

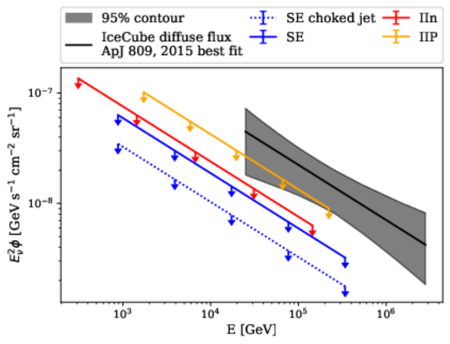
Particle acceleration in CCSNe?

SN 1987A brought to us only **low-energy** (thermal) neutrinos. So what about high energy?

- **Choked-jet supernovae (Ibc)**: jet fueled by the core collapse stalls in the photosphere (N. Senno, K. Murase, and P. Mészáros, Physical Review D 93 (2016) 083003.)
- **Interacting supernovae (Ibc, IIn, IIP)**: the SN ejecta creates shocks in the interstellar medium (Pitik, Tamborra, Lincetto, Franckowiak. *MNRAS* 524 (2023))

Constraints on neutrino emission from CCSNe

IceCube: search for neutrino emission from Ibc, IIn, IIP SNe → ApJL 949 L12, 2023



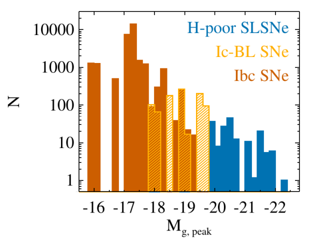
No significant excess from the CCSN population.

But are we looking at the right sources?

SLSNe: exceptionally bright (M < -19.5) supernovae with rise/fall time scales longer than ordinary SNe → Gal-Yam 2018, 1812.01428

Hundreds of SLSNe have been discovered by ZTF in the last few years!

- **SLSN-I** (H-poor) photometry similar to Ibc (Ic-BL) but very peculiar spectroscopy and minor interaction signatures.
- **SLSN-II** (H-rich) are less common, but homogeneous to type IIn → narrow em. lines, signs of **CSM interaction**.



Gal-Yam, 2019

Looking for a power source

SLSN are the **brightest class of optical transients**, so what is their power source?

Magnetar models fits well the observed light curves and spectra of SLSN-I, but not minor photometric features.

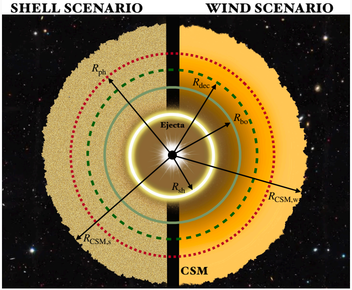
Central engine model would see accretion onto a newly formed black-hole. Predictions similar to magnetar but less fitting of light-curves.

CSM interaction: main mechanism proposed for SLSN-II, given the similar features type IIn. Possibly relevant also for (at least some) SLSN-I.

Could SLSN be sources of astrophysical neutrinos?

Particle acceleration in interaction-powered supernovae?

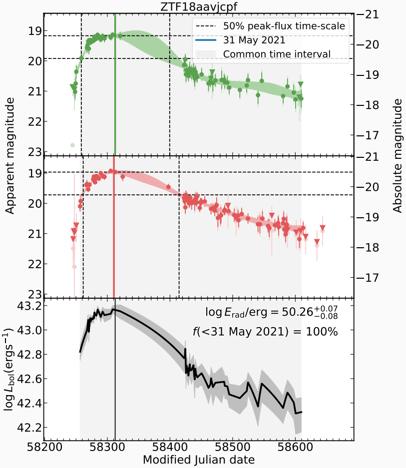
Shock-interaction model (Pitik, Tamborra, Lincetto, Franckowiak. *MNRAS* 524 (2023)) .



- Protons accelerated to relativistic energies in the SN forward shock.
- Neutrinos produced in inelastic p-p collisions with cold CSM material.
- SN optical properties connected to neutrino luminosity.

The model connects the ejecta + CSM configuration to the optical properties of the SN (L_{pk} and T_{rise}).

High-energy neutrinos from IPSNe?

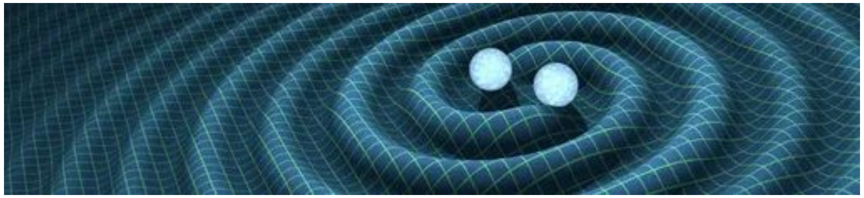


- Optical properties inferred by the SN light curve allow to identify allowed parameter space for a given source;
- Work in progress: search targeting **intrinsically bright sources**;
- analysis currently under internal IceCube review (see M. Lincetto et al. PoS(ICRC2023)1105).

Final words...

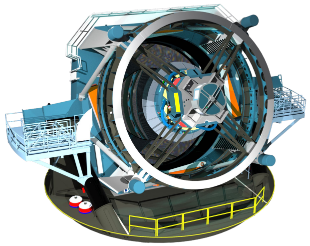
Present and future of multimessenger searches

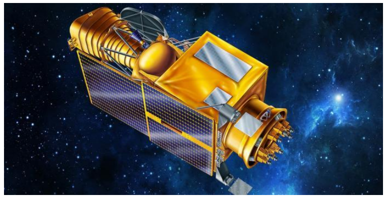
Gravitational waves



IceCube follow-up of **LIGO-Virgo-Kagra O4** alerts has begun.

Electromagnetic spectrum

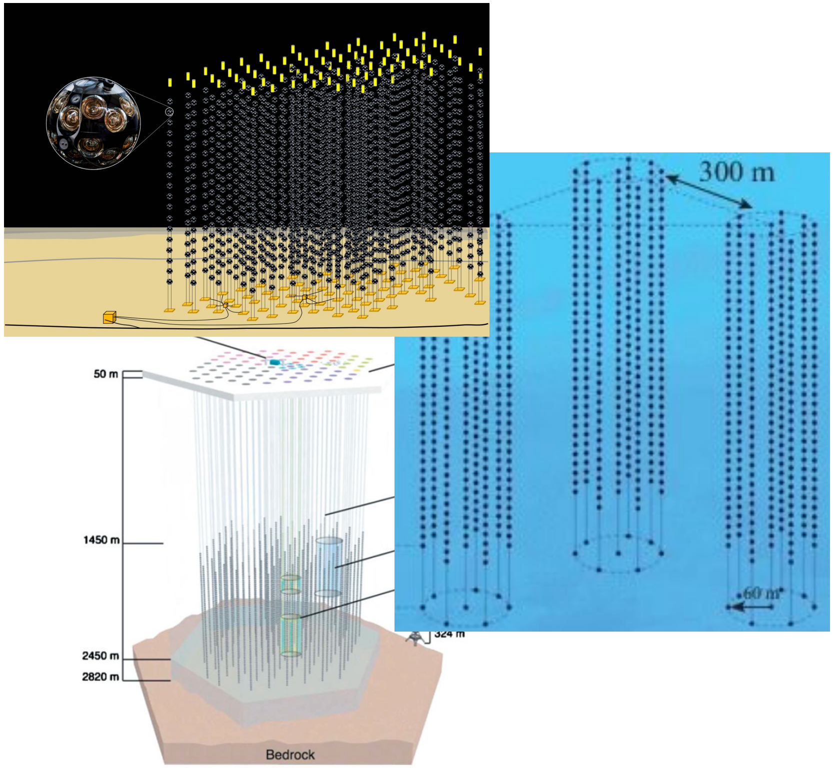




Will future facilities (e.g. Rubin Observatory, ULTRASAT) allow to unveil new counterparts to IceCube neutrinos?

Neutrino telescopes

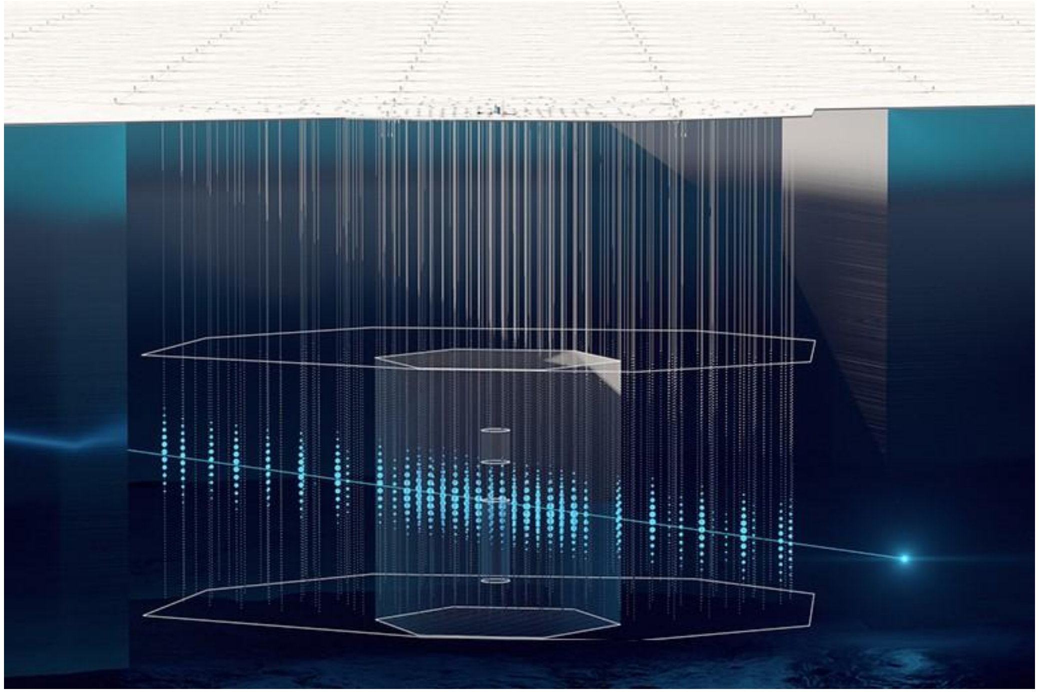
Possible synergies with KM3NeT and Baikal-GVD for realtime searches.



The future of IceCube: IceCube-Gen2

Optical and radio array.

5 times improvement of IceCube point-source sensitivity.



Beginning of construction expected in 2026.

What to make of neutrino astronomy?

Neutrino astronomy is going in **many directions at the same time**!

It is **challenging** to break down the astrophysical flux in different **source category**, whereas each class shows a **high diversity**.

A combination of **new and more powerful** detectors combined with instruments covering the entire **multi-wavelength** and **multi-messenger spectrum** will be the key to answer the many standing questions.

Thanks for the attention!