Table of content: Part 3

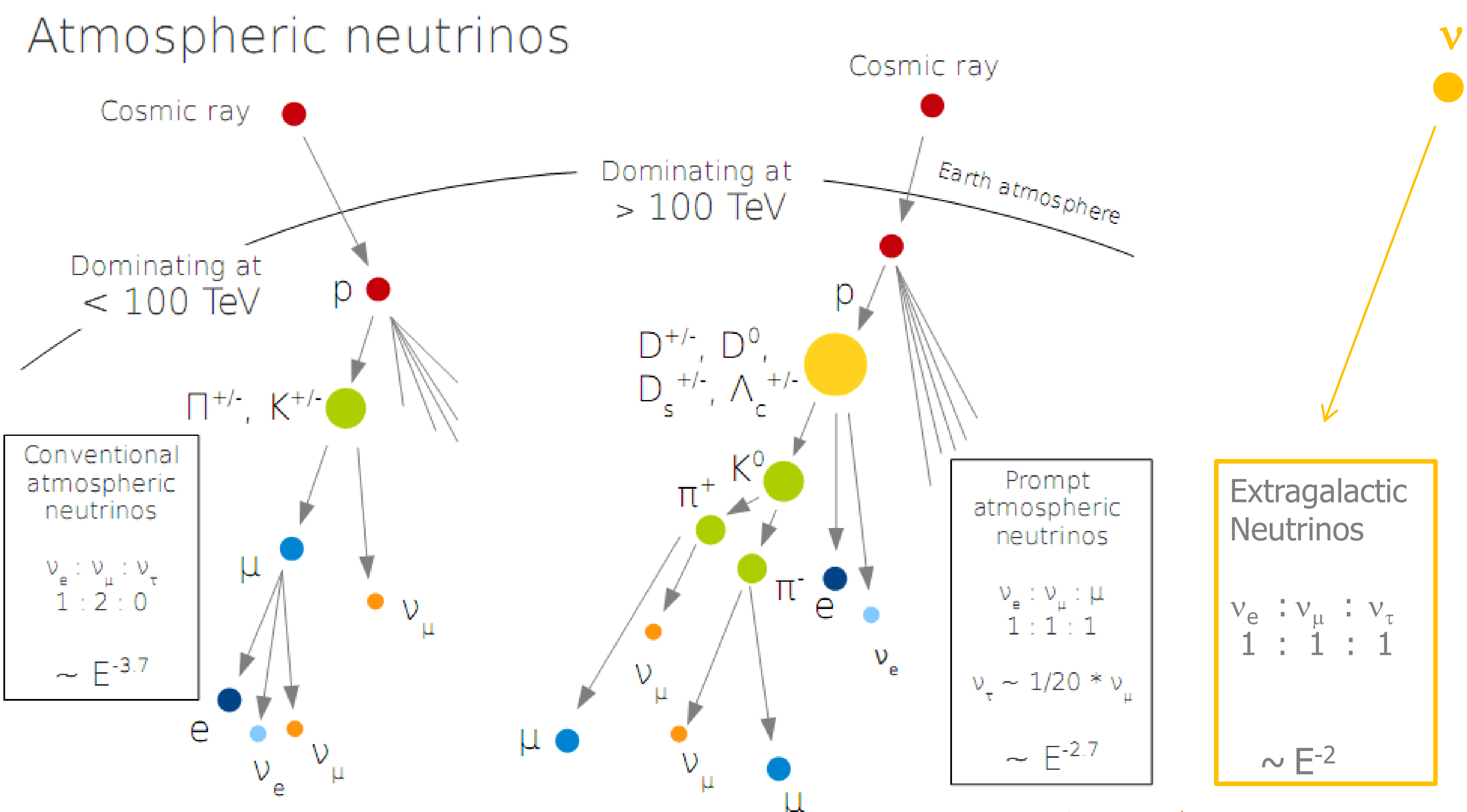
- Diffuse searches
- Neutrino flavors
- Multimessenger Astronomy
- TXS 0506+056: Finally an identified source!
- The future (IceCube Upgrade and IceCube-Gen2)
- Summarizing the results


Diffuse ν search

inclusive („diffuse“) searches

Reminder:

©Anne Schukraft



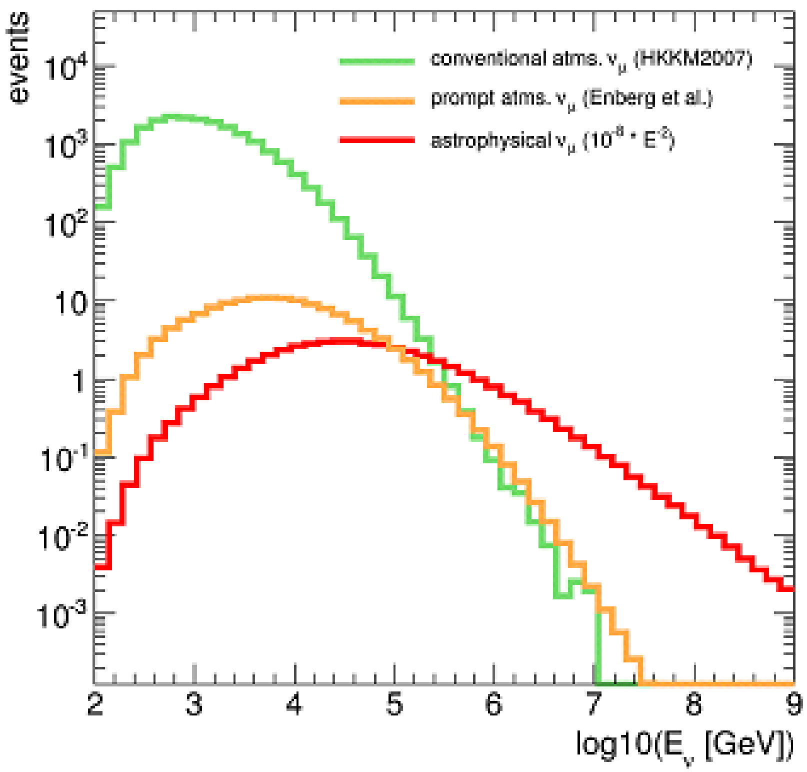
ν_τ only from $D^{\pm}_s$

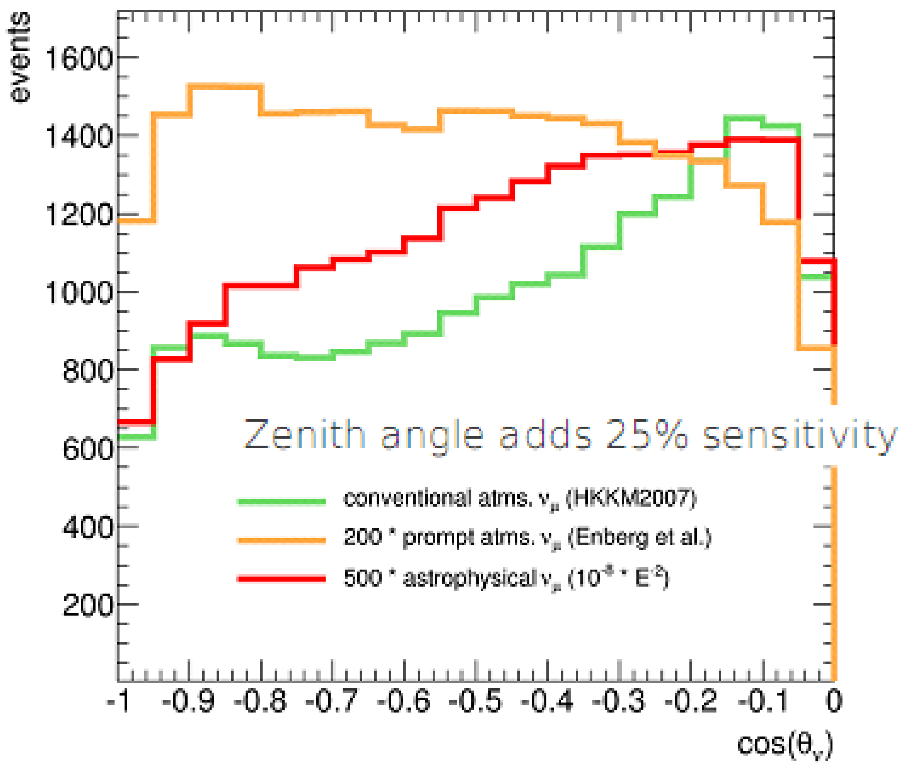
Different energies, flavor ratios, angles …

prompt flux very badly known (LHC!)

Signatures for υ_μ

… components can be distinguished statistically by energy and angular distribution

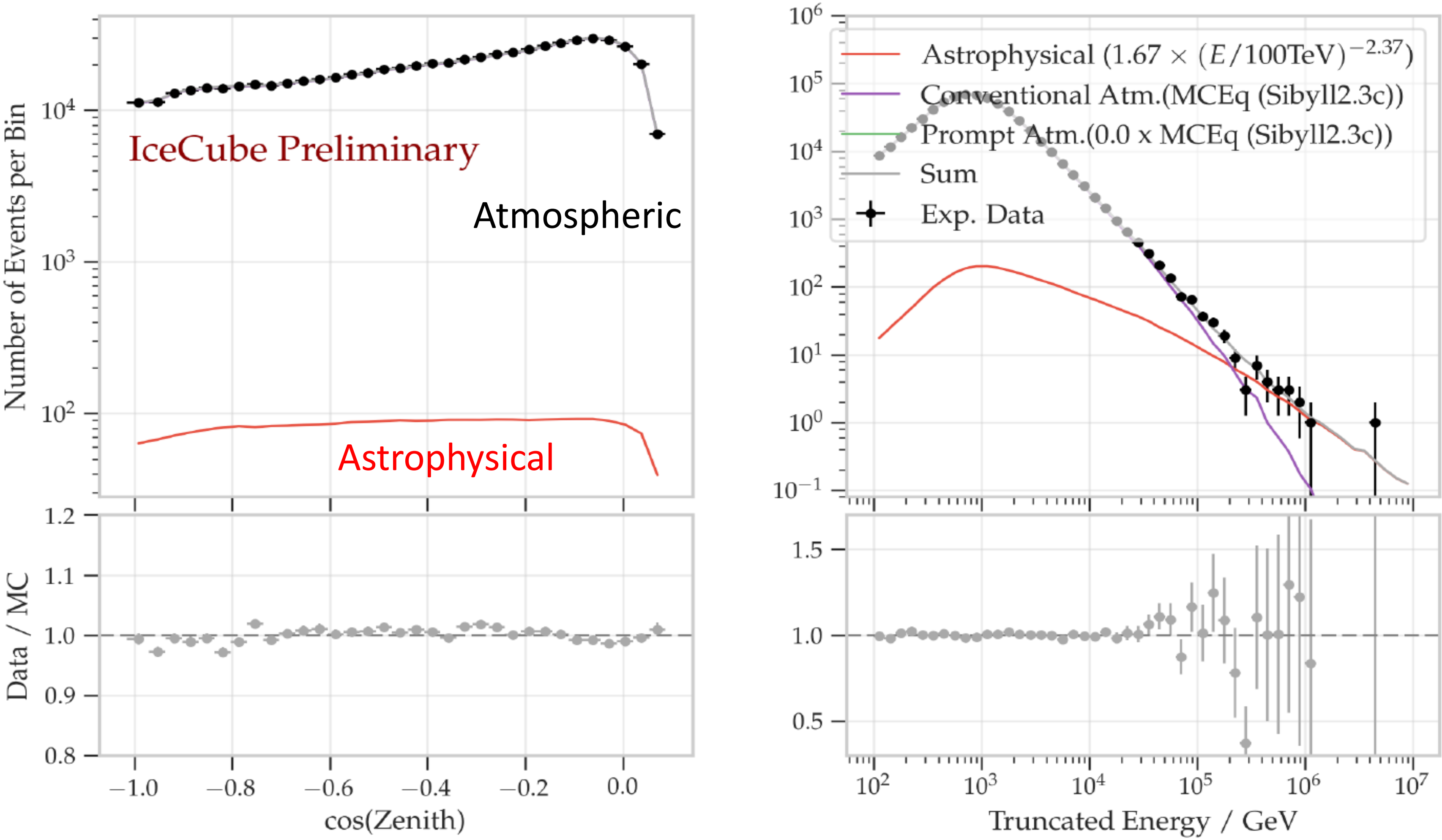




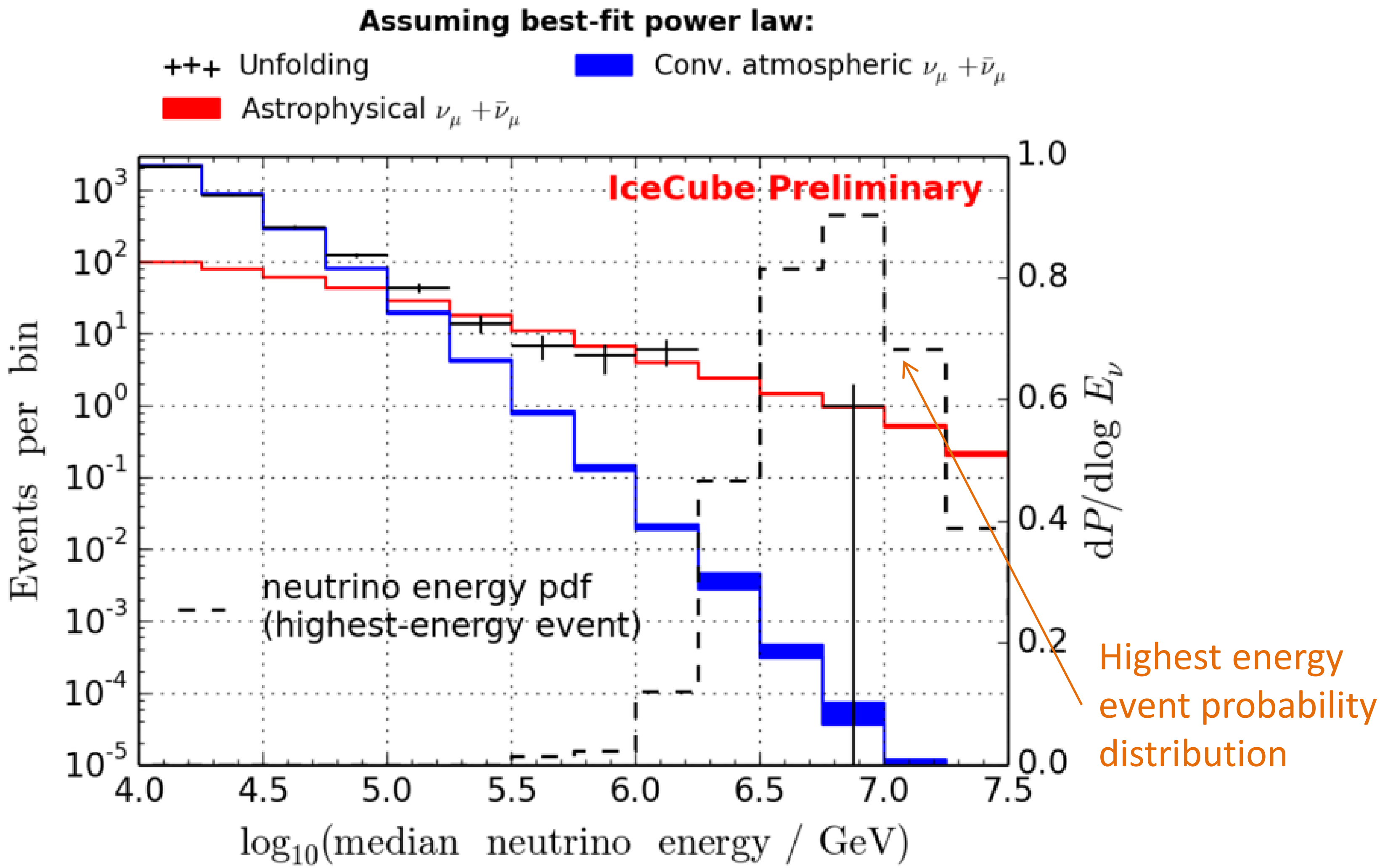
At high energies, cosmic ray beam, cross sections (e.g. charm at $x \sim 10^{-6}$) carry large uncertainties

… perform likelihood analysis to determine fluxes from data …

9.5 years diffuse

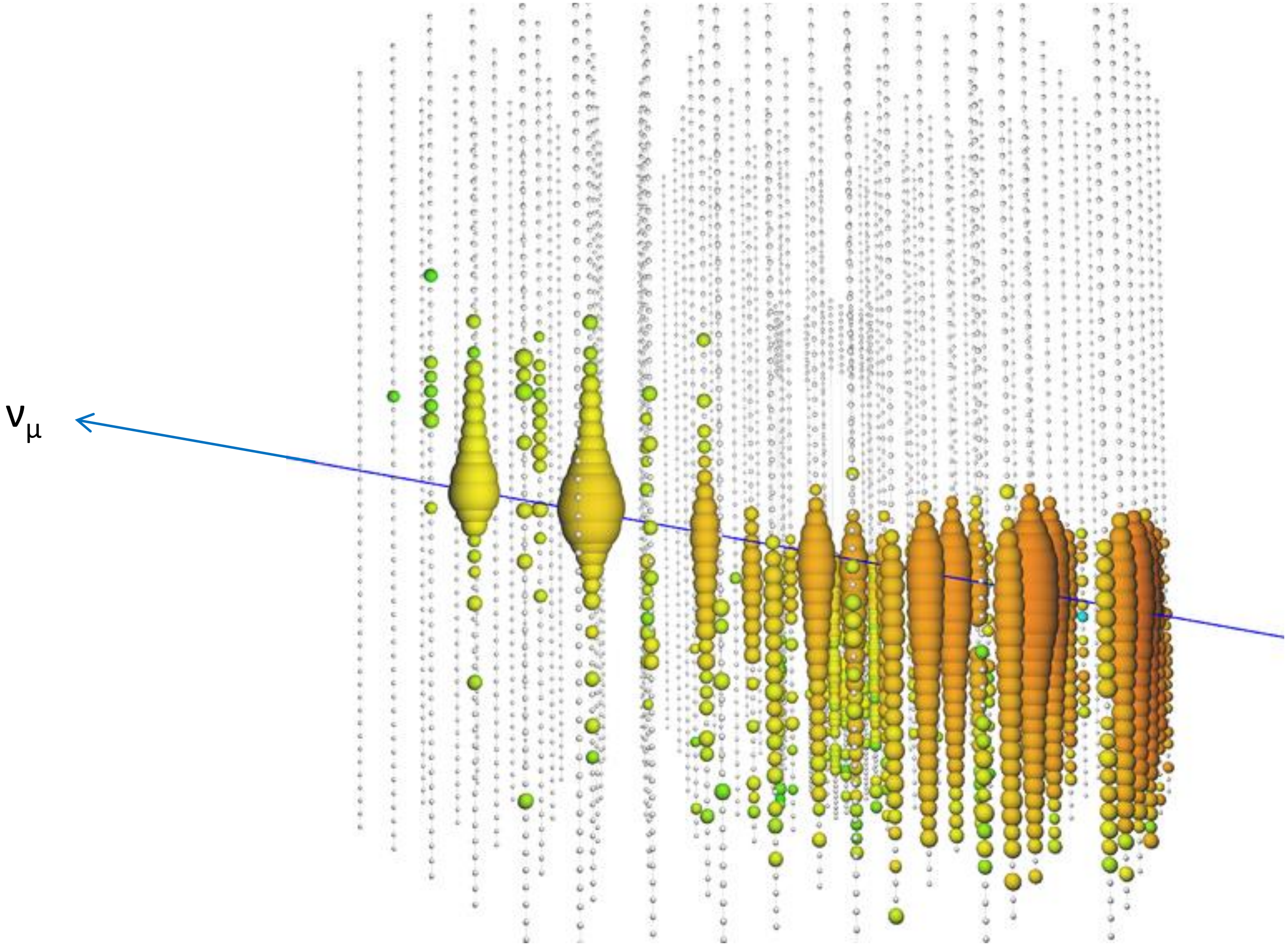


Unfolded spectrum



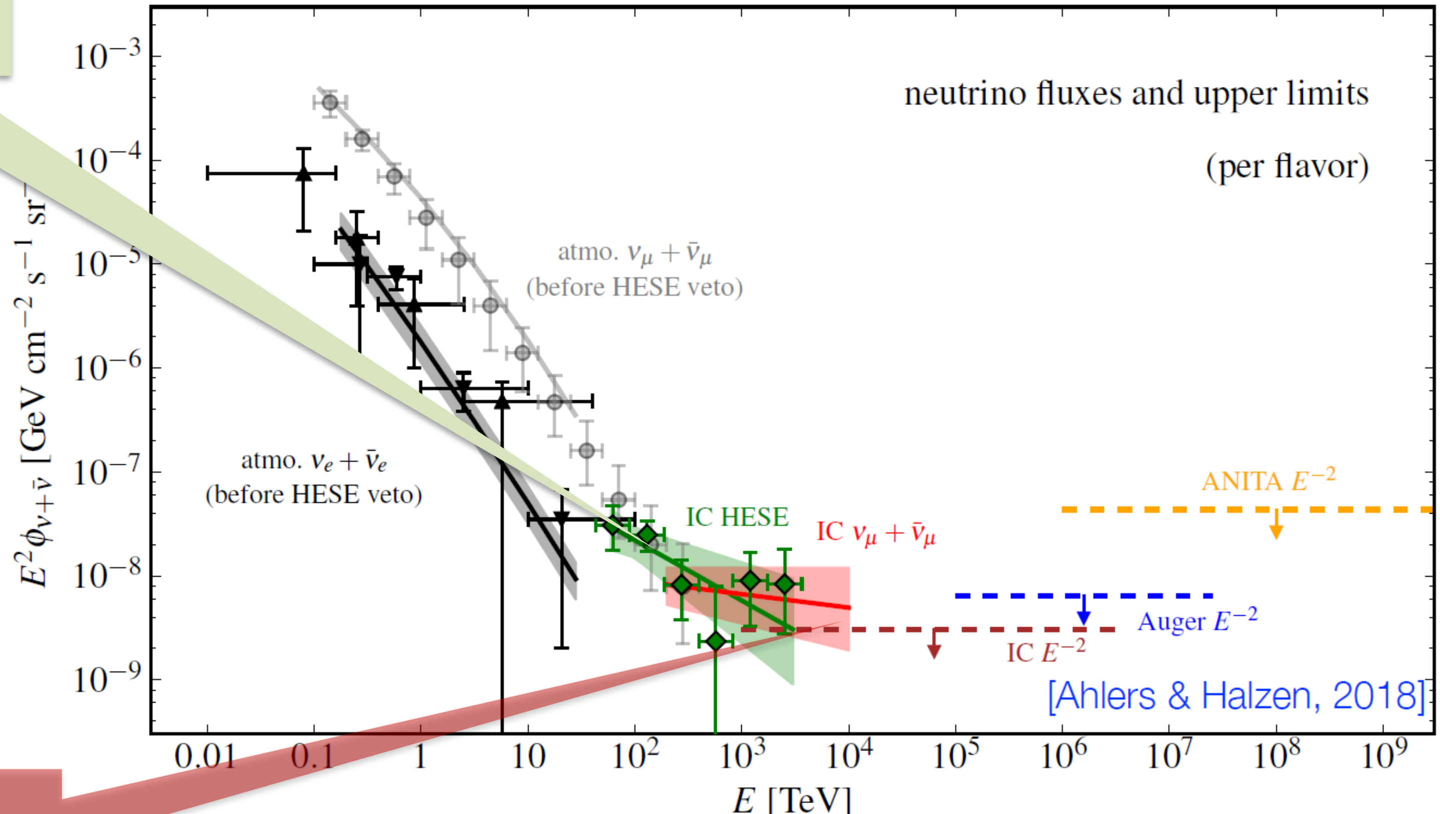
Highest energy neutrino so far

Highest energy neutrino event seen: 2.6+- 0.4 PeV deposited energy
Estimated neutrino energy: ≈ 10 PeV



Neutrino fluxes

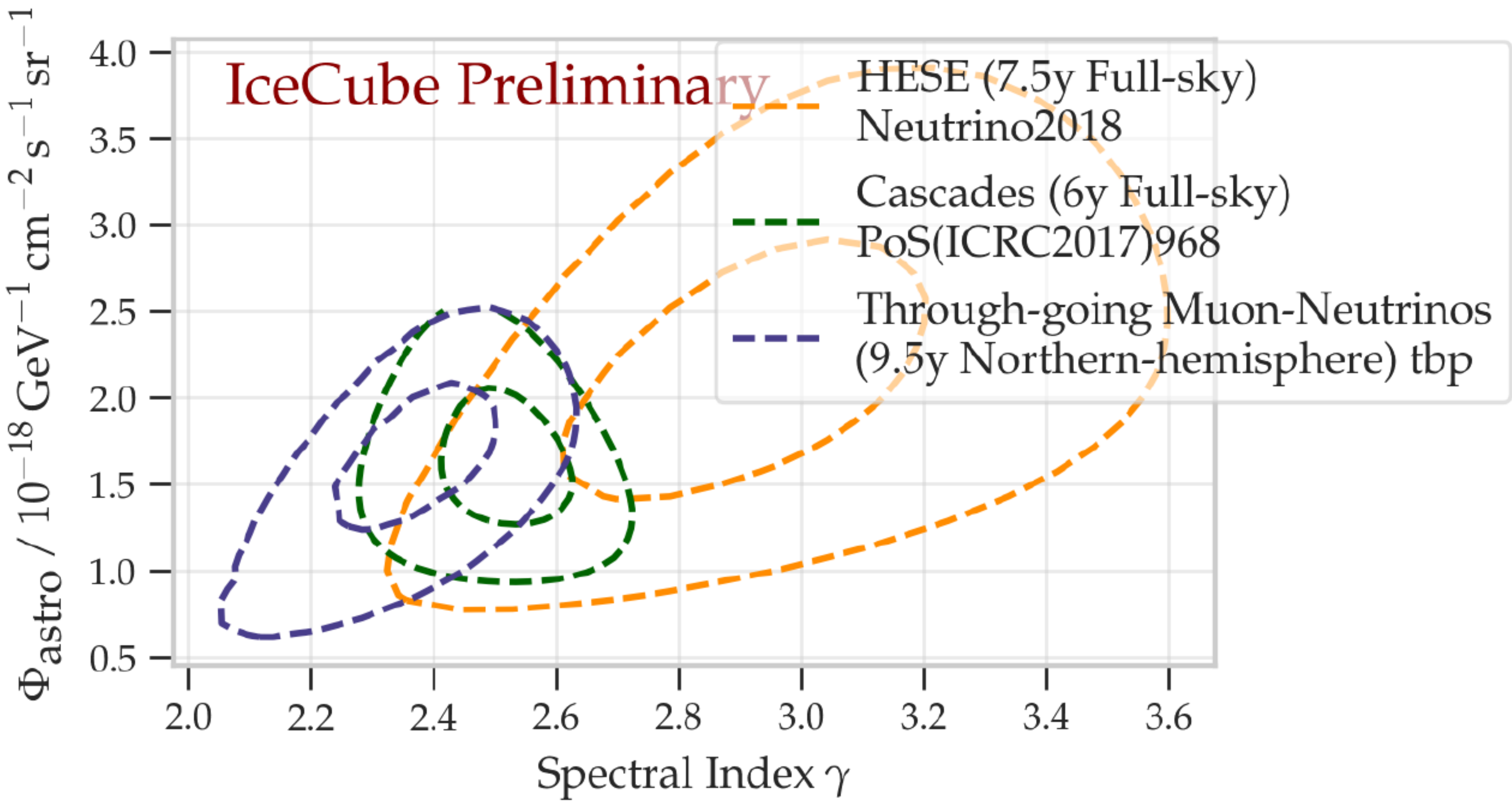
HESE 7.5 y:
~100 events (8 σ)



Tracks 8 (9.5) y:
~500 events (8 σ)

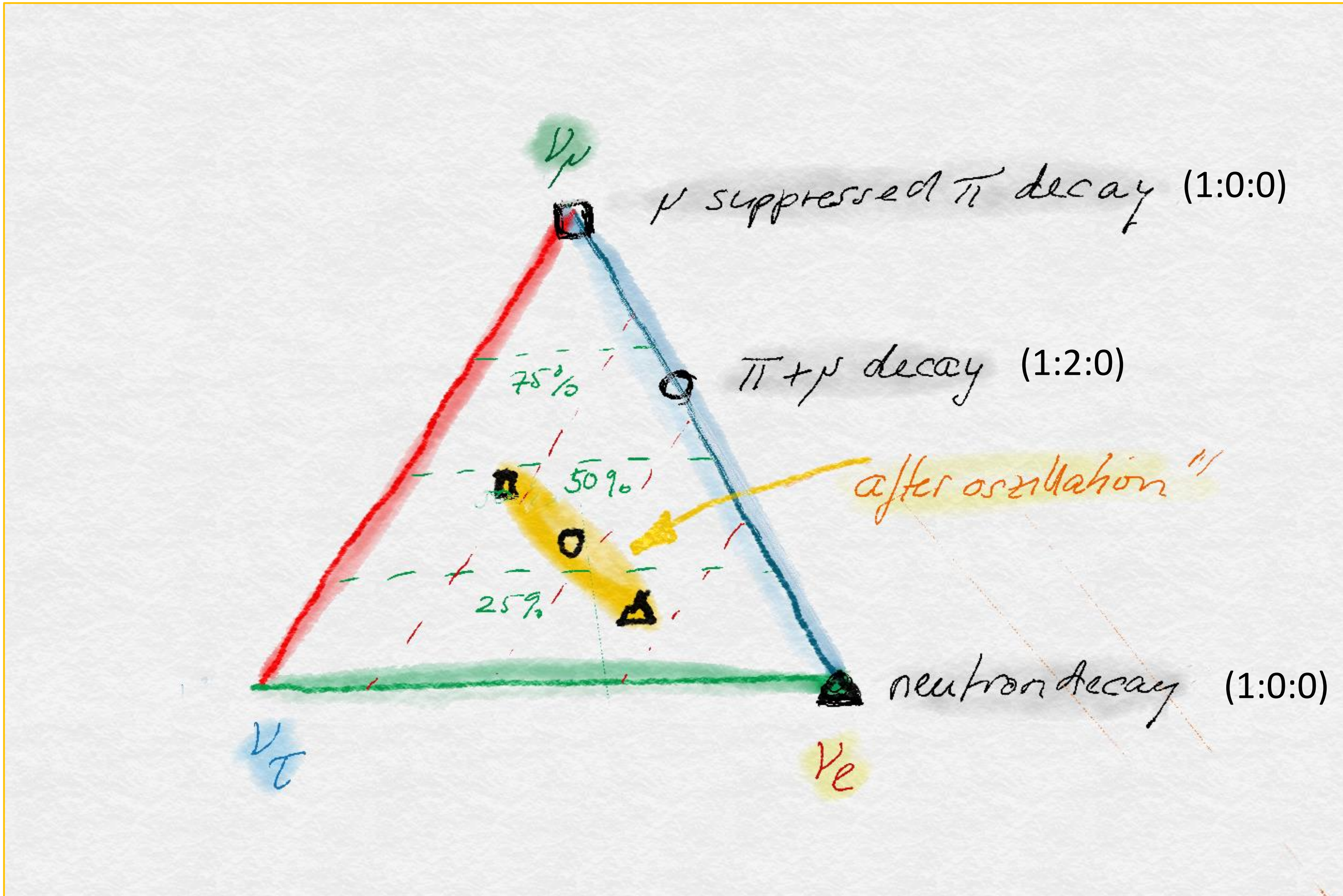
+ results on cascades …

Roughly consistent measurements



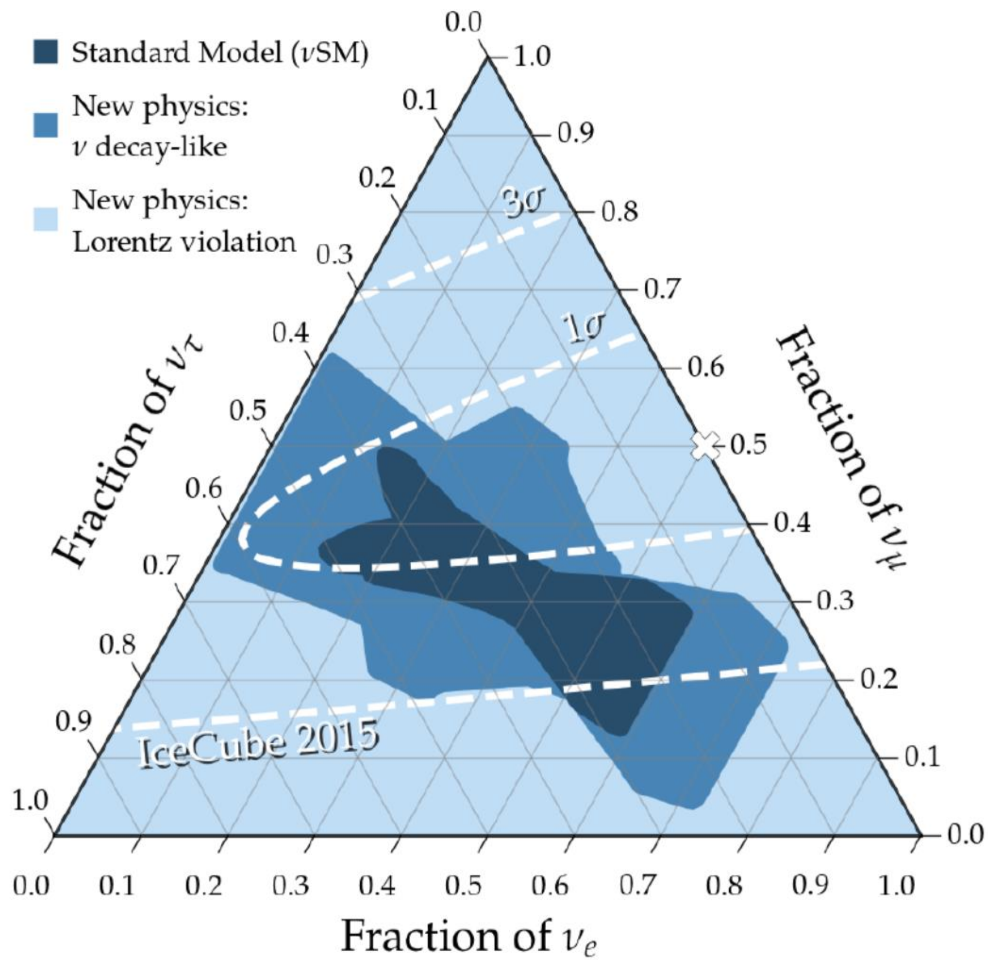
But hint that different energy ranges / angular coverage make difference …

Flavor ratios (ν_e, ν_μ, ν_τ)



Ratio after oscillations depend on production, mixing angles and CP violation phase

Flavor ratios measurement (2015)

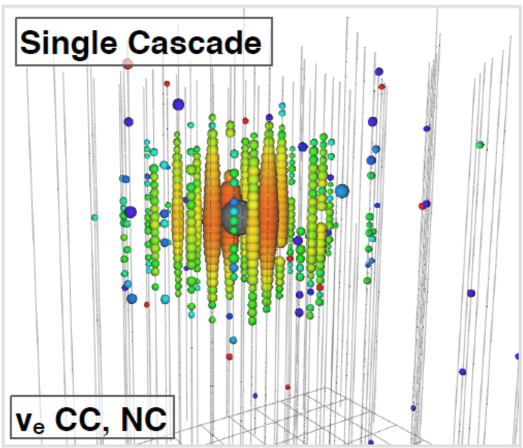


Decadal Survey, https://arxiv.org/abs/1903.04333

Can we see tau-neutrinos?

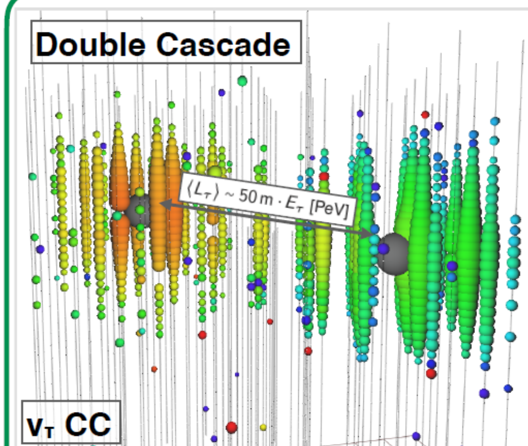
Simulation

early → late



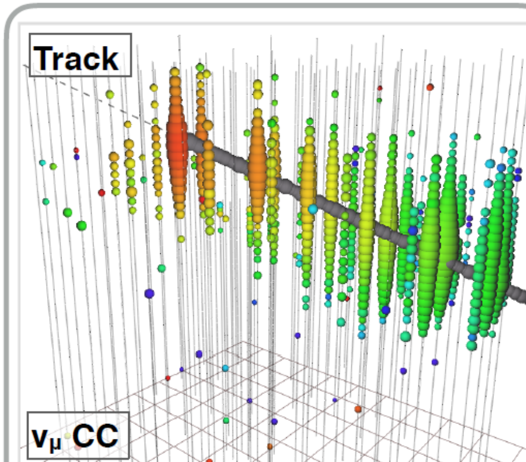
All NC interactions
ν_e CC interactions

Good energy resolution
Bad angular resolution



ν_τ CC interactions with hadronic / electronic tau decay

Good energy resolution
Angular resolution gets better with larger lengths



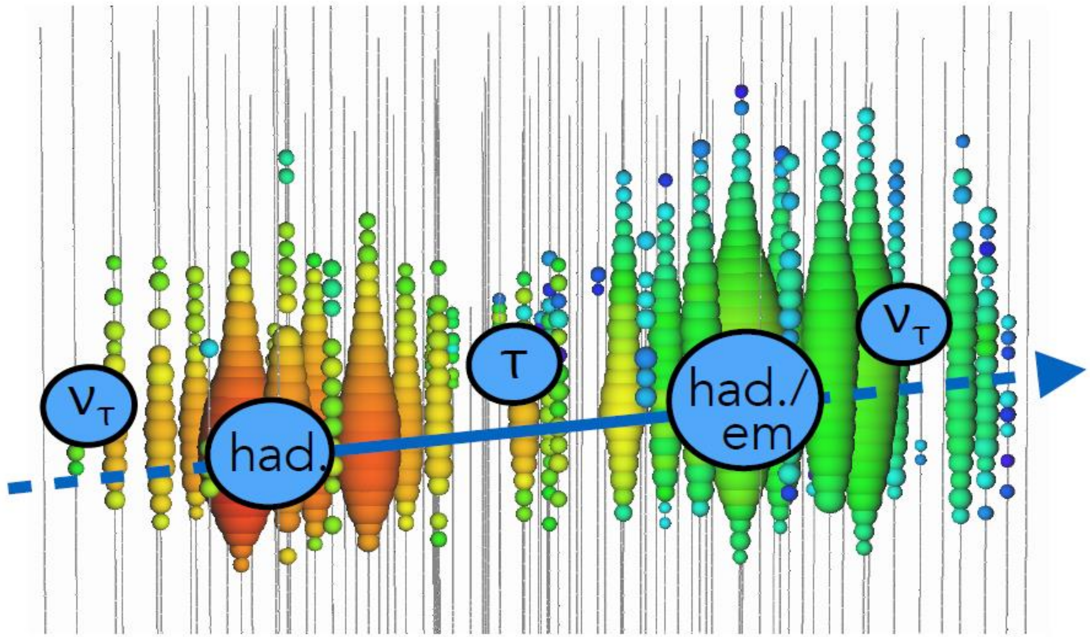
ν_μ CC interactions
Atmospheric μ
ν_τ CC interactions with muonic tau decay

Bad energy resolution
Good angular resolution

… can we see tau-neutrinos?

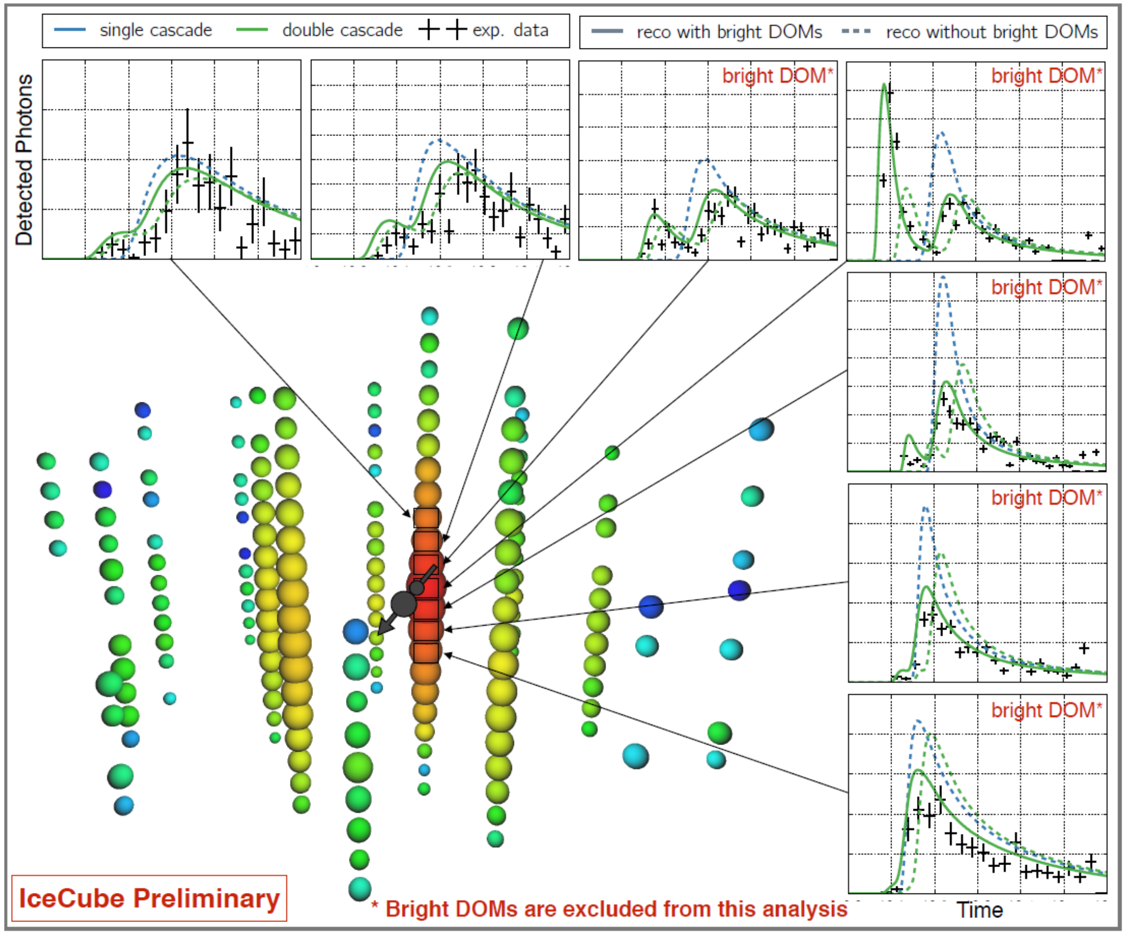
Simulation

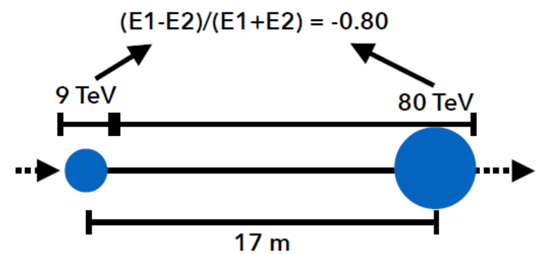
- Charged current (71%)
- Tau decays into hadrons / electrons (83%)
- Mean length: 50m x energy/1PeV



simulated 10PeV Double Cascade event

τ - neutrino candidate events



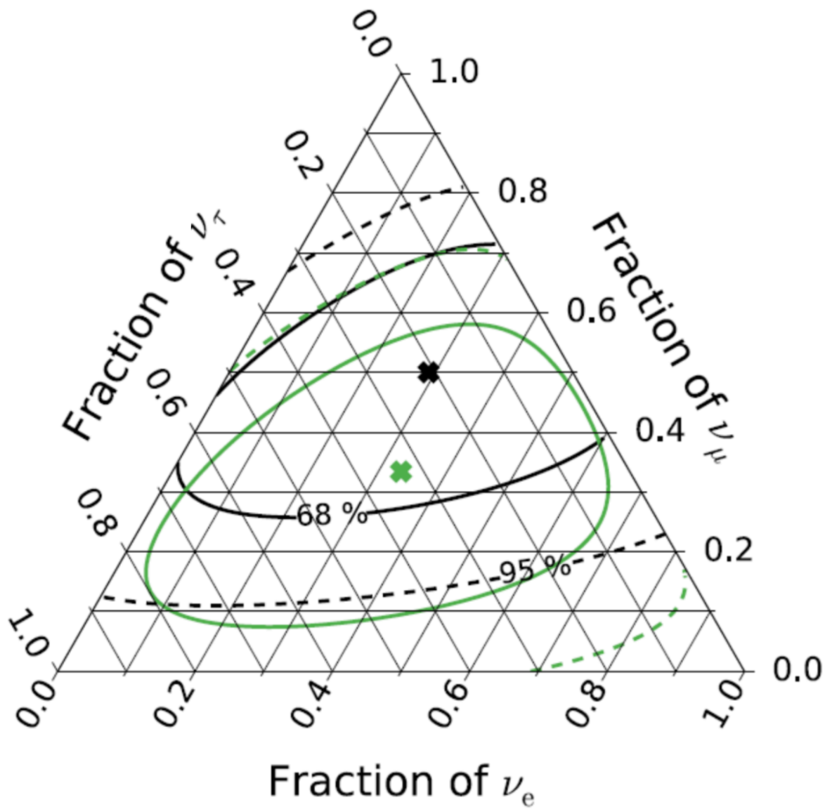


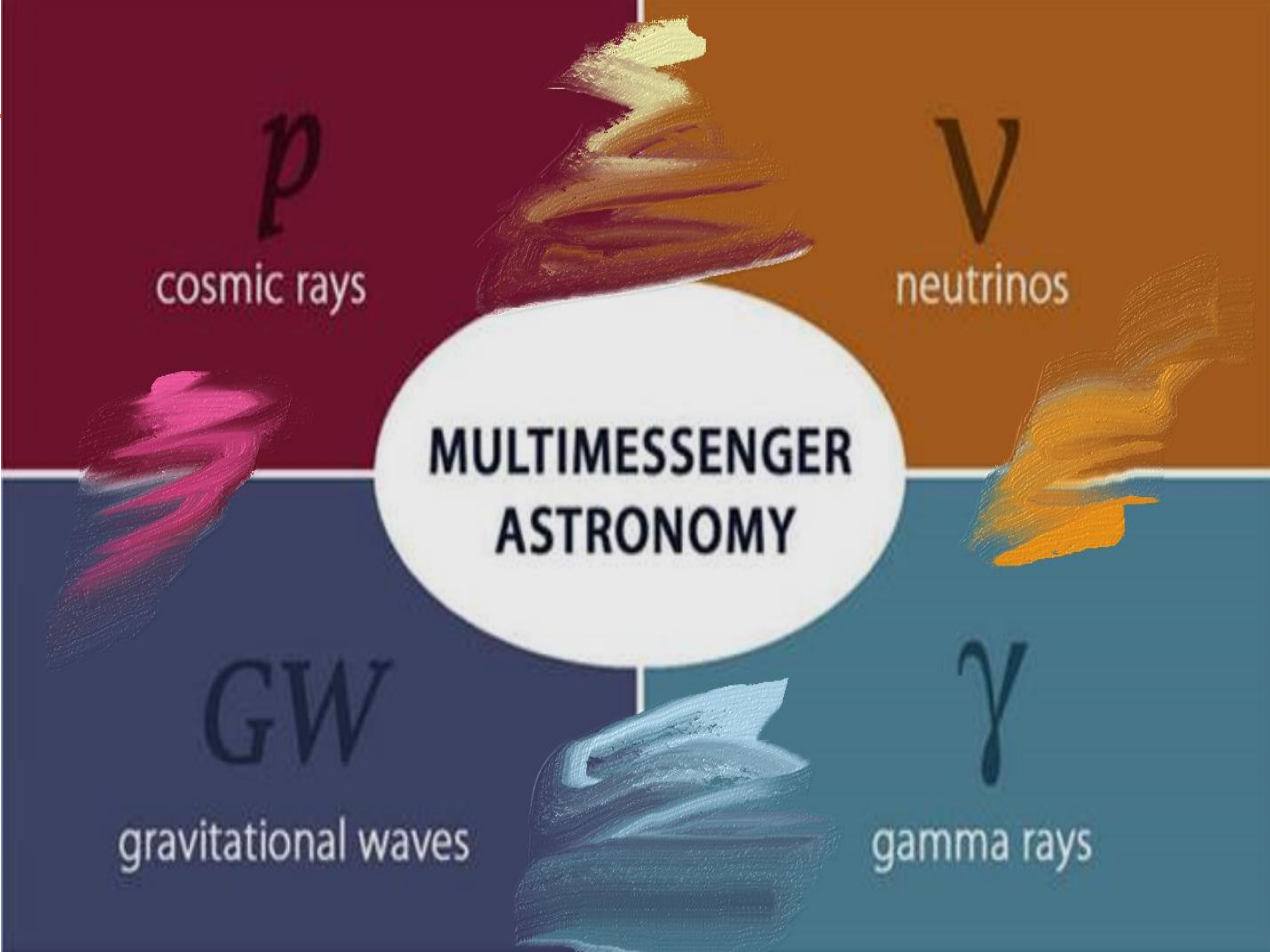
- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

early → late

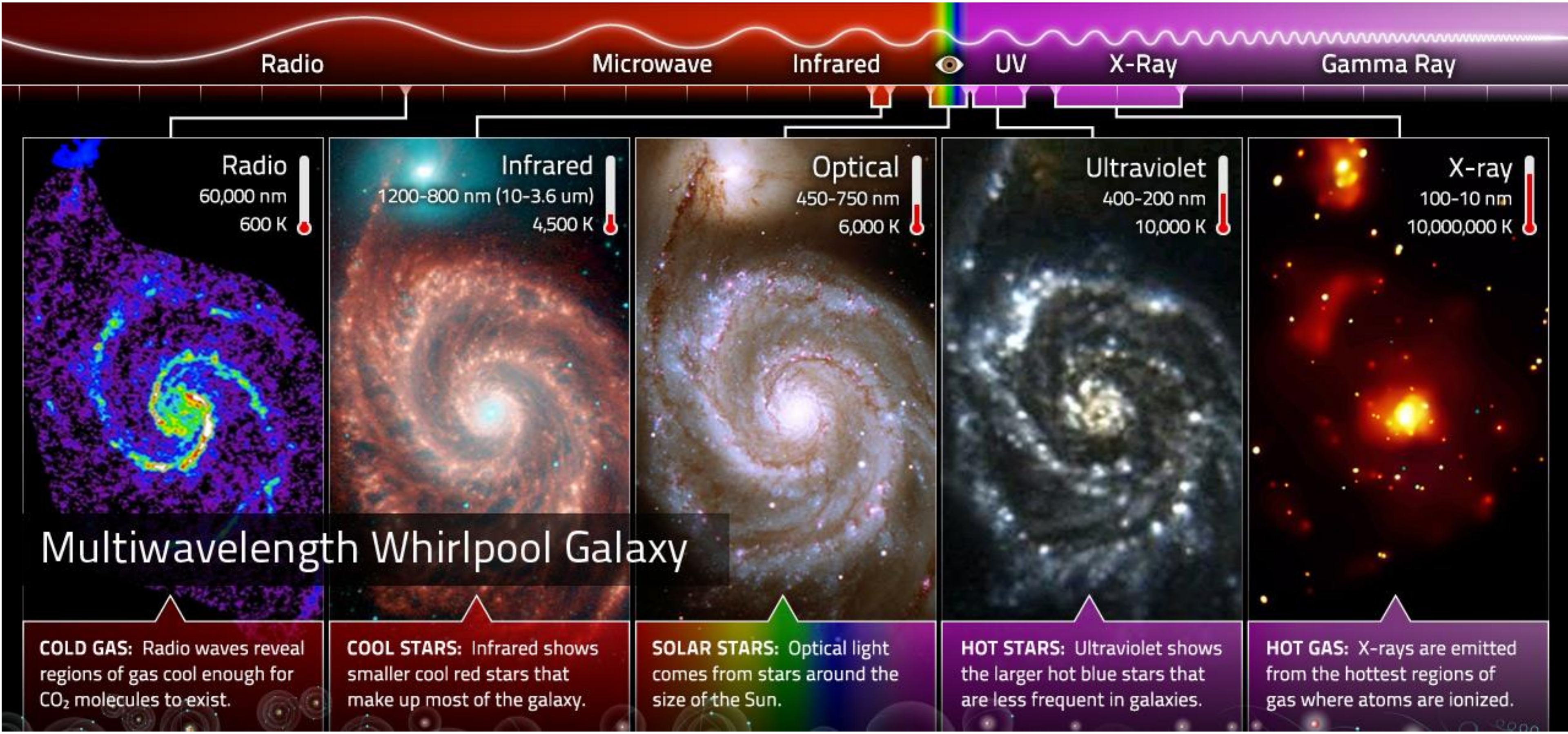
Flavor ratios measurement with ν_τ

Consistent with 1 : 1 : 1 hypothesis
Zero ν_τ cannot be excluded yet




p
cosmic rays
ν
neutrinos
MULTIMESSENGER
ASTRONOMY
GW
gravitational waves
γ
gamma rays

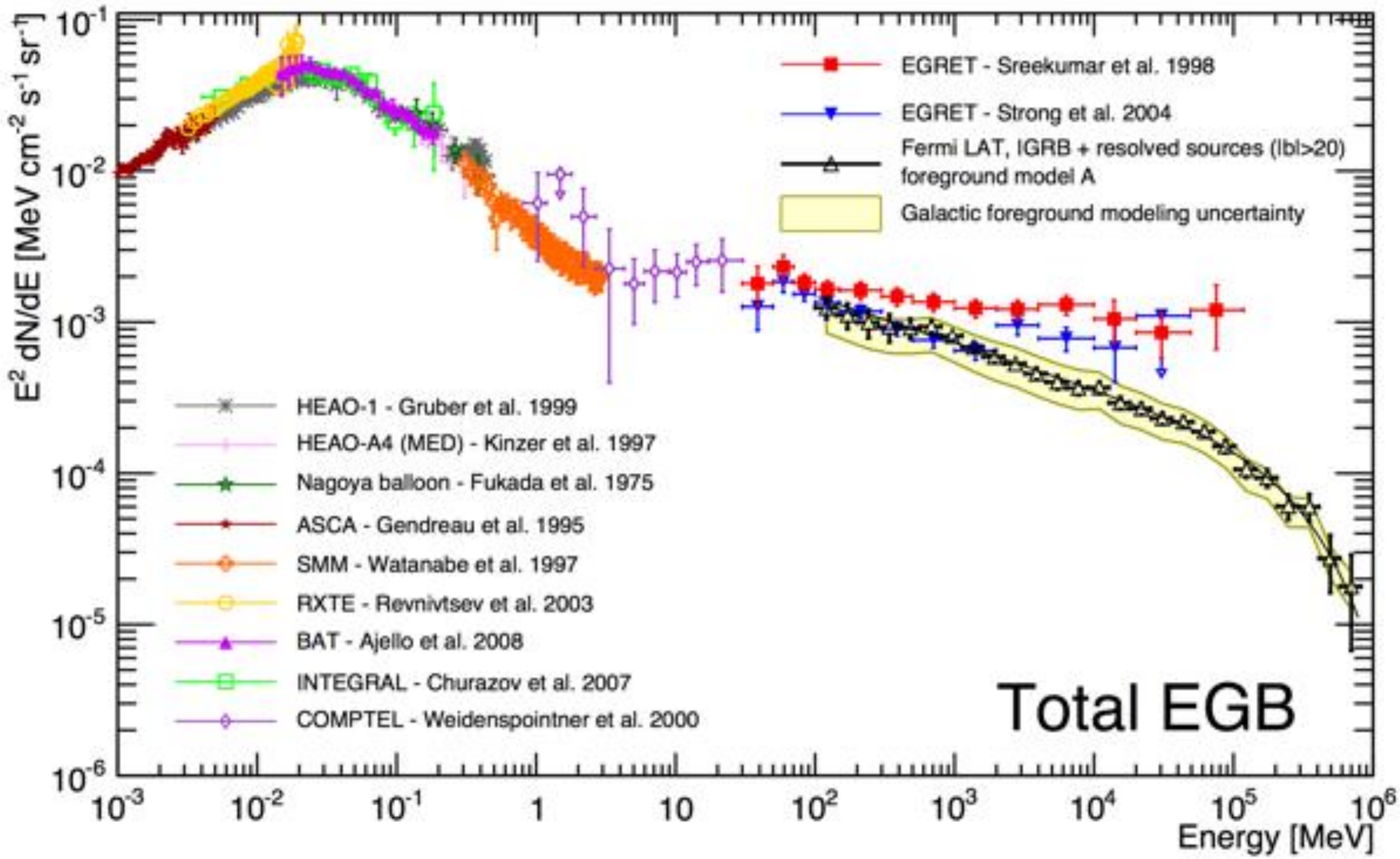
Multiwavelength astronomy



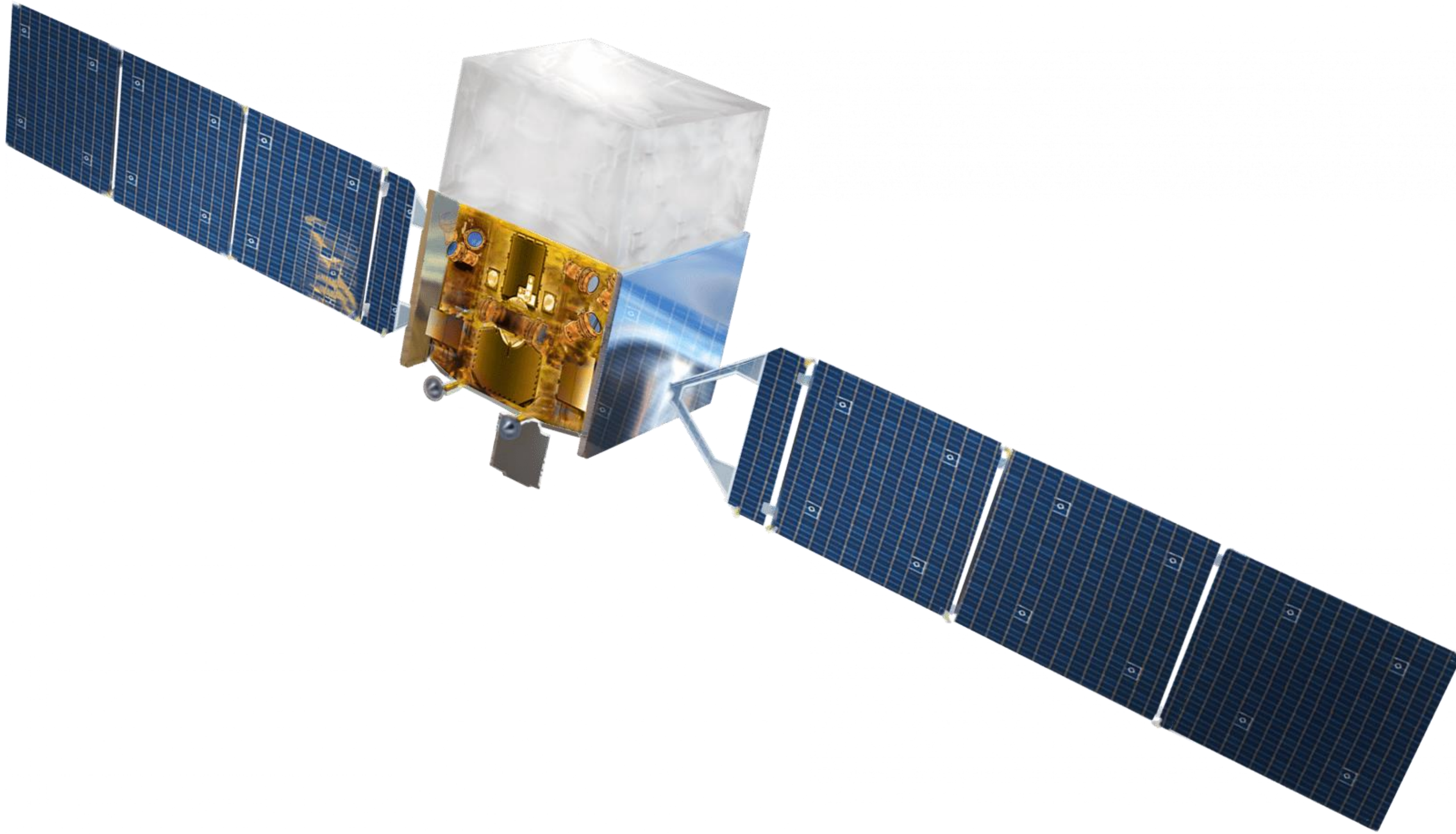
Satellites, baloons, airplanes, ground based telescopes and arrays

Example: Multi wavelength

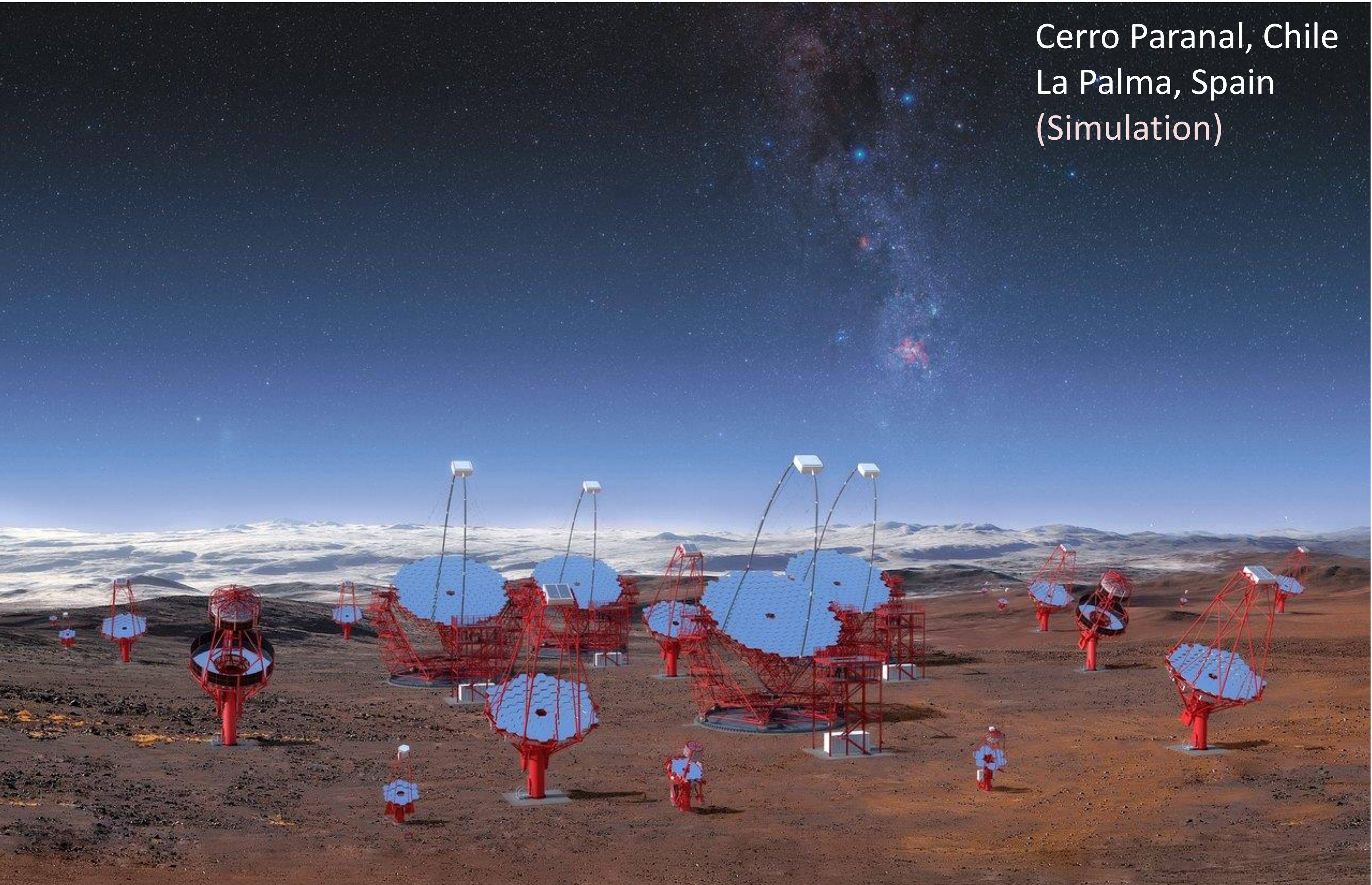
Extragalactic background electromagnetic radiation



Satellite based γ detector (FERMI)



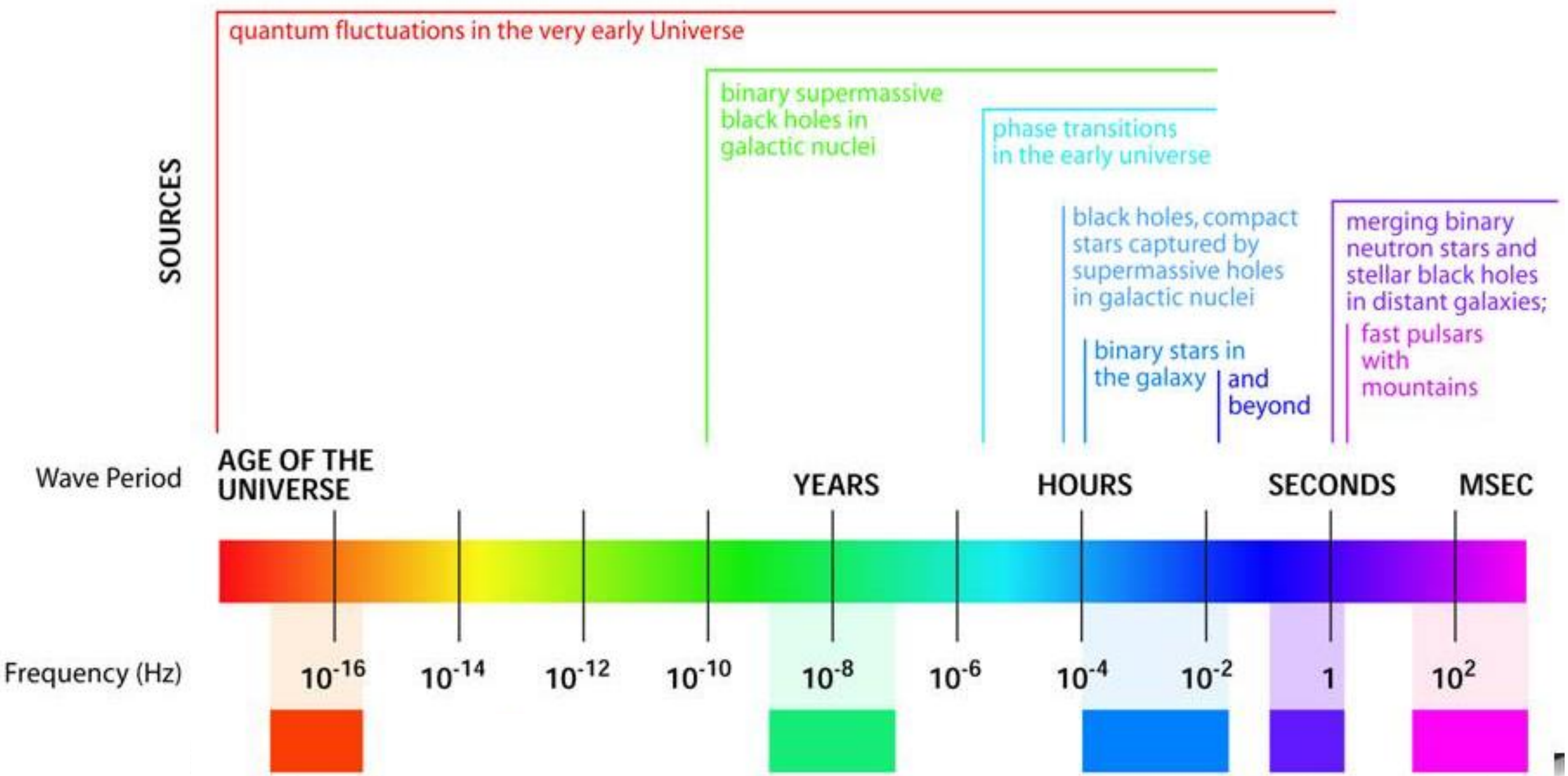
Cherenkov telescope (CTA)



All sky gamma detector (HAWK)

Cosmic Rays (Auger)

Multi-wavelength: Gravitational Waves



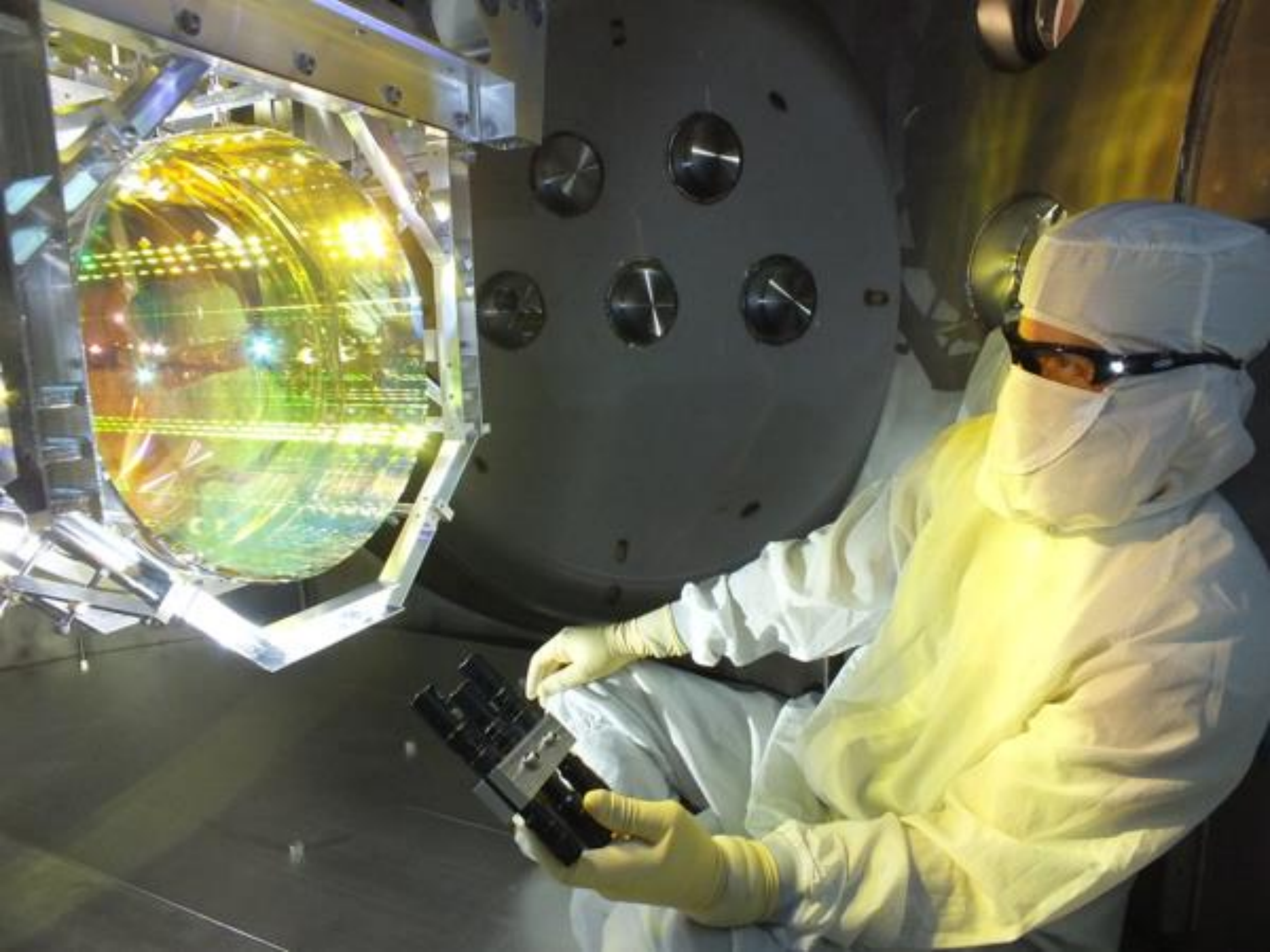
CMB polarization

ms pulsars timing

space terrestrial interferometers

Gravitational Waves with LIGO

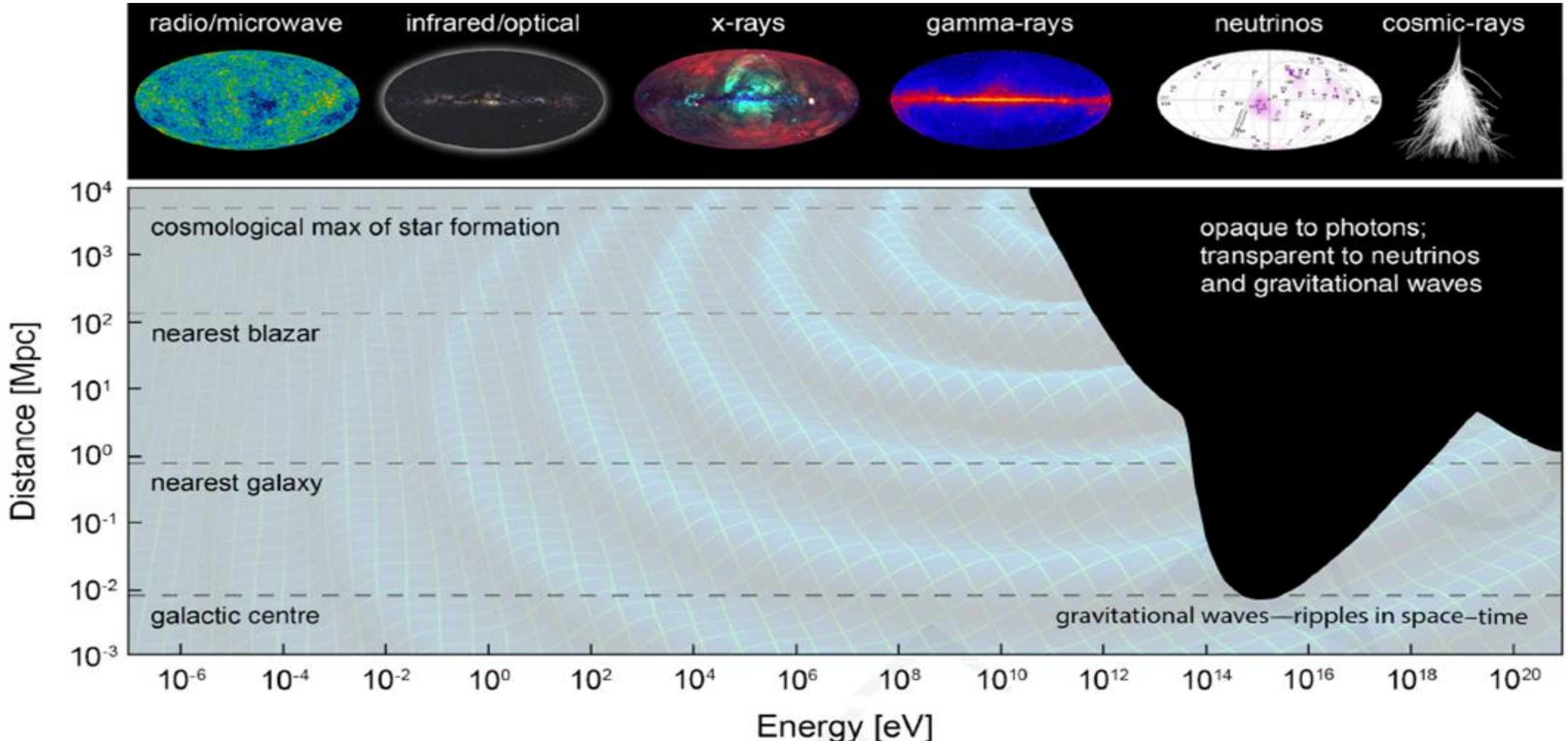
Ligo: Livingston



Rationale: Multi-Messenger Astrophysics

obtain complete knowledge on astrophysical sources, their emission engines and complementary insight into the physics of the progenitors and their environment

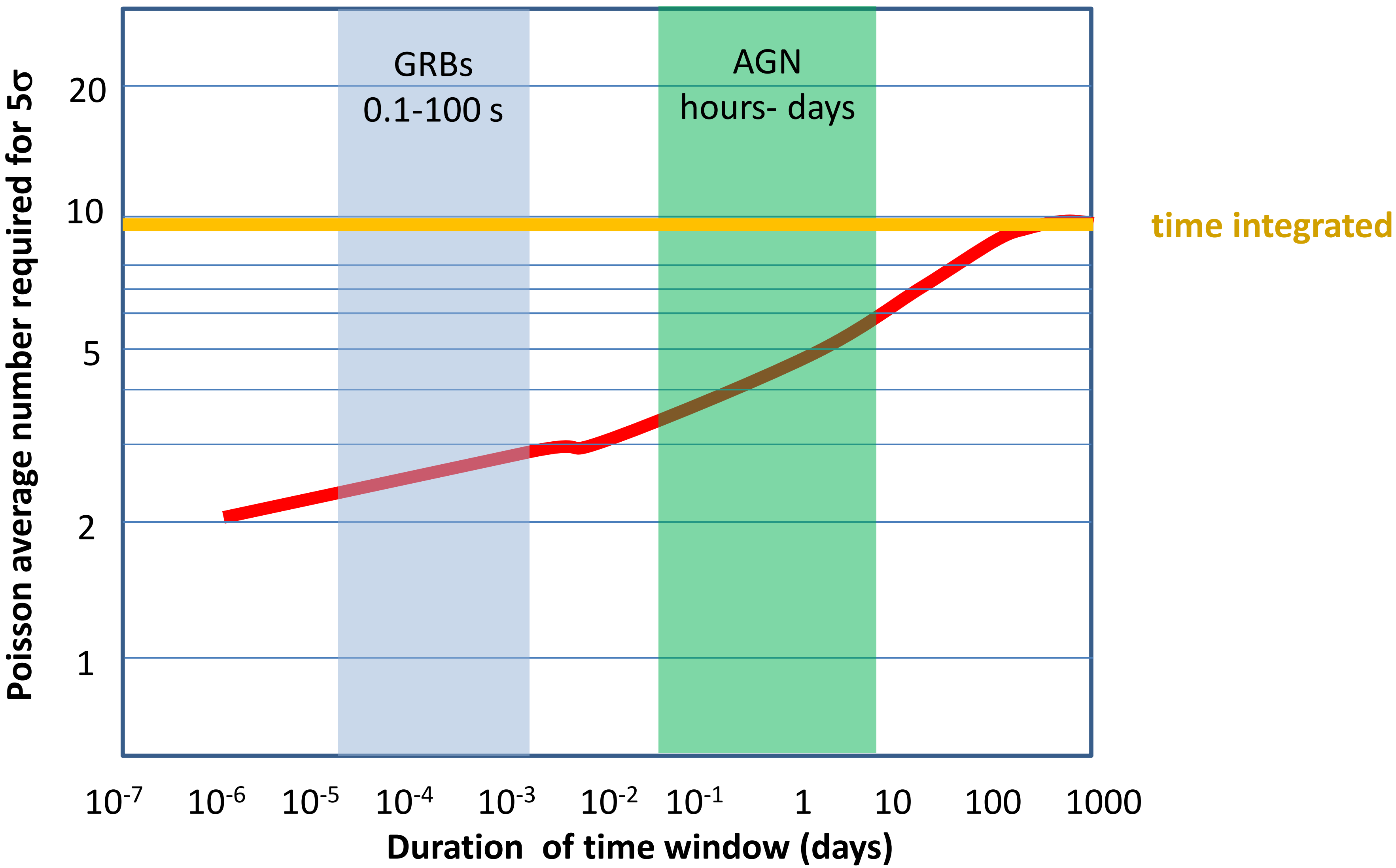
- **In general:** Span large energy/frequency ranges with different sensitivity, resolutions and coverage
- **Transients:** Beat *look elsewhere effect* (trial factor)
- **Ultimately:** Illuminate dynamics as function of energy, time, position, …



Kowalski/Bartos: ISBN: 978-0-7503-1369-8

Transients: Beat the Look Elsewhere Effect

… a didactical example for neutrino telescopes



Some Multi-messenger physics goals

- Nature of compact objects? (Black Holes, Neutron Stars …)
- Physics behind supernovae and gamma-ray bursts
- Origin and acceleration mechanisms of ultra-relativistic cosmic particles
- Propagation and role of cosmic rays in environment (3d-B-fields, star formation, chemistry …)
- Search for the nature of Dark Matter (direct/indirect/cosmology)
- Tests of SRT, ART, and Standard Models of Particle Physics and Cosmology

Some Multi-messenger physics goals

- Nature of compact objects?
- Physics behind supernovae and gamma-ray bursts?
- Origin and acceleration mechanisms of ultra-relativistic cosmic particles
- Propagation and role of ultra-relativistic particles in environment
- Search for the nature of Dark Matter
- Tests of SRT, ART, and Standard Models of Particle Physics and Cosmology

Specific to cosmic ray production:

- Point-sources of UHE cosmic rays, neutrinos; production mechanism?
- Relationship between neutrino/gamma production at high energies?
- Energy dependence of galactic/extragalactic contribution?
- Will we be able to follow up GW sources with high energy probes?

Some Multi-messenger physics goals

- Nature of compact objects?
- Physics behind supernovae and gamma-ray bursts?
- Origin and acceleration mechanisms of ultra-relativistic cosmic particles
- Propagation and role of (ultra-)relativistic particles in environment
- Search for the nature of Dark Matter
- Tests of SRT, ART, and Standard Models of Particle Physics and Cosmology

Specific to cosmic ray production:

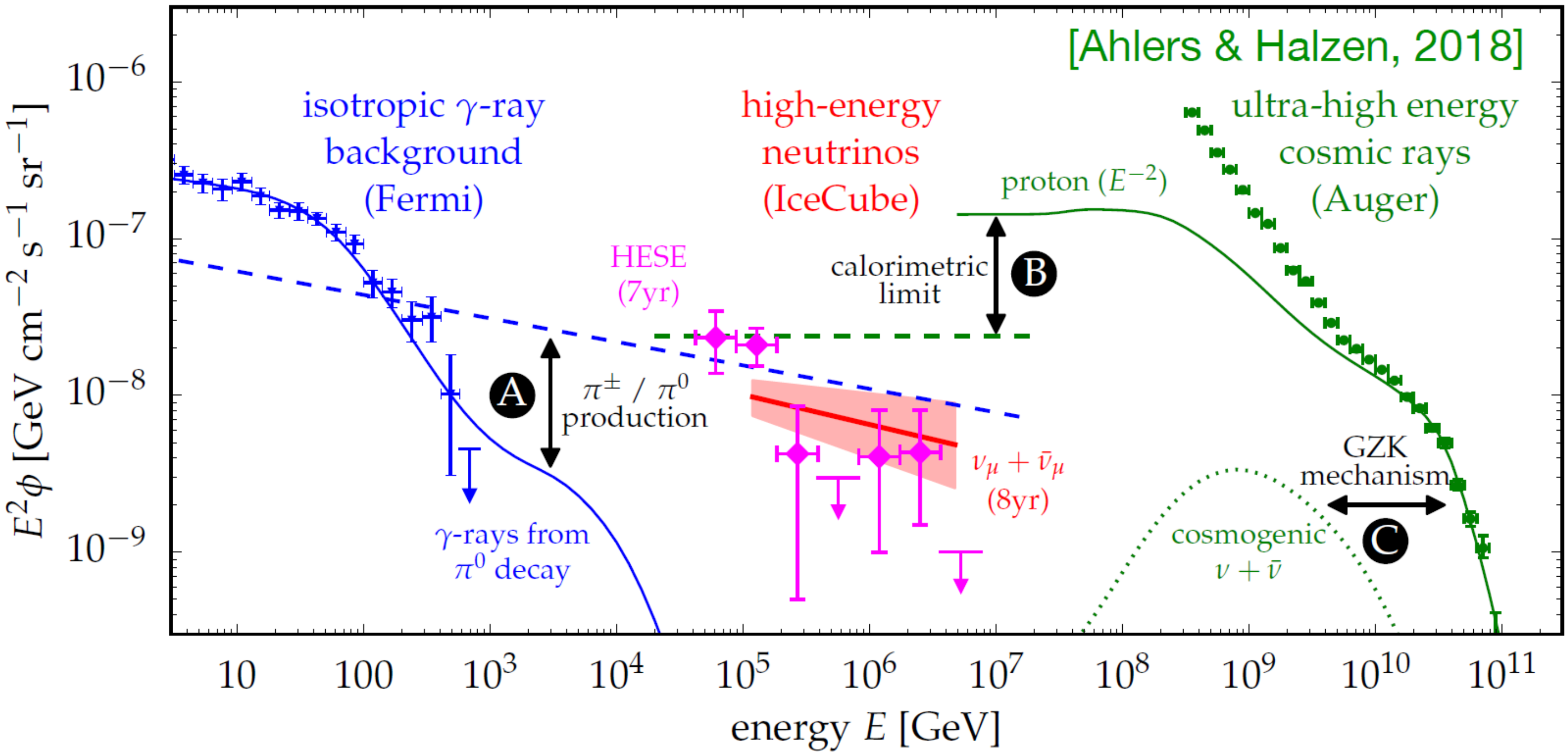
- Point-sources of UHE cosmic rays, neutrinos and their production mechanism?
- Relationship between neutrino/gamma production?
- Energy dependent galactic/extragalactic contribution?
- Will we be able to follow up GW sources with high energy probes?

Specific to dark matter in underground labs, indirect searches (and LHC):

- Separate standard astrophysical processes from DM annihilation or decay
- Once discovered, pin down its properties (mass, x-section, distribution…?

Example: multi messenger

Compare integrated fluxes of distant objects: ***similar magnitude for γ, ν and cosmic rays***



But what about specific objects?

Monitoring, circulars & early warning systems

Full/large sky monitoring:

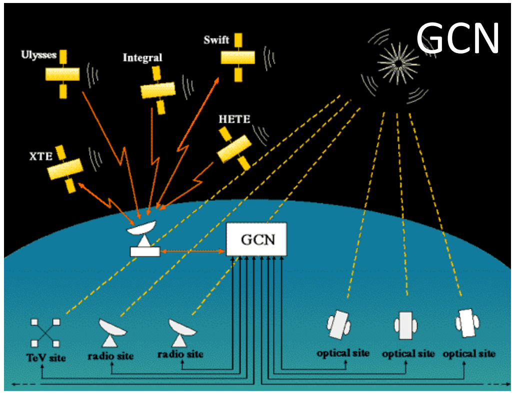
GW observations, ν-detectors and telescopes, all-sky HE-γ, UHE-CR observations …

Frequent sky scans:

- ASAS-SN: ´18: complete sky 1/day, SN → 250 MPc
- Pan-STARRS: complete sky 4 x per month
- Zwicky Transient Facility: ´18: sky every 3 nights
- LSST: full operation in ´22: visible sky once per night
- Radio surveys: MeerKat, SKA …

Circulars:

- Gamma-ray Coordinates Network GCN (since 1997)
- Astronomers telegram (ATEL, since 1997)



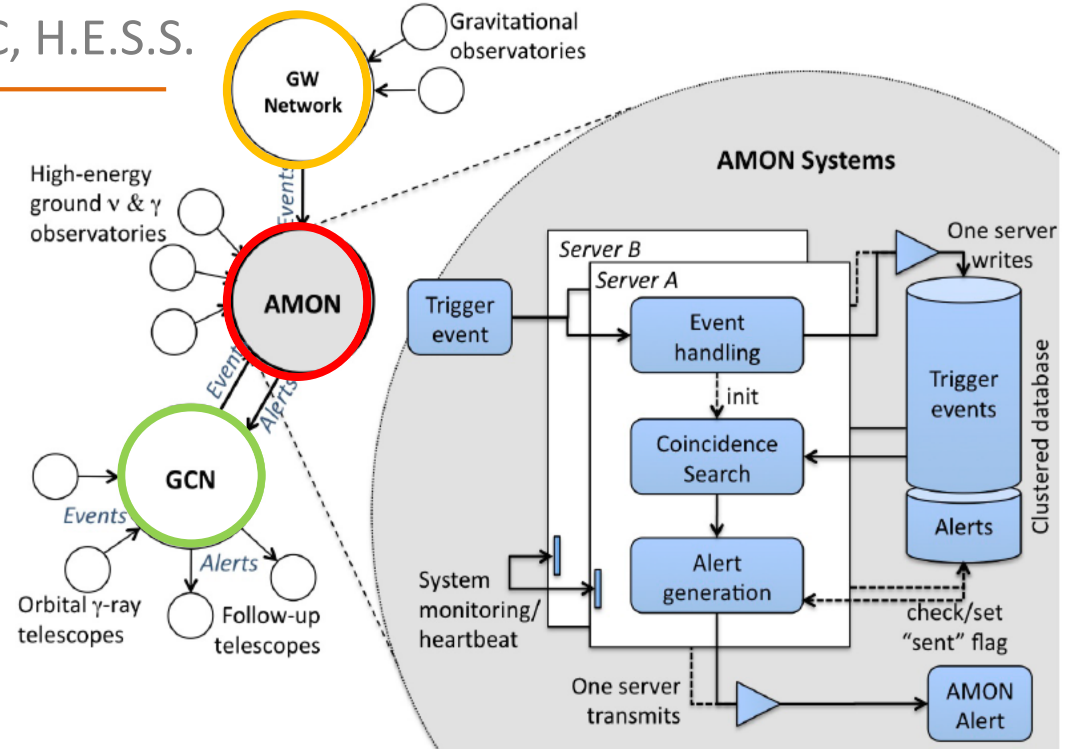
Coincidence generation tools:

- Supernova Early Warning System SNEWS (since 1999)
- GW network: *from O3/2019 open public alerts !*
- Astrophysical Multimessenger Observatory AMON (since 2013) *see next slide*

AMON

Astrophysical Multimessenger Observatory Network

- **Archival** searches
- **Realtime** searches (sub-threshold candidates from ANTARES, Auger, HAWC, VERITAS, FACT, Swift BAT, Fermi,LIGO/VIRGO)
- **Passthrough** (e.g. to **GCN**)
- **Follow-up** by Swift XRT VERITAS, FACT, MASTER, LCOGT, PTF, LMT, MAGIC, H.E.S.S.



Multi-experiment publications:

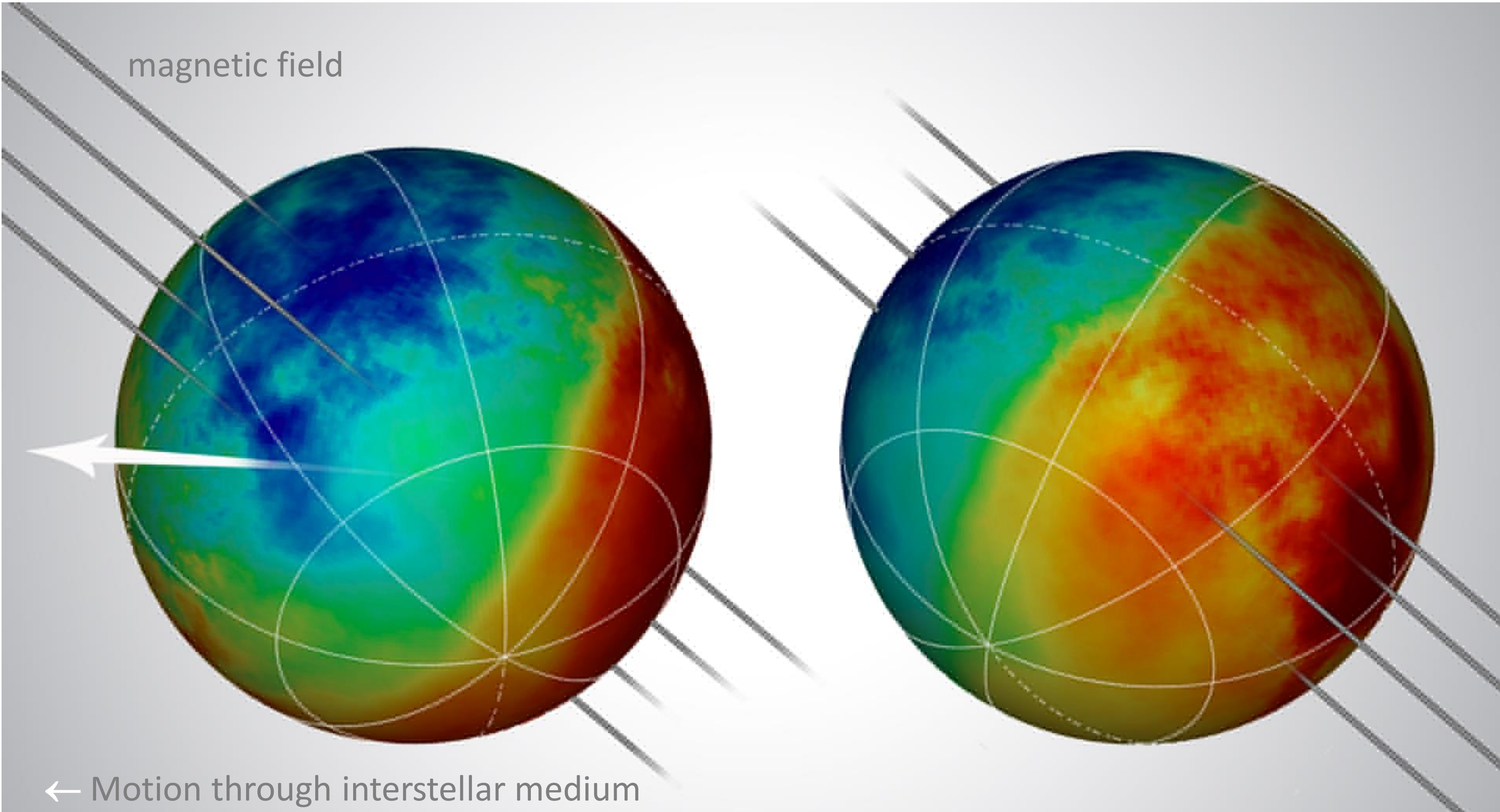
Example for high energy messengers (from 2013)

	ArXiv	ANTARES	AUGER	FERMI	HAWC	H.E.S.S.	IceCube	LIGO (V)	MAGIC	VERITAS	*comment*
	1310.7913			✓						✓	
	1407.0862			✓		✓					
	1407.1042						✓	✓			
	1508.05827			✓					✓		
2016	1601.06590			✓					✓		
	1602.05411	✓					✓				
	1609.00600			✓		✓					
	1610.03311			✓		✓					
2017	1703.06298	✓					✓				
	1707.03658					✓			✓		
	1708.03005				✓		✓				
	1708.03137				✓	✓					
	1708.08945					✓			✓		*FACT*
	1710.05833	✓	✓	✓	✓	✓	✓	✓	✓		*more! NS*
2018	1710.05839	✓	✓				✓				
	1806.03866			✓		✓					
	1807.07375			✓		✓					
	1807.08816..				✓	✓	✓	✓	✓	✓	*more! TXS*
	1808.03531	✓					✓				
	1808.10423			✓						✓	
	1810.02764			✓				✓			
	1810.10693	✓					✓	✓			

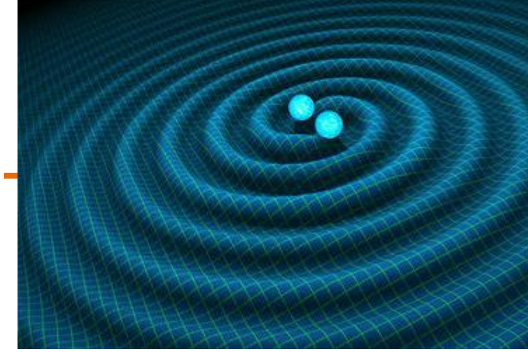
+ analyses using public data by experimentalists/phenomenologists

HAWK+IceCube

Example: Cosmic ray anisotopy (0.1% effect)



Multimessenger example



Two prime examples highlighted by Wikipedia:

1: **17.8.2017:** Combined LIGO/VIRGO binary neutron star merger observation
gravitational wave detection @ 1.3×10^8 LJ distance
multmessenger analyses by > 64 facilities

12:41: **GW** → +2 s: **GRB** → +10:52h: optical → +11:36h: Infrared → +15h: UV → +9 days: X-ray → +16 days: radio

kilonova (optical, Infrared, UV)

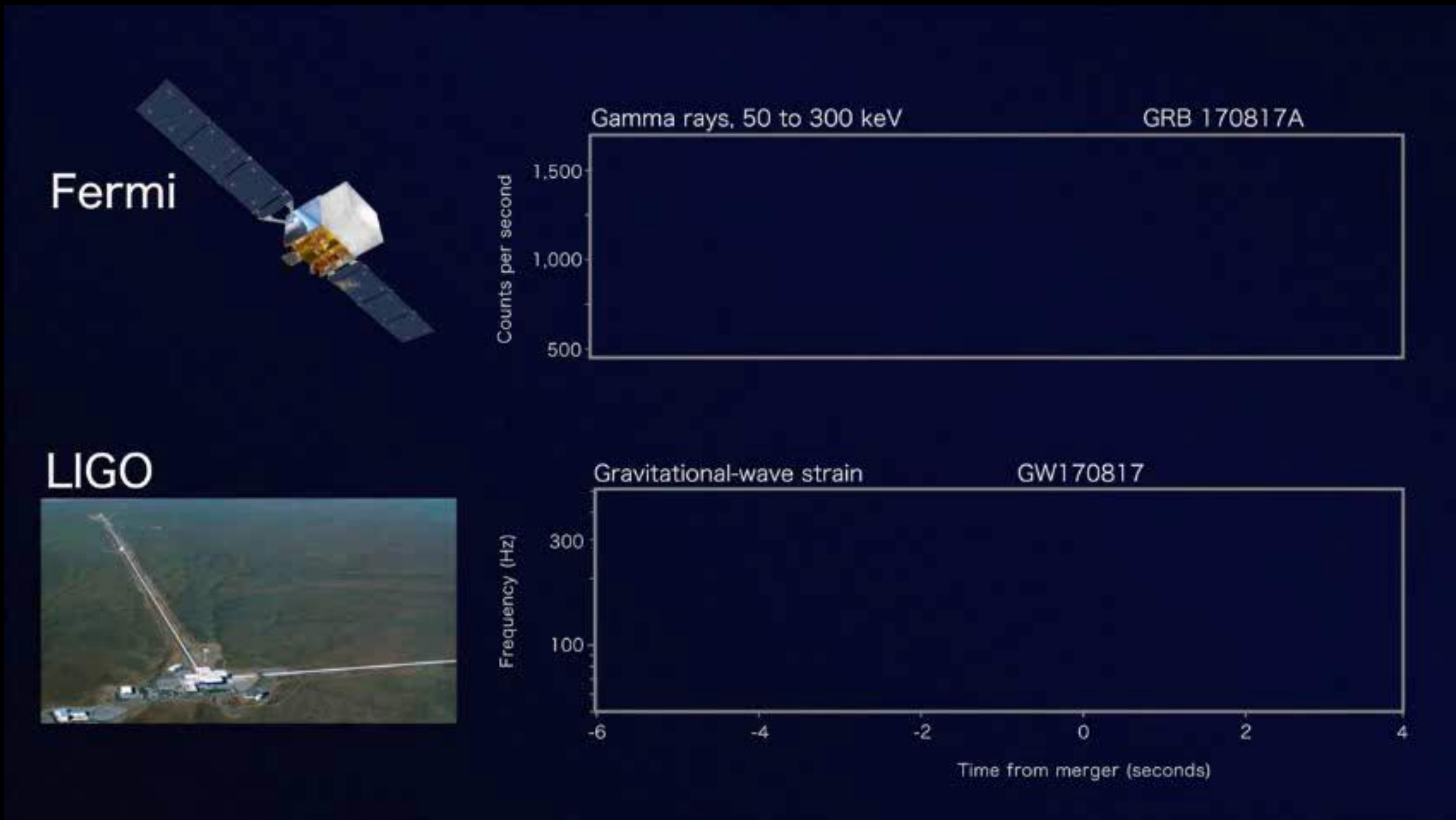
radio remnant

Major findings:

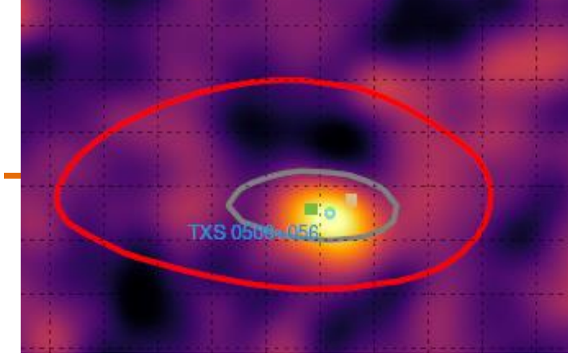
GW: expansion rate of Universe / neutron star characteristics
GRB: neutron star mergers produce short GRBs!
Kilonova: neutron star mergers responsible for heavy metal production
SRT/ART: same speed GW & γ : rule out several modified gravity models

Astrophys. J. Lett., 848, L12, Oct. 2017

GW 170817 (Neutron star merger)



TXS 0506+056



2:

22.9.2017: 290 TeV ν_μ alert by IceCube Collaboration; identified by **FERMI** & **MAGIC** as blazar TXS 0506+056 @ ~4.5×10^9 LJ distance
evidence supported by archival search in IceCube data
multimessenger analyses by > 17 facilities

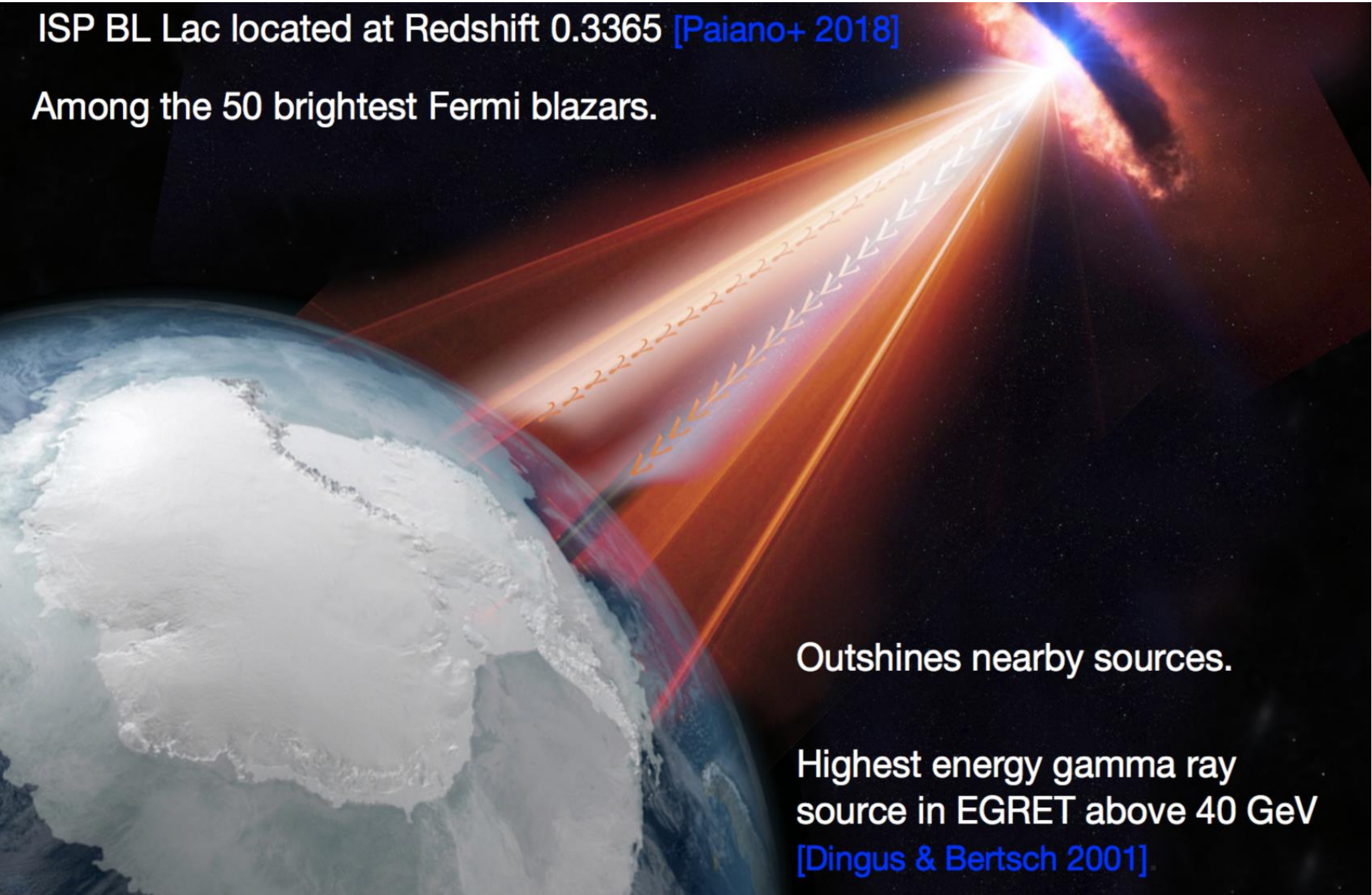
12:54: ν_μ → Swift → Fermi → Magic → ... → Veritas

Major findings:

Cosmic ray: first extragalactic cosmic ray source identified
blazar: one *of probably several* source classes of high energy ν's/cosmic rays
TXS 0506+056: $10^{45} - 4 \times 10^{46}$ erg/s jet power
SRT/ART: Shapiro delay consistent with Lorentz invariance

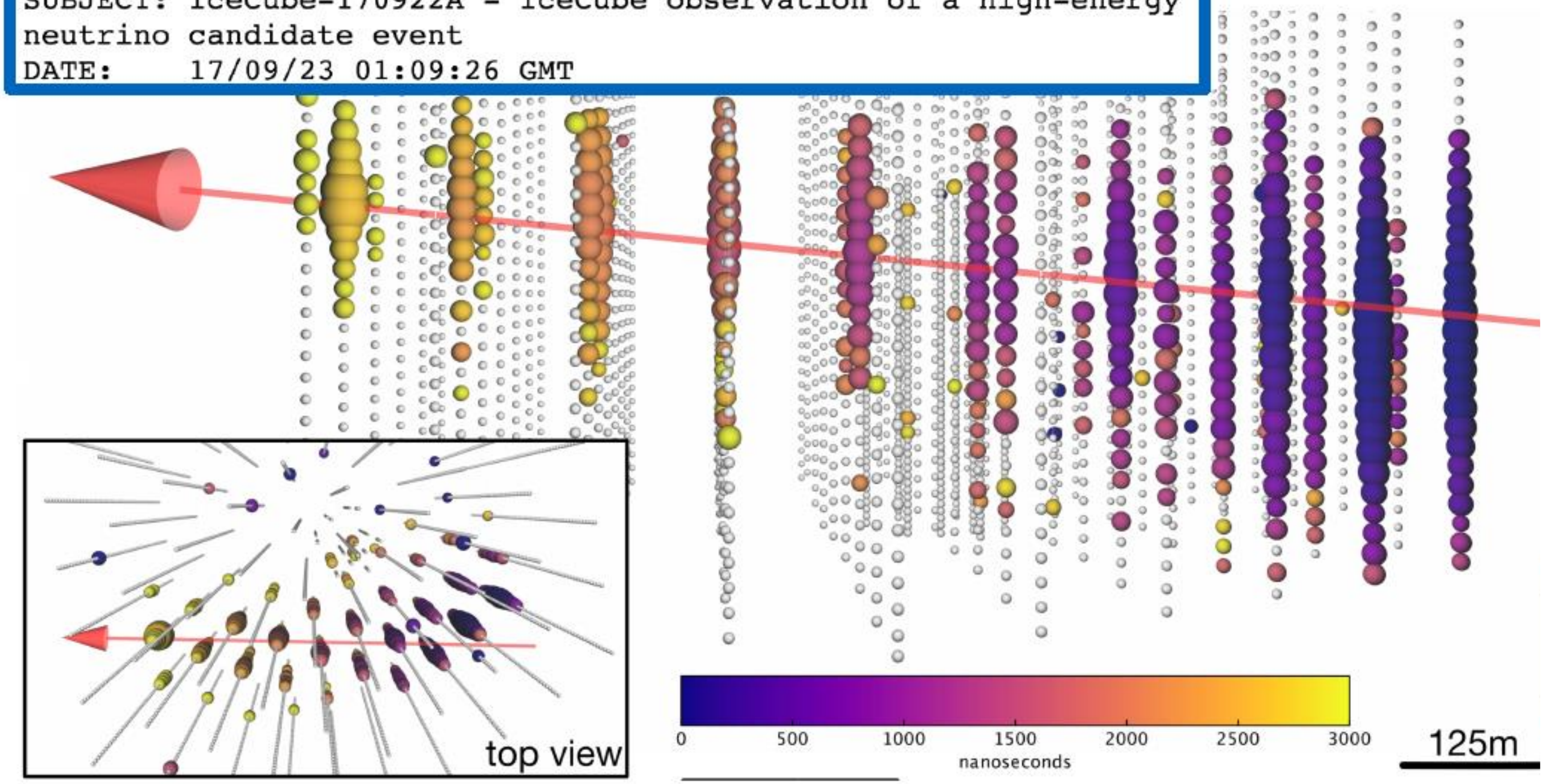
Science, 361, 6398, July, 2018

TXS 0506+056


ISP BL Lac located at Redshift 0.3365 [Paiano+ 2018]
Among the 50 brightest Fermi blazars.
Outshines nearby sources.
Highest energy gamma ray source in EGRET above 40 GeV [Dingus & Bertsch 2001]

...TXS 0506+056

```
TITLE:    GCN CIRCULAR
NUMBER:   21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event
DATE:     17/09/23 01:09:26 GMT
```

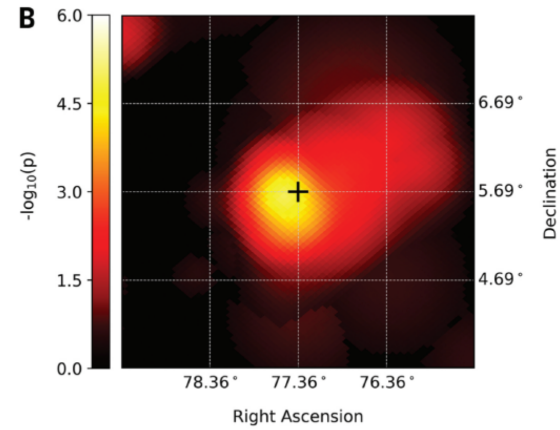


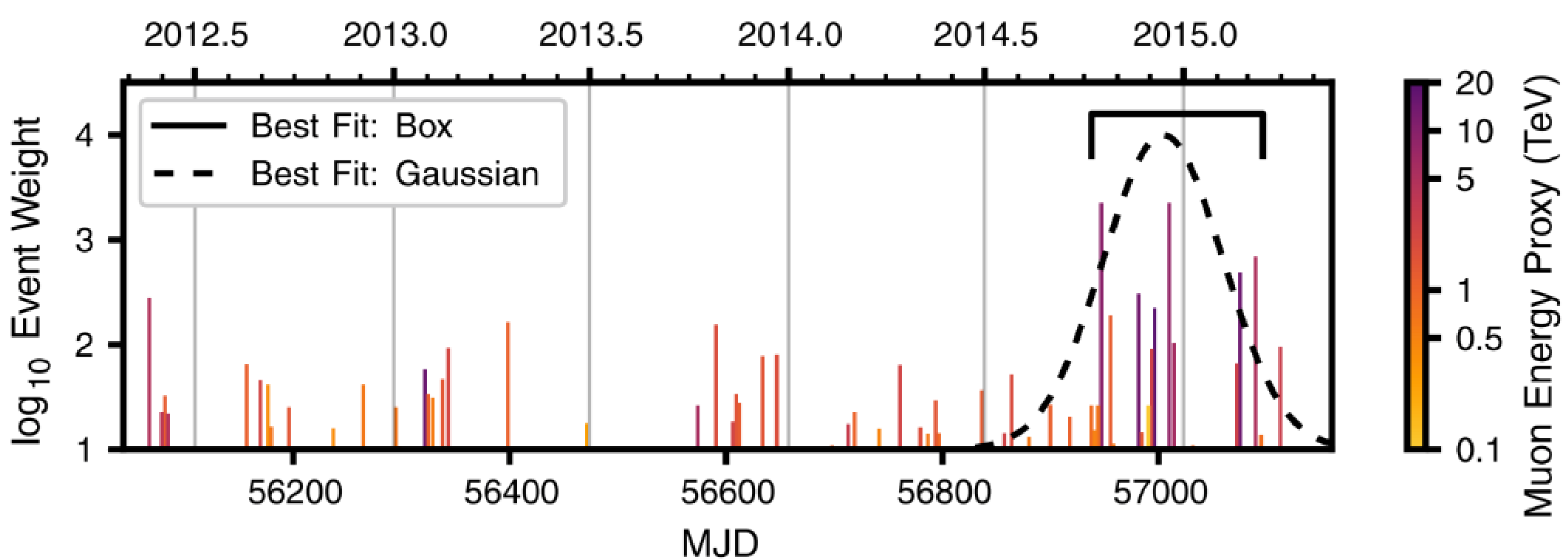
290 TeV likely energy

archival search in IceCube

- Found **13 ±5 neutrinos** consistent with TXS direction in a 110 day window (December 2014, archival data set)
- Rejection of background-only hypothesis at 3.5 σ significance
- Consistent with energetic neutrinos

Science 361 (2018)





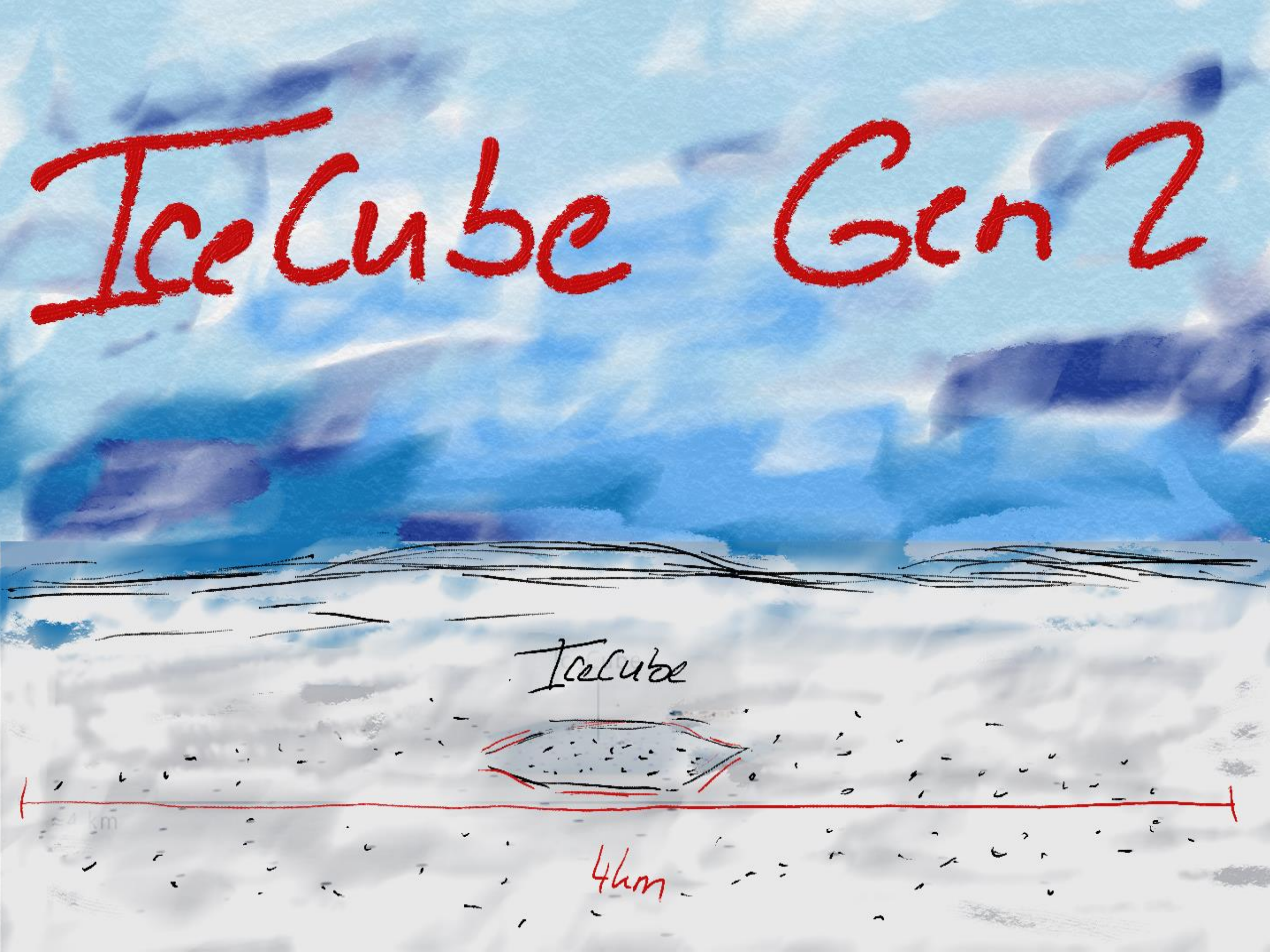
Summary so far

- **Only one identified source**; need at least 100 weak sources to explain diffuse flux
- **Stacking of sources show that there are many different kinds of sources**

Blazars	< 17% (preliminary)
Nearby Starburst Galaxy	< 8% (preliminary)
Young galactic supernova remnants	< 5% (preliminary)
Galactic Plane	< 14% (preliminary)

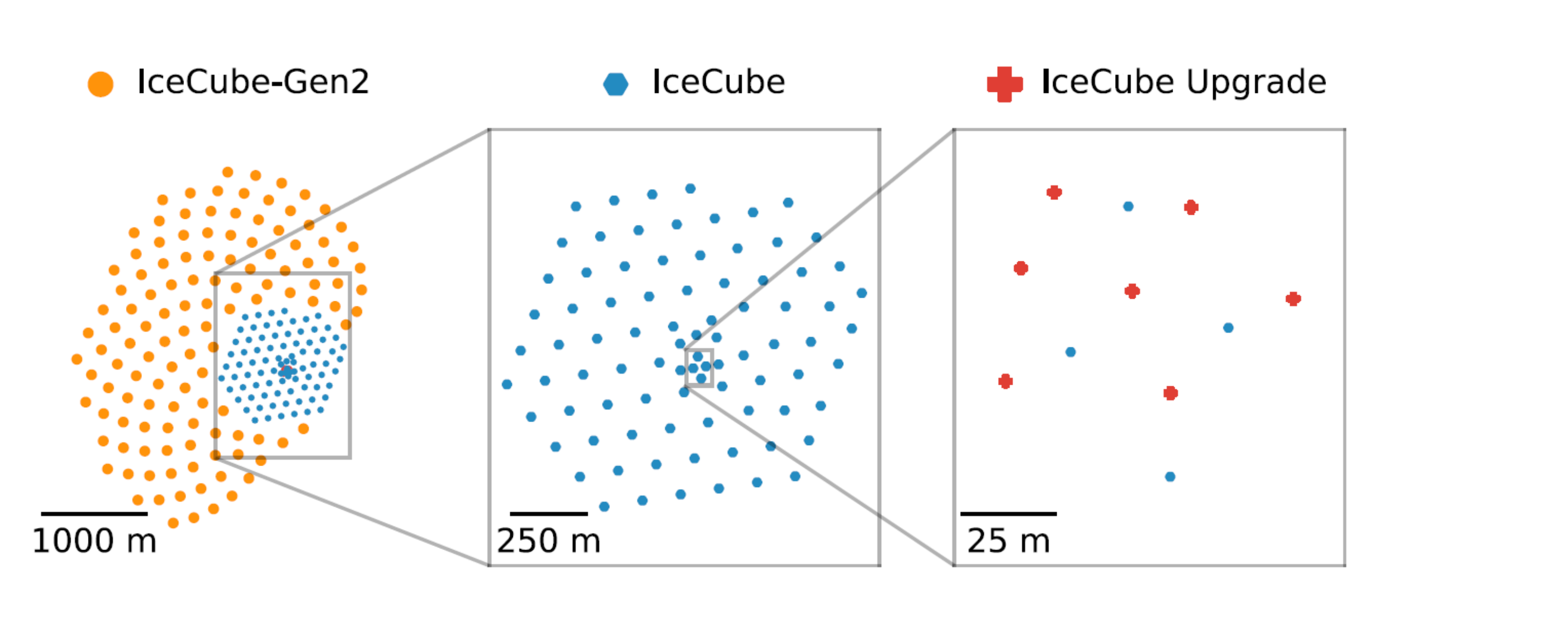
- **80% of sources with redshift > 0.5** (7 Billion light years) arXiv:1602.06625
- Discovery limit not yet $1/\sqrt{time}$ dependent, **chance to see galactic source**
- Probably identified υ_τ interactions
- **Indication of a complex spectrum**

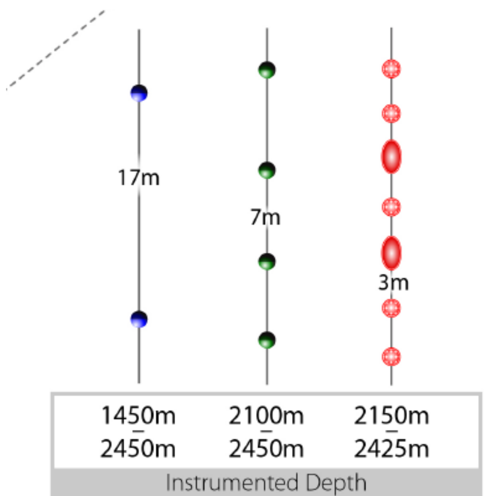
Need more data and a bigger detector !


IceCube Gen2
IceCube
4km

16.7.2019: IceCube upgrade official !!

2 Mton detector in 1-10 GeV range to be installed in 2022/23





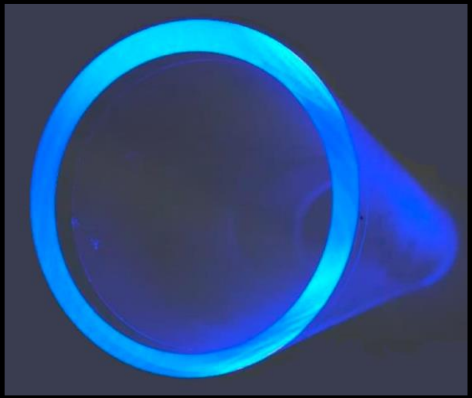
Goals (Upgrade):

- High precision ν_τ appearance
- ν mass ordering (with JUNO)
- Improved oscillation param.

- Test new detectors for Gen-2
- IceCube re-calibration

Upgrade detectors

New detector types deployed ... and tested



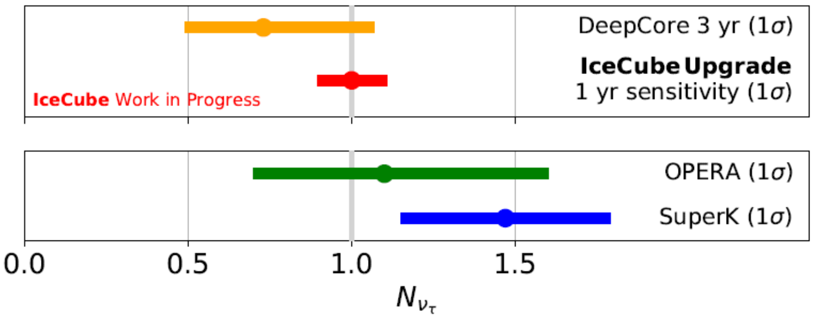
module mit 24 photomultipliers
(direction resolution, 2x sensitive)

module with two 8“ PMTs

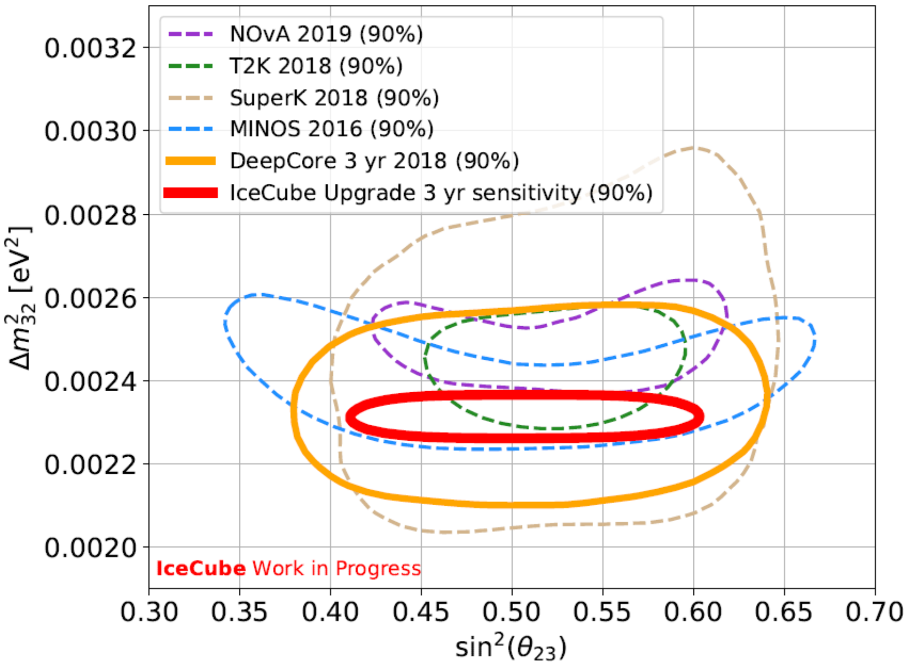
module with wavelength shifter
(narrow, long, higher efficiency)

Some expected upgrade results

Tau neutrino normalization:



Oscillation parameters:

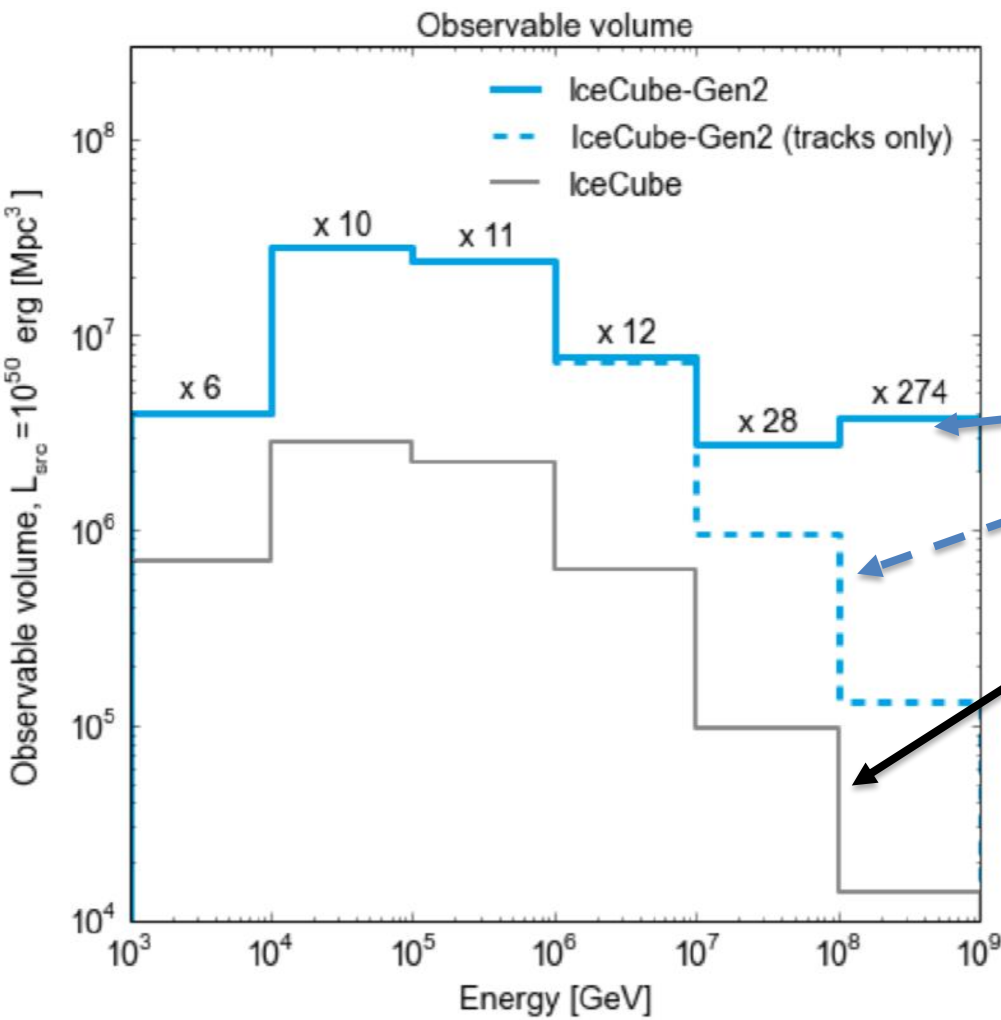


Mass hierarchy together with JUNO (and Orca)?

First step towards IceCube-Gen2

Gen2: Improved observable volume

For example: contained events:

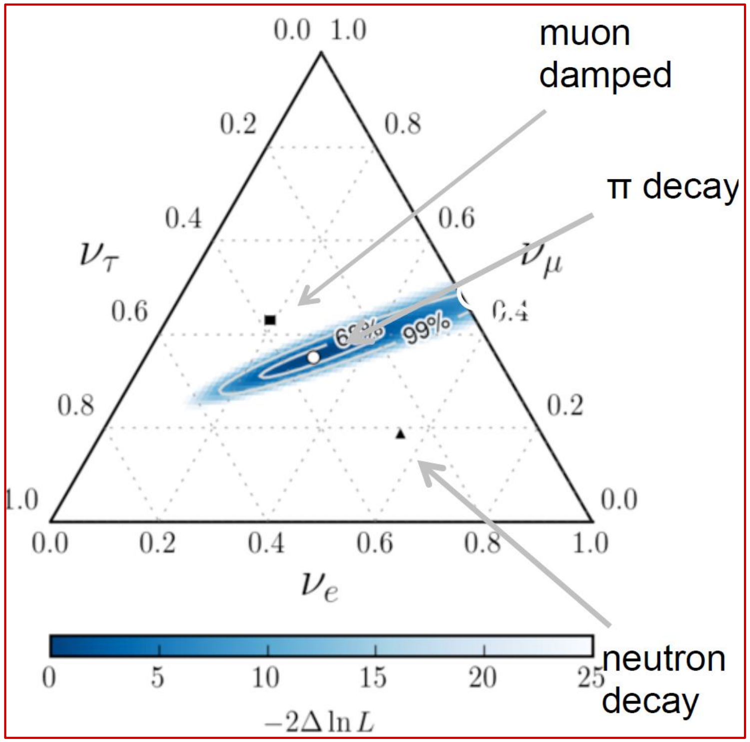


Gen2: optical + radio
Gen2: optical only

IceCube

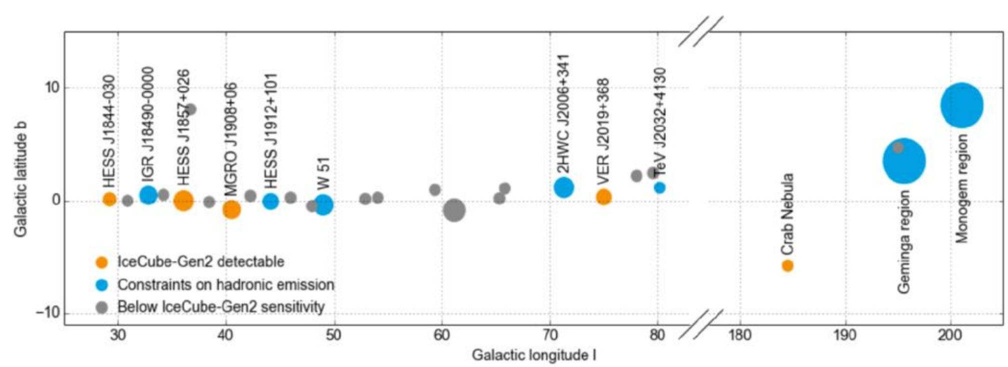
IceCube-Gen2 anticipation

Example Flavor-Triangle



- Understand astrophysical ν flux and composition
- Galactic sources
- Mass ordering/Θ_{23}
- + surprises ….

Detectability of sources if gamma ray emission is produced by pion decays



- Uses measured HAWC spectrum between 2 TeV - 40 TeV
- Neutrino flux between 1 TeV - 20 TeV

Summary and outlook

- **Full IceCube data taking from May 2011 (~ 99.8% of the time available)**
- **IceCube rather „multi-purpose“ for an astroparticle experiment …**
  - largest detector for atmospheric and astrophysical neutrinos
  - excellent cosmic ray detector
  - highest statistics supernova detector
  - best sensitivities for spin-dependent WIMP cross sections, monopoles and other exotics
  - competitive for determining θ_{23} and Δm^2_{23}
- **IceCube has sensitivity of astrophysical importance**
  - evidence for astrophysical neutrinos, óne identified source, probably detected ν_τ
- **Future**
  - Km3Net (ORCA/ARCA) in Mediterranean, GVD (Baikal)
  - IceCube Upgrade (funded) $\rightarrow$ **IceCube-Gen2**

The End