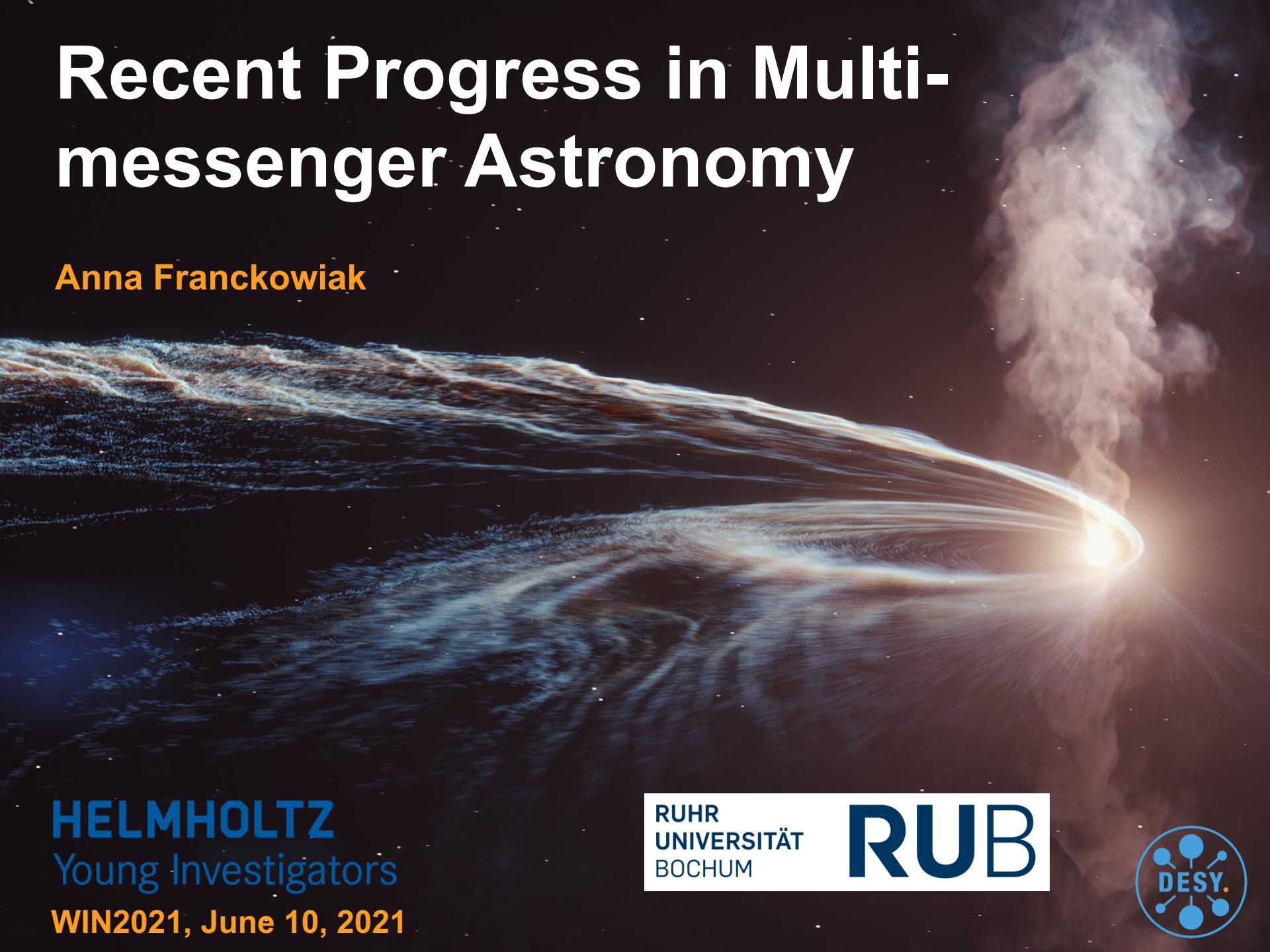


Recent Progress in Multi-messenger Astronomy

Anna Franckowiak



HELMHOLTZ
Young Investigators
WIN2021, June 10, 2021

RUHR
UNIVERSITÄT
BOCHUM

RUB



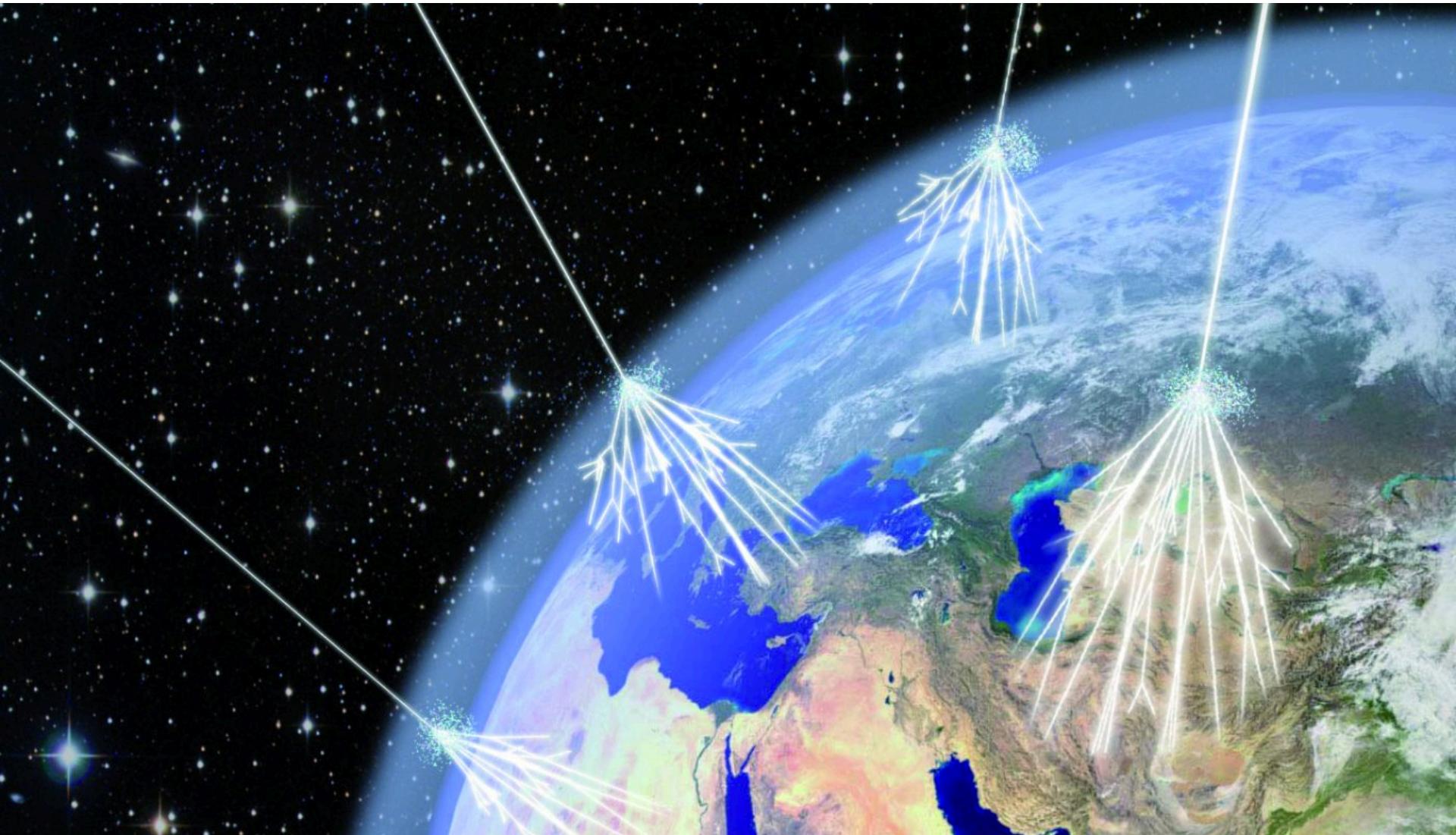
The Multi-Messenger Picture



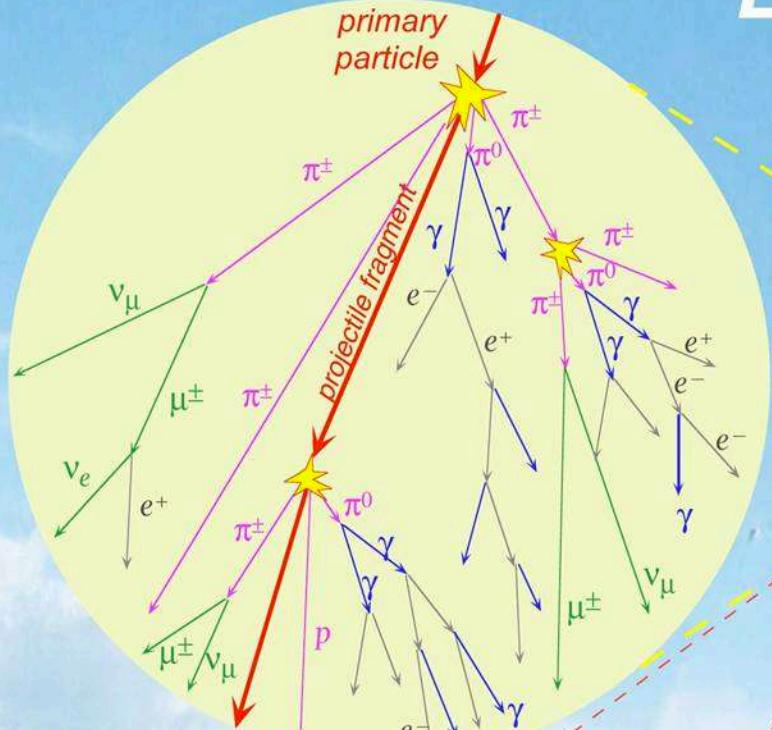
New Windows to the Universe



Cosmic rays



Extended Air Showers



primary
particle

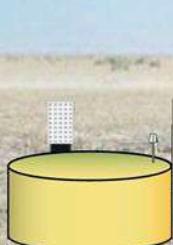
Pierre Auger Observatory:
 10^{19} eV < E < 10^{21++} eV

Fluorescence light - isotropic
Cherenkov light

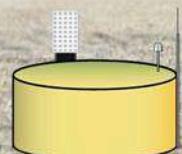
Electronic
Schmidt telescope

1 m thickness

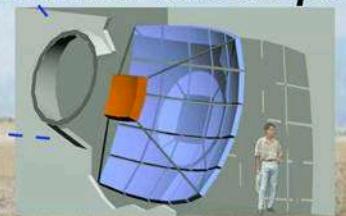
1,5 km



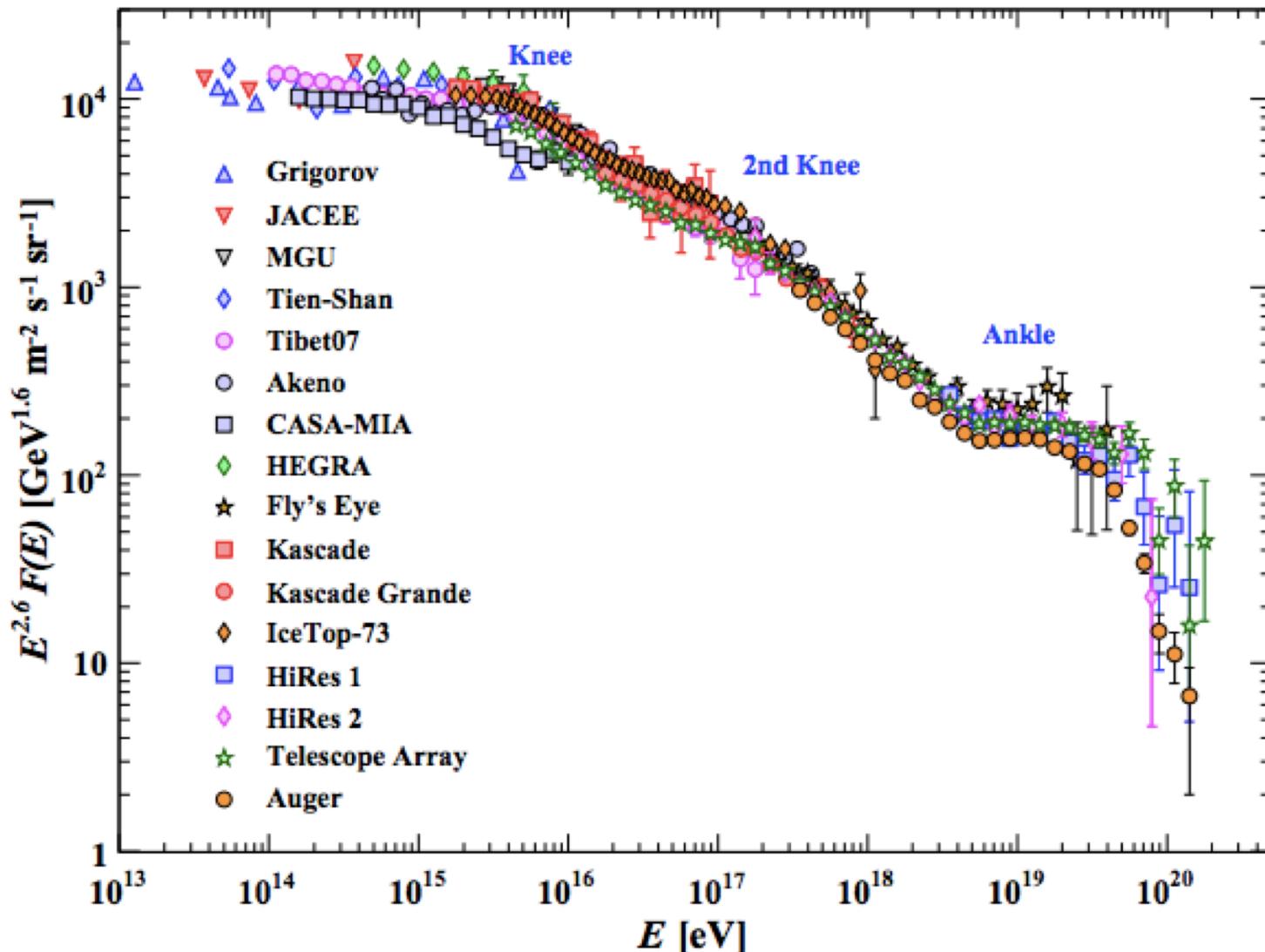
Water-
Cherenkov detectors

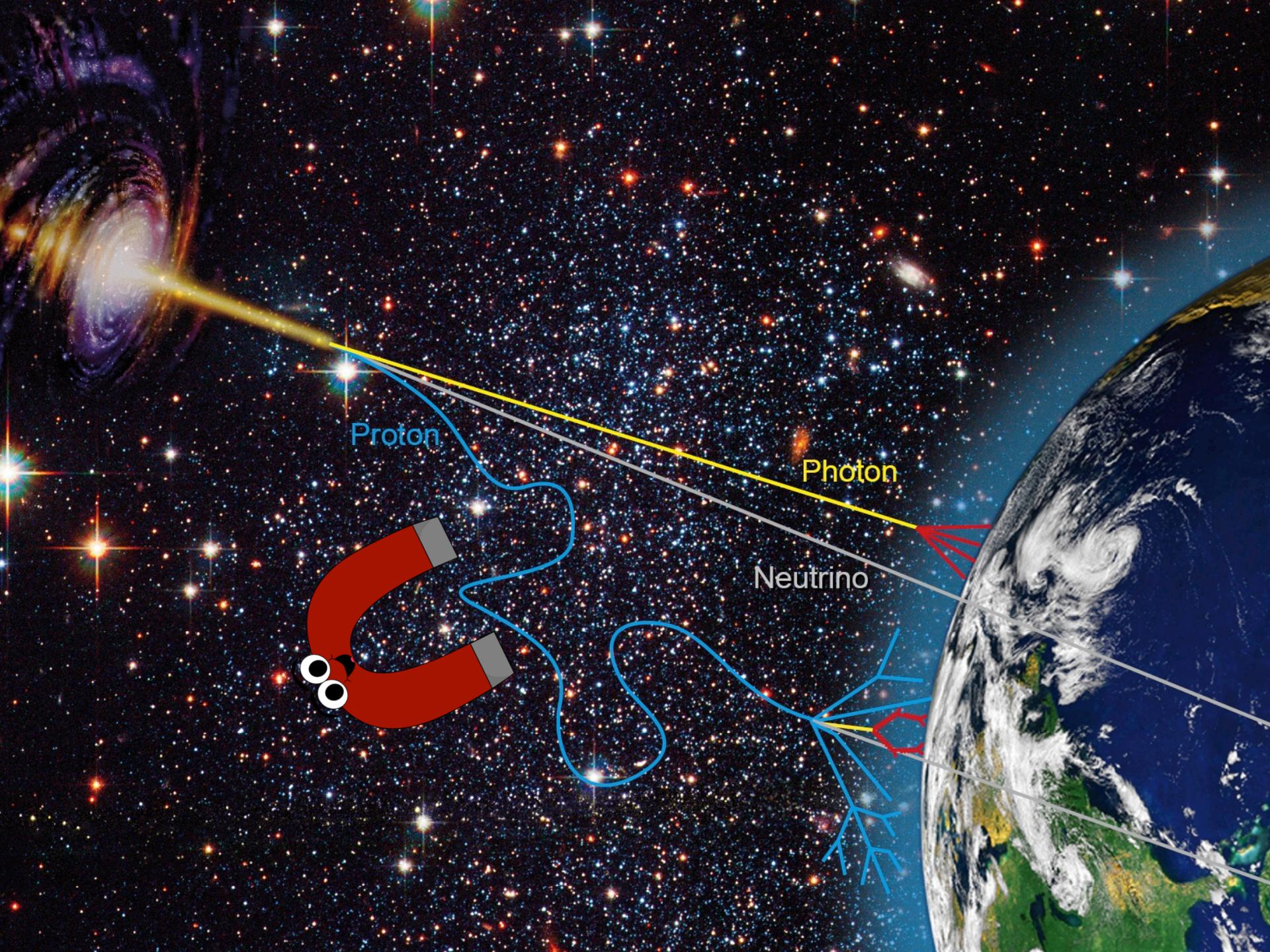


1,5 km

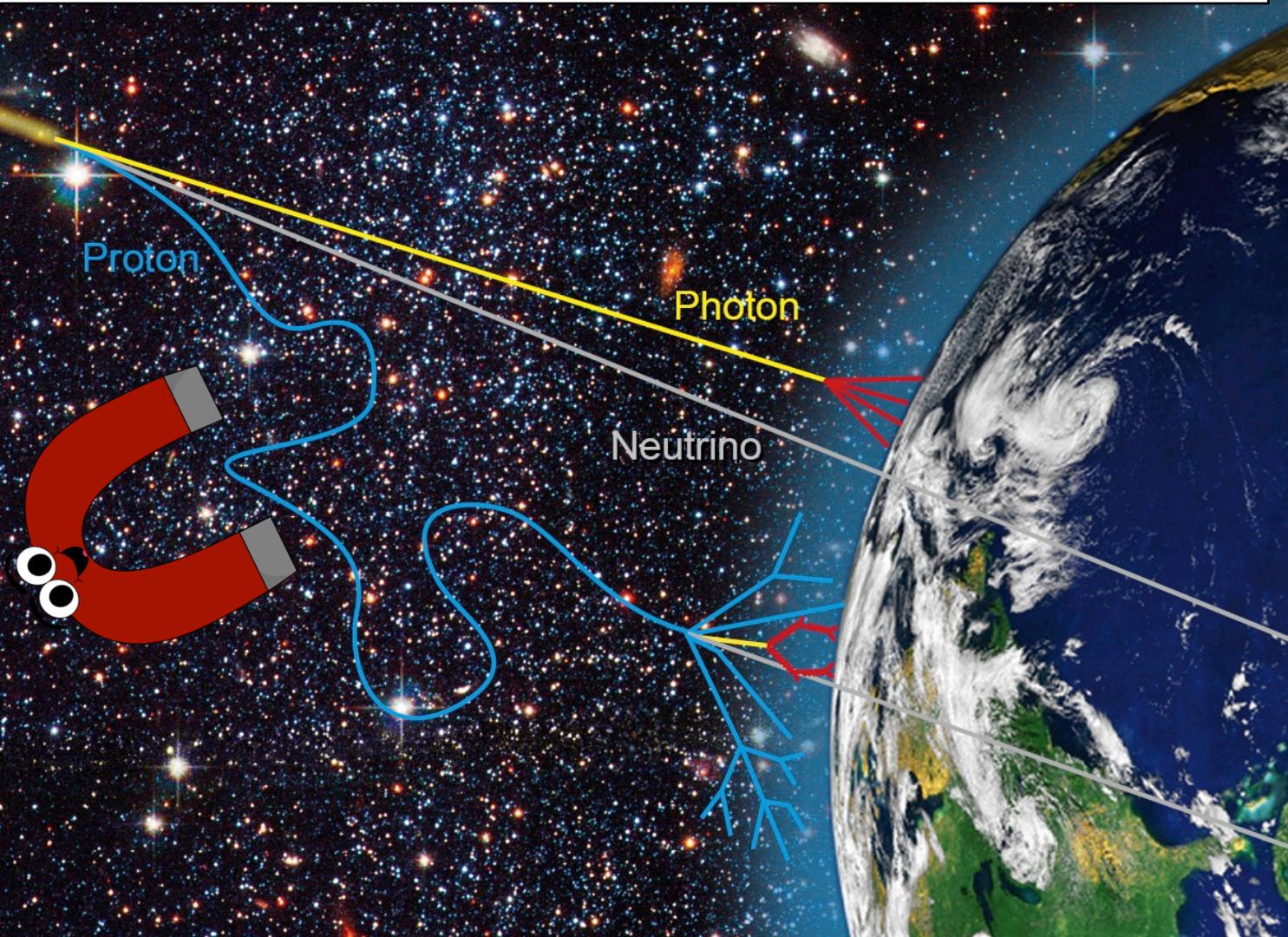


Cosmic rays reach $>10^{20}$ eV



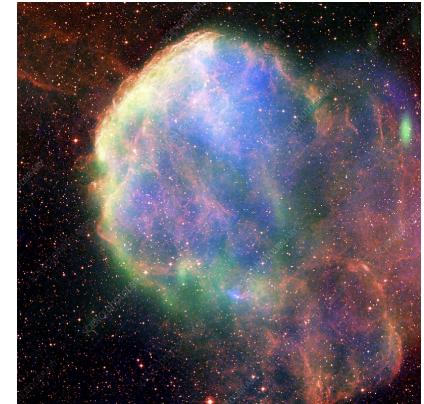
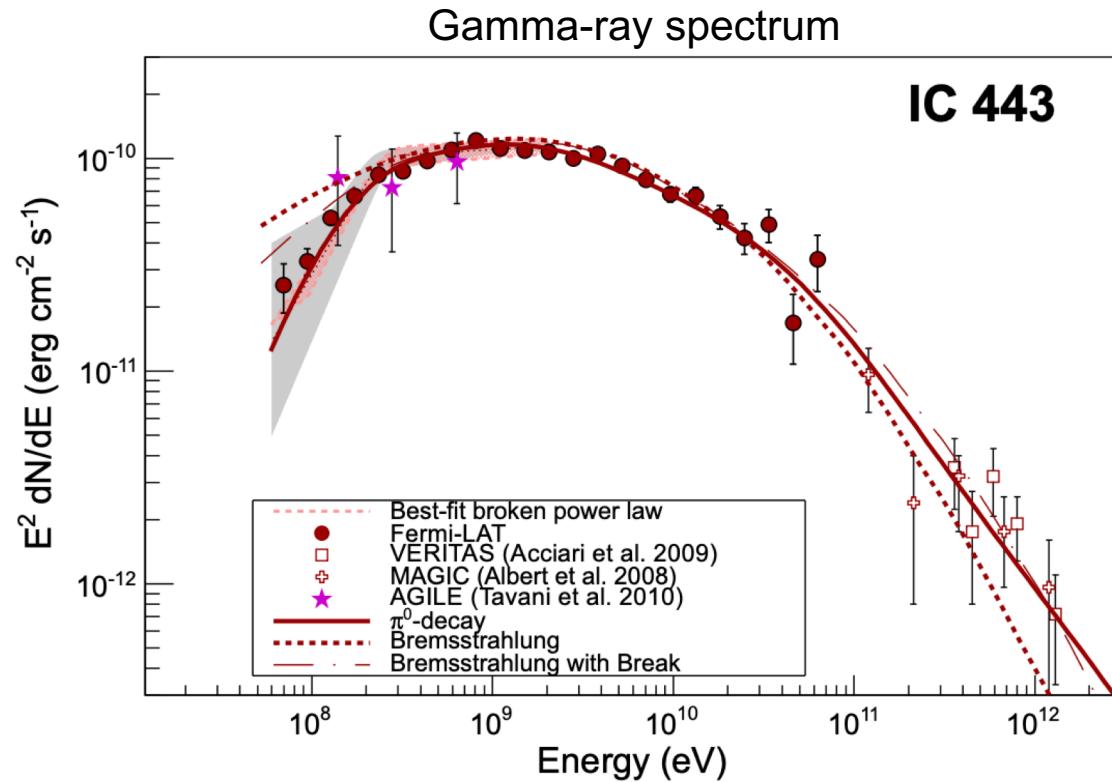


$$pp / p\gamma \rightarrow \dots \left\{ \begin{array}{l} X + \pi^0 \rightarrow \gamma \gamma \\ X + \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \\ X + \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu \end{array} \right.$$



Where do galactic cosmic rays come from?

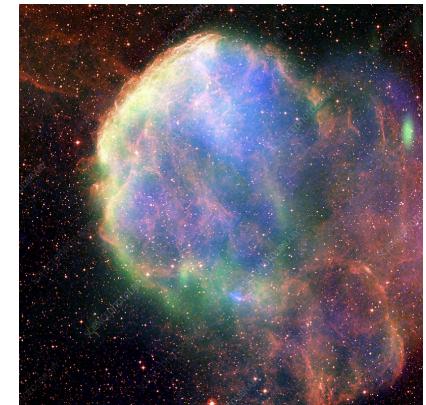
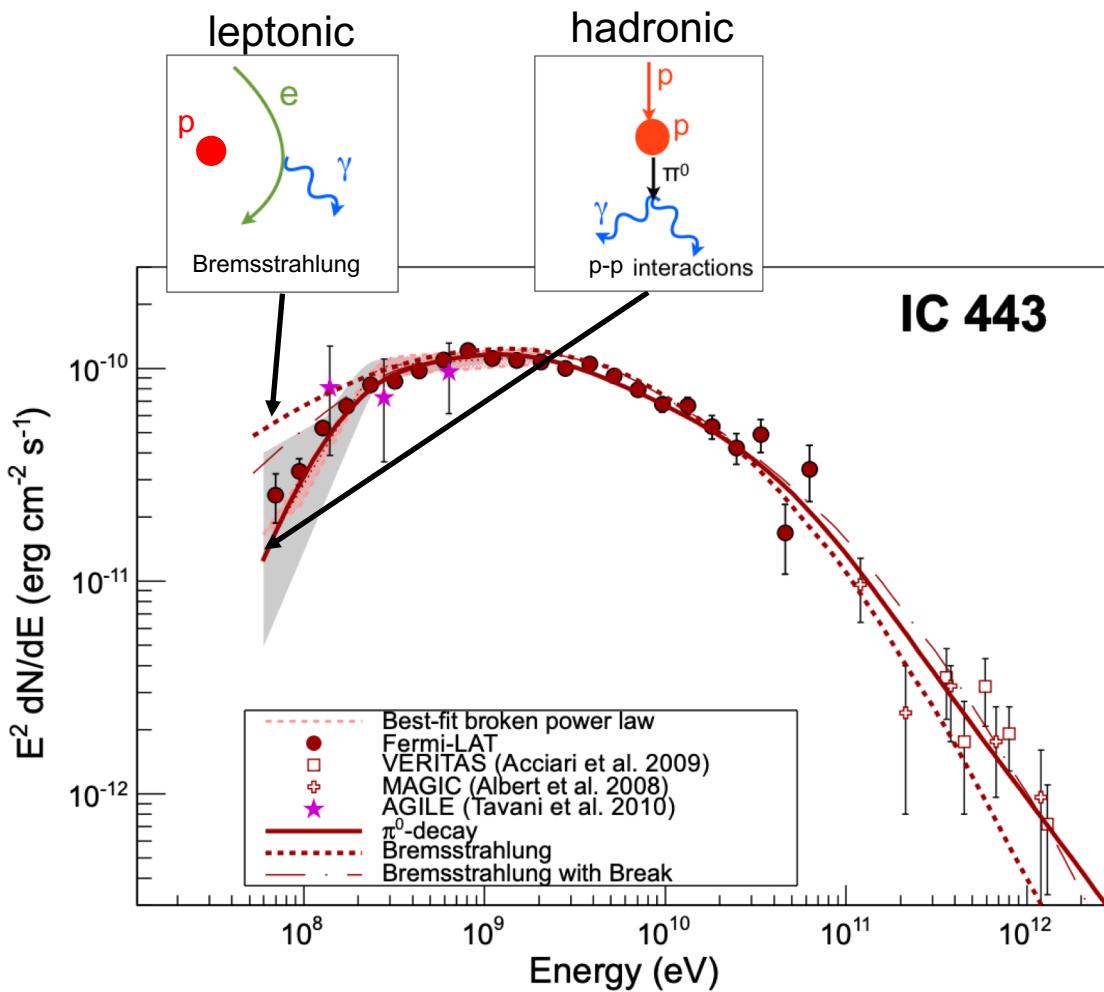
Direct evidence that cosmic-ray protons are accelerated in Supernova Remnants



“Pion bump”
signature

Where do galactic cosmic rays come from?

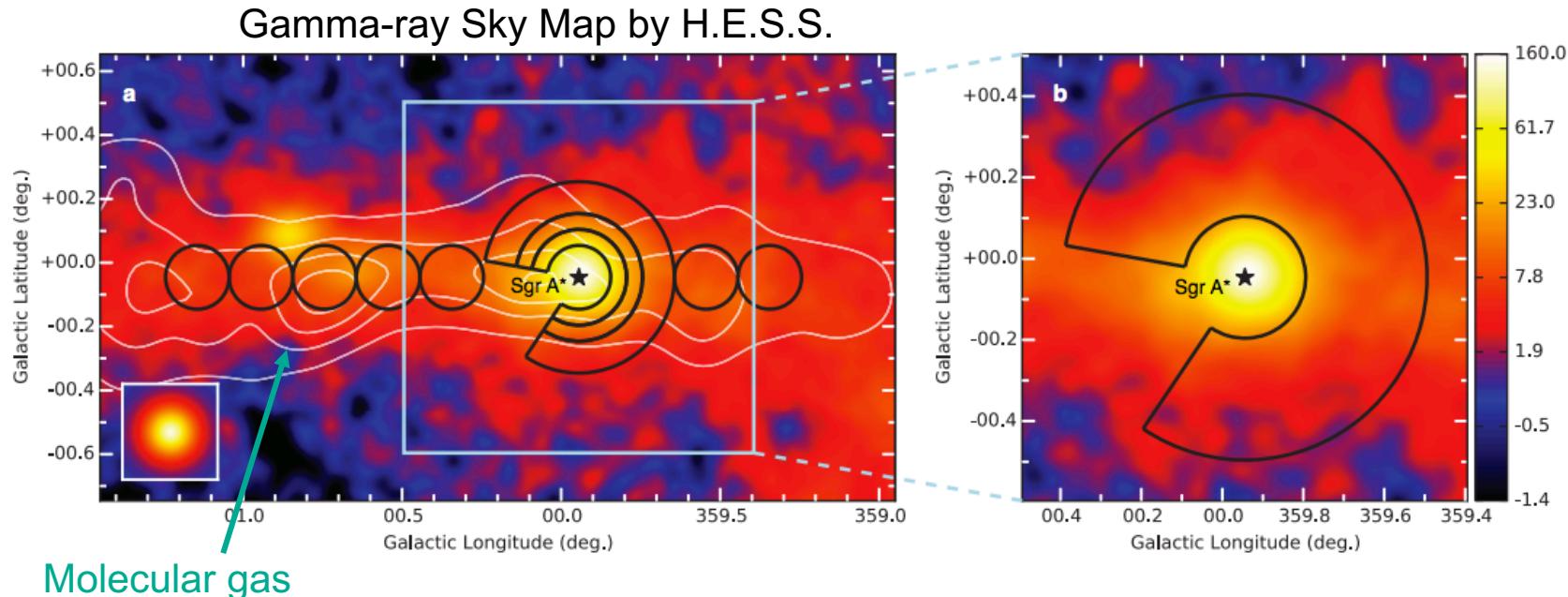
Direct evidence that cosmic-ray protons are accelerated in Supernova Remnants



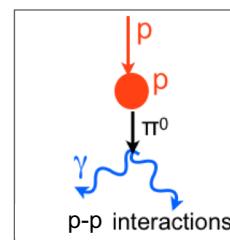
“Pion bump”
signature

Where do galactic cosmic rays come from?

Indication for ``PeVatron'' at Galactic Center

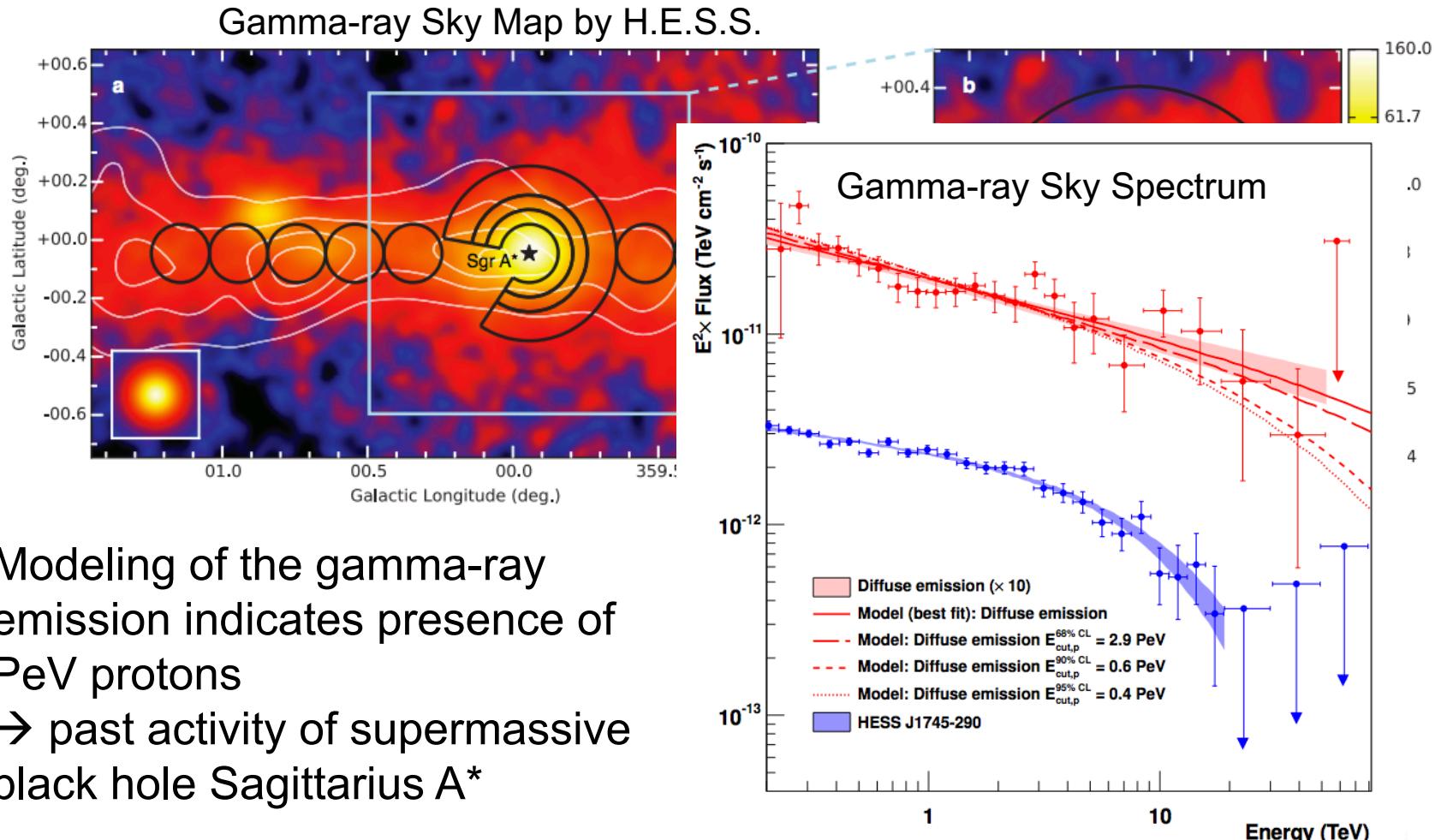


Correlation of gamma rays with
molecular gas → pion decay origin



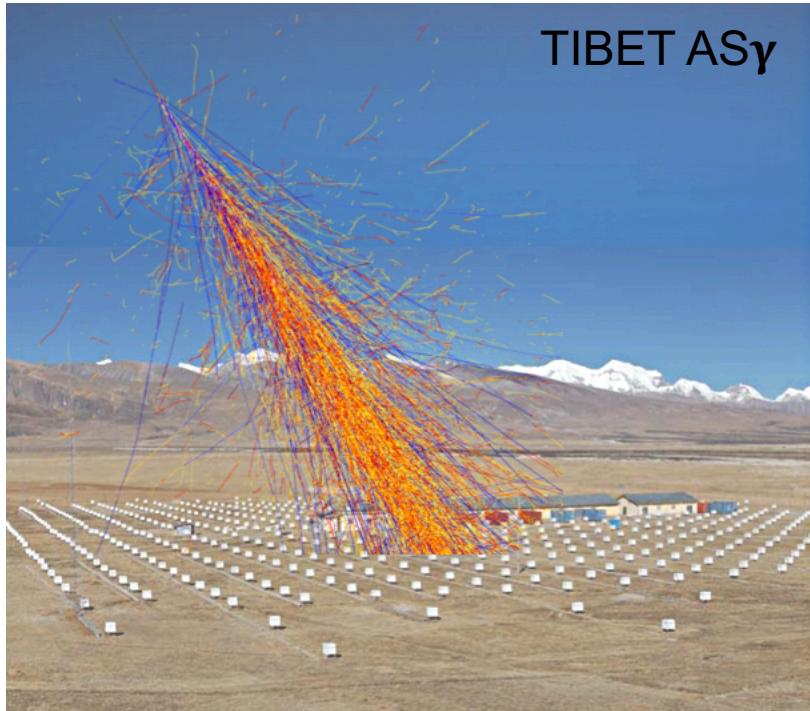
Where do galactic cosmic rays come from?

Indication for ``PeVatron'' at Galactic Center

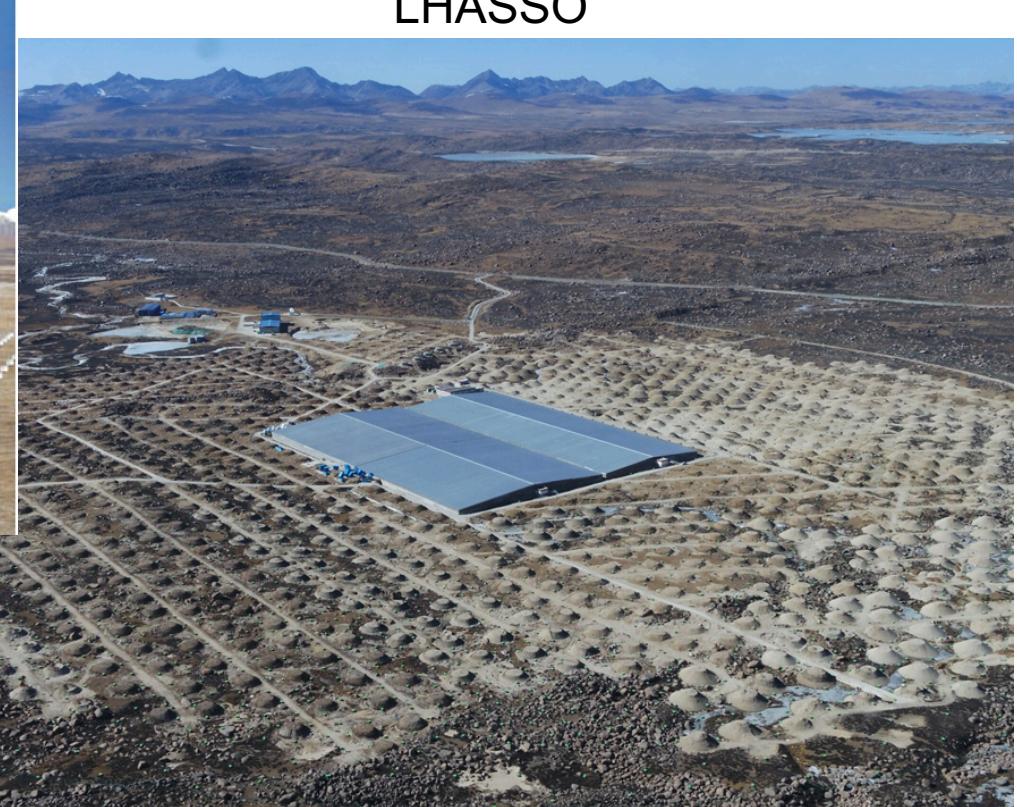


Where do galactic cosmic rays come from?

Two new detectors sensitive to air showers from $>100\text{TeV}$ gamma rays

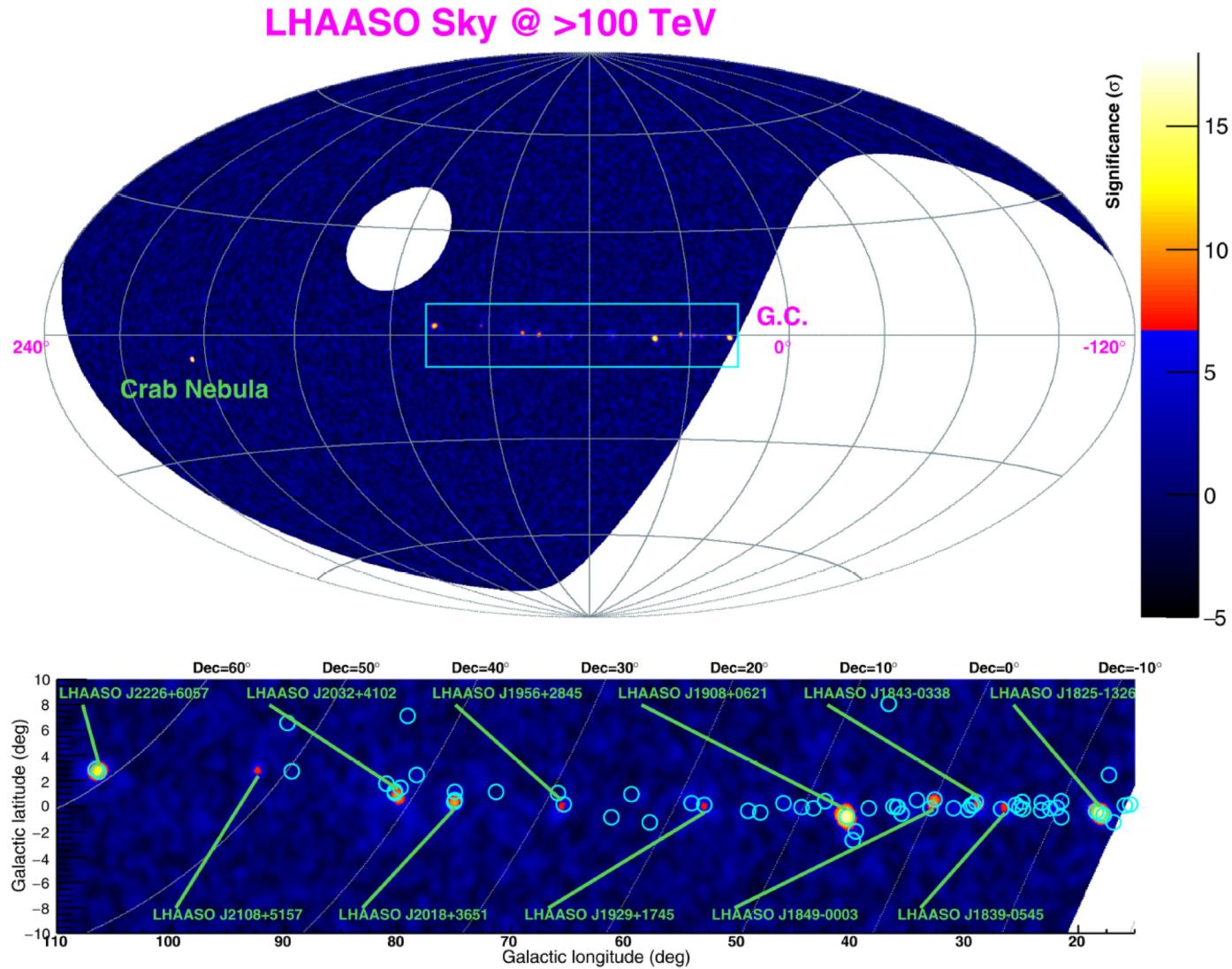


TIBET AS γ



LHASSO

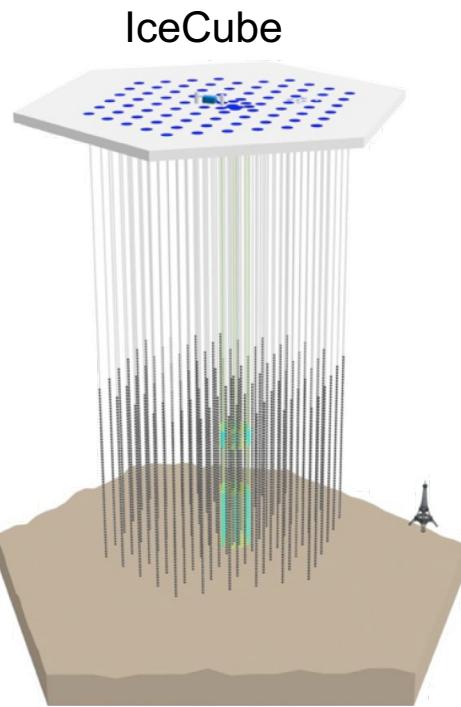
Where do galactic cosmic rays come from?



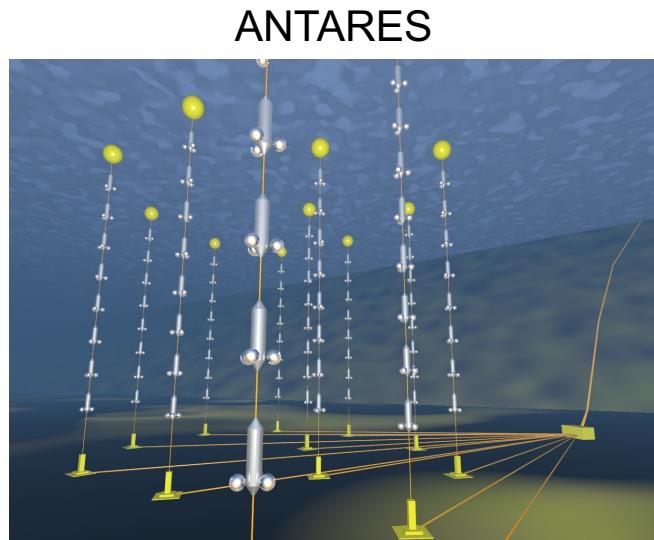
Existence of PeVatrons confirmed. Leptonic or hadronic origin?

Cao, Aharonian et al. Nature 594, 2021

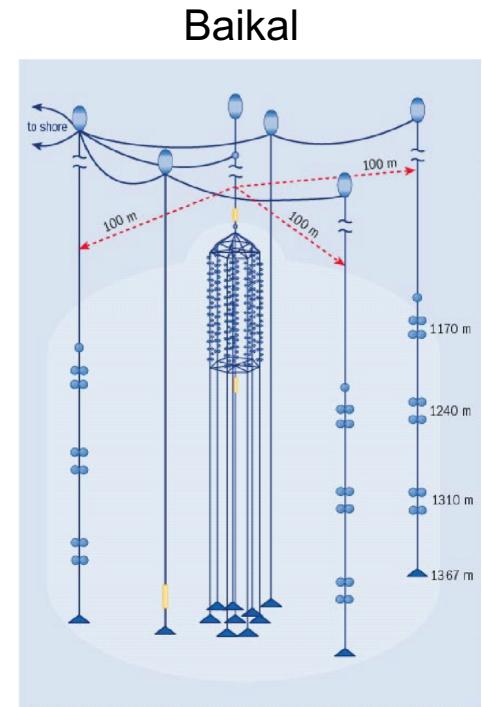
What about Neutrinos?



IceCube



ANTARES



Baikal

Volume: 1 Gton
Energy threshold: 100 GeV

IceCube-Gen2 planned

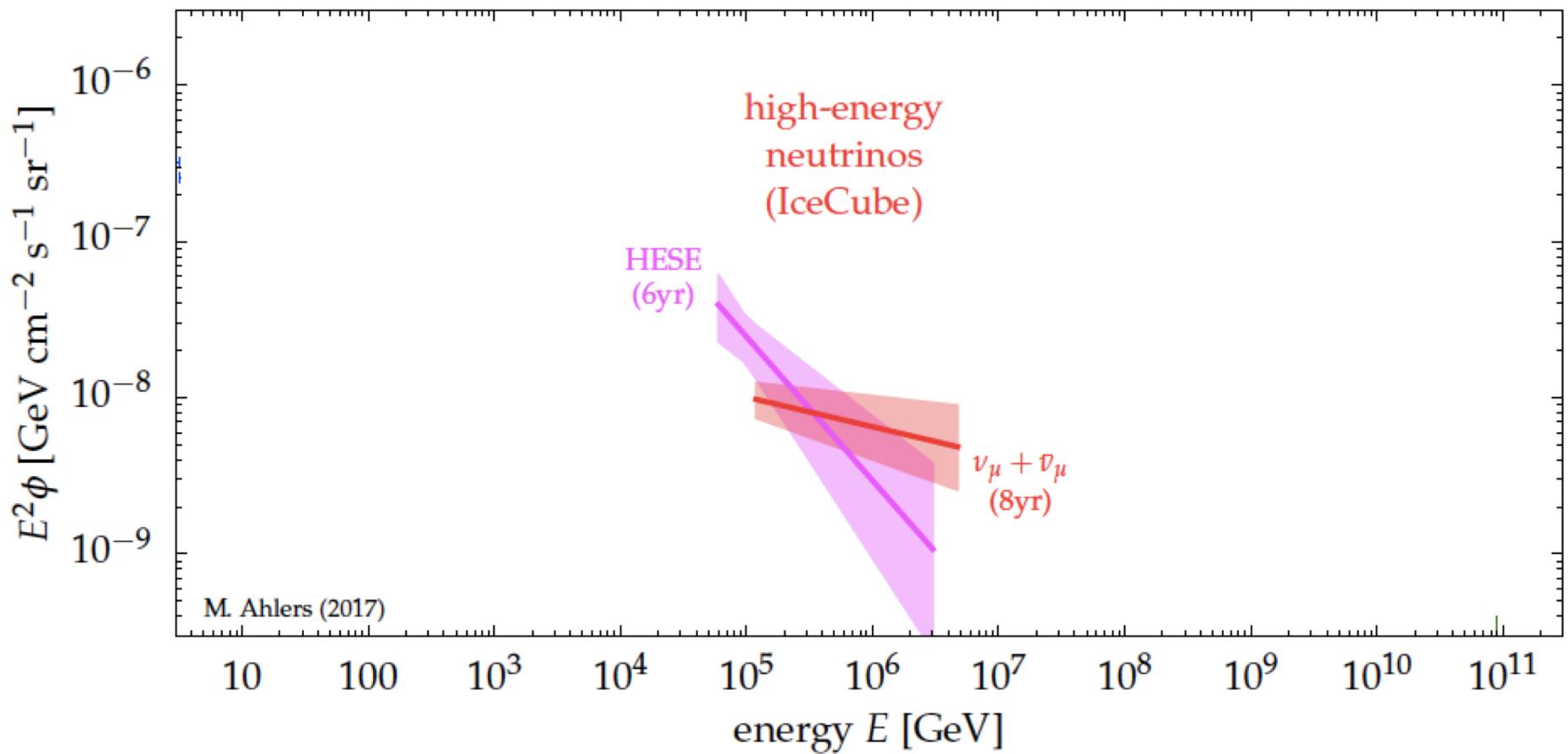
Volume: 10 Mtons
Energy threshold: 10 GeV

Km3NET under construction

Volume: 100 ktons
Energy threshold: 10 GeV

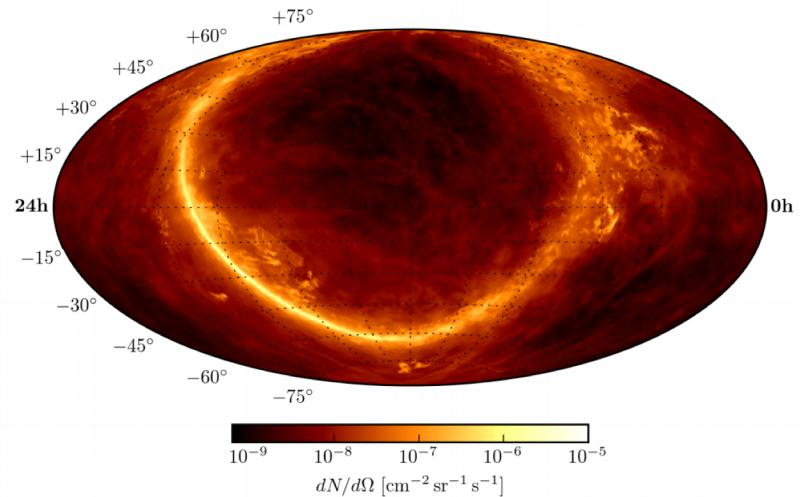
GVD under construction

Diffuse Neutrino Flux



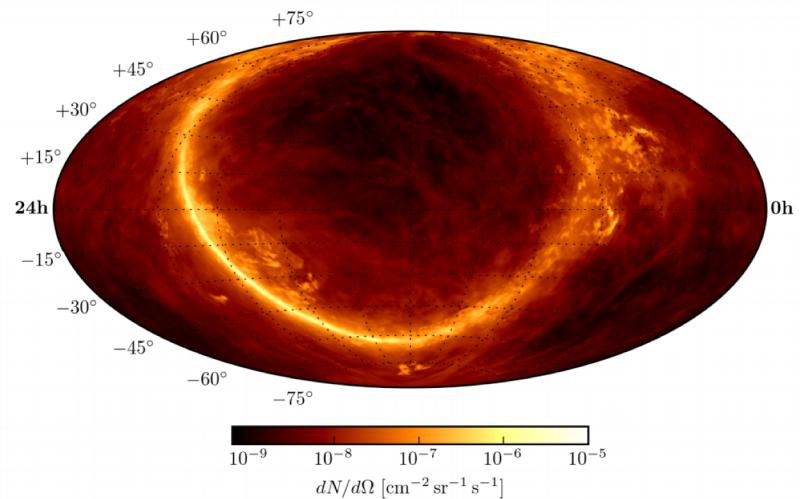
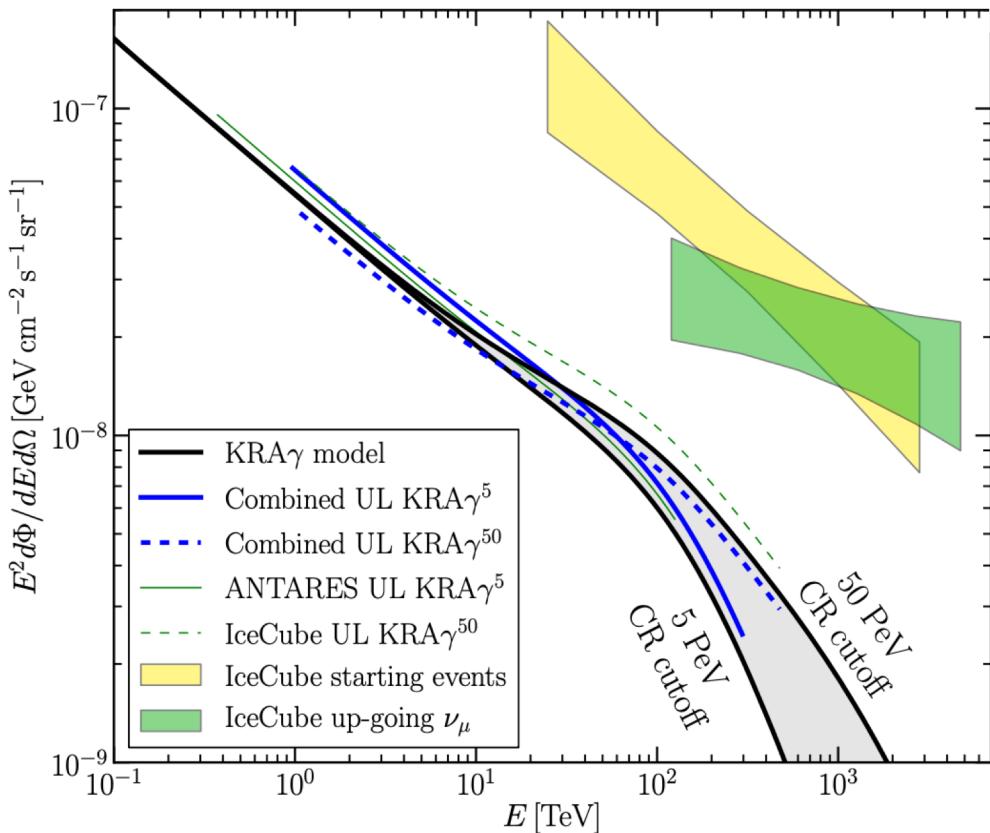
Galactic Neutrinos?

Neutrino flux modeled by Galactic propagation code constraint by gamma-ray and cosmic-ray measurements



Galactic Neutrinos?

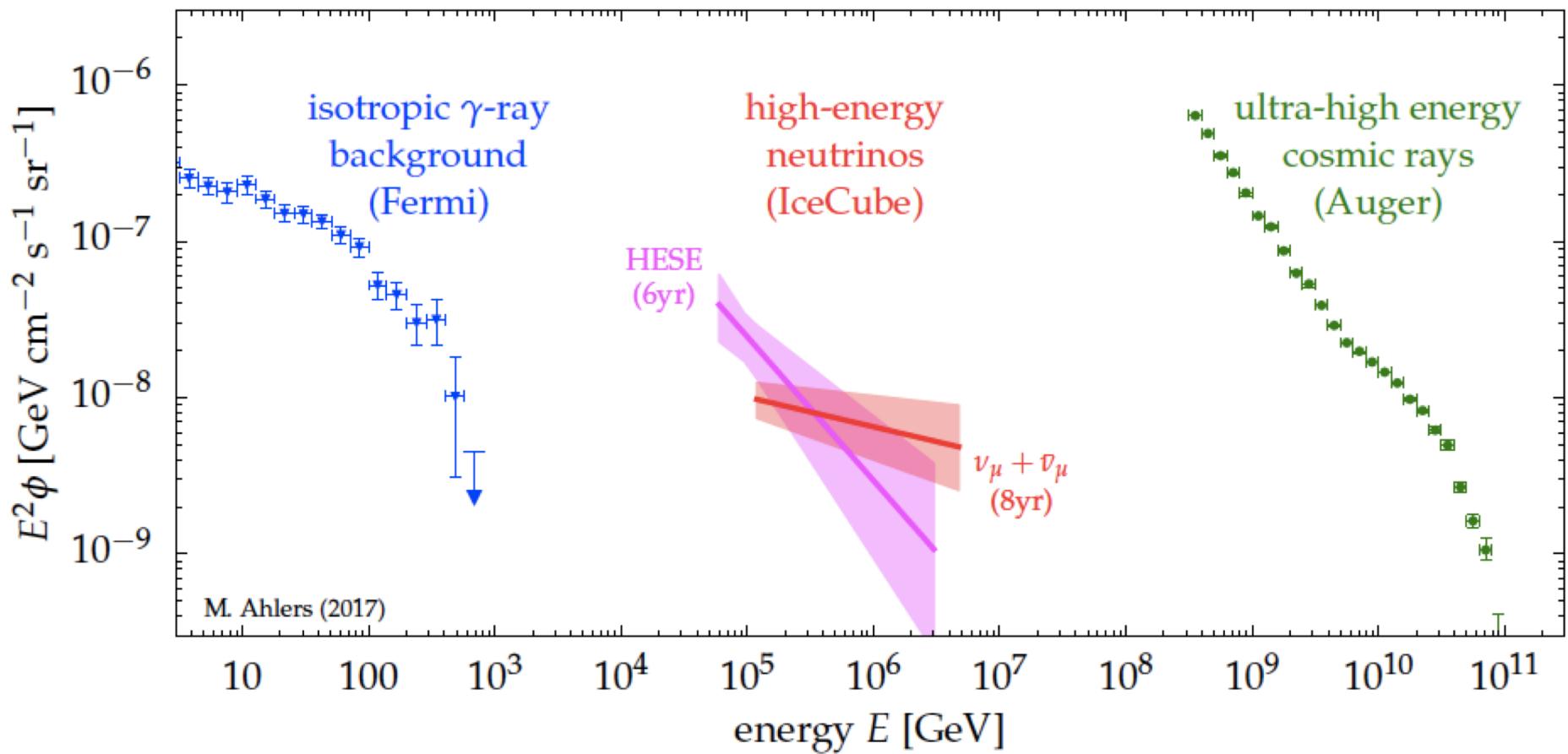
Neutrino flux modeled by Galactic propagation code constraint by gamma-ray and cosmic-ray measurements



No significant neutrino excess found from Galactic plane yet

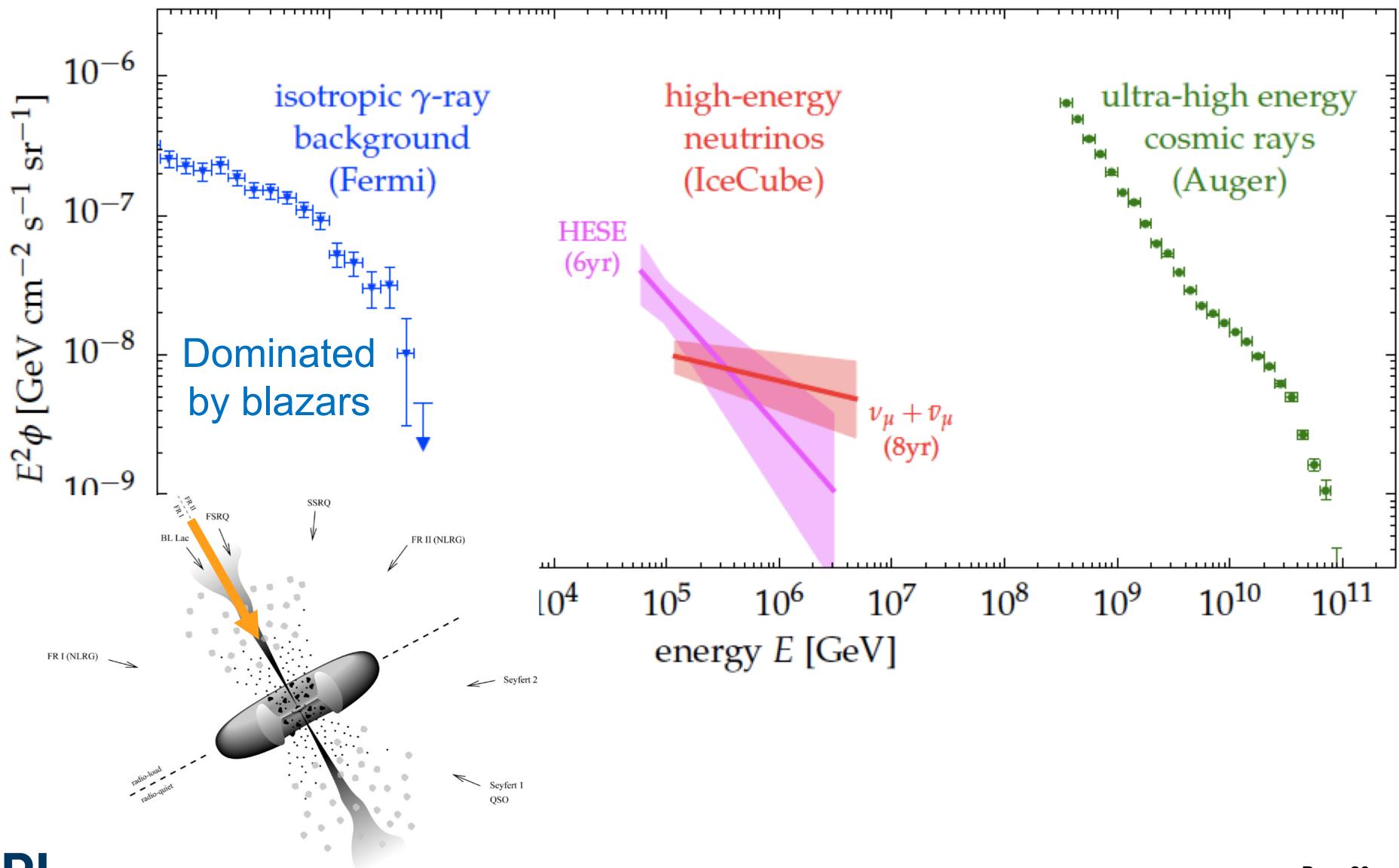
Contribution to diffuse flux <8.5%

Diffuse Neutrino Flux



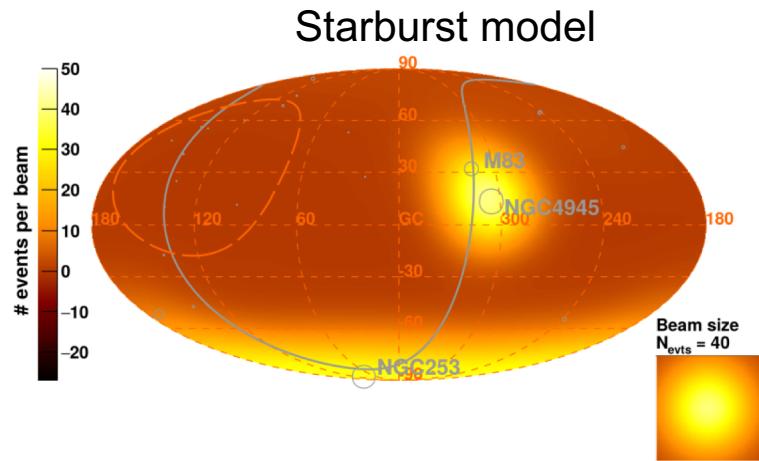
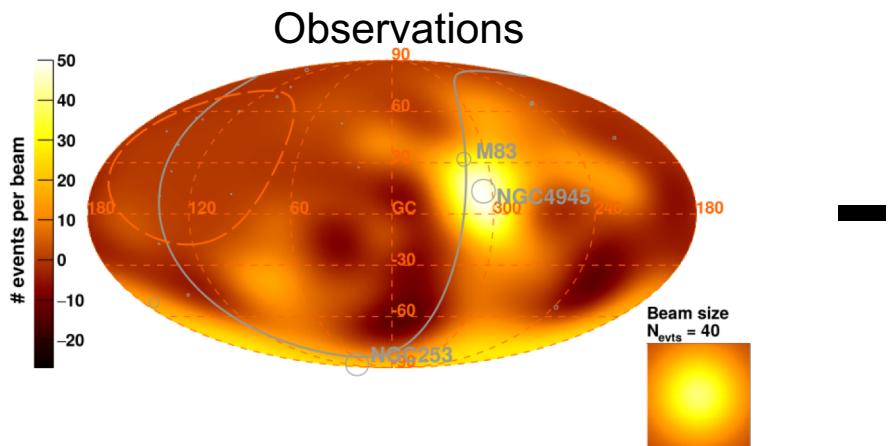
Similar energies in gamma rays,
neutrinos & cosmic rays injected into
our Universe!

Diffuse Neutrino Flux

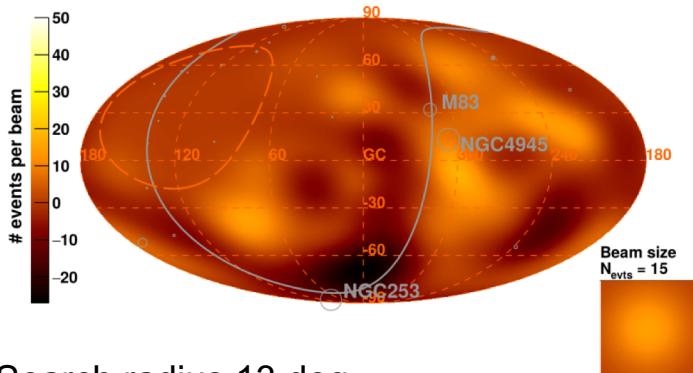


Where do extragalactic cosmic rays come from?

Anisotropy found at energies $E > 39$ EeV



Residuals



starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4.0σ ,

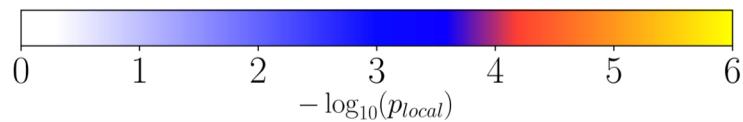
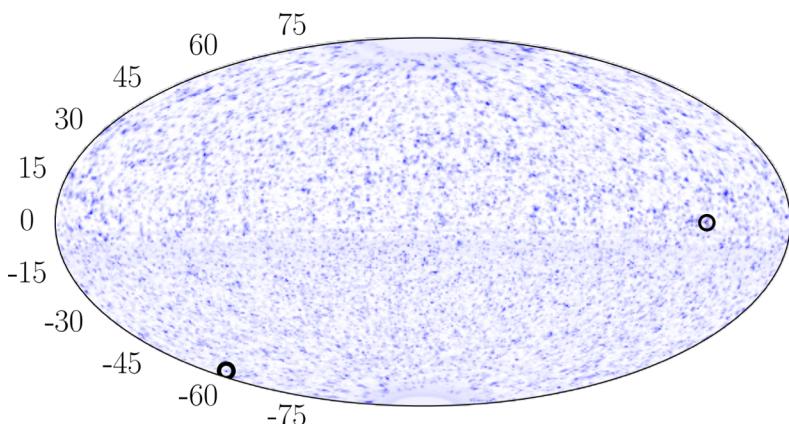
Gamma-ray AGN reach 2.7σ

Fit parameters: Search radius 13 deg,
fraction of events due to sources: 0.1

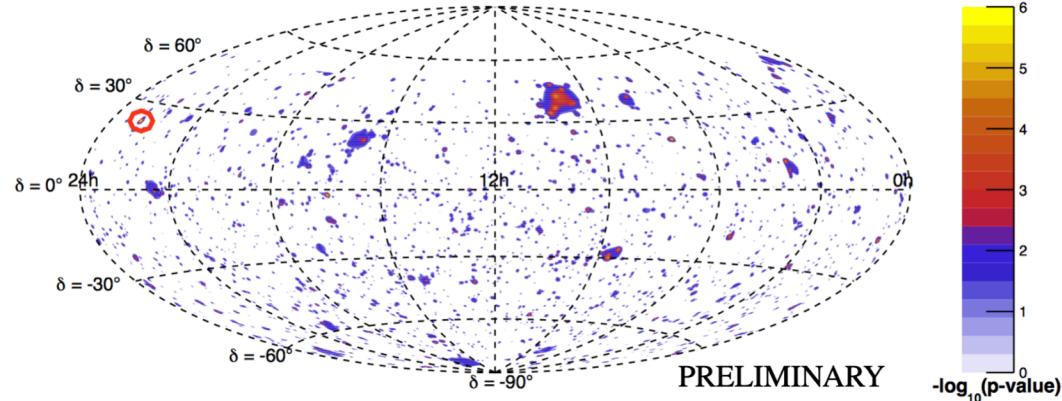
Where do the Neutrinos come from?

All sky analysis

10 years of
IceCube data



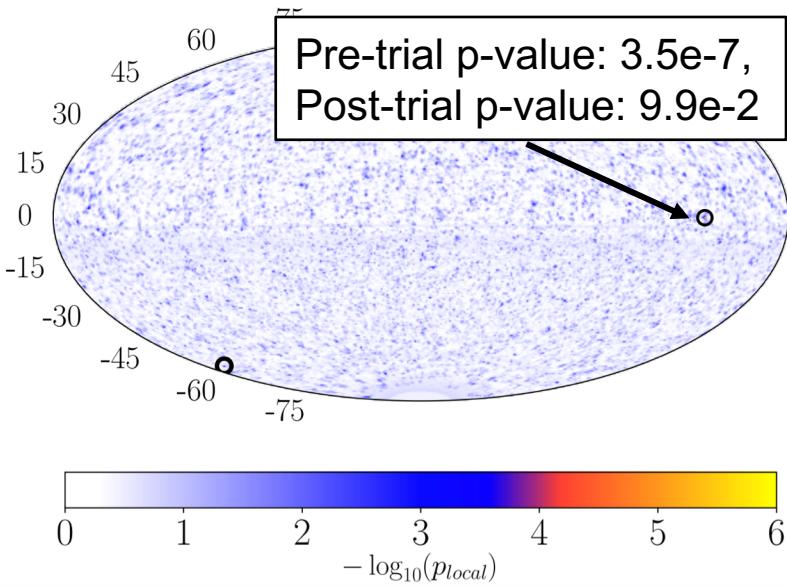
11 years of
ANTARES data



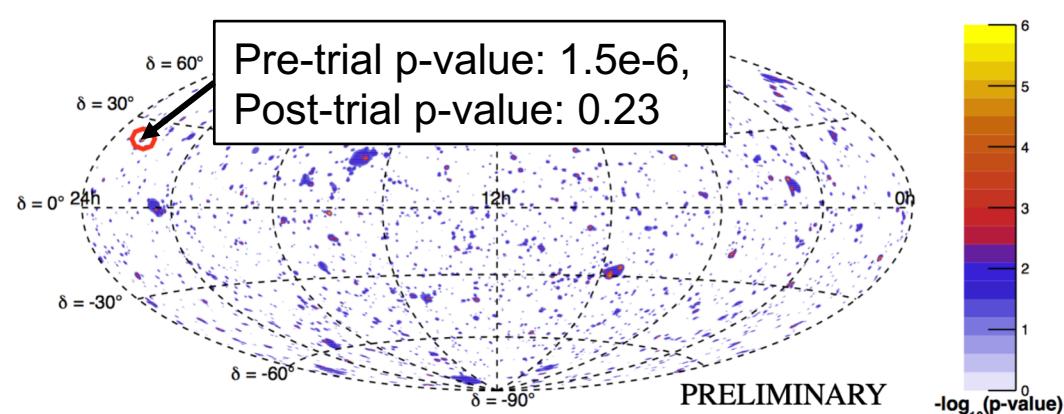
Where do the Neutrinos come from?

All sky analysis

10 years of
IceCube data



11 years of
ANTARES data



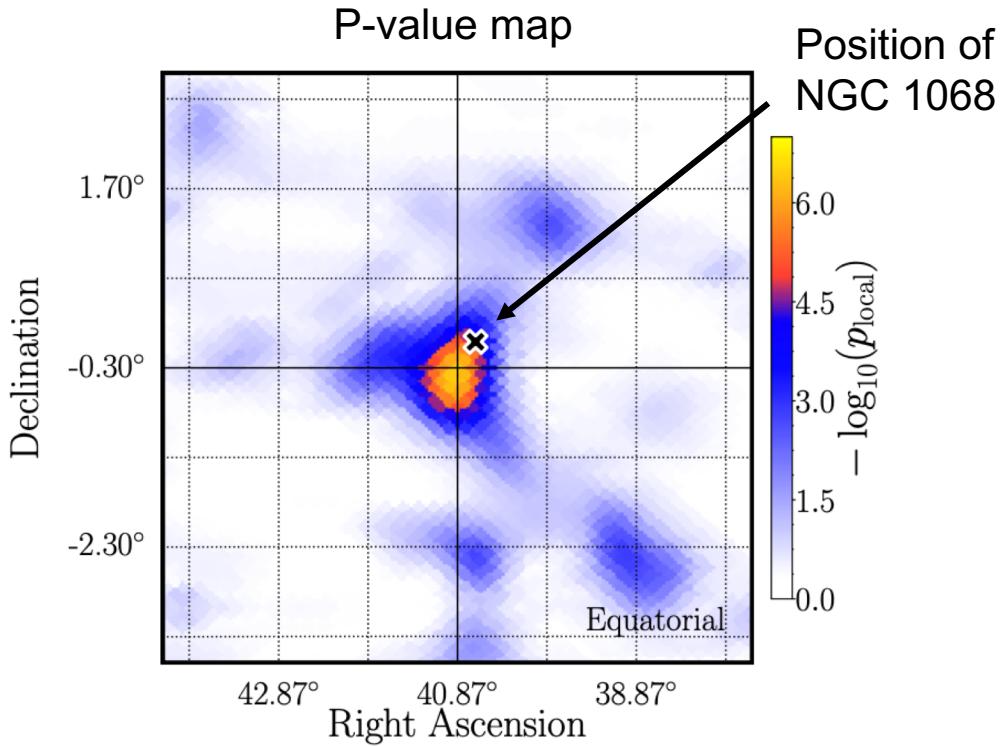
**Knowing where to look significantly
reduces the number of trials**

Neutrinos from 110 predefined sources

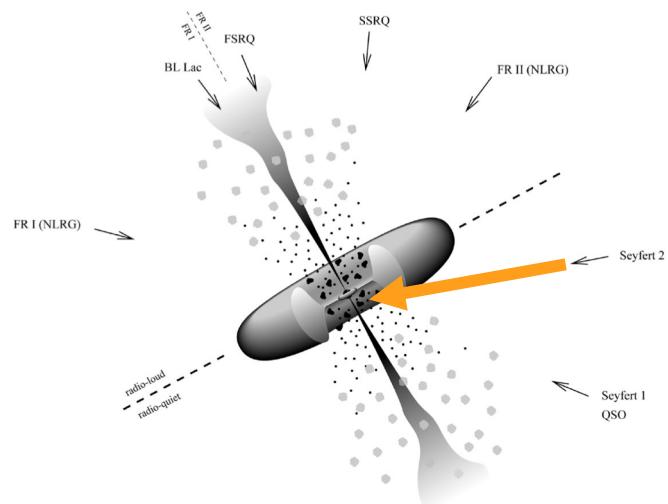
Source List Results							
Name	Class	α [deg]	δ [deg]	\hat{n}_s	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	2.8
...							
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5
NGC 1068	SBG	40.67	-0.01	50.4	3.2	4.74	10.5
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1
...							
4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4
M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6
PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4

Hottest spot in Northern sky close to **NGC 1068**, most significant source in predefined list: Post-trial: 2e-3 (**2.9 sigma**)

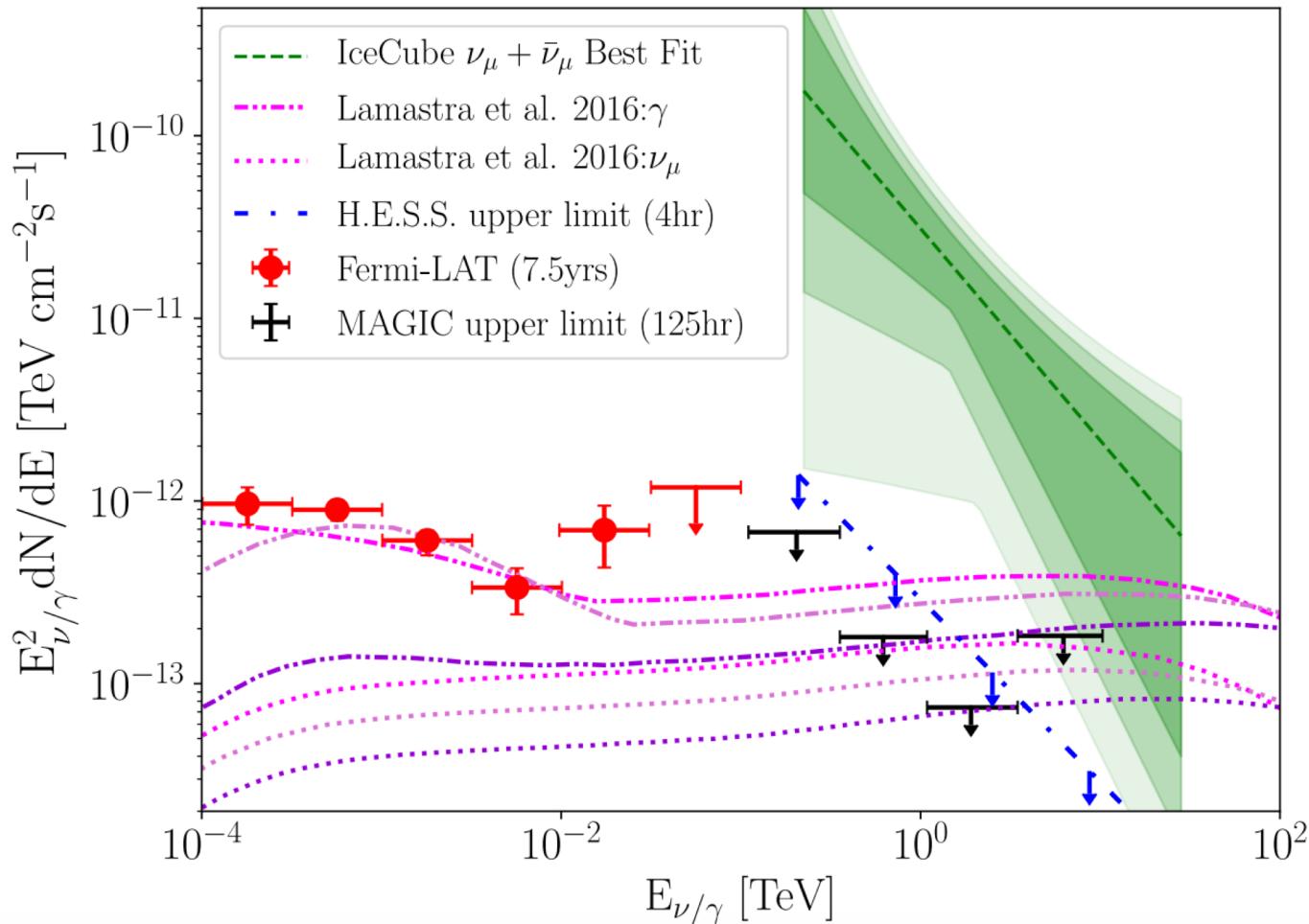
Neutrino Excess from NGC 1068 (M77)



- Nearby ($M=14\text{Mpc}$) Seyfert 2 galaxy
- AGN and starforming activity
- Soft neutrino spectrum



Spectrum of NGC 1068 (M77)

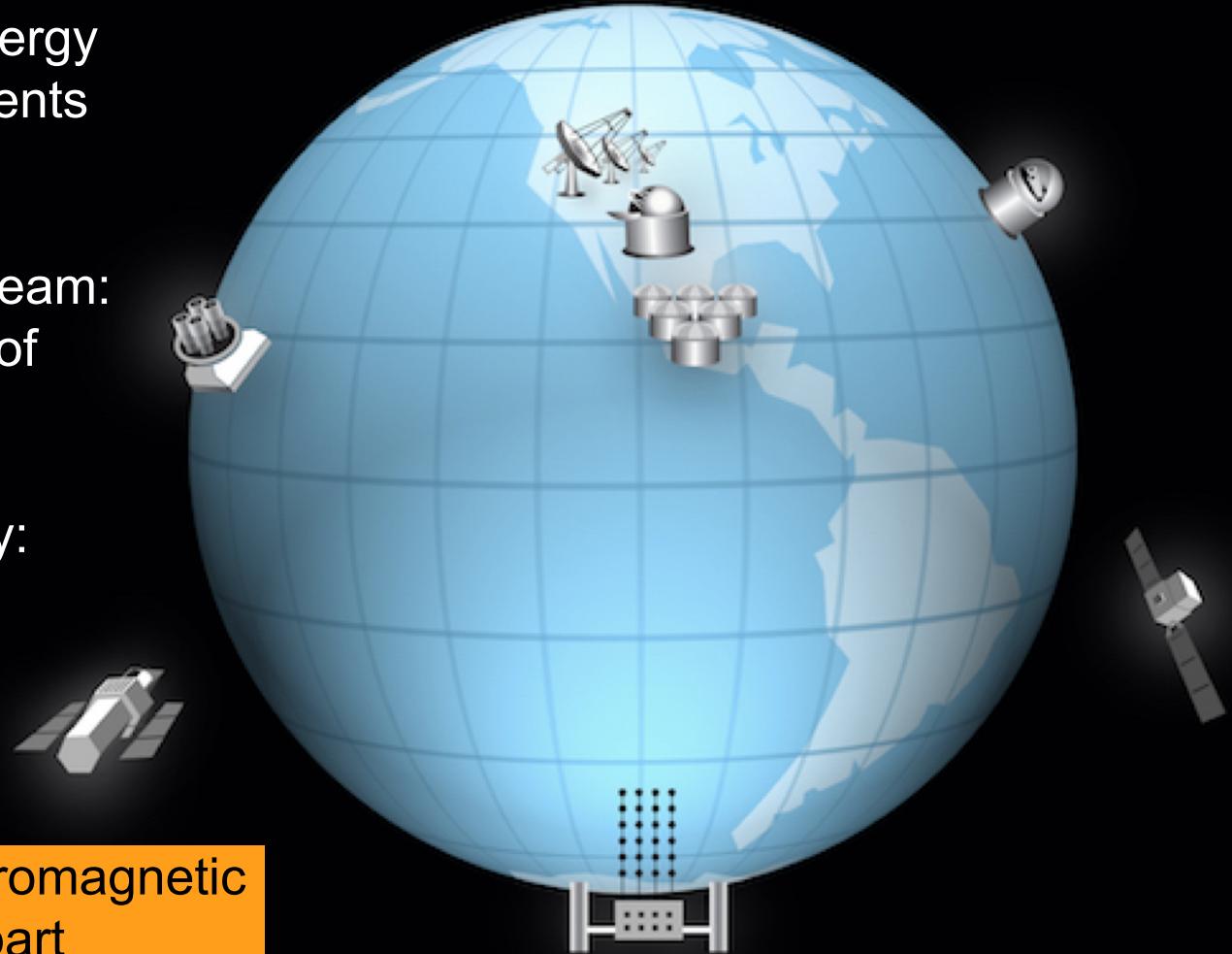


Gamma rays need to be absorbed

Target of Opportunity Program

Public alerts since April 2016

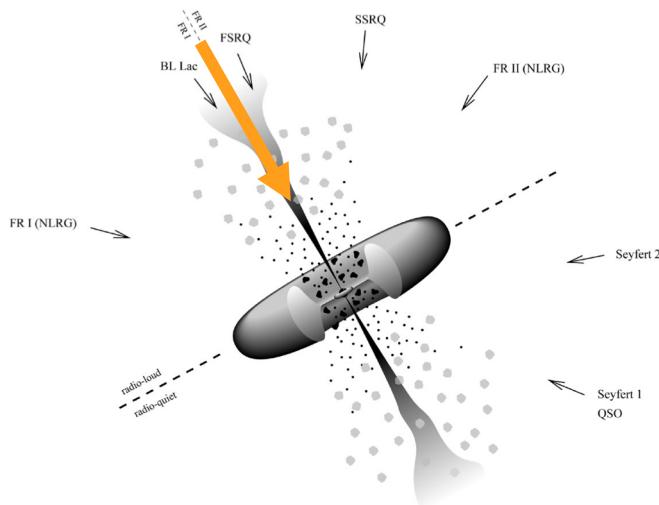
- Single high-energy muon track events ($> \sim 100\text{TeV}$)
- “Gold” alert stream:
10 / yr, ~ 5 / yr of cosmic origin
- Median latency:
30 sec



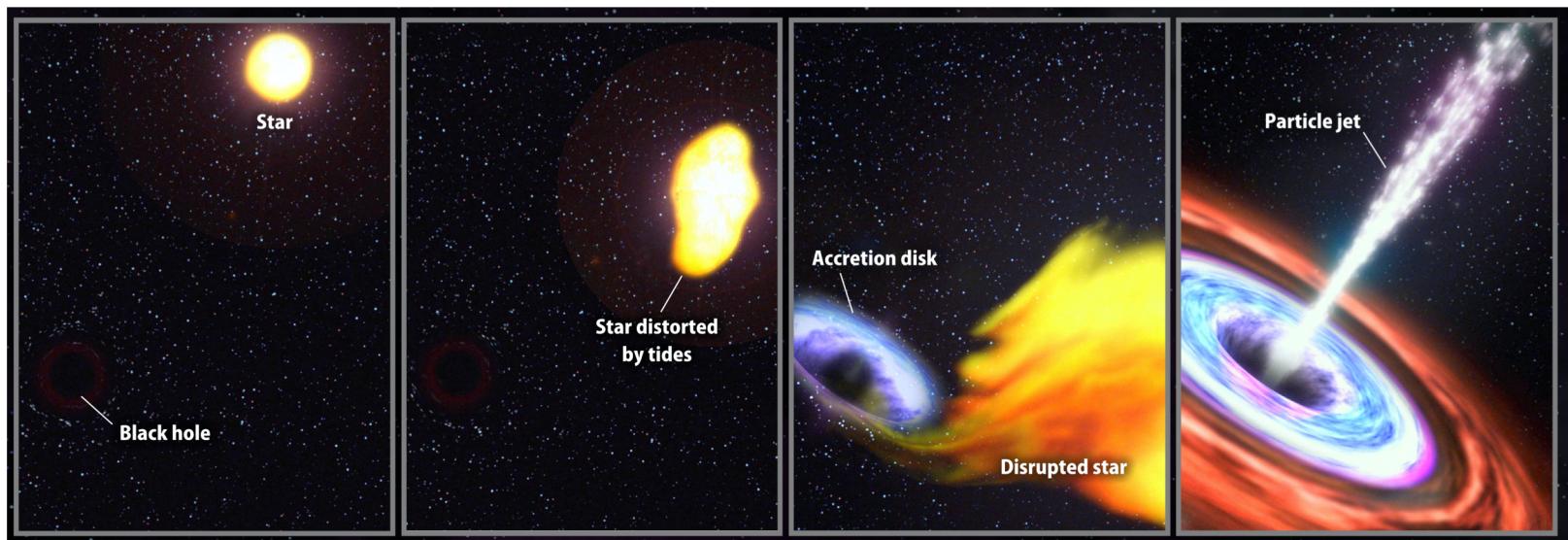
Goal: Find electromagnetic counterpart

Two interesting sources identified

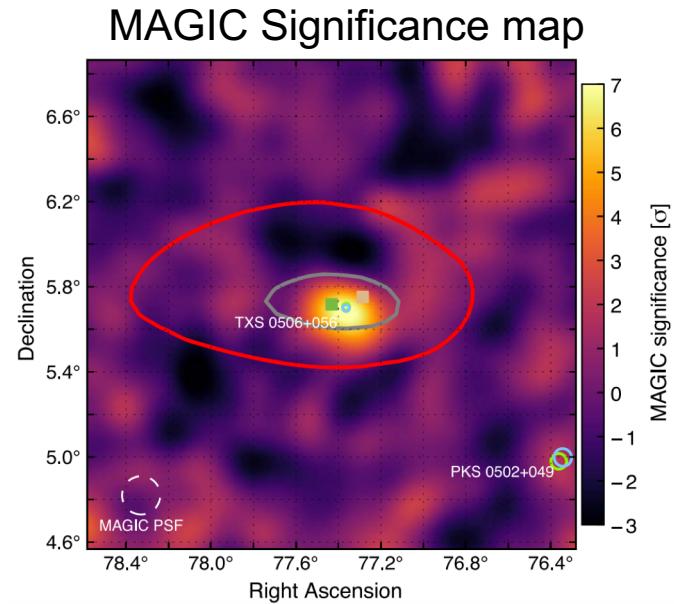
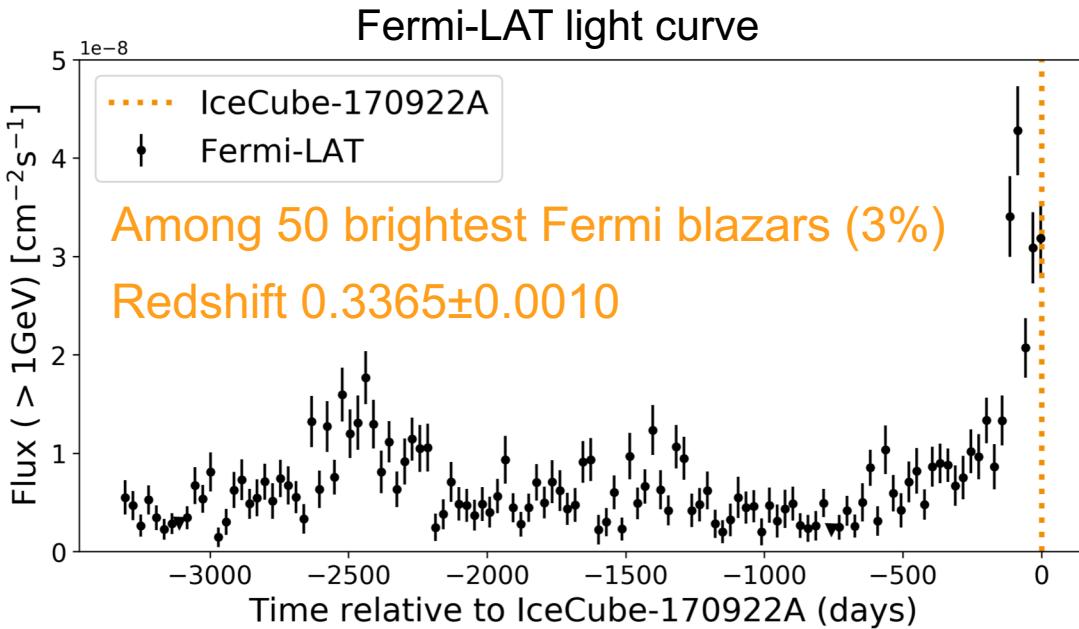
Gamma-ray blazar TXS 0506+056



Tidal Disruption events AT 2019dsg

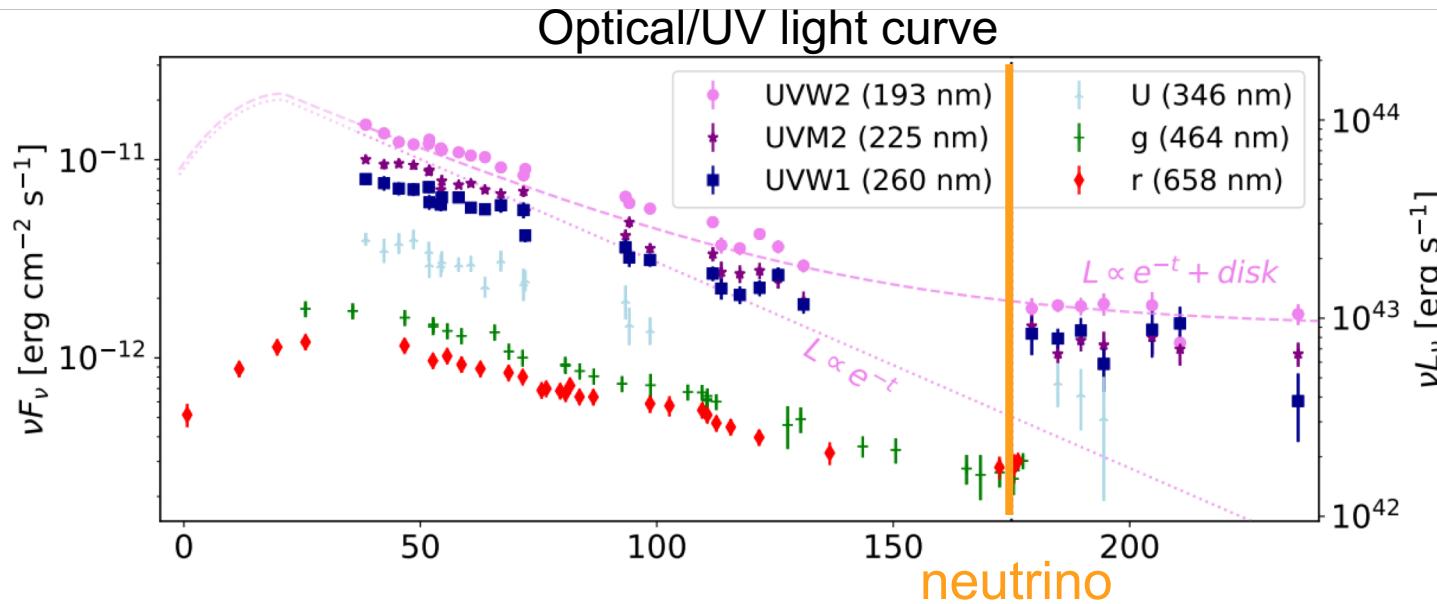


Fermi-LAT finds Flaring Blazar, TXS 0506+056 coincident with IC-170922A



Chance coincidence: 0.1% (3 σ significance, including trials)
> 6 PeV protons accelerated in the source

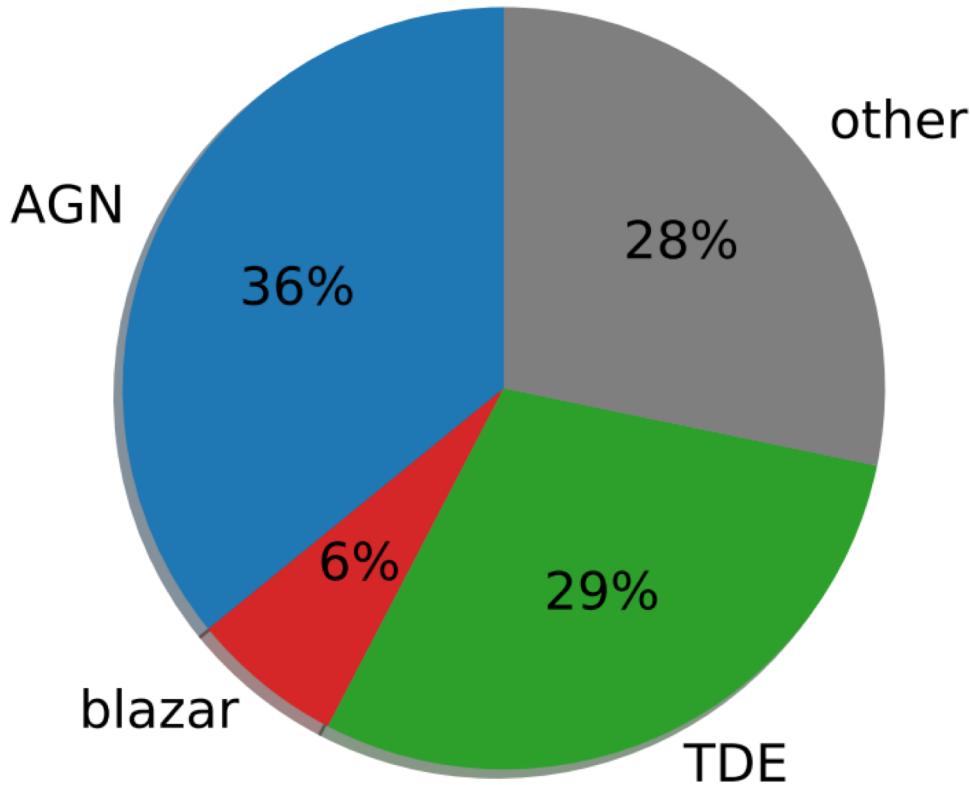
Zwicky Transient Facility identifies tidal disruption event AT2019dsg (“Bran Stark”) coincident with IC-191001A



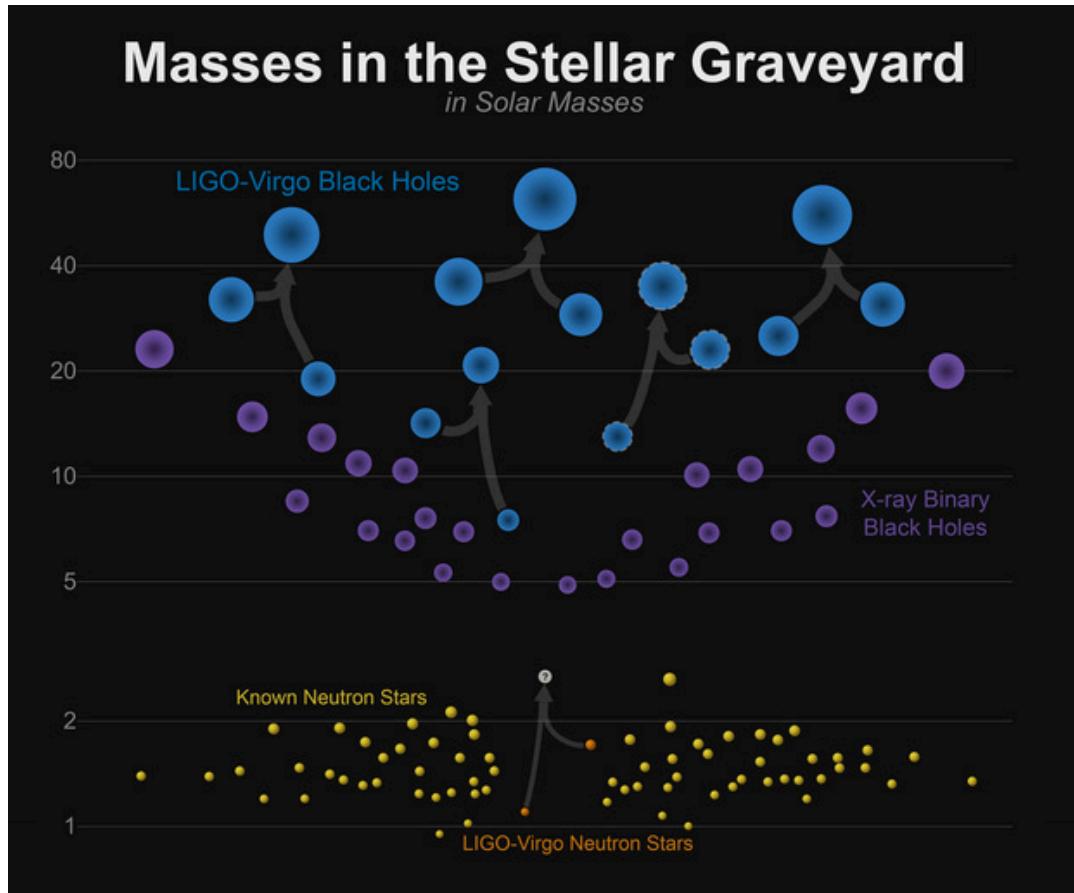
Distance: $z = 0.05$ ($d=230\text{Mpc}$)

Chance coincidence: 0.2% to find a TDE that bright
(including trials)

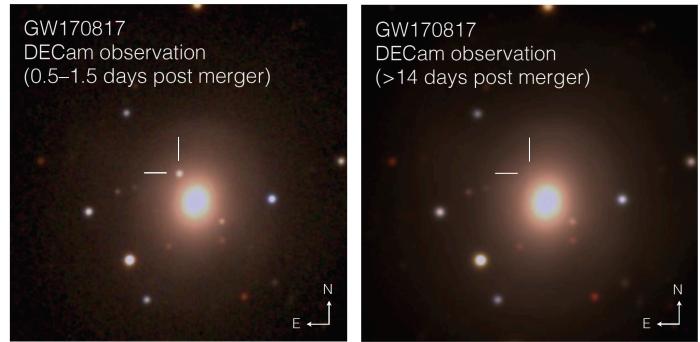
Other source candidates



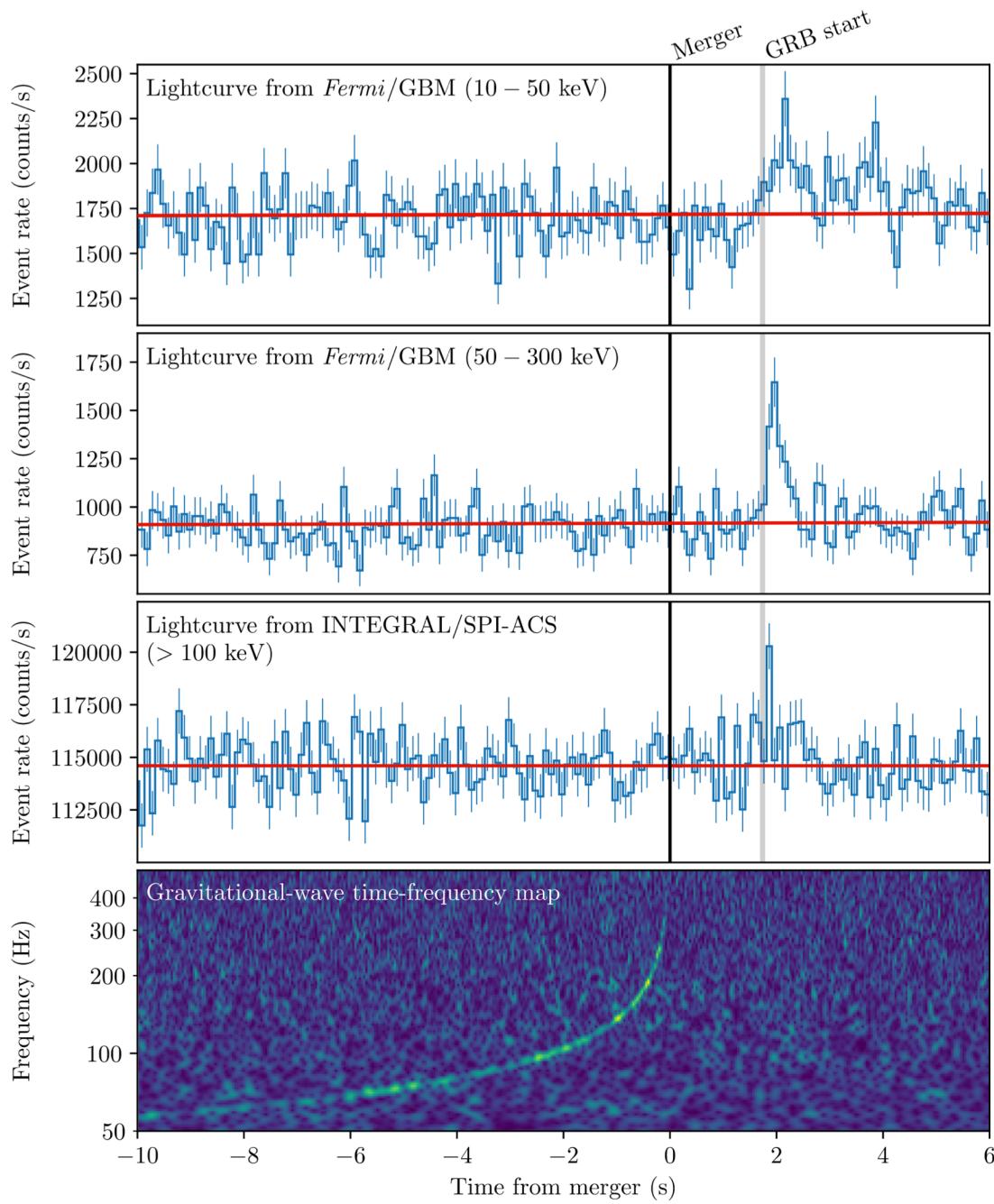
Gravitational Waves



Binary neutron star merger – GW170917

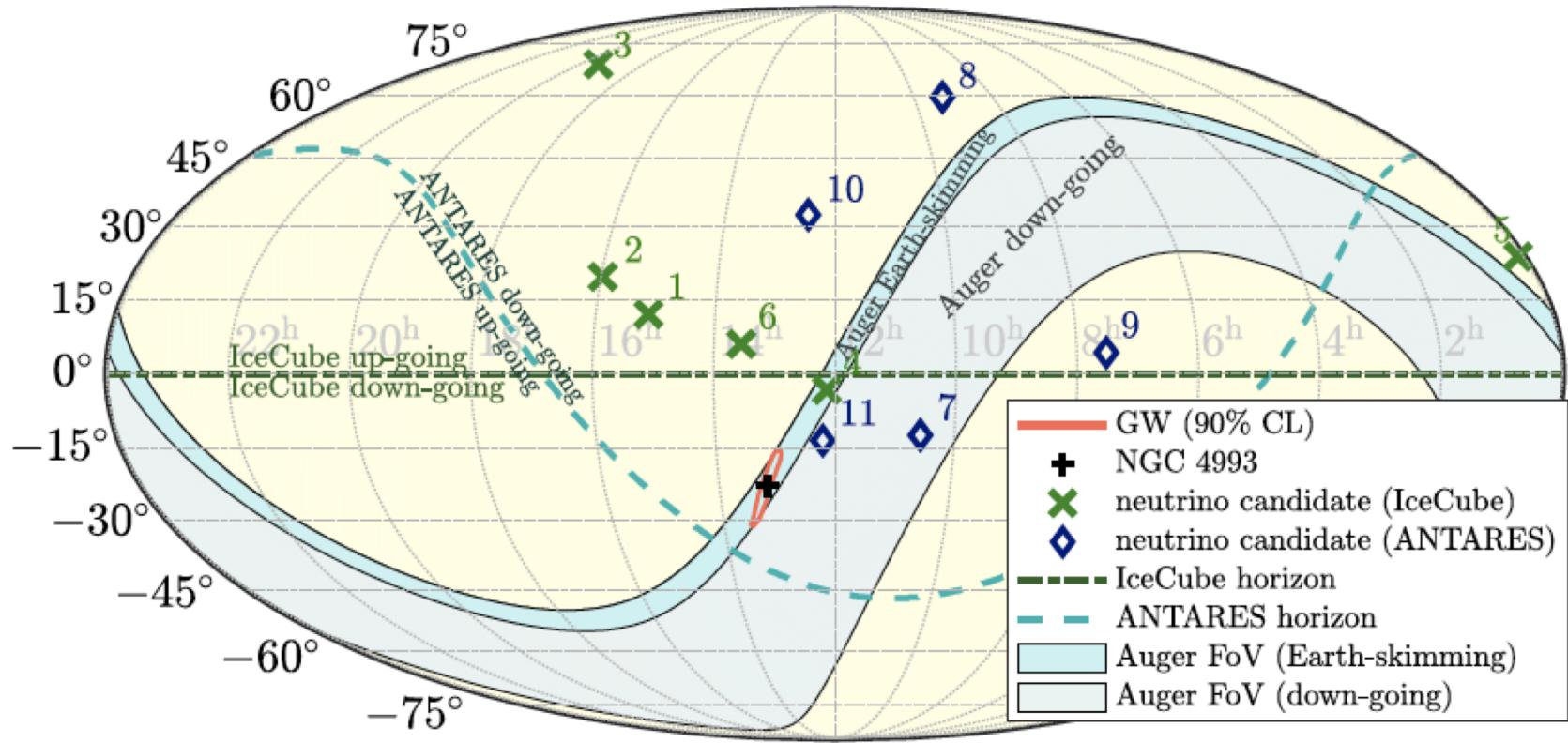


- Short GRBs are produced by neutron star mergers
- contribution to rapid neutron capture → significant sources of elements heavier than iron
- Probe of Lorentz invariance
- Independend cosmological distance ladder



Gravitational Waves and Neutrinos

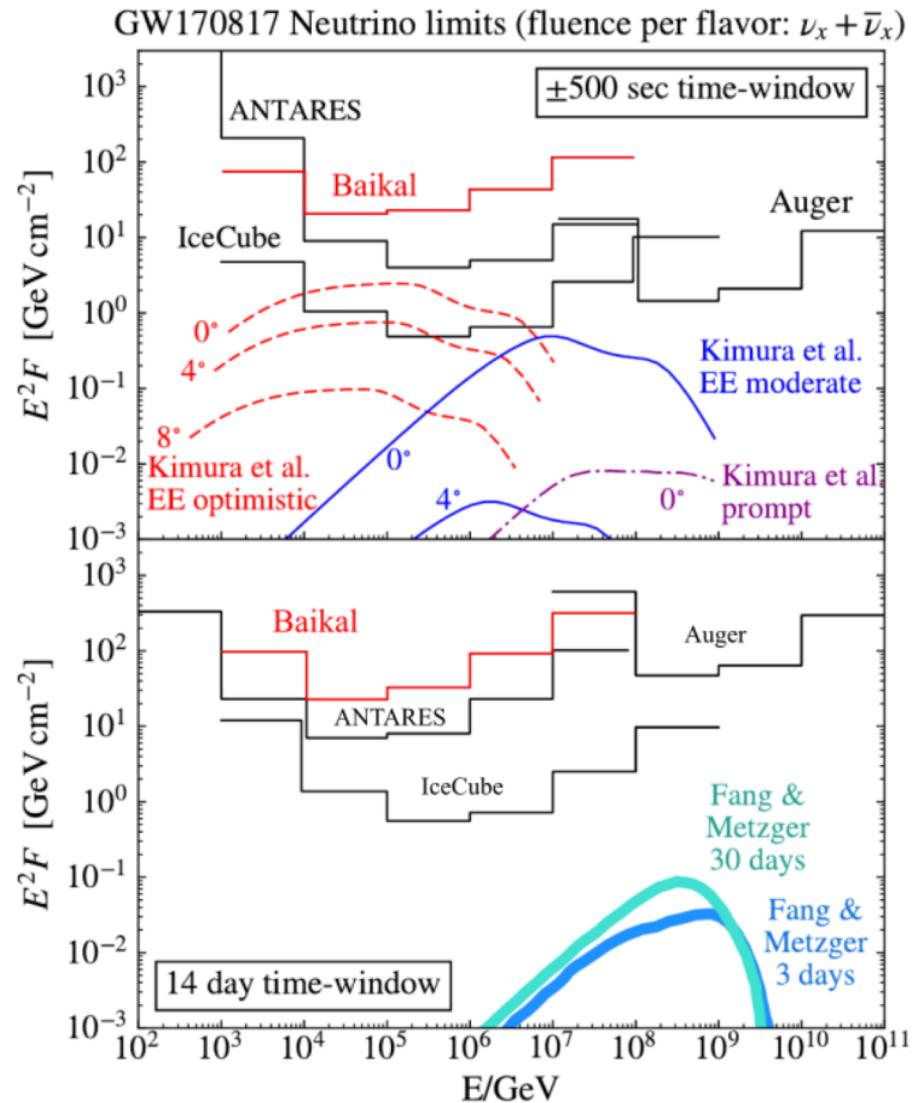
Search for neutrinos from GW170817 in ANTARES, Auger and IceCube data in +/-500 sec → no counterpart found



Neutrino could help to constrain direction and teach us about the GW source environment

Gravitational Waves (GW) and Neutrinos

Non-observation is consistent with off-axis short GRB scenario



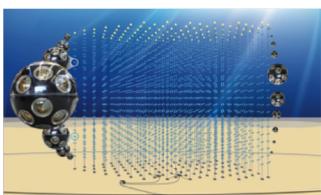
The Future is Bright

Neutrino sources
on the southern sky



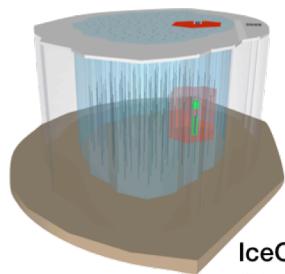
Today's neutrino telescopes

Neutrinos bei EeV
Energien

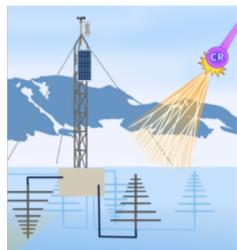


KM3NeT
(construction started)

5x better sensitivity
in the TeV-PeV
energy range



IceCube-Gen2
(Phase 1 started)



ARA/ARIANNA,
RNO, Gen2-Radio
(proposals in)

Vera Rubin Observatory



AMEGO, MeV Satellite ?



And many more ...

World-wide GW detector network

GEO 600m



LIGO (Livingston) 4km



advanced LIGO

LIGO (Hanford) 4km



Virgo 3km



advanced Virgo



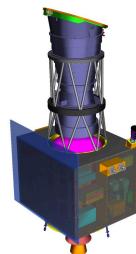
LIGO-India
Approved

KAGRA

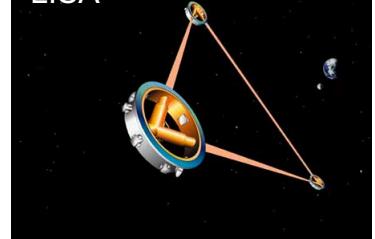


(Kamioka) 3km

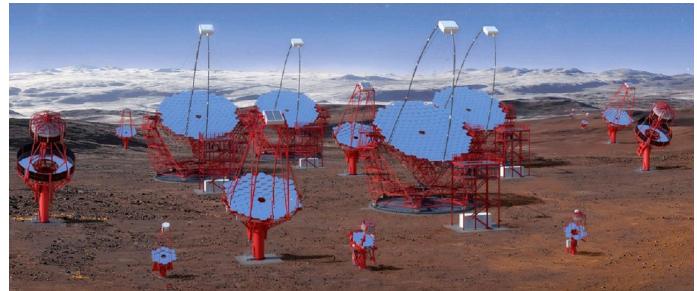
ULTRASAT



LISA



Cherenkov Telescope Array



Summary



Stay tuned!

