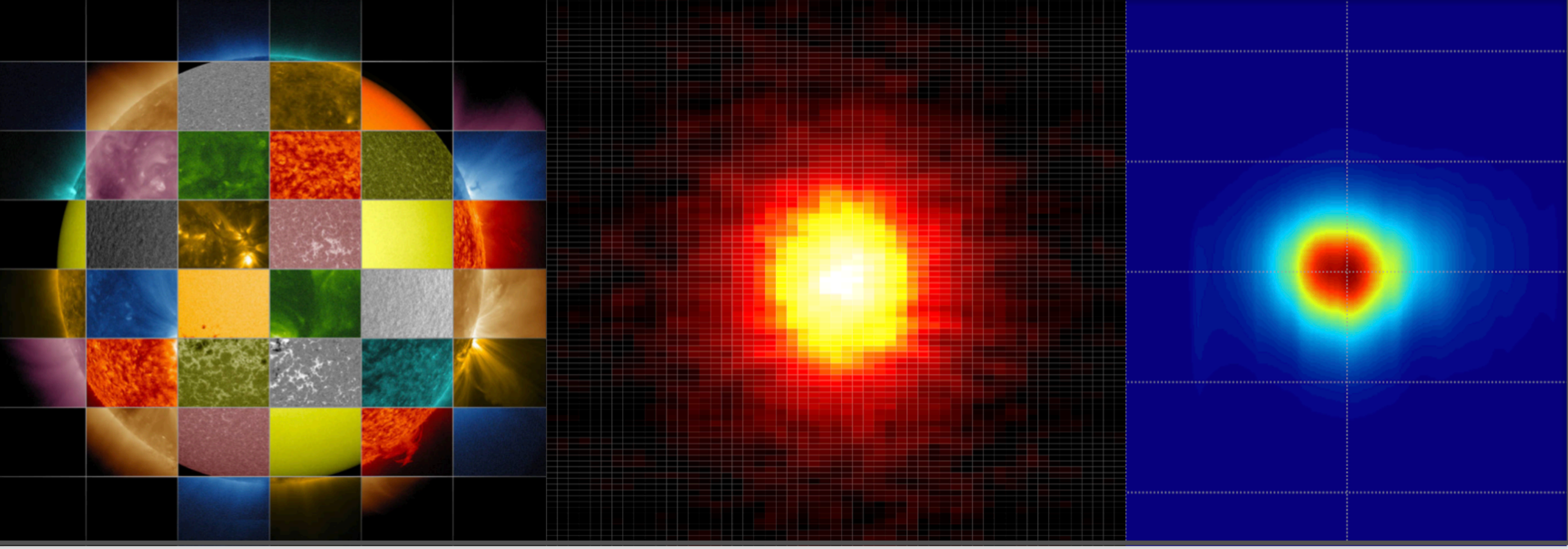


Credits: NASA/SDO/Goddard Space Flight Center, SuperKamiokande, Chang'E-1 Solar Wind Ion Detector (F. Nozzoli and P. Giommi)

ELISA RESCONI (TUM)

SFB 1258 Neutrinos Dark Matter Messengers

HIGH ENERGY MULTI-MESSENGER ASTRONOMY

in collaboration with P. Padovani, P. Giommi, A. Turcati, S. Coenders, L. Caccianiga, and M. Petropoulou, B. Arsioli, Y.L. Chang.

talk based on ICRC'17

THE IDEA

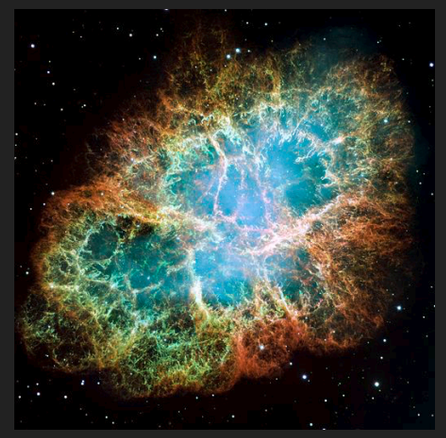
K. Greisen, "Cosmic ray showers," Ann. Rev. Nucl. Part. Sci. 10 (1960) 63–108.
F. Reines, "Neutrino interactions," Ann. Rev. Nucl. Part. Sci. 10 (1960) 1–26.
M. A. Markov, "On high energy neutrino physics," Proc. Int. Conference on High Energy Physics at Rochester (1960) 578–581.

- *interest in the possibility of detecting cosmic neutrinos ,,stems from the **weak interaction of neutrinos** with matter, which means that **they propagate essentially unchanged in direction and energy** from their point of origin [..] and so carry information which may be unique in character." (F. Reines)*

- *use a large volume of water in **mine** (Greisen)*

- *use the **deep ocean** or water in a lake to study atmospheric neutrinos (Markov)*

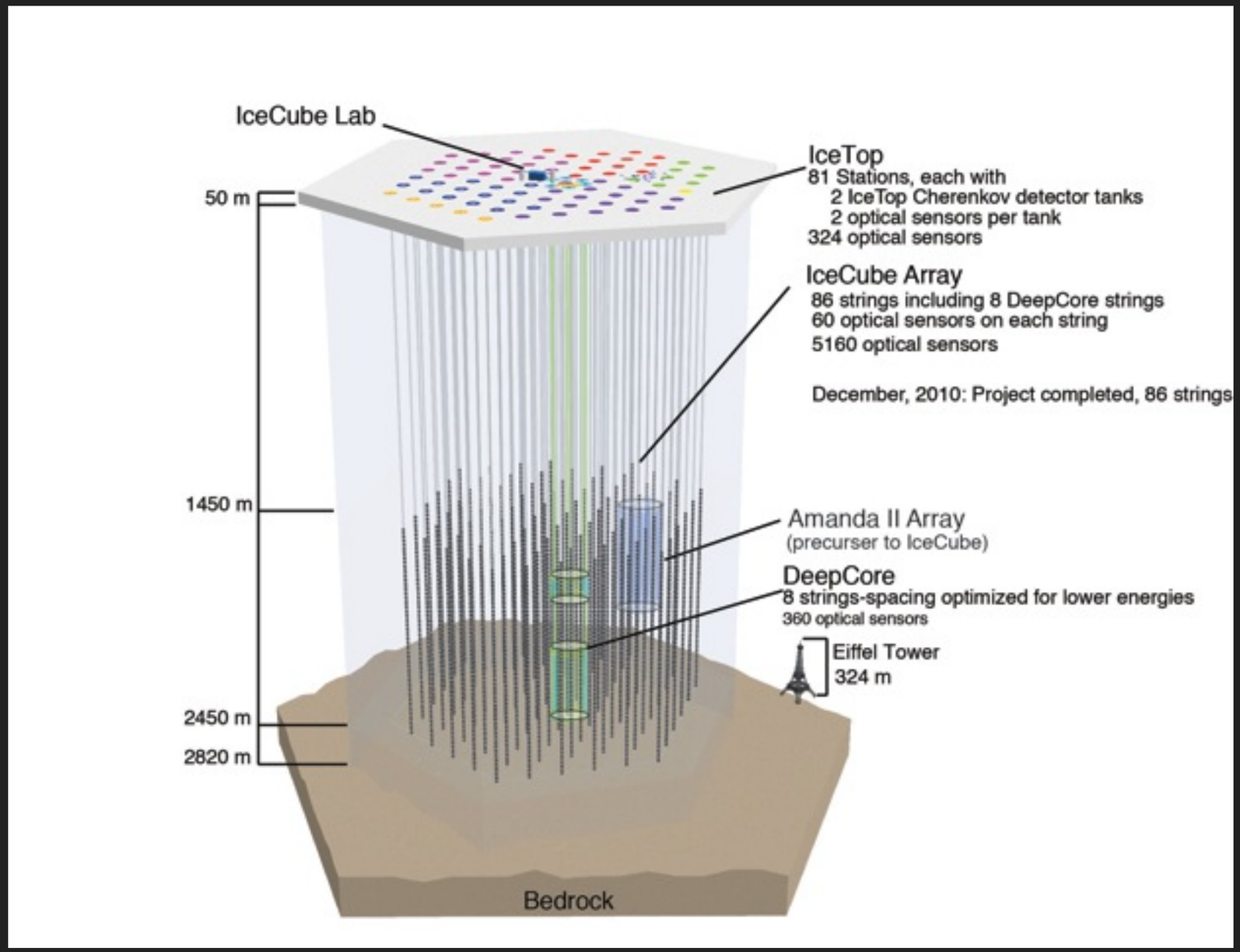
THE SCALE: KM3



- compare with TeV sources of γ-rays
- Crab Nebulae (~TeV): $dNv / d\ln(E) \sim 3 \times 10^{-11} cm^{-2} s^{-1}$
- neutrino cross section is $\sim 10^{-35}$ cm^2
- One km^3 of water contains 6×10^{38} target nucleons
- ~ 10 neutrino interactions per year
- few background neutrino-induced muon.

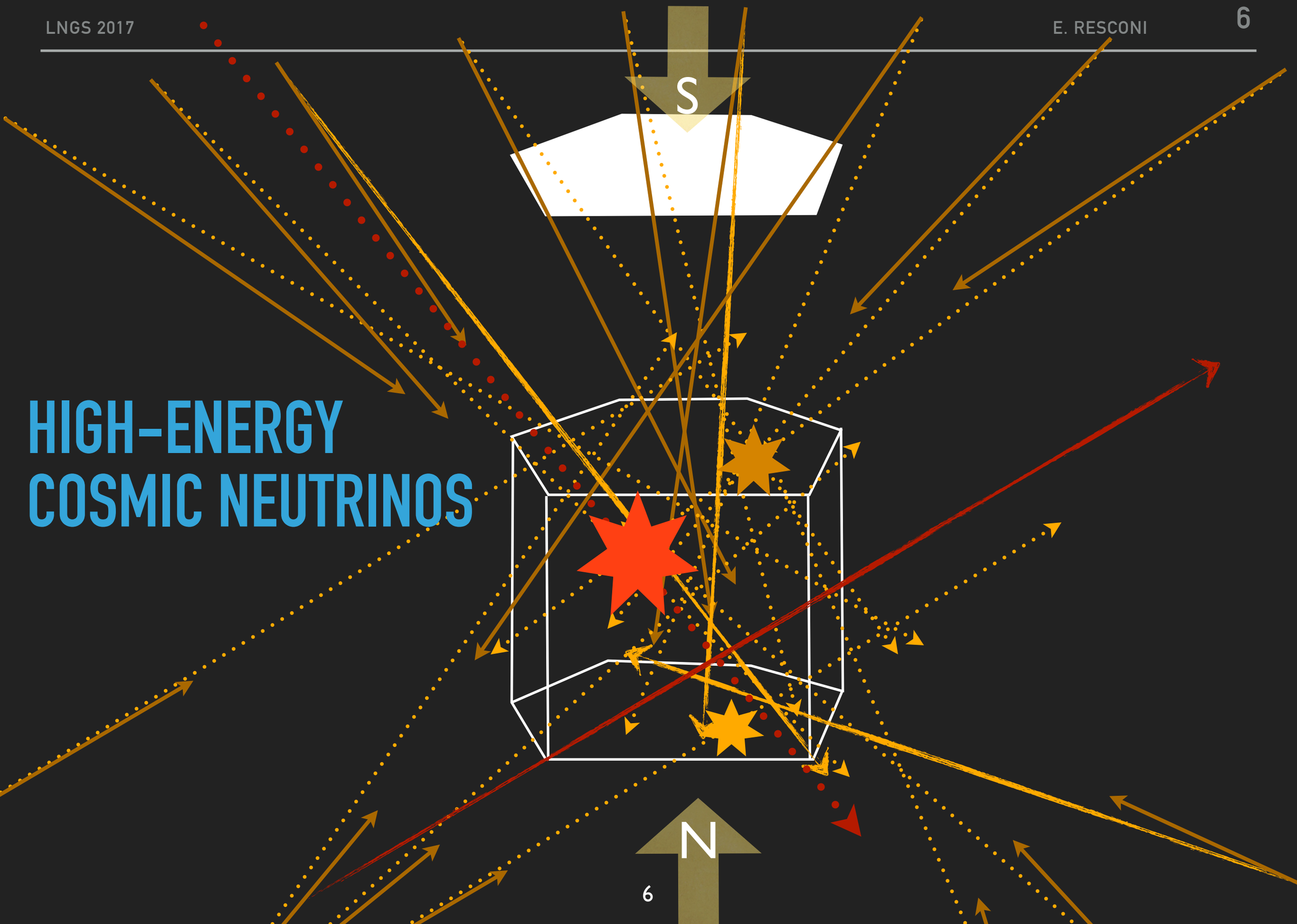
ICECUBE

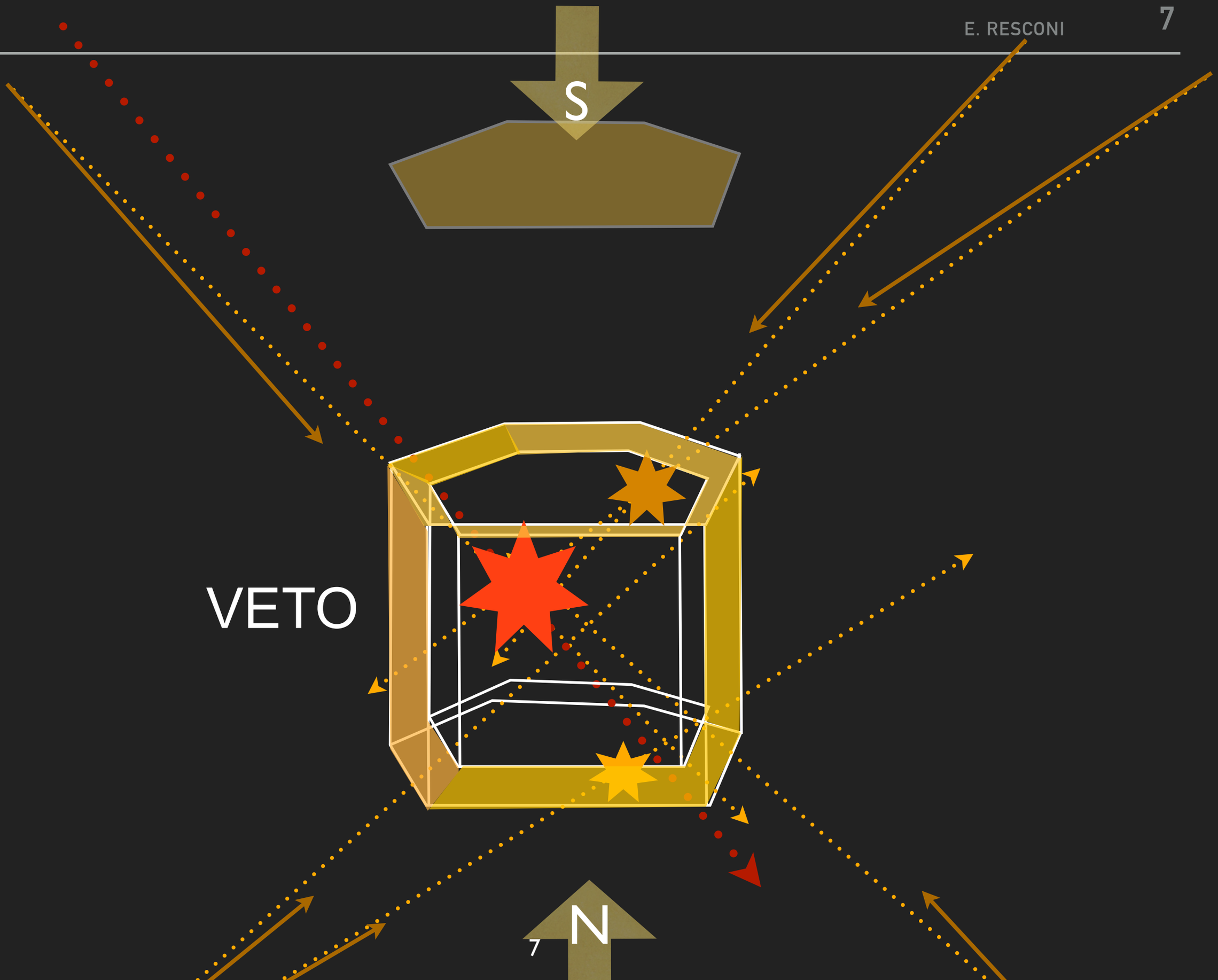
- AMANDA (2000-2006)
- IceCube:
  - 2004 - 2010 construction
  - 2010 - now data taken
- IceTop
- “in-ice”
  - DeepCore: Extension at lower energies (~100 GeV - ~10 GeV)



December 2010

HIGH-ENERGY COSMIC NEUTRINOS

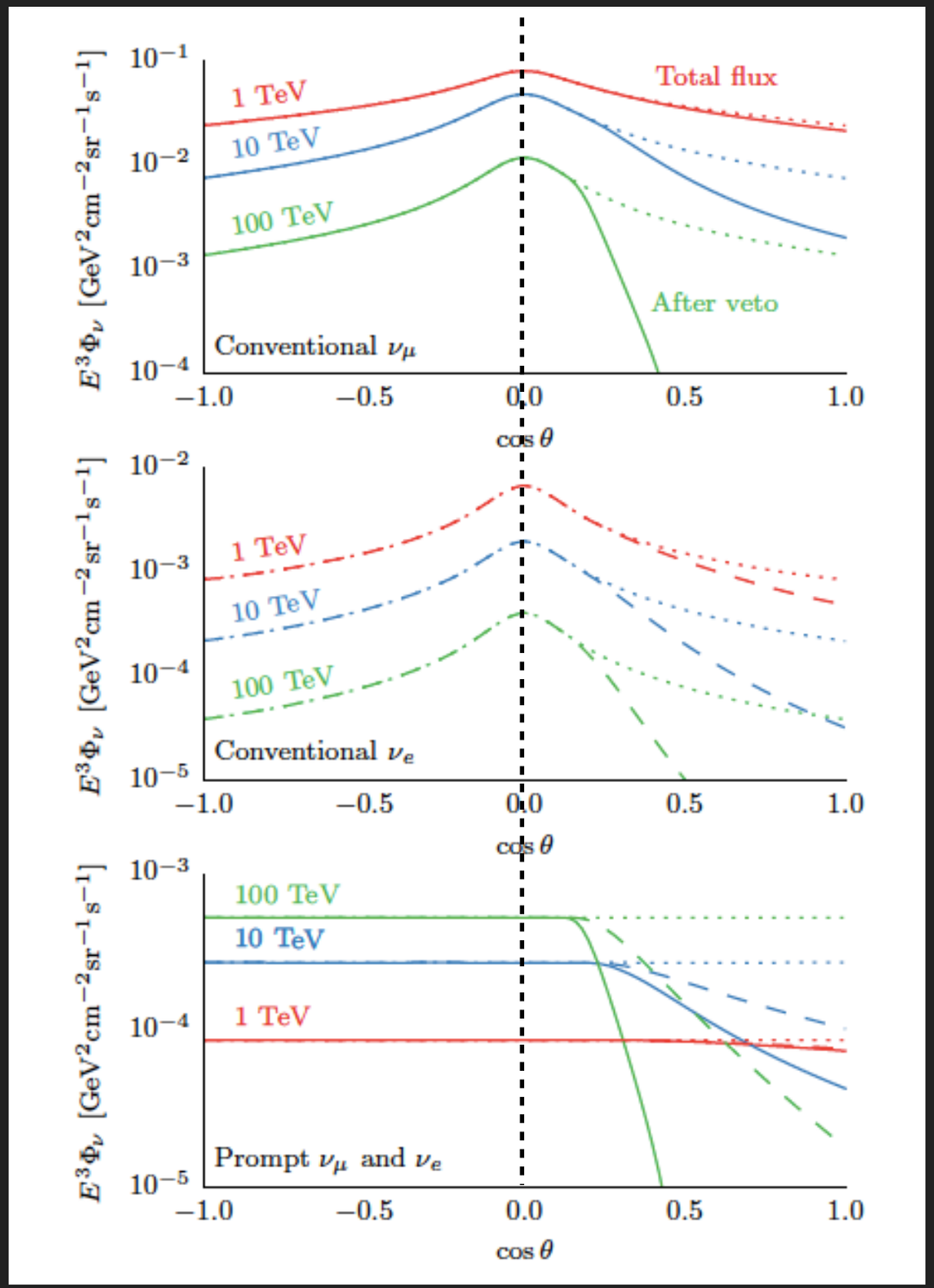


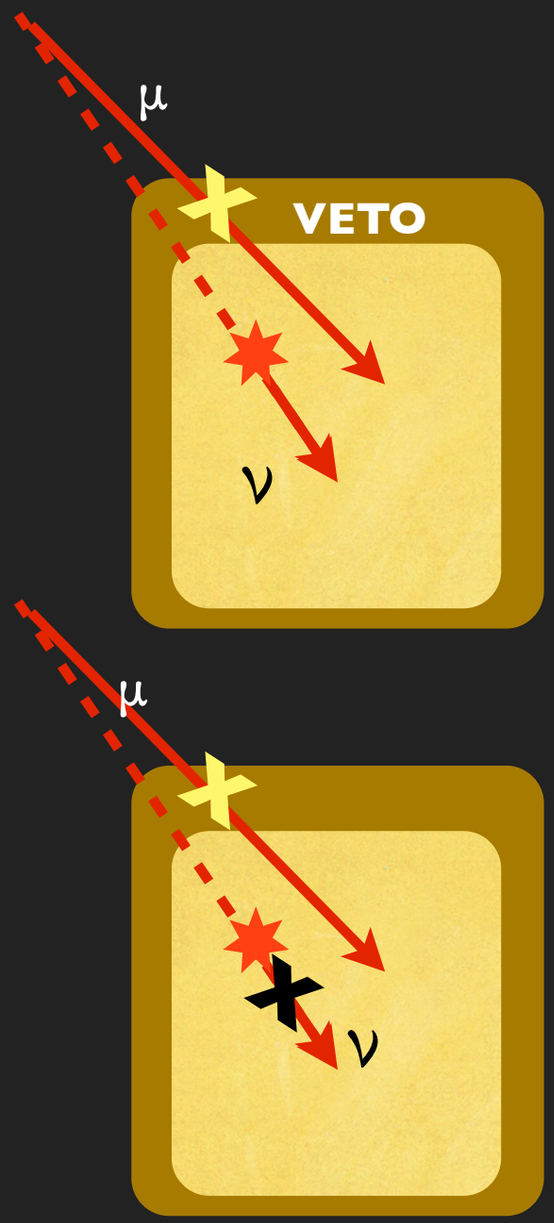

S
VETO
N

ATMOSPHERIC NEUTRINOS VETO

[S. Schönert, T. K. Gaisser, E.R., O. Schulz, PRD (2009),

T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, Phys. Rev. D (2014)]

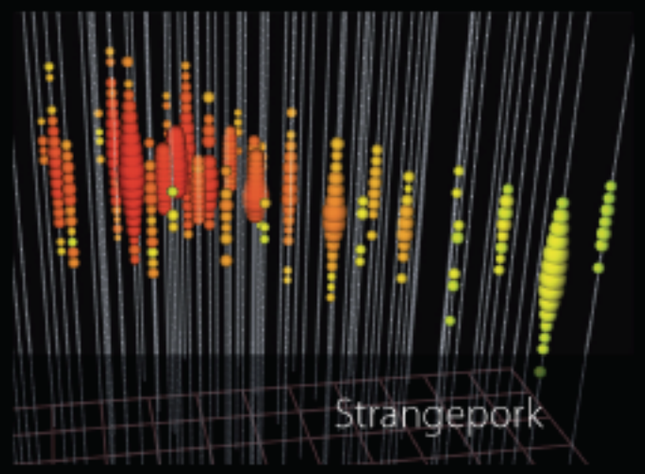


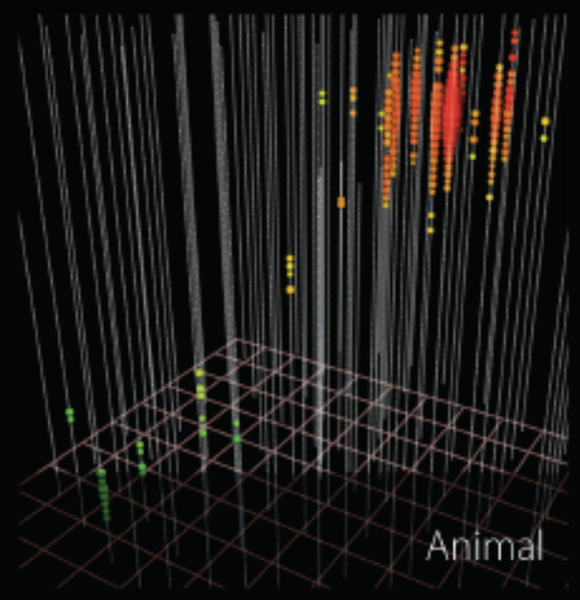


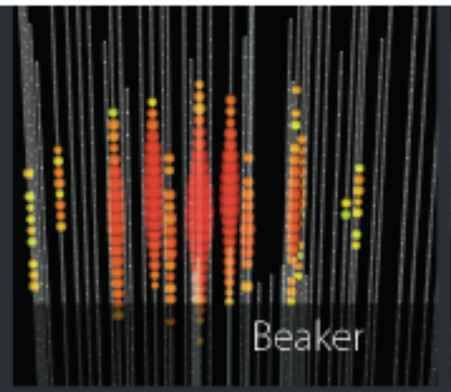
Examples of events:

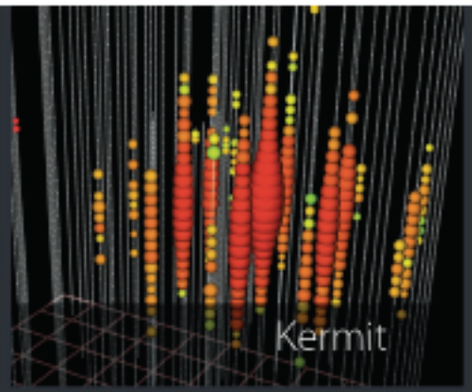
charge threshold > 6000 p.e.
& < 3 p.e. in veto region

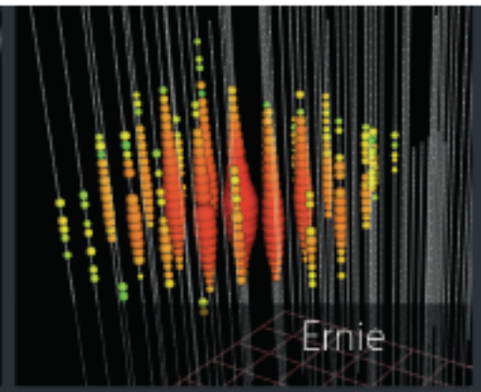
2078-day sample: 82 events

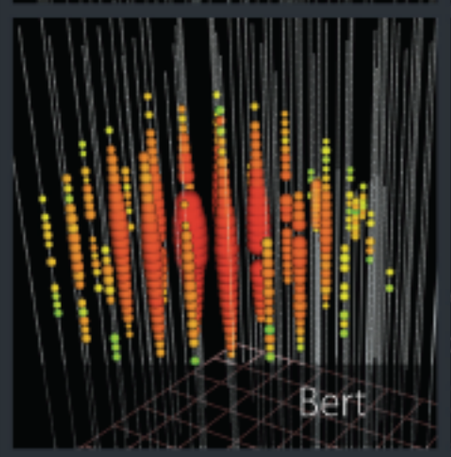


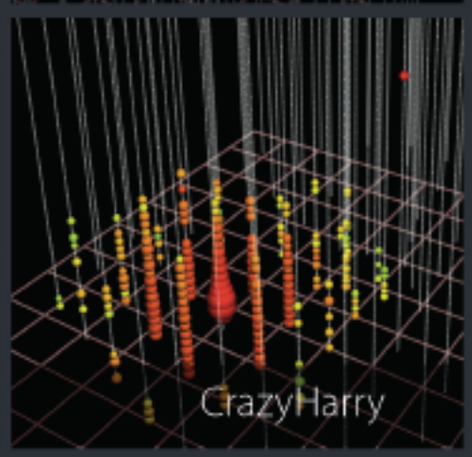


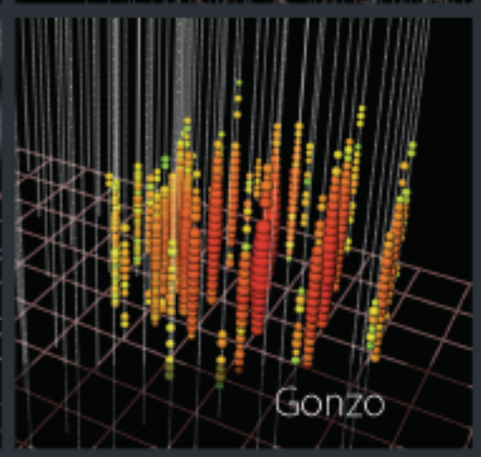


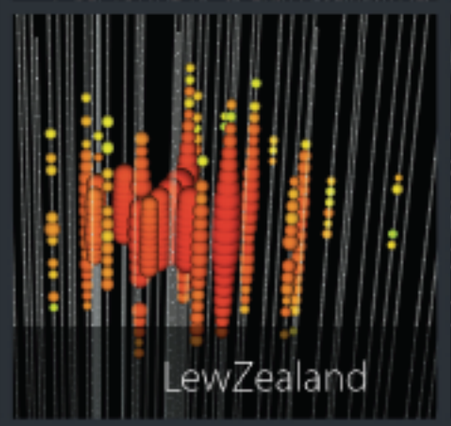


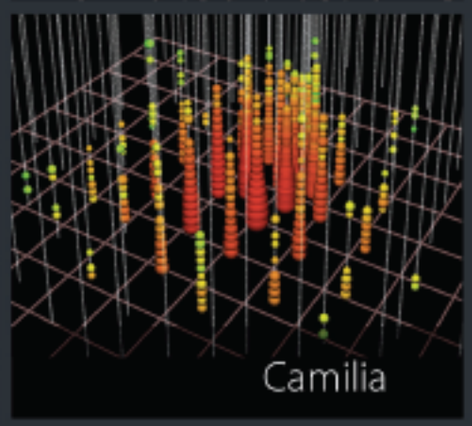


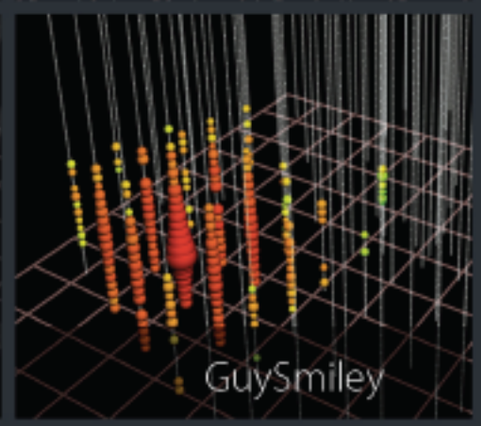


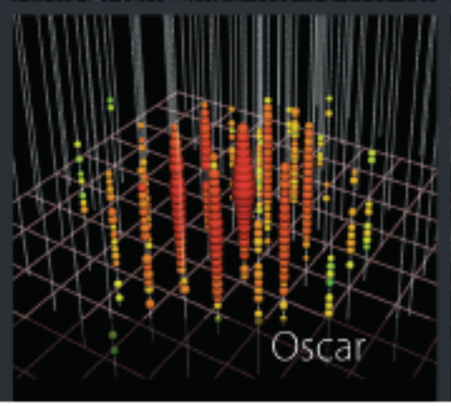


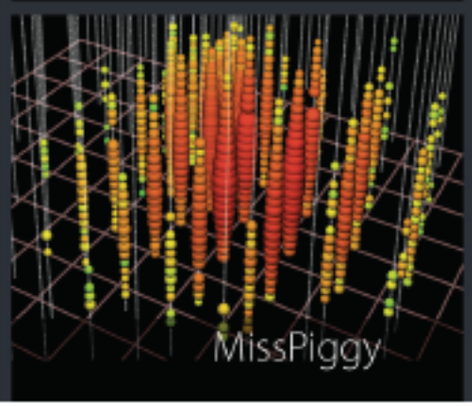


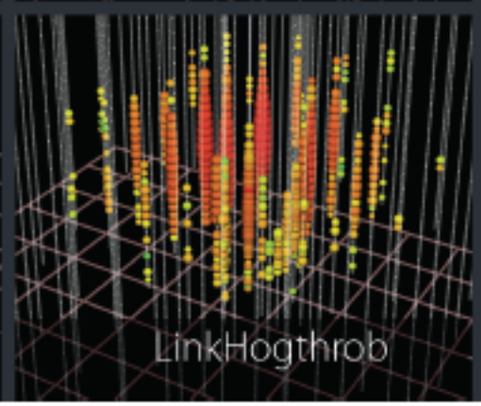






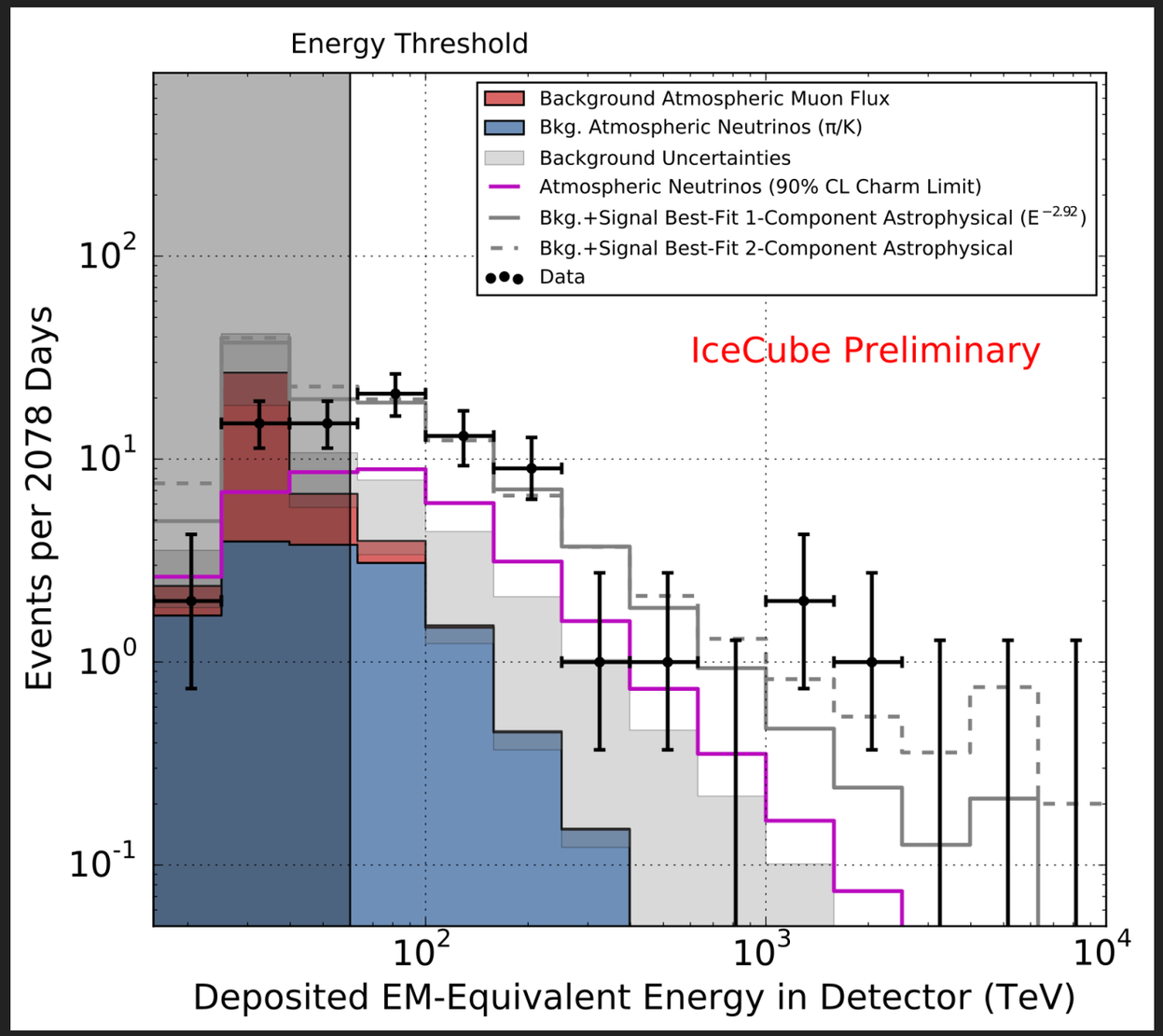


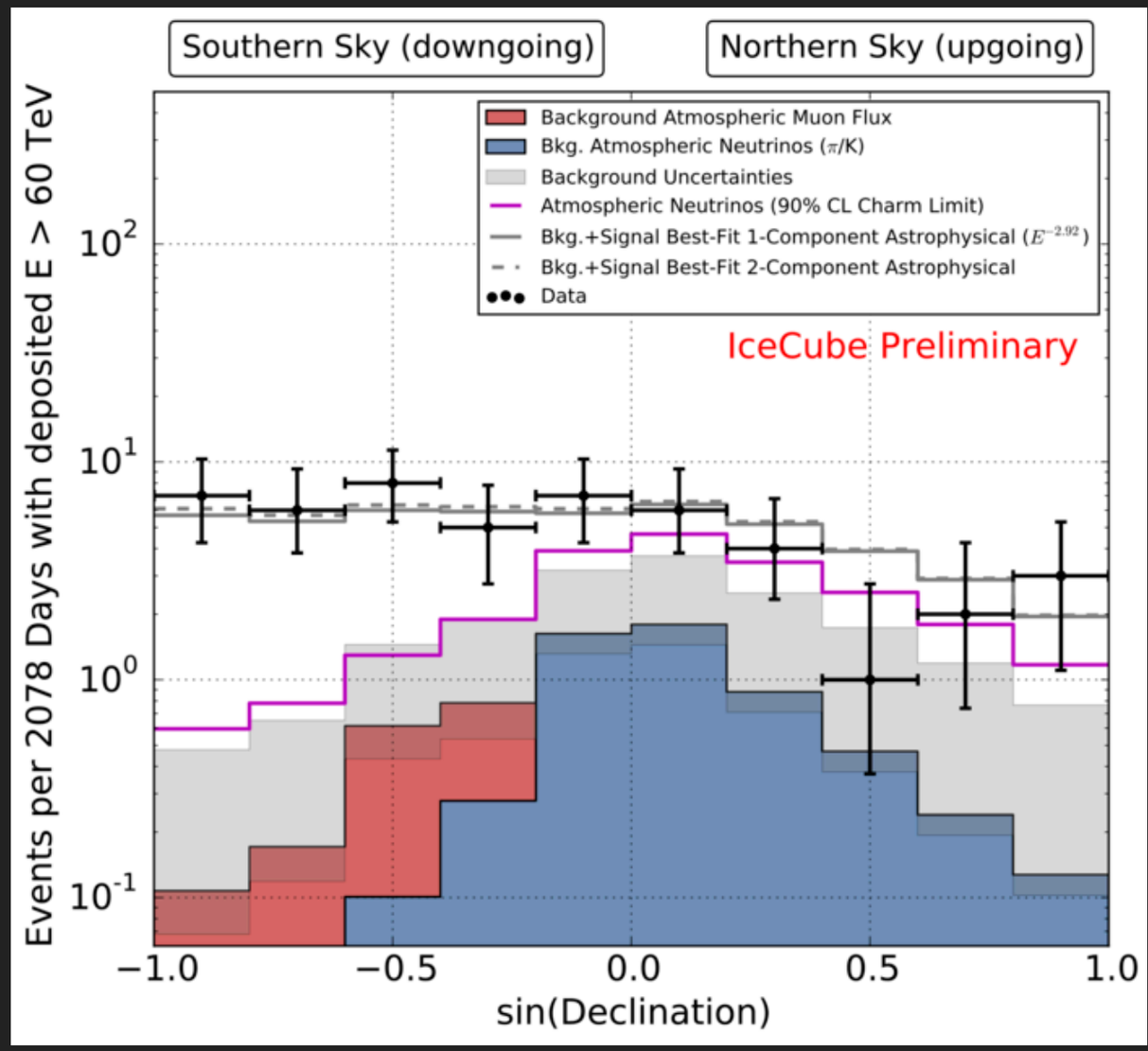




DISCOVERY OF HIGH ENERGY COSMIC NEUTRINOS

[The IceCube Coll., ICRC'17]



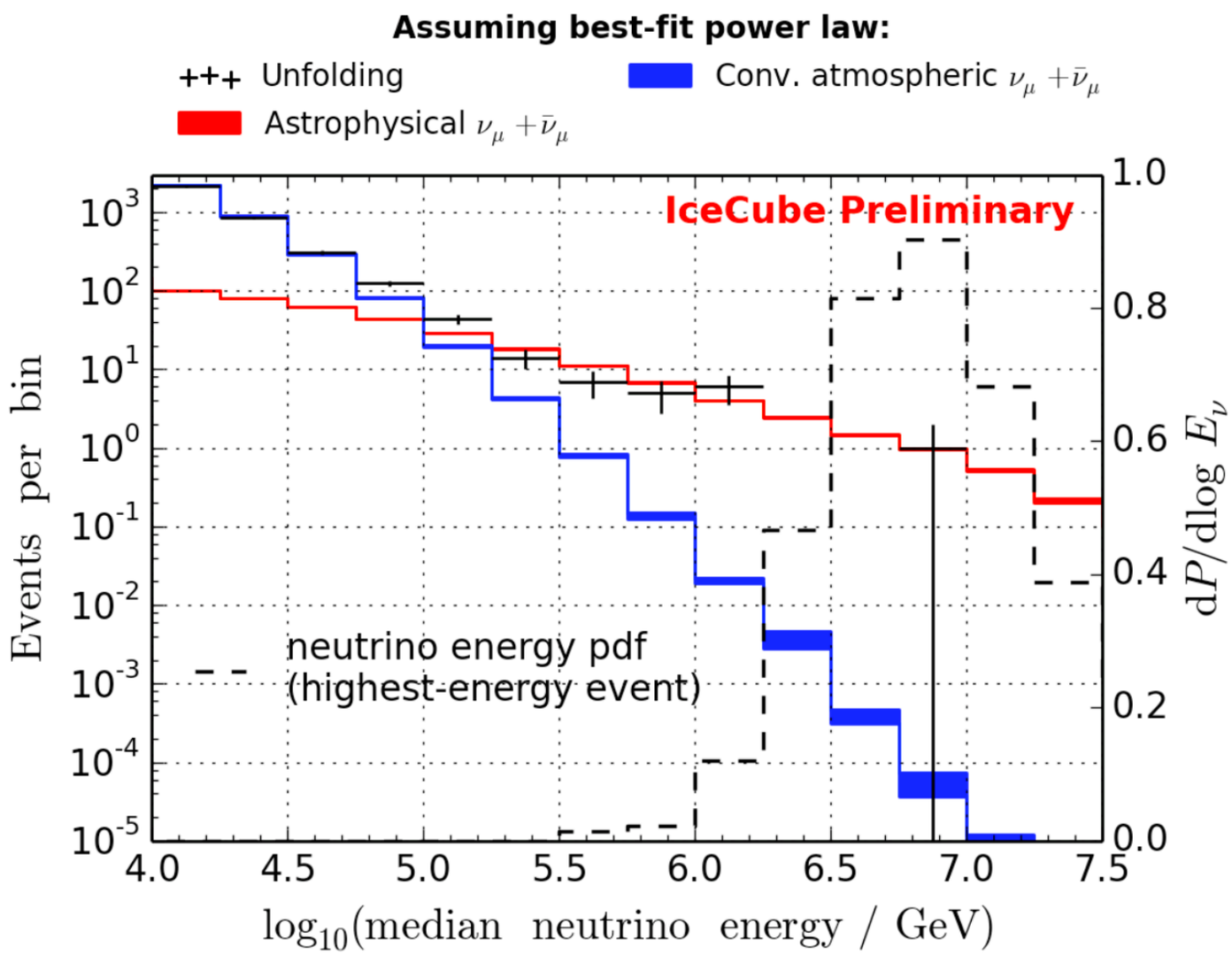


$E^2\varphi(E) = 2.46\pm0.8\times10^{-8}(E/100\text{TeV})^{-0.92}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (single component hypothesis) > 5 σ excess

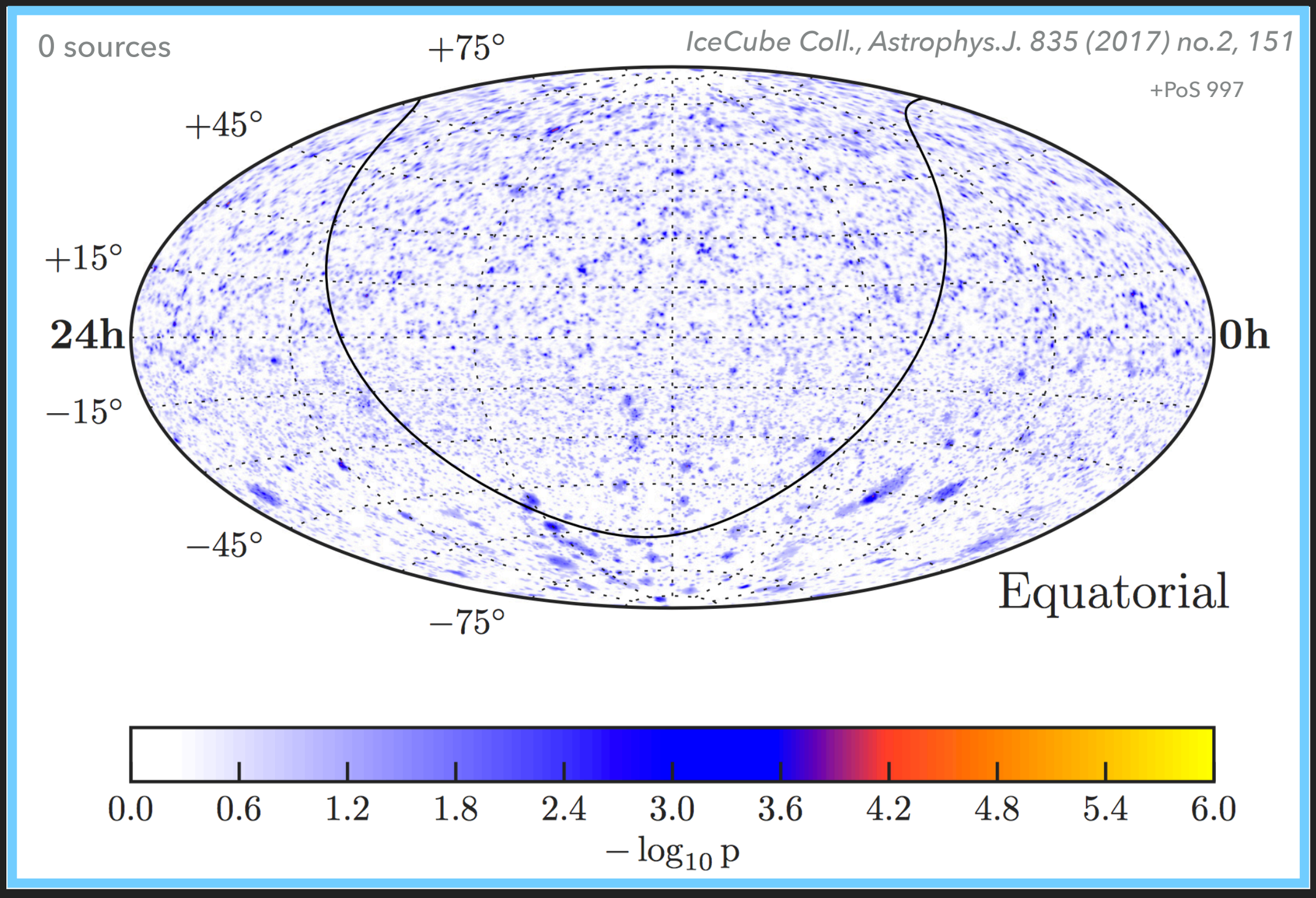
DISCOVERY OF HIGH ENERGY COSMIC NEUTRINOS

[The IceCube Coll., ICRC'17]

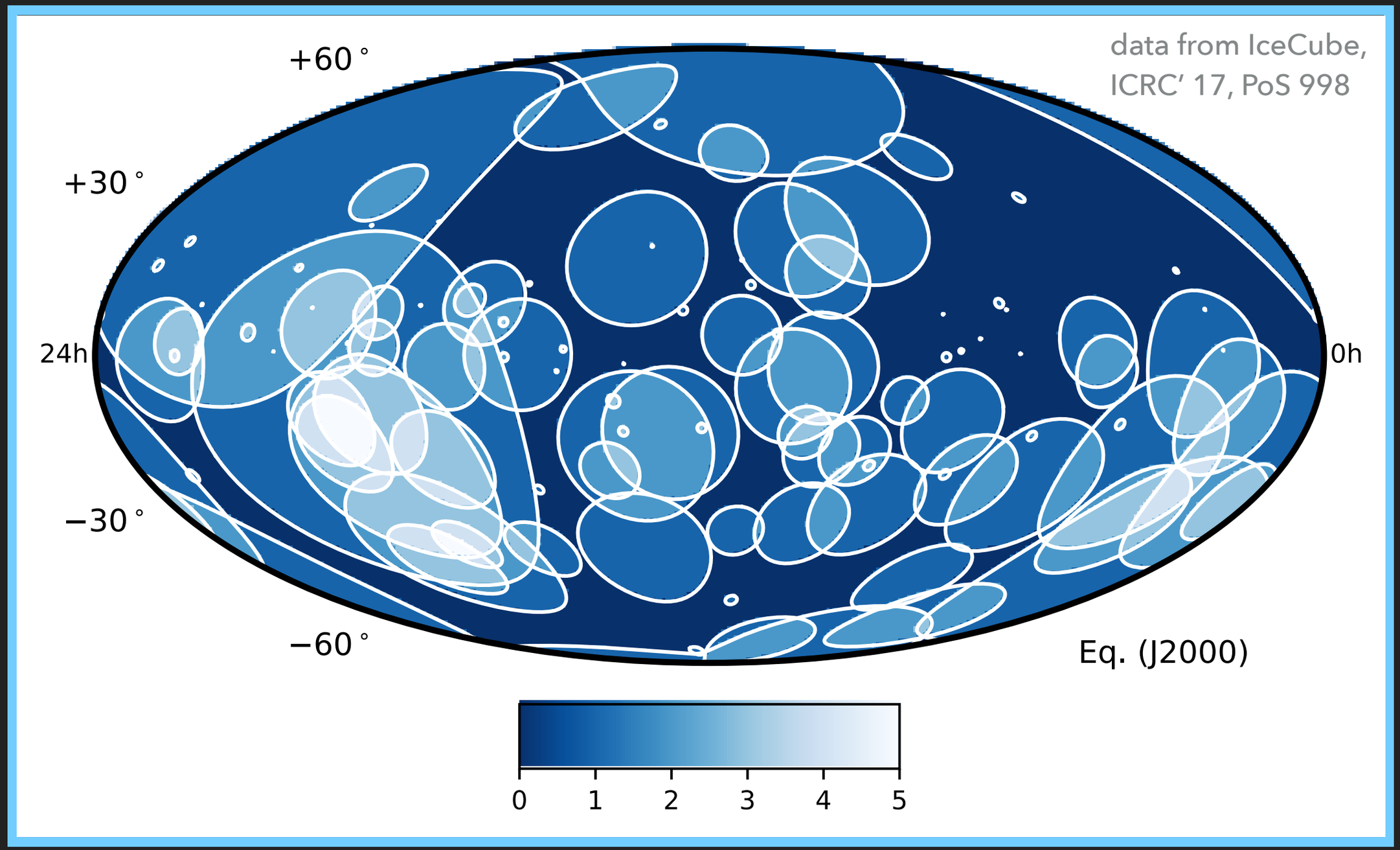
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric atmospheric background: less than one event/deg^2/year



THE OBSERVATIONS: 10^{12}–10^{15} eV SKY IN NEUTRINOS



THE OBSERVATIONS: 10^{12}–10^{15} eV SKY IN NEUTRINOS



THE MESSENGERS

(UHE) Cosmic Rays

↳Primaries

↳Charged

↳Composition

↳Interact, limited horizon

Reconstruction:

↳good angular resolution, bending

↳good energy resolution

(HE) Neutrinos

↳Secondaries

↳Not charged

↳Three flavours

↳Interact weakly, nearly unlimited horizon

Reconstruction:

↳poor angular resolution in shower, good in tracks

↳poor energy resolution in tracks, good in showers

(Gamma) Photons

↳Secondaries

↳Not charged

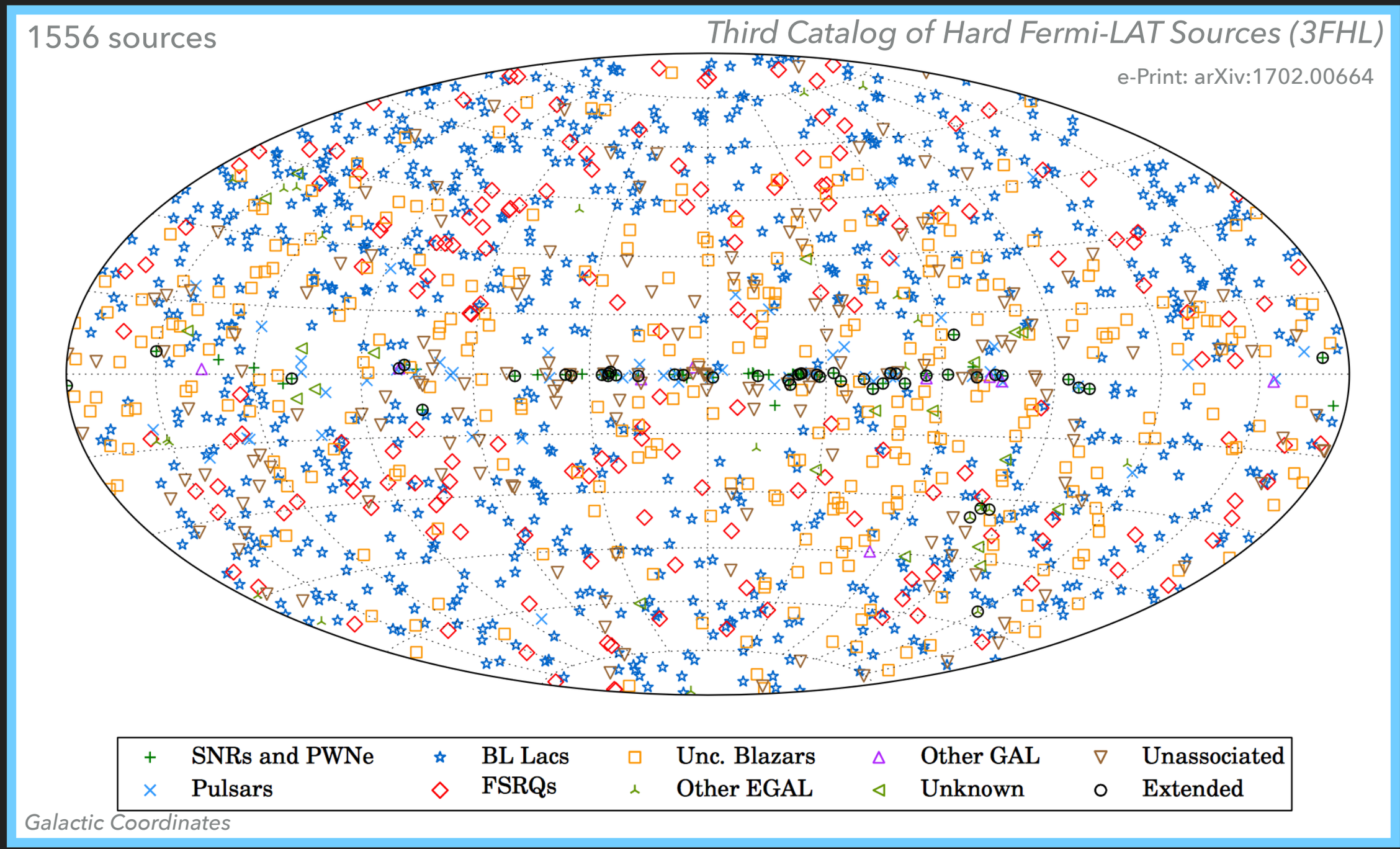
↳Interact, limited horizon

Reconstruction:

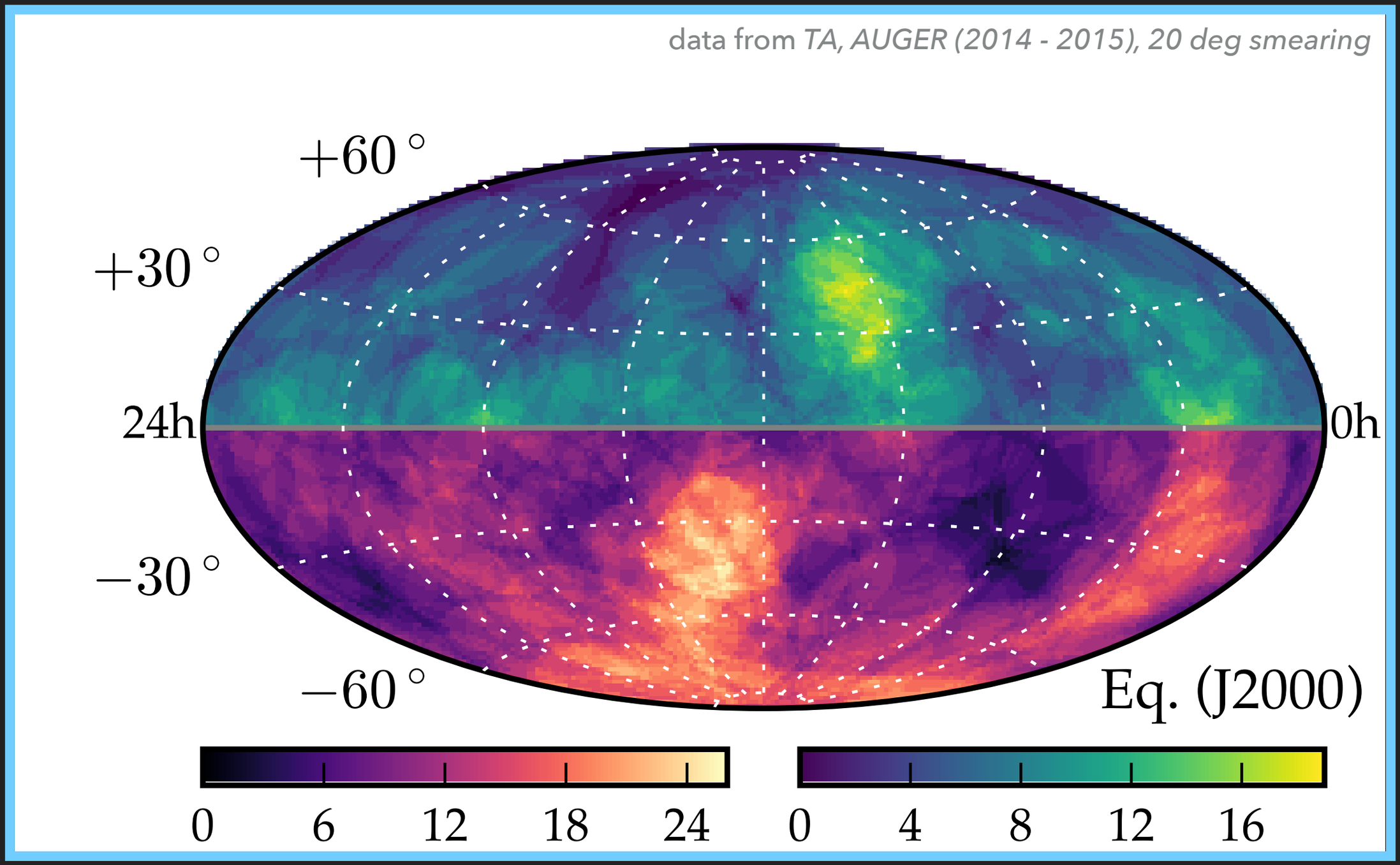
↳excellent angular resolution

↳excellent energy resolution

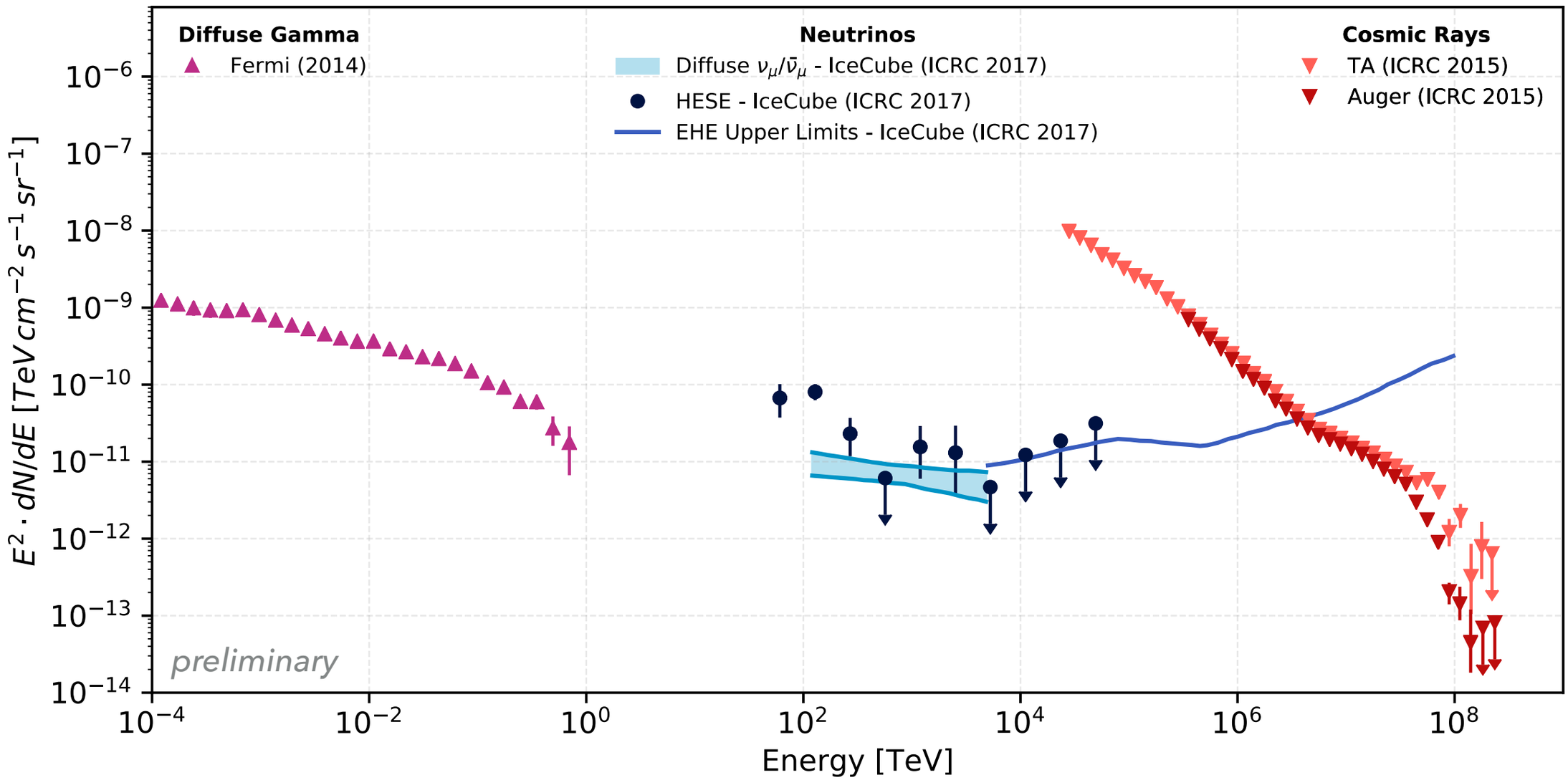
THE OBSERVATIONS: 10^{10}–10^{12} eV SKY IN PHOTONS



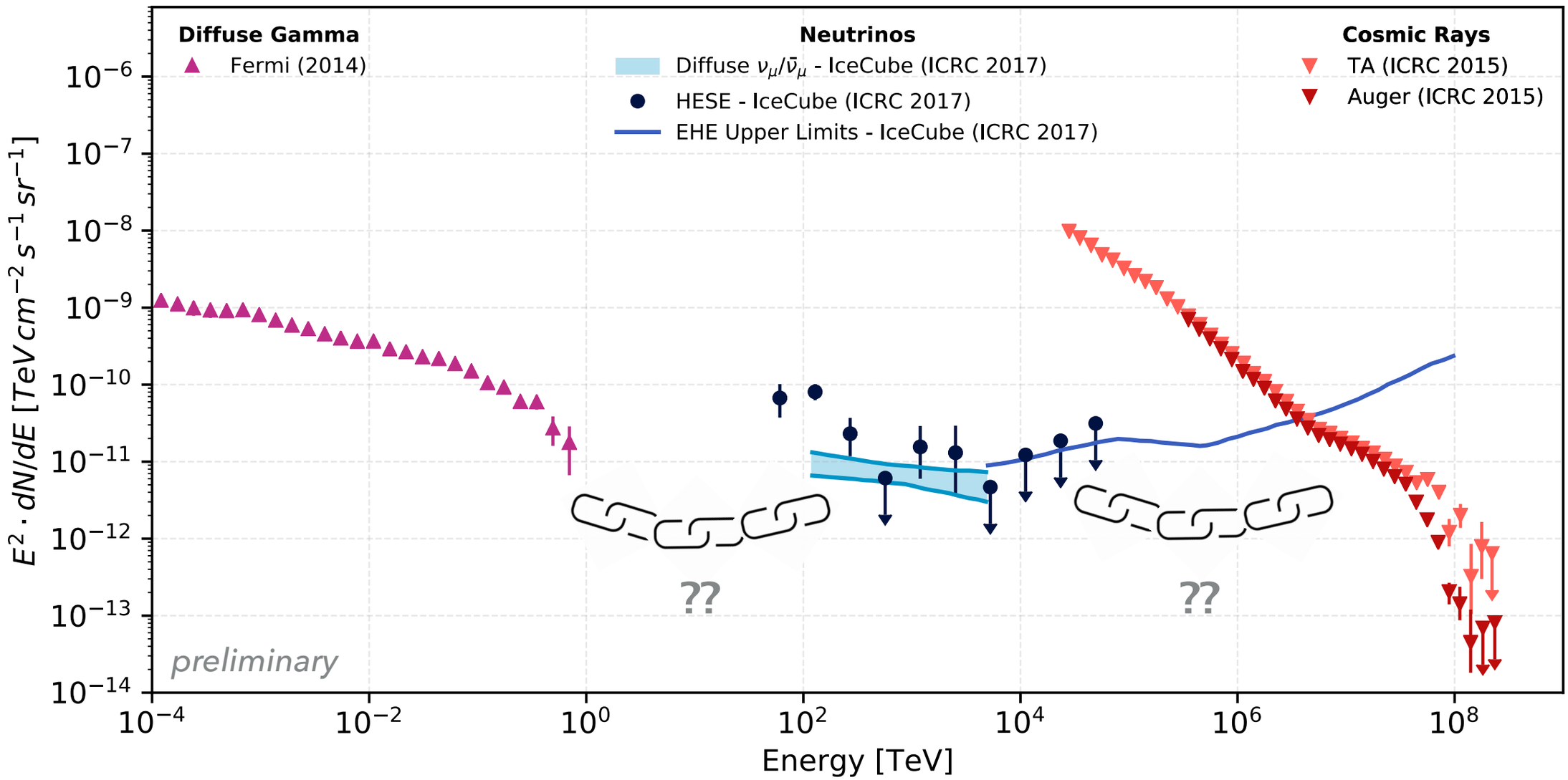
THE OBSERVATIONS: 10^{18}–10^{20} eV SKY IN COSMIC RAYS



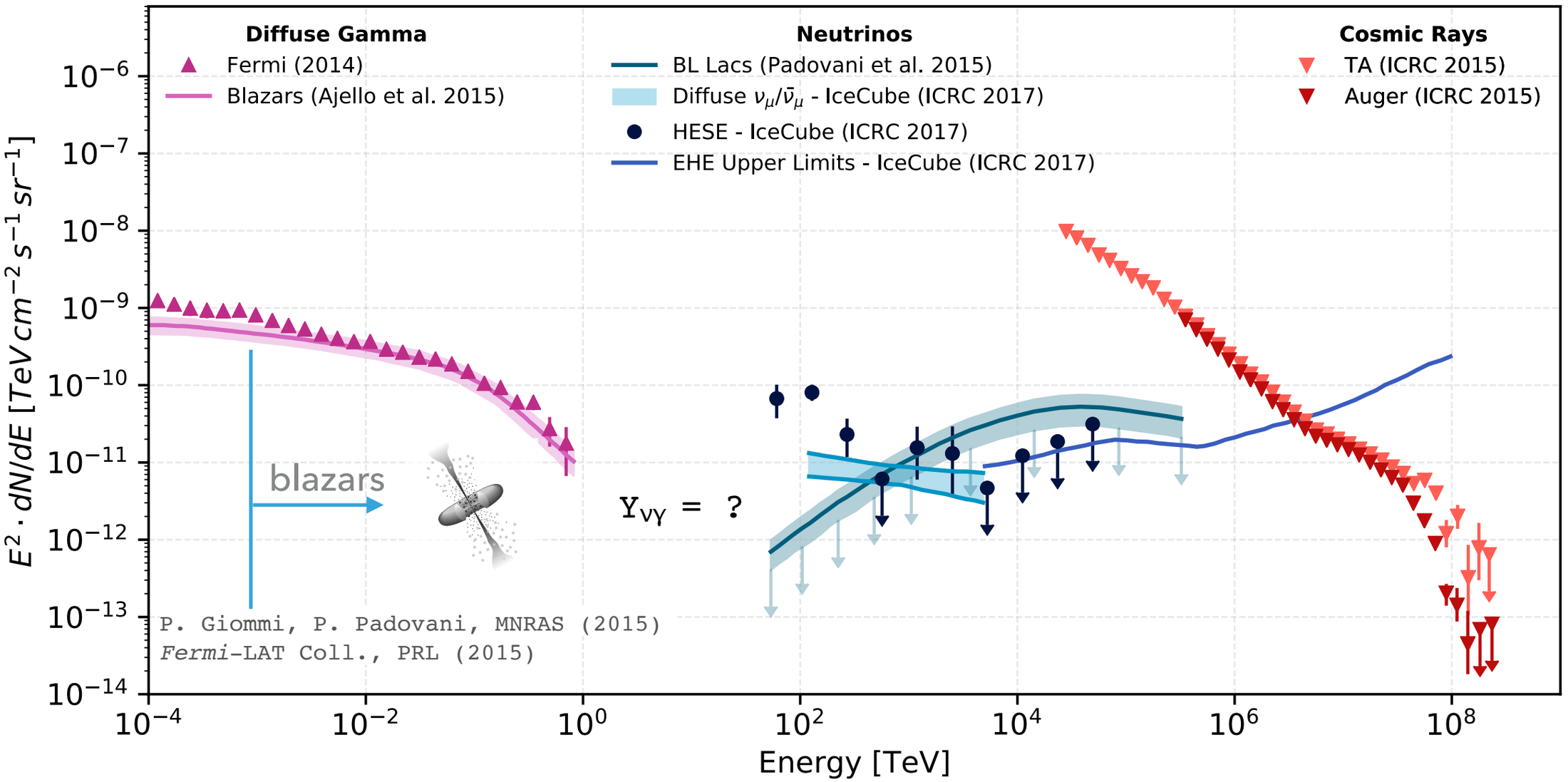
THE OBSERVATIONS: HYBRID SPECTRAL ENERGY DISTRIBUTION



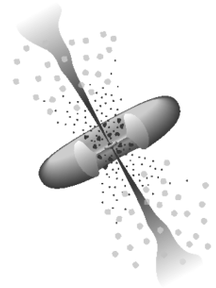
THE OBSERVATIONS: HYBRID SPECTRAL ENERGY DISTRIBUTION



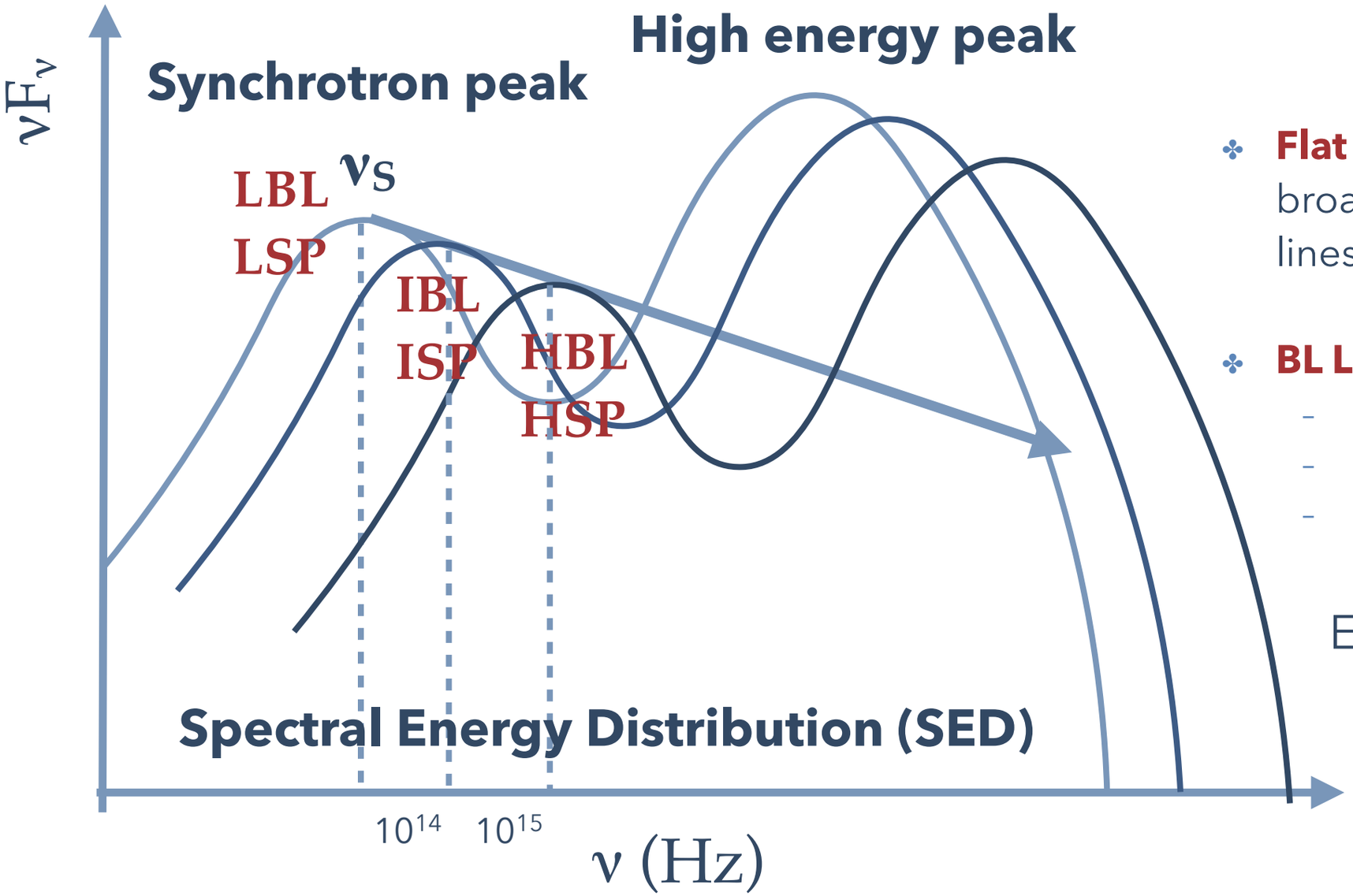
THE OBSERVATIONS: HYBRID SPECTRAL ENERGY DISTRIBUTION



THE SCENARIOS



1- Blazars: Jet dominated AGN. The radiation output is mostly due to non-thermal radia.on from a rela.vis.c jet. ~ 10% of all AGN



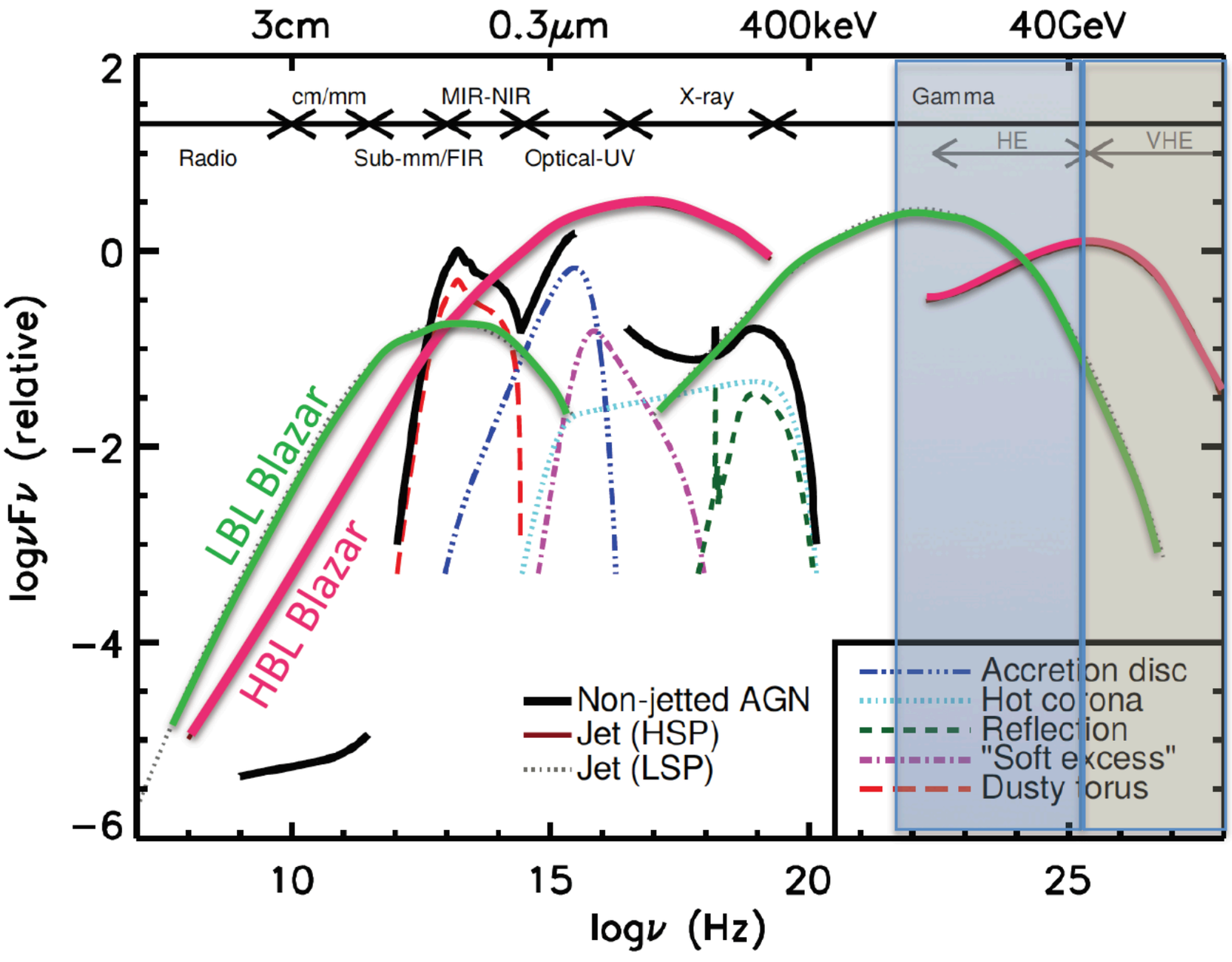
- **Flat Spectrum Radio Quasars**: broad emission features (emission lines) in the optical spectrum
- **BL Lacs**: no broad emission lines.
  - **LBL/LSP**, $\nu_S < 10^{14}$ Hz,
  - **IBL/ISP**, 10^{14} Hz$<\nu_S<10^{15}$
  - **HBL/HSP**, $\nu_S > 10^{15}$ Hz

$E_{em}(\text{FSRQ}) < E_{em}(\text{BL Lacs})$

[Padovani, Giommi, '95]

THE SCENARIOS

1- Blazars: in reality



Active Galactic Nuclei: what's in a name?

P. Padovani · D. M. Alexander · R. J. Assef · B. De Marco · P. Giommi · R. C. Hickox · G. T. Richards · V. Smolčić · E. Hatziminaoglou · V. Mainieri · M. Salvato

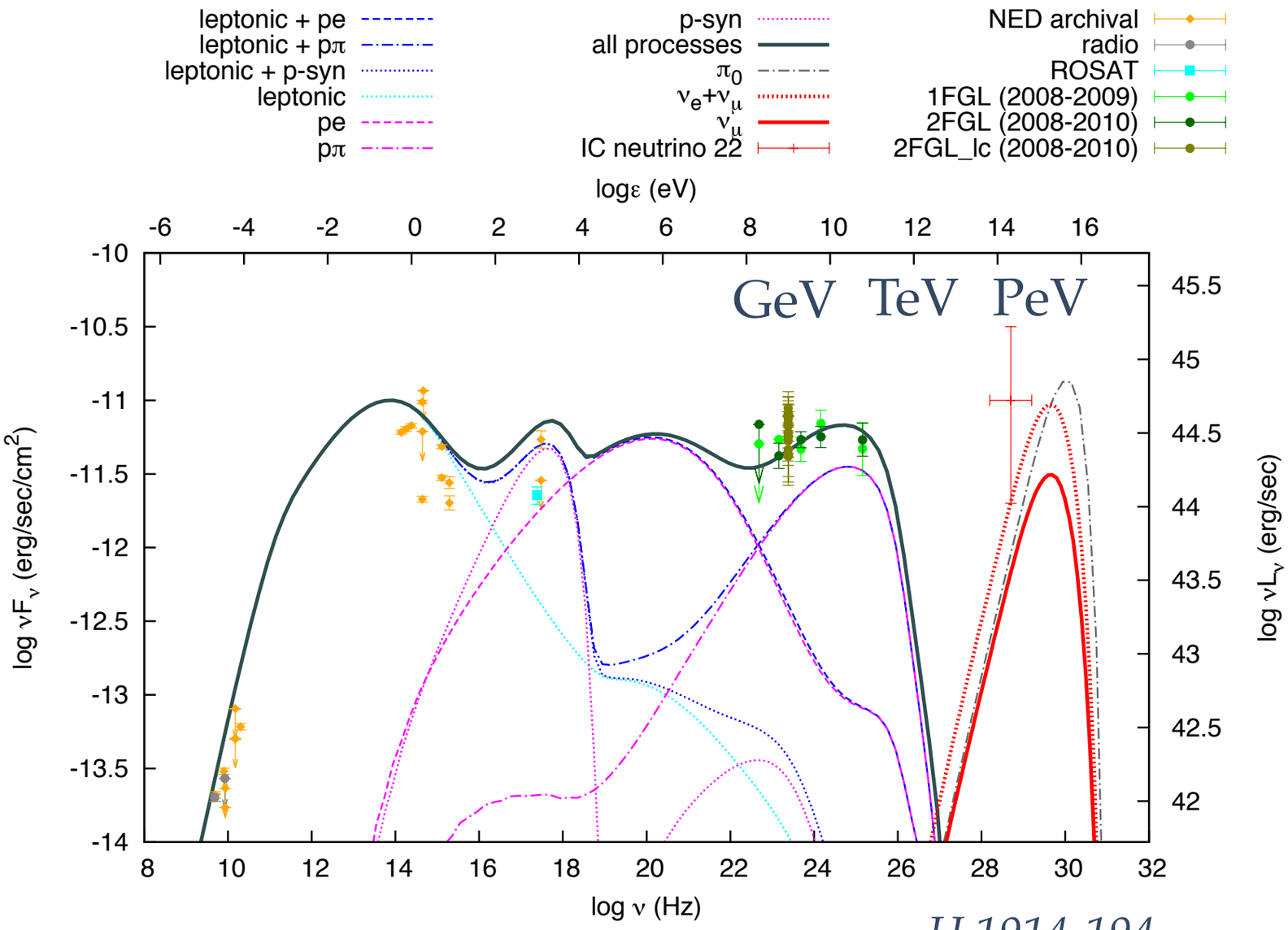
~ 90 pages review submitted to The Astronomy and Astrophysics Review 2017 - To appear on ArXiv soon

THE SCENARIOS

1- Blazars: γ ∝ ν

[M. Petropoulou, S. Dimitrakoudis, P. Padovani, A. Mastichiadis, E.R., MNRAS (2015)]

z	0,137
B(G)	5
R(cm)	3×10^{15}
δ	18
$\ell_{(e,inj)}$	6×10^{-5}
$\ell_{(p,inj)}$	10^{-2}
$\Upsilon_{\nu\gamma}$	2,0



H 1914-194

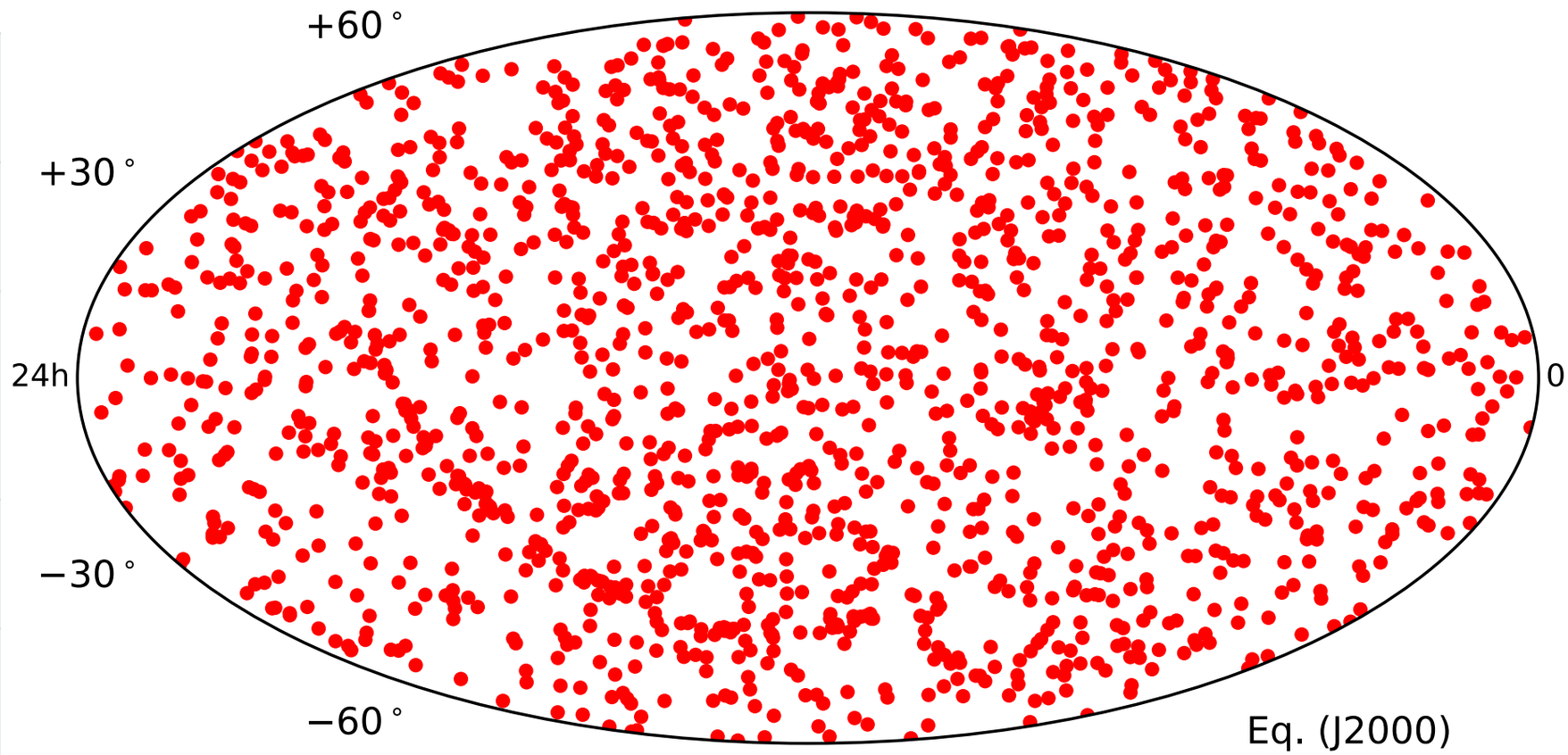
THE SCENARIOS

1- Blazars: Bzcat5; 2WHSP; 3FHL [10GeV– 2TeV]

[Massaro et al. (2015); Y. L. Chang et al., A&A (2016); Fermi Collaboration, arXiv:1702.00664]

3FHL: 1556 objects

BL Lac	712
FSRQ	141
blazar candidate	309
SFR, SBG	1, 4
SNR	17
PWN	8

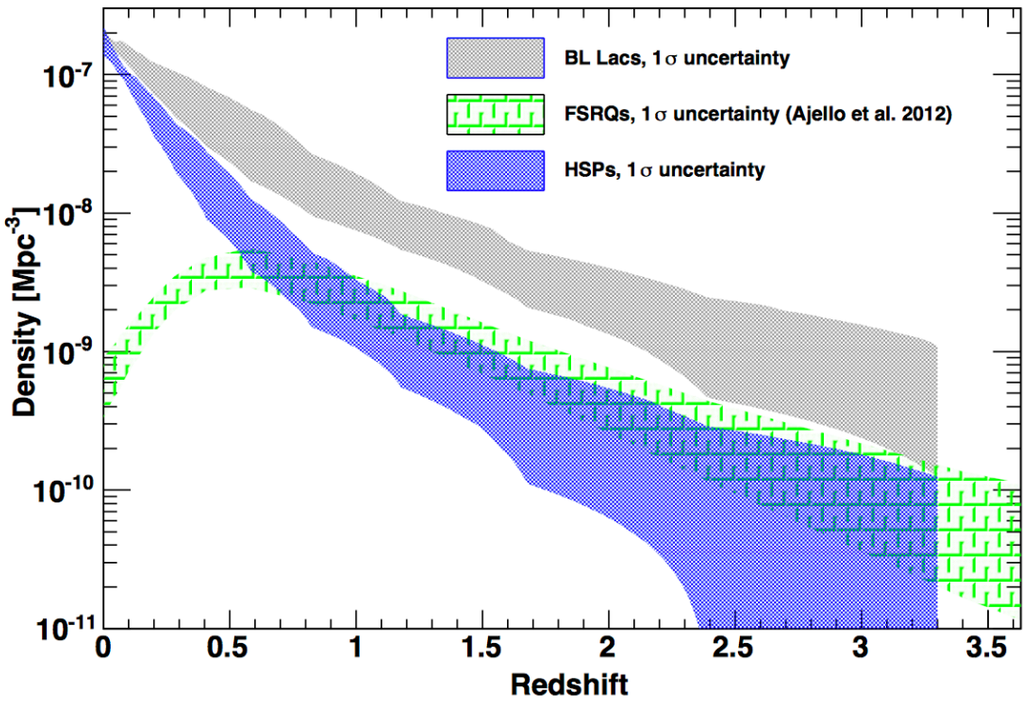


As of today, well over 4,000 blazars are known. This number is increasing rapidly but it remains a small percentage of the over one million AGN known

THE SCENARIOS

1- Blazars: cosmic evolution is different for HSP

[M. Ajello 2013, P. Giommi et al. 1999; V. Beckmann et al. 2003]



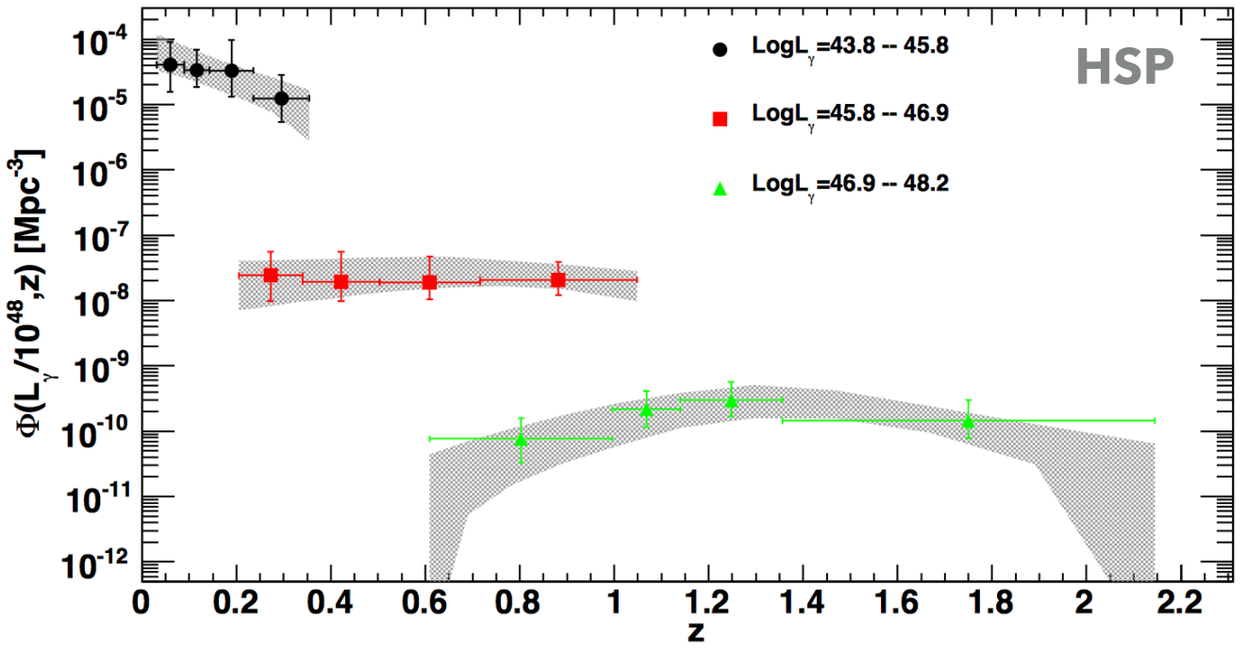


Fig. 10.— Number density (per unit co-moving volume) of BL Lacs, FSRQs and HSPs.

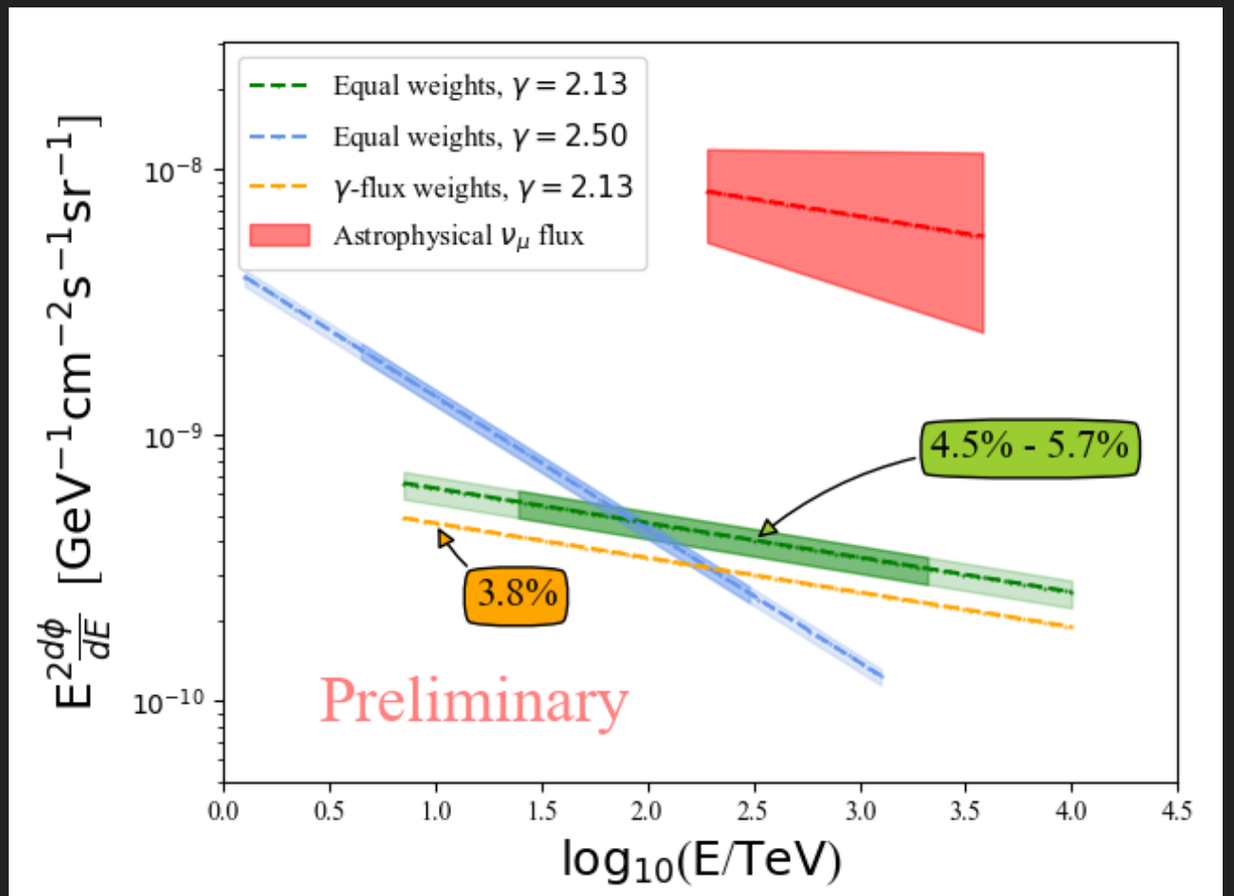
… the evolution of BL Lacs slows down with luminosity, becoming negative for objects with Lγ ≤$10^{45.5}$ erg s^{-1}[…] Subdividing the sample in HSP, ISP and LSP objects we find that the **negative evolution is in fact isolated to the HSP population**, while the ISP and LSP evolve positively from the lowest luminosities.

THE SEARCHES

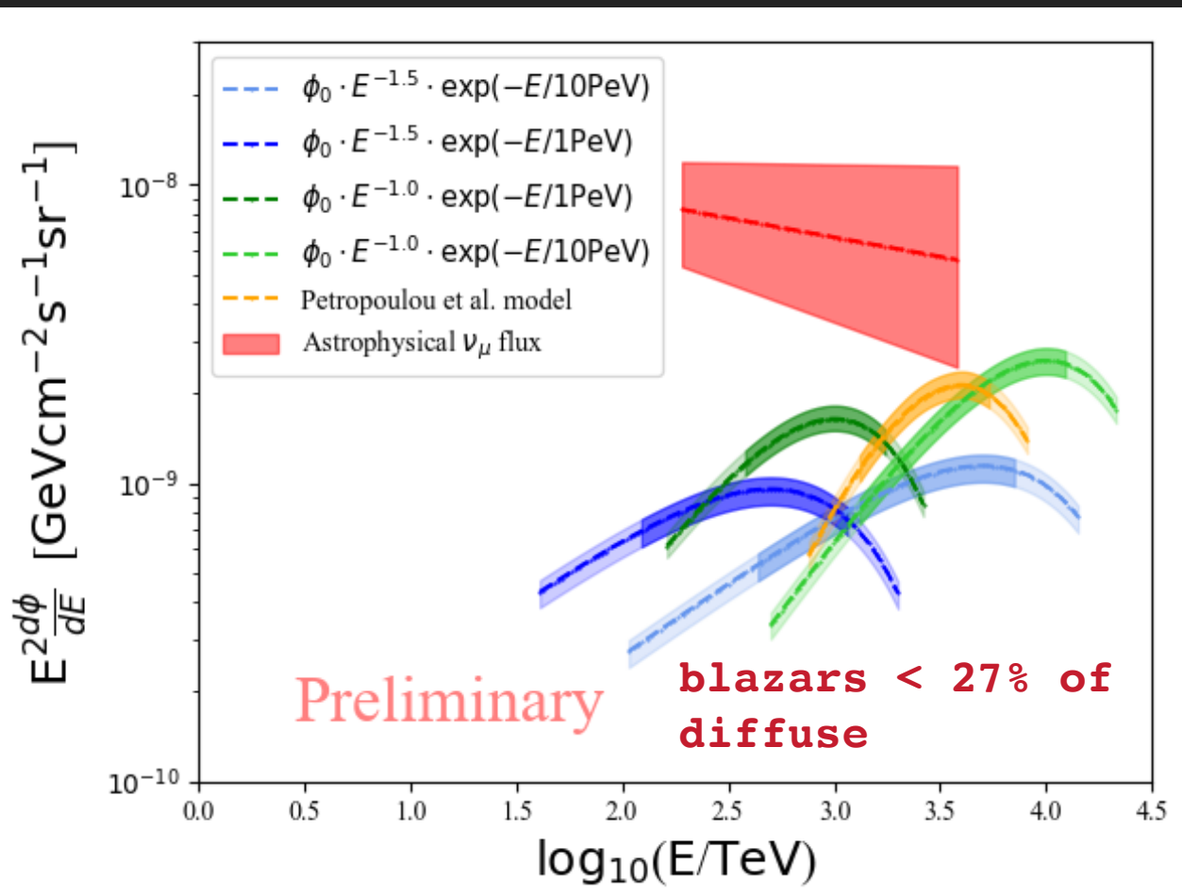
1- Blazars

[IceCube, PoS(ICRC2017)994]

Stacking based on 7 years through going muon sample and 2FHL, 2WHSP, 3LAC catalogues



Unbroken power law assumption



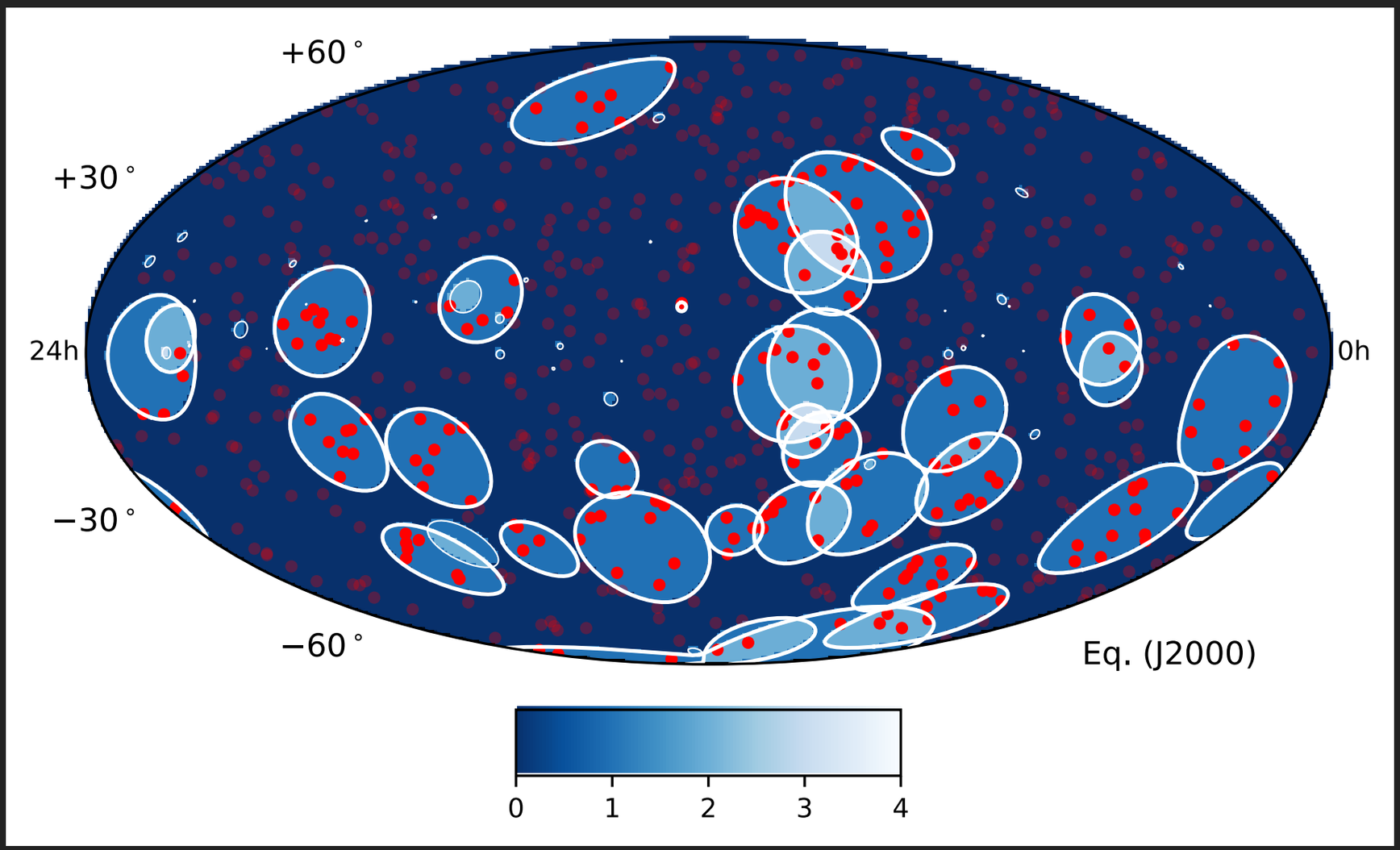
Model dependent assumption

THE SEARCHES

1- Blazars

[P. Padovani et al., MNRAS (2016); E.R. et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]

Neutrinos filter (2FHL, 2WHSP, 3LAT)

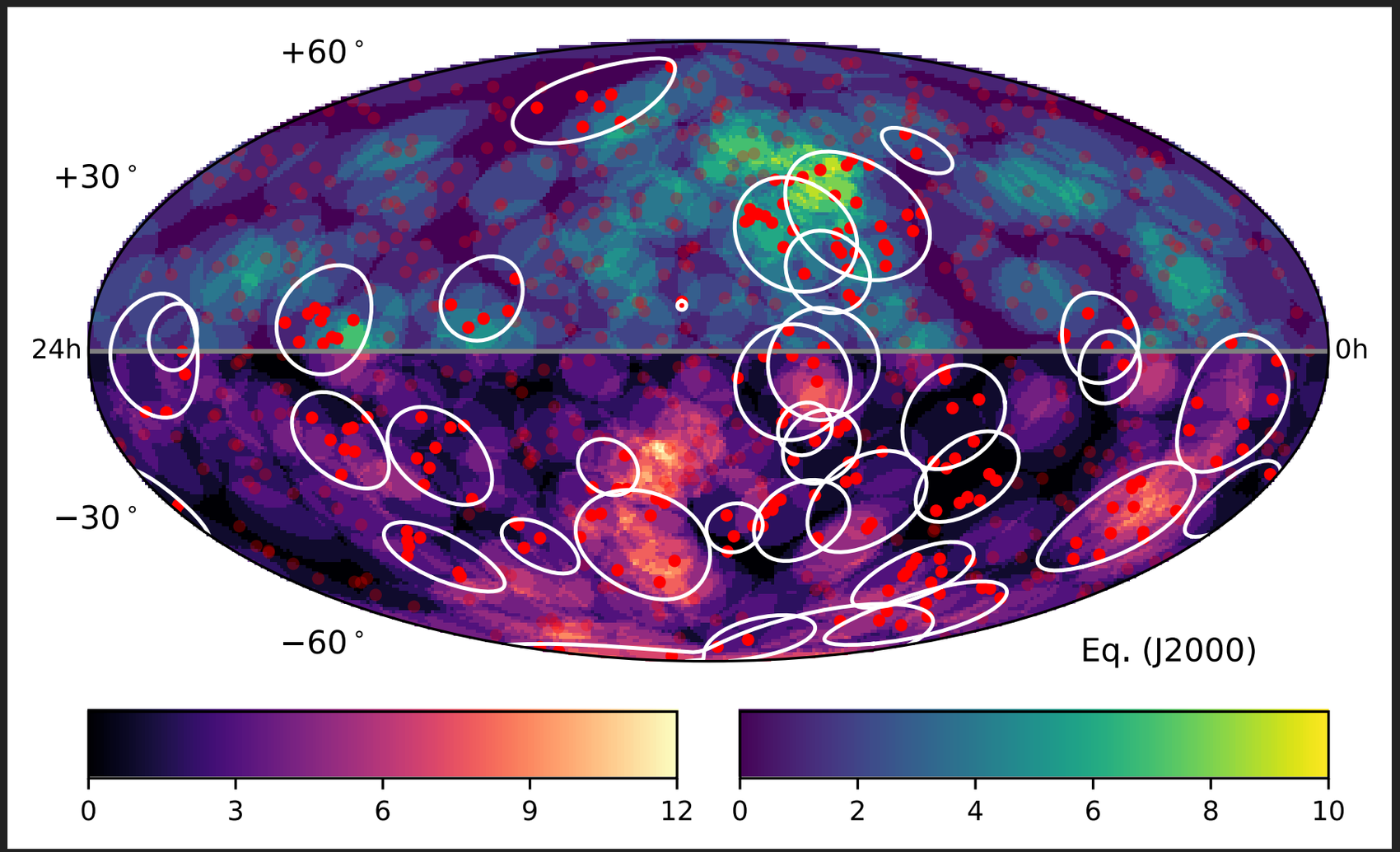


THE SEARCHES

1- Blazars

[P. Padovani et al., MNRAS (2016); E.R. et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]

Neutrinos filter updated to 3FHL, 6 years IceCube HESE

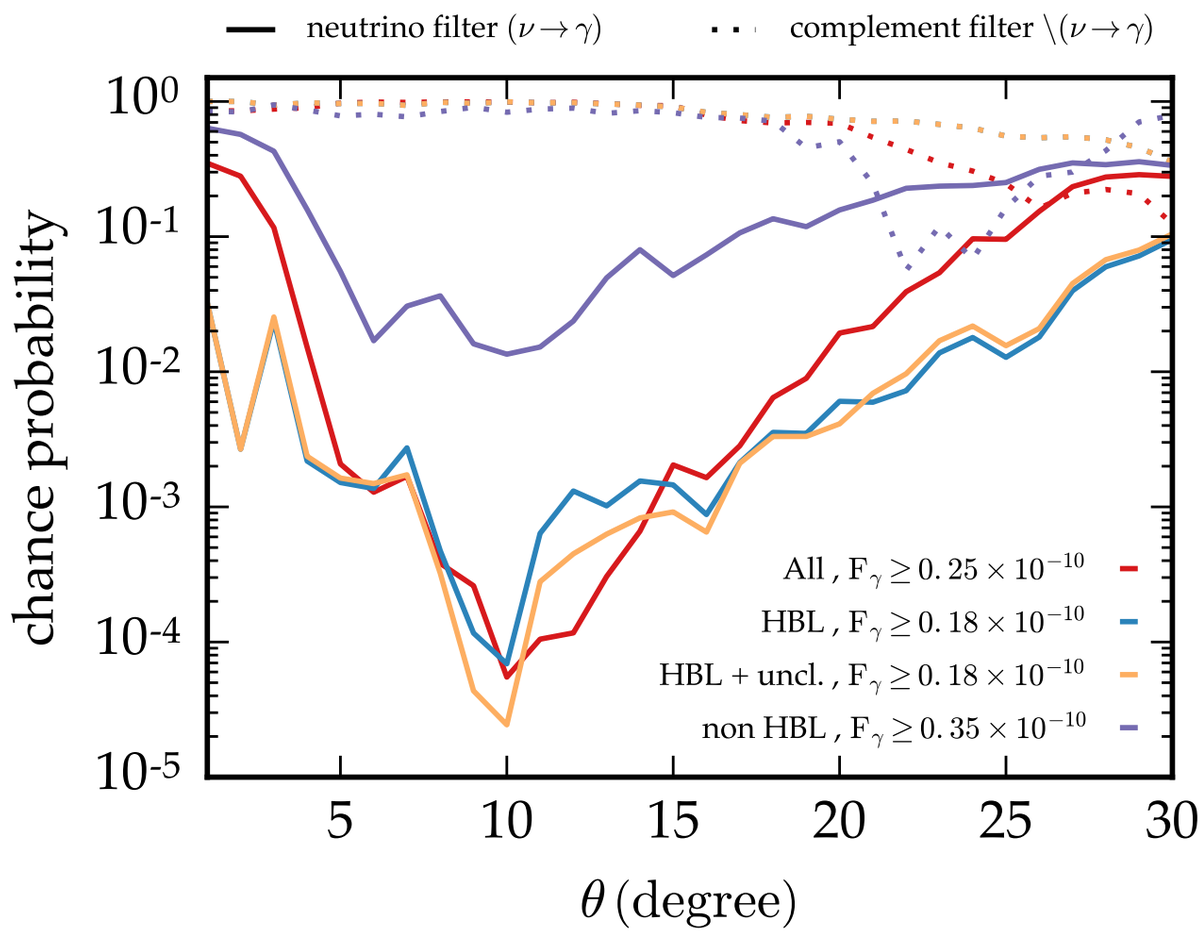


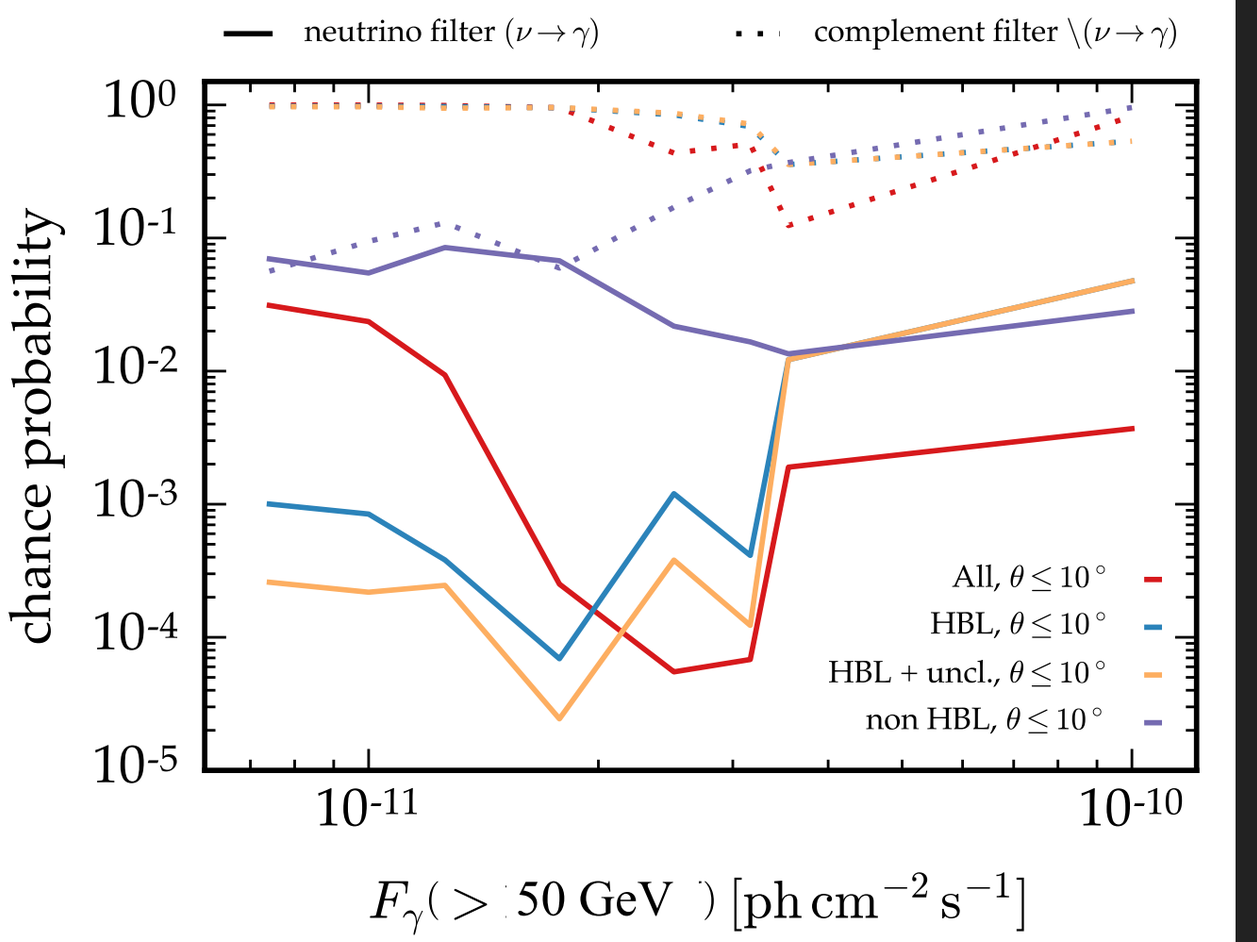
THE SEARCHES

1- Blazars

[P. Padovani et al., MNRAS (2016); E.R. et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]

2FHL, 4 years HESE, 2.9 σ (trial corrected)



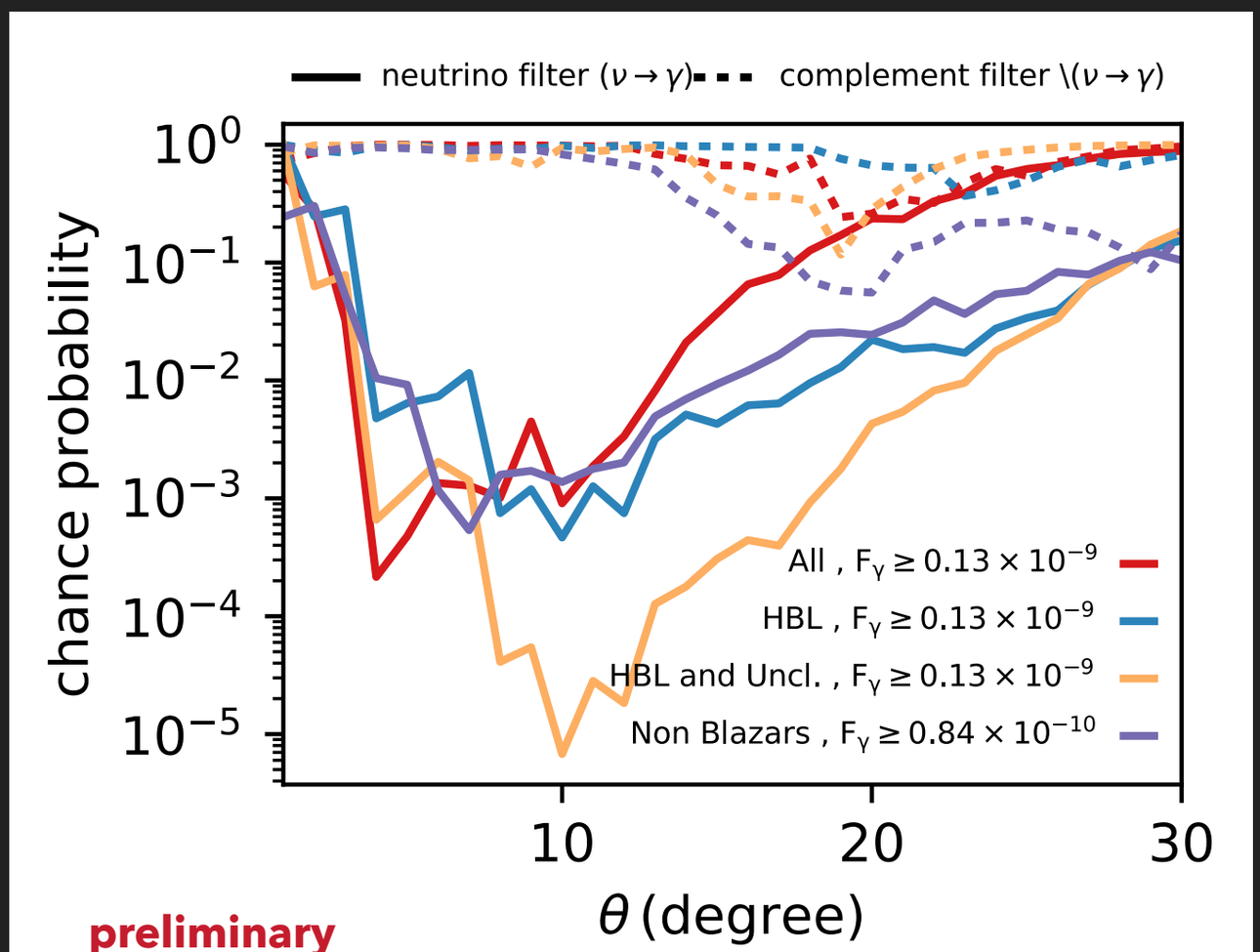


THE SEARCHES

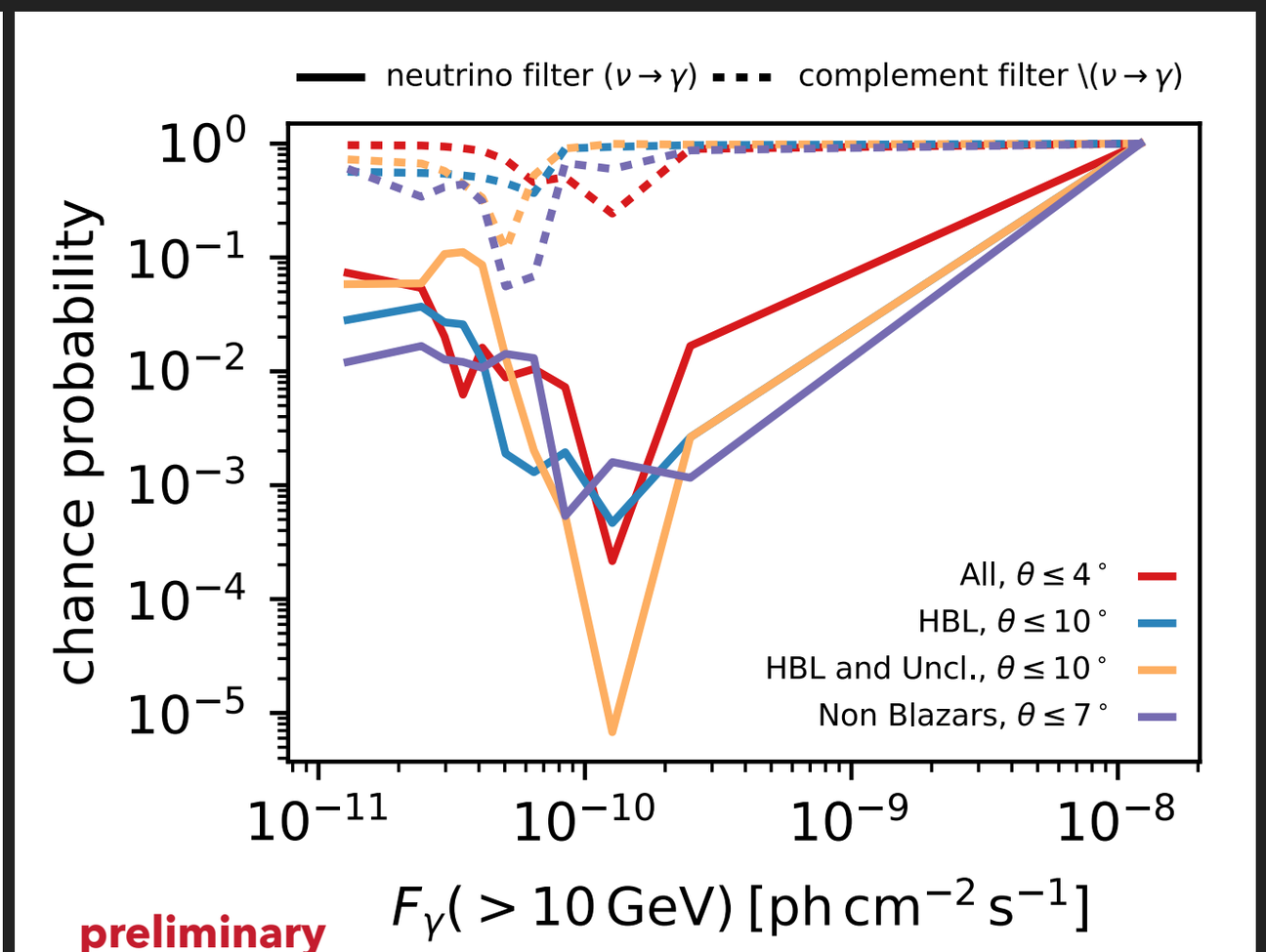
1- Blazars

[P. Padovani et al., MNRAS (2016); E.R. et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]

3FHL, 4 years HESE, 3.35 σ (trial corrected)



preliminary



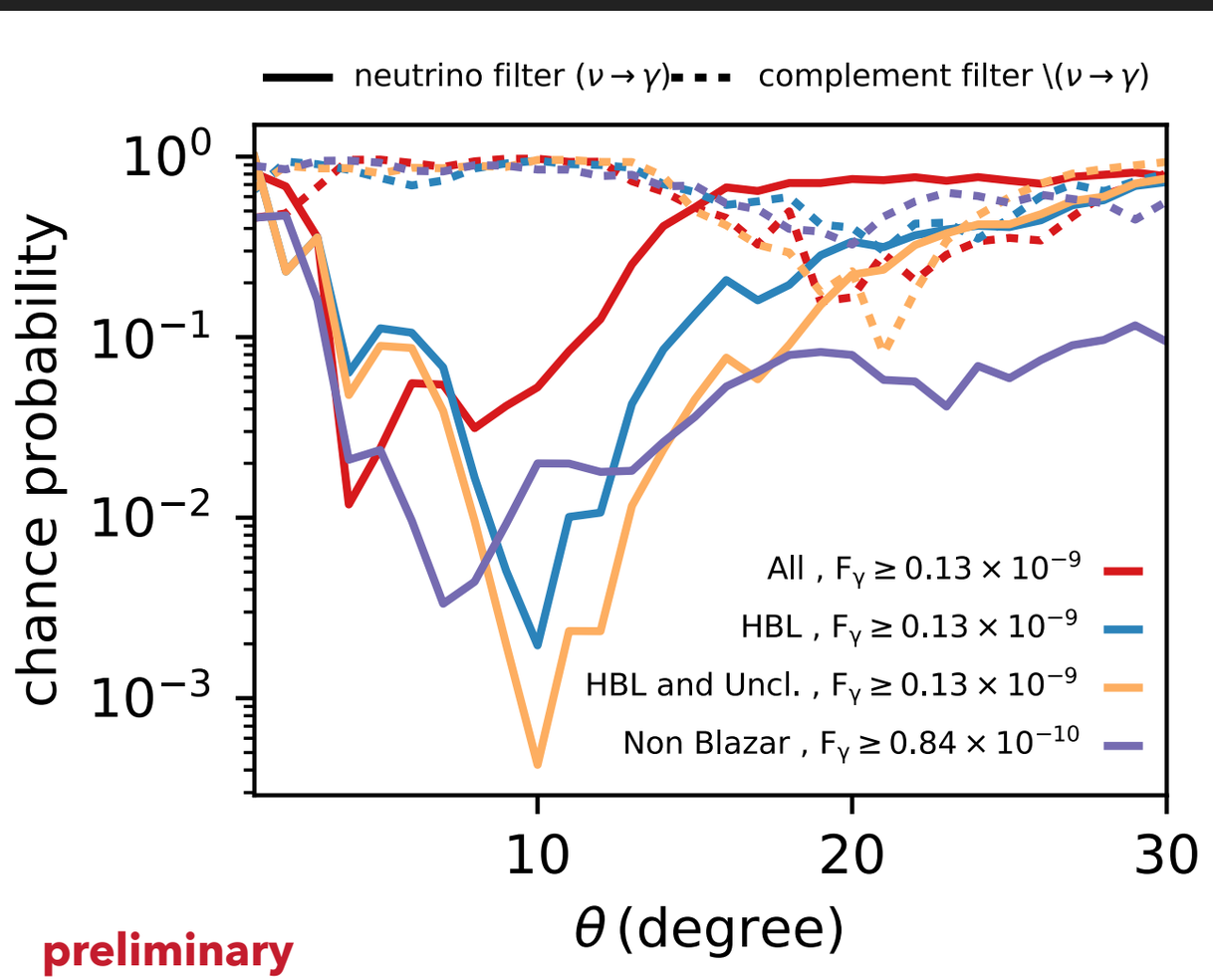
preliminary

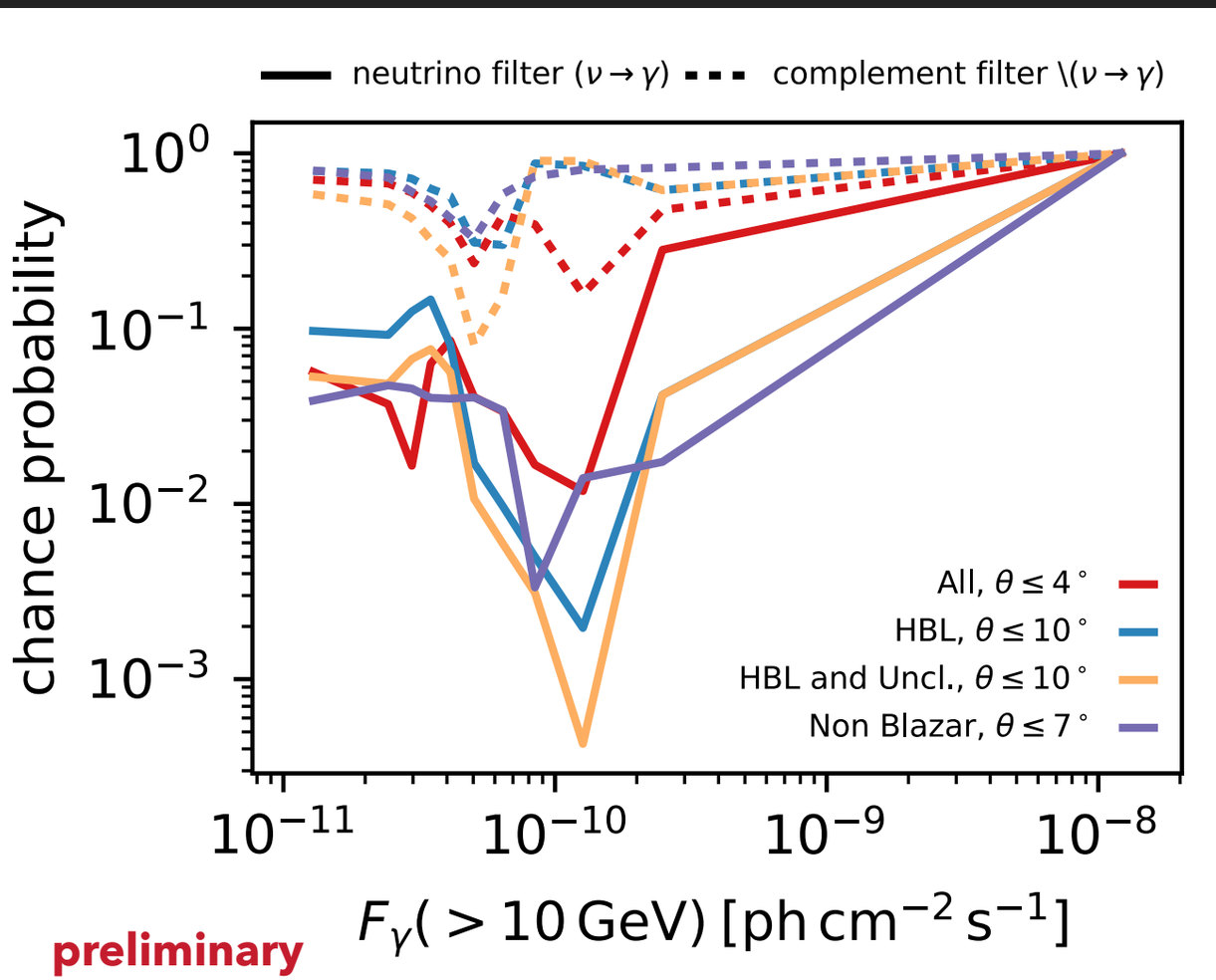
THE SEARCHES

1- Blazars

[P. Padovani et al., MNRAS (2016); E.R et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]

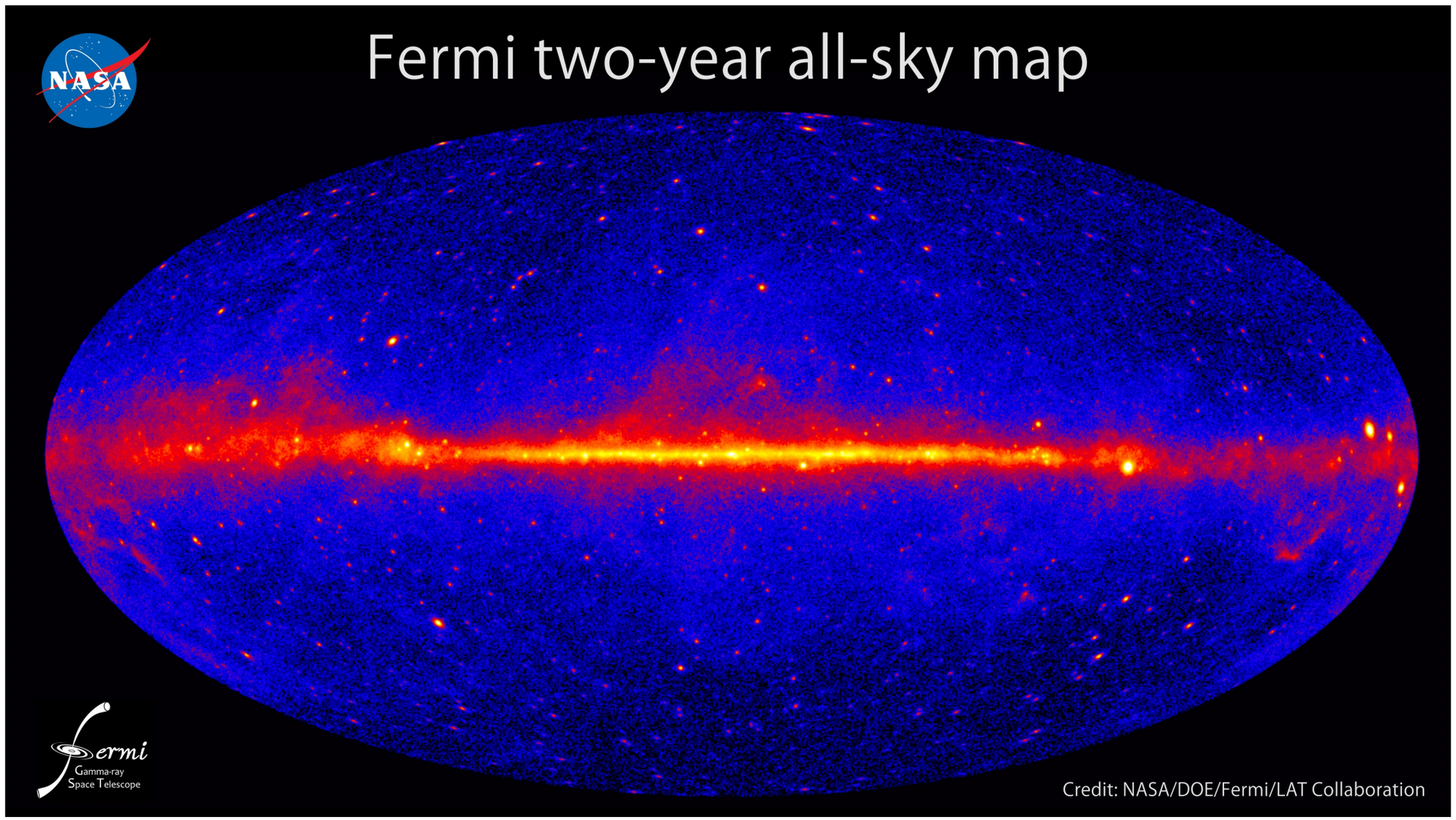
3FHL, 6 years HESE, 2.3 σ (trial corrected)





THE SCENARIOS

2- The Galaxy: also a MM source

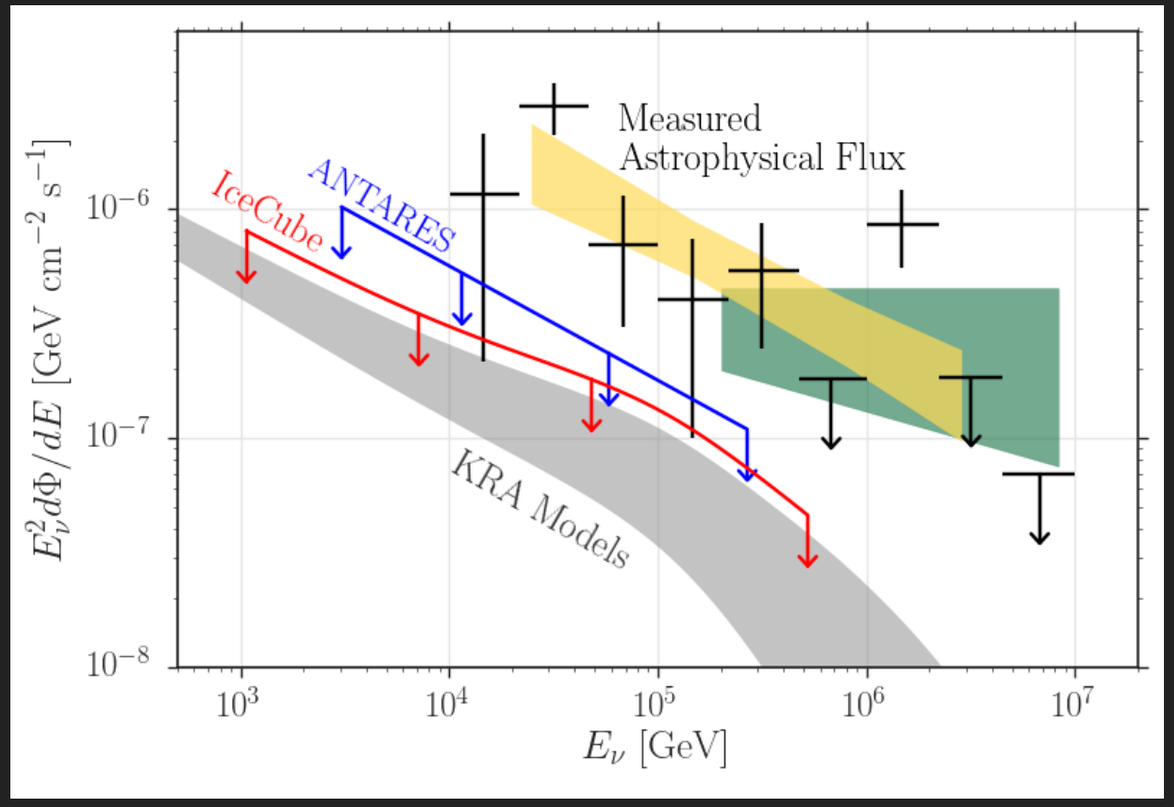


THE SEARCHES

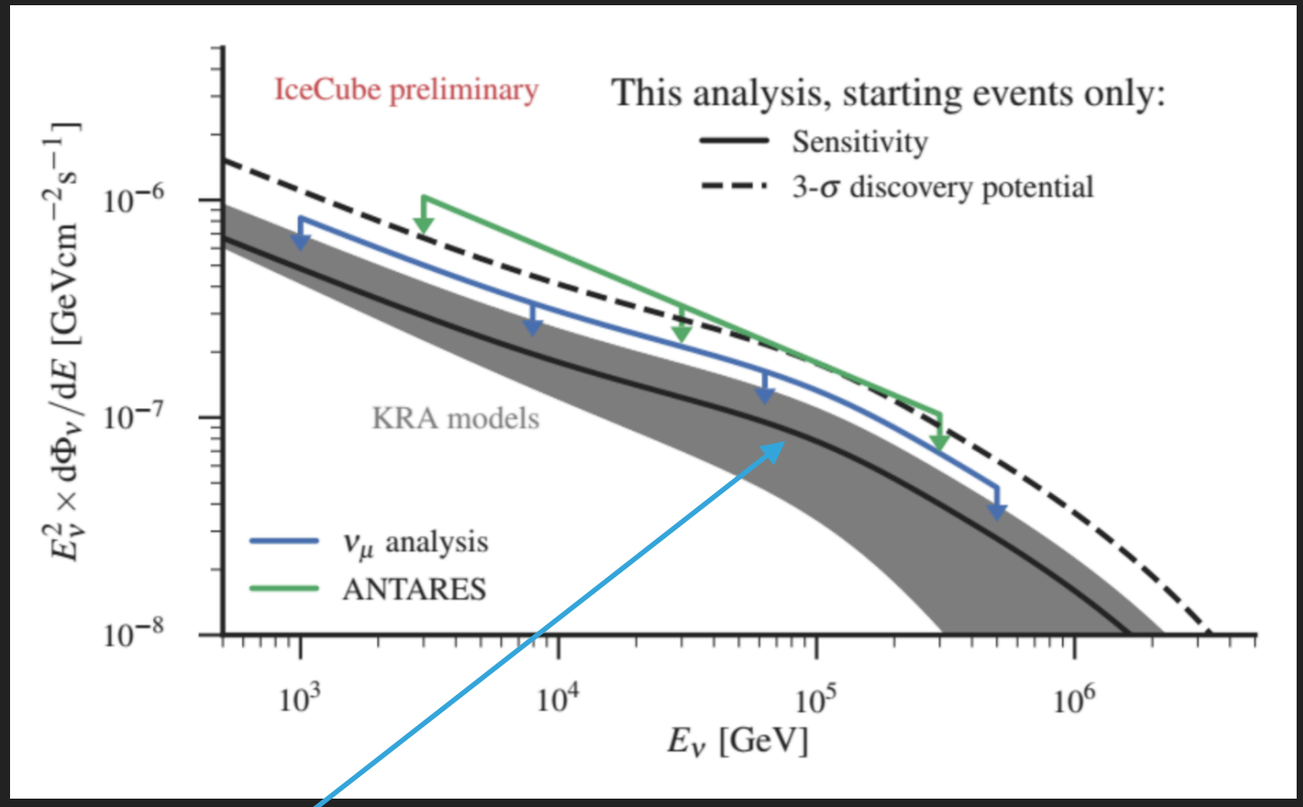
2- The Galaxy: is a MM source

[D. Gaggero et al., ApJL (2015)]

The IceCube Coll., PoS(ICRC2017)1005

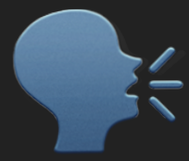


The IceCube Coll., PoS(ICRC2017)995



Entering in the model prediction soon with IceCube

WE NEED MORE COSMIC NEUTRINOS!!!!!!!



THE FUTURE

IceCube-Gen2

PINGU

↳Atmospheric mix. param.

↳Neutrino Mass Ordering

HE array

↳Neutrino astronomy

HE surface array

↳Cosmic ray

KM3NeT

ORCA

↳Atmospheric mix. param.

↳Neutrino Mass Ordering

ARCA

↳Neutrino astronomy

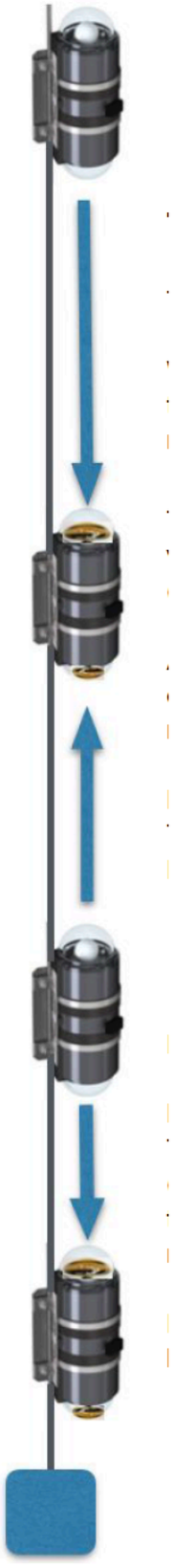
GVD

Focus on UHE showers

↳Neutrino astronomy

STRONG INTEREST FROM A LARGE INTERNATIONAL COMMUNITY

NEXT TO THE FUTURE



OCEAN NETWORK CANADA: A NEW OPPORTUNITY?

Short-term: measurement of the *in-situ* optical properties

Long-term: if optical properties good (and they will be good) run forecasts for

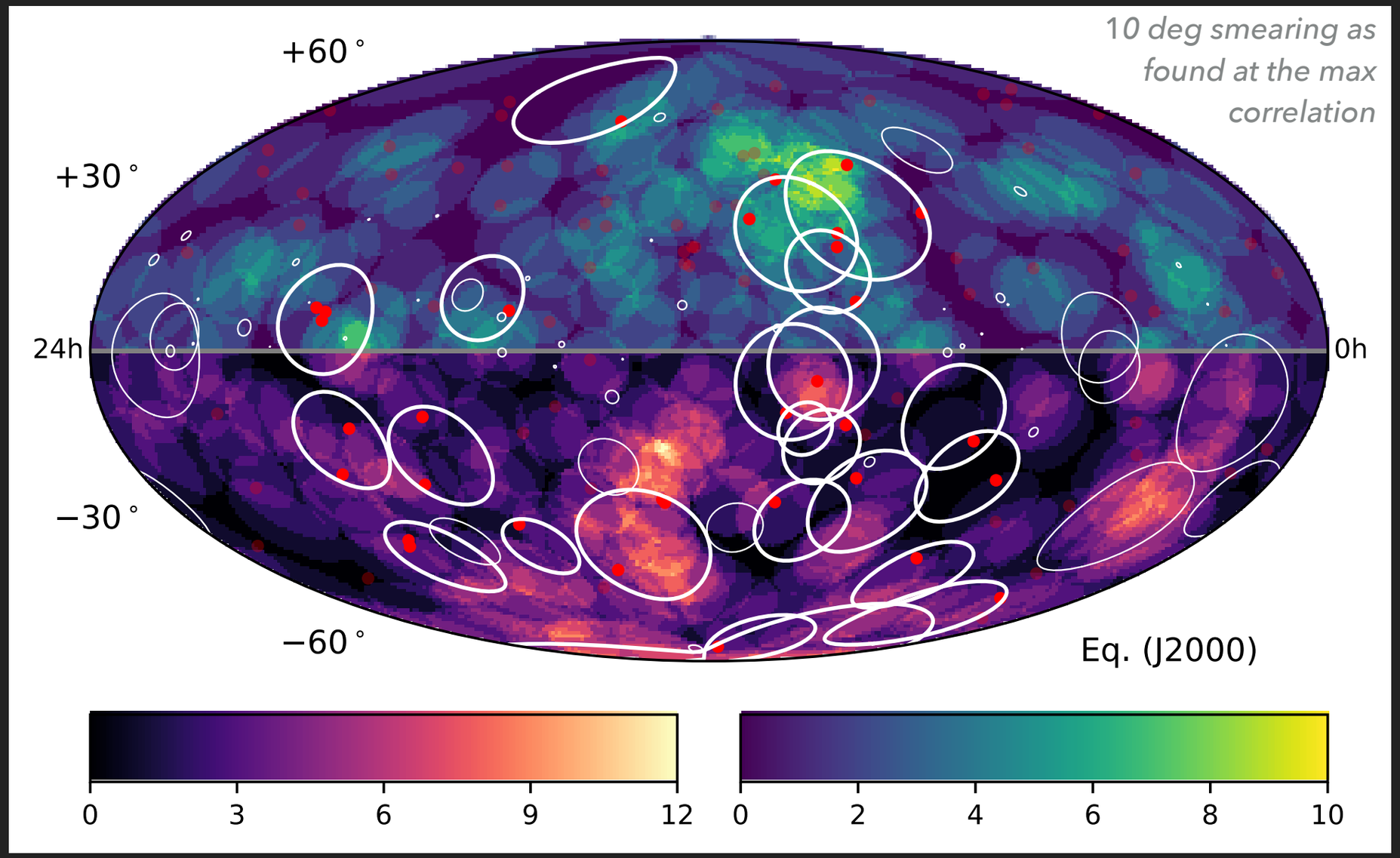
- Multimessenger
- Atmospheric neutrinos
- CP phase, beam lines

"neutrinos are never boring!" (F. Halzen)

THE SEARCHES

1- Blazars

[P. Padovani et al., MNRAS (2016); E.R. et al., MNRAS (2017); E.R. et al., PoS(ICRC2017)1016]



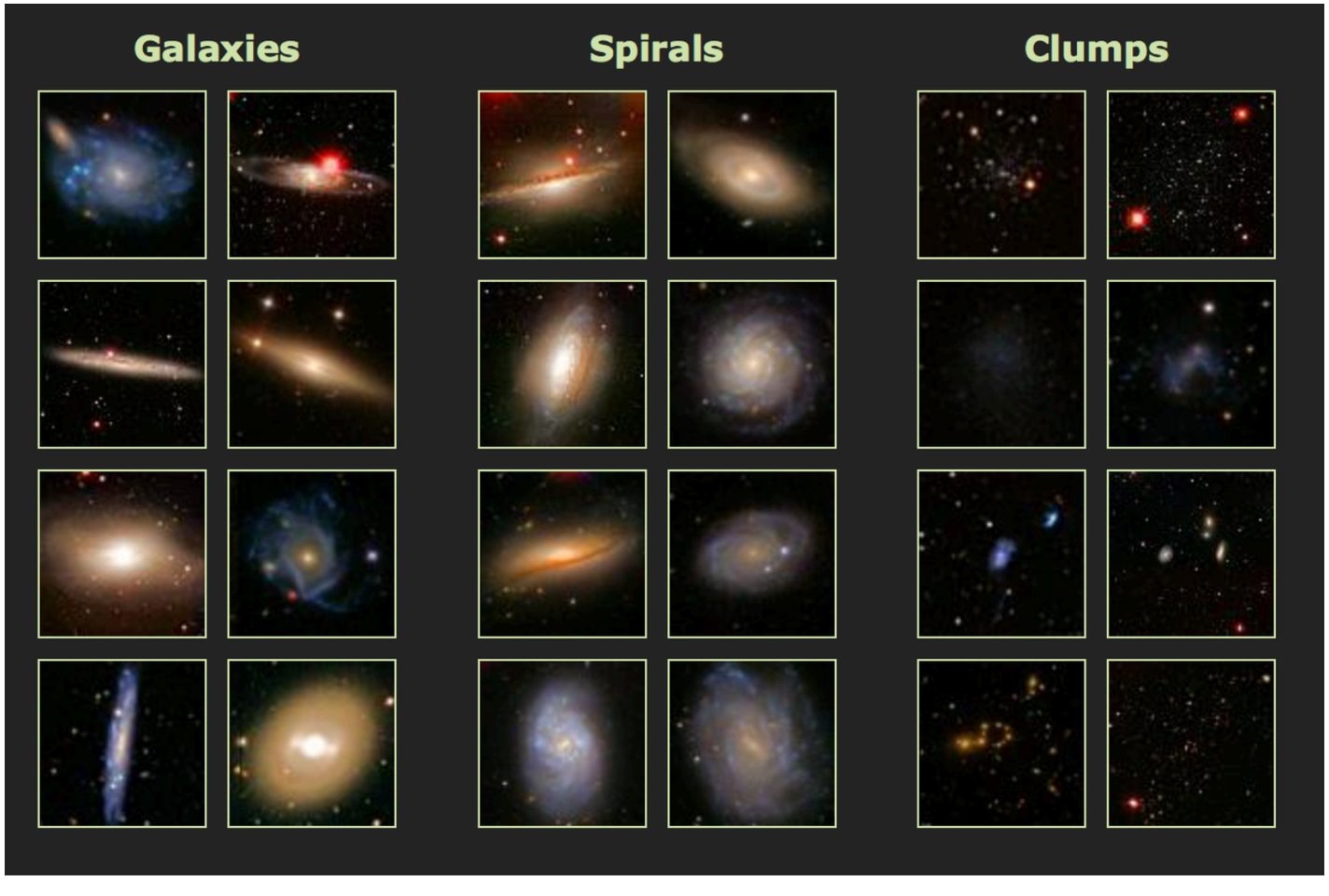
FINAL REMARKS

- The infancy of multi-messenger astronomy
- Rich set of observations in all messengers: best time ever for multi-messenger astronomy
- Many scenarios: equally probable?
- Many searches, few hints, a lot to discover
- We need more / larger neutrino talescopes
  - GVD, KM3NeT, IceCube-Gen2 and ….

SLOAN DIGITAL SKY SURVEY HAS CHANGED THE FACE OF ASTRONOMY

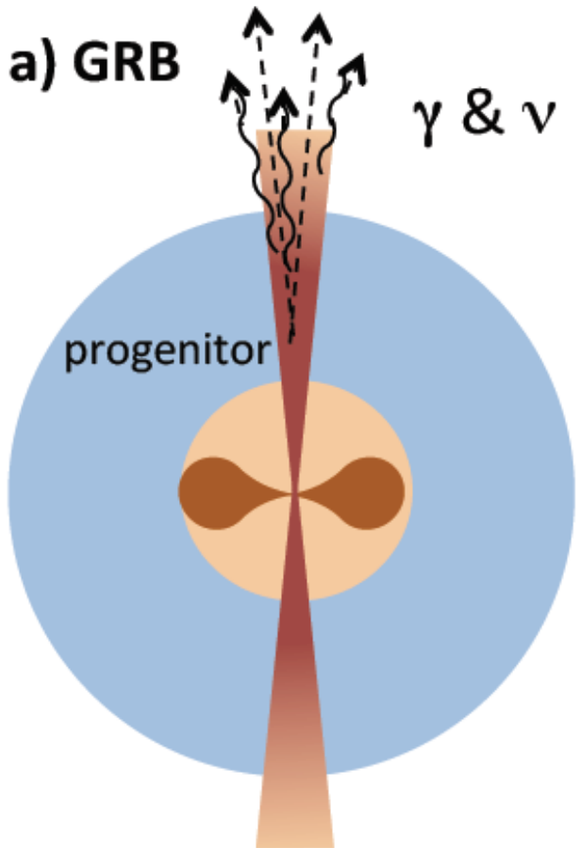
http://www.uchicago.edu/features/20080218_sloan/

- The SDSS began taking data in 1998, following years of planning by scientists at Chicago and elsewhere. The planners include Donald York, the survey's founding director and the Horace B. Horton Professor in Astronomy & Astrophysics and the College, and current director Richard Kron, Professor in Astronomy & Astrophysics and the College. **"Everybody said we were crazy,"** York recalled. But now, added Kron: **"Other collaborations look to us to see how we've done it."**

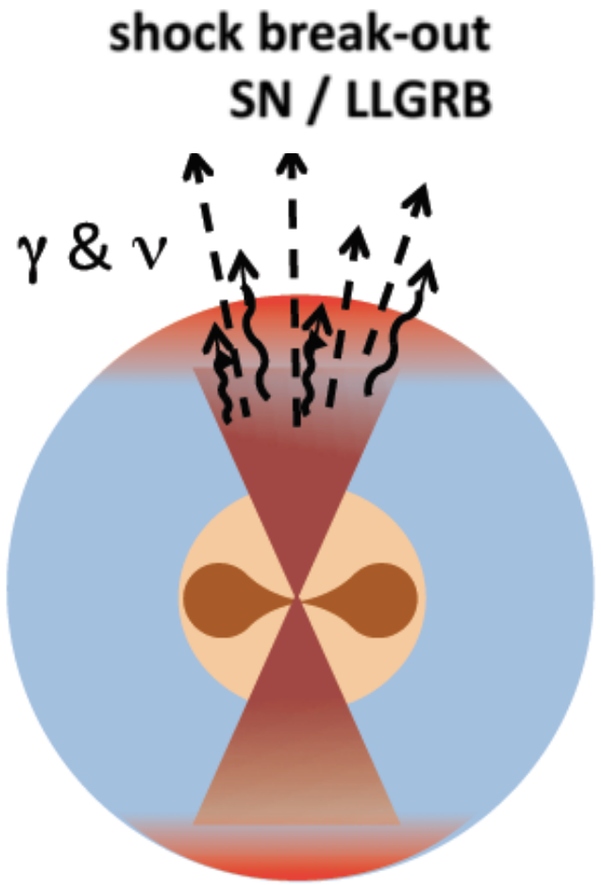


THE SCENARIOS

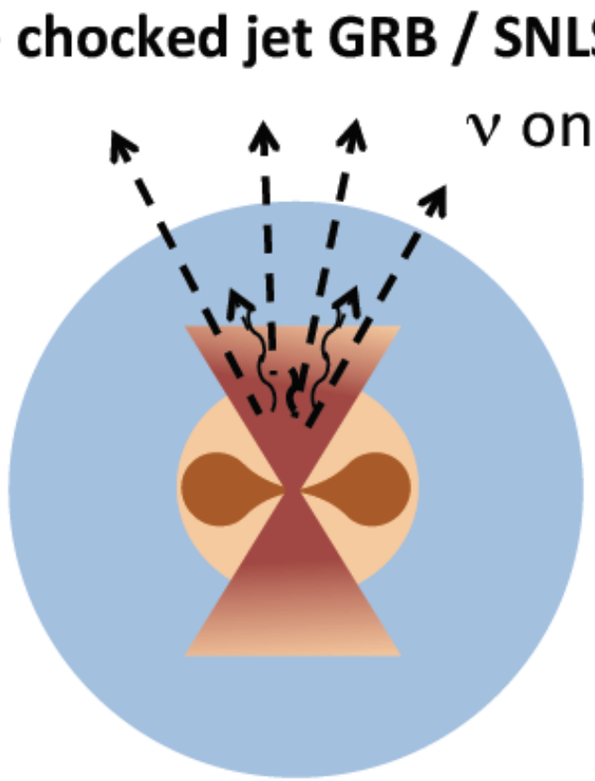
2- Stellar collapses



[E. Waxman & J. Bahcall, (1997)]



[Murase et al, ApJL,651 (2006)]



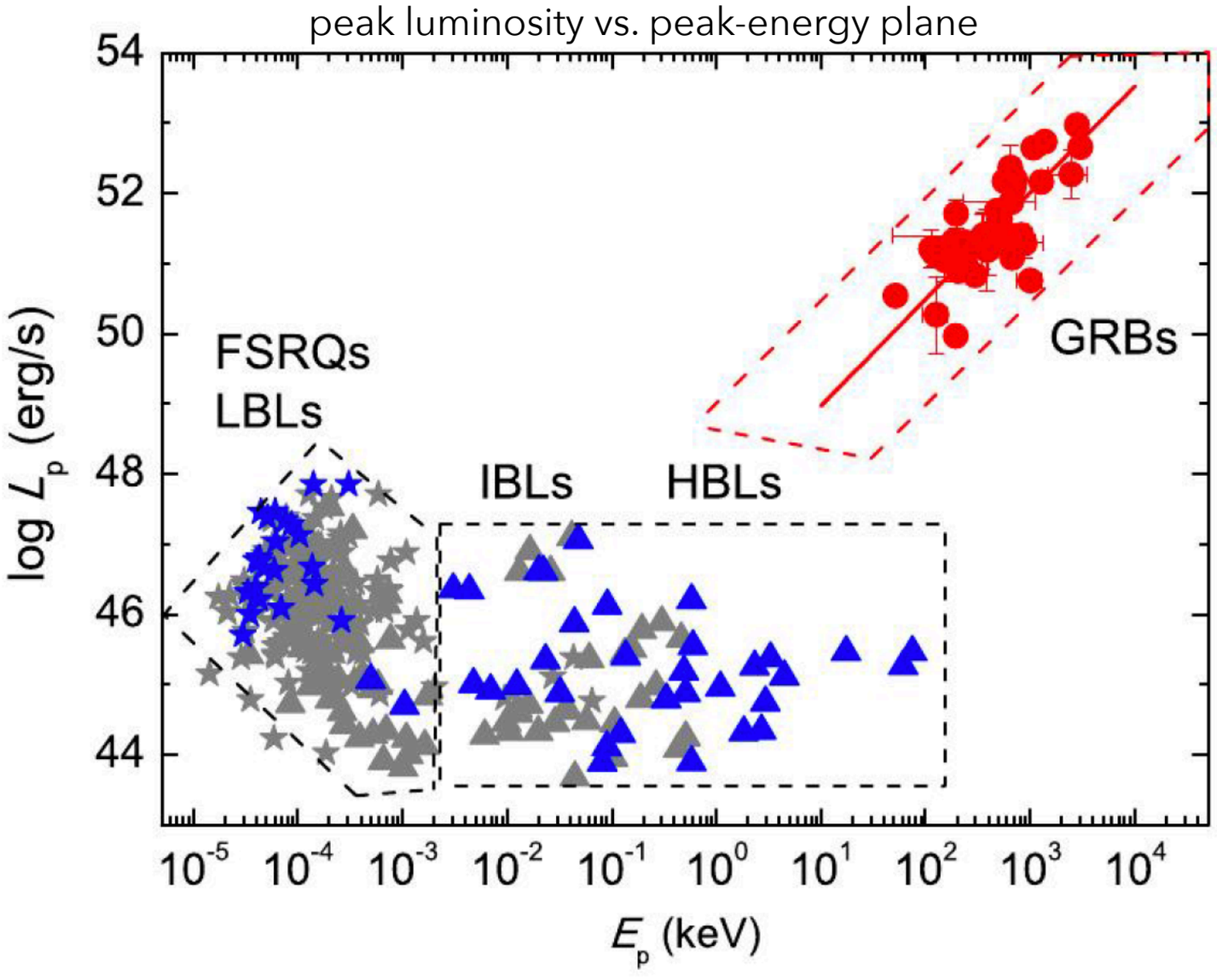
[Ando, Beacom, (2005)
Razzaque, Meszaros,(2004)]

credit to Anna Franckowiak

THE SCENARIOS

2- Stellar collapses: GRBs

[F. Lyu, et al., (2014); H.F. Yu, H.J. Eerten, J. Greiner, et al.,(2015)]



Physical understanding of GRBs incomplete:

(i) most γ-ray spectra of the prompt emission are too sharp to be consistent with synchrotron emission;

(ii) simultaneous optical/ γ-ray observations of the prompt emission suggest that the emission is non-isotropic in the co-moving blast-wave frame;

(iii) plateaus in the X-ray light curves of GRB afterglows as well as bright supernovae related to GRBs suggest energy injection over days to weeks, rather than seconds, giving preference to magnetic models rather than black hole formation.

THE SCENARIOS

3- Star-forming galaxies, starburst galaxies

[D.A. Perley et al., arXiv:1602.00770; S. Ohm, arXiv:1601.06386; X. Wang and B. D. Fields arXiv:1612.07290; A. Loeb, E. Waxman, JCAP(2006)]

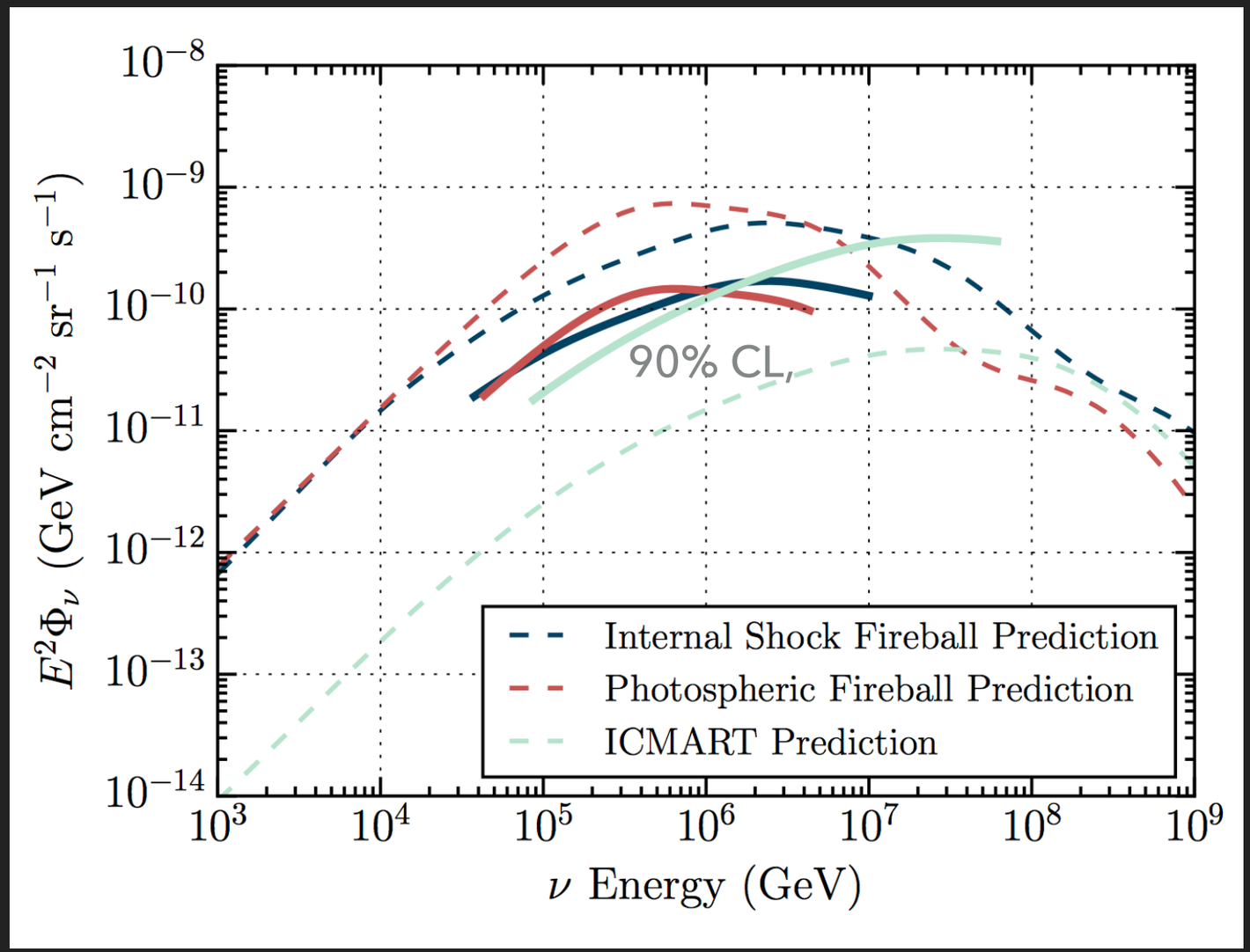
- Long-duration GRBs: host galaxies are star-forming
- Star-forming galaxies as proton calorimeters, high-energy neutrinos and photons sources
- CR as important star-formation regulator or even galaxy formation
- Few objects detected in γ-rays: M82, NGC253, NGC4945, NGC1068, Circinus and the ultraluminous infrared galaxy Arp220
- Evolve cosmologically with peak z~1-2:
  - if UHECRs sources, where is the diffuse produced by the far away objects?

THE SEARCHES

2- Stellar collapses: GRBs

[IceCube Coll., Nature, (2012); IceCube Coll., ApJ (2017); ANTARES Eur.Phys.J. C77 (2017) no.1, 20]

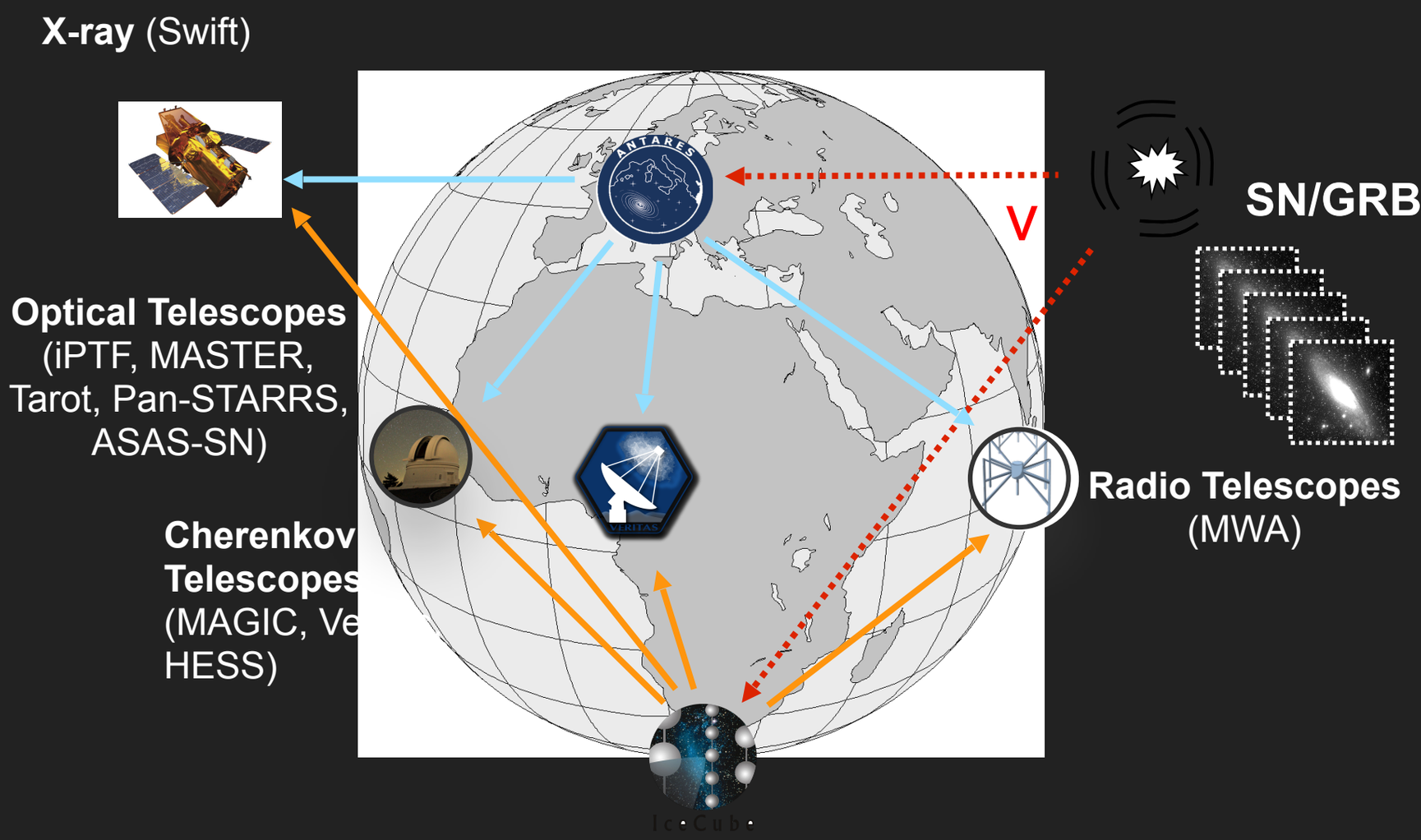
constraining single-zone fireball models of GRB neutrino



THE SEARCHES

2- Stellar collapses

[IceCube, MAGIC, VERITAS, arXiv: 1610.01814
ANTARES JCAP 1602 (2016)
Ackermann et al.arXiv:0709.2640
IceCube A&A 539, A60 (2012)]



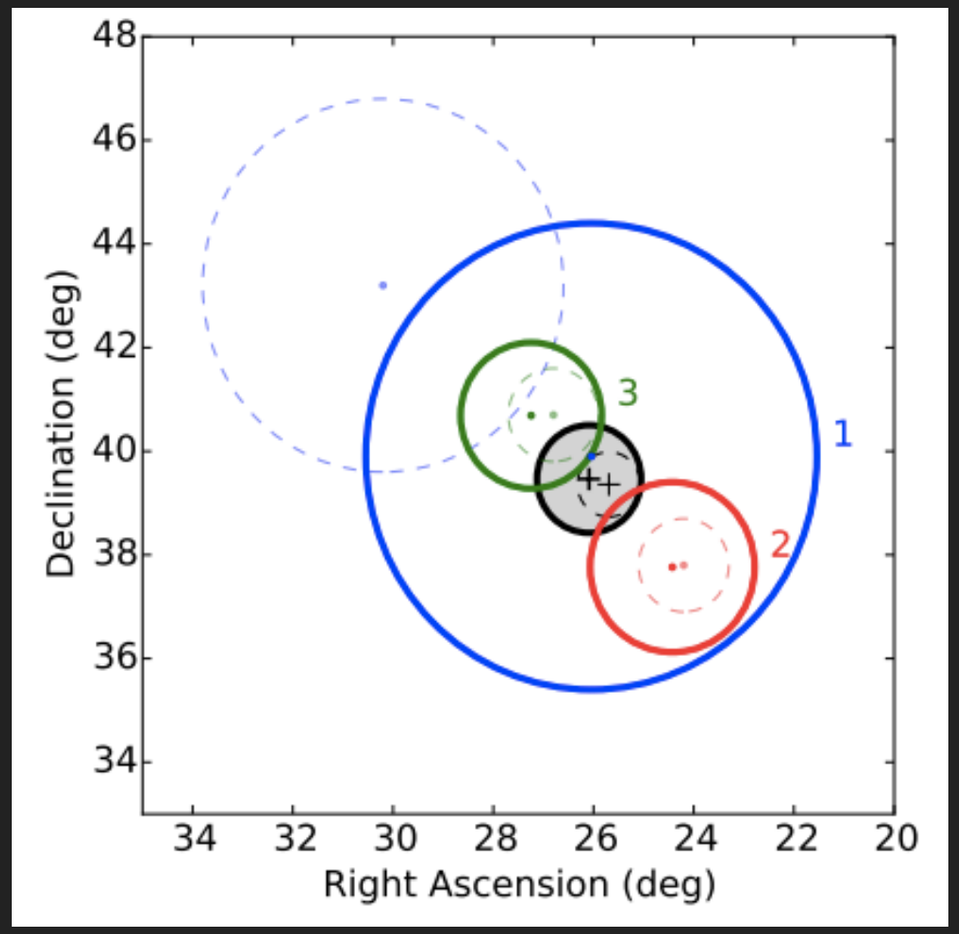
credit to Anna Franckowiak

THE SEARCHES

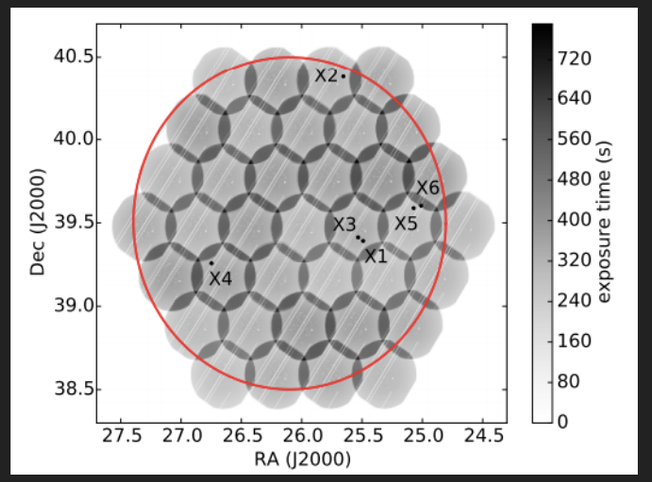
2- Stellar collapses

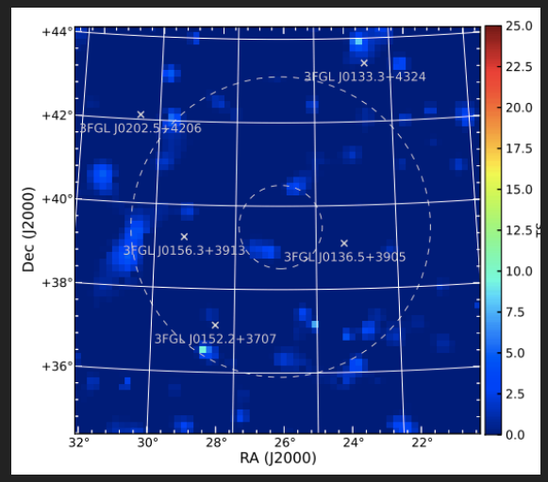
[IceCube, ASAS-SN, AMON, Fermi, VERITAS, HAWC, LCO, Swift, MASTER, arXiv:1702.06131]

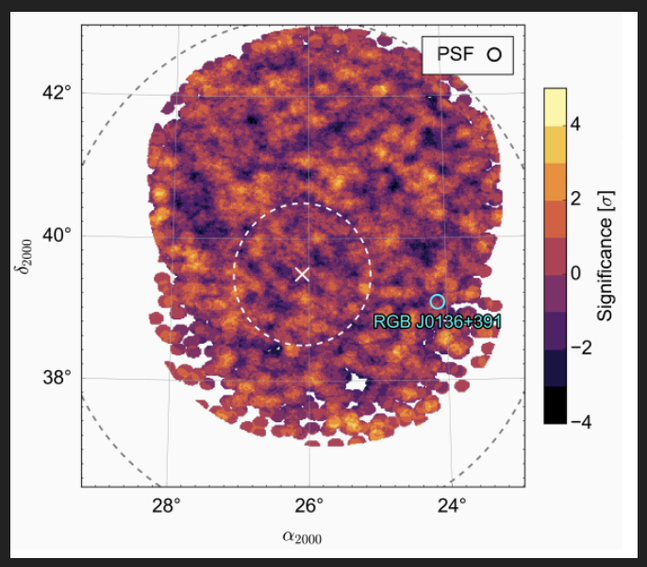
> Expected from background once every 13.7 yrs

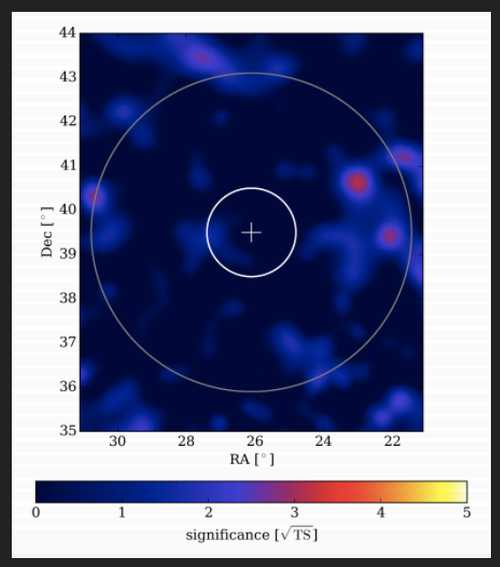


credit to Anna Franckowiak





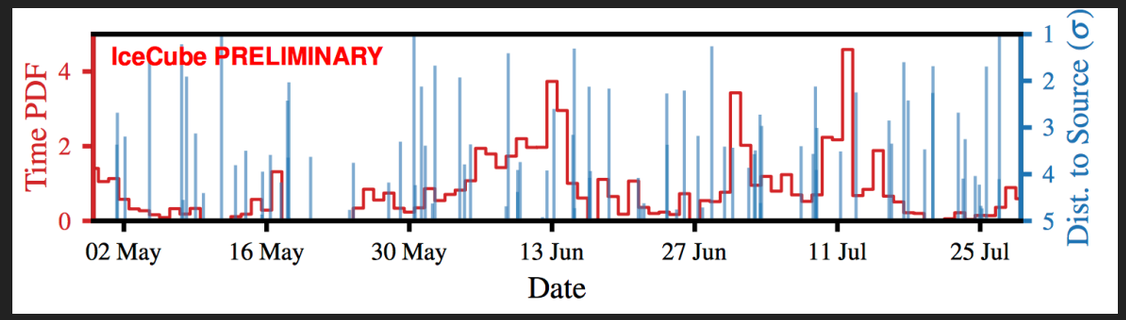




> no obvious counterpart found

THE SEARCHES

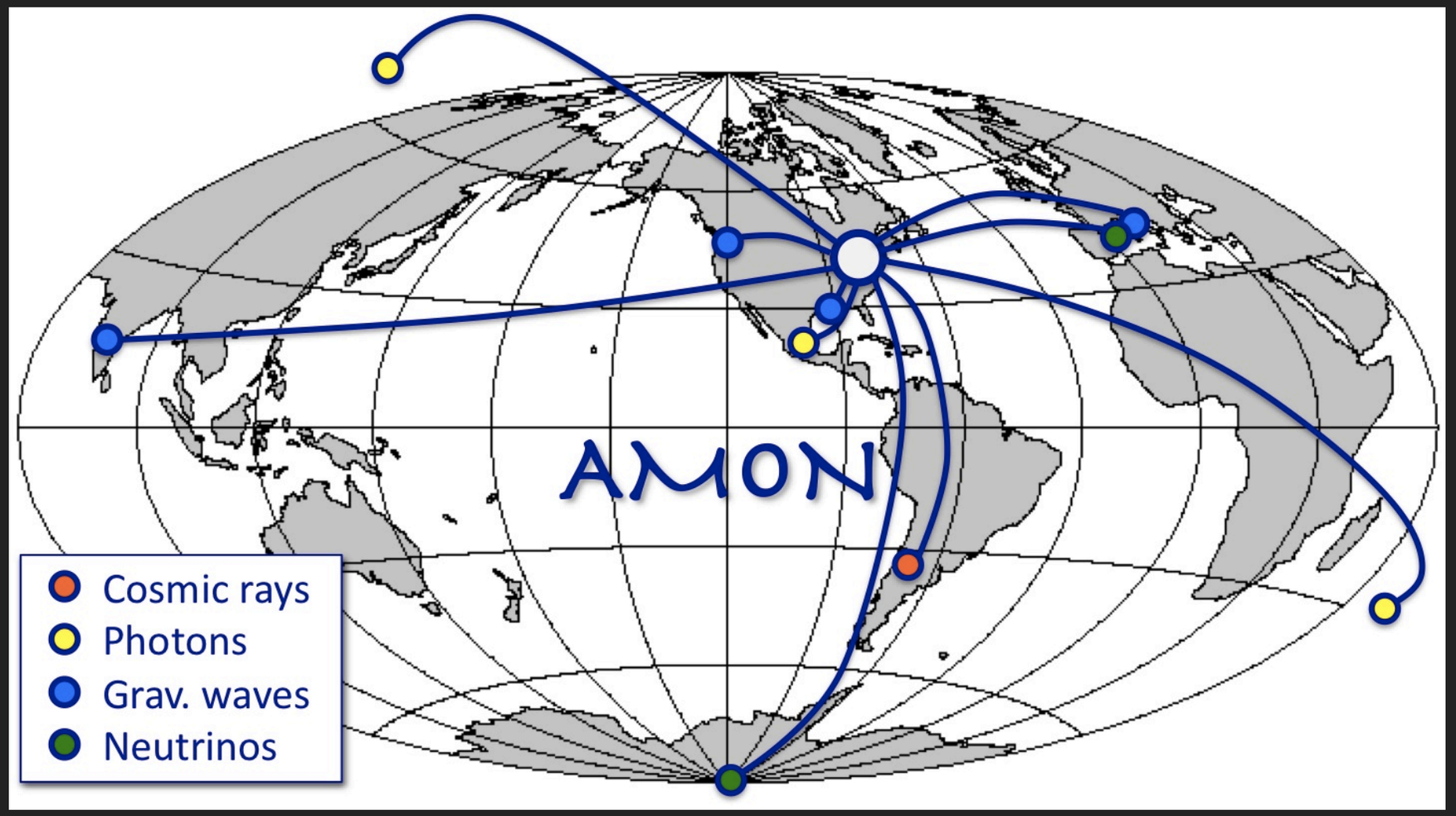
M. Santander for IceCube, FACT, Magic, Veritas PoS(ICRC2017)618



IceCube, FACT, Magic, PoS(ICRC2017)969

2- Flares and transients

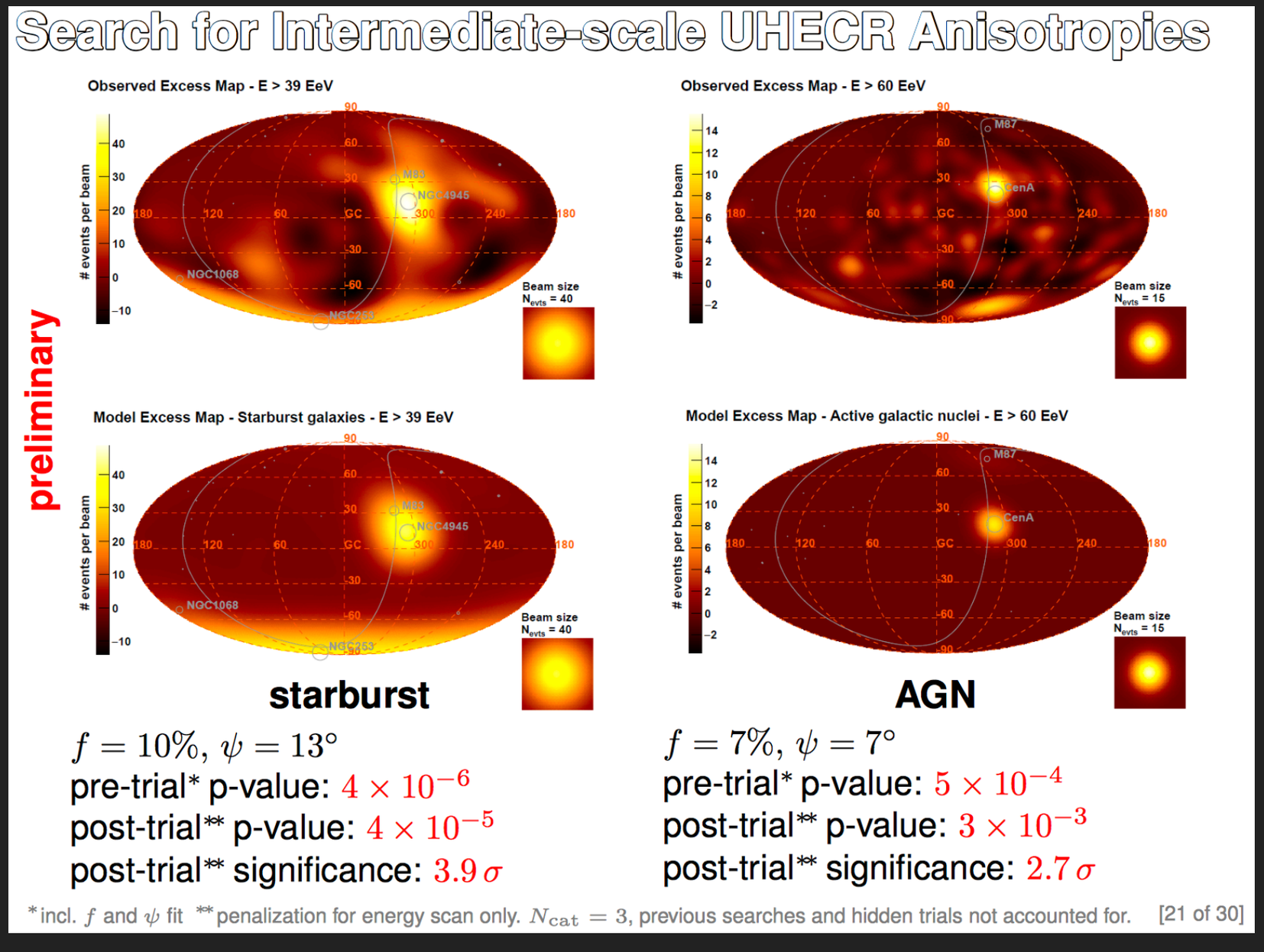
http://amon.gravity.psu.edu
Smith et al., Astropart. Phys., 45 (2013)



THE SEARCHES

3- Star-forming galaxies, starburst galaxies

[Michael Unger, Auger Coll., ICRC 2017]

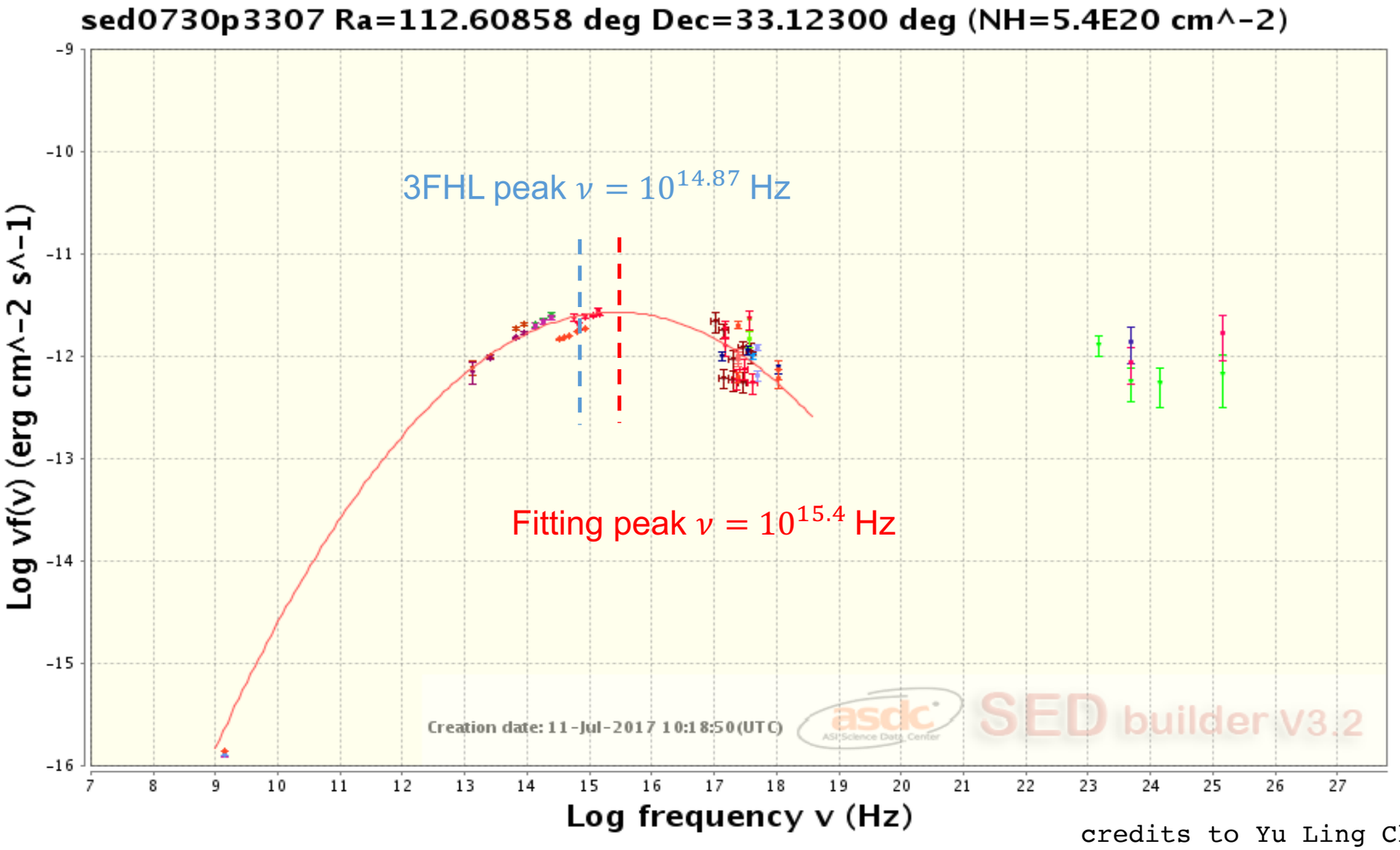


Note:

- NGC 4945, NCS 1068 (Seyfert galaxy with star forming component)
- 2FHL vs UHECRs tested in E.R et al., MNRAS (2017)

THE SCENARIOS

1- Blazars: multi-wavelength analysis, time domain very important



credits to Yu Ling Chang

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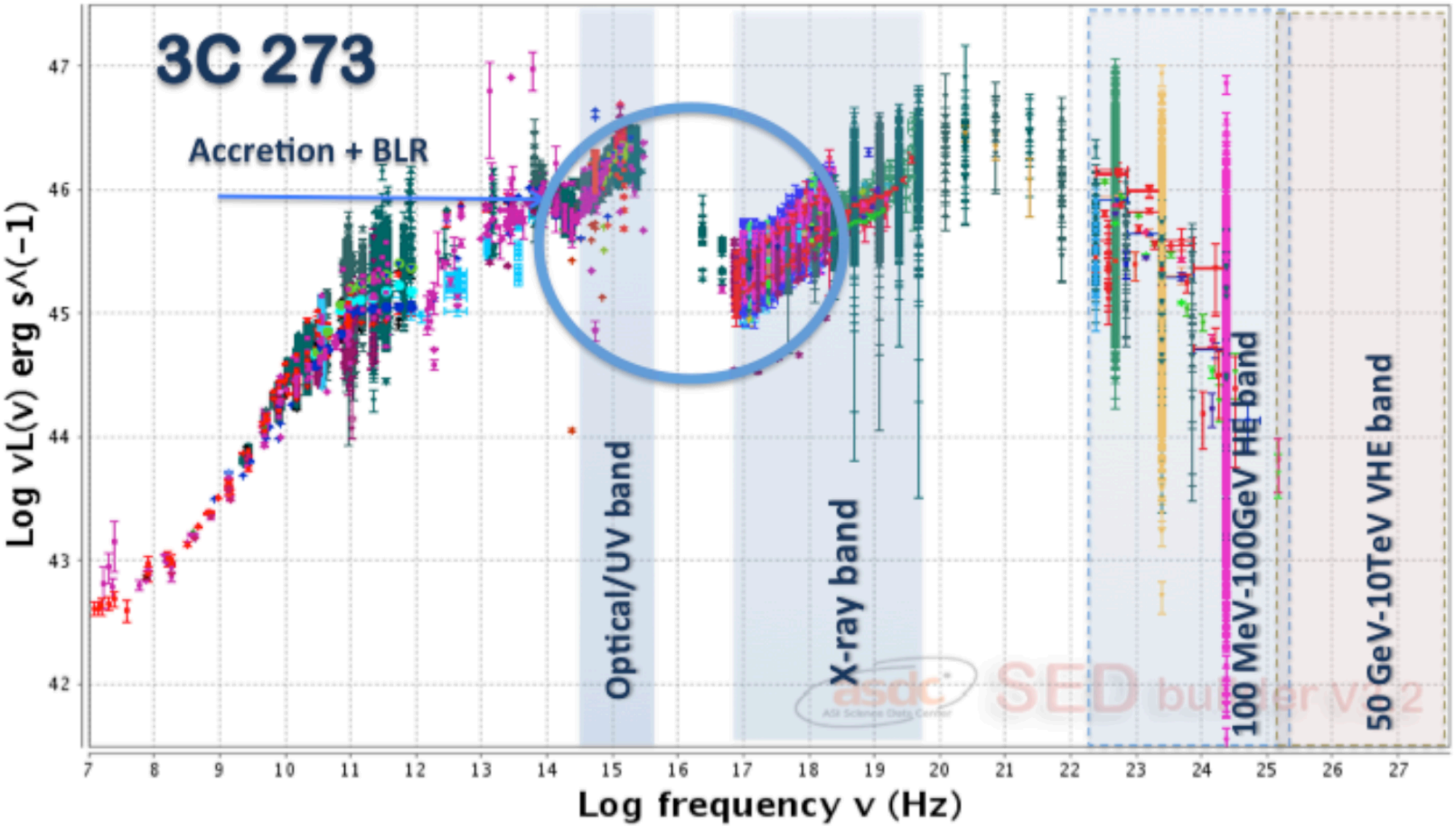
agenzia spaziale italiana



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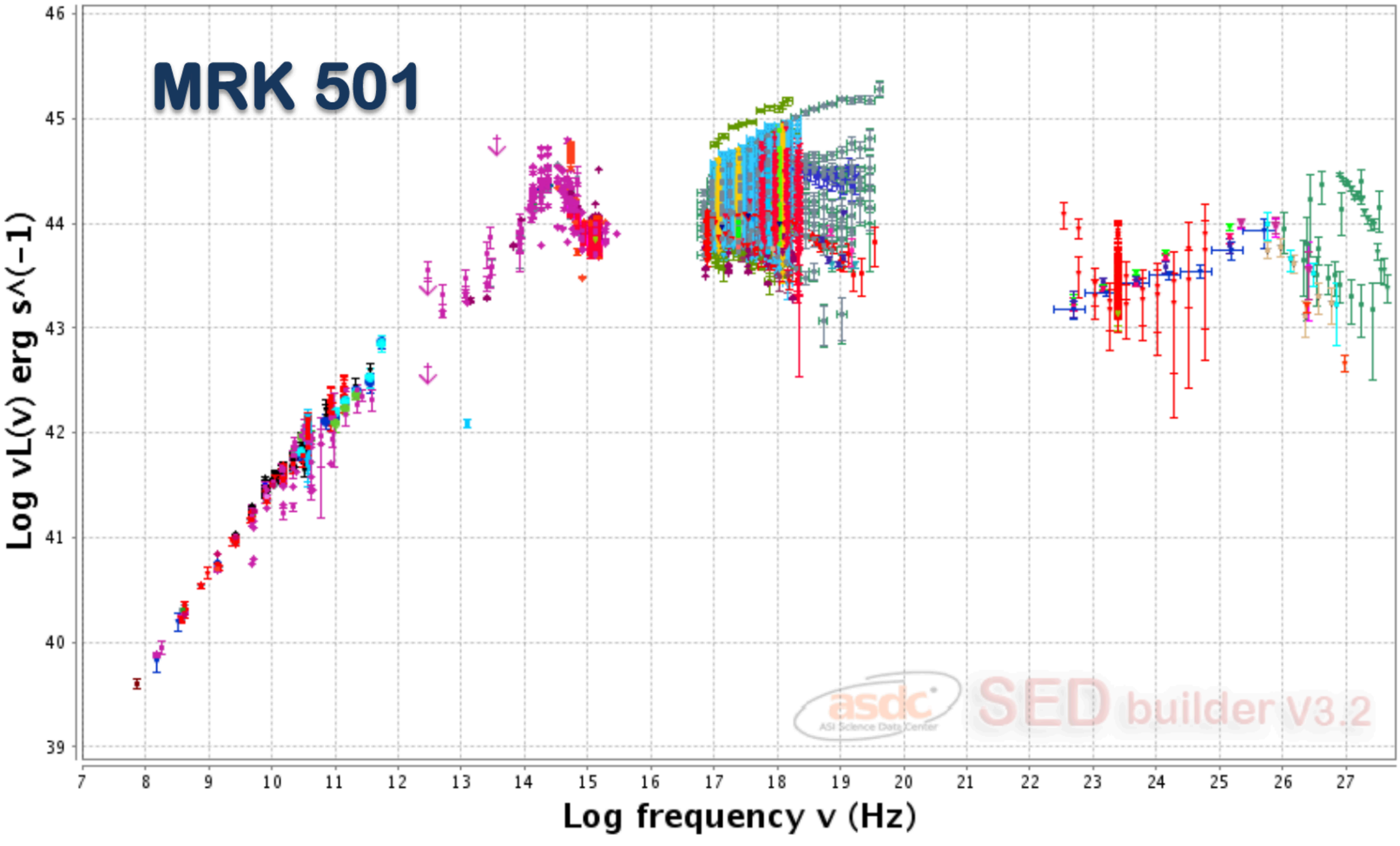

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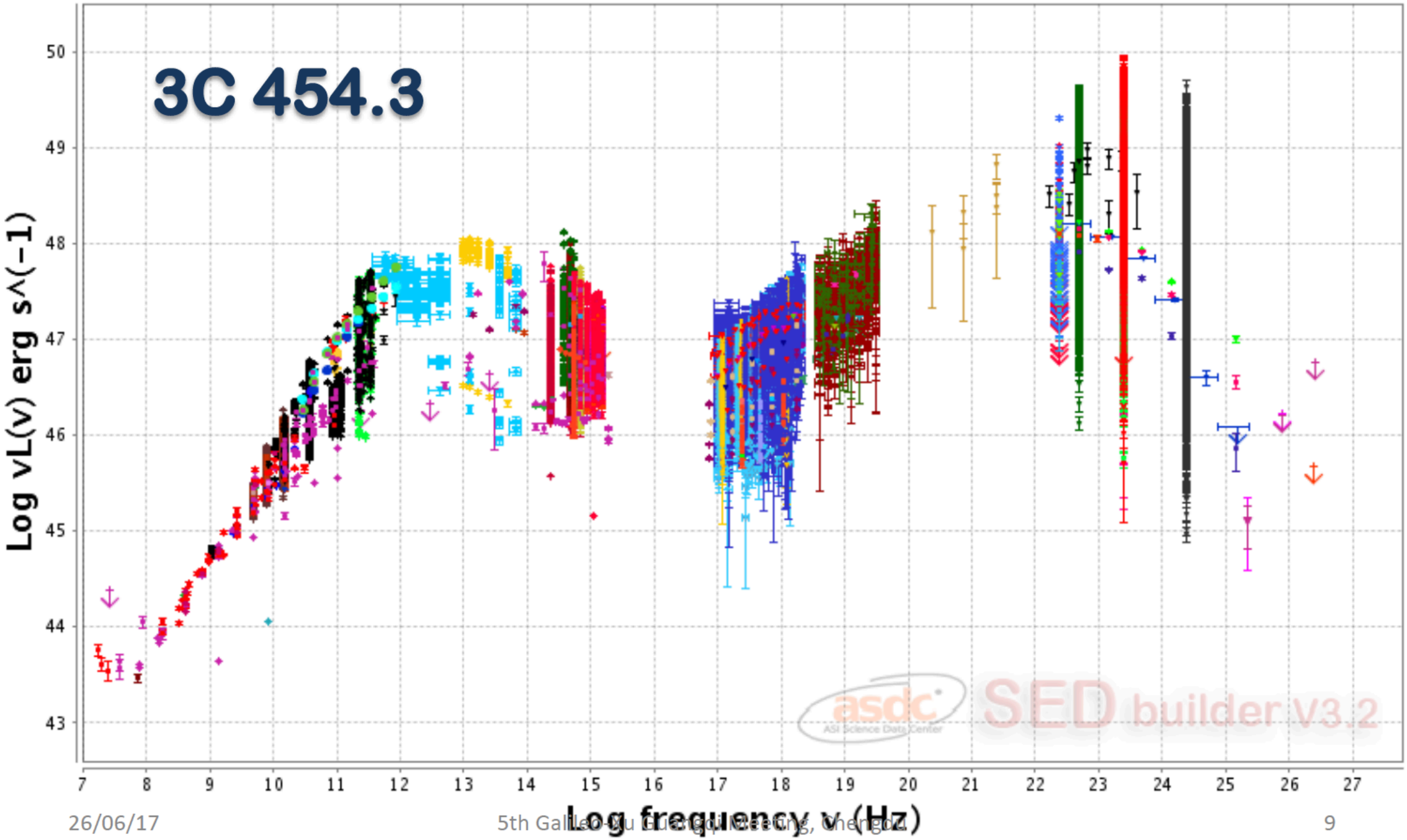

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