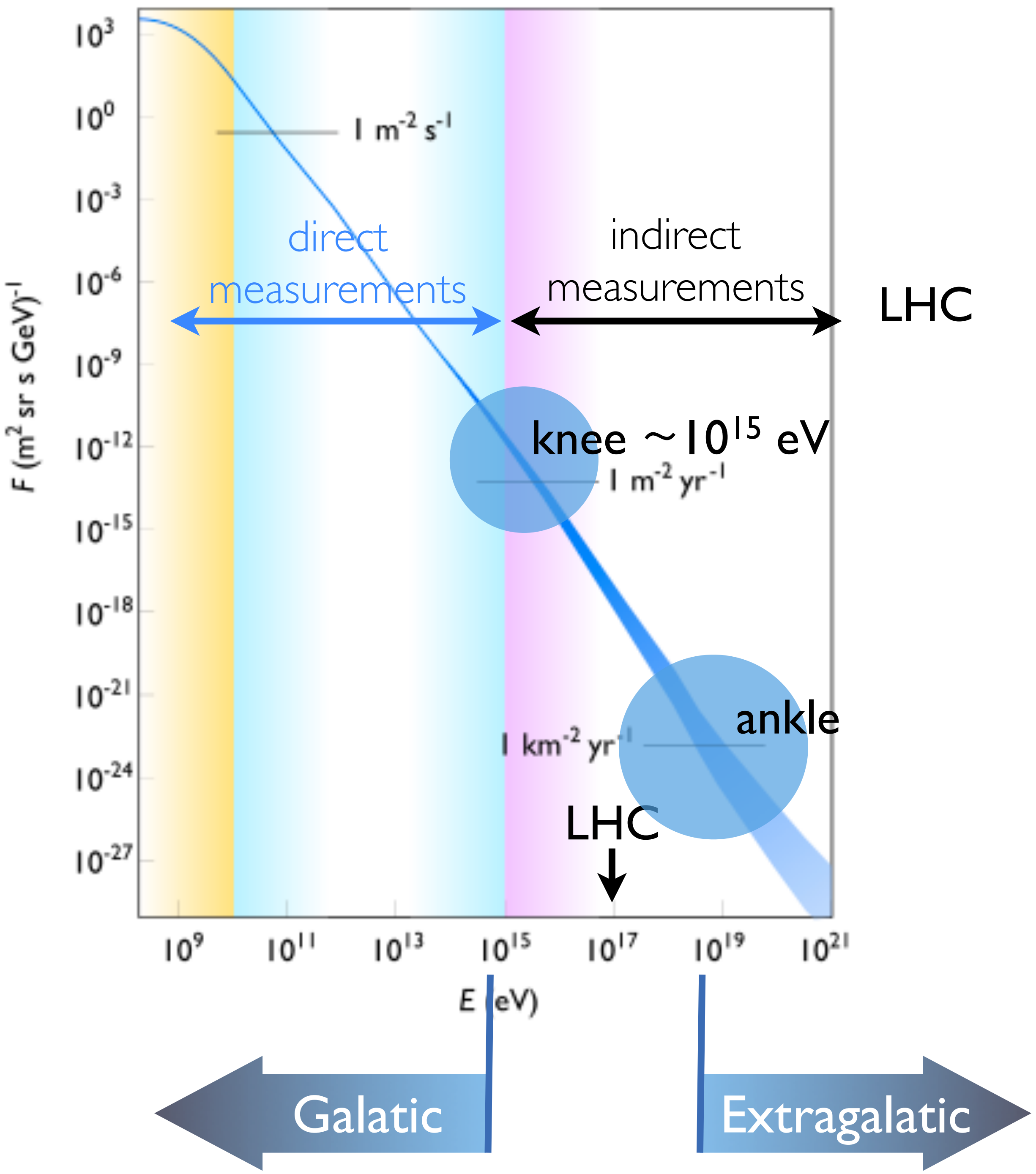
COSMIC RAYS


10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
F (m^2 sr s GeV)$^{-1}$
1 m^{-2} s^{-1}
direct measurements
indirect measurements
LHC
knee ~10^{15} eV
1 m^{-2} yr^{-1}
ankle
1 km^{-2} yr^{-1}
LHC
10^9
10^{11}
10^{13}
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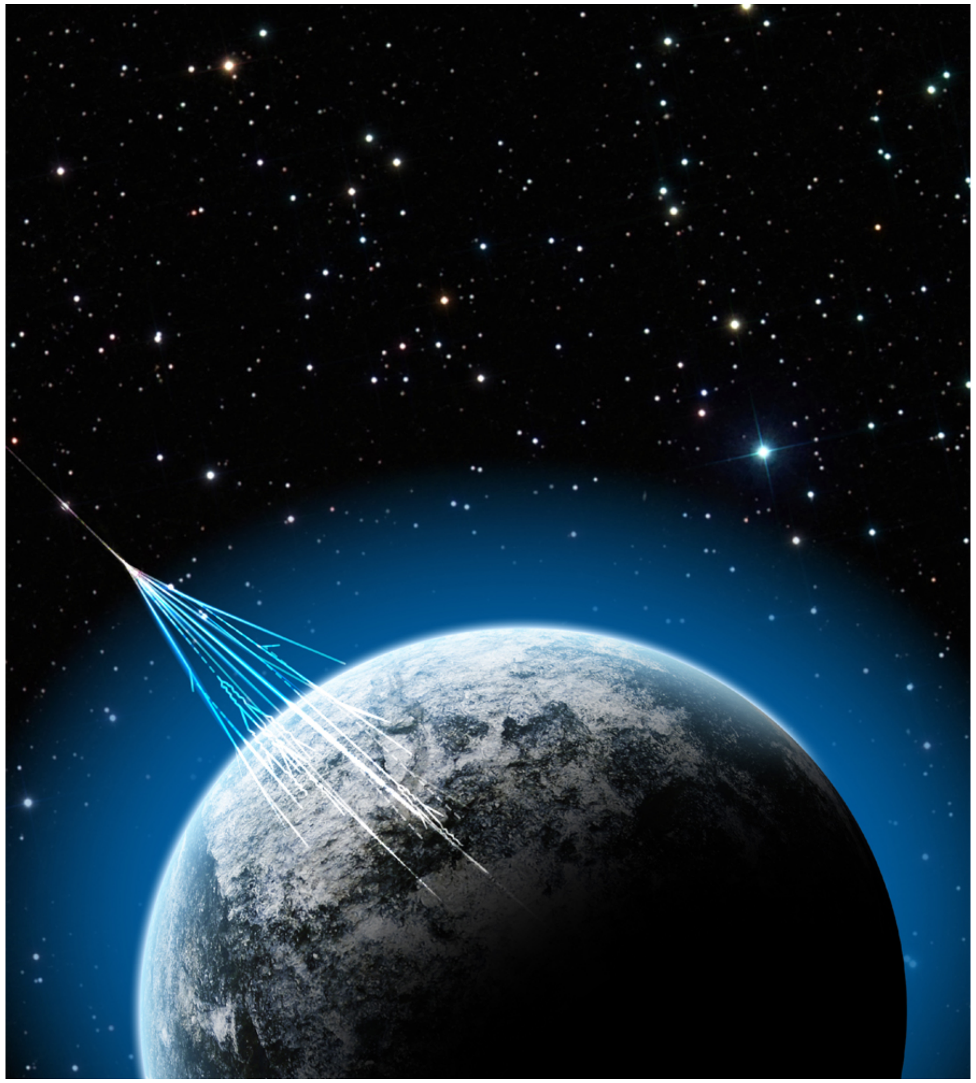
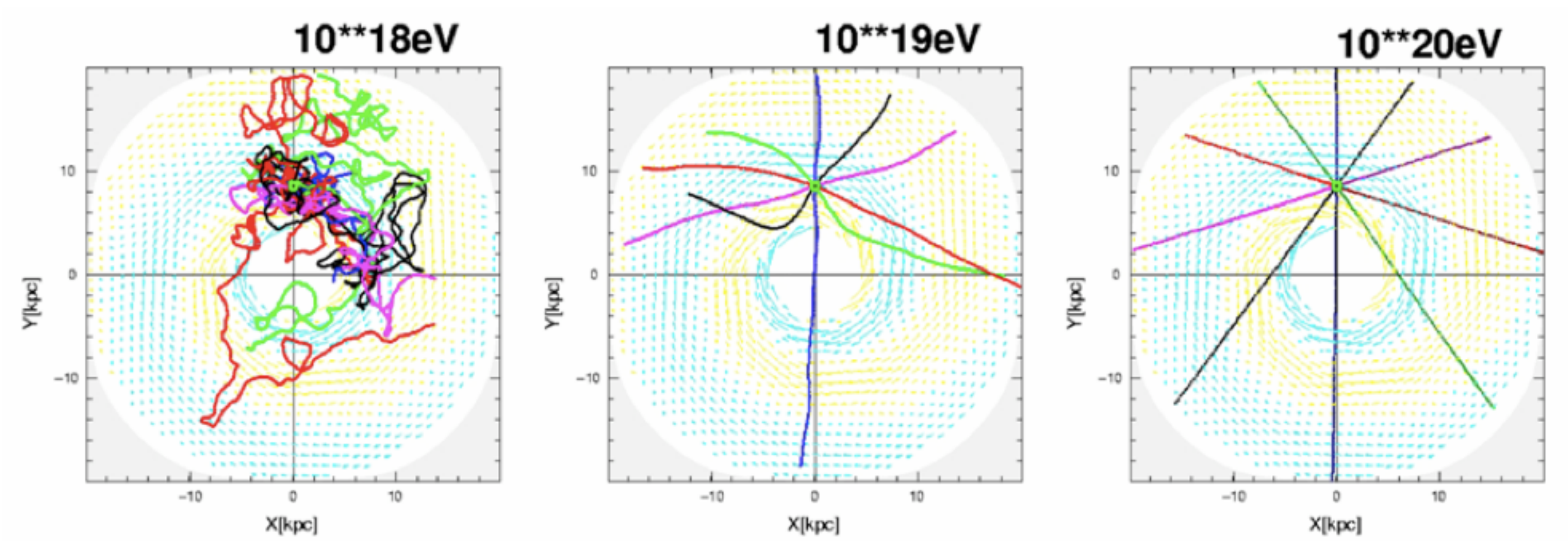
E (eV)
Galatic
Extragalatic



OPEN QUESTIONS

- What and where are the sources? How do they work? Are the particles really accelerated?…or do we see signs of new physics at large mass scales?
- And how do cosmic rays manage to reach us?
- We cannot look at Cosmic Rays themselves to tell their origin

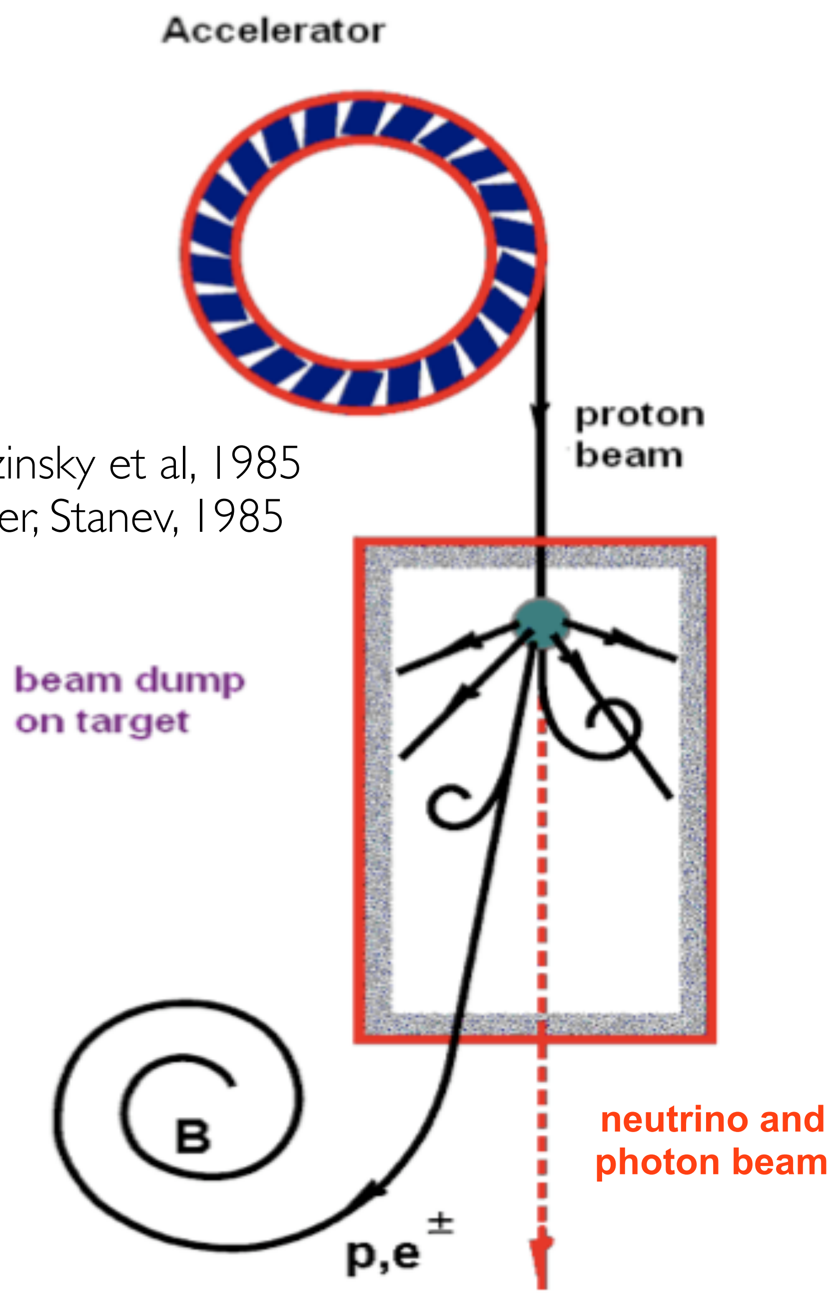
At energies below ~10^{18} eV cosmic rays are confined in the Galaxy, while above ~10^{20} eV the deflection in the Galaxy is less than 1° but they interact with the Cosmic Microwave Background!

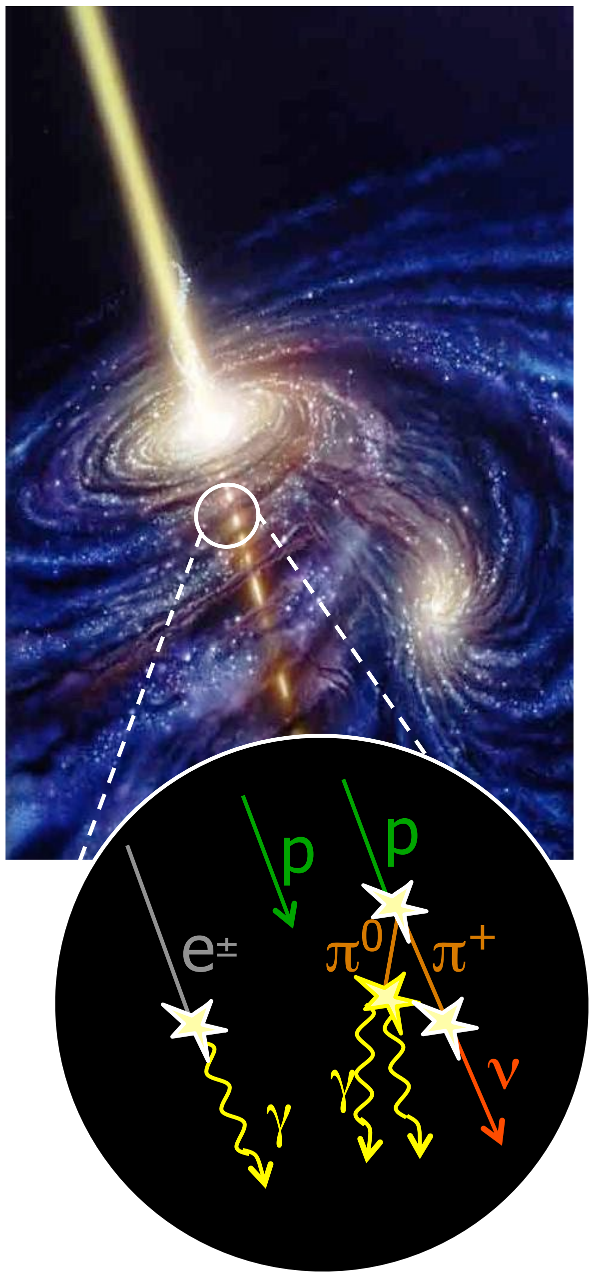


Simulation of deflection of cosmic rays in the Galaxy

ASTROPHYSICAL BEAM DUMP

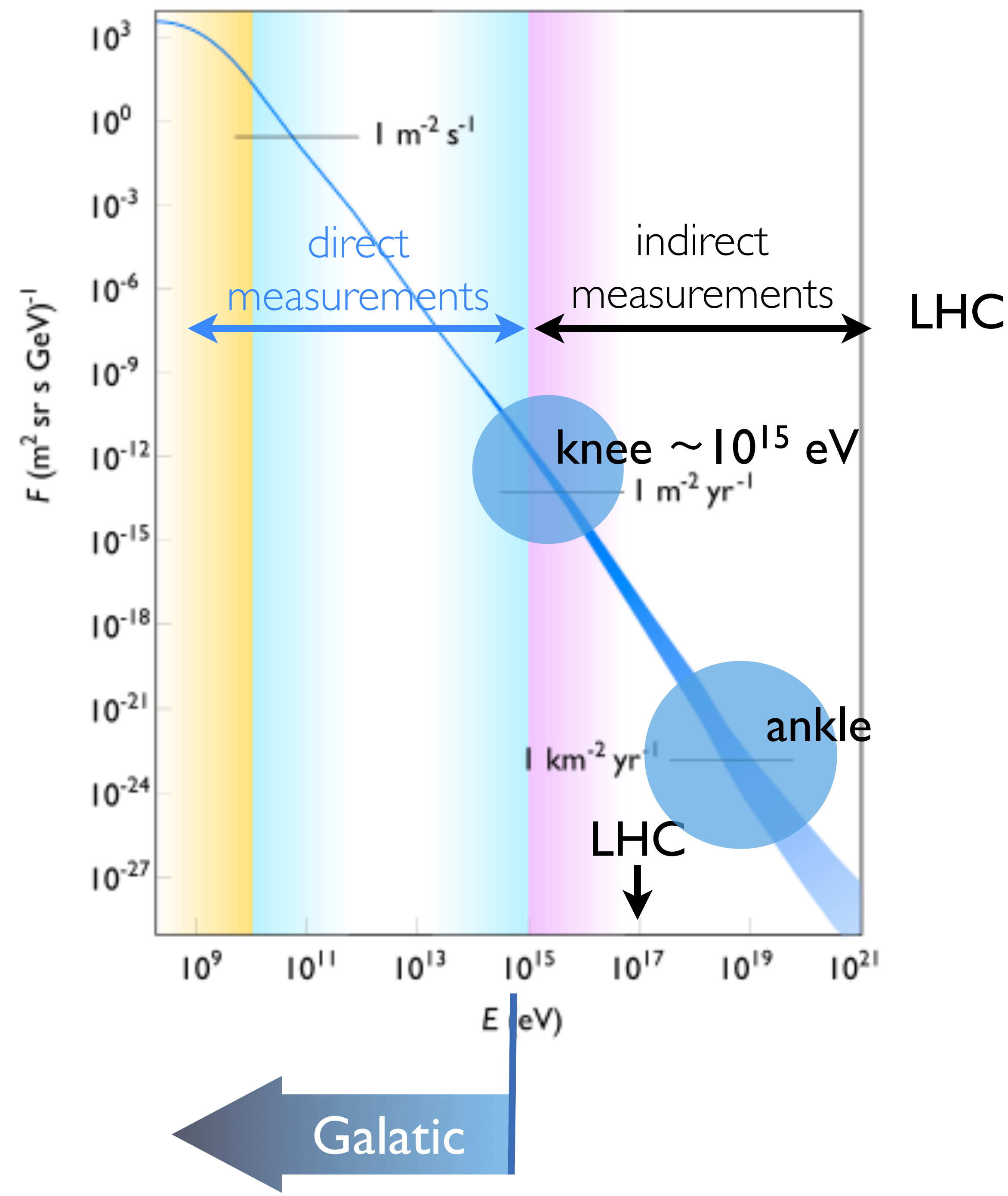
Berezinsky et al, 1985
Gaisser, Stanev, 1985





COSMIC RAYS BELOW THE KNEE

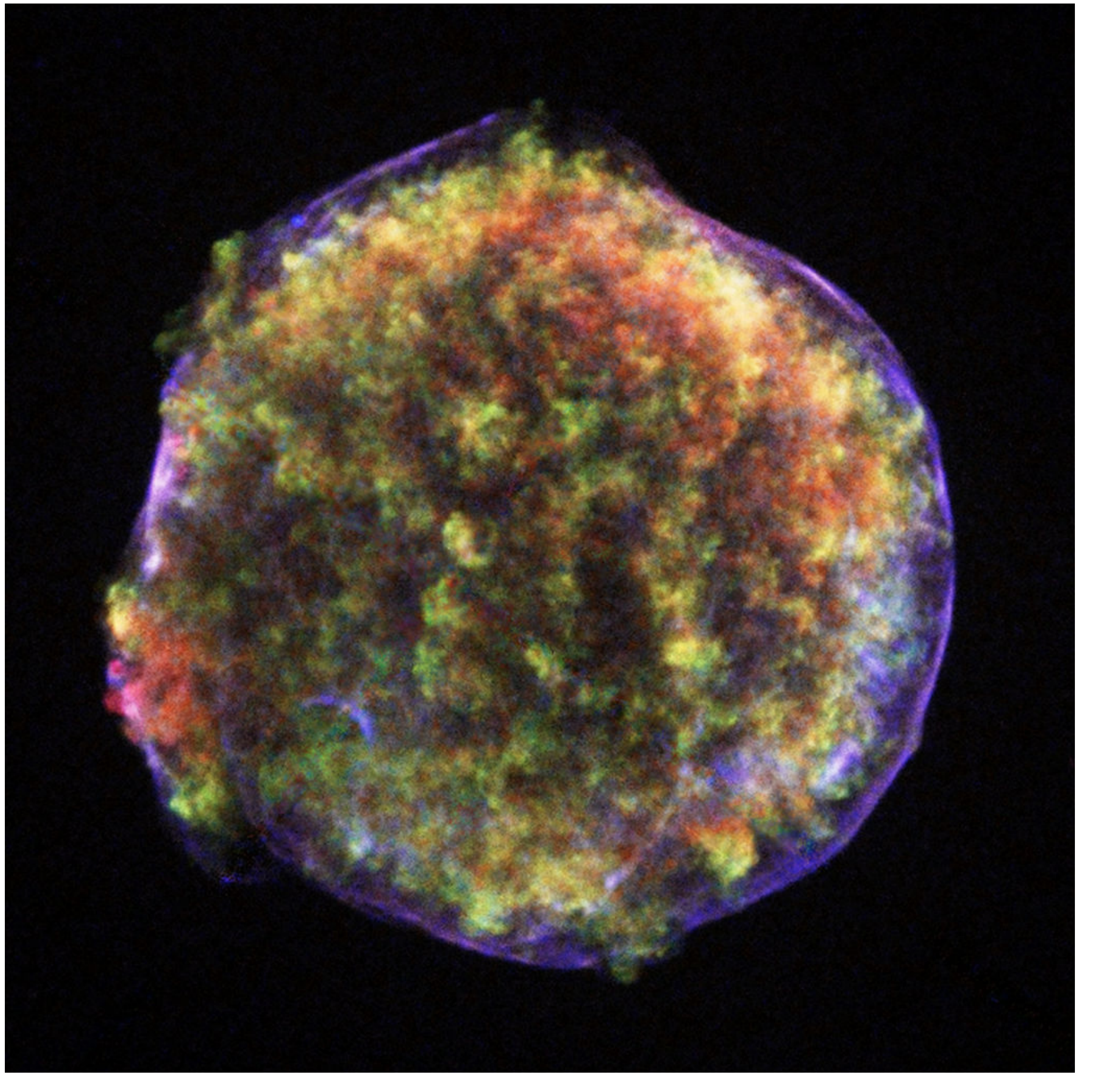
- Observed energy density (integrated below the Knee):
  $\rho_E \sim 10^{-12}$ erg/cm^3
- Escape time from Galaxy:
  $t_{esc} \sim 3\times10^7$ yr
- Power needed to keep a stationary state:
  $\rho_E/t_{esc}\times V_{Galaxy} \sim 10^{41}$ erg/s



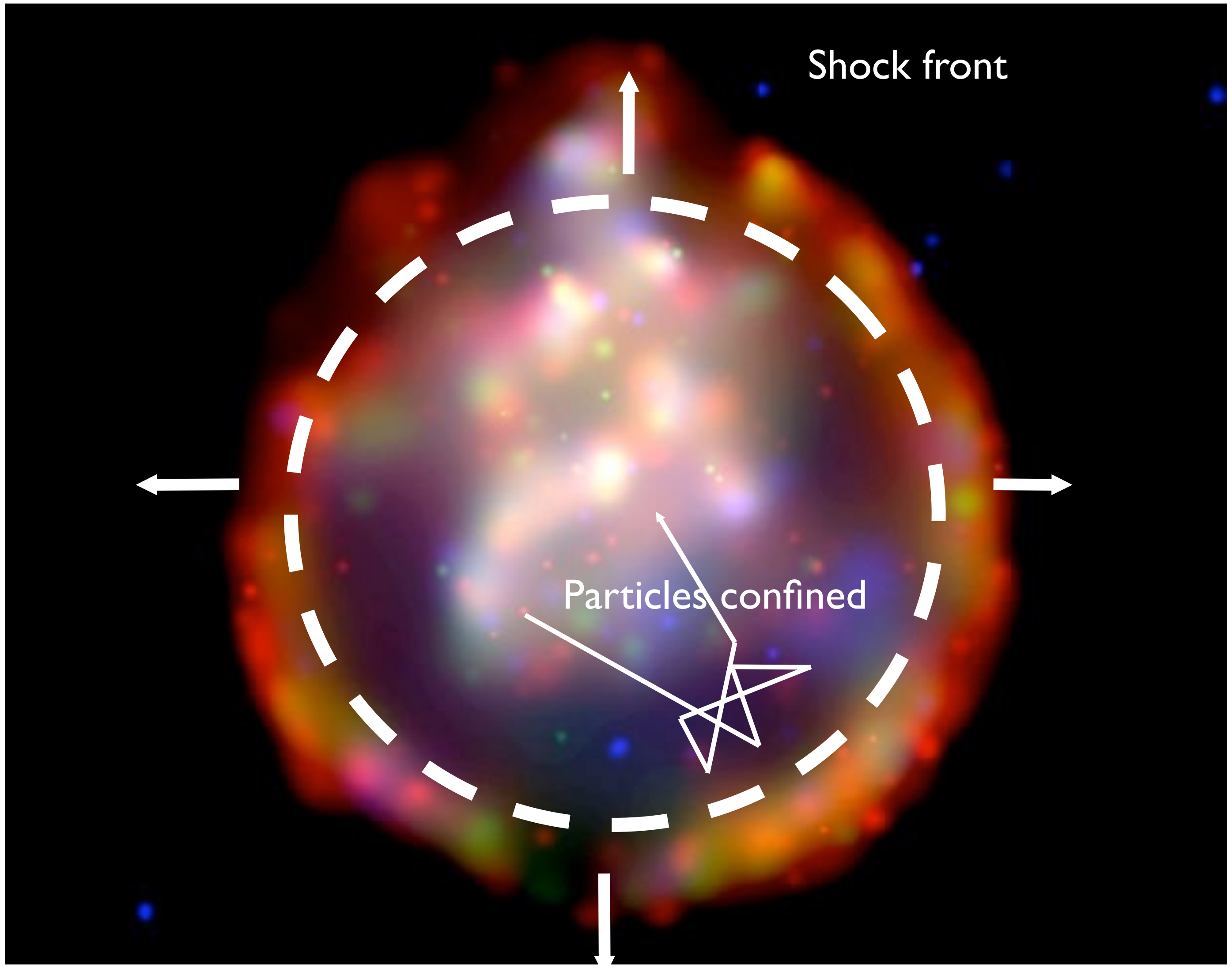
SUPERNOVA REMNANTS

- In a Supernova explosion the star's material is expelled at enormous velocities, thus driving a shock wave through the interstellar medium
- Cosmic rays can be accelerated at the shock front via the first order Fermi mechanism

X-ray image of Tycho's supernova remnant. The shock wave is clearly visible at the outer edges of the remnant.



SUPERNOVA REMNANTS (SNRS): GALACTIC COSMIC RAYS?



Elastic collisions of particles at the shock front (Fermi acceleration):

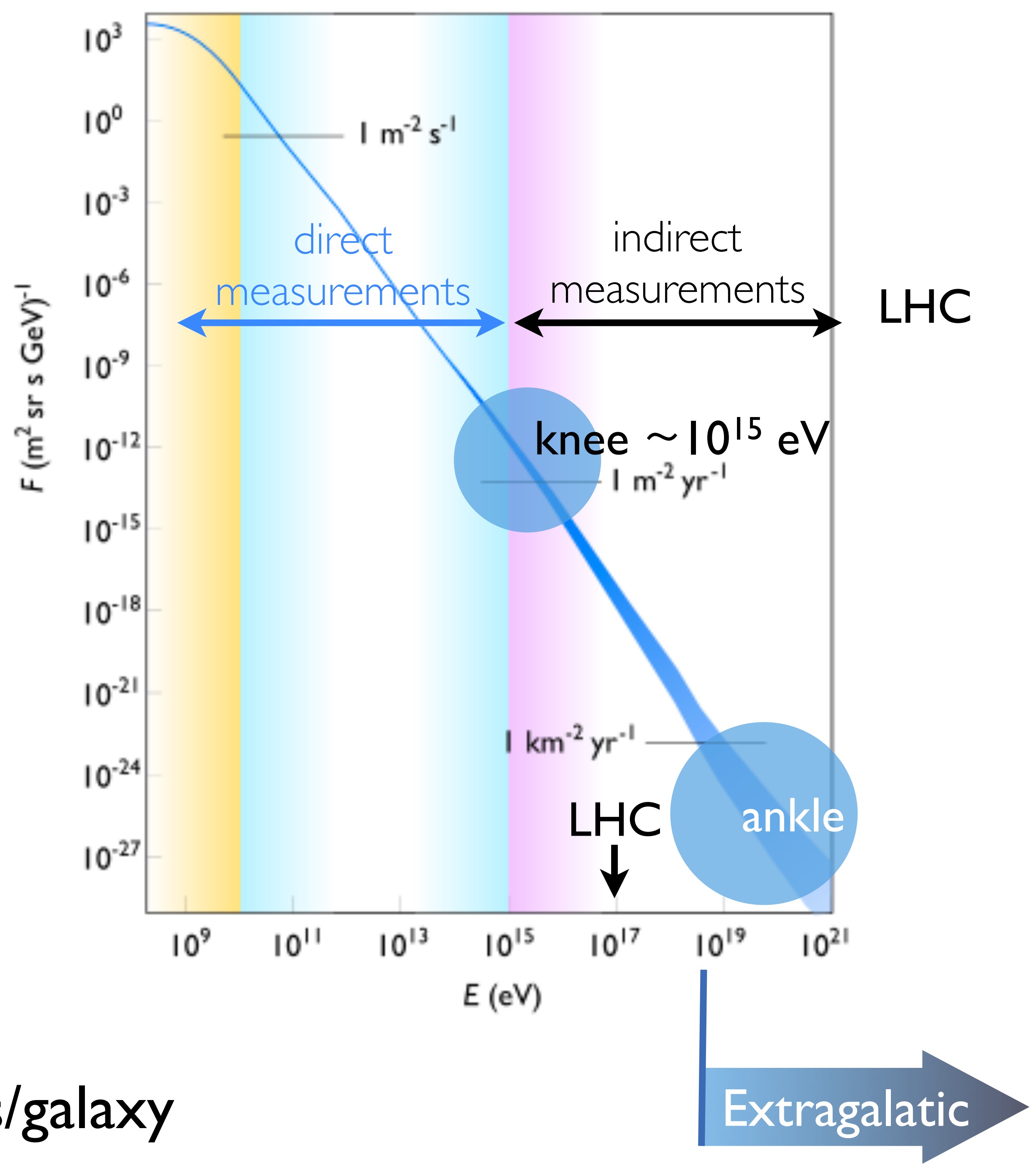
- $dN/dE \sim E^{-\alpha}$; $\alpha \sim 2.1$

Energy budget:

- Frequency: O(1 / (30 - 70)) SN/yr
- Energy released $\sim 10^{51}$ erg each
- Power released:
  $\sim 10^{51}$ erg$/t_{esc}/30 \sim 10^{42}$ erg/s
- 5 - 10 % efficiency of conversion into C.R. would be sufficient (Baade & Zwicky 1933, Ginzburg & Syrovatskii 1964)

COSMIC RAYS AT HIGHEST ENERGIES

- Observed energy density (extra-galactic): $\rho_E \sim 2\times10^{-20}$ erg/cm^3
- Age of Universe: $t_{Univ} \sim 10^{10}$ yr
- Power needed: ρ_E/t_{Univ} $>10^{37}$ erg/Mpc^3/s



10^{-7} AGN/Mpc^3 → 10^{44} erg/s/AGN

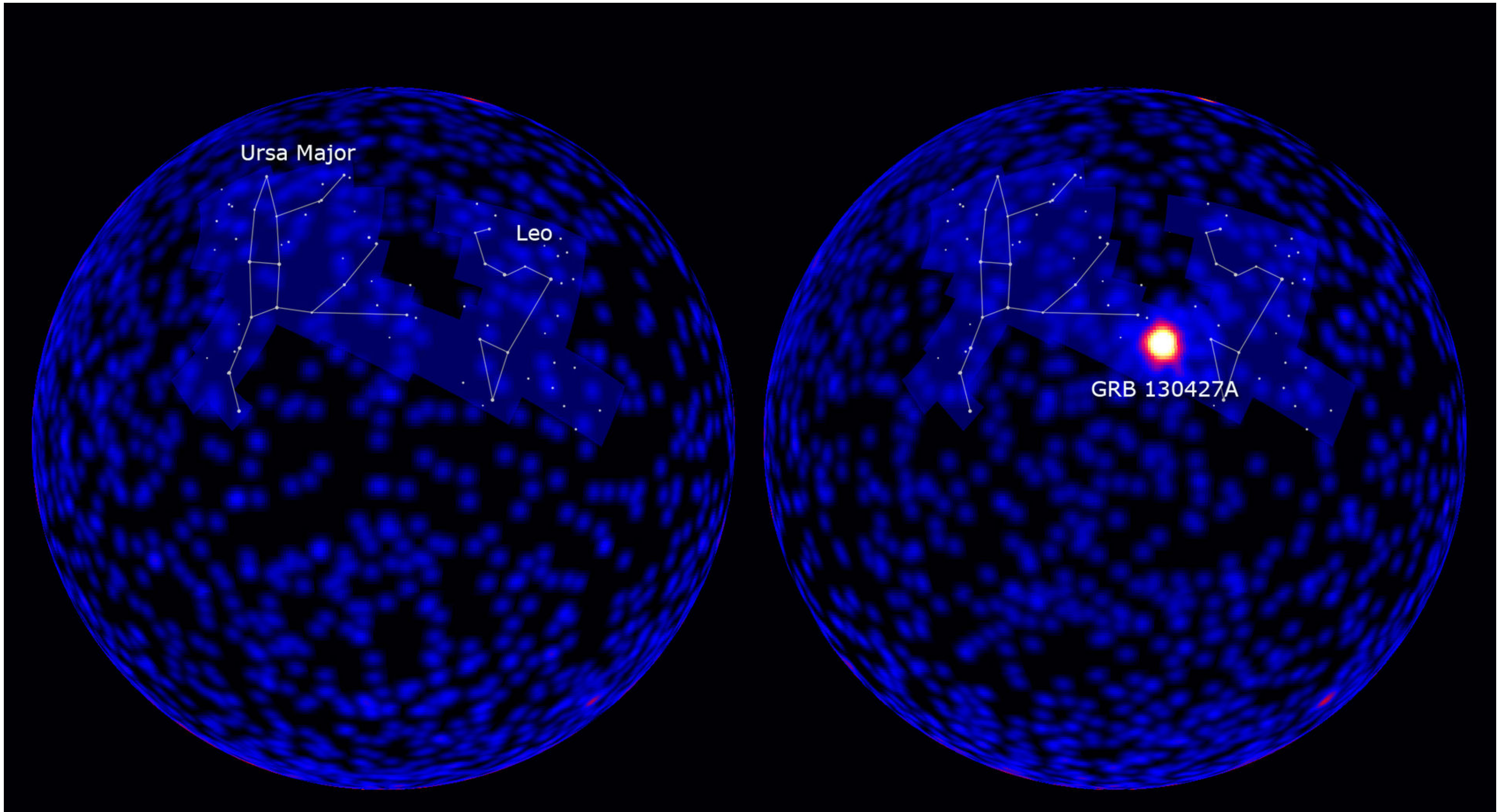
~1000 GRB/yr → 3×10^{52} erg/GRB

3×10^{-3} galaxies/Mpc^3 → 5×10^{39} erg/s/galaxy

3×10^{-6} clusters/Mpc^3 → 4×10^{42} erg/s/galaxy cluster

Γ-RAY BURSTS (GRBS)

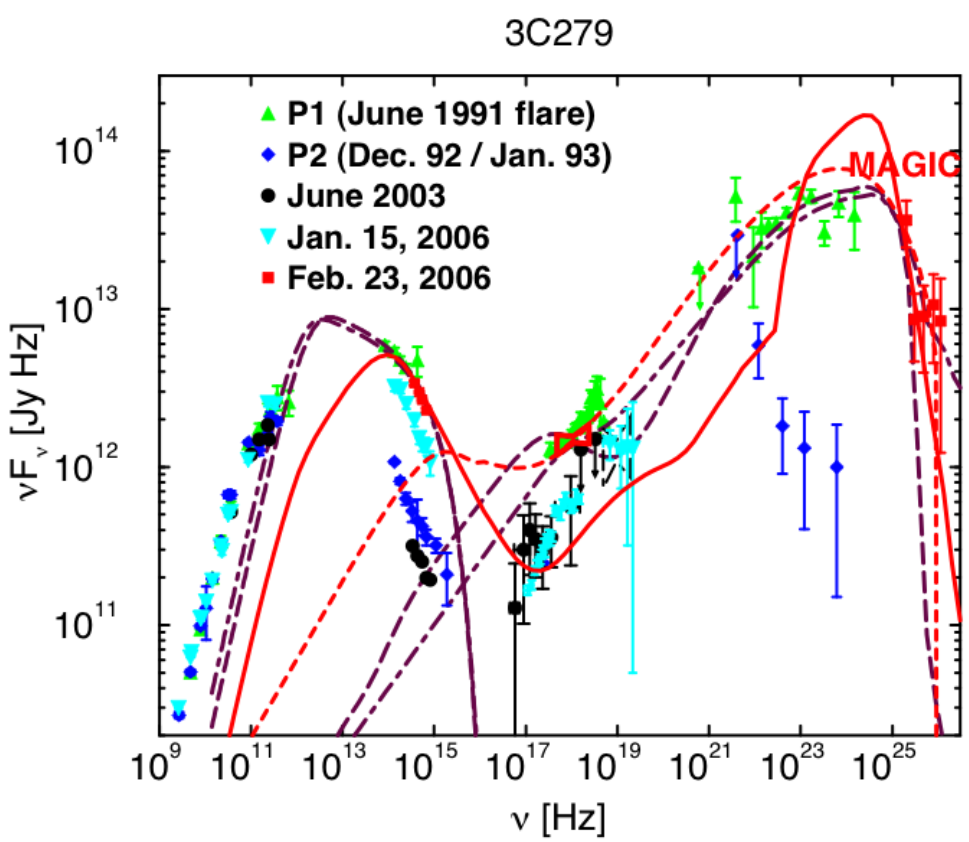
- $2{\times}10^{51}$ erg × 300/yr/Gpc^3 ~ $6{\times}10^{44}$ erg/yr/Mpc^3



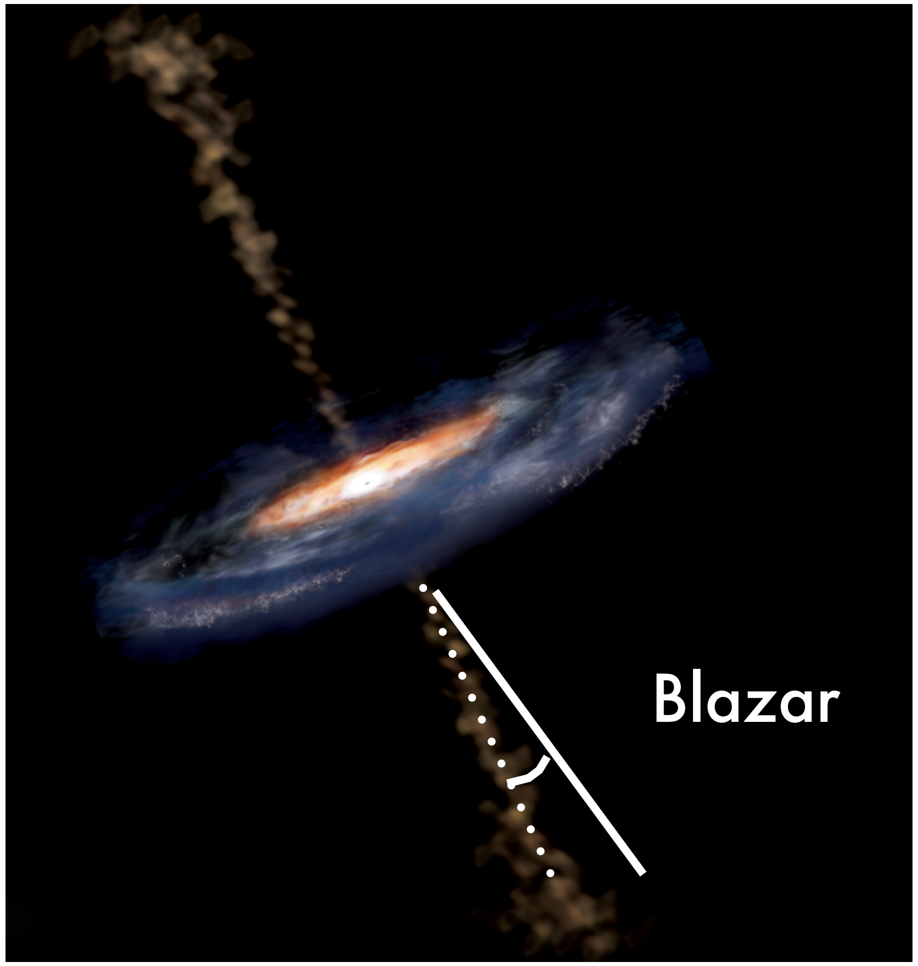
Before and after Fermi LAT views of GRB 130427A, centered on the north galactic pole

ACTIVE GALACTIC NUCLEI (AGNS)

- Some AGNs emit most of their luminosity at TeV energies (10^{45}-10^{49} erg/s): their energetics requires accretion on a large-mass Black Hole
- Some of the matter is accelerated in highly beamed jets ⇒ buildup of large magnetic fields and shock acceleration
- Their emission is largely variable (on a time scale down to minutes)

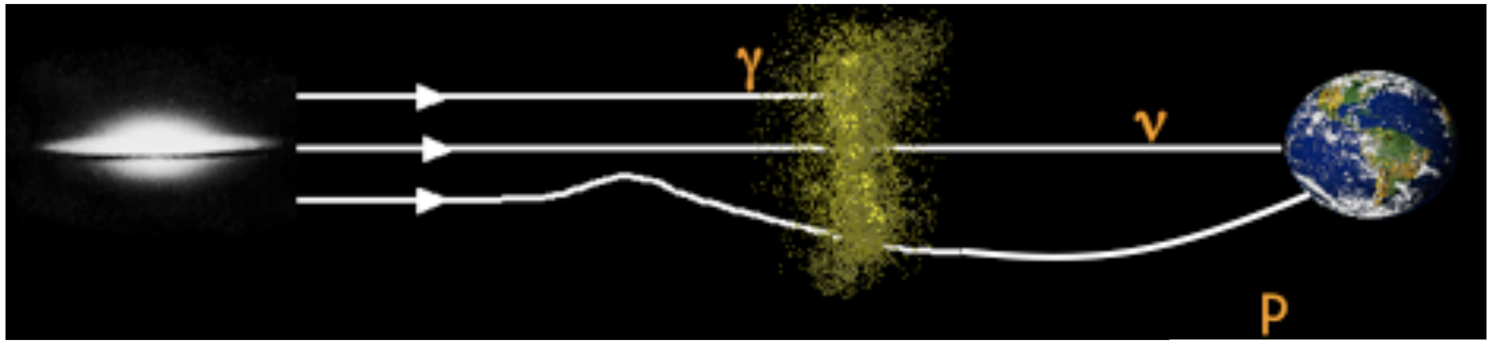


Böttcher, Reimer & Marscher 2008



WHY NEUTRINO ASTRONOMY?

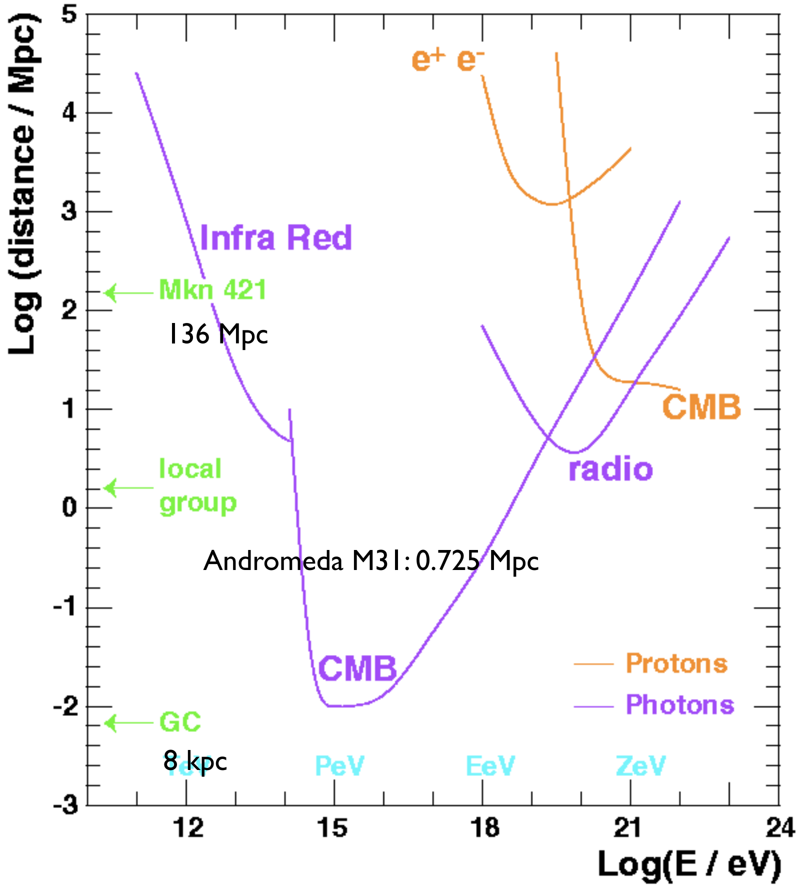
- Why neutrinos?
  - Mean free path of Very High Energy (VHE) photons is much less than the cosmological distance (Universe c/H0=13.7 billion year (WMAP) ～4000 Mpc)
  - Mean free path of VHE neutrinos is longer than cosmological distance



	process	cut-off	mean free
γ-rays	$\gamma+\gamma_{2.7°K}$	>100 TeV	10 Mpc
proton	$p+\gamma_{2.7°K}$	>50 EeV	50 Mpc
neutrinos	$\nu+\nu_{1.95°K}$	>40 ZeV	40 Gpc

Photons are absorbed in the Extragalactic Background Light (EBL)

Protons ($E>10^{20}$ eV) interact with the Cosmic Microwave Background (CMB)



NEUTRINOS FROM ASTROPHYSICAL BEAM DUMP

- If neutrinos are produced by cosmic accelerators, two scenarios are possible: neutrinos

$$pp \longrightarrow pp(np, nn) + \quad n_1\pi^{\pm} + \qquad n_2\pi^0 + \quad (n_3K^{\pm} + n_4K^0 + ...)$$

Case 1:

proto-proton

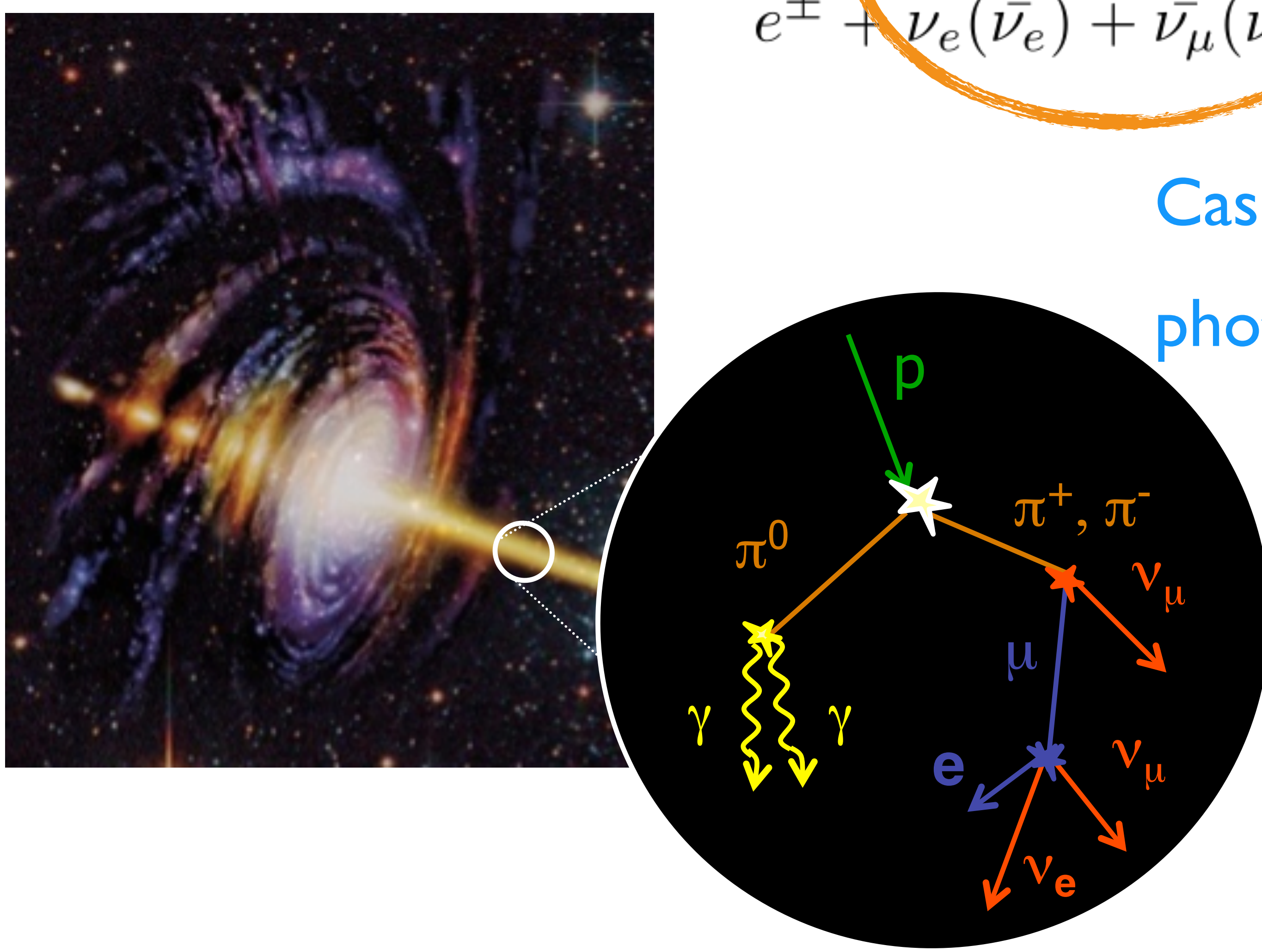
$$n_1\pi^{\pm} \downarrow \mu^{\pm} + \nu_\mu(\bar{\nu_\mu}) \downarrow e^{\pm} + \nu_e(\bar{\nu_e}) + \bar{\nu_\mu}(\nu_\mu)$$

$$n_2\pi^0 \downarrow \gamma\gamma$$

Case 2:

photo-hadronic

$$p\gamma \rightarrow \Delta \rightarrow \begin{array}{l} p + \pi^0 \; [2/3] \\ n + \pi^+ \; [1/3] \end{array}$$



- In all cases:

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

NEUTRINOS FROM ASTROPHYSICAL BEAM DUMP

- In case of pγ (photo-hadronic) interactions:
  - if Cosmic Rays are heavy nuclei, few neutrinos are produced since photo-dissociations dominates
  - the photon field which serves as a target, will likely absorb photons and the multi-messenger connection can be less tight
  - secondary spectra have a strong energy dependence (rise very fast >> GeV energies) because of the Δ resonance, will pp spectra tend to follow power-laws
  - less anti-electron neutrinos are produced compared to the pp (hadro-nuclear) case and this property could be exploited if we can distinguish neutrino types!? likely not … [D. Biehl, et al., JCAP 1701 (2017) 033]

NEUTRINO OSCILLATIONS

- Neutrinos can change their type (or flavor) during propagation if they are massive and if the mass eigenstates do not coincide with the flavor eigenstates
- They are connected through a unitary rotation (U PMNS matrix):

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} \, |\nu_j\rangle$$

- The temporal evolution is dictated by the mass eigenstates (vacuum case):

$$|\nu_j(t)\rangle = e^{-iE_j t} \, |\nu_j(t=0)\rangle$$

- The probability to detect a neutrino with initial flavor state alpha as state beta is:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | e^{-iE_j t} | \nu_\alpha \rangle \right|^2 = \left| \sum_j U^*_{\alpha j} U_{\beta j} \; e^{-iE_j t} \right|^2$$

$$= \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \; e^{-i(E_j - E_k)t}$$

NEUTRINO OSCILLATIONS

- In the relativistic case and with t ≃ L (propagation distance of neutrinos, c=1):

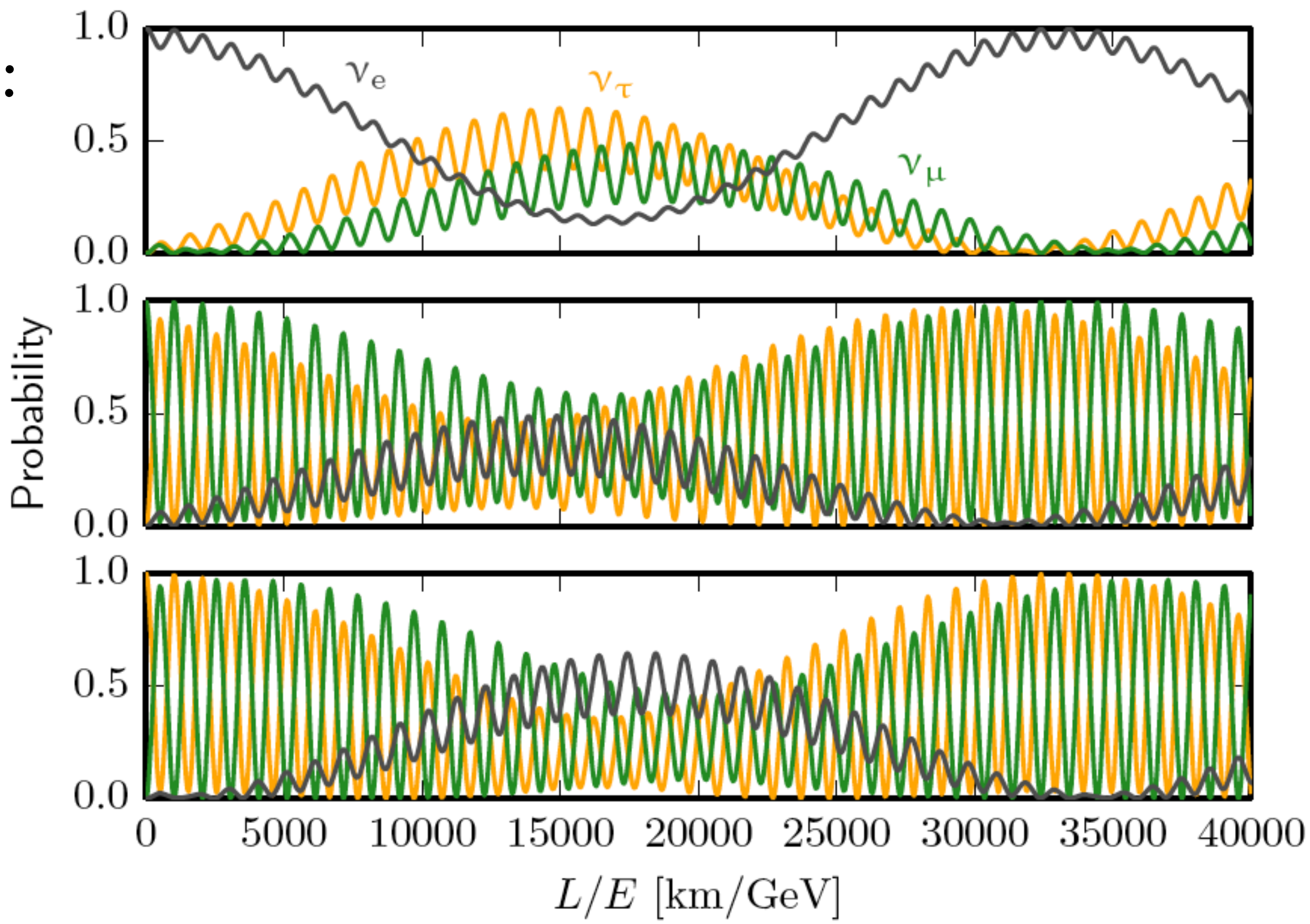
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

- The oscillatory phase becomes:

$$\frac{\Delta m^2_{jk} L}{4E} \approx$$

$$\approx 1.267 \times \frac{\Delta m^2_{jk}}{\text{eV}^2} \frac{L}{\text{km}} \frac{\text{GeV}}{E}$$

Probabilities for a given an initial flavor to be detected as an electron neutrino (gray), muon neutrino (green), or tau neutrino (yellow) [L. Mohrmann PhD]



NEUTRINO OSCILLATIONS

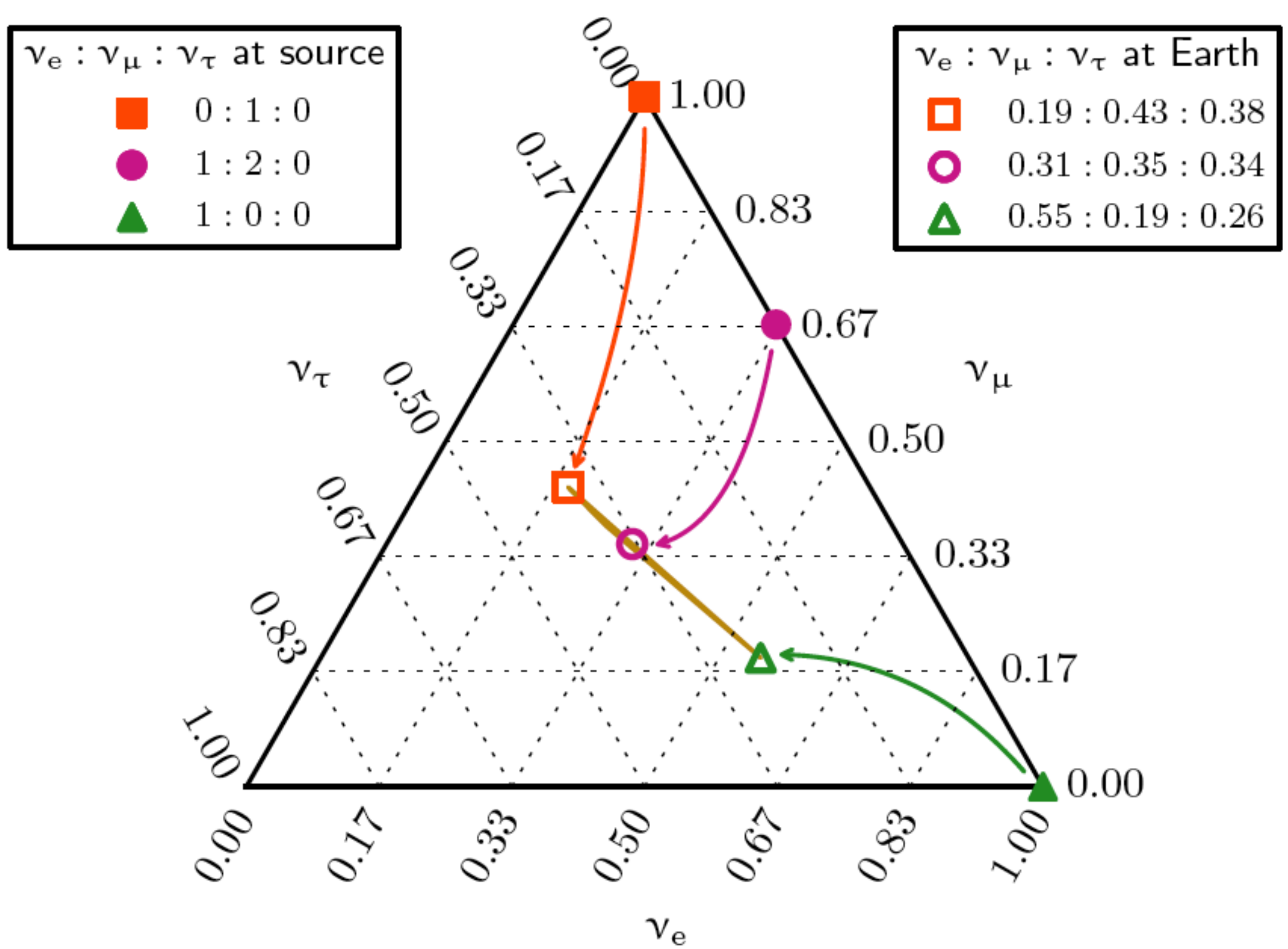
- In astrophysical environments neutrinos are produced with a distribution of energy and they can travel sufficiently far.
- We observe an average transition probability, which is fully determined by the input energy spectrum and flavor composition of the neutrinos
- We can distinguish three benchmark scenarios for flavor composition at source:

1. PION-DECAY:

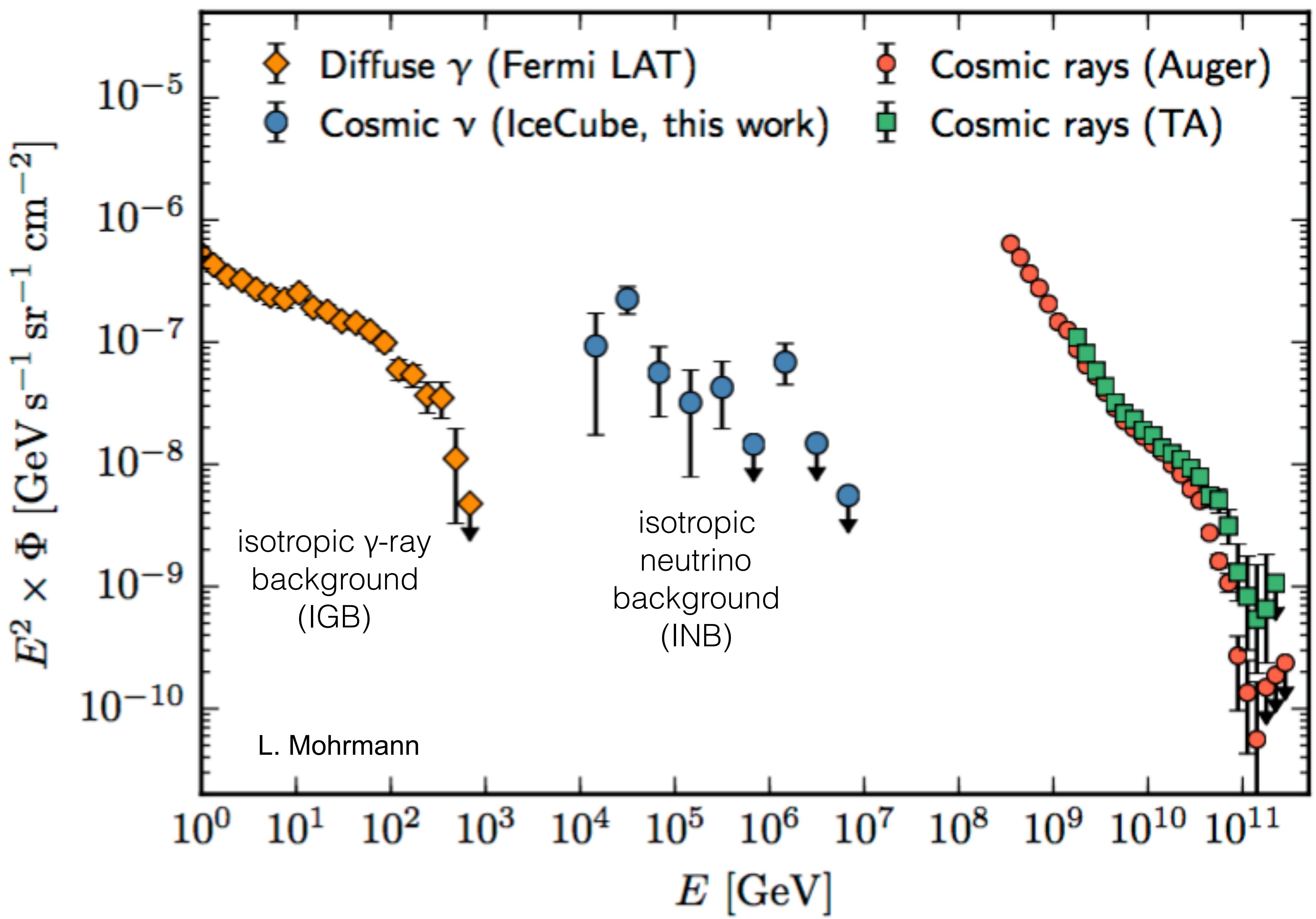
2. M $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

3. N $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$



MULTI-MESSENGER ASTROPHYSICS

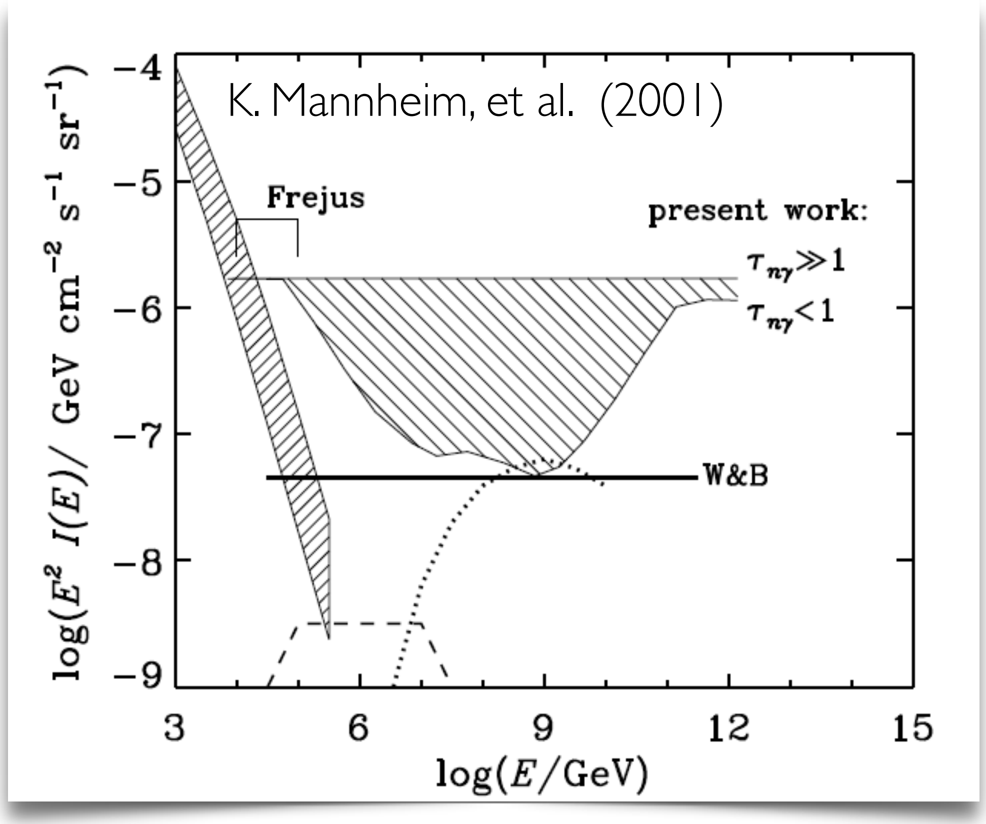


POSSIBLE SOURCES OF >TEV NEUTRINOS

- Galactic:
  - diffuse neutrino emission of galactic Cosmic Rays
  - individual galactic PeV point-source
  - extended galactic structures like the Fermi Bubbles or the Galactic halo
- Extragalactic:
  - galaxies with intense star formation
  - cores or jets of active galactic nuclei (AGN), low-luminosity AGN
  - Gamma Ray Bursts (GRB)
  - intergalactic shocks
  - active galaxies embedded in structured regions
- Dark Matter

WAXMANN BAHCALL BOUND

- Starting from the observed CRs with energies $>10^{19}$ eV a limit was derived on the neutrinos produced within the same sources assuming:
  1. Protons are accelerated at the sources with a power-law index 2
  2. All protons undergo photo-hadronic interactions giving neutrons, neutrinos and gamma-rays
  3. The sources are optically "thin" to neutrinos, which escape and decay into protons giving the observed CRs
  4. The luminosity evolution of far away sources (whose CR we do not observe) is not stronger than any class we know
- Mannheim Protheroe and Rachen (MPR) showed that different CR spectra can considerably weaken the limit



NEUTRINO CONNECTION TO CR

- Hadronic interactions of CRs with gas (pp) or radiation (pgamma) produce a flux of neutrinos with an energy of about 5% of the initial CR nucleon
- The CRs responsible for the observed neutrino flux have corresponding energies reaching 20 PeV (proton) to 1 EeV (iron)
- Comparing to the CR "knee" (around 3 PeV) and the "ankle" around 3 EeV it is not entirely clear from an energetics point of view if Galactic or extragalactic sources are responsible for the neutrino flux
- CR data set a model independent upper bound of (Waxman-Bahcall):

$$E^2\Phi < 3 \times 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$$

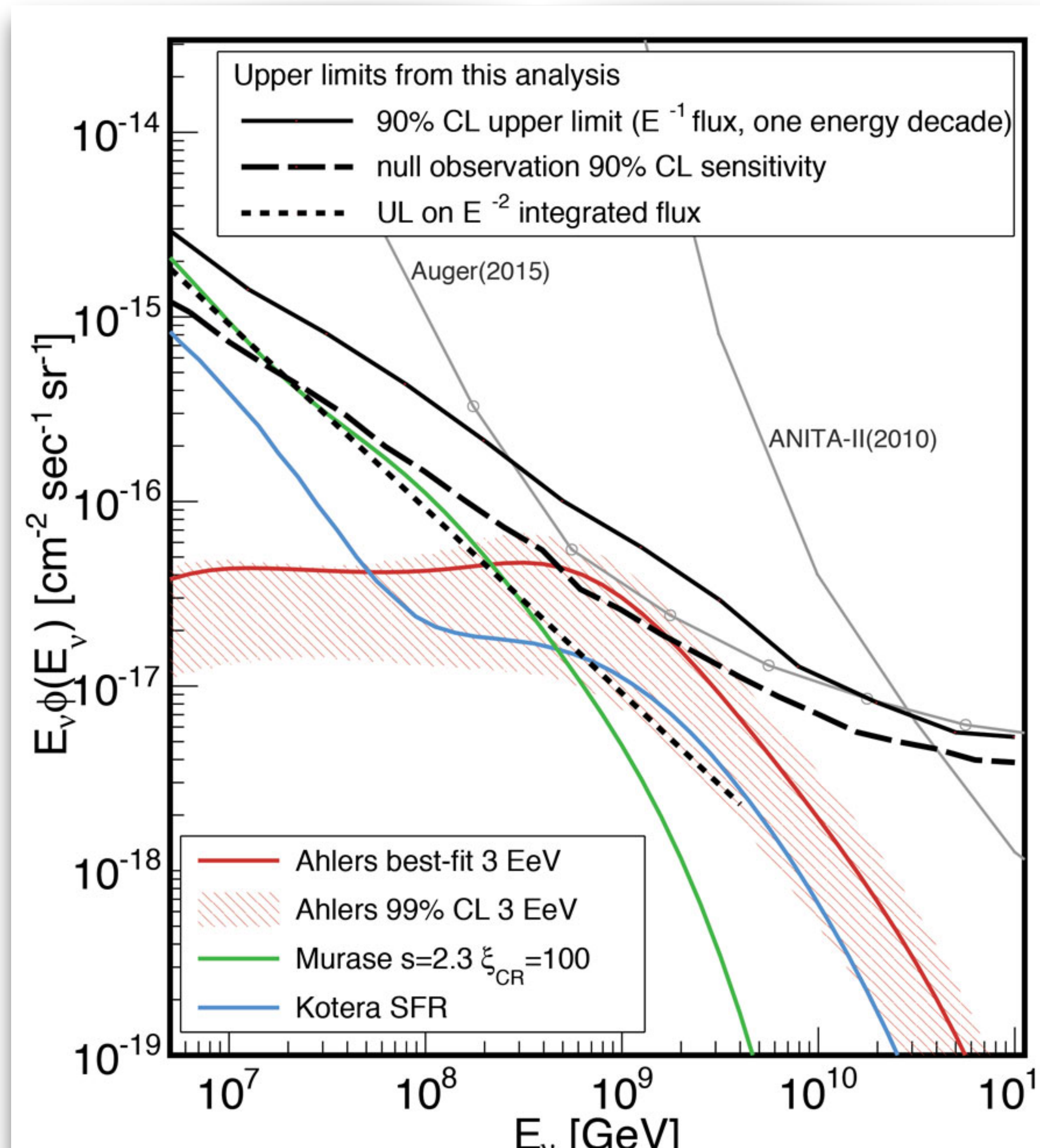
- The observed flux is very close to this limit: a coincidence or a deeper multi-messenger connection?
- The observed neutrinos do not arise from CR with energies > EeV and an extrapolation of two orders of magnitude would be required!

COSMOGENIC NEUTRINOS

- Protons with energies exceeding 10^{19} eV interact with the cosmic microwave background photons:

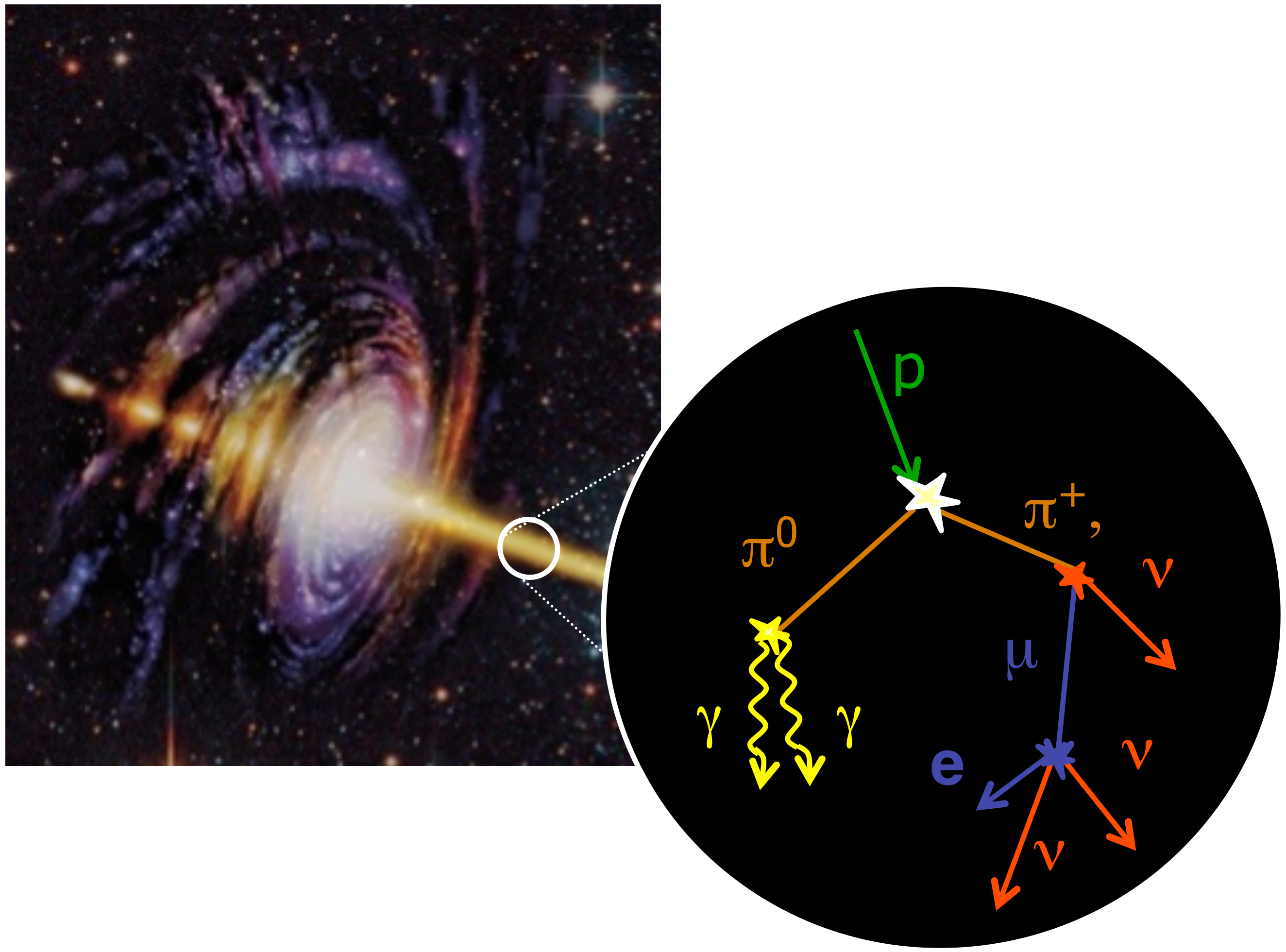
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

- leading to a suppression of the UHECR flux at the highest energies (the Greisen–Zatsepin–Kuzmin, GZK cut-off) giving a flux of neutrinos.
- Cosmogenic neutrinos are expected to carry energies around 10^{18} eV at the level of sensitivity of current neutrino instruments, but no such neutrino has been observed so far



All-flavor-sum neutrino flux quasi-differential 90%-CL upper limit on one energy decade E^–1 flux energy decade E^–1 flux windows. Credit: IceCube Collaboration

CONNECTION TO GAMMA-RAYS

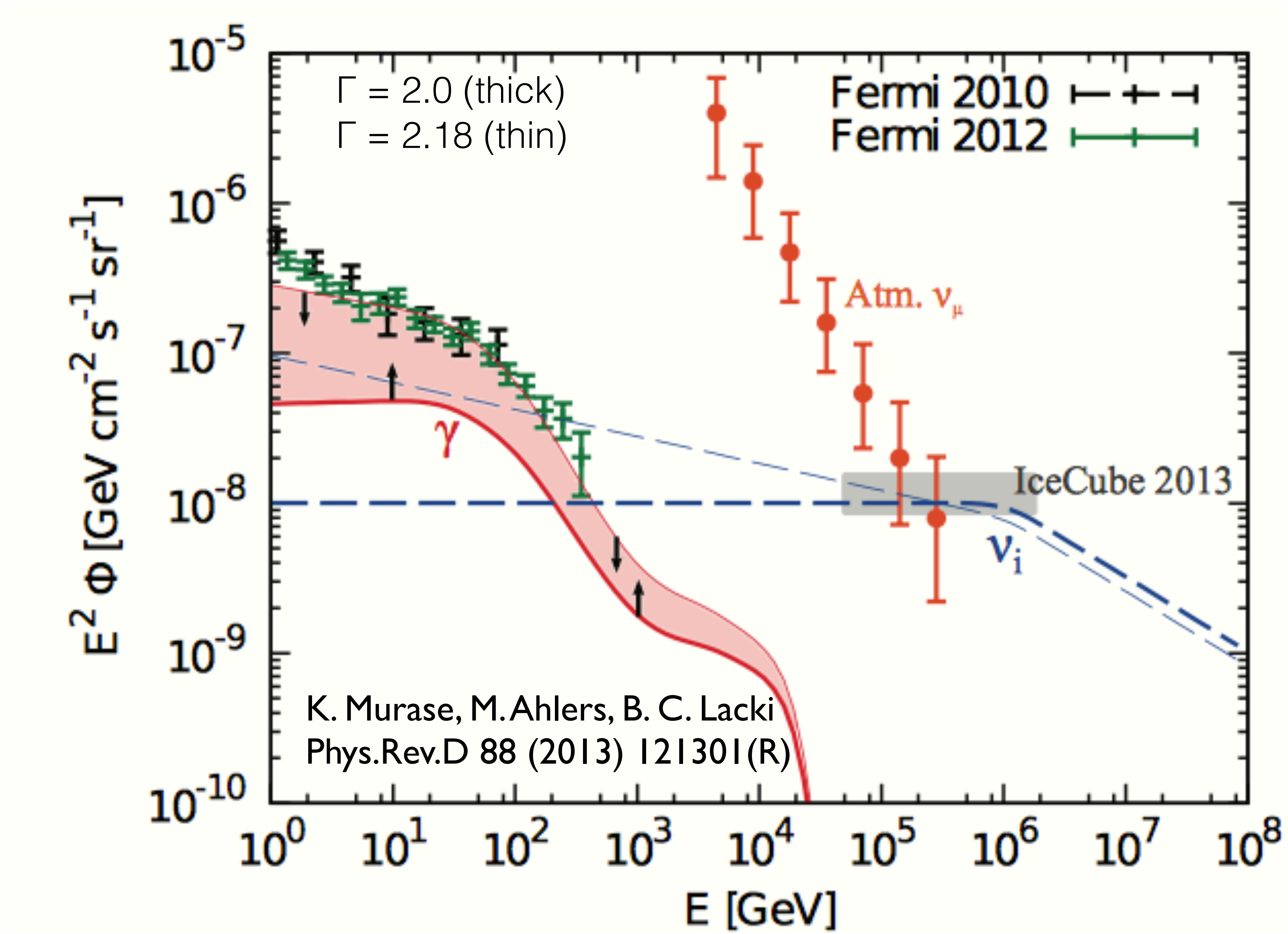


- Measurements of the *extragalactic* diffuse gamma-ray background can be used to derive constraints on the diffuse flux of neutrinos from the same sources.
- The constraints depend on the production mechanism, i.e. whether the neutrinos and gamma rays are produced in pp or pγ interactions.

- The case of pγ constraints are more easily circumvented because the neutrino energy spectrum depends on the target photon spectrum and the produced gamma rays are often attenuated on the ambient photons (e.g. AGNs, GRBs)
- In case of pp interactions in sources that are transparent to gamma rays up to 10 TeV (e.g. galaxy clusters or star-forming galaxies) a strong upper limit on the source spectral index can be derived

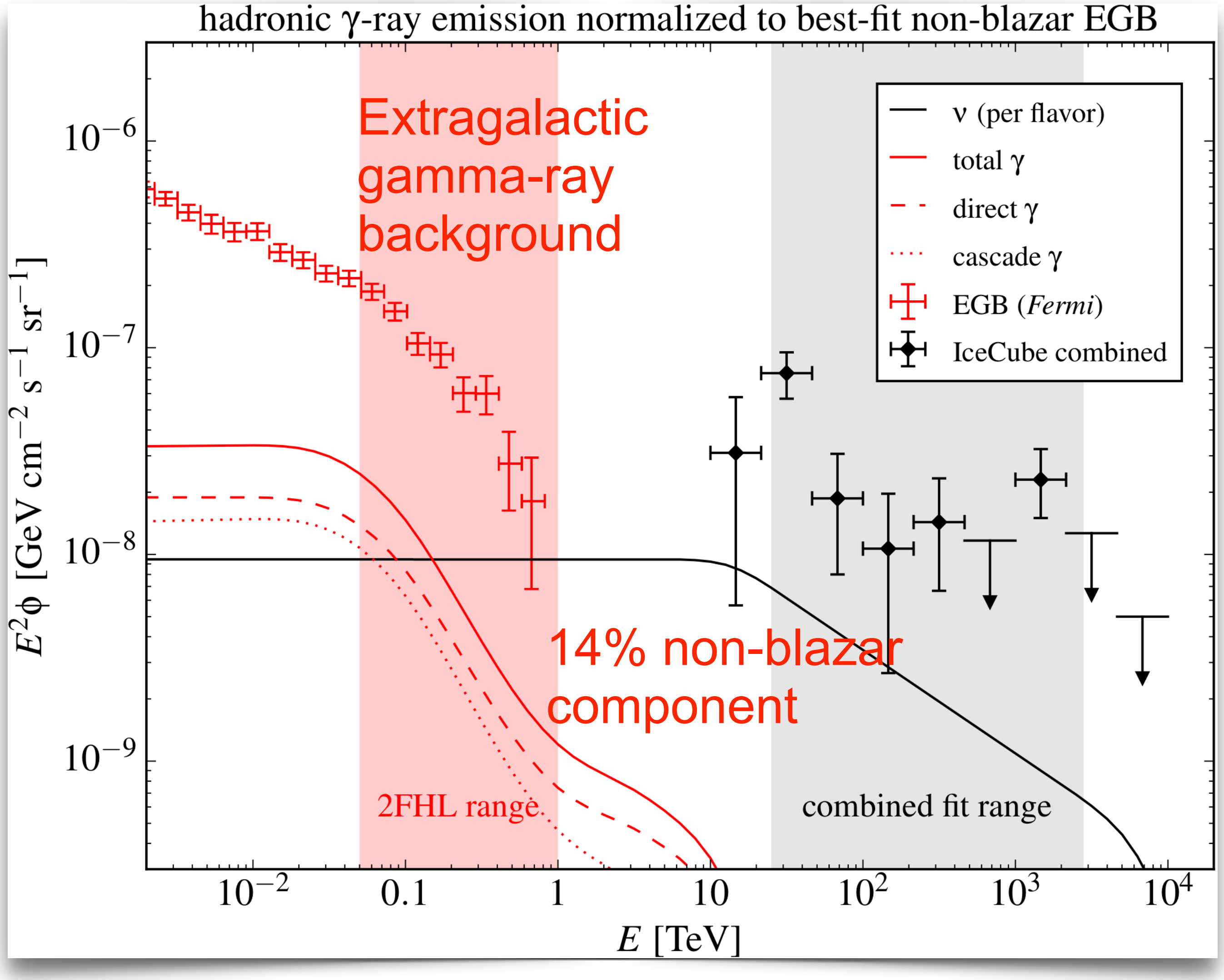
CONNECTION TO GAMMA-RAYS

- For pp scenarios, combing the new IceCube and recent Fermi data leads to strong upper limits on $\Gamma \leq 2.1 - 2.2$ and lower limit on the arising diffuse IGB contribution.



CONNECTION TO GAMMA-RAYS

- Star-forming galaxies contribute at most ~15% of extragalactic gamma-ray background (EGB)
  - can make up to 28% of IceCube signal
  - are now disfavoured as a dominant component of the IceCube astrophysical neutrino signal!!



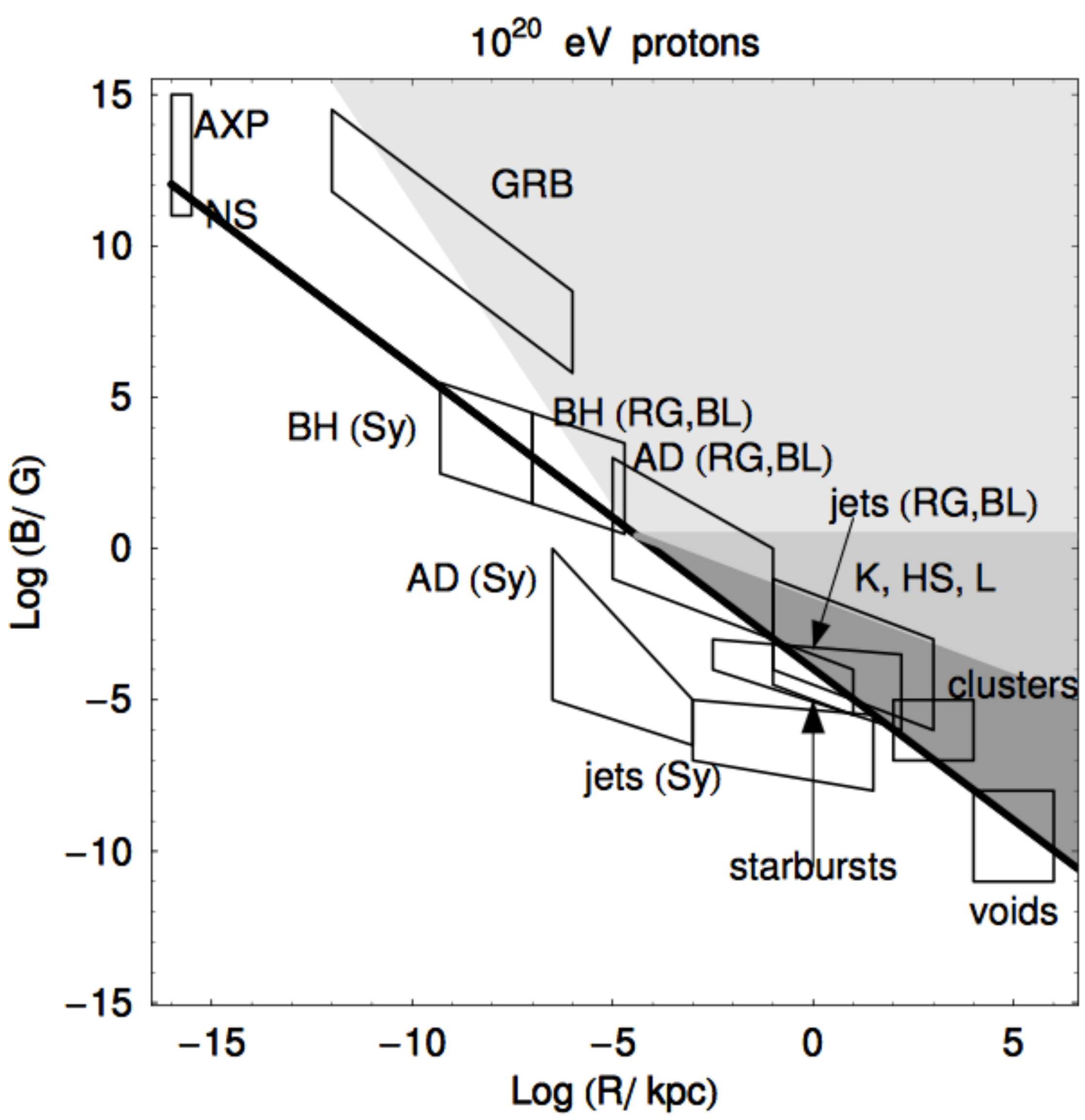
Bechtol et al. arXiv:1511.00688

WHAT ARE THEN THE SOURCES?

- A starting point is the "Hillas criterion"

$$E_{max} \simeq 10^{18}\mathrm{eV}\ Z\,\beta \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)$$

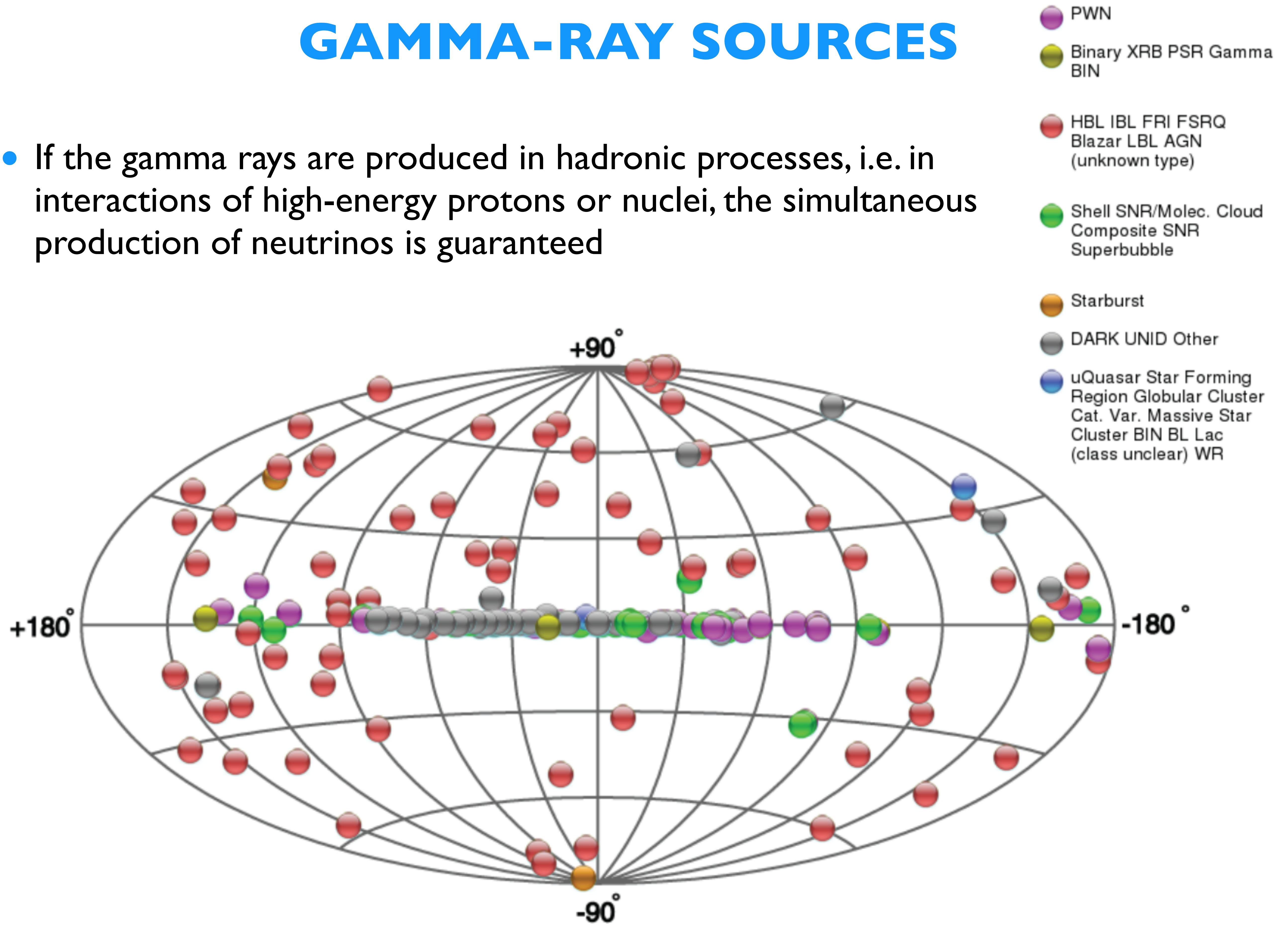
- Environments theoretically capable of acceleration to lower energies (according to the Hillas criterion) are more numerous though, and not all possible candidates are displayed in the figure.
- There is hence a variety of astrophysical objects that need to be considered in the context of TeV–PeV neutrinos.



K. Ptitsyna & S. Troitsky, Phys.Usp.53:691-701, 2010

GAMMA-RAY SOURCES

- If the gamma rays are produced in hadronic processes, i.e. in interactions of high-energy protons or nuclei, the simultaneous production of neutrinos is guaranteed



PREDICTED NEUTRINO LUMINOSITY

- Rich ambient matter allows for proton-proton inelastic collisions
- Based on SIBYLL simulations of such interactions, energy spectral of secondary particles extracted and analytically parametrised for *arbitrary incident proton spectra* [S. R. Kelner, F. A. Aharonian, and V. V. Bugayov Phys. Rev. D 74, 034018 (2009)]
- If primary proton spectrum dNp/dEp is given by a power-law with index α and an exponential cut-off energy epsilon,

$$\frac{\mathrm{d}N_p}{\mathrm{d}E_p} = k_p \left(\frac{E_p}{1\,\mathrm{TeV}}\right)^{-\alpha} \exp\left(-\frac{E_p}{\epsilon_p}\right)$$

- it is possible to calculate the resulting summed electron and muon neutrino spectrum dNν/dEν at the source (νe :νμ = 1 : 2)
- Assuming full neutrino mixing the muon neutrino spectrum at Earth is then given by one-third of dNν/dEν

PARAMETRISATION: SECONDARY SPECTRA

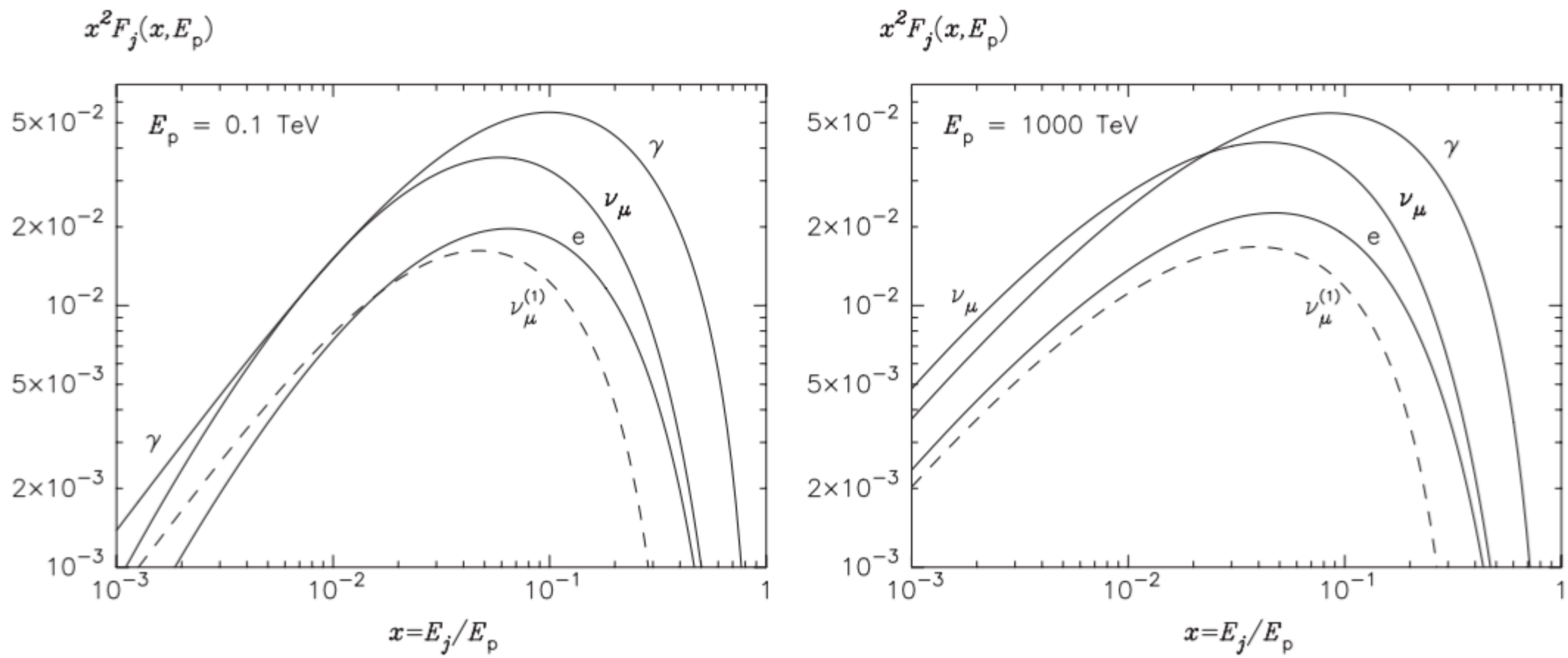


FIG. 10. Energy spectra of all decay products produced at p-p interactions for two energies of incident protons: (a) 0.1 TeV and (b) 1000 TeV. The spectrum of electronic neutrinos is not shown because it practically coincides with the spectrum of electrons.

- **It does also exist for pgamma** [S.R. Kelner, F.A. Aharonian, Phys.Rev.D78:034013,2008]

PREDICTED NEUTRINO LUMINOSITY

- Considering spectra with $1.8 < \alpha < 3.0$ and 10 TeV < ϵ_p < 1 PeV [Kappes et al. Astrophys.J.656:870-896,2007] find that the spectra of γ-rays and muon neutrinos at the Earth can be described by:

$$\frac{\mathrm{d}N_{\gamma/\nu}}{\mathrm{d}E_{\gamma/\nu}} \approx k_{\gamma/\nu} \left(\frac{E_{\gamma/\nu}}{1\,\mathrm{TeV}}\right)^{-\Gamma_{\gamma/\nu}} \exp\left(-\sqrt{\frac{E_{\gamma/\nu}}{\epsilon_{\gamma/\nu}}}\right)$$

$$\begin{aligned} k_\nu &\approx (0.71 - 0.16\alpha)\, k_\gamma \\ \Gamma_\nu &\approx \Gamma_\gamma \approx \alpha - 0.1 \\ \epsilon_\nu &\approx 0.59\, \epsilon_\gamma \approx \epsilon_p/40\ . \end{aligned}$$

- if:

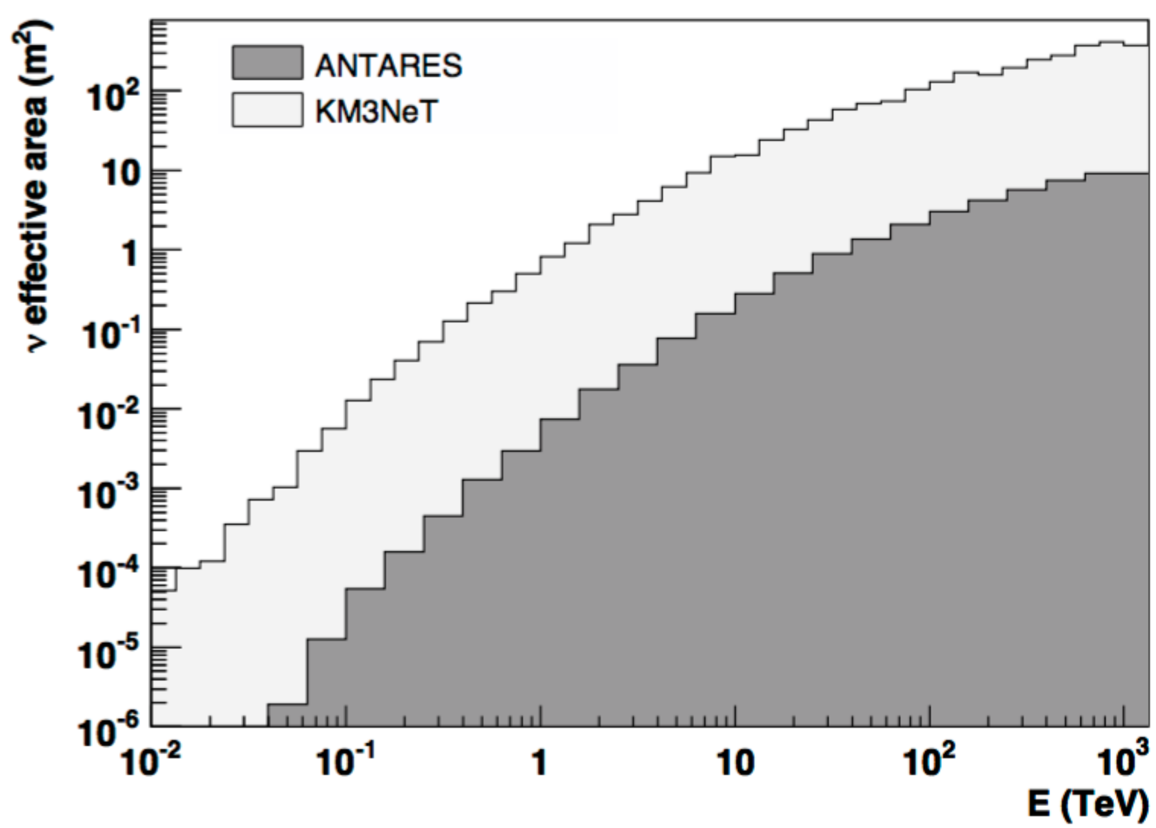
1. no significant contribution of non hadronic processes
2. no significant γ-ray absorption within the source
3. no significant pγ interaction (radiation density low)
4. charged pions decay before interacting (matter density is low)
5. muons decay without significant energy loss (magnetic field is low)
6. nucleus-nucleus interactions produce pion spectra that are similar enough to the p-p case that they can be treated in the same way
7. the size of the emitting region within each source is large enough that oscillations will produce a fully mixed neutrino signal at the Earth

PREDICTED RATE OF MEASURABLE EVENTS

- Given a neutrino spectrum dNν/dEν at the Earth from a source the event rate in a neutrino telescope can be calculated as:

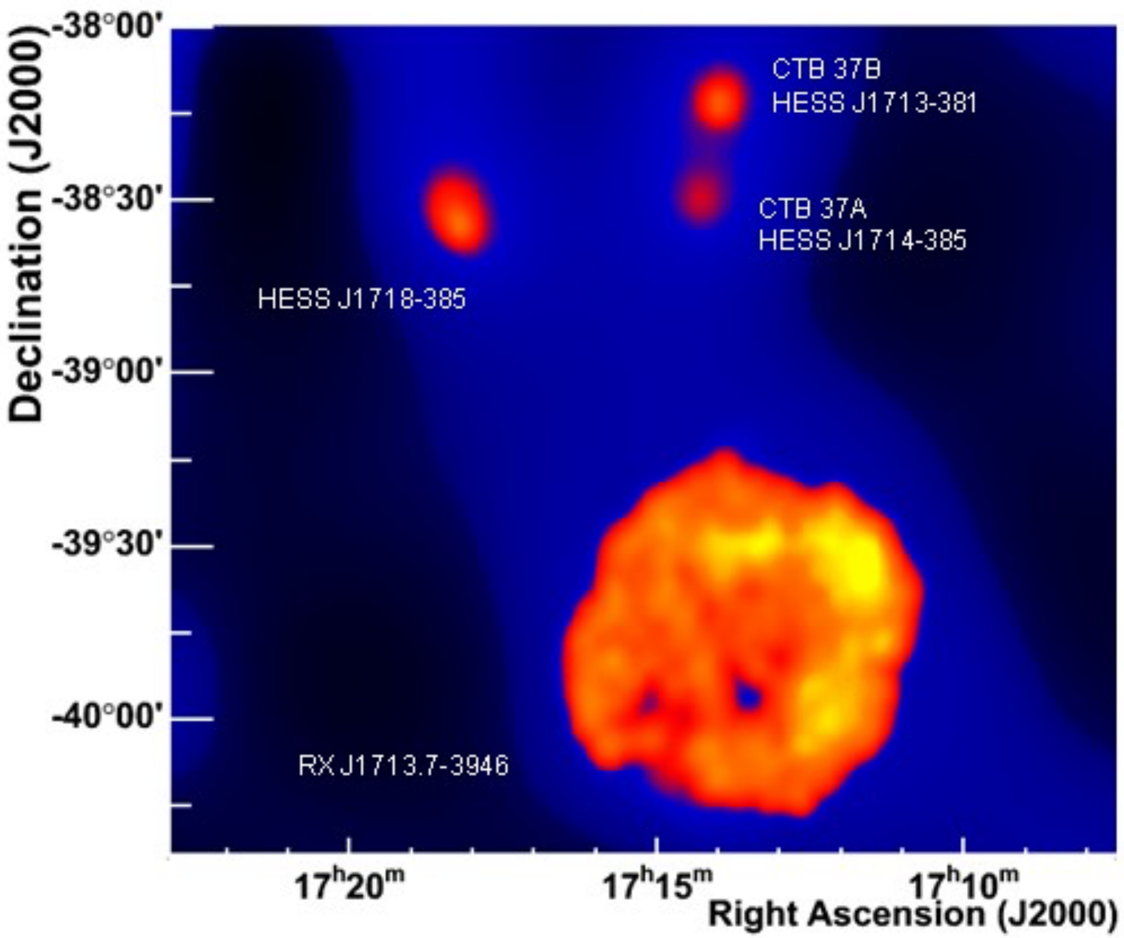
$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} = \int \mathrm{d}E_\nu \; A_\nu^{\mathrm{eff}} \, \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}$$

- Aeff is the neutrino effective area of the detector comprising the neutrino interaction probability and the lepton detection efficiency after analysis cuts
- Due to the increase of the neutrino cross section and the muon range and its light yield per unit path length with energy the effective area is energy-dependent



PREDICTED RATE OF MEASURABLE EVENTS

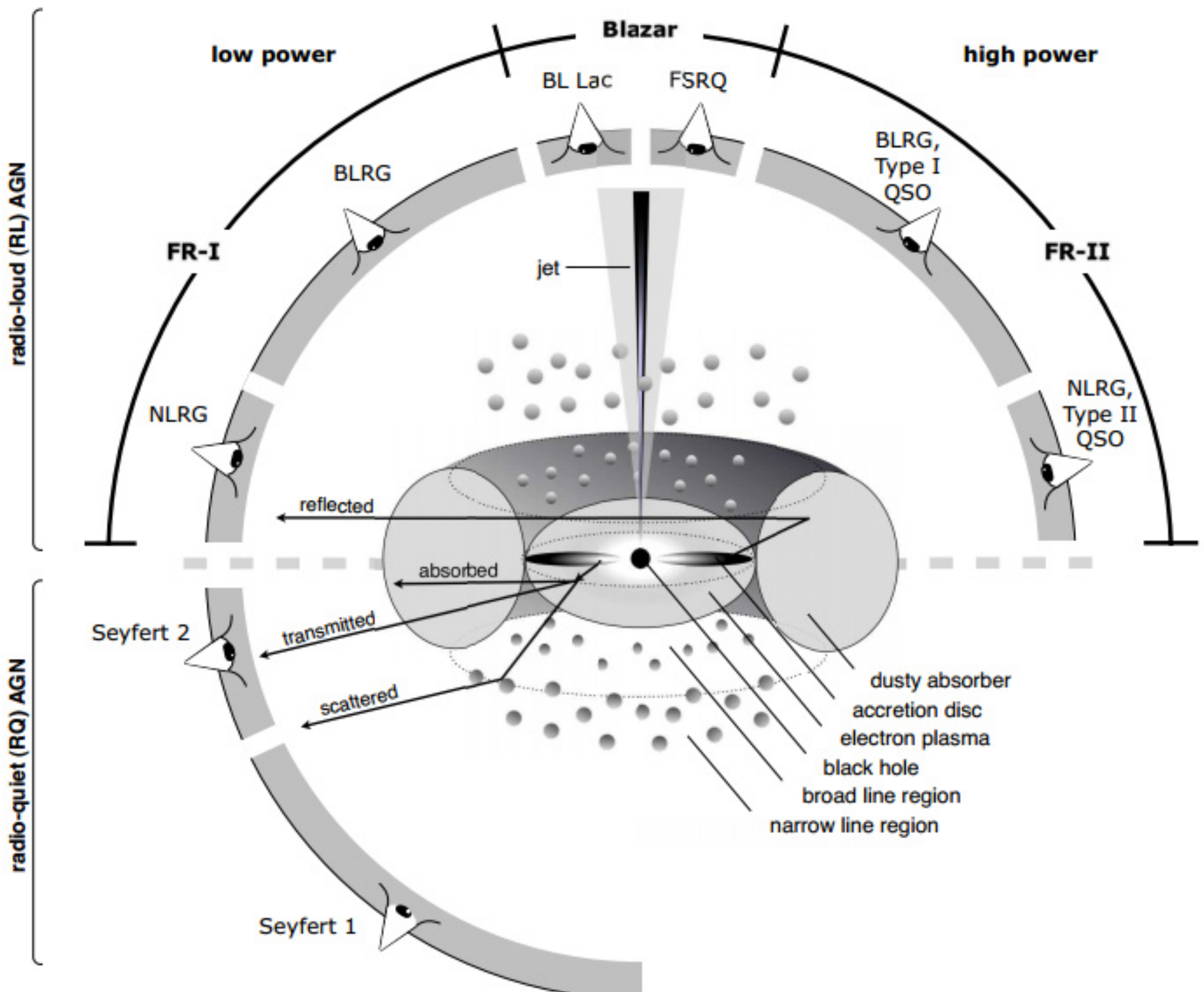
- the brightest γ-ray sources produce neutrino rates above 1 TeV, comparable to the background from atmospheric neutrinos
- For KM3NeT, with an instrumented volume of 1km3, an event rate of a few neutrinos per year (Eν > 1TeV) from each of the three brightest γ-ray sources (RXJ1713.7−3946, VelaX, and RXJ0852−4622) can be expected, and the detection of individual sources seems possible after several years of stable detector operation



Adaptively smoothed very high energy gamma ray image of the 2.5 degree field showing the large supernova remnant RX J1713.7-3946. Credits: The H.E.S.S. collaboration.

ACTIVE GALACTIC NUCLEI

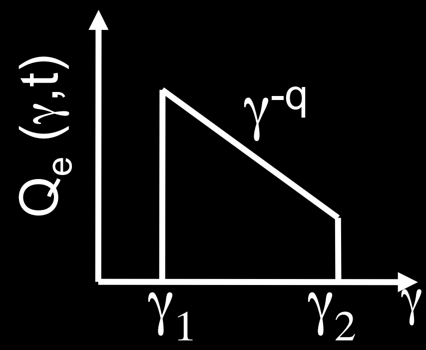
- Several regions of AGNs are thought to accelerate CR:
  - relativistic jets
  - inner region close to the black
- Generally photohadronic neutrino production is assumed



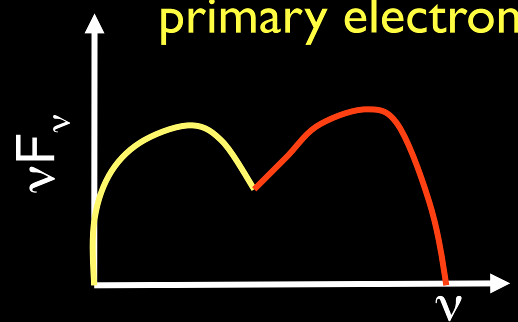
http://arxiv.org/pdf/1302.1397v1.pdf

BLAZAR MODELS: LEPTONIC

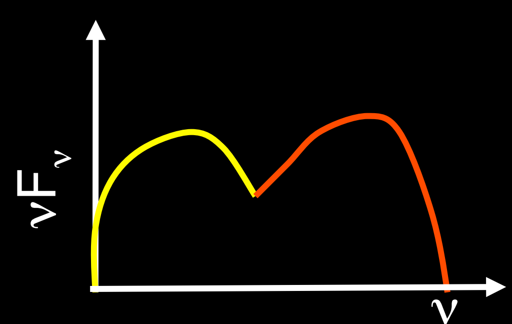
Injection, acceleration of ultra-relativistic electrons

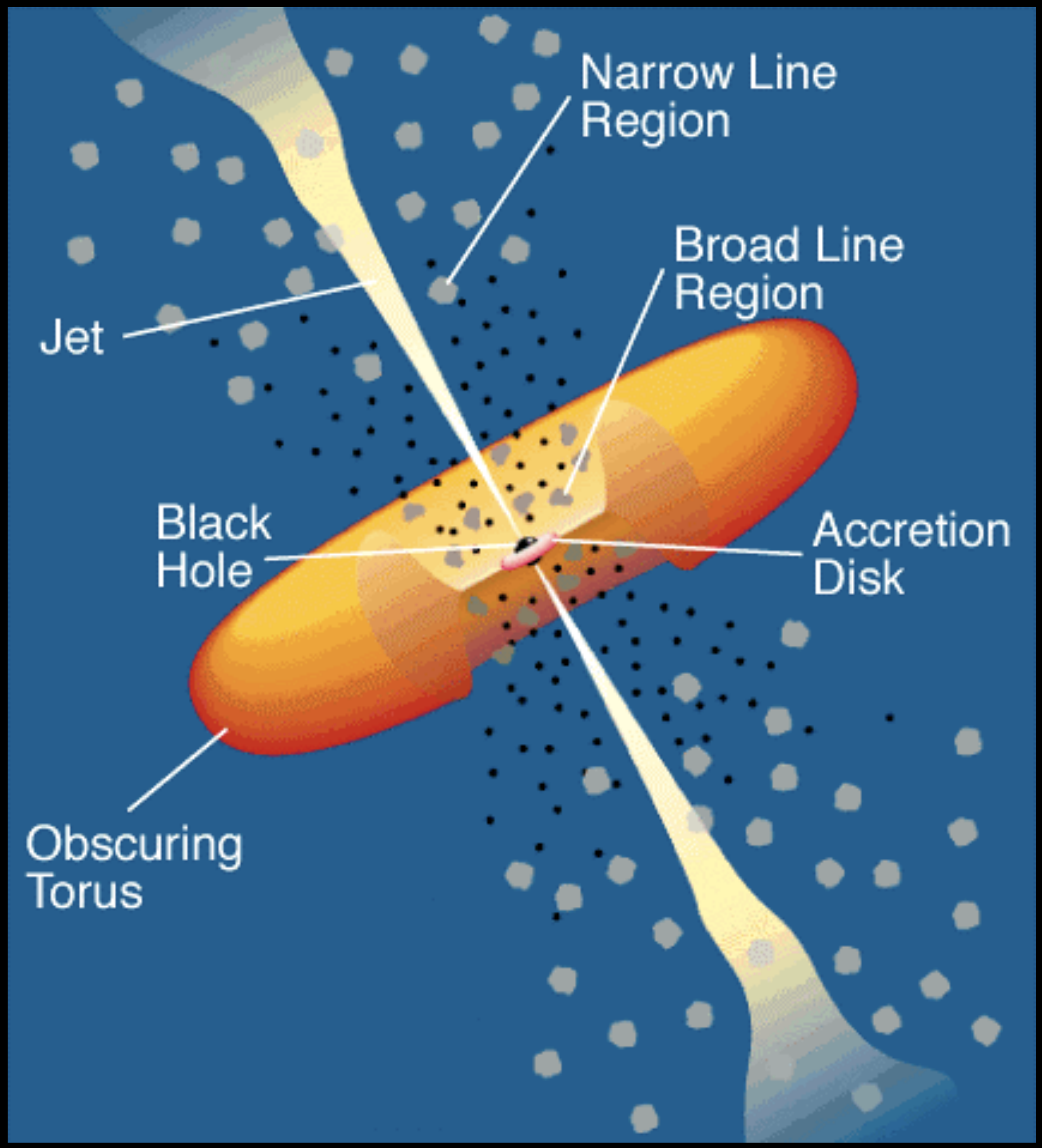


Synchrotron emission of primary electrons



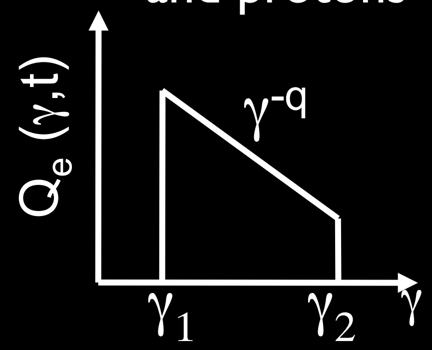
Compton emission, seed photons: Synchrotron (SSC), Accr. Disk + BLR (EC)



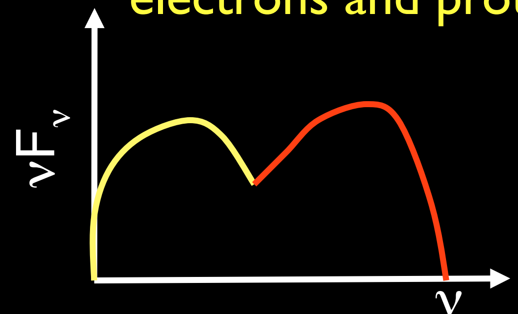


BLAZAR MODELS: HADRONIC

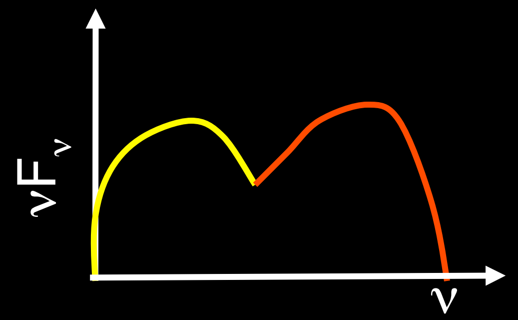
Injection, acceleration of ultra-relativistic electrons and protons

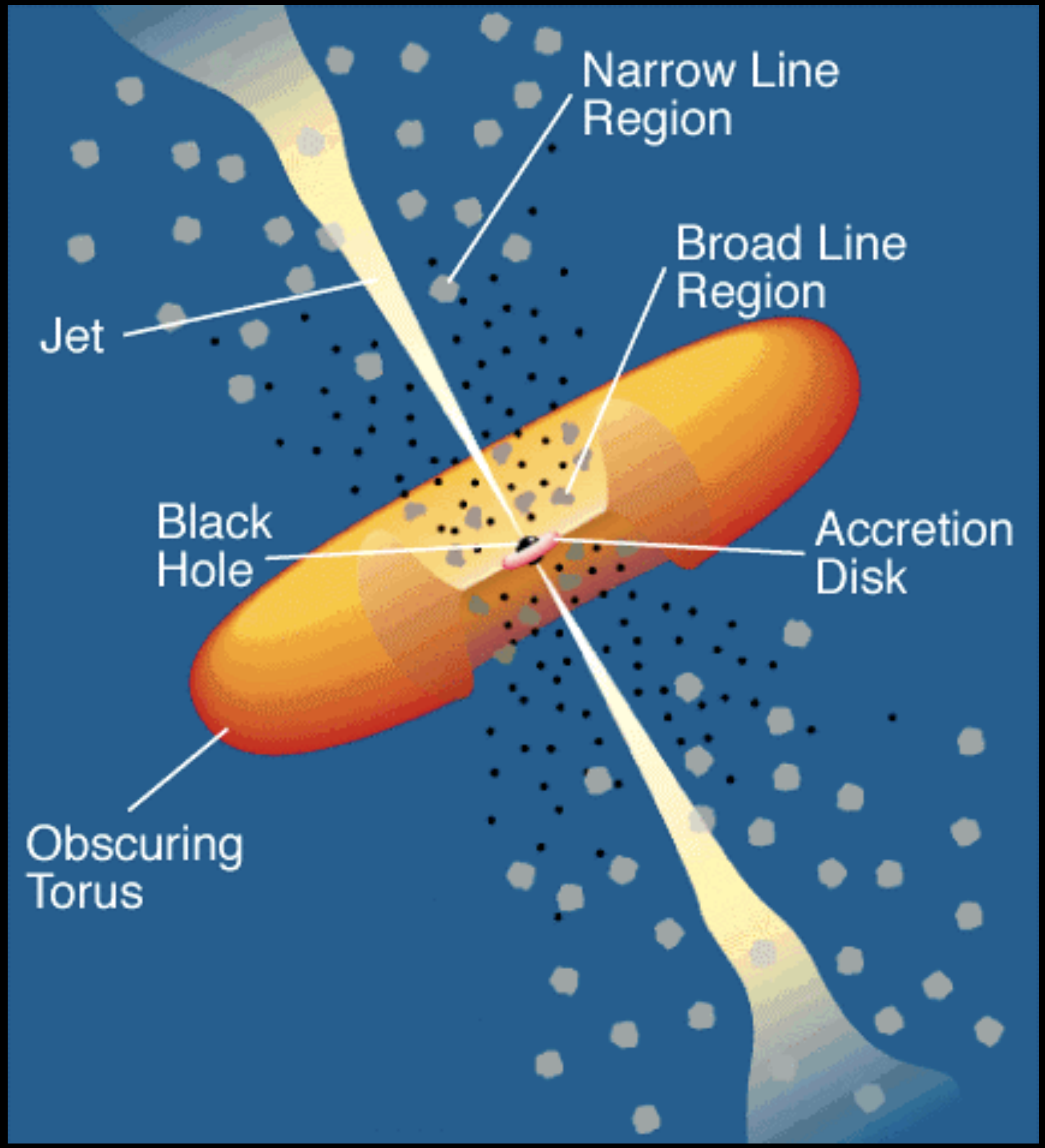


Synchrotron emission of primary electrons and protons



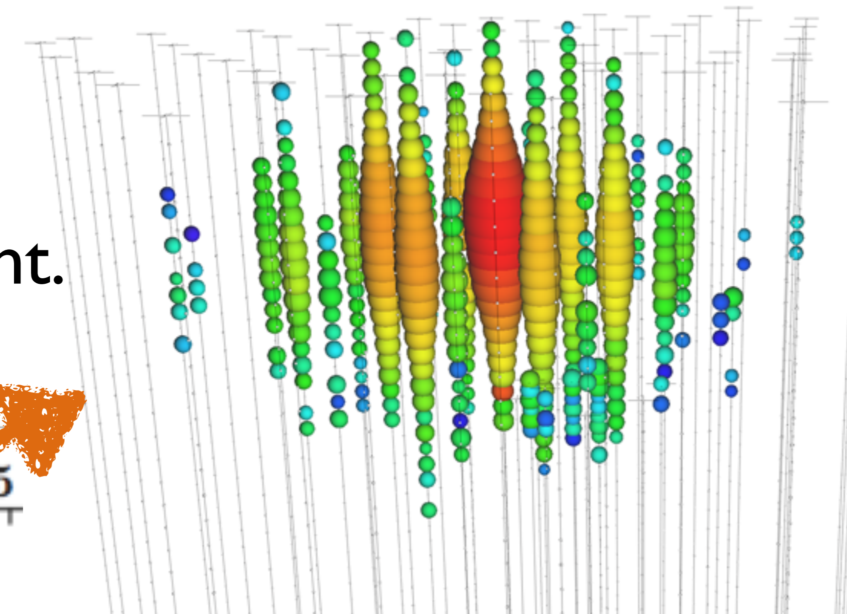
Proton-induced radiation, proton synchrotron, secondary μ-, e-synchrotron, cascades ...



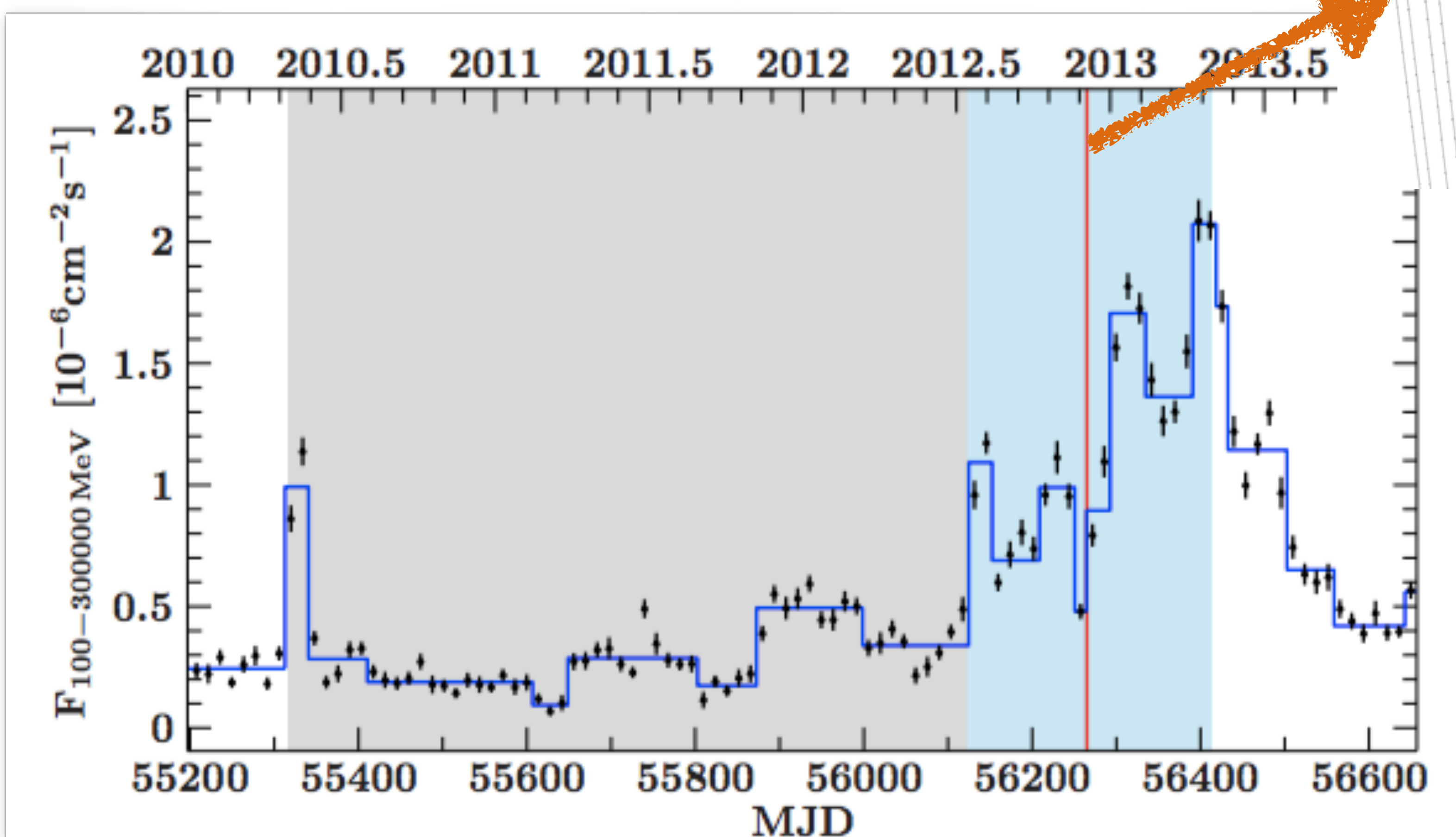


EXAMPLE: NEUTRINO PRODUCTION IN AGN FLARES

- Major outburst of FSRQ PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino (Big Bird)
- 5% chance coincidence
- If HE gamma-rays hadronic, explain the observed event.



$2.0^{+0.26}_{-0.24}$ PeV



Kadler et al., Nature 520, 266 (2016)

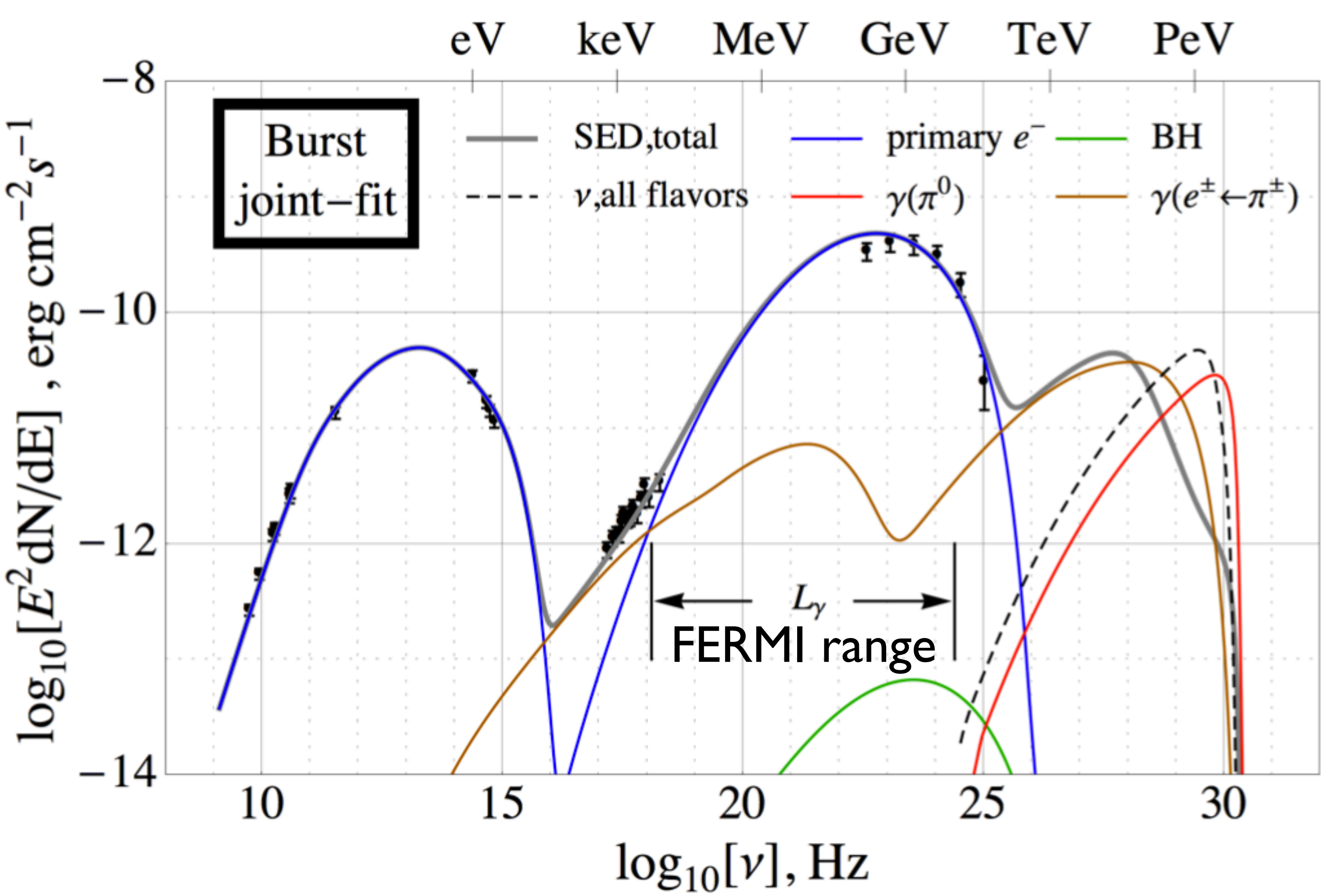
EXAMPLE: NEUTRINO PRODUCTION IN AGN FLARES

- **If a full multi-messenger modelling is implemented, hadronic dominance of gamma-rays in the FERMI range is disfavoured** [S. Gao et al. arXiv:1610.05306 accepted by ApJ]

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\rm esc}} + Q(E)$$

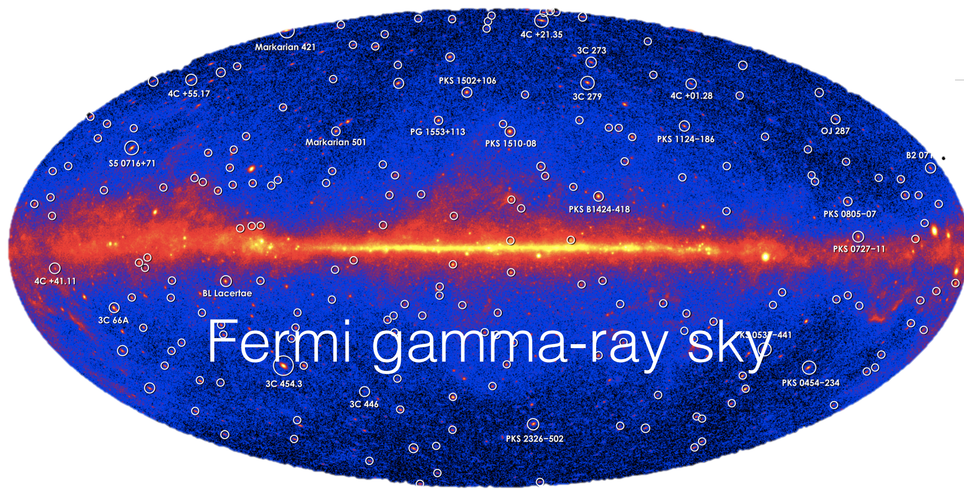
Cooling/acceleration | Escape | Injection

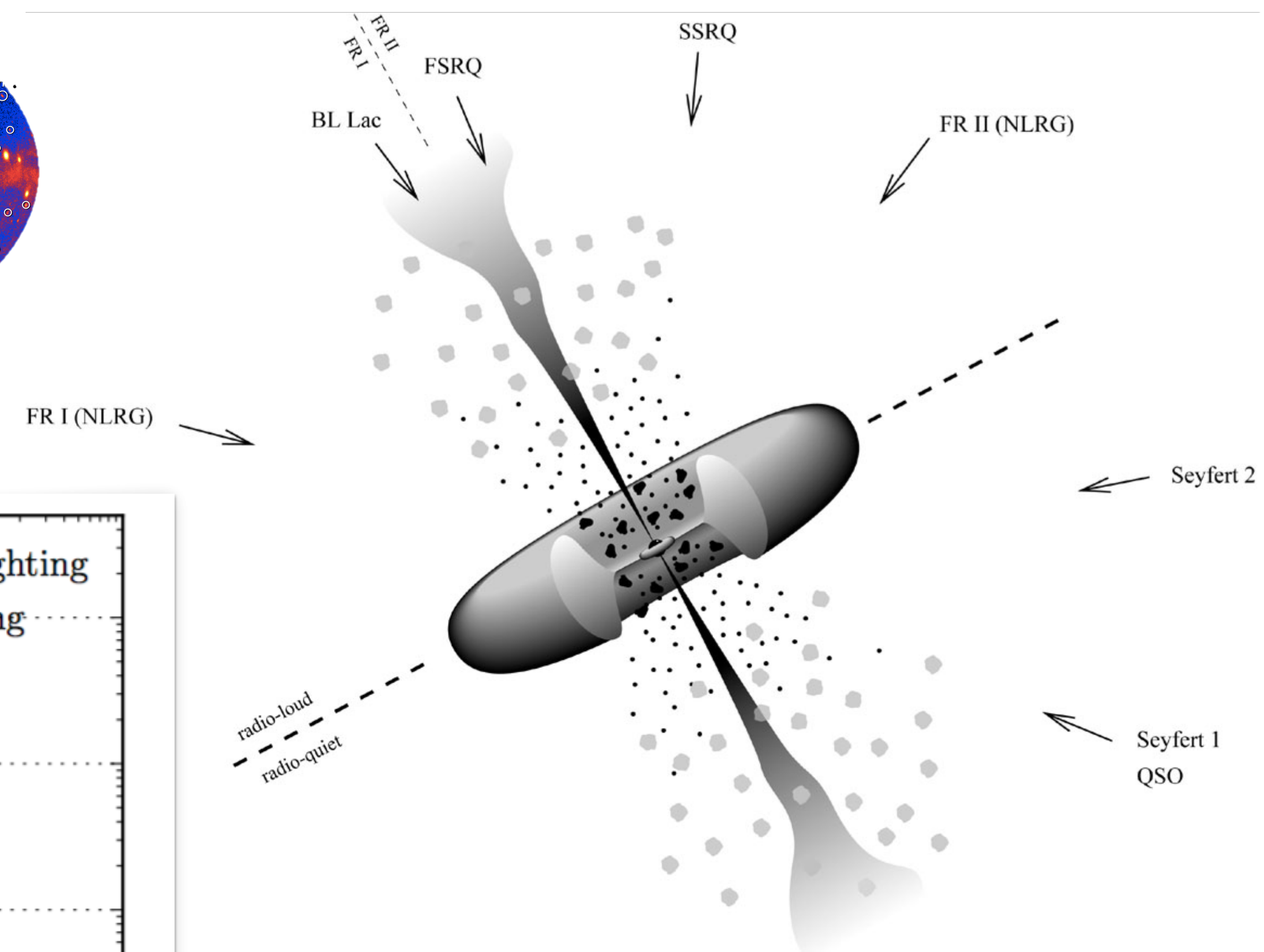
S. GAO ET AL.

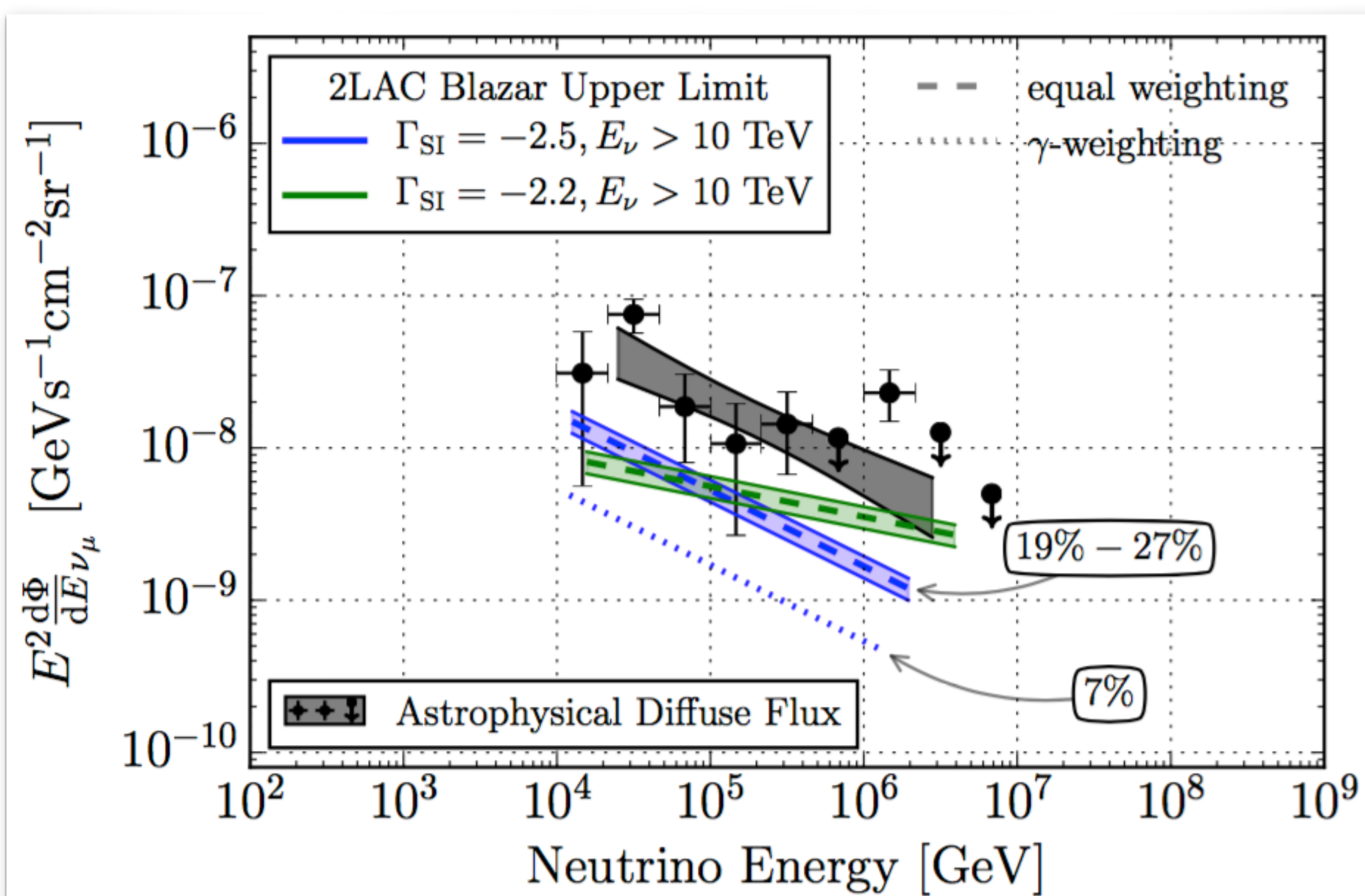


WHAT DOES ICECUBE DATA SAY?

- Correlation study of 3 years of IceCube data and 862 Fermi- LAT Blazars







IceCube Coll.,

arXiv:1502.03104

LIKELIHOOD ANALYSIS

- The likelihood function consists of two PDFs, one B(x) for a background hypothesis and one S(x) for a signal hypothesis
- Requiring the total number of observed events N to be the sum of the signal and background events:

$$\ln(L)\{n_s, \Gamma_{\rm SI}\} = \sum_{i=1}^{N} \ln\left(\frac{n_s}{N}\cdot S(\delta_i, RA_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI}) + \left(1-\frac{n_s}{N}\right)\cdot B(\sin(\delta_i), \varepsilon_i)\right)$$

- Two free parameters: normalization factor ns and spectral index ΓSI of the signal

$$B(\sin(\delta_i), \varepsilon_i) = \frac{1}{2\pi}\cdot f(\sin(\delta_i), \varepsilon_i)$$

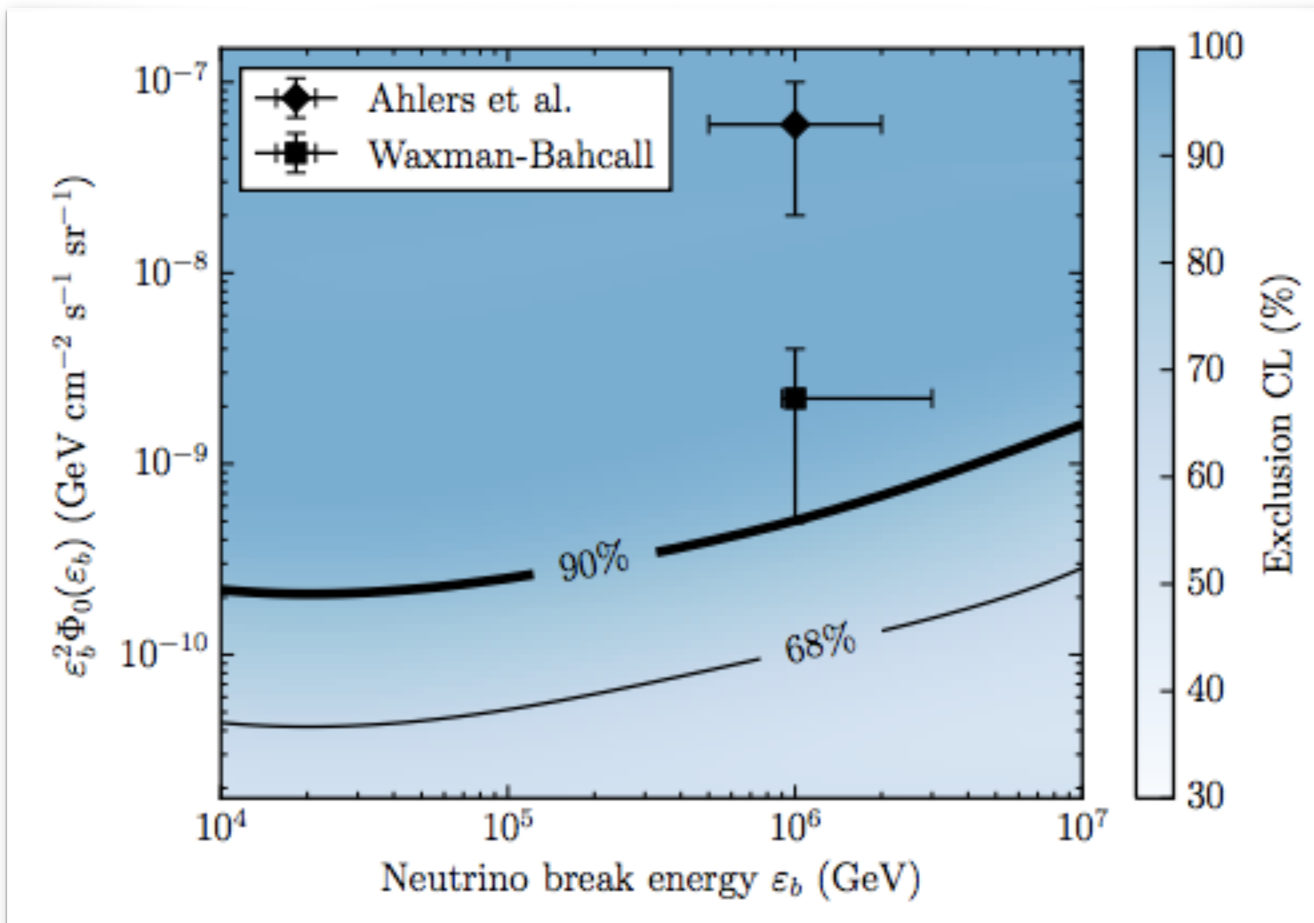
$$S(\delta_i, \mathrm{RA}_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI}) = \frac{\sum_{j=1}^{N_{src}} w_j \cdot S_j(\delta_i, \mathrm{RA}_i, \sigma_i, \varepsilon_i; \Gamma_{\rm SI})}{\sum_{j=1}^{N_{src}} w_j}$$

GAMMA-RAY BURSTS

- **In most models neutrinos shall be produced (pγ) in coincidence with the prompt gamma-ray emission** [Waxman& Bahcall Physical Review D 59 (1998), 023002; Physical Review Letters 78 (1997), 2292, Guetta et al. Astroparticle Physics 20 (2004), 429]
- **These models have been ruled out by IceCube**
- **Revisions by** [Hummer et al. Physical Review Letters 108 (2012), 231101]**, predict significantly lower fluxes**
- **High-energy neutrinos are also predicted to be emitted during other phases of GRBs. For instance, during prebursts of the stellar progenitor** [Razzaque et al. Physical Review D 68 (2003), 083001]**, or afterglow** [Waxman & Bahcall Astrophysical Journal 541 (2000), 707]

WHAT DOES ICECUBE DATA SAY?

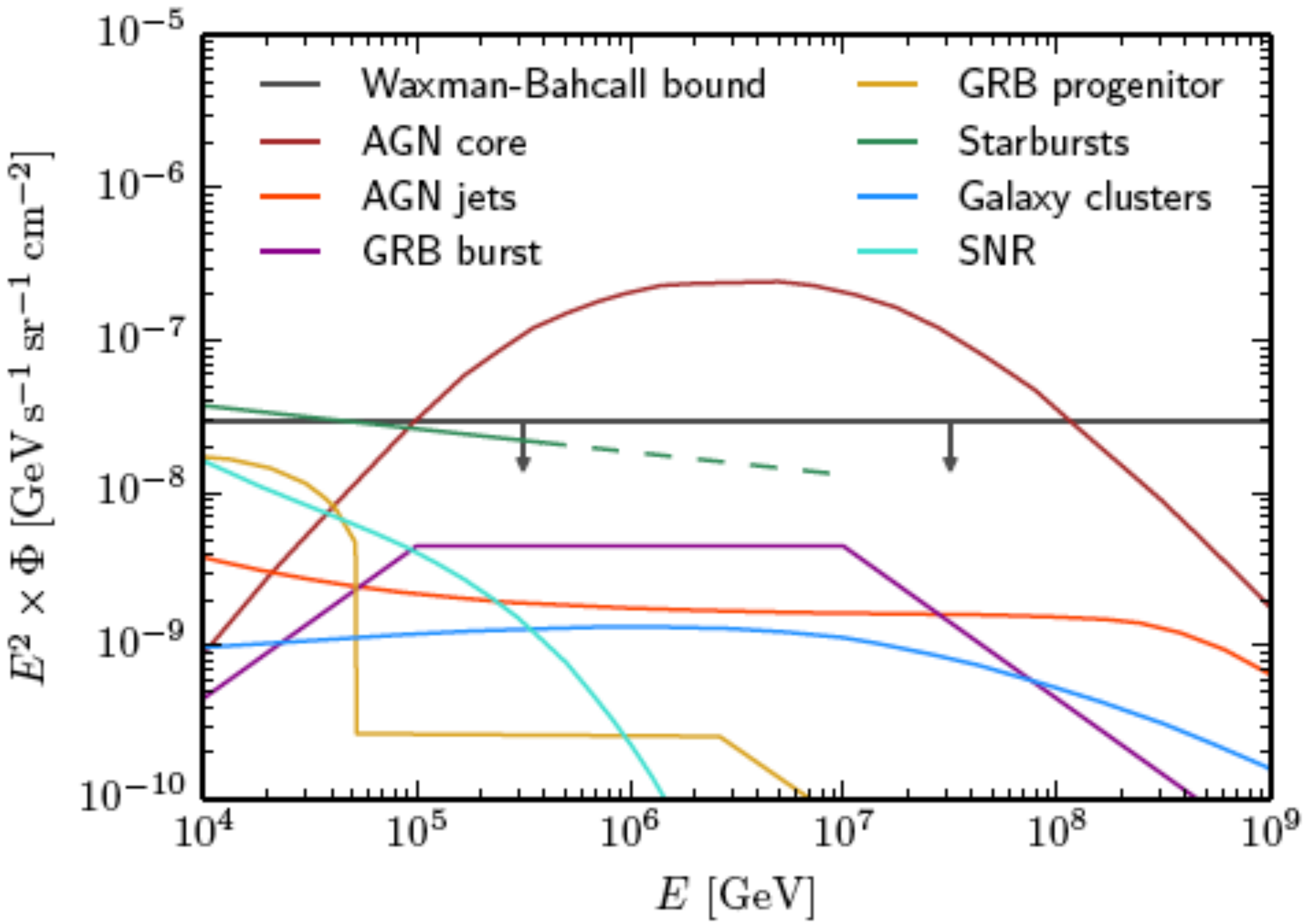
- > 800 GRBs correlated with IceCube data
- GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained.



IceCube Coll., ApJ 805, 2015 arXiv:1601.06484

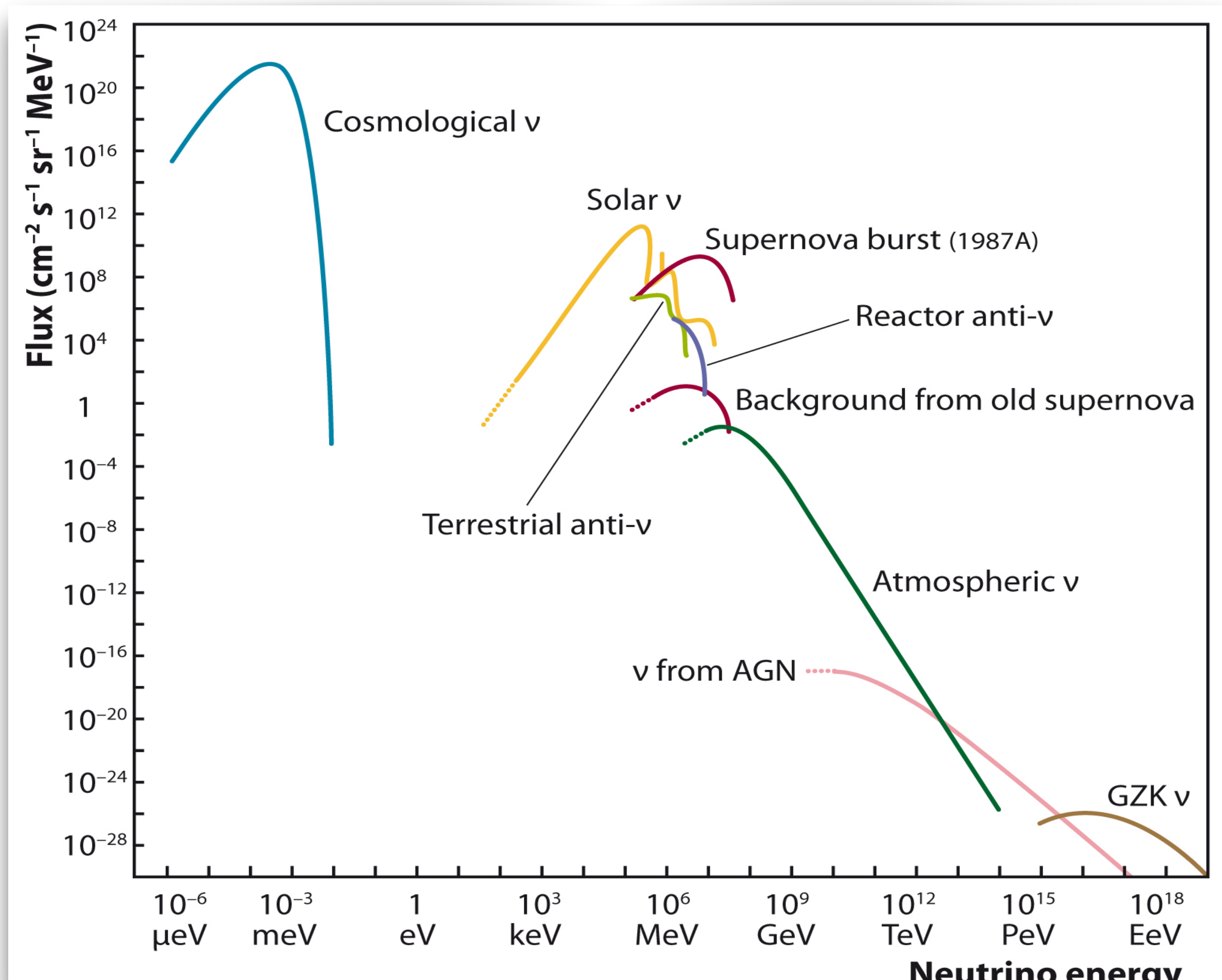
DIFFUSE FLUX PREDICTIONS

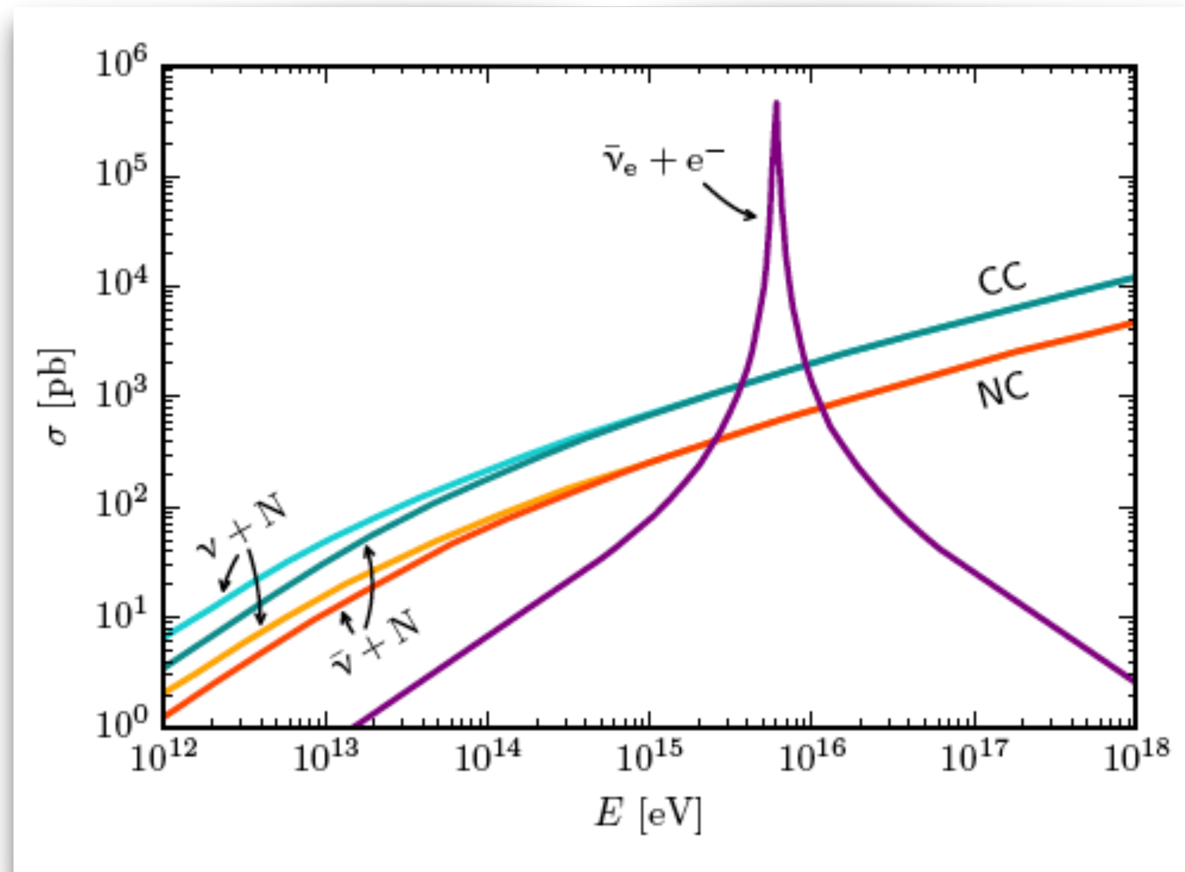
- Before IceCube discovery



HOW TO DETECT NEUTRINOS

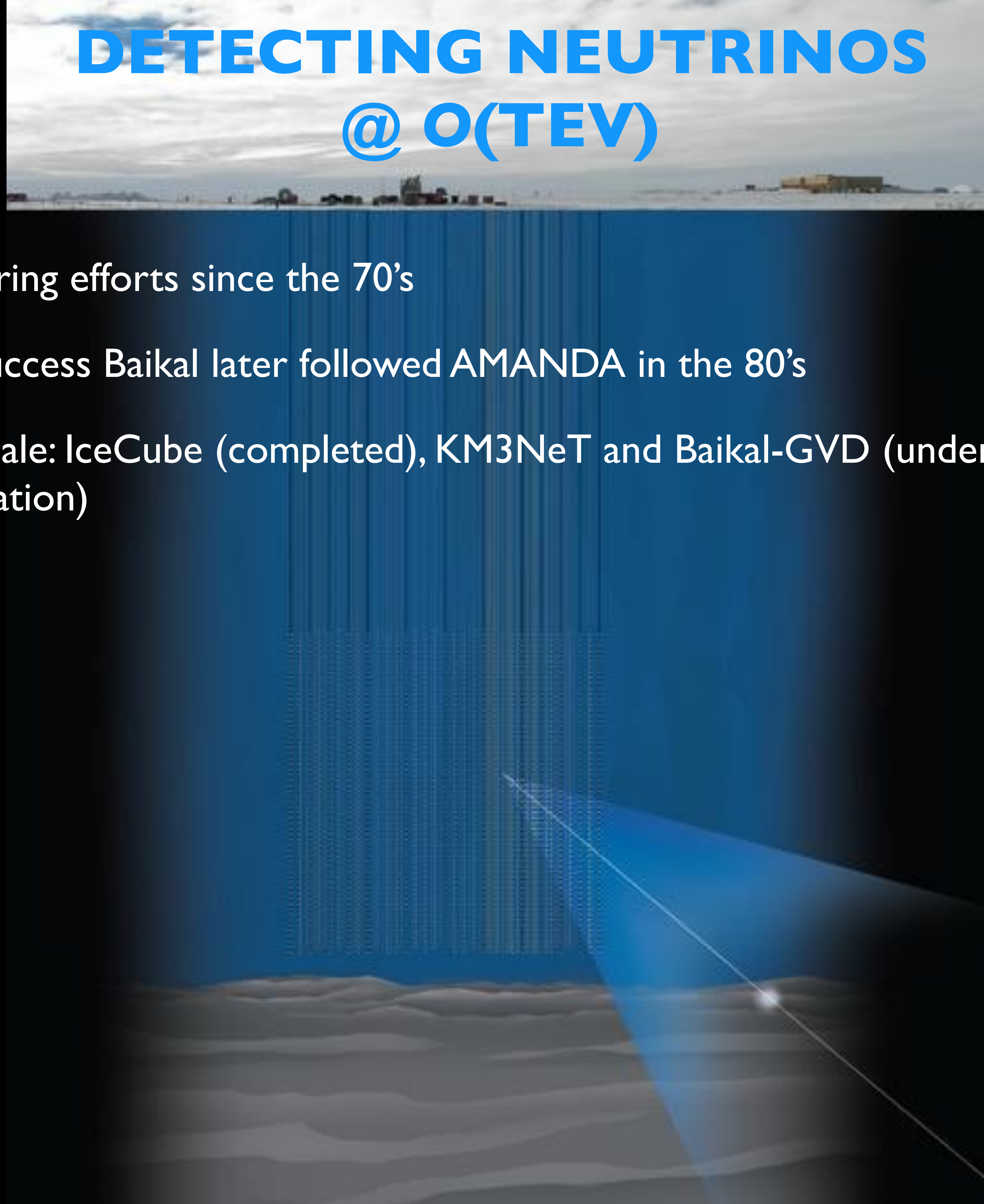
- Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV
- Need km^3-scale detectors!
- Large volumes, use natural water or ice

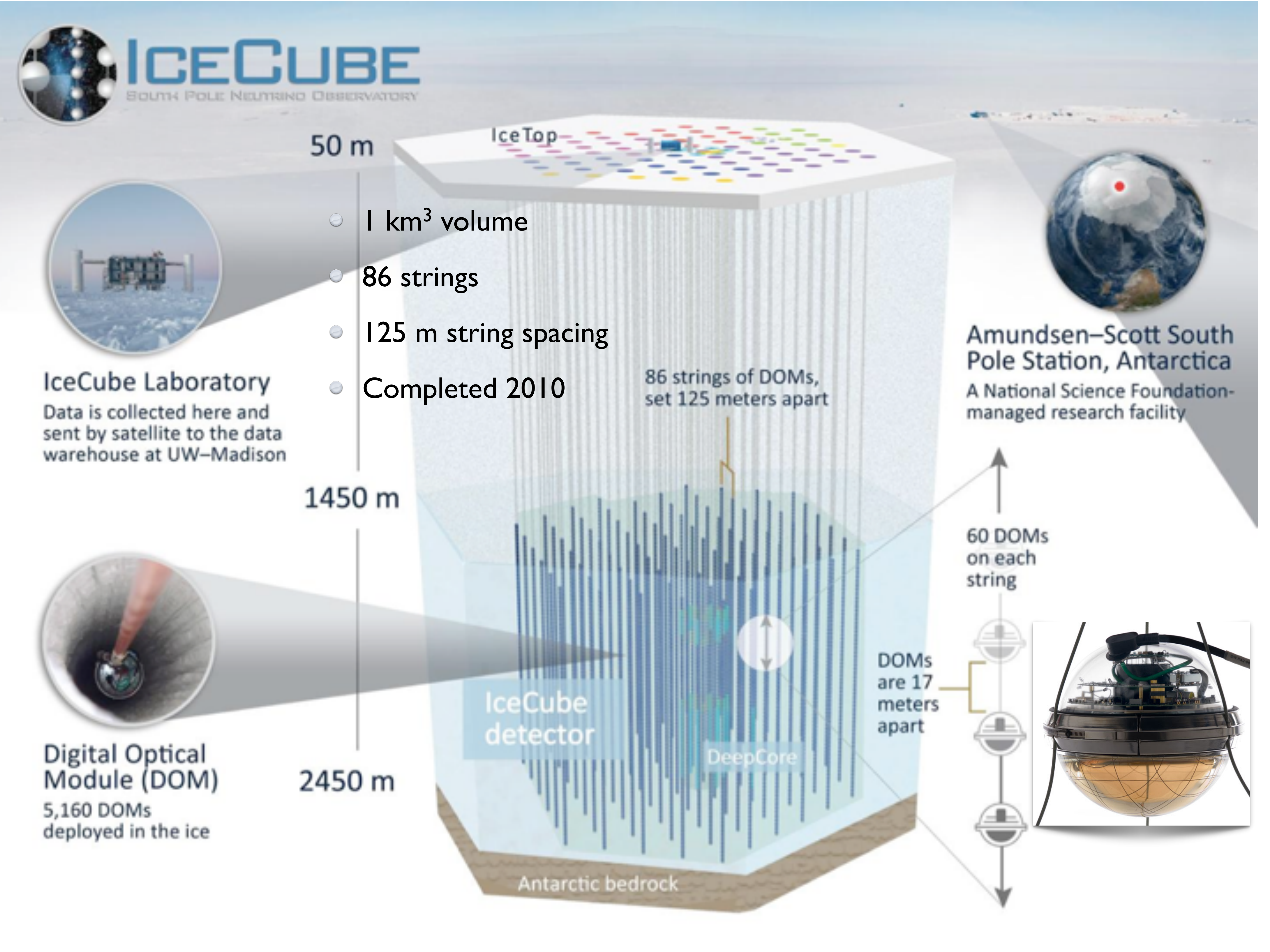




DETECTING NEUTRINOS @ O(TEV)

- Pioneering efforts since the 70's
- First success Baikal later followed AMANDA in the 80's
- Km^3-scale: IceCube (completed), KM3NeT and Baikal-GVD (under construction/ preparation)

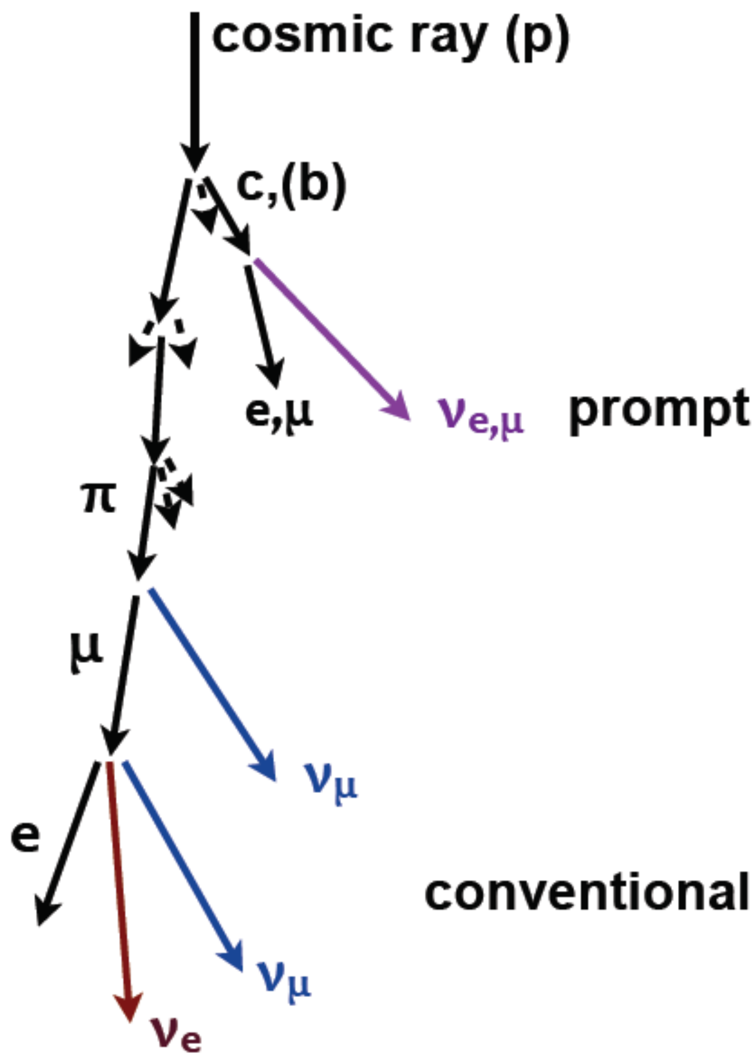


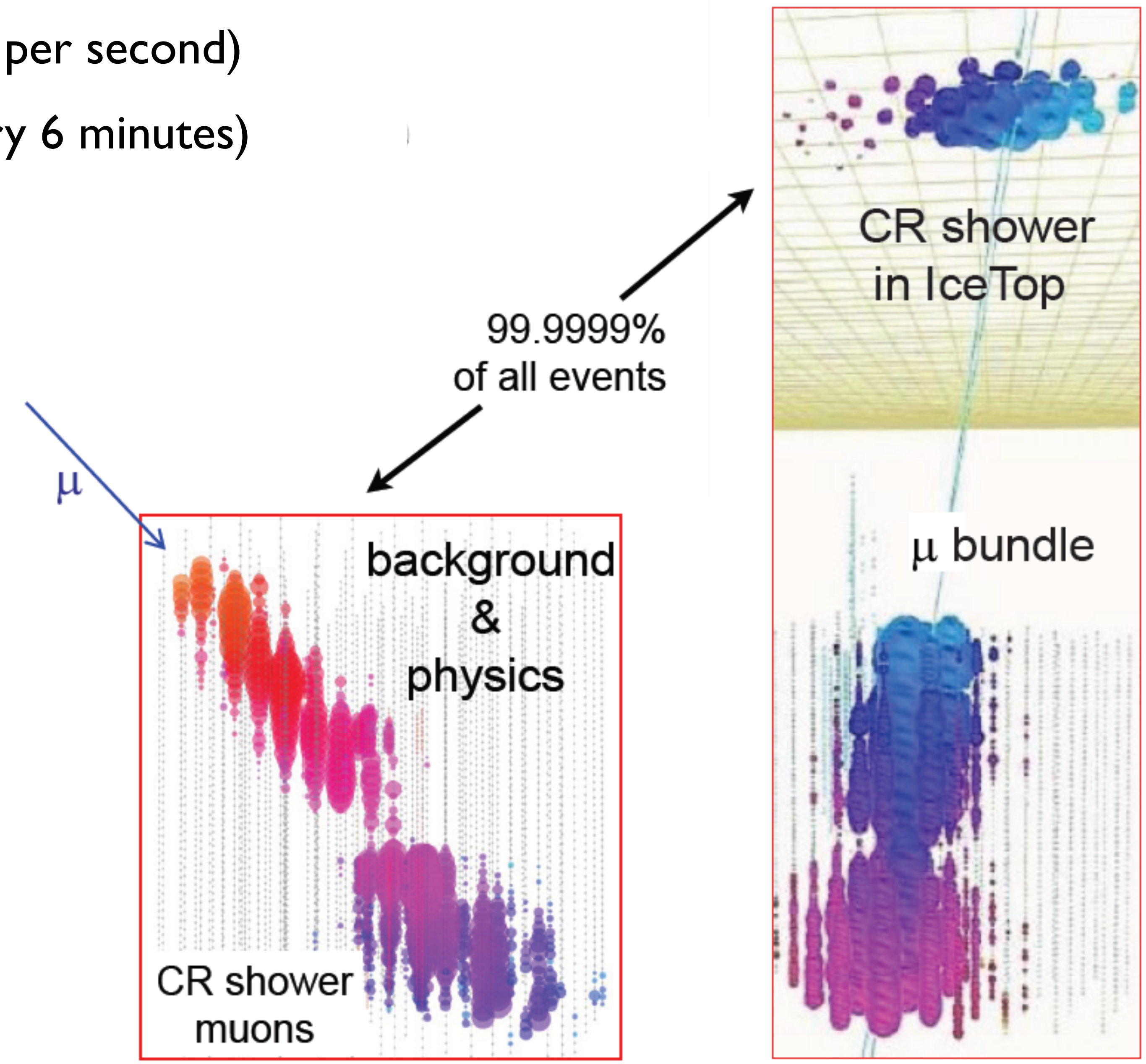


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1 km³ volume
86 strings
125 m string spacing
Completed 2010
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

CHALLENGE: BACKGROUND(S)

- Expected signals are weak and mimicked by irreducible backgrounds
- Event rates in IceCube (year^{-1}):
  - atmospheric muons 7×10^{10} (2000 per second)
  - atmospheric neutrinos 5×10^{4} (1 every 6 minutes)
  - astrophysical $O(10)$





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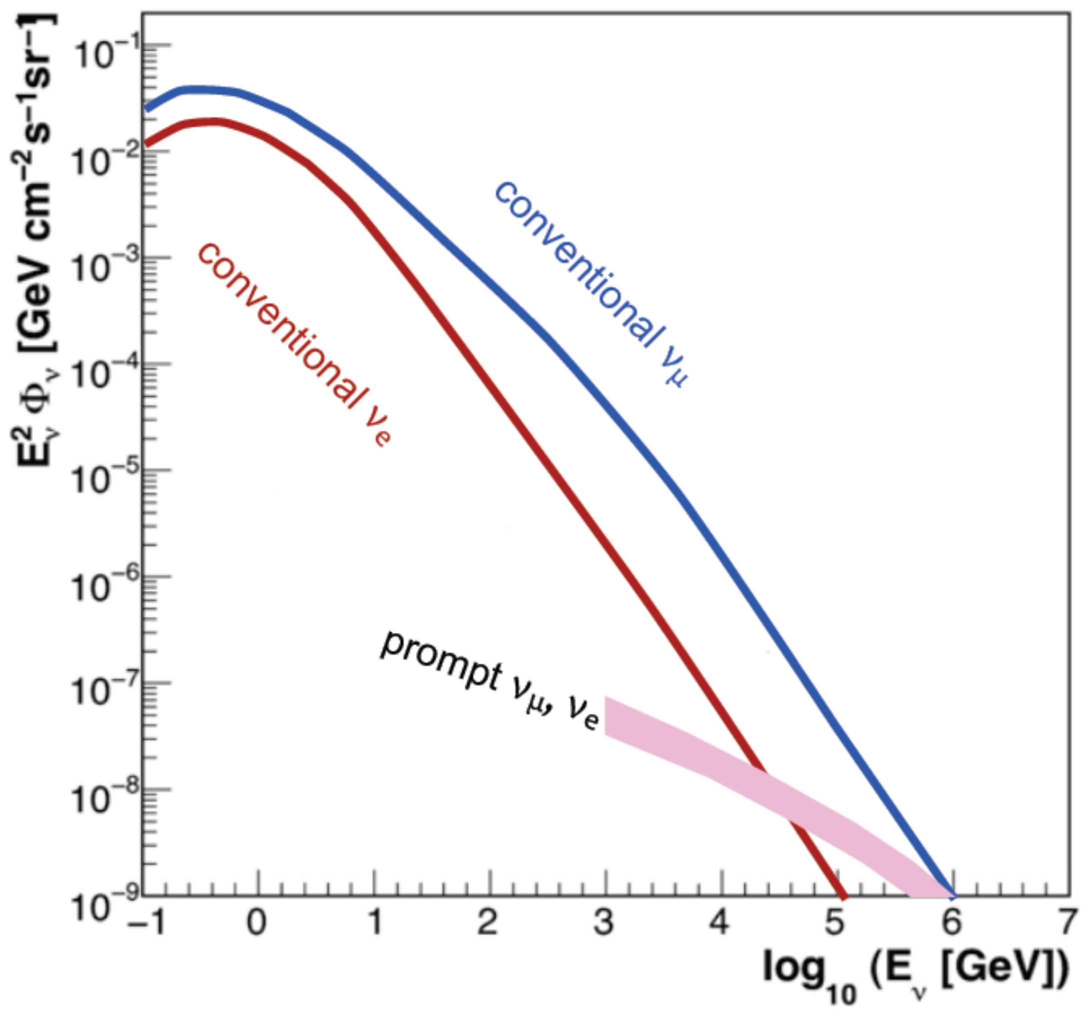
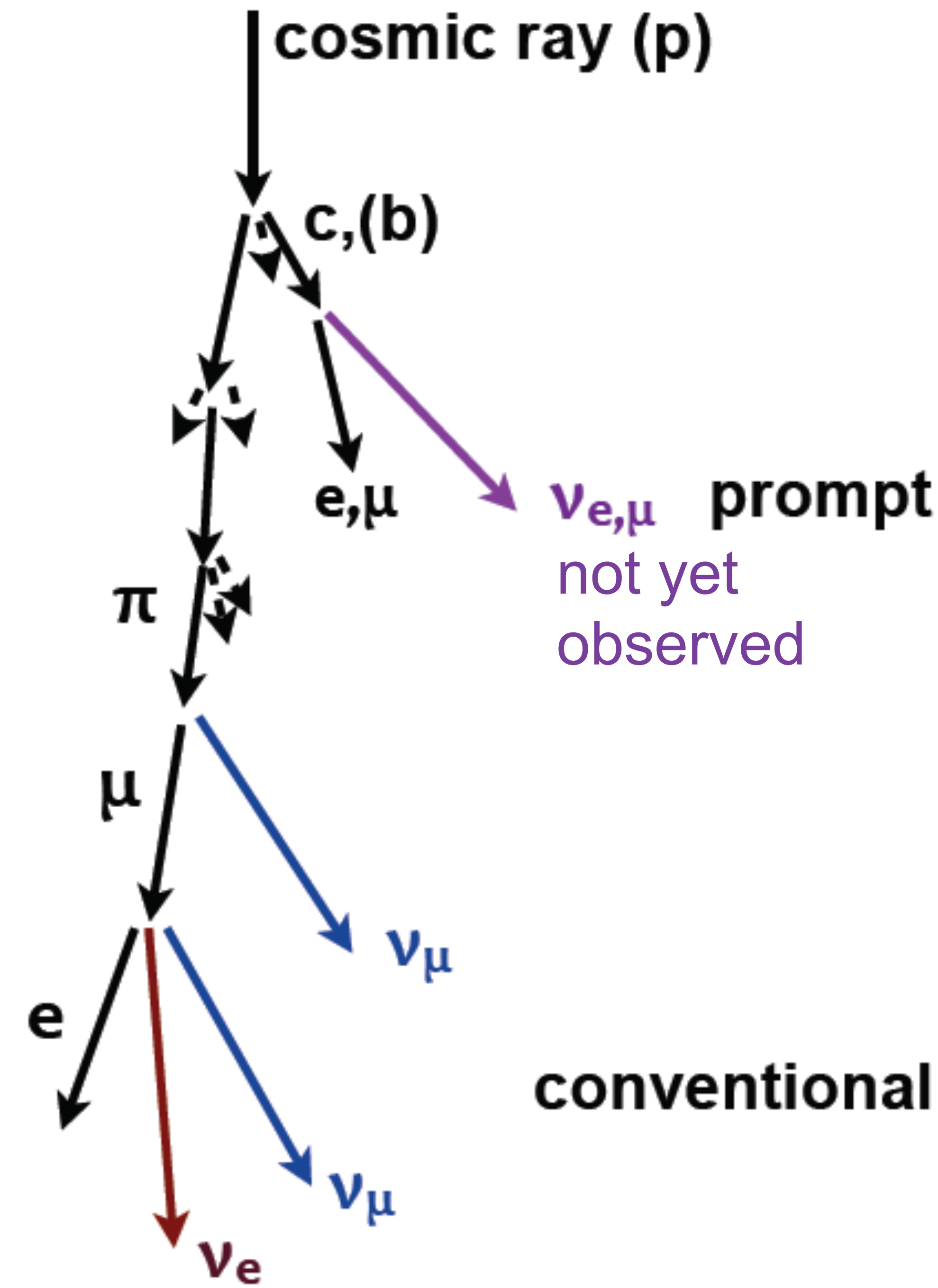
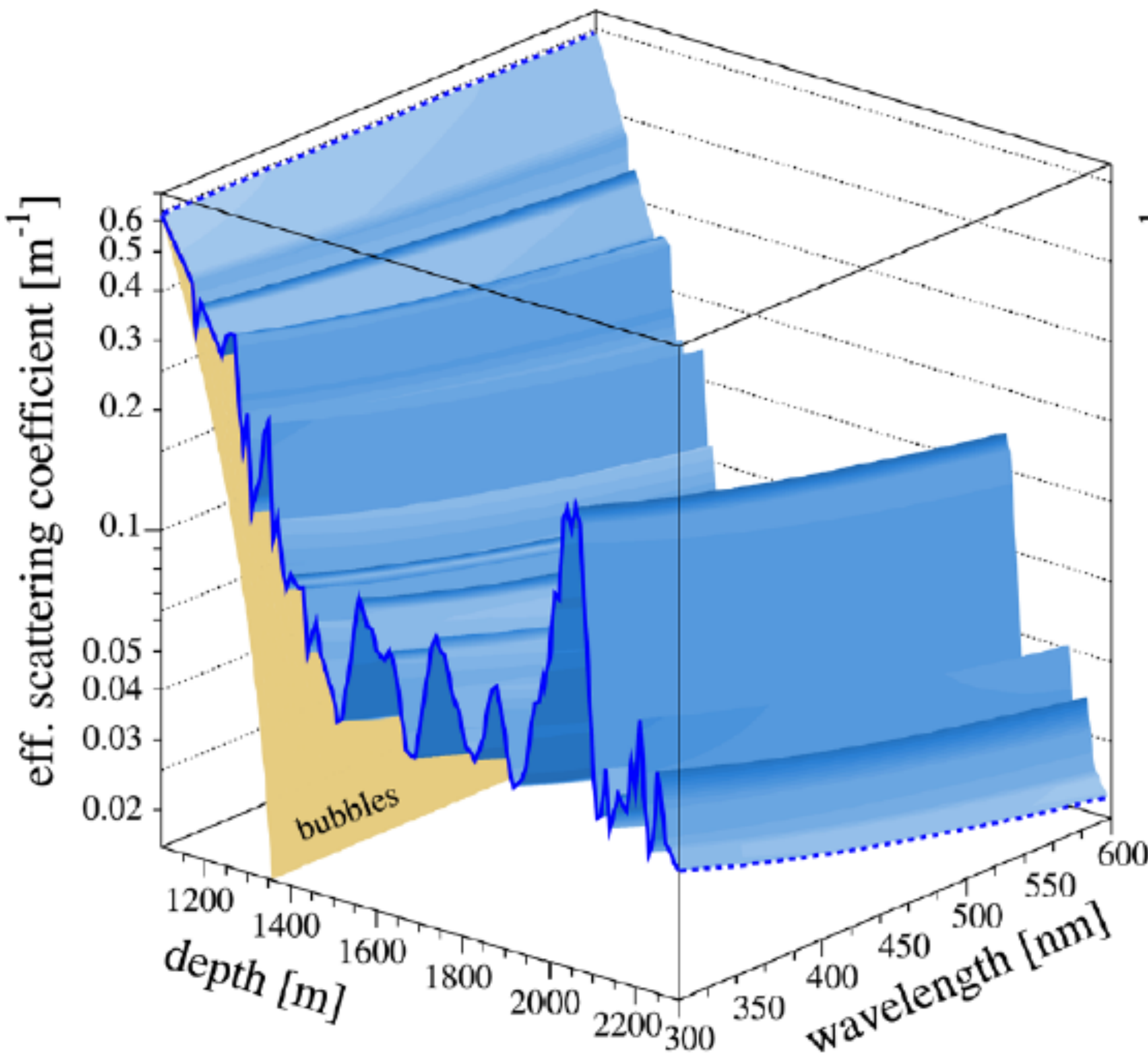
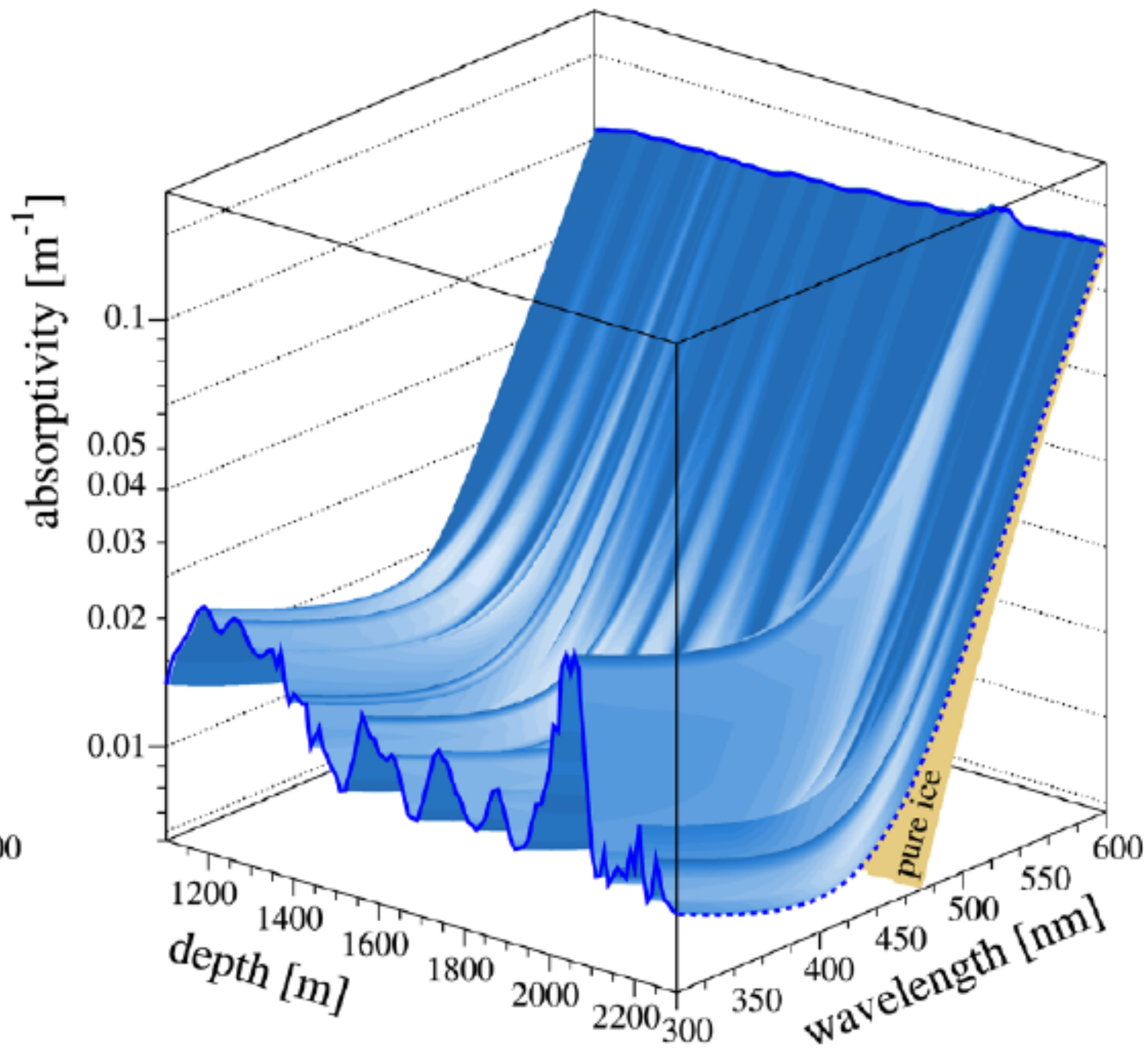
  - astrophysical *O*(10)





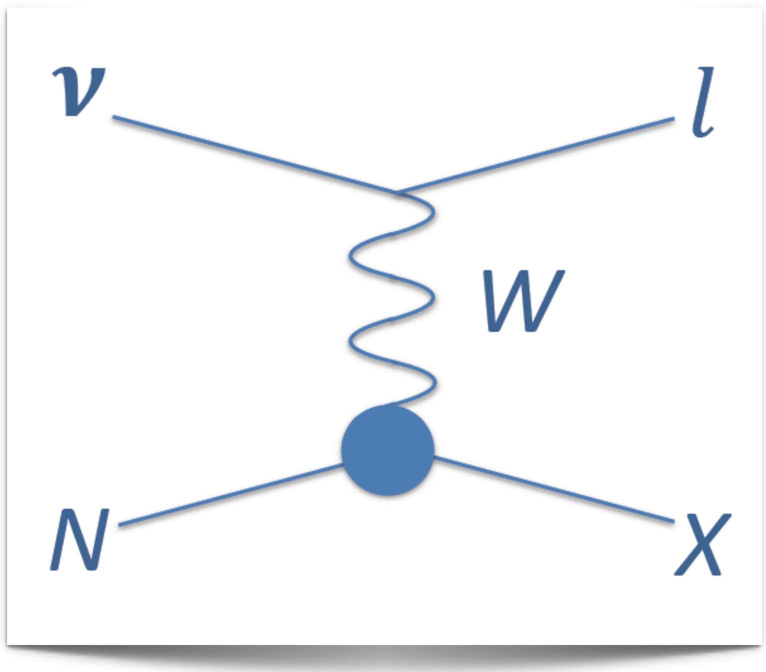
CHALLENGE: ICE OPTICAL PROPERTIES

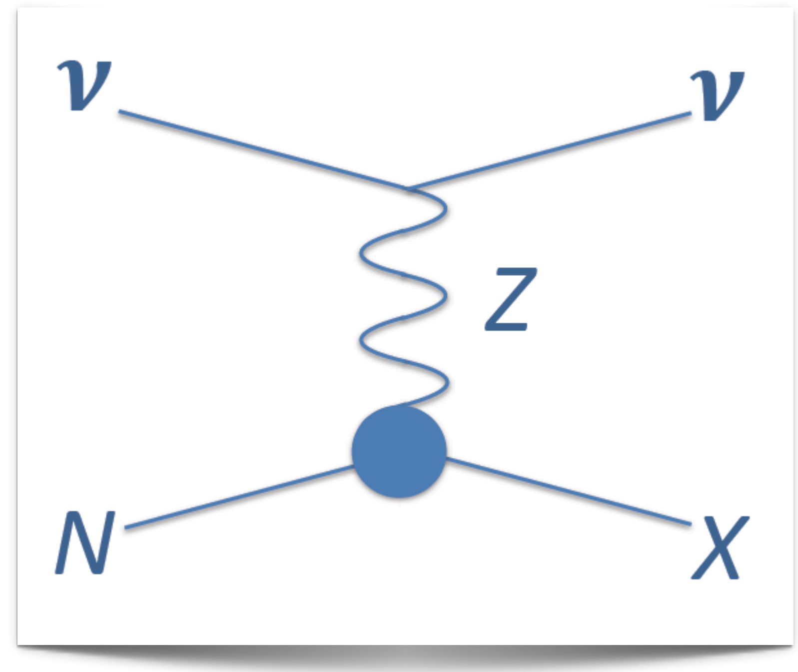




NEUTRINO INTERACTIONS AT HIGH ENERGIES

- At E>10 GeV neutrinos interacting with nucleons can resolve the fundamental constituents (DIS)





- The interacting nucleon is ripped apart giving rise to a hadronic cascade.
- The final state includes a charged lepton (CC) or a neutrino (NC)

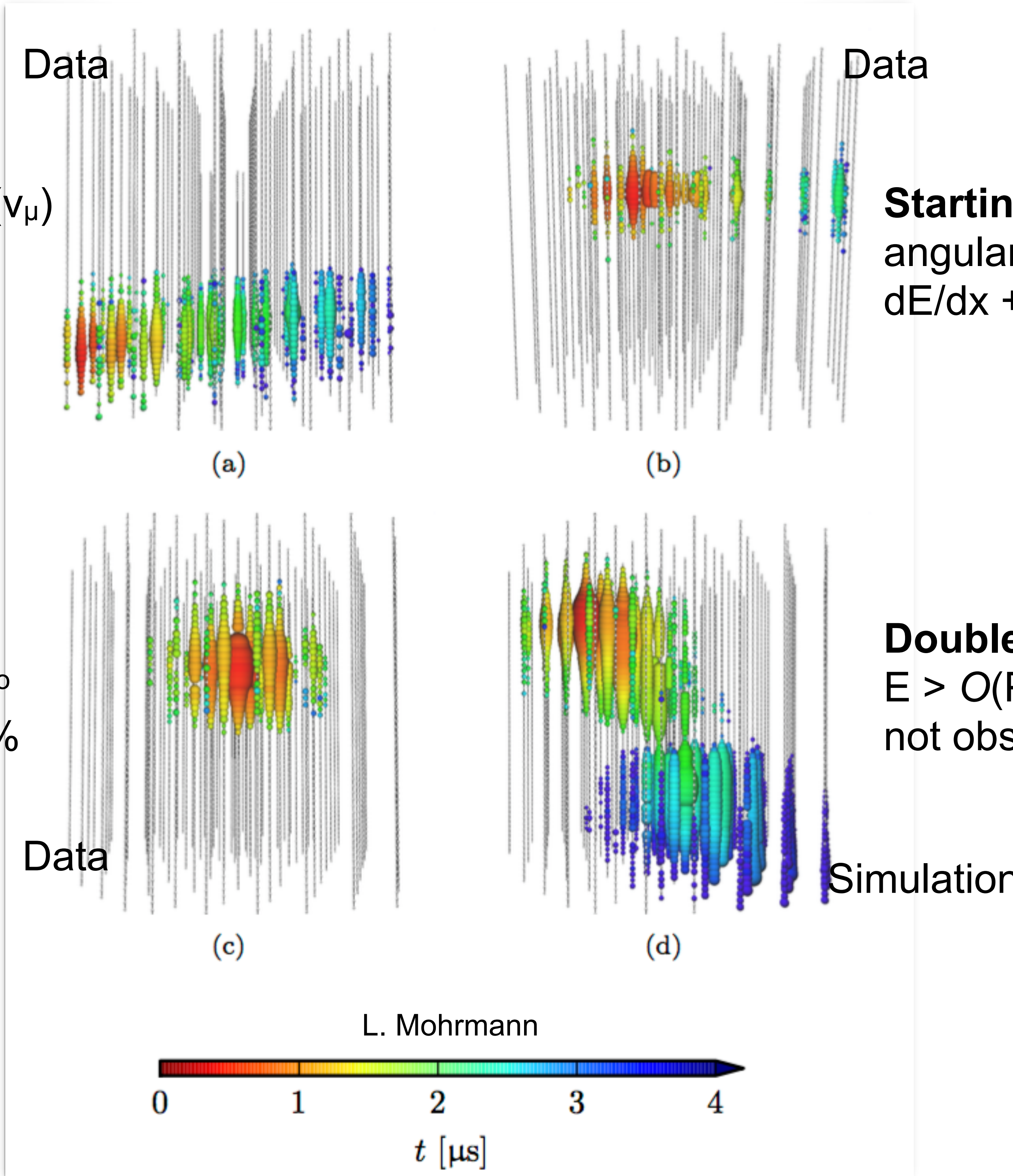
NEUTRINO DETECTION CHANNELS

Through-going track (ν_μ)
angular resolution < 1°
only dE/dx

Starting track (ν_μ)
angular resolution < 1°
dE/dx + energy at vertex

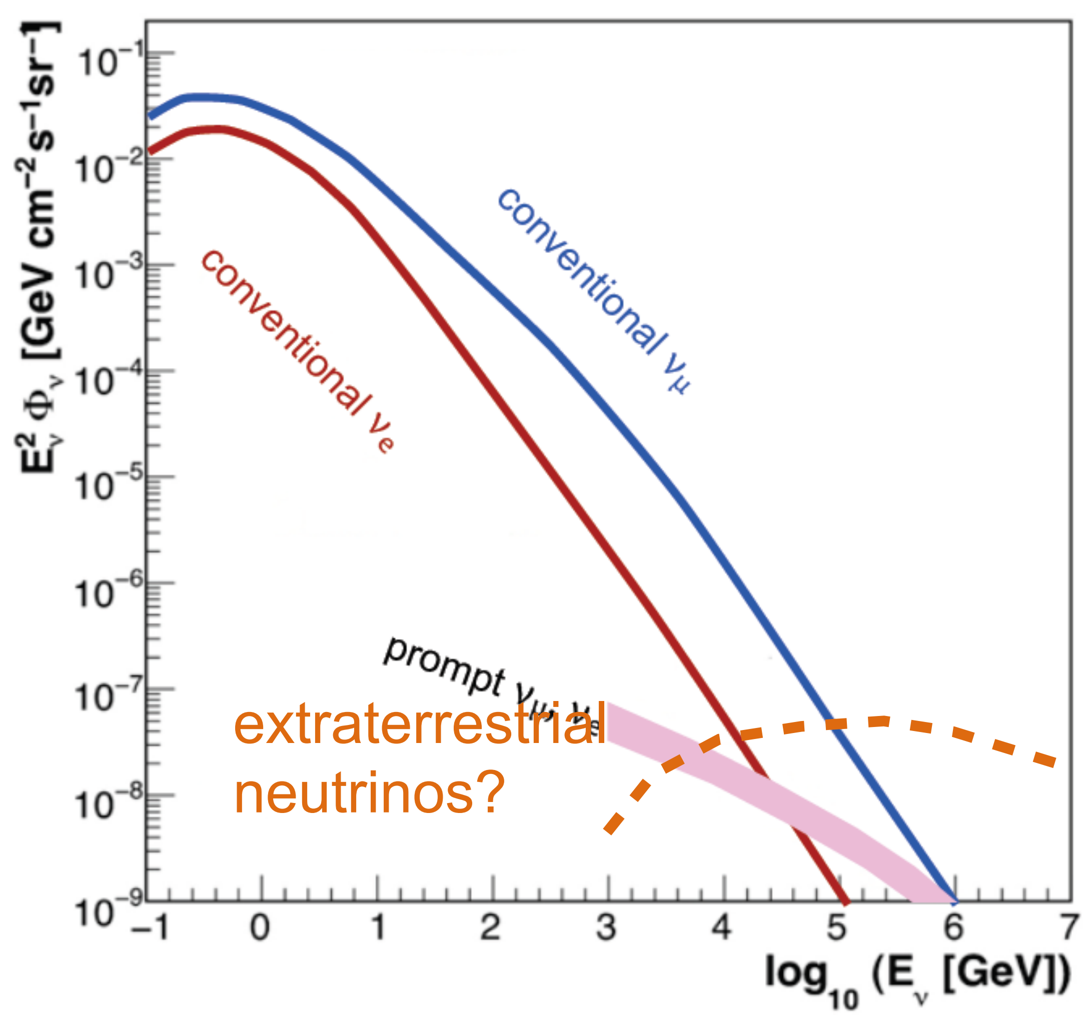
Cascade (ν_e, ν_μ, ν_τ)
angular resolution > 10°
energy resolution ~ 15%

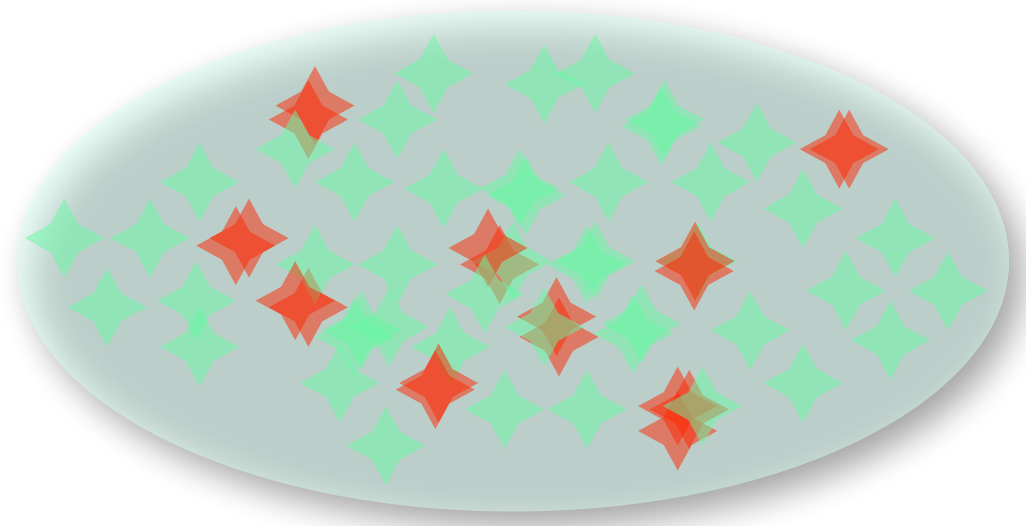
Double-Bang (ν_τ)
E > *O*(PeV)
not observed yet!



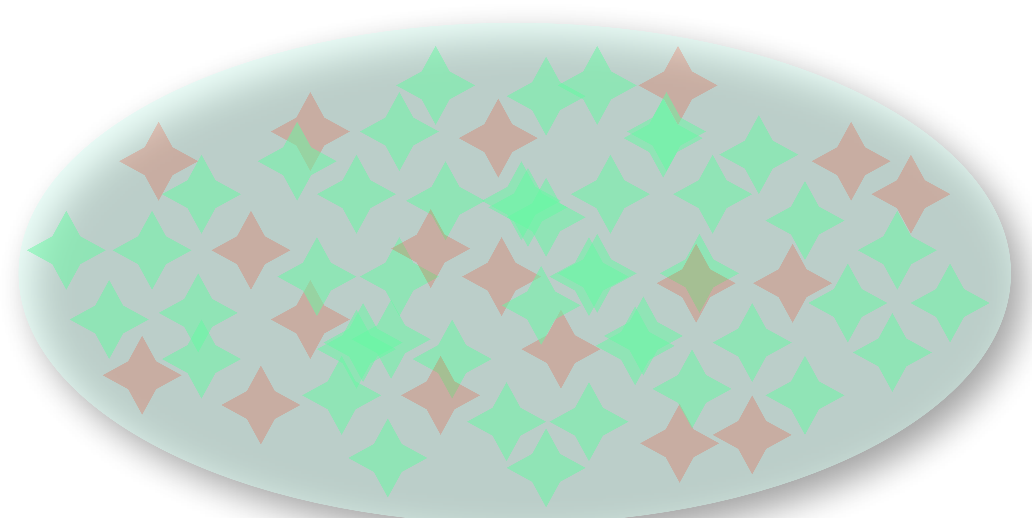
SEARCHING FOR COSMIC NEUTRINOS

- The signal is expected to exhibit a differed spectrum compared to atmospheric neutrinos
- Search for deviations from background
  - in energy (diffuse-like searches)
  - in energy and direction (look for individual sources)





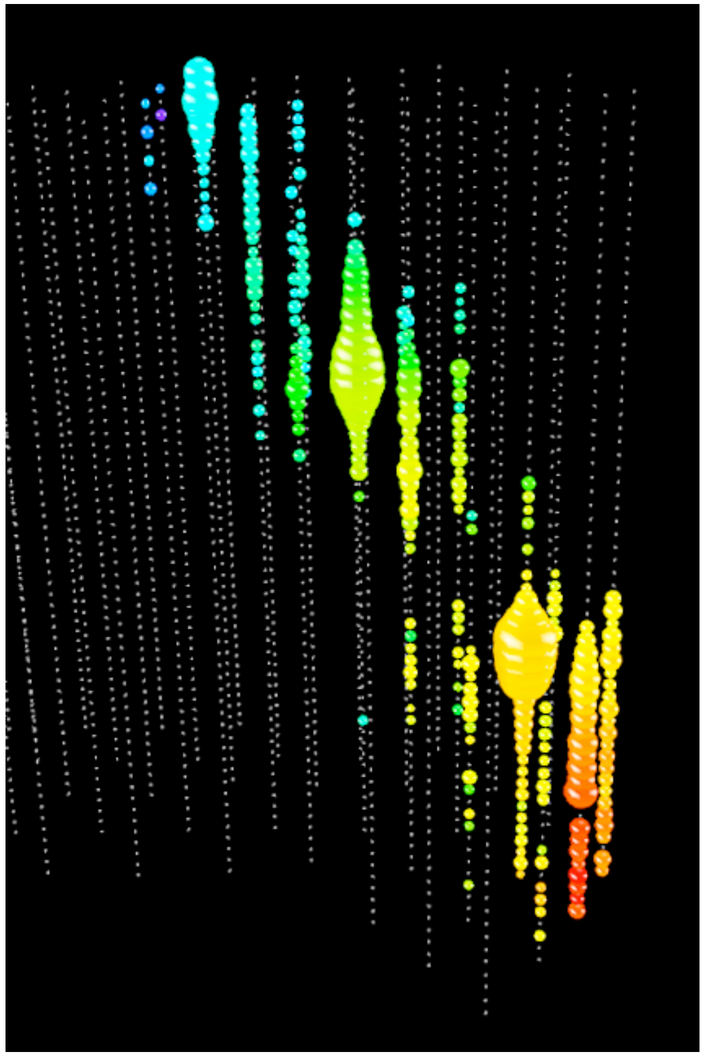
Individual sources: search for excesses from few strong objects. Localised (in space and/or time)

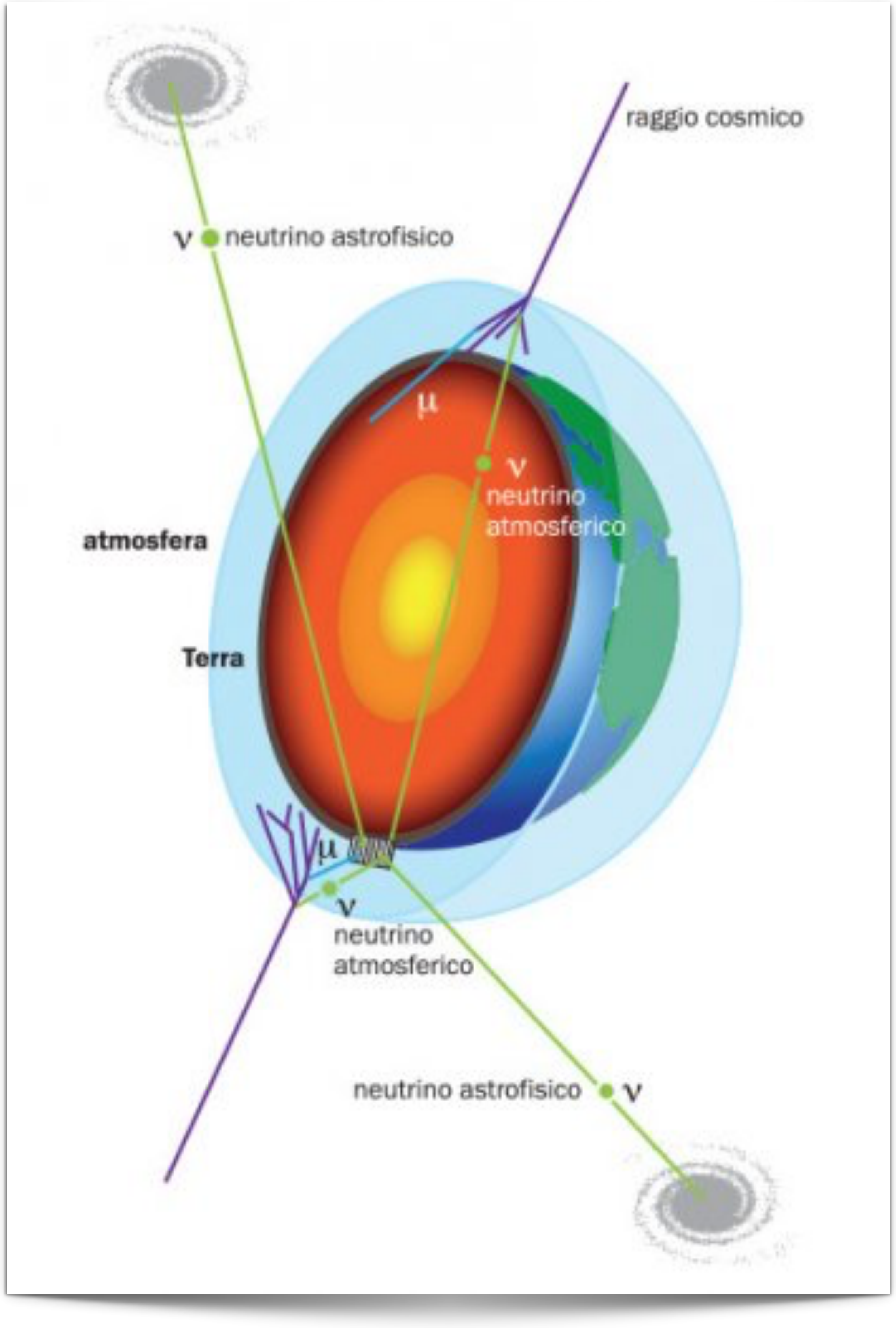


Diffuse searches: search for an overall excess from an ensemble of many weak sources. Deviation in energy spectrum

ISOLATING NEUTRINO EVENTS: DIRECTION

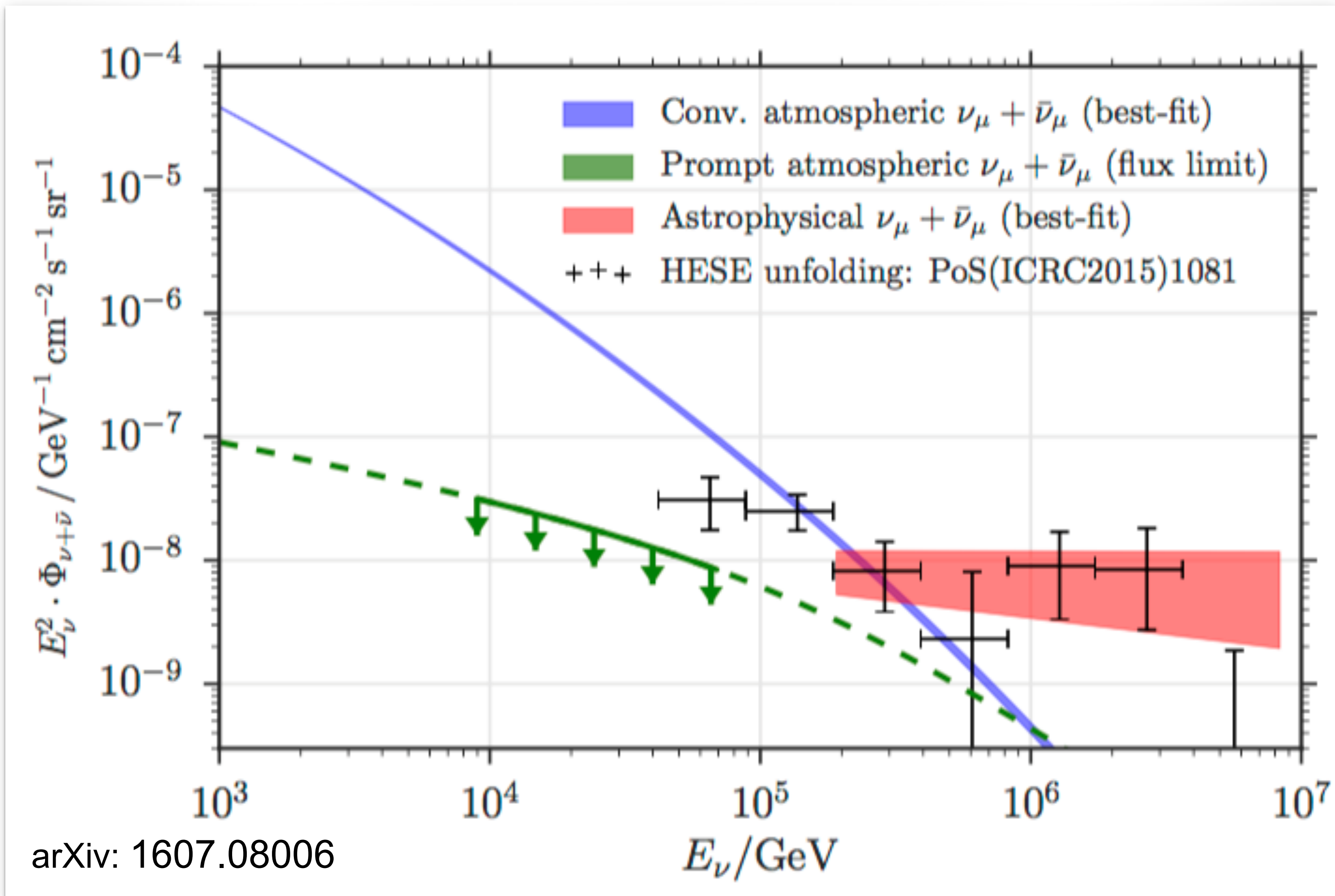
- Earth stops penetrating muons from below
- Apply direction cuts (select up-going)
  - Effective volume larger than detector
  - E > O(100 GeV)
  - Sensitive to ν_μ only
  - Sensitive to "half" the sky (the North)





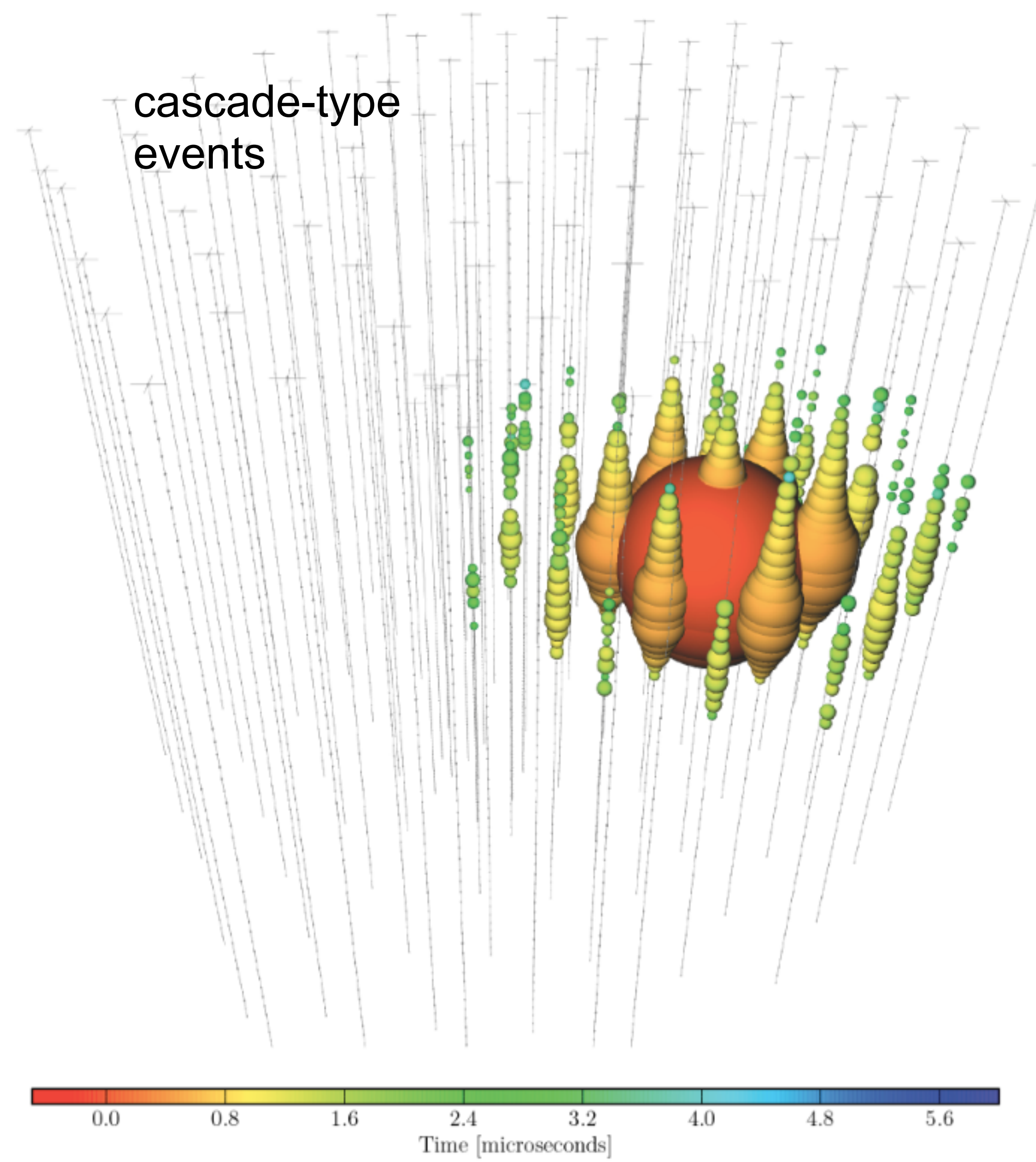
DIFFUSE SEARCHES WITH UP-GOING MUONS

- Between 191 TeV and 8.3 PeV a significant astrophysical contribution is observed, excluding a purely atmospheric origin at 5.6 σ significance
- Data well described by an isotropic, unbroken power law flux with
  - normalisation at 100 TeV neutrino energy of $0.90^{+0.30}_{-0.27} \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} and a hard spectral index of $\gamma = 2.13 \pm 0.13$



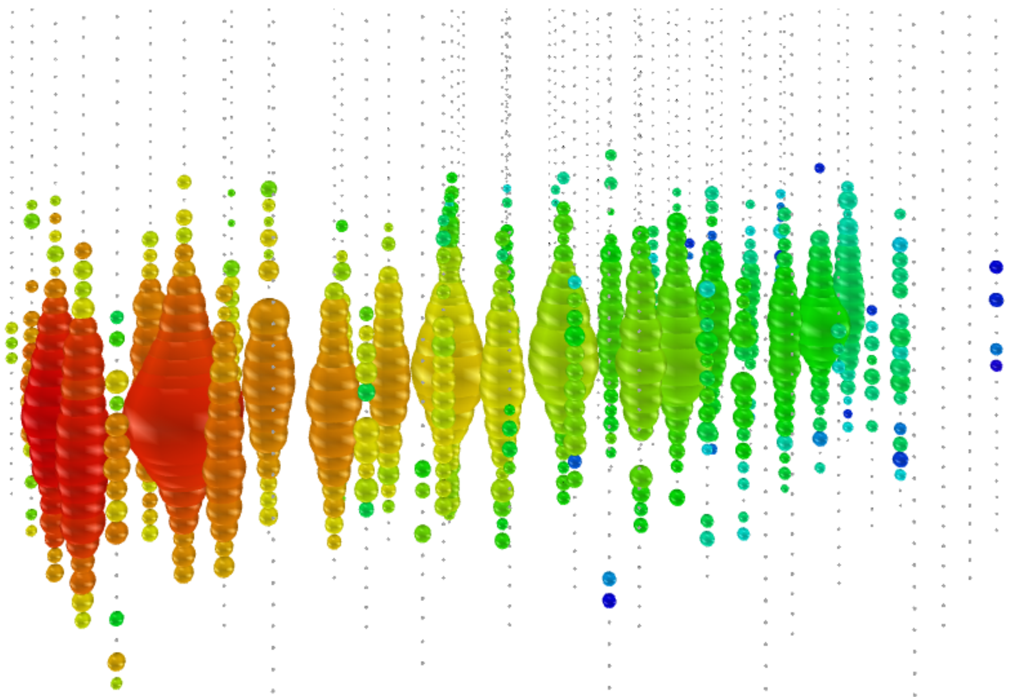
ISOLATING NEUTRINO EVENTS: INTERACTION TYPE

- Looking for cascades
  - Effective volume smaller than detector
  - E > O(30 TeV)
  - Sensitive to all flavours
  - Sensitive to full sky
  - almost background-free!

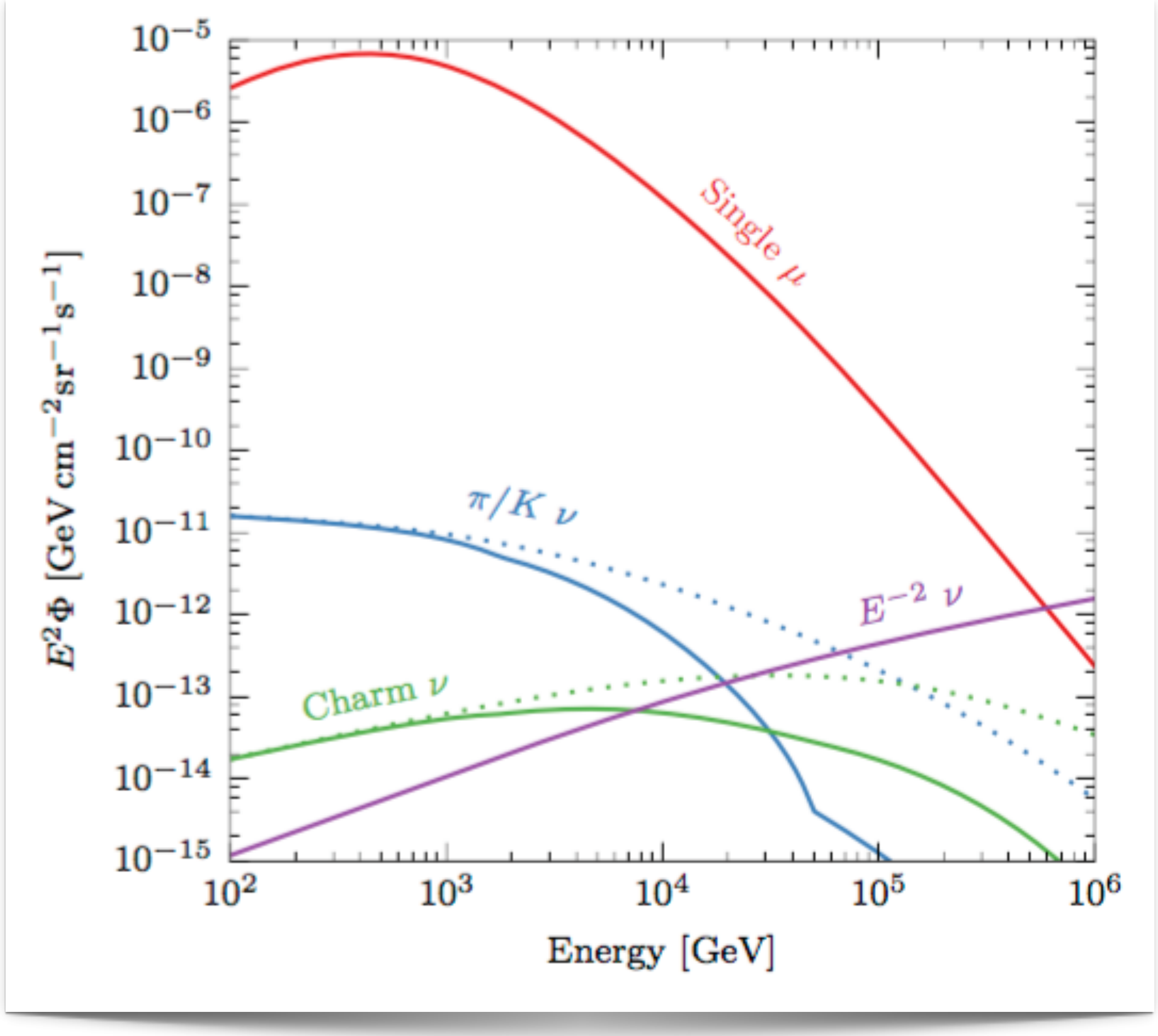


ISOLATING NEUTRINO EVENTS: ENERGY

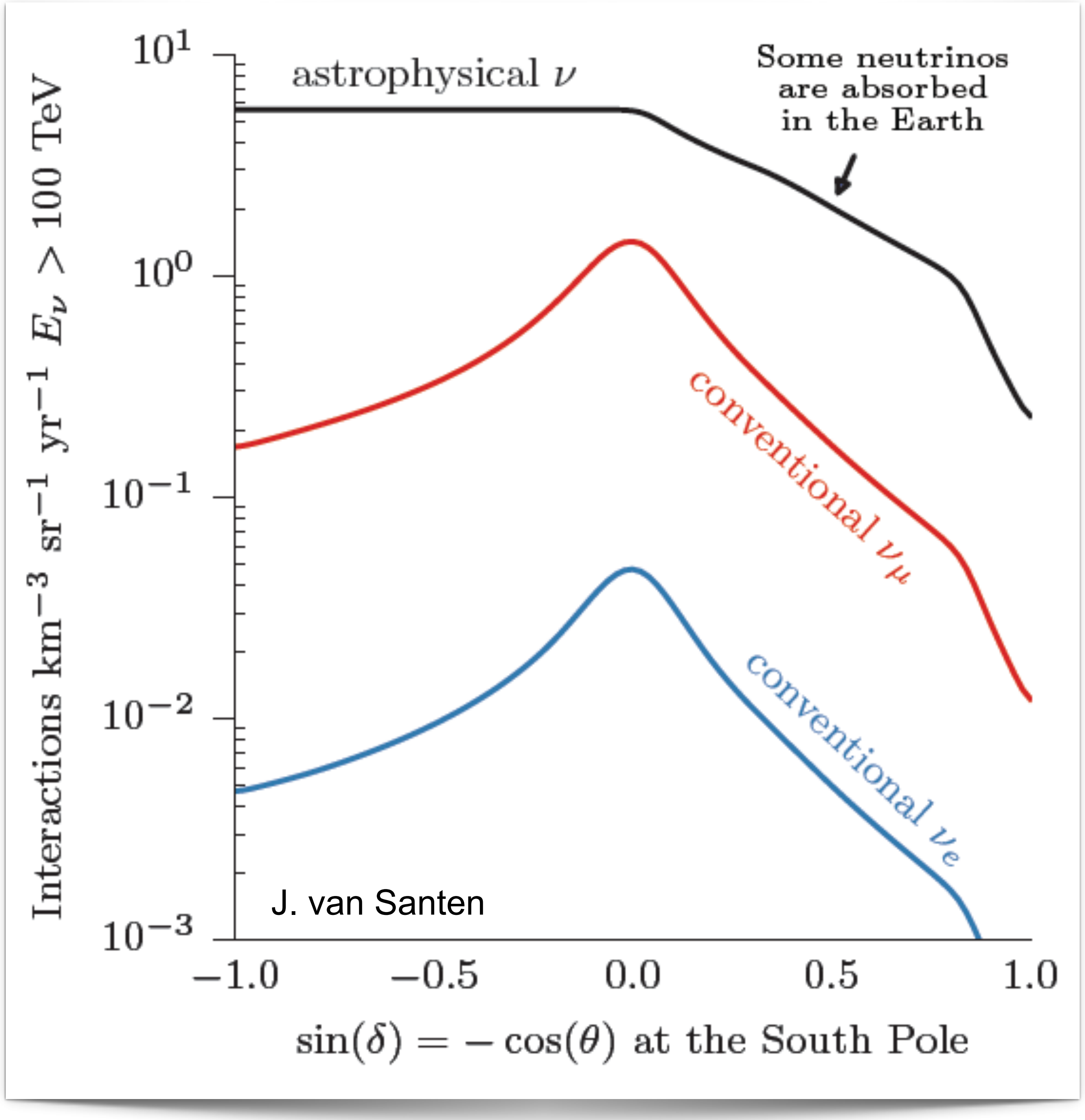
- Energy spectrum looks different for background and signal
- Select high-energy events
  - reject atmospheric μ
  - reject atmospheric ν_μ
  - requires strong energy cuts
  - mostly sensitive to the horizon



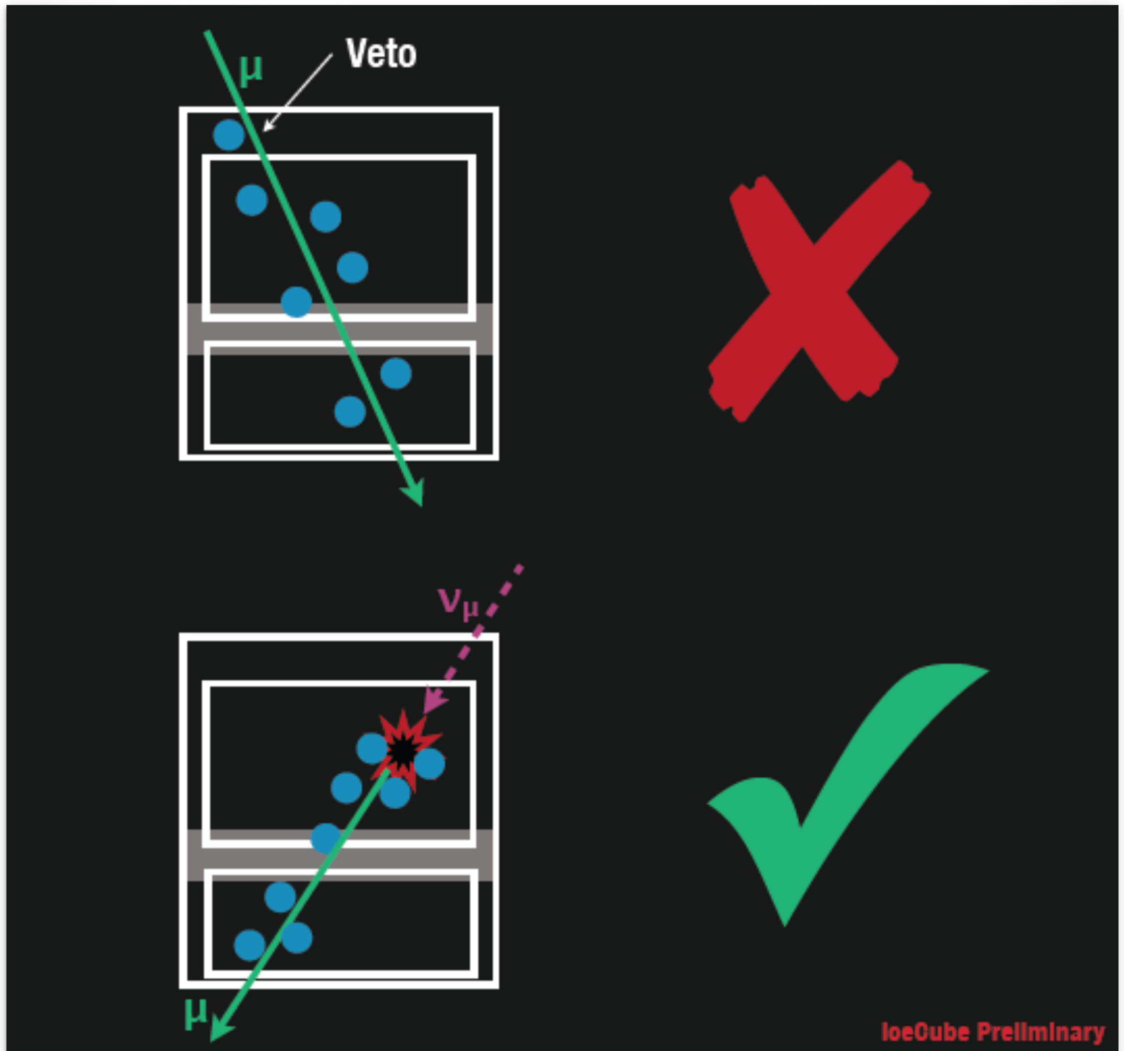
IceCube Coll. Phys. Rev. D 91, 022001 (2015)



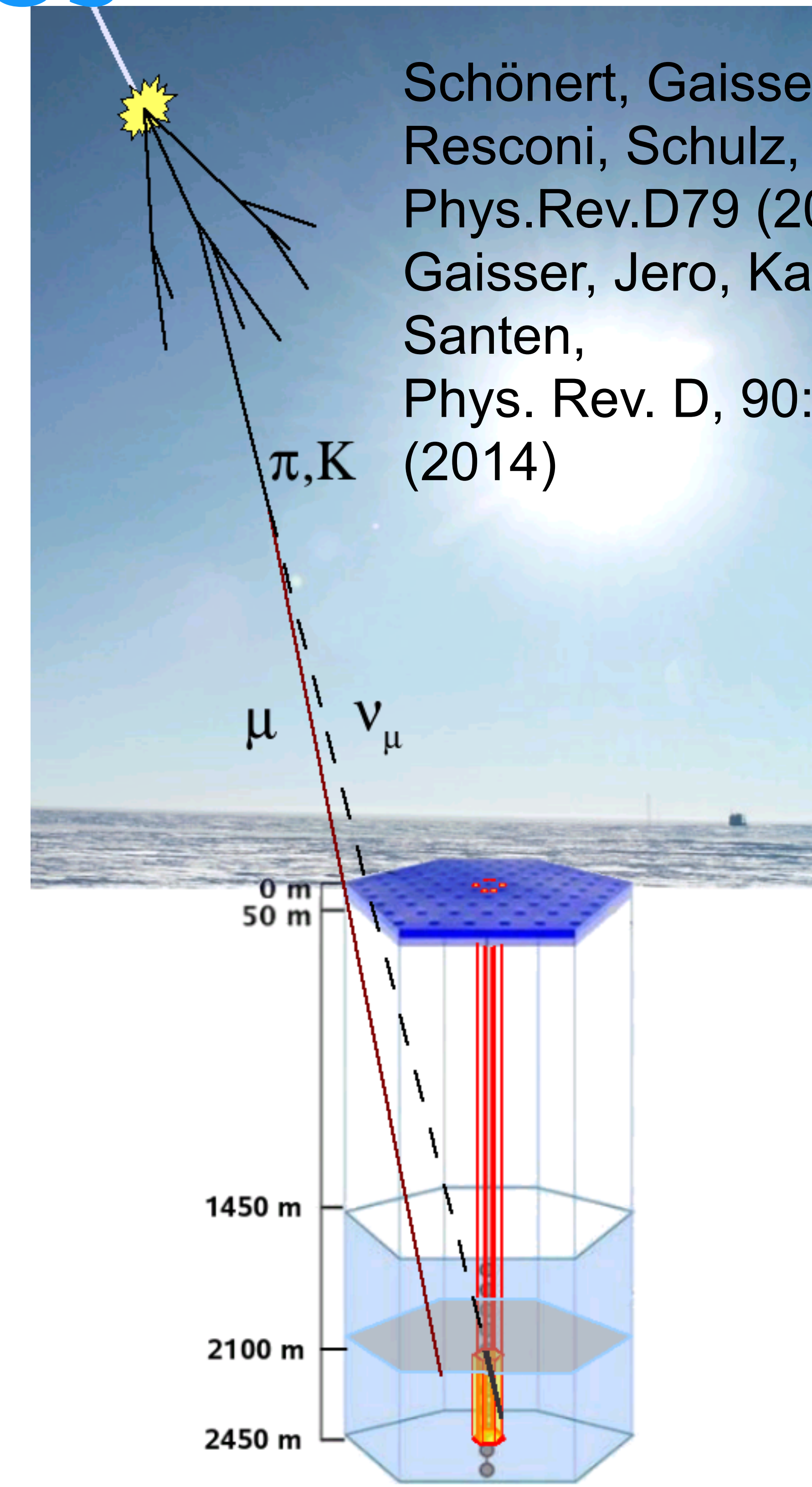
ISOLATING NEUTRINO EVENTS: ENERGY



HOW TO VETO DOWN-GOING ATMOSPHERIC NEUTRINOS



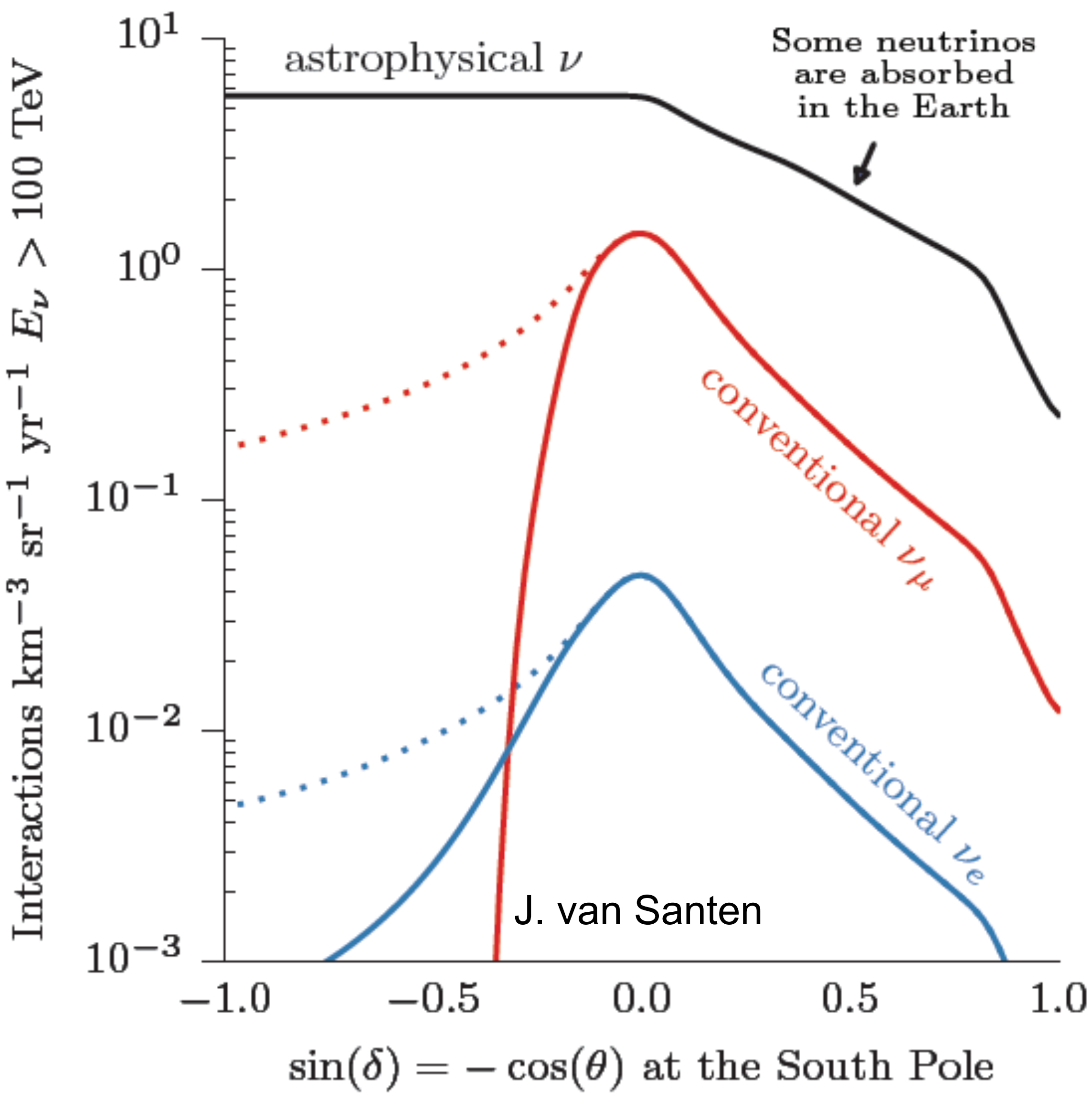
- Atmospheric neutrinos will, in general, be accompanied by muons produced in the same parent air shower
- Golden channel: "down-going starting events"

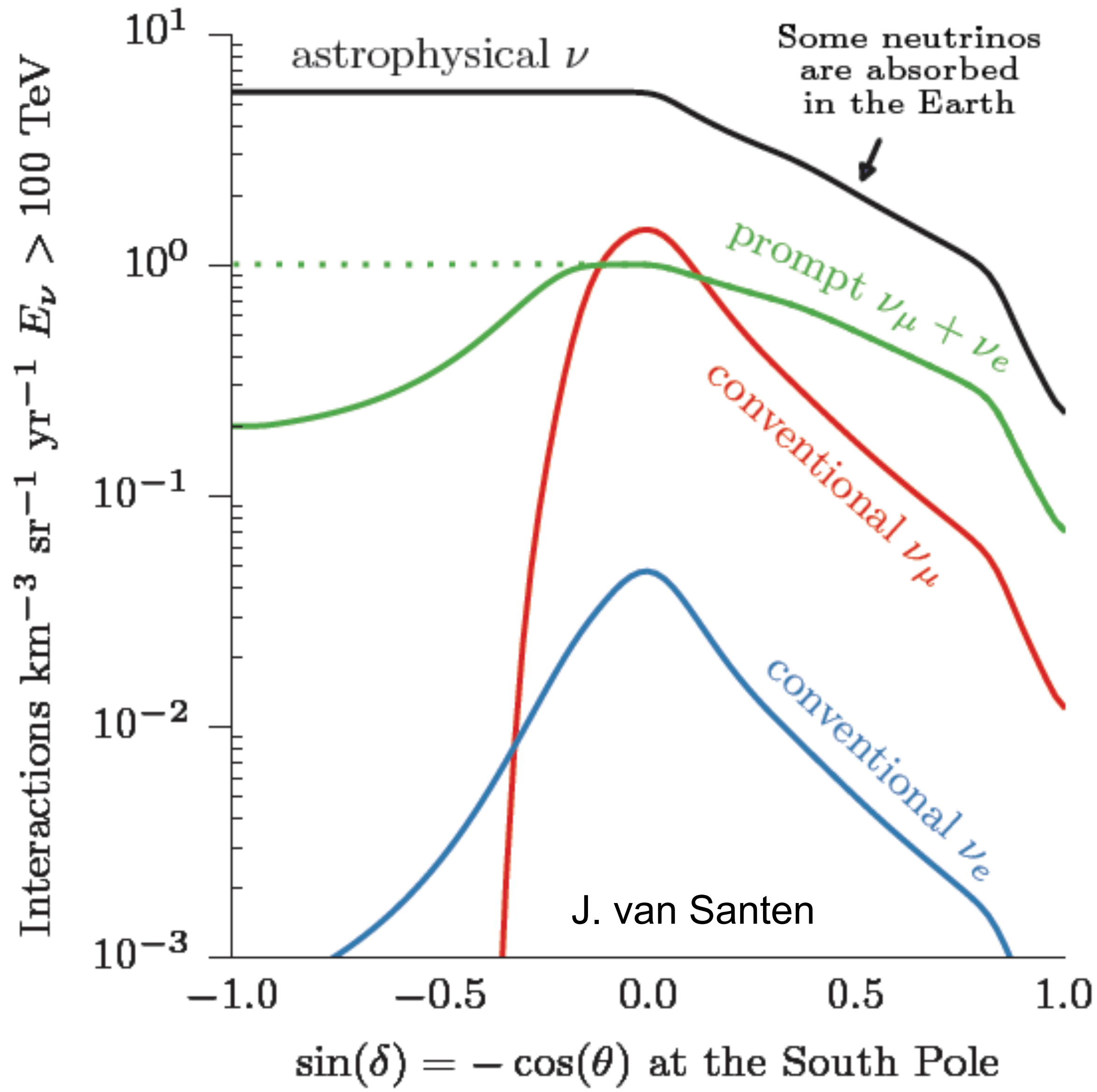


Schönert, Gaisser, Resconi, Schulz, Phys.Rev.D79 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

VETOING ATMOSPHERIC NEUTRINOS

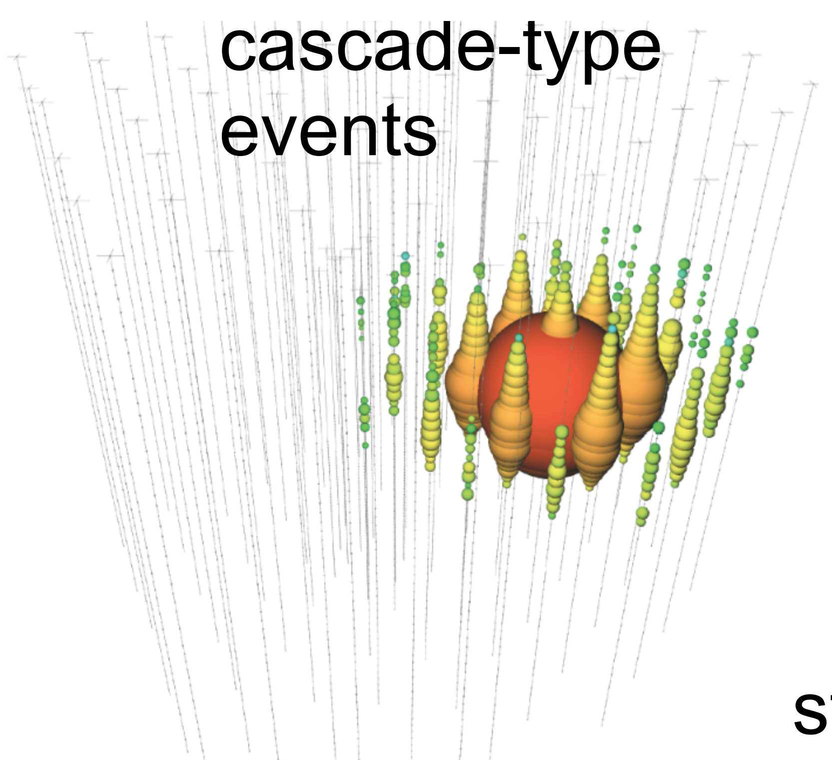
- The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different

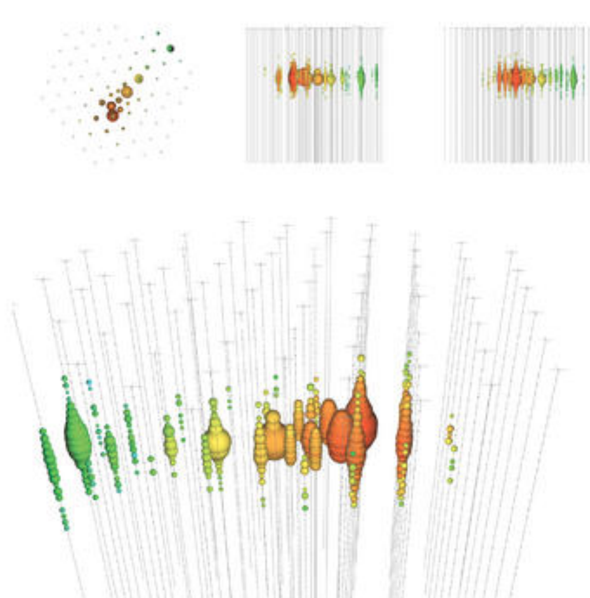




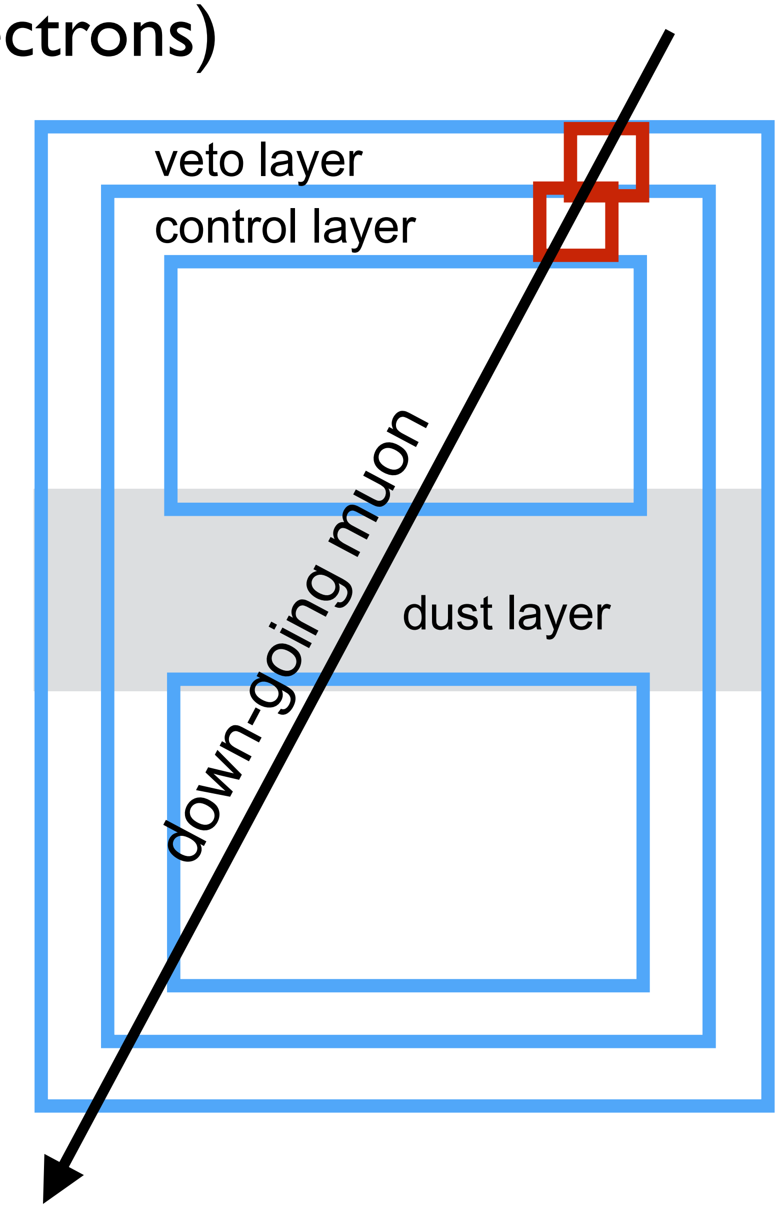
THE BREAKTHROUGH

- Search for well reconstructed contained and semi-contained events
- Veto atmospheric muons and neutrinos
- Use data to measure muon background (inner veto layer)
- Only study very high energies (> 4000 photo-electrons)
- Energy threshold: ~ 30 TeV



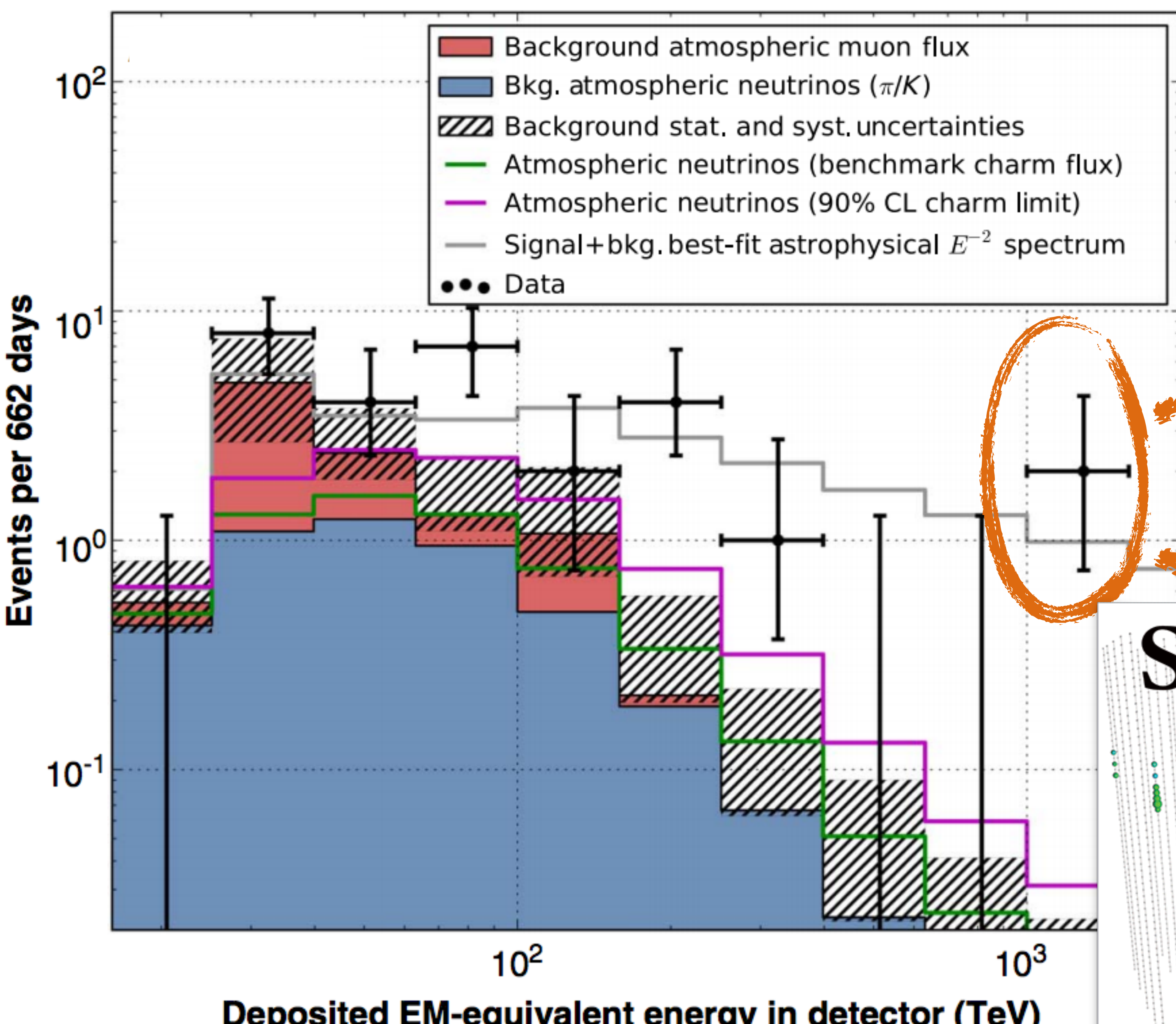


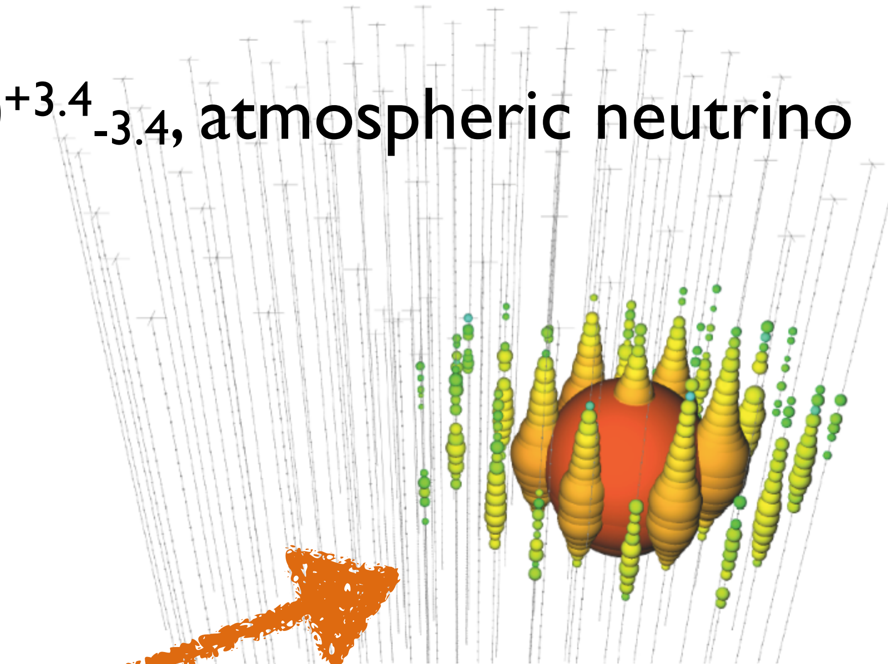
starting tracks



FIRST CLEAR EVIDENCE FOR EXTRATERRESTRIAL NEUTRINOS

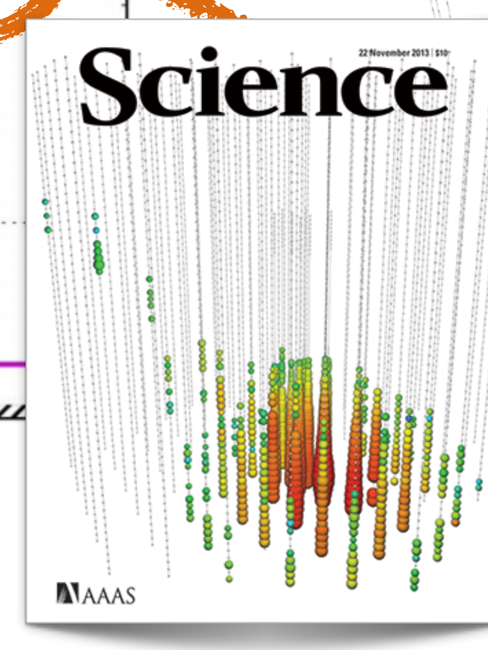
- 28 events found above 30 TeV, muon background $6.0^{+3.4}_{-3.4}$, atmospheric neutrino background $4.6^{+3.7}_{-1.2}$, significance 4.1 σ

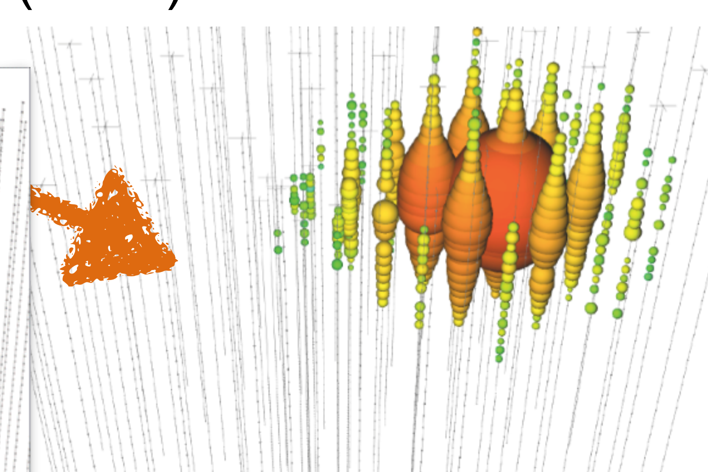




1.1 ± 0.17 PeV

IceCube Collaboration: M. G. Aartsen et al Science 342 (2013) 1242856

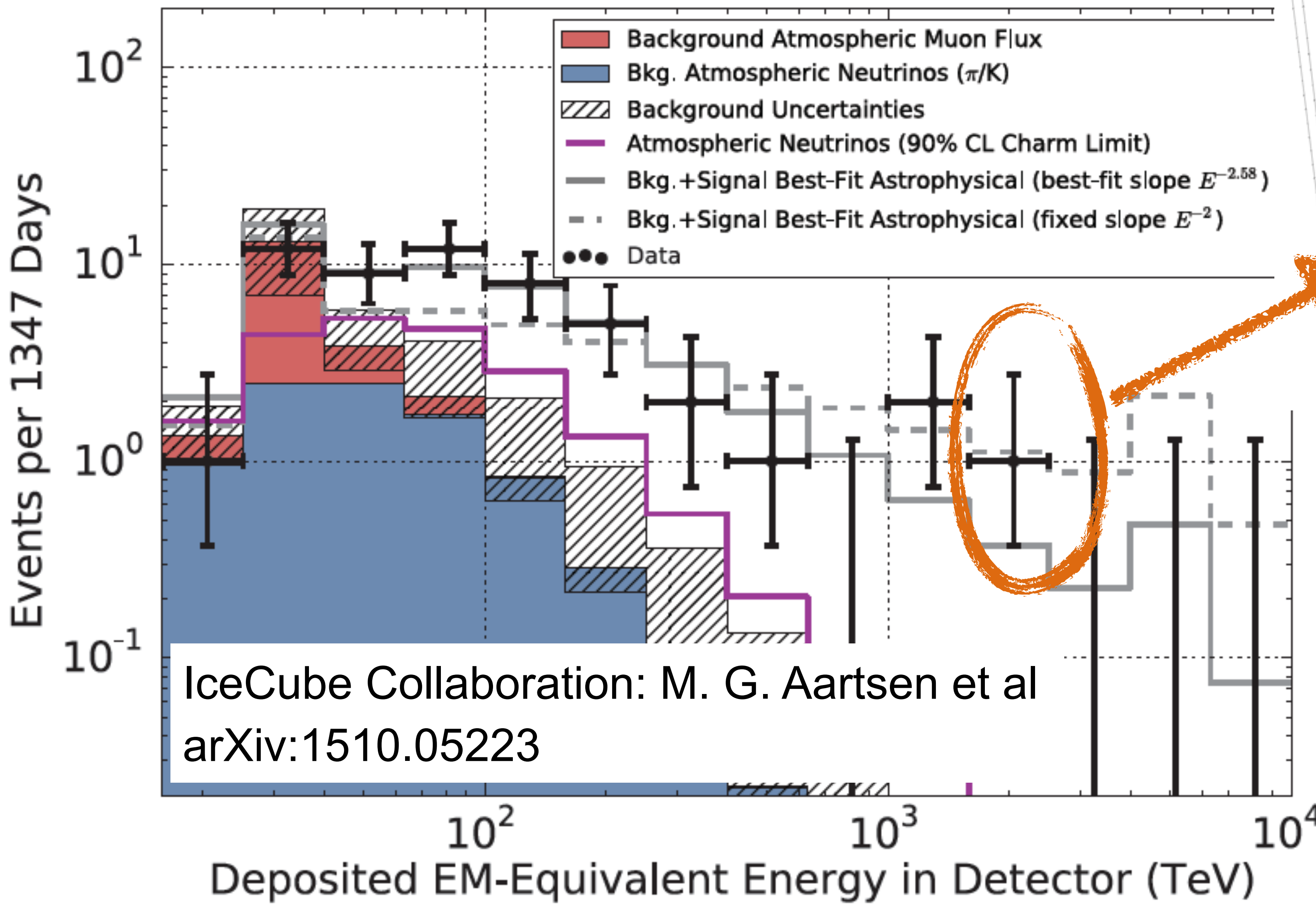


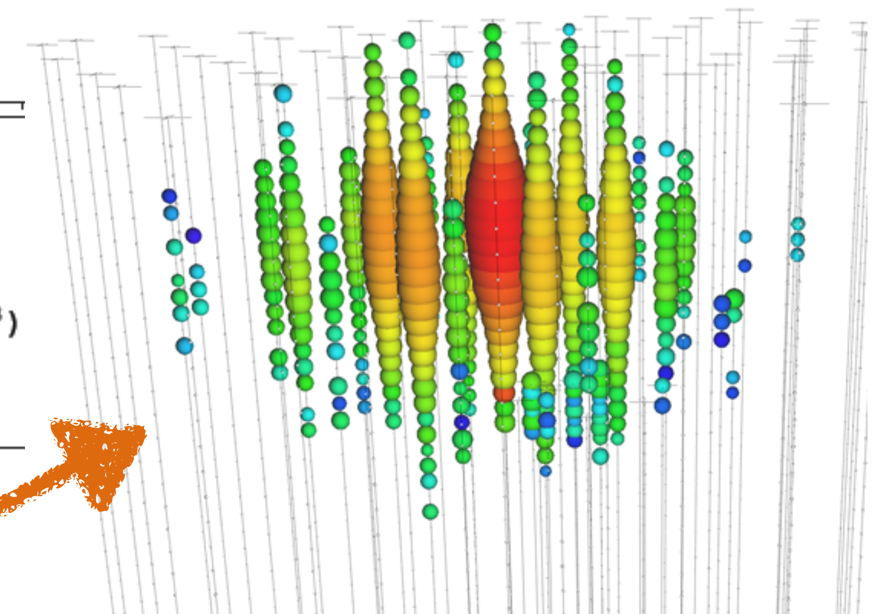


1.0 ± 0.15 PeV

MORE DATA

- 54 events found, muon background $12.6^{+5.1}_{-5.1}$, atmospheric neutrino background $9.0^{+8.0}_{-1=2.2}$, significance >7 σ
- 39 cascades, 13 tracks, 2 likely background

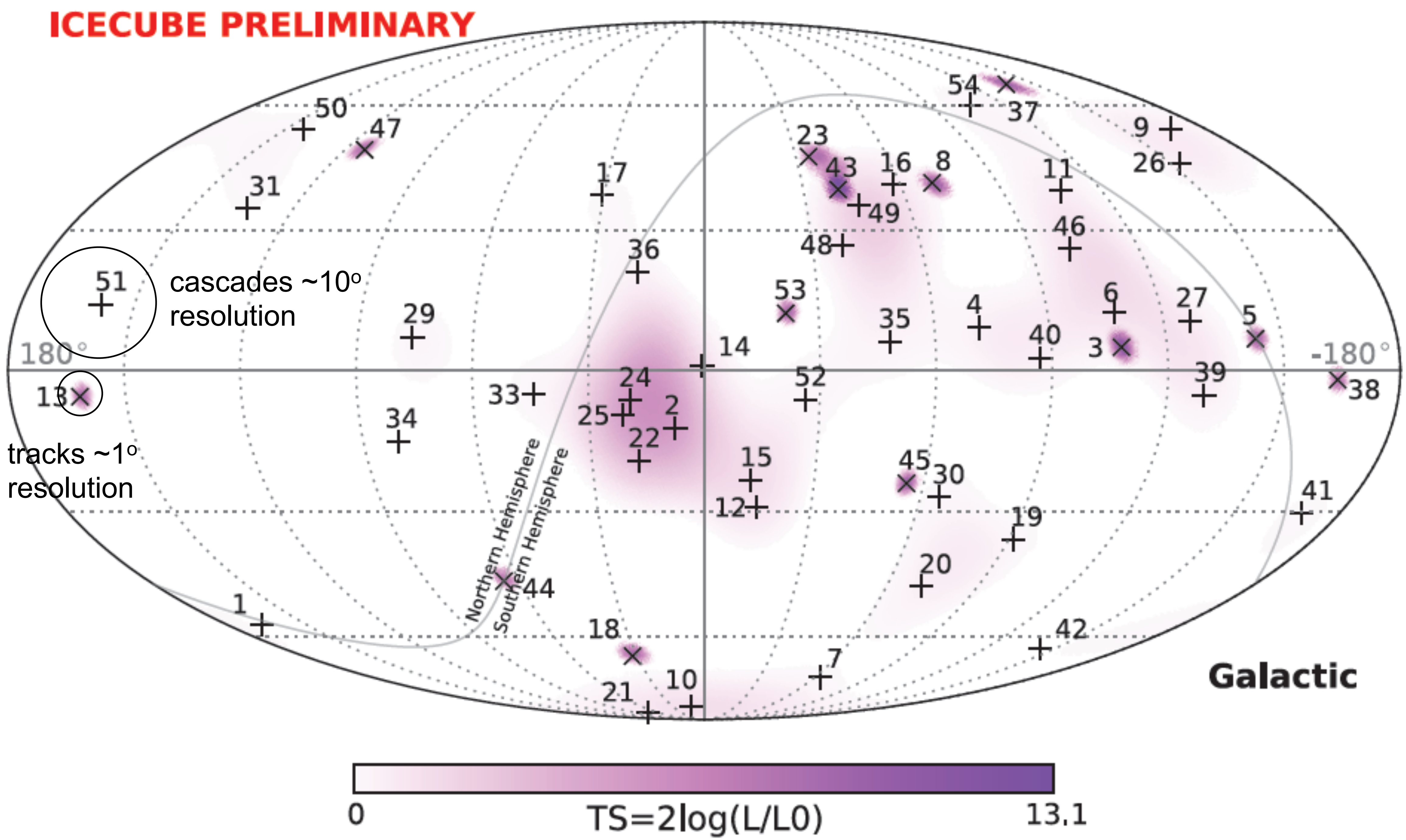




$2.0^{+0.26}_{-0.24}$ PeV

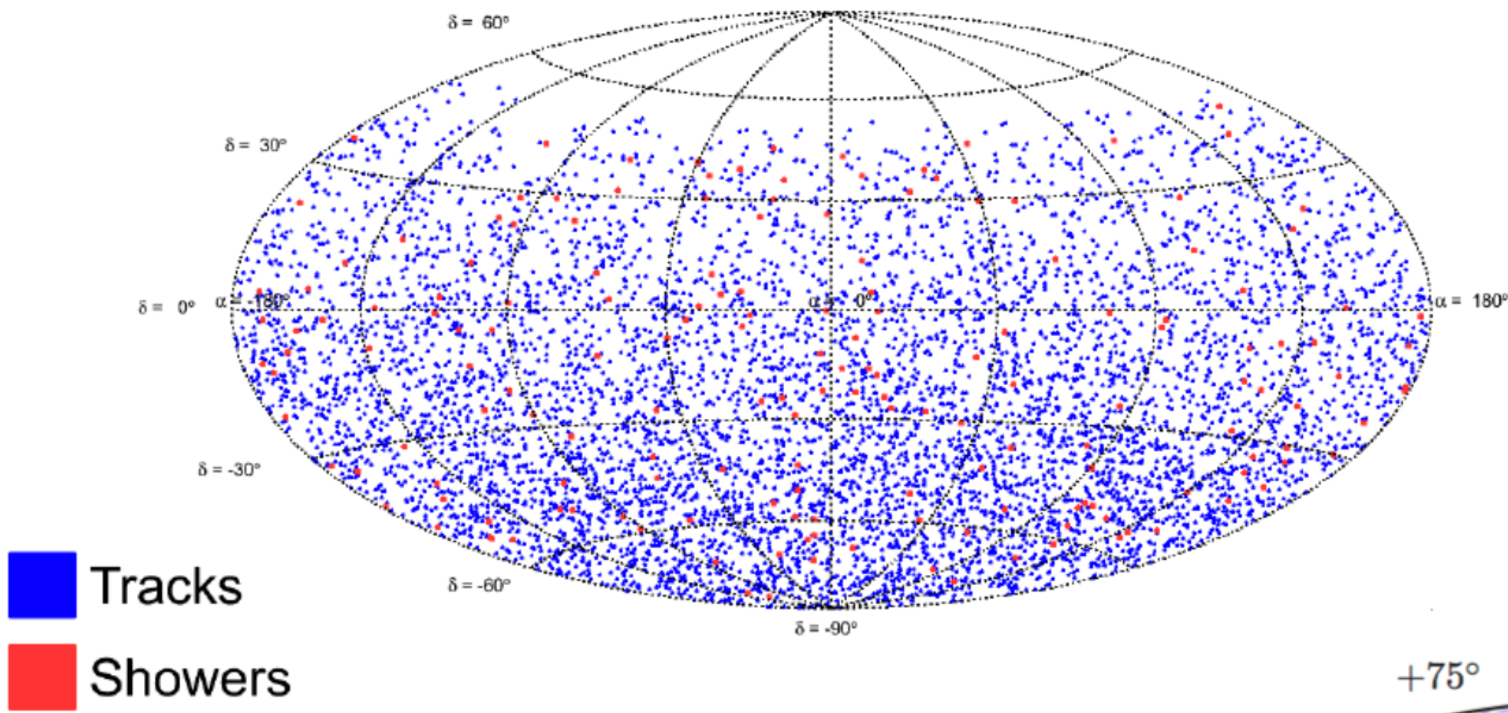
SKY MAP

- No significant clustering in space and time
- p-value for cascade events clustering is ~ 44%



AREN'T THERE POINT SOURCES?

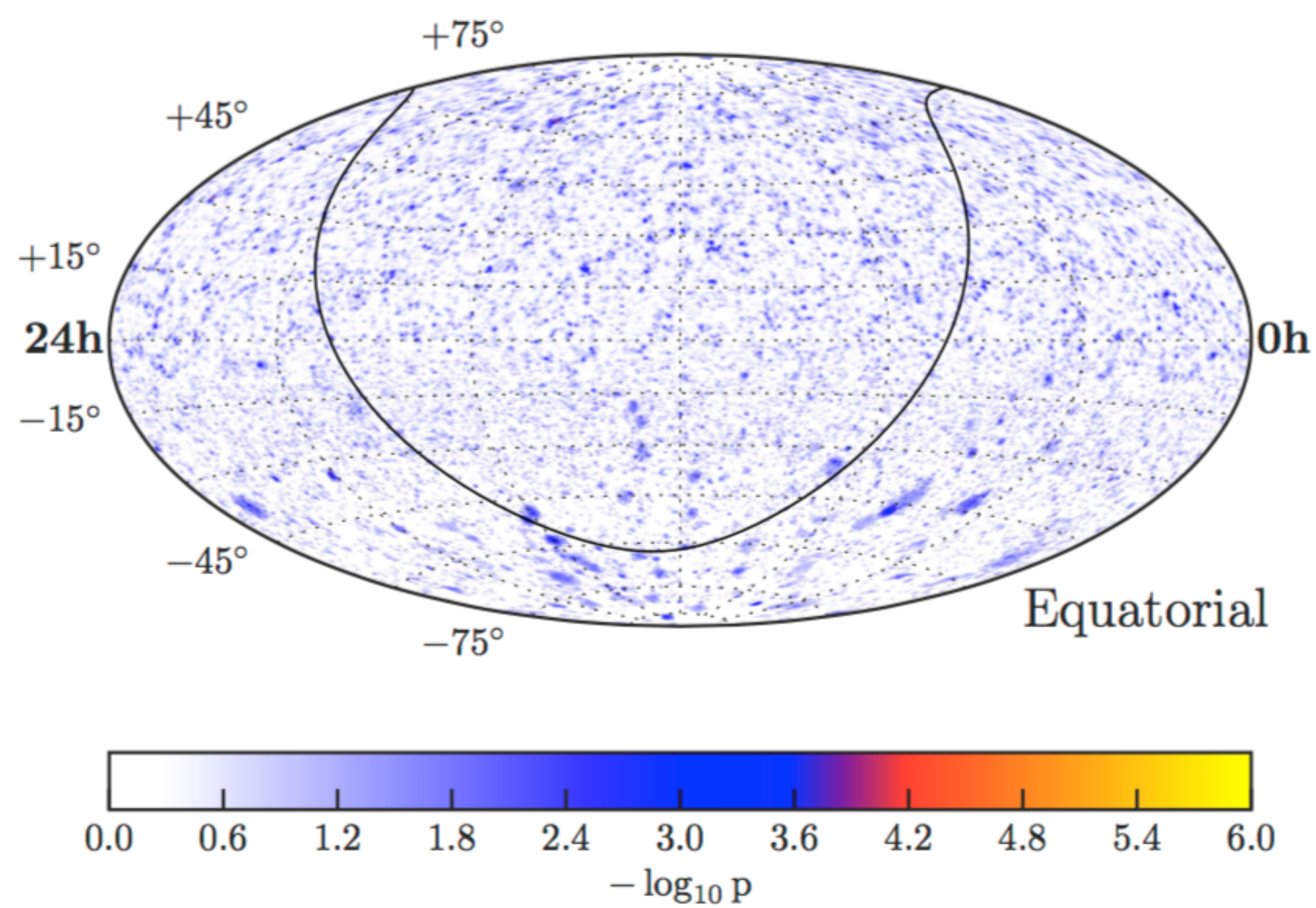
- Neutrinos alone do not (yet) reveal a source



ANTARES ApJ 786 2014

North: post-trial 29%

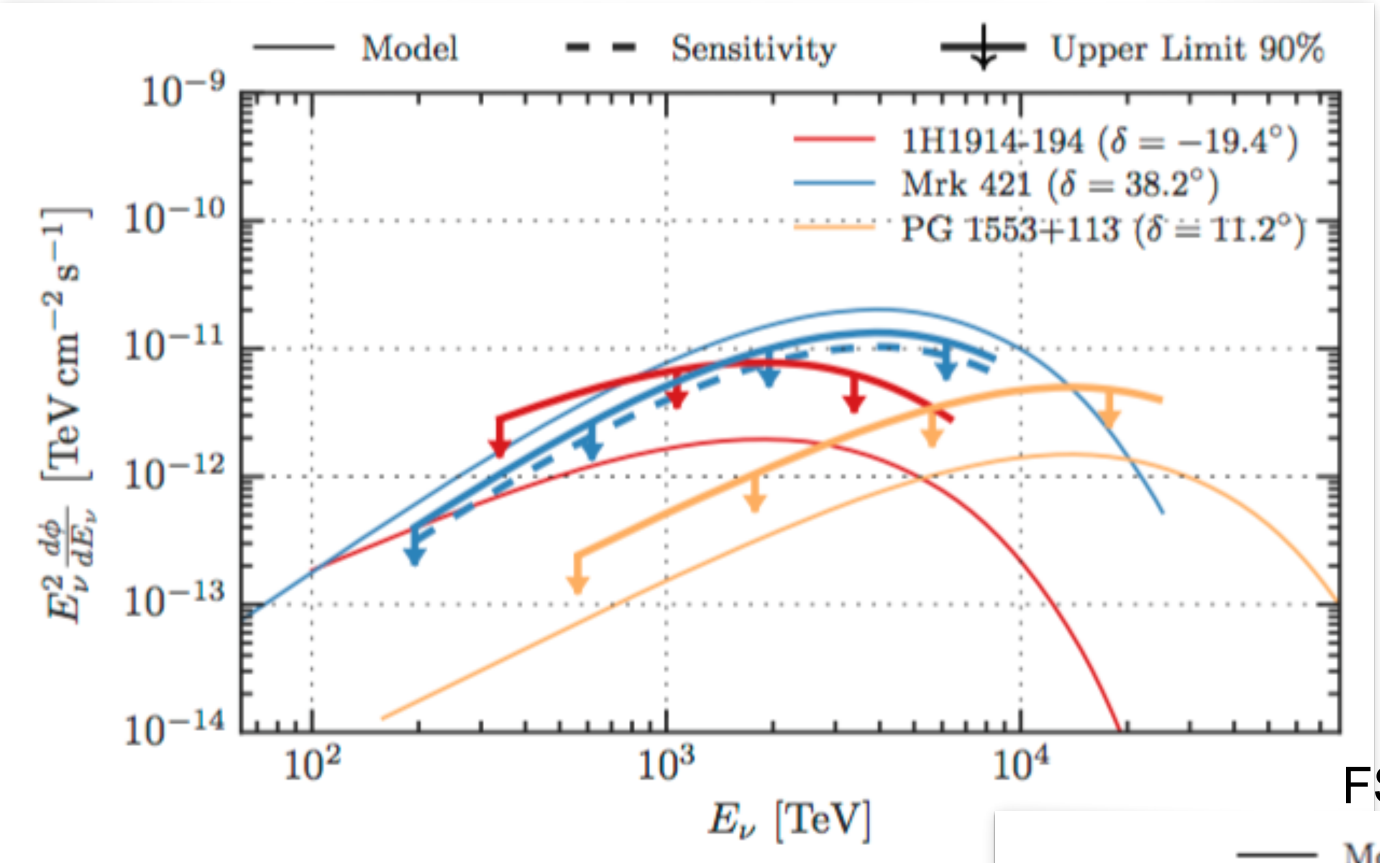
South: post-trial 17%



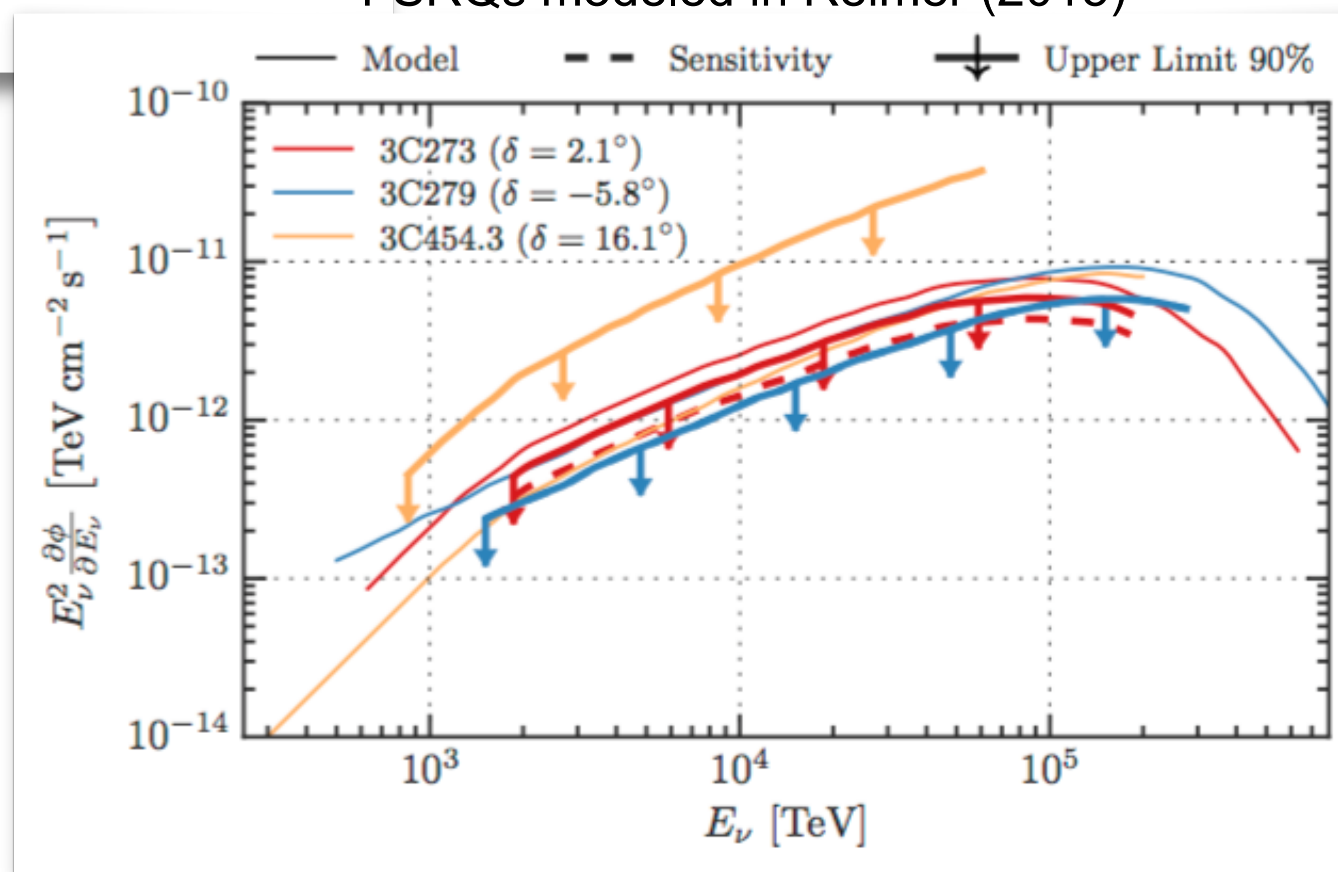
IceCube, arXiv:1609.04981

... LIMITS

BL-Lacs modeled in Petropoulou et al. (2015)



FSRQs modeled in Reimer (2015)



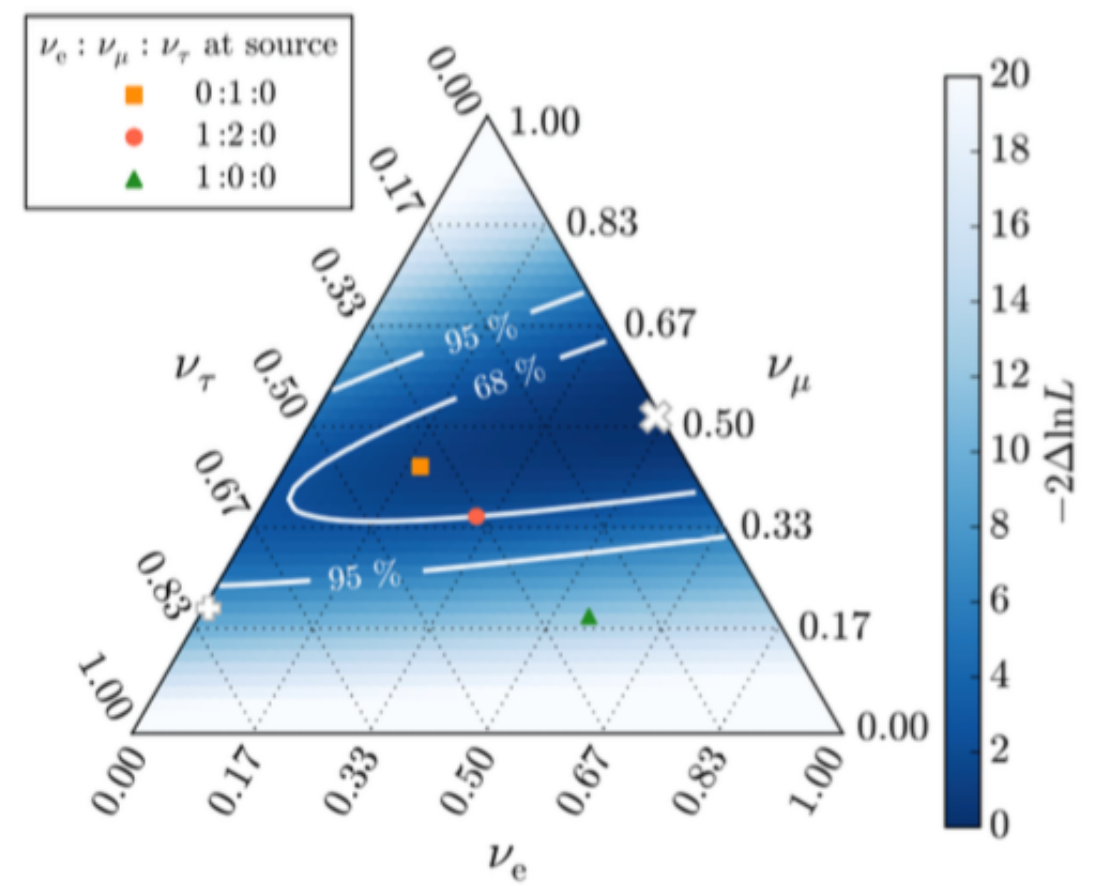
IceCube, arXiv:1609.04981

FLAVOURS

Sources → Earth

	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
Pion Decay	1	2	0	1	1	1
Muon damped	0	1	0	0.2	0.39	0.39
Neutron decay	1	0	0	0.56	0.22	0.22

ApJ 809, 98 (2015), arXiv:1507.03991



SO, WHAT DO WE KNOW?

- Astrophysical neutrinos: spectrum, declination, flavour admixture
- Data shows some extra-galactic component
- Data deviates from an unbroken E^{-2} spectrum
- Few bright sources are disfavoured by point source searches
- FERMI Blazars disfavoured by point source searches
- Star forming galaxies disfavoured by diffuse FERMI extragalactic flux
- Gamma-ray bursts also also disfavoured by dedicated searches

CHOKED JETS AND LOW-LUMINOSITY GRBS?

- IceCube neutrinos could originate from environments with high γ-ray opacity

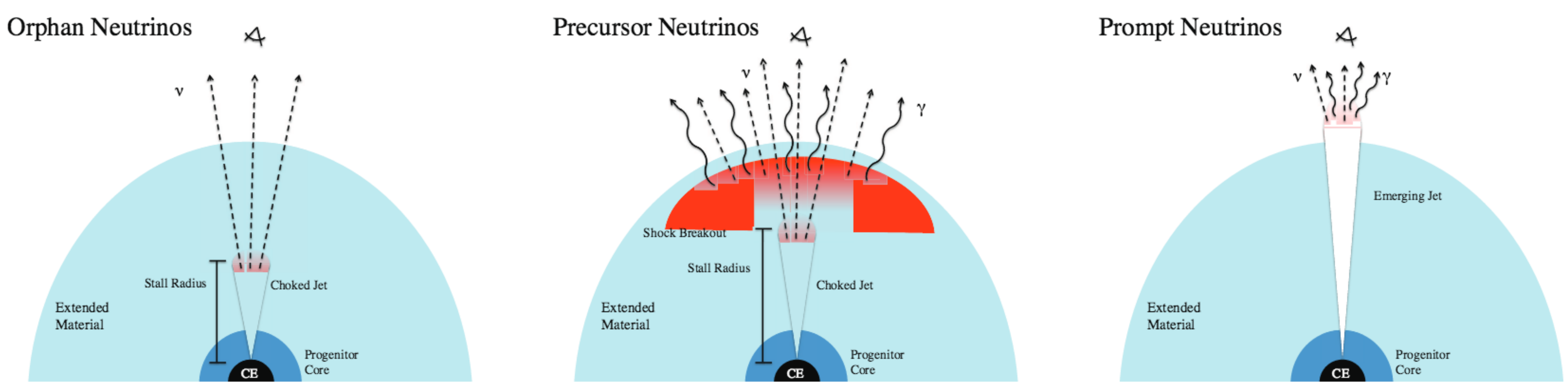


FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic SNe are driven by choked jets. Choked jets produce precursor neutrinos since the gamma-ray emission comes from the SN shock breakout later than the neutrinos (e.g., [25]). **Right panel:** The emerging jet model for GRBs and LL GRBs. Both neutrinos and gamma rays are produced by the successful jet, and both messengers can be observed as prompt emission.

N. Senno, K. Murase, P. Meszaros (arxiv: 1512.08513)

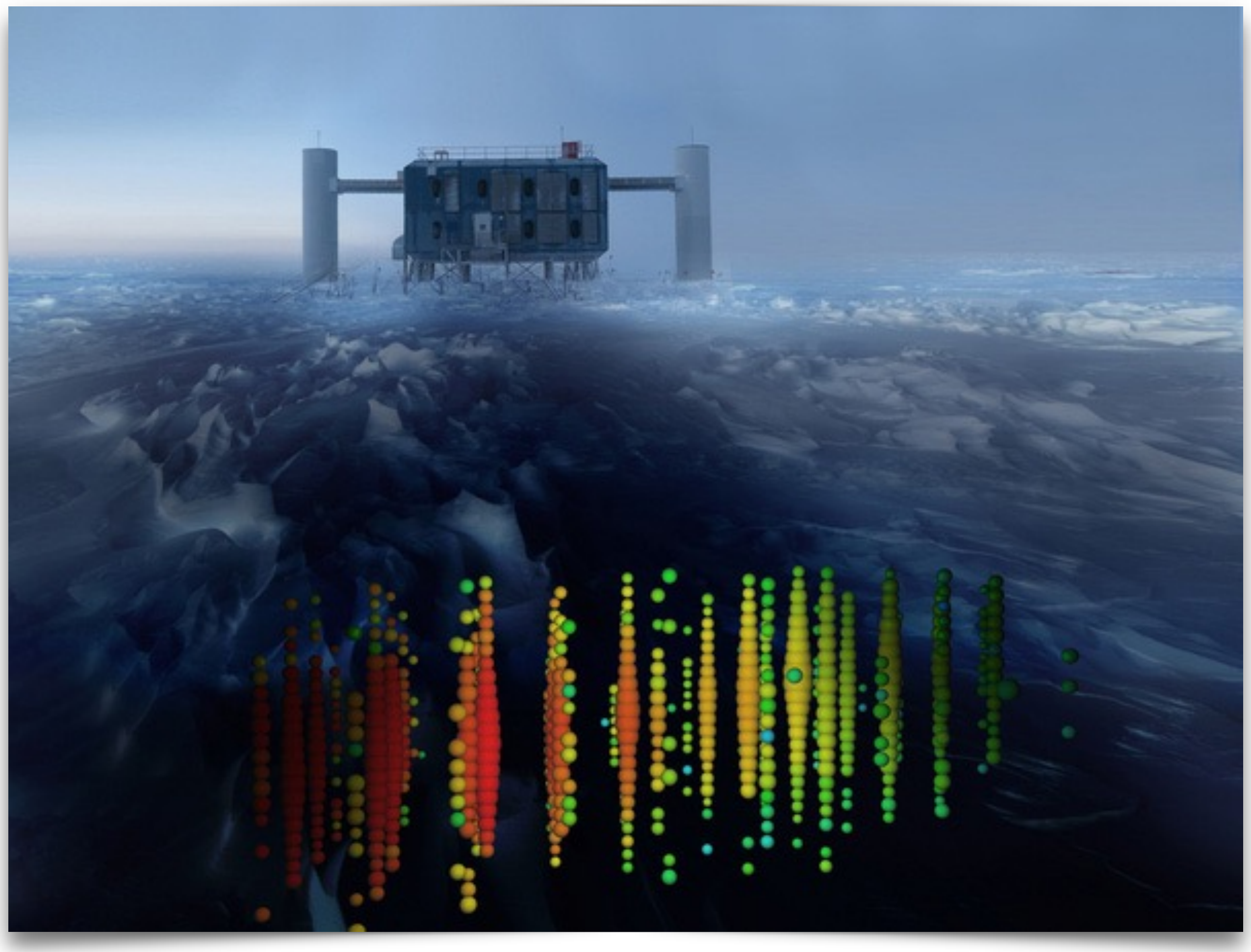
neutrinos only!
can account for diffuse
neutrino flux

neutrino precursor & γ-rays
Time scale: 10 -1000 s

neutrino & γ-rays
Constrained by IceCube

THE DAWN OF NEUTRINO ASTRONOMY

- IceCube has paved the road for neutrino astrophysics!
- No evidence yet of neutrino point and extended sources
- The sources of IceCube neutrinos are not readily traced by extragalactic gamma-ray emitters
- Large number of weak sources or transients?

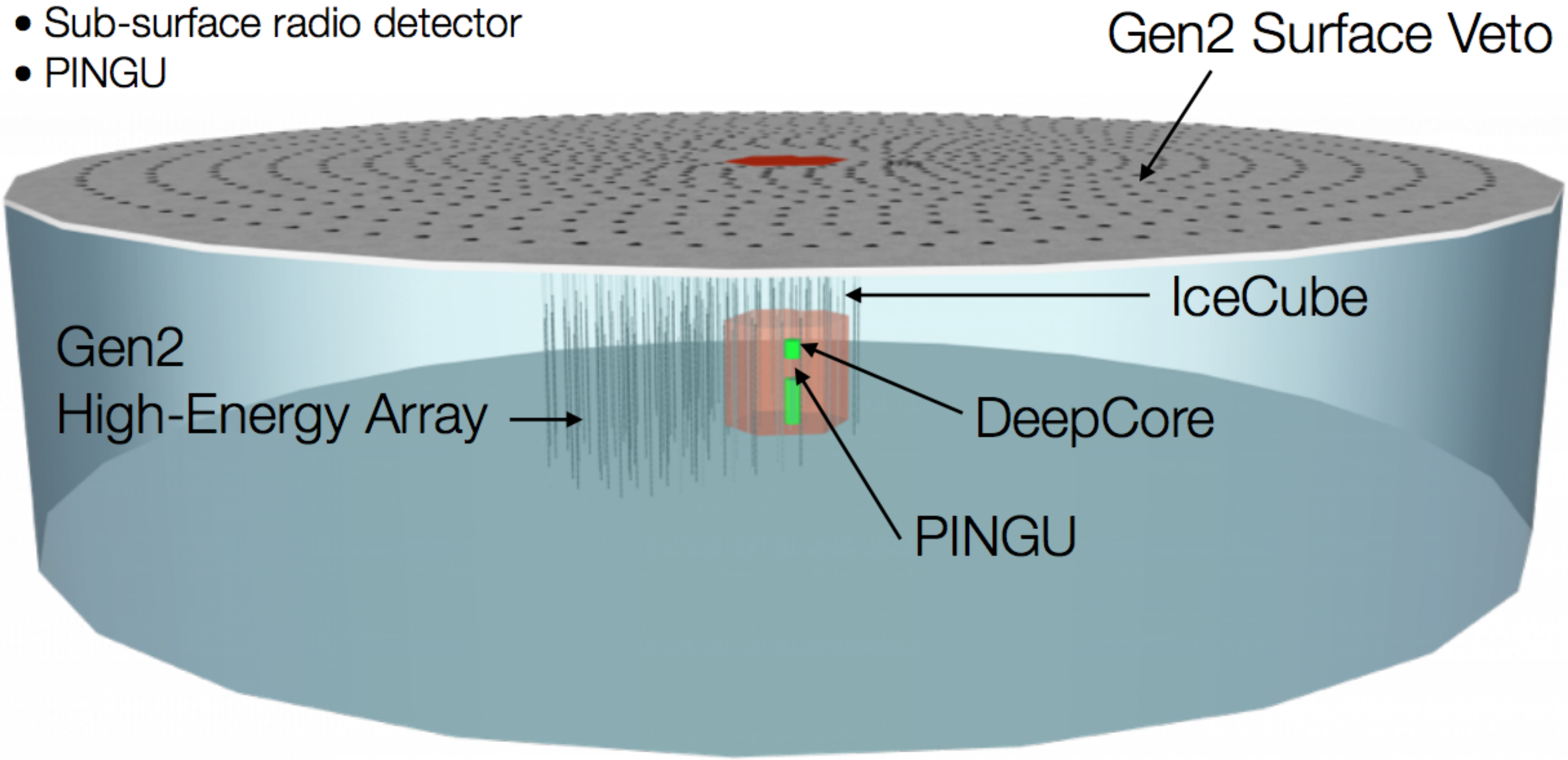


ICECUBE-GEN2

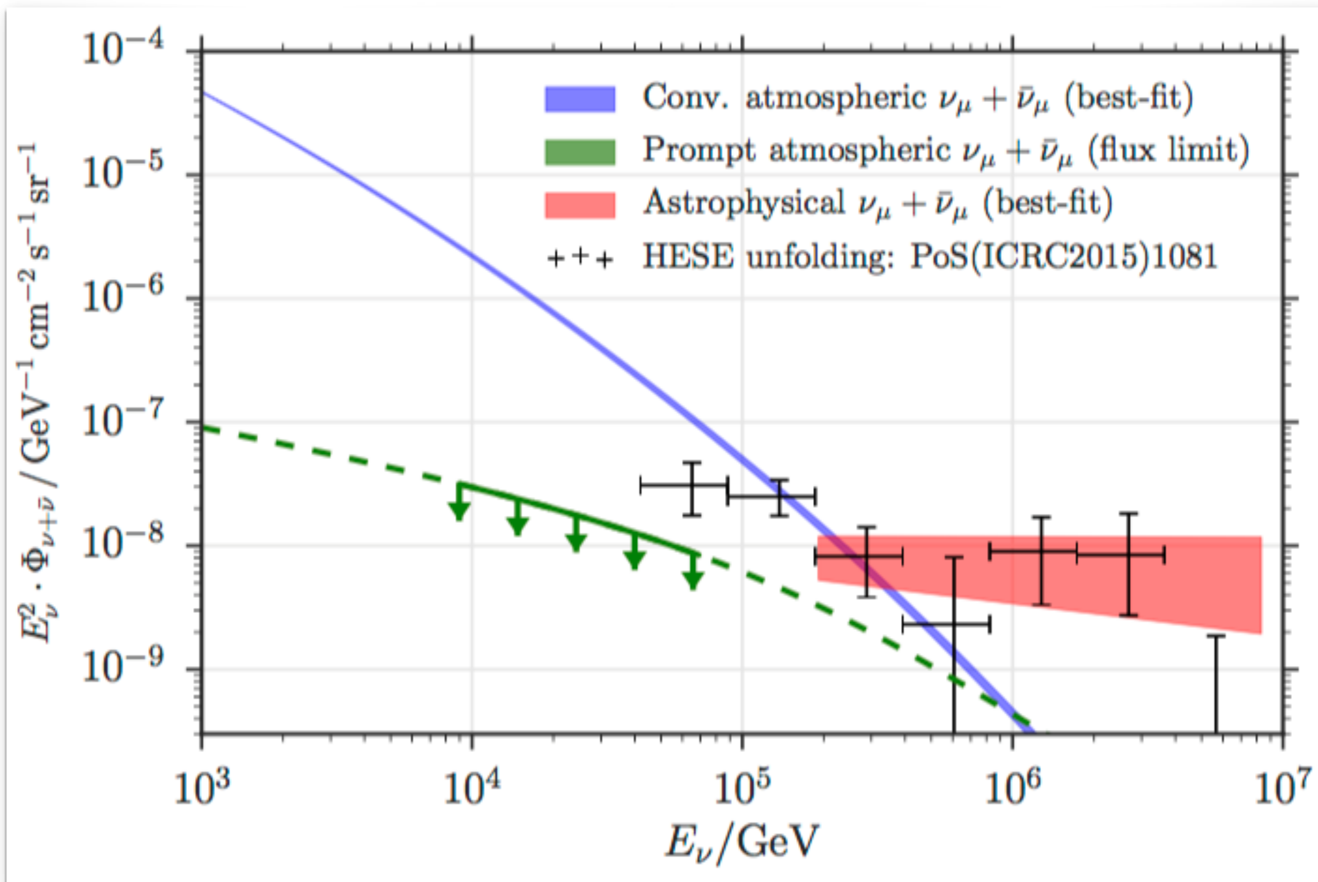
A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

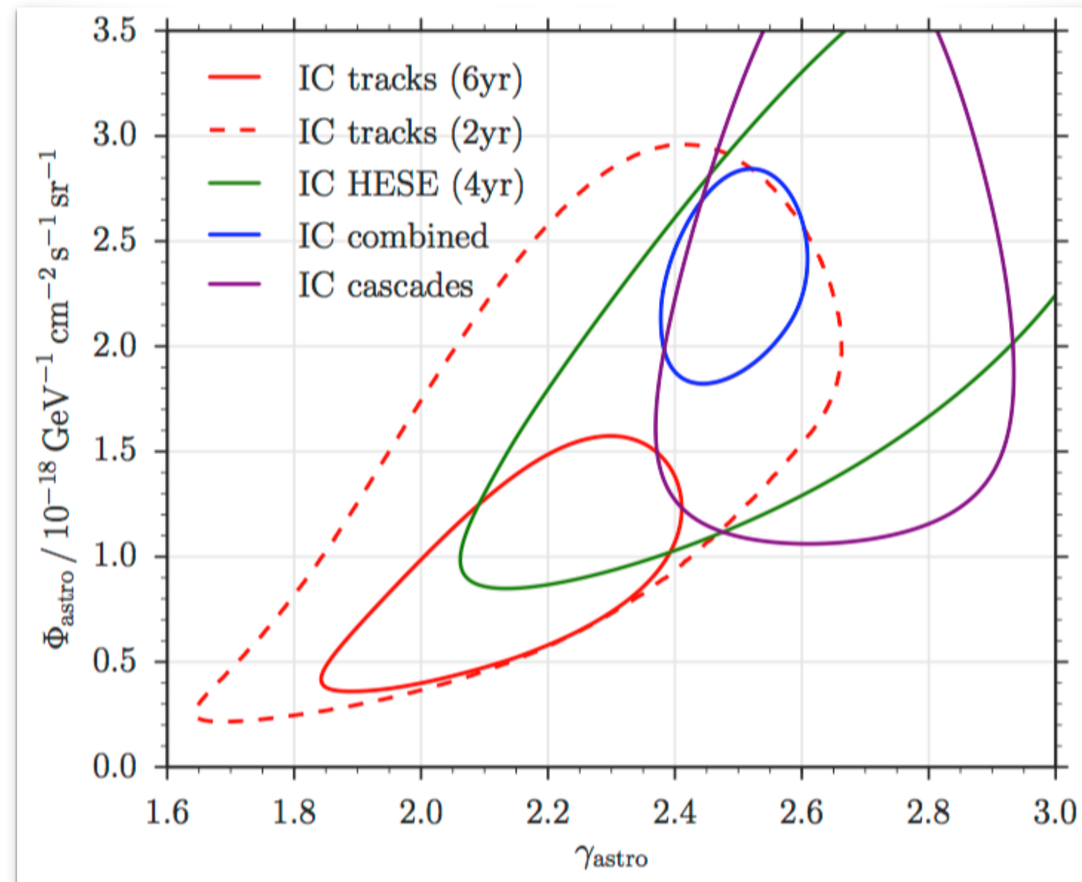
Multi-component observatory:

- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



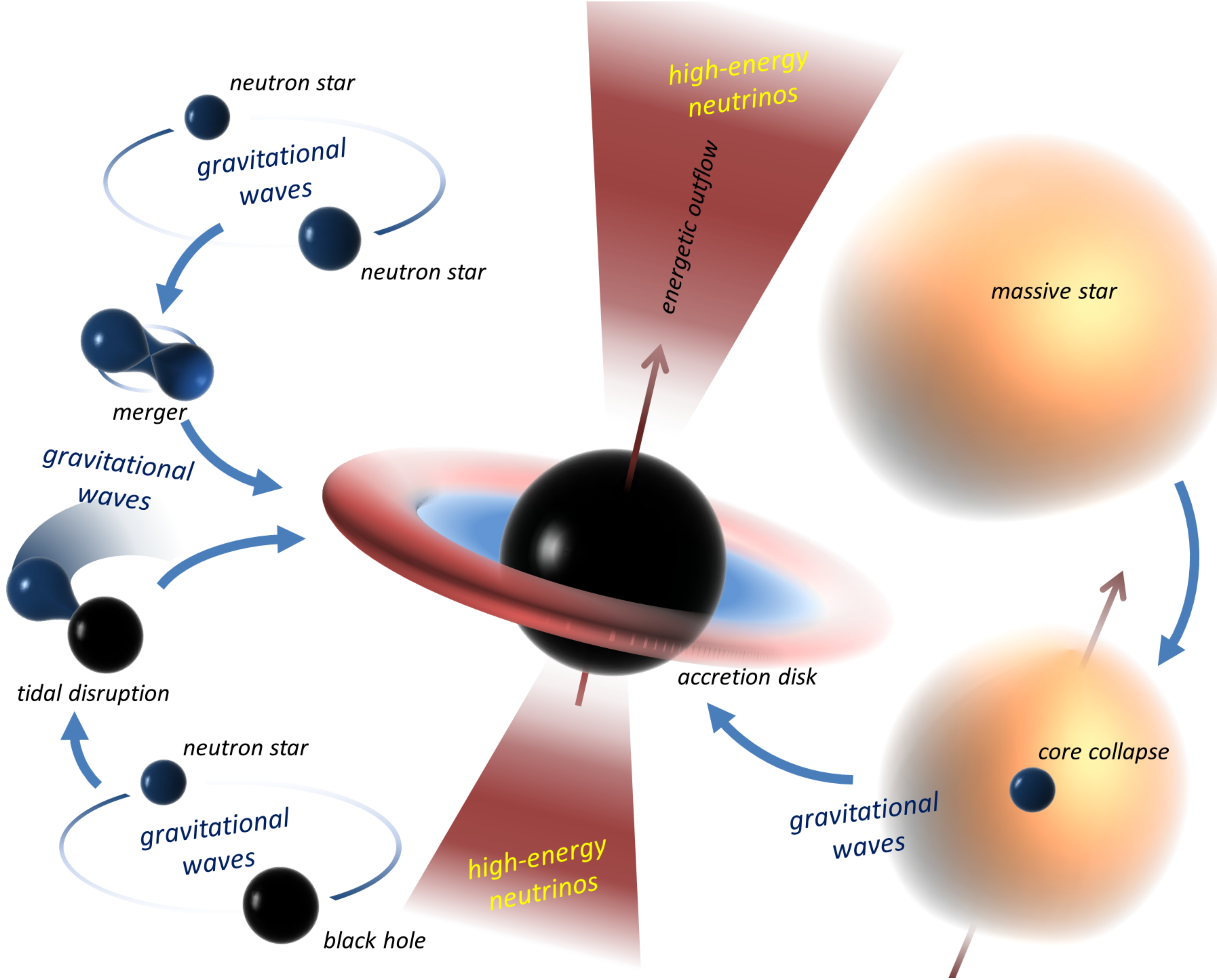
TENSION BETWEEN ICECUBE ANALYSES?





arXiv: 1607.08006

GRAVITATIONAL WAVES AND HIGH-ENERGY NEUTRINOS

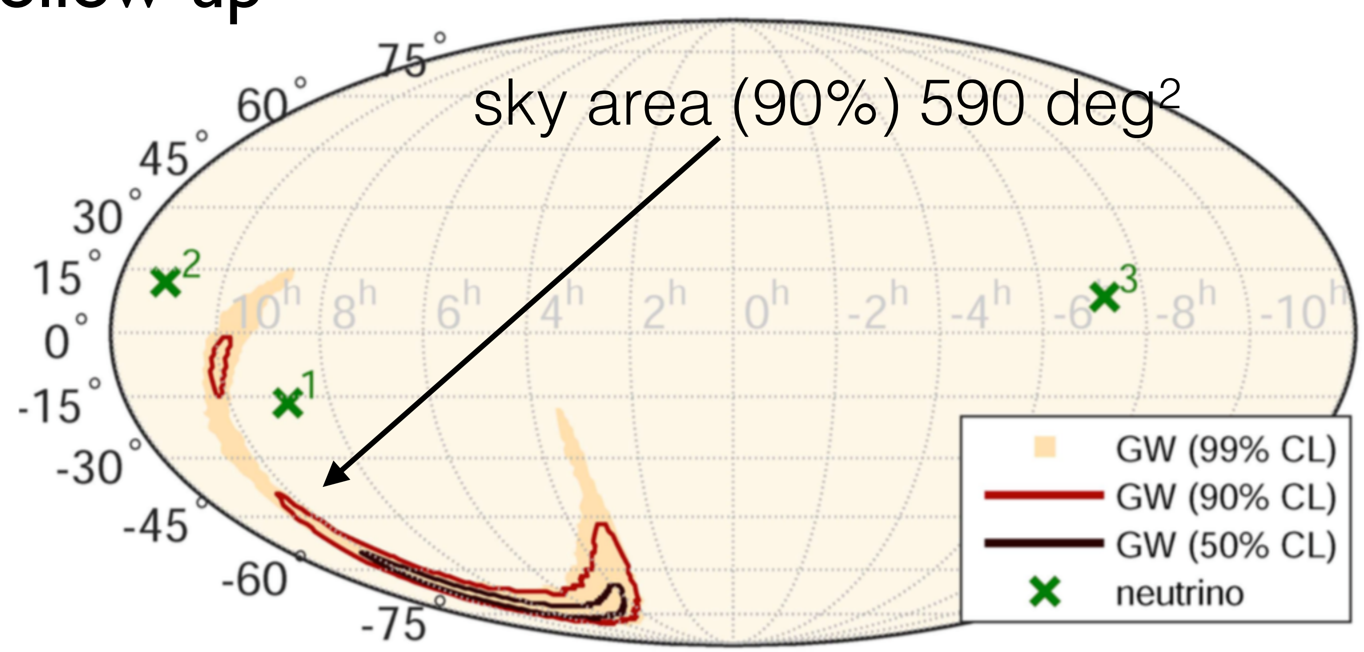


http://ligo.org

IceCube, LIGO and Virgo, Phys. Rev. D 90, 102002 (2014)

ANY NEUTRINO IN COINCIDENCE WITH GRAVITATIONAL WAVES?

- **GW 150914 (D=410 Mpc, 5x10^{54} erg/s)** [B. Abbott et al (2016)] **could have had associated high energy neutrinos**
- Within ± 500 s of GW 150914 ANTARES found 0 events and IceCube 3 events from online pipelines
  - Rates compatible with expected background
  - IceCube event energies are not significant (p-value 33%)
  - Directional coincidence not significant (probability of at least one neutrino to be accidentally coincident would have been 4%)
- **If positive coincidences will be observed it can improve the efficiency of electromagnetic follow-up**



ANTARES, IceCube, LIGO and Virgo arXiv: 1602.05411