Astro and particle physics with neutrino telescopes in the next decade

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HETG Seminar, Institute of Physics, Academia Sinica

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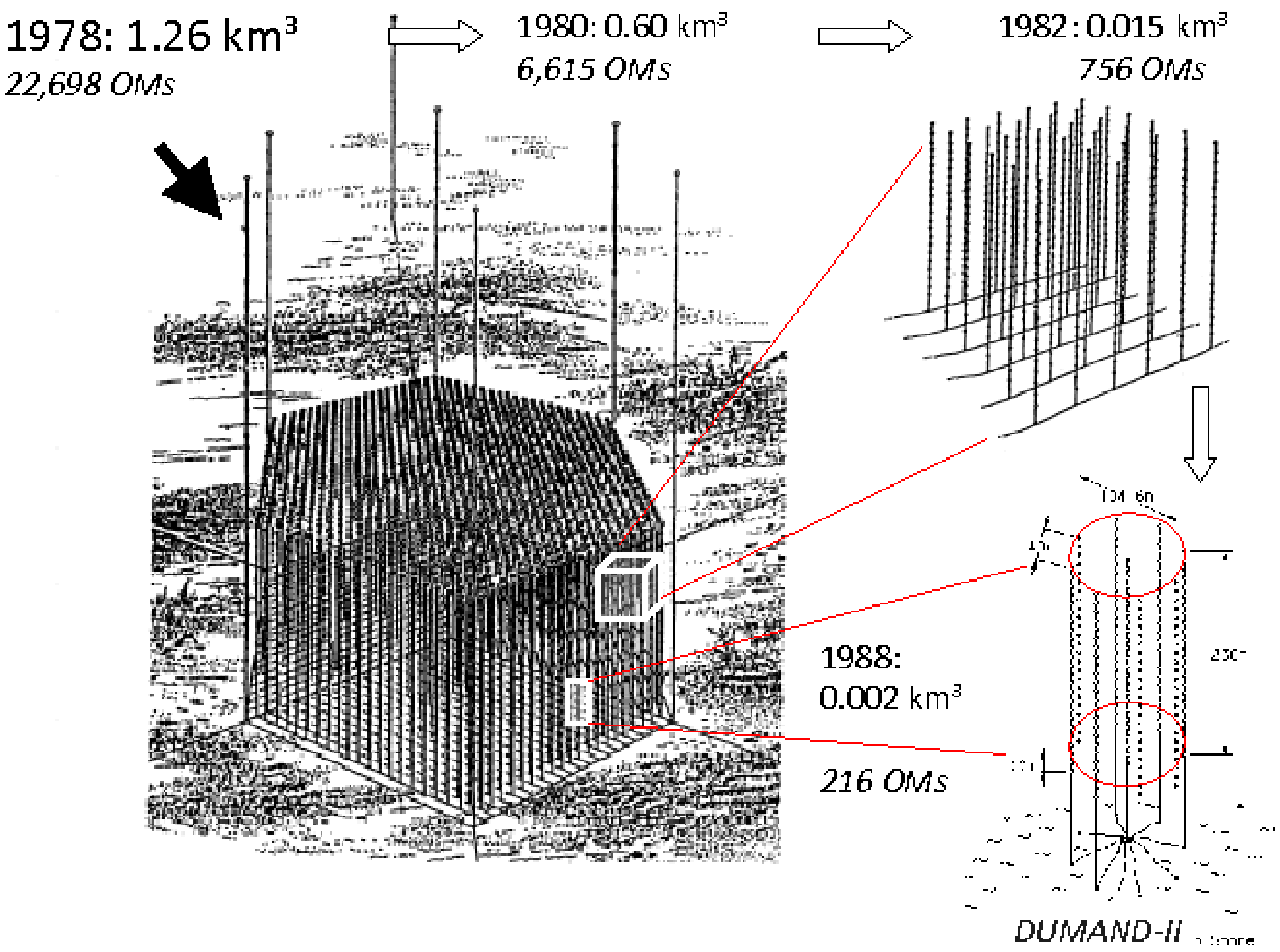
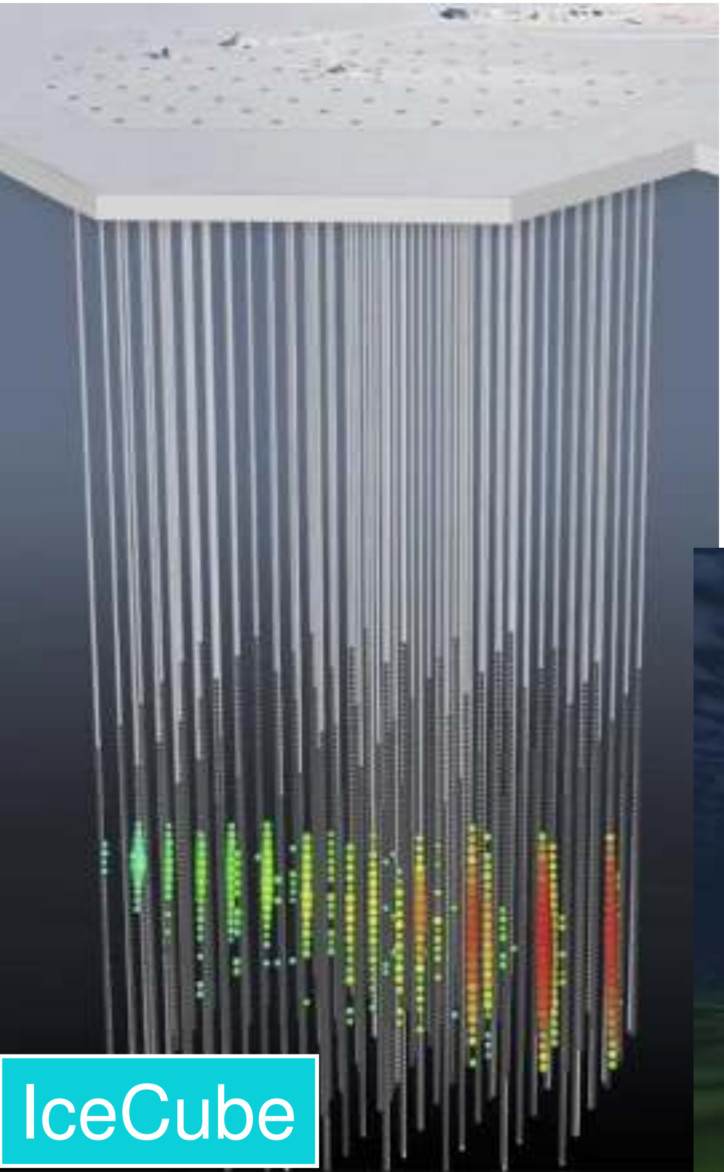
University of Tokyo

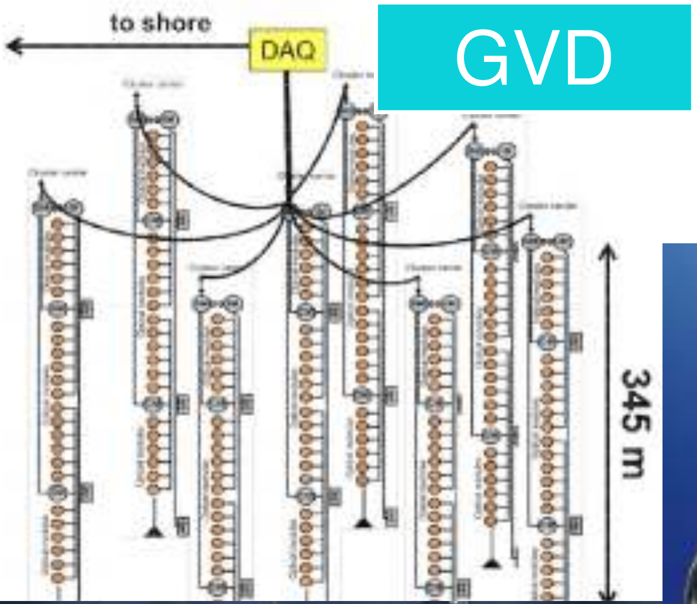
DUMAND – the dawn of neutrino astronomy



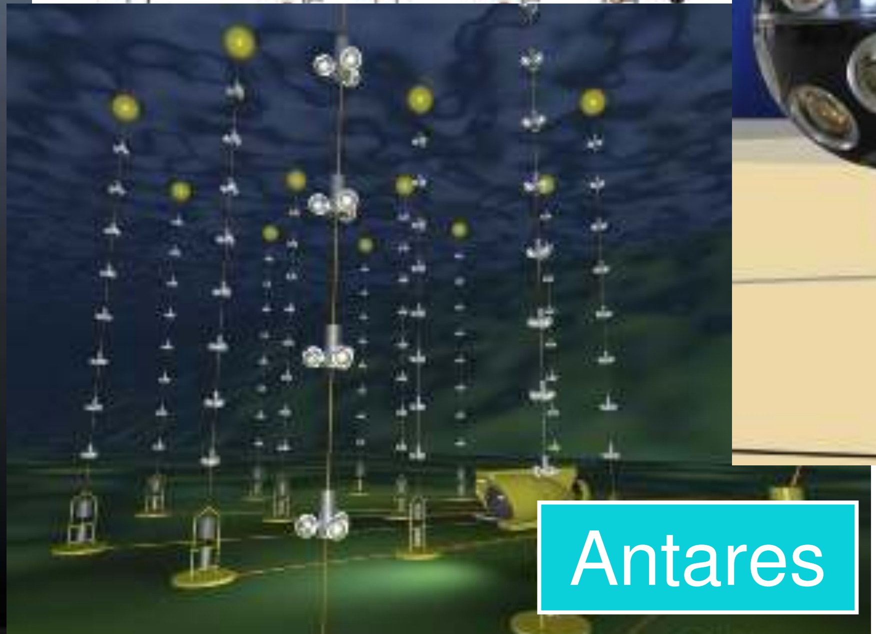
- After the initial idea of M.A. Markov in 1960
- ..in 1975 an international group of scientists
  - Organized a series of workshops, despite the cold war going at full pace
  - Developed first ideas of experimental detection of astrophysical neutrinos
  - Realized that a gigaton volume detector is needed
  - Considered optical, radio and acoustic detection
  - Found a design that is capable of simultaneously detecting tracks of secondary muons and cascades
- The DUMAND Project ran ~20 years
  - Aiming to deploy a detector at a depth of 4800m near Hawaii
  - Develop the hardware necessary to realize the concept of a "string", i.e. optical modules, junction boxes, cabling etc.
  - At the beginning, nobody had an idea about the expected fluxes, backgrounds, reconstruction etc.
- Ultimately canceled in 1996 by the US DOE

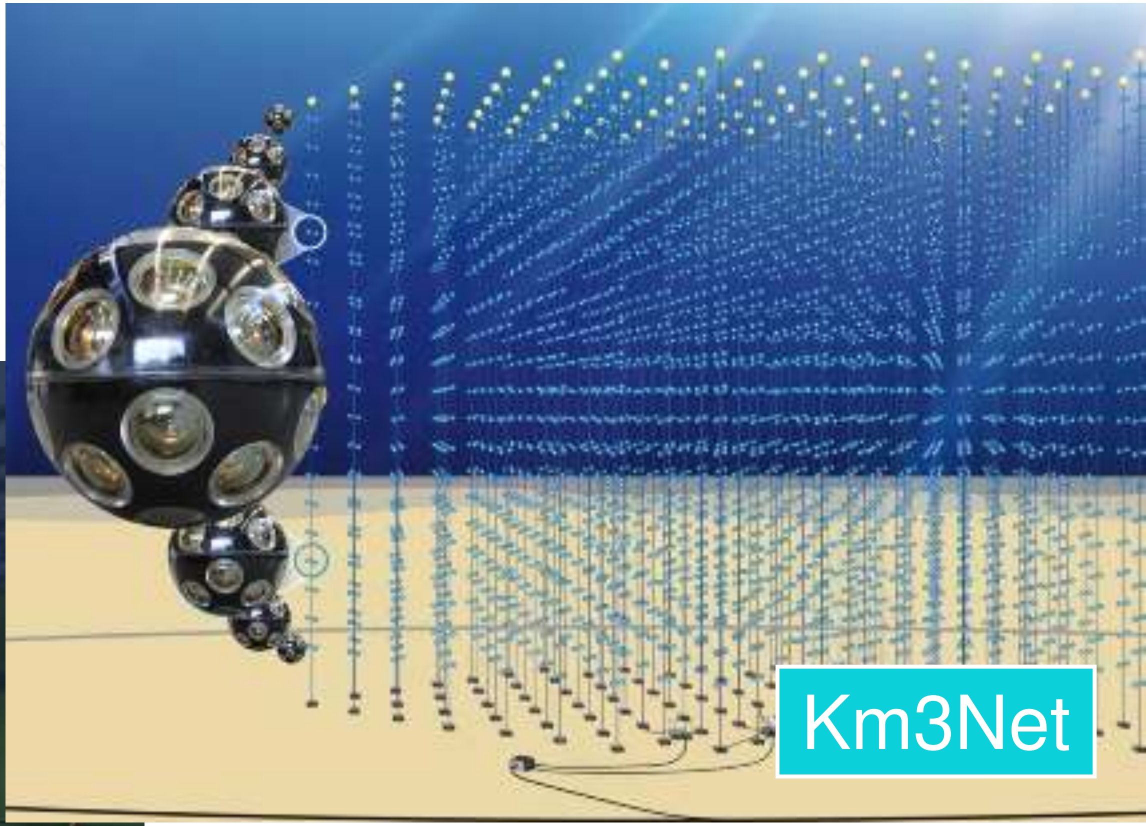
30 years later: Large volume neutrino detectors

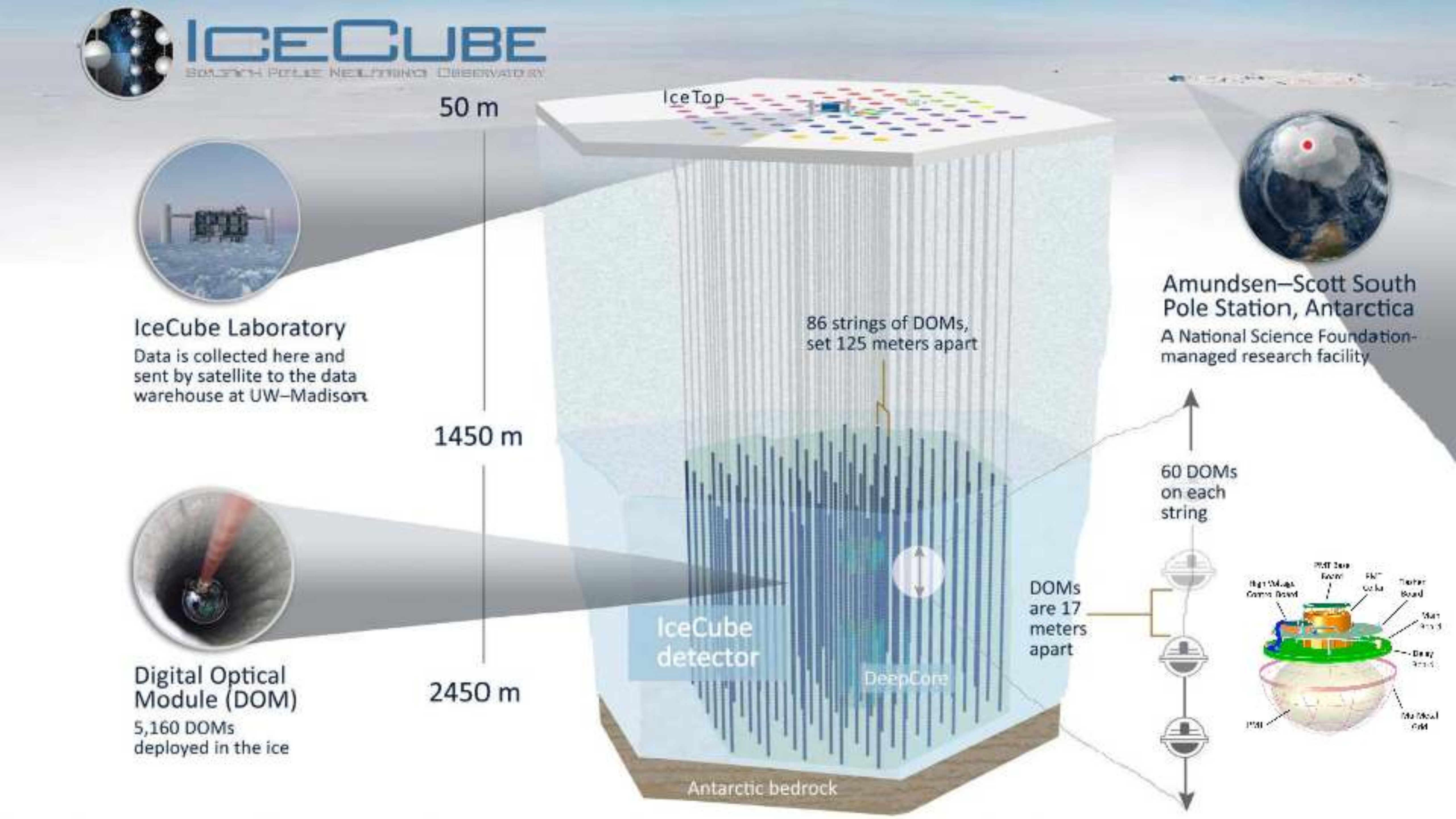




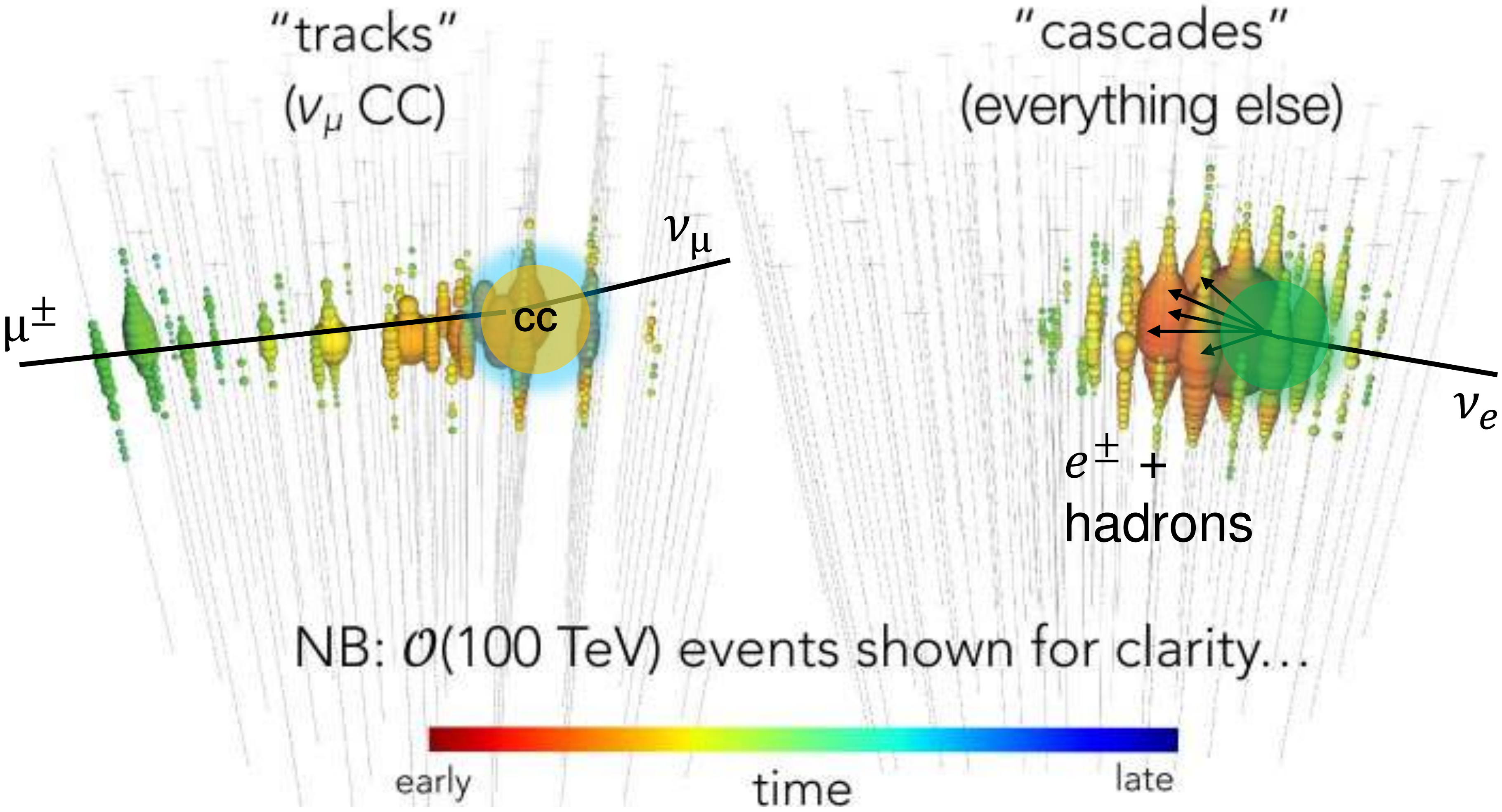
The dreams from the DUMAND era are reality






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

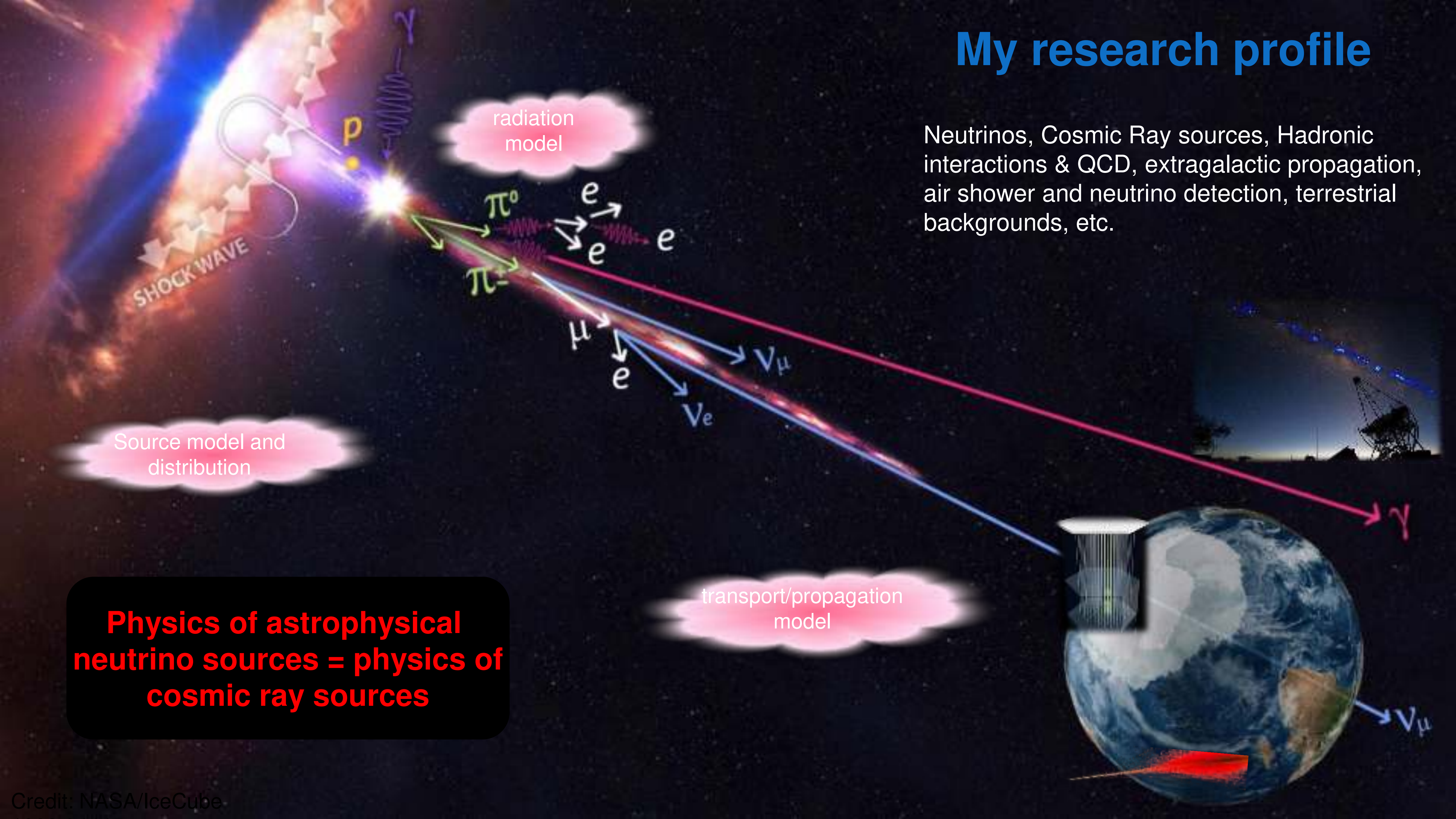
Detects tracks and cascades



Tyce DeYoung (IceCube)

My research profile

Neutrinos, Cosmic Ray sources, Hadronic interactions & QCD, extragalactic propagation, air shower and neutrino detection, terrestrial backgrounds, etc.



Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube

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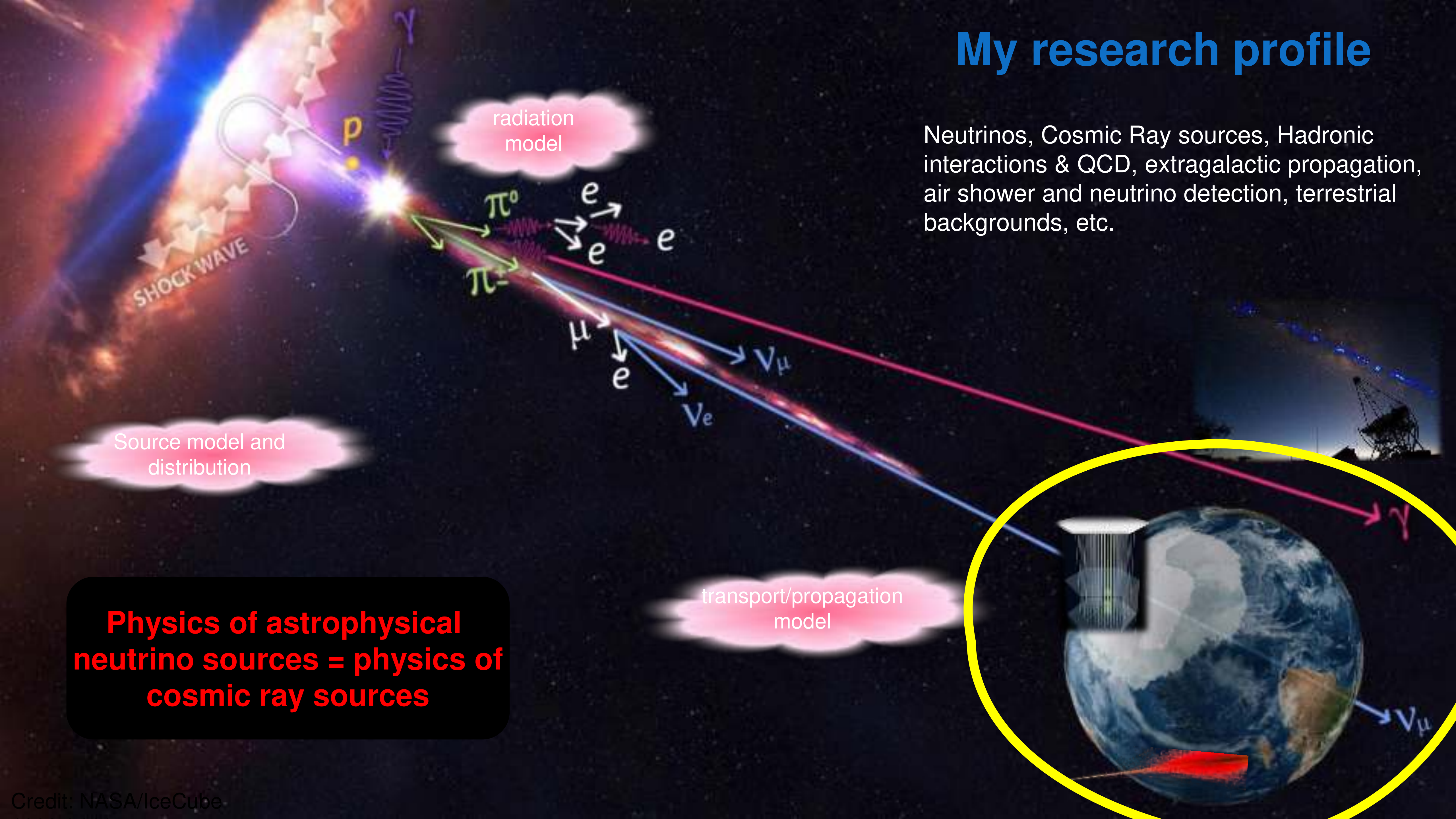
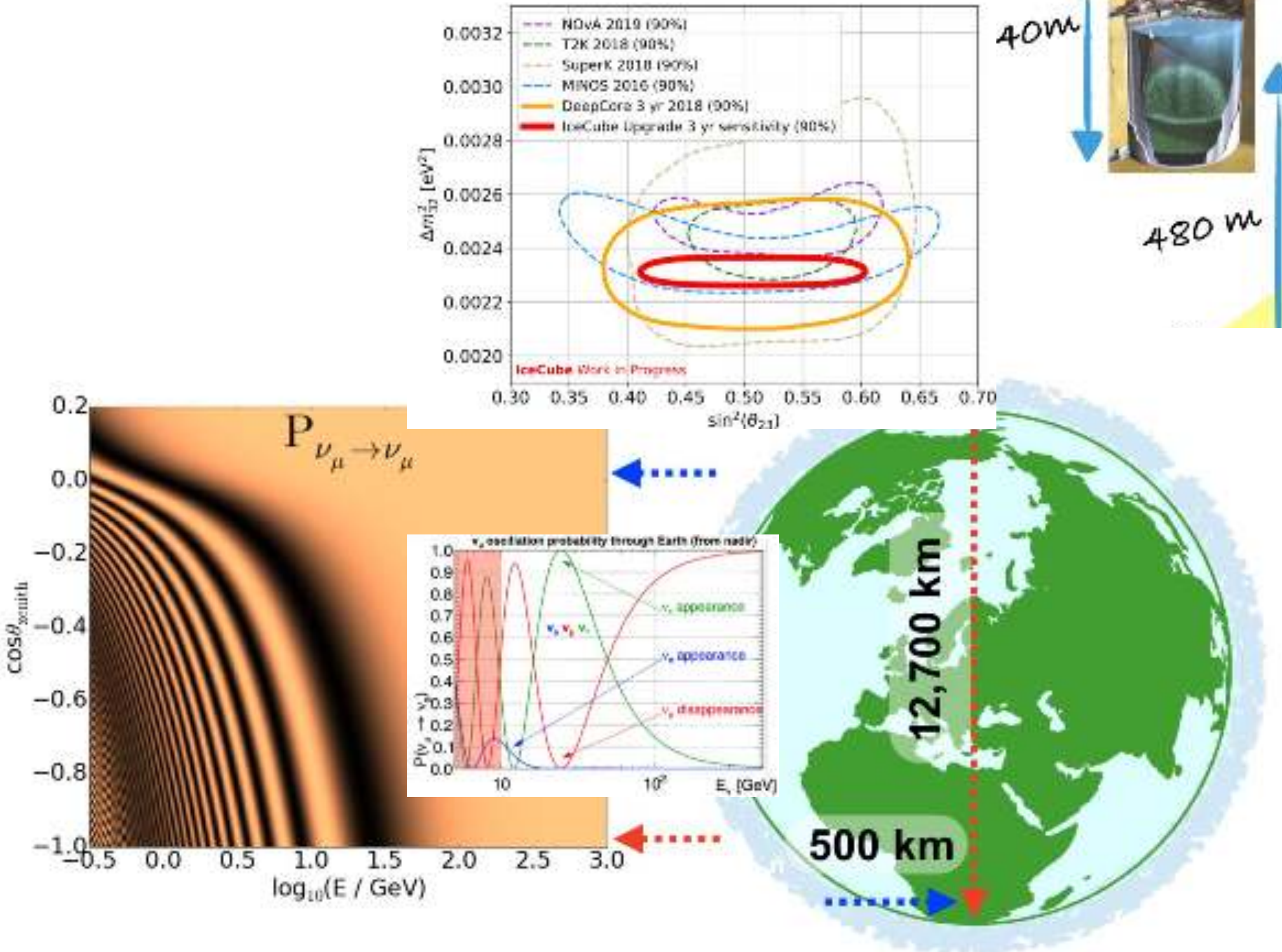
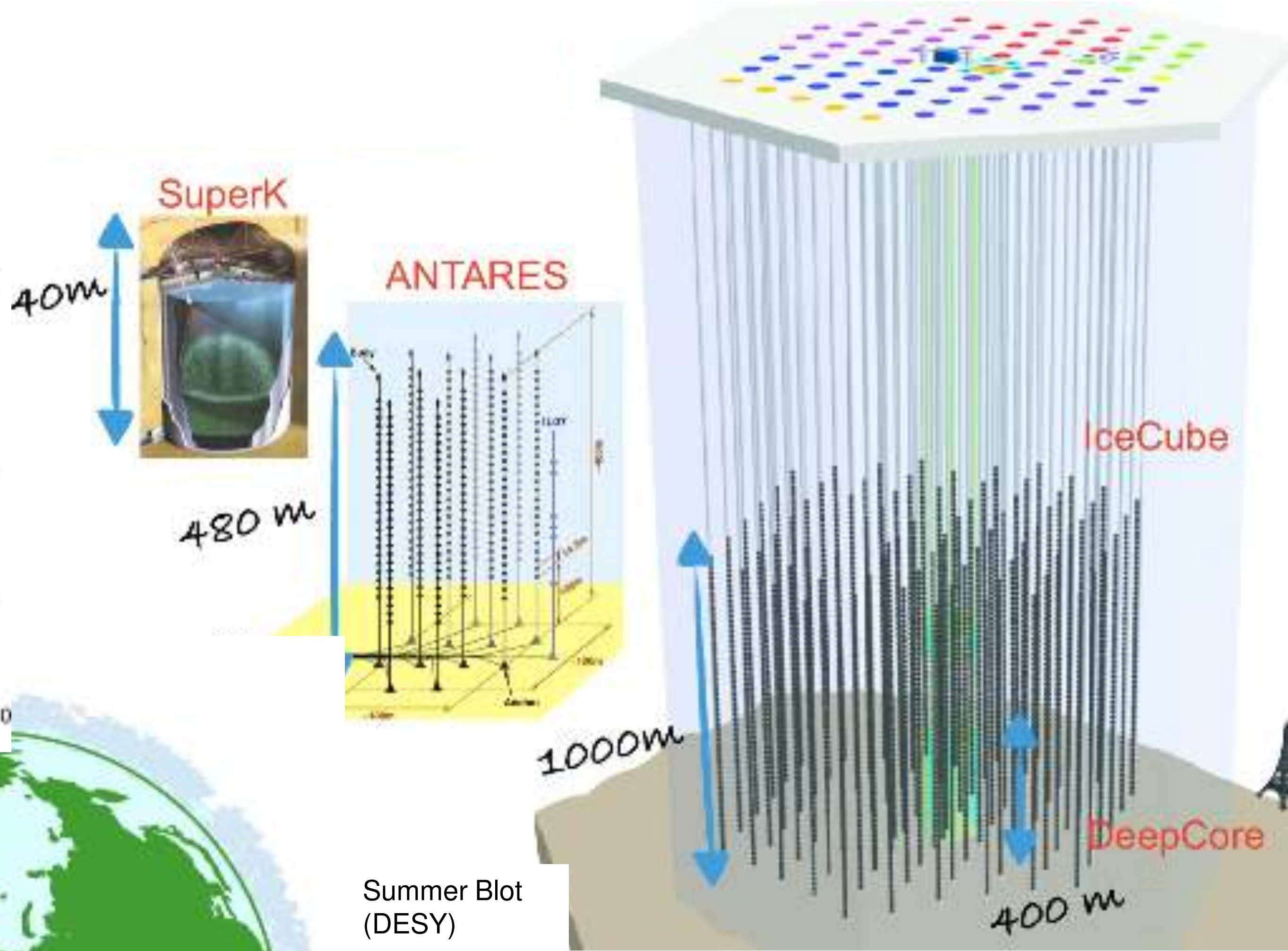


Physics of astrophysical neutrino sources = physics of cosmic ray sources

Neutrino physics with Cherenkov telescopes



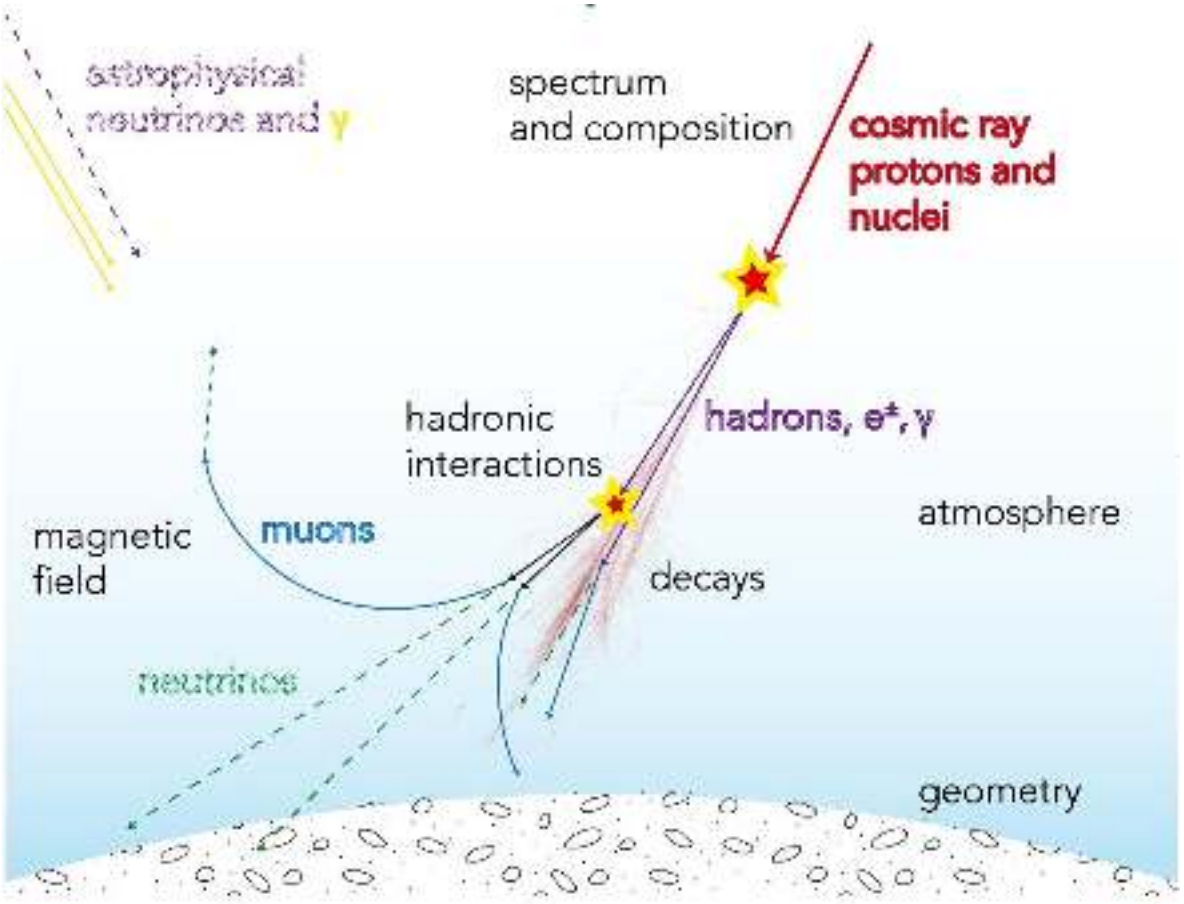


Summer Blot (DESY)

Search for oscillation patterns in atmospheric neutrino flux
Energy: MeV – TeV & direction: 4π

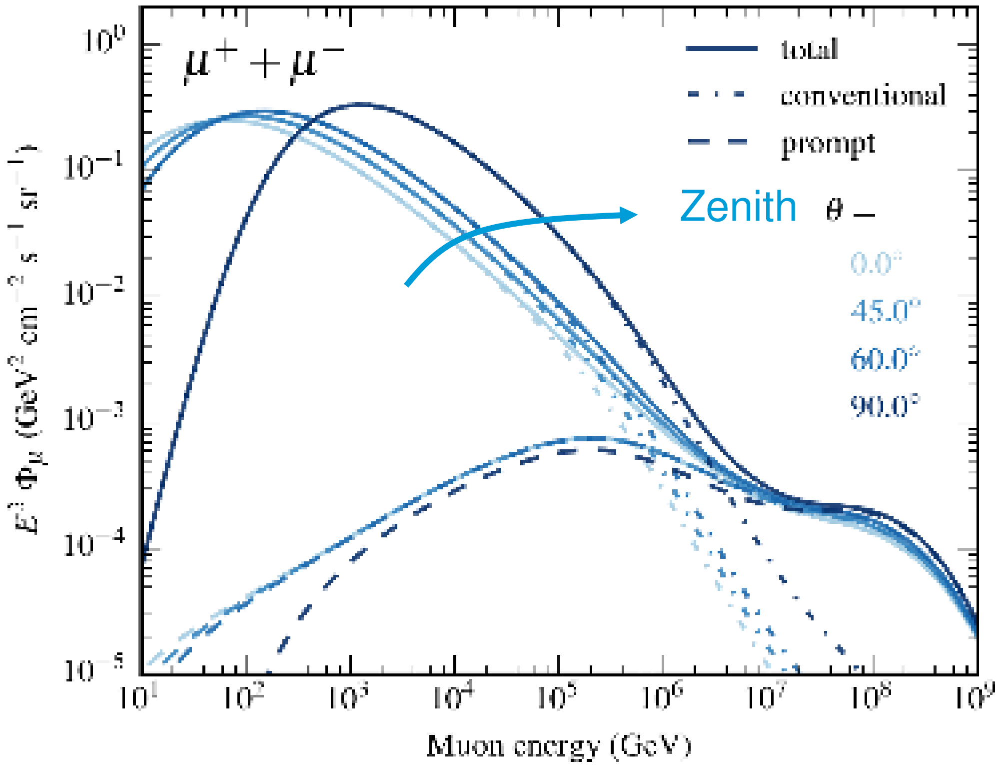
Origin of atmospheric neutrinos

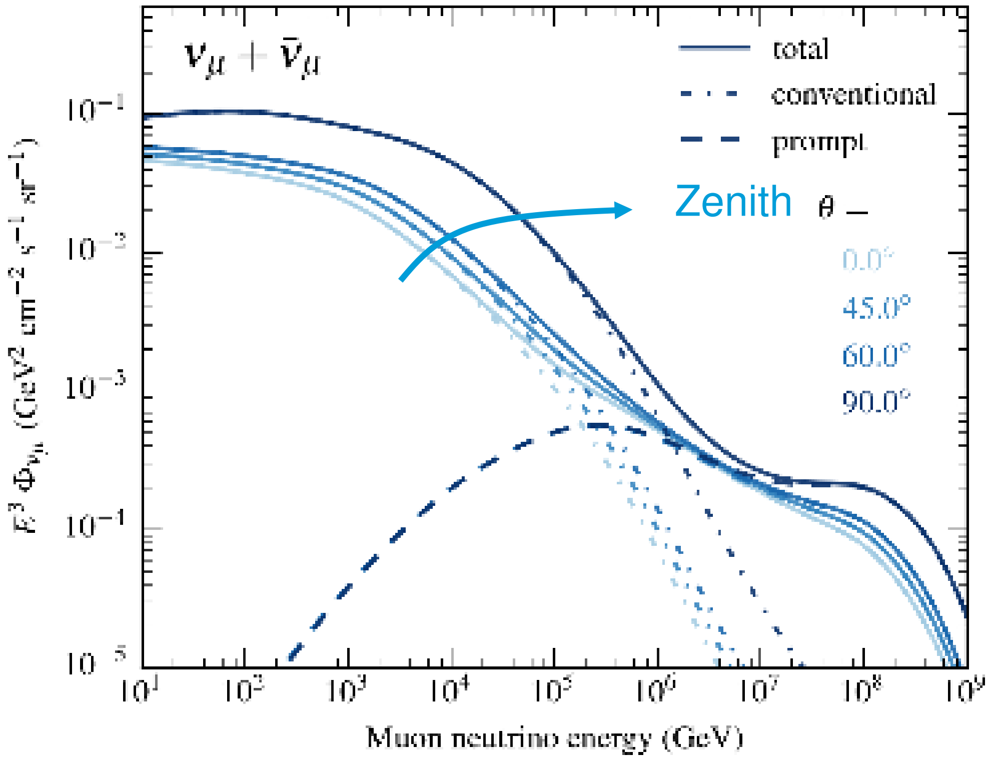
Input for high-precision atmospheric neutrino flux calculations



- For <u>high precision</u> calculations all phenomena need accurate modeling
- Uncertain “ingredients”:
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere (dynamic, depends on use case)
  - (Rare) decays
  - Geometry, magnetic fields, solar modulation
- No clear prescription how to handle uncertainties.
- Methods: Monte Carlo, analytical, <u>numerical</u>
- Energy range MeV – EeV!

Two components in muon and neutrino fluxes





conventional: from decays of light and strange hadrons (longer lived)

prompt: from decays of short-lived hadrons, mostly charm and bottom

Transport equations (hadronic cascade equations)

System of coupled PDE for each particle species *h* :

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)}$$

cosmic ray physics

Interactions with air

$$-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)}$$

atmospheric physics

Decays

$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X))$$

Continuous losses

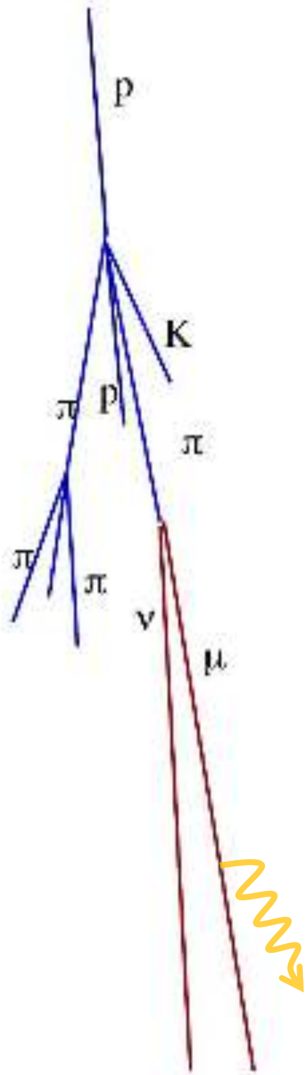
$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)}$$

Re-injection from interactions

$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$

Re-injection from decays

particle physics



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

Transport equations (hadronic cascade equations)

System of coupled PDE for each particle species *h* :

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$

cosmic ray physics

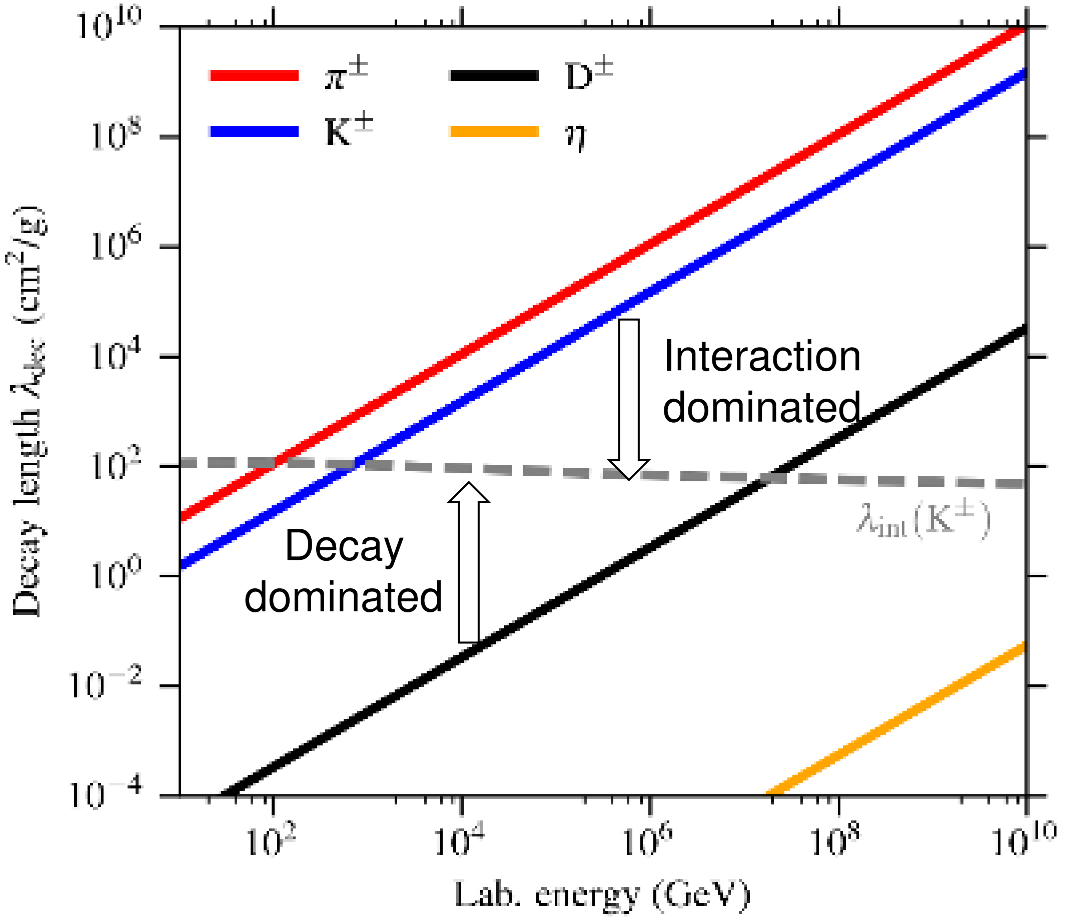
Interactions with air

Decays

atmospheric physics

Continuous losses

particle physics



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor
PoS ICRC 2015, 1129 (2015), EPJ Web Conf. 99, 08001 (2015)
and EPJ Web Conf. 116, 11010 (2016)

MCEq: Matrix Cascade Equations

$$\begin{aligned}\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = &-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} \\ &-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} \\ &-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) \\ &+\sum_\ell \int_E^\infty \mathrm{d}E_\ell \, \frac{\mathrm{d}N_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{int},l}(E_\ell)} \\ &+\sum_\ell \int_E^\infty \mathrm{d}E_\ell \, \frac{\mathrm{d}N^{\mathrm{dec}}_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E} \frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{dec},l}(E_\ell,X)}\end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}\Phi^h_{E_i}}{\mathrm{d}X} = &-\frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{int},E_i}} \\ &-\frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{dec},E_i}(X)} \\ &-\vec{\nabla}_i(\mu^h_{E_i}\Phi^h_{E_i}) \\ &+\sum_{E_k\geq E_i}^{E_N}\sum_\ell \frac{c_{\ell(E_k)\to h(E_i)}}{\lambda^\ell_{\mathrm{int},E_k}}\Phi^\ell_{E_k} \\ &+\sum_{E_k\geq E_i}^{E_N}\sum_\ell \frac{d_{\ell(E_k)\to h(E_i)}}{\lambda^\ell_{\mathrm{dec},E_k}(X)}\Phi^\ell_{E_k}\end{aligned}$$

State (or flux) vector

$$\vec{\Phi} = \left(\vec{\Phi}^{\mathrm{p}} \quad \vec{\Phi}^{\mathrm{n}} \quad \vec{\Phi}^{\pi^+} \quad \dots \quad \vec{\Phi}^{\bar{\nu}_\mu} \quad \dots\right)^T$$

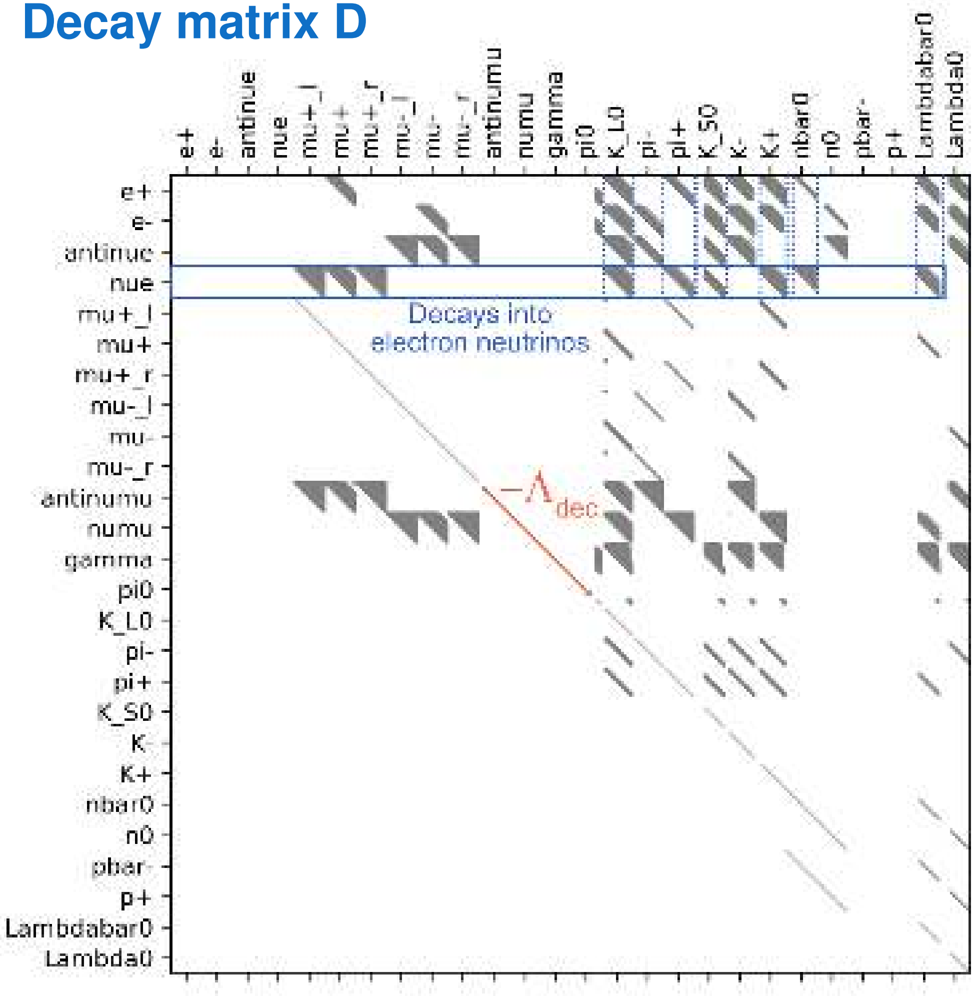
$$\vec{\Phi}^{\mathrm{p}} = \left(\Phi^{\mathrm{p}}_{E_0} \quad \Phi^{\mathrm{p}}_{E_1} \quad \cdots \quad \Phi^{\mathrm{p}}_{E_N}\right)^T$$

“Matrix form”

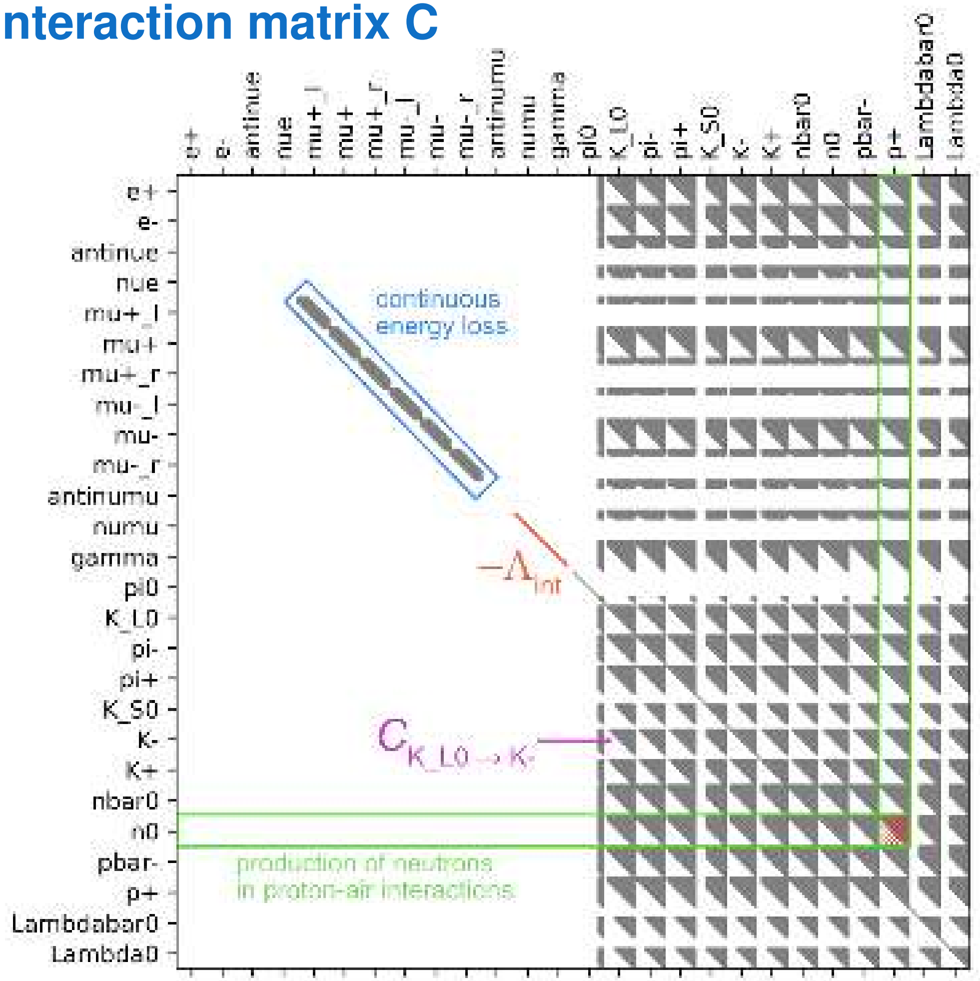
$$\frac{\mathrm{d}}{\mathrm{d}X}\vec{\Phi} = -\vec{\nabla}_E(\mathrm{diag}(\vec{\mu})\vec{\Phi}) + (-\mathbf{1}+\mathbf{C})\mathbf{\Lambda}_{\mathrm{int}}\vec{\Phi} + \frac{1}{\rho(X)}(-\mathbf{1}+\mathbf{D})\mathbf{\Lambda}_{\mathrm{dec}}\vec{\Phi}$$

Sparse matrix structure

Decay matrix D

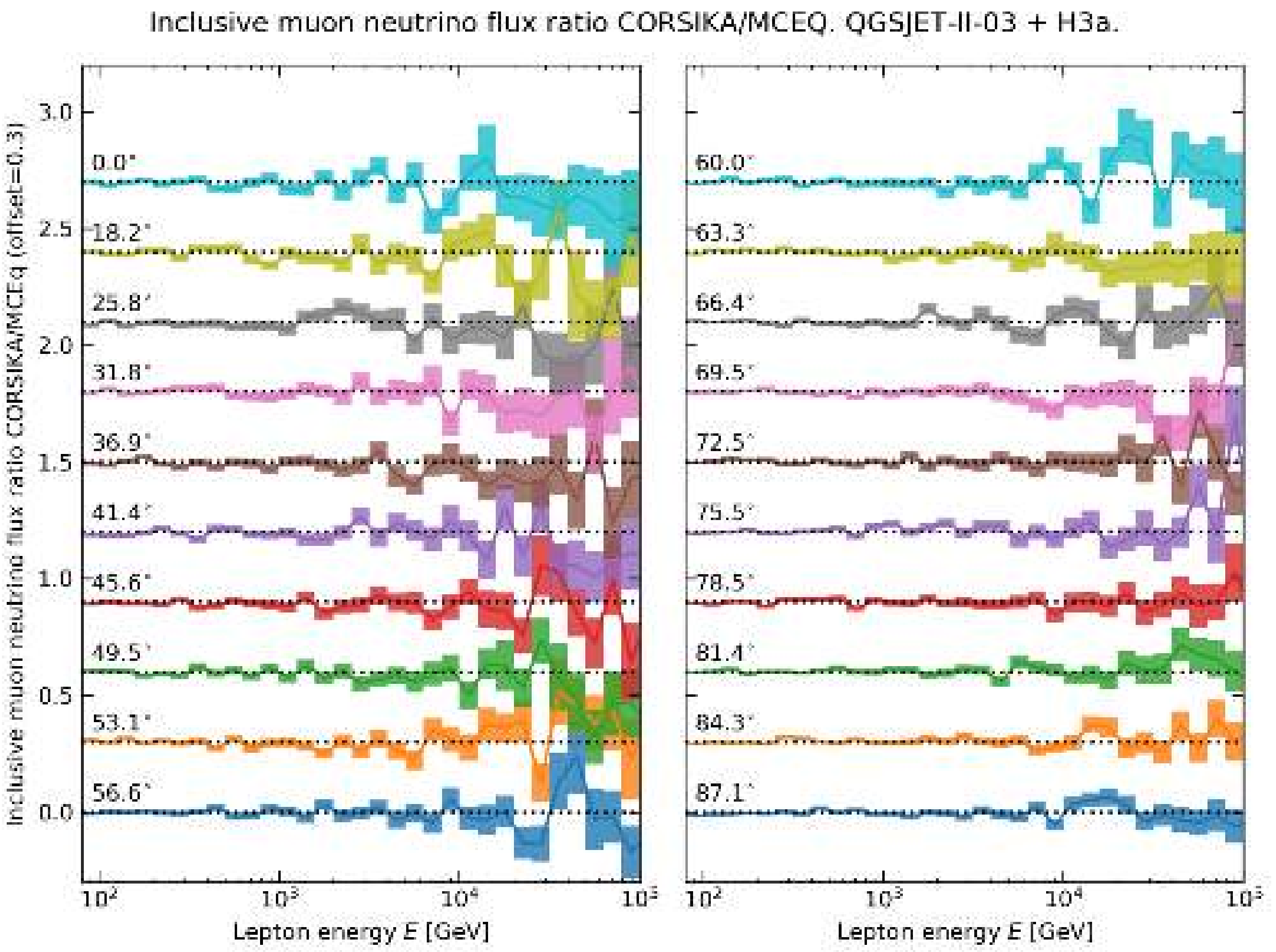


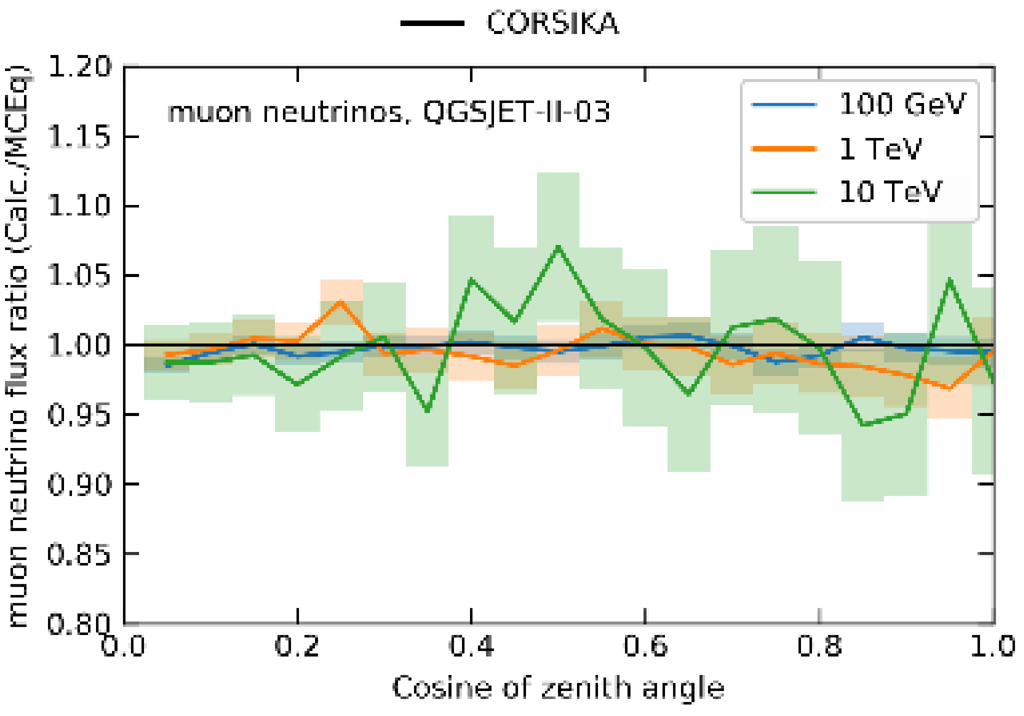
Interaction matrix C



matrices are sparse → high performance

MCEq vs (thinned) CORSIKA calculation in 1D





> BSD licensed @ https://github.com/afedynitch/MCEq

Calculation of conventional and prompt lepton fluxes at very high energy

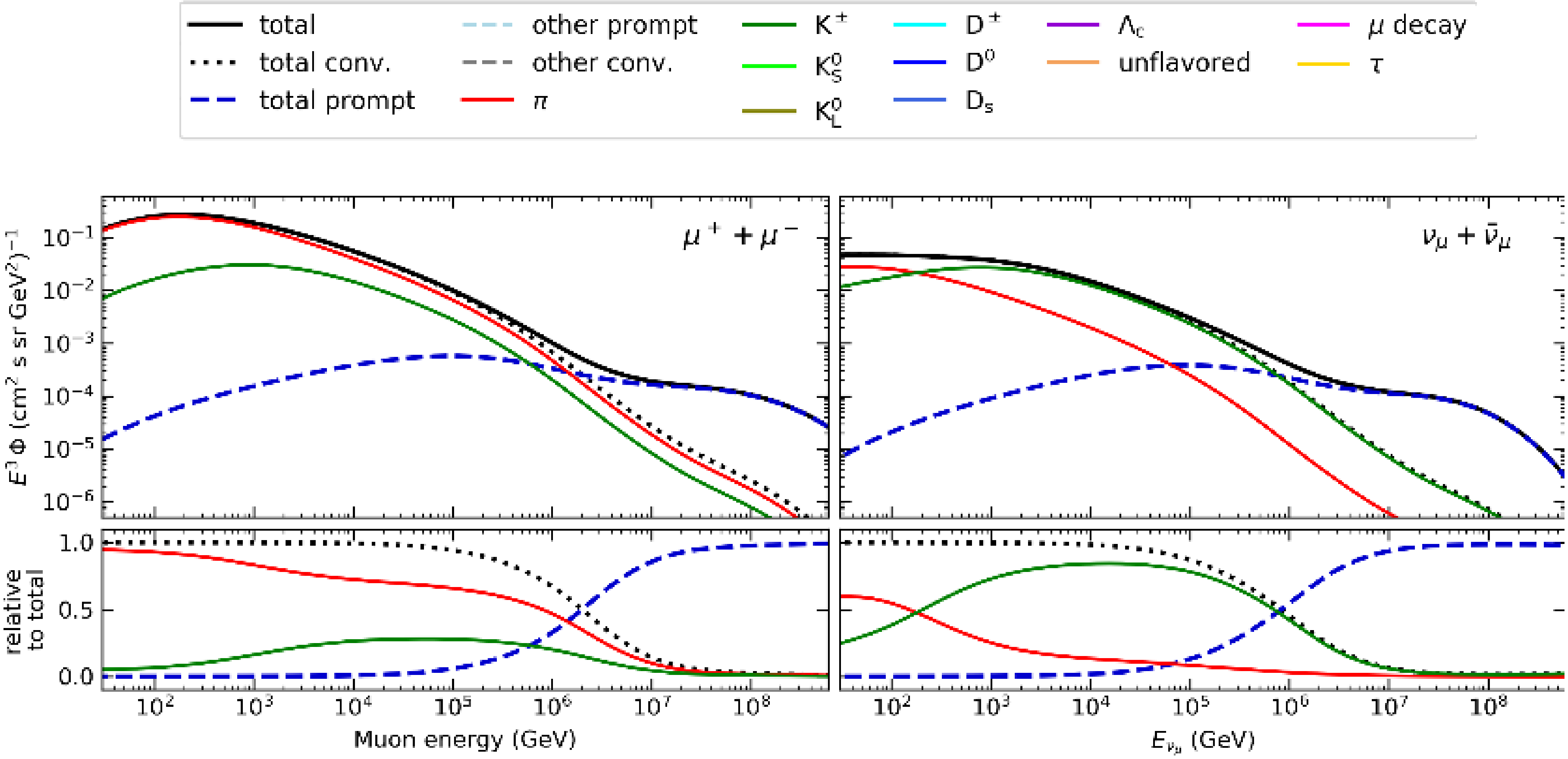
Anatoli Fedynitch (KIT, Karlsruhe and KIT, Karlsruhe, Dept. Phys. and CERN), Ralph Engel (KIT, Karlsruhe and KIT, Karlsruhe, Dept. Phys.), Thomas K. Gaisser (Delaware U., Bartol Inst.), Felix Riehn (KIT, Karlsruhe and KIT, Karlsruhe, Dept. Phys.), Todor Stanev (Delaware U., Bartol Inst.) (Mar 2, 2015)

Published in: EPJ Web Conf. 99 (2015) 08001 • Contribution to: ISVHECRI 2014 • e-Print: 1503.00544 [hep-ph]

pdf DOI cite 85 citations

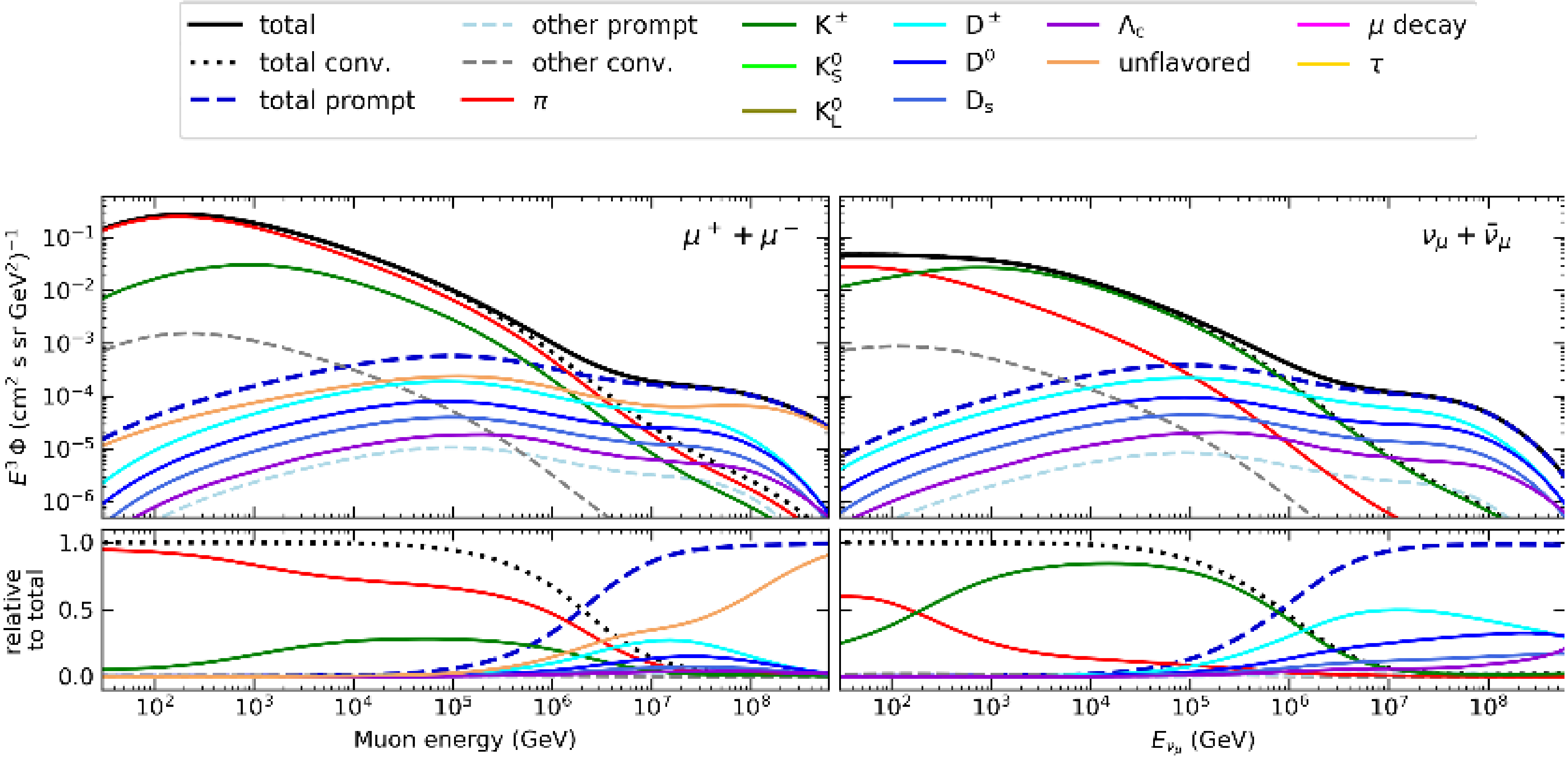
CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: Full code paper, AF, R. Engel, in prep.

Hadrons contributing to muonic leptons



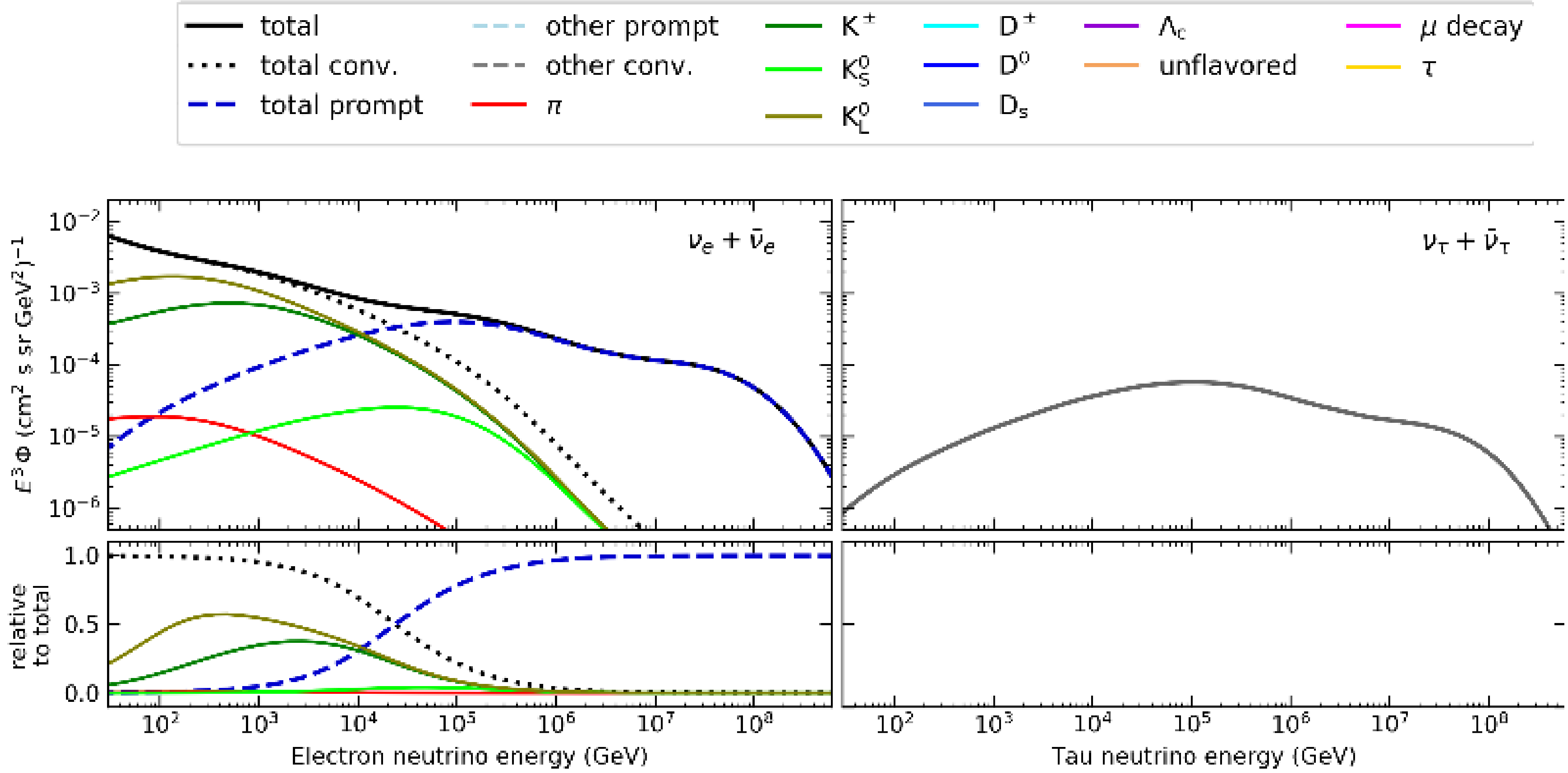
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

Hadrons contributing to muonic leptons



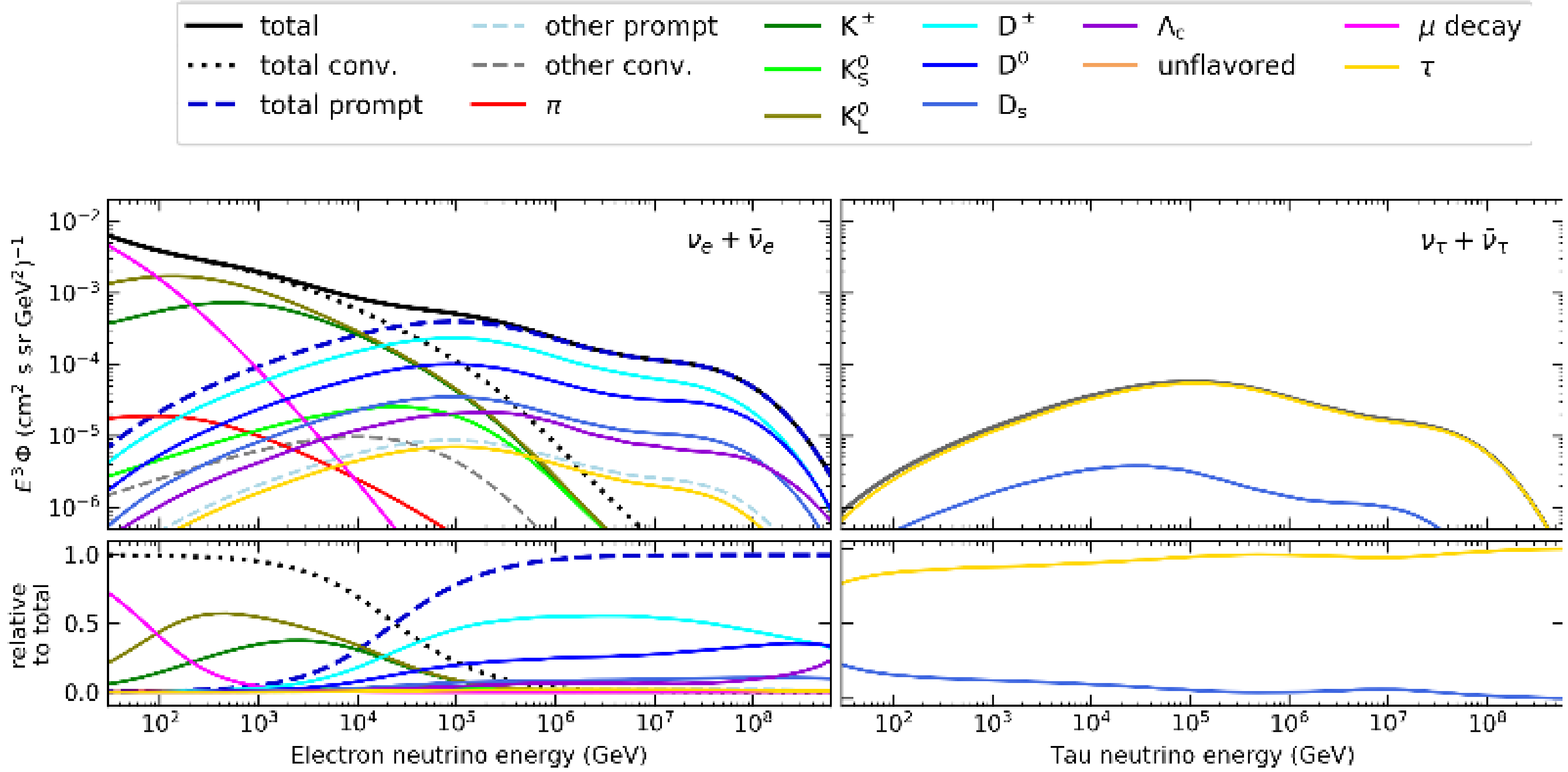
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

Hadrons contributing to electron and tau neutrinos



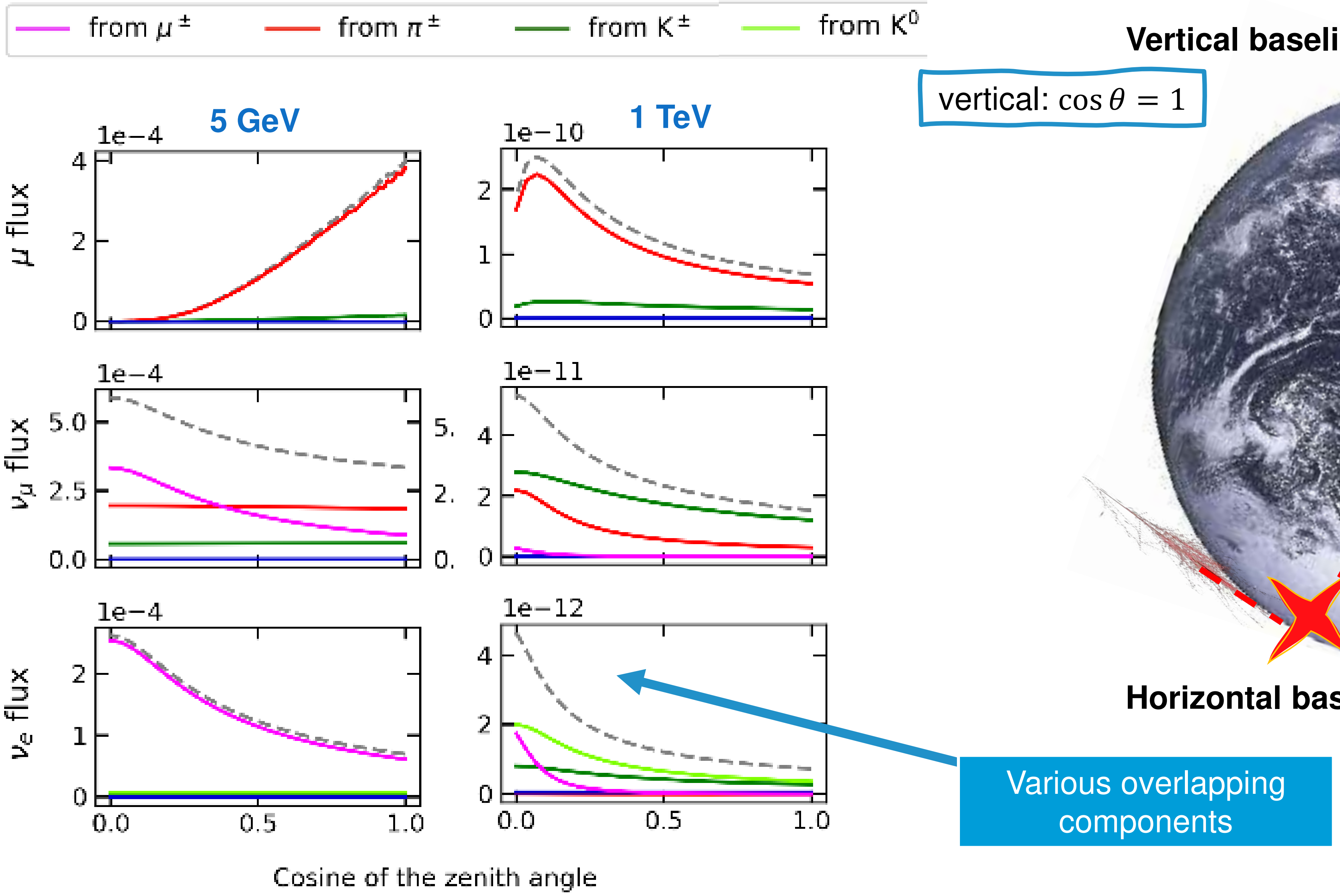
AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

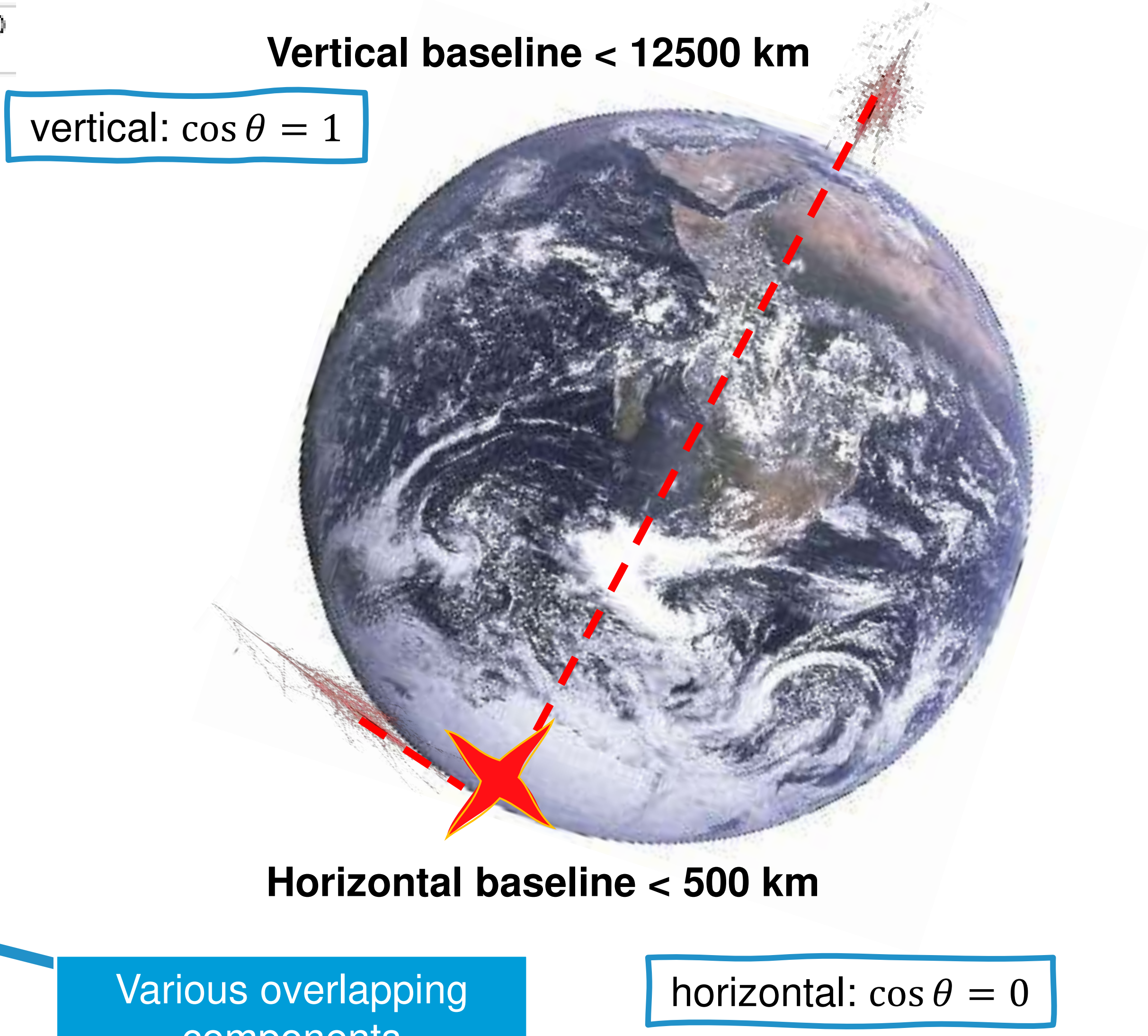
Hadrons contributing to electron and tau neutrinos



AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

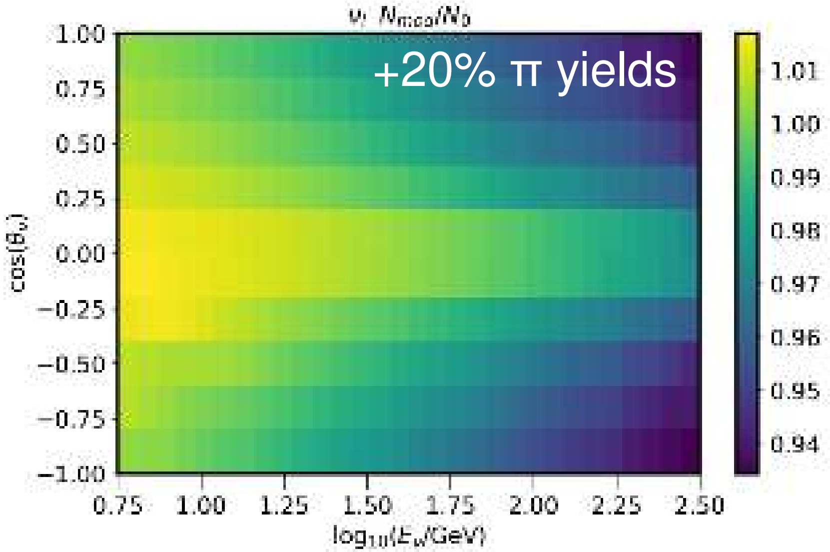
Hadronic components give shape to zenith distribution



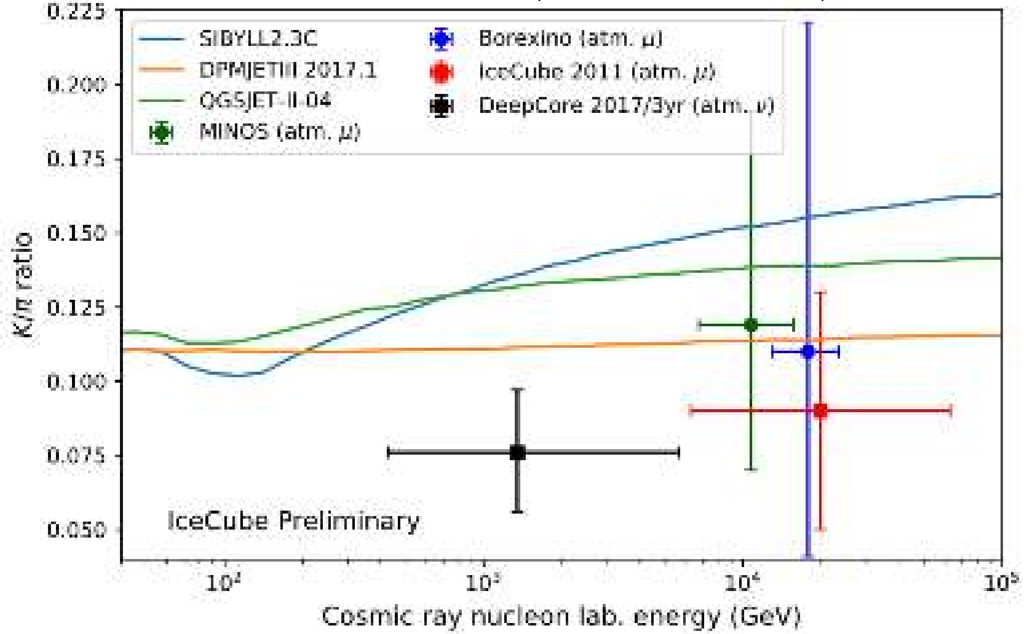


AF, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, PRD 100 2019

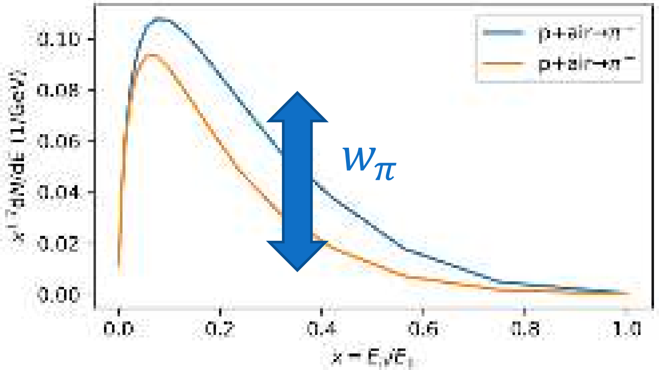
Use zenith distribution to measure K/pi ratio with IceCube

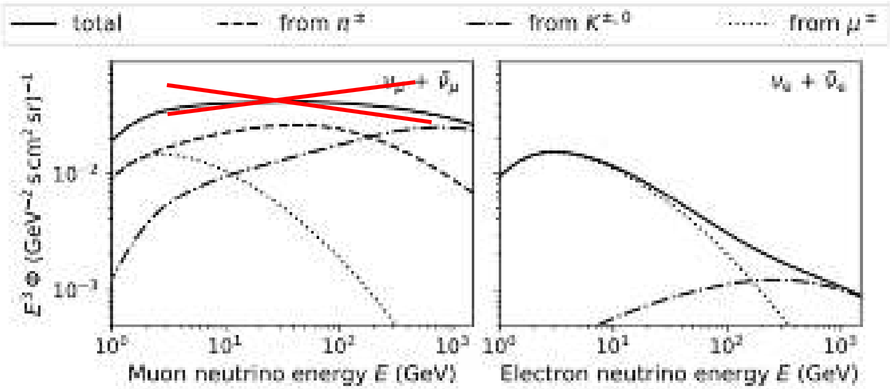


AF, JP Yanez (IceCube Collaboration), ICRC 2019



Variation of particle production yield modifies spectrum and angular distribution

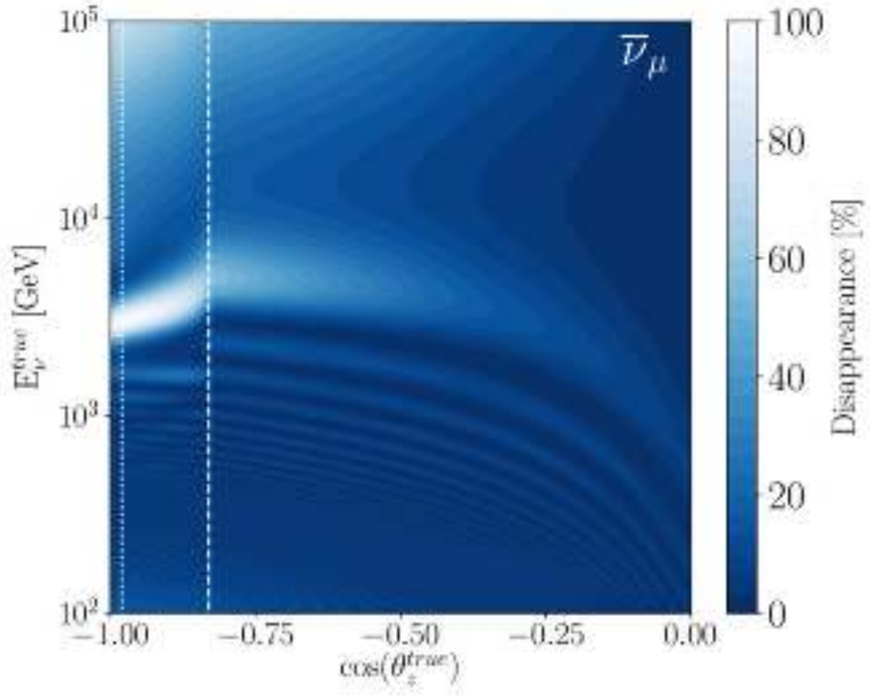




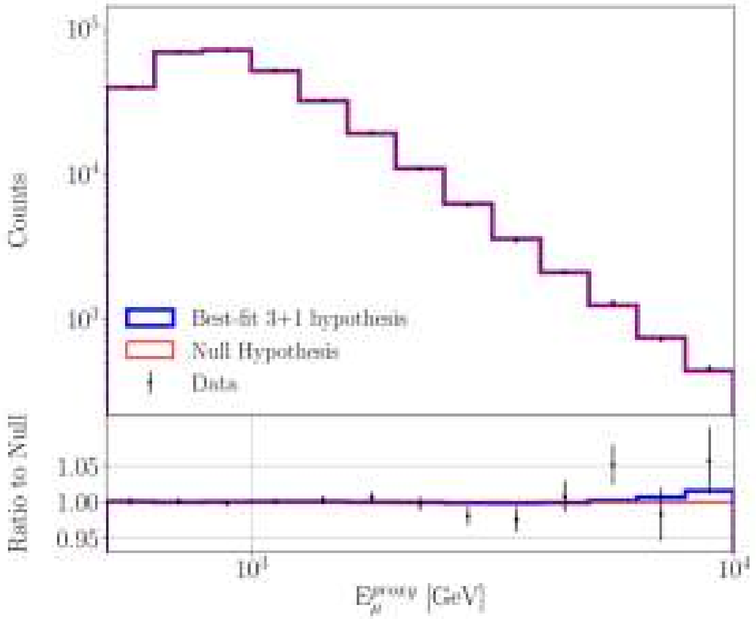
- DeepCore < **Energy** < IceCube
- Bias from mis-reconstruction
- Will repeat with new MC and 7yr data sample

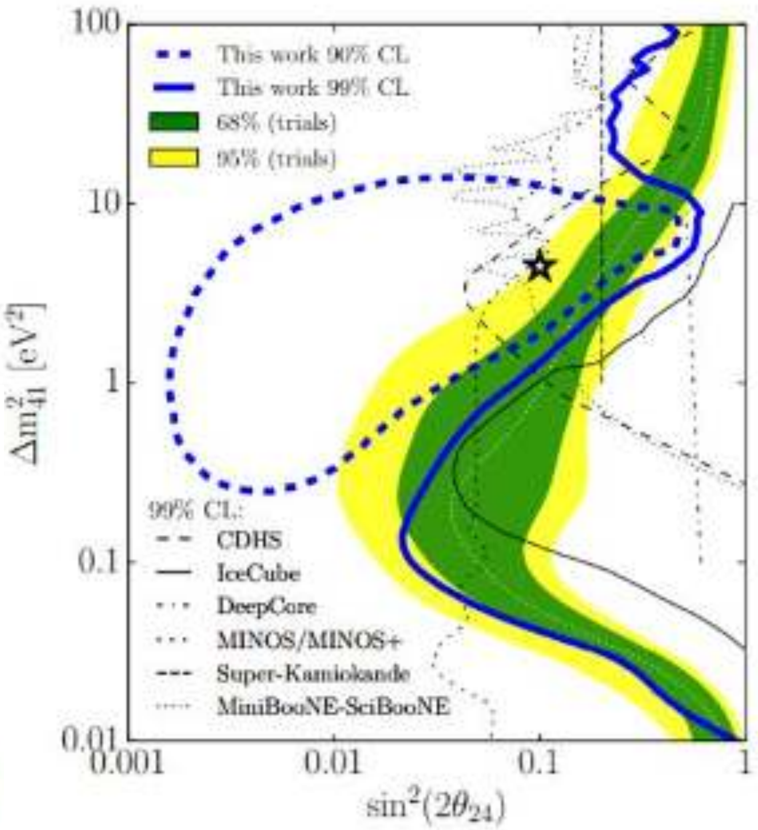
Recent IceCube result on 3+1 sterile neutrinos

IceCube, PRL 125, 2020



Muon-antineutrino disappearance oscillogram for best-fit parameters



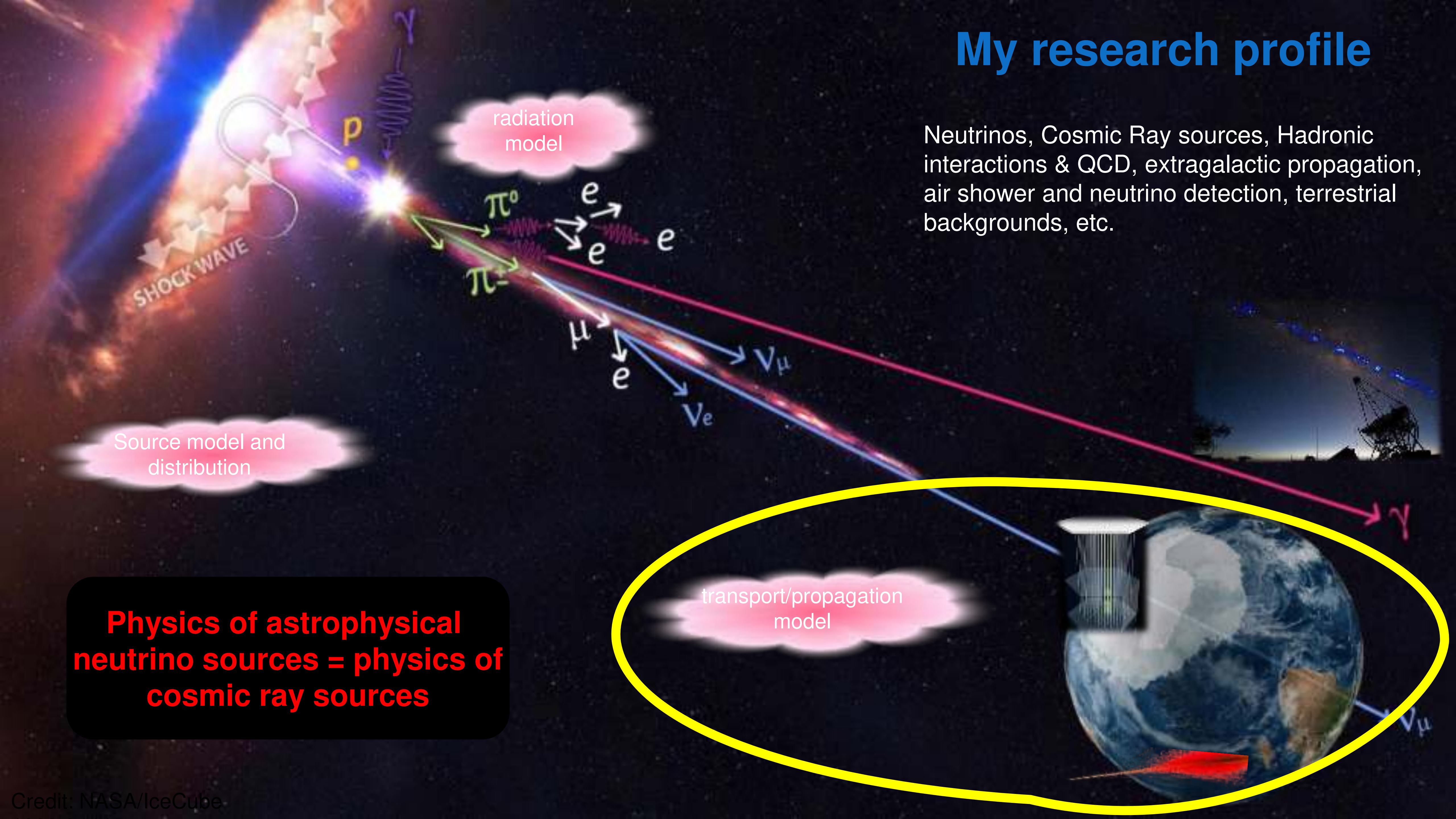


Consistent with null hypothesis

MCEq became de-factor baseline tool in IceCube

My research profile

Neutrinos, Cosmic Ray sources, Hadronic interactions & QCD, extragalactic propagation, air shower and neutrino detection, terrestrial backgrounds, etc.

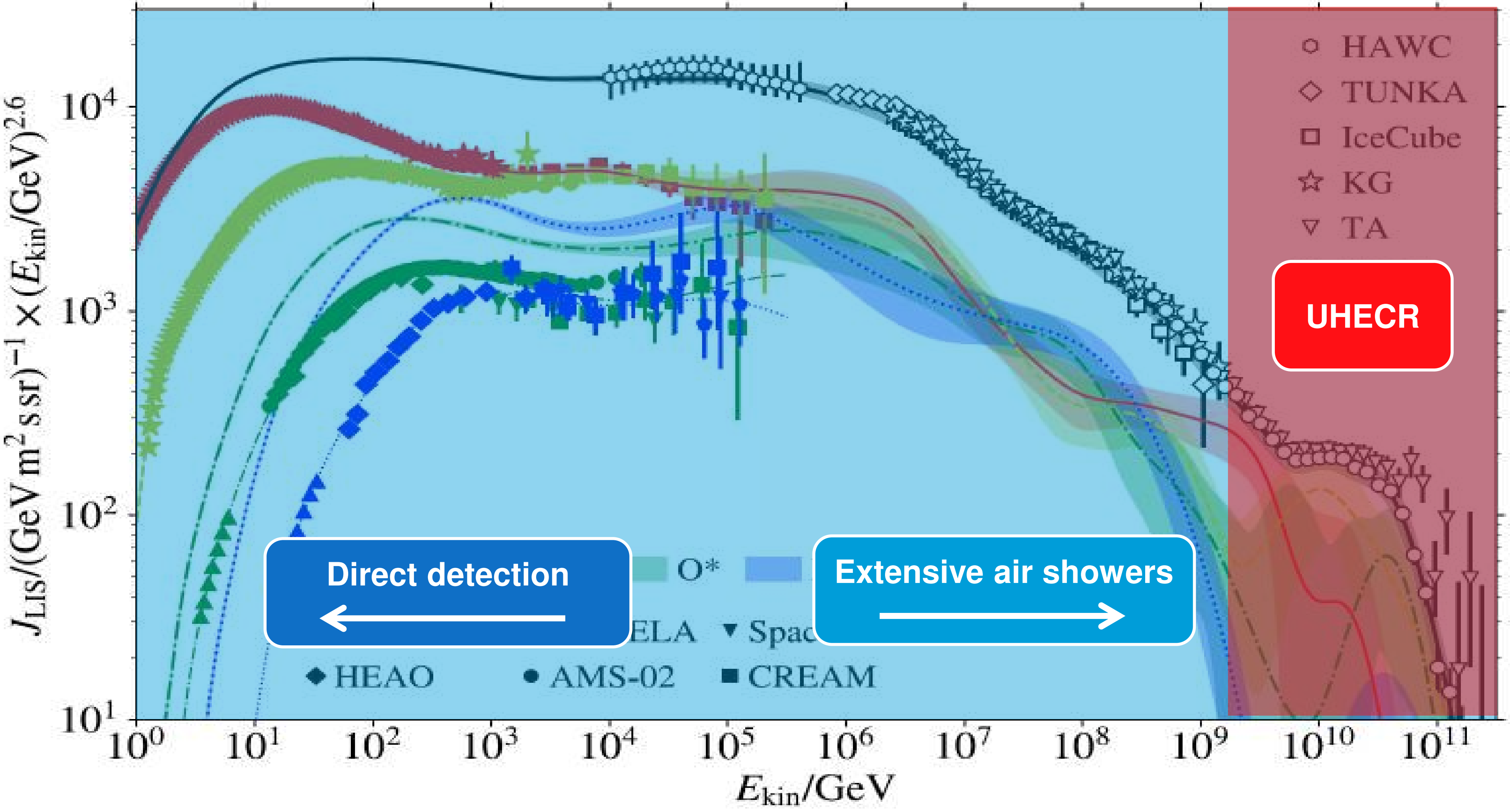


Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube

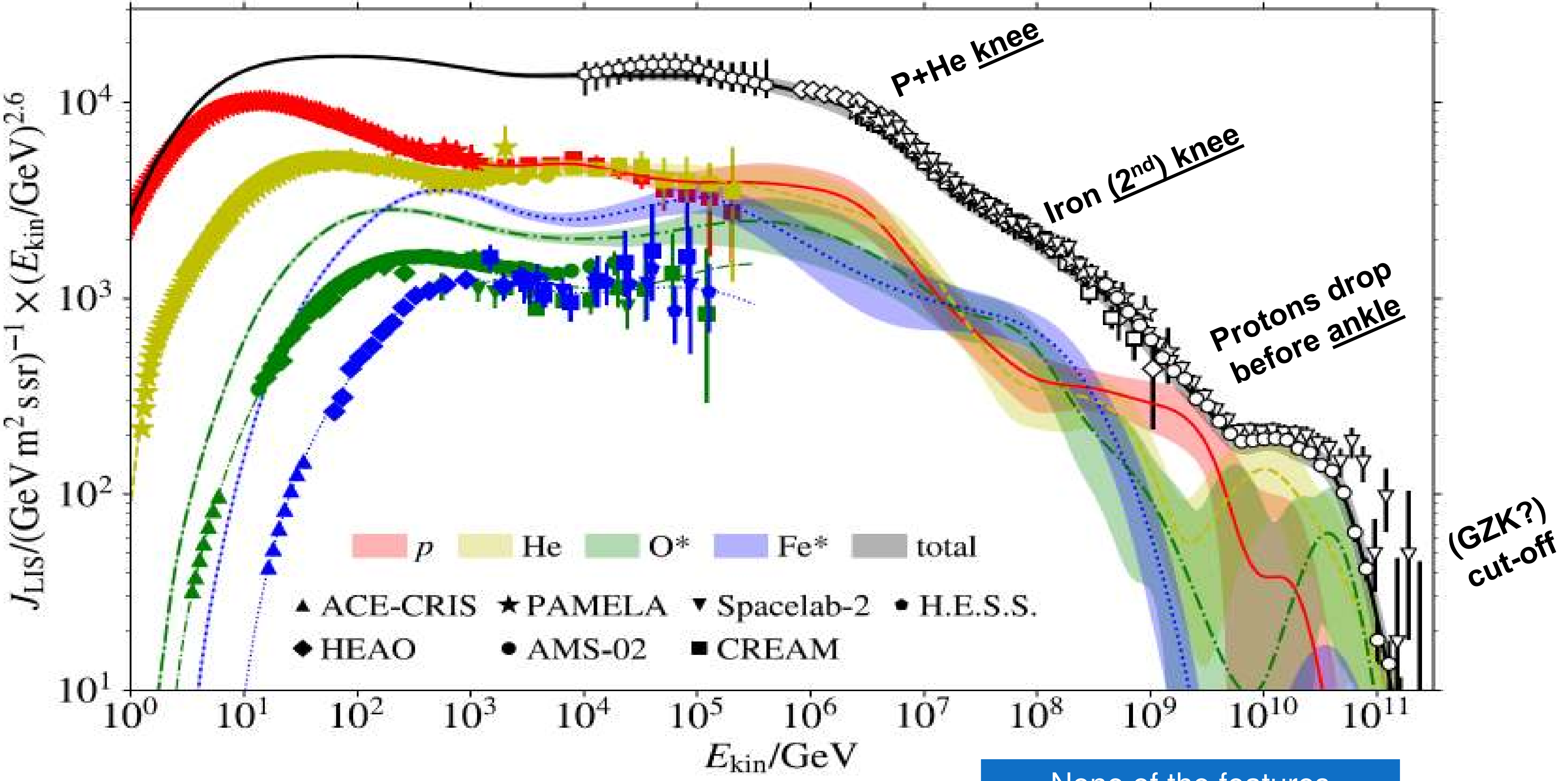
Cosmic Ray observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



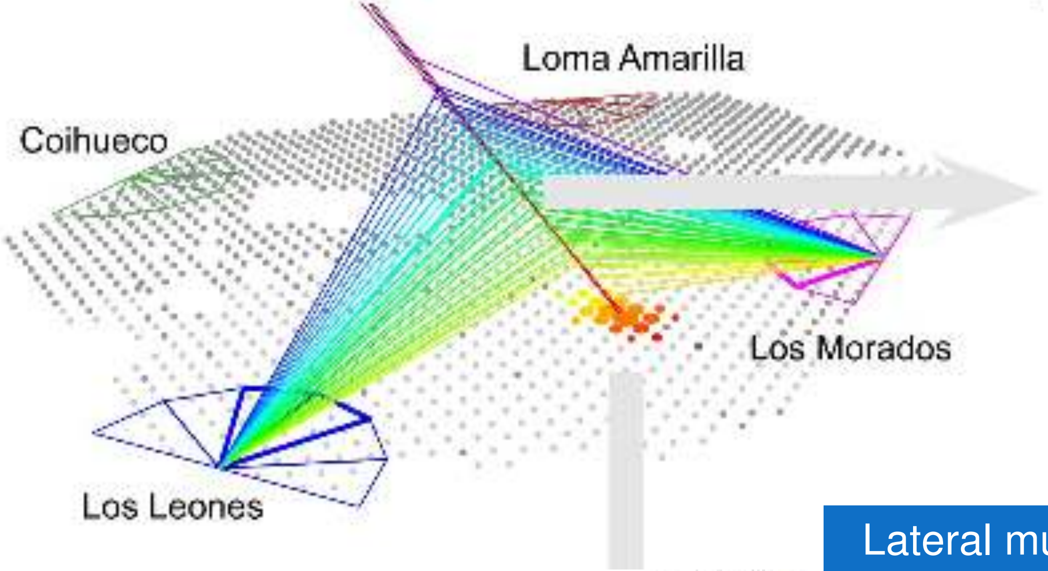
Cosmic Ray observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.



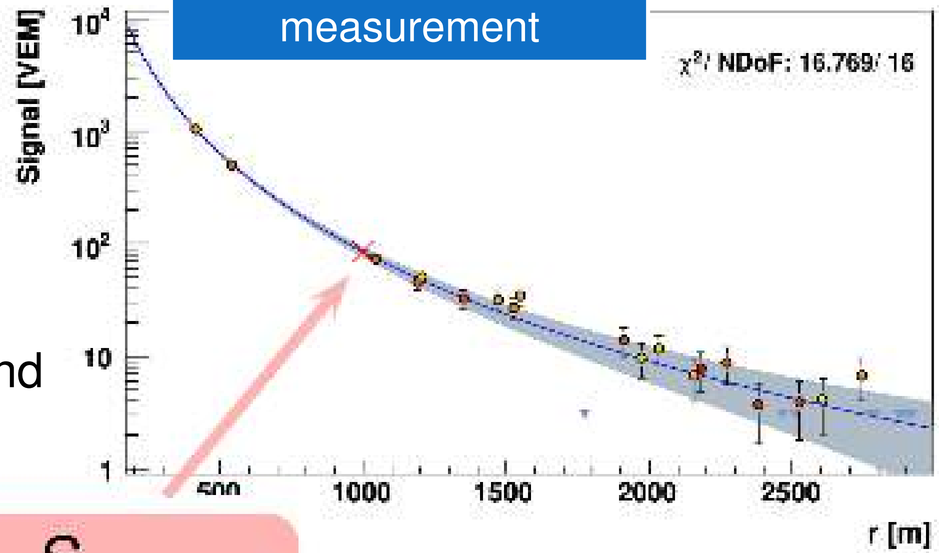
None of the features unambiguously explained!

Hybrid air shower detection @ Pierre Auger (&Telescope Array)



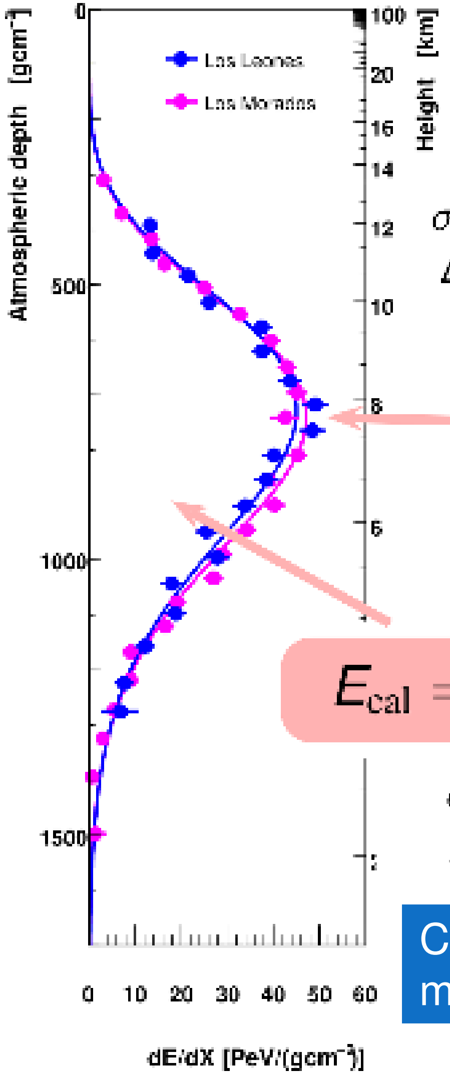
1. Energy
2. Xmax
3. Direction
4. Distribution of muons at ground
5. +More complex observables

Lateral muon density measurement



S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



$\sigma X_{\mathrm{max}} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

X_{max}

$E_{\mathrm{cal}} = \int \frac{dE}{dX}\, dX$

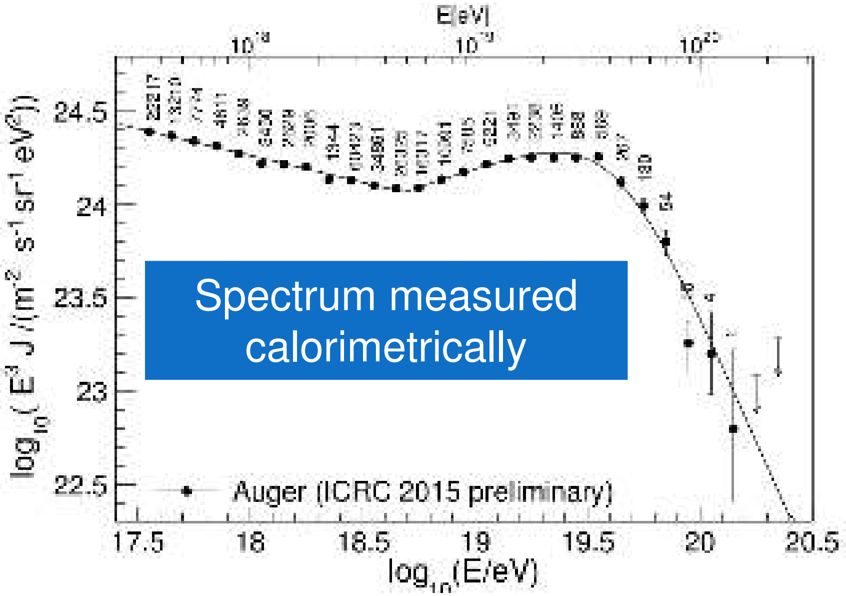
$\sigma_E / E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

Calorimetric energy measurement

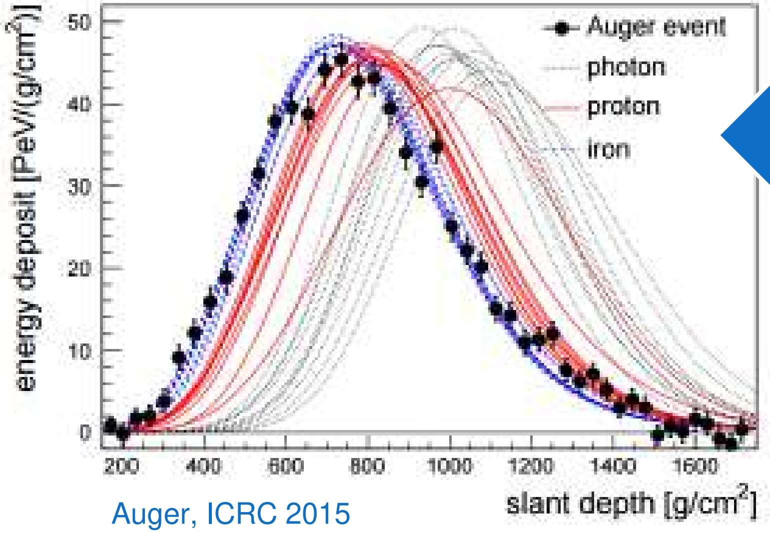
M. Unger, ICRC2017

UHECR composition

Data



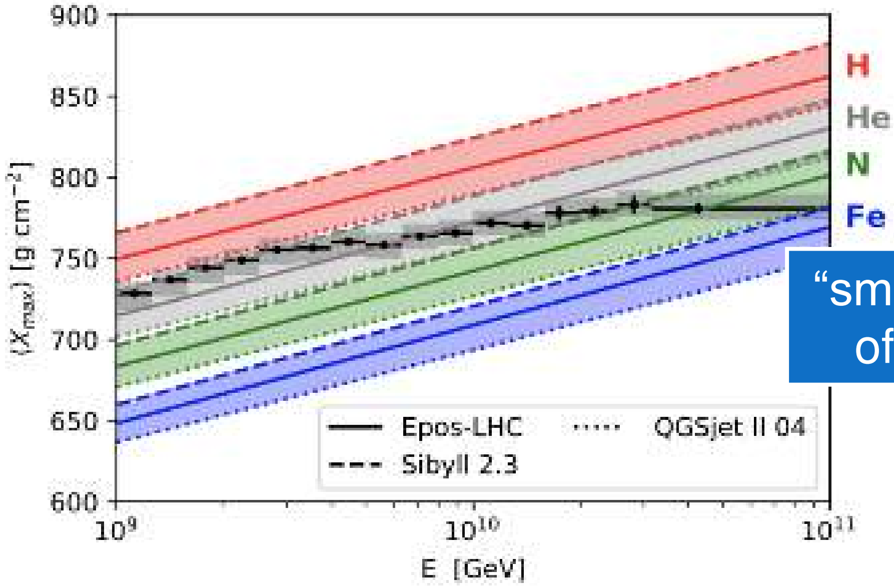
Spectrum measured calorimetrically



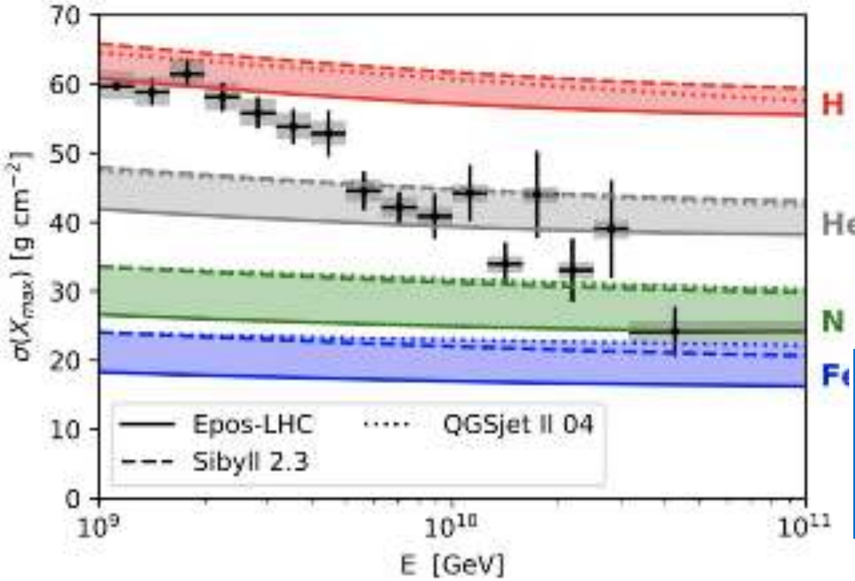
Auger, ICRC 2015

UHECR are nuclei(?)

Model territory



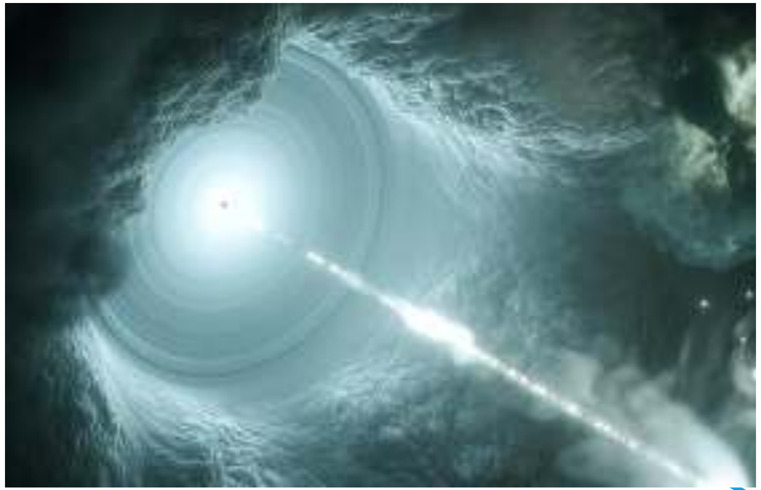
"smooth" increase of mean mass



Decreasing fluctuations → mixture masses

Origin of the features in UHECR spectrum and composition?

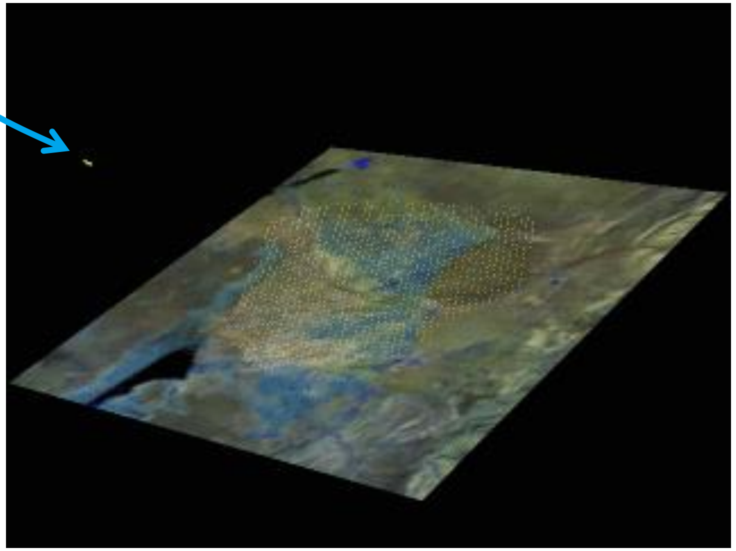
Generic accelerator



Assume that there is **one dominant type** of UHECR accelerators

Simulate transport of cosmic rays through extragalactic medium

Interpret Pierre Auger data



Heinze, AF, Boncioli, Winter, ApJ 873

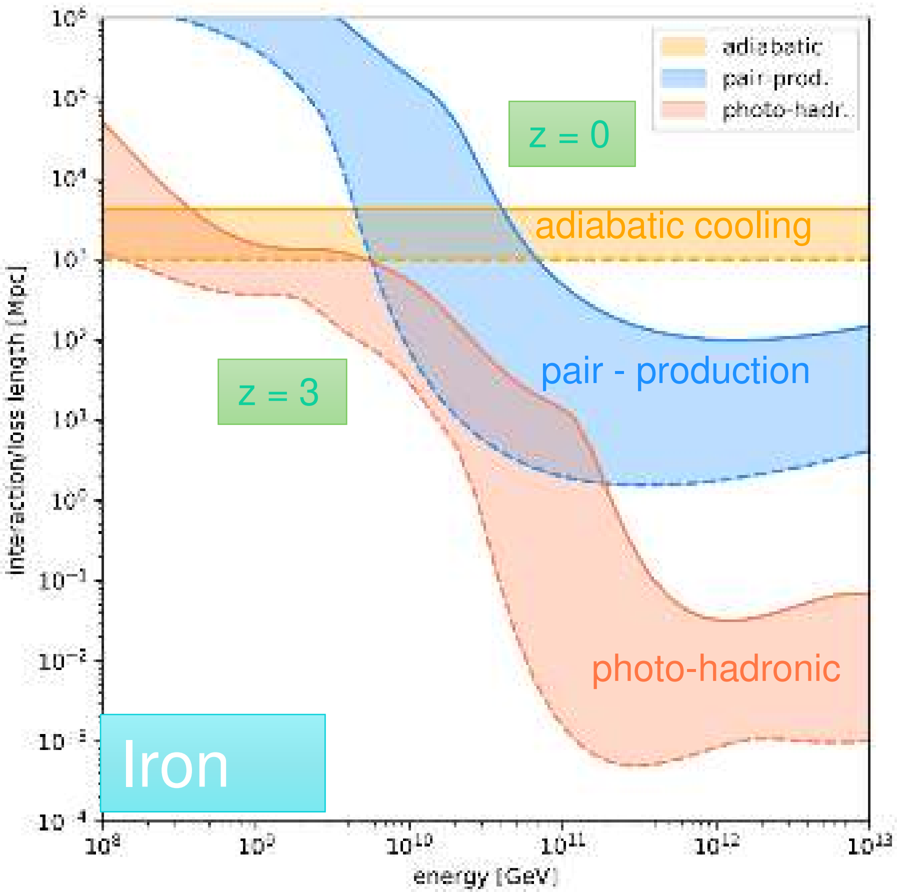
Extragalactic transport of UHECR

$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

comoving particle density | adiabatic cooling | pair - production | photo-nuclear | Injection

- Initial injection of **nuclei up to iron**
- Disintegration (Giant Dipole Resonance + photo-meson production)
- About 50 species × size of E-grid (~150) coupled partial differential equations (~8000)
- All coefficients **time and energy dependent**

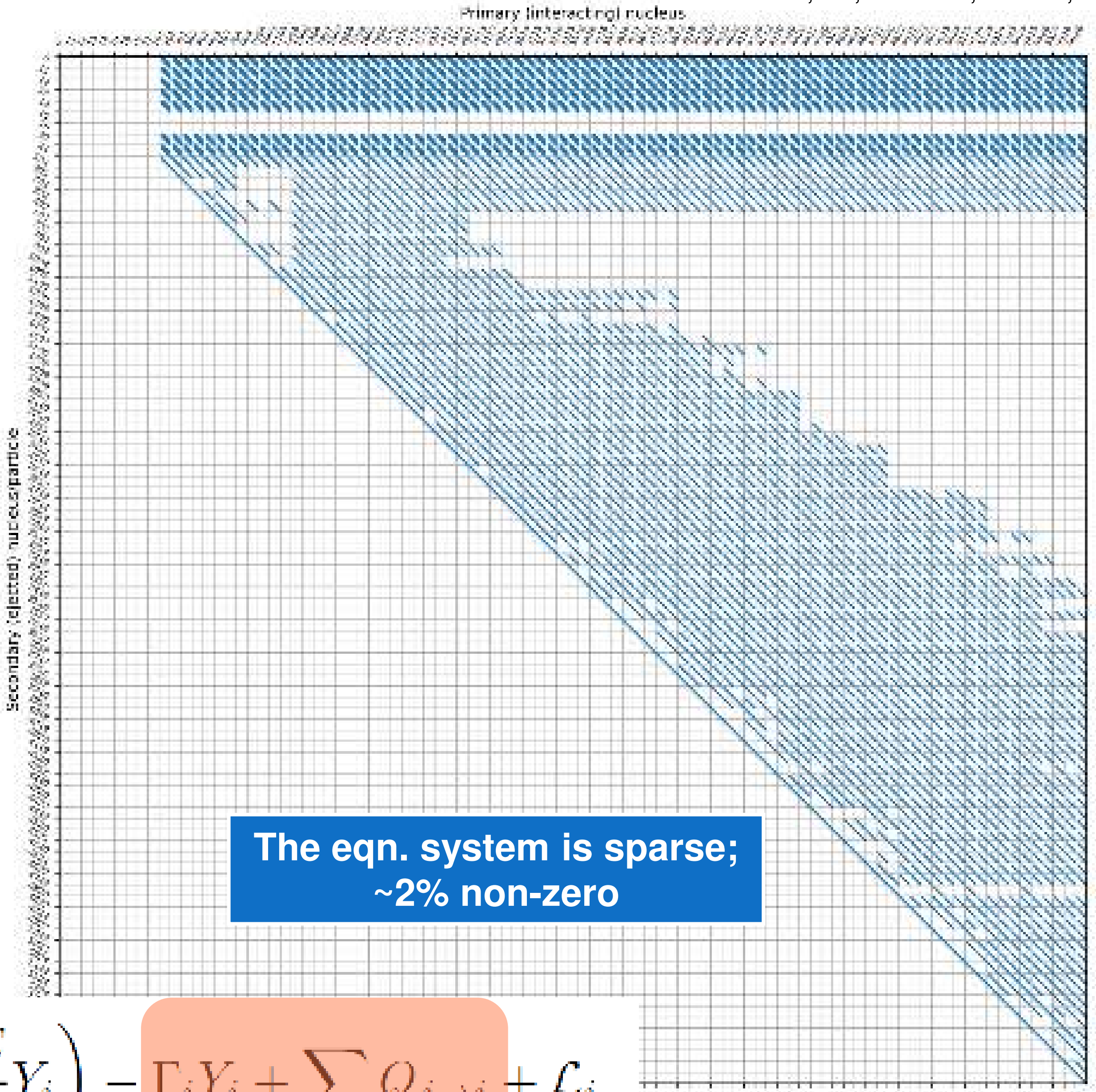
New code: *(with Jonas Heinze)*
PriNCe = Propagation including Nuclear Cascade equations



Heinze, AF, Boncioli, Winter, ApJ 873

Propagation Code - PriNCe

- Pure **Python** + **Numpy, Scipy, Intel MKL**
- Computational acceleration through **vectorization**/parallelization & **sparse matrix** formats
- **20s – 40s** for one complete calculation (depending on number of nuclear species)
- **More efficient** for studies of model uncertainties **than Monte Carlo** (cross-section, photon fields etc.)
- Another factor 10 speed feasible, larger systems (spatial coordinate), GPUs



The eqn. system is sparse; ~2% non-zero

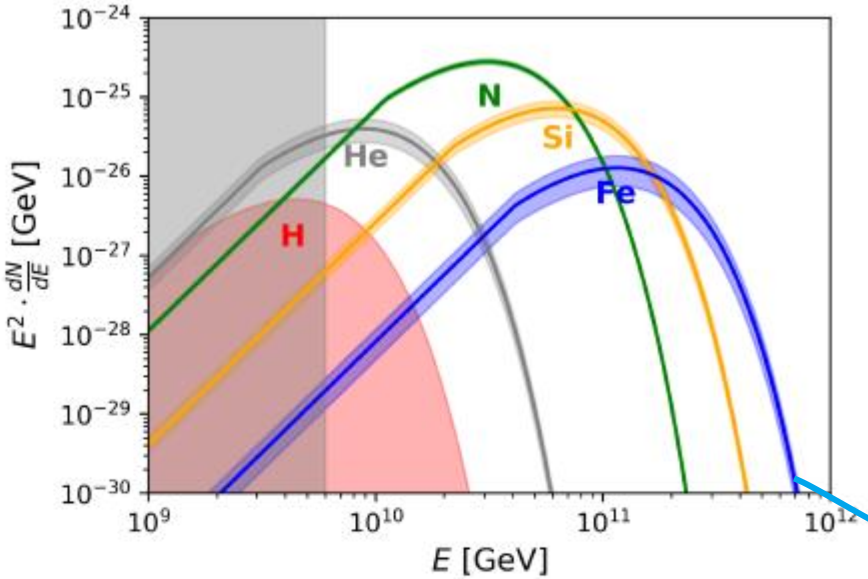
$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

photo-nuclear

Heinze, AF, Boncioli, Winter, ApJ 873

Origin of the features in UHECR spectrum and composition?

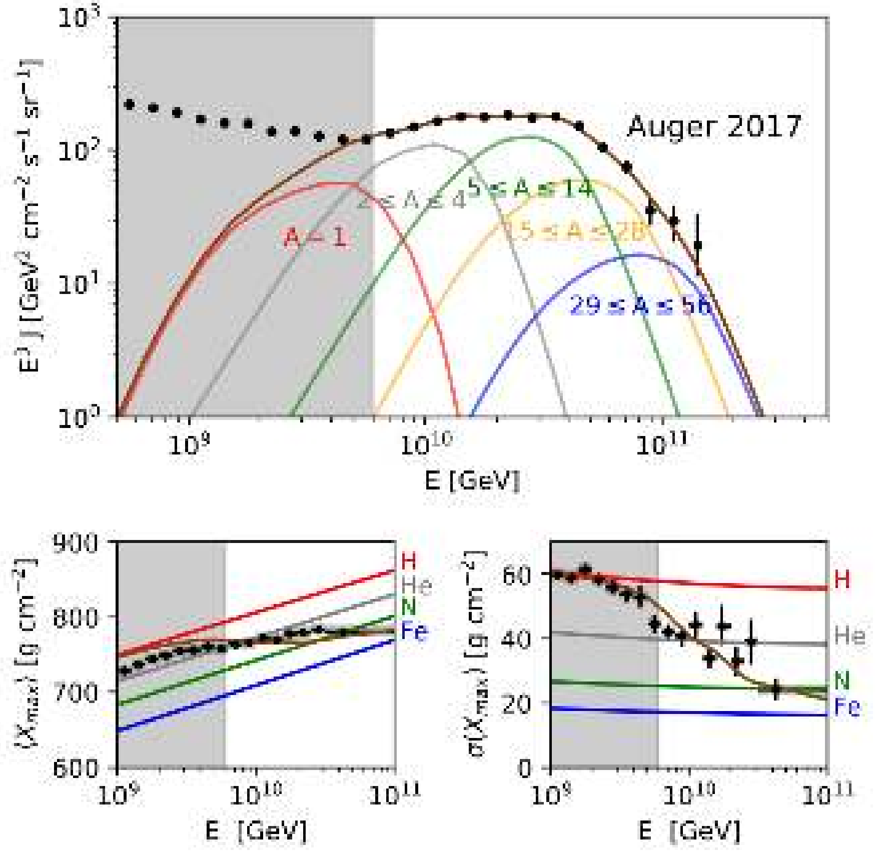
Rigidity dependent accelerator



Assumption: there is one dominant source type, accelerating nuclei according to their rigidity (~Z)

Simulate transport of cosmic rays through extragalactic medium

Fit: free parameters of the accelerator and the evolution m



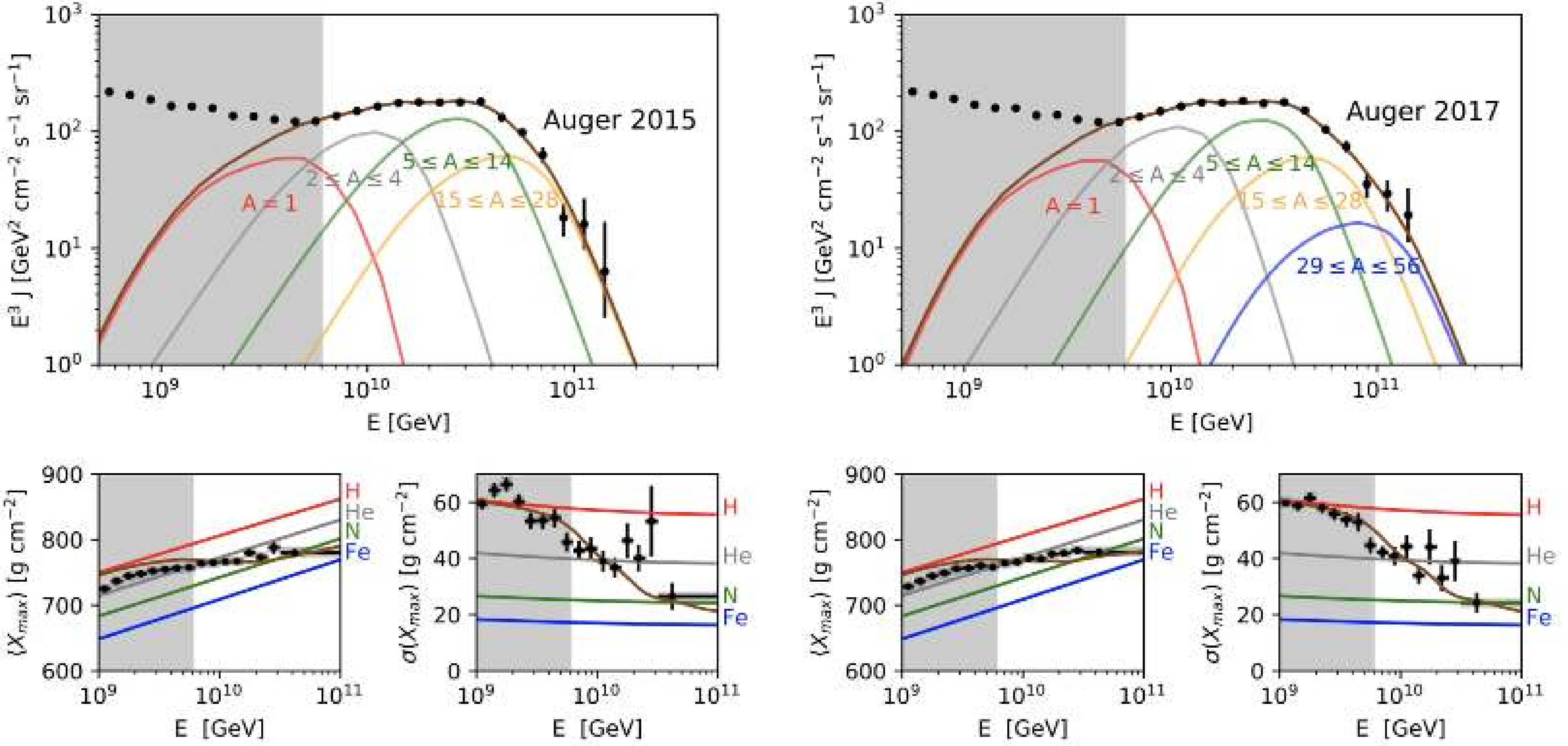
Spectrum:

$$J_A(E) = \mathcal{J}_A \left(\frac{E}{10^9 \text{ GeV}} \right)^{-\gamma} \times f_{\text{cut}}(E, Z_A, R_{\text{max}}) \times n_{\text{evol}}(z)$$

Cosmological density evolution: $n_{\text{evol}}(z) = (1 + z)^m$

Heinze, AF, Boncioli, Winter, ApJ 873

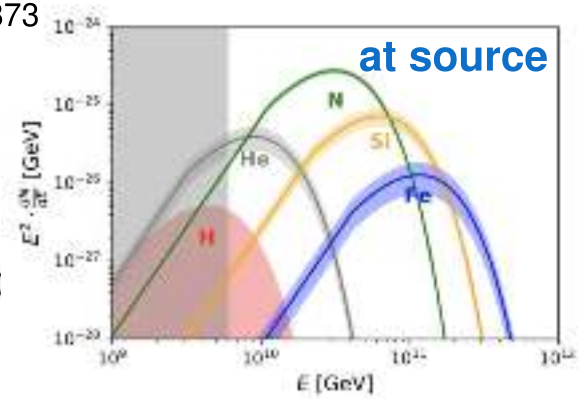
Impact of "more data" on the fit

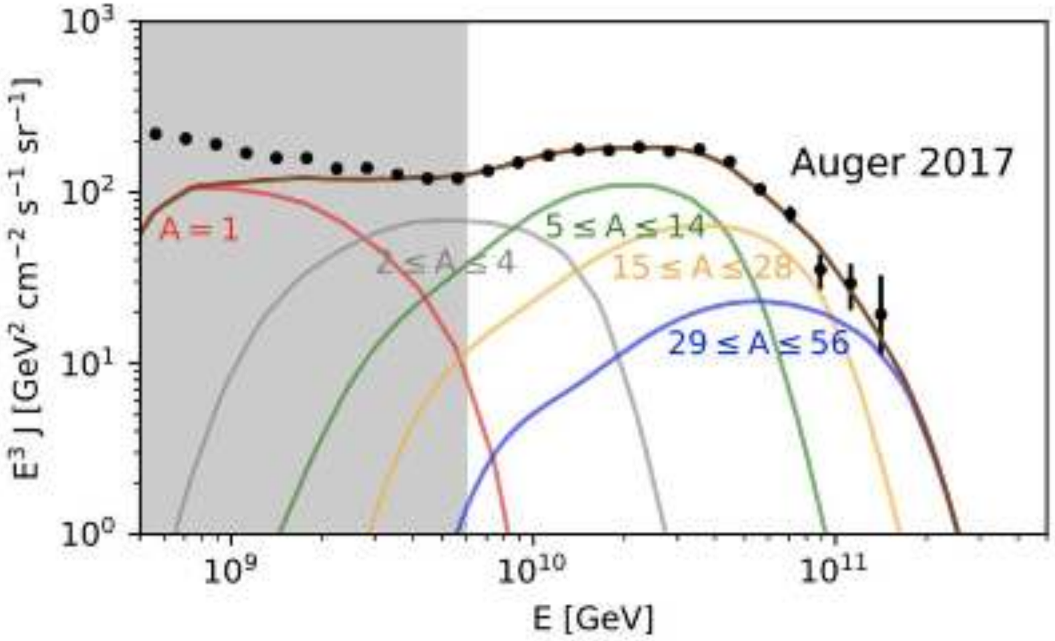


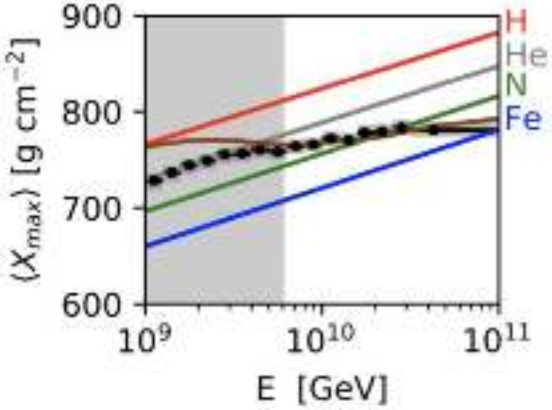
Fit conditions identical to Auger's "Combined Fit" (JCAP04(2017)038), i.e. flat evolution (m=0)

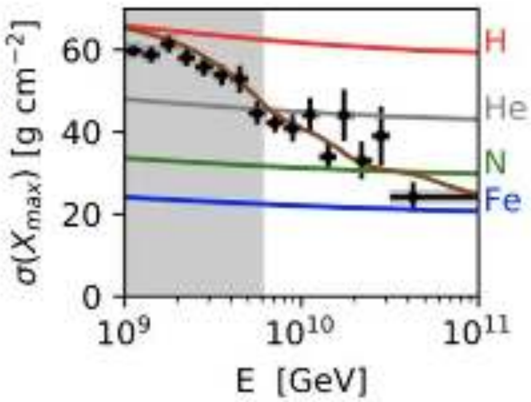
Best ‘3D’ fit

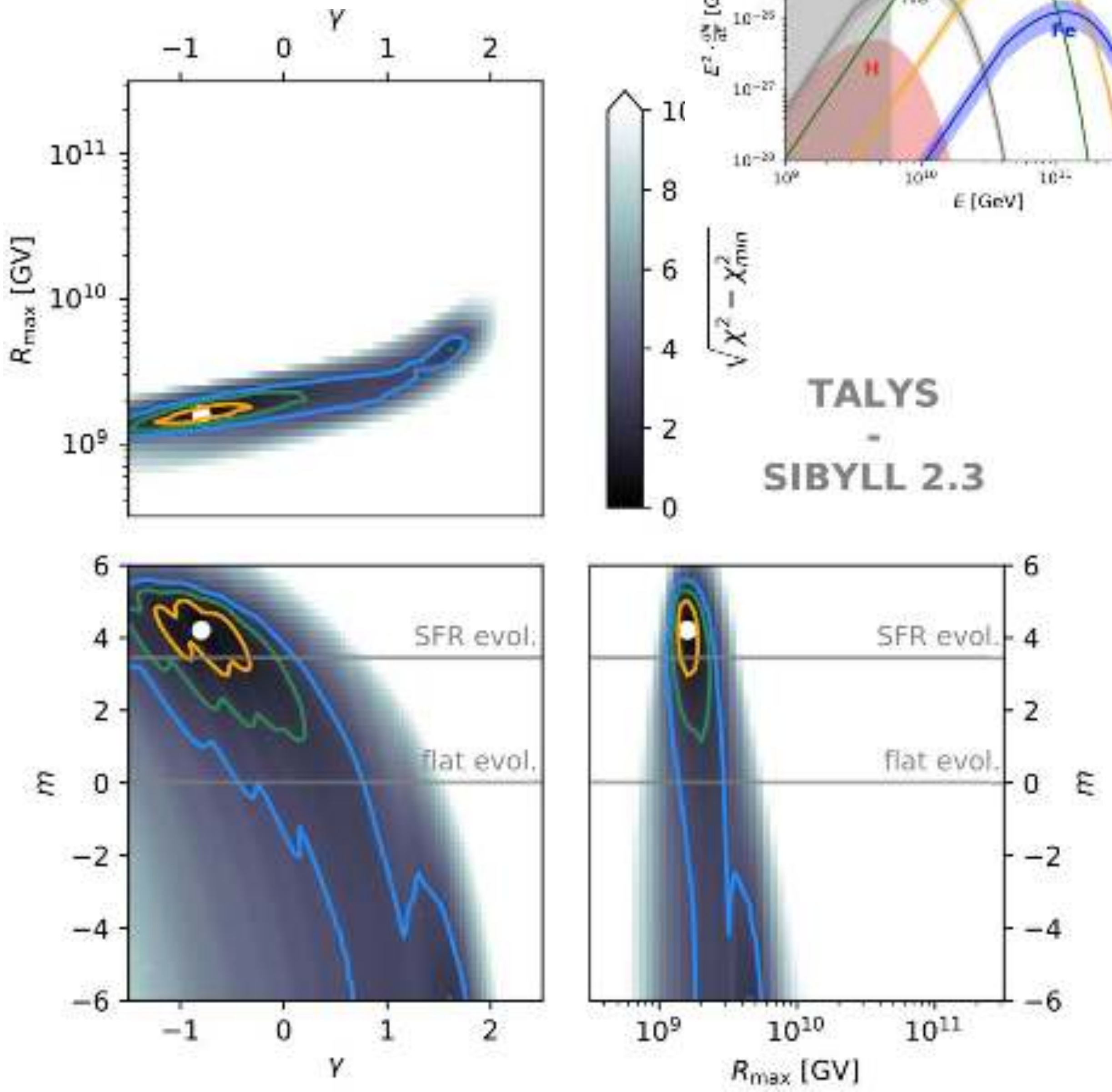
Heinze, AF, Boncioli, Winter, ApJ 873









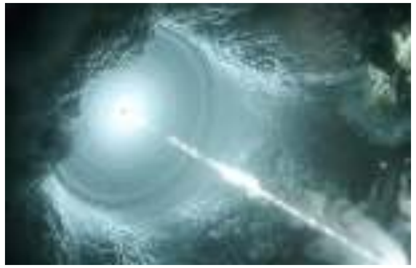


Heinze, AF, Boncioli, Winter, ApJ 873

Model dependence of the interpretation

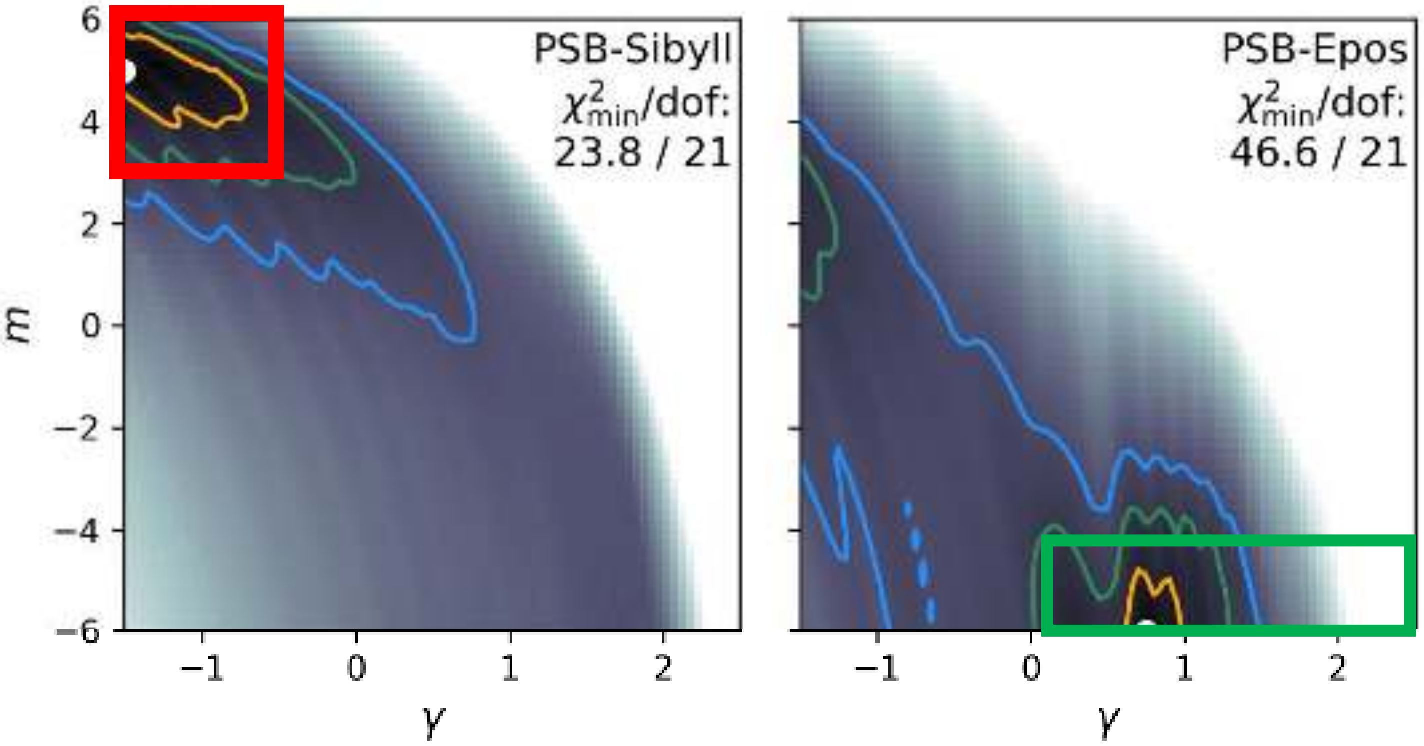
Compared in $\gamma - m$ space

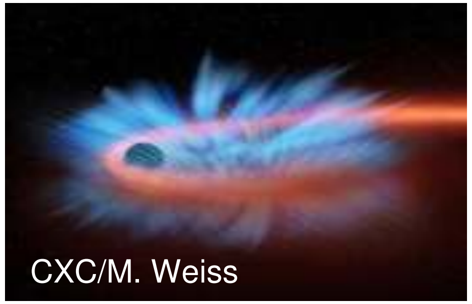
Density evolves like: Stars, Galaxies, Supernovae, AGN



Sibyll 2.3

Epos-LHC





Few strong local sources, or intermediate mass black holes

Auger Upgrade may improve the situation within few years.

See also: Auger Collaboration JCAP02(2013)026
Auger Collaboration JCAP04(2017)038

Model dependence of the interpretation

Compared in $\gamma - m$ space

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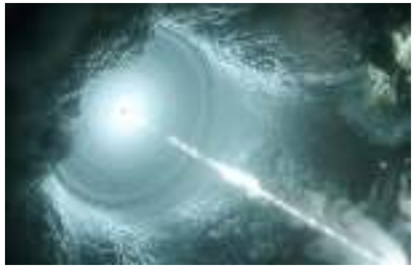
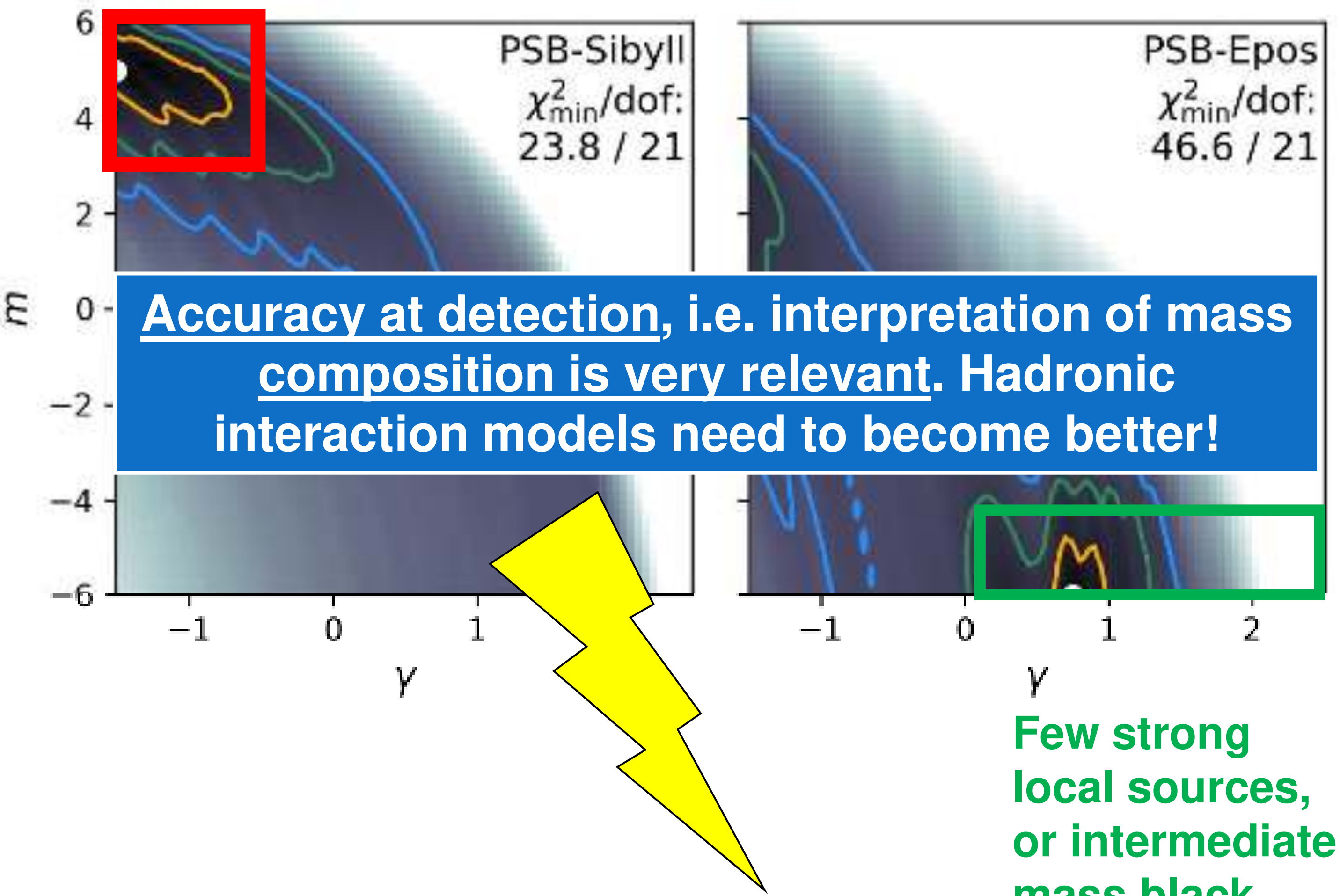
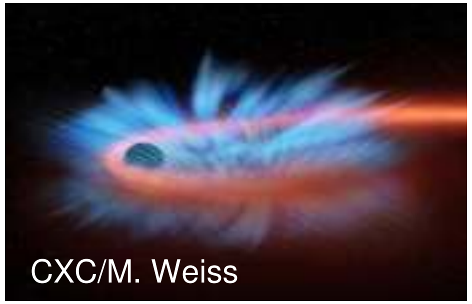


Sibyll 2.3 **Epos-LHC**



Accuracy at detection, i.e. interpretation of mass composition is very relevant. Hadronic interaction models need to become better!



Few strong local sources, or intermediate mass black holes

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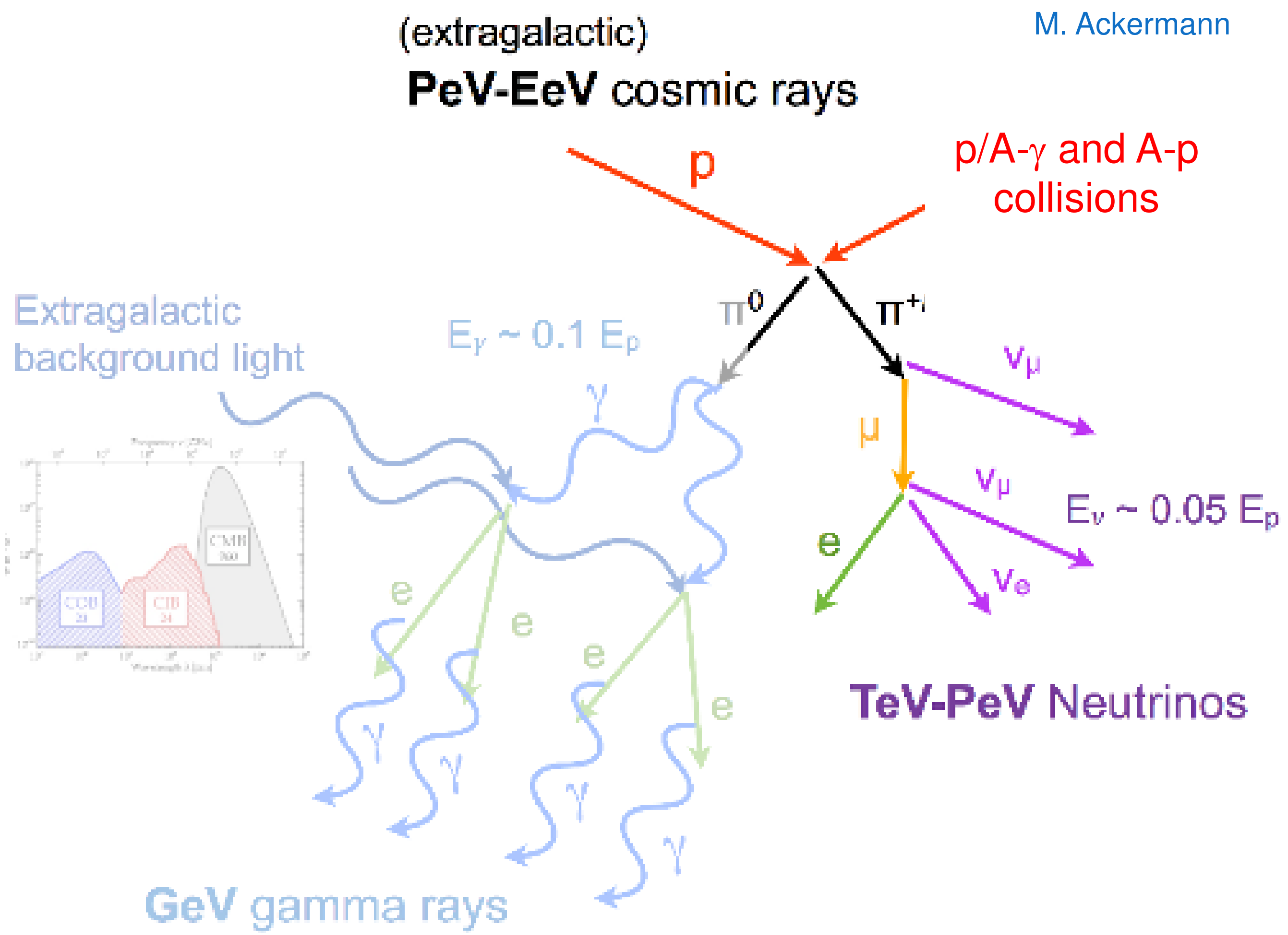
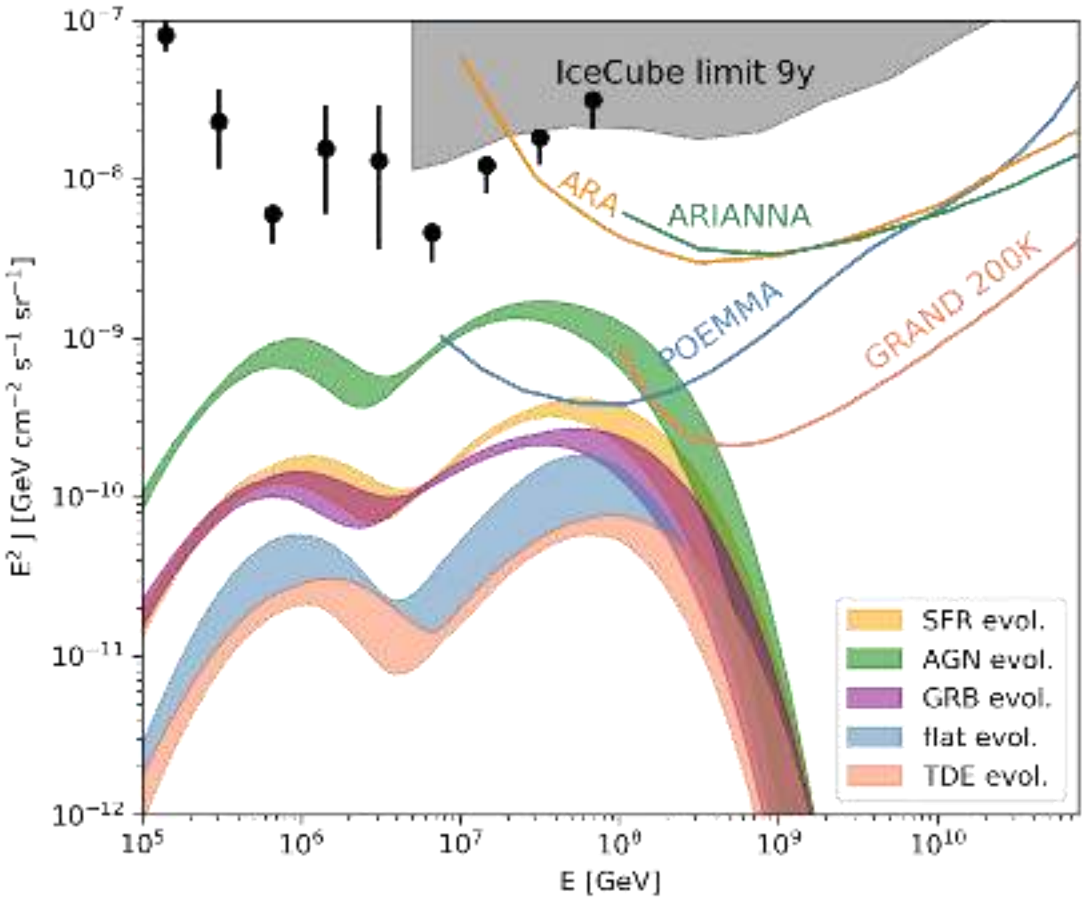
Auger Collaboration JCAP04(2017)038

Heinze, AF, Boncioli, Winter, ApJ 873

Additional multi-messenger constraints on UHECR sources?

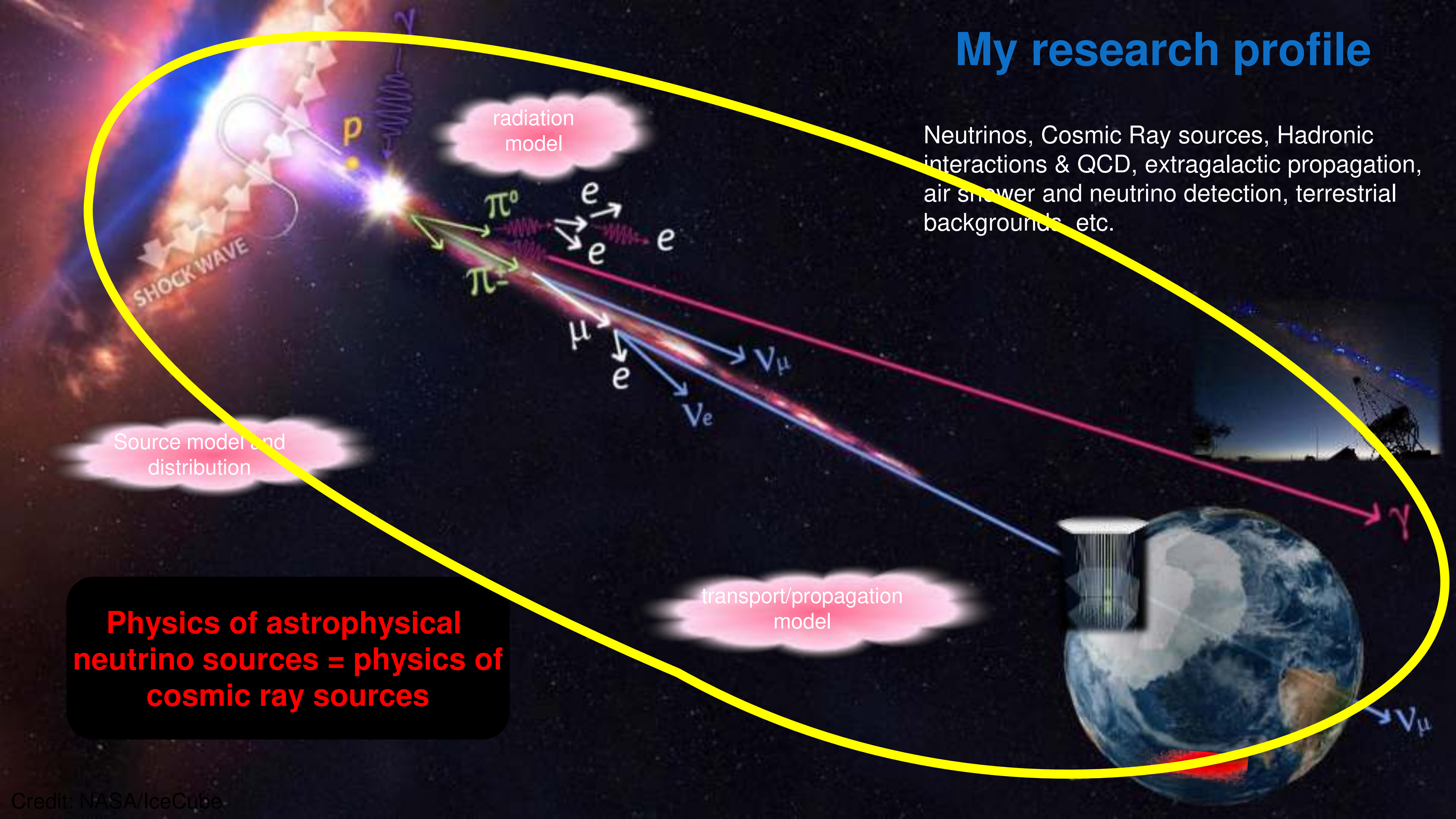
M. Ackermann





My research profile

Neutrinos, Cosmic Ray sources, Hadronic interactions & QCD, extragalactic propagation, air shower and neutrino detection, terrestrial backgrounds, etc.



Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube

What happens if we get per-source data

RESEARCH ARTICLE

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverp...

+ See all authors and affiliations

Science 13 Jul 2018:
Vol. 361, Issue 6398, eaat1378
DOI: 10.1126/science.aat1378

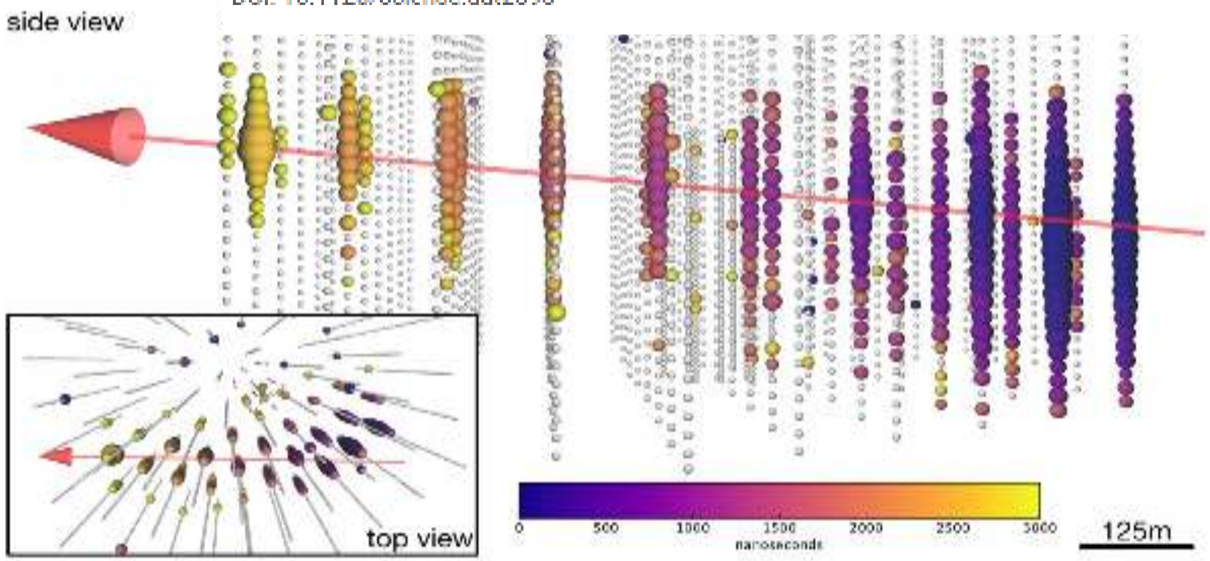
RESEARCH ARTICLE

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*,†

+ See all authors and affiliations

Science 13 Jul 2018:
Vol. 361, Issue 6398, pp. 147-151
DOI: 10.1126/science.aat2890

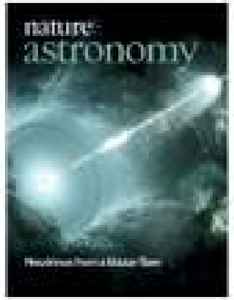


+ ~10 papers on day 1

nature astronomy

« Previous Issue | Volume 3 | Next Issue »

Volume 3 Issue 1, January 2019

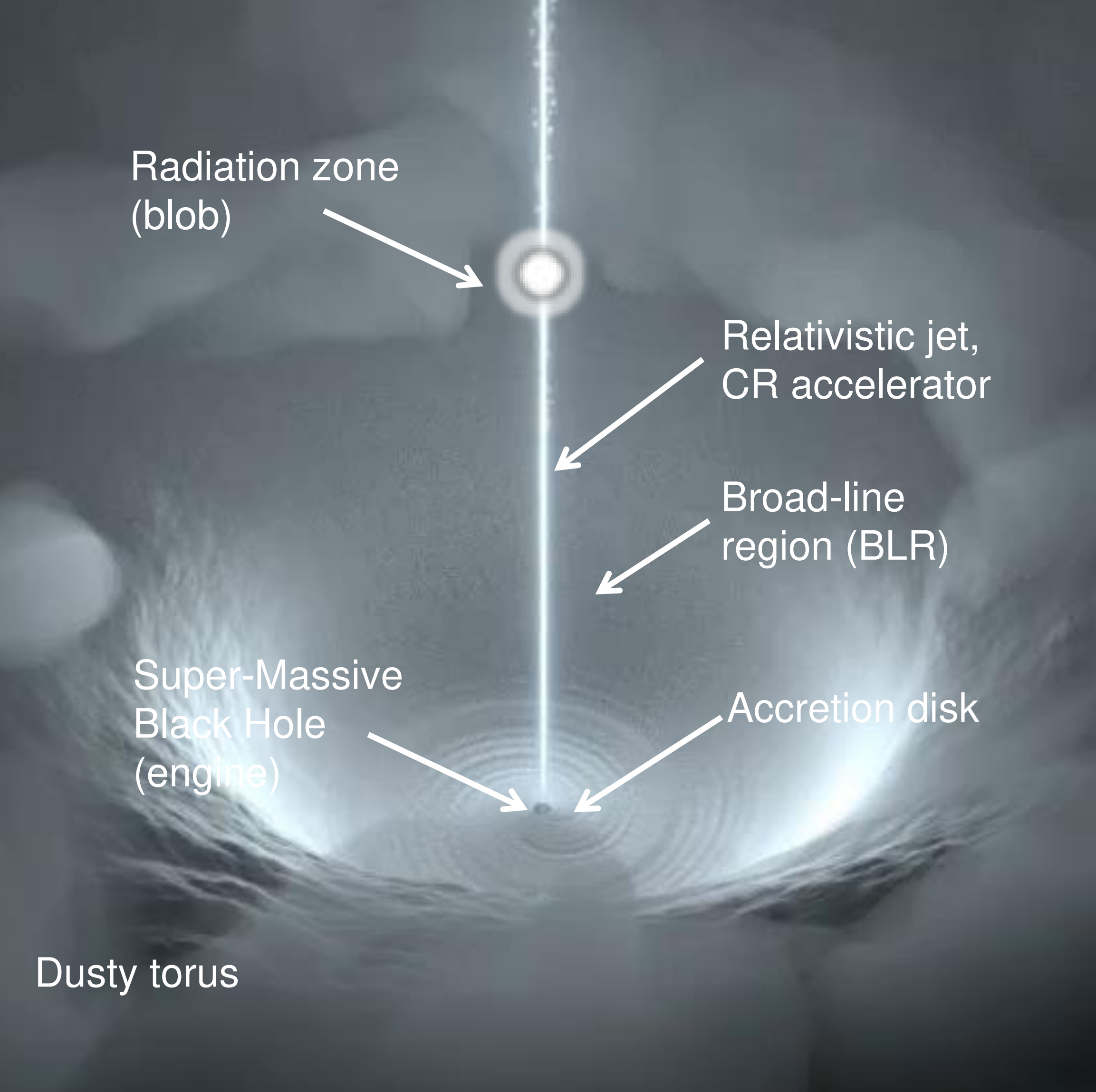


Neutrinos from a blazar flare

Blazars, powered by an accreting supermassive black hole, launch collimated relativistic outflows (pictured) that are among the brightest persistent radiation sources in the Universe. The recent IceCube detection of a very-high-energy neutrino from the blazar TXS0506+056 in coincidence with a multi-wavelength flare implies that blazars can accelerate cosmic rays beyond petaelectronvolt energies, challenging conventional theoretical... show more

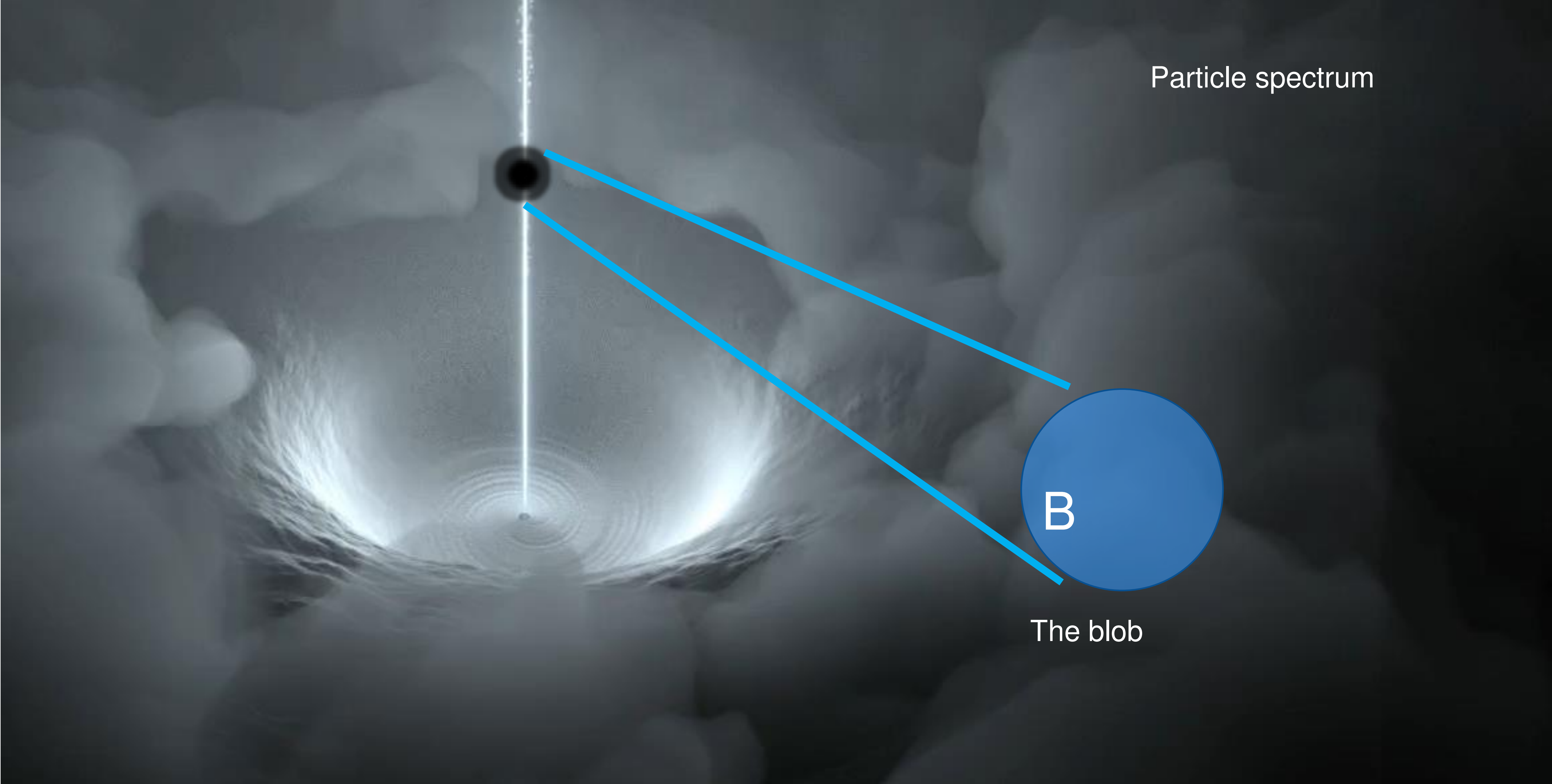
Image: DESY, Science Communication Lab. Cover Design: Allen Beattie.

Radiation from blazars



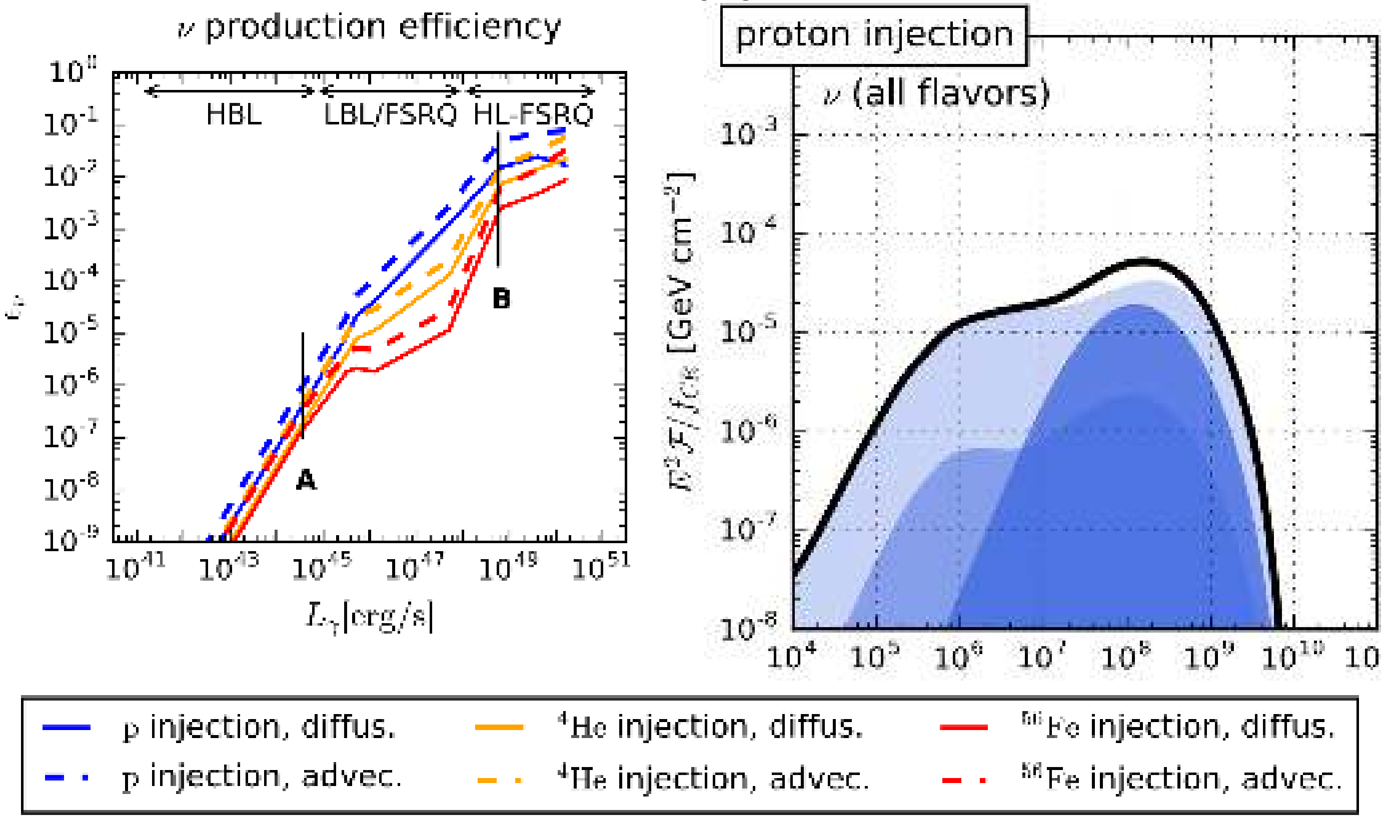
- SMBH drives accretion disk
- The radiation from the disk heats the environment; BLR and Torus
- Accretion of matter drives jet (galactic dimensions ~ kpc)
- Turbulent flow and plasma instabilities in the jet form radiation zones (blobs)
- Electrons and **protons** accelerate to ~PeV energies
- Radiation off relativistic particles produces observed spectrum

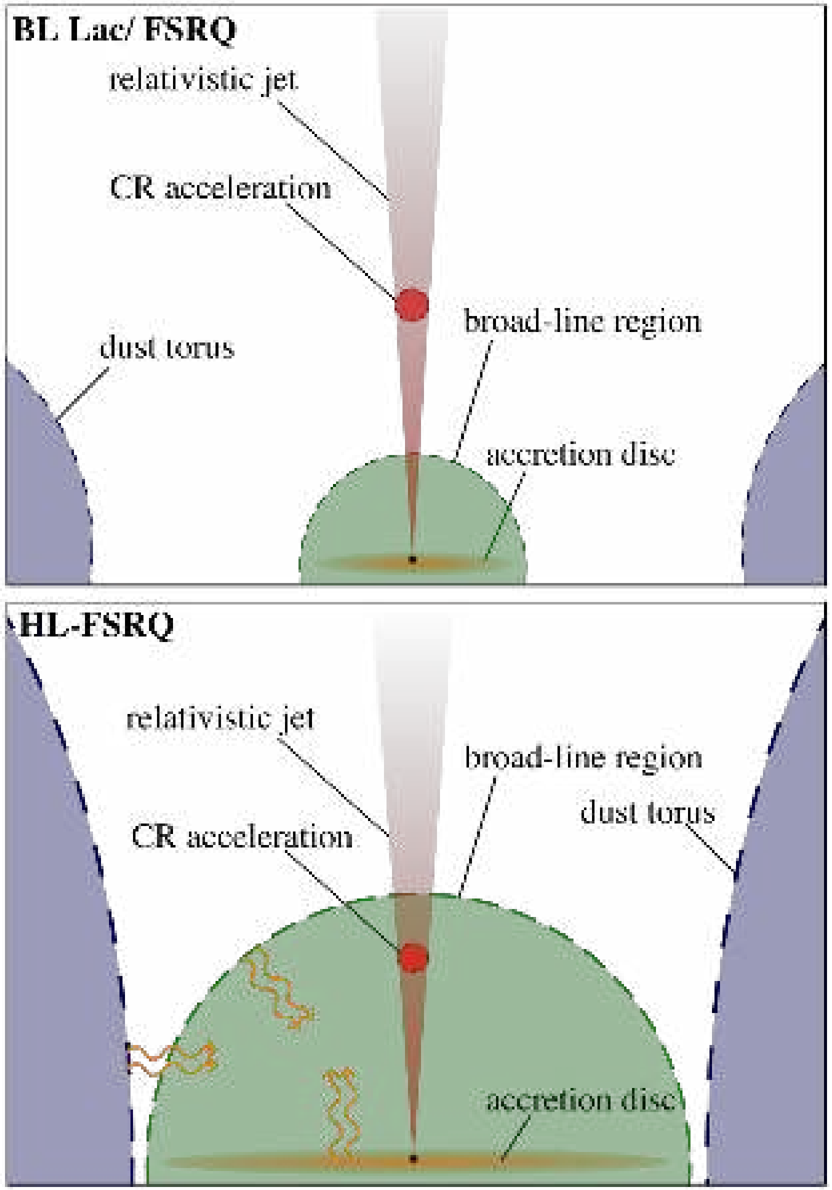
Radiation from blazars



Blazars as neutrino sources

X. Rodigues, AF, Gao, Boncioli, Winter, ApJ 2018

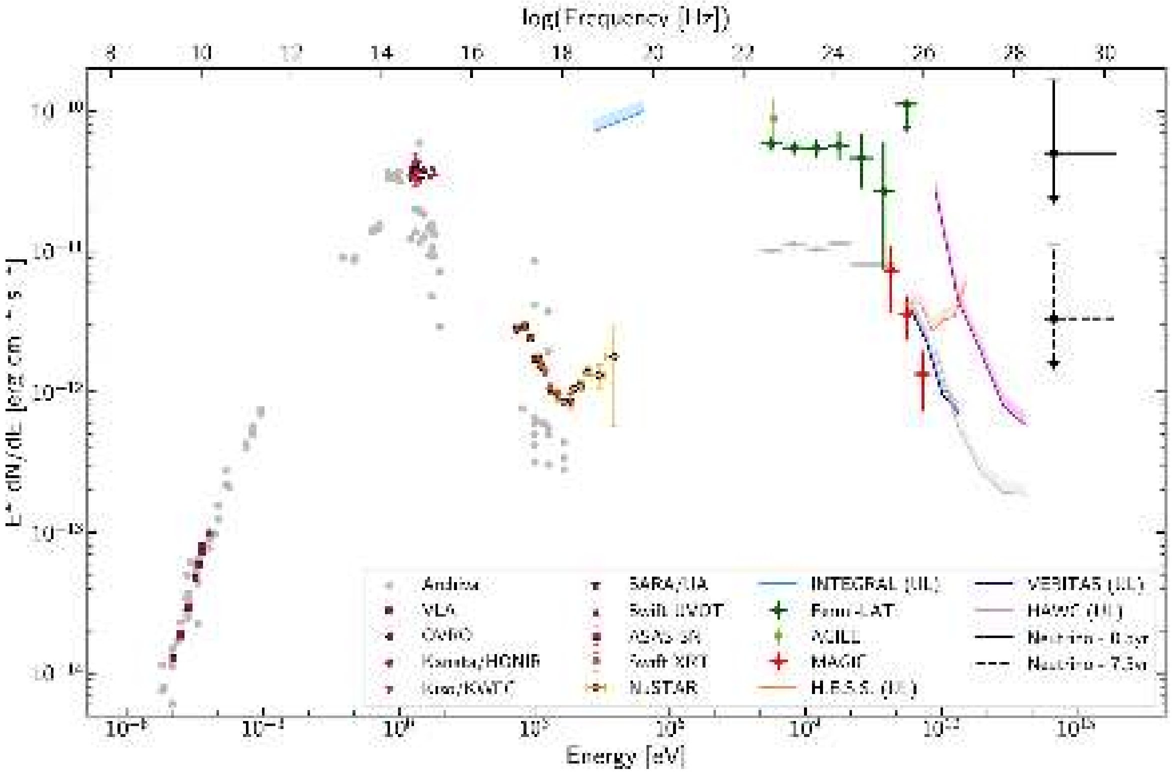


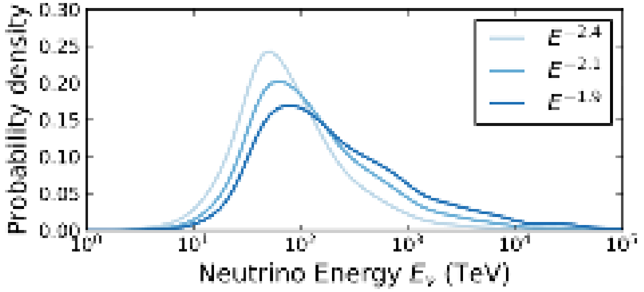


Low-luminosity blazars are <u>very inefficient</u> neutrino sources

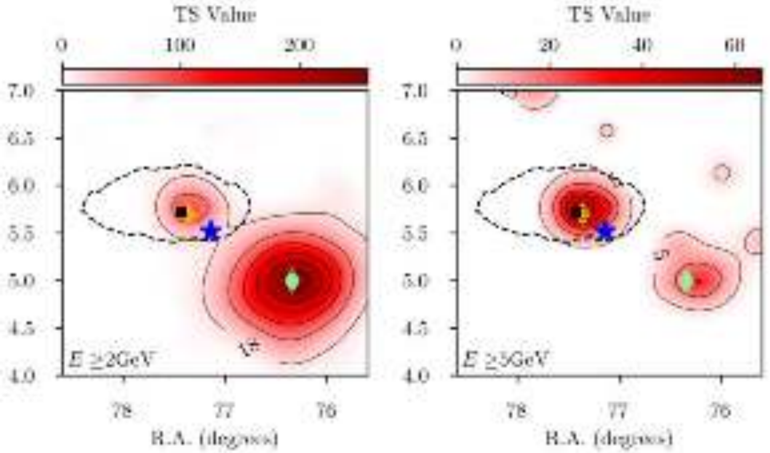
Theoretical challenges of the TXS0506+056 MM observation

IceCube, Fermi, MAGIC,++, Science 2018



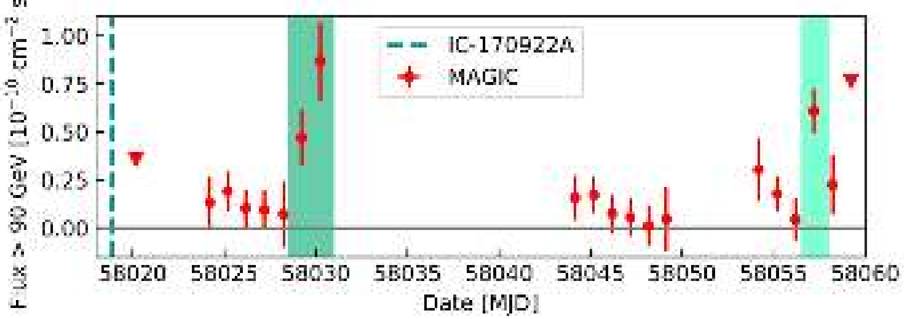


Padovani, Resconi, Glauch, Huber, et al. (MNRAS 2018)



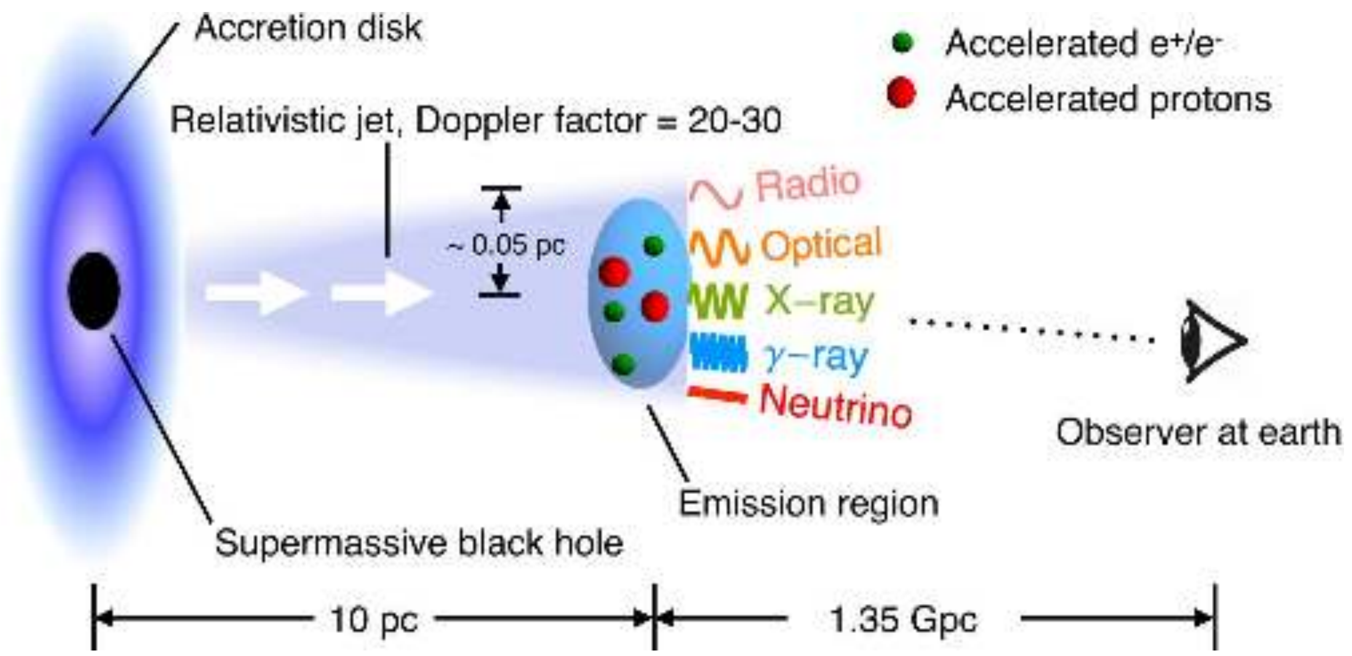
Source confusion unlikely

MAGIC, ApJL, 2018



Delayed or **flikering** emission of **TeV photons**

Modeling TXS



- **One or multiple** emission regions (**blob** or plasmoid)
- **Spherical** in its rest frame
- Particle momenta and radiation **isotropic**
- **Injection** of accelerated particles (**no** explicit **simulation**)
- Particles **escape** at **constant** rate

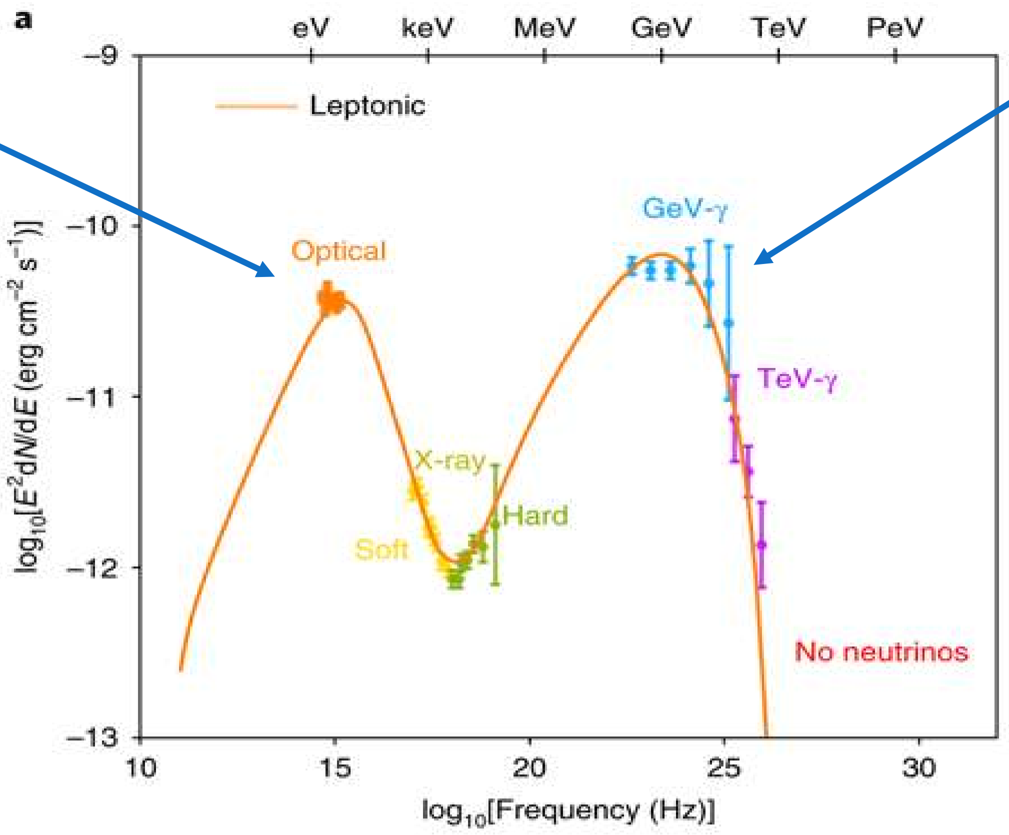
Time-dependent lepto-hadronic Code (**AM**^{3}) (Gao, Pohl, Winter APJ 843, 2017)

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

The “canonical” blazar SED – synchrotron self-Compton model

Synchrotron peak:

- off electrons
- Defines..
  - **magnetic field**
  - **doppler factor**
  - **shape of** electron **spectrum**



Synchrotron self-Compton (SSC) peak:

- synchrotron spectrum up-scattered by prim. electrons
- Depends on all variables
- In particular target densities

Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

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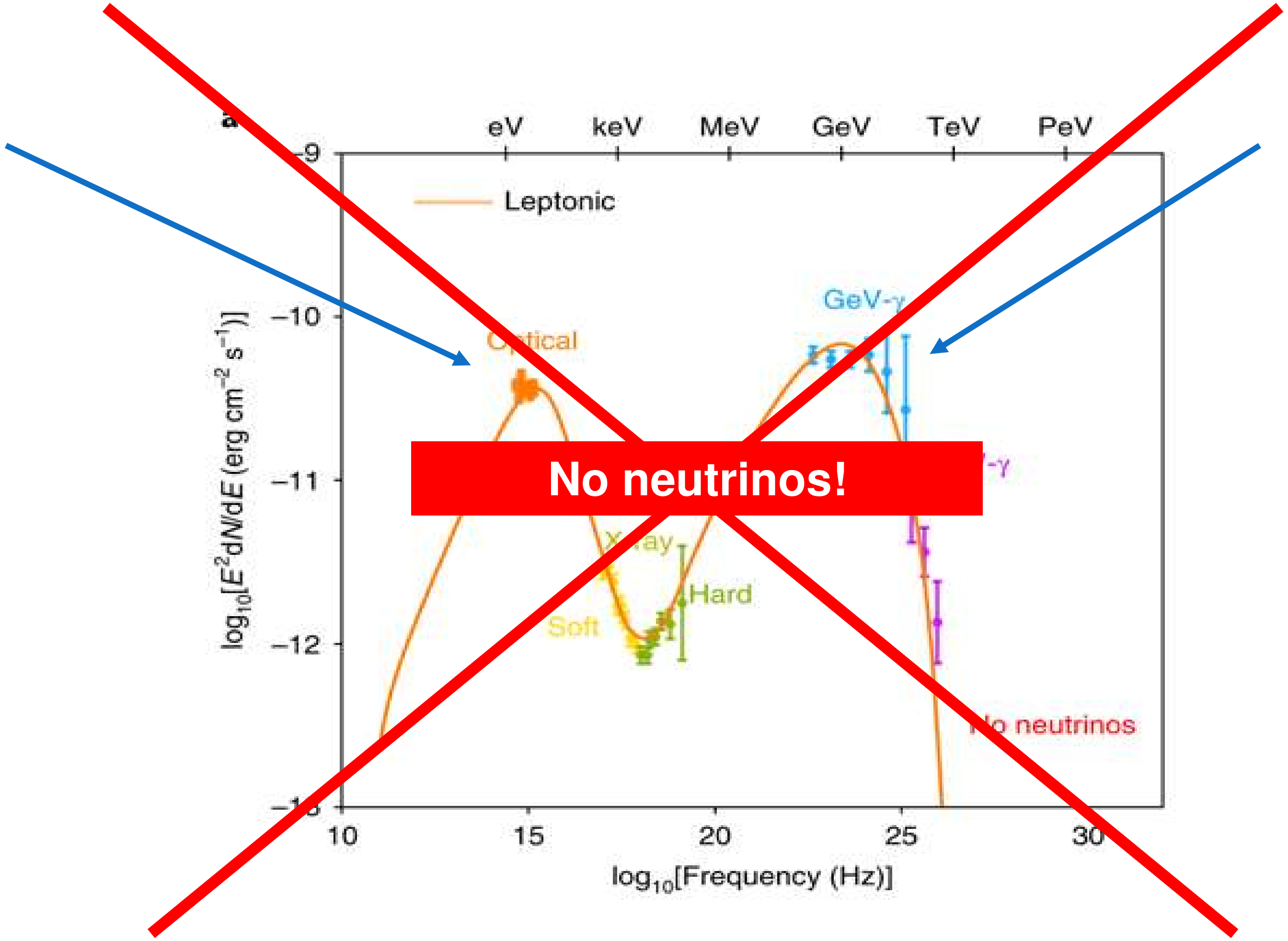

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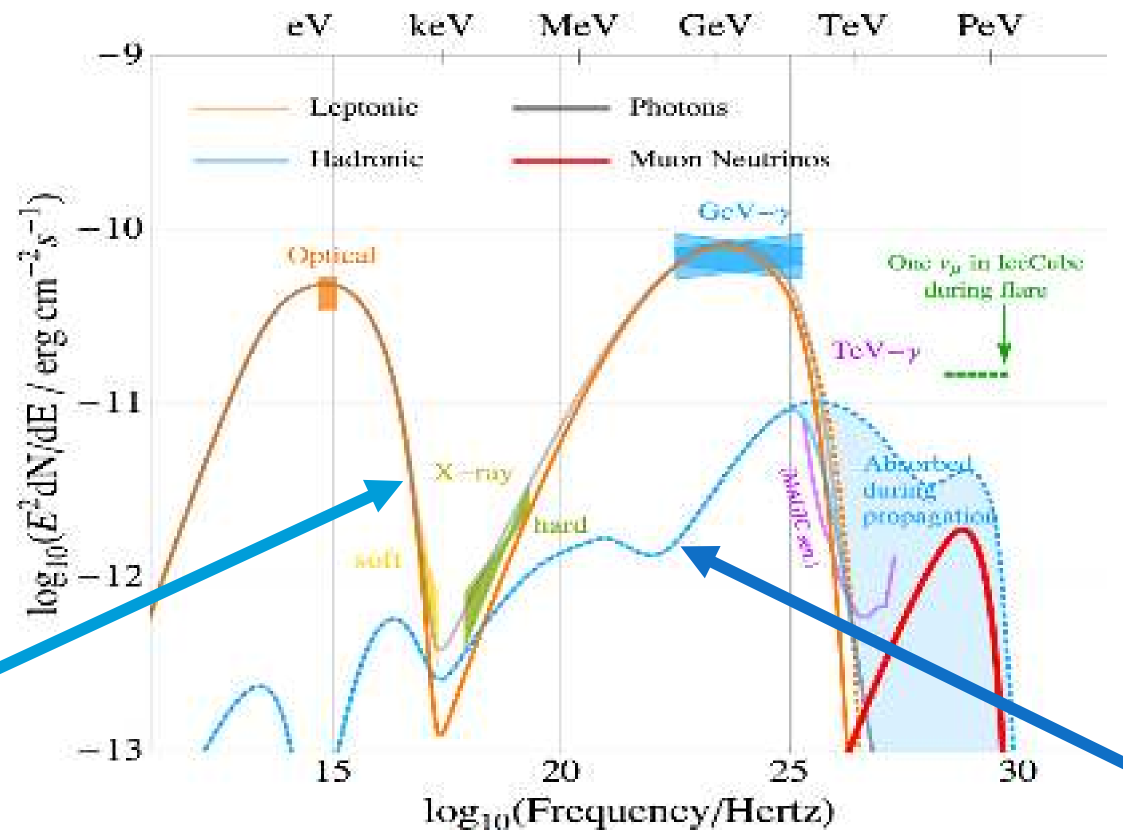
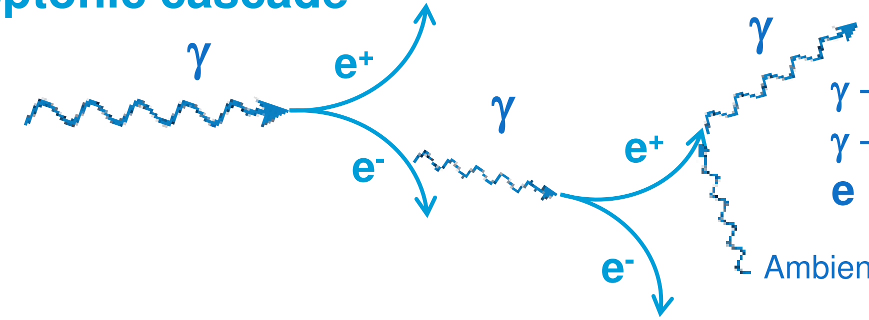
Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

Lepto-hadronic (one-zone) model

Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)



Leptonic cascade

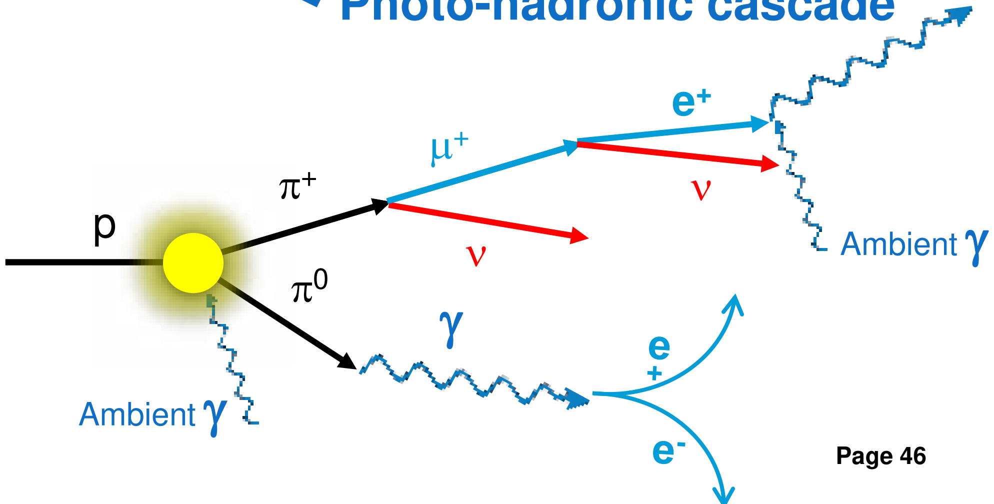


$\gamma + \gamma \rightarrow e^+ + e^-$

$\gamma + e \rightarrow \gamma + e$ (IC)

$e + B \rightarrow e + \gamma$ (syn.)

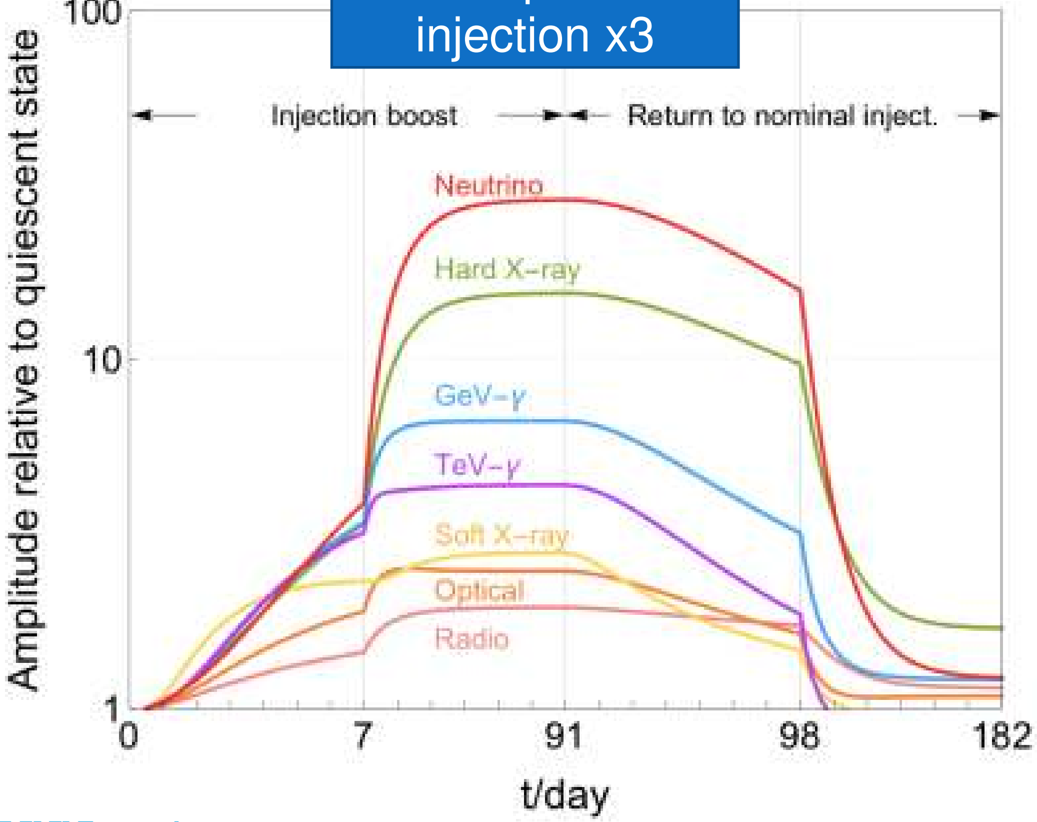
Photo-hadronic cascade

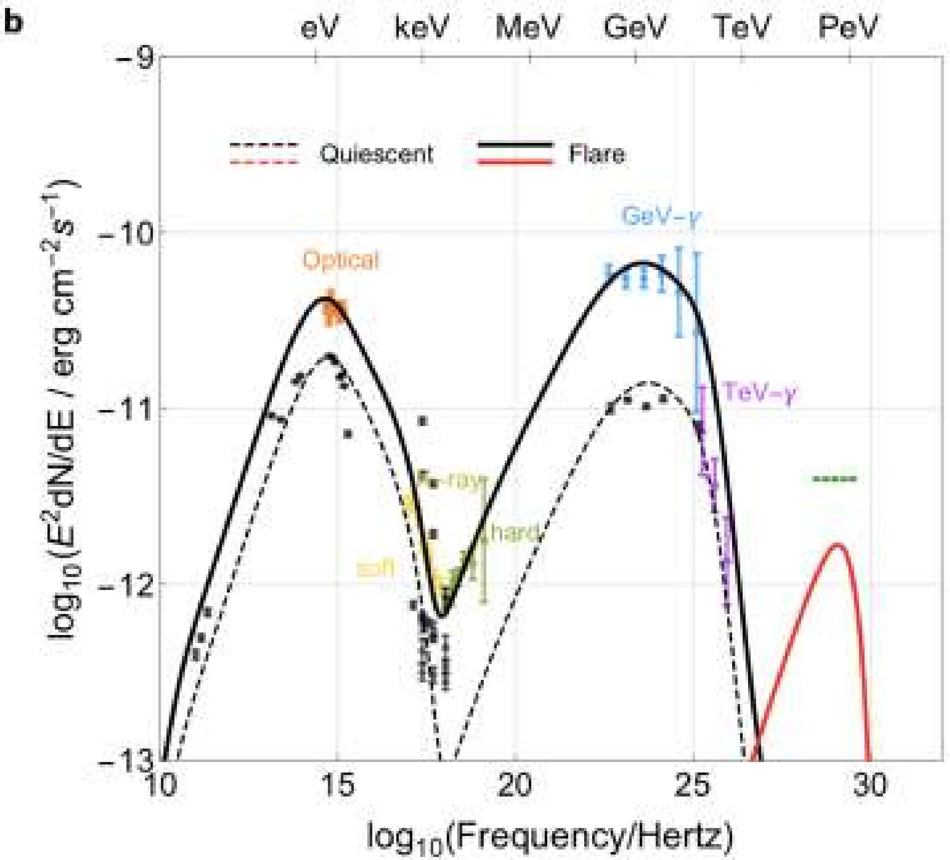


Lepto-hadronic (one-zone) model

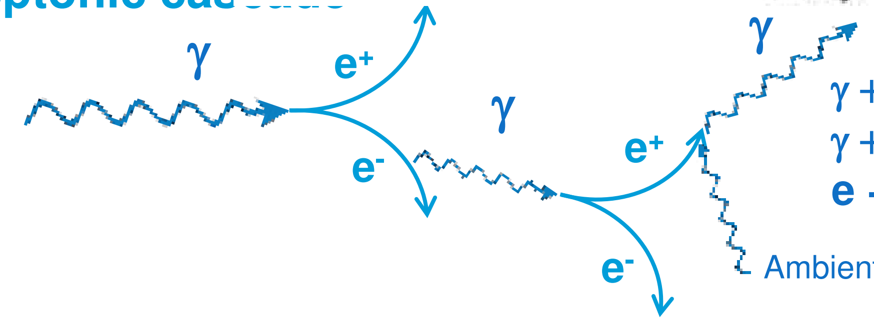
Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

Boost p and e injection x3





Leptonic cas



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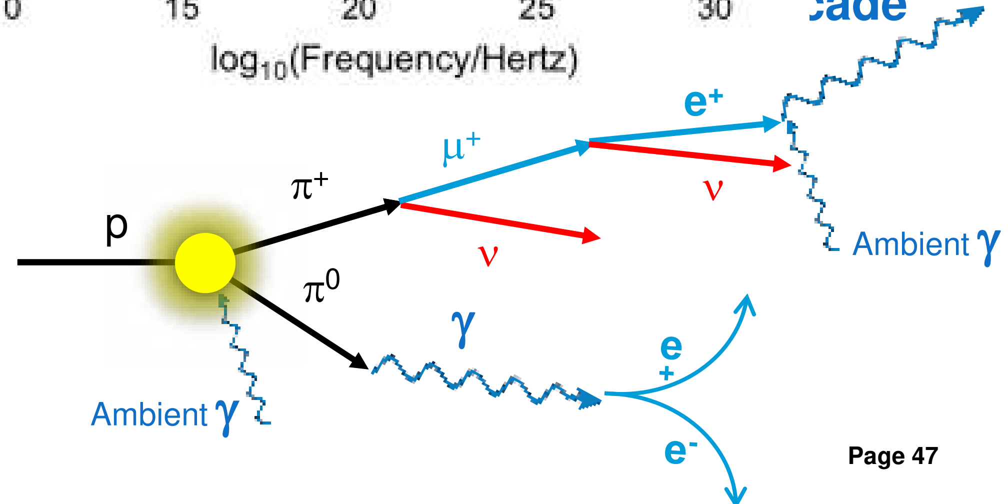
cade



Lepto-hadronic (one-zone) model

Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

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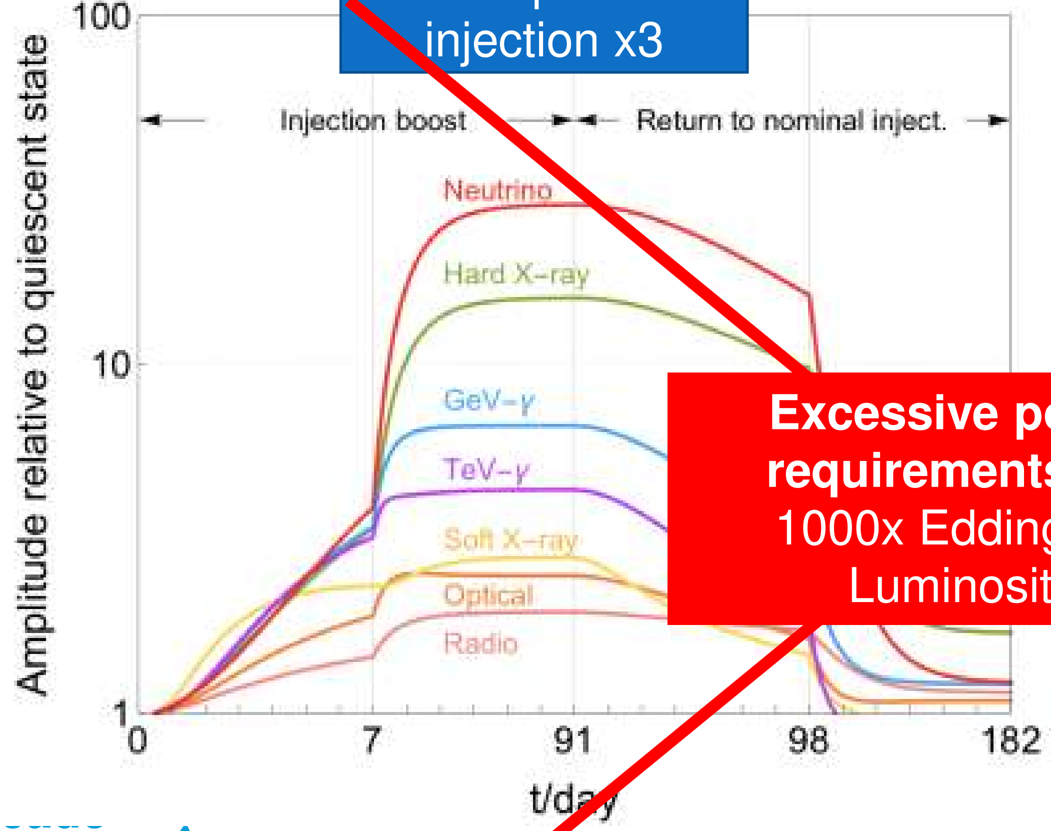
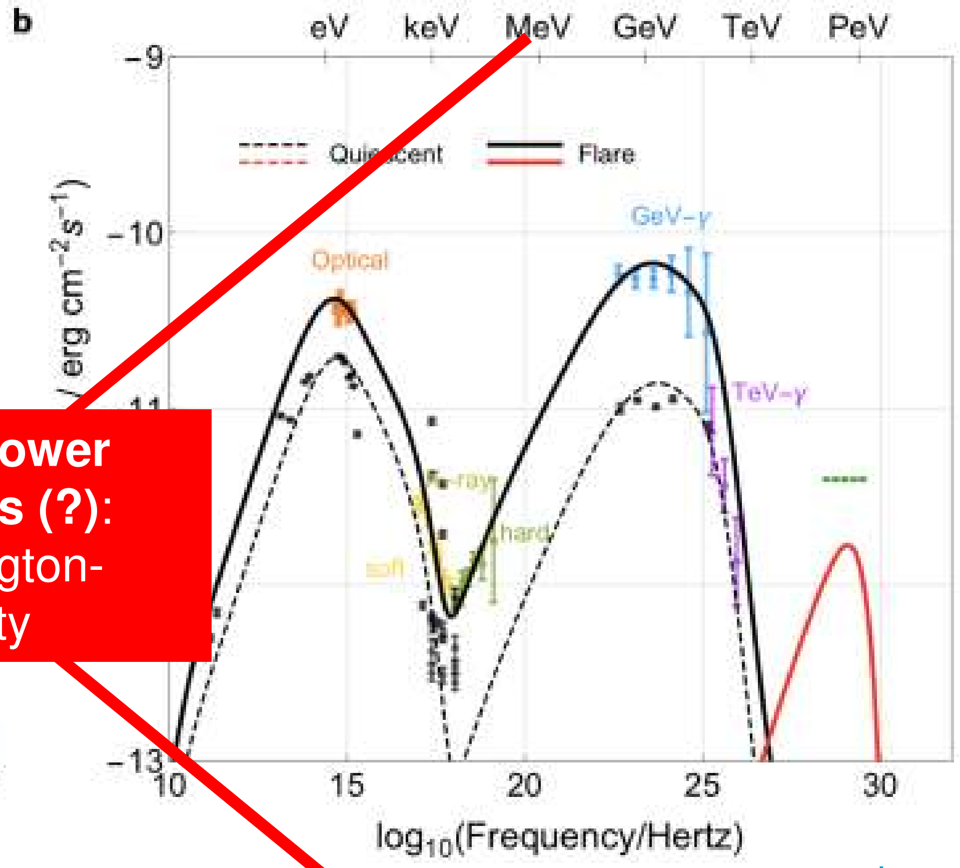
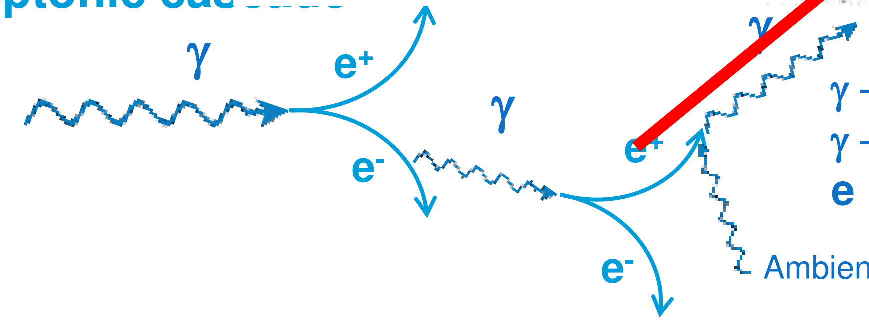




Excessive power requirements (?): 1000x Eddington-Luminosity

Leptonic cas…



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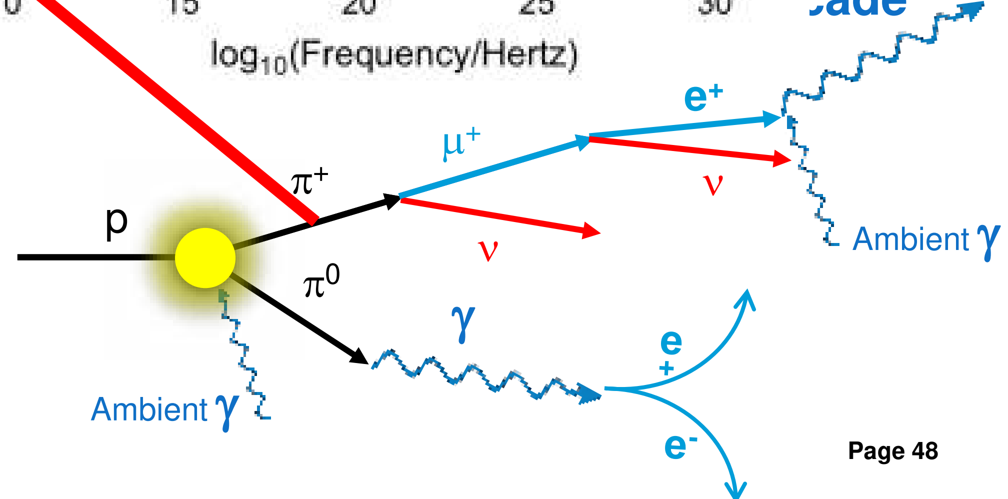
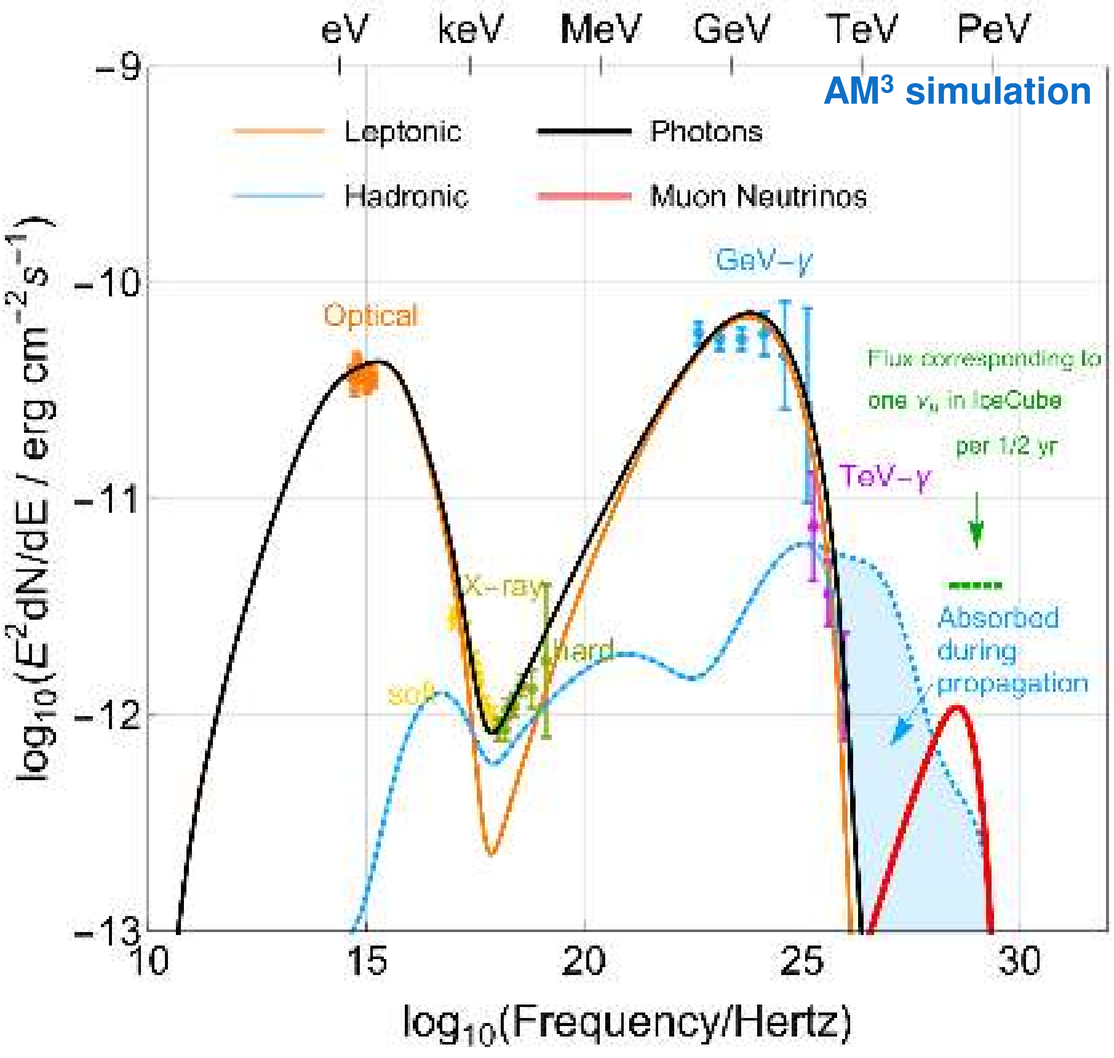
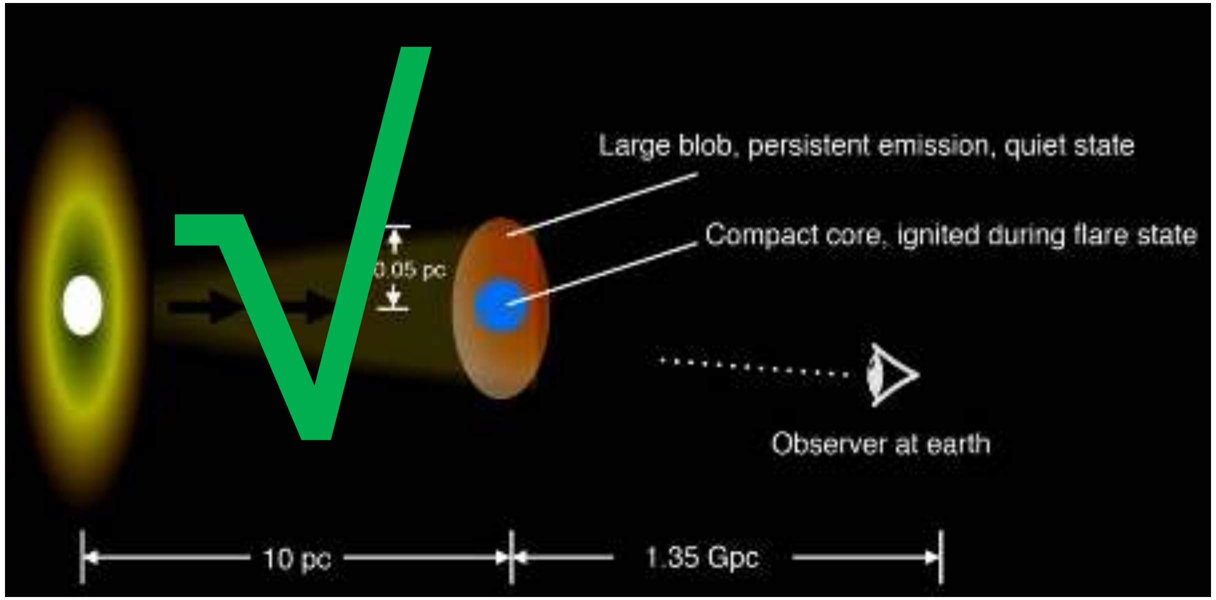
…cade



More complex geometry required – two-zone (core) model





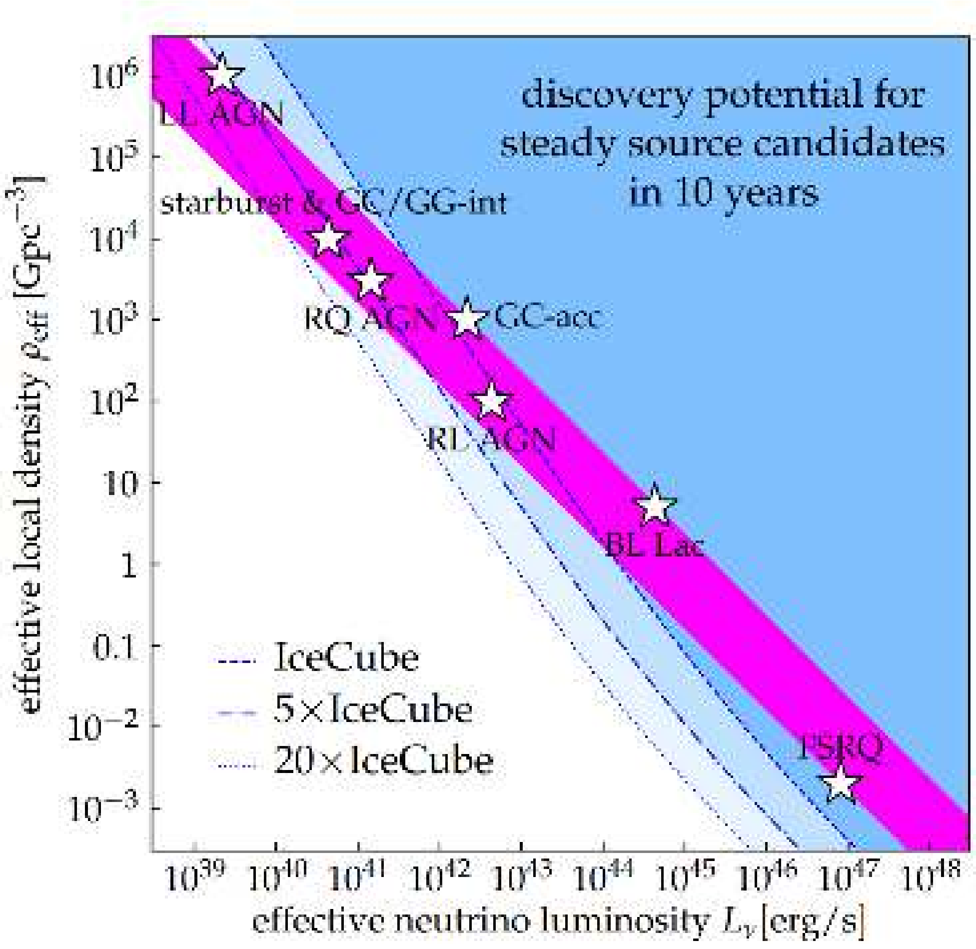
- **Large zone** $r \sim 10^{17.5}$ cm for **quiescent** state
- **Flare** generated through formation of a **compact core** $r_{core} \sim 10^{16}$ cm during the short period of the flare
- To power the core **7xL_{Edd} needed** to saturate X-ray flux, quiescent state is sub-Eddington
- **Neutrino rate is ~0.3/yr**, consistent with the observation of one neutrino during the flare

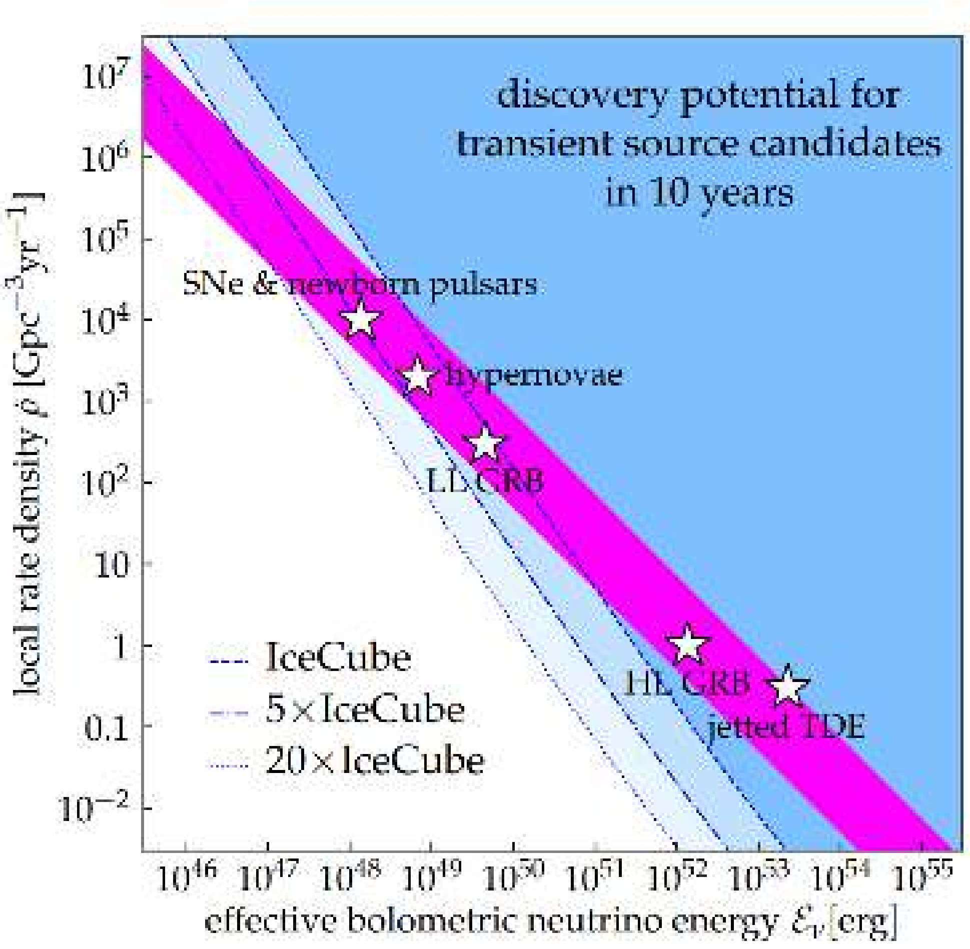
Gao, AF, Winter, Pohl, Nat.Astron. 3 (2019)

Lessons from one Multimessenger observation with a single neutrino

1. Some blazars may be PeV cosmic ray accelerators
2. These blazar jets must contain a significant amount of protons/nuclei
3. Simplified expectations $L_{\gamma}^{(2)} \sim L_{\nu}$ not generalizable, and hence simplified exclusion limits not to be taken at face value
4. Multi-wavelength observations crucial, for TXS: X-ray and not the γ-ray flux is the more robust ν flux proxy
5. Efficient neutrino emission requires super-Eddington accretion, at least for some time period
6. Most modeling attempts arrive at similar conclusions and usually more exotic models have to be considered

Remaining candidates after 10 years of IceCube

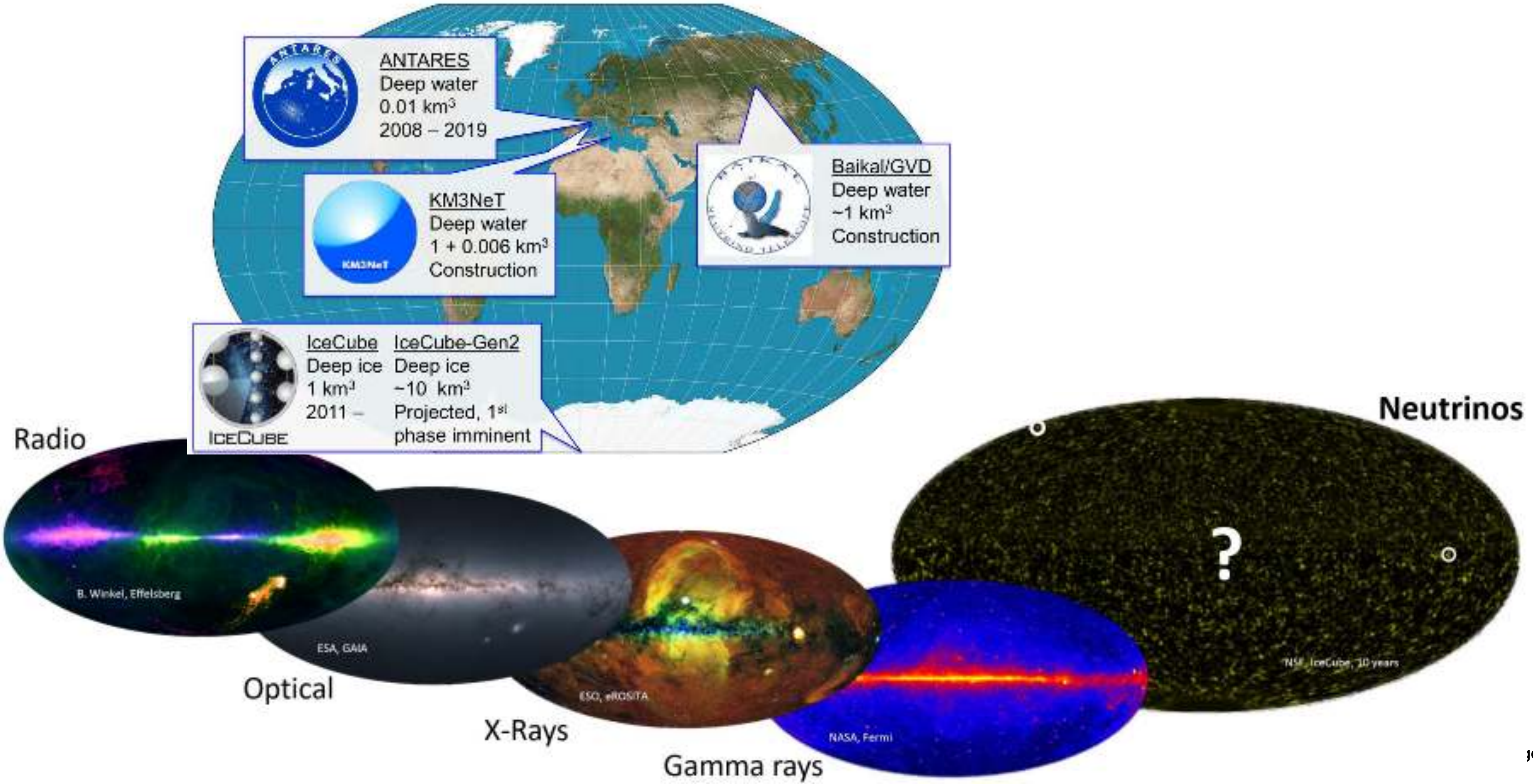




Many source types still can contribute, 5xIC will find/kill few candidates. <u>10-20xIC will nail the sources down in 10 years.</u>

IceCube
1903.04334 (Astro2020 WP)

Neutrino astronomy until 2020



We have a “newcomer”: GVD completed.

D. Naumov (Dubna) @ IHEP, 2020

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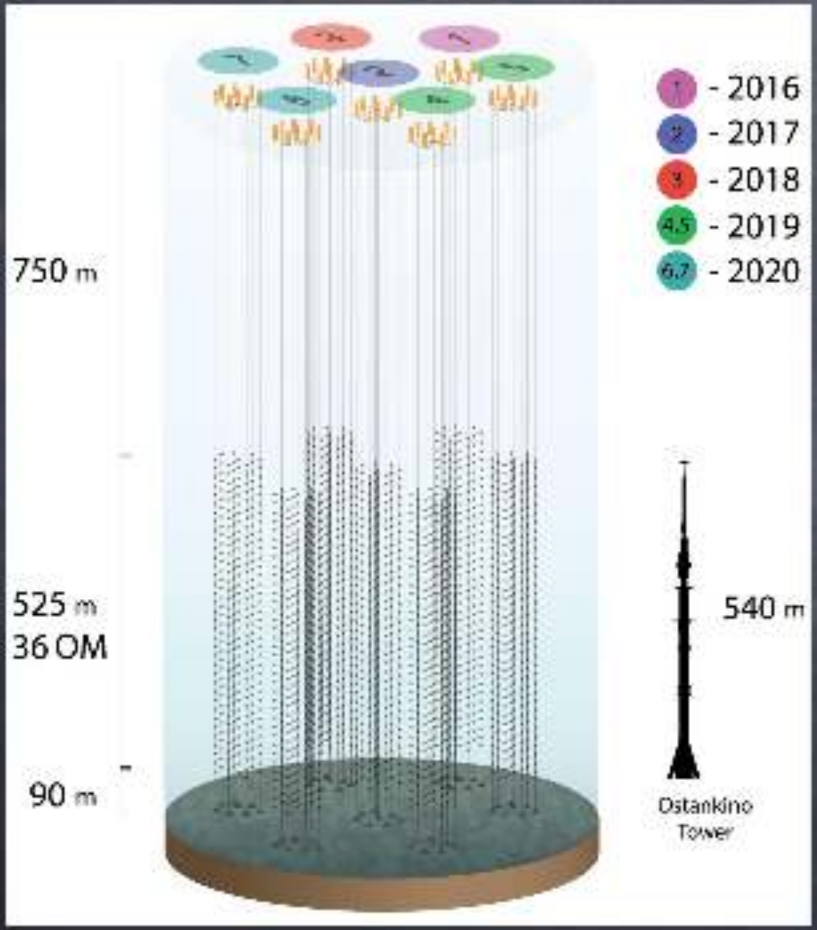
Baikal Neutrino Detector

→ Seven clusters @2020



Year	Number of Clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	9	2592

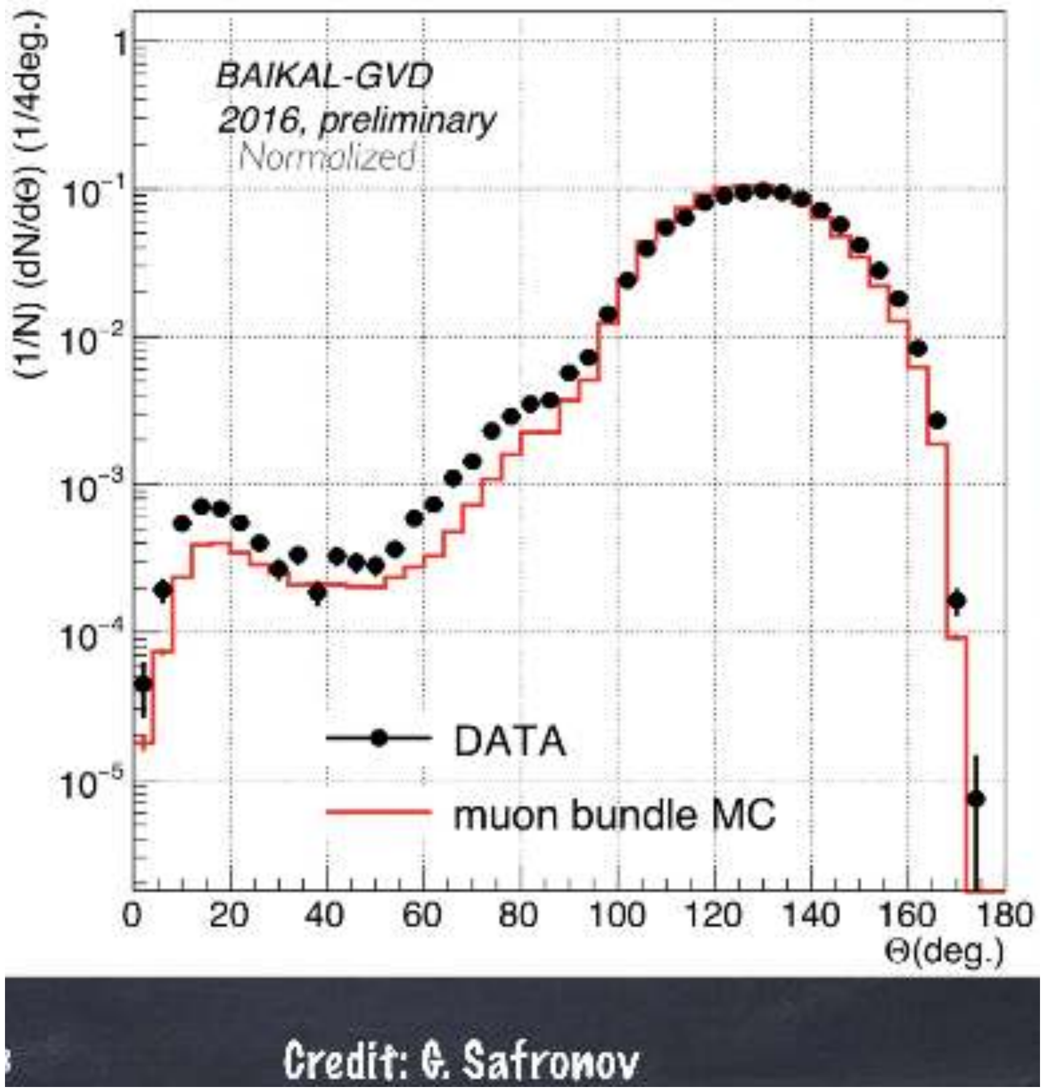
- ~300 m between clusters
- + experimental string with optical link
  - Lower trigger thresholds
  - 1GB/s
  - Synchronized clocks
  - New FPGA Zync
- $V_{shower} = 0.35\ km^3$

22

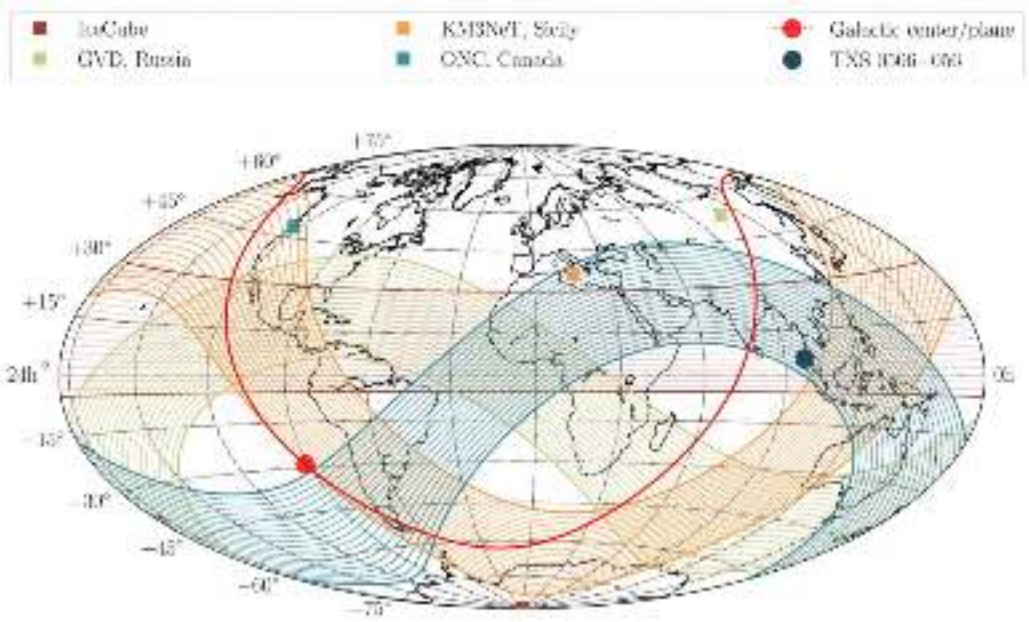
Current GVD status (personal viewpoint)

D. Naumov (Dubna) @ IHEP, 2020

- Deployment under control
- Calibration under control
- DAQ under control, etc.
- Old-(90's-)style simulation needs to be re-done from scratch
- Mainly Institute Dubna has a new, young group doing this at high pace
- Data analysis mostly missing
- Physics program mostly missing
- Fancy machine learning stuff (like what is happening in IceCube) "not even thought of"
- Catalog analyses, atmospheric neutrino analyses, multi-messenger,….?
- …



Concluding remarks



- Sources of HE neutrinos and cosmic rays not identified, except one candidate at 3-sigma. At least one more telescope required (cf. ATLAS + CMS)
- Detect “guaranteed” neutrino sources:
  - Sensitivity increase >~ factor 10 required
  - Factor 5-8, as projected for IC-Gen2 may leave neutrino astronomy in an inconclusive state
- “Low hanging fruit” for first active km^3 detector in the North → This detector is Baikal GVD
- Effective transient events search: a global collaboration and alert system, as it is already evolving in the community, will overcome limitation of single telescopes
- Theory is not ready to process multi-telescope time-domain data, but there is a path forward. We have 10 years.