Astroparticle physics and EIC
- combining the largest and the smallest scales in the Universe

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Stony Brook University
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Astroparticle physics and EIC
- combining the largest and the smallest scales in the Universe

Outline

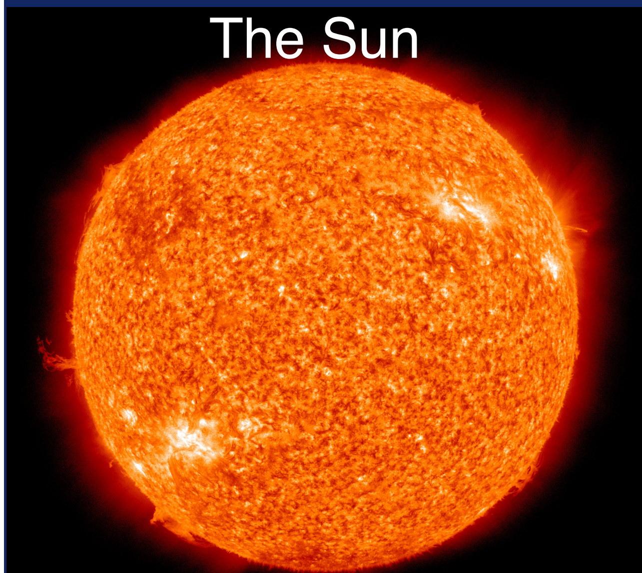
1. Introduction
2. Cosmic Rays (Auger & Telescope Array)
   - Spectrum, composition & hadronic interactions
3. High Energy Neutrinos (IceCube)
   - Atmospheric and astrophysical flux
   - ν-p Cross section
4. Summary

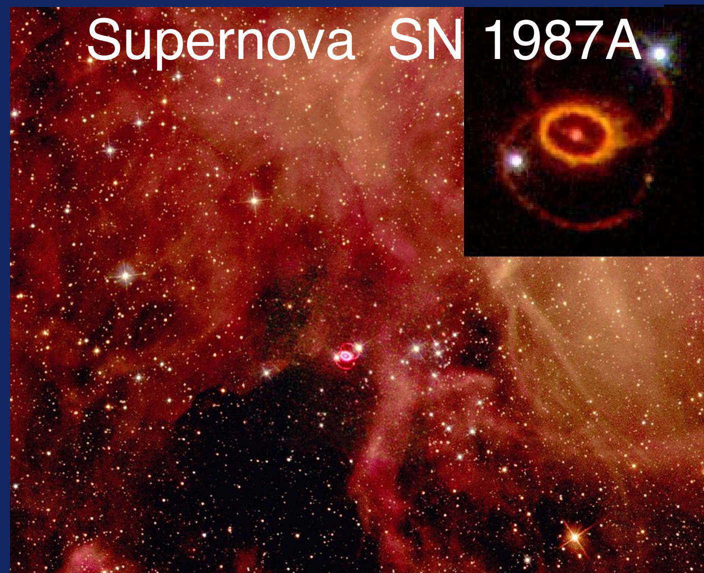
Acknowledgement: Overview of relevant results in the field; heavy reliance on other people contributions (physics/results/figures) as indicated on slides.

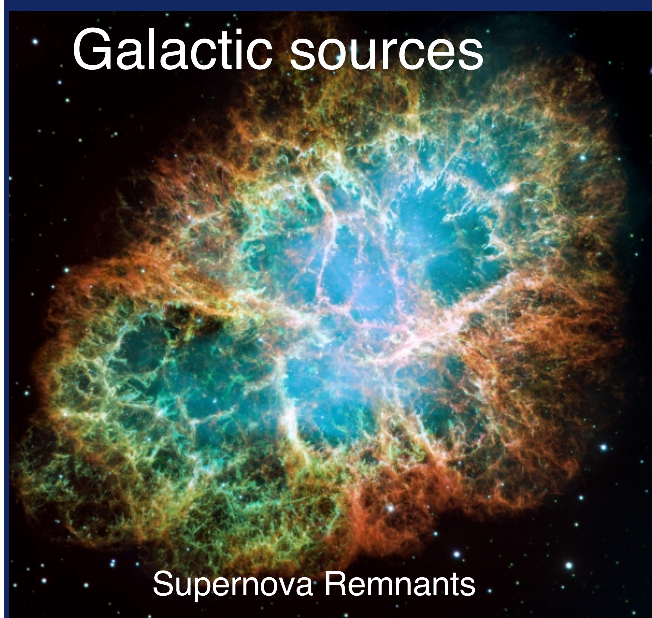
Introduction
High Energy Universe

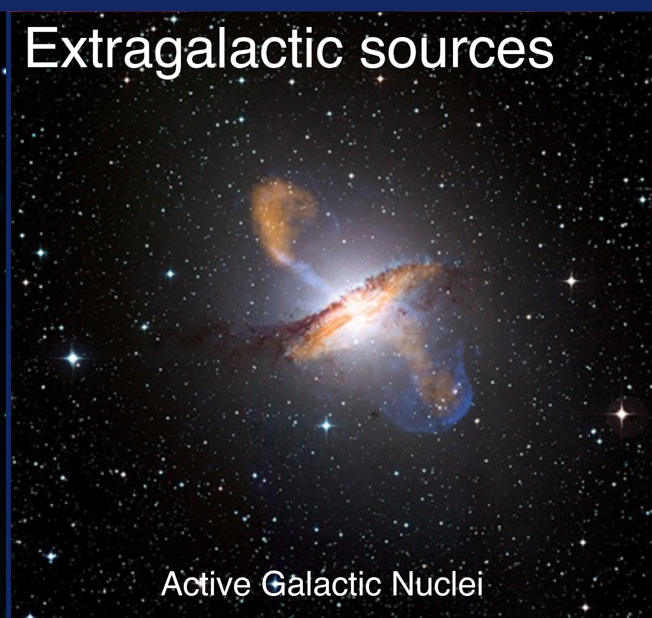
Astrophysical Sources, probes, fluxes

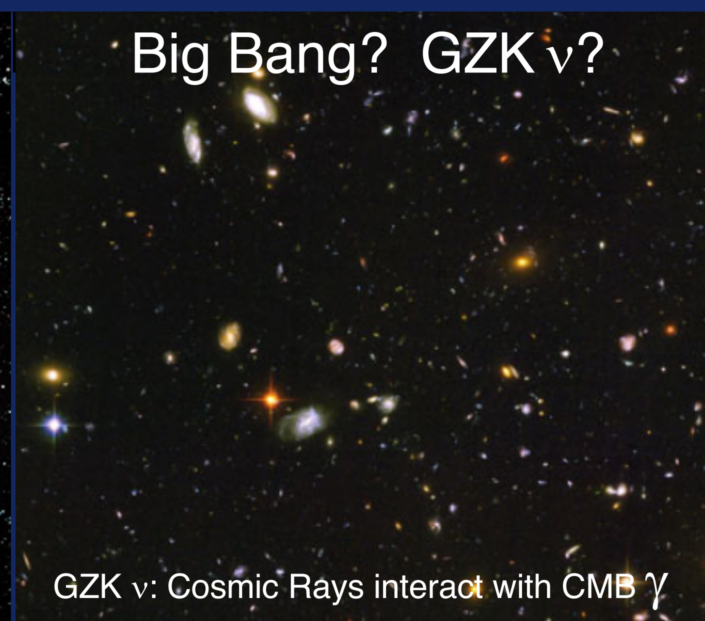
High Energy Universe: Astrophysical Sources





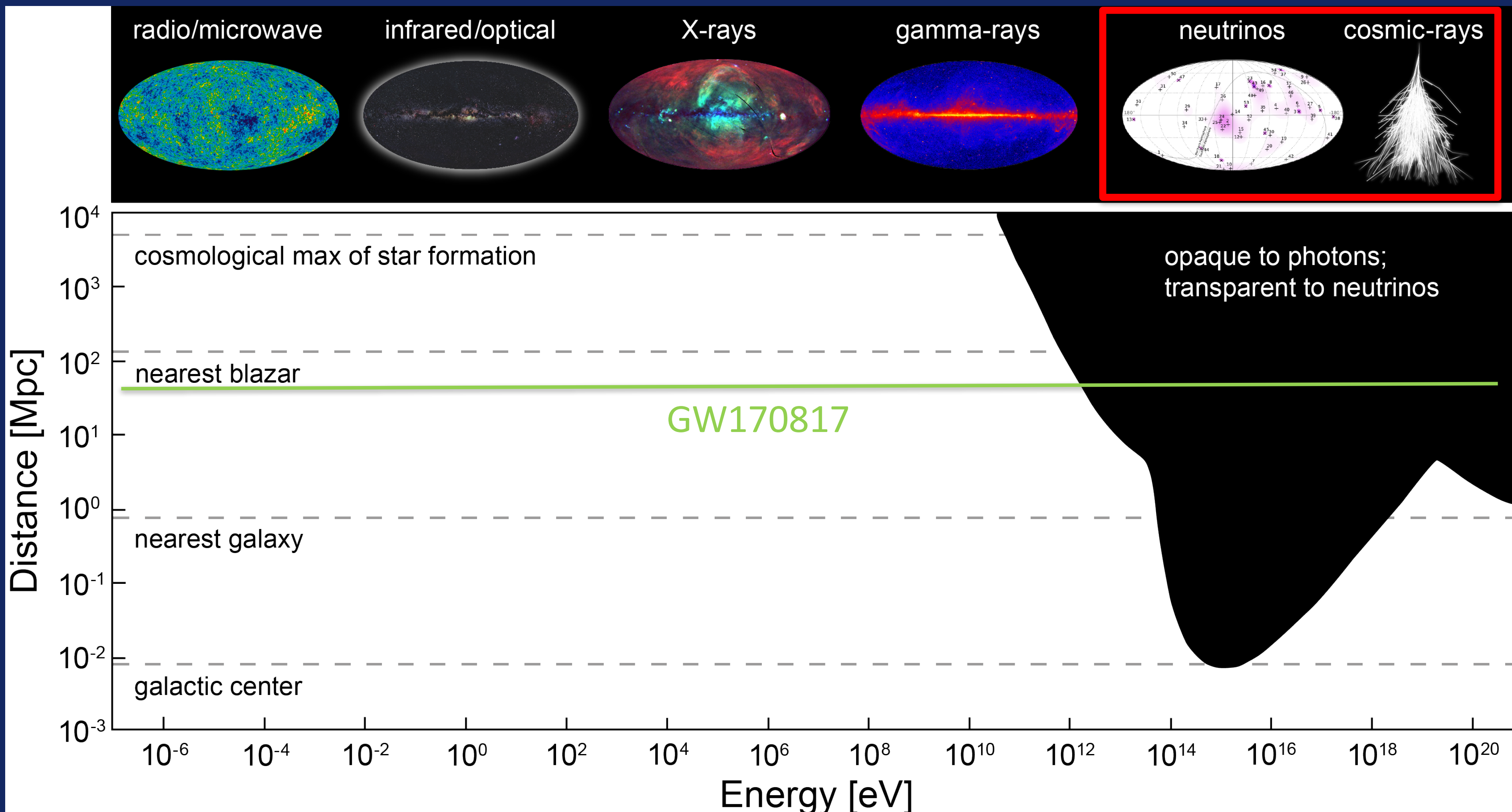






High Energy Universe: Probes
Multi-messenger Astronomy

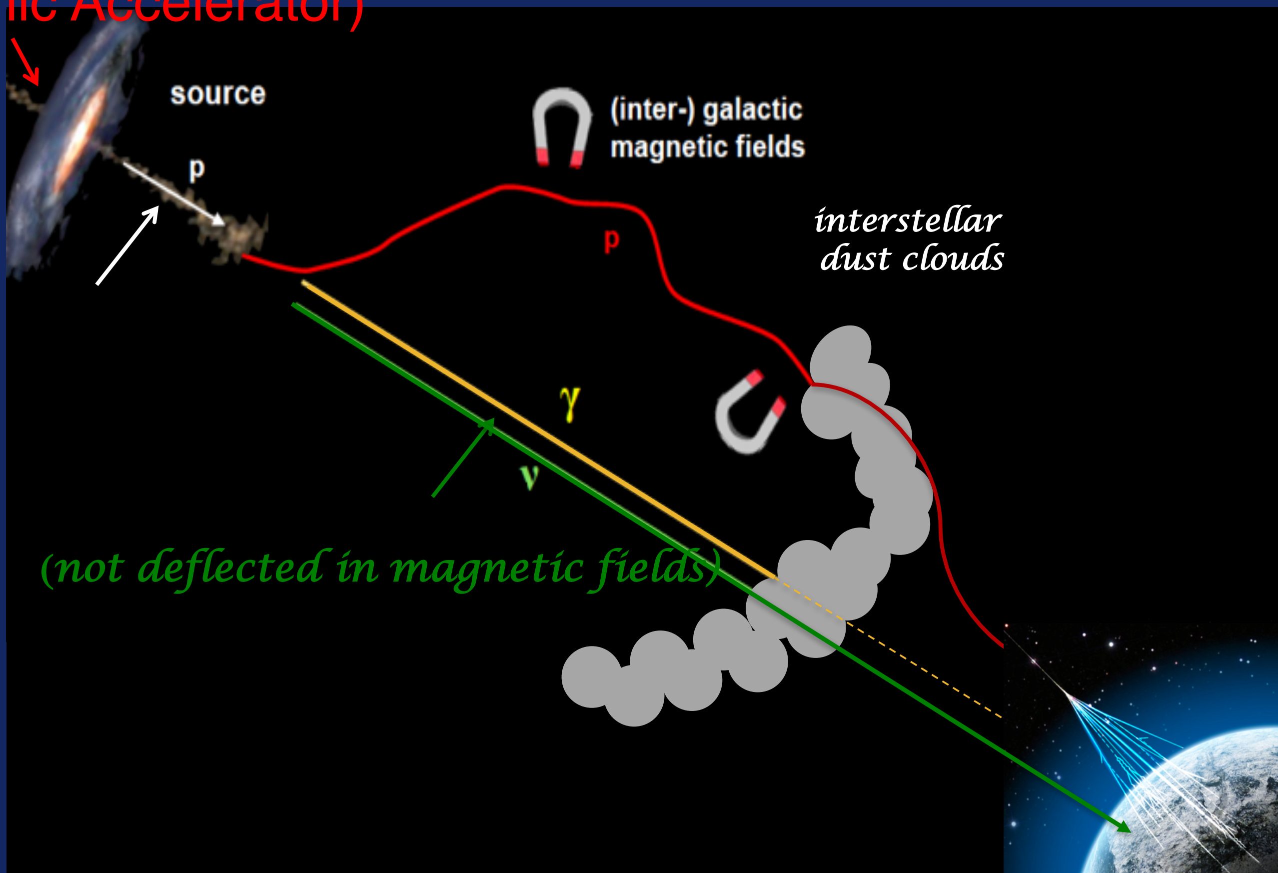
This talk



High Energy Universe: Probes

What is the origin of Cosmic Rays with E up to 10^{20} eV ?

Astrophysical Source
(Cosmic Accelerator)



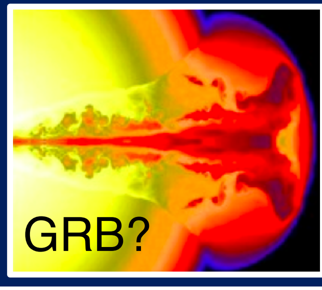
- **Cosmic Rays**
- Gamma Rays
- **Neutrinos**
- Gravitational waves

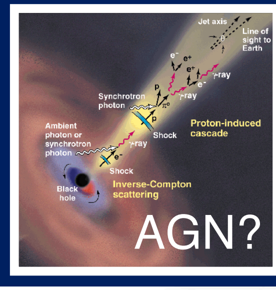
Objective: We want to find/study astophysical objects that are sources of CR's and ν's

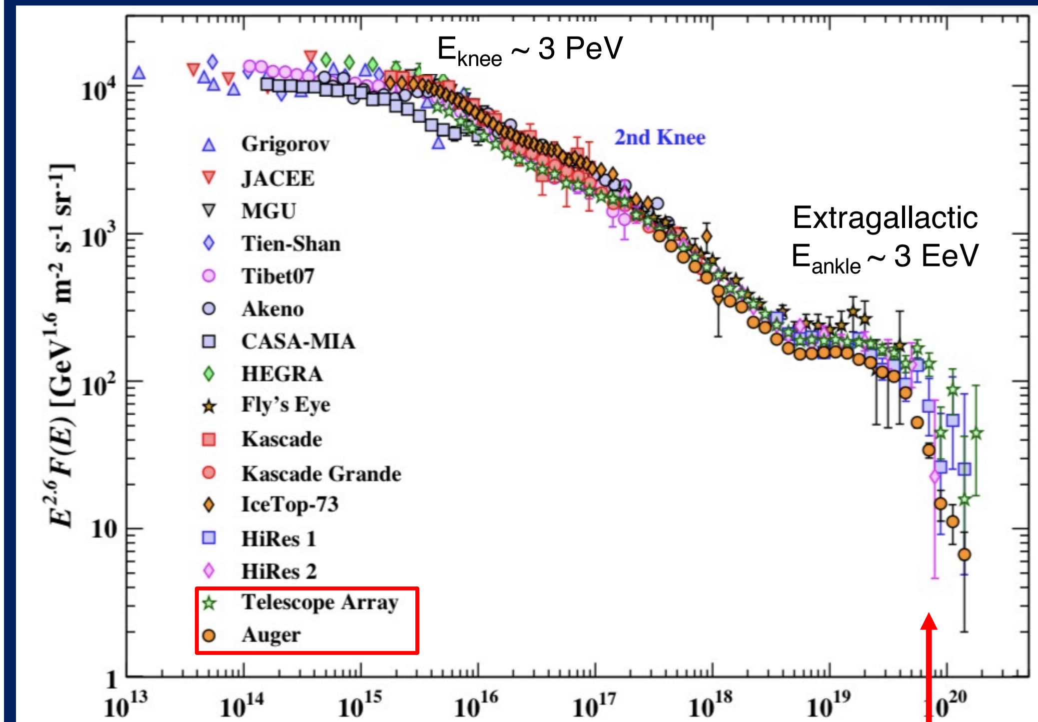
High Energy Universe: Cosmic Rays

What is the origin of Cosmic Rays with E up to 10^{20} eV ?

Confirmed by Fermi-LAT
Science 339 (2013) 807.







Particle Data Group (2017)

- 2 scenarios of Cosmic Rays (CR) origin:
  - Bottom-Up: charged particles accelerated from lower to high energies in astrophysical environments
  - Top-Down: the energetic particles arise from decay of massive particles originating from physical processes in the early Universe.

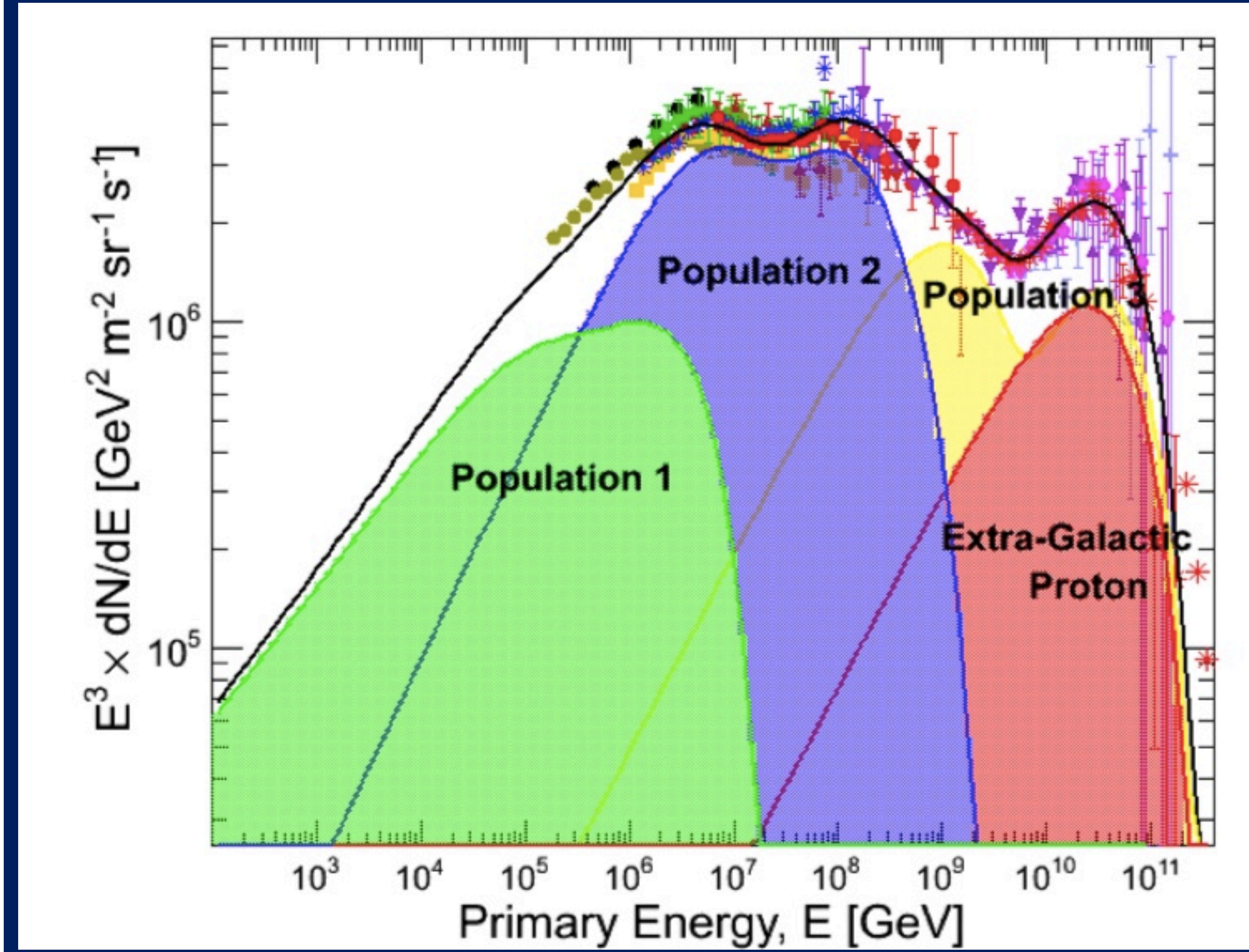
- CR spectrum formation & composition
- CR acceleration
  - Fermi mechanism: $\gamma_{CR} \sim 2$
- CR propagation
- CR interaction in atmosphere (strong interactions)

$$\Phi_{CR} \sim E_{CR}^{-\gamma_{CR}}$$

Sources unknown
Composition uncertain

Cosmic Rays: Understanding the spectrum

Fit the spectrum (Gaisser's formulation of Peters cycle)



Gaisser, Stanev,Tilav, arXiv:1303.3565 [astro-ph.HE]
Fig. from S. Tilav

$$E\frac{dN}{dE} = \sum_{i_{elements}} A_i E^{-\gamma_i} e^{-\frac{E}{Z_i E_{cutoff}}}$$

H,He,C,O,Fe nuclei groups

Net CR Spectral index is the superposition of harder indices of different elements

Population 1: supernovae cutting around 100 TeV

$E^p{}_{cutoff}$ = 120 TeV

$E^{Fe}{}_{cutoff}$ = 26 x 120 TeV = 3.1 PeV

Population 2: "Galactic PeVatronTeV neutrinos

$E^p{}_{cutoff}$ = 4 PeV

$E^{Fe}{}_{cutoff}$ = 26 x 4 TeV = 104 PeV

Population 3: "Galactic EeVatron" PeV neutrinos

The best fit is achieved with p and Fe

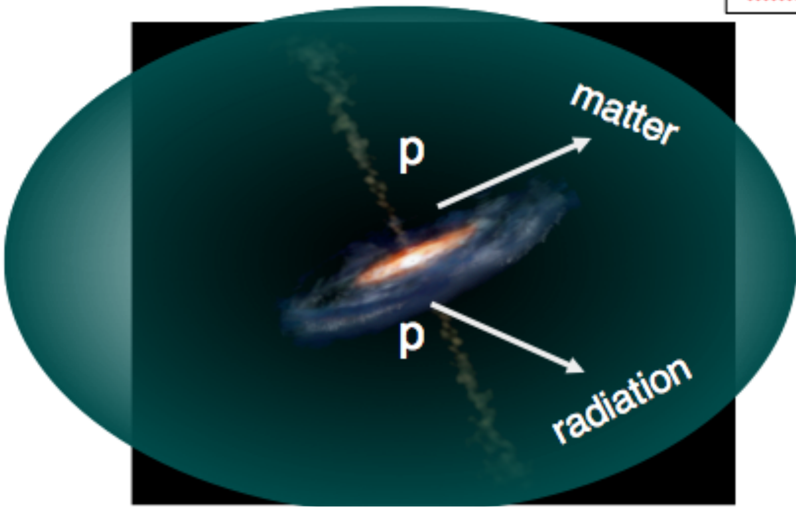
Population 4: Extragalactic Proton: cut off due to GZK effect

The Cosmic Neutrinos Production Mechanisms

From: S. Yoshida

- “On-source” astro-ν

TeV - PeV



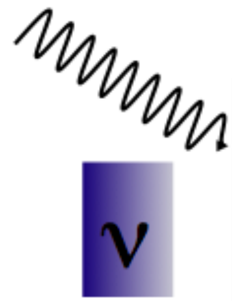
$p+p\rightarrow\pi+\ldots\rightarrow\nu+\ldots$

hadro production

$p+\gamma\rightarrow\Delta\rightarrow(p+\pi\rightarrow p+\gamma\gamma)$
$\rightarrow n+\pi\rightarrow n+\nu+\ldots$

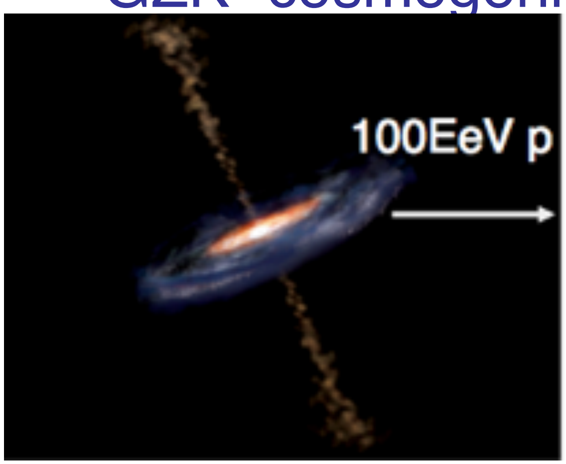
photo production

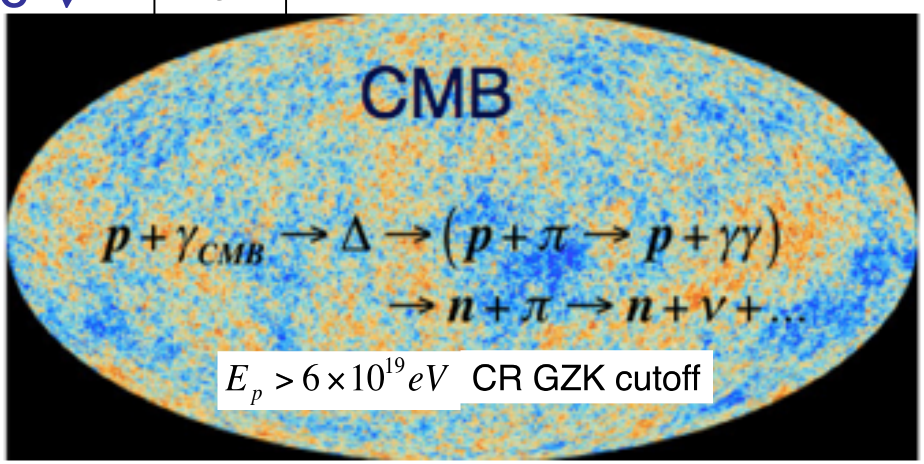
$\Phi_\nu \sim E_\nu^{-\gamma_\nu}$



- “GZK” cosmogenic ν

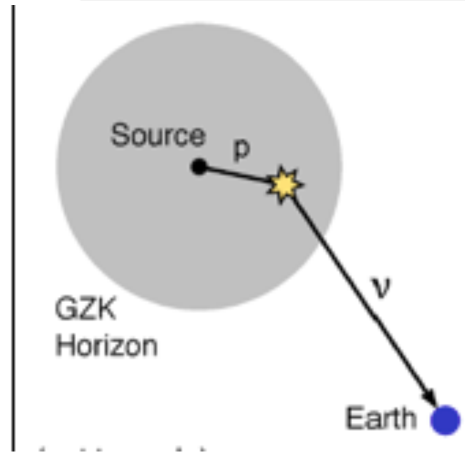
EeV





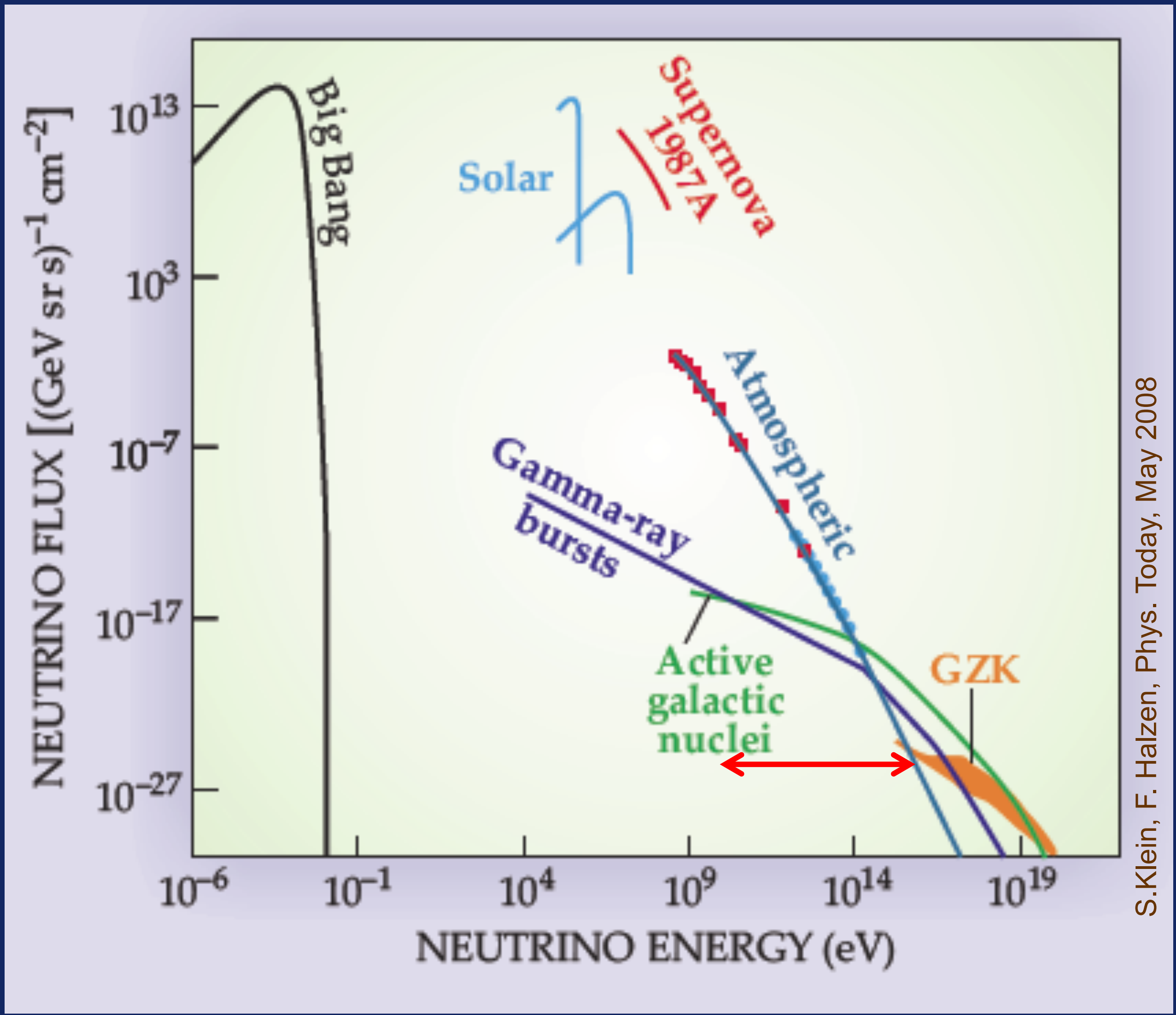
$p+\gamma_{CMB}\rightarrow\Delta\rightarrow(p+\pi\rightarrow p+\gamma\gamma)$
$\rightarrow n+\pi\rightarrow n+\nu+\ldots$

$E_p > 6\times10^{19}eV$ CR GZK cutoff



Extremely HE Universe beyond GZK sphere (50-100 Mpc) inaccessible with CR or γ-rays

High Energy Universe: ν



S.Klein, F. Halzen, Phys. Today, May 2008

Neutrino telescopes:

Discovery of astrophysical diffuse ν flux & ν source searches

Connection to EIC: strong interactions

- **pA (AA)** HE Cosmic Rays:
  - *'beam' flux from astro sources, (fixed) target nuclei (=Earth atmosphere)*
- **νp(n) (νA)** HE Neutrinos:
  - *production of atm. ν's (hadronic interactions)*
  - *'beam' flux from astro sources and from Earth atmosphere, (fixed) target = H_2O (water/ice).*

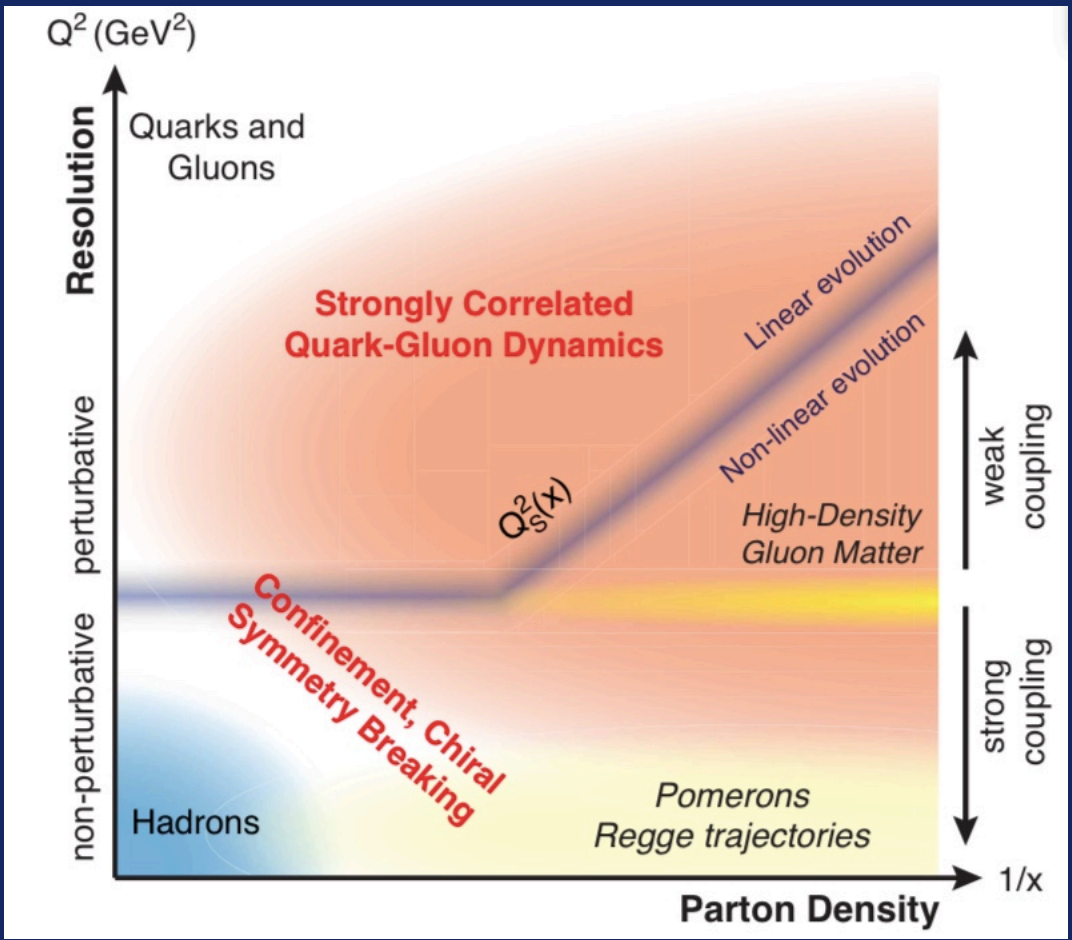


Fig. from: E.C. Aschenauer et al: arXiv:1708.01527

UHECR CR & ν's

Saturated gluons, Dipole picture, Color Glass Condensate

See talk by Raju Venugopalan this morning

CR:
Low x-Low Q^2: largest part of cross section

Connection to EIC: strong interactions

- **pA (AA)** HE Cosmic Rays:
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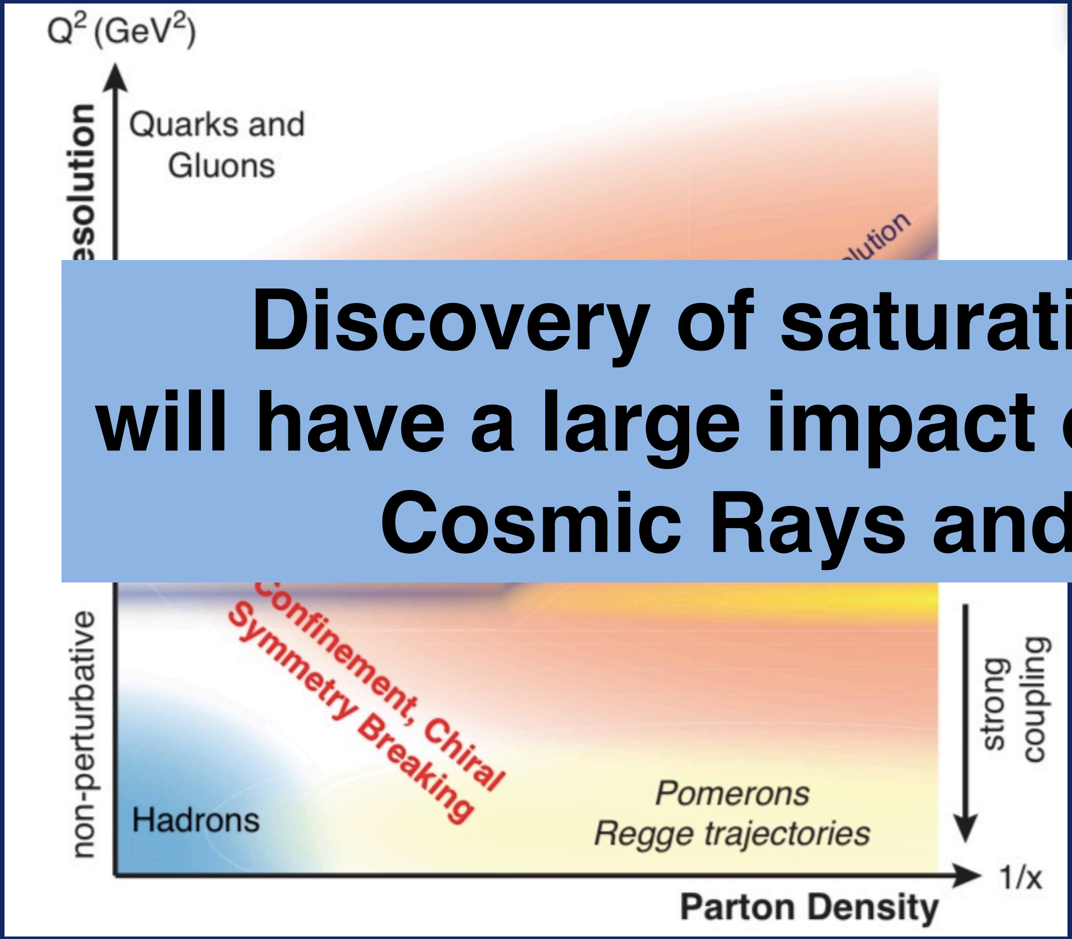


Fig. from: E.C. Aschenauer et al: arXiv:1708.01527

UHECR CR & ν's

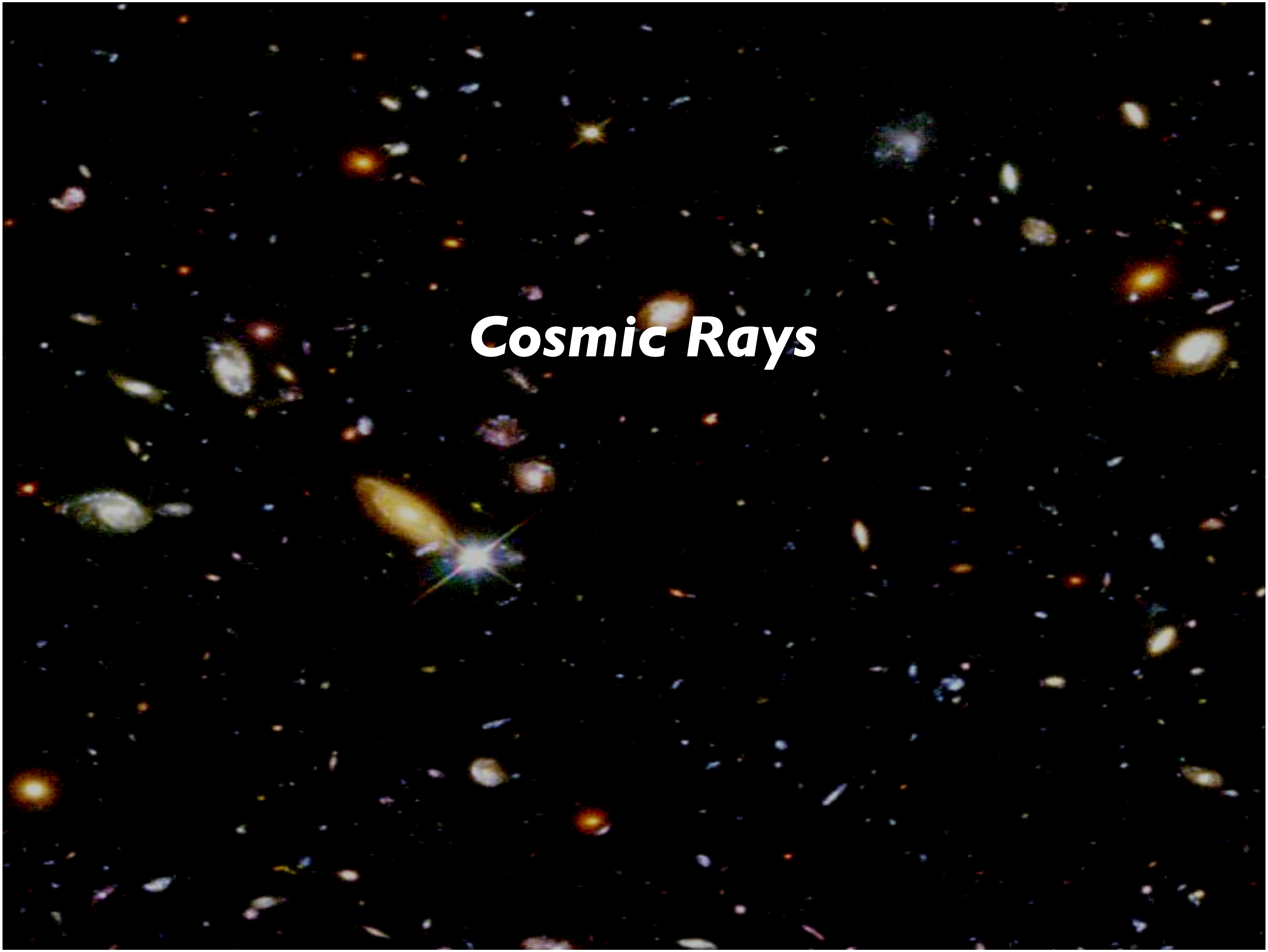
Saturated gluons,

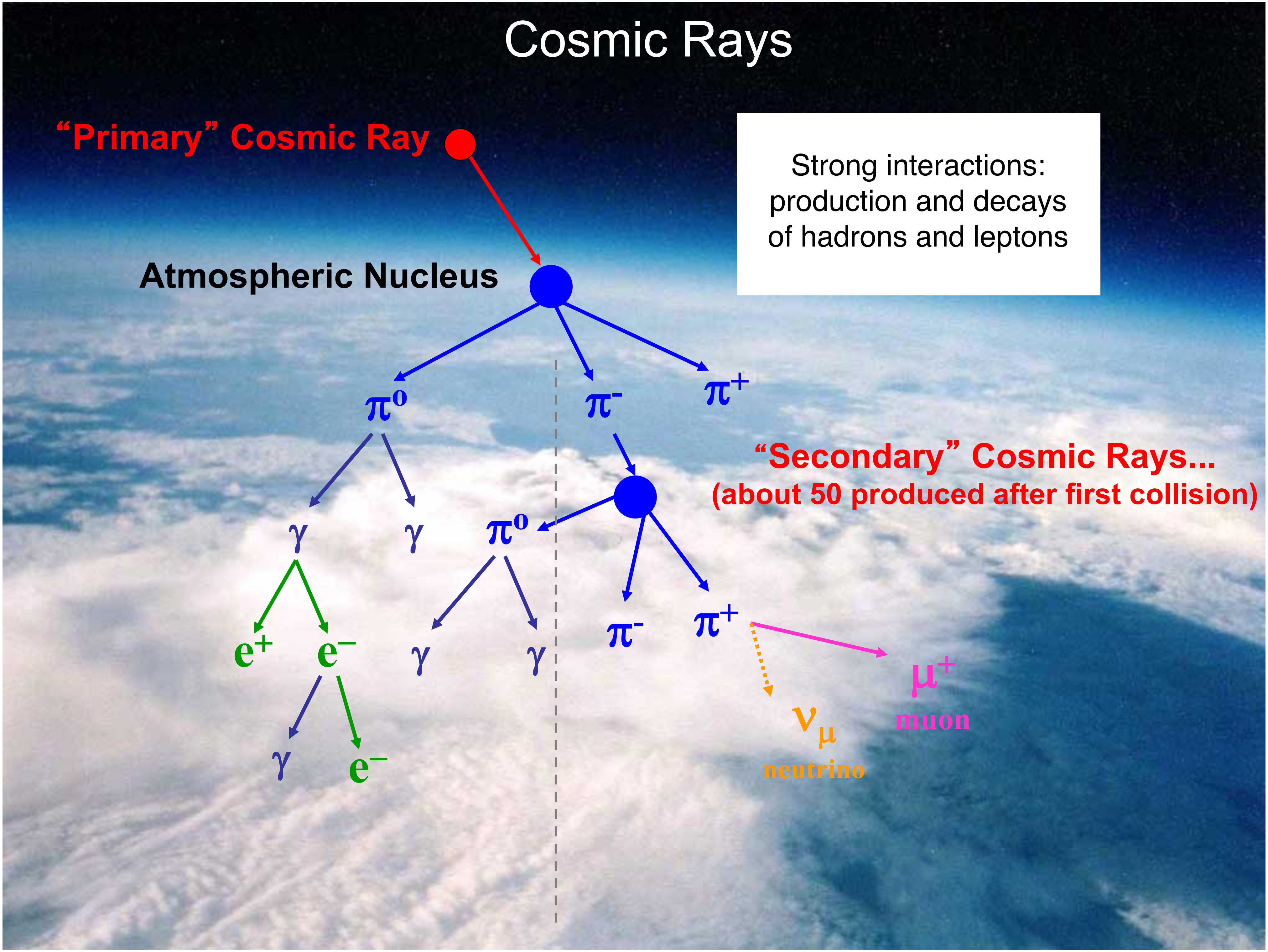
Dipole picture, Color Glass Condensate

Discovery of saturation at the EIC will have a large impact on the physics of Cosmic Rays and Neurinos

CR:
Low x-Low Q^2: largest part of cross section

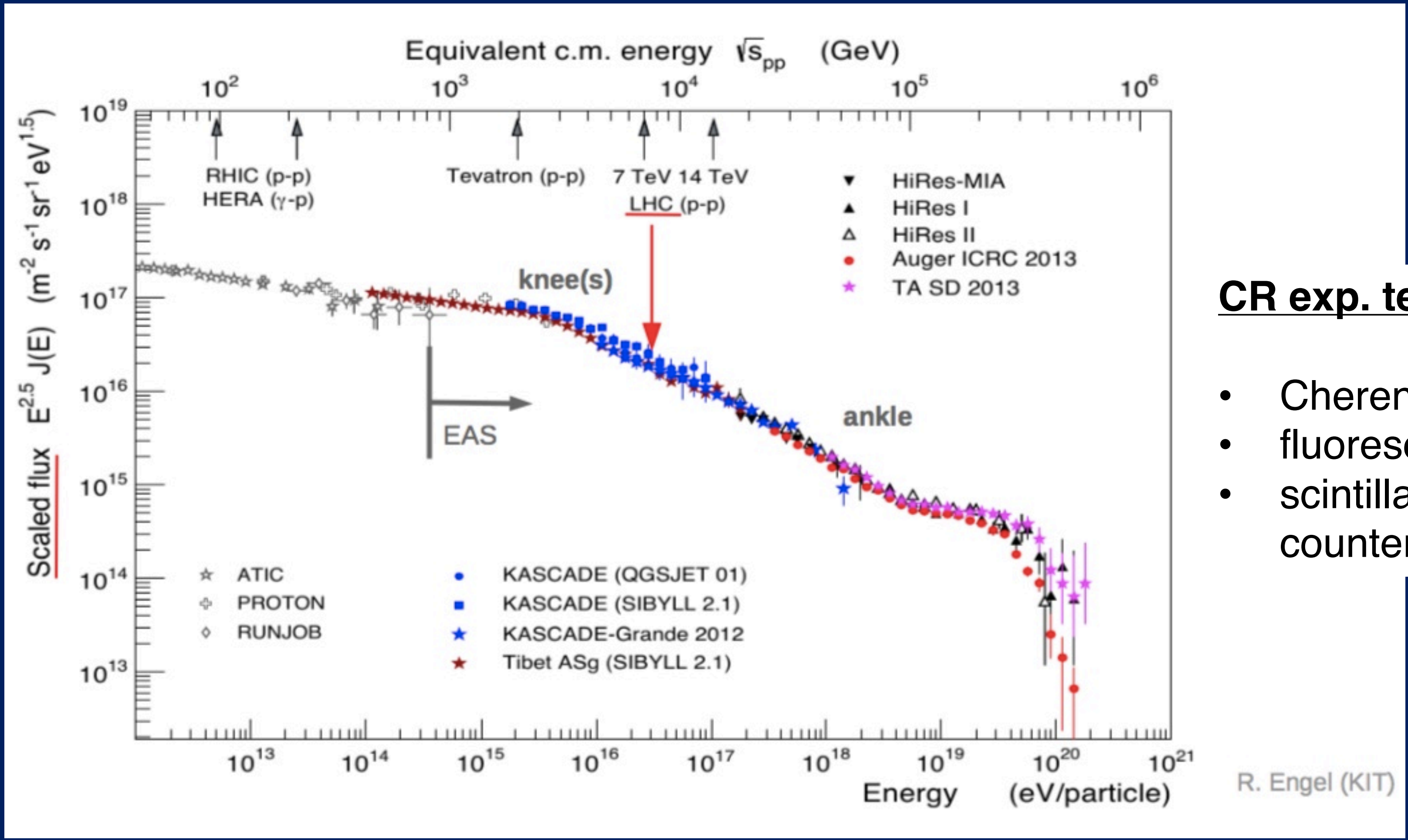
Cosmic Rays




Cosmic Rays
"Primary" Cosmic Ray
Strong interactions:
production and decays
of hadrons and leptons
Atmospheric Nucleus
π^o
π^-
π^+
"Secondary" Cosmic Rays...
(about 50 produced after first collision)
γ
γ
π^o
e^+
e^-
γ
γ
π^-
π^+
μ^+
muon
ν_μ
neutrino
γ
e^-

Cosmic Rays

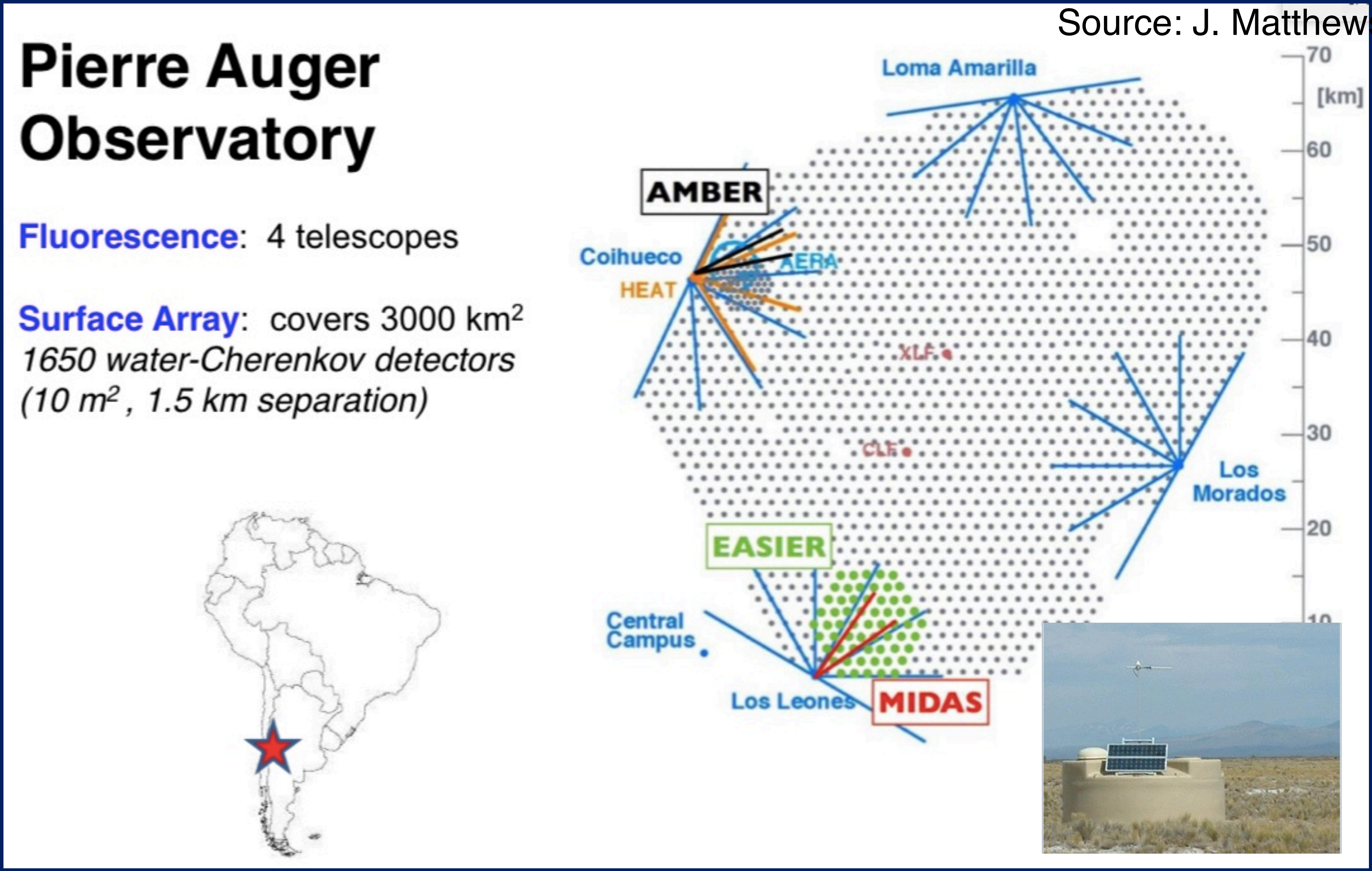
Ultra High Energy Cosmic Rays – reach well beyond LHC c.m. energy



CR exp. techniques

- Cherenkov
- fluorescence
- scintillators muon counters

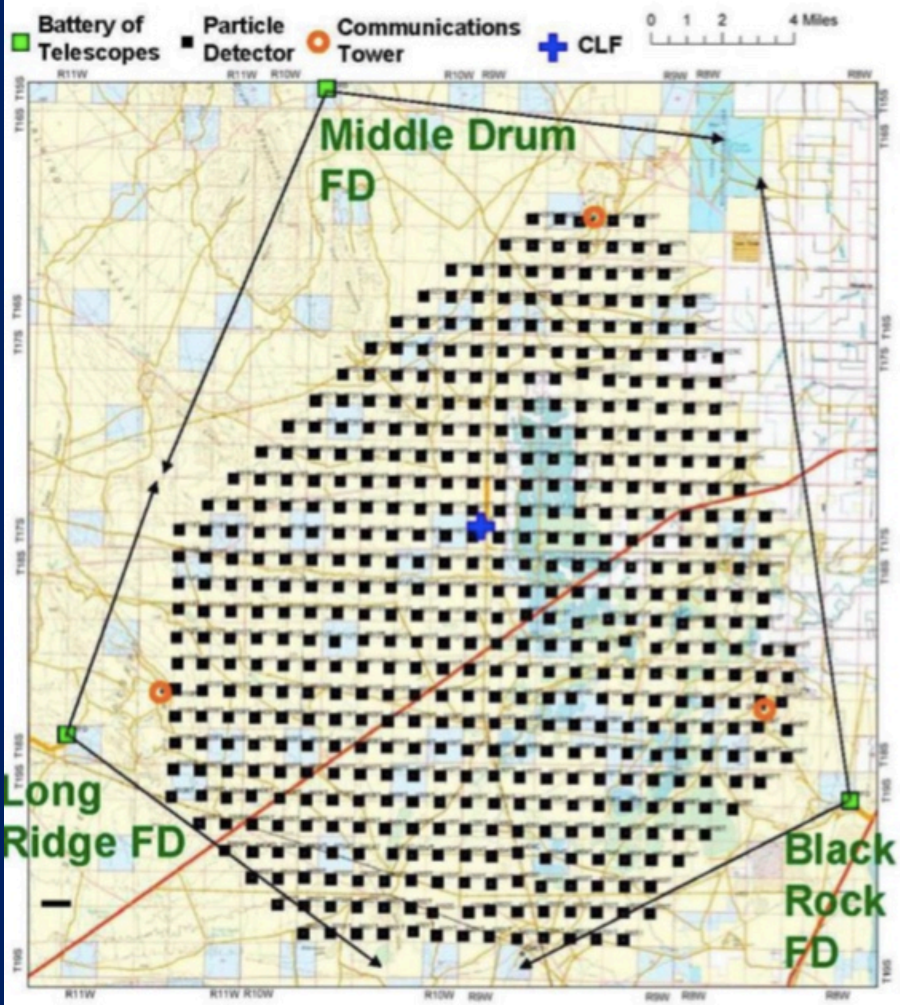
Cosmic Rays: Experiments



Source: J. Matthews

Largest CR experiment

Cosmic Rays: Experiments



Telescope Array

Fluorescence: 3 telescopes

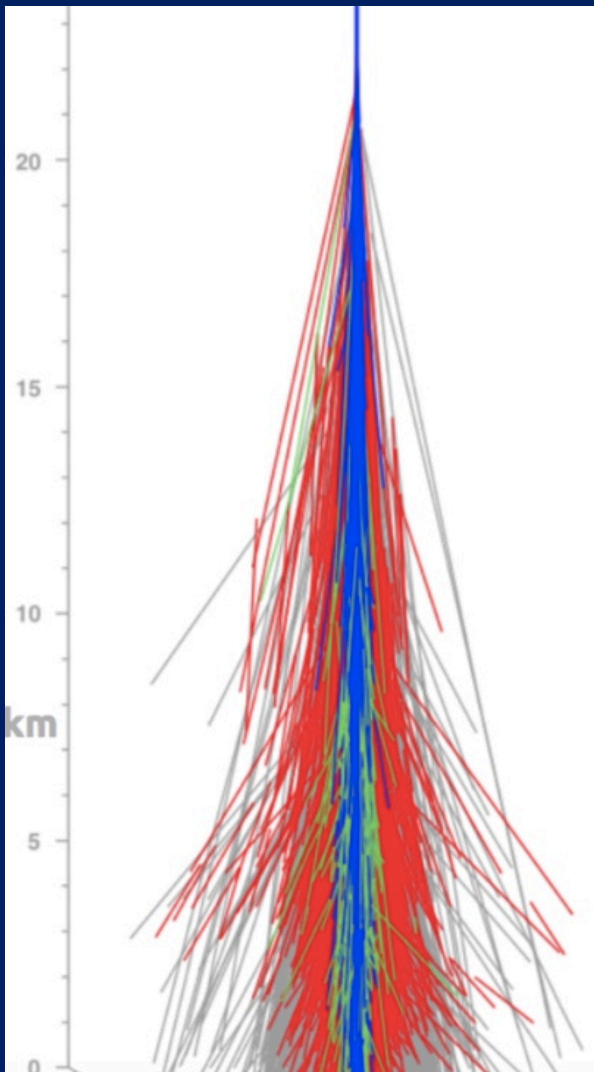
Surface Array: covers 700 km^2

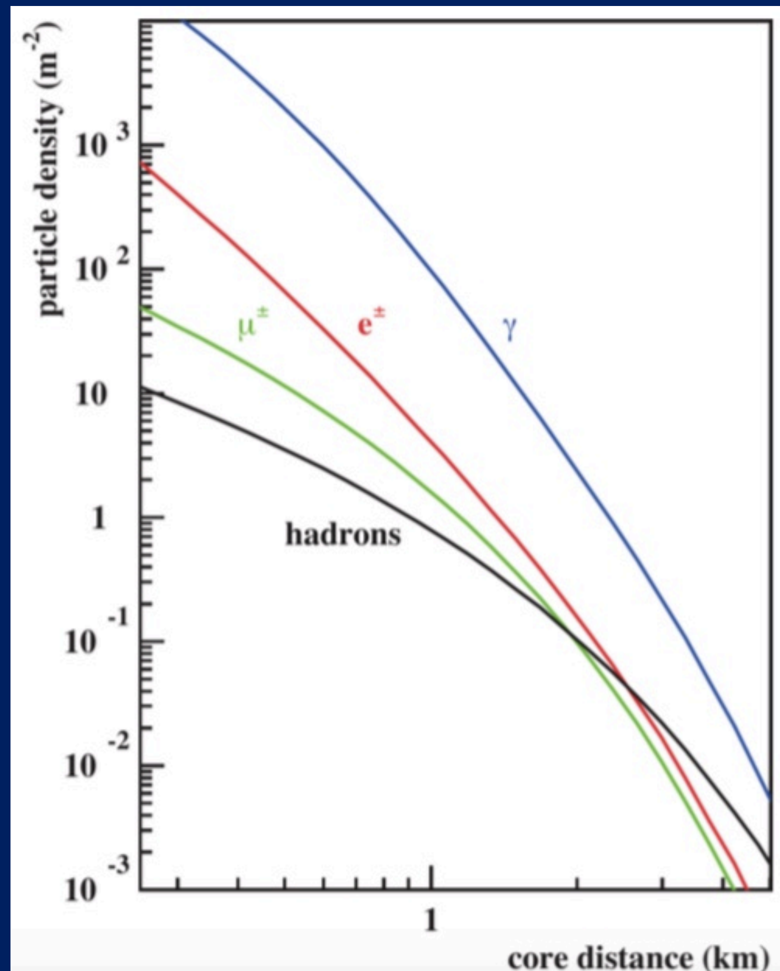
507 scintillator stations (3 m^2, 1.2 km separation)

Source: J. Matthews

Japan's funding to upgrade/expand TA (4xsize~2500km^2)
Largest CR experiment in the Northern Hemisphere

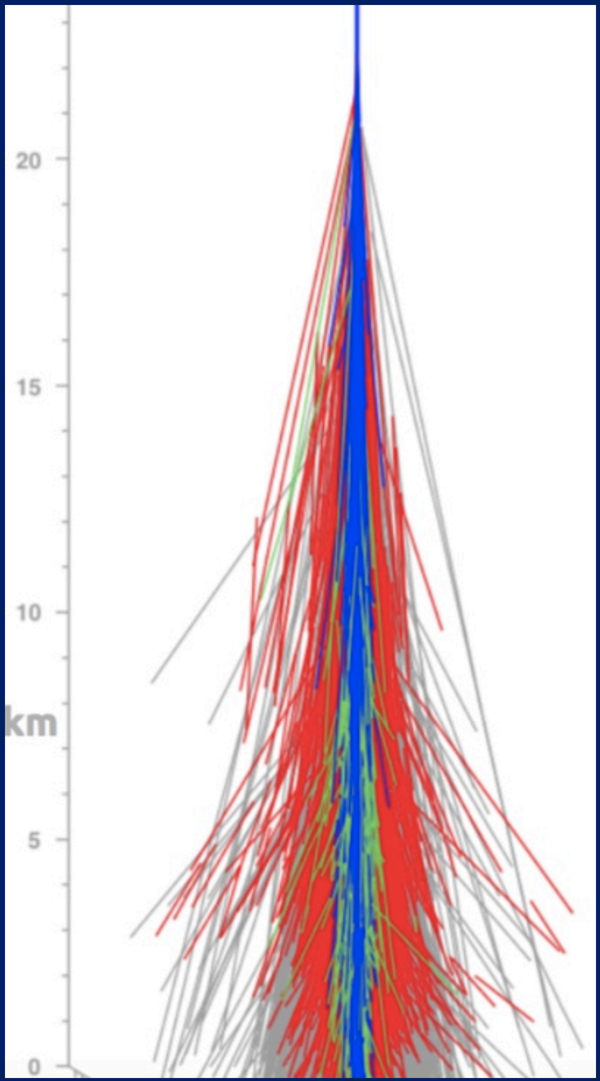
Cosmic Rays: Showers



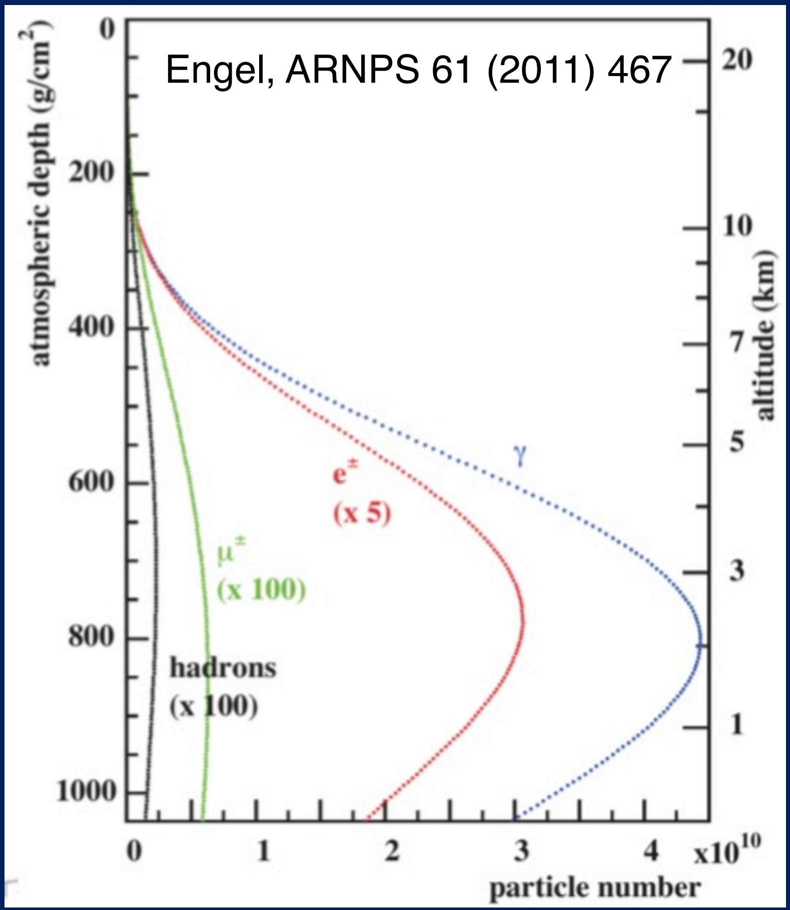


Figs. from D.Veberic

Cosmic Rays: Showers



Figs. from D.Veberic



EM, X_{max} first interactions

μ are produced late: sensitive to hadronic interactions

Use hybrid events to disentangle particle physics and composition

Cosmic Rays: Showers

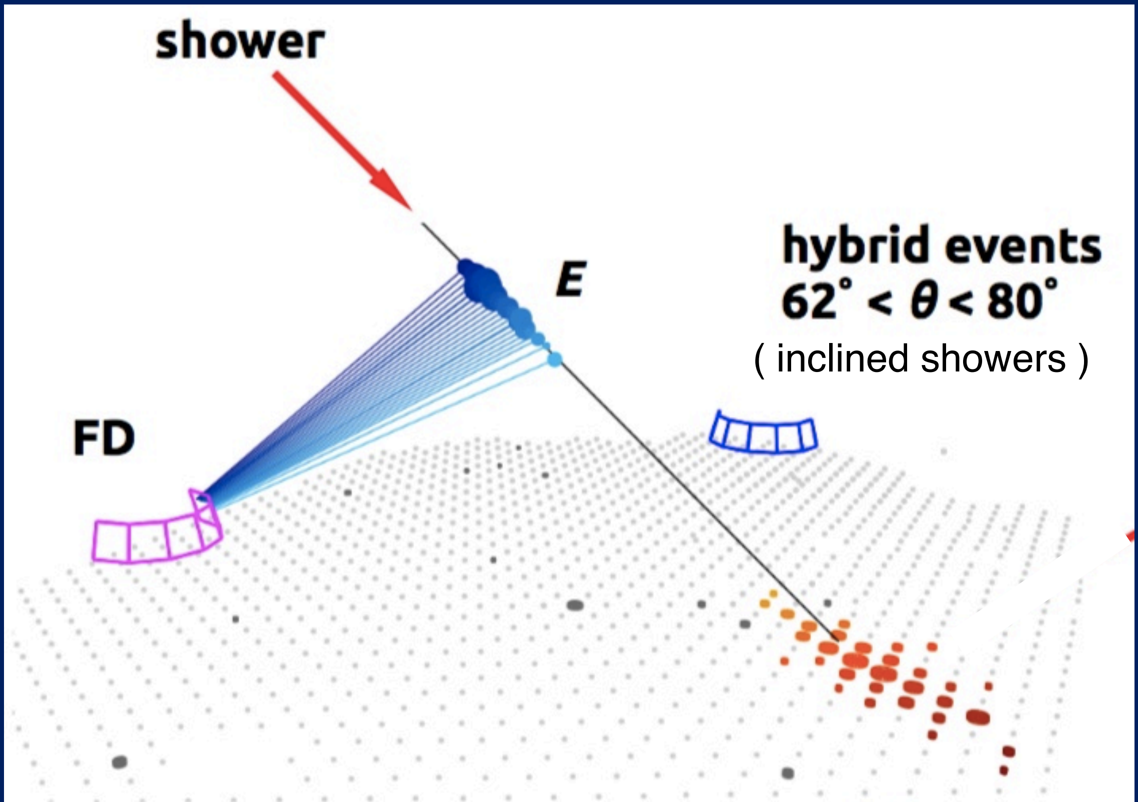


Fig. from D.Veberic

<u>Surface Arrays:</u>
continuous operation, large size (statistics)

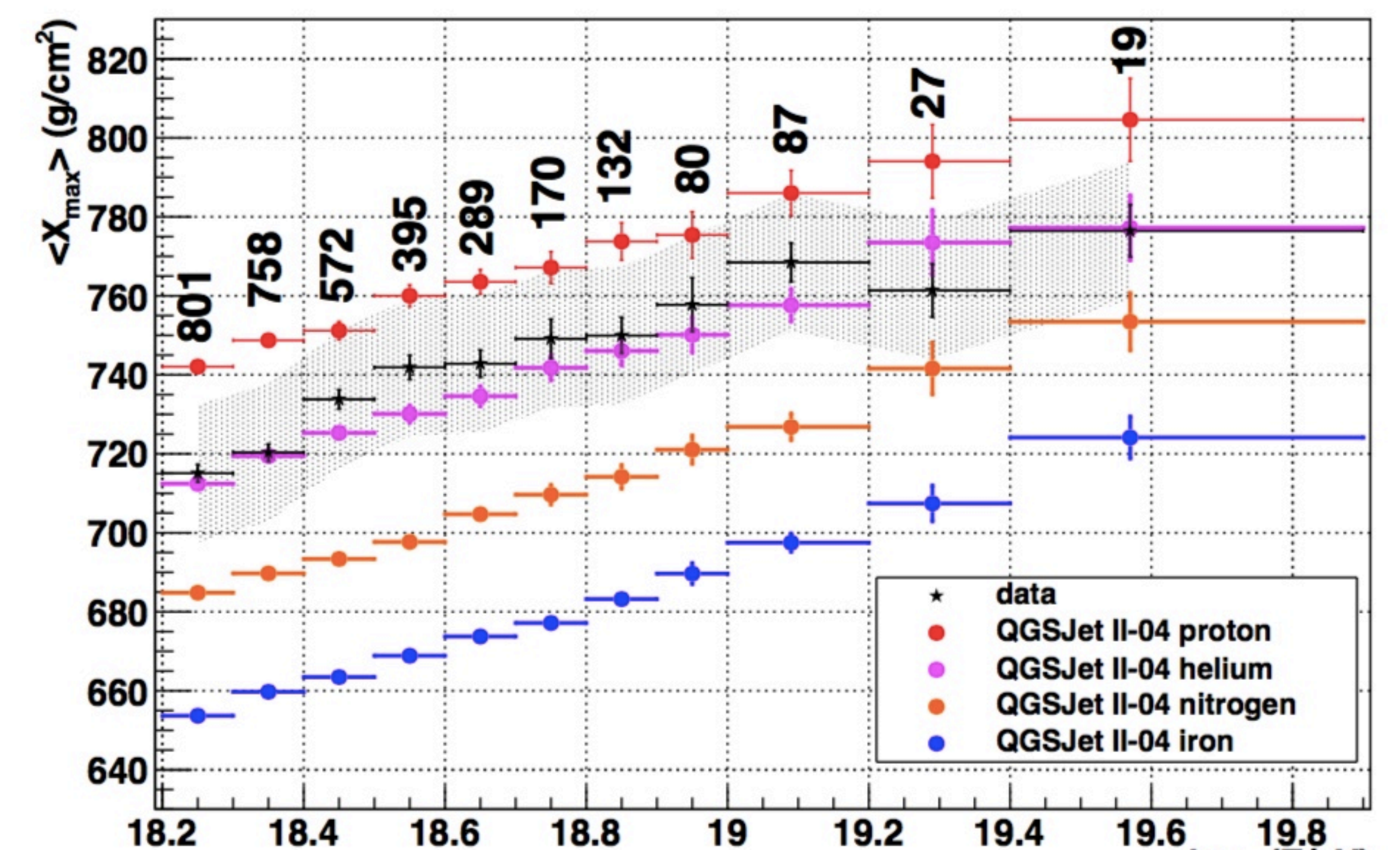
<u>Fluorescence:</u>
'calorimetry' = good energy resolution (spectrum)

EM, X_{max} first interactions
μ are produced late: sensitive to hadronic interactions

Use hybrid events to disentangle particle physics and composition

Cosmic Rays: Composition (Telescope Array)

Depth of shower maximum

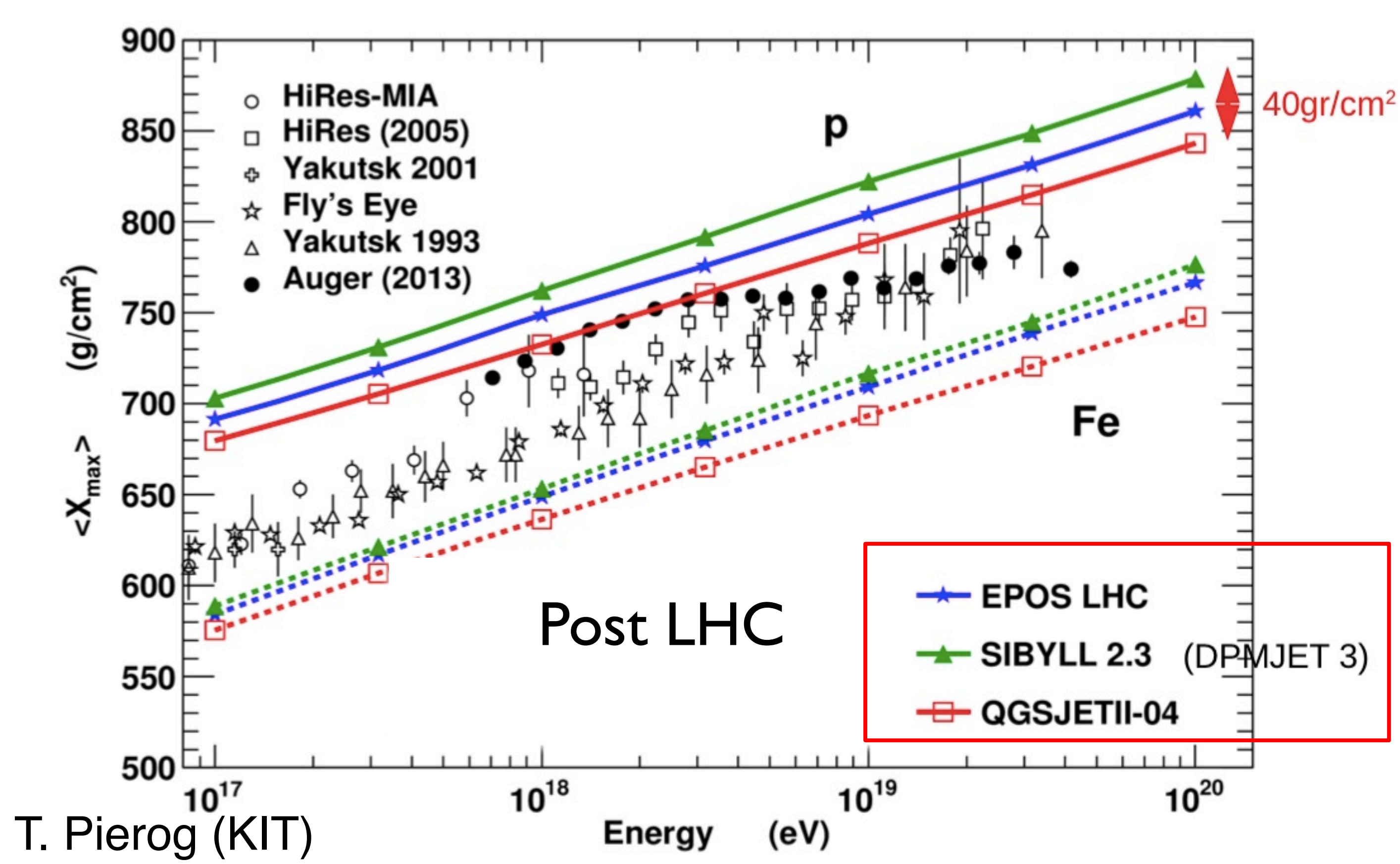


Telescope Array: arXiv:1801.09784

TA composition measurement indicates CR's are <u>protons</u> at ultra high energies.
Conclusion relies on correct hadronic interaction modelling.

Cosmic Rays: Composition (Auger)

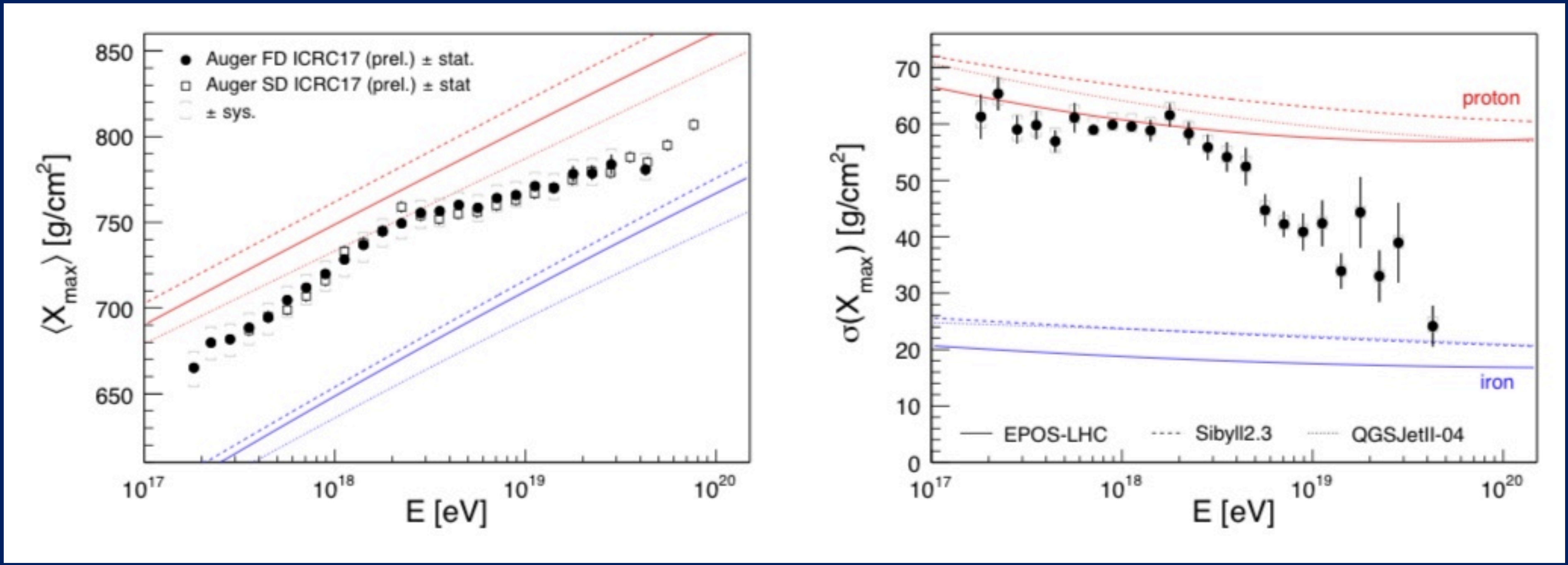
Depth of shower maximum



- ❑ Data compared with predictions of recent versions (> 2016) of Hadronic Interactions (HI) MC models (LHC-inspired/tuned)
- ❑ Xmax, sources of HI uncertainties
  - Forward physics: photon spectra and diffraction
  - Nuclear interactions (extrapolations from p-p to p-Air: p-O needed, p-Pb not well reproduced)

Cosmic Rays: Composition (Auger)

Depth of shower maximum

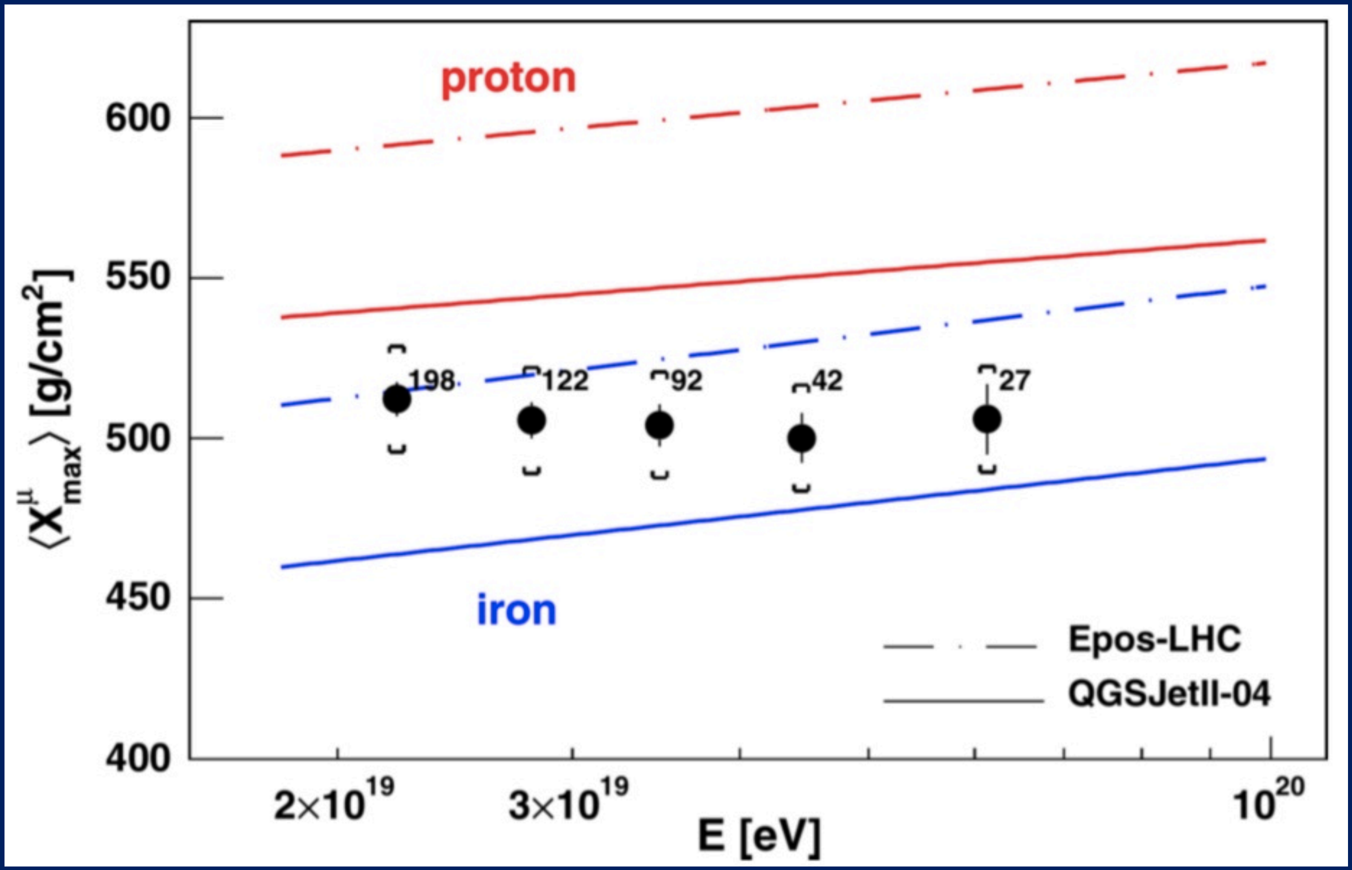


Auger data, fig. from arXiv:1710.09478

- ❑ Auger composition measurement indicates CR's are <u>heavier than protons</u> at ultra high energies.
- ❑ Tension between TA and Auger results

Cosmic Rays: Composition (Auger)

Muon depth of maximum

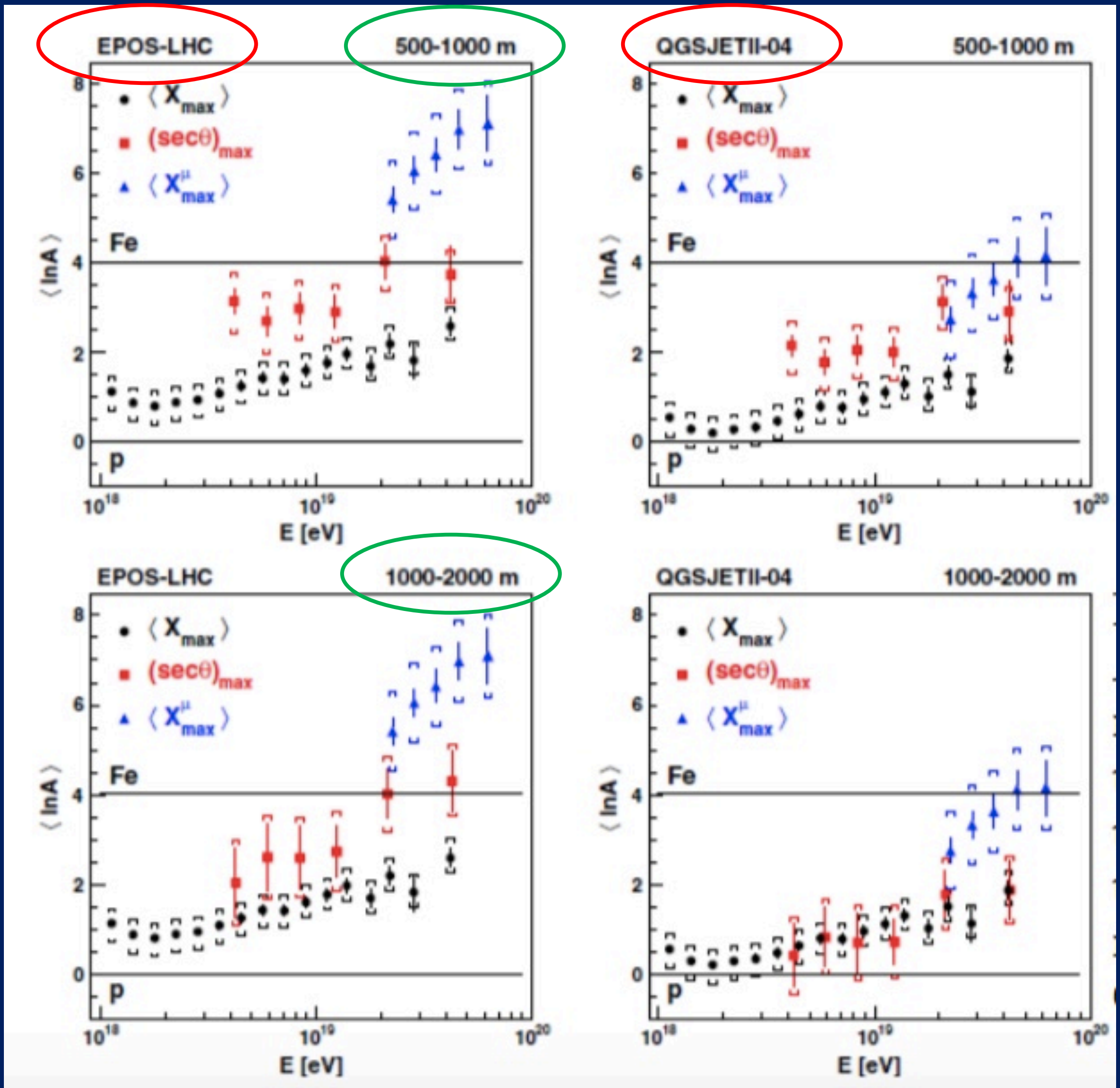


Auger, PRD 90 (2014) 012012

Auger composition measurement with muons indicates CR's are <u>iron's</u> at ultra high energies.

Cosmic Rays: Composition

Average primary CR mass ⟨lnA⟩ predicted by each HI model from ⟨X_{max}⟩ and ⟨X_{max}^{μ}⟩ and the data.

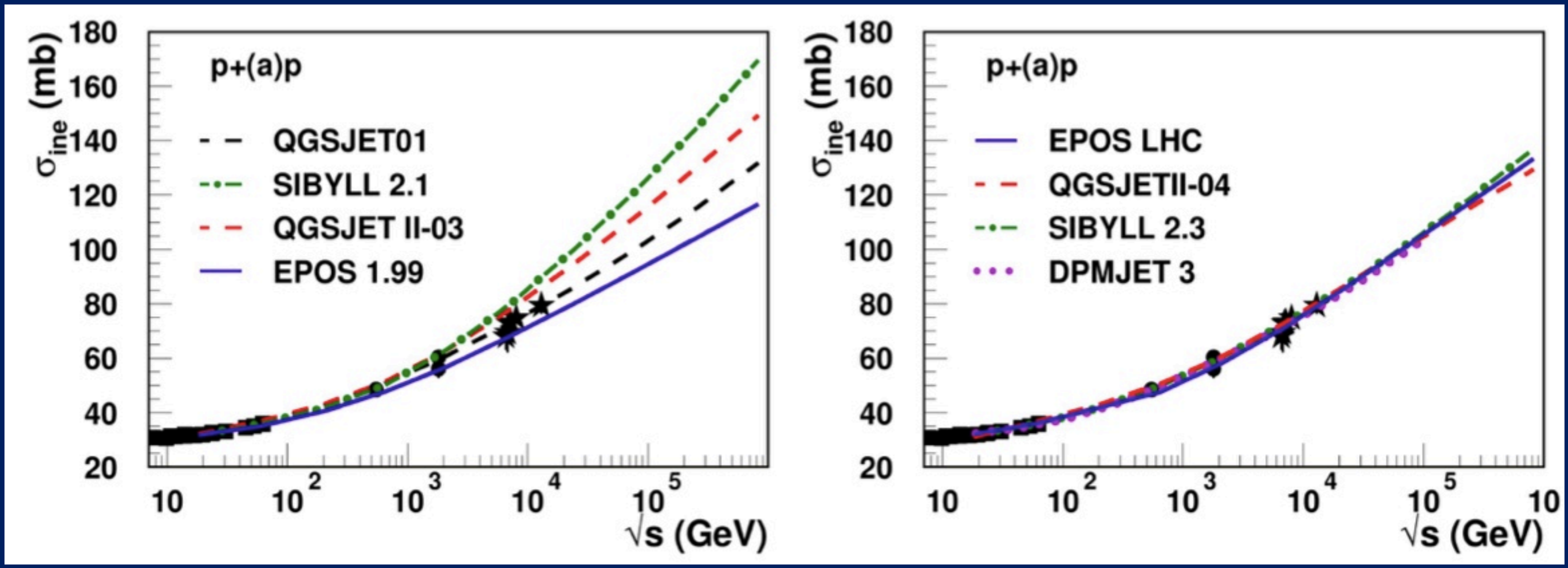


Inconsistency between FD (e-m shower component) and SD (hadronic shower component) Auger data

SD not described by models (observed strong 30%-60% and increasing with energy deficit of muons). The same effect observed by TA [arXiv:1804.03877]

Modelling Hadronic Interactions: Impact of LHC

Before LHC data After LHC data

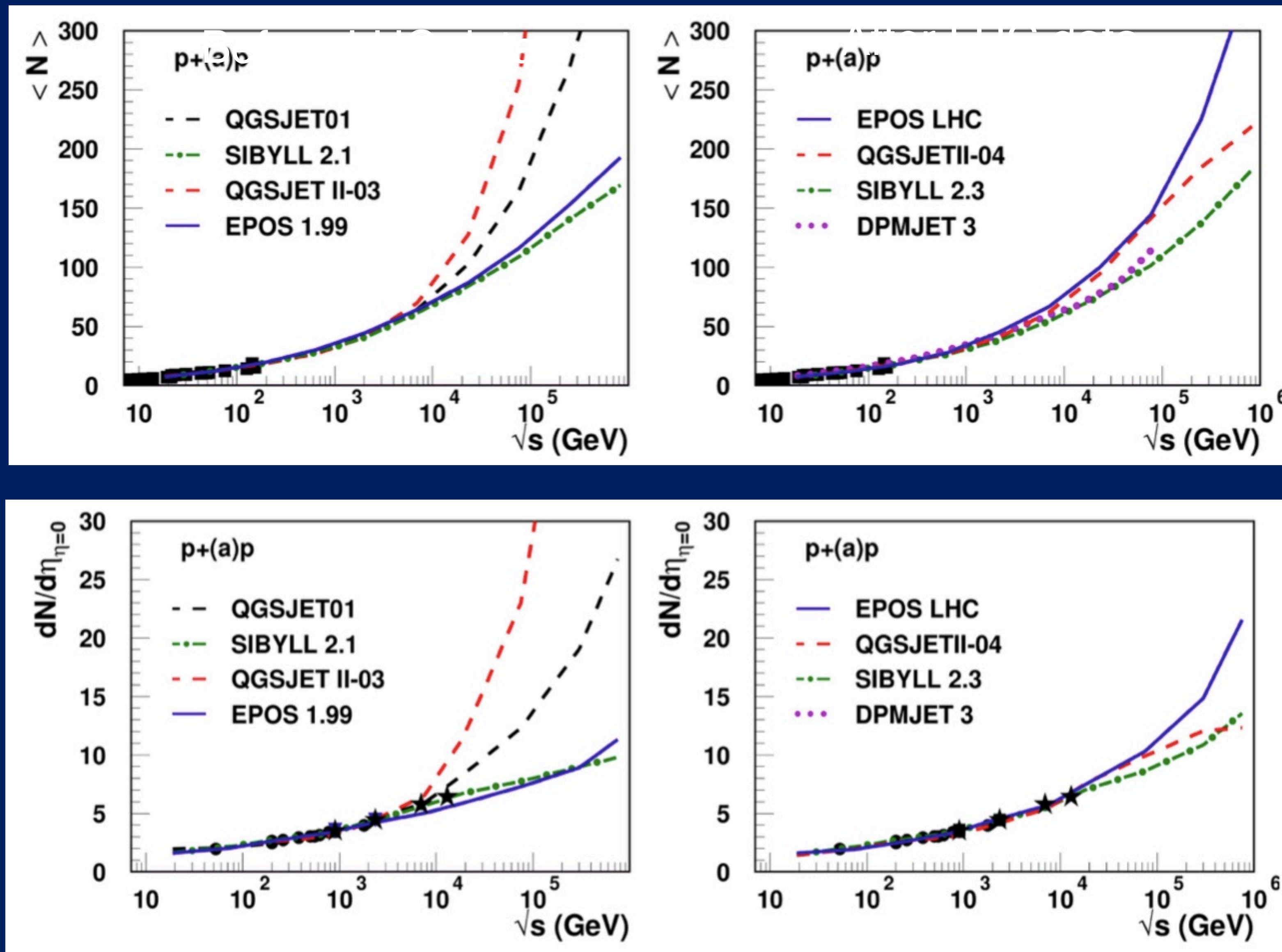


- All pre-LHC extrapolation models excluded.
- After LHC models predict the same pp cross section (low energies + extrapolations)

Figs from: T. Pierog (KIT)

Modelling Hadronic Interactions: Impact of LHC

Before LHC data | After LHC data



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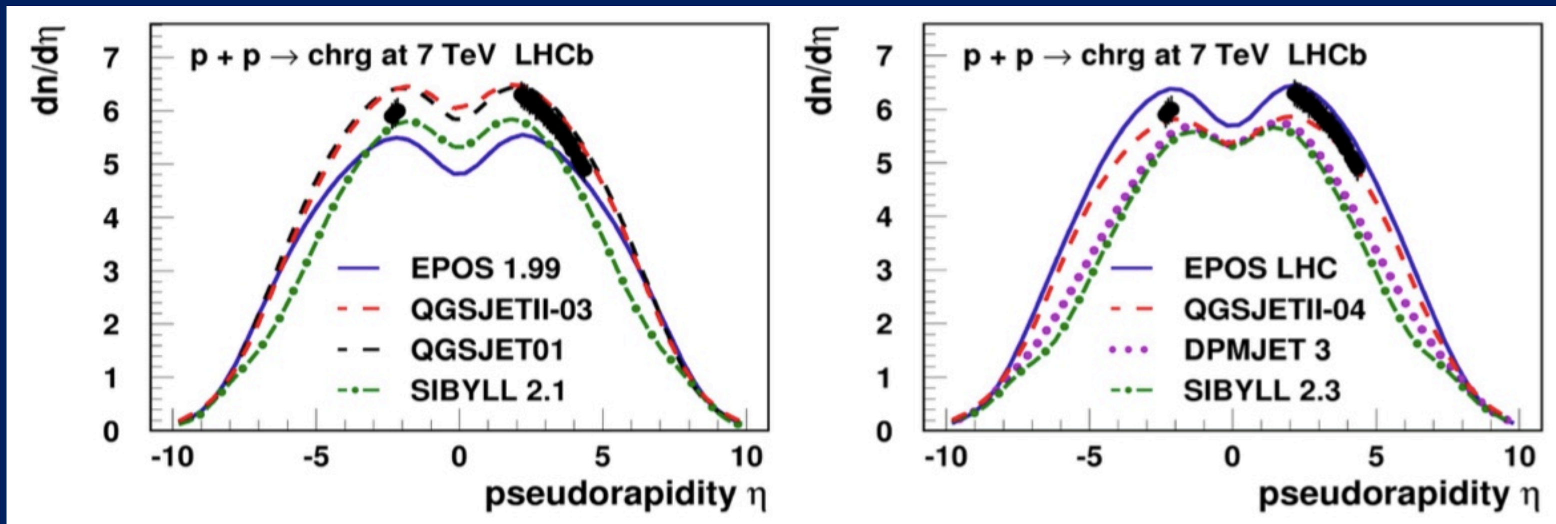
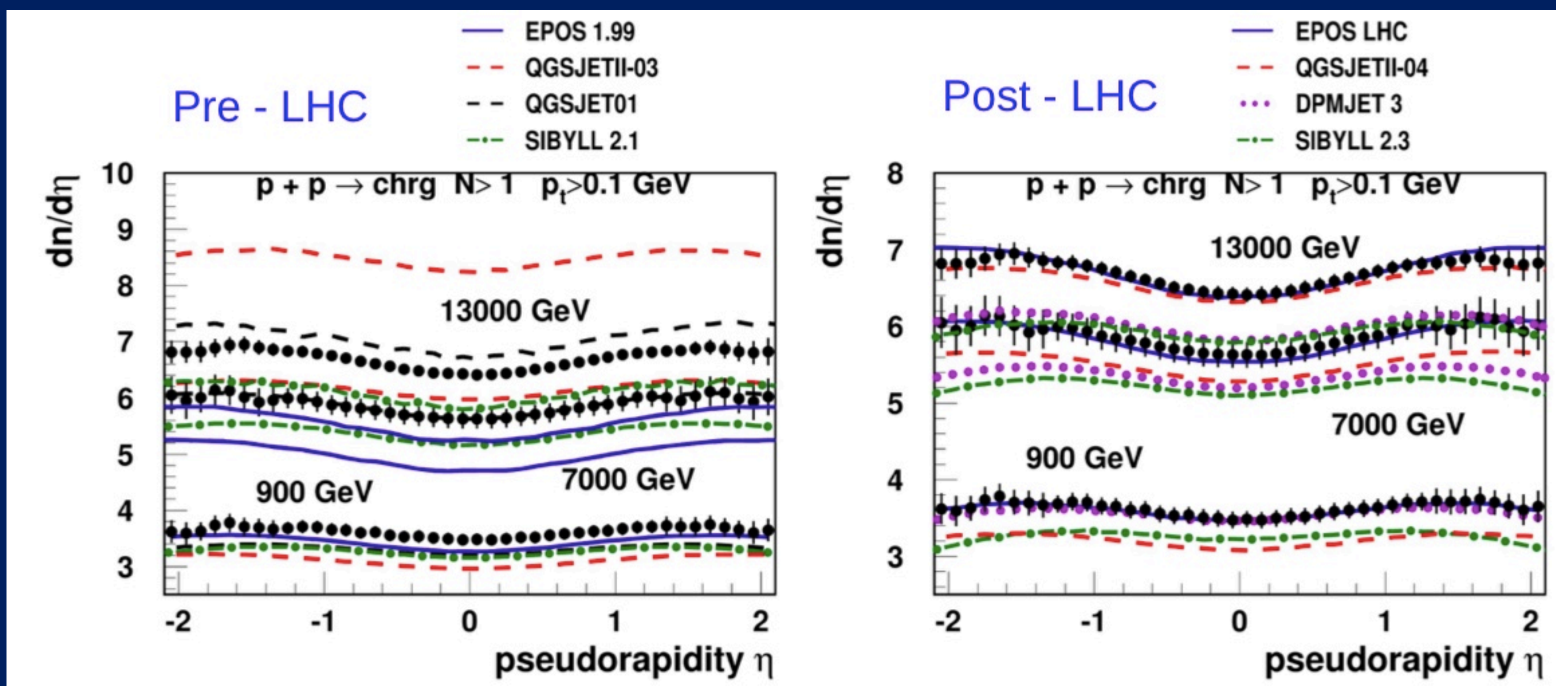
Modelling Hadronic Interactions: Impact of LHC

Before LHC data

After LHC data





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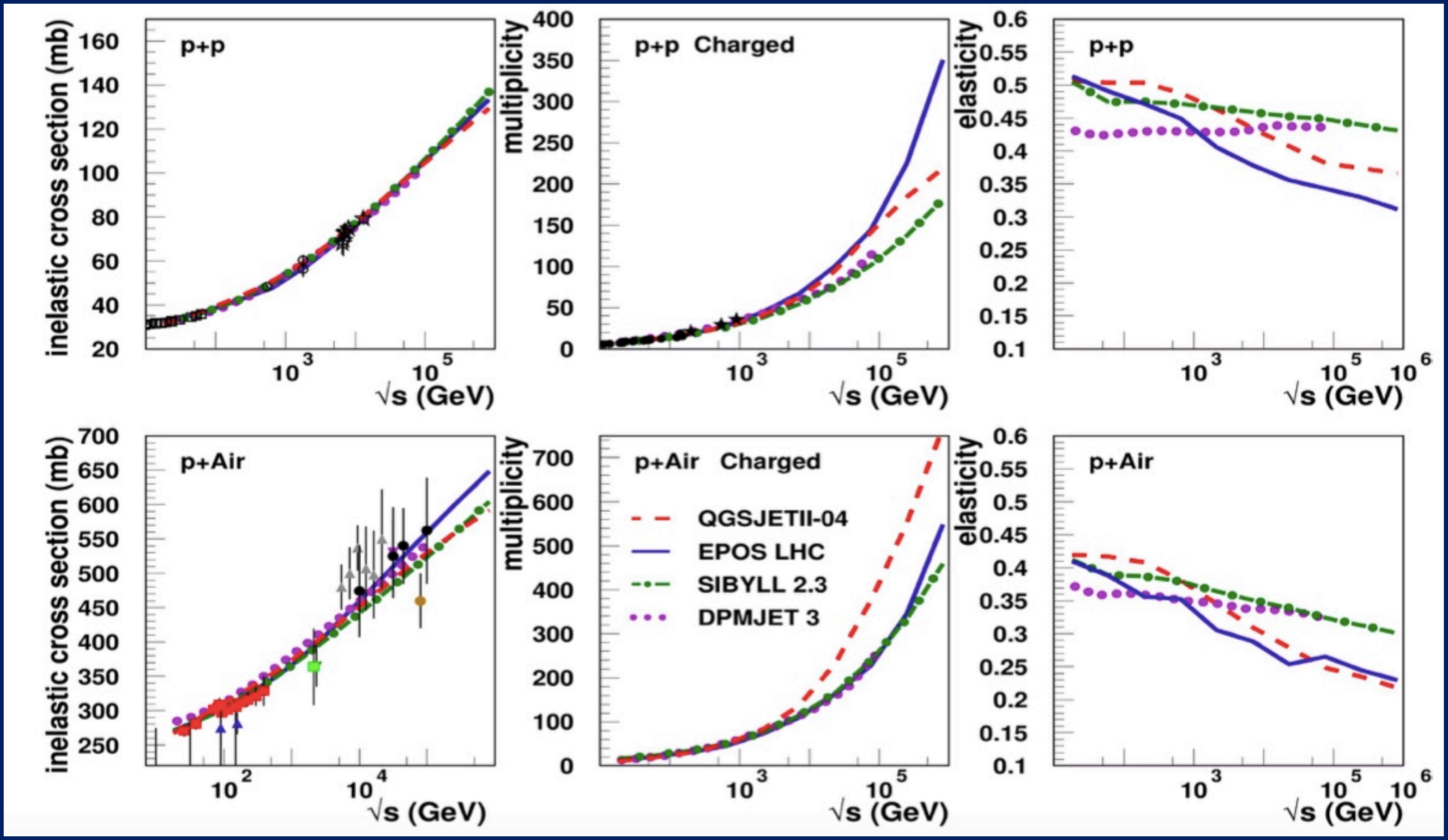
Modelling Hadronic Interactions: Impact of LHC

Before LHC data

After LHC data



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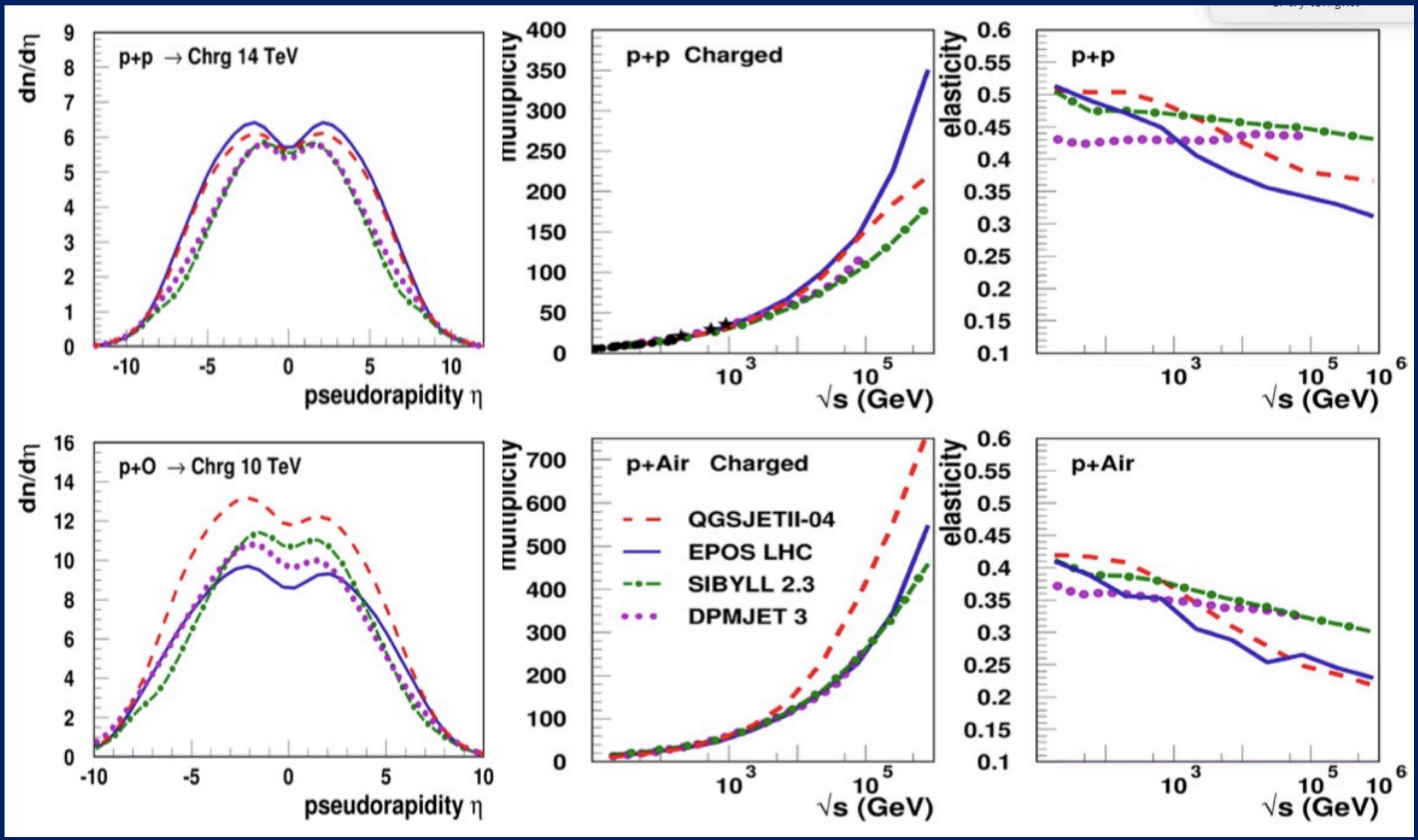
Modelling Hadronic Interactions: Impact of LHC

Before LHC data

After LHC data



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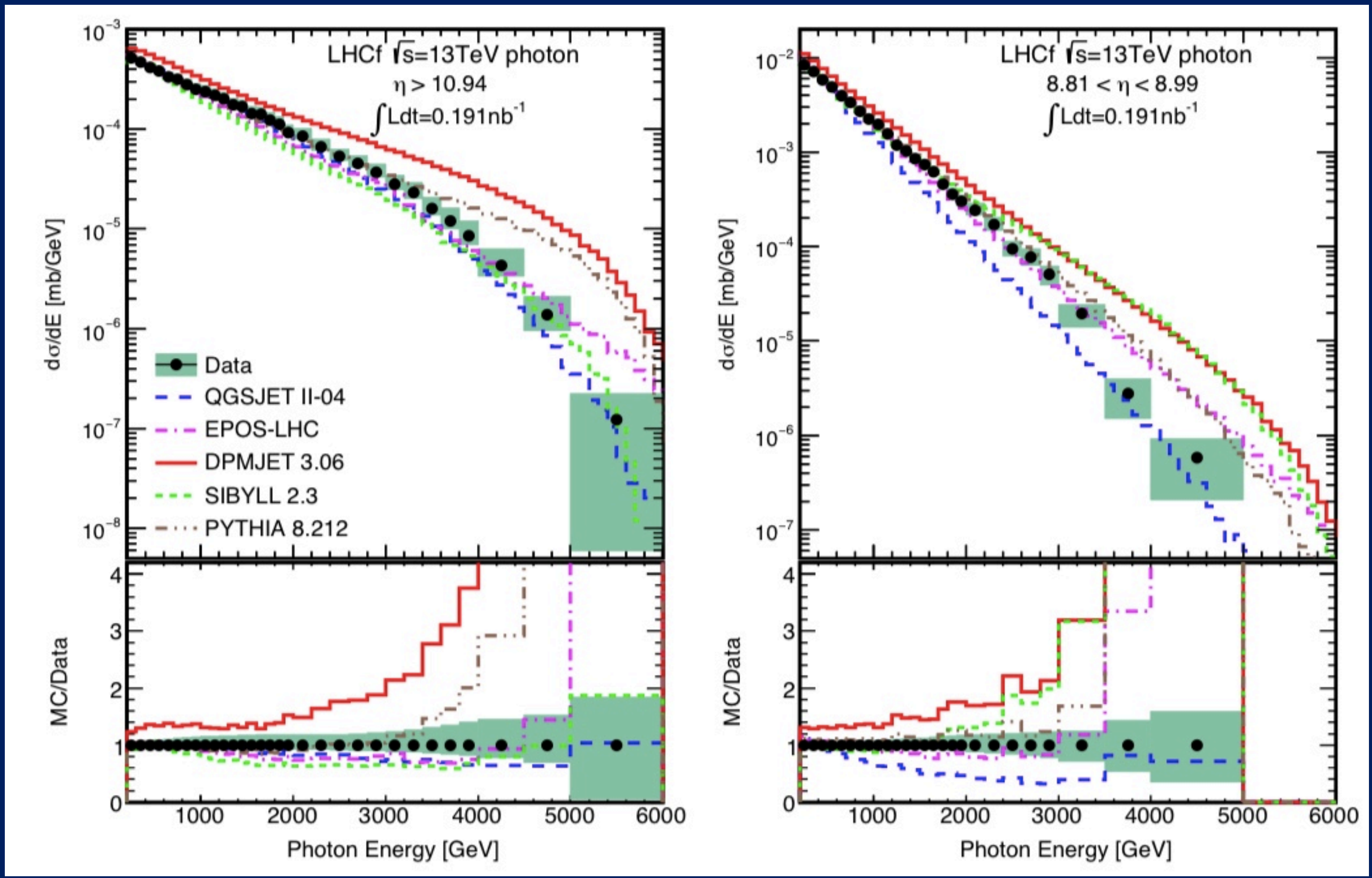
Modelling Hadronic Interactions: Impact of LHC

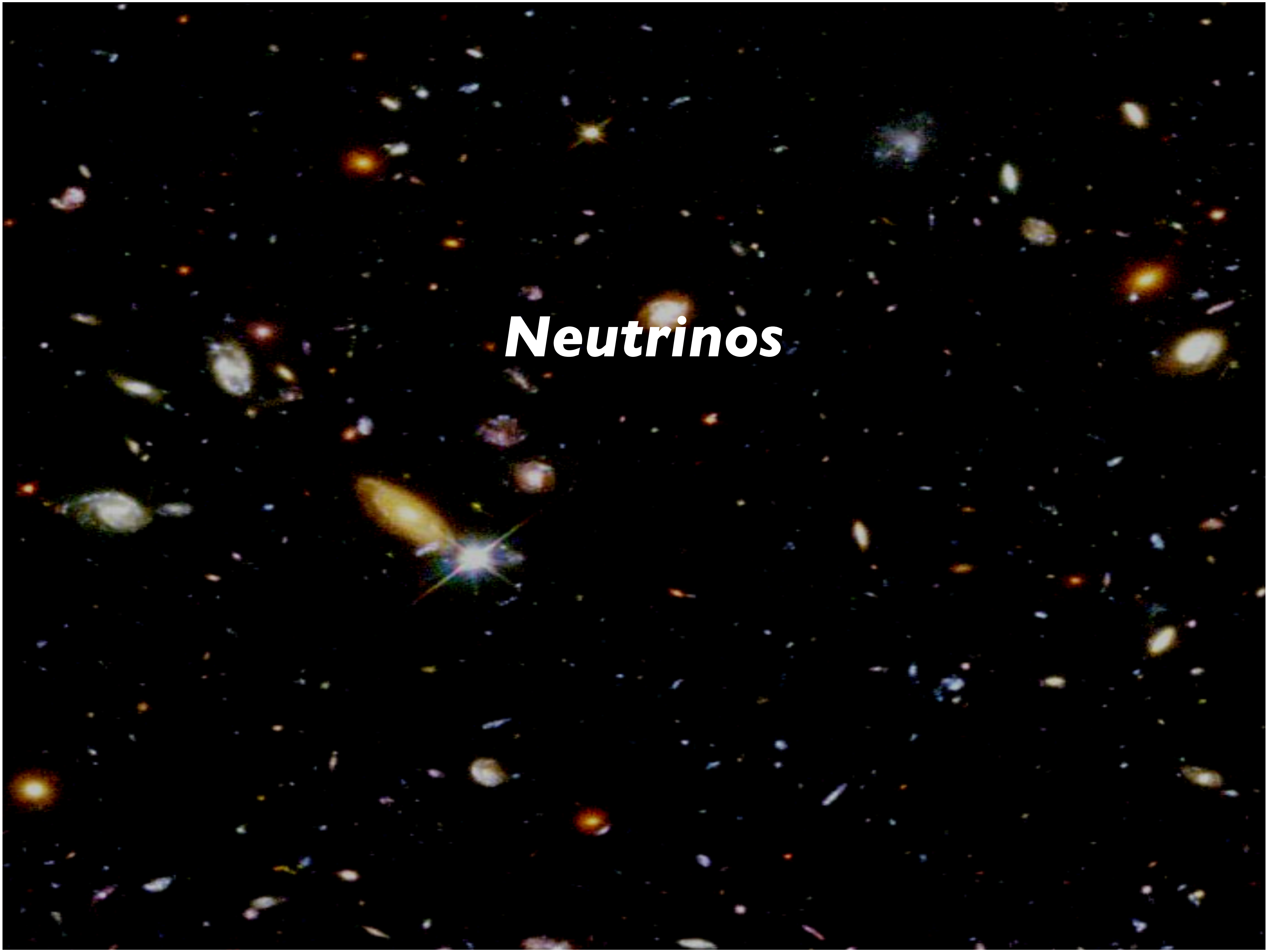
LHCf Forward Photon production



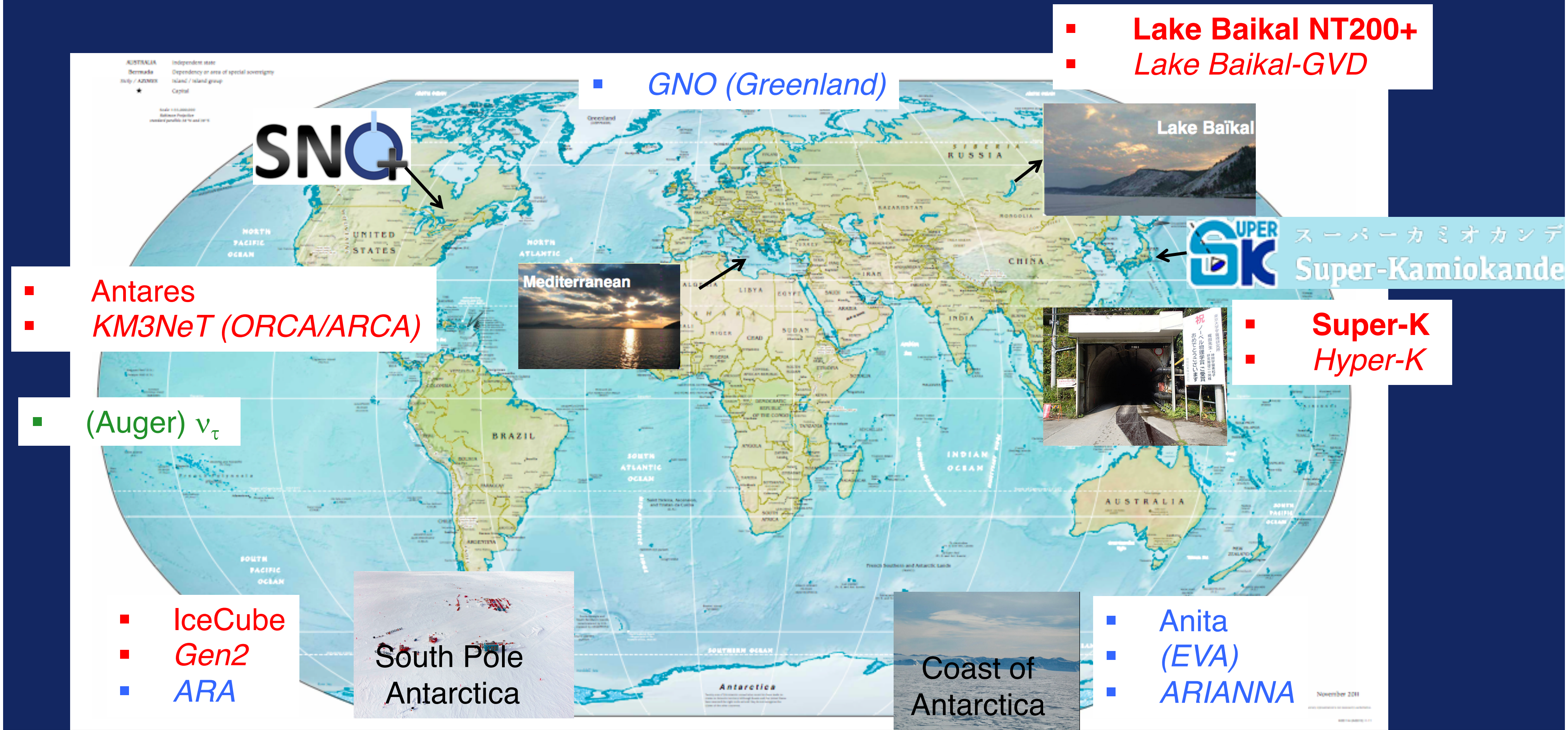
arXiv:1703.07678

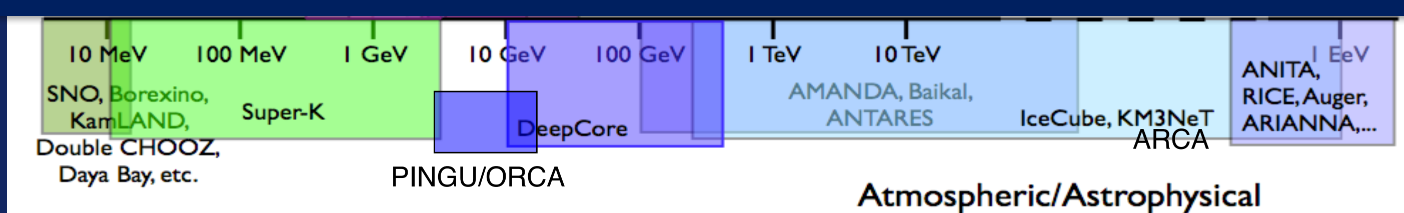
Disagreement between Data and Models

Room for further models improvement


Neutrinos

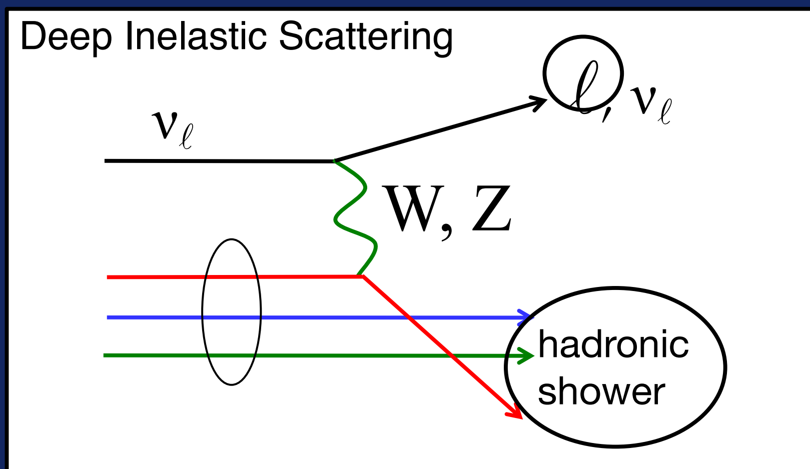
Neutrino Observatories: Present & Future



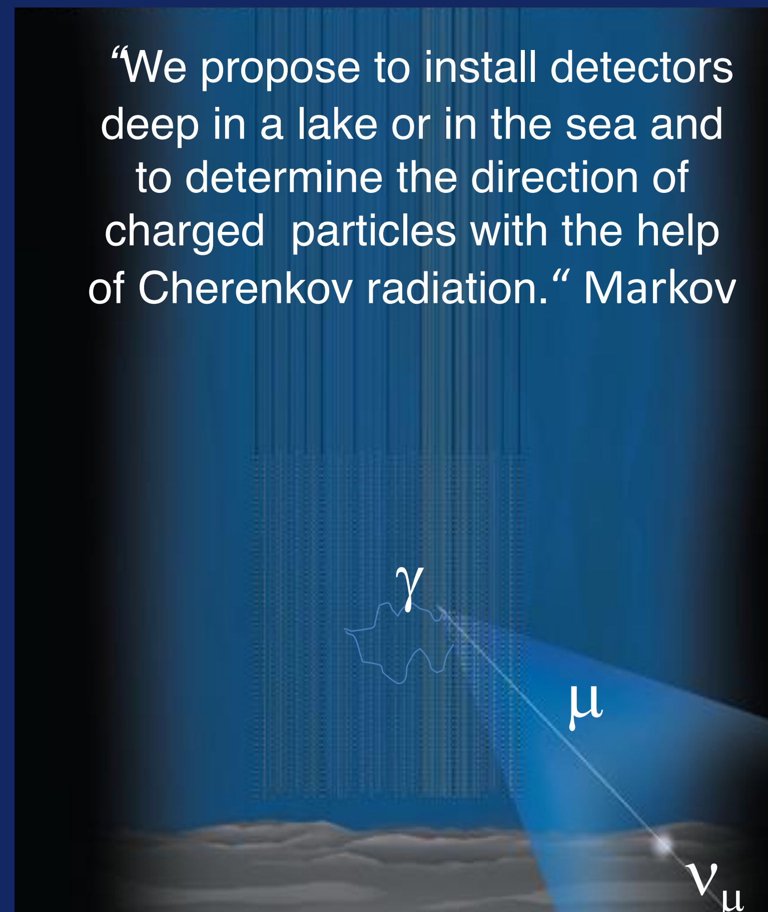


Neutrinos: Detection method

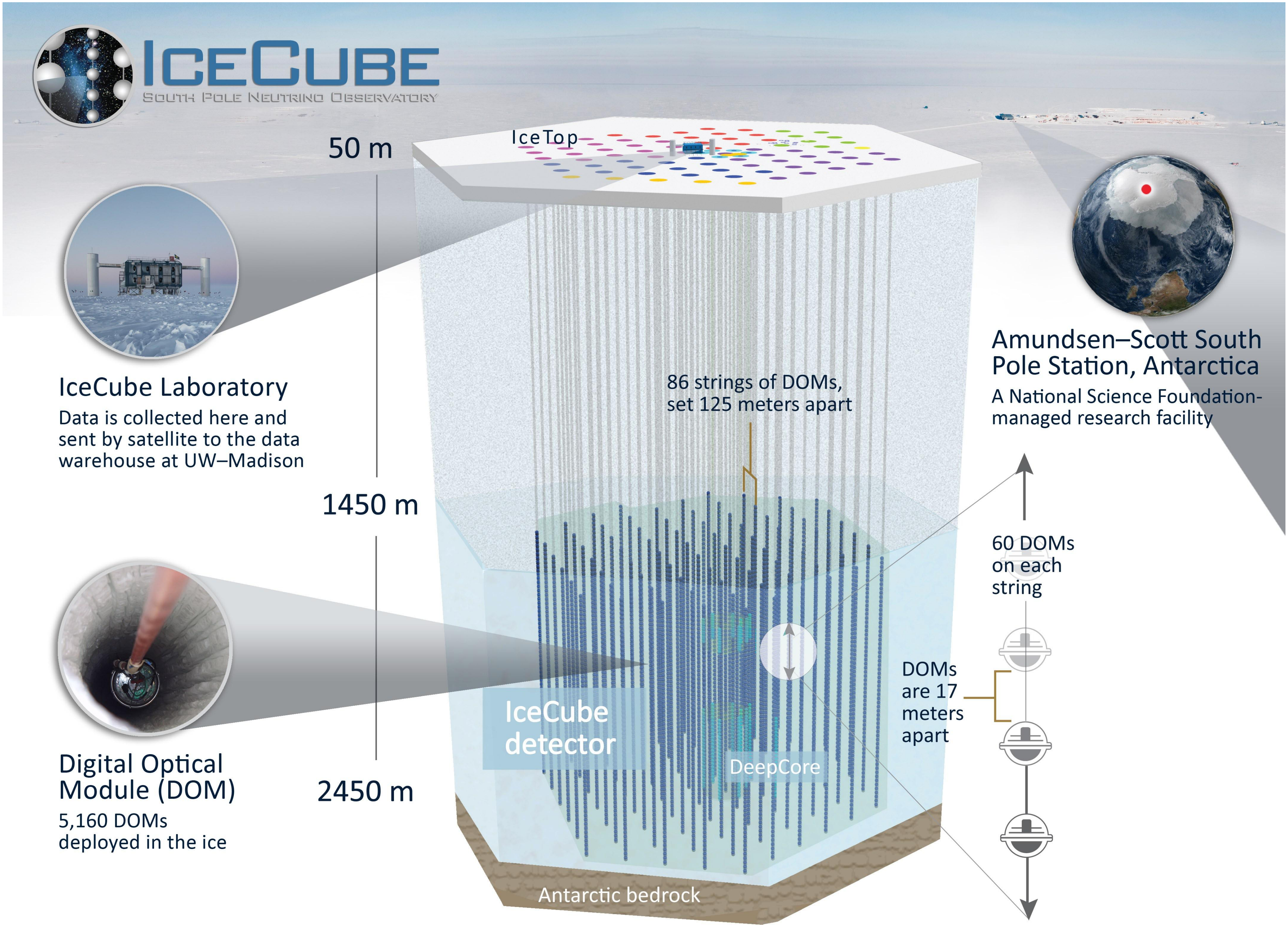
- Neutrino weak interaction



- 1960's: Method by M. Markov
Observe the <u>secondaries</u> via Cherenkov radiation
  - O(km) <u>muon tracks</u> from ν_μ CC
    1 TeV ~ 2.5 km, 1PeV ~ 15 km
  - O(10 m) e-m and/or hadronic <u>cascades</u>
  from ν_e CC, low energy ν_τ CC, and ν_x NC

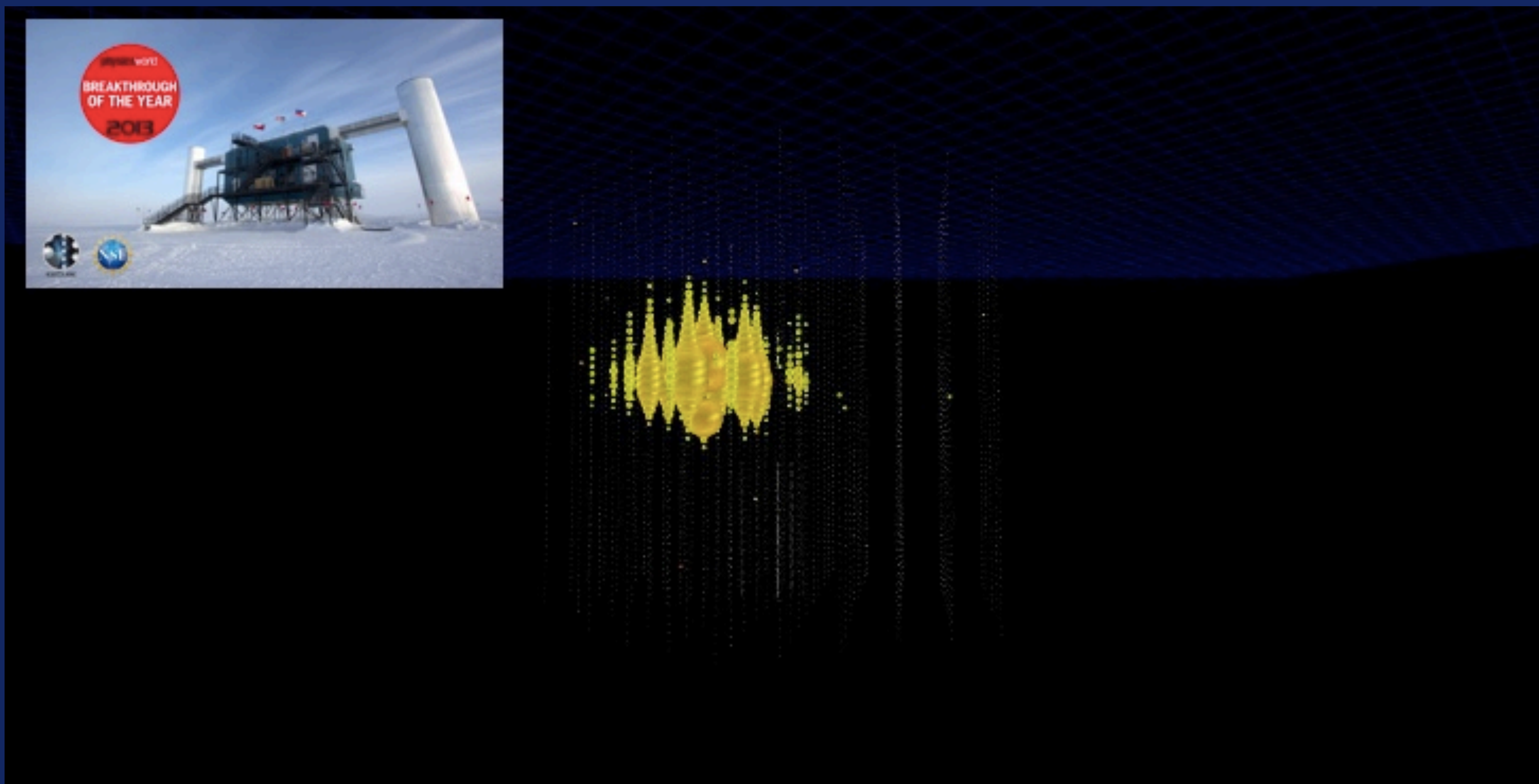


Neutrino telescopes: at least 1 km^3 detection volumes must be instrumented with optical sensors

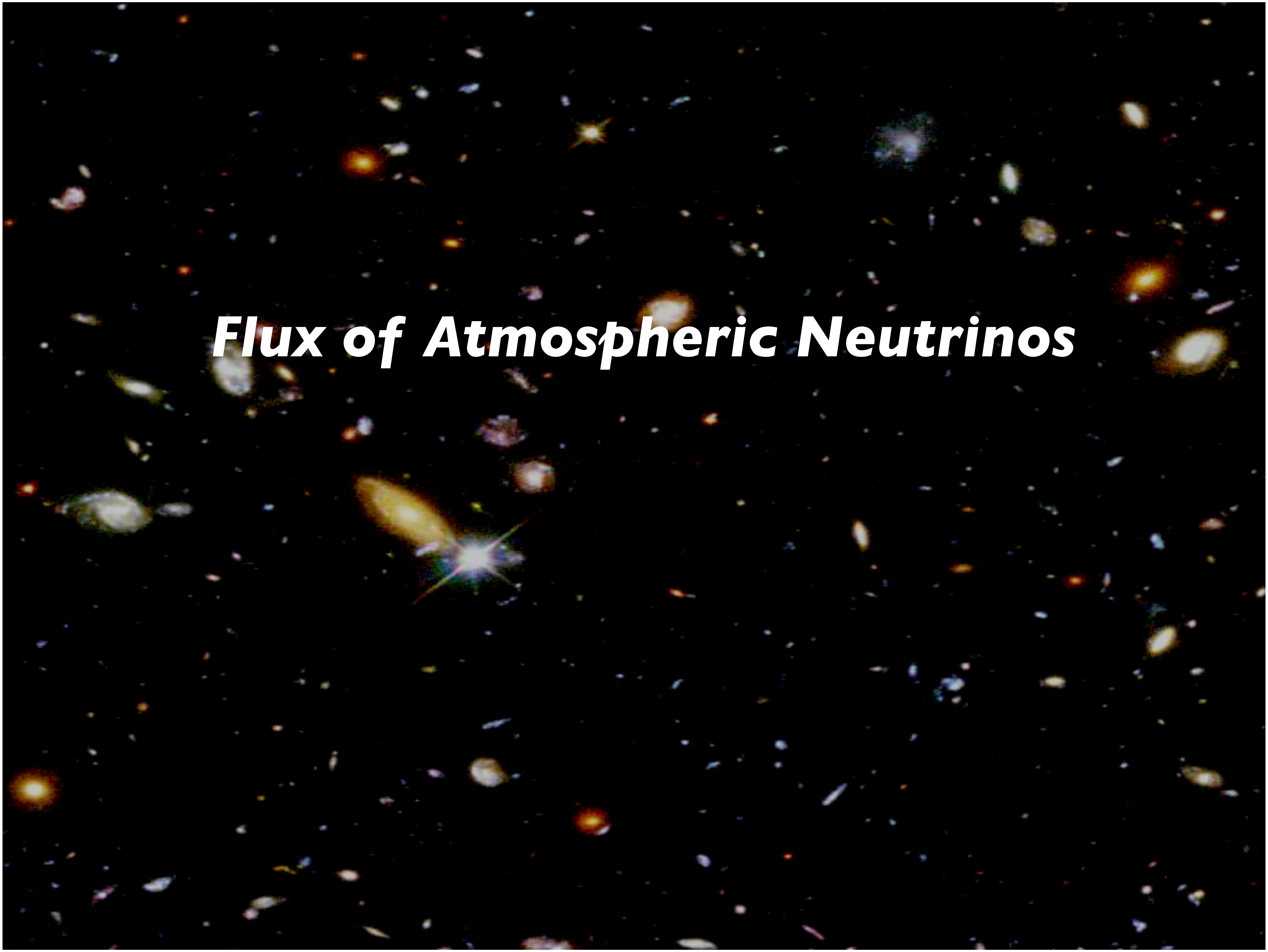


IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility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

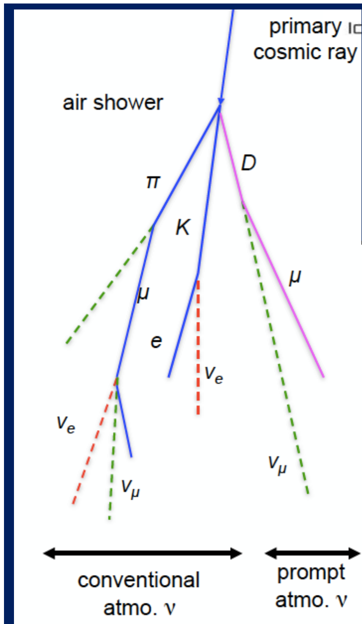
First observation of PeV-energy cosmic neutrino

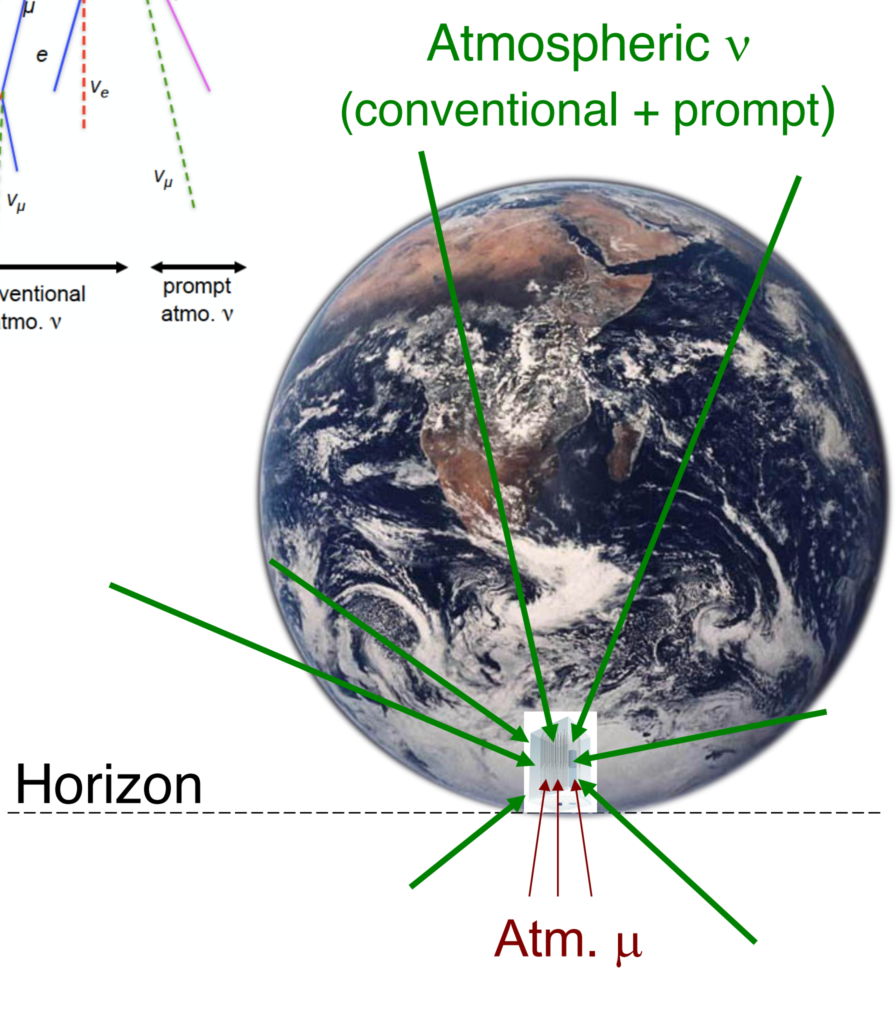


Flux of Atmospheric Neutrinos



Atmospheric Neutrinos (1)

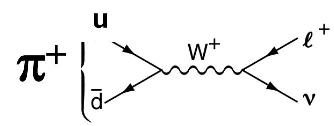




- **Conventional ν's**

Decays of π,K mesons

$$\pi, K \rightarrow \mu + \nu_\mu \rightarrow e + \nu_e + \nu_\mu$$

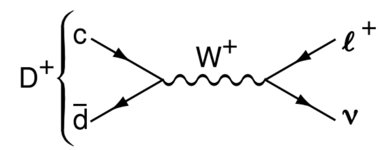


- **Prompt ν's**

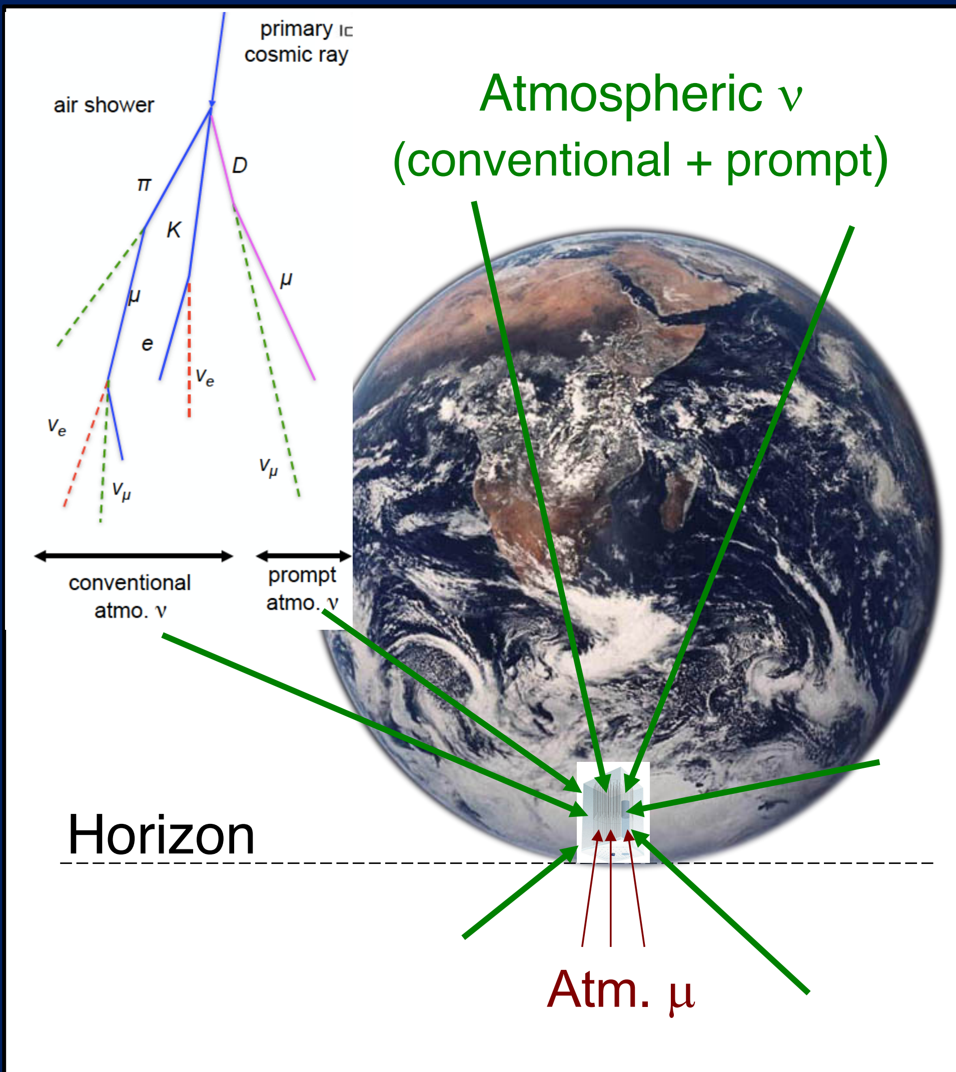
Decays of Heavy Flavor mesons/baryons

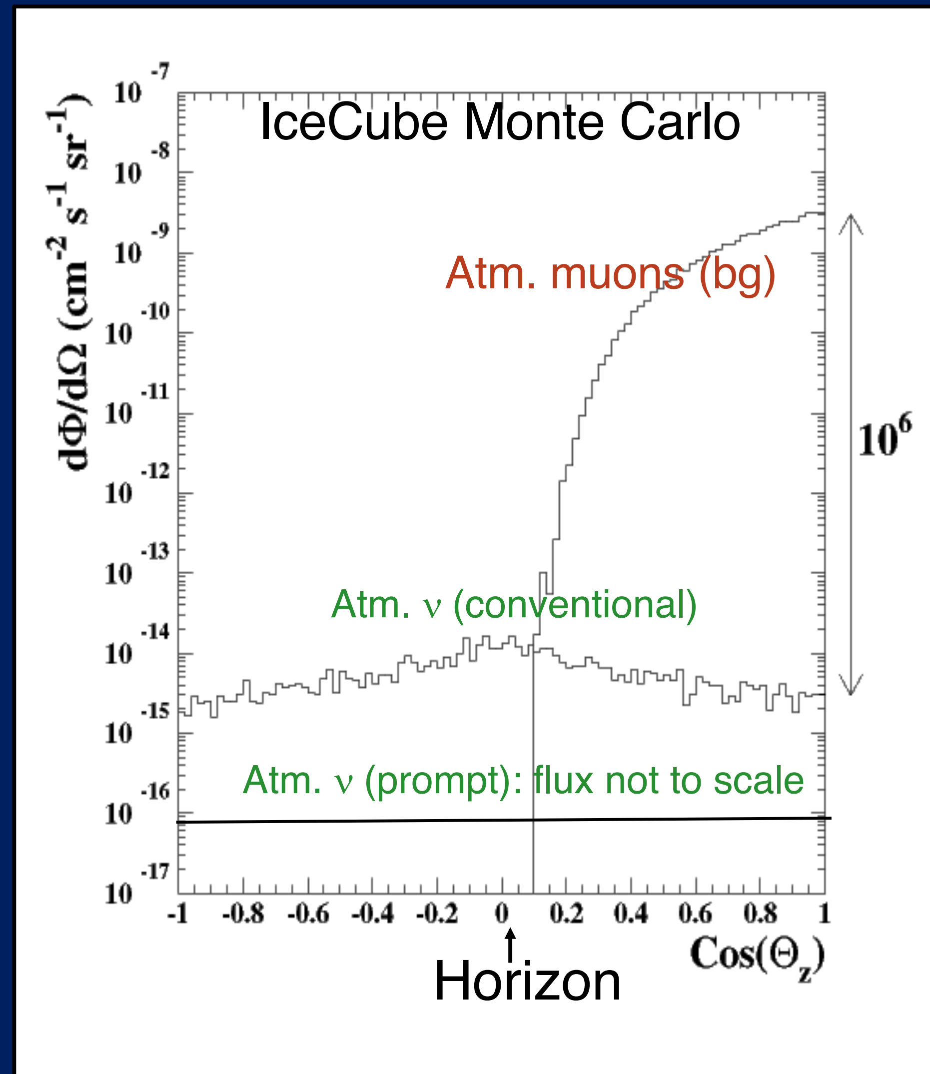
(prompt ν's not yet directly observed)

$$D^\pm, D^0, D_s, \Lambda_c$$



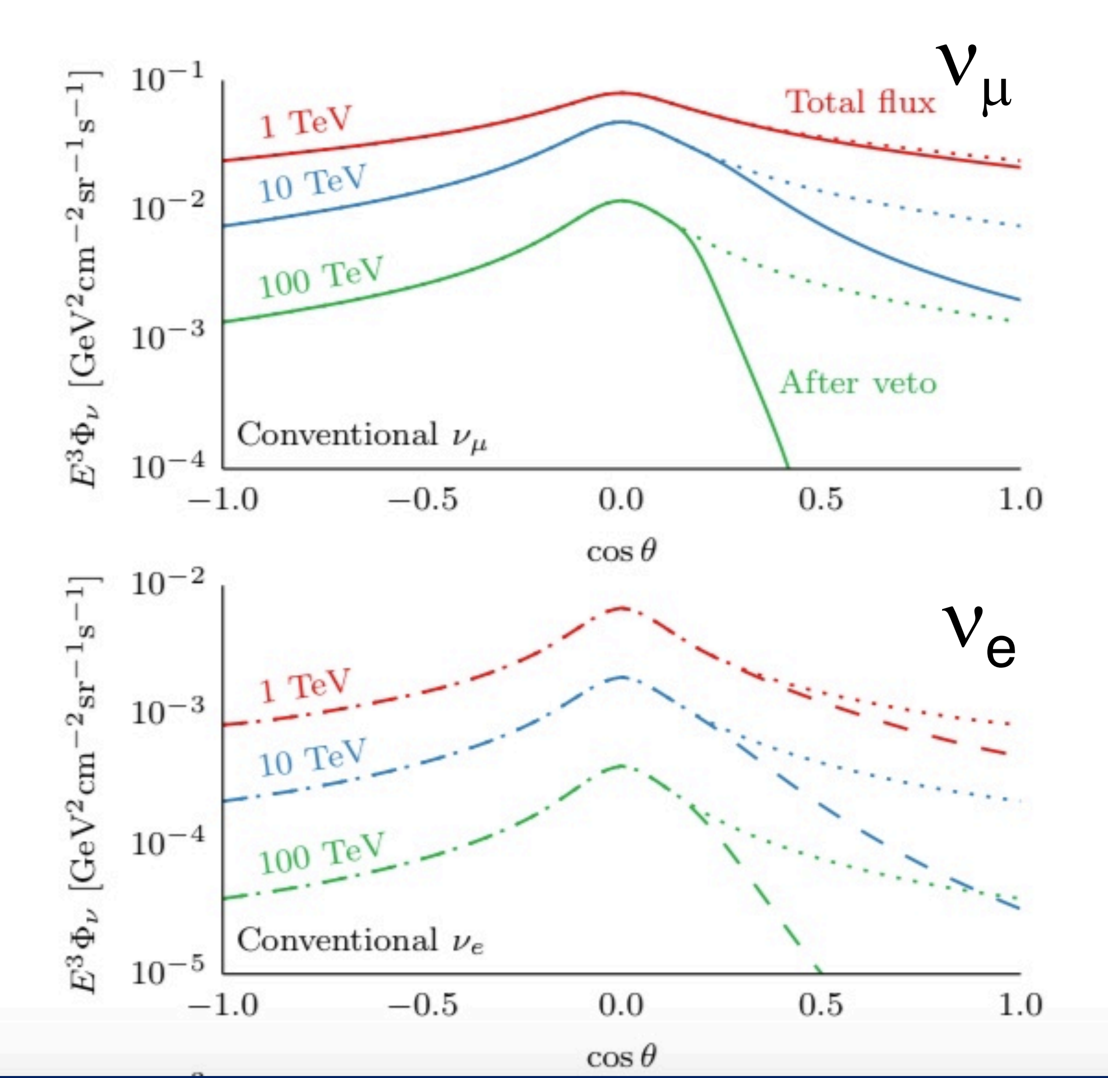
Atmospheric Neutrinos (2)





Self-veto (experimental technique) will modify atm. ν distribution

Atmospheric Neutrinos: conventional



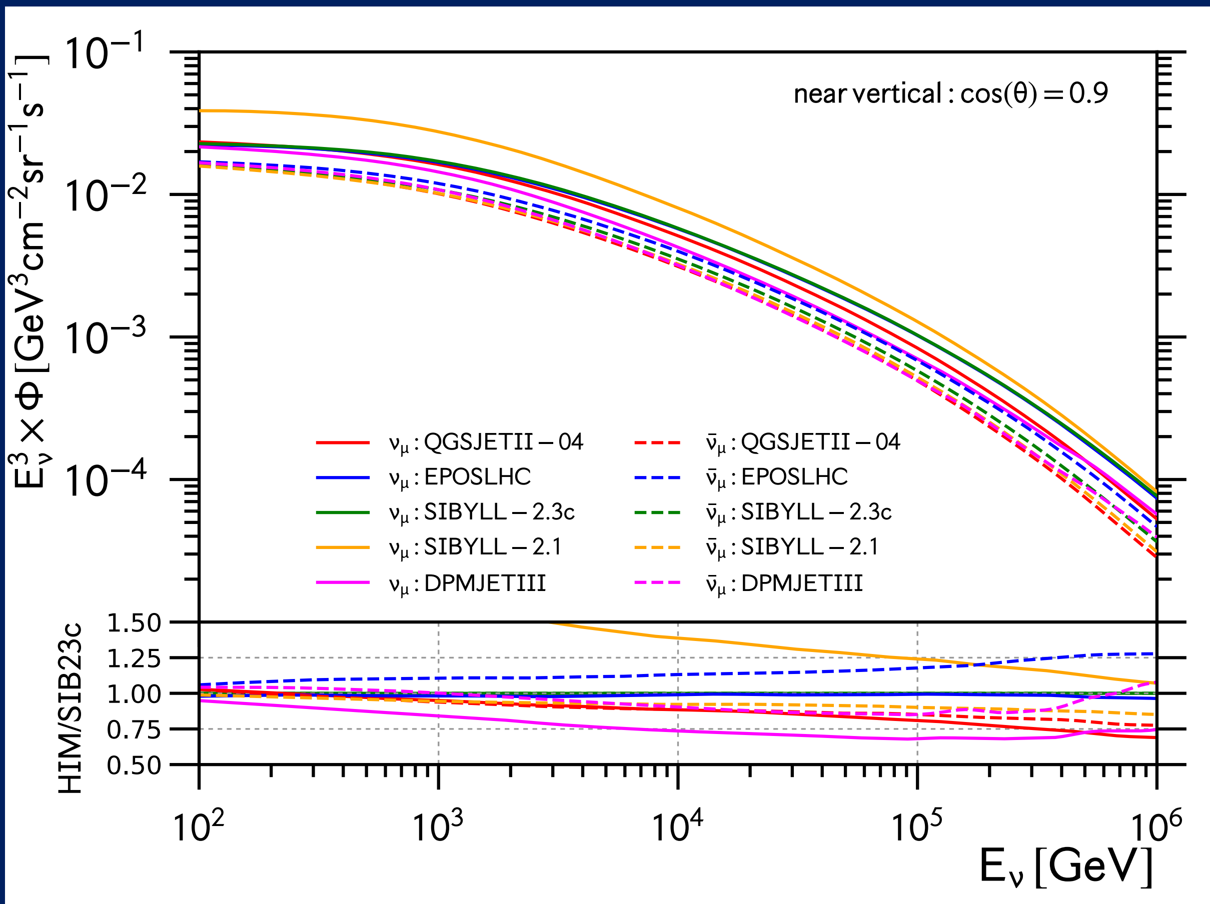
- **Conventional ν's**

Decays of π,K mesons

- flux peaked at horizon
- ν_μ dominated
- steeply falling flux spectrum $E^{-3.7}$
  - long lived mesons interact/loose energy before decay ($\tau \sim 10^{-8}$s)
- Hadronic Interactions important

ν_e flux much smaller than of ν_μ

Atmospheric Neutrinos: conventional



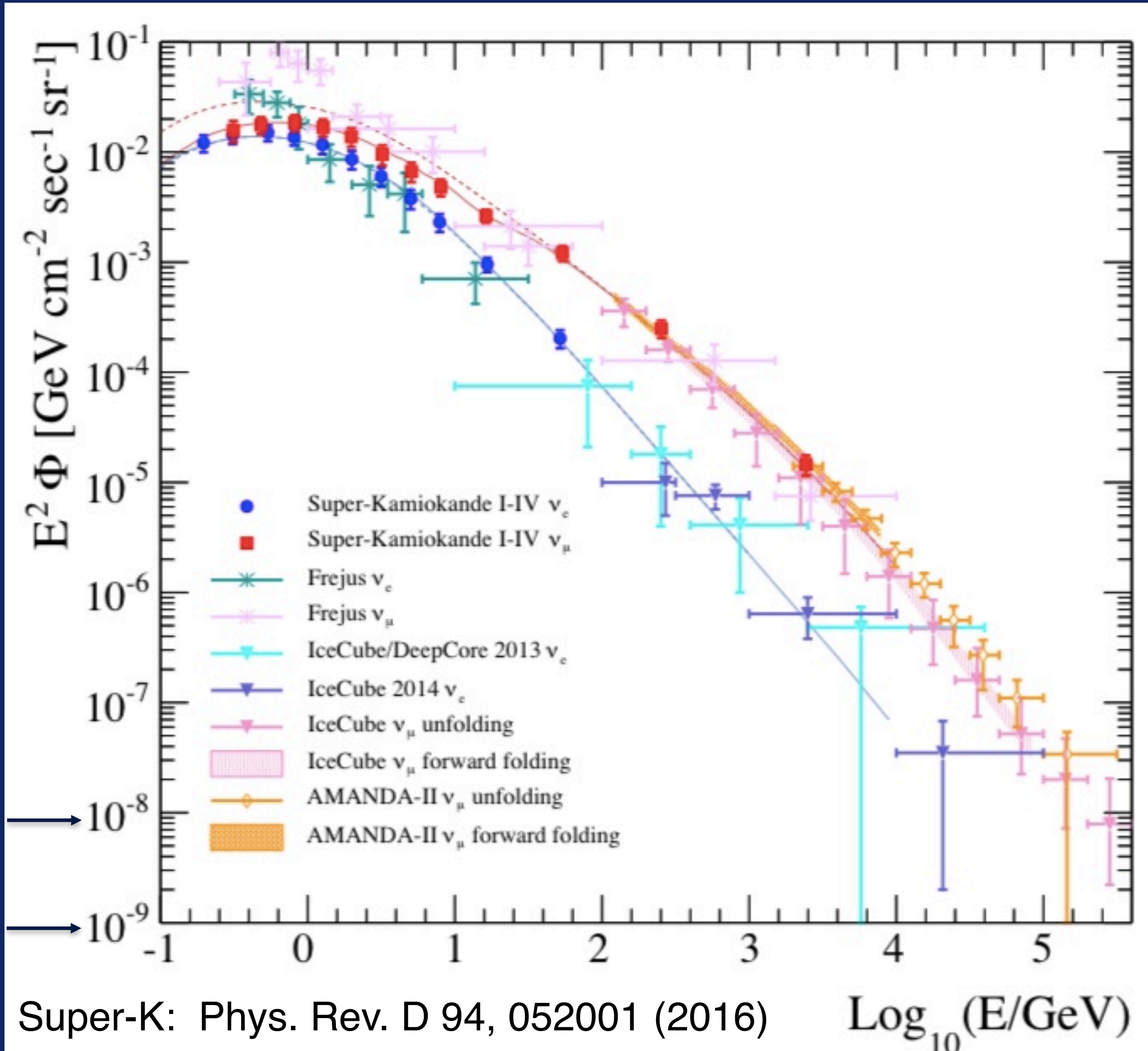
A. Fedynich et. al, arXiv:1503.00544
Figure made by H. Niederhausen

Hadronic interactions

- DPMJETIII
- SIBYLL 2.3c
- EPOSLHC
- QGSJETII

- Effects on atmospheric neutrino fluxes

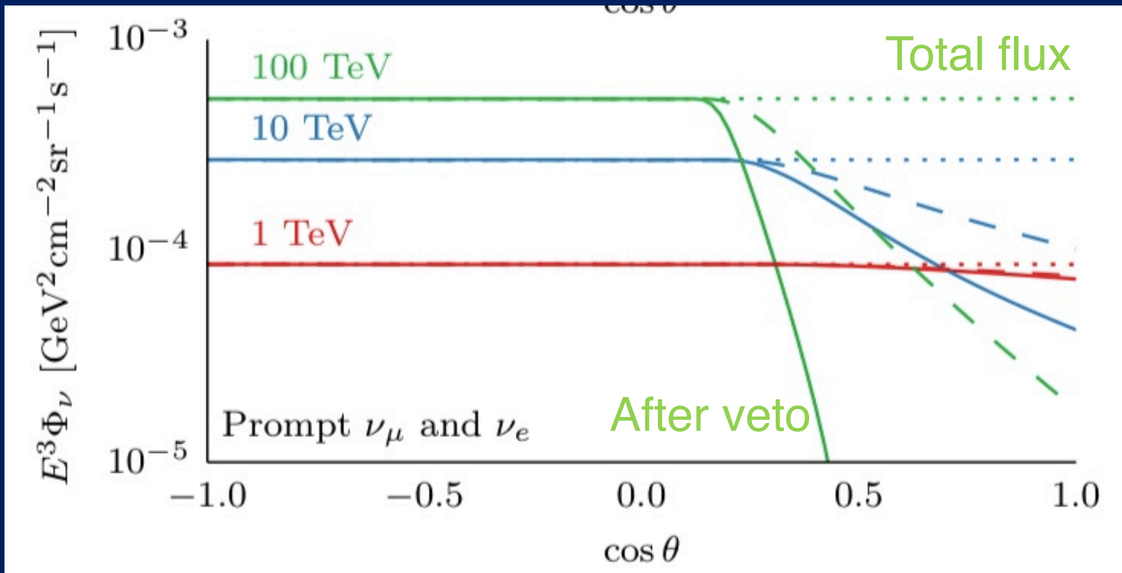
Flux of Atmospheric Neutrinos



10—100 events per year for fully efficient 1 km^3 detector

Super-K: Phys. Rev. D 94, 052001 (2016)

Atmospheric Neutrinos: prompt

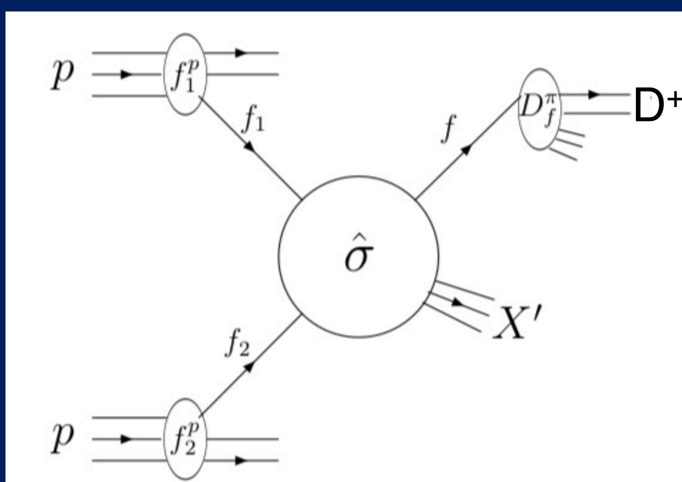


- **Prompt ν's**

Decays of Heavy Flavor mesons/baryons

(prompt ν's not yet directly observed)

- flux isotropic
- equal parts ν_μ and ν_e
- spectrum follows Cosmic Rays ($E^{-2.7}$)
  - short lifetime: interact/loose energy before decay ($\tau \sim 10^{-12}$s)
- (Forward) heavy flavor production & fragmentation decays



$$\sigma^{pp\to Q\bar{Q}} = \sum_{i,j} \iint_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1,\mu_f^2) f_j(x_2,\mu_f^2) \times \hat{\sigma}_{ij\to Q\bar{Q}}(x_1, x_2, \mu_f^2, \mu_r^2, \ldots).$$

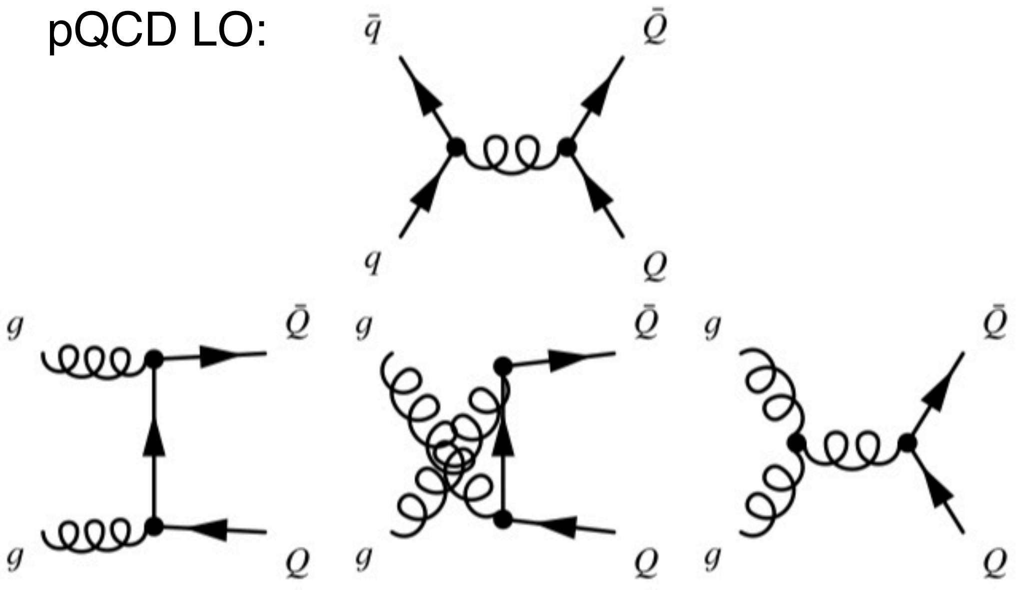
CosmicRay-Air (composition)
pdfs,nuclear effects
small-x / saturation, gluons

Atmospheric Neutrinos: prompt

(<u>Forward</u>) heavy flavor production in CR – Air interactions, fragmentation and decays

$$\sigma^{pp\to Q\bar{Q}} = \sum_{i,j} \iint_0^1 \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1,\mu_f^2) f_j(x_2,\mu_f^2) \boxed{\times \hat{\sigma}_{ij\to Q\bar{Q}}(x_1,x_2,\mu_f^2,\mu_r^2,\ldots)}$$

pQCD LO:



Color dipole picture:
Lowx/saturation effects
gluon fluctuates into $Q\bar{Q}$ and interacts with hadronic target

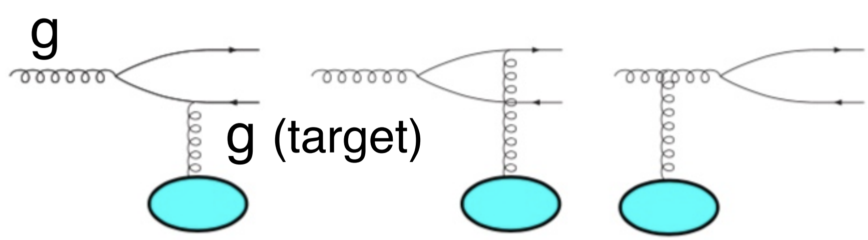


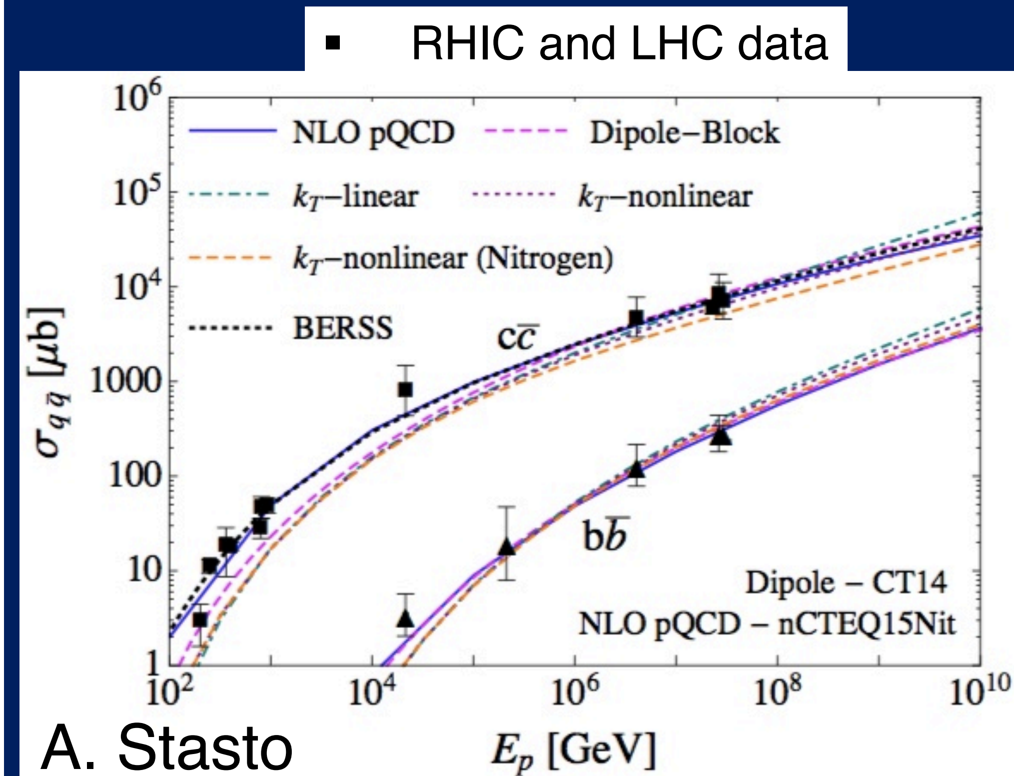
Fig. from A. Stasto

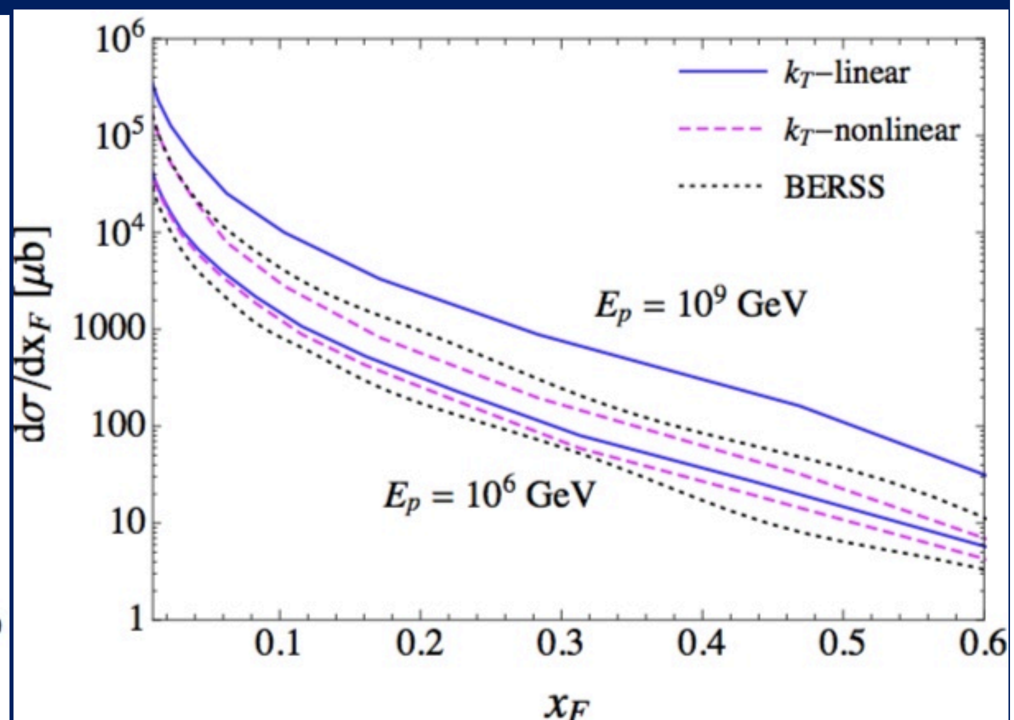
Atmospheric Neutrinos: prompt

(<u>Forward</u>) heavy flavor production in CR – Air interactions, fragmentation and decays

$$\sigma^{pp\to Q\bar{Q}} = \sum_{i,j}\iint_0^1 \mathrm{d}x_1\mathrm{d}x_2 f_i(x_1,\mu_f^2)f_j(x_2,\mu_f^2)\times\hat{\sigma}_{ij\to Q\bar{Q}}(x_1,x_2,\mu_f^2,\mu_r^2,\ldots)$$

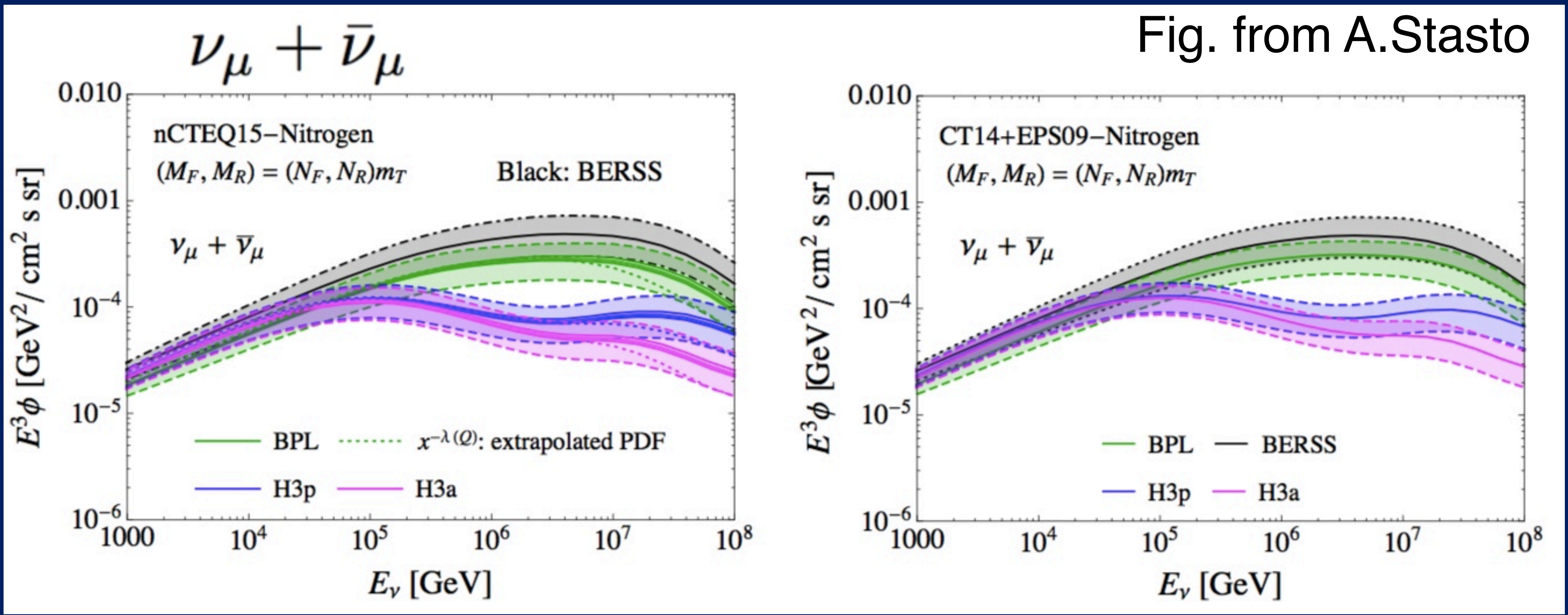
Charm production cross section (Data from RHIC and LHC):





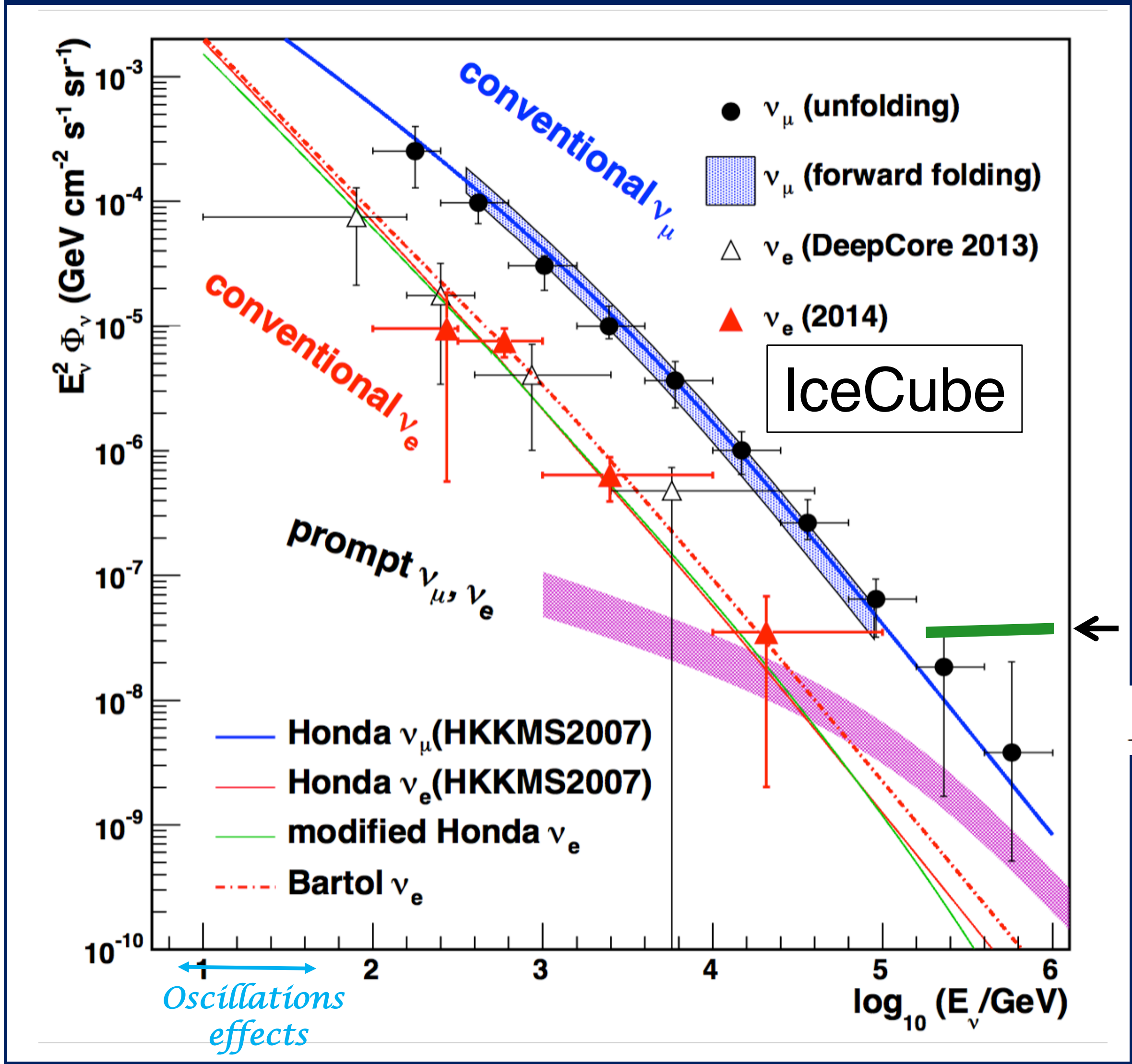
Nuclear corrections to the total cross section $(\sigma_{pA}/A)/\sigma_{pp}$ are small (5-15%), but large for the differential $d\sigma_{pp}/dx_F$ cross section

Atmospheric Neutrinos: prompt



BRESS A. Bhattacharya et.al. (2015), arXiv:1502.01076.

Atmospheric and Astrophysical Neutrinos



Atmospheric ν:

- "background" for cosmic ν
- Oscillation physics

Prompt:
ERS: R. Enberg et. Al.,Phys. Rev. D78, 043005 (2008)
BRESS A. Bhattacharya et.al. (2015), arXiv:1502.01076.

Astrophysical neutrinos

Waxman-Bahcall Bound (all flavor)

$$E_\nu^2 \Phi_{\rm WB} \approx 3.4 \times 10^{-8}\ \mathrm{GeV/cm^2 sr\, s}$$

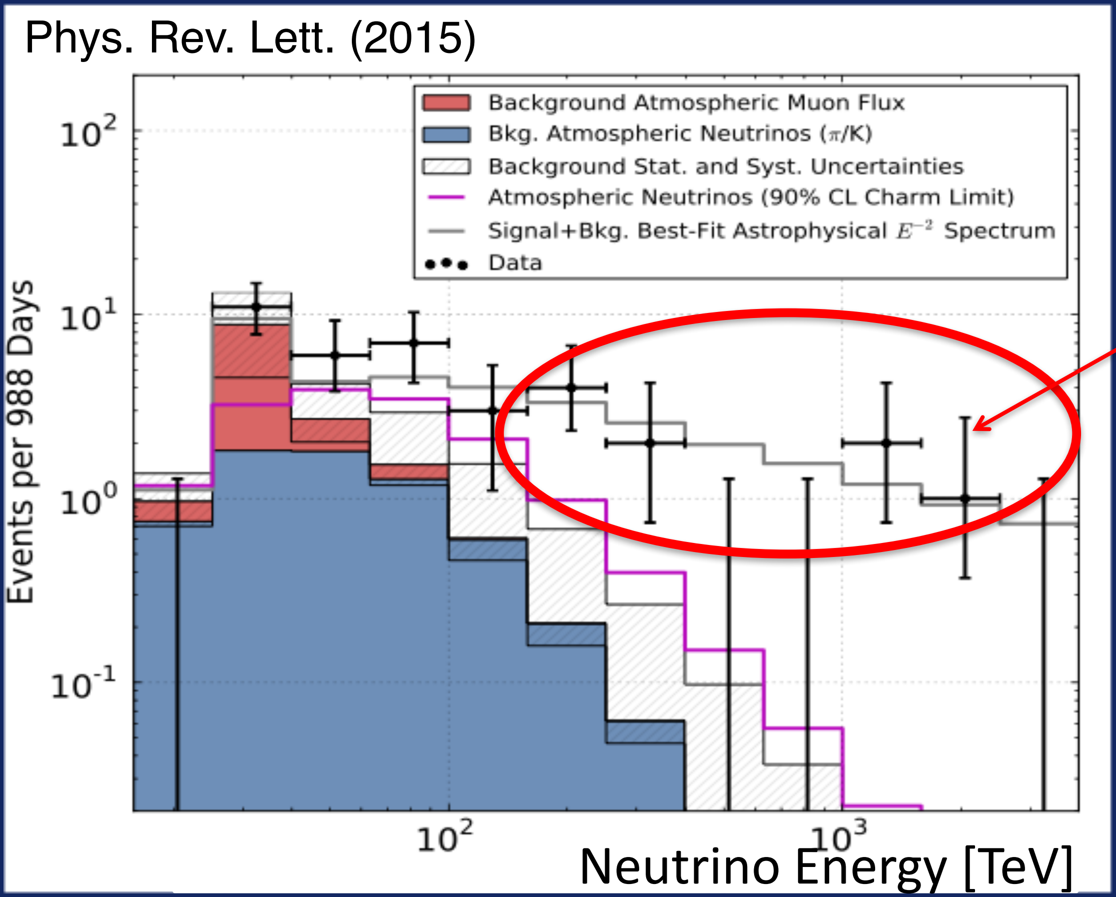
Benchmark model:
Fermi acceleration at shock fronts

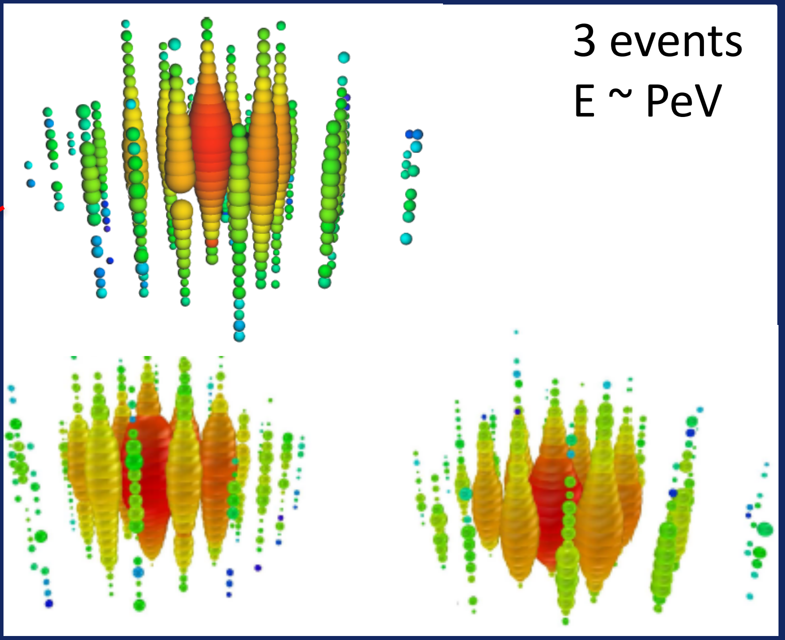
Flux of Astrophysical Neutrinos

Discovery of Cosmic Neutrinos with IceCube

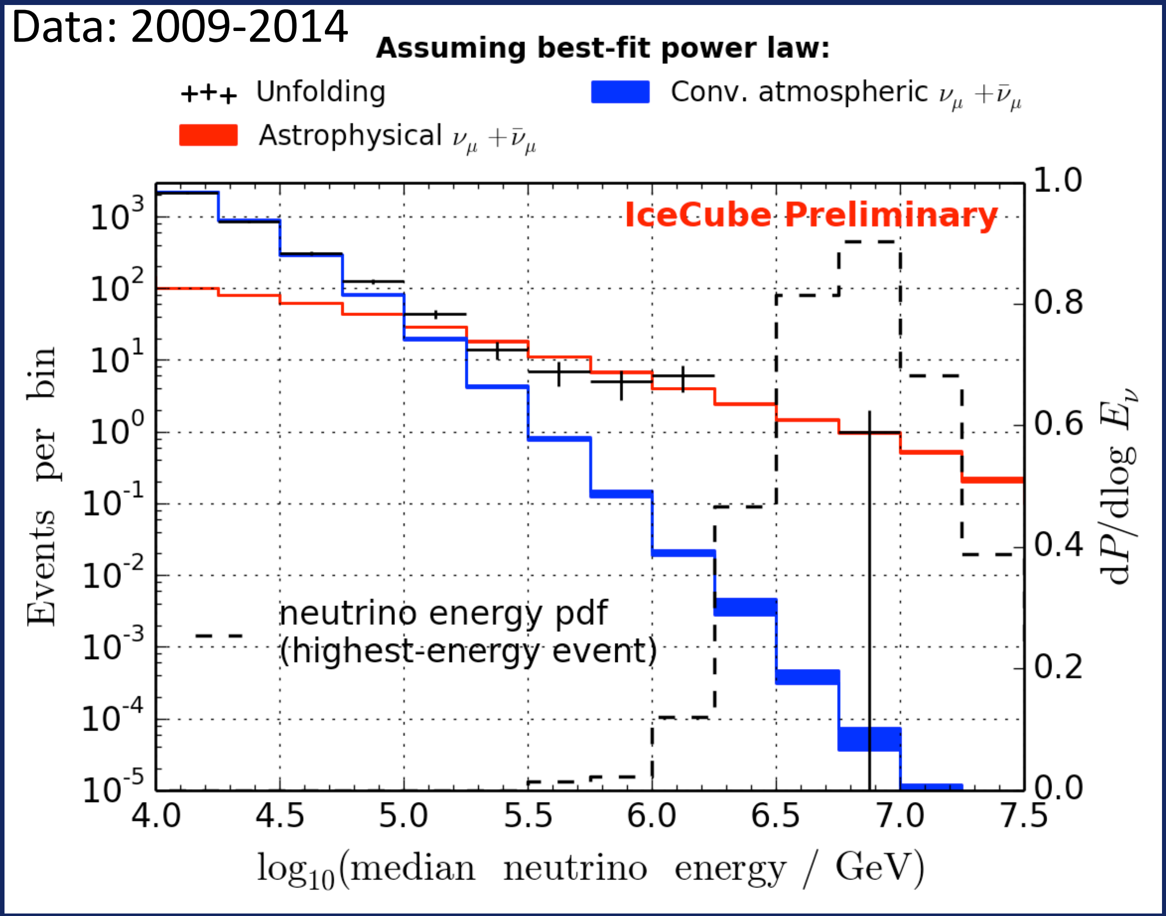
"$\nu_\mu + \nu_e + \nu_\tau$ All-Sky High Energy Starting Events" (HESE) analysis

Contained Cascades + Starting Tracks





ν_μ Northern-Sky Astrophysical Neutrinos



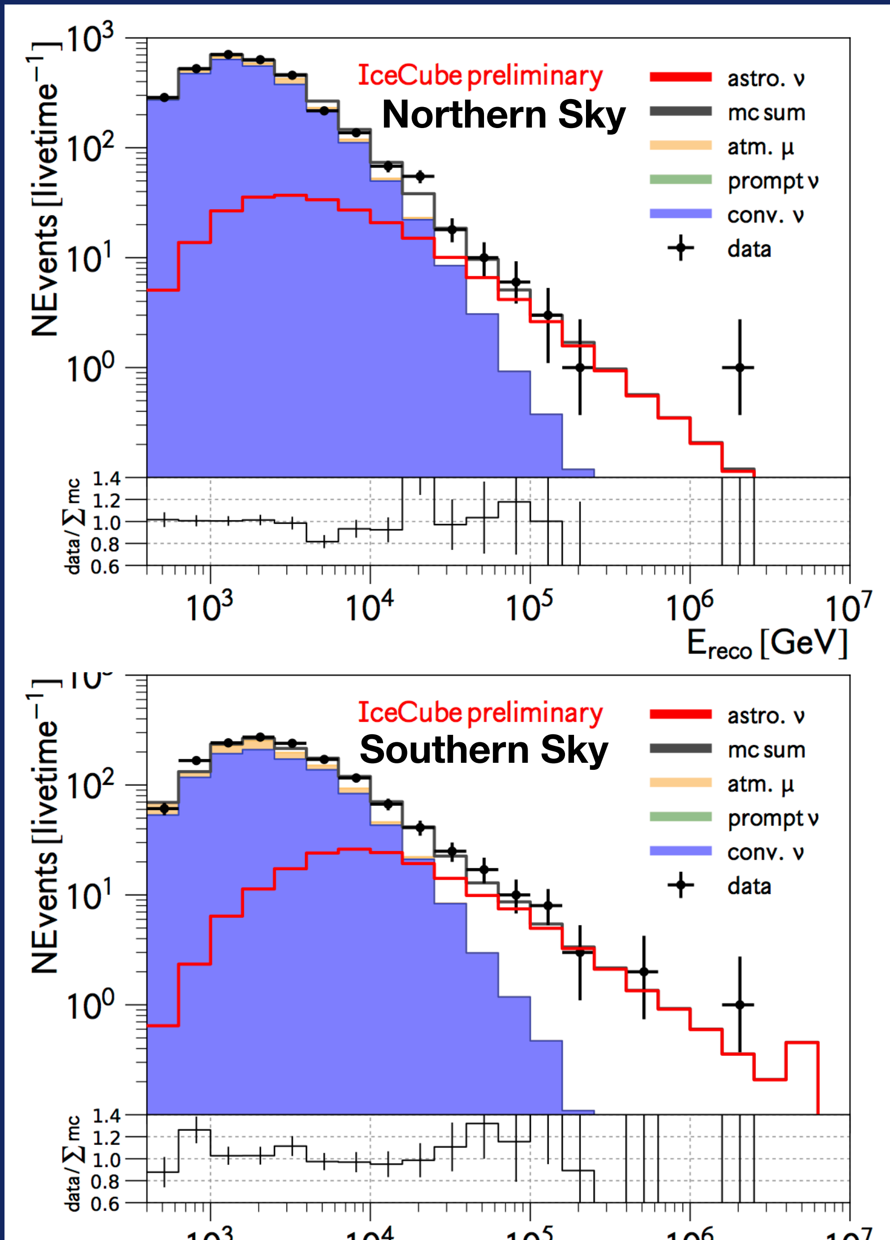
Astrophys.J. 833 (2016) no.1, 3

- Data: 2009-2014 (6yr)
- Signature: tracks
- Fit assumption: $\Phi(E_\nu)=\Phi_0 x[E/100TeV]^{-\gamma}$
- Result: (best fit) γ=2.08 +/- 0.13
- Energy range: 240 TeV – 10 PeV

5.6σ detection of astrophysical flux
Atmospheric-only hypothesis excluded at 6σ

$\nu_e + \nu_\tau$ All-Sky Astrophysical Neutrinos

IceCube: H. Niederhausen, Y. Xu , ICRC2017

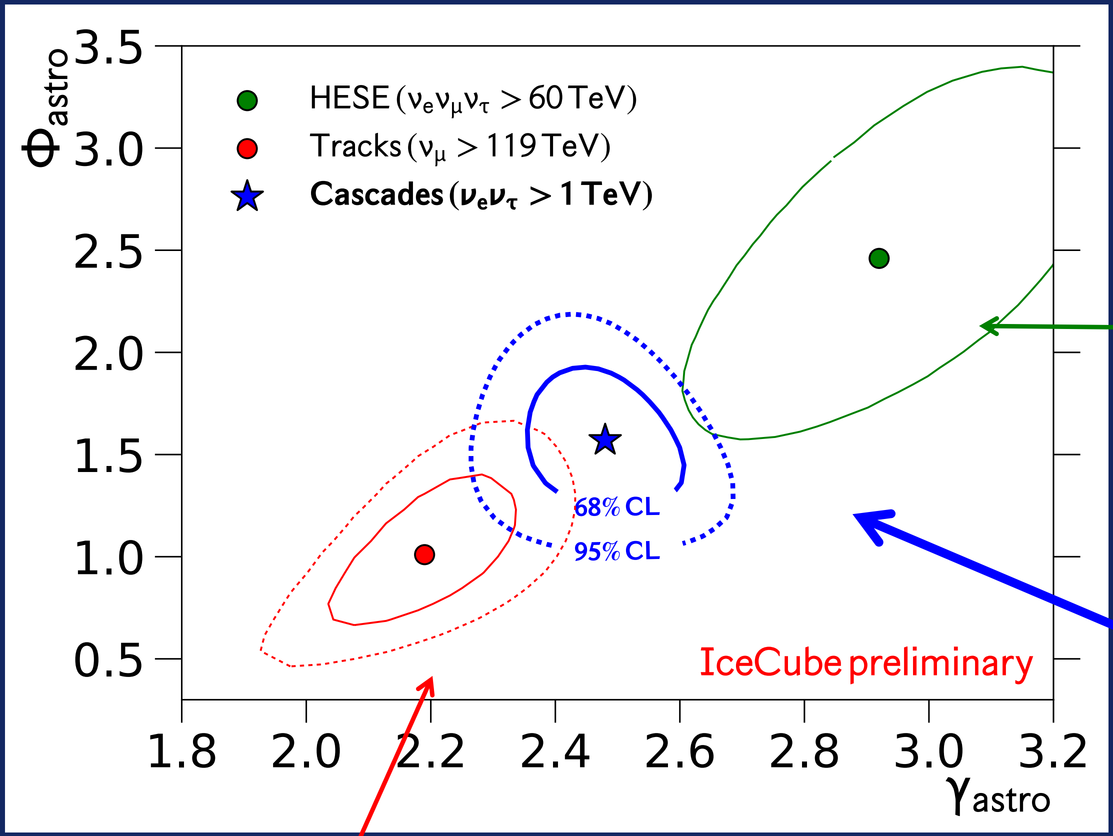


PoS(ICRC2017)968

- Data: 2012-2015 (4yr)
- Signature: cascades
- Astrophysical $\nu_e + \nu_\tau$ Flux
  - fit assumption: $\Phi(E_\nu)=\Phi_0 \times [E/100\text{TeV}]^{-\gamma}$
  - Result: (best fit)
    γ=2.48 +/- 0.08
    $\Phi_0 = 1.57^{+0.23}_{-0.22} \times 10^{-18}$ [$\text{GeV}^{-1}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$]
  - Energy range: 10 TeV – 2 PeV
- "Background" fluxes
  - Conventional ν: HKKMS06 (30% uncertainty) A. Fedynitch et al., PRD86 114024, 2012
  - Prompt ν: BERSS15 (uncertainty from IceCube upper-limit ApJ 833, No 1, 2016)
  - Cosmic Rays μ: Gaisser12

Astrophysical Neutrino Flux: Comparison

IceCube: H. Niederhausen, ICRC2017



Flux: Single Power-Law
$\Phi(E_\nu)=\Phi_0 x[E/100\text{TeV}]^{-\gamma}$

PoS(ICRC2017)1109
$\nu_e + \nu_\mu + \nu_\tau$
60 TeV – 2 PeV

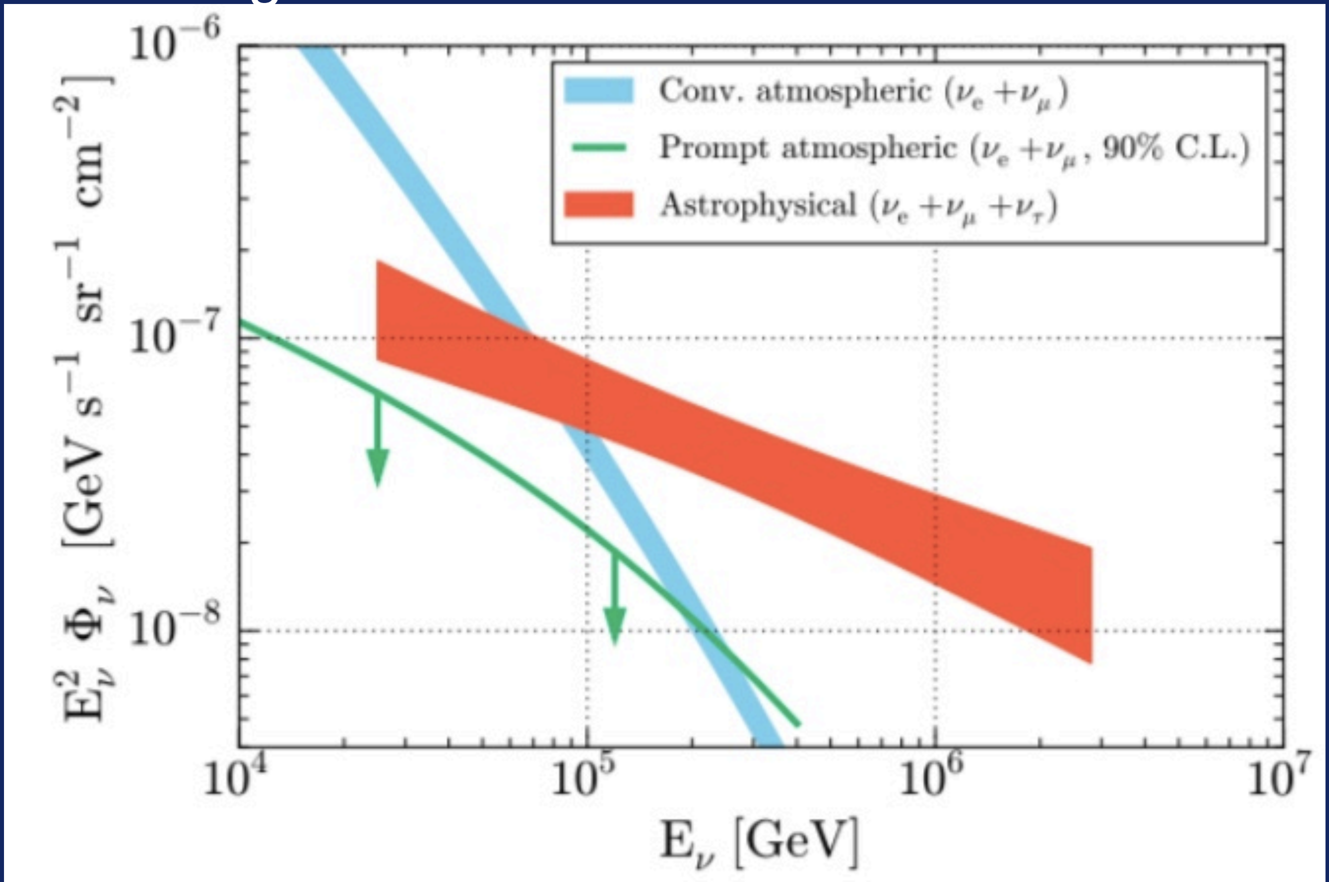
PoS(ICRC2017)968
$\nu_e + \nu_\tau$
10 TeV – 2 PeV

PoS(ICRC2017)1005
ν_μ Northern Sky
119 TeV – 4.8 PeV

Astrophysical $\nu_e + \nu_\tau$ flux consistent with ν_μ : p=0.04

Where are Prompt Neutrions?

IceCube global fit



Large astrophysical & small prompt ν's flux

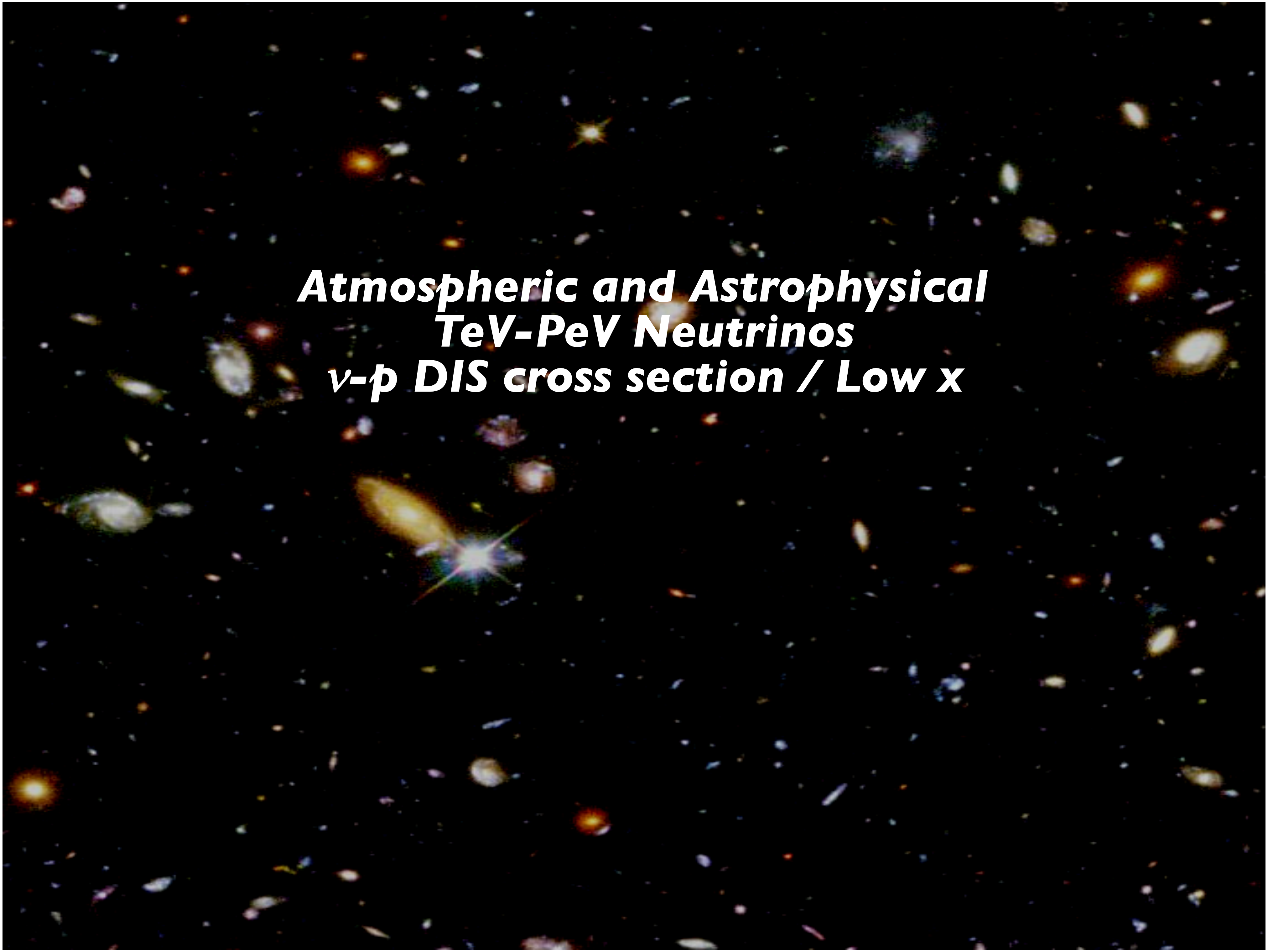
IceCube: Astrophysical Journal 809, 98 (2015)

Where are Prompt Neutrions?

Parameter	Best Fit	68% C.L.	90% C.L.	Pull
ϕ_{conv}	1.10	0.94–1.31	0.87–1.49	...
ϕ_{prompt}	0.00	0.00–1.04	0.00–2.11	...
ϕ	6.7	5.5–7.8	4.6–8.6	...
γ	2.50	2.41–2.59	2.35–2.65	...
$\Delta\gamma_{\mathrm{cr}}$	0.017	−0.008–0.041	−0.023–0.057	0.34
$\phi_{\mu,\mathrm{S1}}$	1.09	0.72–1.51	0.52–1.80	0.18
$\phi_{\mu,\mathrm{S2}}$	0.84	0.31–1.37	0.00–1.71	−0.32
$\phi_{\mu,\mathrm{H1}}$	1.12	0.75–1.54	0.56–1.84	0.23
$\phi_{\mu,\mathrm{H2}}$	1.27	0.94–1.61	0.73–1.84	0.54
$\phi_{E,\mathrm{S1}}$	0.95	0.88–1.04	0.84–1.12	−0.34
$\phi_{E,\mathrm{S2}}$	1.00	0.88–1.22	0.83–1.32	0.03
$\phi_{E,\mathrm{T1}}$	1.02	0.95–1.09	0.90–1.14	0.10
$\phi_{E,\mathrm{T2}}$	1.05	0.97–1.12	0.93–1.17	0.30
$\phi_{E,\mathrm{H1}}$	0.96	0.88–1.06	0.84–1.12	−0.29
$\phi_{E,\mathrm{H2}}$	0.95	0.86–1.04	0.81–1.10	−0.35

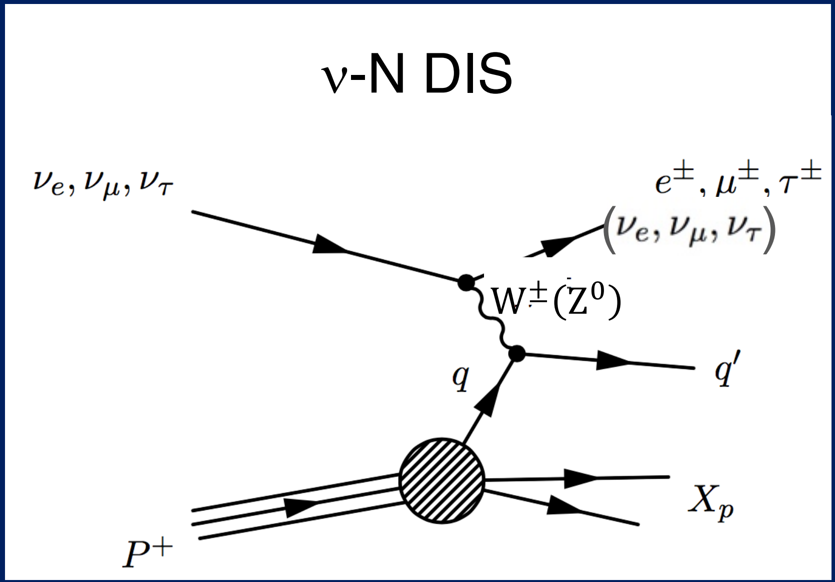
Note. ϕ is the value of the all-flavor neutrino flux at 100 TeV and is given in units of $10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{cm}^{-2}$. ϕ_{conv} and ϕ_{prompt} are given as multiples of the model predictions (see Table 2). "Pull" denotes the deviation of a nuisance parameter from its default value in units of the prior width σ.

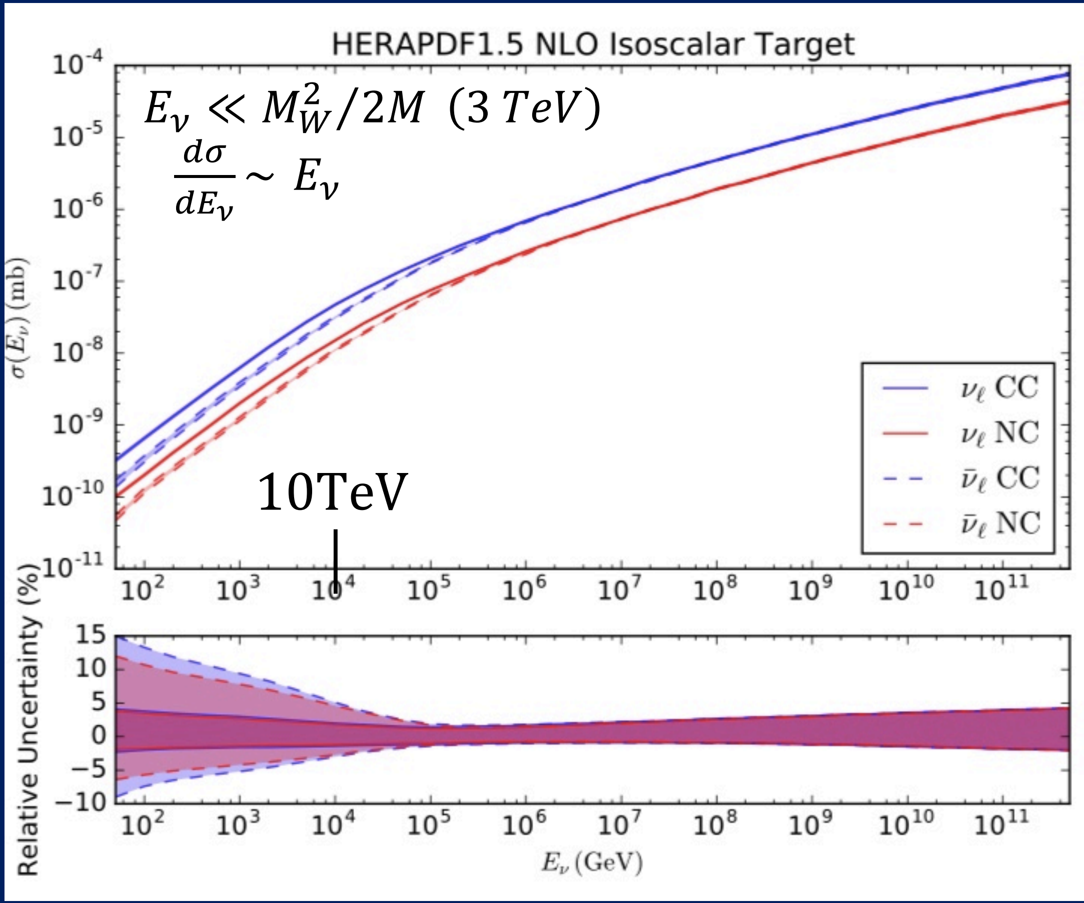
IceCube: Astrophysical Journal 809, 98 (2015)


Atmospheric and Astrophysical
TeV-PeV Neutrinos
ν-p DIS cross section / Low x

DIS ν-N cross section: Standard Model

A. Cooper-Sarkar, P. Mertsch, S. Sarkar JHEP 08 (2011) 042



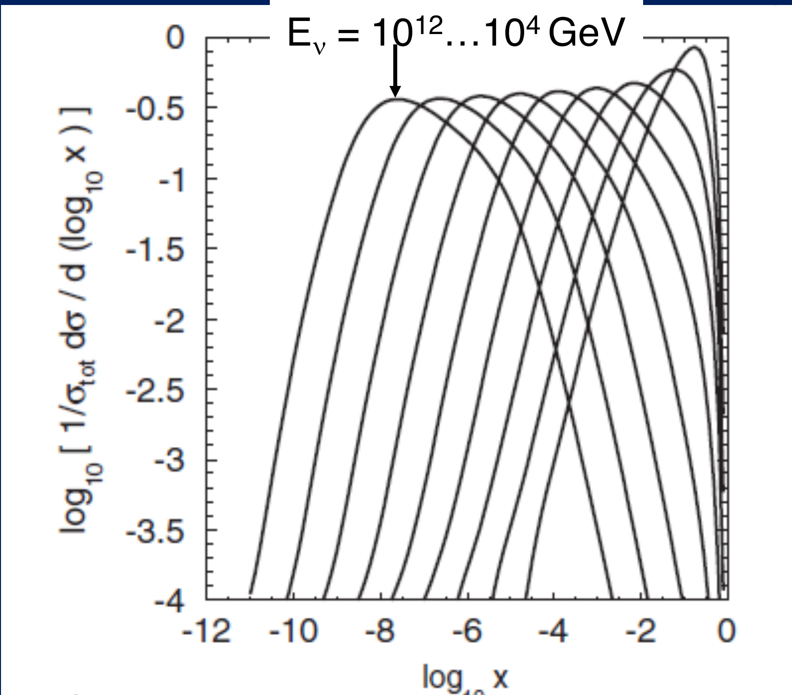


G_F=1.17x10^{-5}GeV^{-2} ,M_W=80.398 GeV,
M_Z=91.187 GeV, M_N=0.938 GeV
q,q^0 - combinations of quark distributions
y - fraction of the incoming neutrino energy transferred to the nucleon
Q^2 - 4-momentum transfer

$$\sigma_{CC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \left[q + (1-y)^2 \bar{q} \right]$$

$$\sigma_{NC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_Z^2}{Q^2 + M_Z^2} \right)^2 \left[q^0 + (1-y)^2 \bar{q}^0 \right]$$

DIS ν-N cross section: Standard Model



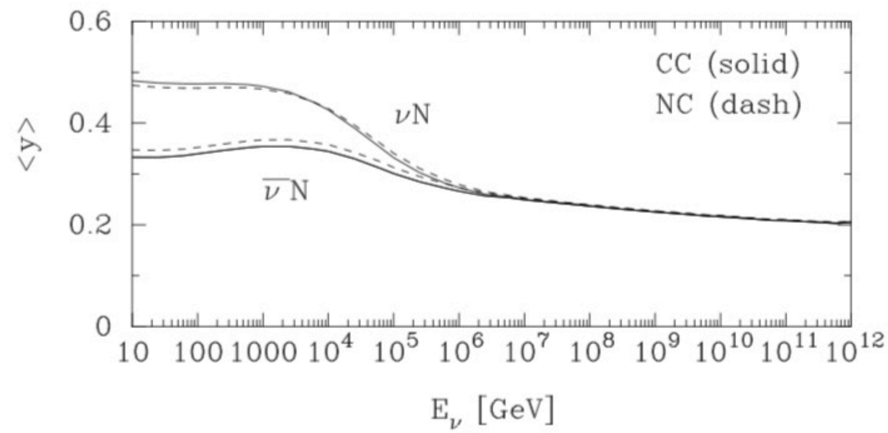
A. Connoly et.al.,PRD 83, 113009 (2011)

Ultra HE ν:

$$x_{Bj} \sim M_W^2/2ME_\nu$$

$$M_W^2 \sim 6400\ \mathrm{GeV}^2$$

$x_{Bj}=10^{-2}$	$E_\nu=3\times10^5$ GeV	[0.3 PeV]
$x_{Bj}=10^{-4}$	$E_\nu=3\times10^7$ GeV	[30 PeV]
$x_{Bj}=10^{-6}$	$E_\nu=3\times10^9$ GeV	[3 EeV]
$x_{Bj}=10^{-9}$	$E_\nu=3\times10^{12}$ GeV	[3 ZeV]

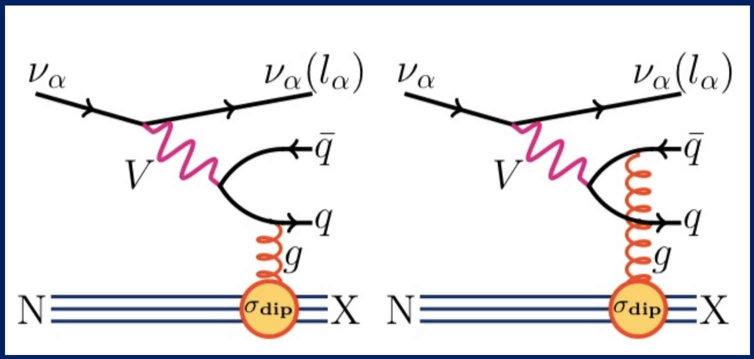


R.Gandhi et.al.,Astropart.Phys.5:81-110,1996

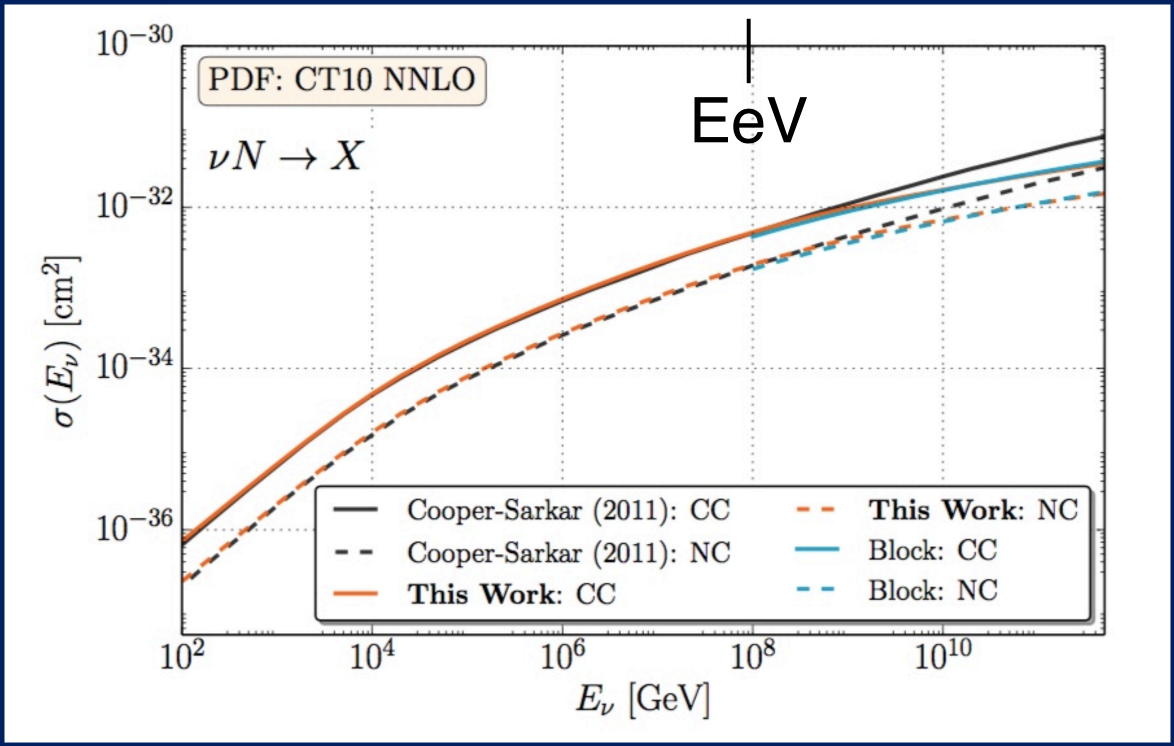
As the neutrino energy increases, the dominant contributions come from smaller values of x.

DIS ν-N cross section: Color Dipole Picture

New Information about Nucleon Structure @ low x



C. Arguelles et. al., Phys. Rev. D 92, 074040 (2015)

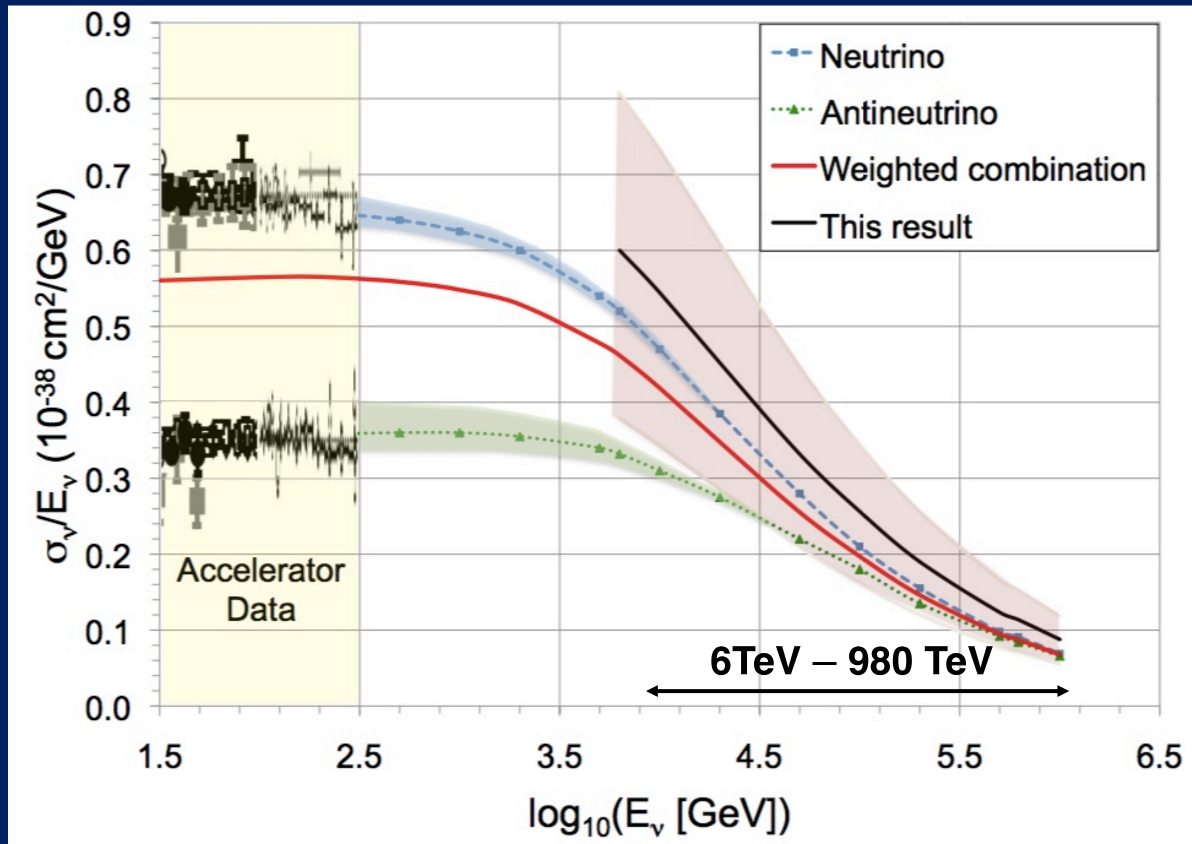


Extrapolation of pQCD into small-x regime using color dipol description (asymptotic $\ln^2(s)$ behavior of c. sections)

Beyond SM physics: leptoquarks, low scale quantum gravity models ..

DIS ν-N cross section: IceCube TeV ν_μ data

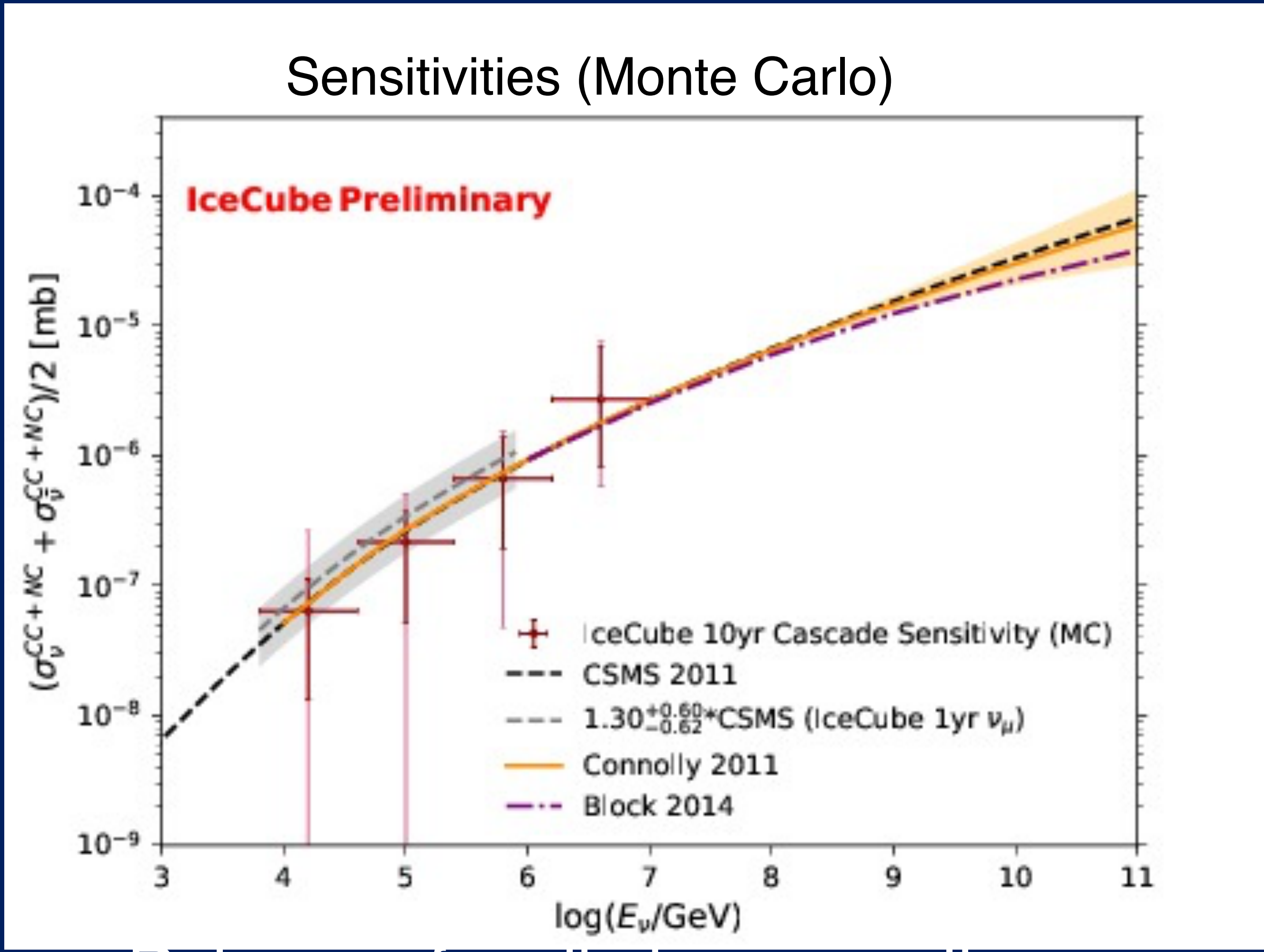
IceCube: Nature 551 (2017) 596



$$\frac{\sigma_{\text{meas.}}}{\sigma_{SM}} = 1.30^{+0.21}_{-0.19}\,(\text{stat.})\,{}^{+0.39}_{-0.43}\,(\text{syst.})$$

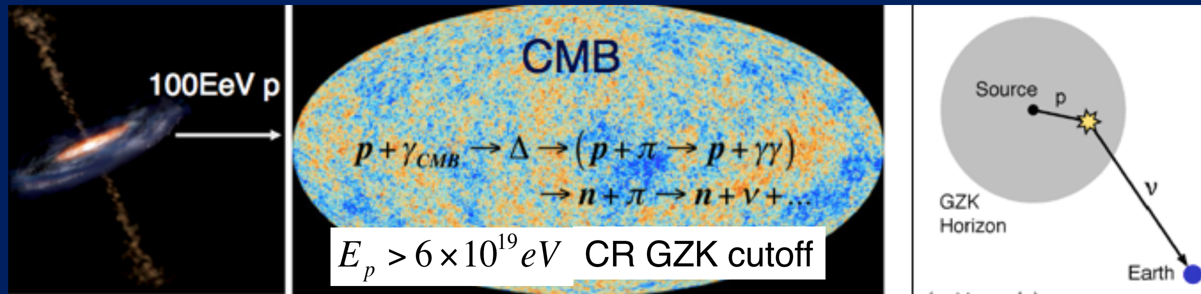
Consistent with current Standard Model calculations

DIS ν-N cross section: IceCube TeV-PeV $\nu_e+\nu_\tau$ data



Release of preliminary results:
See Y. Xu (Stony Brook U.), for the IceCube Collab.
DIS2018 Tuesday session

Cosmogenic GZK Neutrinos

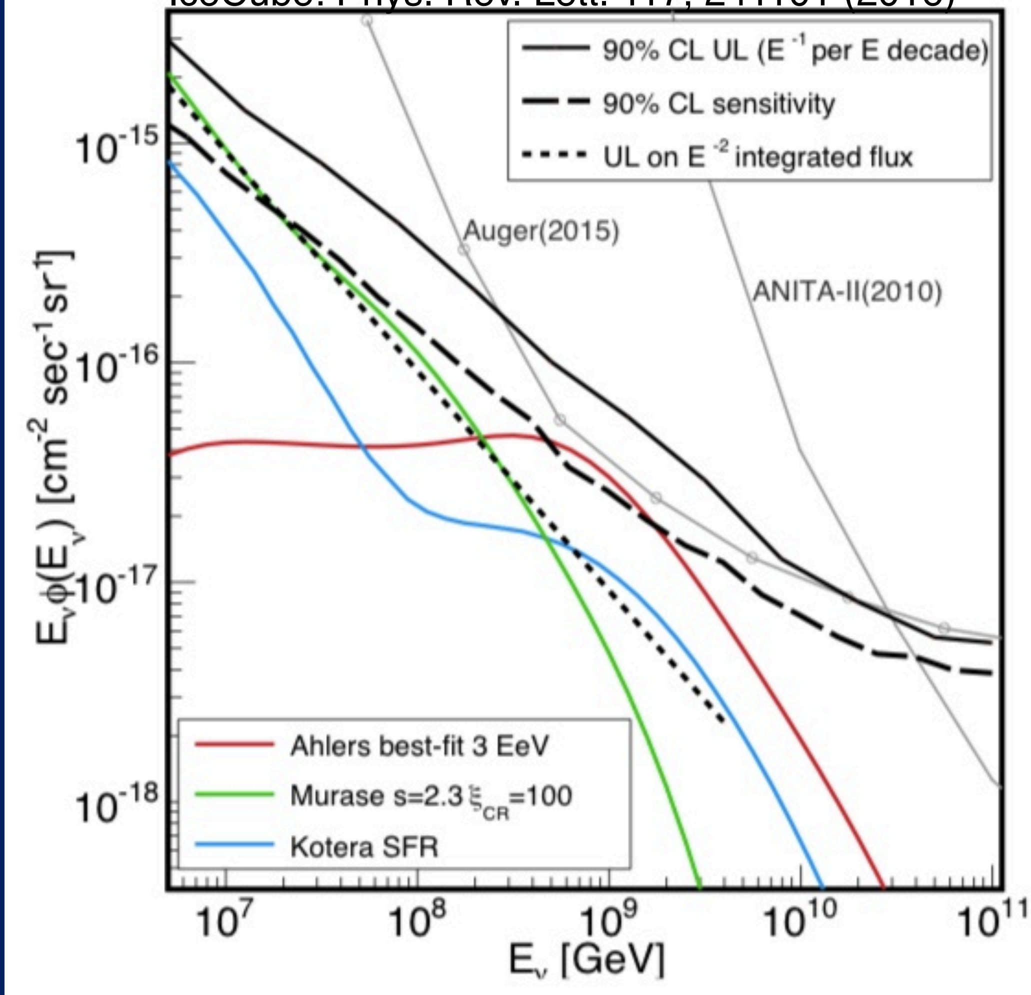


Extremely High Energy Universe beyond GZK (Greisen–Zatsepin–Kuzmin) sphere (50-100 Mpc) inaccessible with cosmic- or γ-rays but not ν’s

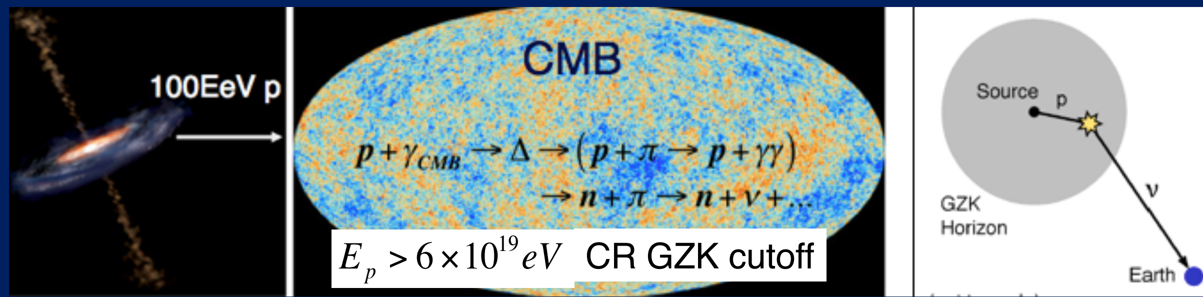
- **GZK flux guaranteed for proton CR**
- **Optical & radio detection**
- **No GZK ν observed (yet)**

- Tight upper limits on GZK models are placed and constrains the UHE CR sources. Heavier CR composition?

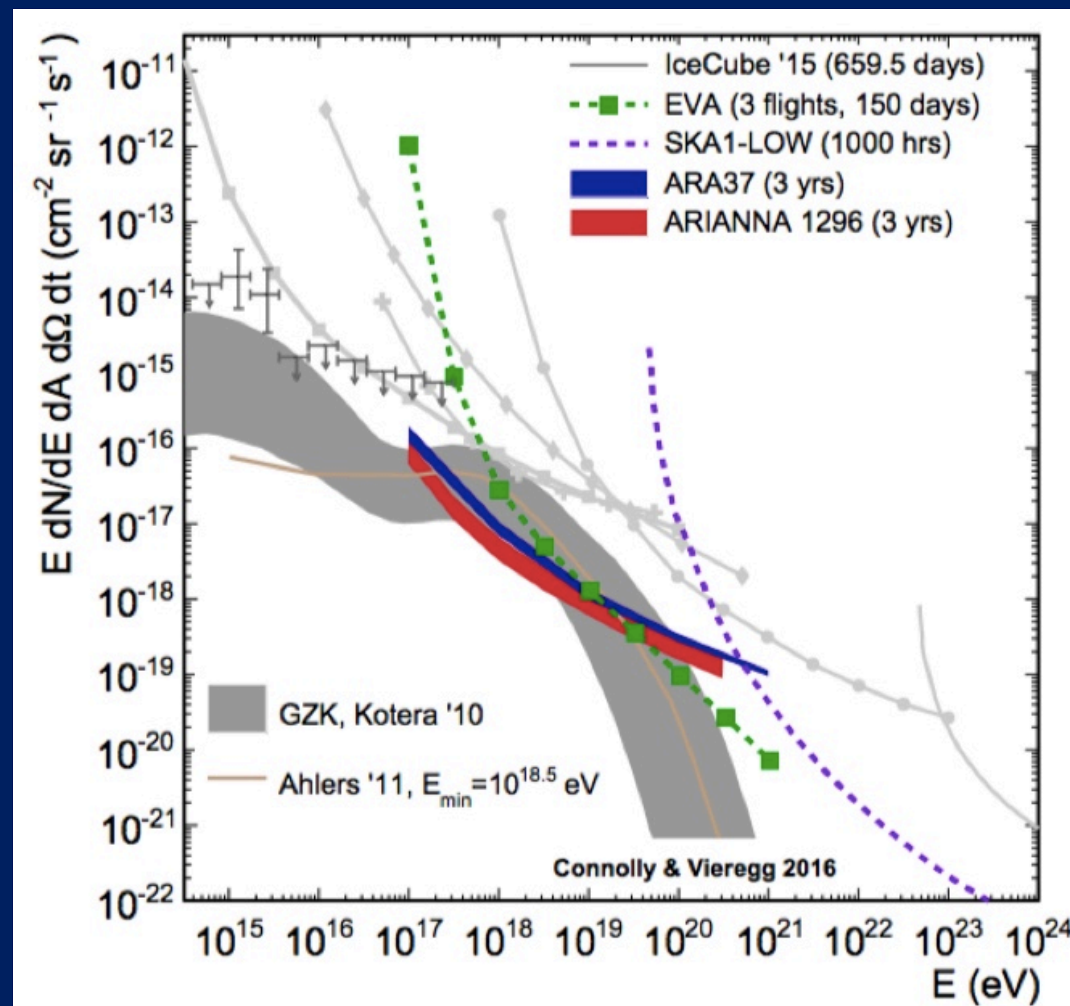
IceCube: Phys. Rev. Lett. 117, 241101 (2016)



Cosmogenic GZK Neutrinos



Extremely High Energy Universe beyond GZK (Greisen–Zatsepin–Kuzmin) sphere (50-100 Mpc) inaccessible with cosmic- or γ-rays but not ν's



- **GZK flux guaranteed for proton CR**
- **Optical & radio detection**
- **No GZK ν observed (yet)**

- Ongoing GZK ν detection (E >100 PeV) effort with radio technique


Connections of Astroparticle physics and EIC
via cosmic rays and neutrino physics
low-x, low Q2, gluons, saturation, diffraction, hadronic
interactions, forward region, heavy flavor, nuclear effects
Goal of this talk: inspire to work out details
Thank you!