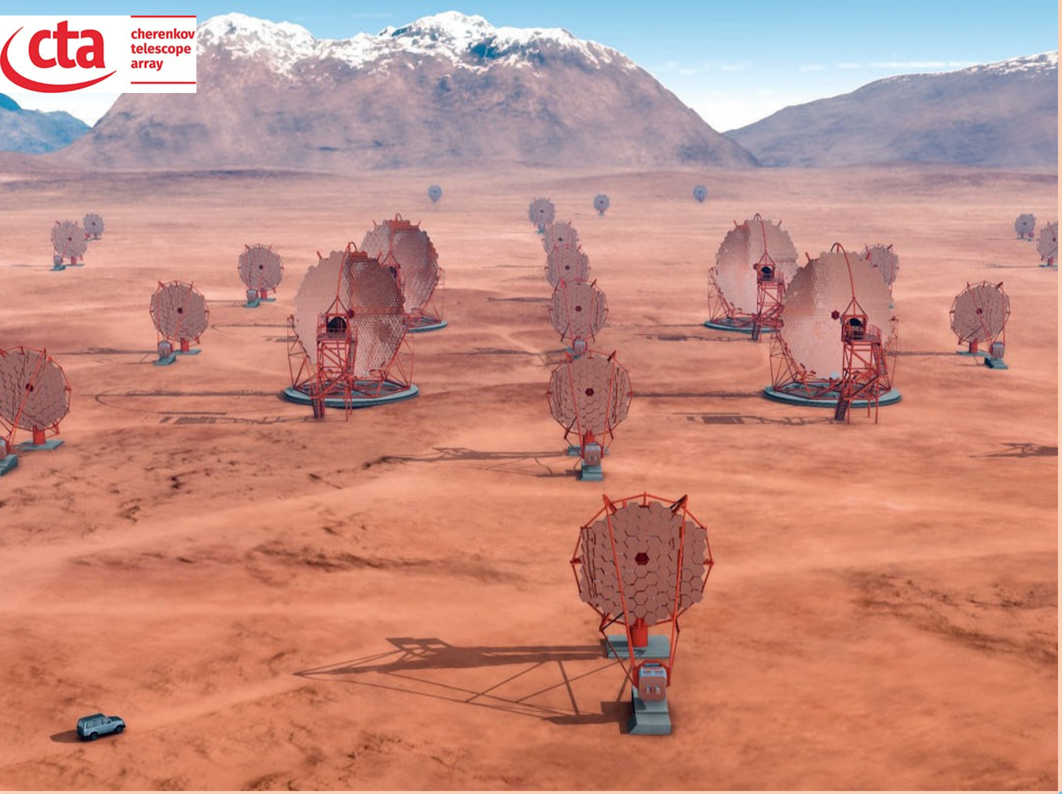
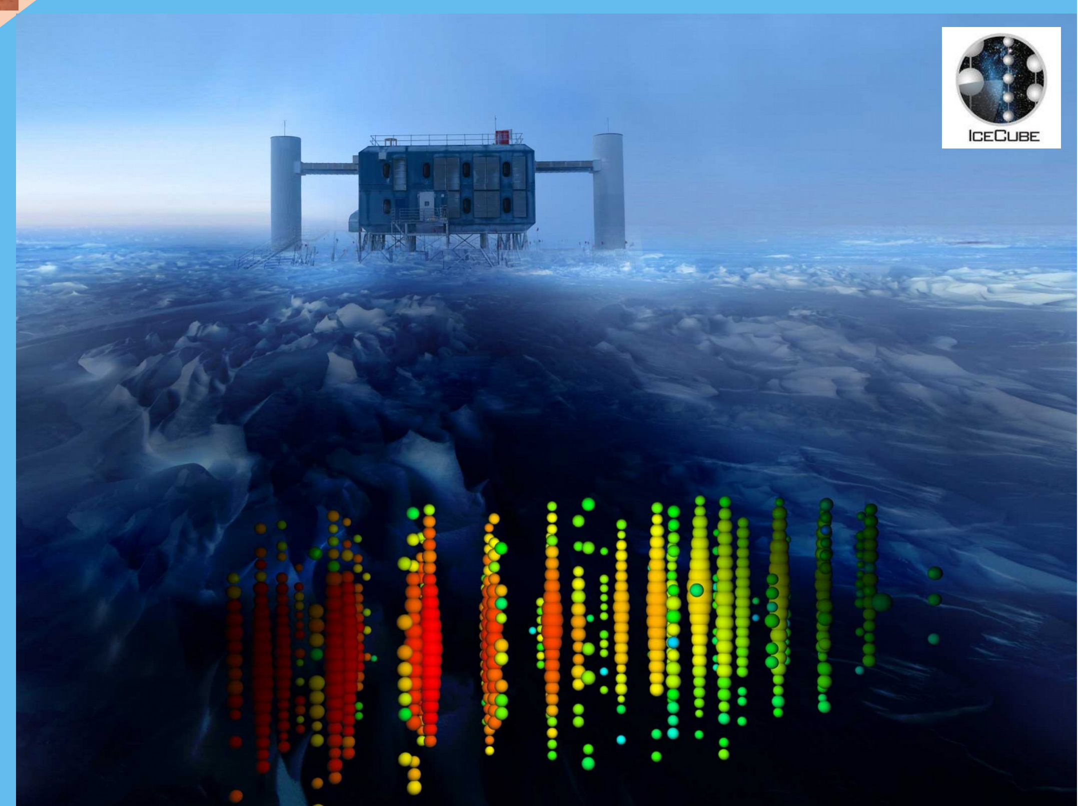


1km^2 of desert & 1 km^3 of ice

search for VHE gamma-ray counterparts of neutrinos

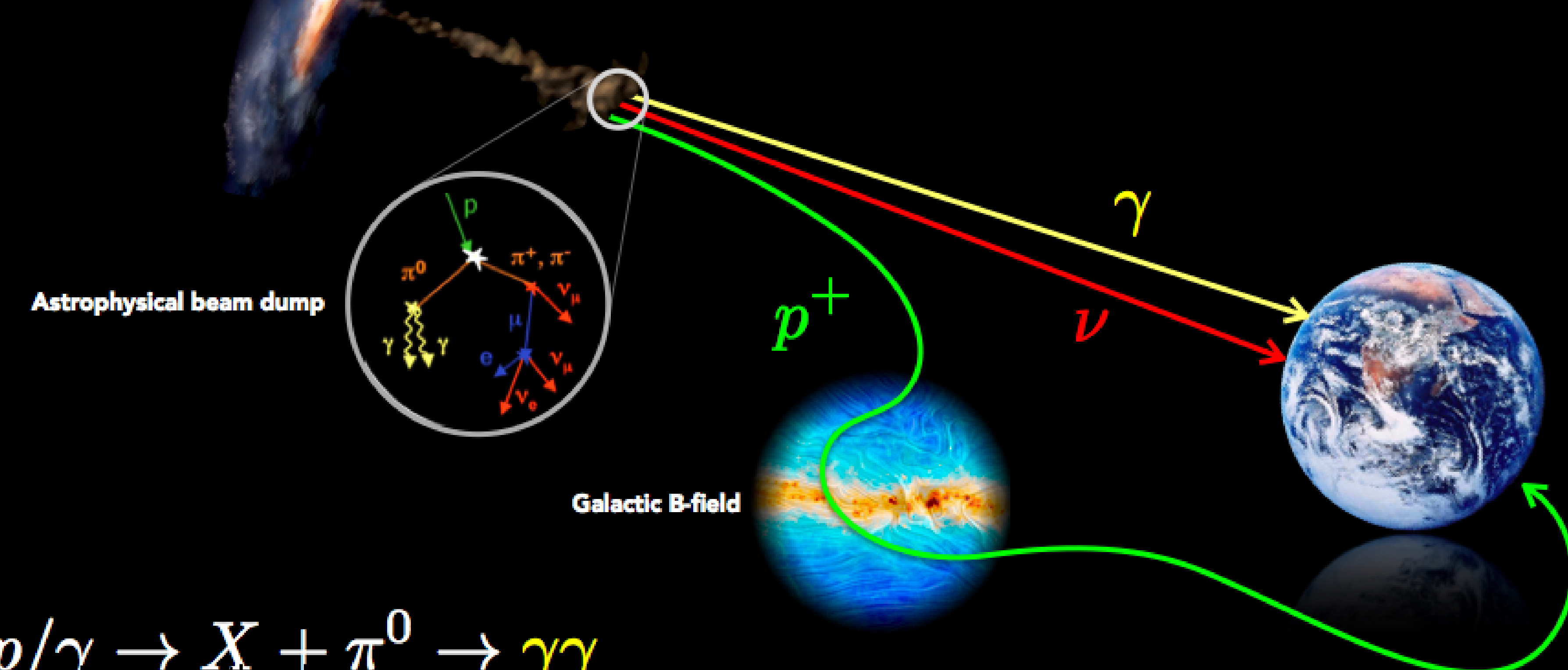


Konstancja Satalecka
(DESY)

CTA Astrophysics School
Sexten, July 25th 2017

Neutrinos, γ–rays & CRs

Spatial/Temporal correlations between **neutrinos** and **gamma rays** can trace **cosmic-ray** acceleration/interaction sites

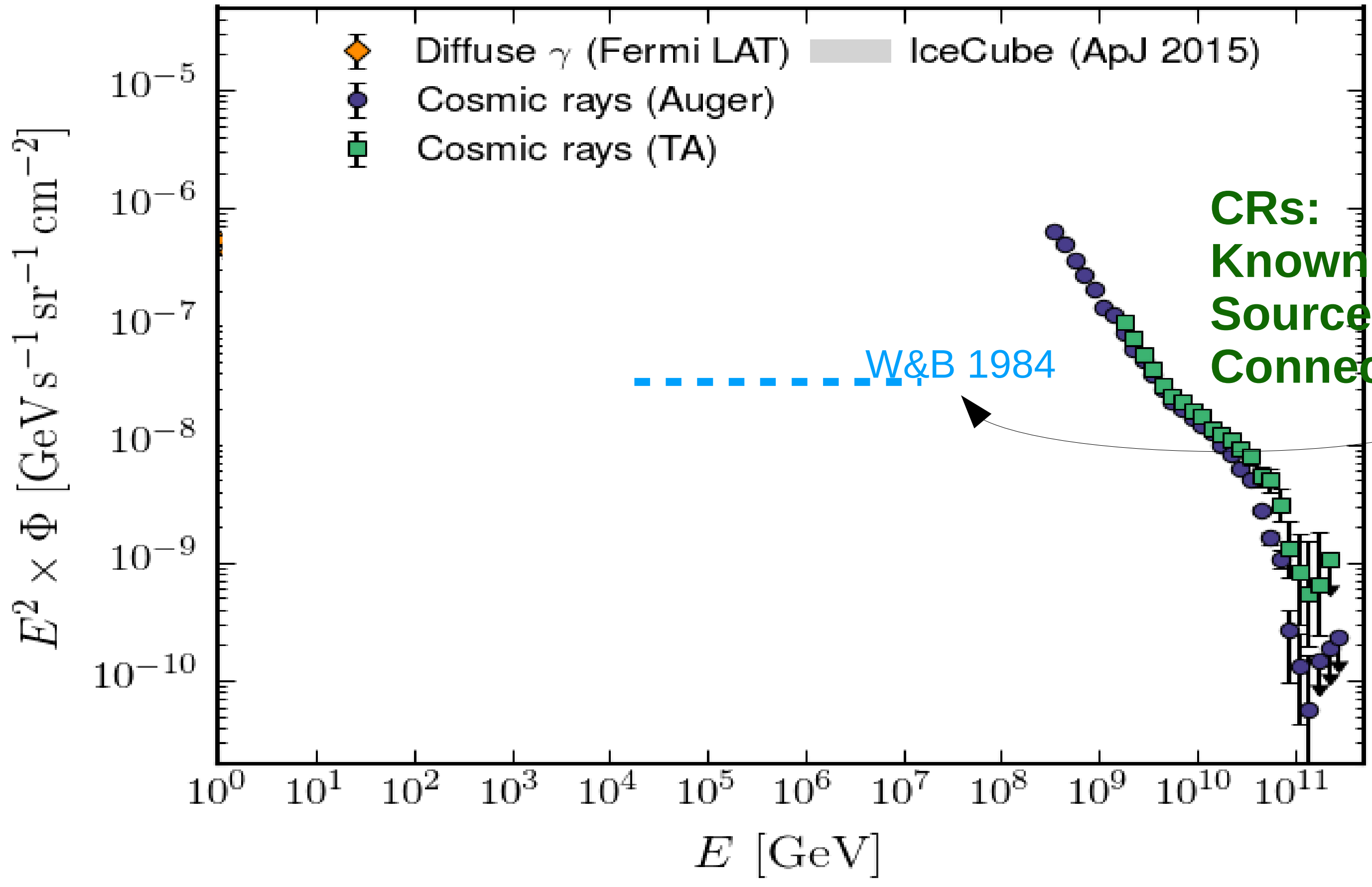


$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

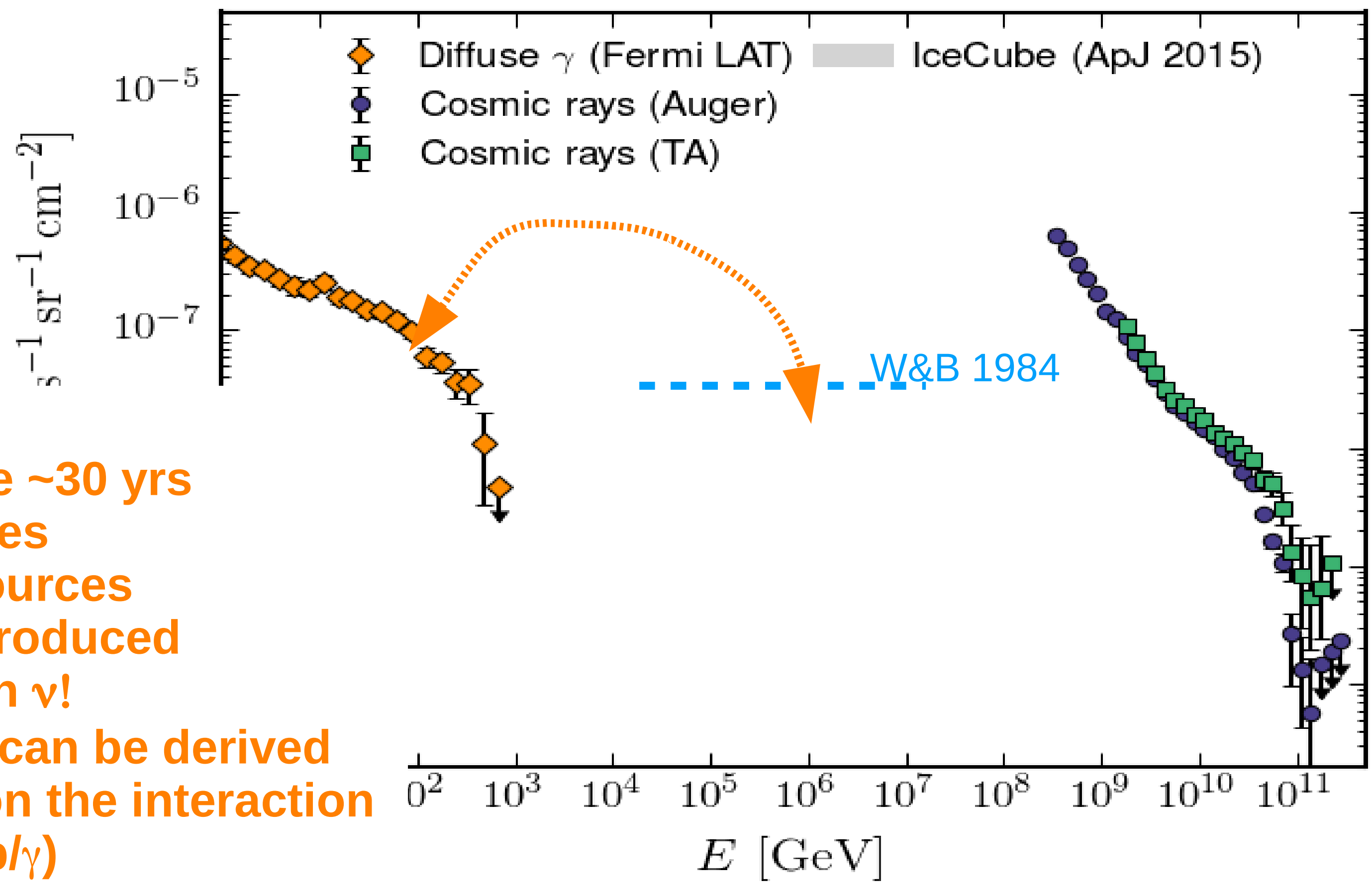
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

Neutrinos, γ–rays & CRs



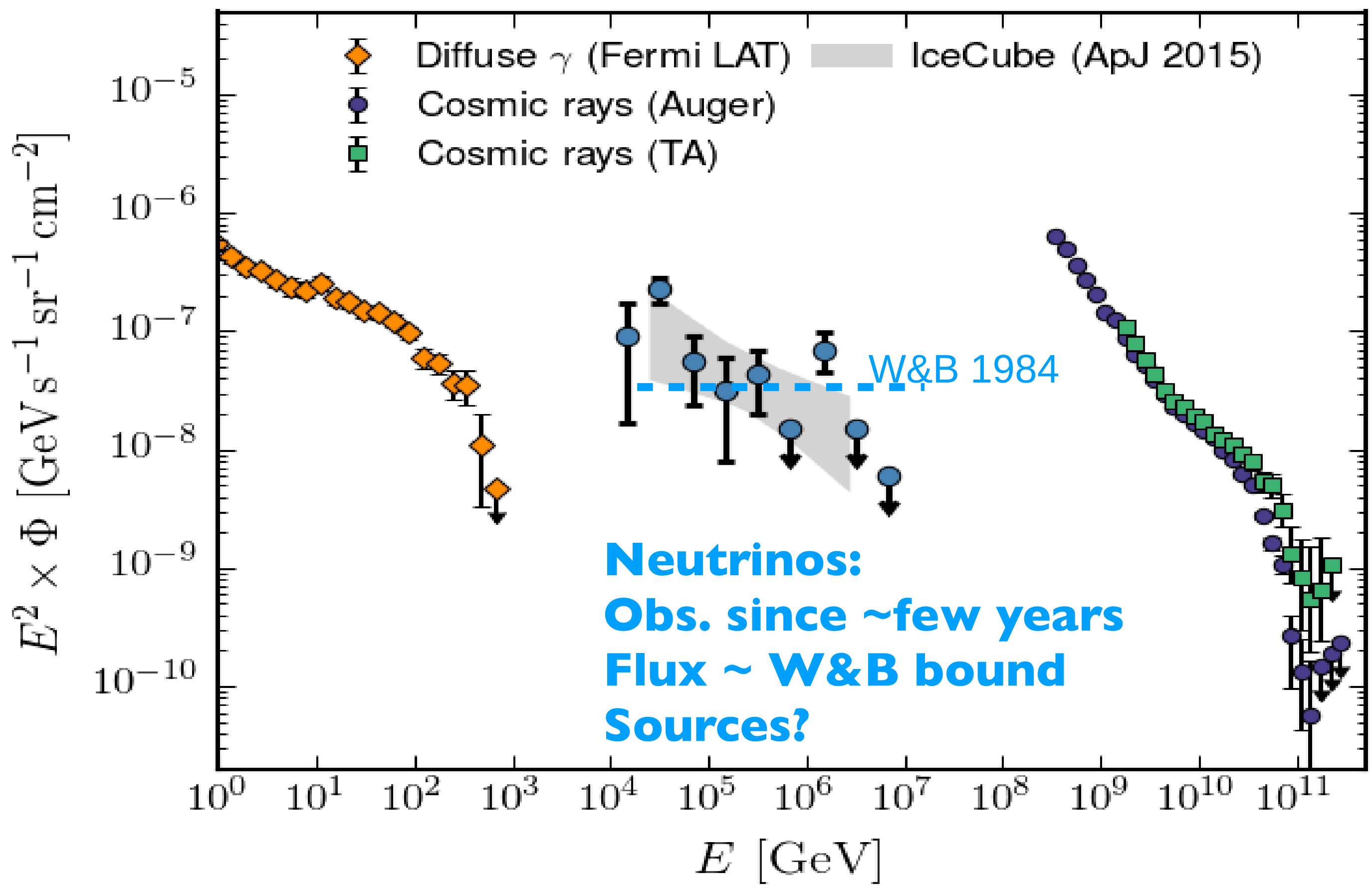
CRs:
Known since 100 yrs!
Sources?
Connection to ν?

Neutrinos, γ–rays & CRs

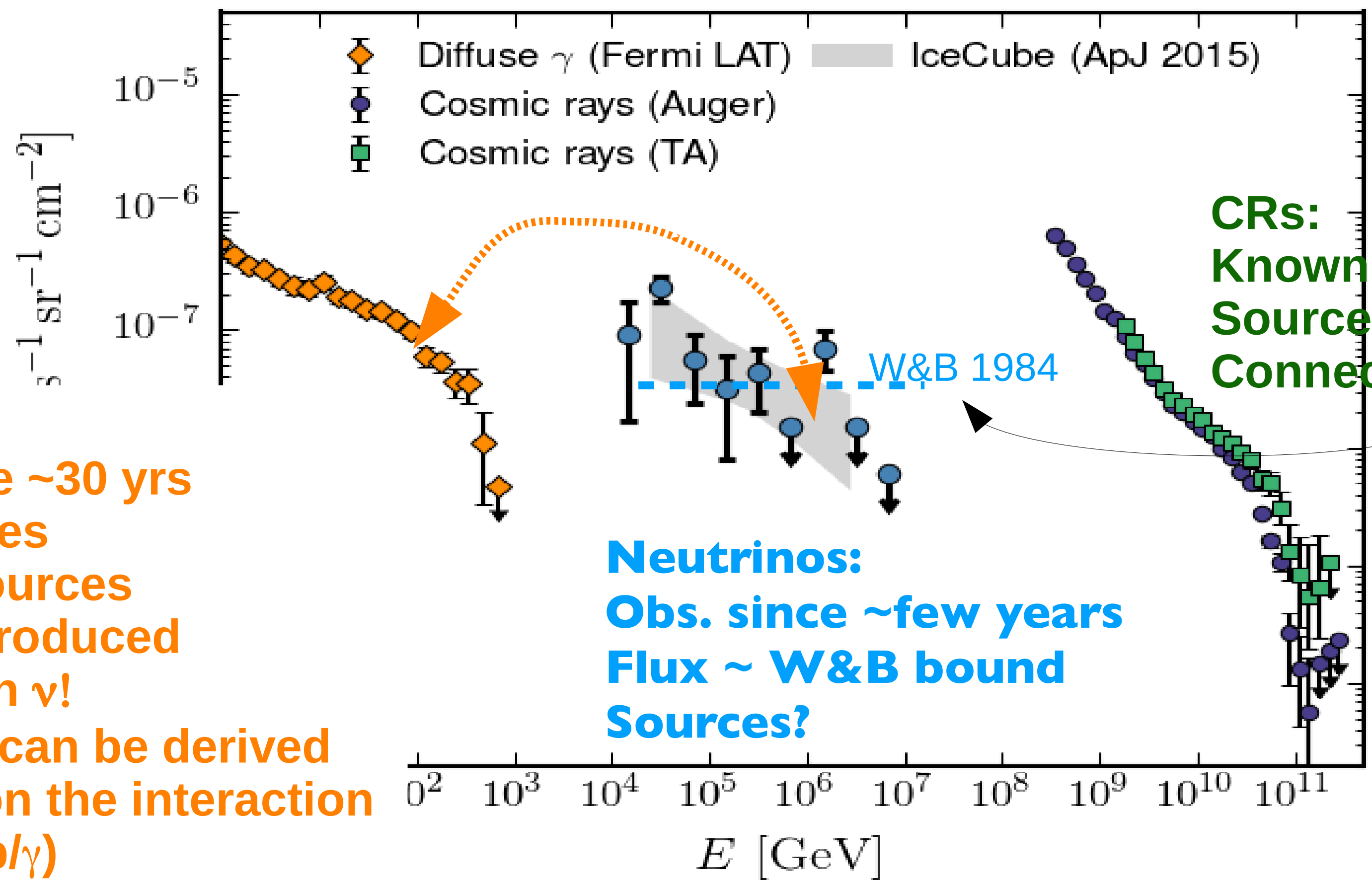


γ-rays:
Known since ~30 yrs
~3000 sources
> 100 TeV sources
Should be produced together with ν!
Constraints can be derived depending on the interaction type (pp or p/γ)

Neutrinos, γ–rays & CRs



Neutrinos, γ–rays & CRs



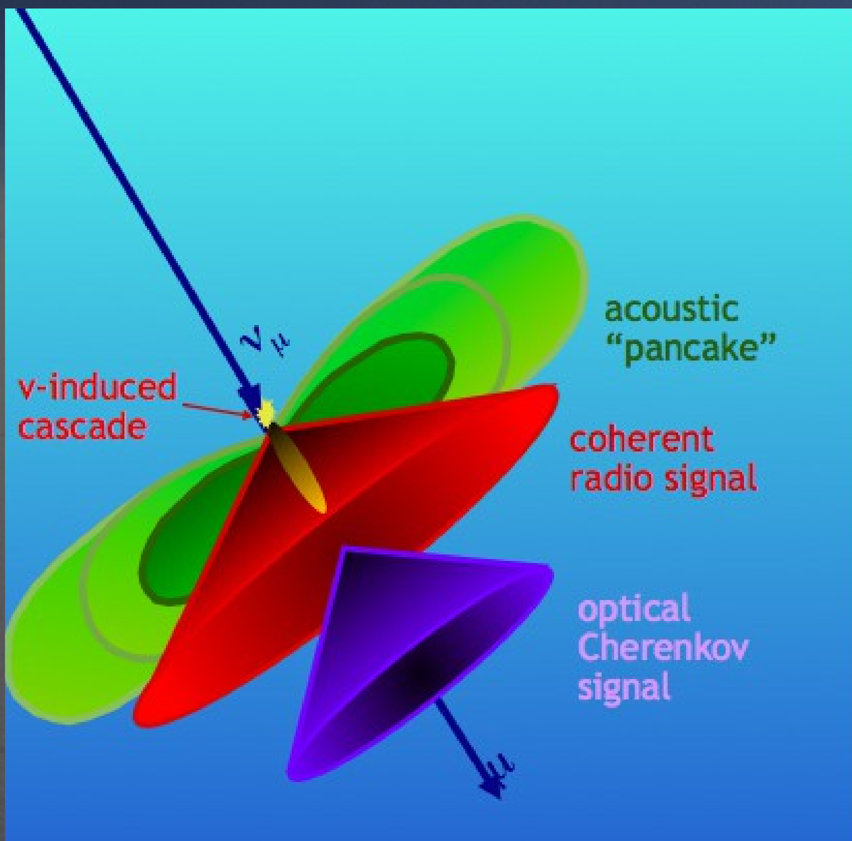
γ-rays:
Known since ~30 yrs
~3000 sources
> 100 TeV sources
Should be produced together with ν!
Constraints can be derived depending on the interaction type (pp or p/γ)

Neutrinos:
Obs. since ~few years
Flux ~ W&B bound
Sources?

CRs:
Known since 100 yrs!
Sources?
Connection to ν?

- How are the different messengers connected?
- What are their sources?
- What are the acceleration/emission/propagation processes?
- Neutrino flux ~ W&B bound → real connection or accident?

Neutrinos: experimental techniques



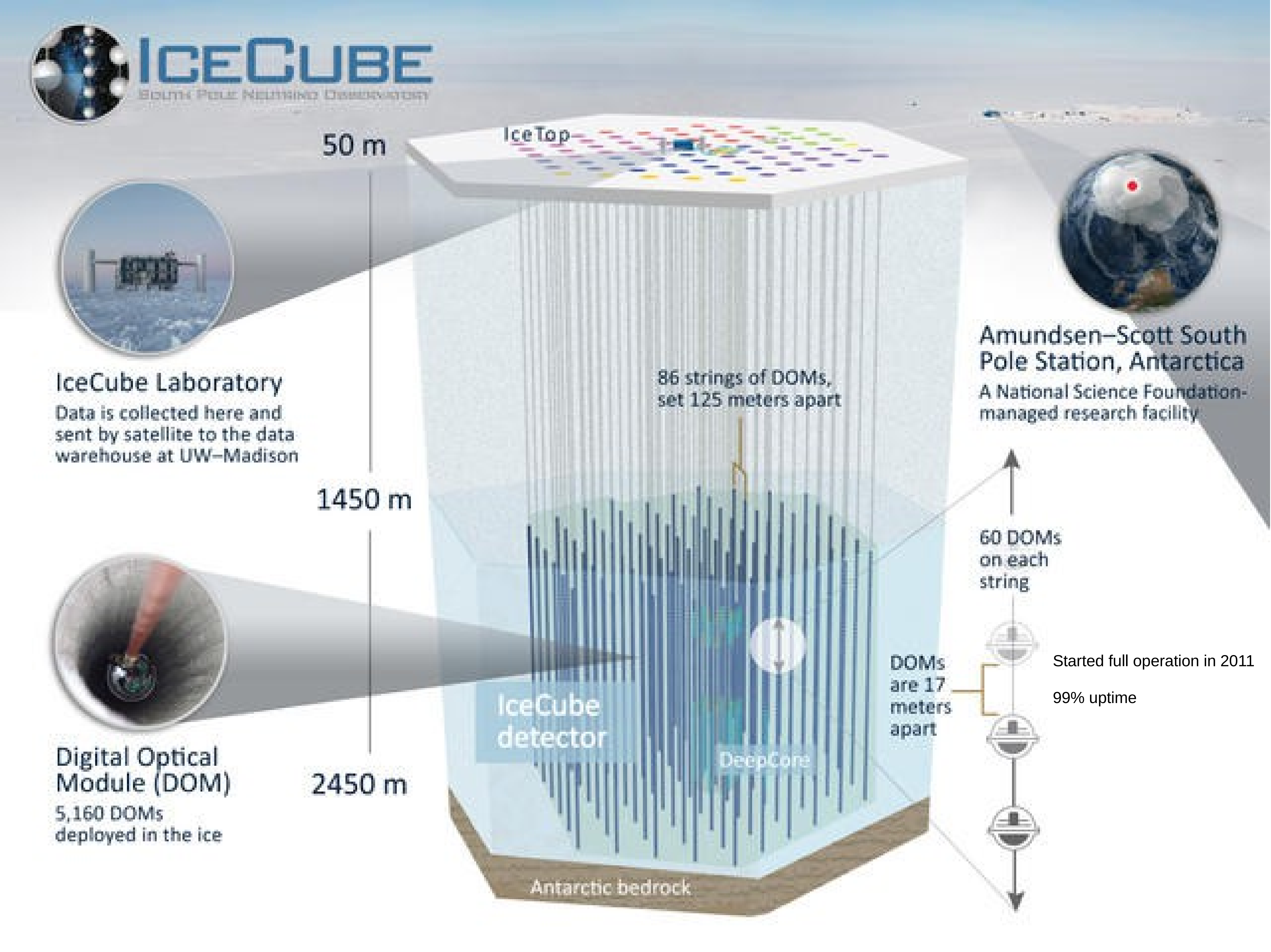
- Small x-section + flux ~10^{15} / km / yr > 100 TeV
  → large volumes needed!!!

- 10^9 eV to 10^{16} eV
  Cherenkov photons in water/ice
  (IceCube, ANTARES, future: KM3Net, Baikal-GVD)

- 10^{17} eV to 10^{23} eV
  Coherent radio pulses in ice, salt and Moon regolith
  (ANITA, RICE)

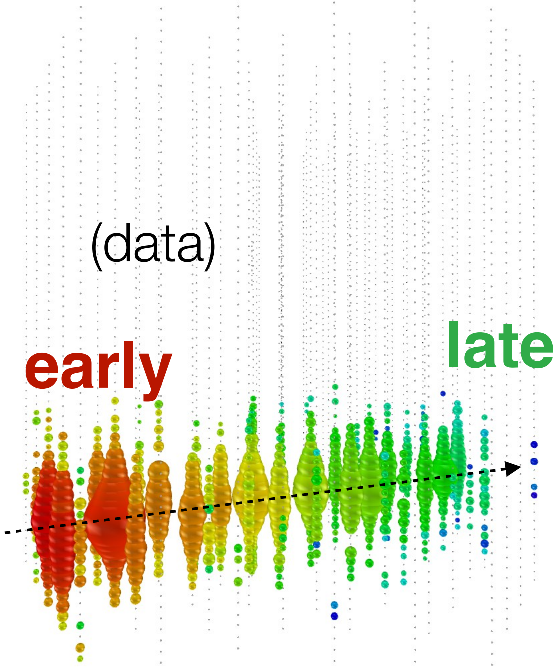
- > 10^{19} eV
  Acoustic waves in water/ice and salt
  (AMADEUS, SPATS - feasibility study)

- 10^{17} to 10^{19} eV
  Extensive air showers (AUGER)


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
Started full operation in 2011
99% uptime

Event topology in IC

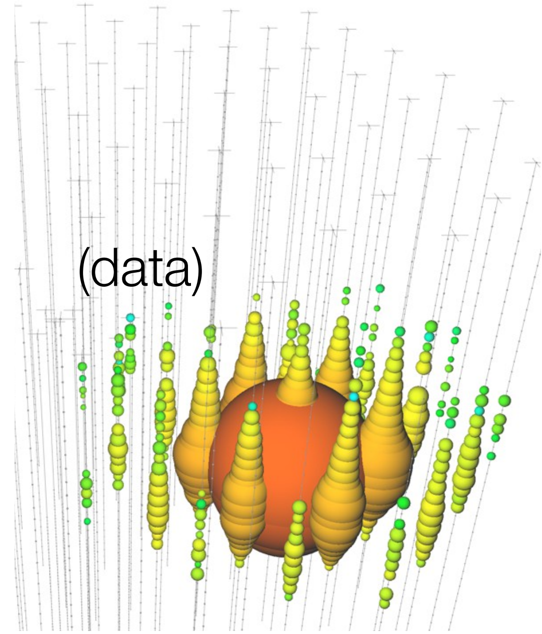
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

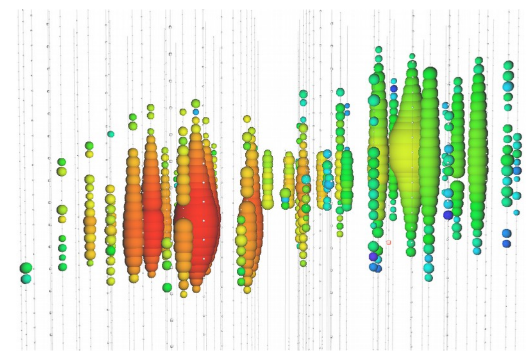


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

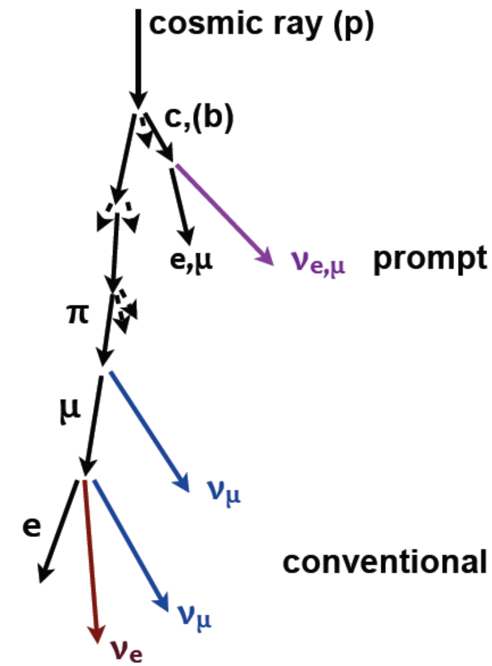
(simulation)



Double cascade

(resolvable above ~100 TeV deposited energy)

IceCube: background & signal



Event rates:

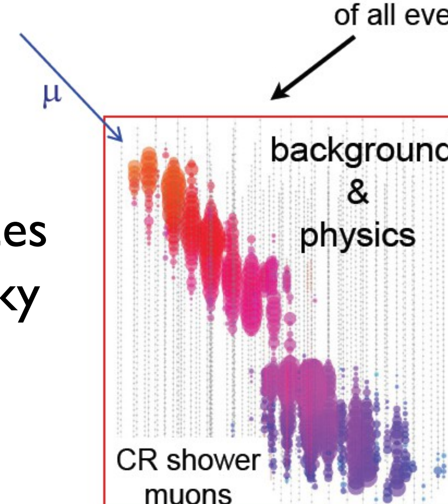
- atmospheric μ (99.999% of triggered events) 7×10^{10} (2000 per second)
- atmospheric ν (residual background) 5×10^{4} (1 every 6 minutes)
- astrophysical neutrinos: ~ *O*(10) per year
  → We need clever background rejection techniques!!

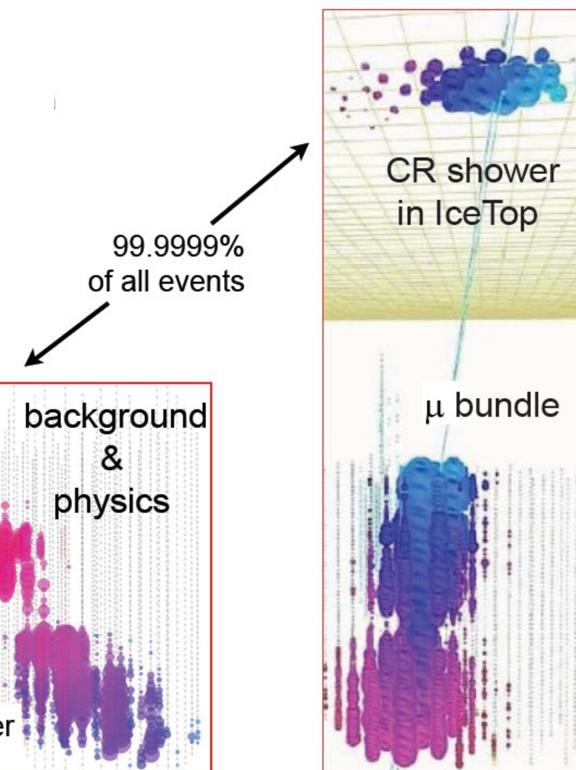
Background rejection:

- By direction: accept only events coming from North (up-going)
- By event type: cascades – only produced by NC and ne CC
- By energy: expected astrophysical flux harder than atmospheric - accept only high energy events

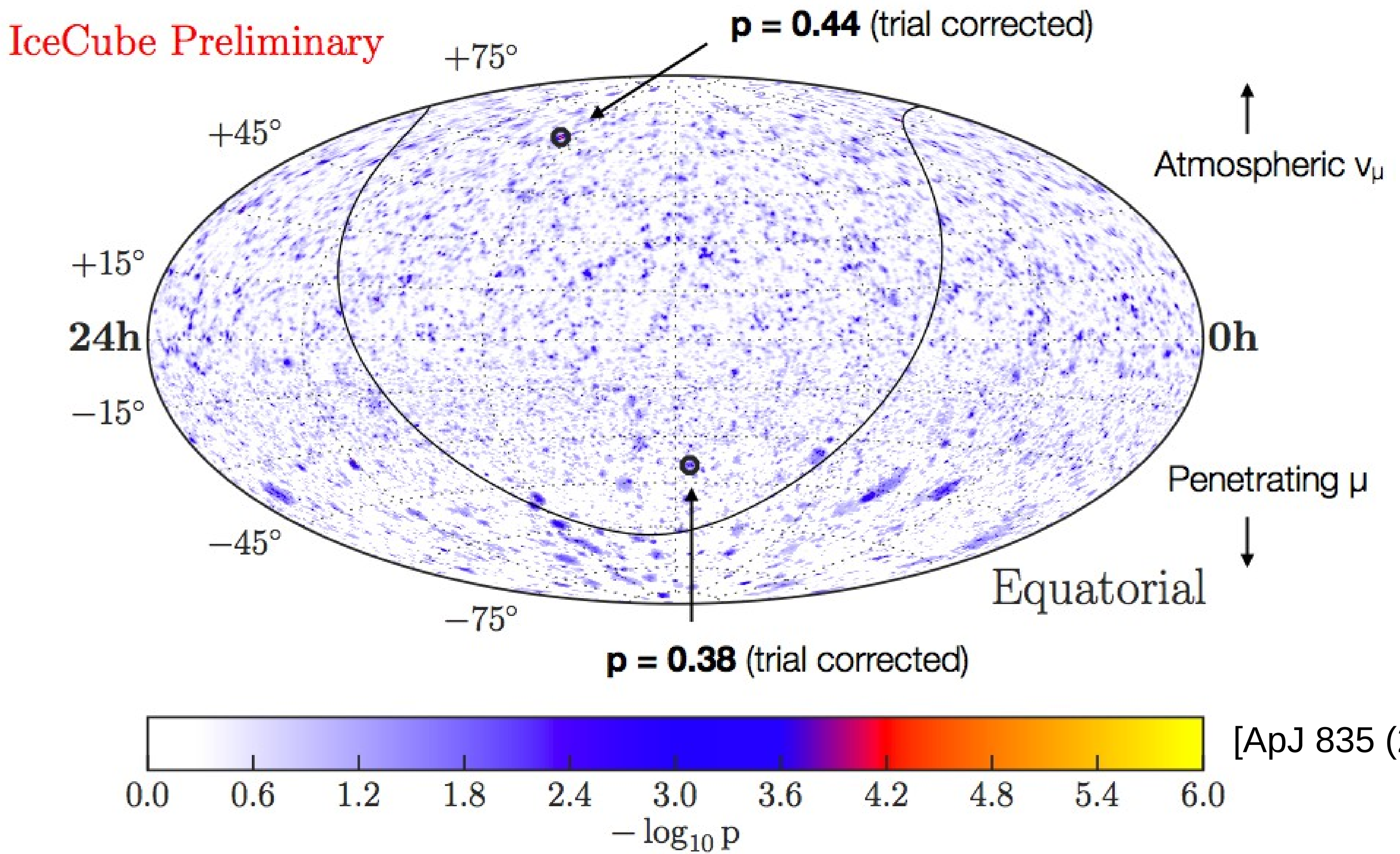
Analysis:

- Look for excess in space and/or time → point sources
- Look for excess of high energy events from whole sky
  → diffuse flux





Search for point-sources, all-sky, time integrated

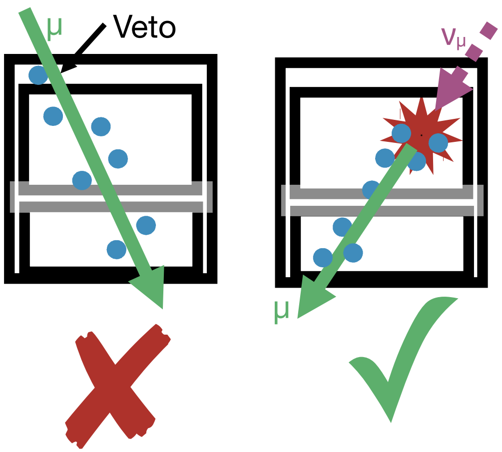


[ApJ 835 (2017) 151]

No significant event clustering, no point sources identified so far (7 yrs)

$N_{sources}$ in the North > 100, in the South > 10

High-Energy Starting Events in IceCube

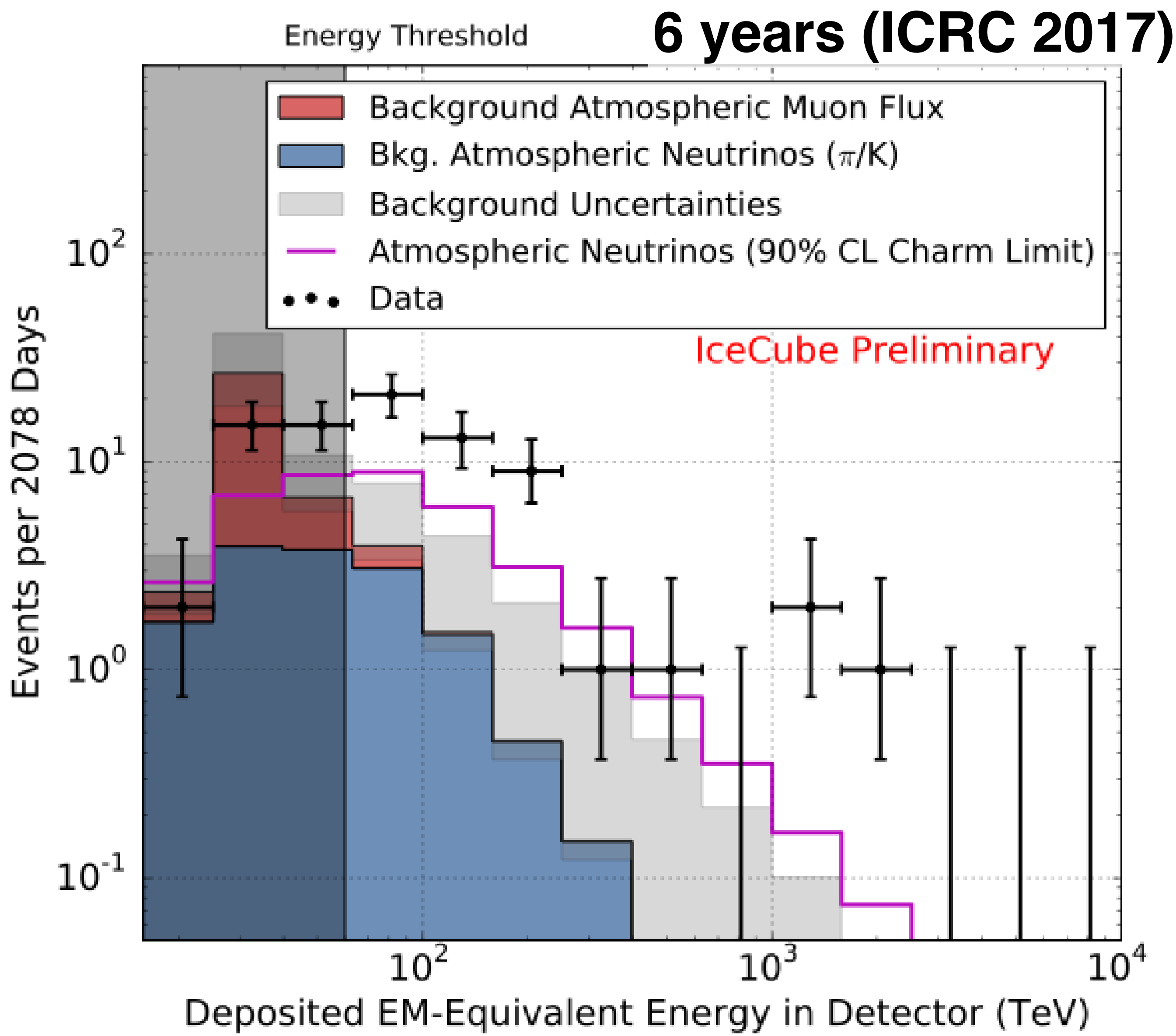


Selected events that start in IceCube volume

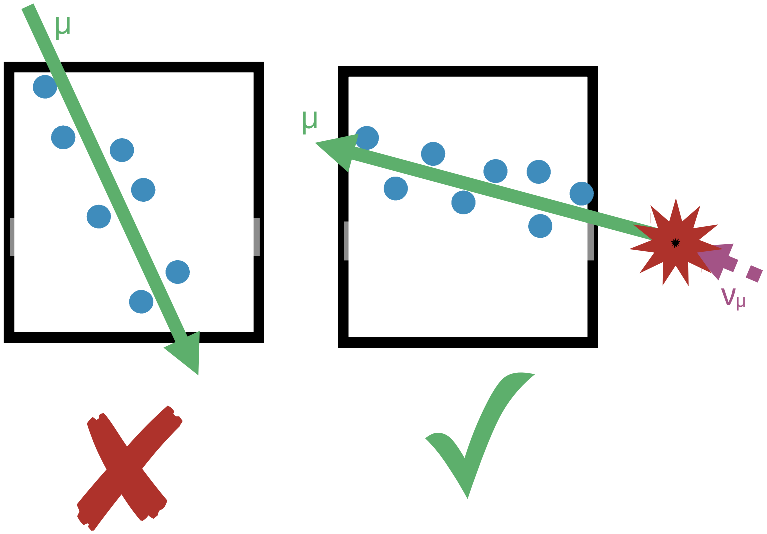
82 HESE in 6 yrs (54 in 4 years)

PL index ~ 2.5-2.7

Flavor composition 1:1:1 (as expected)



ν_μ from the Northern sky

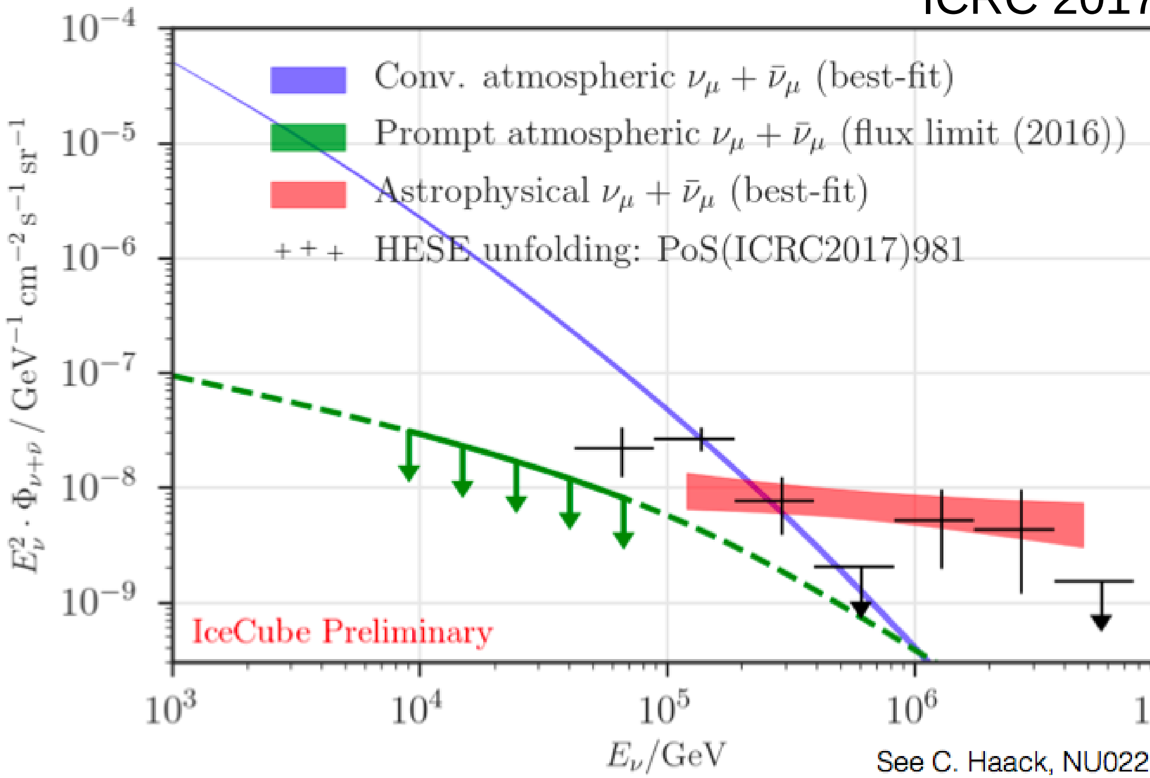


Selected horizontal
and up-going muon tracks

Sensitive to astrophysical neutrinos above ~120 TeV

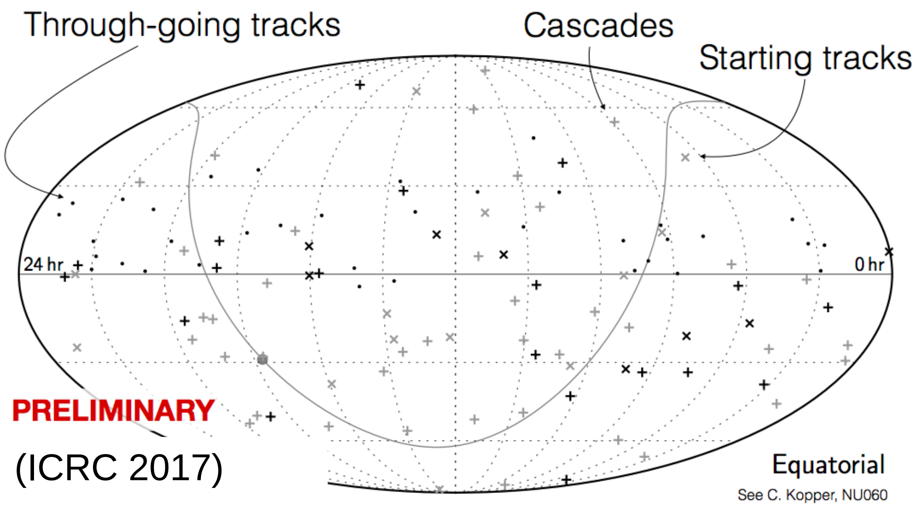
Power law index: 2.19±0.10

ICRC 2017

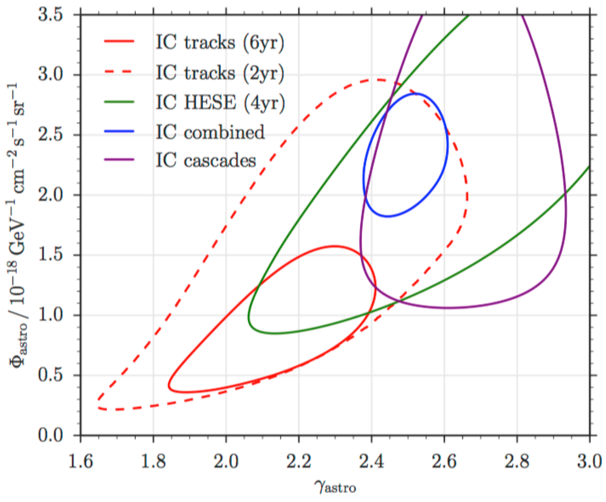


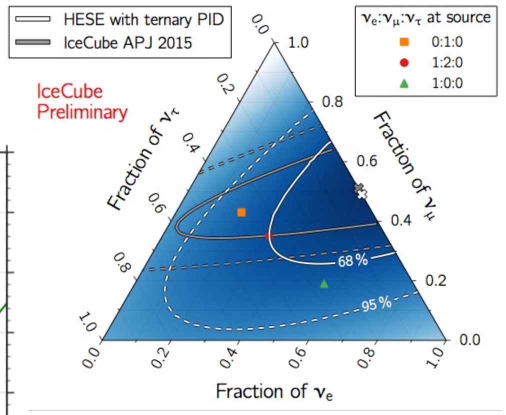
See C. Haack, NU022

6 years of astrophysical neutrinos



(ICRC 2017)





(ICRC 2017)

Tension in spectral index between event classes → 2 components?

Flavor ration – as expected

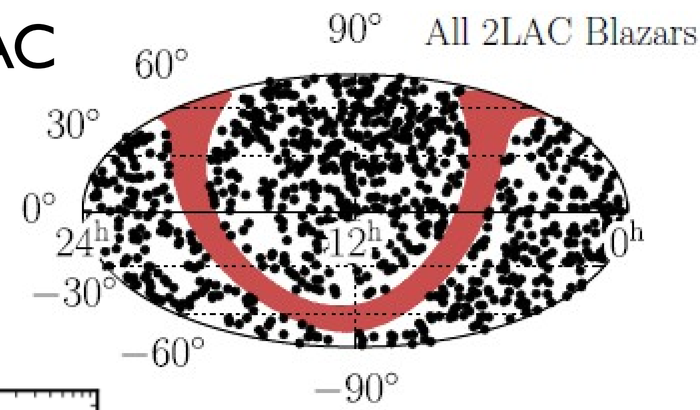
No significant event clustering, no point sources identified so far

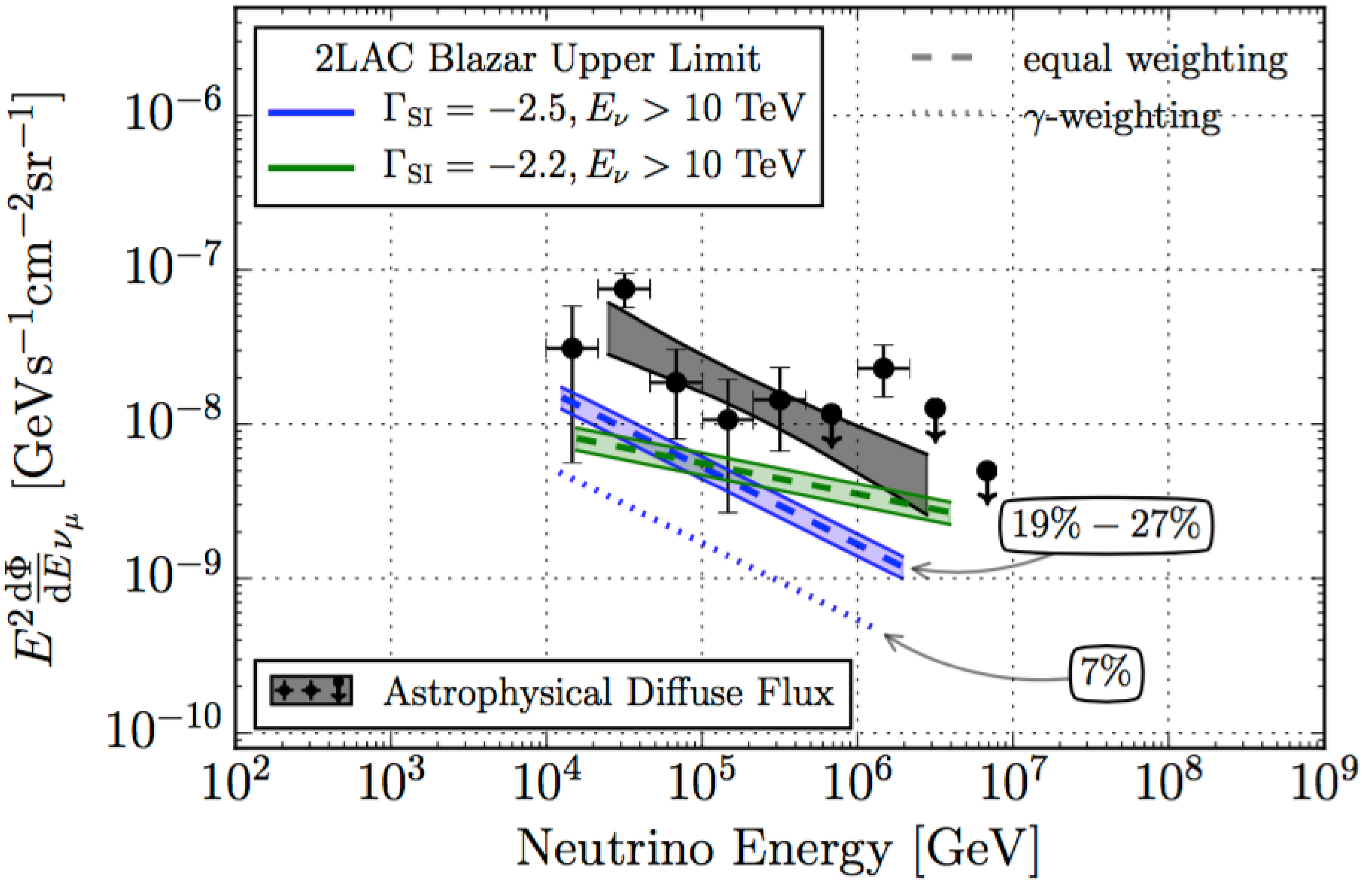
Mostly isotropic → extragalactic (?)


AGN?

Population studies: blazar catalog search

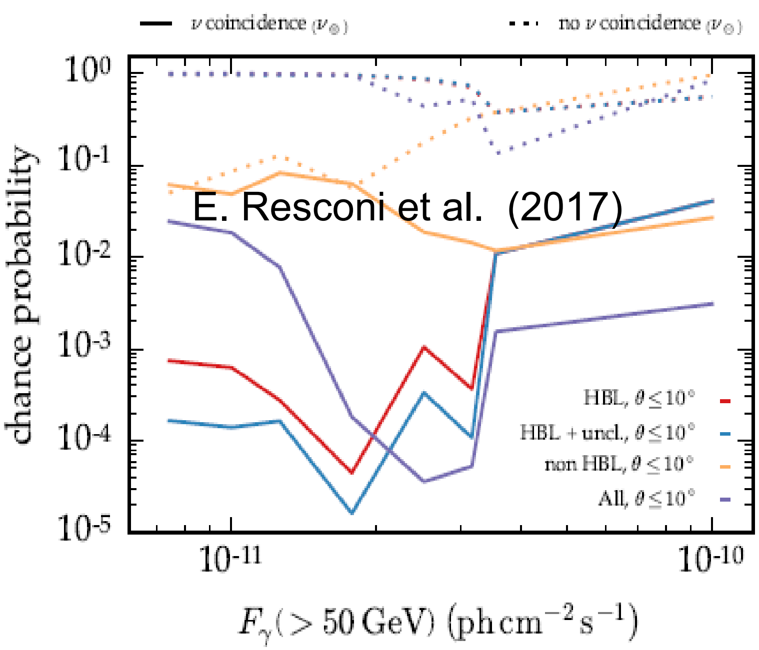
Nu event correlation with > 860 blazars from 2LAC
Blazars account for:
85% of extragalactic γ background
< 20% of the IceCube neutrino flux



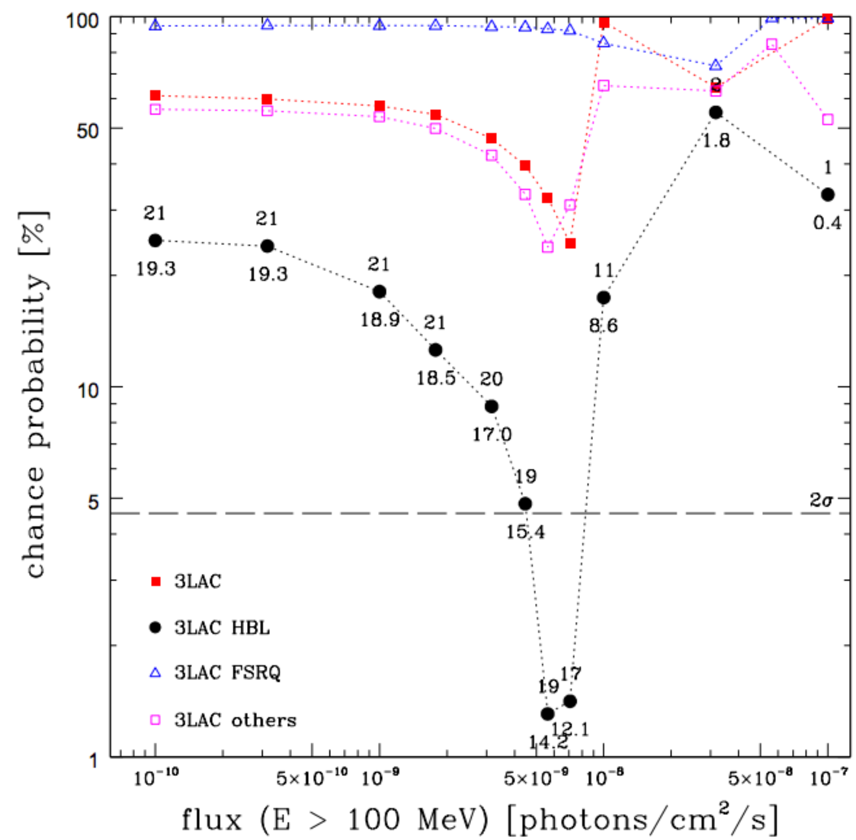


High Frequency Peaked Blazars...?

- Hint for correlation of extreme blazars (HBLs from 3LAC) & high-energy neutrinos → chance probability 1.3%
- 10-20% of diffuse flux could be produced by high frequency peaked blazars (not in tension with IceCube limit)
- 2FHL HBLs + HE ν + CRs → 0.4%

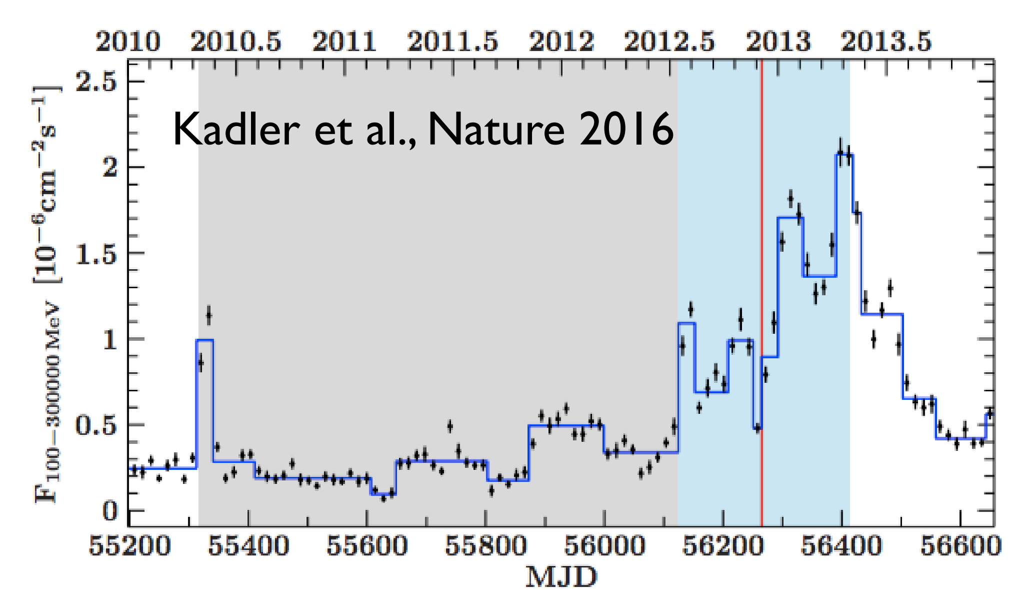


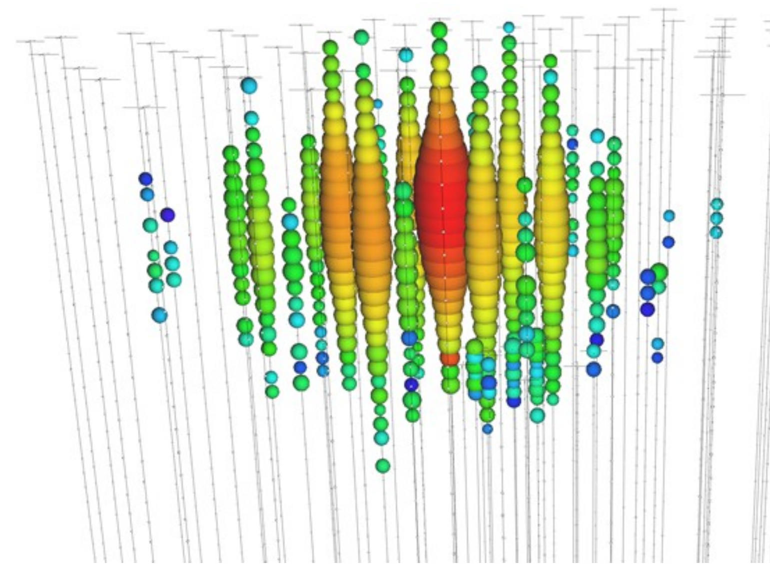
P. Padovani et al. (2016)



High fluence FSRQs…?

- Major outburst of FSRQ PKS B1424−418 (Fermi/LAT) occurred in temporal and positional coincidence PeV neutrino (Big Bird)
- 5% chance coincidence

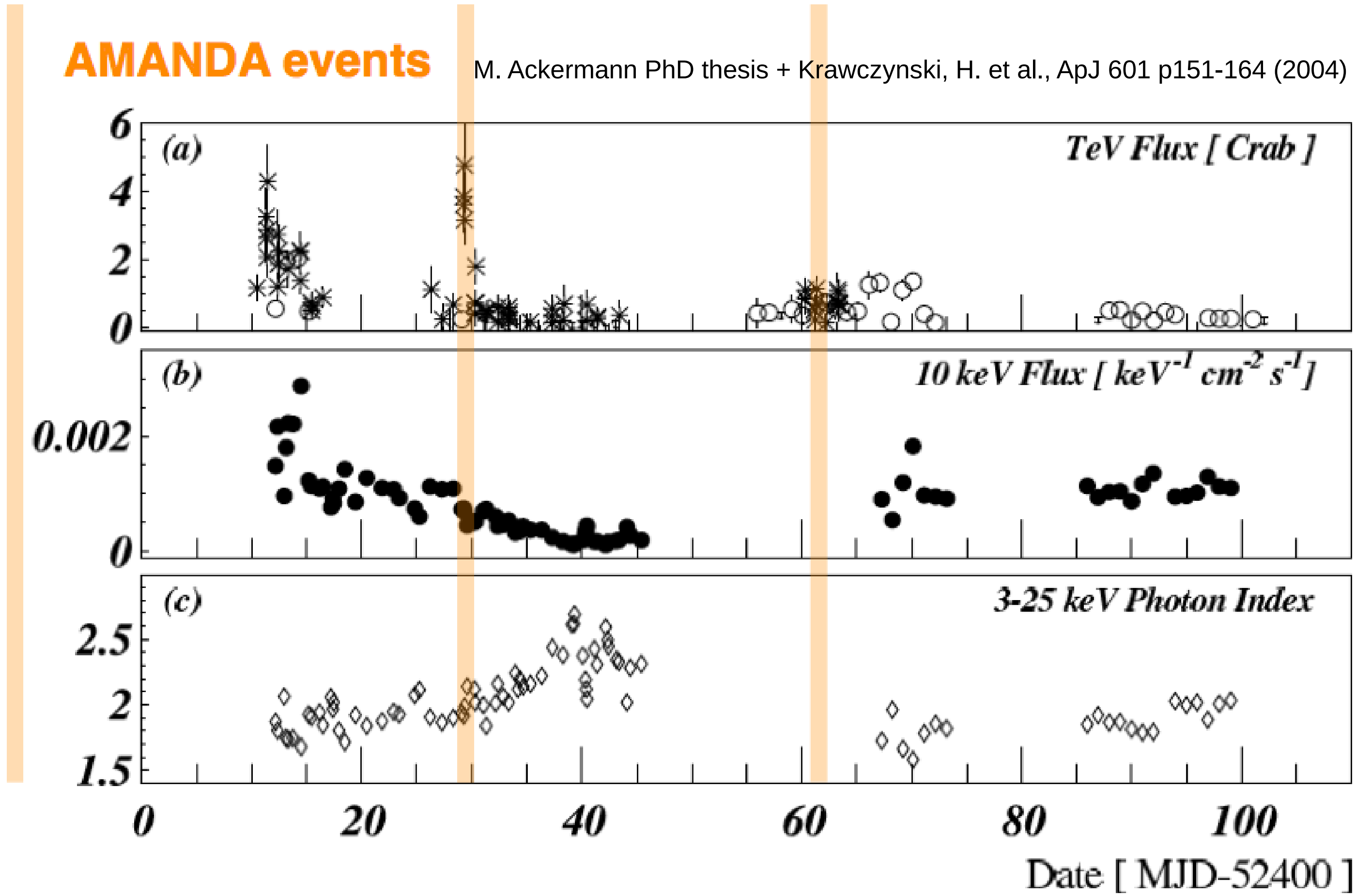




$2.0^{+0.26}_{-0.24}$ PeV, ang. res. ~10°

- Alternative model proposed in: Gao et al. (2016), γ-ray flare due to purely leptonic interactions, no connection to neutrino emission

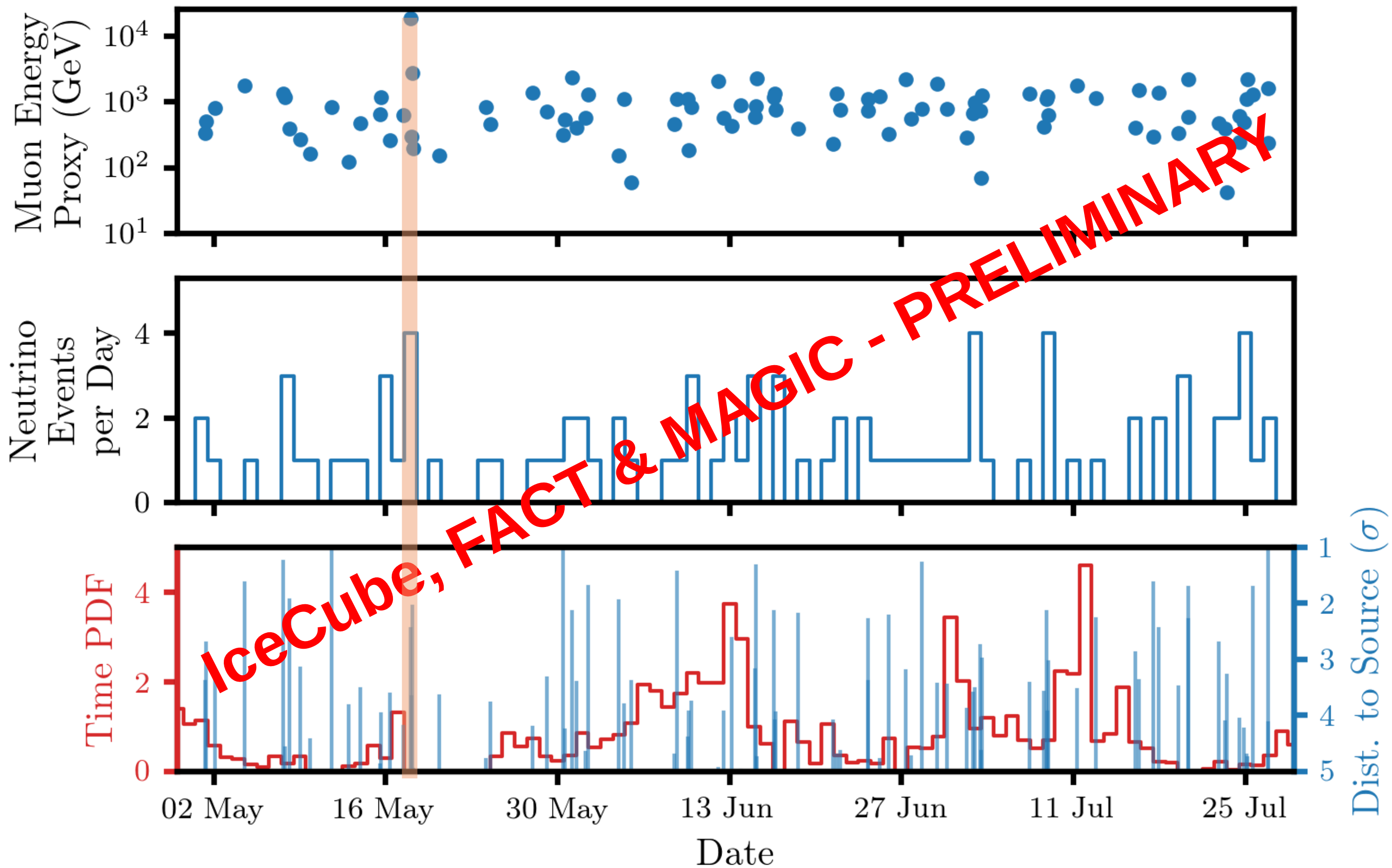
1ES 1959+650: a case of a flare



- 2002: "orphan flare" (Whipple/HEGRA): high state in γ-rays + low state in X-rays
- A-posteriori analysis revealed: 3 ν from AMANDA
- Quiescent until ~ 3 months of significant flares in spring 2016

1ES 1959+650: a case of a flare

T. Kintcher et al., ICRC 2017



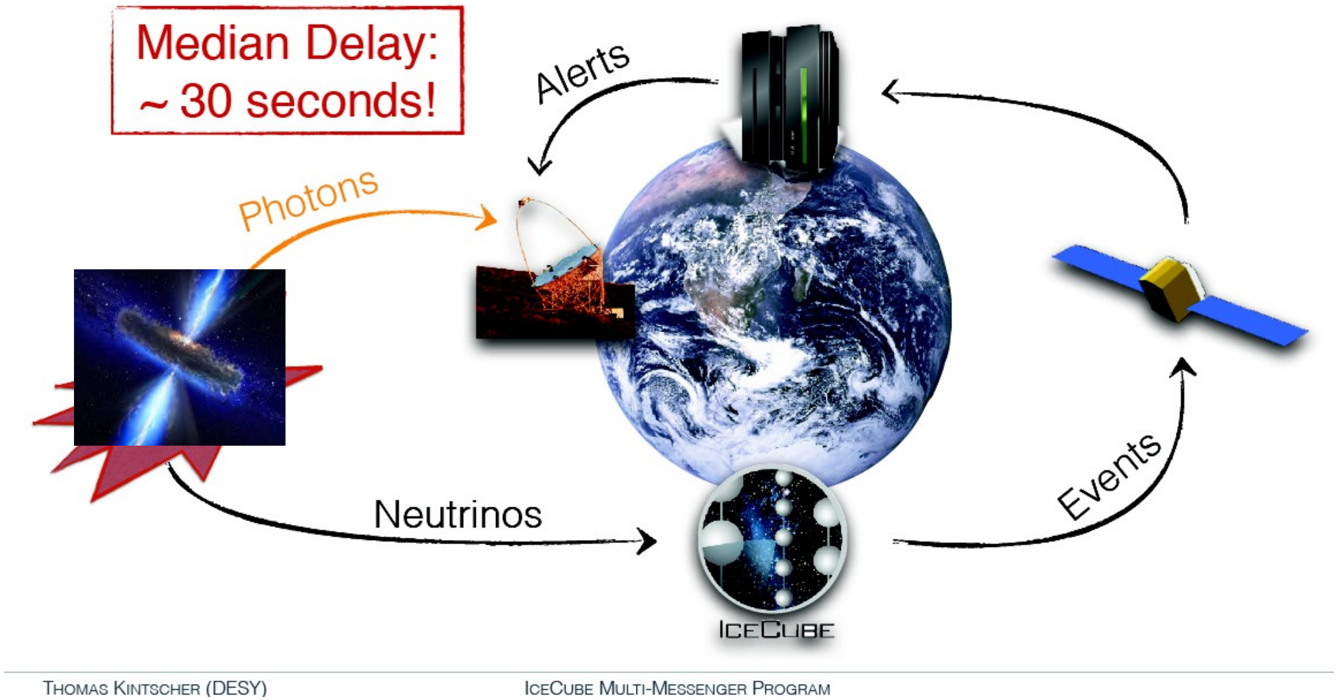
1. Time-Integrated Analysis: excess of neutrino flux during whole time period?
2. Clustering Analysis: excess on short time scales?
3. Correlation Test: neutrino distribution following the gamma-ray light curve?

→ **No significant exces of neutrinos was observed :(**

Kc

Gamma-ray Follow-up Program

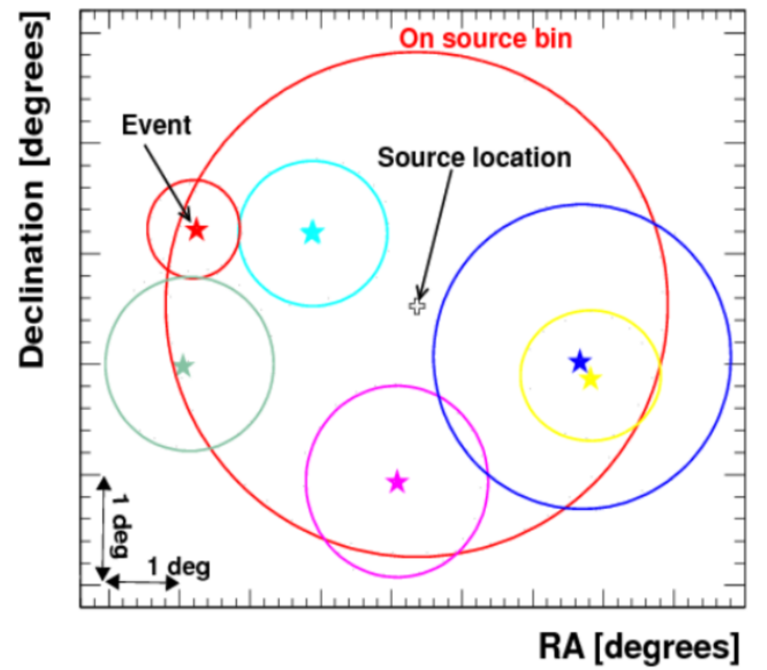
IC, MAGIC & VERITAS, JINST (2016) 11 P11009



- Event multiplets - "neutrino flares" , E_{th} ~ 100 GeV, duration up to 3 weeks
- Pre-defined source list (known AGN, established and potential TeV γ-ray emitters)
- Expected bg alert rate: 4/yr at ~3.5 sigma threshold
- Private alert – MWL data not always available
- In collaboration with MAGIC & VERITAS since 2012

Gamma-ray Follow-up Program

- Most significant alert on Nov. 9th 2012
- Source: SBS 1150+497
- 6 events in 4.2 days
- Alert forwarded to VERITAS
  - No significant gamma-ray emission found
  - F(> 300 GeV) < 3×10^{-10} $cm^{-2}s^{-1}$ (99% CL)



IC, MAGIC & VERITAS, JINST (2016) 11 P11009

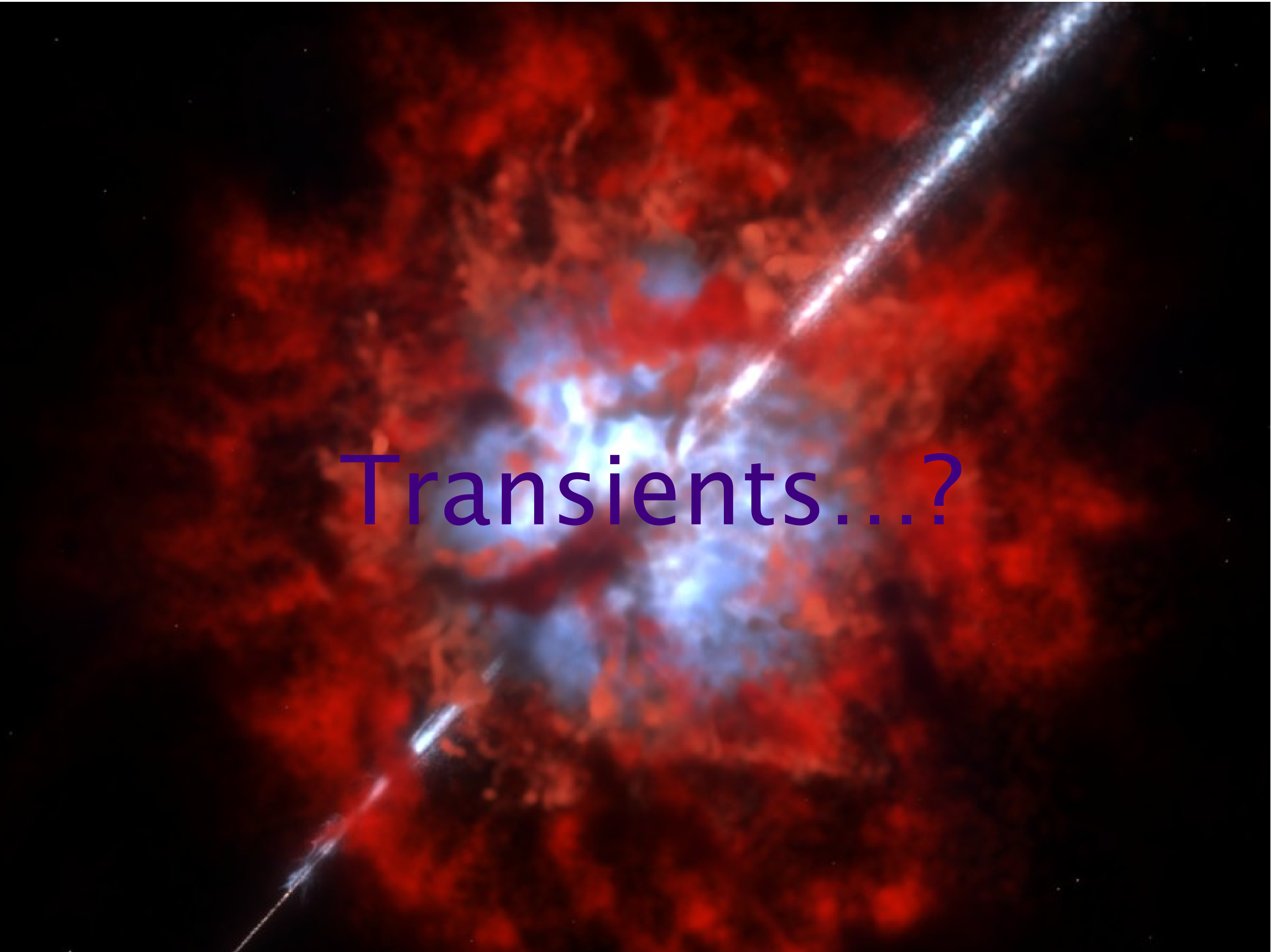
- Extension to Fermi, HESS and HAWC planned for this year

What can CTA do?

- Most of the objectives, already present in the Extragalactic KSP :)
  - AGN monitoring → flare probability
  - MWL campaigns → detailed SED modeling → hints of hadronic processes

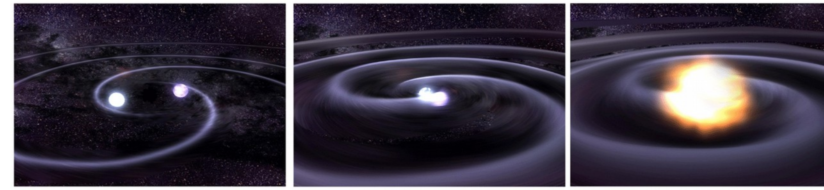
- Join GFU
- Alert about observed flares → data exchange & correlation studie

Transients...?

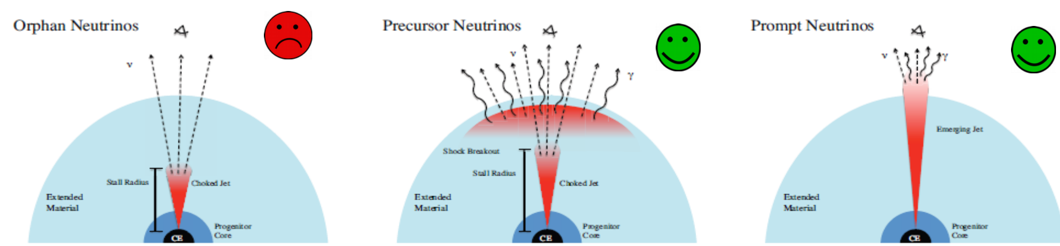


Neutrino sources – transients…?

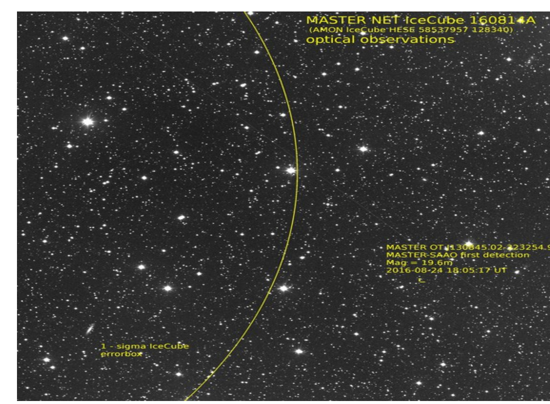
- Possible connection of ν and γ-rays in short-GRBs and GW events caused by mergers (NS-NS) [Bartos et al. (2013)]



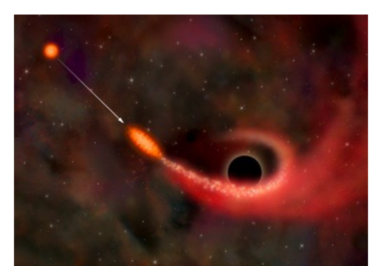
> GRBs with jets "choked" in surrounding medium [Senno et al. (2016)]: explains hypernovae and Low Luminosity GRBs (rate ~100-1000 $Gpc^{-3}yr^{-1}$), predicts neutrino & γ-ray emission



> GCN#19888, MASTERS follow-up of IC alert, reports a delayed optical transient in FoV → white dwarf in binary system or other cataclismic variable?! Possible prompt γ-ray emission: see models by [Bednarek&Pabich (2010)] and refs in GCN#19888

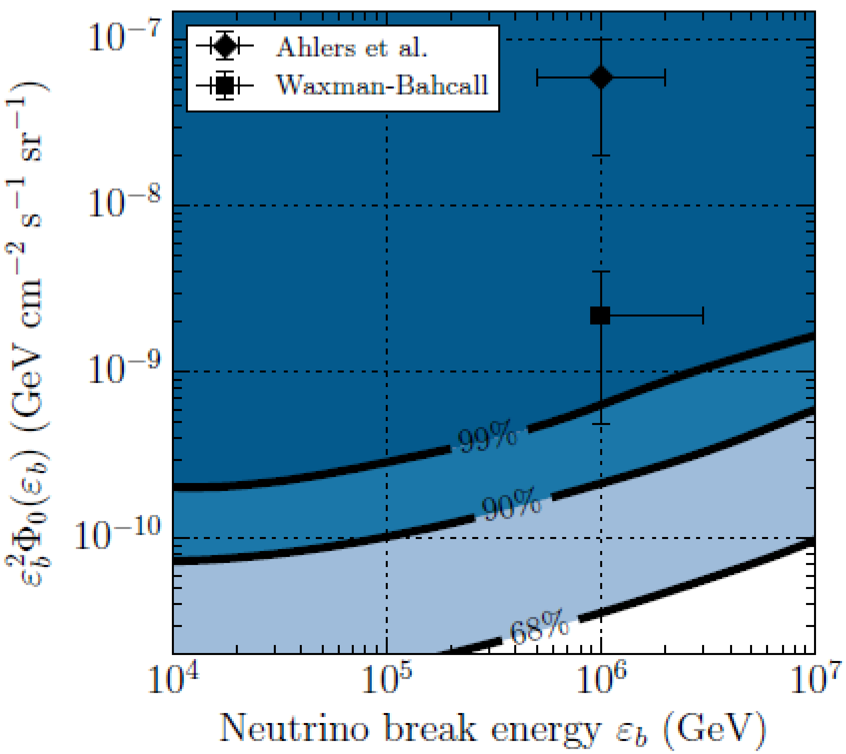


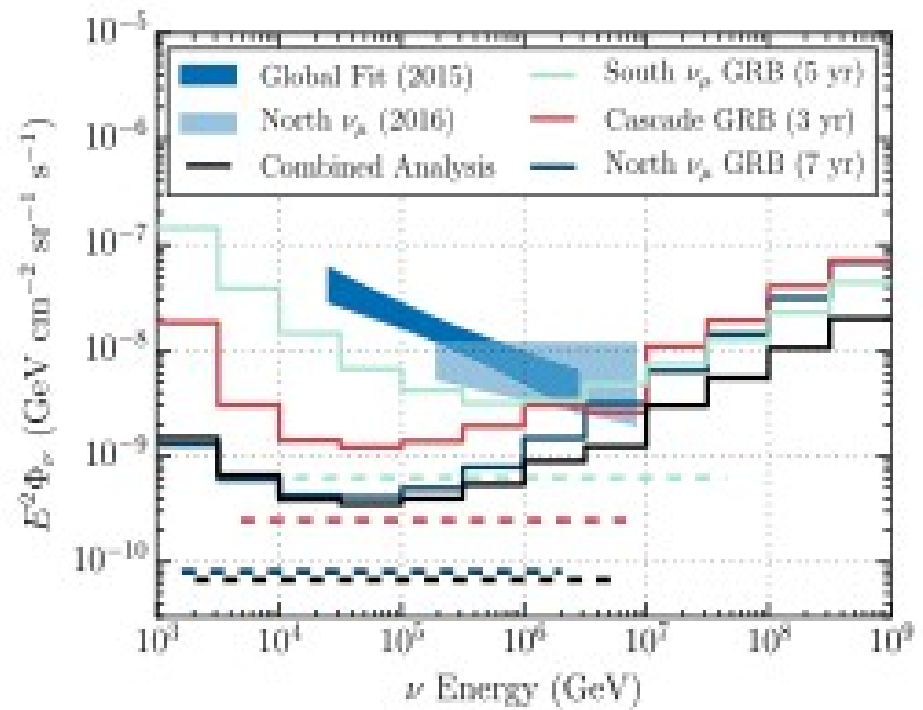
> Tidal Disruption Events (BH eating a star) → jet + surrounding material → ν? γ-ray? [Lunardini&Winter (2016)]



Neutrinos from GRBs

- > 1100 GRBs correlated with IceCube data
- GRBs contribute less than 1% to observed diffuse neutrino flux
- Most popular neutrino emission models excluded (production in prompt phase)



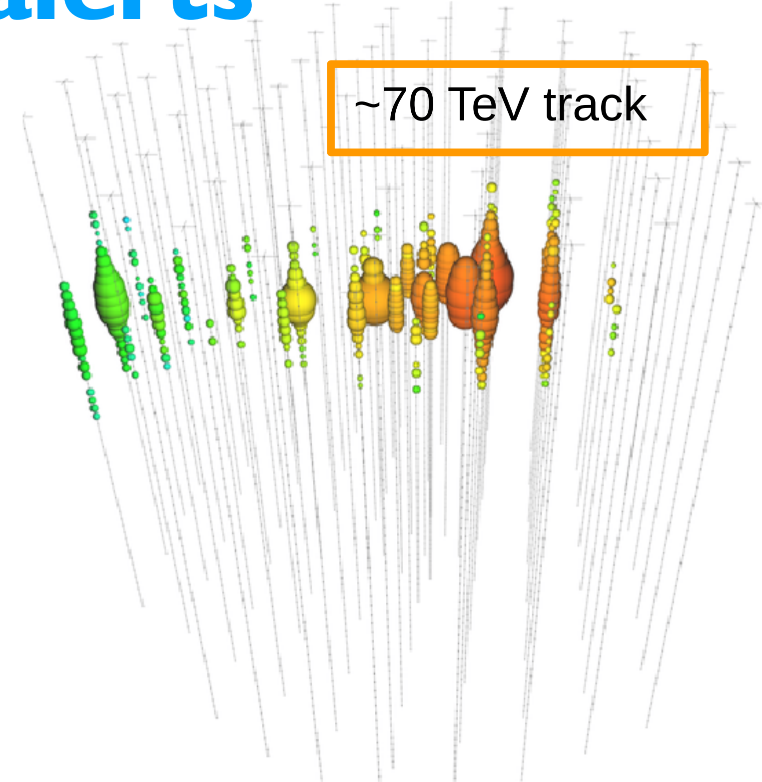


IC Coll., Ap J 843 (2017) 2

IceCube public alerts

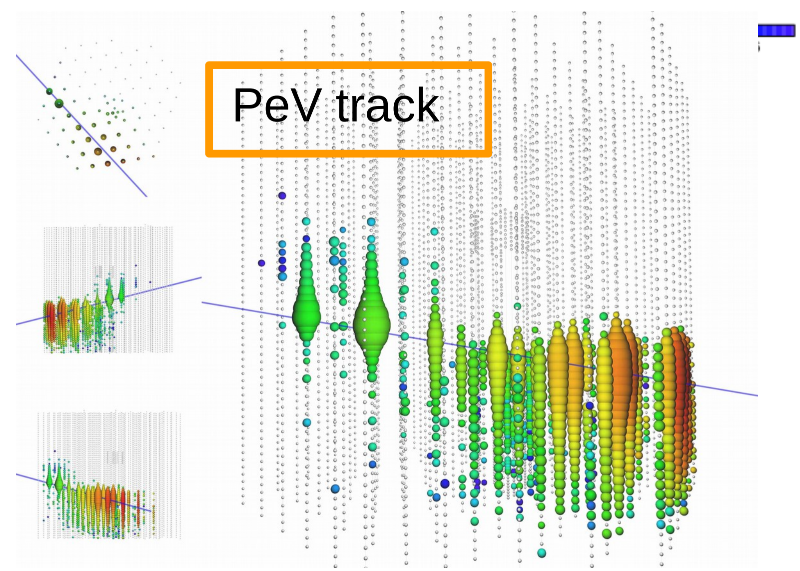
HESE = High Energy Starting Event (since Apr 2016):

- Muon track starting inside the detector
- E_{th} ~ 60 TeV
- median angular resolution 0.4-0.6 deg
- expected rate: 4/yr all-sky (50% signal probability)



EHE = Extremely High Energy (since Jun 2016):

- Muon track going through the detector
- E_{th} ~ 100 TeV
- median angular resolution 0.22 deg
- expected rate: 4/yr all-sky (75% signal probability)



Planned extensions: all-sky nu event clusters,

lower E threshold single events

IC real-time system: M.G. Aartsen et al., Astropart. Phys. 92 (2017) 30-41s

IACT follow-up example: HESE-160427A

FACT

GCN Cicular #19427

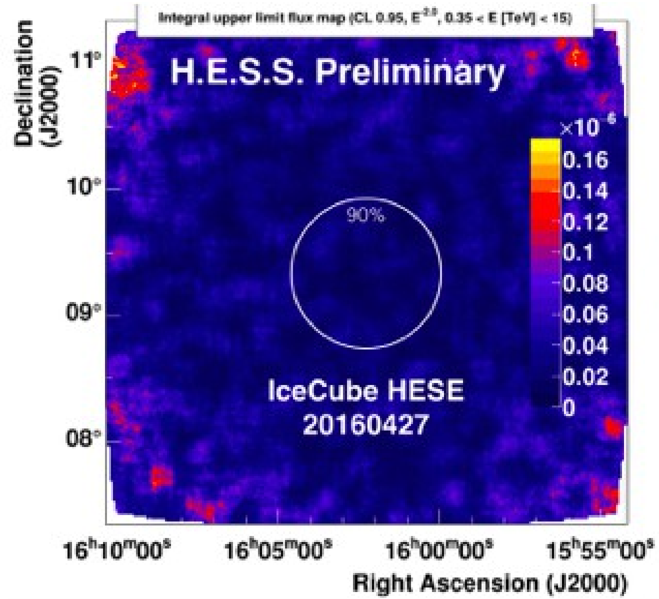
4.2 hr obs, ~20 hr delay

```
TITLE:   GCN CIRCULAR
NUMBER:  19427
SUBJECT: FACT follow-up of the IceCube event 160427A
DATE:    16/05/13 13:02:18 GMT
FROM:    Daniela Dorner at U of Wuerzburg  <dorner@astro.uni-wuerzburg.de>

A. Biland (ETH Zurich) and D. Dorner (University of Wuerzburg, FAU
Erlangen) report on behalf of the FACT collaboration:

On April 27th, 2016, the IceCube collaboration reported the detection
of a high-energy neutrino (GCN #19363) with the updated position of
RA=240.57d and DEC=+9.34d (J2000) and a position error of 0.6 degrees
radius provided at 23:24:24 UTC on April 27th.
```

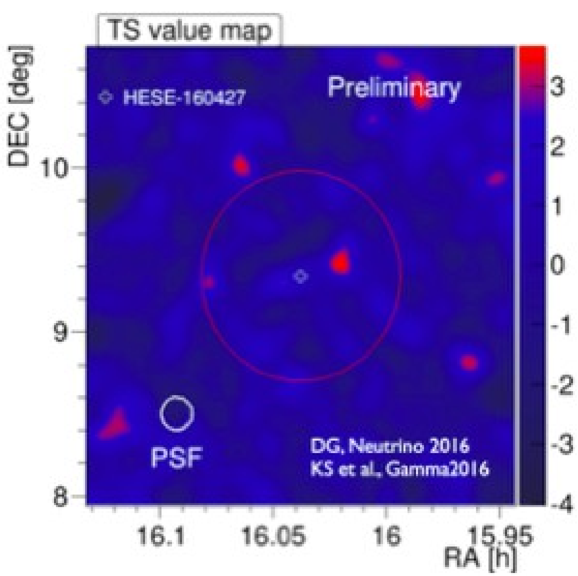
Other follow-ups: 160731A (Circ. #19377), 161103A, AMON160218



H.E.S.S.

- 1.7 hrs obs
- ~ 63 hr delay
- E_{thres} ~ 350 GeV

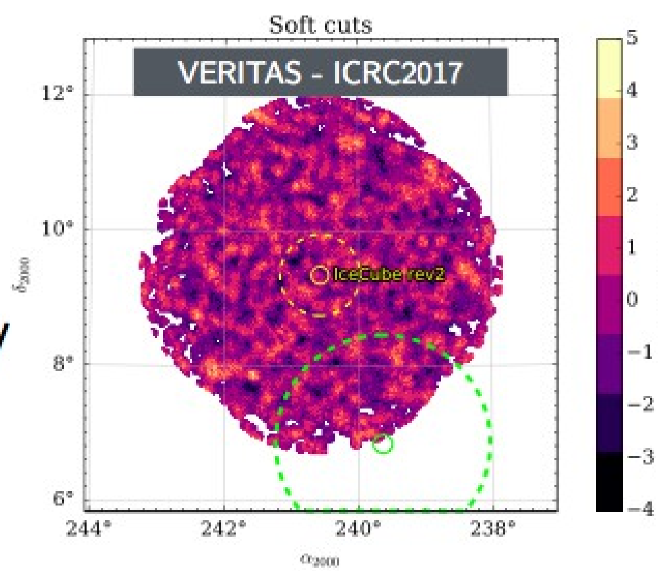
F. Schüssler
Poster GA071



MAGIC

- 2 hrs obs
- 42 hr delay
- E_{thres} ~ 120 GeV

Other follow-ups: 160731A, ATel #9315



VERITAS

- 3.2 hrs obs
- 120s delay

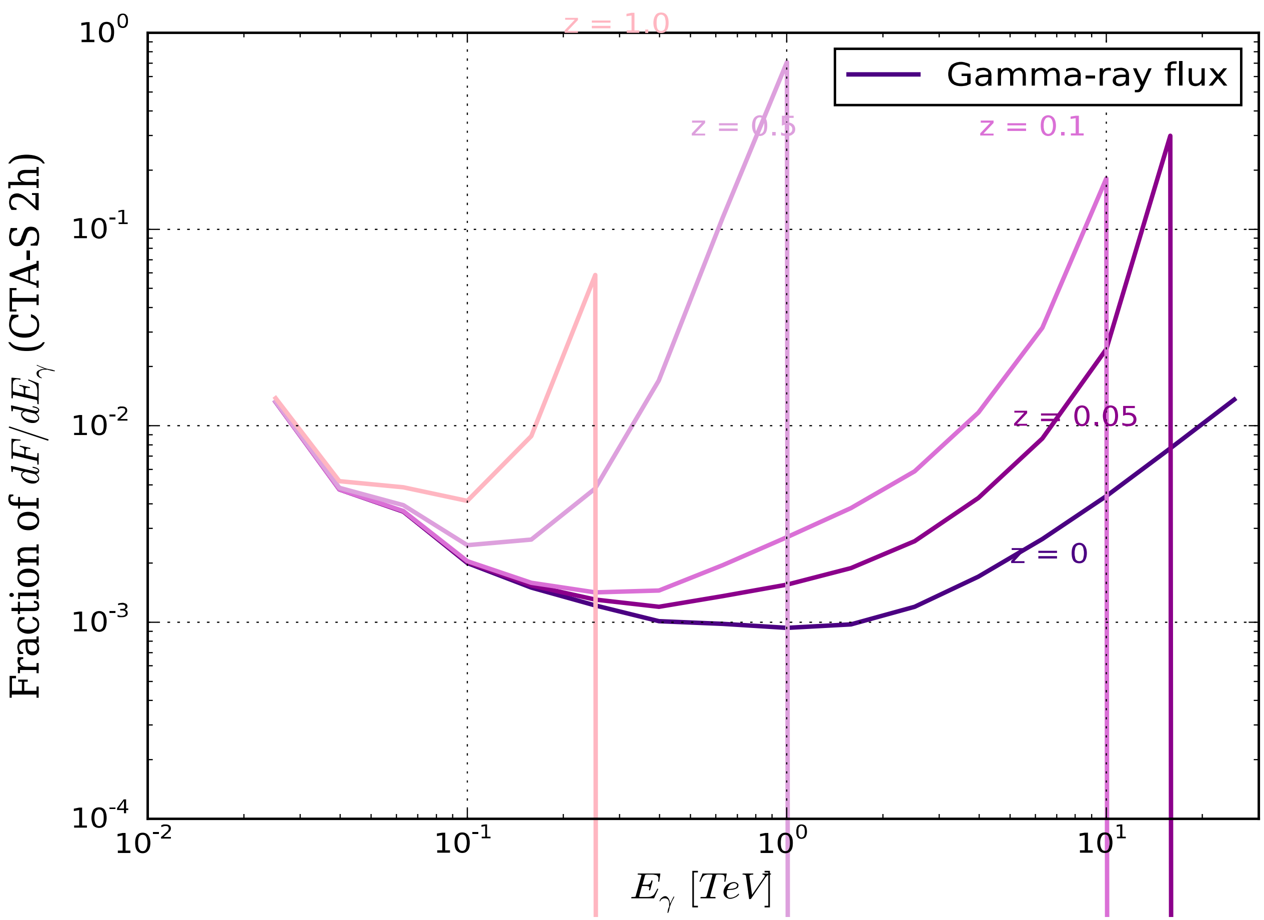
GCN Circular #19377

Other follow-ups: 161103A

M.Santander et al. ICRC 2017

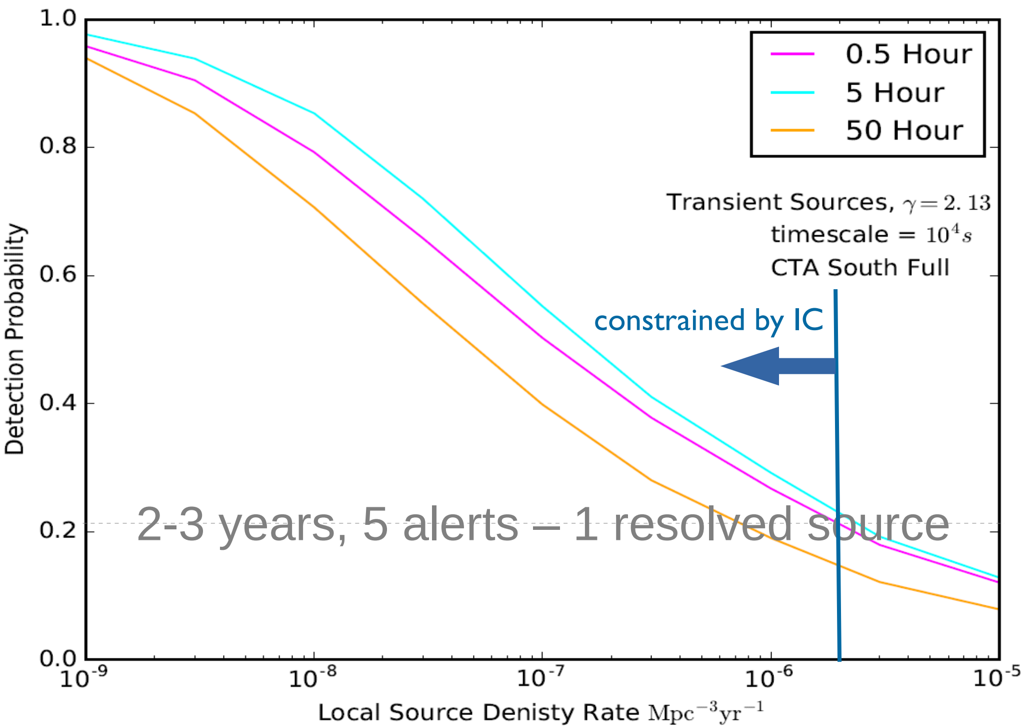
Gamma-rays from nu sources

- Can we set a limit on number of potential neutrino & γ-ray sources?
- Naive picture: 1:1 nu:gamma flux, all sources located at redshift z
- Example: CTA South, 2h of observation



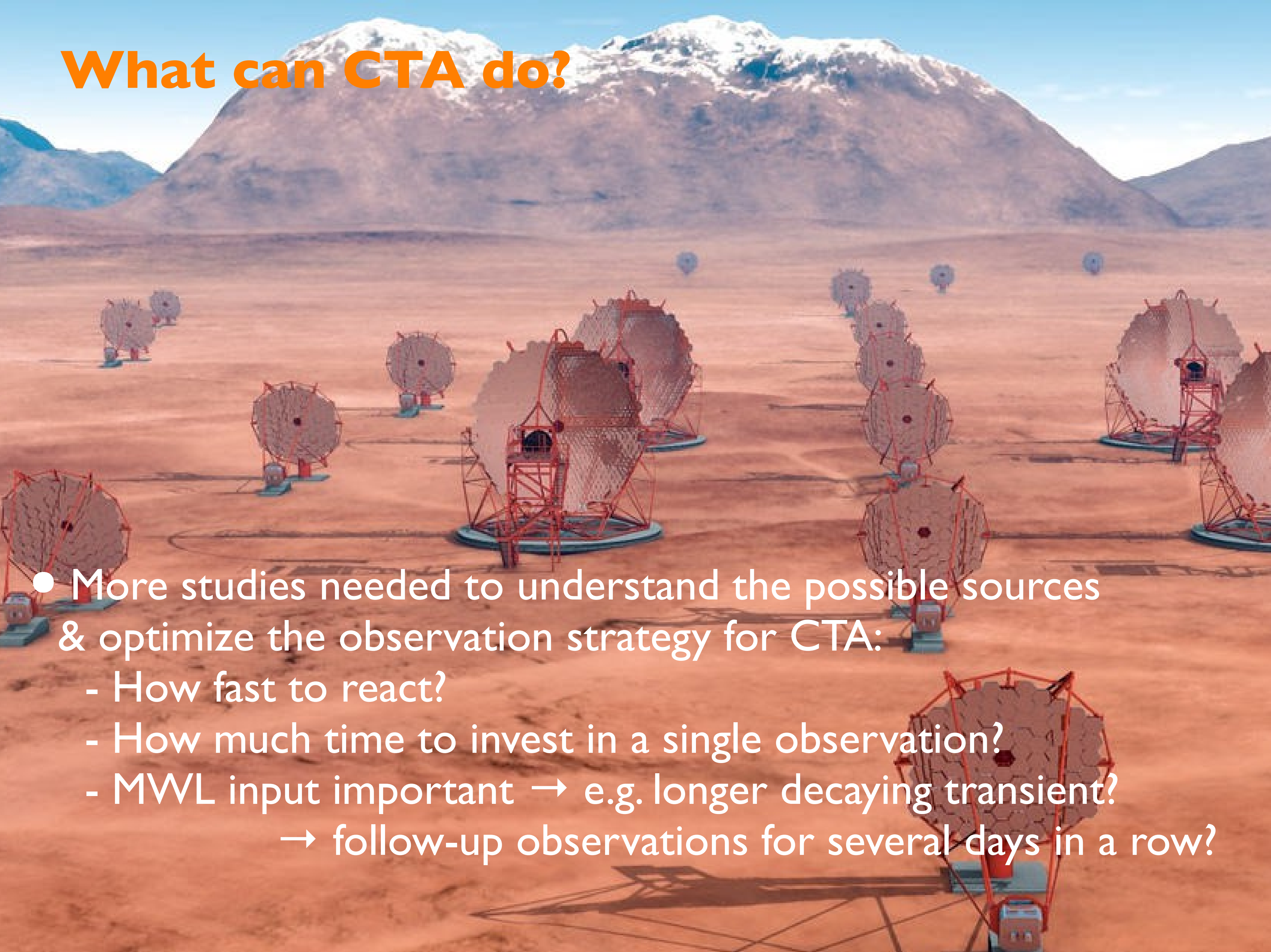
Gamma-rays from nu sources

- More refined assumptions: sources follow Star Formation Rate, standard candles, different local densities tested
- FIRESONG code used for neutrino sources and alert simulations (https://github.com/ChrisCFTung/FIRESONG)
- Prediction: detection/constraints of γ-ray flux from neutrino sources depending on local source density



- Work in-progress

  → join the CTA Neutrino Team! :)

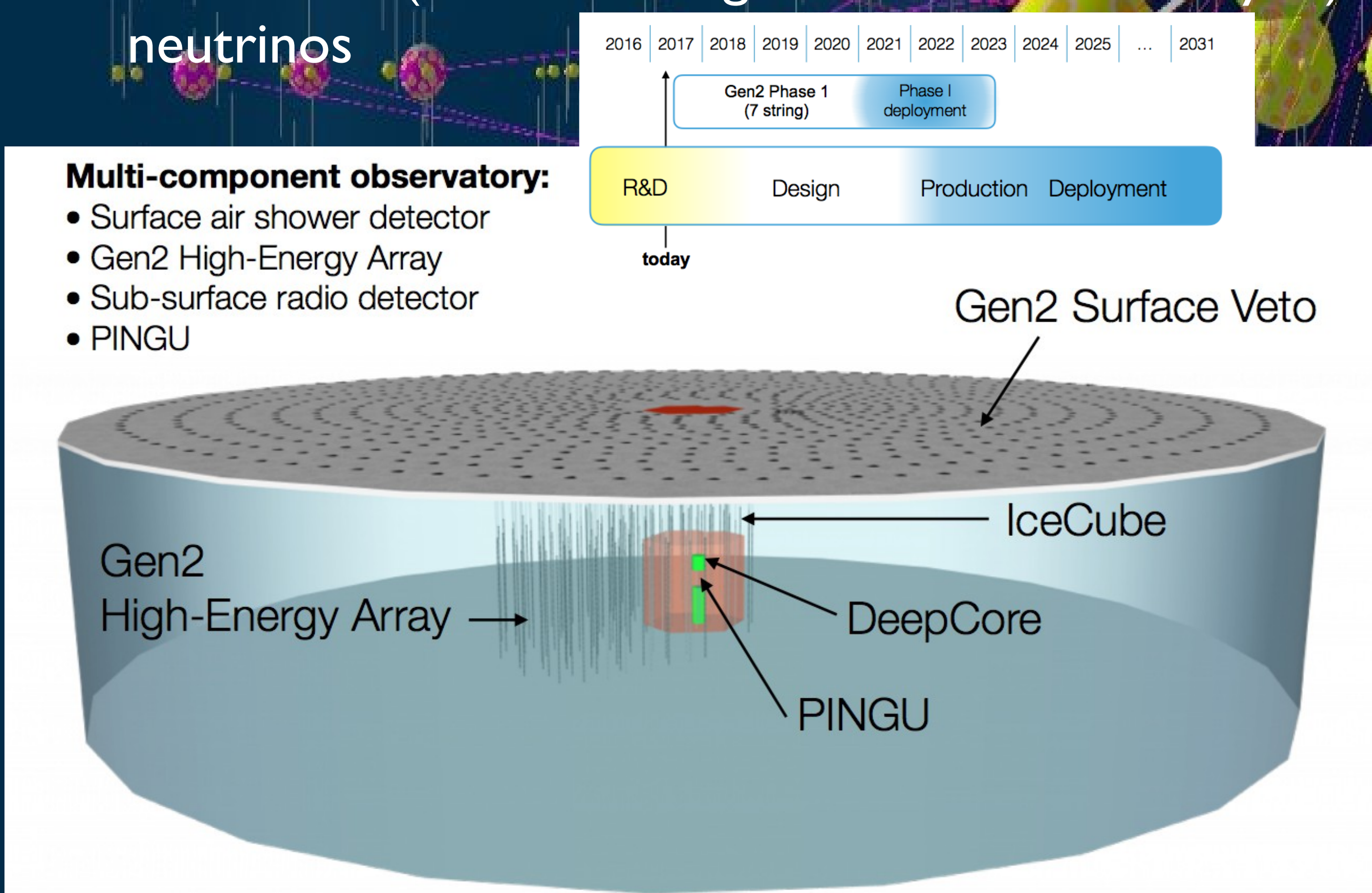


What can CTA do?

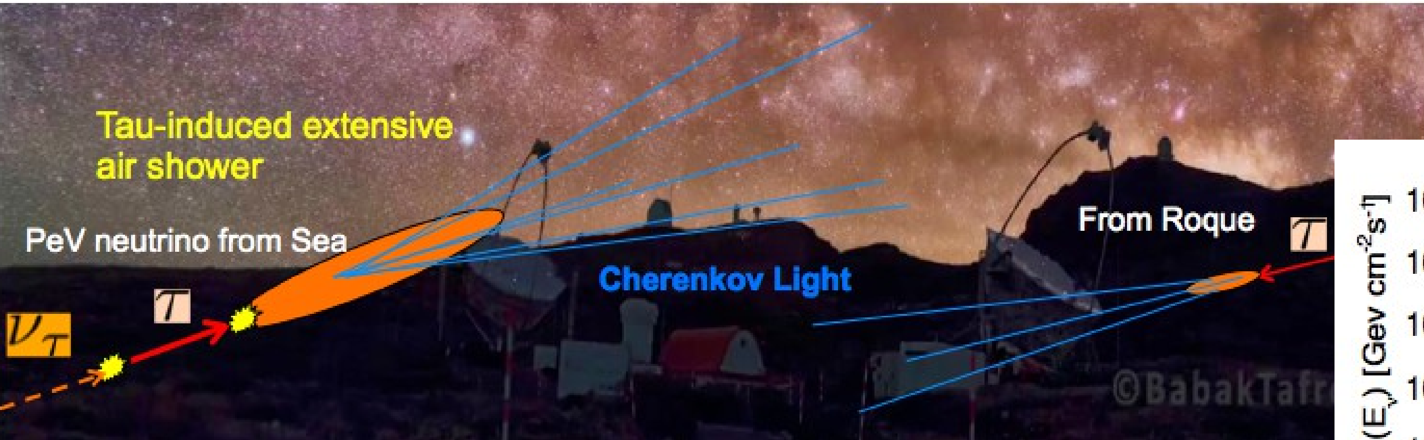
- More studies needed to understand the possible sources & optimize the observation strategy for CTA:
  - How fast to react?
  - How much time to invest in a single observation?
  - MWL input important → e.g. longer decaying transient?
    → follow-up observations for several days in a row?

Future of neutrino astrophysics

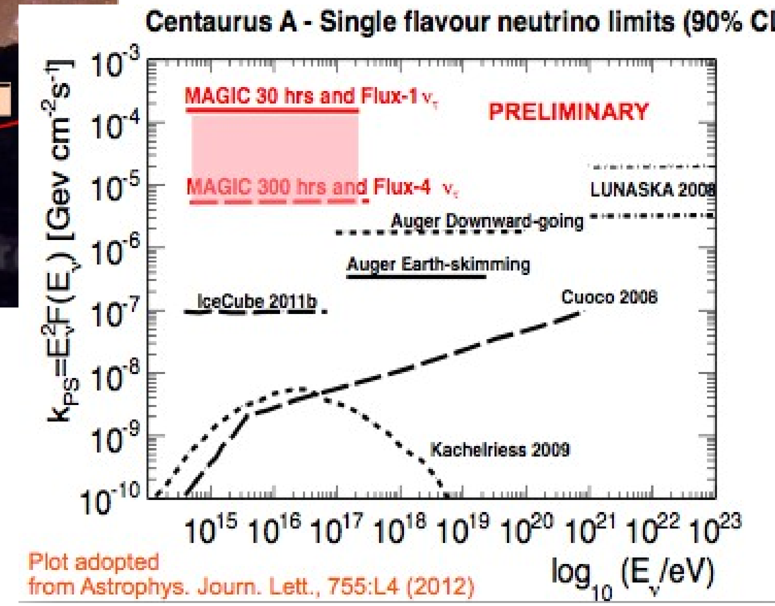
- In the North: KM3Net started deployment, first data ~2020, great view on Galactic Center, good for neutrino oscillations studies, cascade ang. res ~few degrees!
- In the South: IceCube Gen2, R&D started, first data ~2030, multi-detector instrument (Cherenkov light, radio, surface array…), sensitive to MeV-EeV neutrinos

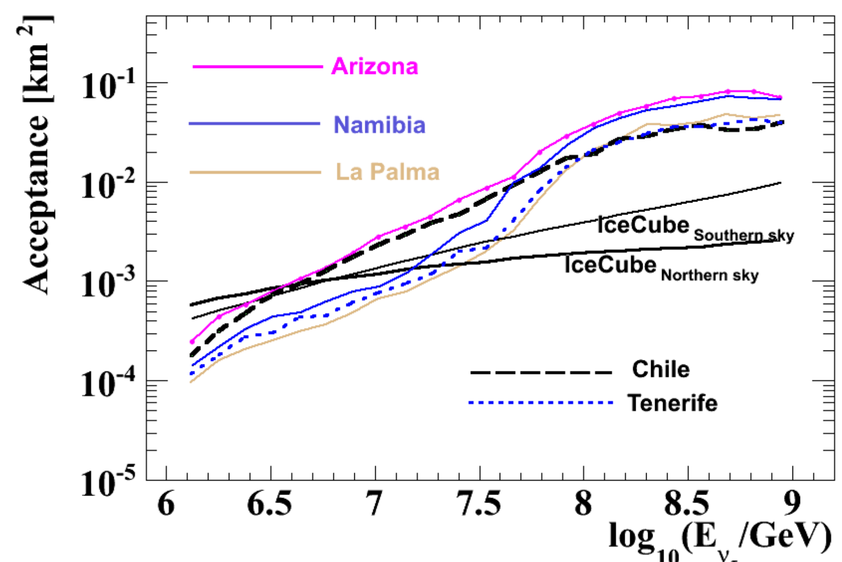


IACTs as neutrino detectors



D.Gora, HEP 2017



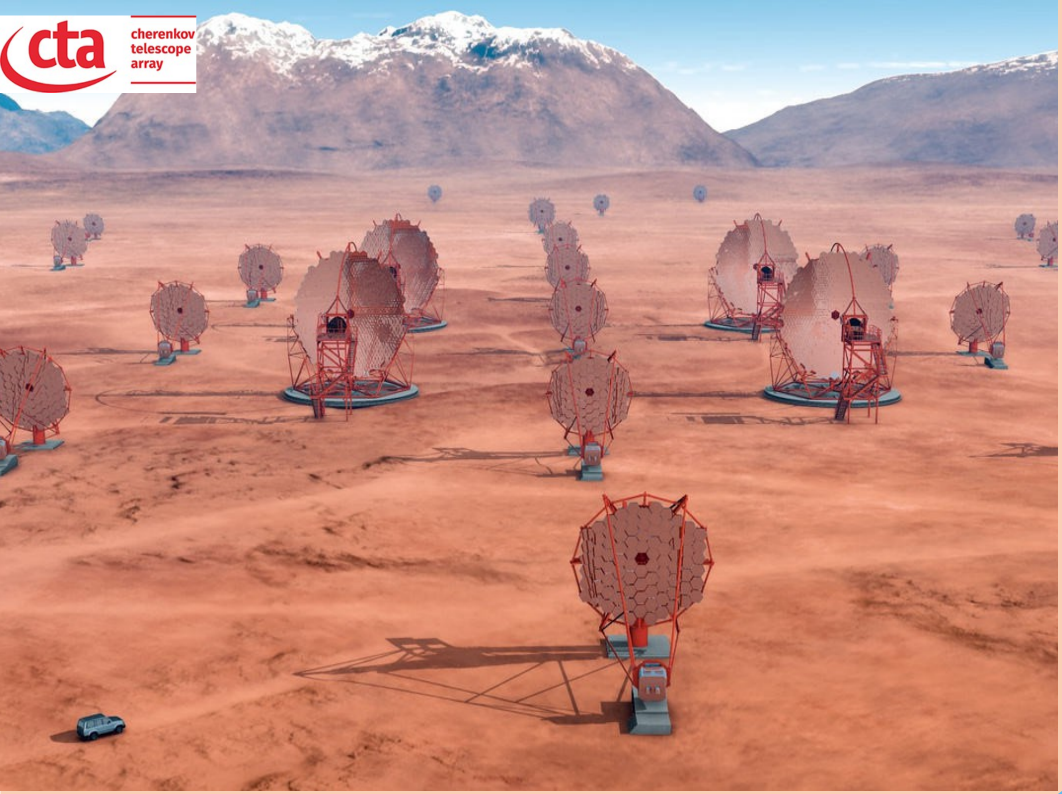


- Look for tau induced showers from the see/rock
- Tau neutrinos HAVE TO be astrophysical!!!
- Cheap observation time (cloudy weather)
- Feasibility studies with MAGIC – for most optimisitc models, ULs ~ AUGER can be set
- CTA: event rates comparable or higher than for IC

Summary

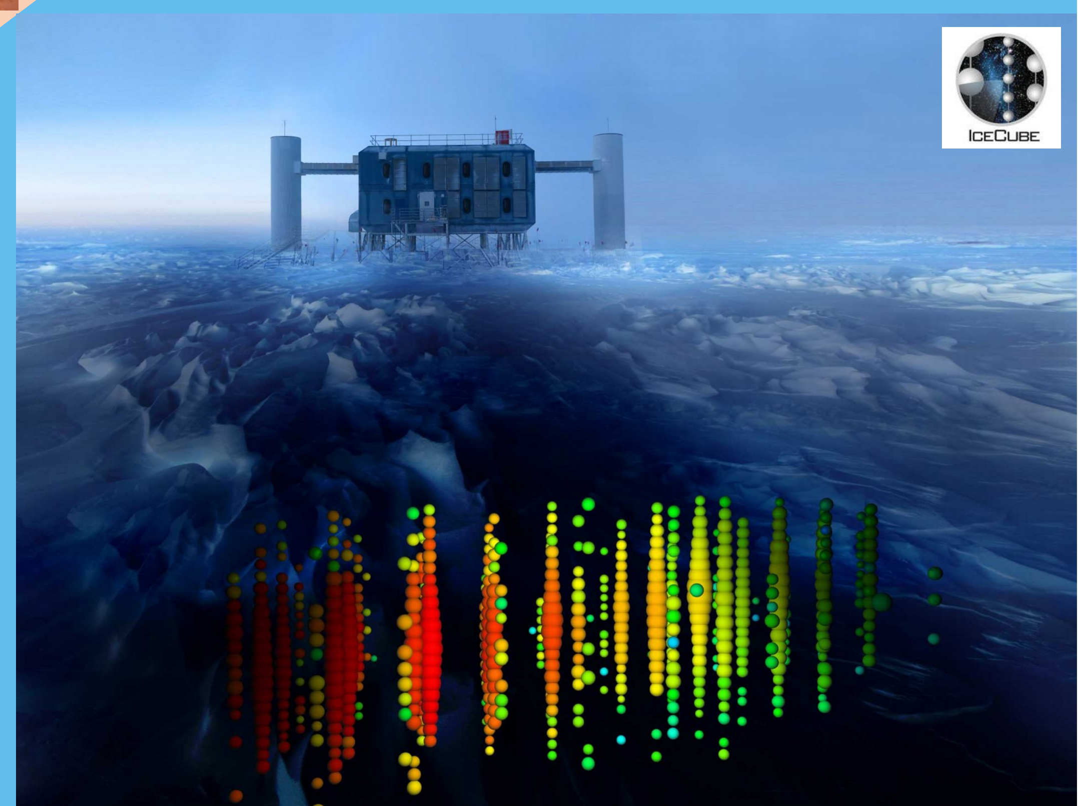
- Astro-beam-dump: HE nu always produced in conjunction with HE γ-rays in CR interactions
- High-energy neutrino diffuse flux measured by IC!
- No event clustering in space/time, no point sources so far…
- Population studies: blazars responsible for max. ~20% diffuse neutrino flux, GRB max. ~1%
- Hints of correlations between high power AGN & HE neutrinos
- Neutrino sources: extragalactic? Faint? Transient?
- CTA advantages:
  - Low E threshold → high z sources
  - High sensitivity → fainter sources
  - Tau neutrino detector?!
  - Start operation with IC & KM3Net present

→ **Smart observation strategies & analysis methods needed!**

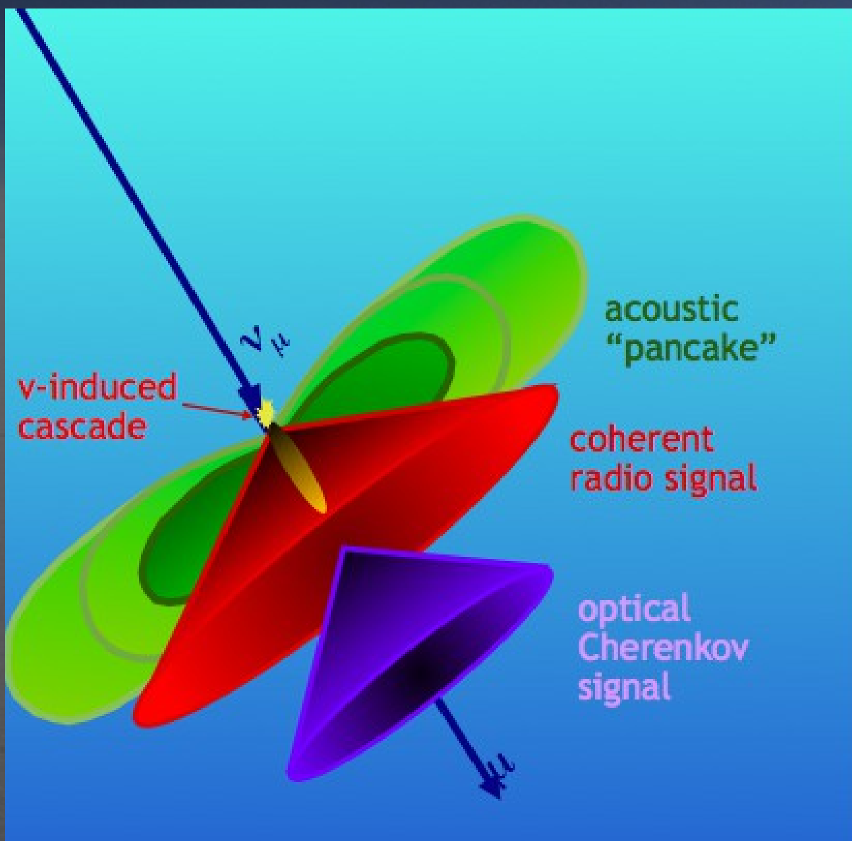


Back-up

Back-up



NEUTRINOS: EXPERIMENTAL TECHNIQUES



- Small x-section + flux ~10^{15} / km / yr > 100 TeV
  → large volumes needed!!!

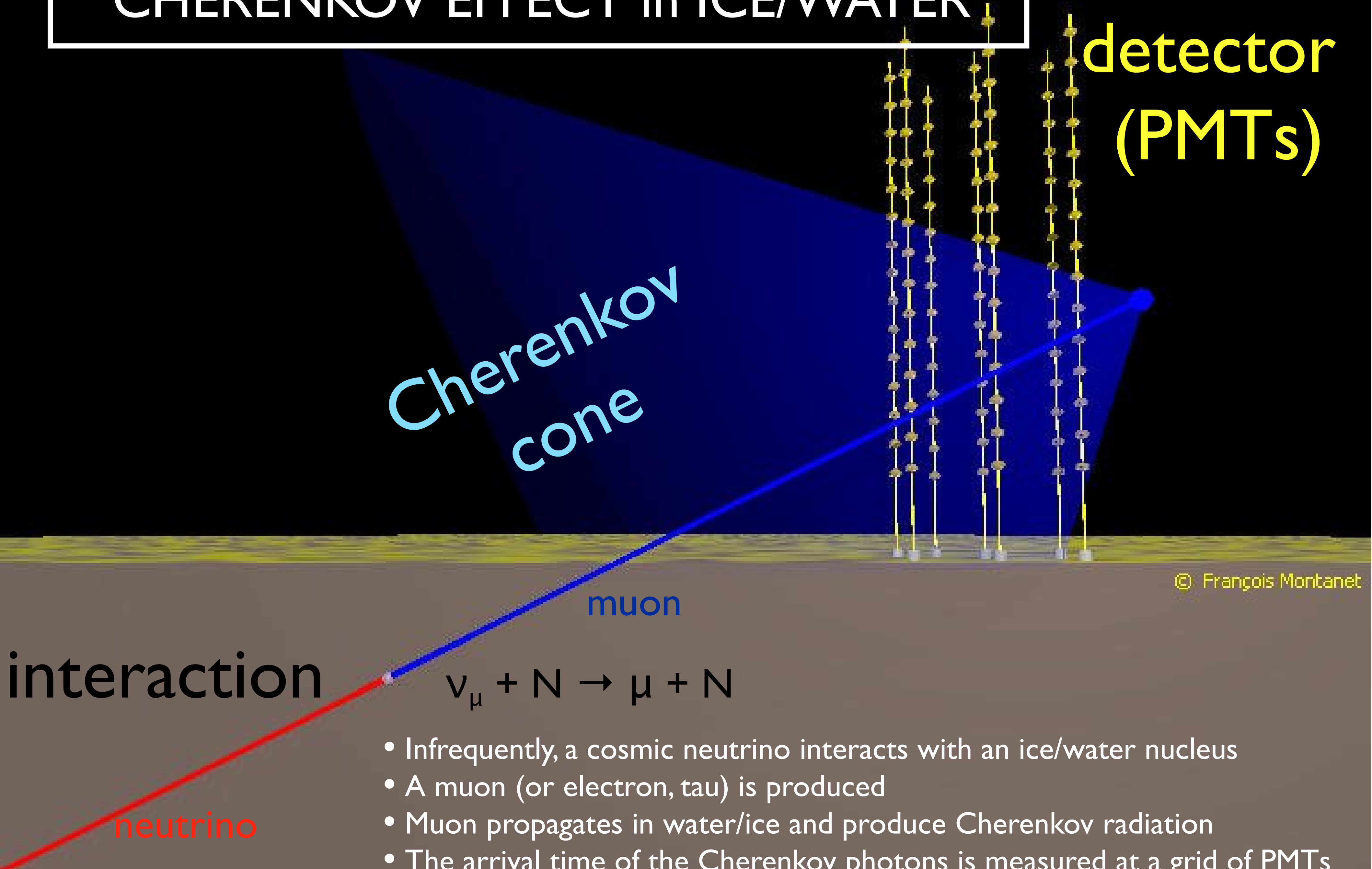
- 10^9 eV to 10^{16} eV
  Cherenkov photons in water/ice
  (IceCube, ANTARES, future: KM3Net, Baikal-GVD)

- 10^{17} eV to 10^{23} eV
  Coherent radio pulses in ice, salt and Moon regolith
  (ANITA, RICE)

- > 10^{19} eV
  Acoustic waves in water/ice and salt
  (AMADEUS, SPATS - feasibility study)

- 10^{17} to 10^{19} eV
  Extensive air showers (AUGER)

CHERENKOV EFFECT in ICE/WATER

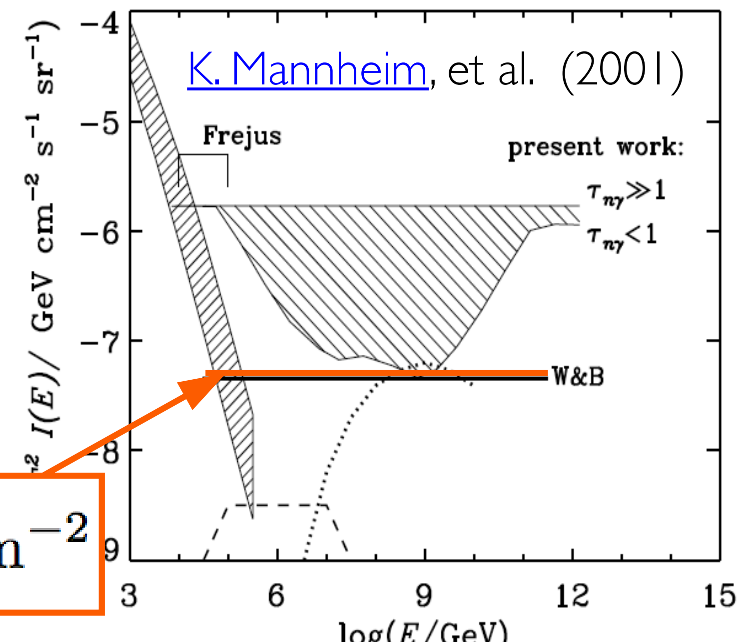


$\nu_\mu + N \rightarrow \mu + N$

- Infrequently, a cosmic neutrino interacts with an ice/water nucleus
- A muon (or electron, tau) is produced
- Muon propagates in water/ice and produce Cherenkov radiation
- The arrival time of the Cherenkov photons is measured at a grid of PMTs
- Goals: detect ν of all flavors at energies 10^{10} eV to 10^{20} eV

CR & ν: WAXMANN BAHCALL BOUND

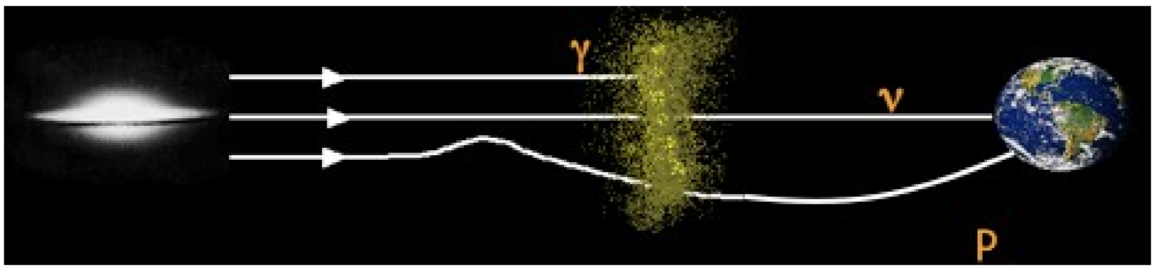
- Starting from the observed CRs with energies >10^{19} eV a limit was derived on the neutrinos produced within the same sources assuming:
    1. Protons are accelerated at the sources with a power-law index 2
    2. All protons undergo photo-hadronic interactions giving neutrons, neutrinos and g-rays
    3. The sources are optically "thin" to neutrons, 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
- The observed flux is very close to WB limit: a coincidence or a deeper multi-messenger connection?



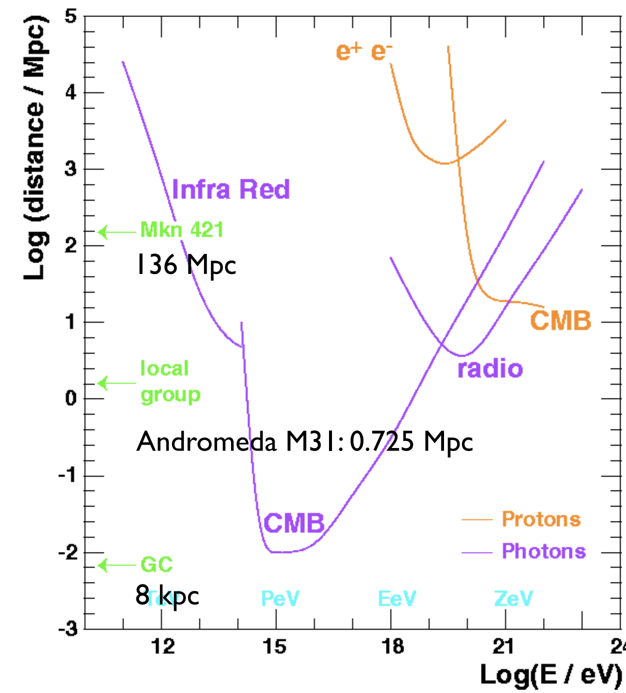
$$E^2\Phi < 3 \times 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$$

WHY NEUTRINO ASTRONOMY?

- 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 path
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)

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):

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

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

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

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

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

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

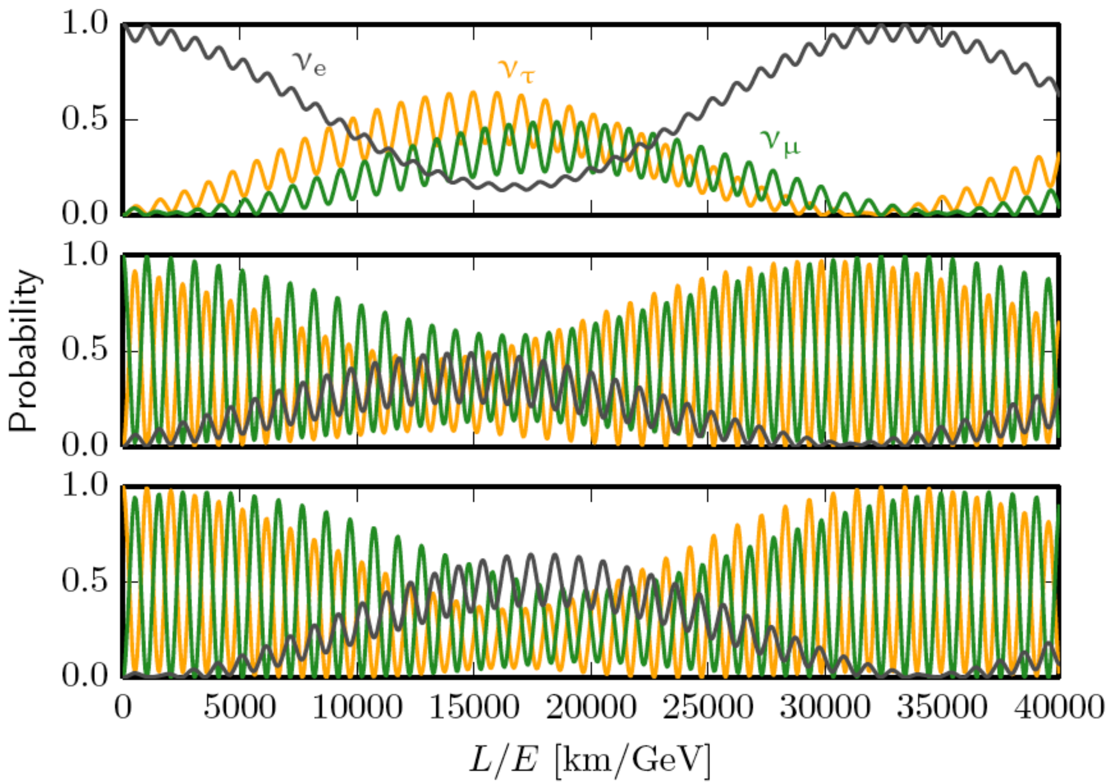
NEUTRINO OSCILLATIONS

- 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: $\dfrac{\Delta m^2_{jk} L}{4E} \approx 1.267 \times \dfrac{\Delta m^2_{jk}}{\mathrm{eV}^2}\,\dfrac{L}{\mathrm{km}}\,\dfrac{\mathrm{GeV}}{E}$

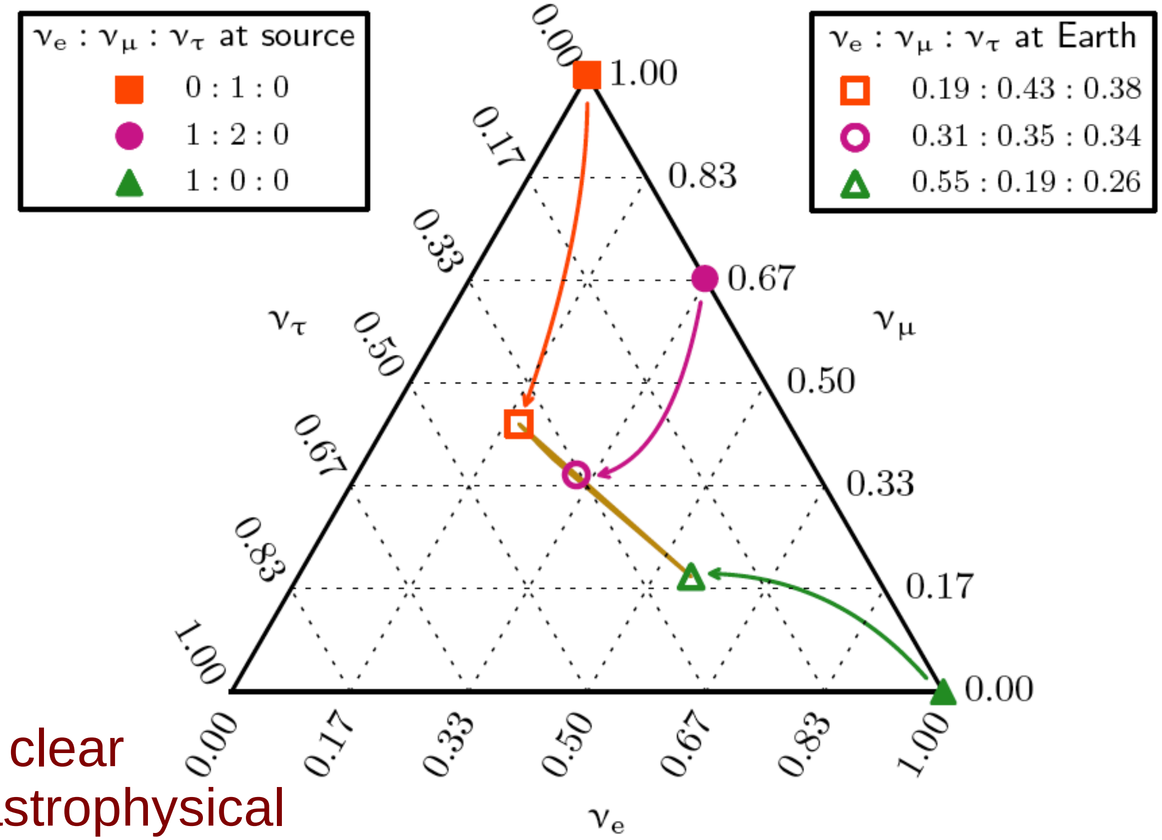
Probabilities for a given an initial flavor to be detected as an electron neutrino (gray), muon neutrino (green), or tau neutrino (yellow) [L. Mohrmann PhD]



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 flavour composition at source:

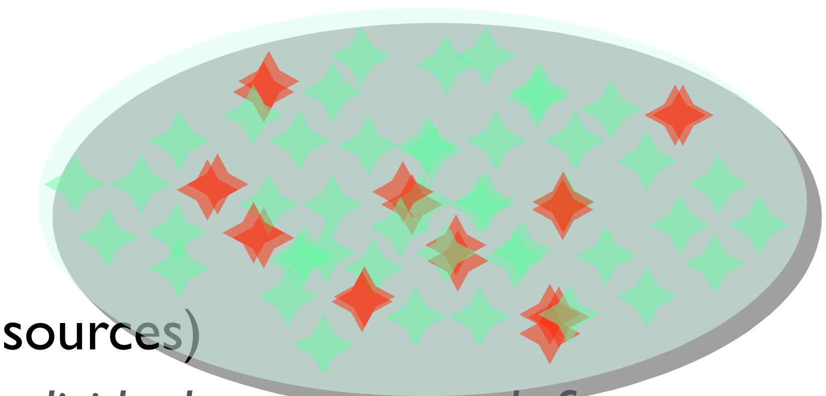
1. PION-DECAY:
   $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
2. MUON-DAMPED
   $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$
3. NEUTRON-BEAM
   $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$



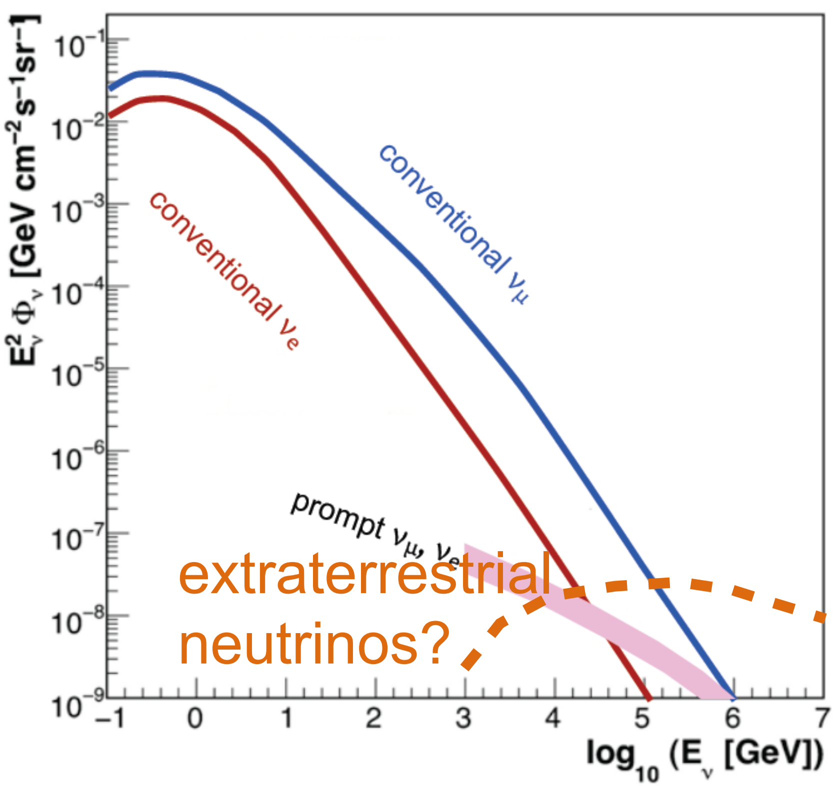
Appearance of tau neutrinos is a clear evidence that the neutrinos are astrophysical

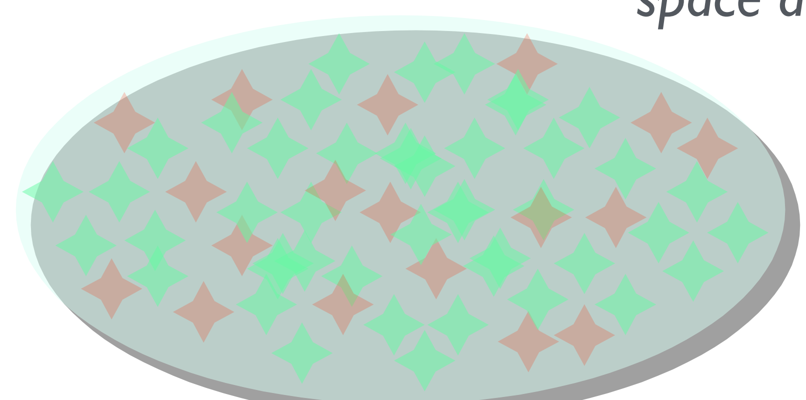
SERACH FOR COSMIC Nu SIGNAL

- 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)



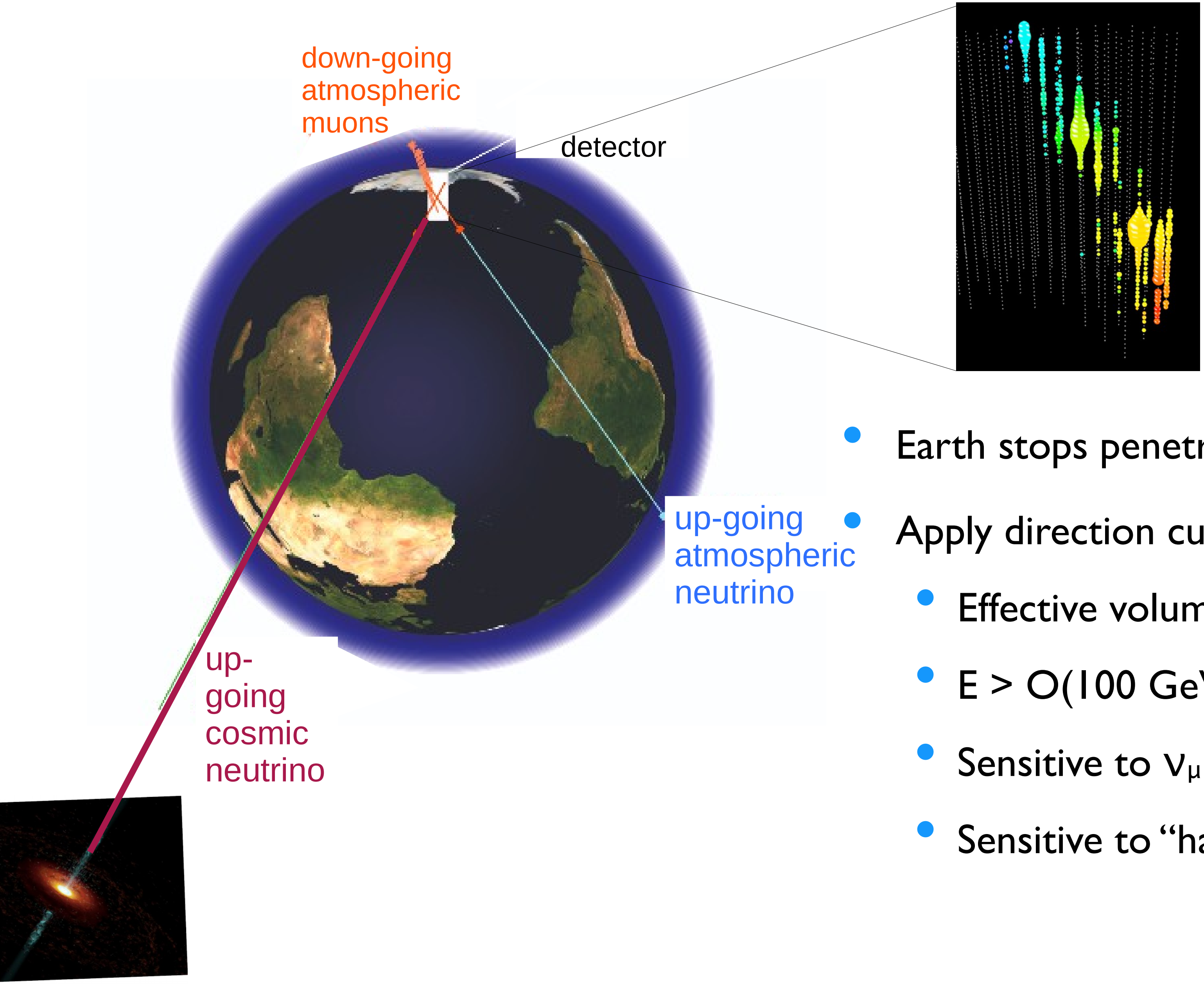
Individual sources: search for excesses from few strong objects. Localised (in space and/or time)





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

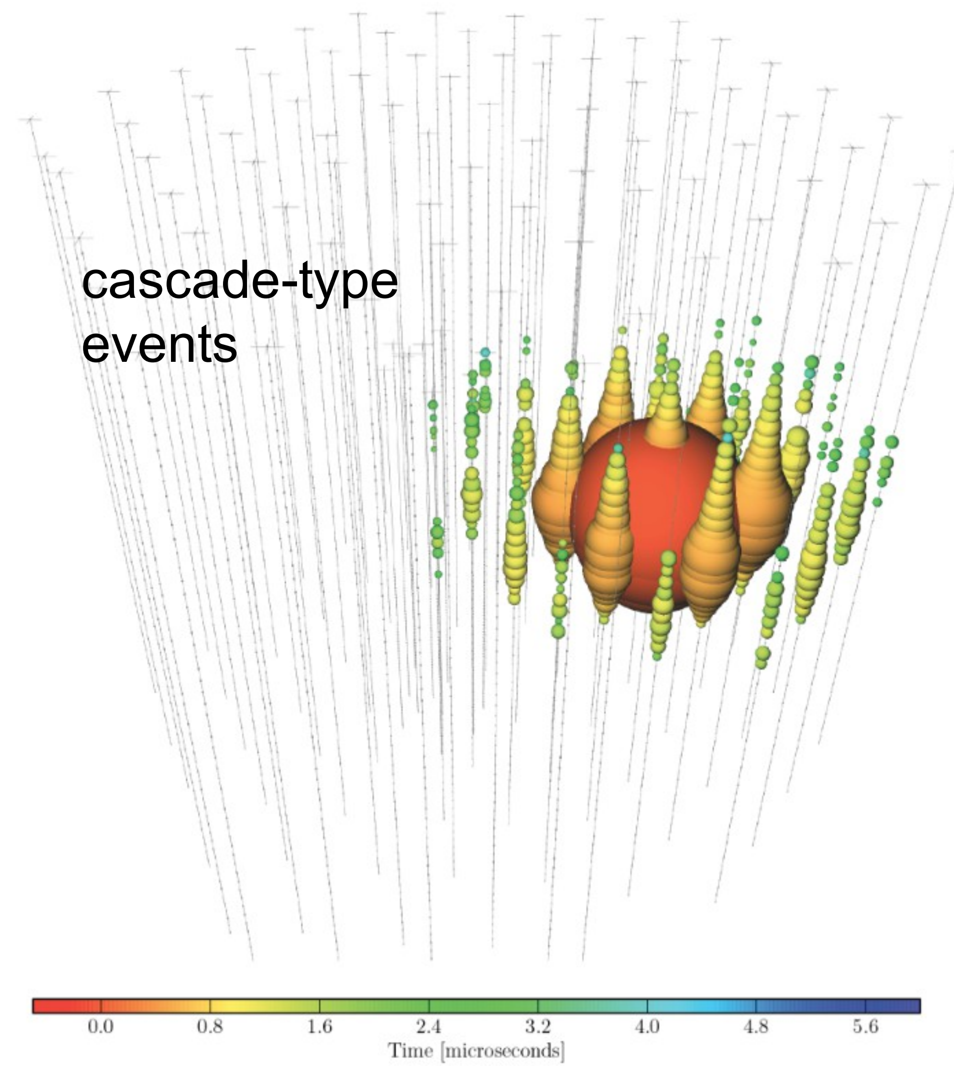
BACKGROUND SUPPRESSION: DIRECTION



- 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)

BACKGROUND SUPPRESSION: EVENT TYPE

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

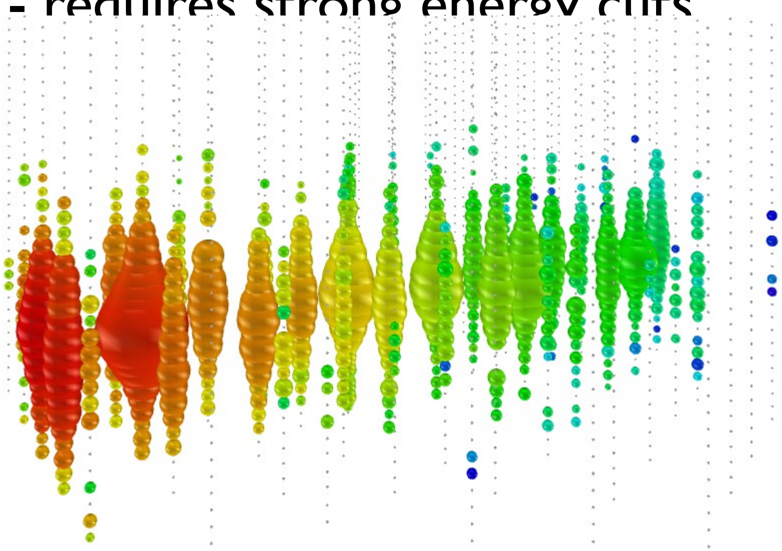


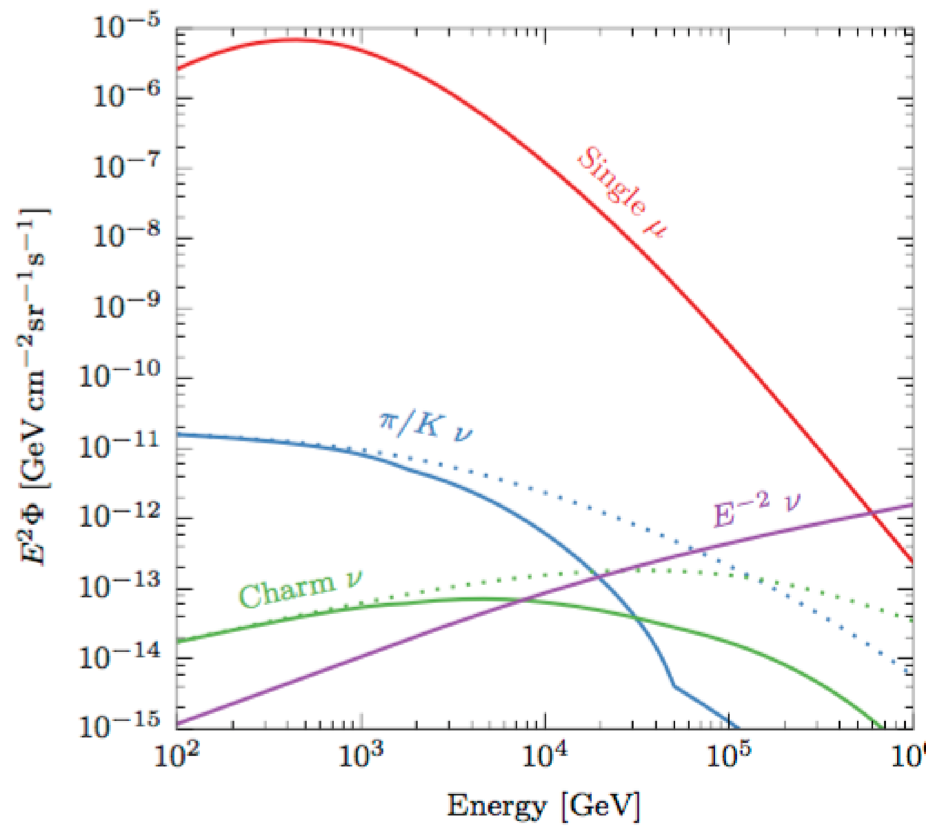
BACKGROUND SUPPRESSION: ENERGY

- Energy spectrum looks different for background and signal
- Select high-energy events:

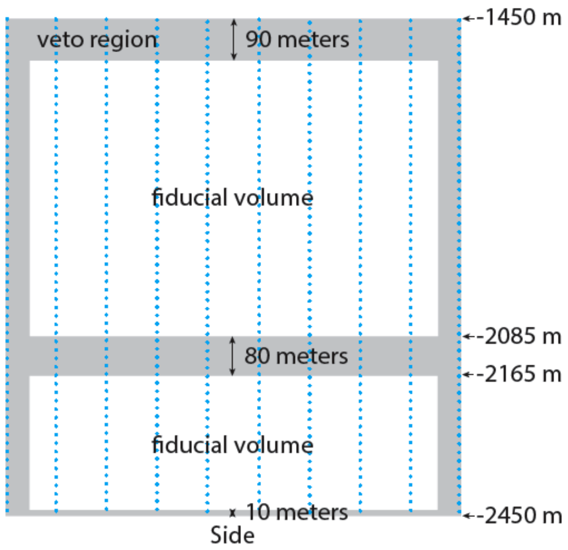
IceCube Coll. Phys. Rev. D 91, 022001 (2015)

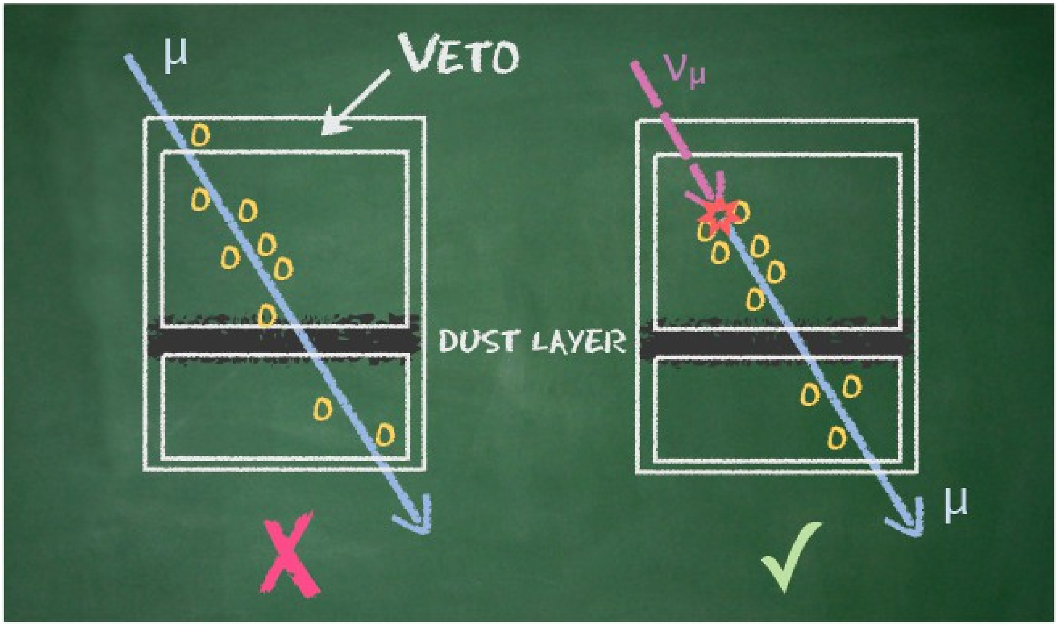
- reject atmospheric μ
- reject atmospheric ν_μ
- requires strong energy cuts





ASTROPHYSICAL NEUTRINOS FROM ALL-SKY





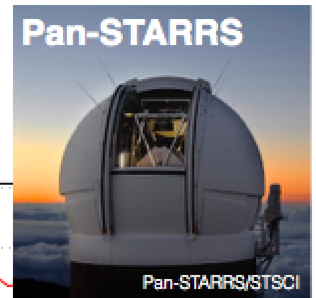
for atms. μ
→ reject tracks entering the detector from outside, expected background: 6±3.4 /year

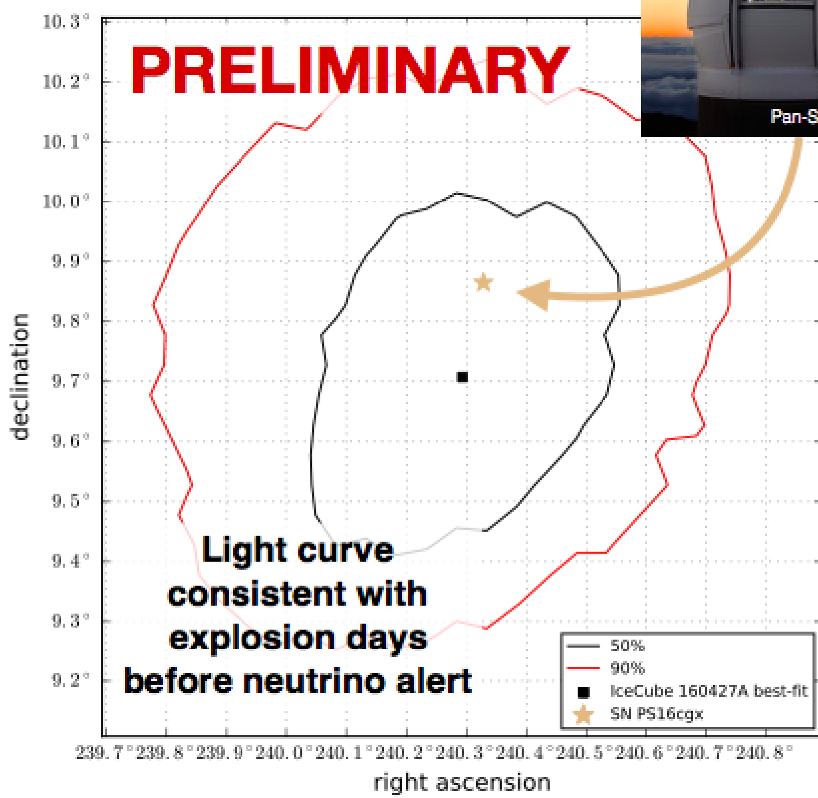
for atms. ν
→ reject tracks accompanied by air showers with muons, expected background: $4^{+3.6}_{-1.2}$ /year
(detectable when coming from the Southern hemisphere)

+ charge cut (> 4000 phe) to select very high energy events
→ "golden channel": High Energy Starting Events (HESE)

EXAMPLE: HESE-160427A IN OPTICAL

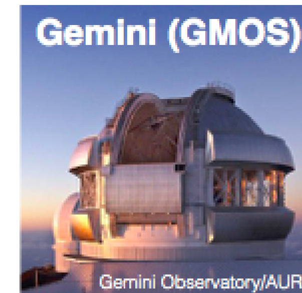
PAN-Starrs followed up IceCube HESE alert on 2016-04-27 and found a recent supernova at z=0.3:

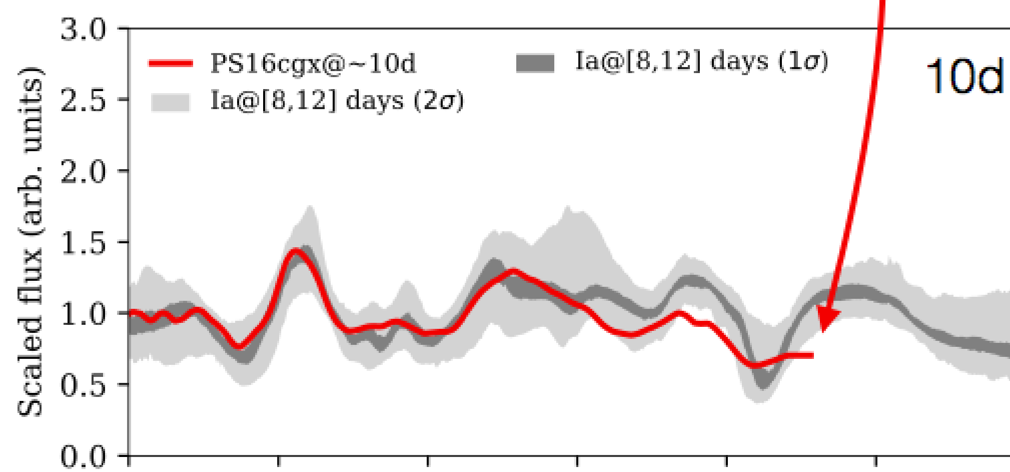




Light curve consistent with explosion days before neutrino alert

Optical spectroscopy 10, 20 days post-peak





Features atypical for SNIa, but not sufficient to exclude

Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**