Cosmic Ray Science Potential
for an
Extended Surface Array
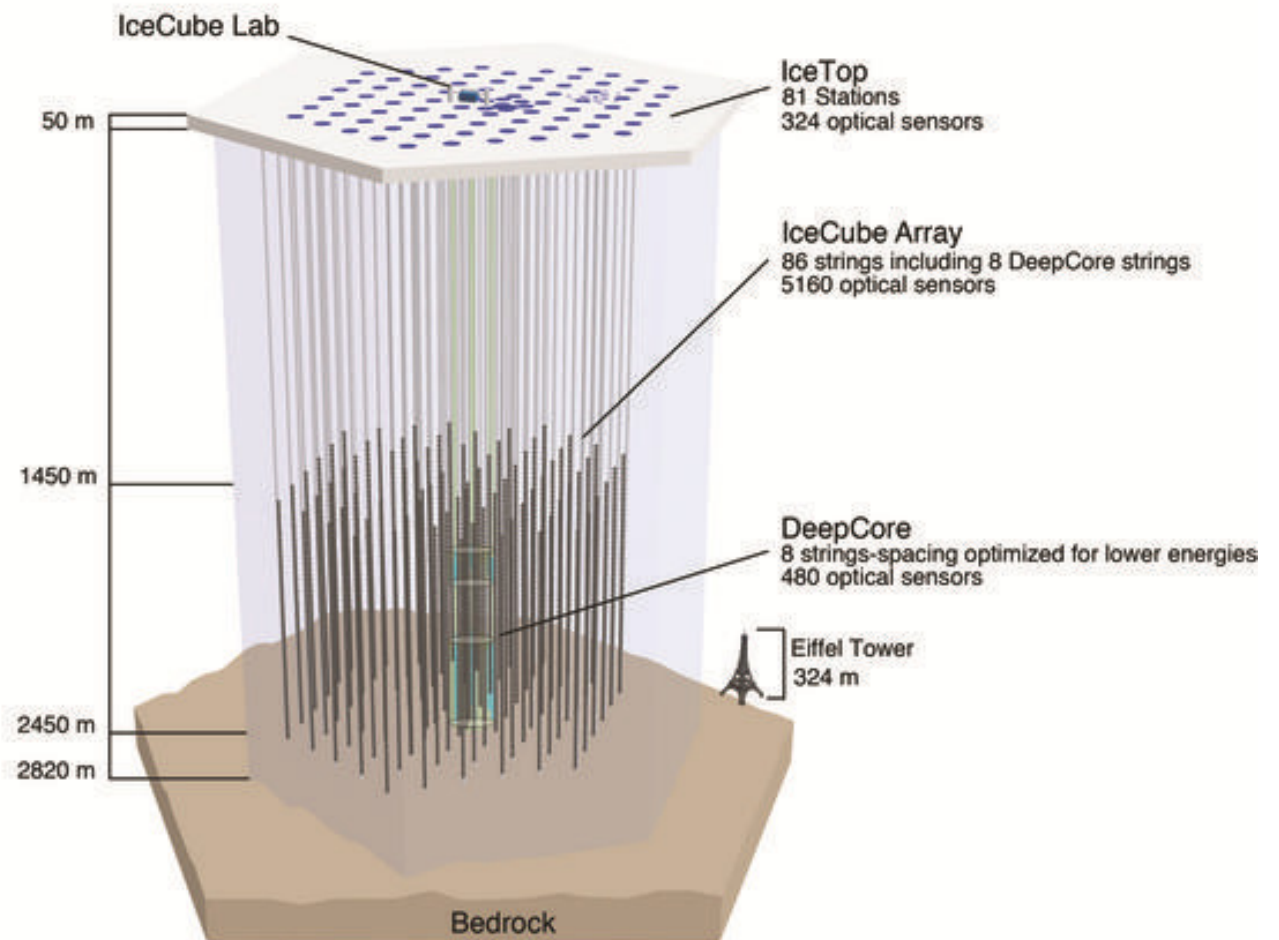## at the
IceCube Observatory

or

Cosmic Rays w/IceCube-Gen2

David Seckel for the IceCube Collaboration Aug 5, 2015
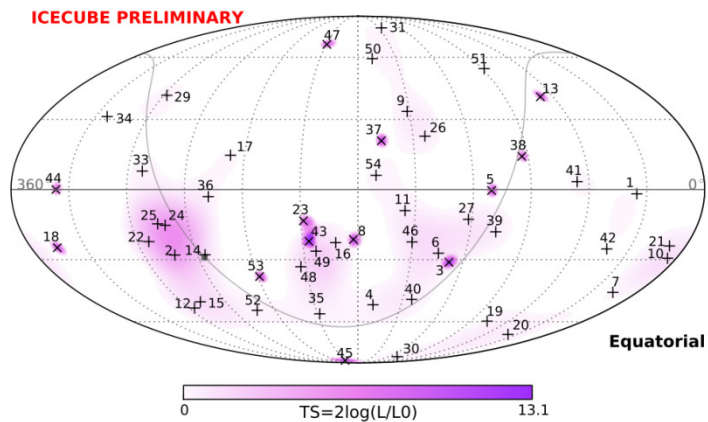
IceCube w/IceTop

- ## IceTop
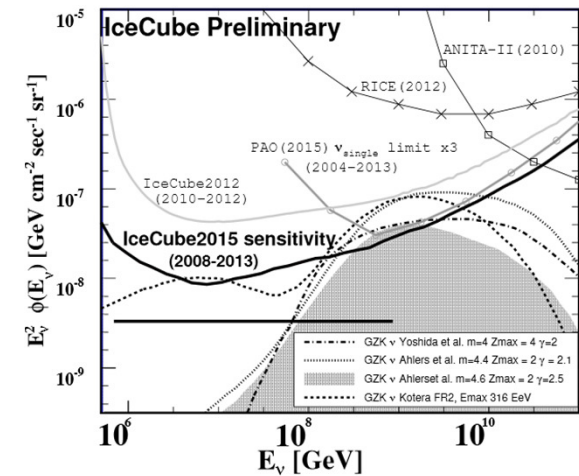   - Calibration
    - Veto
    - Cosmic Ray Science

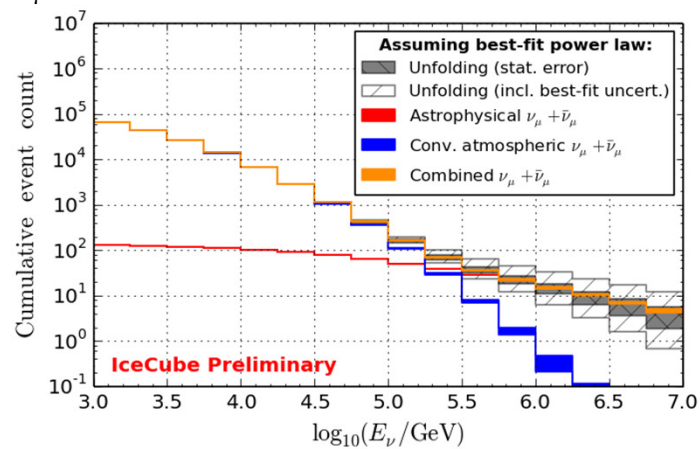# IceCube is all about astrophysical neutrinos!

PoS721

Starting events: astrophysical ν
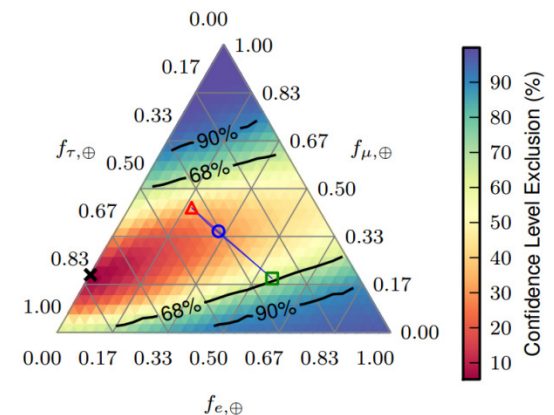

Search for Extreme High Energy (EHE)

Diffuse ν_μ: astrophysical ν

Flavor and ν: $\bar{\nu}$

HE ν discovered …
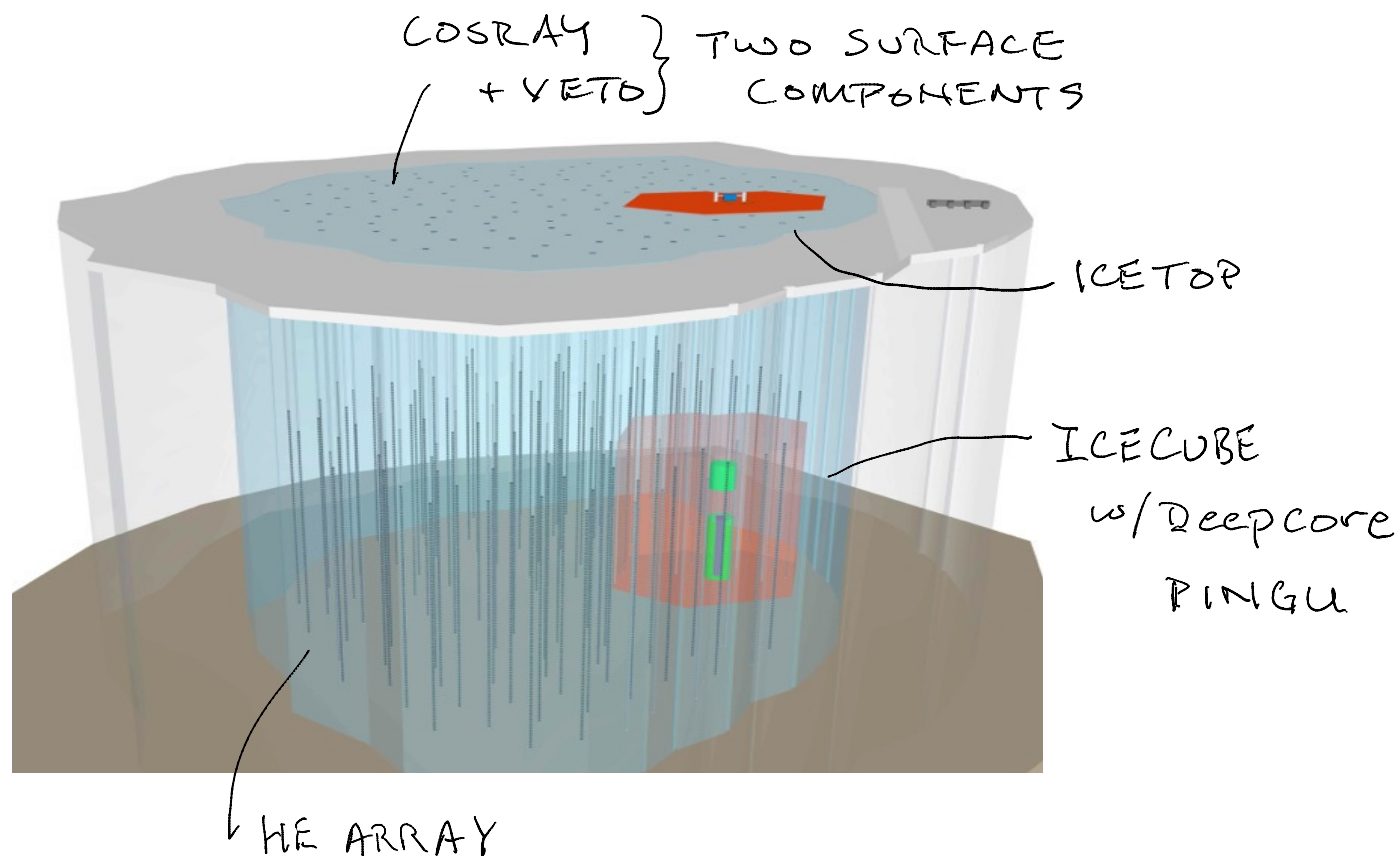
- **Q's**
  - Sources?
  - Mechanism?

- **Need**
  - MORE events
  - Pointing (to sources)

- **$\Rightarrow$ IceCube Gen-2**

IceCube Gen-2

PoS1146
PoS1174

COSRAY
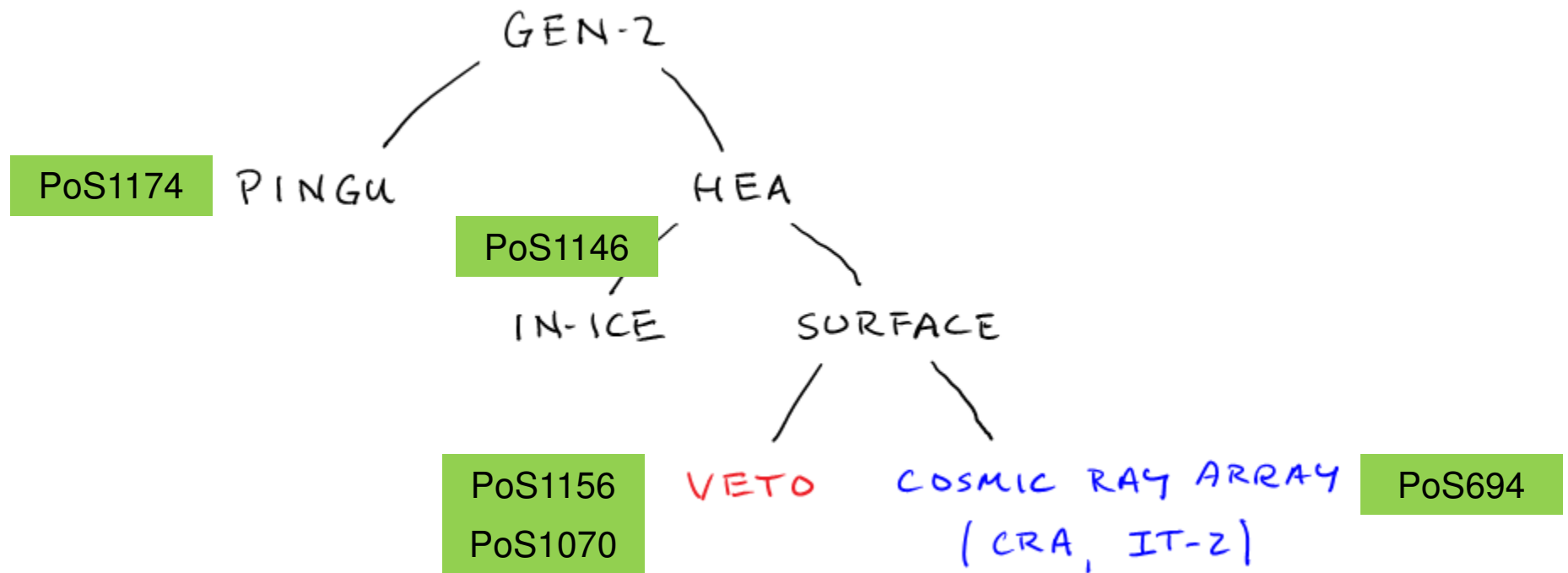+ VETO
} TWO SURFACE
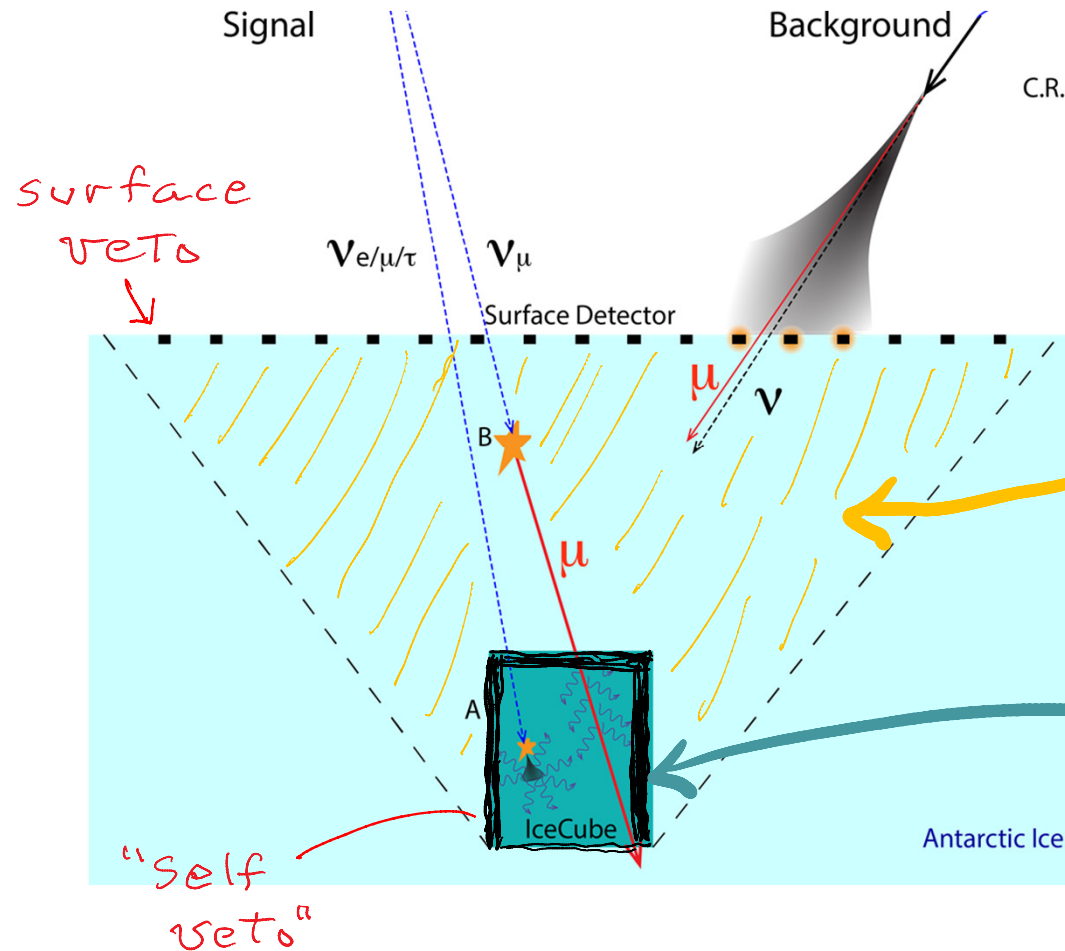COMPONENTS

ICETOP

ICECUBE
w/Deepcore
PINGU

HE ARRAY
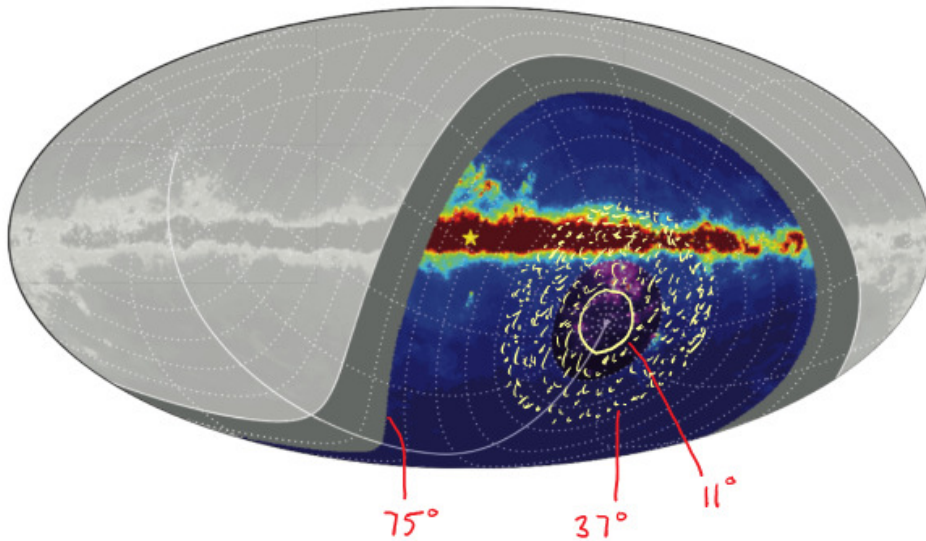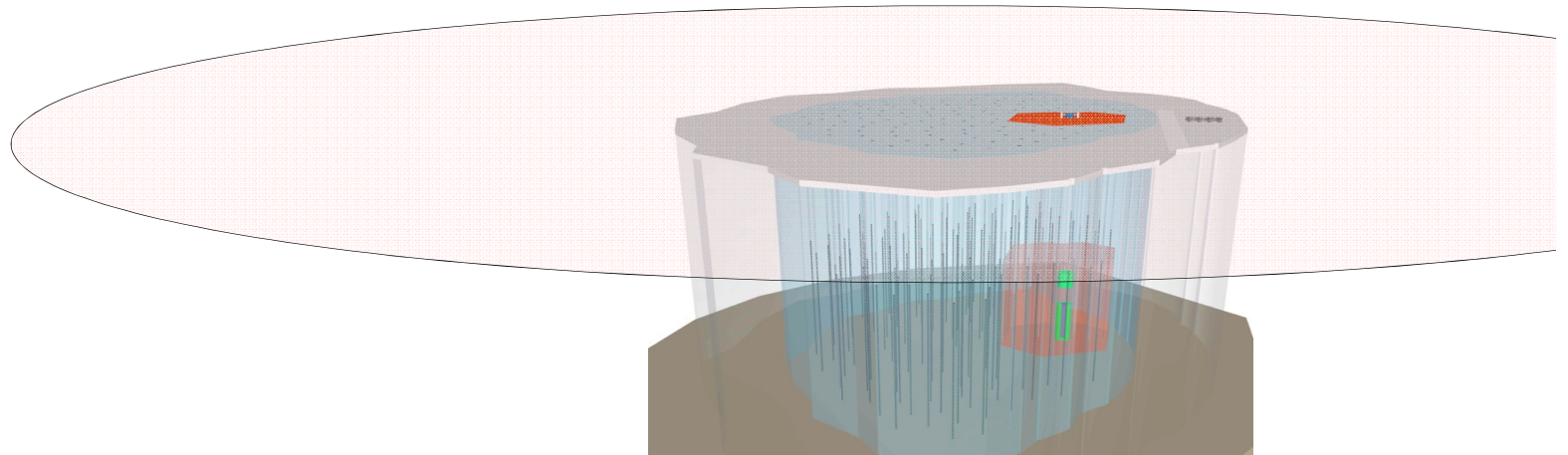
Surface components for Gen2

Veto concepts

PoS1156
PoS1070
PoS1086

- External volume for muons (pointing)

- Fiducial volume (all events)

Sky coverage

PoS1156

Some questions about Veto

- ## Scope
  - Gen-2 footprint   or   extended ?
  - Energy range: 100 TeV entering μ ?

- ## Technology
  - secondary particles (scintillator/Cherenkov)
  - Atmospheric Cherenkov

- ## Baseline (?)
  - Gen-2 footprint with 1000 m^2 scintillator per km^2 (fill 10^{-3})

- ## Cosmic Rays?

  Cosmic Ray Array

  - No … Reconstruction requires timing and dynamic range
  - Yes … very large collection area for muons

Cosmic Rays in IceCube

PoS916

- ## Spectrum
  - ### surface detector

PoS334

- ## Composition
  - ### coincident (in-ice muons)
  - ### surface muons

Contribute to community wide effort to explore transition from galactic to extragalactic sources.

- ## Other efforts

PoS274
  - ### anisotropy
  - ### γ search

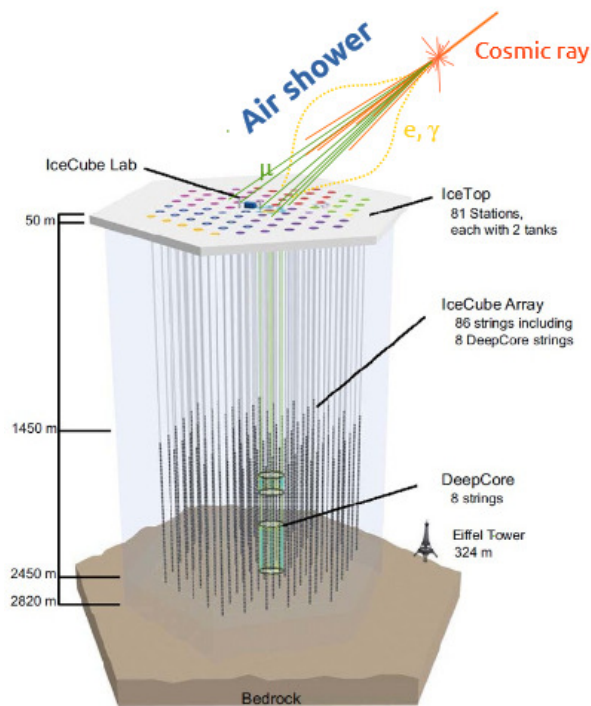PoS250
  - ### neutron

PoS256
  - ### lateral muons – hadronic interaction models
  - ###
  - ###

Surface detection by IceTop

PoS334

Event reconstruction in IceTop

IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004

▸ Cosmic ray direction
  ▸ Timing resolution 3 ns
  ▸ Angular resolution ~1°

▸ Cosmic ray energy { **V**ertical **E**quivalent **M**uon }
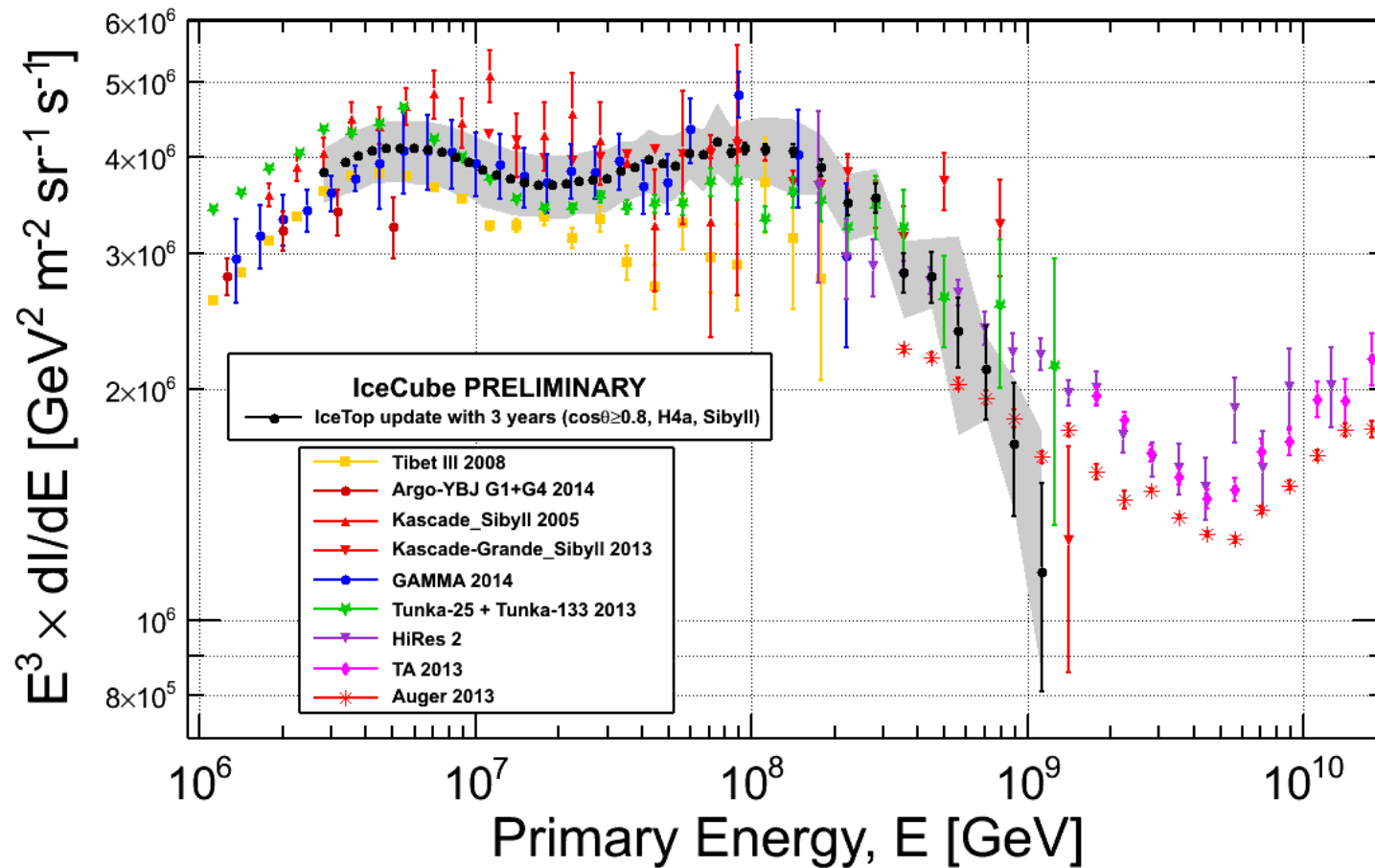 ▸ Energy proxy S_{125} in VEM
  ▸ Simulated-based energy calibration
    • Mixed-composition model H4a
  ▸ Energy resolution <25 %
  ▸ Systematic uncertainty ~10 %

LDF model: double-log-parabola

Shower front model: parabola with Gaussian center
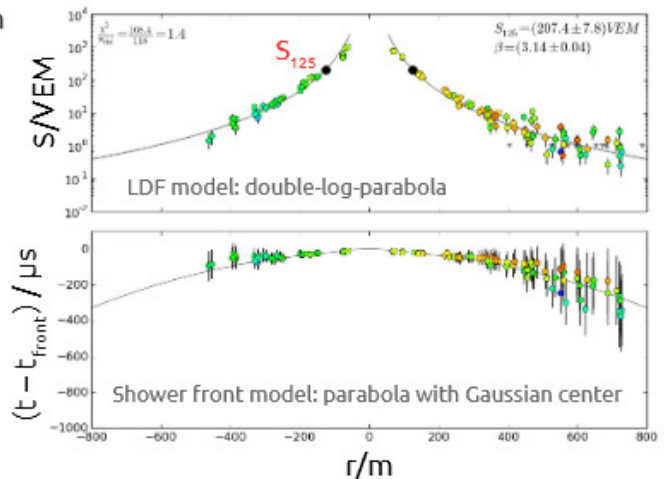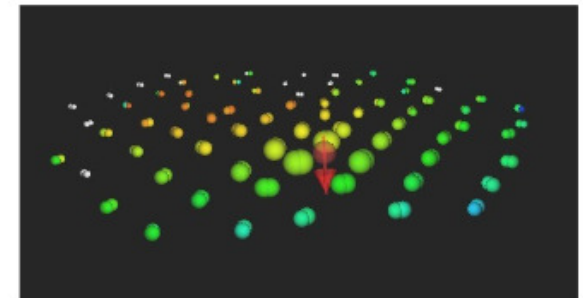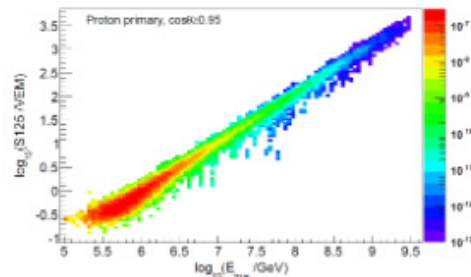
H. Dembinski, J.G. Gonzalez | Bartol institute, University of Delaware | 2015   4

IceTop 3 yr spectrum
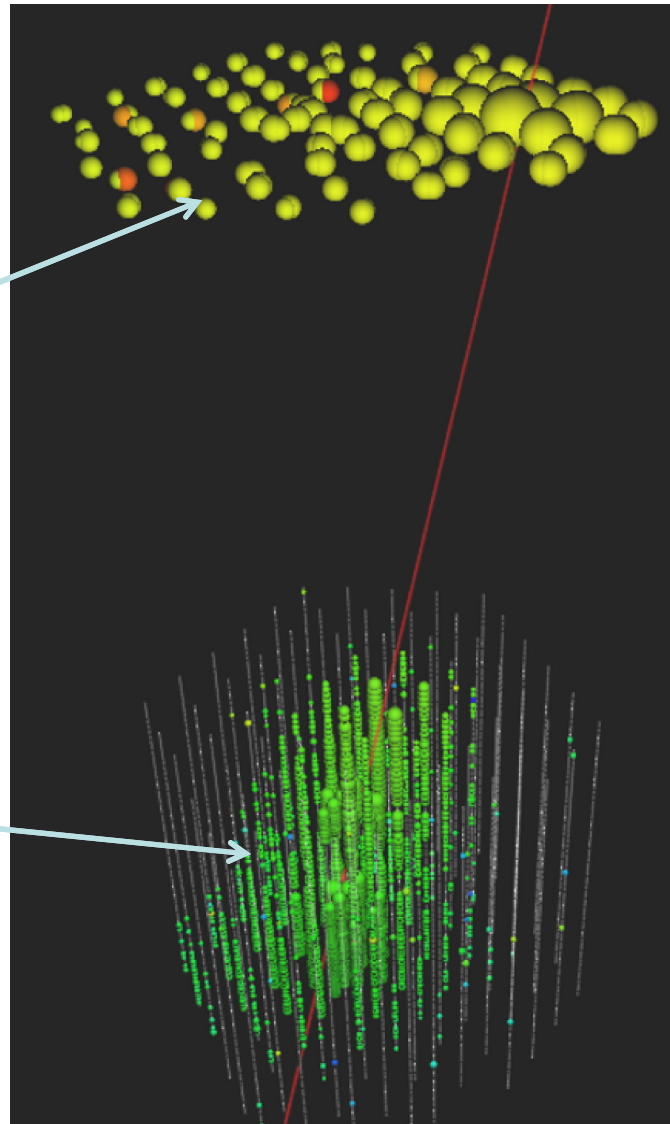
Coincident events

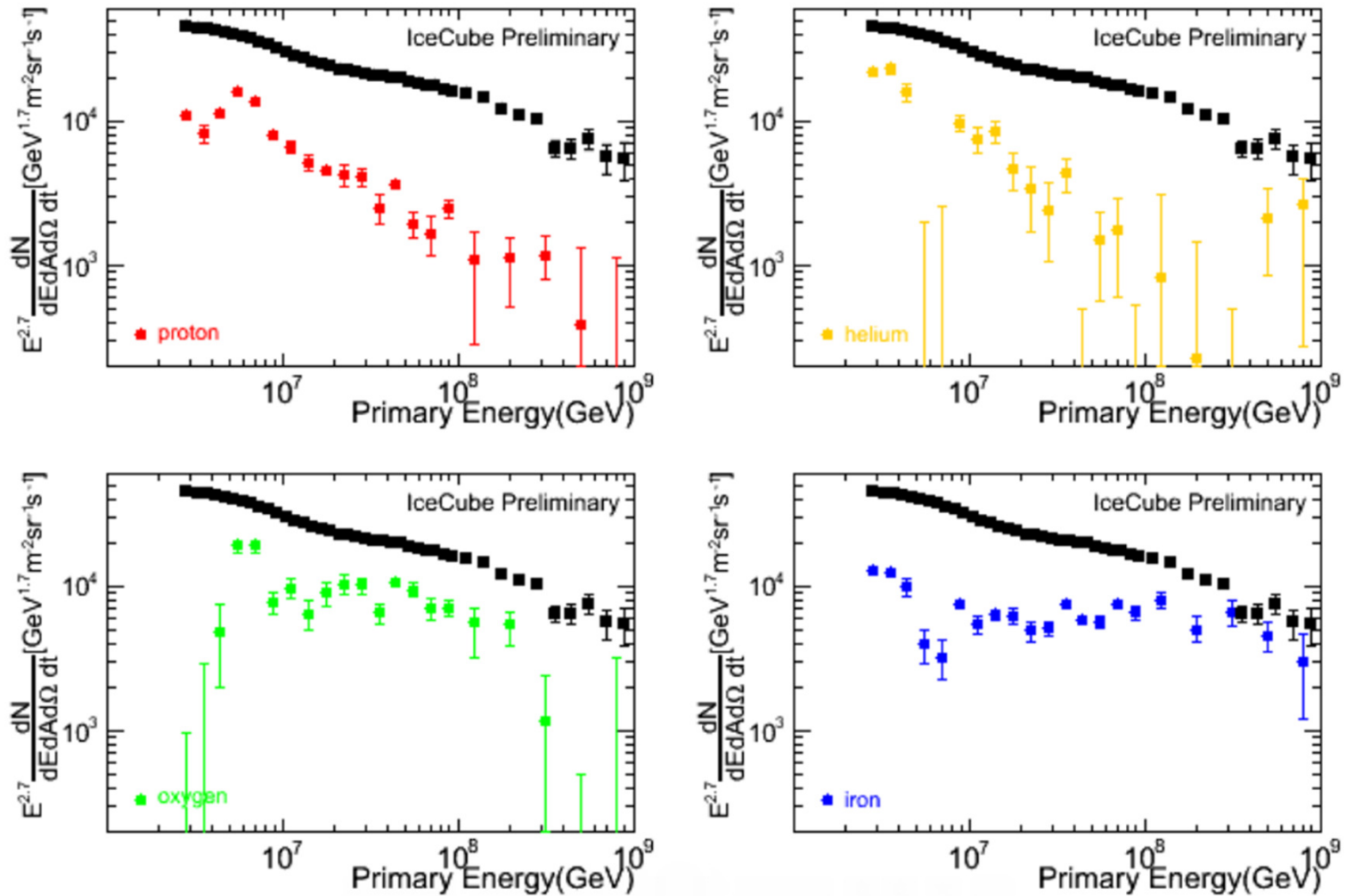

Secondary photons
and low energy
charged particles

TeV muons

Surface: Energy
In-Ice: N_μ

N_μ/E correlates with A

Composition

Gen-2: Cosmic Ray Array

- ## Requirements
  - Timing
  - Dynamic range

  (handwritten, red)
  } • core location
  • Direction
  • Energy

- ## Scope
  - Gen2 footprint

  (handwritten, red)
  { x 8   Surface only
  { x 50   coincident
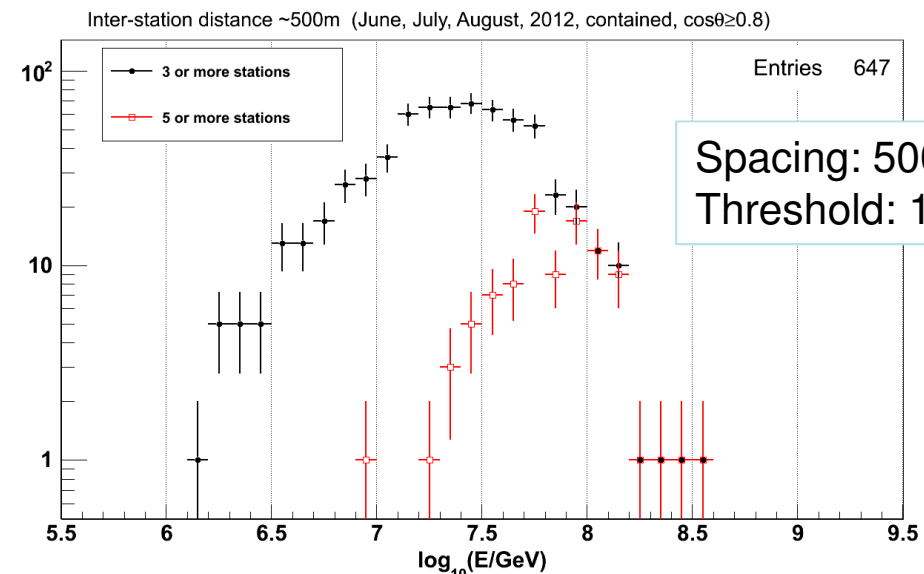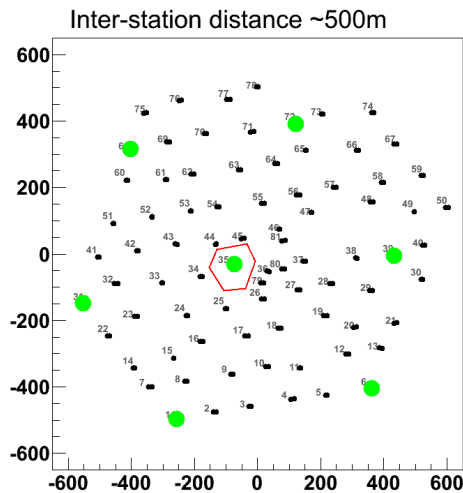
    - at string heads
  - Extended (?)

- ## Technology
  - secondary particle detector (Cherenkov, scintillator)
    - Use Gen-2 DOM mainboard
  - could be a lot like IceTop …

Trigger study: IceTop ⇒ IT-2

Inter-station distance ~250m

Interstation distance ~250m   (July 2012, contained, cosθ≥0.8)

- 3 or more stations
- 5 or more stations
- 7 or more stations

Entries   24858

$\log_{10}(E/GeV)$

Spacing: 250 m
Threshold: 10 PeV

$$E_{th} \sim d^{-3.5}$$

Inter-station distance ~500m

Inter-station distance ~500m (June, July, August, 2012, contained, cosθ≥0.8)

- 3 or more stations
- 5 or more stations

Entries   647

$\log_{10}(E/GeV)$

Spacing: 500 m
Threshold: 100 PeV
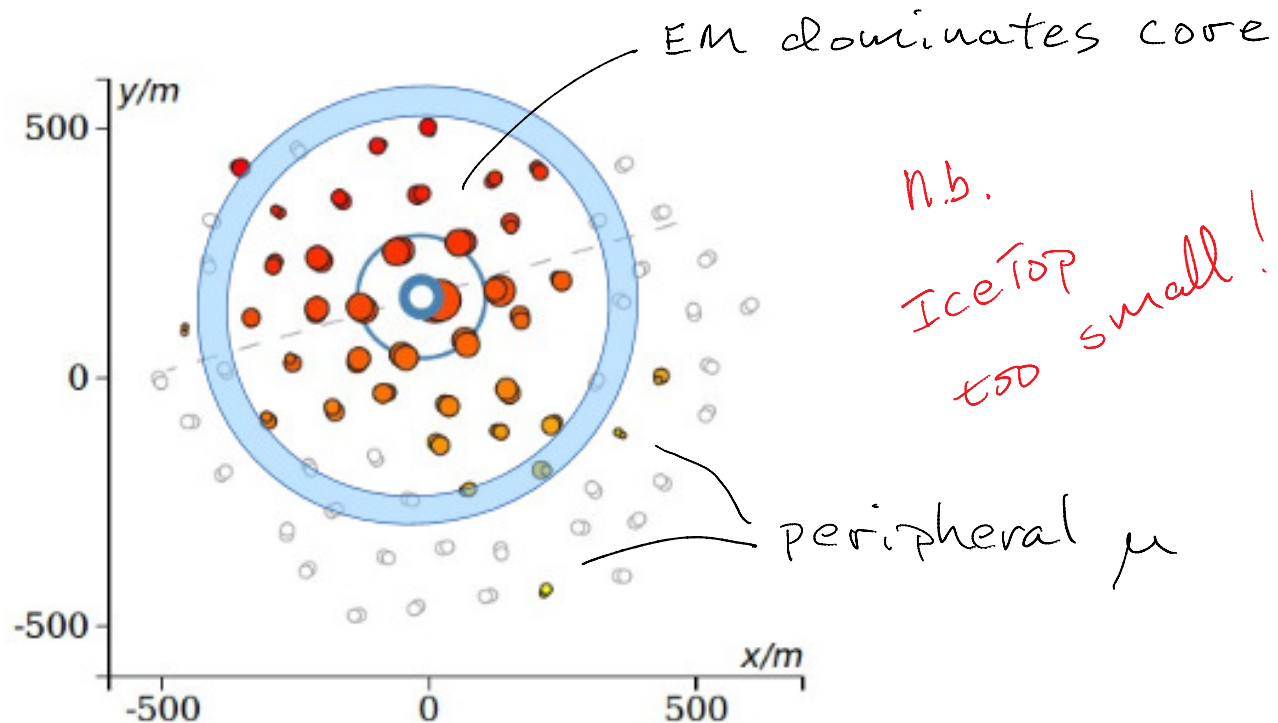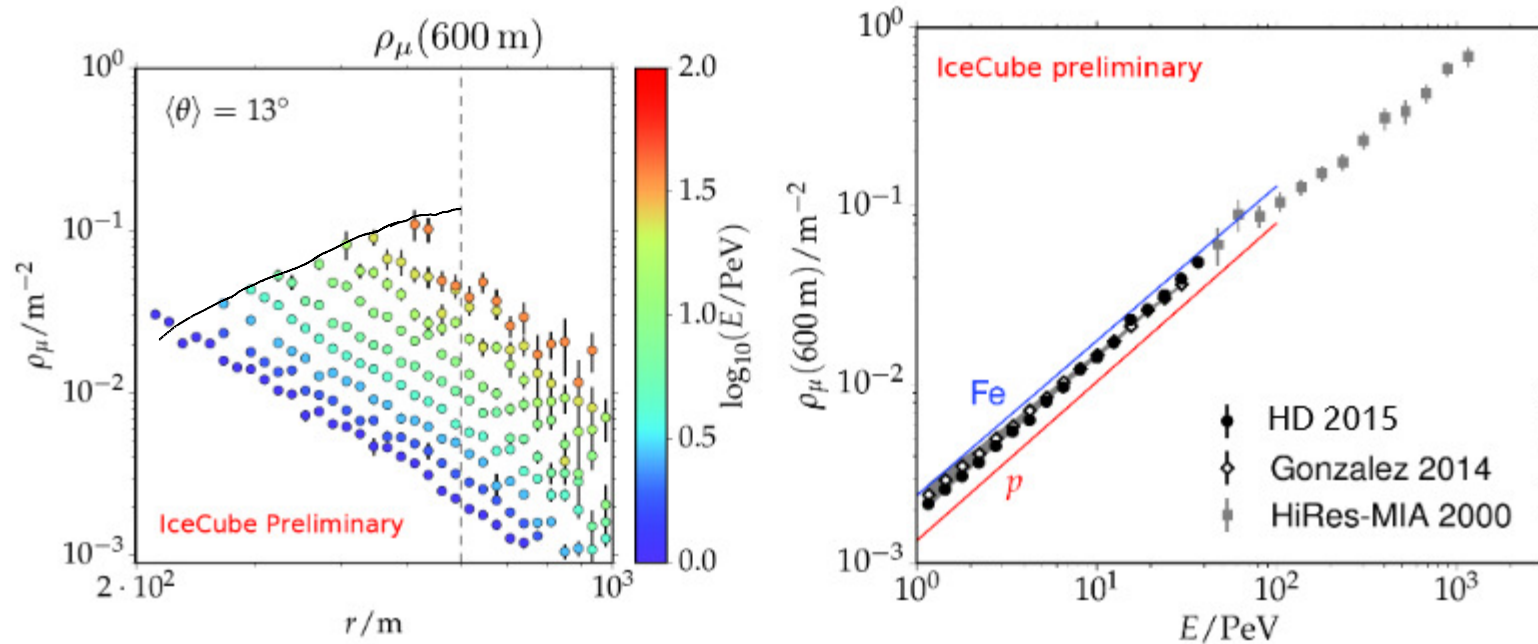
Using the veto … surface muons

- Shielded muon counters (common technique)
- Peripheral muons (Auger, IceTop)

EM dominates core

n.b.
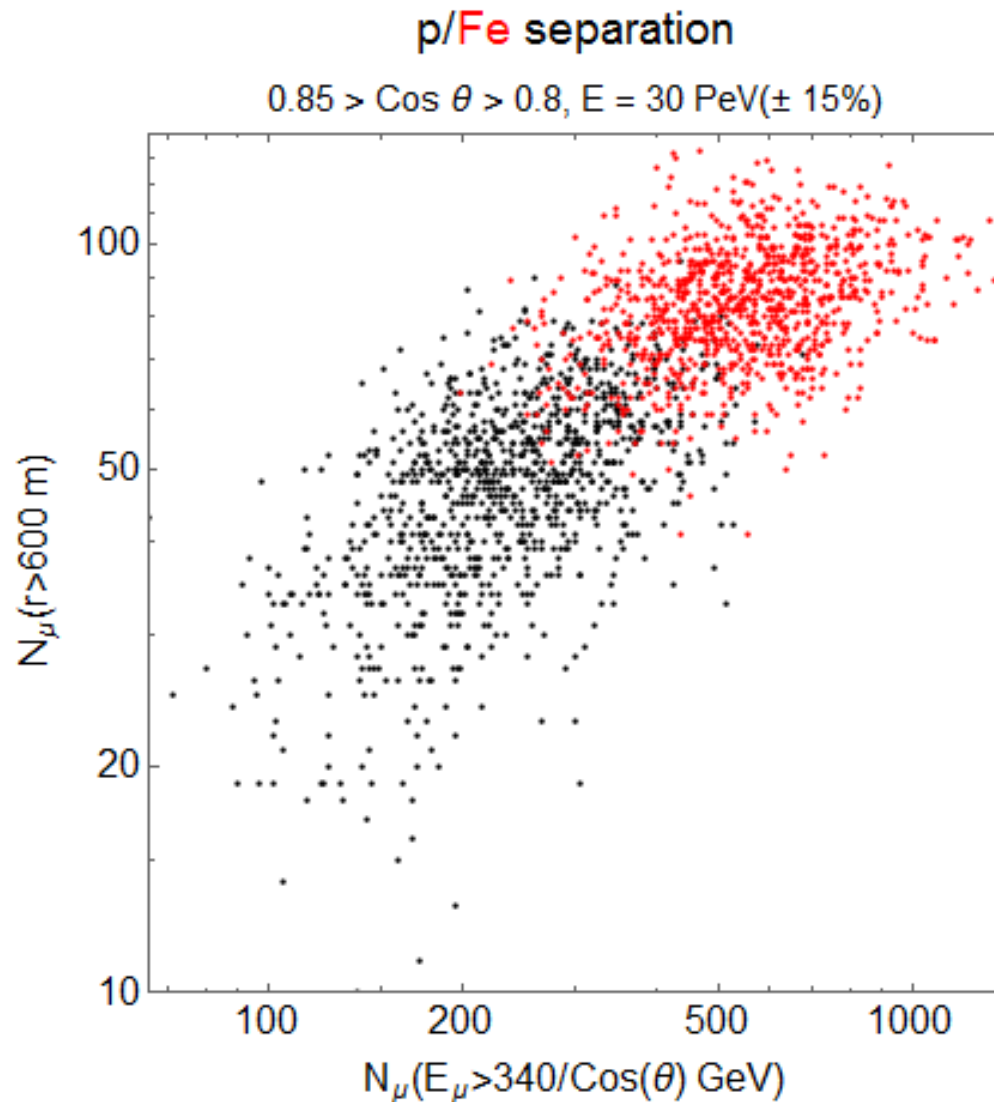IceTop
too small!

peripheral μ

More on peripheral μ

- As energy increase radius of "umbra" increases
- Depth of umbra depends on shielding against EM
- Eventually run into μ −background
- Count muons between (600m :: 3000m), with both increasing with energy

Counting in-ice and surface μ

p/Fe separation

$0.85 > \cos \theta > 0.8$, $E = 30$ PeV($\pm$ 15%)

Corsika simulation

- 30 PeV p & Fe

- energy resolution applied to both in-ice and surface.
- in-ice: applied uncertainty determined from muon bundle analysis
- surface: applied Poisson fluctuation to counts.

- Comparable separation for proposed surface counts and demonstrated in-ice measurement.
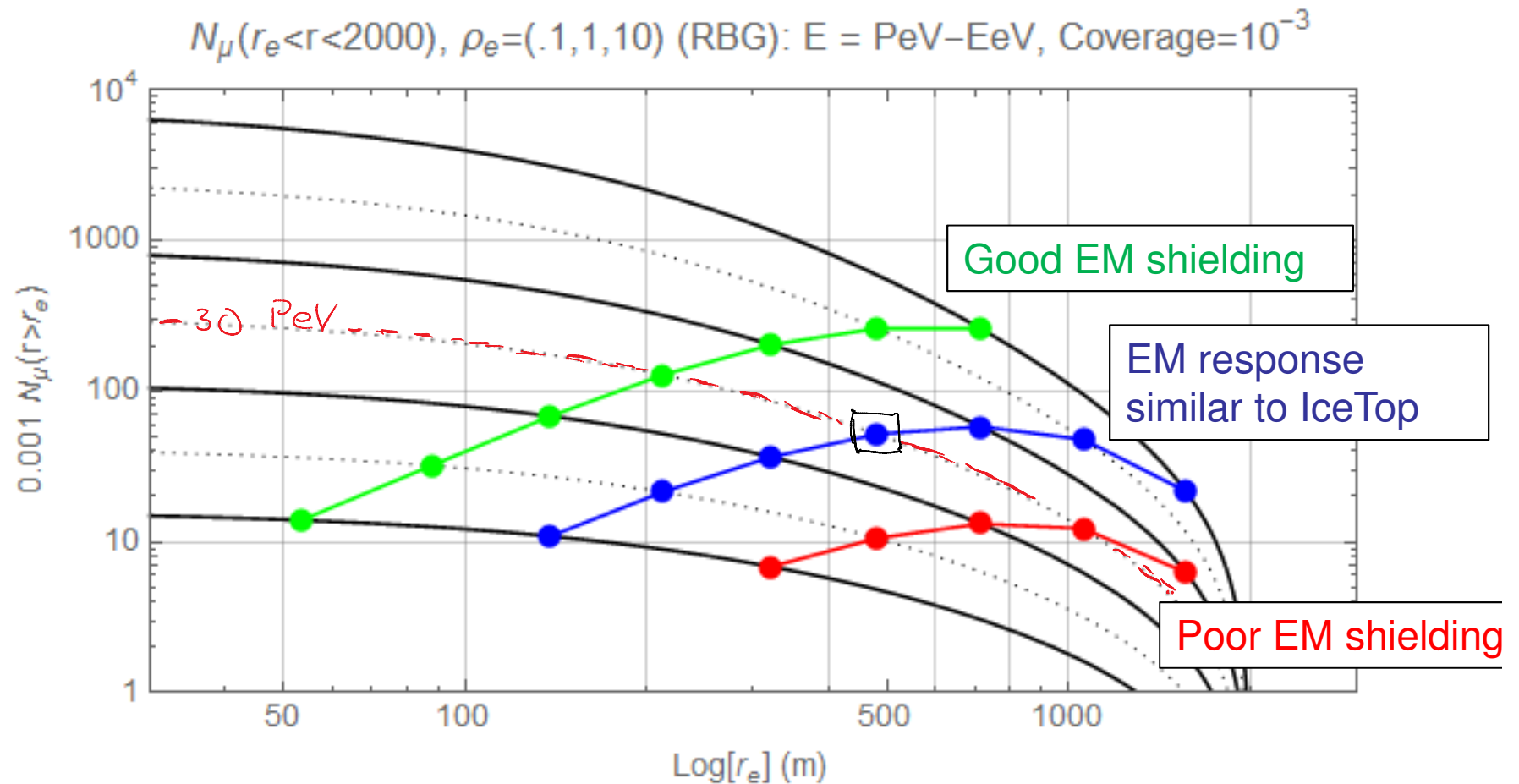
Summary

- ## IceCube Gen-2 will include surface
  - Veto
  - Cosmic Ray Array (CRA or IceTop-2, IT-2)

- ## Increased aperture ⇒ extended energy range
  - x 8   CRA/IT-2 only spectrum
  - x 50 Coincident events within Gen-2 footprint

- ## Veto
  - surface muon component
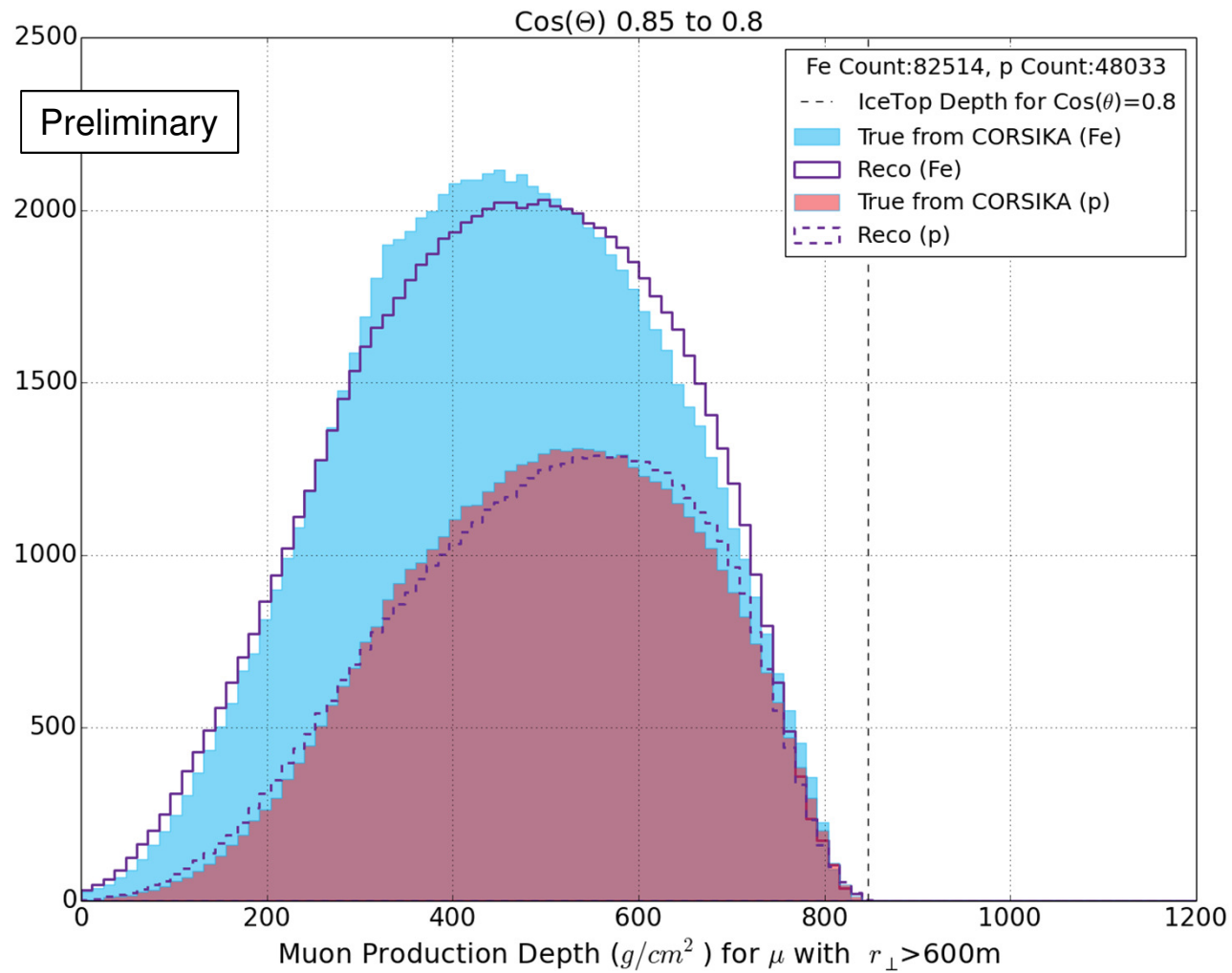
        composition
        hadronic interaction models
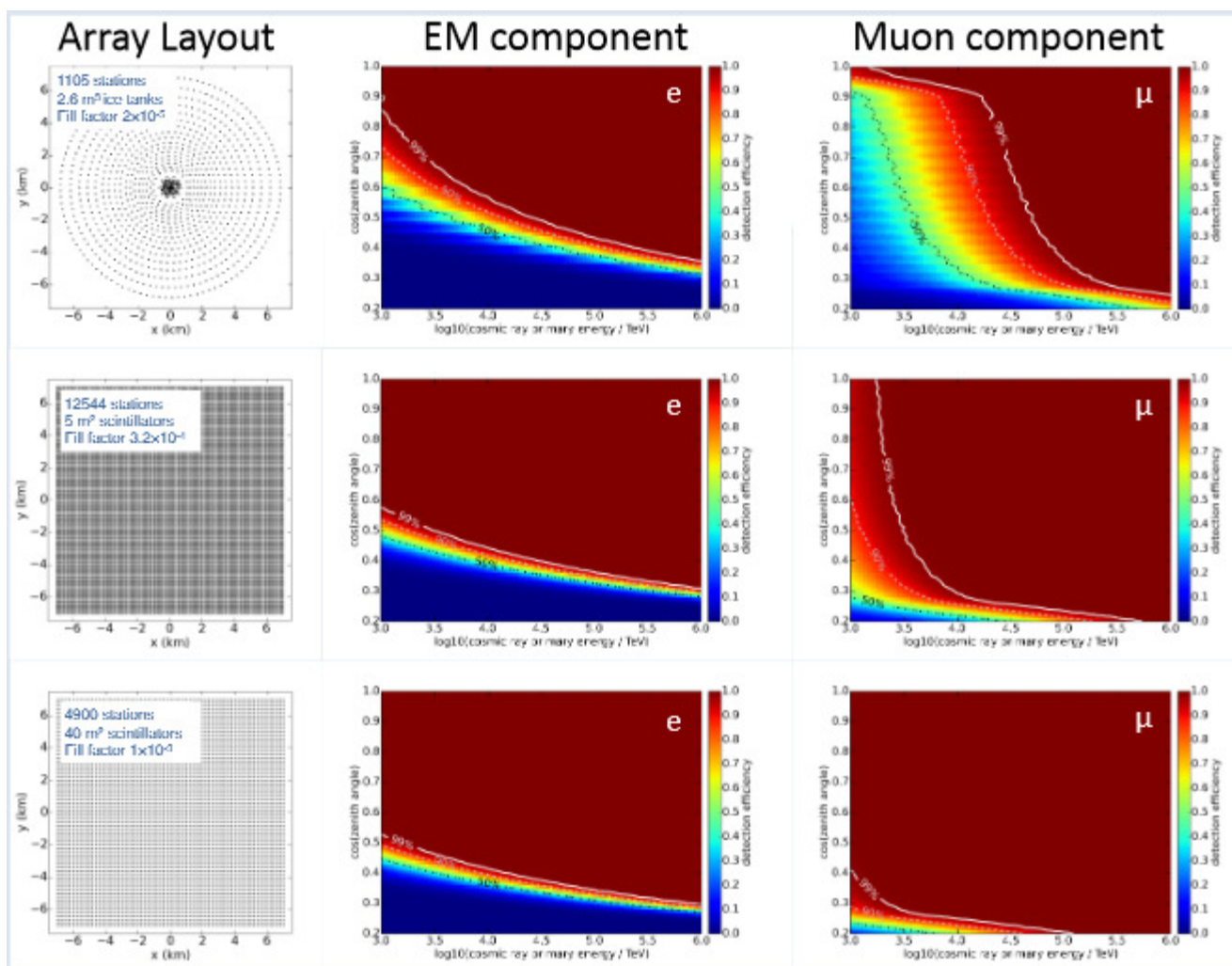
End

Peripheral μ: *very* preliminary

$N_\mu(r_e < r < 2000)$, $\rho_e = (.1, 1, 10)$ (RBG): E = PeV–EeV, Coverage = 10^{-3}

Good EM shielding

EM response similar to IceTop

Poor EM shielding

30 PeV

Muon Production Depth

"LDF" studies (SE)

fill

2·10⁻⁵

3·10⁻⁴

10⁻³

CORSIKA sims (JGG)