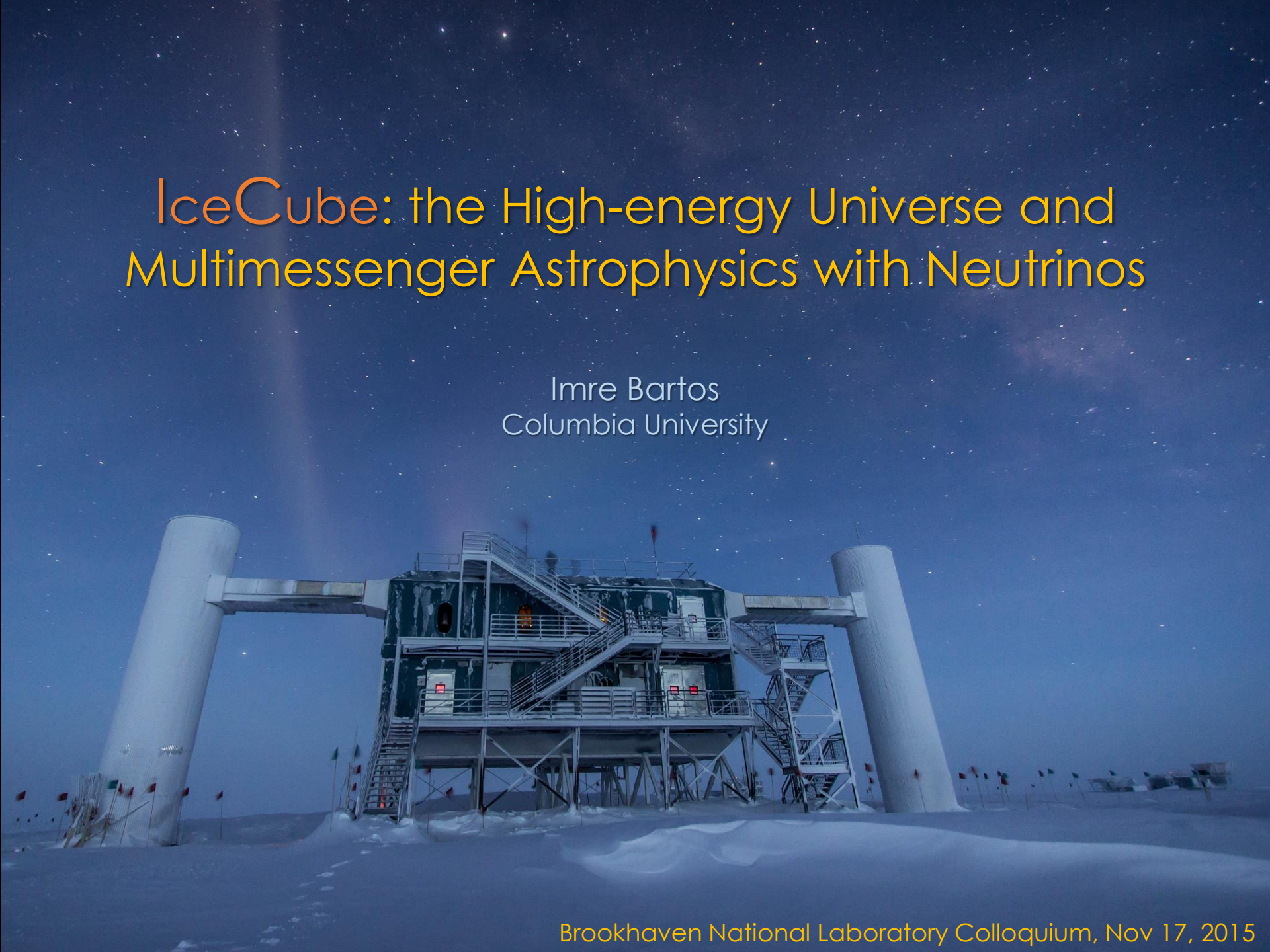
IceCube: the High-energy Universe and Multimessenger Astrophysics with Neutrinos

Imre Bartos
Columbia University



Brookhaven National Laboratory Colloquium, Nov 17, 2015


Cosmic accelerators
non-thermal emission to > 10^{20} eV

outline

I. Cosmic accelerators
   - cosmic rays
   - observational limitations

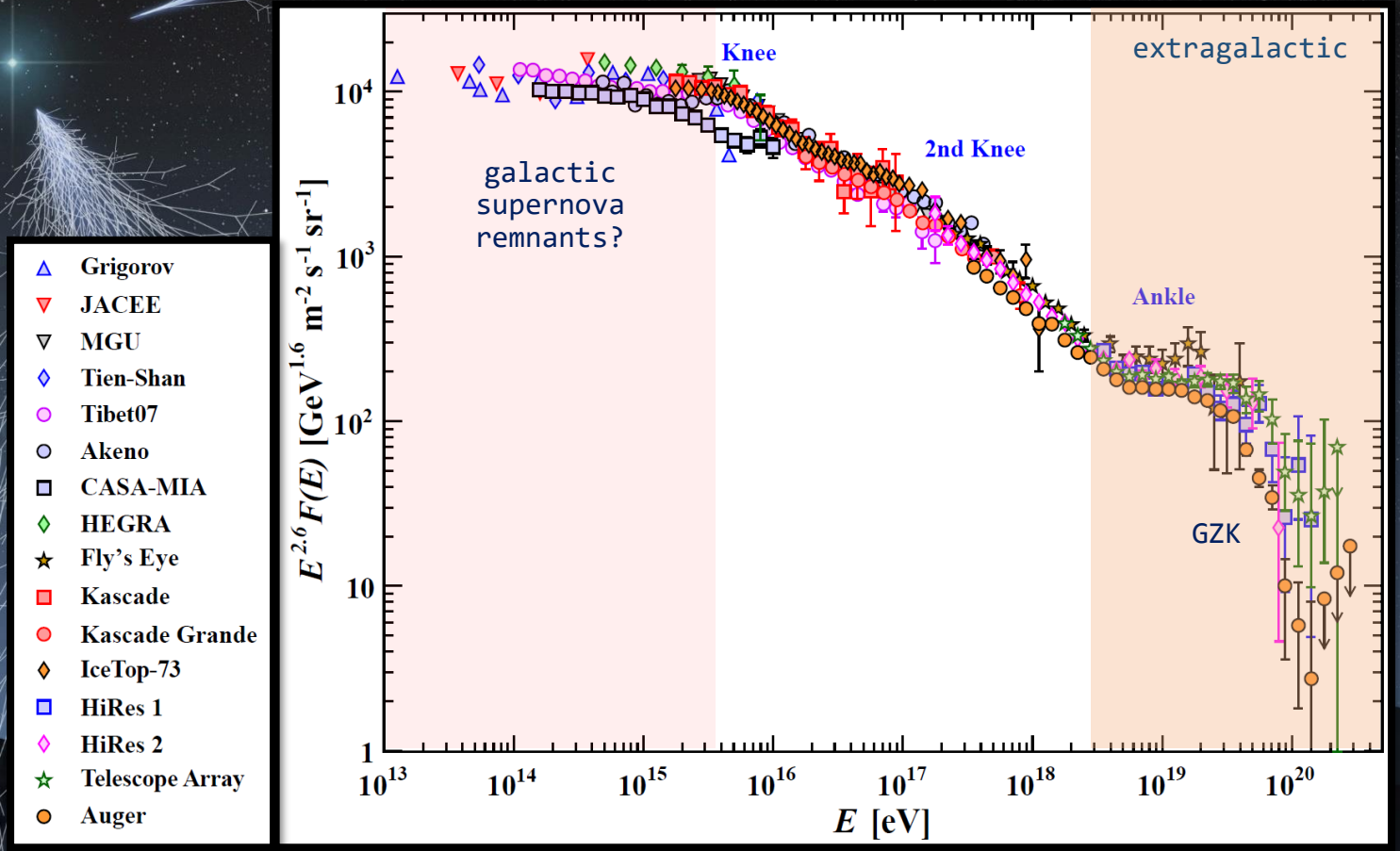
II. High-energy universe
   - gamma-ray bursts
   - active galactic nuclei / blazars
   - supernova remnants

III. IceCube
   - detector
   - astrophysical neutrino flux

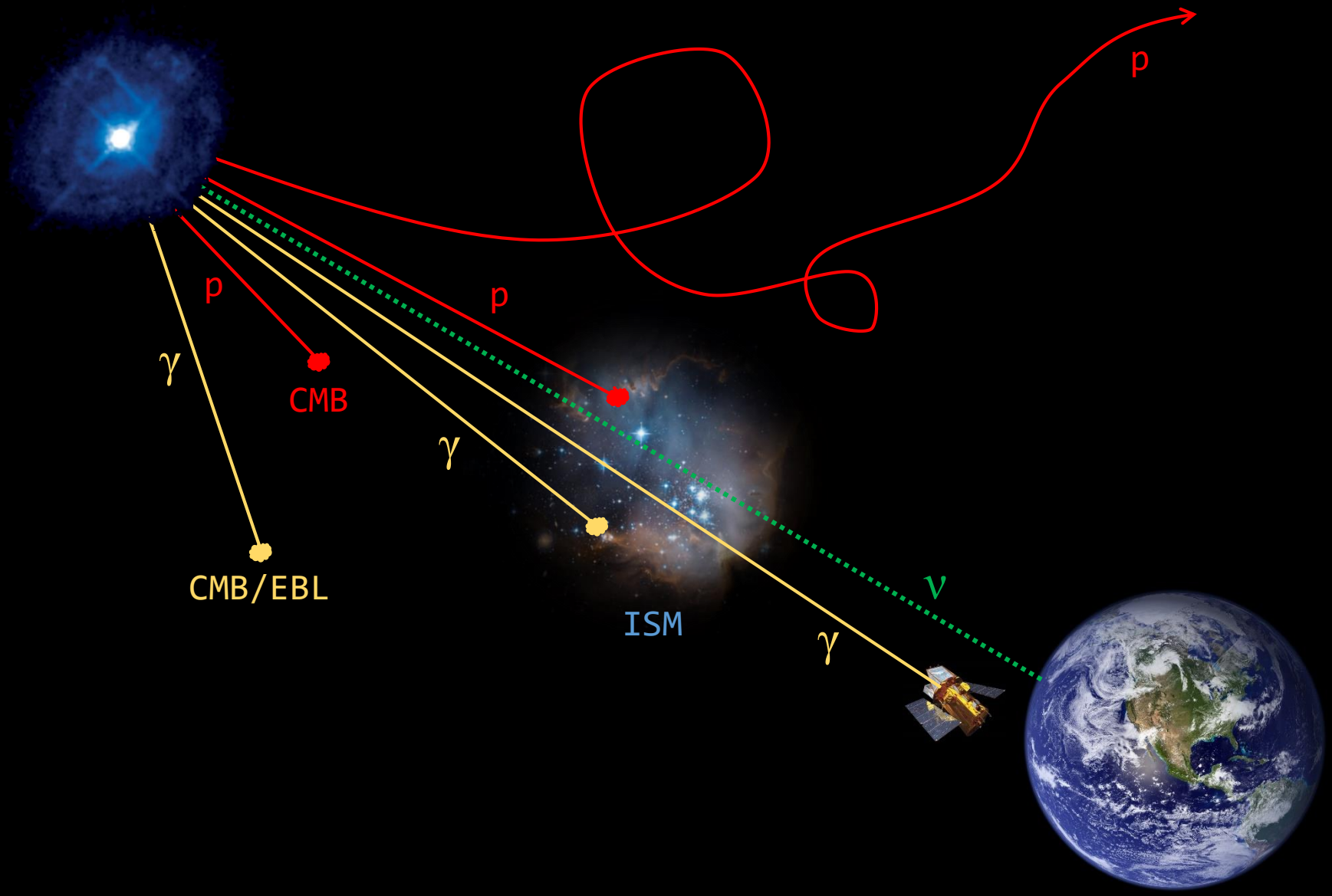
IV. Multimessenger observations
   - source constraints
   - hints

V. Beyond IceCube: Gen2 and others

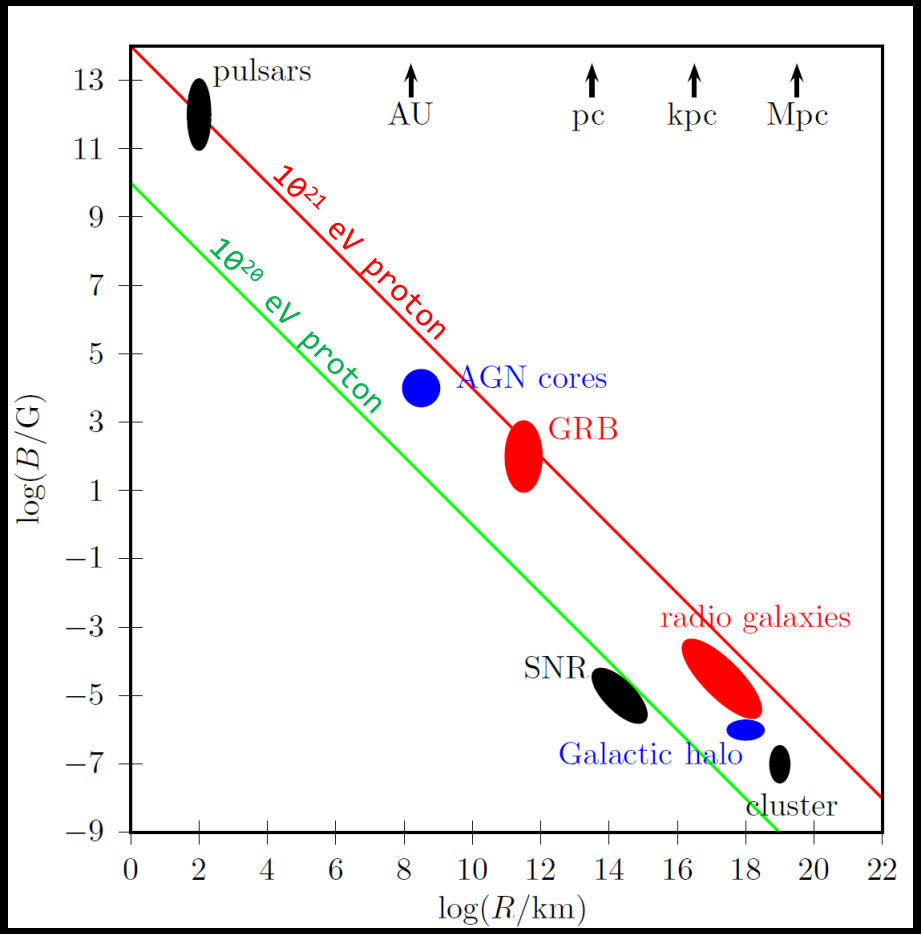
cosmic rays


Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
Knee
2nd Knee
Ankle
GZK
galactic
supernova
remnants?
extragalactic
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

difficulty finding the origin



the high-energy universe



Hillas criterion: $E_{max} = qBR$

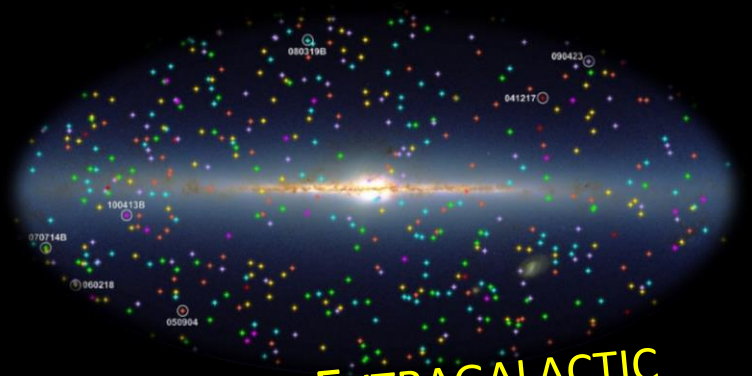
the high-energy (EM) universe

gamma-ray bursts

active galactic nuclei
(blazars)

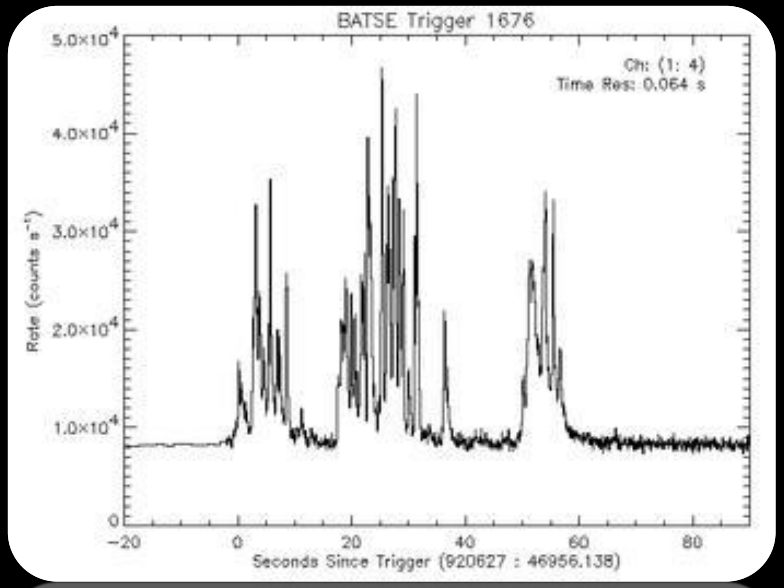
supernova remnants

gamma ray bursts



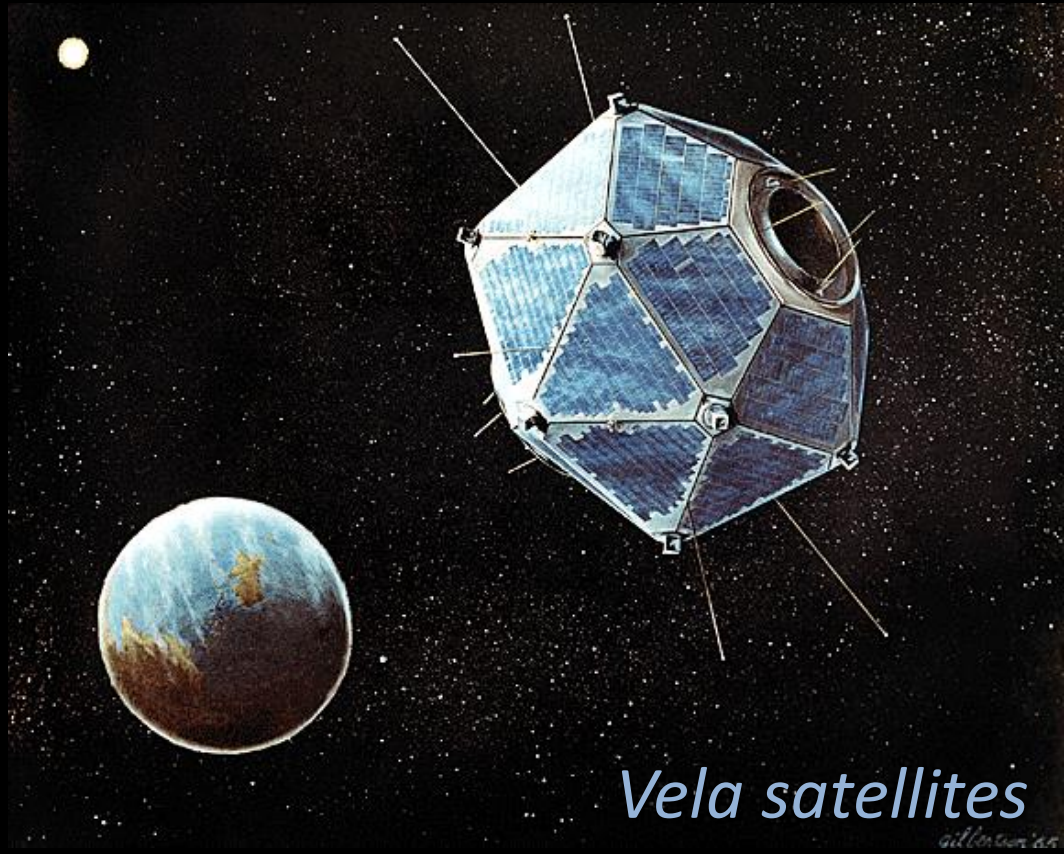
EXTRAGALACTIC

ENERGETIC



SMALL!

(< EARTH)



Vela satellites

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received 1973 March 16; revised 1973 April 2

ABSTRACT

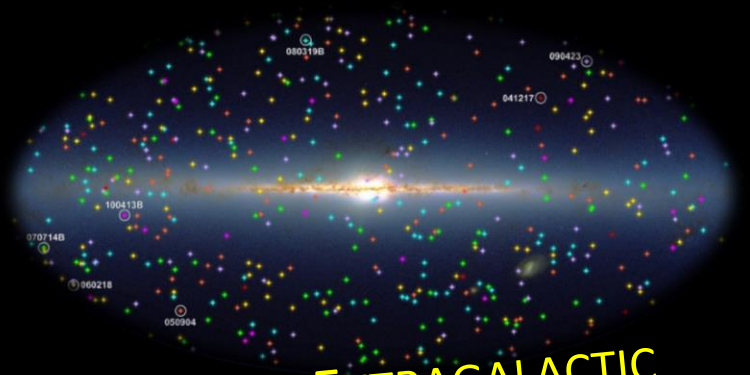
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

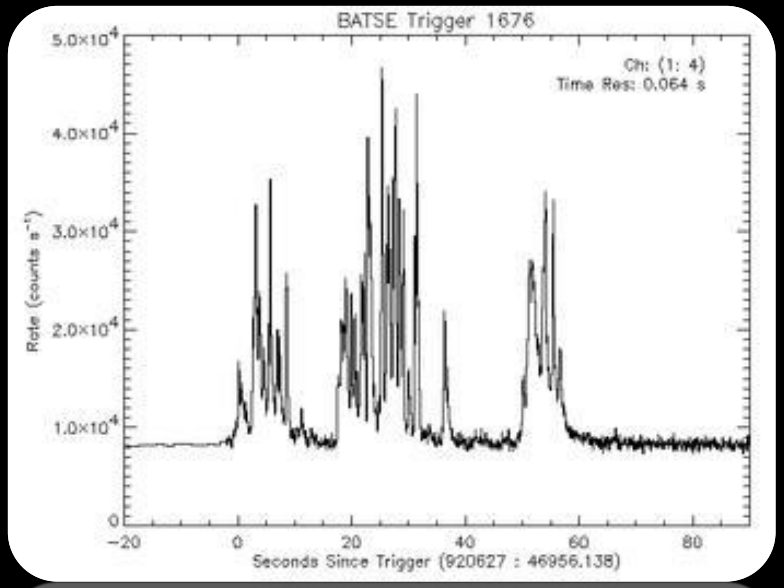
On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-

gamma ray bursts



EXTRAGALACTIC

ENERGETIC



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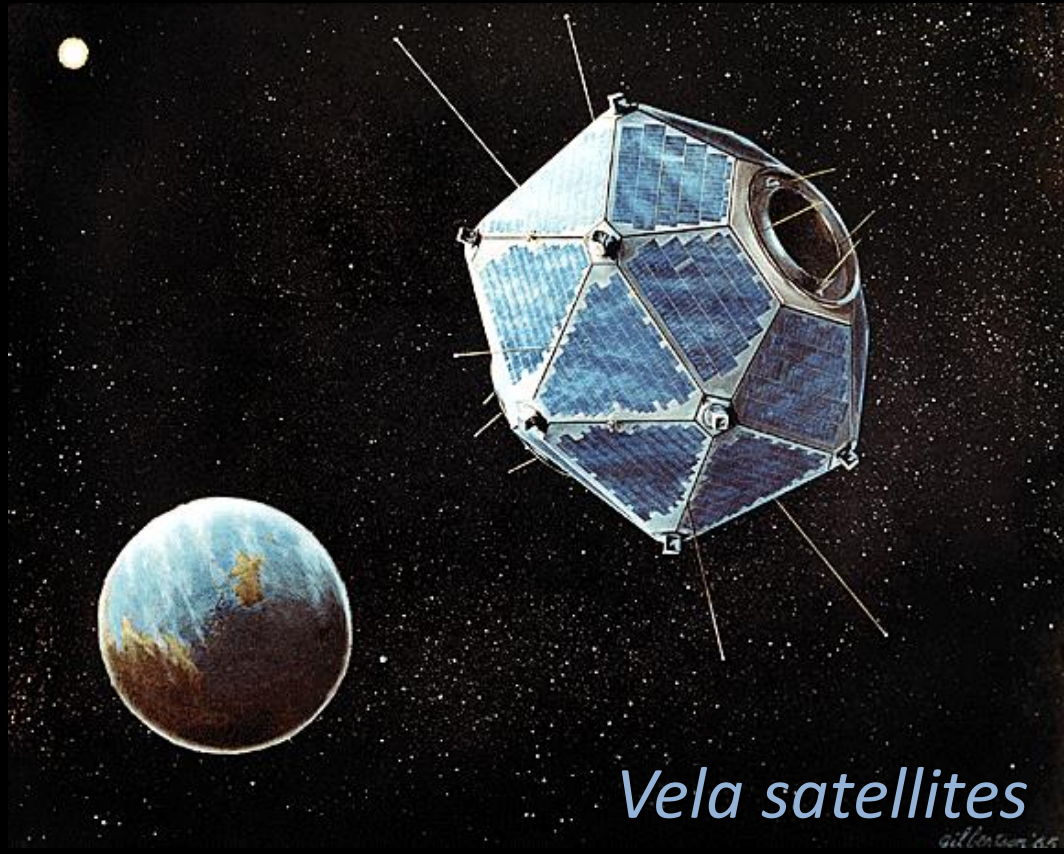
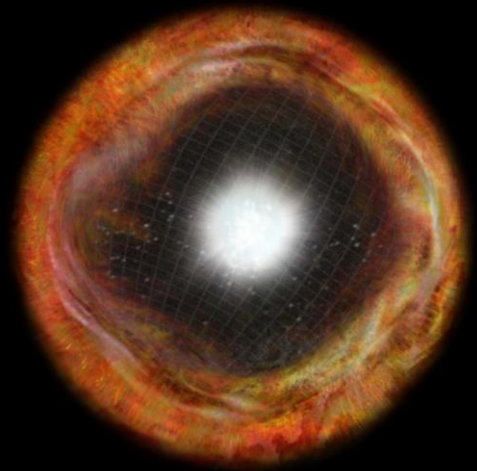
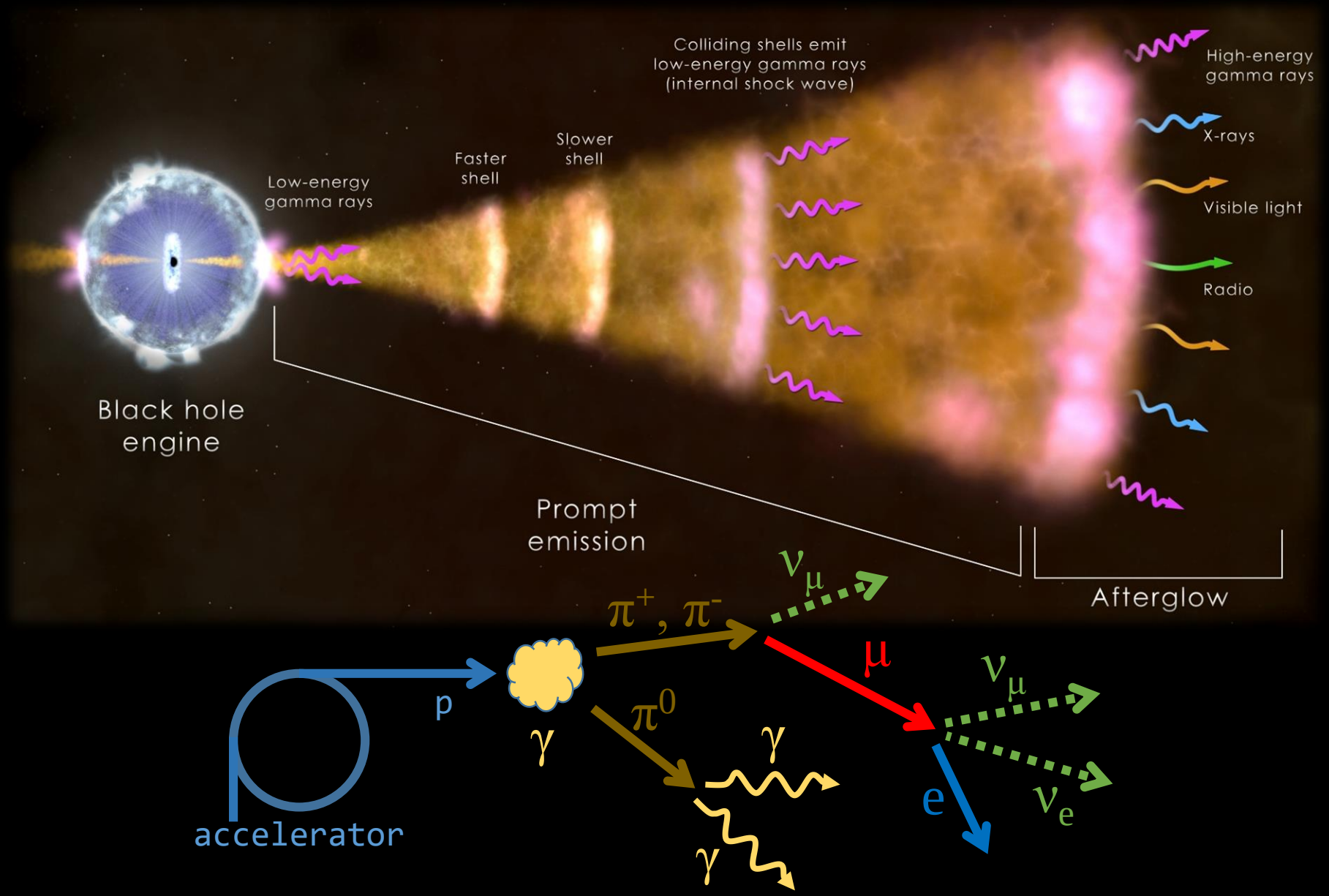
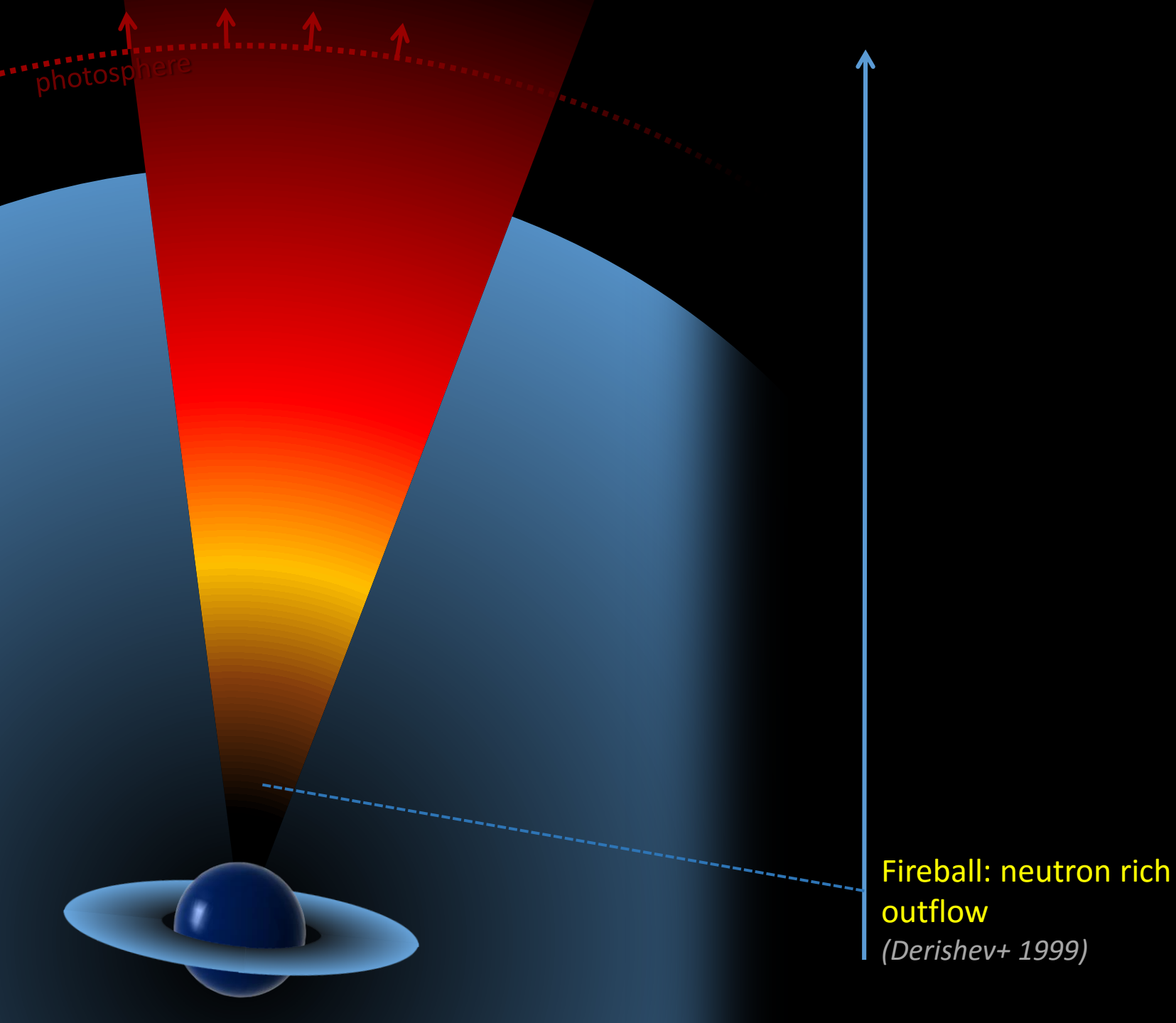


Vela satellites



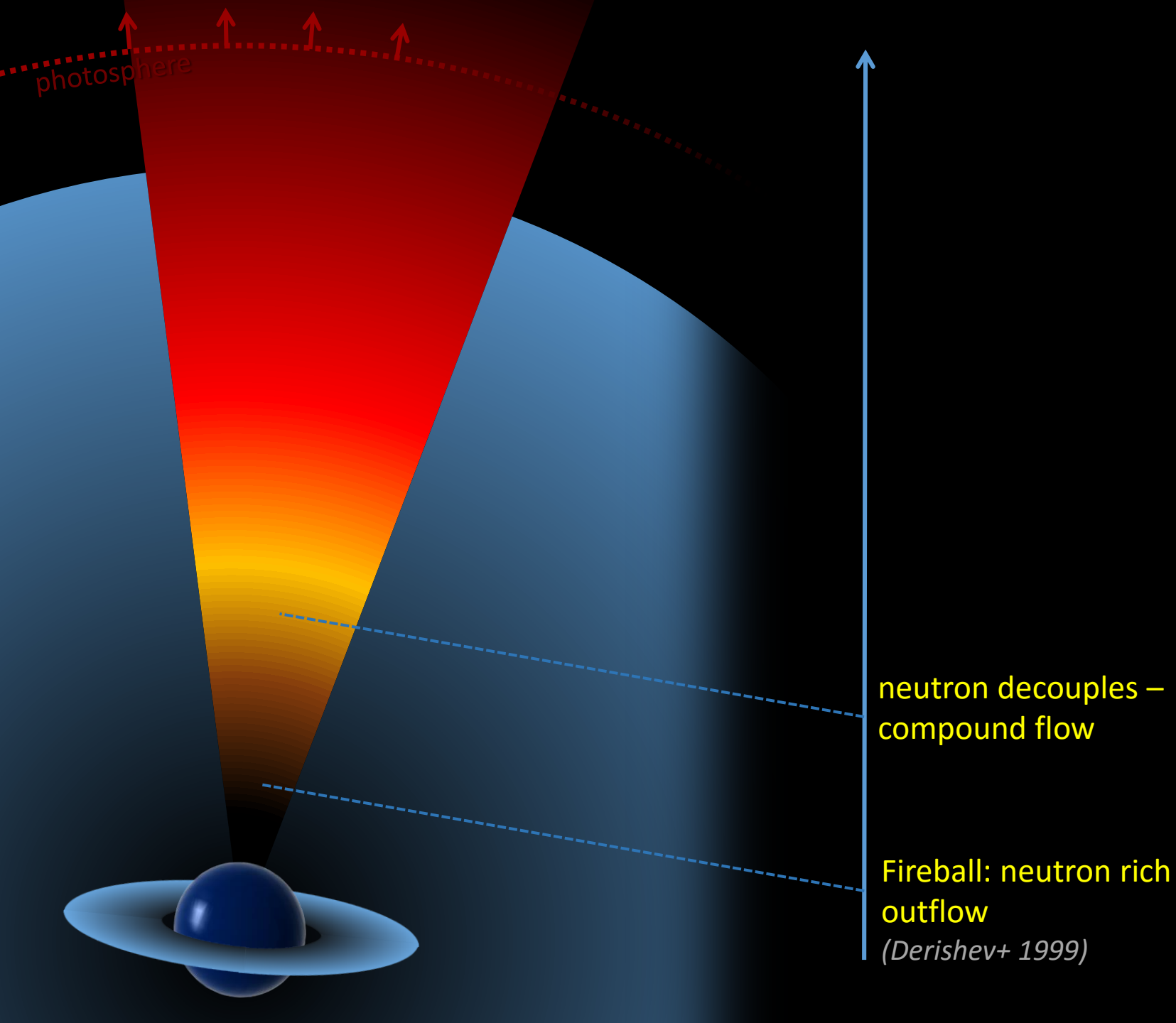
gamma ray bursts

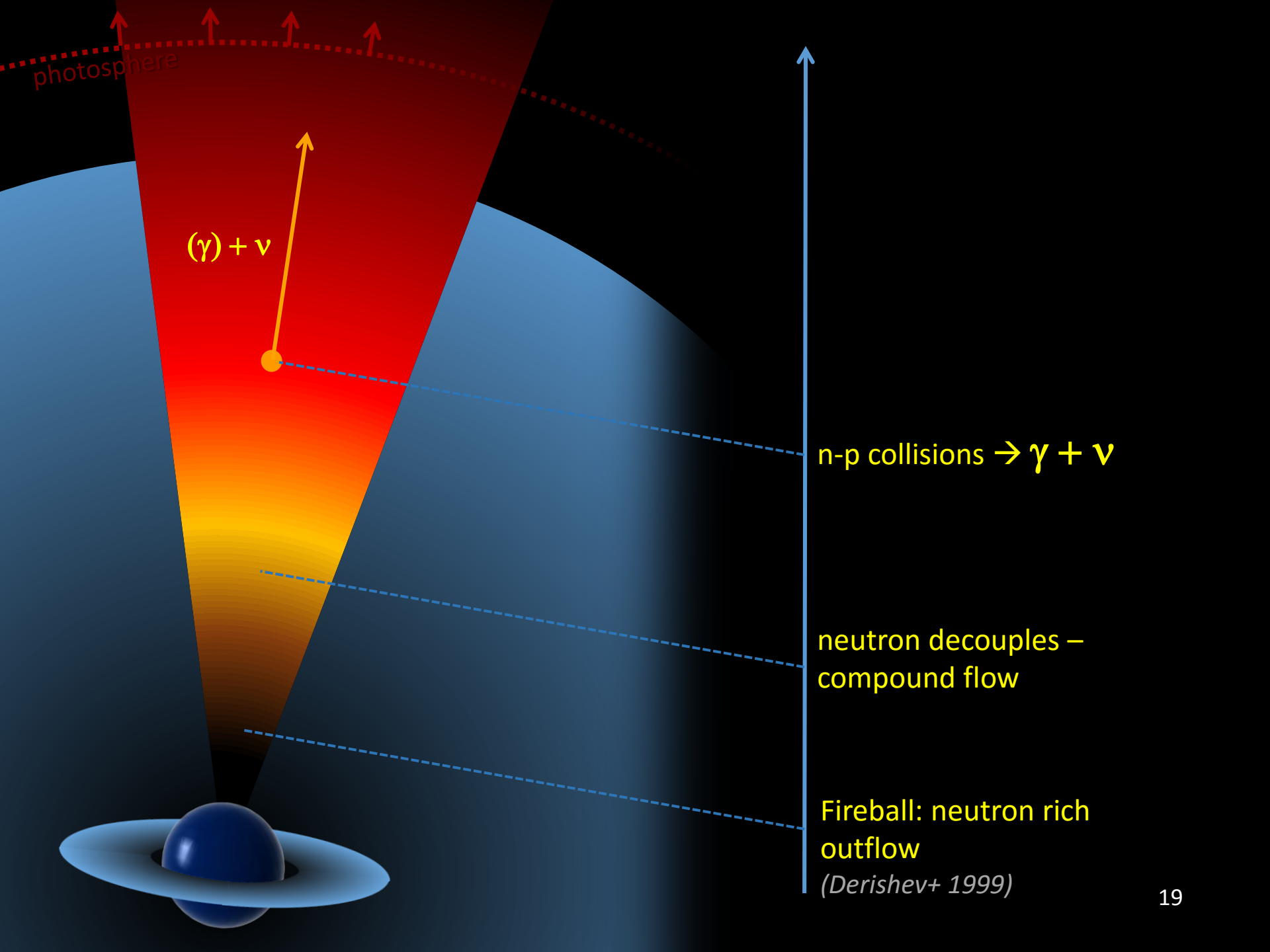


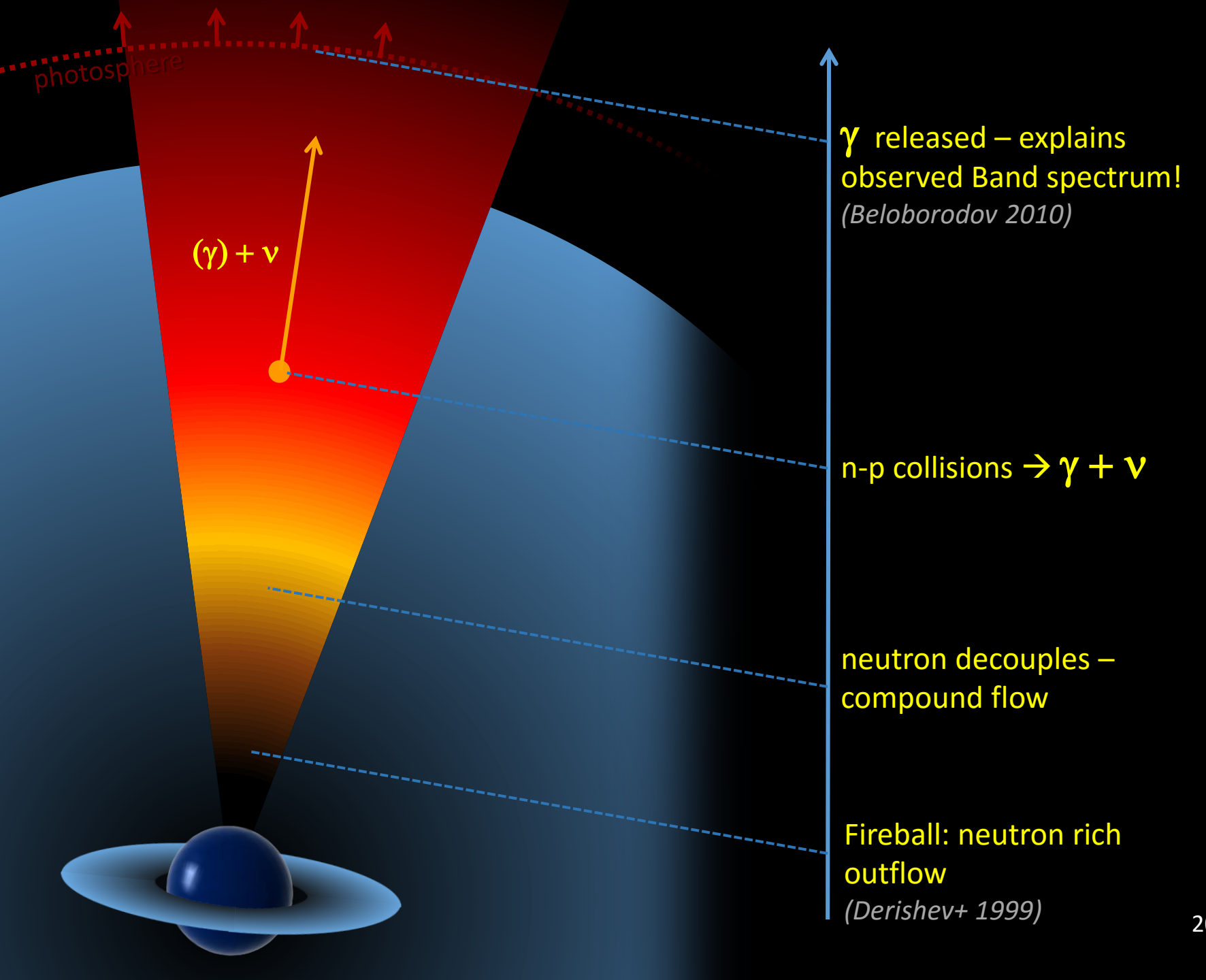


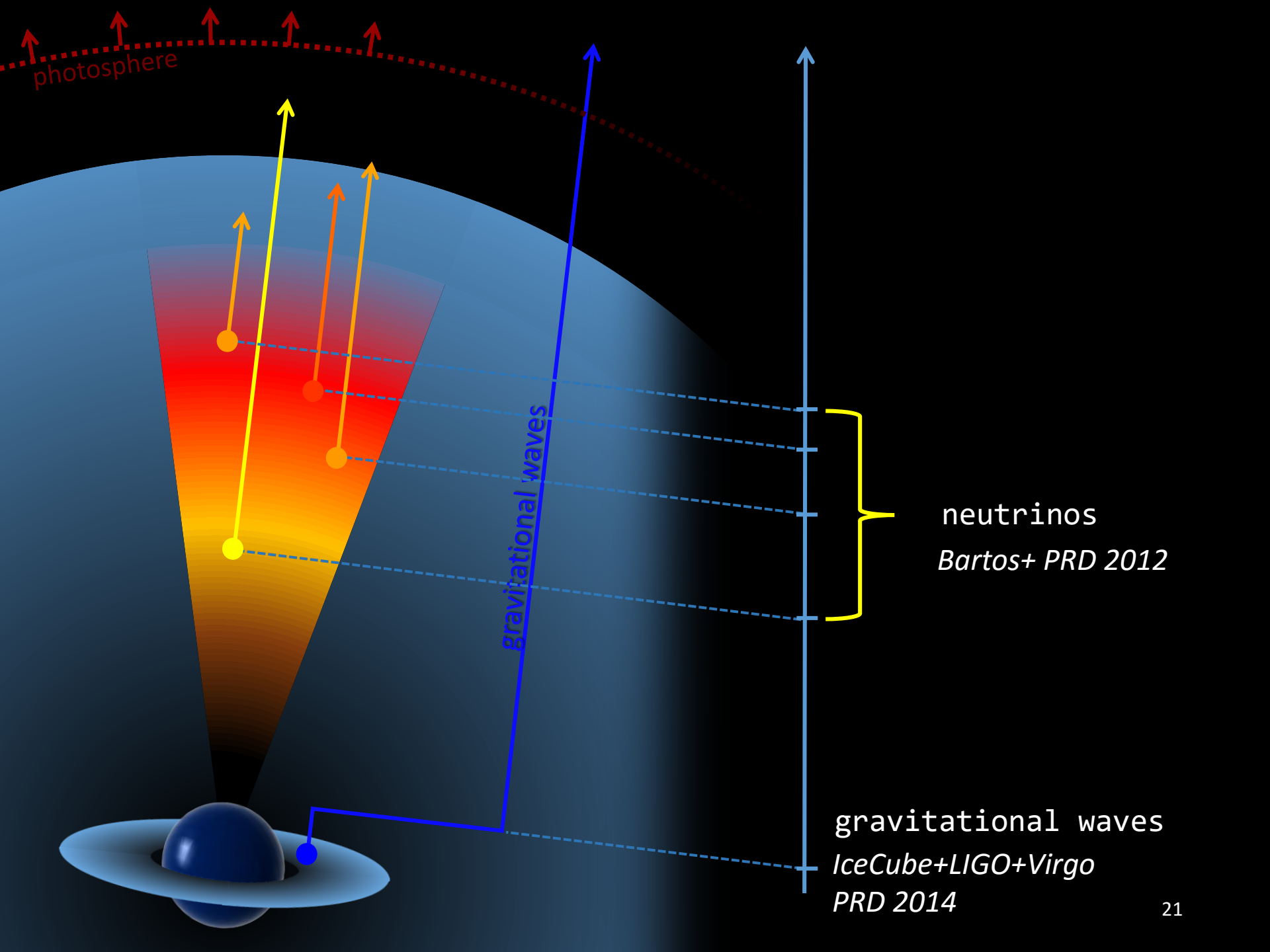
Fireball: neutron rich outflow

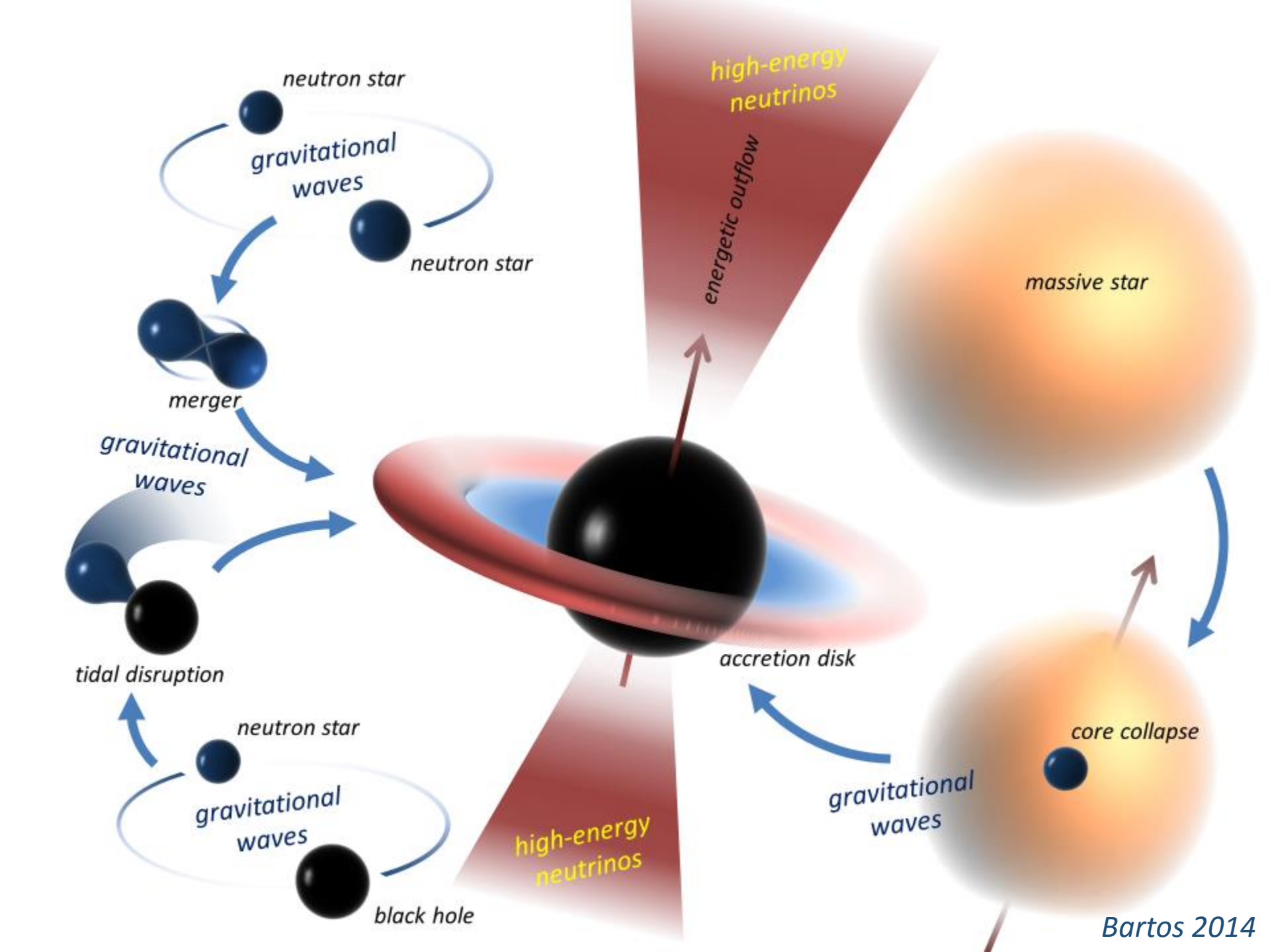
(Derishev+ 1999)


photosphere
neutron decouples –
compound flow
Fireball: neutron rich
outflow
(Derishev+ 1999)


photosphere
(γ) + ν
n-p collisions → γ + ν
neutron decouples –
compound flow
Fireball: neutron rich
outflow
(Derishev+ 1999)


photosphere
(γ) + ν
γ released – explains observed Band spectrum!
(Beloborodov 2010)
n-p collisions → γ + ν
neutron decouples – compound flow
Fireball: neutron rich outflow
(Derishev+ 1999)


photosphere
gravitational waves
neutrinos
Bartos+ PRD 2012
gravitational waves
IceCube+LIGO+Virgo
PRD 2014


neutron star
gravitational waves
neutron star
merger
gravitational waves
tidal disruption
neutron star
gravitational waves
black hole
high-energy neutrinos
energetic outflow
massive star
accretion disk
core collapse
gravitational waves
high-energy neutrinos

Bartos 2014

gamma ray bursts - summary

I. progenitor
   - massive stellar core collapse
   - binary neutron star merger

II. particle acceleration
   - relativistic outflows
   - details not clear

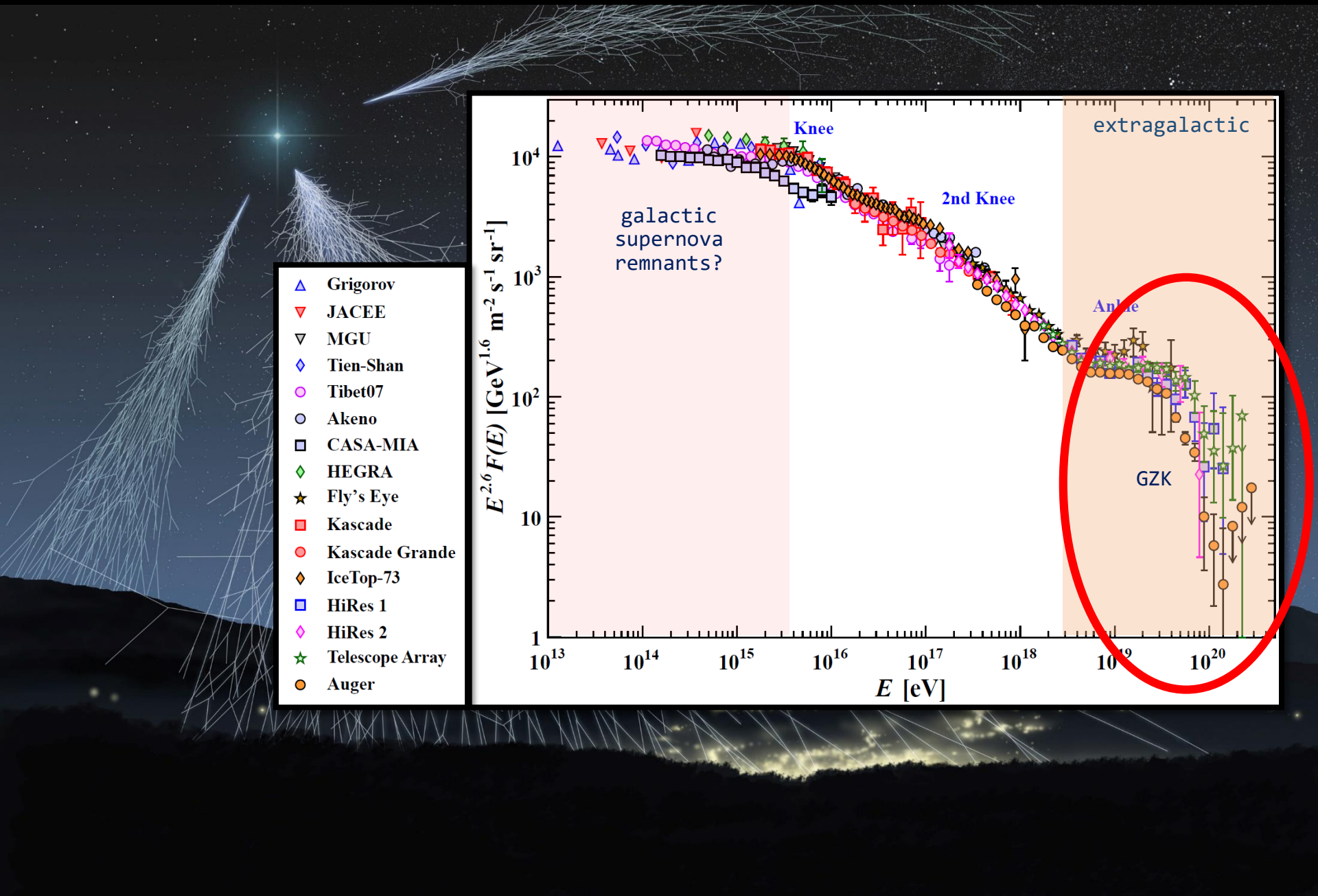
III. typical rate / distance
   - ~ 1 / day (30 $yr^{-1}Gpc^{-3}$)
   - z ~ 2

IV. too far for cosmic ray observation

V. radio to gamma rays up to ~ 100 GeV

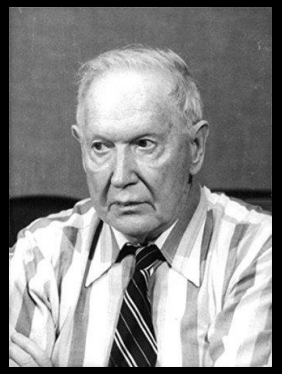
VI. neutrinos
   - no detection so far
   - would determine acceleration
   - test >> 100 GeV

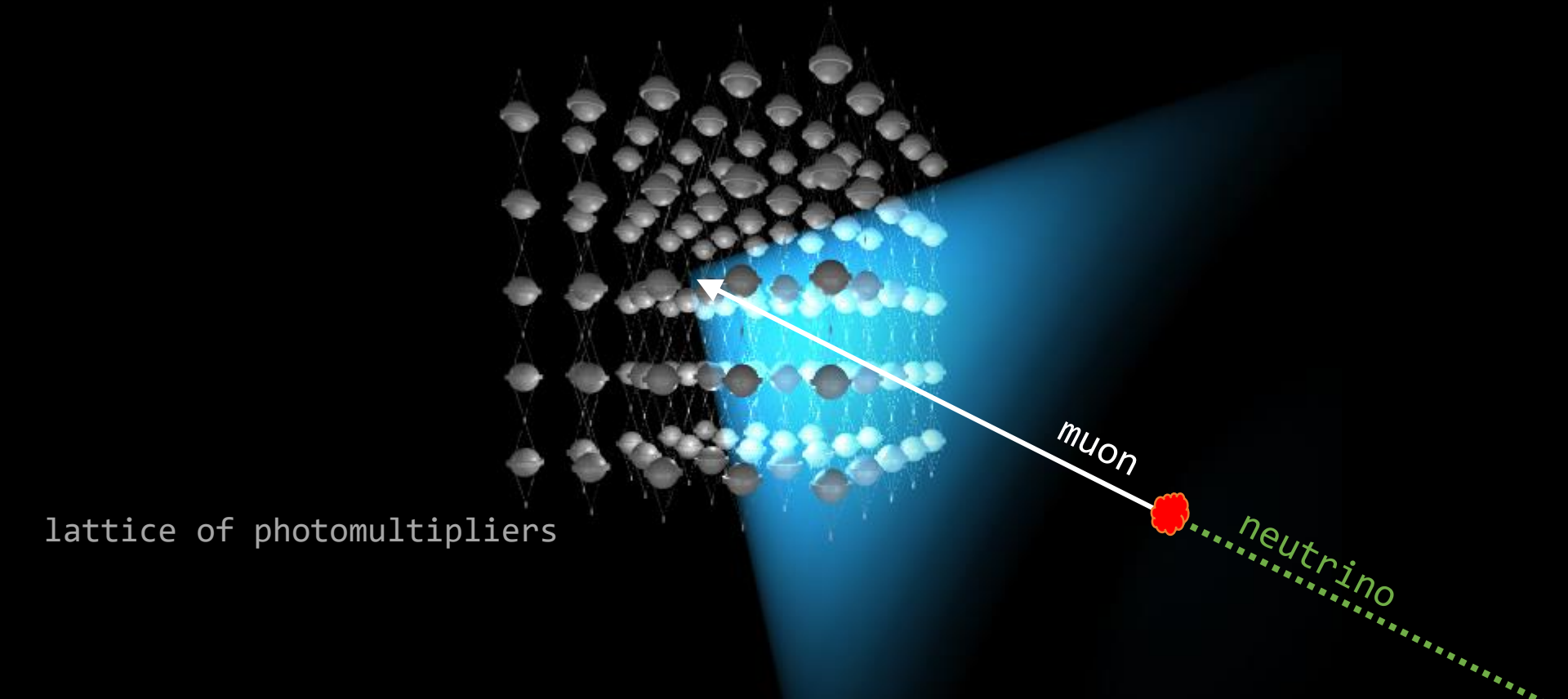
high-energy neutrino detection



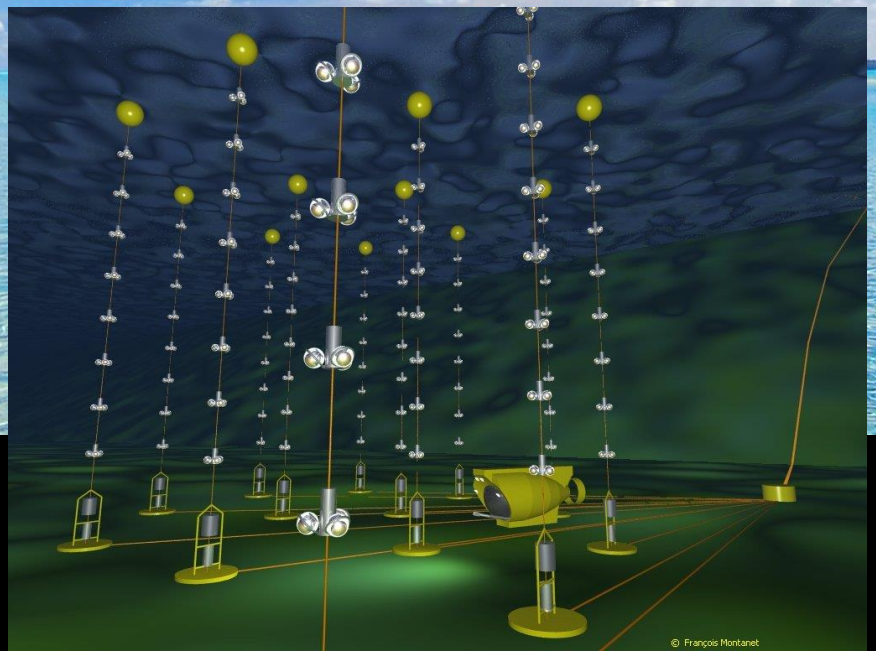
high-energy neutrino detection

Moisey Markov (1960): we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

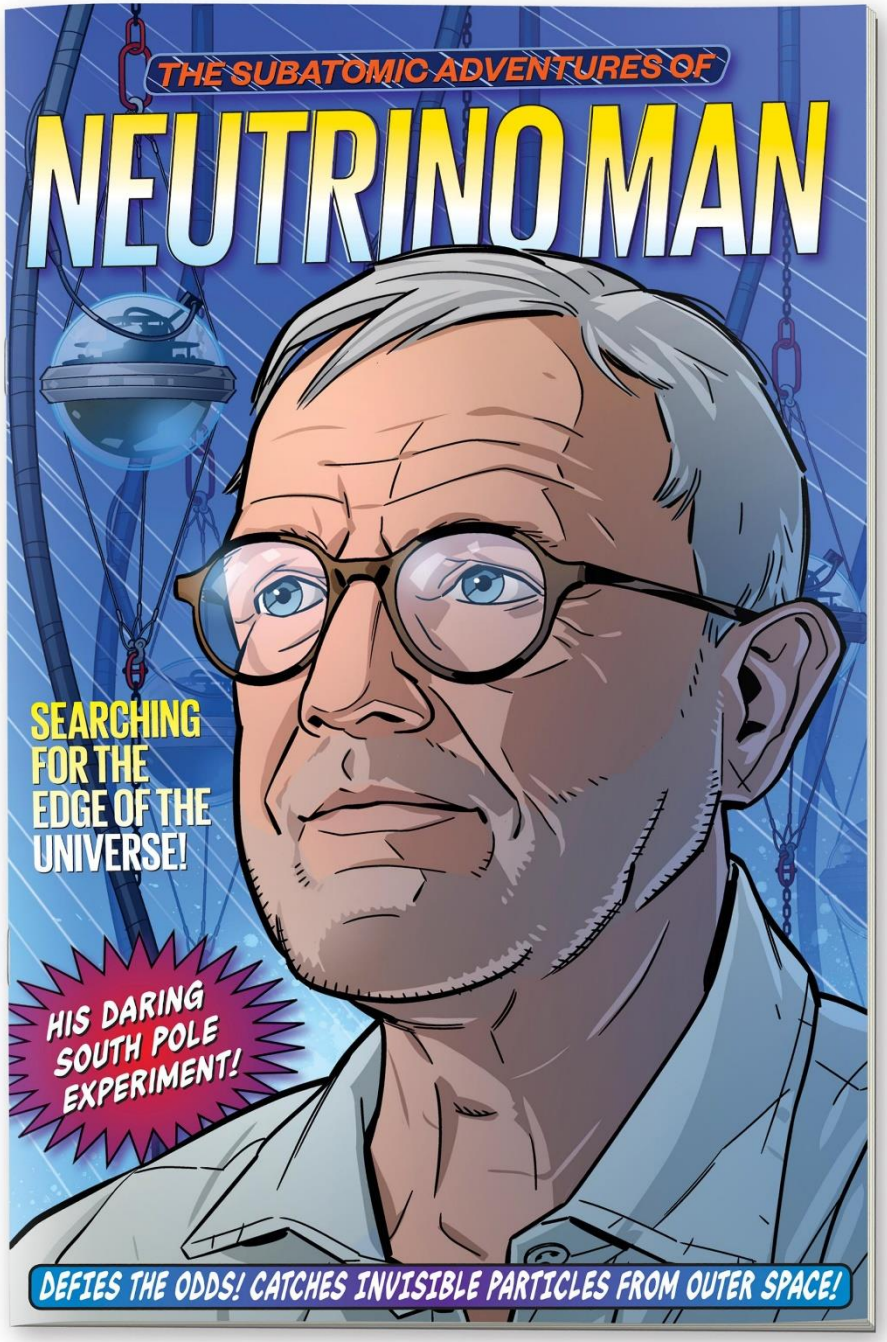




DUMAND *(Deep Underwater Muon And Neutrino Detector)*

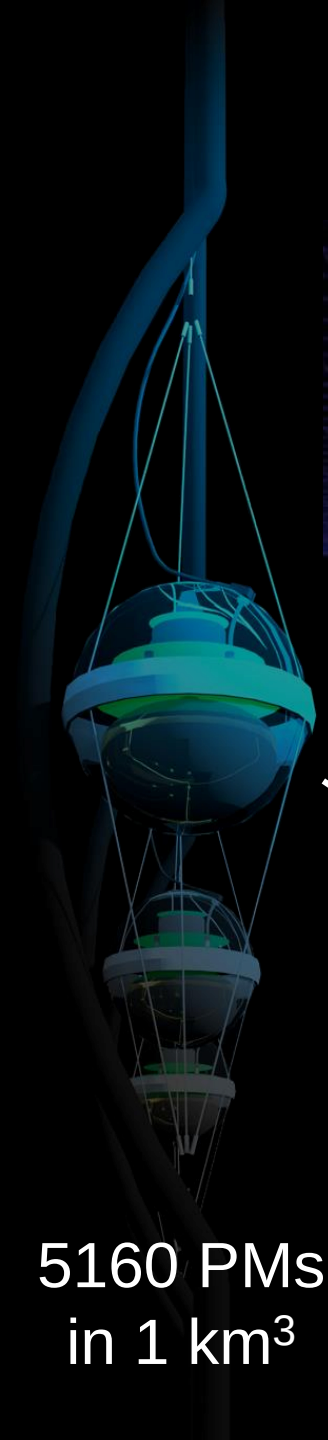


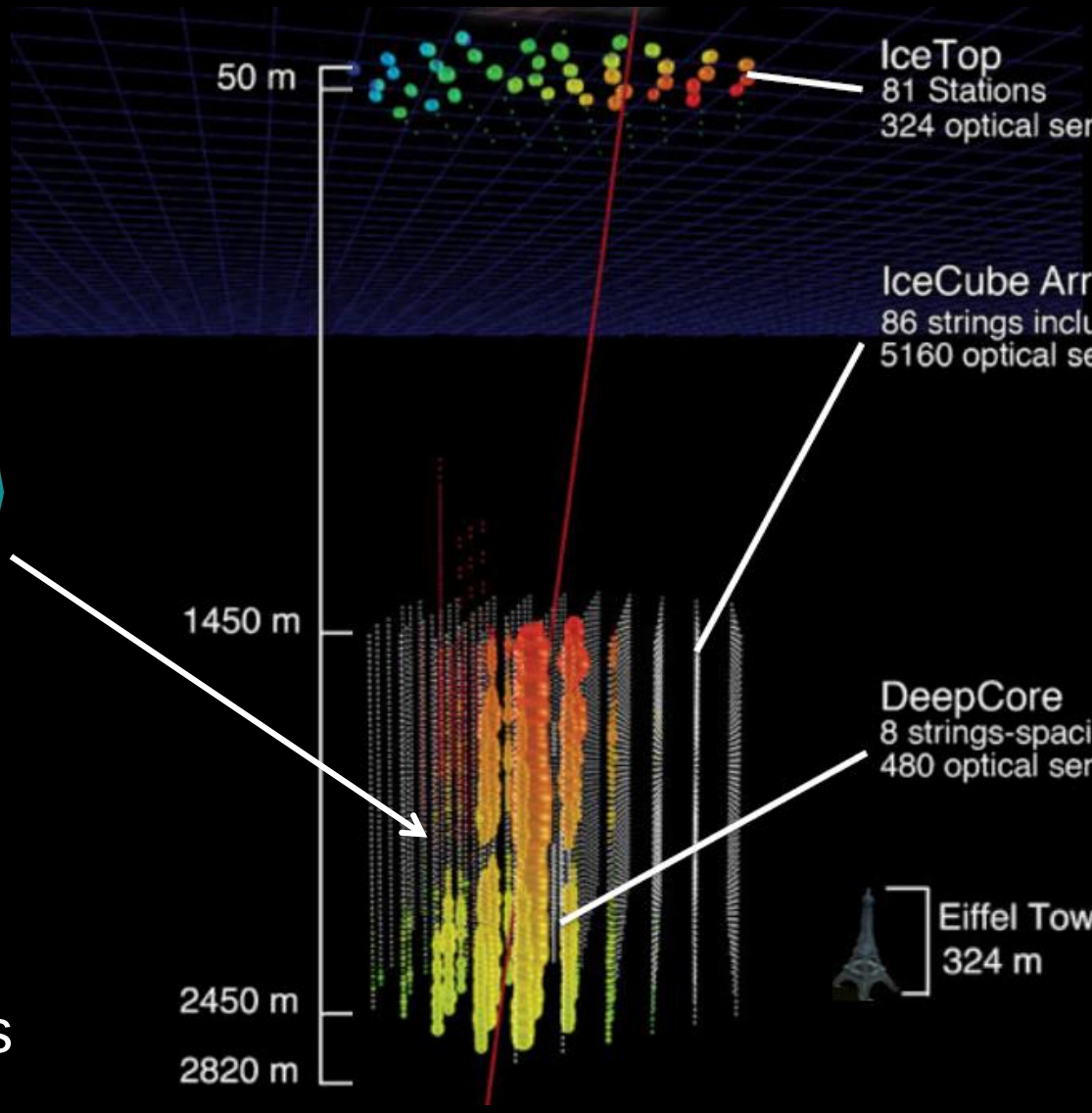
1976–1995


THE SUBATOMIC ADVENTURES OF
NEUTRINO MAN
SEARCHING FOR THE EDGE OF THE UNIVERSE!
HIS DARING SOUTH POLE EXPERIMENT!
DEFIES THE ODDS! CATCHES INVISIBLE PARTICLES FROM OUTER SPACE!


ultra-transparent ice below 1.5 km

IceCube

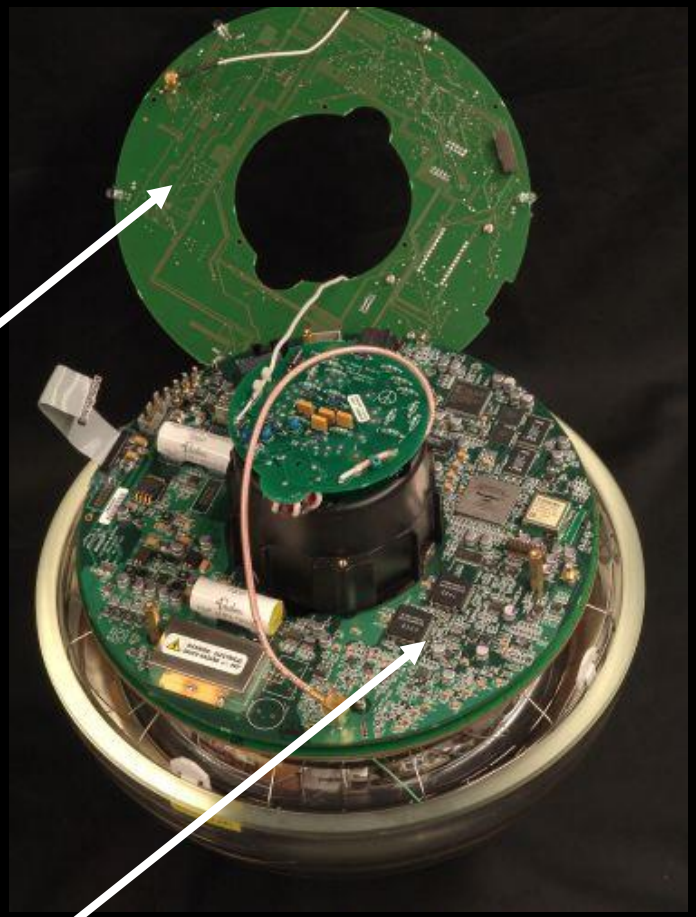


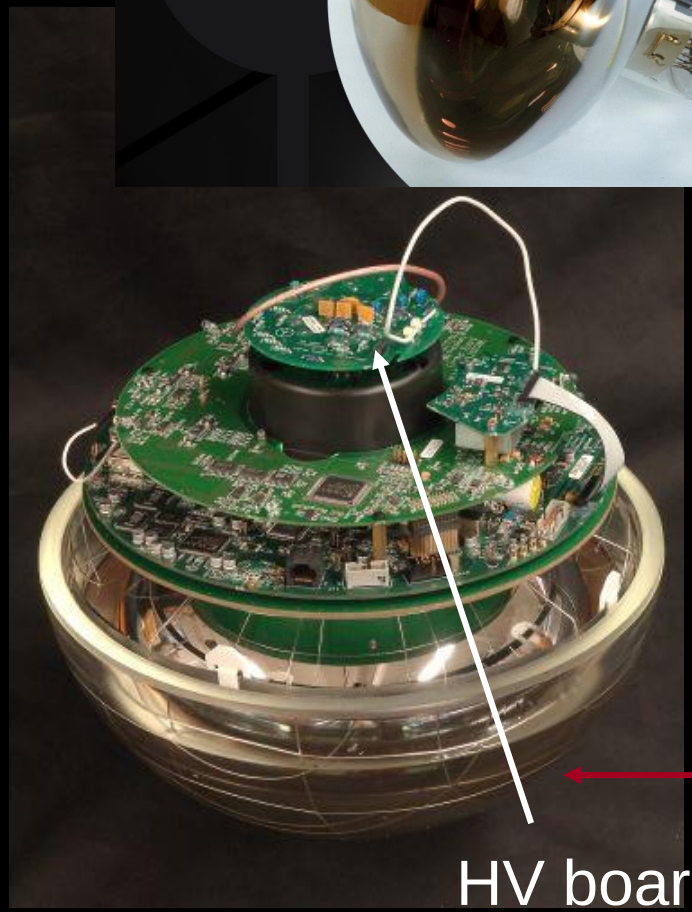


5160 PMs
in 1 km^3

Photomultiplier tube – 10 inch

architecture of independent DOMs



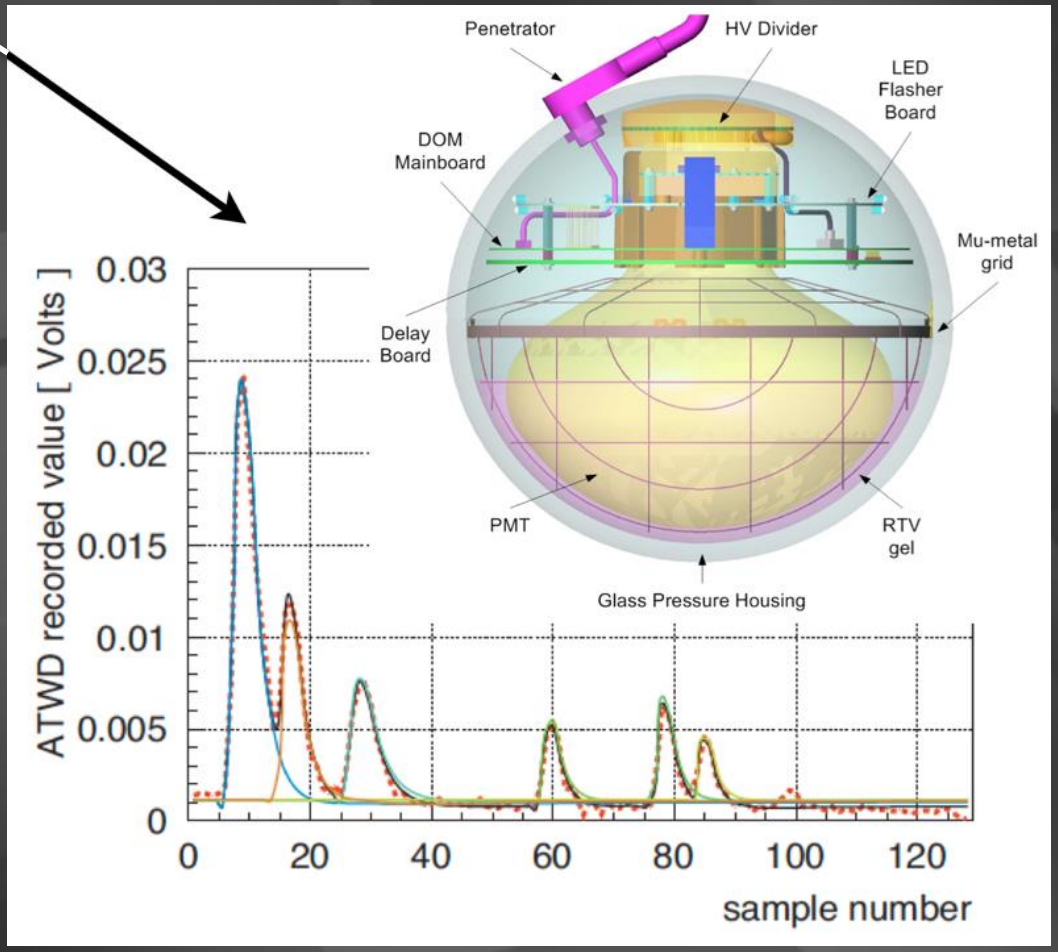


LED
flasher
board

main
board

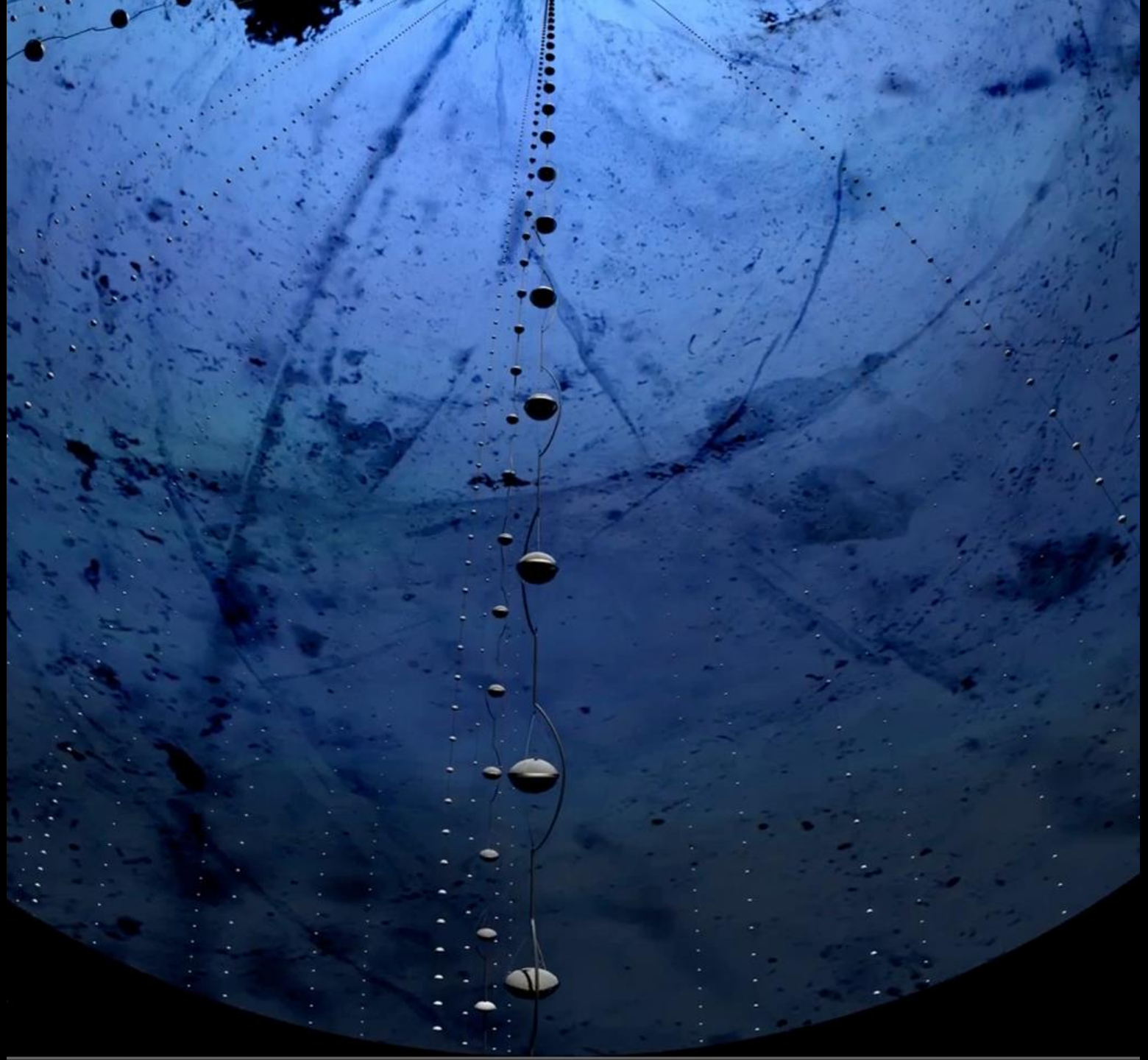
HV board

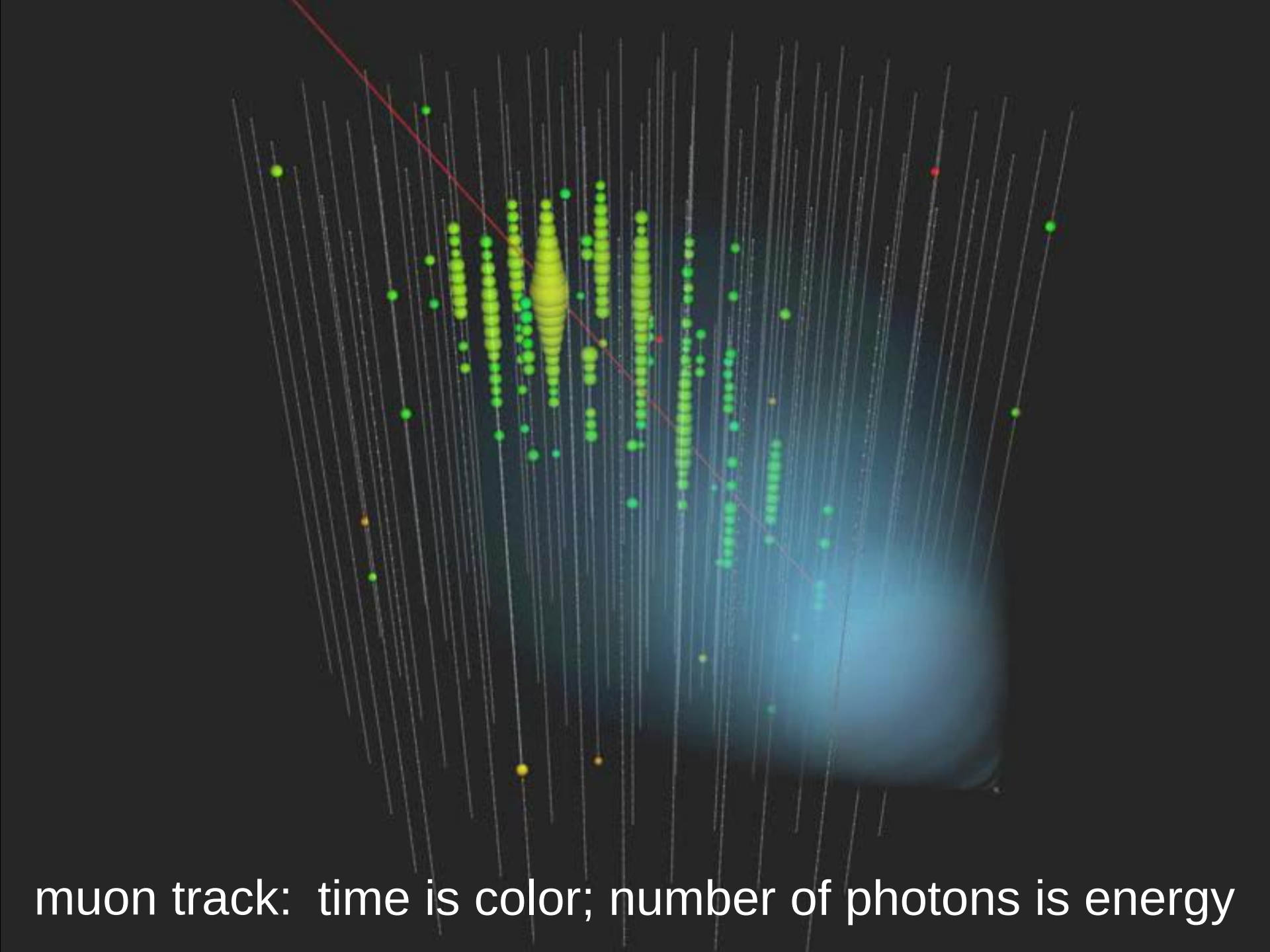
… each Digital Optical Module independently collects light signals like this, digitizes them,



…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…


nozzle delivers:
• 200 gallons per minute
• 7 Mpa
• 90 degree C
4.8 megawatt
heating plant →

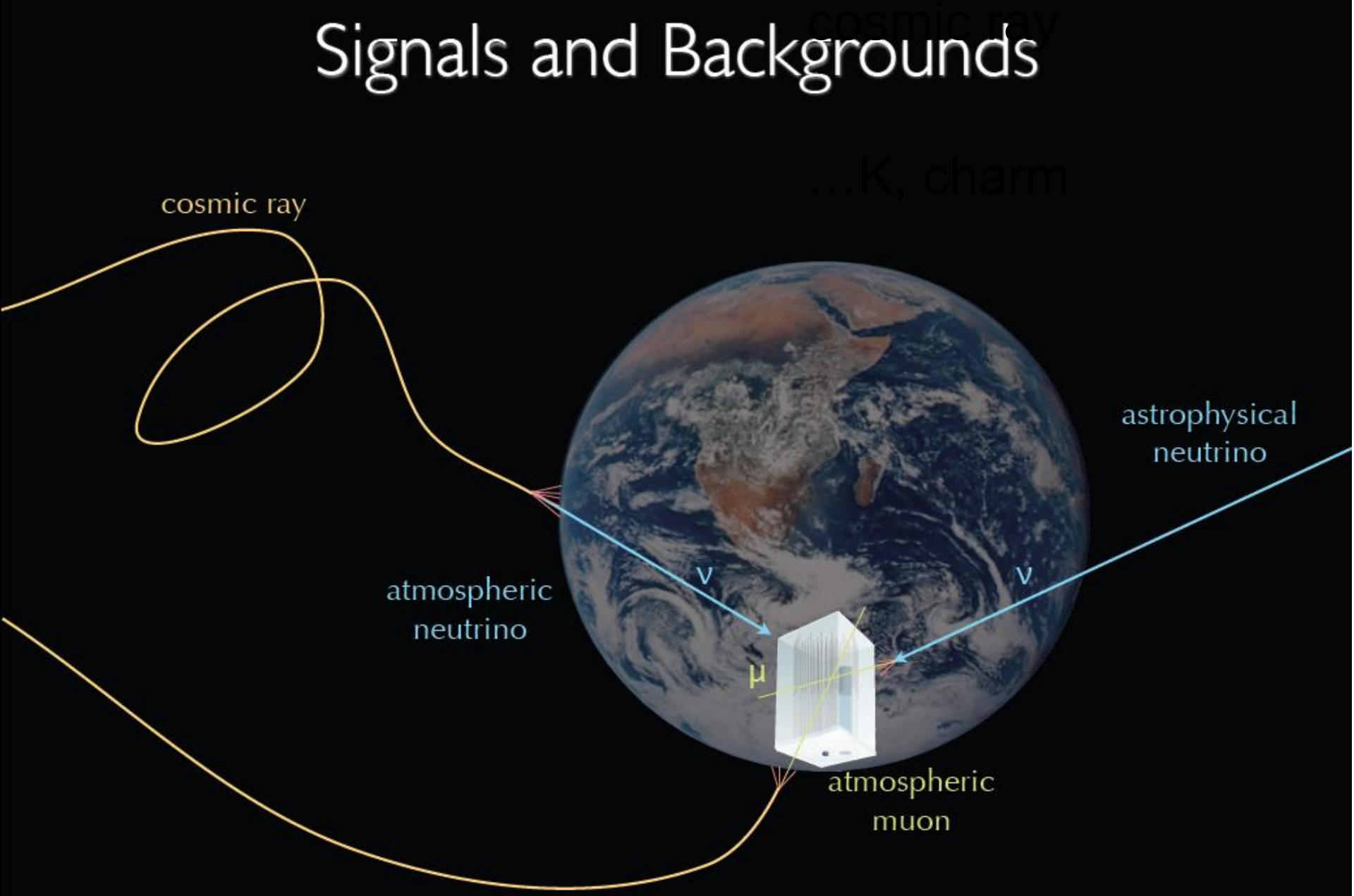


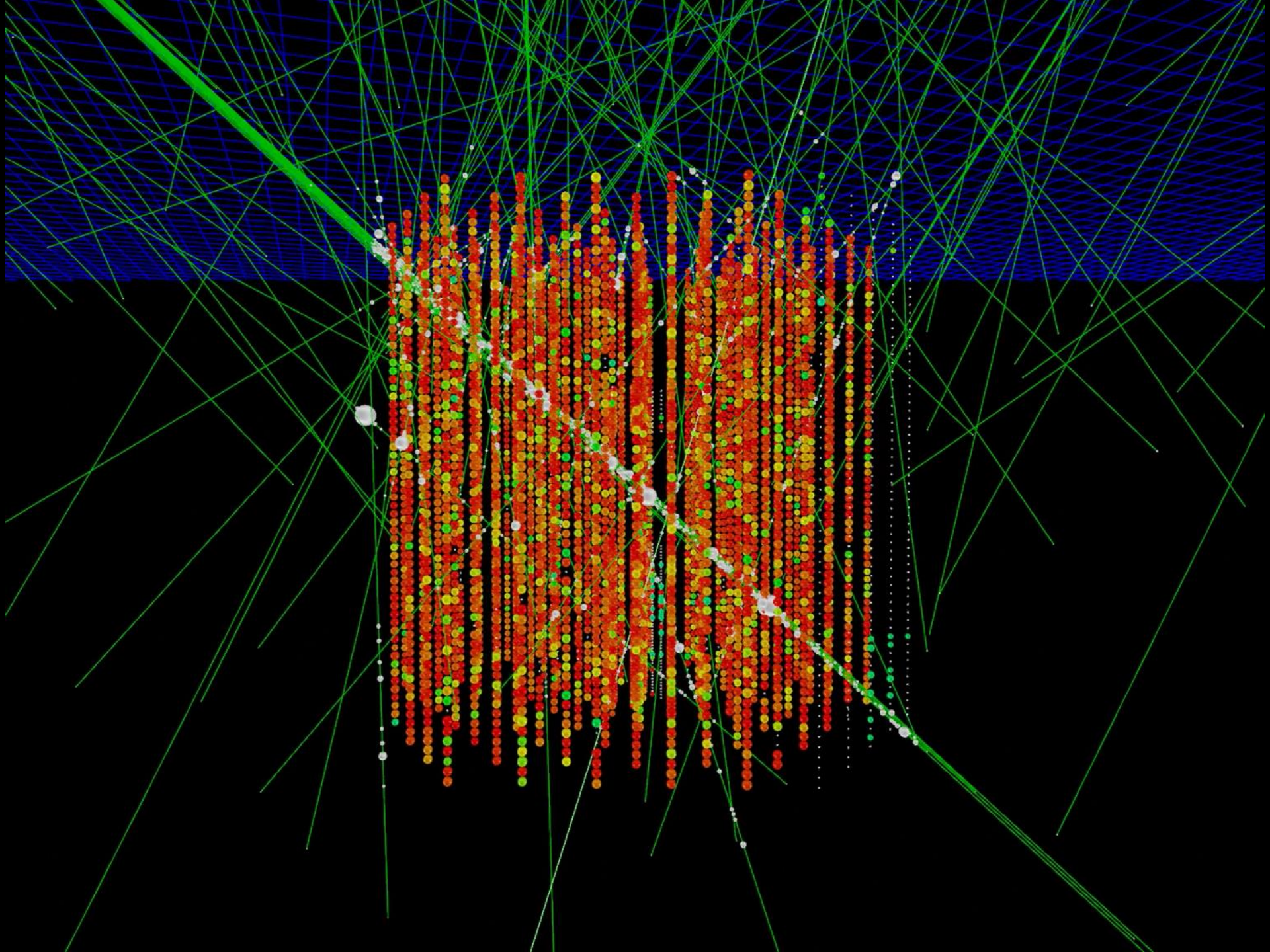


muon track: time is color; number of photons is energy

93 TeV muon: light ~ energy

Signals and Backgrounds



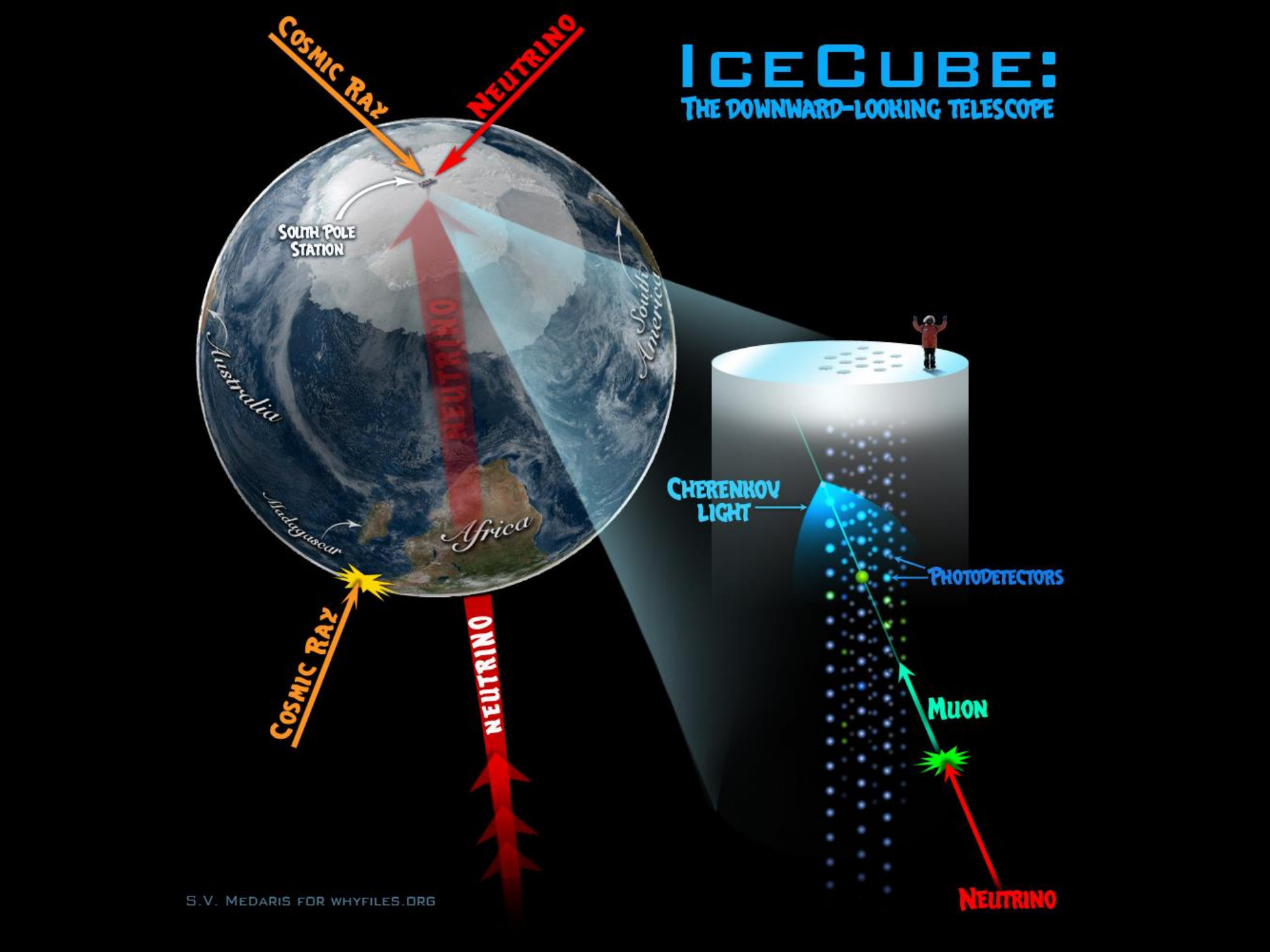


… you looked at 10msec of data !

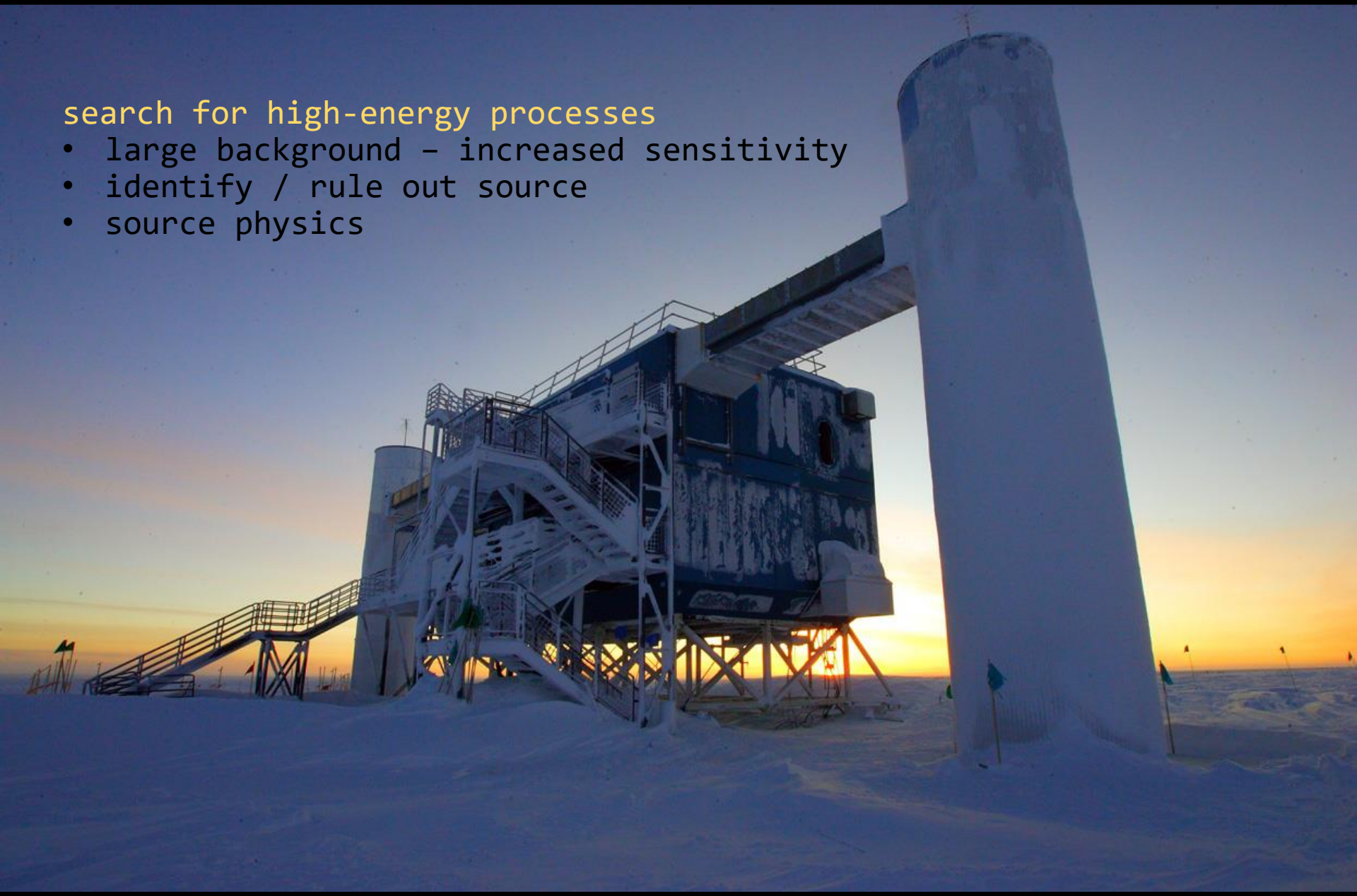
muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^{5}$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second ** 1 every 6 minutes


ICECUBE:
THE DOWNWARD-LOOKING TELESCOPE
COSMIC RAY
NEUTRINO
SOUTH POLE STATION
NEUTRINO
Australia
South America
Madagascar
Africa
COSMIC RAY
NEUTRINO
CHERENKOV LIGHT
PHOTODETECTORS
MUON
NEUTRINO
S.V. MEDARIS FOR WHYFILES.ORG

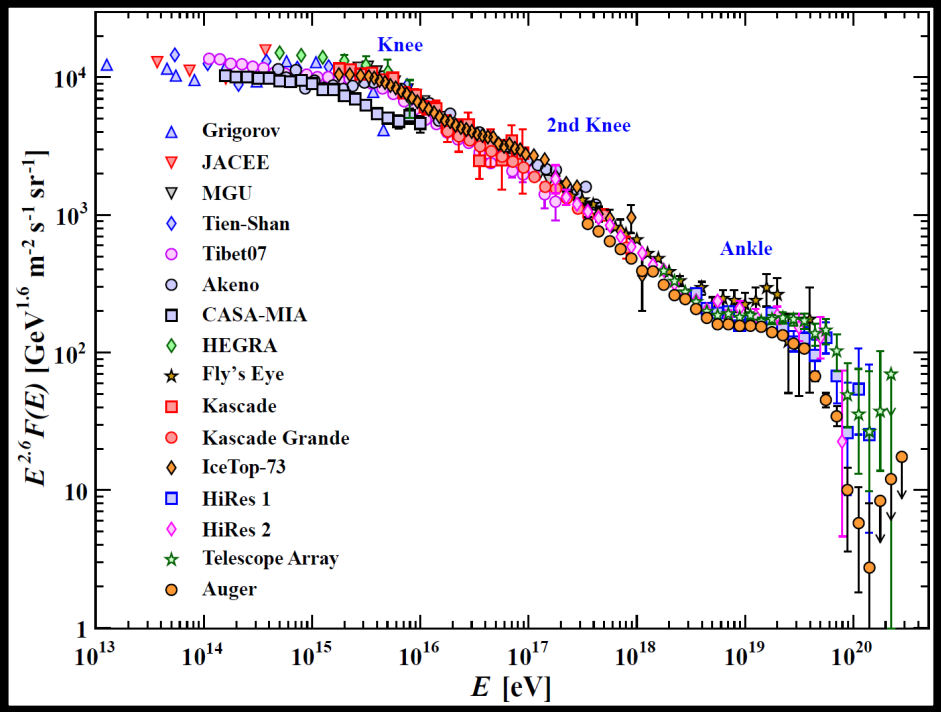
multimessenger astrophysics

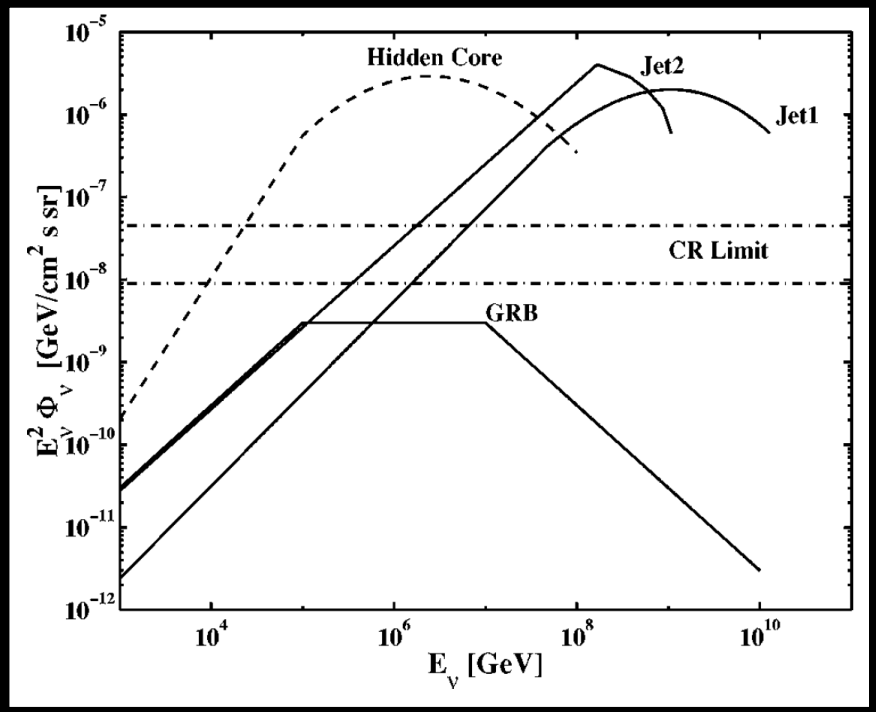


search for high-energy processes

- large background – increased sensitivity
- identify / rule out source
- source physics

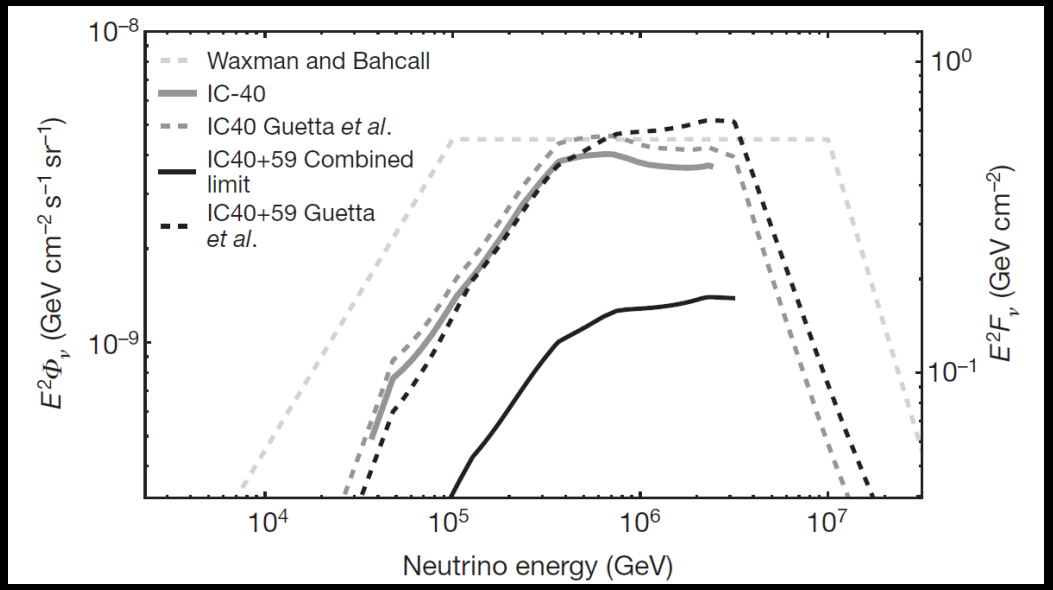
Waxman-Bahcall upper bound

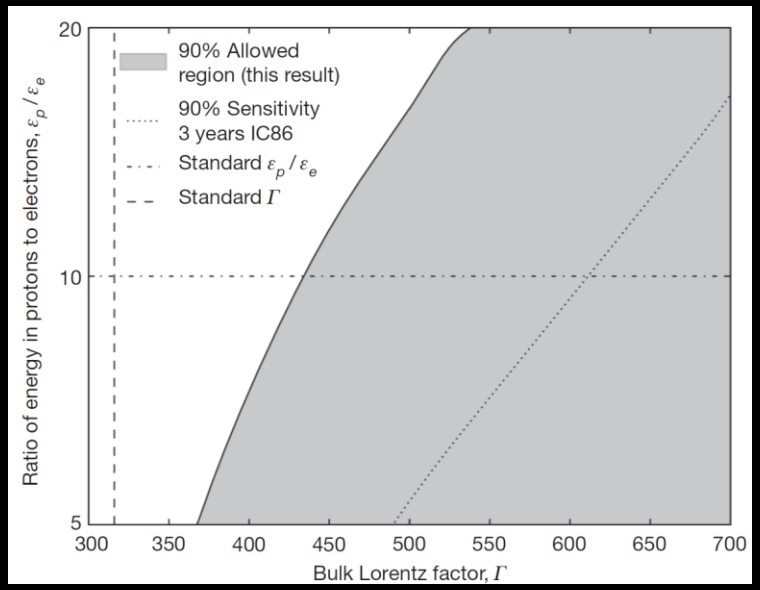




Waxman & Bahcall 1998

multimessenger – GRBs





IceCube Collaboration, Nature 2012

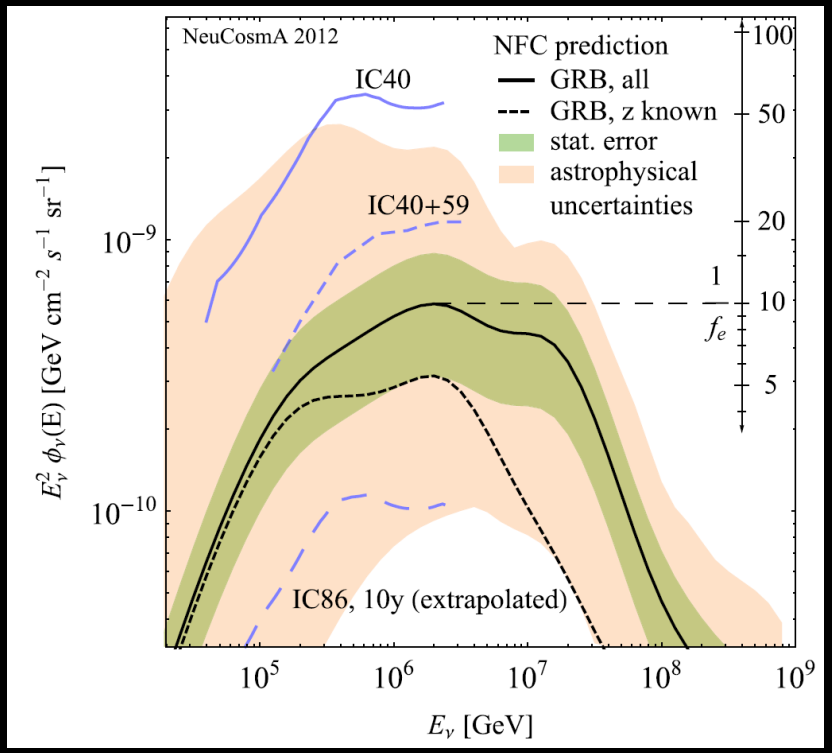
LETTER

doi:10.1038/nature11068

An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts

IceCube Collaboration*

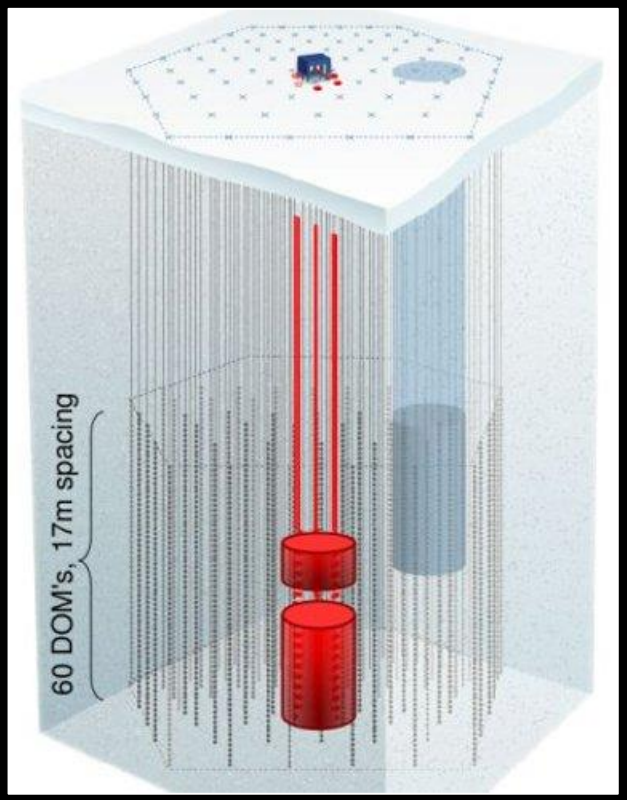
multimessenger – GRBs



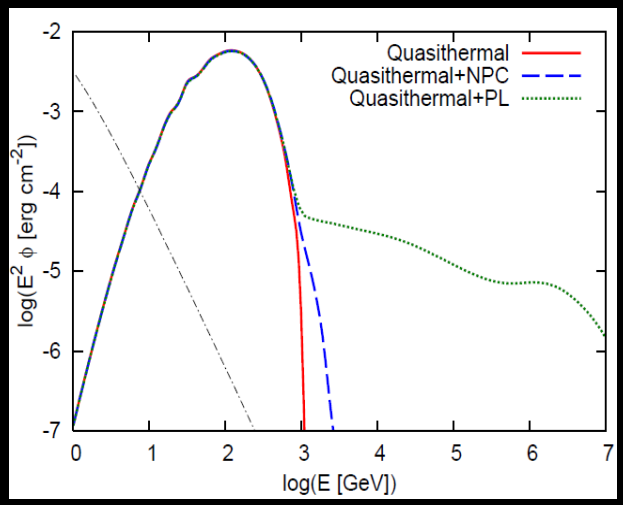
Hummer+ PRL 2012

Not yet sensitive.
Then again if it is collisionless shock emission.

GeV neutrinos from collisional heating promising for IceCube-DeepCore

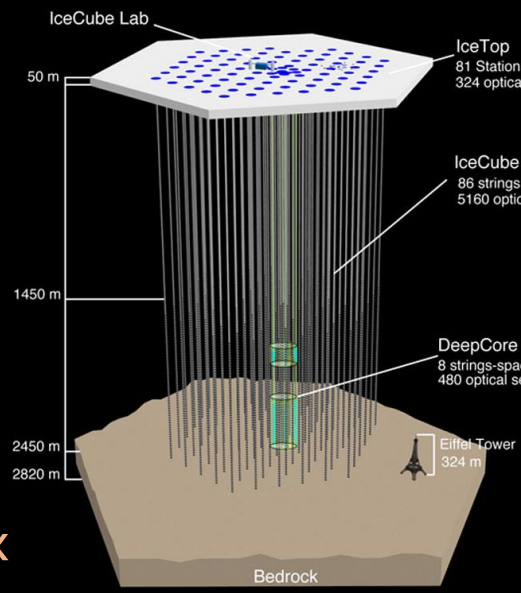


Bartos+ PRL 2013



Murase+ PRL 2013

summary



I. IceCube
- construction complete in 2010
- km^3 detector
- sensitive to Waxman-Bahcall flux

II. Observations
- no significant neutrino point source

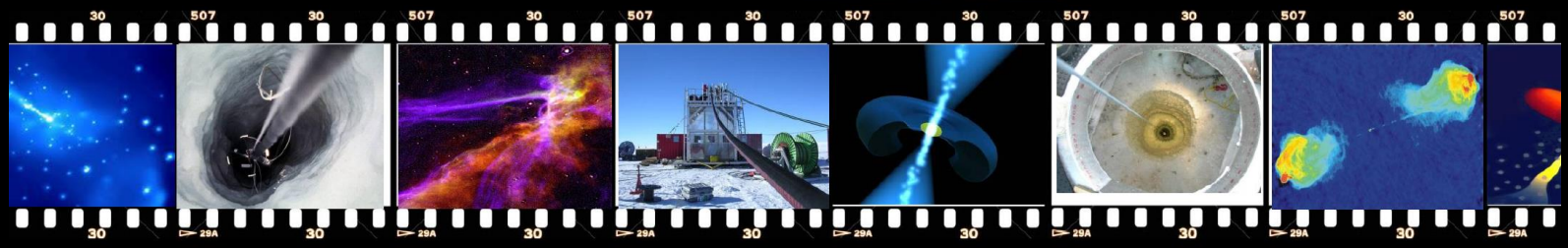
III. Multimessenger searches
- no coincidence with GRBs
- constrain GRB parameters
- GeV neutrino search with DeepCore promising
- no significant coincidence with AGN/blazars
- no significant coincidence with supernova remnants

IceCube: Ultra-high Energy Neutrinos

Aya Ishihara

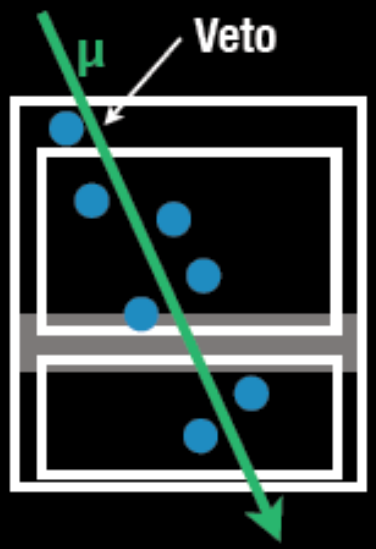
JSPS Research Fellow at **Chiba University**

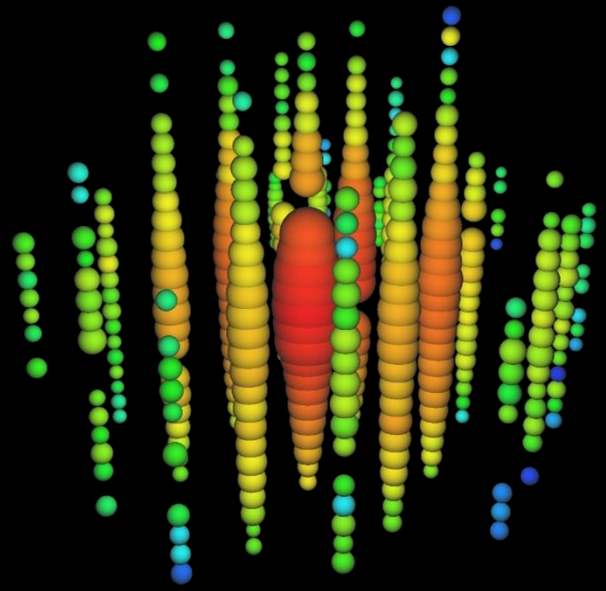
for the **IceCube** collaboration

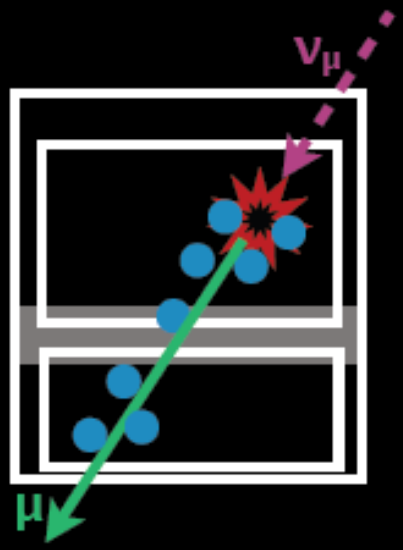


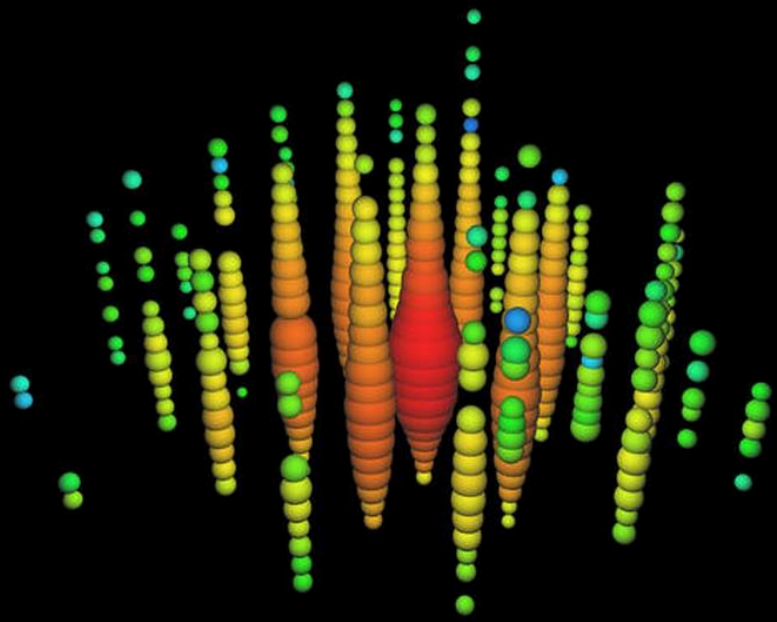
Neutrino2012 at Kyoto June 8th 2012

PeV neutrinos





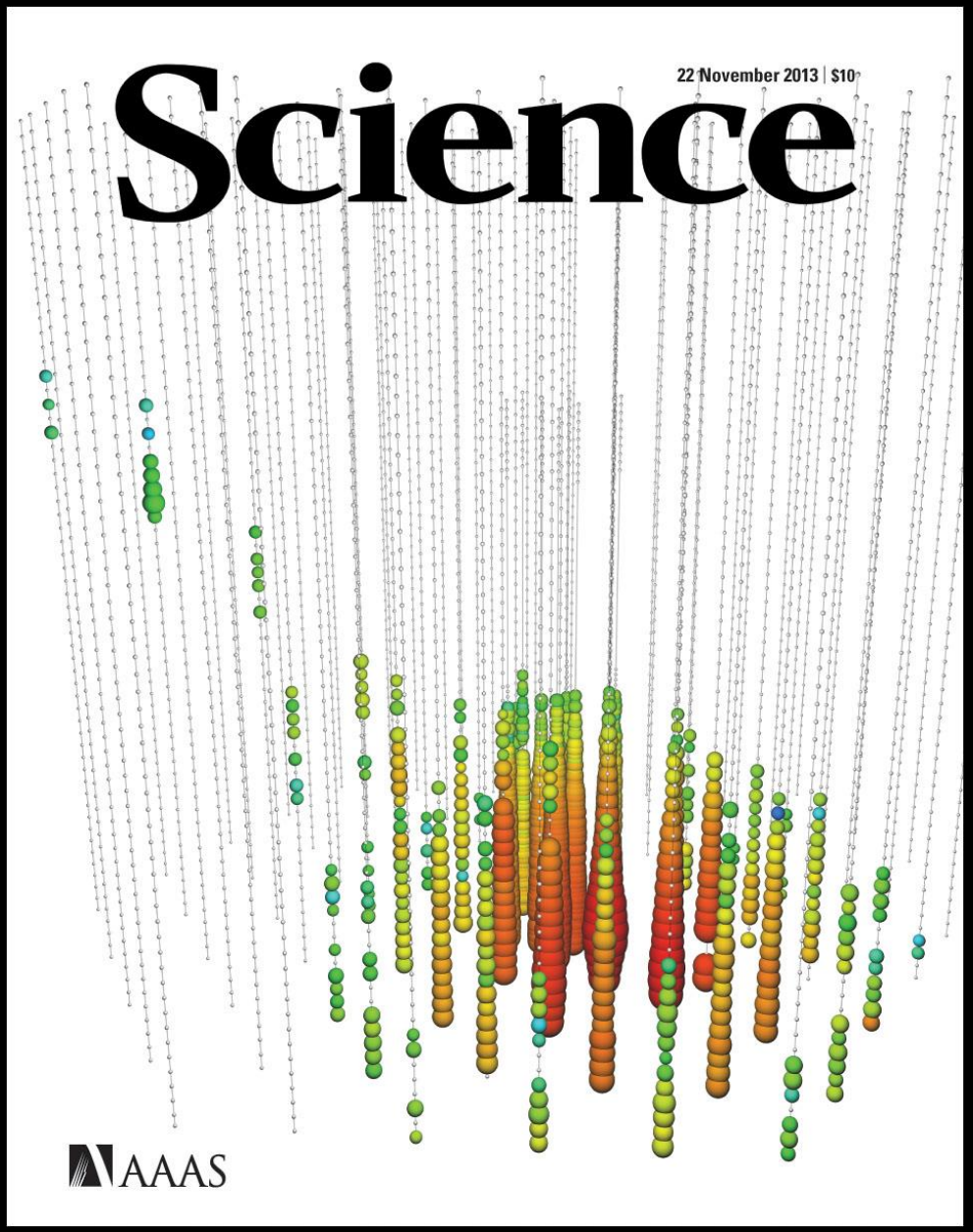




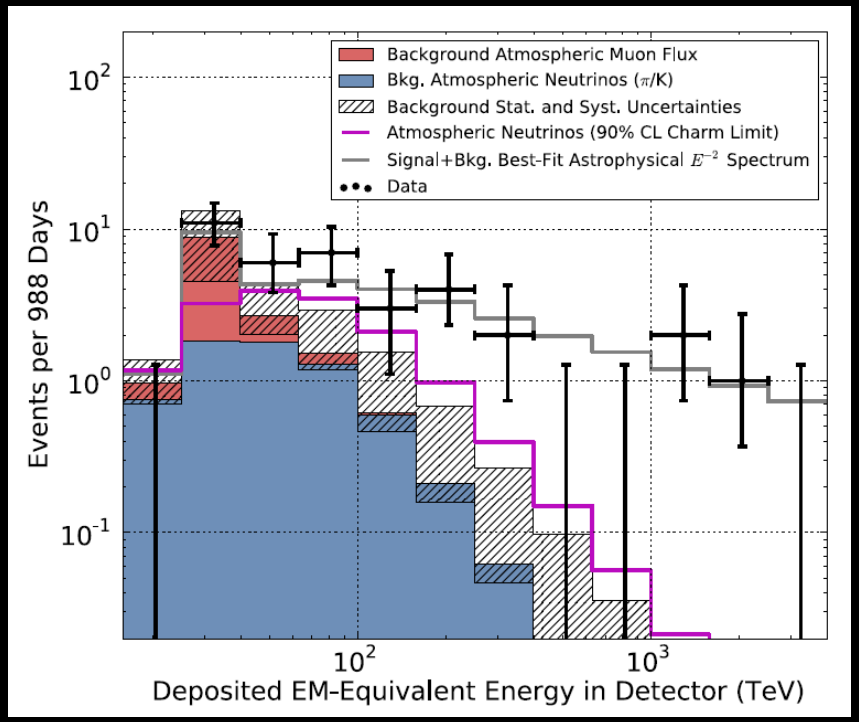
2 events, 1.0 and 1.1 PeV

PeV neutrinos

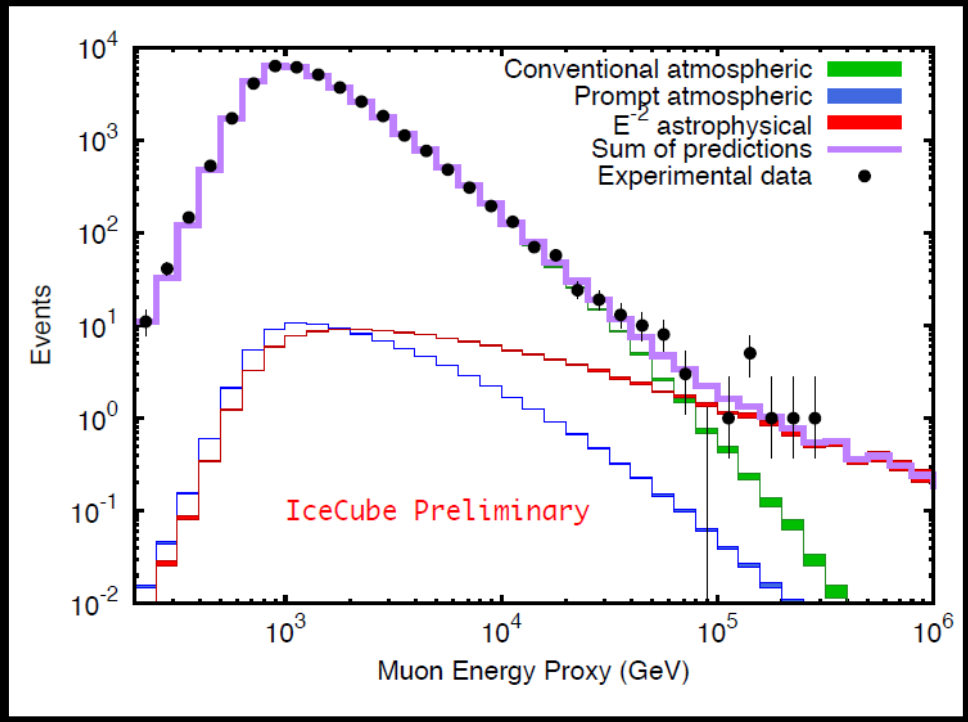
Nov 2013
Science front page



high-energy neutrino flux



neutrinos of all flavors interacting inside IceCube

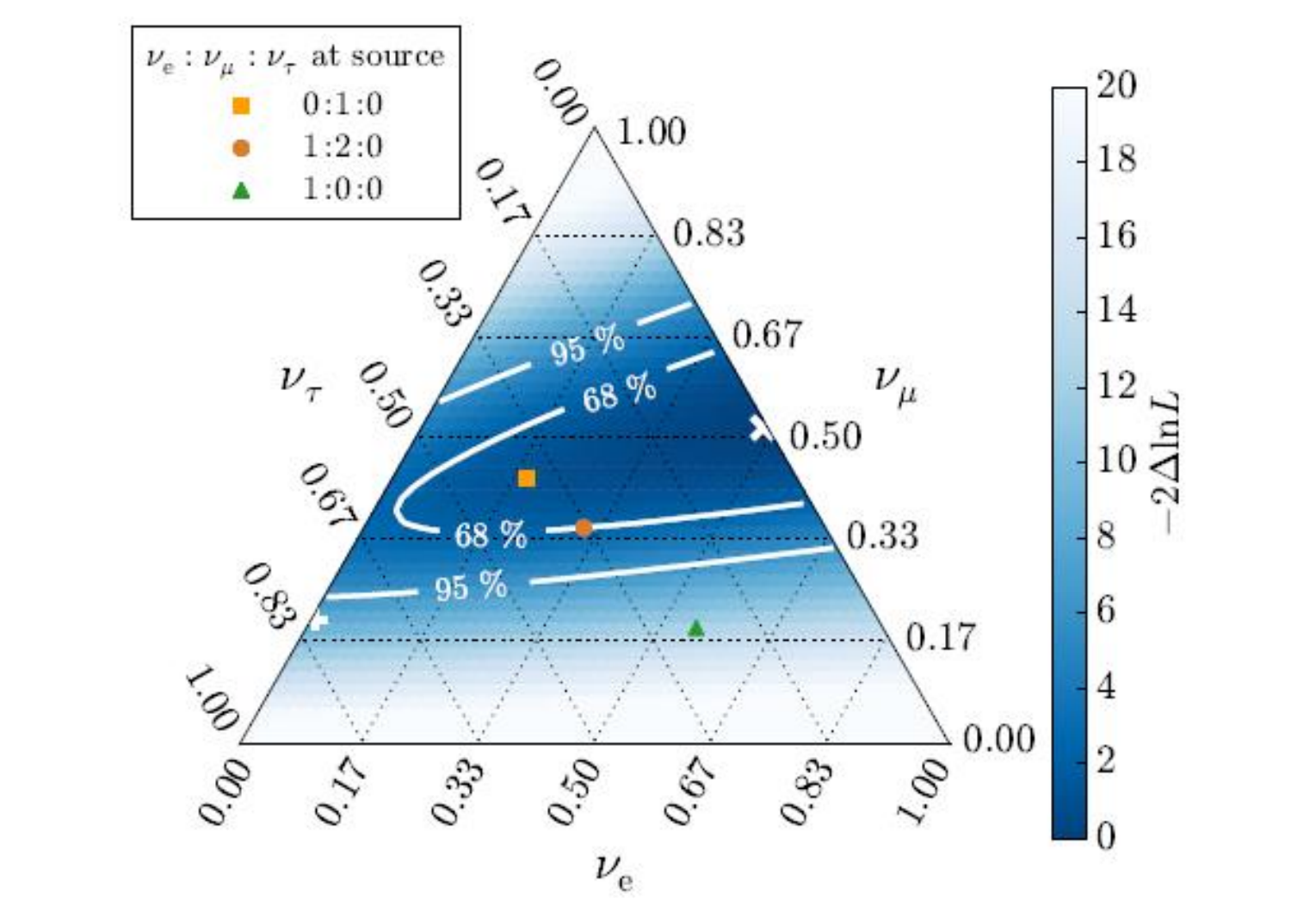


confirmation! Flux of muon neutrinos through the Earth

total: ~ 100 astrophysical neutrinos

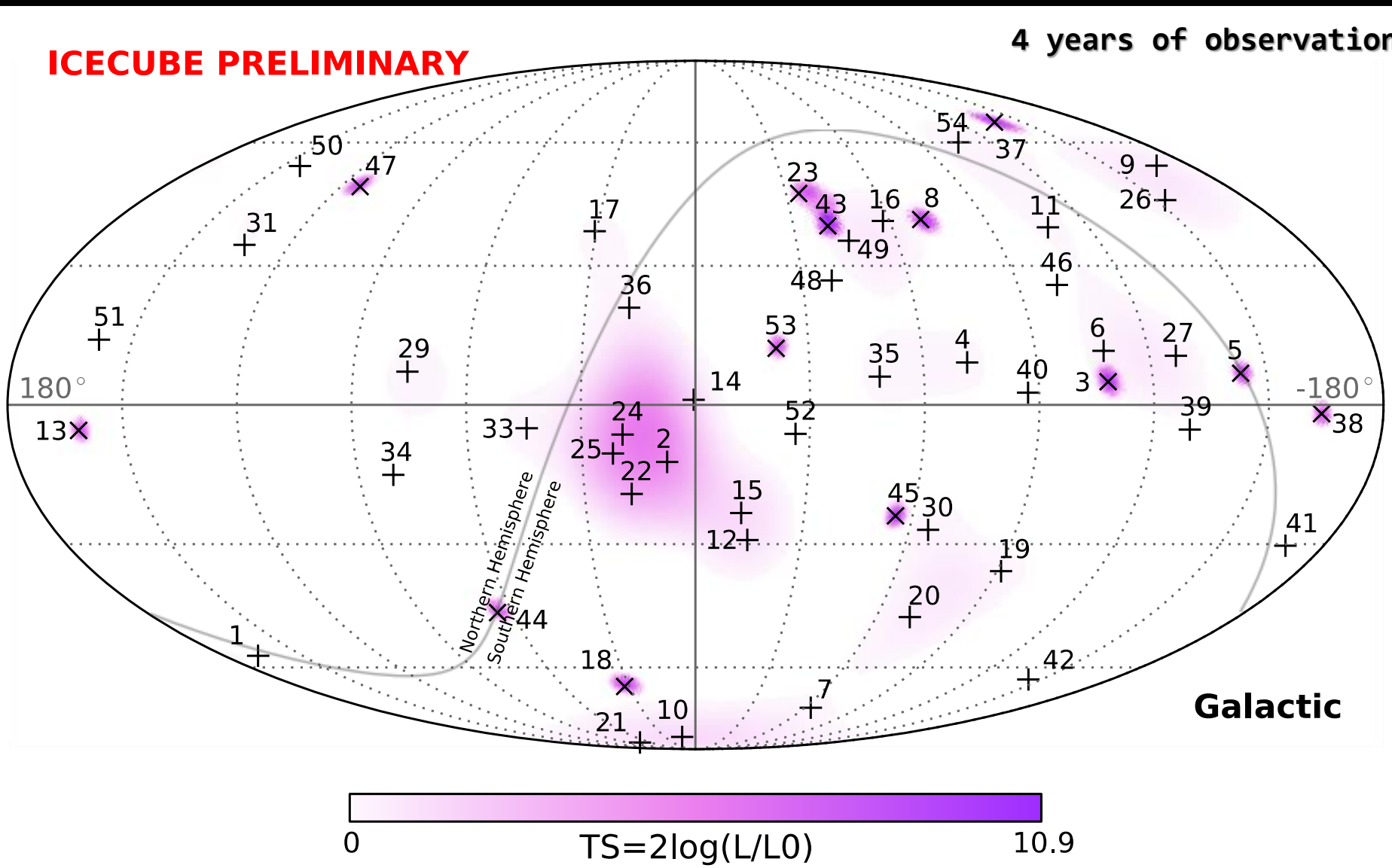
IceCube Collaboration 2014

flavor

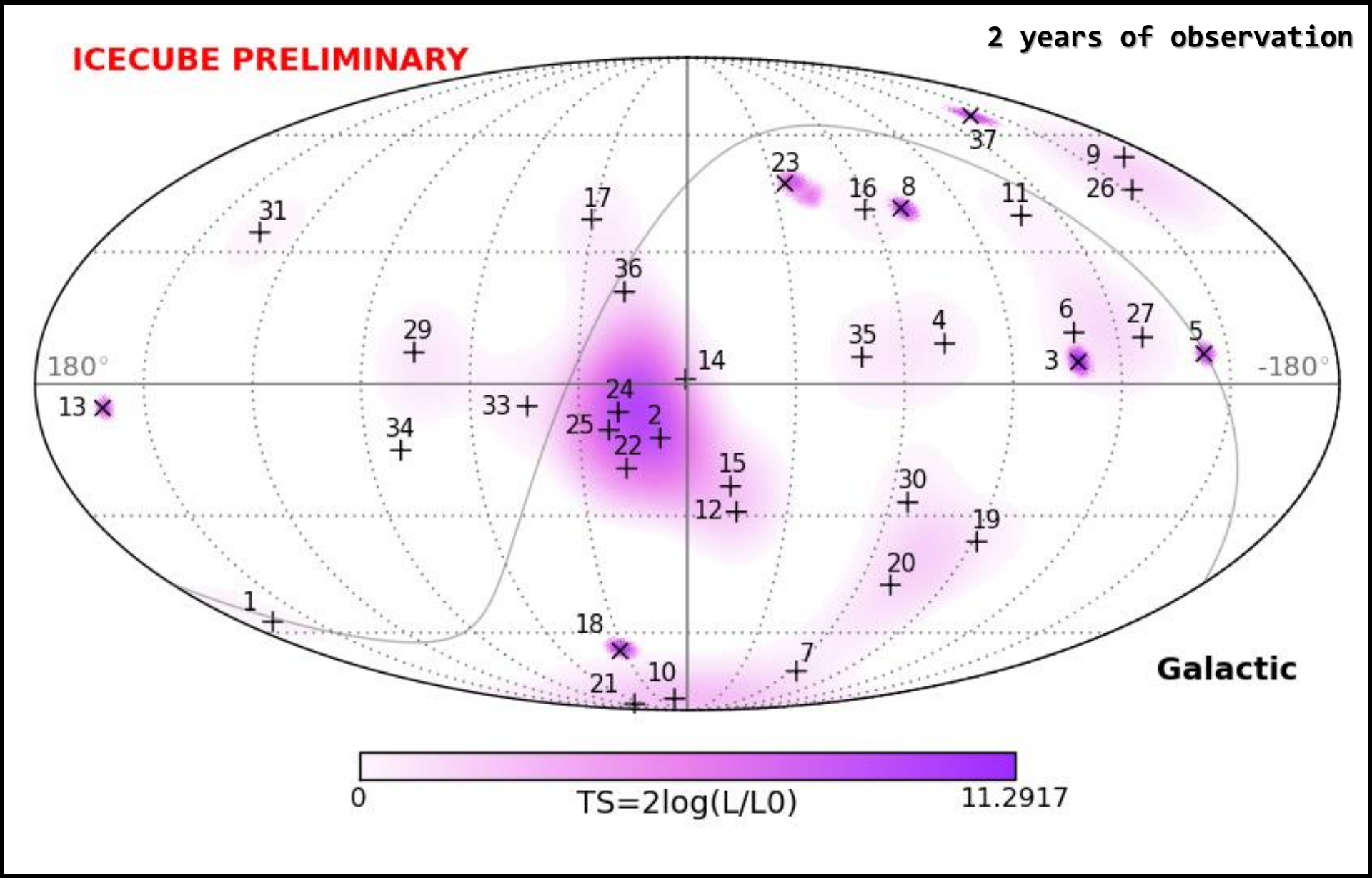


oscillate over cosmic distances to 1:1:1

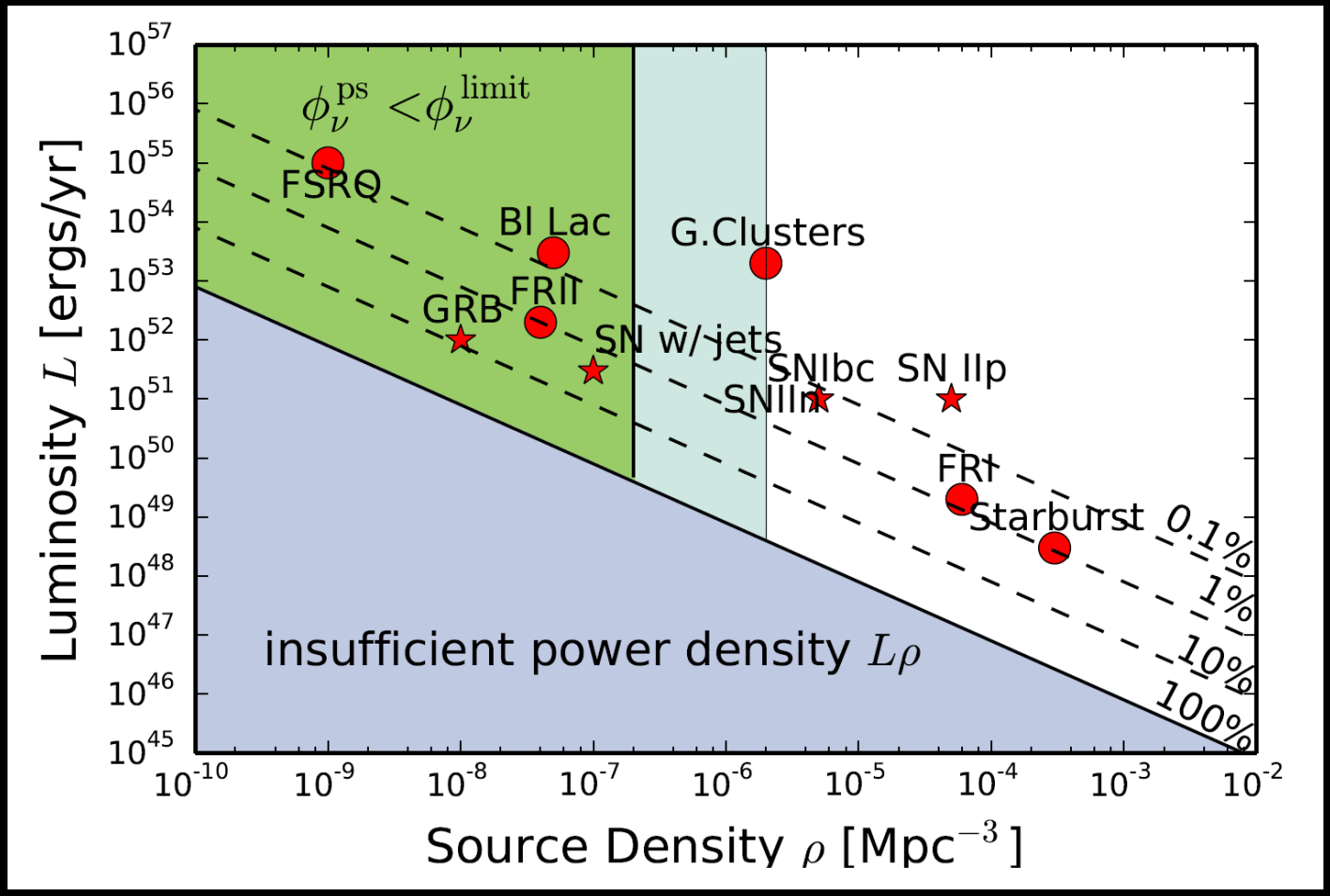
where do they come from?



where do they come from?

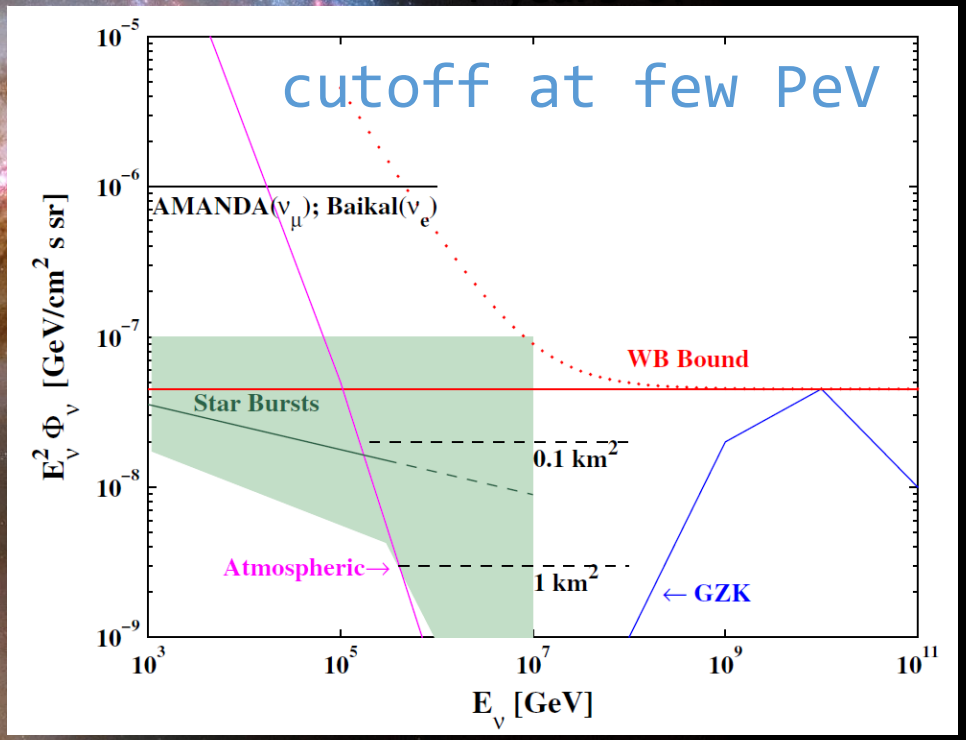


where do they come from?



many of the major source candidates can be excluded as dominant sources using just neutrinos!

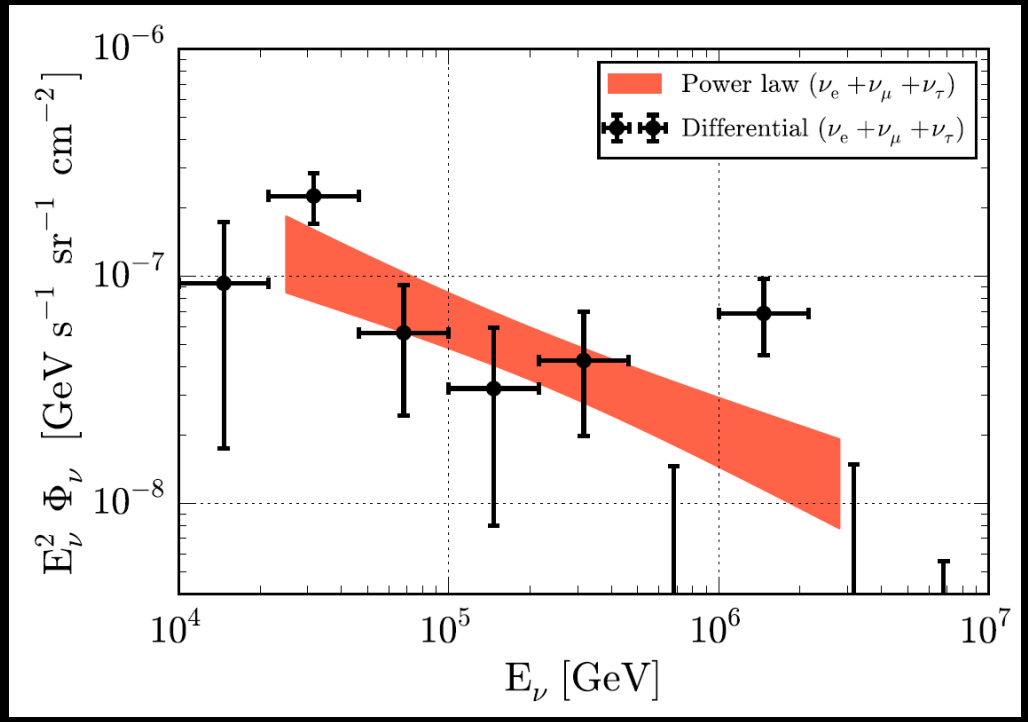
starburst galaxies?



Loeb & Waxman 2006

cosmic ray calorimeters.
high-star formation → cosmic ray injection
strong magnetic fields → traps cosmic rays longer
dense ISM → CRs interact.

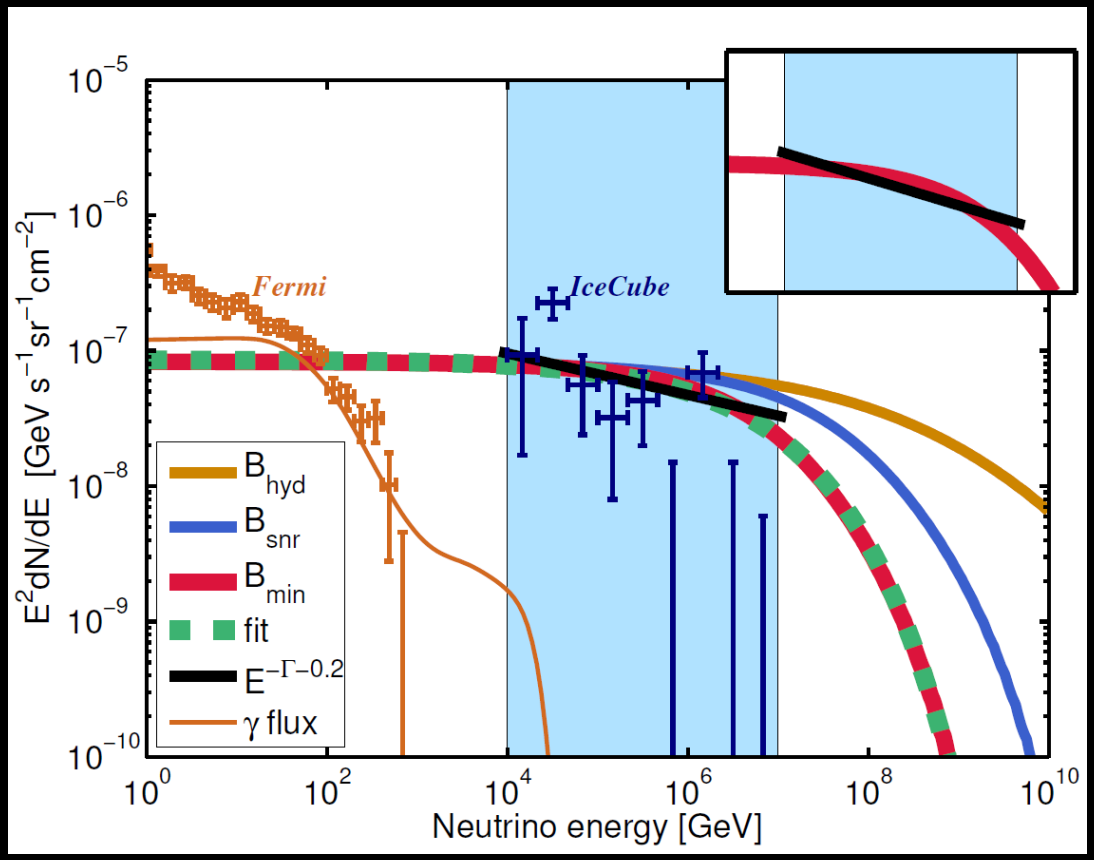
spectral information



consistent with
$E^{-2.5}$ power law spectrum
OR
E^{-2} with cutoff at few PeV

IceCube Collaboration 2015

spectral information



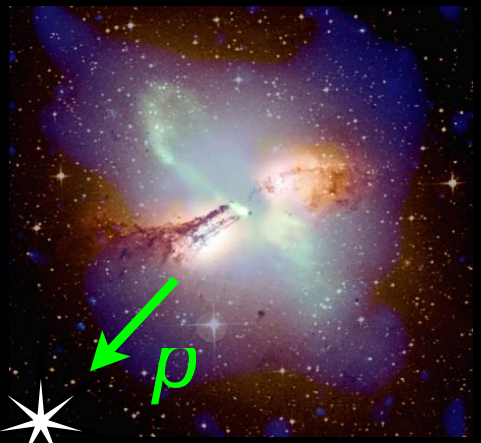
Not all starburst galaxies created equal
→ cutoff distribution
→ steeper-than-power-law spectrum

Bartos & Marka 2015

gamma rays

hadronic gamma rays?

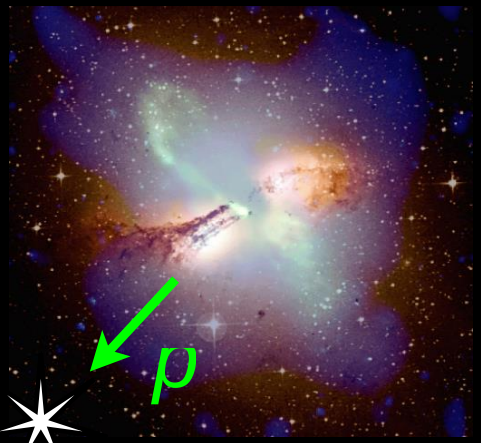
$\pi^+ = \pi^- = \pi^0$



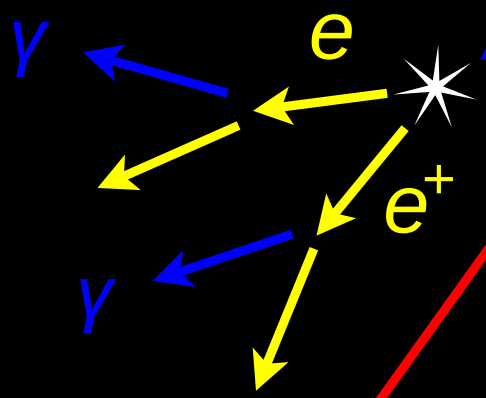
γ

hadronic gamma rays

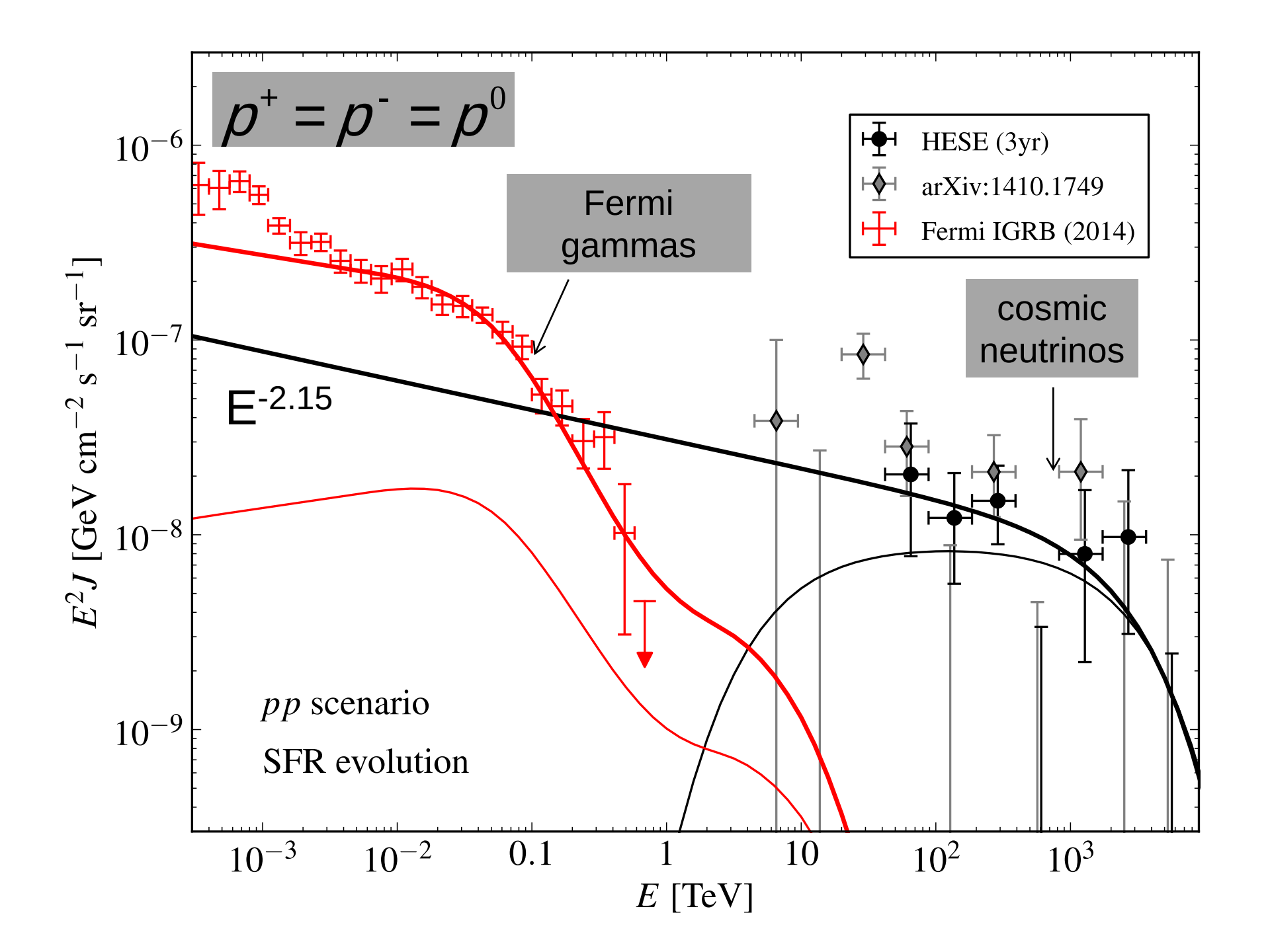
gamma rays



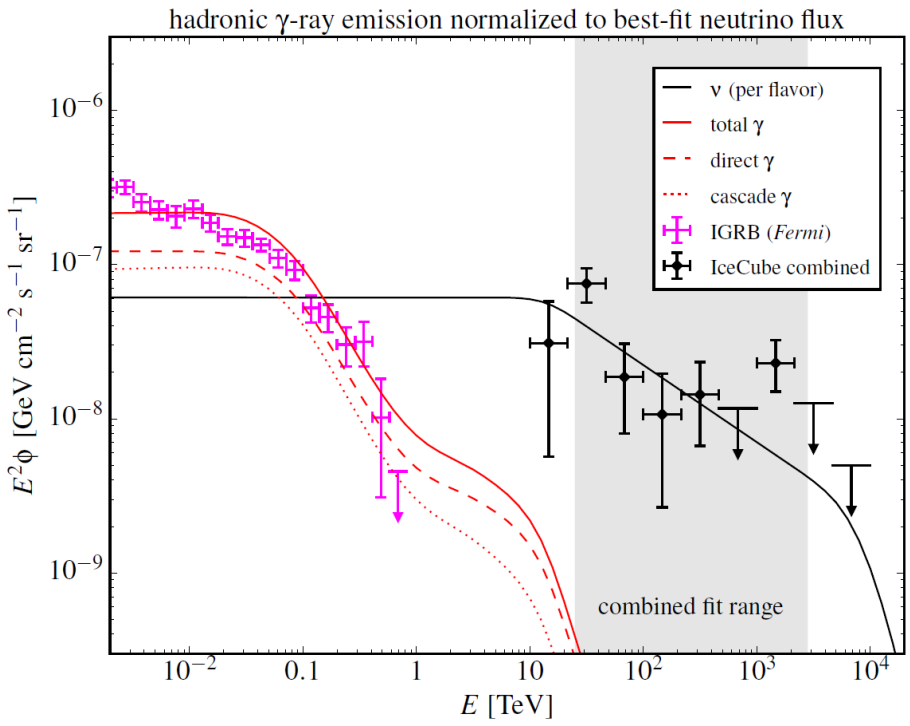
electromagnetic
cascades in CMB

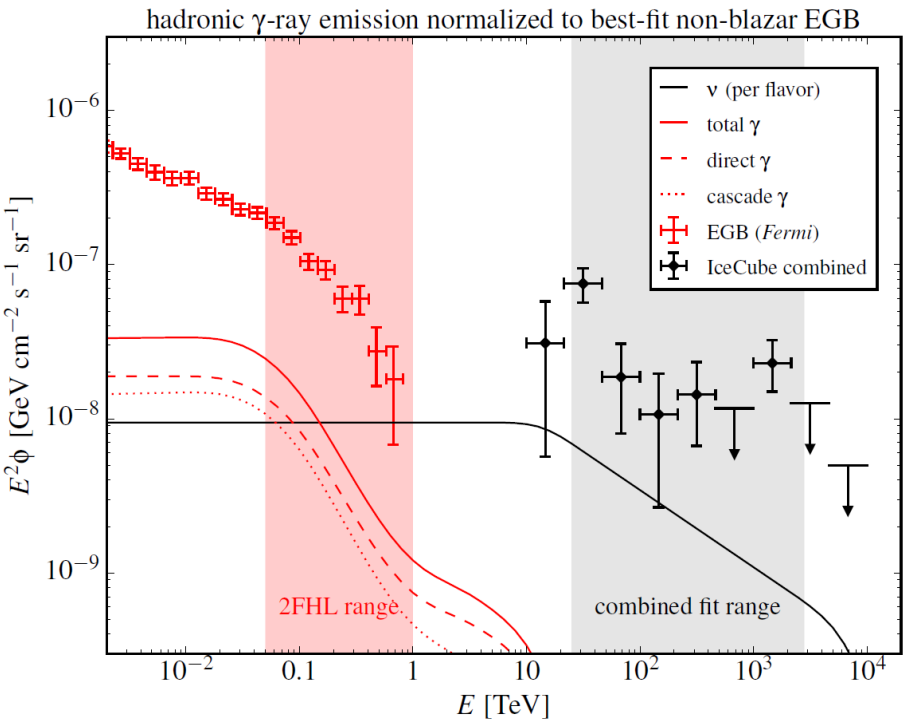


hadronic
gamma rays


$p^+ = p^- = p^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

gamma-ray + neutrinos





Bechtol+ 2015

non-blazar diffuse gamma-ray flux
limited by Fermi-LAT to ~15%

summary

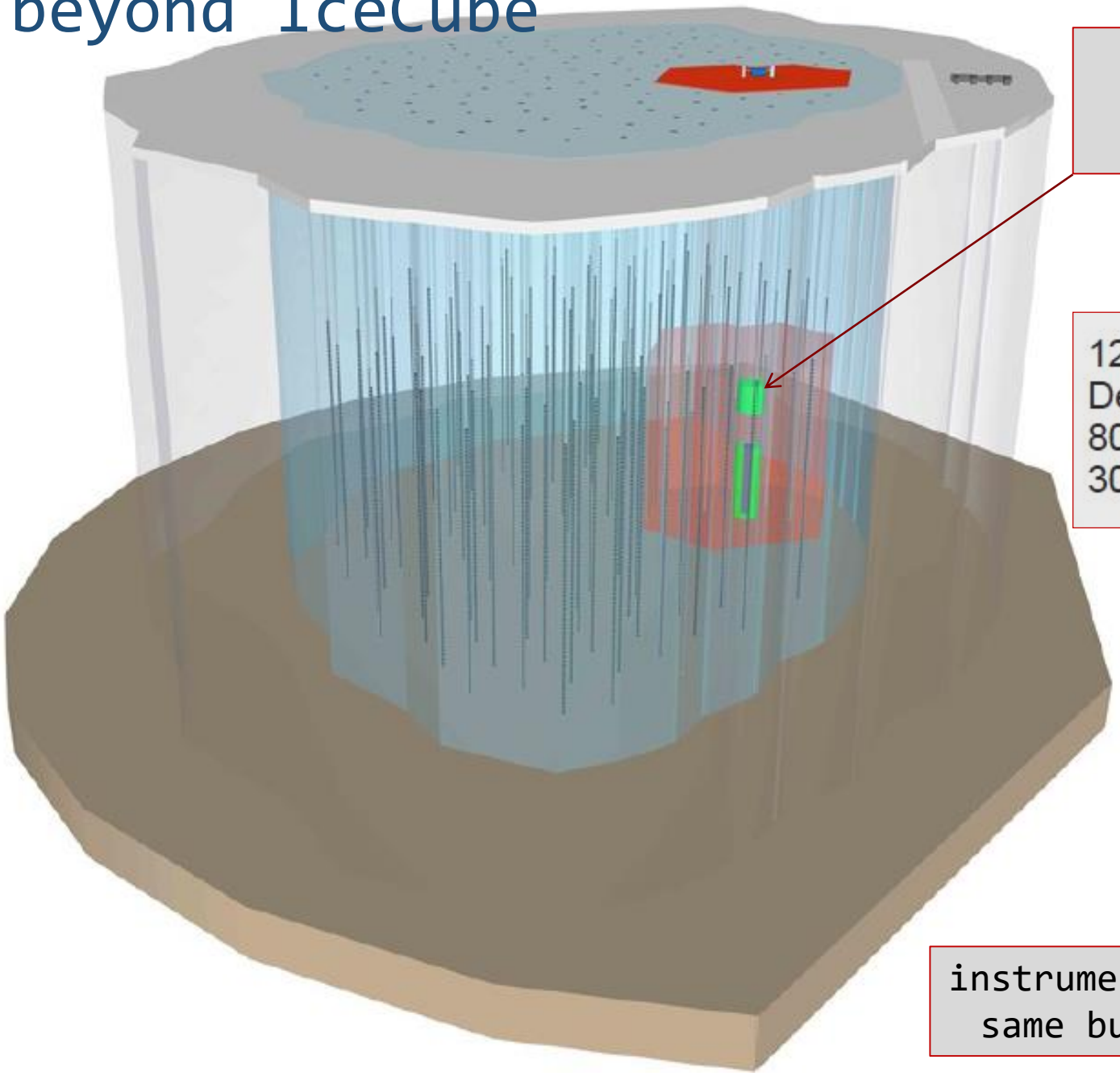
I. Astrophysical neutrino flux discovered
   - flavor ratio consistent with astro. origin

II. No source association so far
   - no spatial/temporal coincidence anything!
   - GRB/AGN (rare) sources excluded!

III. Starburst origin?
   - spectral ‘cutoff’ at few PeV
   - common source – difficult to find coincidence
   - parameter distribution

IV. Quasi diffuse gamma-rays
   - flux matches neutrino flux
   - dominated by blazars → ???

beyond IceCube



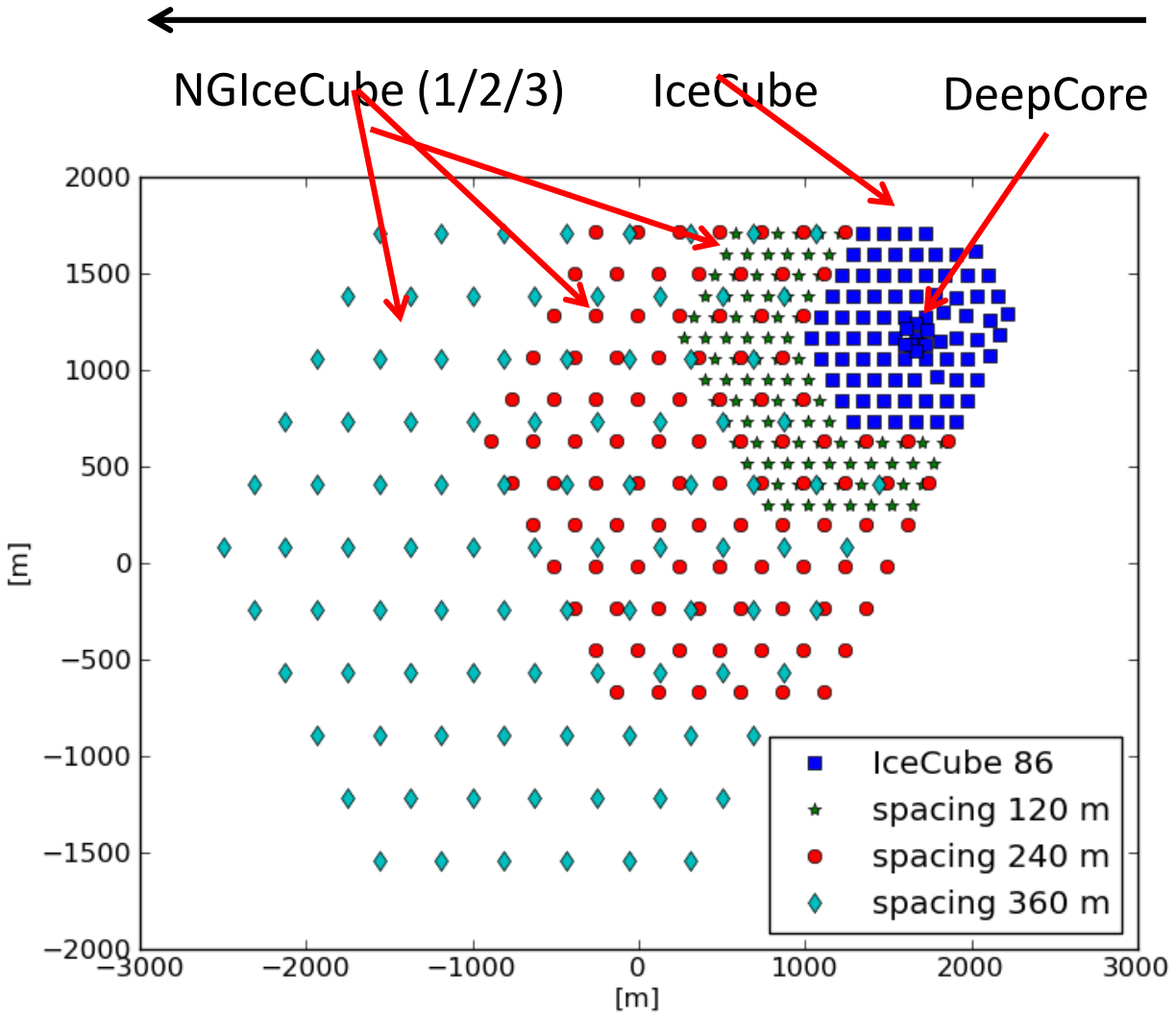
PINGU infill
40 strings
GeV threshold

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 10
same budget as IceCube

measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3


ANTARES → KM3NeT

did not talk about…

- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- …

IceCube

a new window onto the high-energy universe is just opening