新学術領域研究「ニュートリノフロンティア」研究会 2014　公募研究

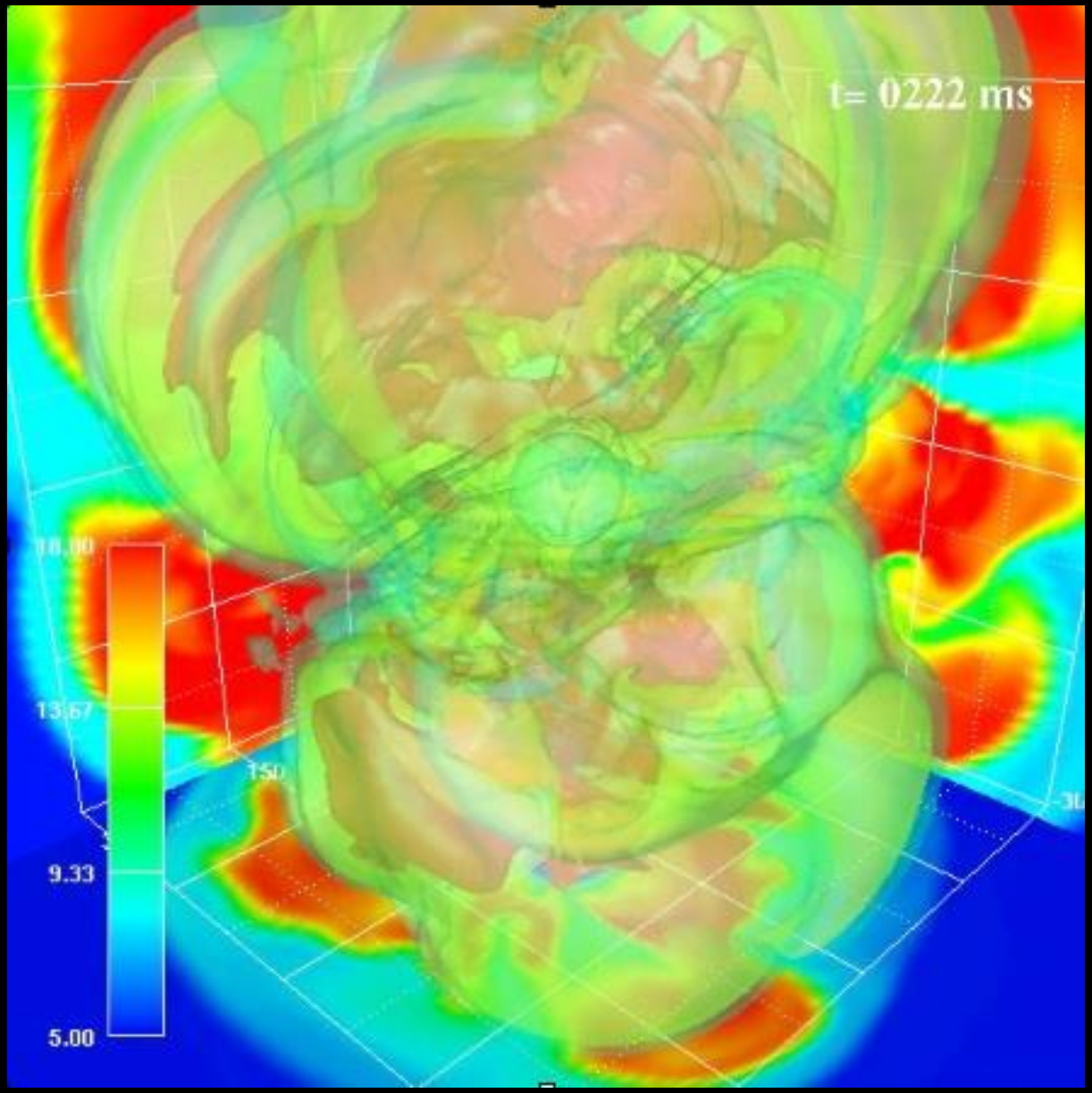
“Theoretical Study for Unveiling the Origins of VHE-Neutrinos in the Near Future ”

Astrophysical Big Bang Laboratory

Shigehiro Nagataki

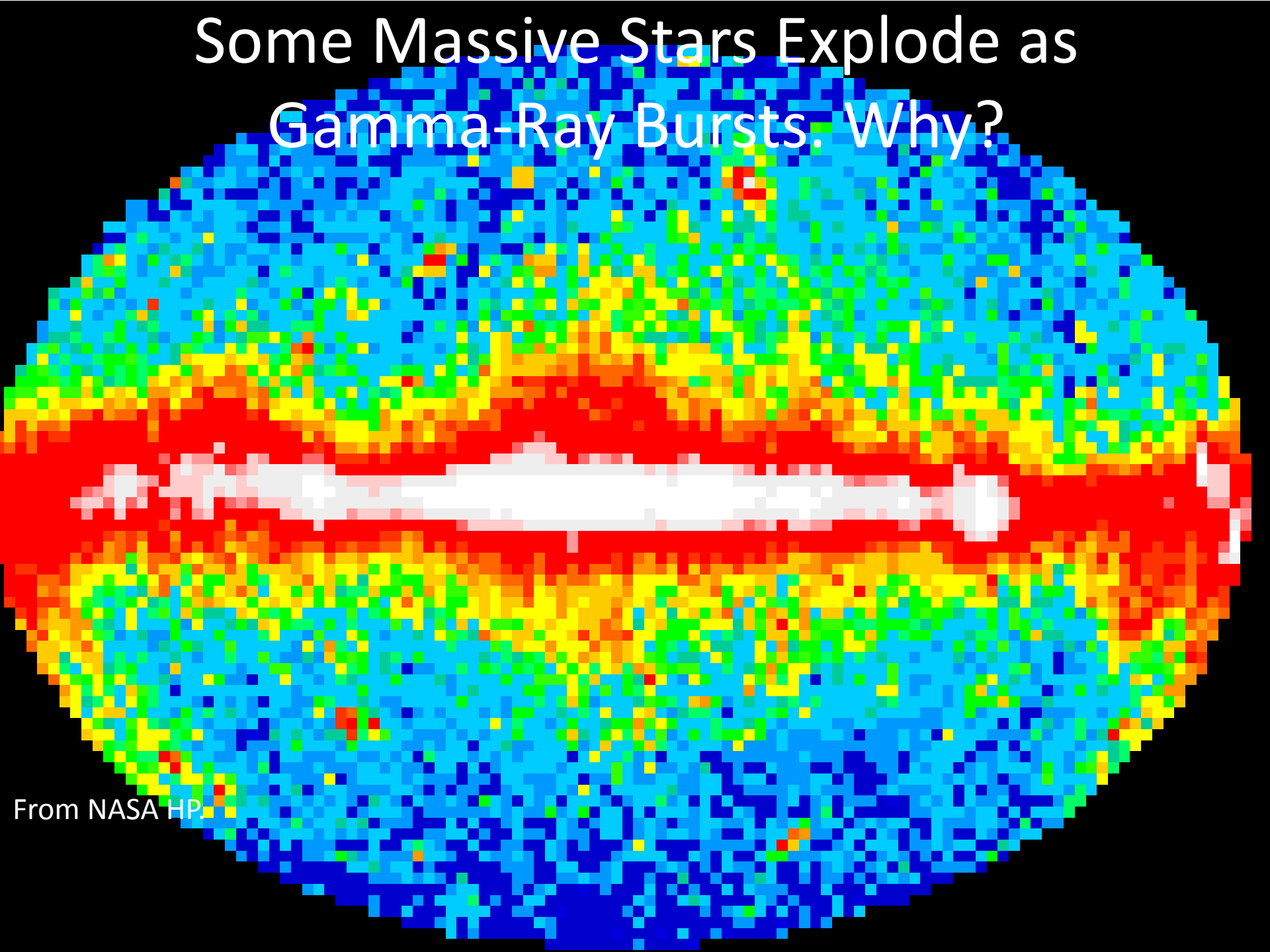
2014年12月21日(日)—23日(火) 富士Calm(山梨県富士吉田市新屋1400)

Massive Stars Explode. Why?



Simulation by
T. Takiwaki
(RIKEN)

Some Massive Stars Explode as Gamma-Ray Bursts. Why?

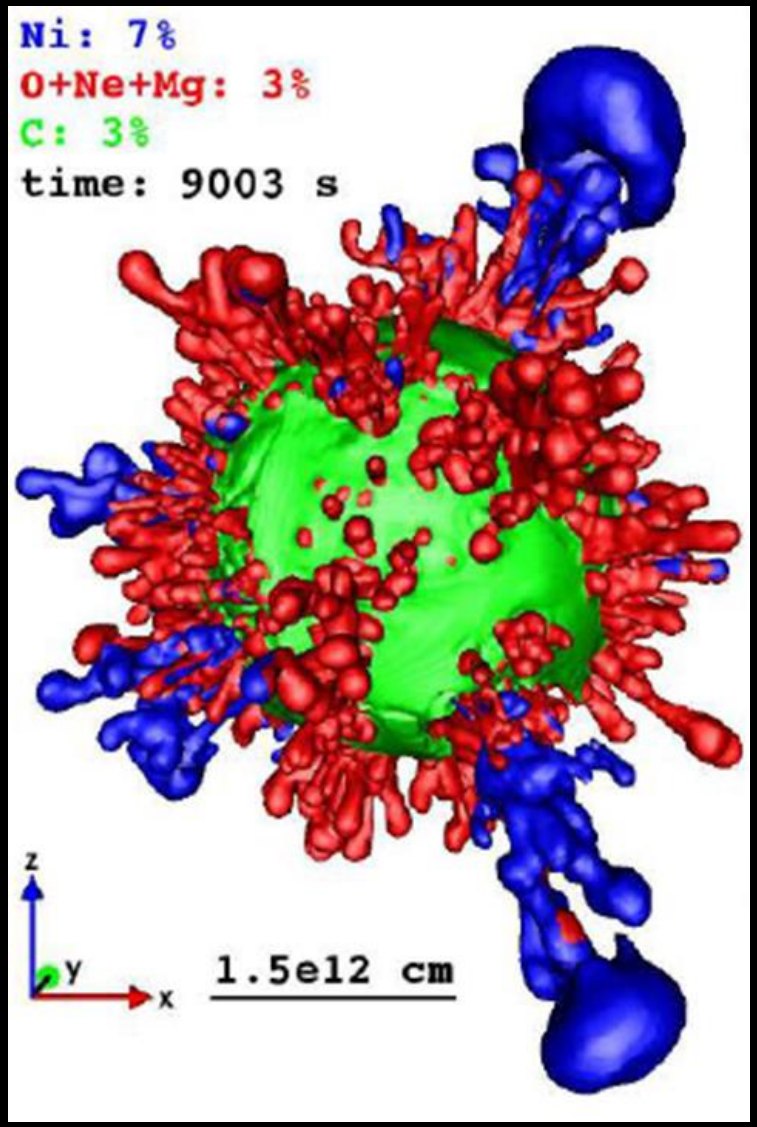


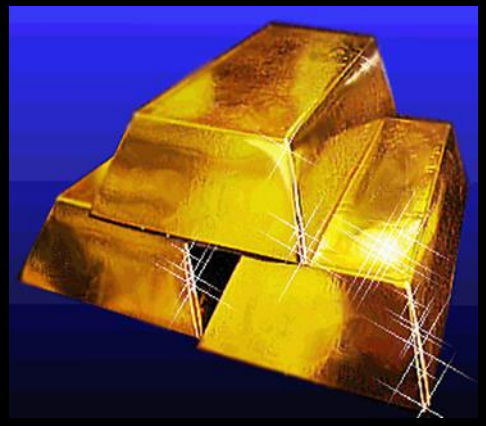
From NASA HP.

Supernovae are Origin of Heavy Metals. But what kind of metals are really produced?

Simulation by
A. Wongwathanarat
(MPA → RIKEN)

S. Wanajo
（RIKEN）



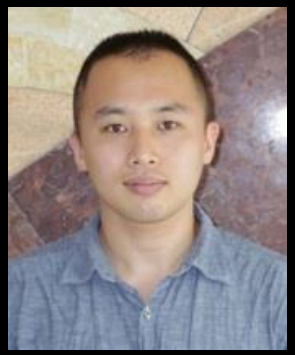


Origin of Gold?

Origin of Uran?

Why are SNe/GRBs so Bright?

A. Tolstov (RIKEN→IPMU)



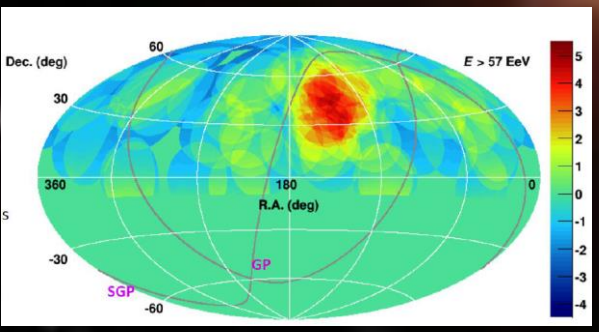
Y. Teraki(RIKEN)

H. Ito (RIKEN)

J. Matsumoto (RIKEN)

Are Gamma-Ray Bursts the Largest Particle Accelerators ?

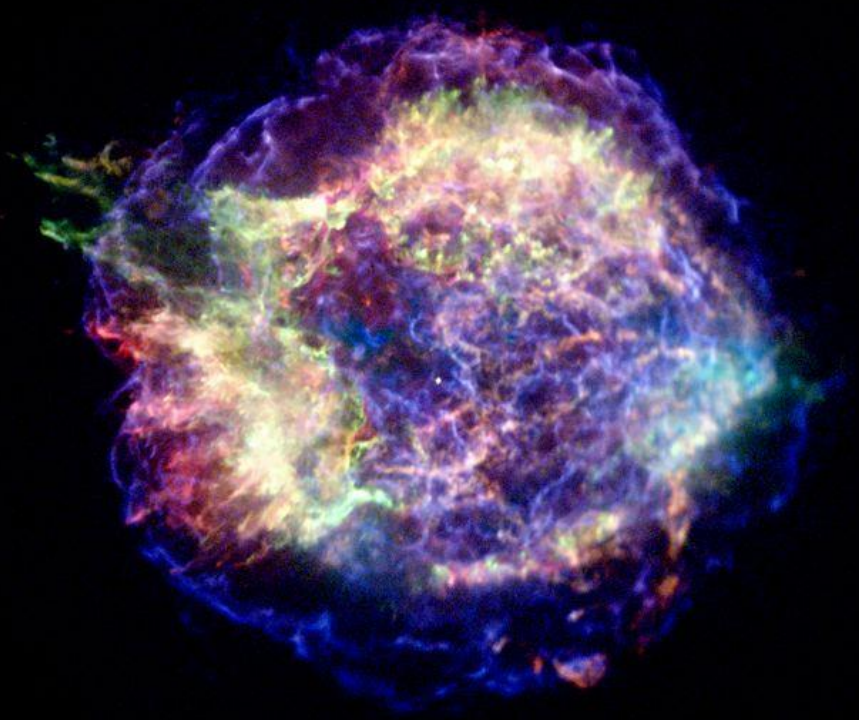
Extra-Galactic Neutrinos?



The Hot Spot of Ultra-High Energy Cosmic Rays found by Telescope Array Experiment 2014

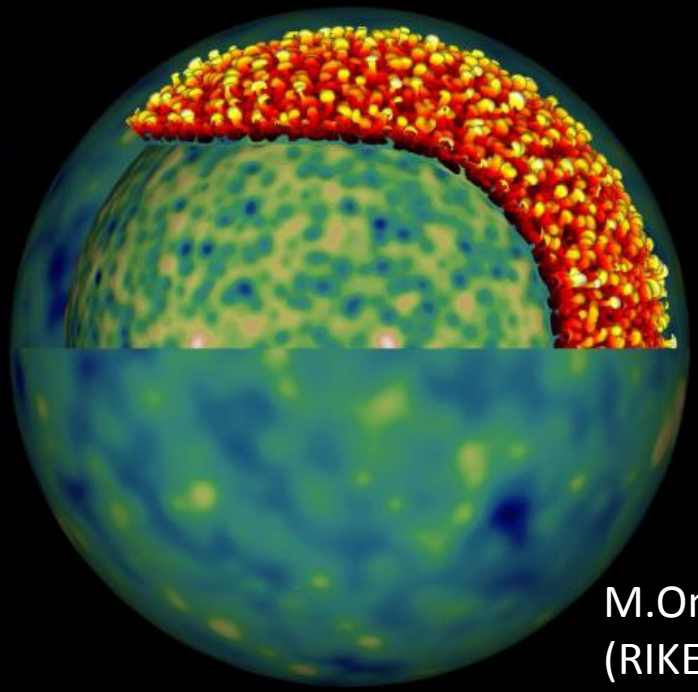
Figure (Imagination):
© A. Roquette (ESO)

Lots of Mysteries & Physics in Supernova Remnants



Observation

Cassiopeia A (350 years old)
By Chandra Satellite



Simulation

by D. Warren

S.H. Lee
(Stanford→
RIKEN→JAXA)

M.Ono
(RIKEN→Kyushu U.)

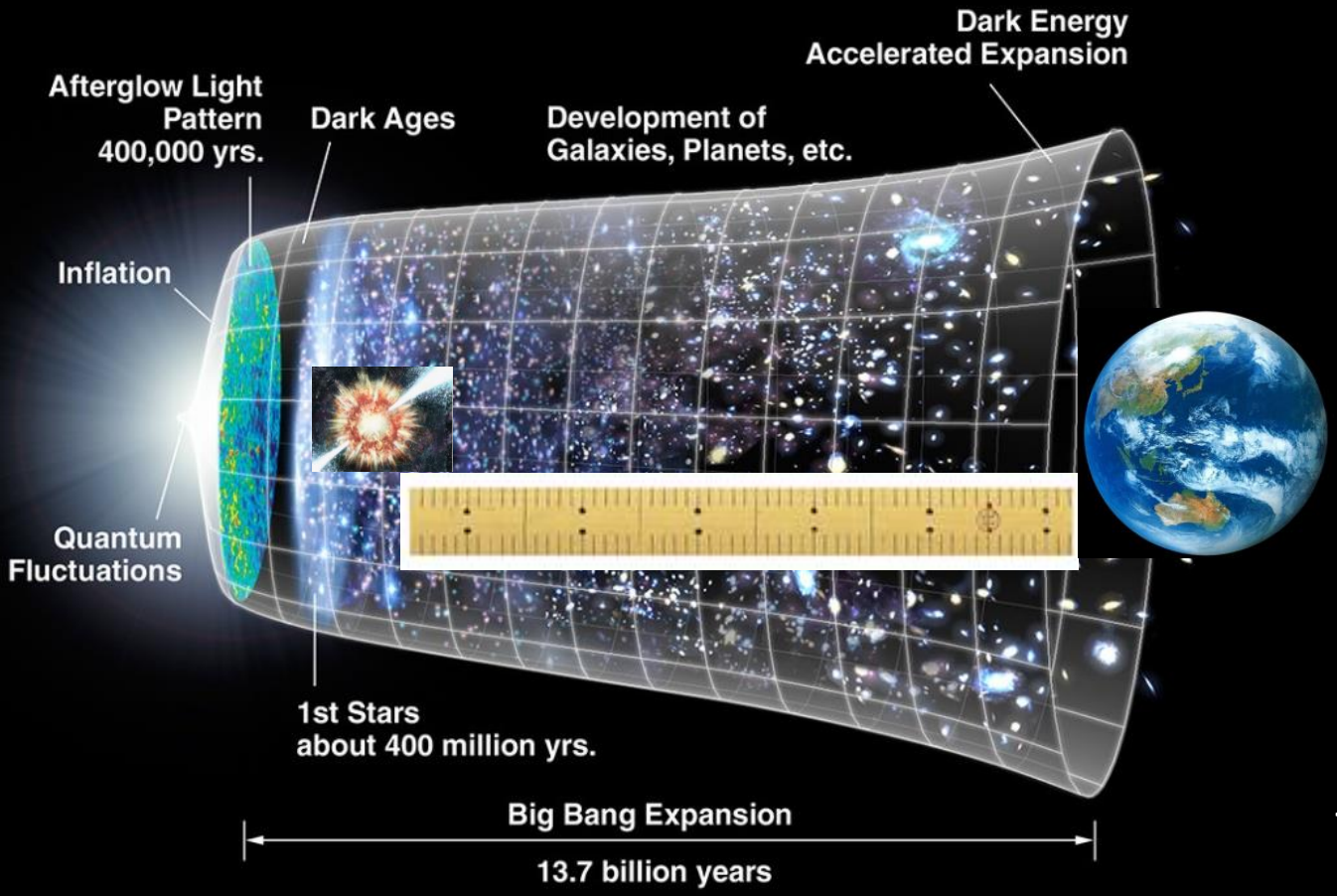
D. Warren
(NCSU→RIKEN)

Cosmic-Ray Production? Morphology? Composition?

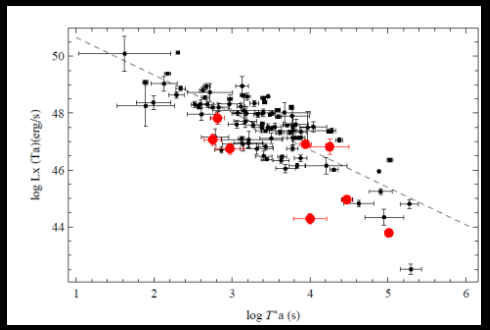
Galactic Neutrinos?

Can Gamma-Ray Bursts be the Longest Cosmic Rulers?

From WMAP HP. Modified.



M. Dainotti
(Stanford→RIKEN)



The Dainotti's Relation

Maria Dainotti, Awarded an Order of Merit of the Italian Republic for the Discovery (2013).

NASA/WMAP Science Team

Our Group Members and Collaborators

From 1st April 2013

～Toward Full-Understanding of Supernovae and GRBs～

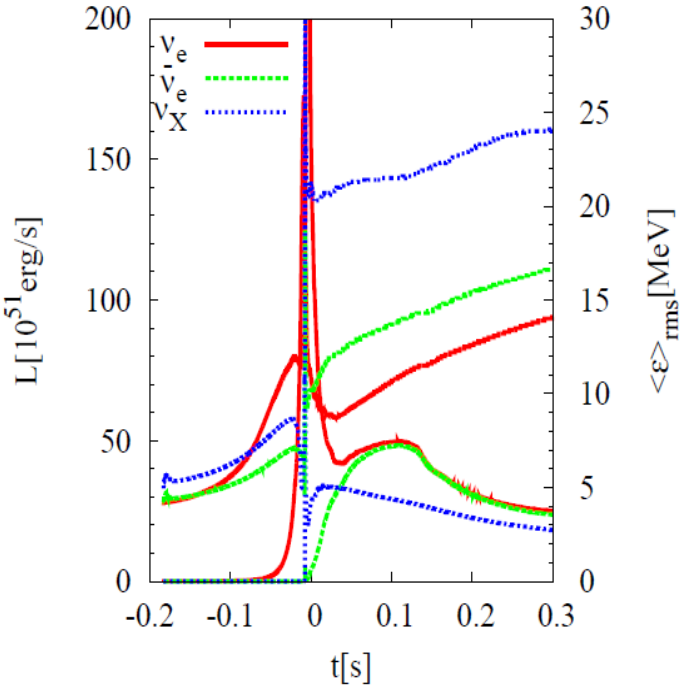
Small Radi

Large Radi

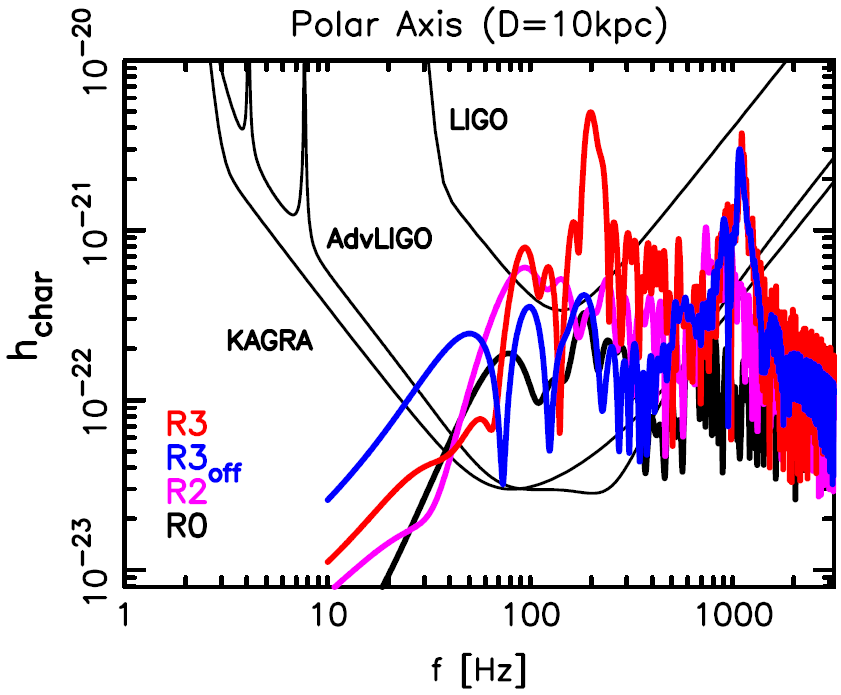
- Central Engine: Nagataki (PI), Takiwaki , Barkov
- Explosive Nucleosynthesis:Wongwathanarat, Wanajo, Mao
- Shock Breakout/Light Curve/Spectrum: Tolstov, Blinnikov (ITEP), Tominaga (Konan), Tanaka (NAOJ), Maeda(Kyoto)
- Propagation of Relativistic Jet: Matsumoto, Mizuta
- Gamma-Ray Burst Emissions: Ito, Teraki, Pe'er (UCC)
- Afterglow (X-ray/Opt/IR/Radio) Emissions: Warren, Ellison (NCSU), MacFadyen(NYU).
- Remnants: Lee, Ono, Warren, Slane (CfA), Patnaude (CfA)
- UHECRs, VHE-neutrinos/gamma-rays: Kusenko (UCLA), He (PAO), Allard(APC)
- GRB Cosmology: Dainotti

… and More!

Neutrino/GW Signals from a SN



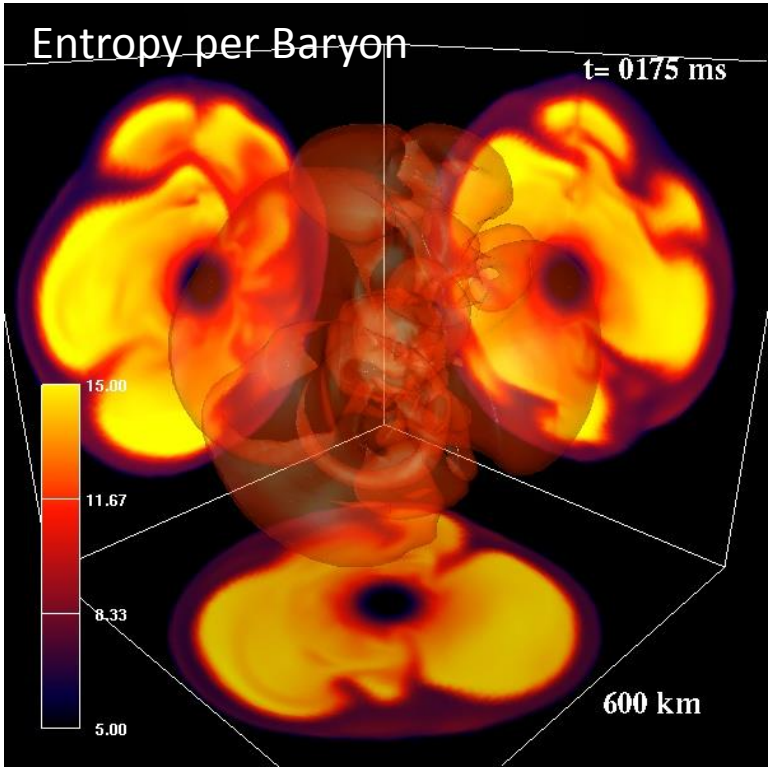
Time Evolution of Neutrino Luminosity



Signal of Gravitational Wave in Freq. Space

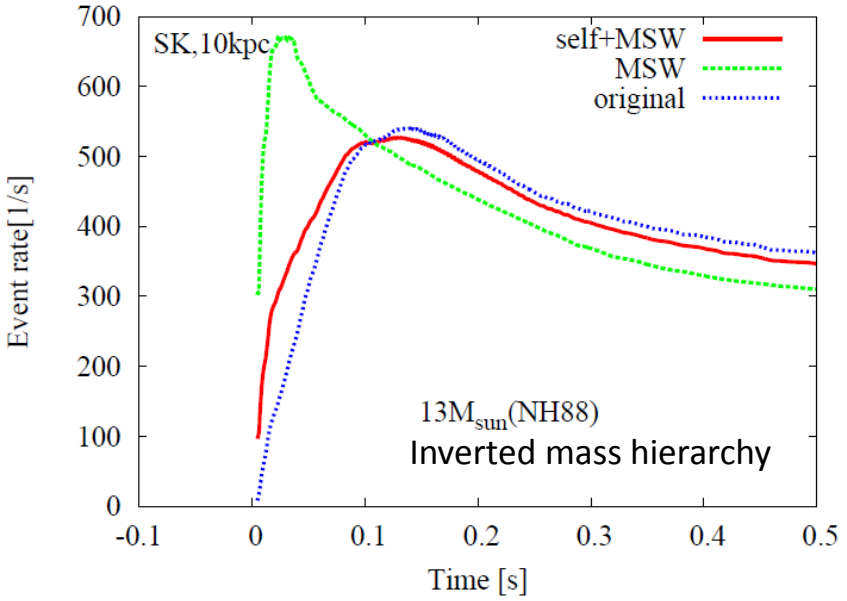
T. Takiwaki
(RIKEN)

Neutrino Oscillations in a Core-Collapse Supernova



Kawagoe. Takiwaki. Kotake in prep

Simulation by T. Takiwaki (RIKEN) with K-Computer.



We are very interested in calculating neutrino spectrum taking into account Neutrino Oscillation Effects, which should be confirmed by SK/HK when a Core-Collapse supernova will happen in Milky Way!

Gravitational Waves by KAGRA are also crucial to confirm our theory on CC-SNe.

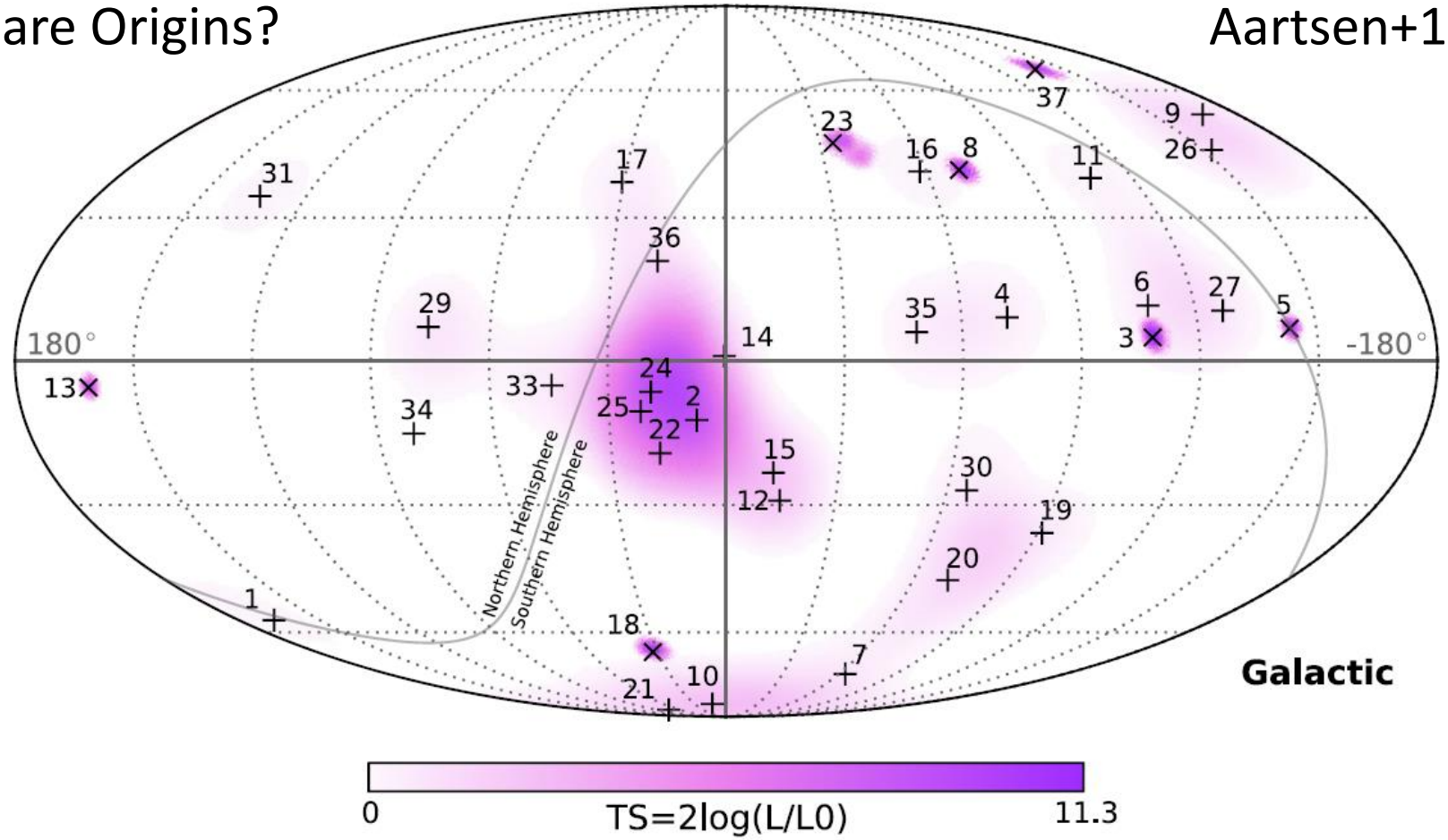
§ Toward Unveiling the Origins of VHE-Neutrinos

A New Window Has Opened!

by the IceCube Collaboration

What are Origins?

Aartsen+14



Source Candidates

Extra-Galactic Objects (= Outside of Milky Way)

(Most) Powerful Obs. in the universe.

Active Galactic Nuclei (AGN)

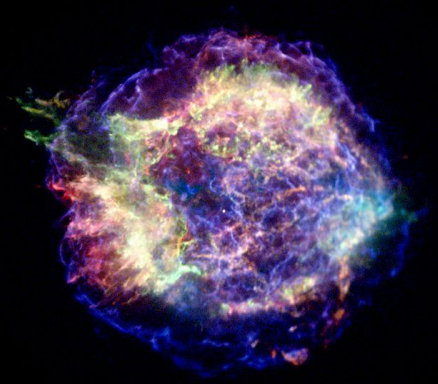
Gamma-Ray Burst (GRB)

Star Burst Galaxy

Galactic Objects (= Inside of Milky Way)

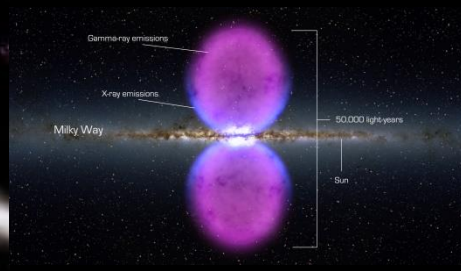
(Most) Powerful Obs. in Milky Way

Pulsar (Neutron Star)
Lack of Power?



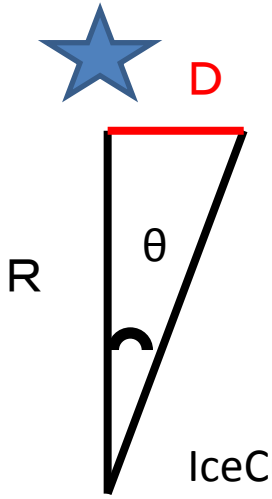
Supernova Remnant (SNR)
Lack of Power?

Hypernova Remnant (HNR)



Fermi Bubble

Bottom Line: Hard to Resolve Distant Objects



$D = R \times \theta$

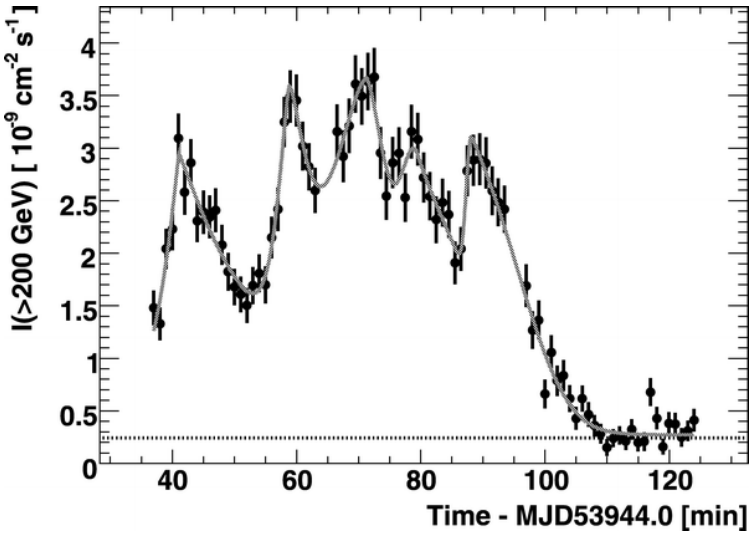
1pc = 3.26ly

Θ \ R	10kpc Milky Way	100Mpc Nearby Galaxies	3000Mpc Distant Galaxies
IceCube 1deg	175pc	1.75Mpc	52.5Mpc
HESS (TeV-Gamma) 0.2deg	35pc	350kpc	10.5Mpc

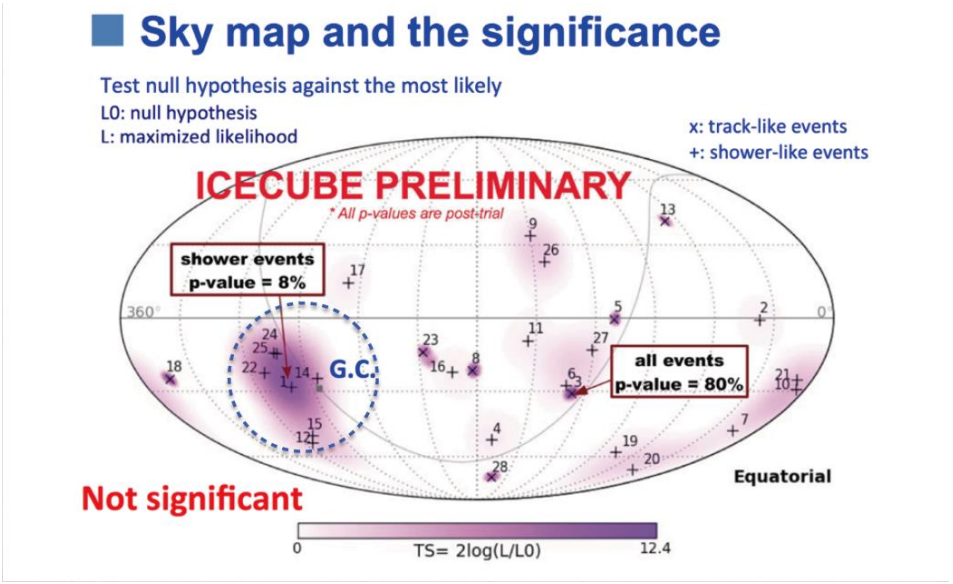
c.f. Size of the Universe～3000Mpc.
Typical Distance between AGNs～50Mpc.
Typical Distance between Galaxies～(1-10)Mpc.
Typical Size of a Galaxy ～10kpc
Typical Size of a Supernova Remnant～10pc.

How to Pin Down the Sources?

- Extra-galactic: Time-Correlation (GRBs, AGN Flares,…).
- Galactic: Anisotropy of Arrival Direction.



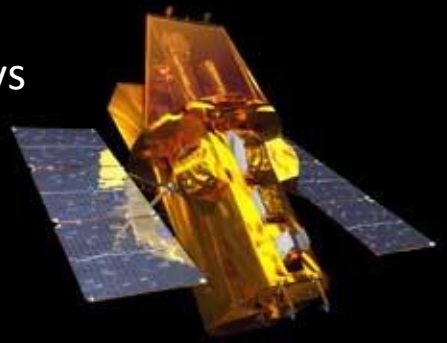
PKS 2155-304 (z=0.116=475Mpc)



A Possible Scenario: Extra-Galactic Case Time & Spatial Correlation

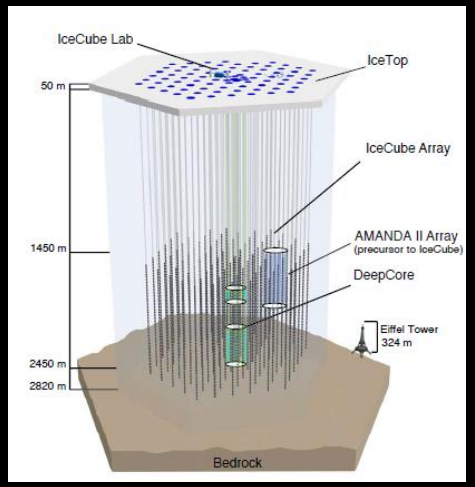
VHE-Neutrinos can be Detected by IceCube with Simultaneous Detection of a Gamma-Ray Burst

Gamma-Rays



Swift

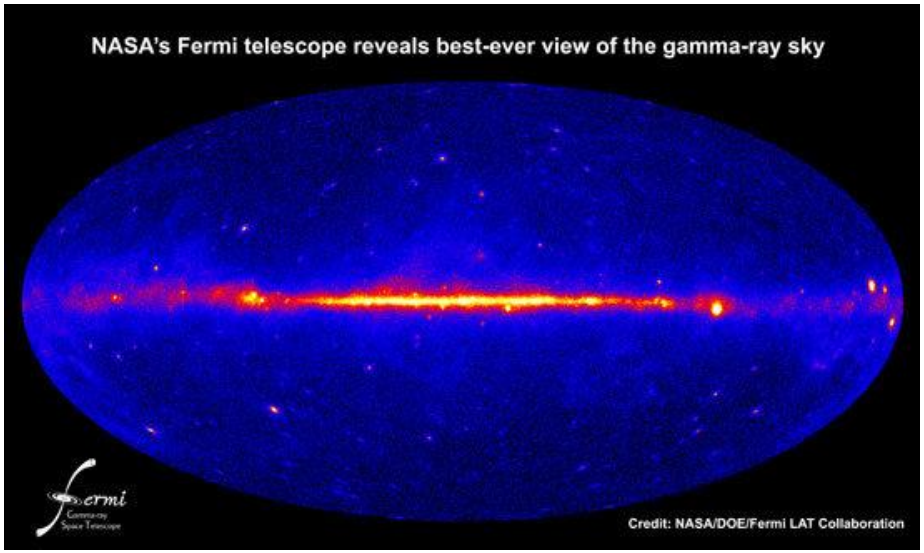
Neutrinos

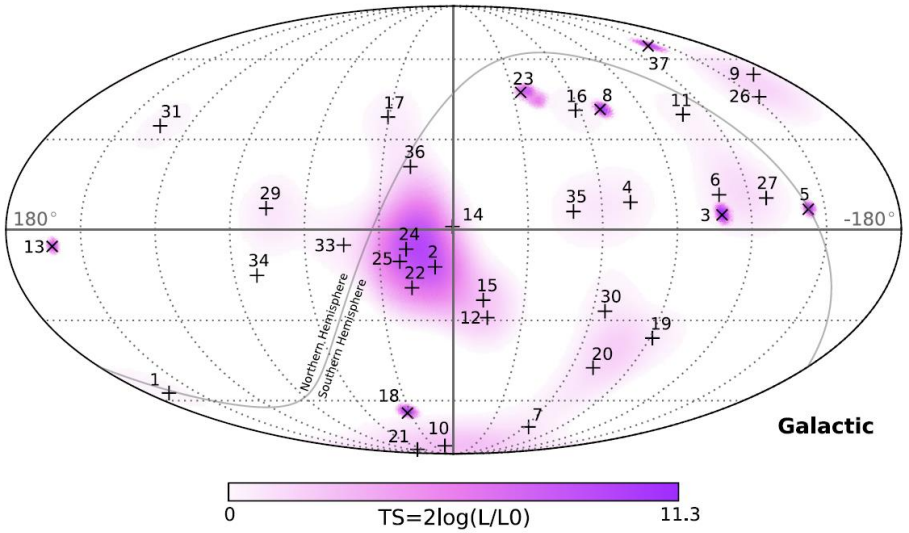


IceCube

e.g.
Murase & S.N. PRD 06
Murase & S.N. PRL 06

Another Possible Scenario: Galactic Case Anisotropic Distribution



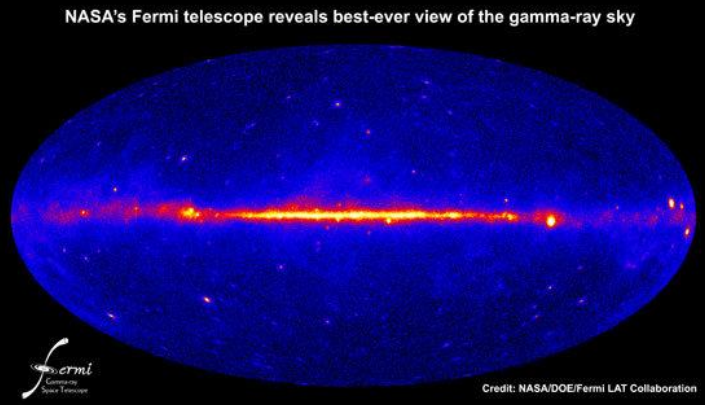


GeV Gamma-Rays

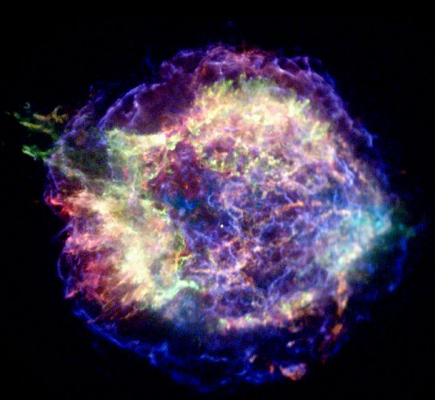
TeV-PeV Neutrinos

TeV-PeV Neutrinos Look More Special than GeV Gamma-Rays?
Something Special at the Galactic Center Region?

Something Special at Galactic Center Region?

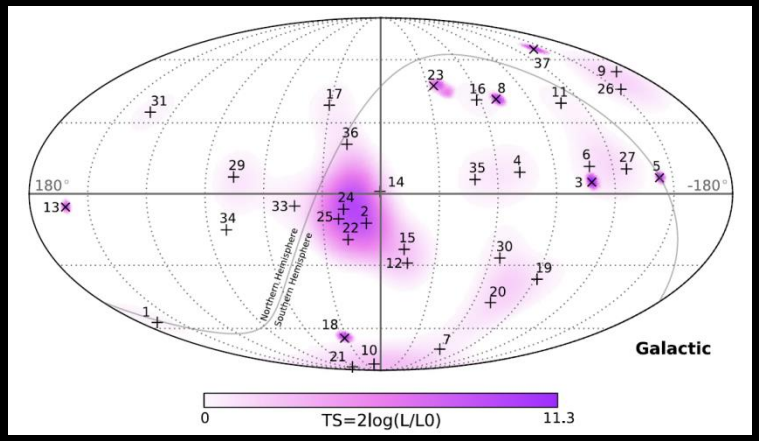


GeV Gamma-Rays



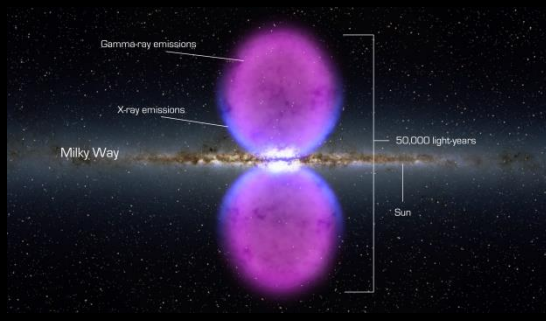
Supernova Remnant (SNR)

Pulsar (Neutron Star)



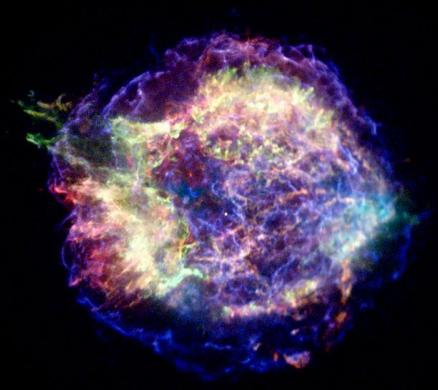
TeV-PeV Neutrinos

Hypernova Remnant (HNR)?



Fermi Bubble?

How Special is a HNR?

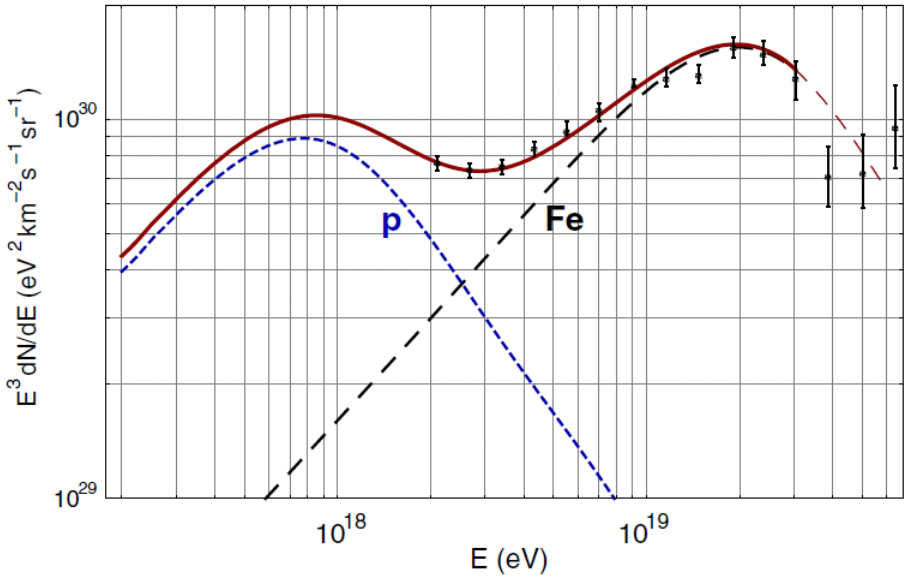


	Event Rate	Energy	Obs.
Supernova Remnant (SNR)	1 per 100yrs	10^51erg	Many

Hypernova Remnant (HNR)?	1 per 10^5yrs	10^52erg	Not Found Yet in Milky Way

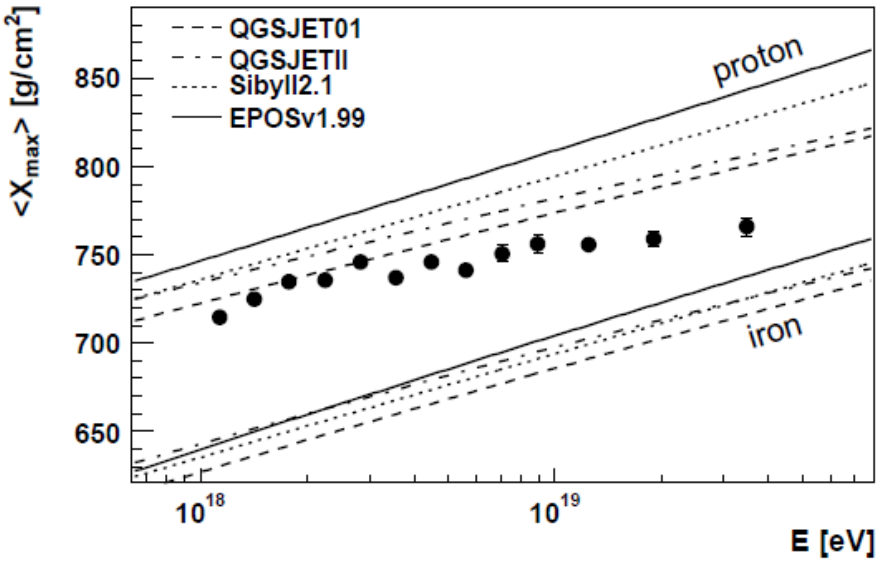
Imagination of a Gamma-Ray Burst **From NASA HP**

UHECRs may be Coming from Past GRBs Happened in Milky Way



Spectrum and Composition of UHECRs

Calvez, Kusenko, S.N. PRL (2010)



Composition of UHE-CRs
Auger Collaboration 10

Our SNR Collaborations

and More!

S.H. Lee
(RIKEN→ JAXA)

M.Ono
(RIKEN→Kyushu U.)

D. Warren
(NCSU→RIKEN)

D. Ellison (NCSU)

P. Slane (Harvard)

D. Patnaude
(Harvard)

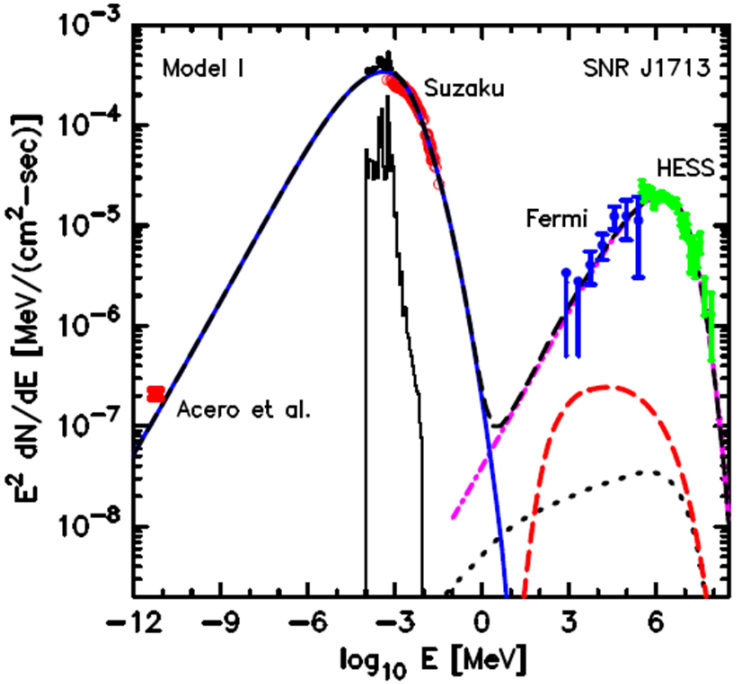
F. Reopke
(Wurzburg Univ.)

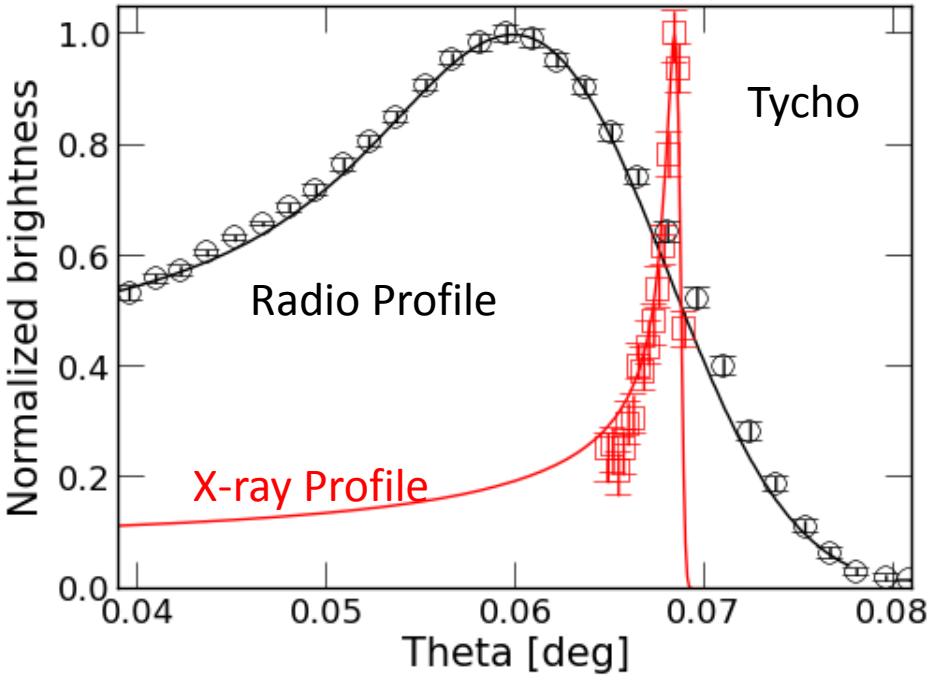
Successful Interpretation & Understanding of SNRs

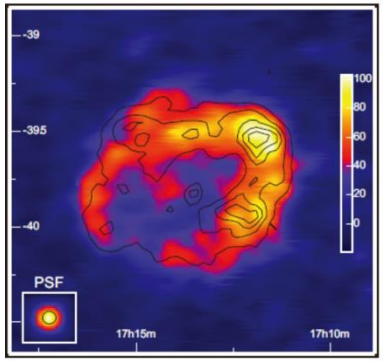
CR-HYDRO-NEI CODE

S.H. Lee (RIKEN→JAXA)

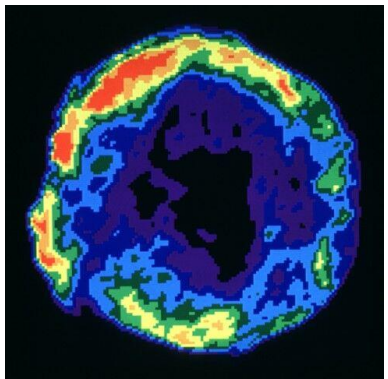
Our SNR Code can Calculate CR Production.
Trapped Component of CRs Explain SNR Obs. Very Well!

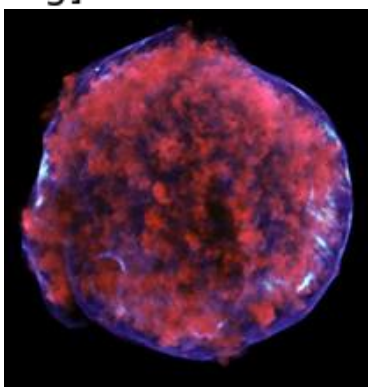






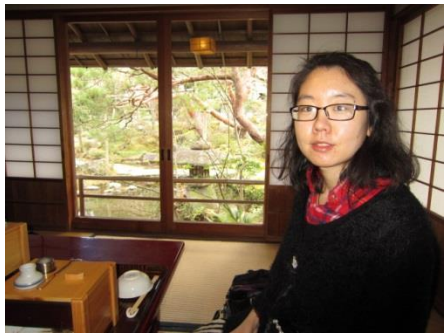
Left : RXJ1713
Rights :
Tycho（Left : Radio
Right : X-ray）.





Let’s Apply Our SNR Code to a HNR

Dr. Lee
(RIKEN→JAXA)



Dr. He
（UCLA/PMO）

Prof. Kusenko
(and his wife)
(UCLA/Kavli IPMU)

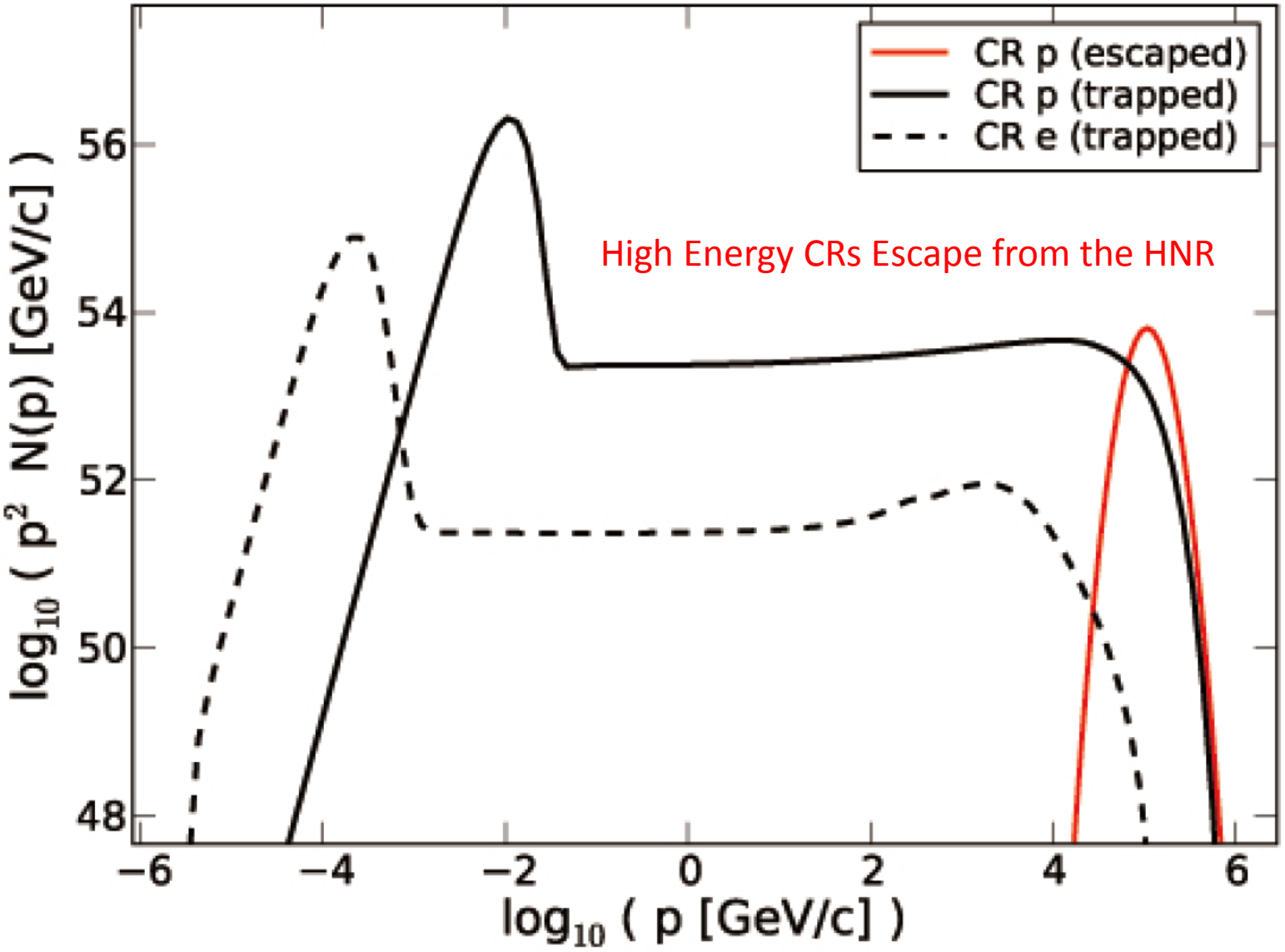
Parameters

- E_{SN} = 3e52 erg (c.f. SN1998bw)
- M_{ejecta} = 14 M_{Sun}
- Age = 1,000 yr (from 20 yr)
- dM/dt = 3e-5 M_{Sun}/yr
- v_{wind} = 10 km/s
- σ_{wind} = 0.03
- d_{HNR} = 8.5 kpc
- Cosmic abundance everywhere
- Instantaneous temp equilibration

Output

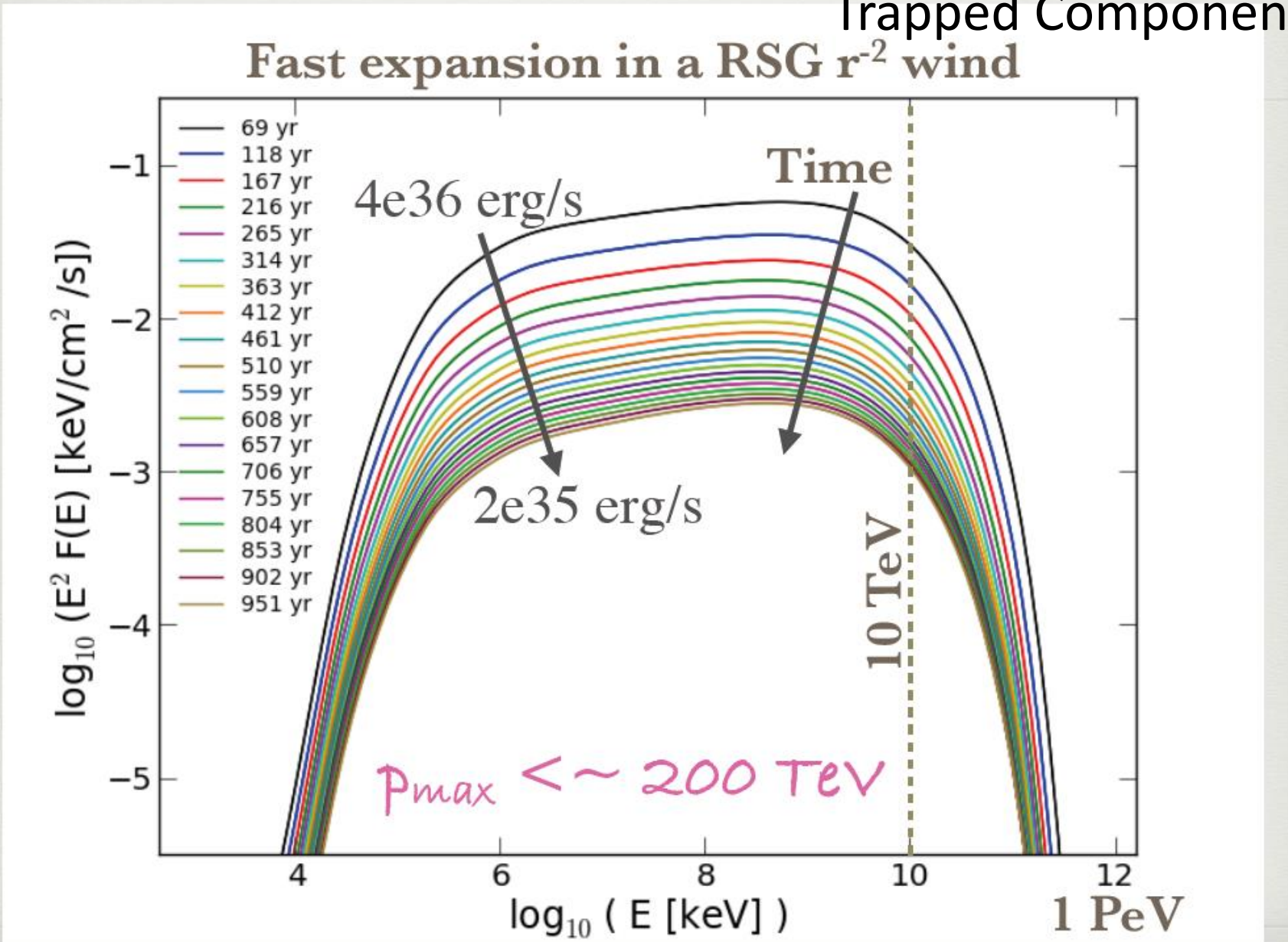
R_{HNR} = 11.7 pc (n_{wind} ~ 0.04/cc)
R_{RS} = 8.1 pc
R_{CD} = 8.7 pc
V_{FS} = 16,500 km/s @ 50 yr
8,900 km/s @ 1,000 yr
(*mildly relativistic shock*!)
E_{CR}/E_{SN} = 30% (χ_{inj} = 3.70)
M_{CD-FS} = 33 M_{Sun}
(need to truncate wind to merge w/ ISM)

Escaping CRs are Relevant for IC Events



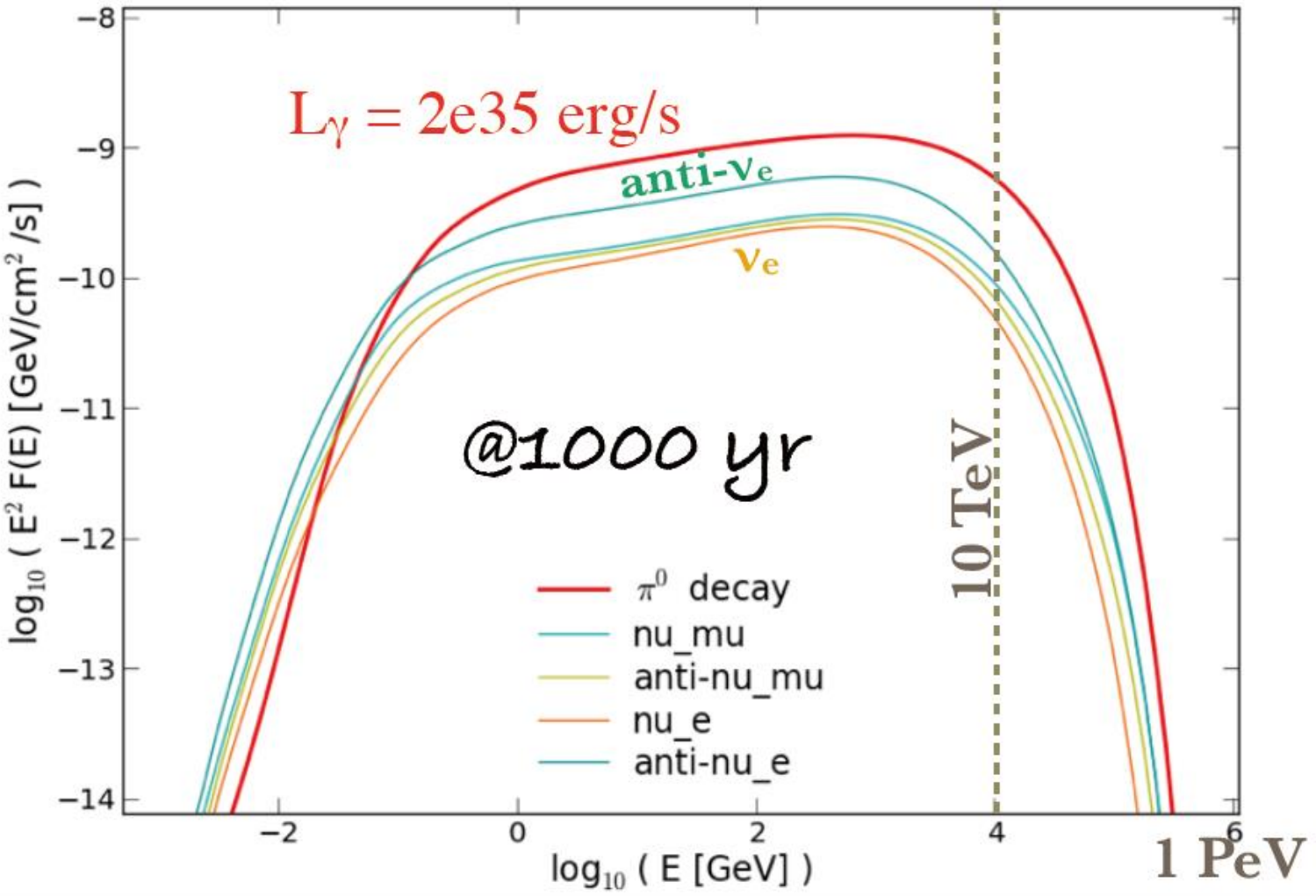
Pion decay gamma-ray (inside HNR)

Trapped Component



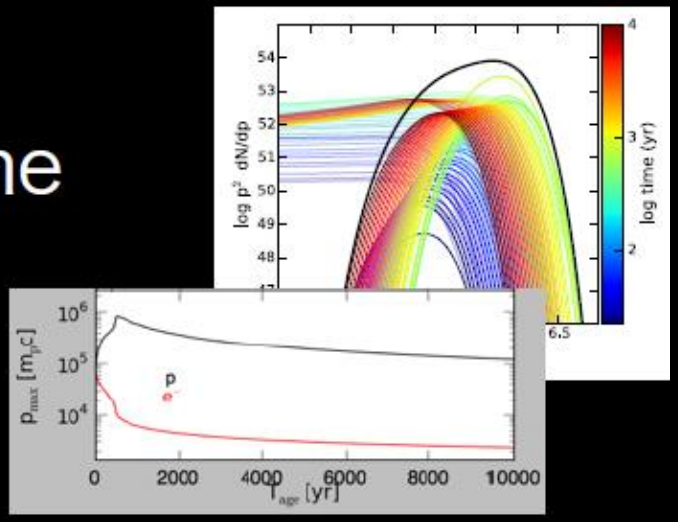
Muon neutrino spectra (with full oscillation mixing)

Trapped Component

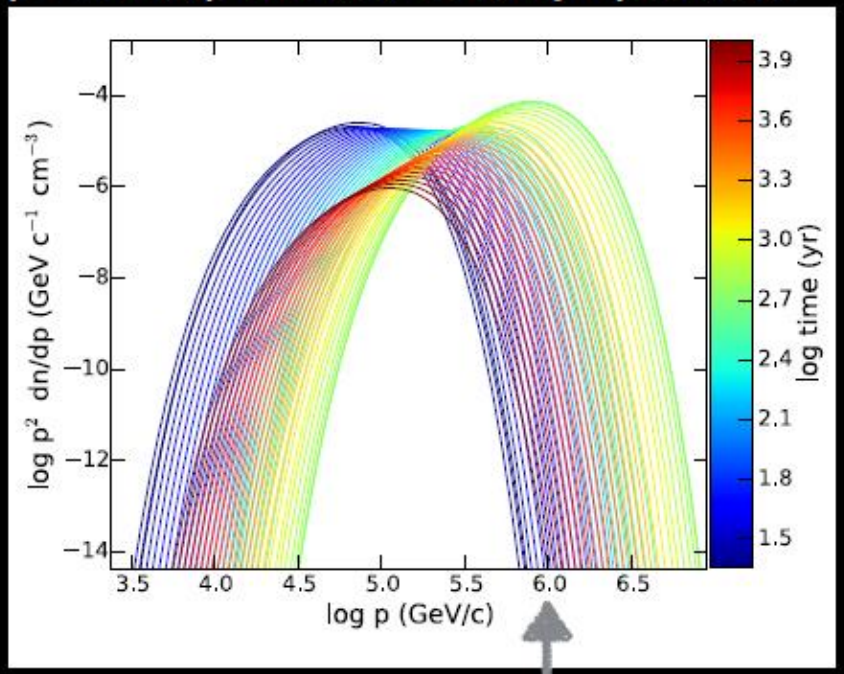


Escaped Component!!

HNR escaping proton vs time as injection term Q(p,r,t) Age = 10^4 yr

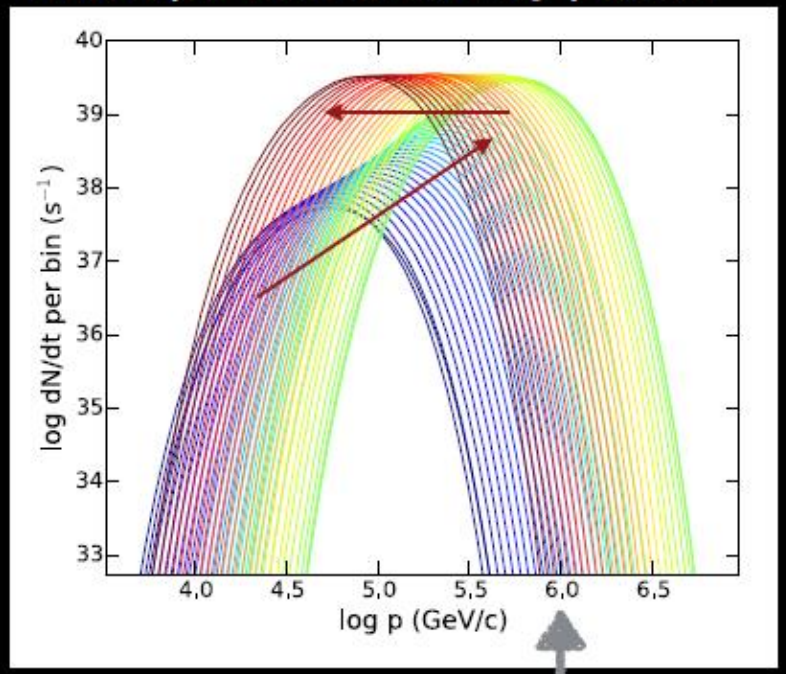


p^2 dn/dp number density spectrum



PeV/c

dN/dt particle luminosity per bin

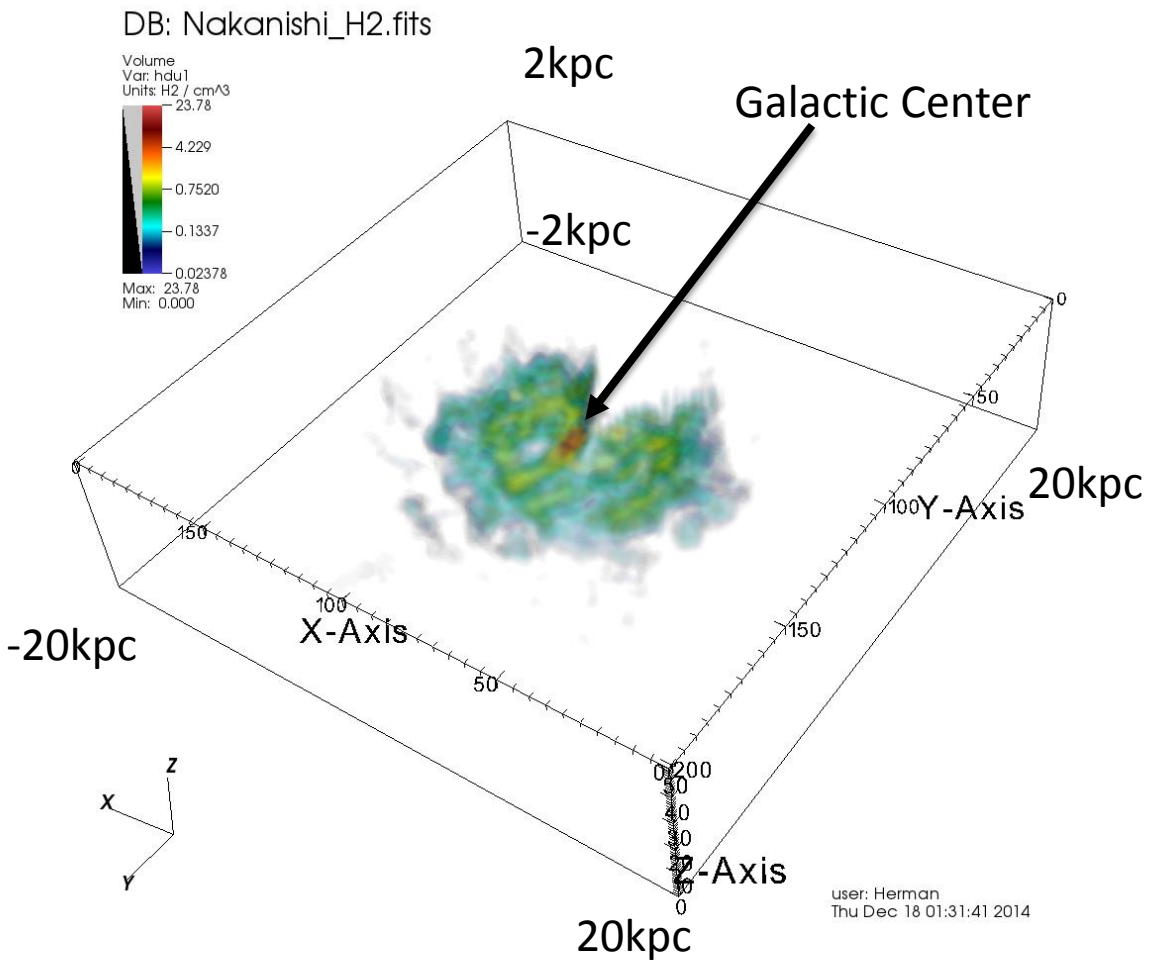


PeV/c

In 50 log time steps

Our Future Step 1: Calculating pp-Interactions between Escaped CRs & gas/molecular clouds

H2+H Density from GALPROP

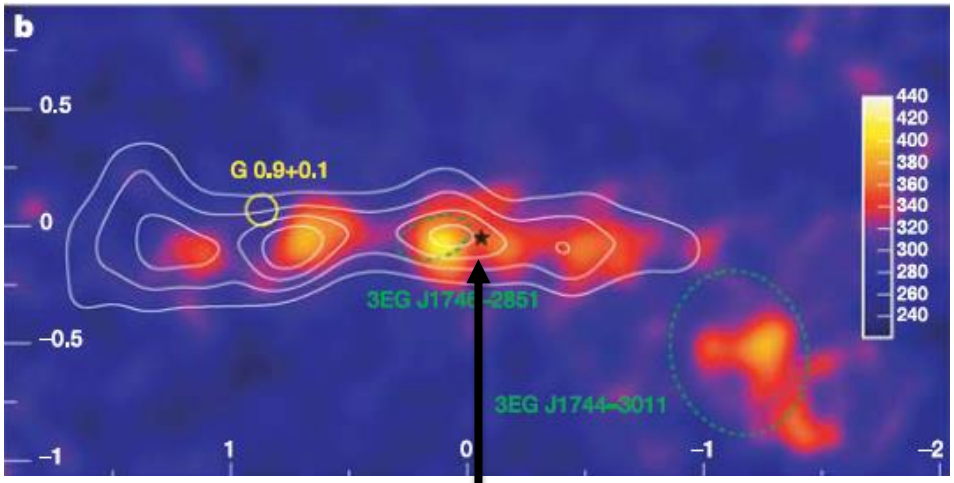


We put a HNR at the Galactic Center Region.

We solve Diffusion Eqs. For the Escaped CRs.

We calculate pp-Interactions Between Escaped CRs & Ambient Matter.

Our Future Step 2:
Need to Care about Galactic Ridge

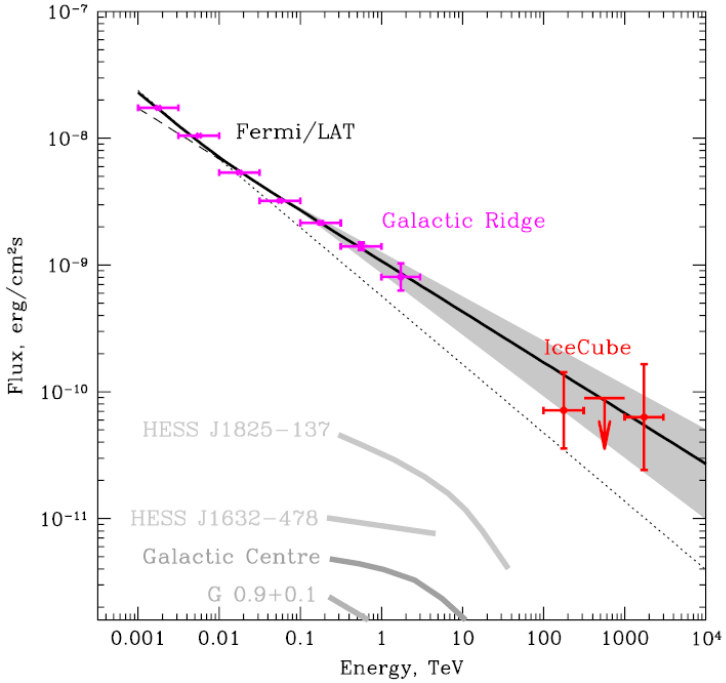


-300pc

Deg.

300pc

Galactic Center



Color: VHE-Gamma-Rays (> 100GeV) by HESS
Contour: Dense Molecular Cloud (CS line)

Aharonian+06

A SNR Happened 10^4yrs ago? Aharonian+06
A SNR Happened 10^4-10^5yrs ago? Macias+14

Comparison of Integrated Flux
Between Gamma-Rays & Neutrinos

$$-30^\circ < l < 30^\circ \quad -4^\circ < b < 4^\circ$$

Our Road Map

- Finding a HNR/CR-Diffusion Model Compatible with Current Gamma-Ray/Neutrino Obs.
- Draw Maps of Arrival Direction of Neutrinos that will be Detected by IceCube in Future (5yr, 10yr, 100yr,…).
- Will the Anisotropy (= Galactic Origin) be Confirmed in Future by IceCube?
- Other Scenarios: Dozens of SNRs, Fermi Bubble, DM…
- …

Thank You Very Much.

- PI: Nagataki From 1st Apr. 2013
- Current PDs: Ito, Matsumoto, Dainotti, Barkov, Teraki, Wongwathanarat, Takiwaki
- Almini: Ono (Kyushu Univ.), Lee(JAXA), Tolstov(Kavli IPMU), Mao(Kyushu Univ.)
- From FY2015: Warren, Yokokura, Tanaka, and More!