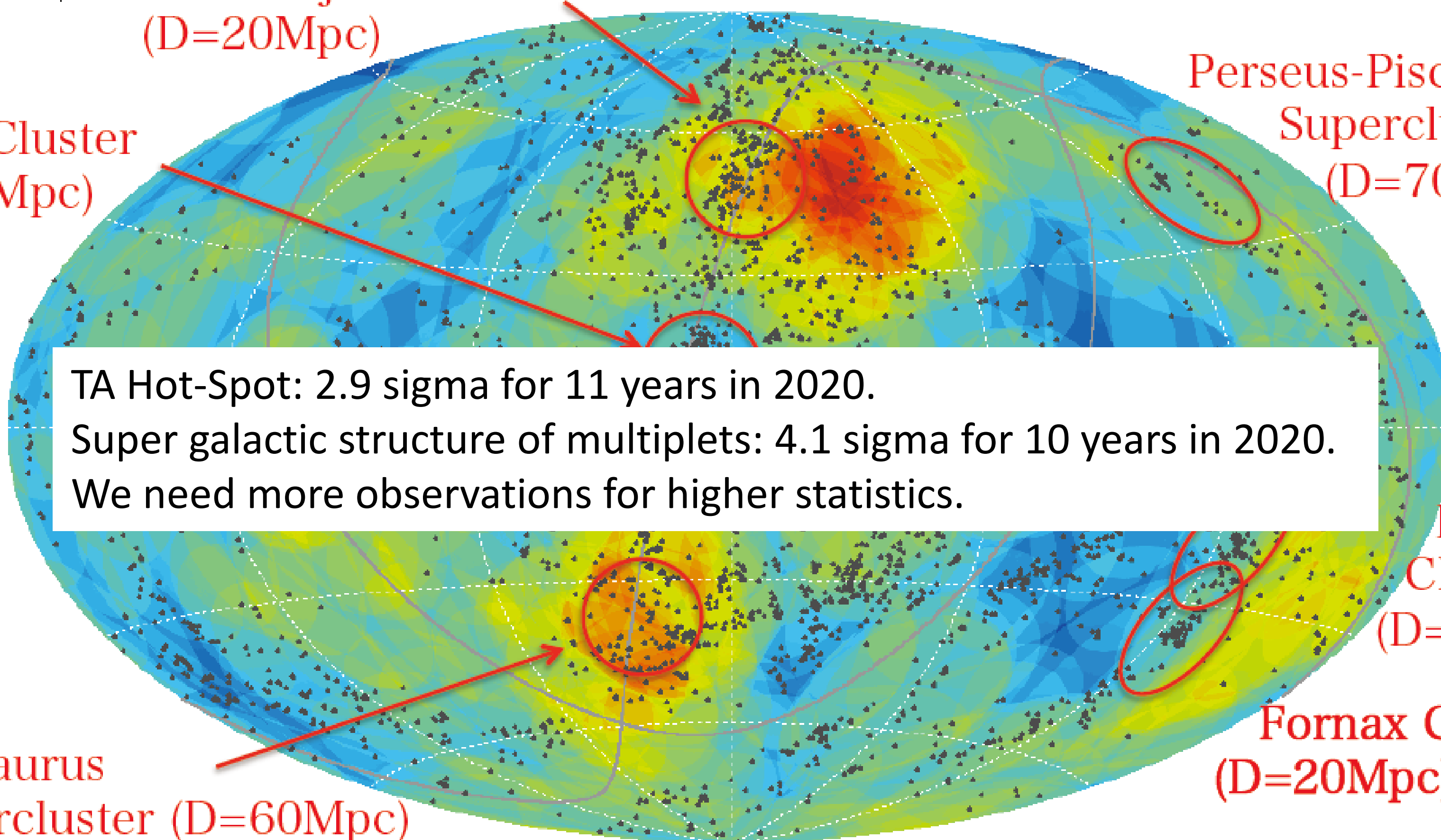
UHECRs from Nuclear & Astro Physical Points of Views

Shigehiro Nagataki

JEM-EUSO-Japan 会合 Presentation Date: 2020/10/06.

Kawata et al. @ ICRC 2015

Nearby Galaxy Clusters



TA Hot-Spot: 2.9 sigma for 11 years in 2020.
Super galactic structure of multiplets: 4.1 sigma for 10 years in 2020.
We need more observations for higher statistics.

Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster
TA & PAO found no excess in the direction of Virgo.

- Hunting the Sources, How?

Why is it difficult to identify the sources of UHECRs?

- This is because the trajectories of UHECRs bend by magnetic fields.
- This also makes time delay (e.g. GRBs).

$$\theta(E,d) \simeq \frac{(2dl_c/9)^{1/2}}{r_g} \simeq 0.8^\circ\, q \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

Q: Charge

$$\tau(E,d) \simeq d\theta(E,d)^2/4 \simeq 1.5\times 10^3\, q^2 \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)^{2} \mathrm{yr}$$

Bhattacharjee 2000

Deflection and Time Delay Due to B-Fields ?

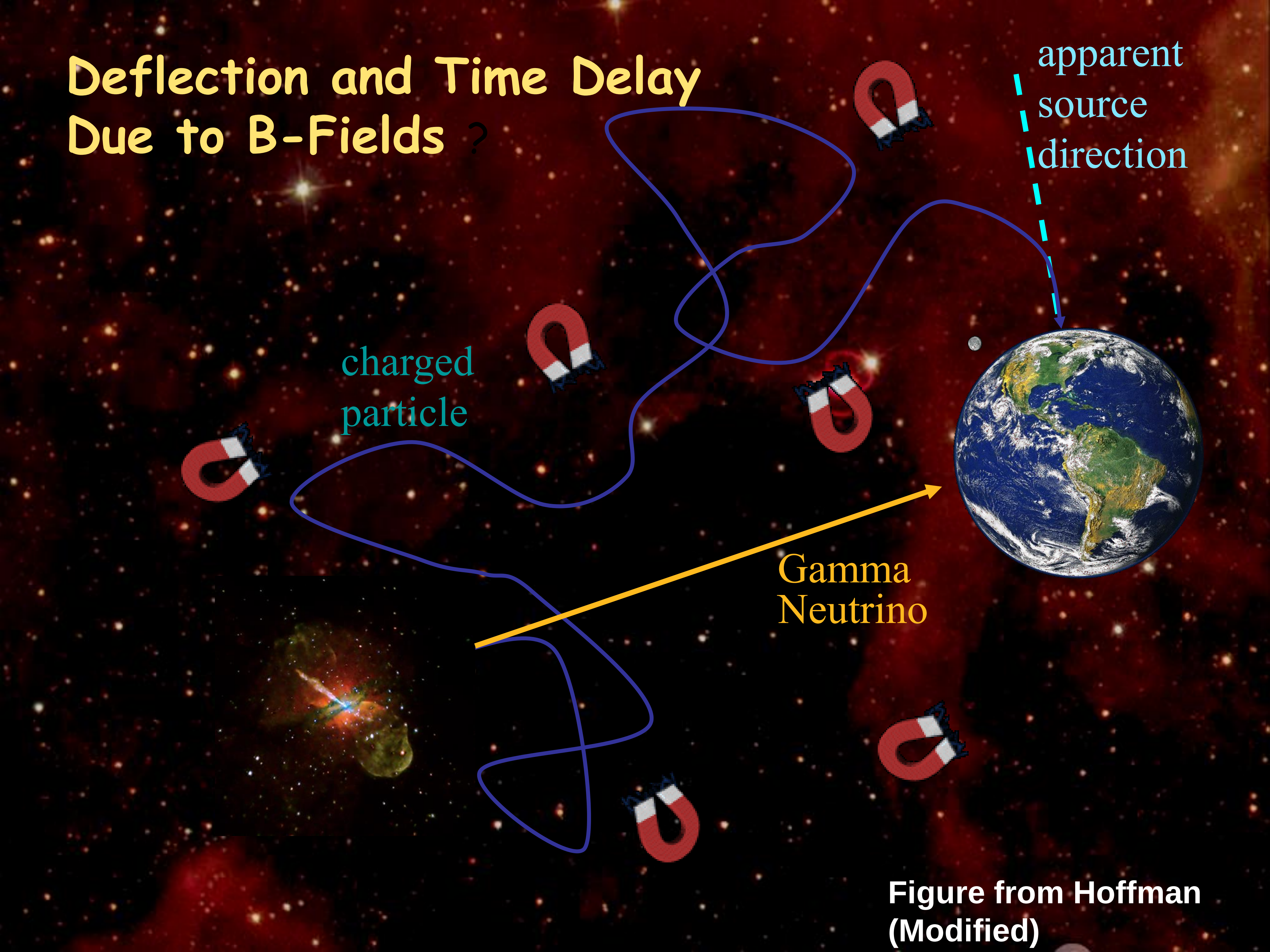


Figure from Hoffman (Modified)

What can we do to identify the sources of UHECRs?

- More Observations. Higher Statistics: Astrophysics, Observations.

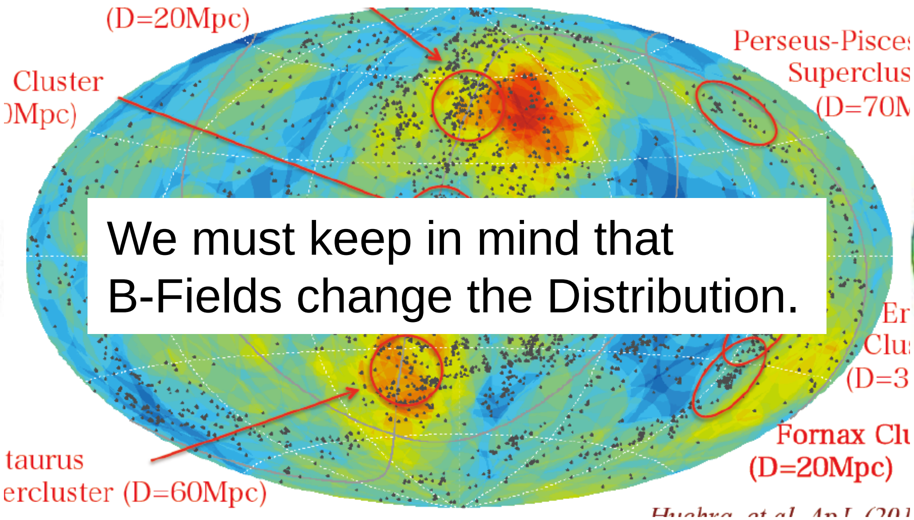
- Simulations of Propagation of UHECRs and comparison with the observations: Astrophysics, Theory.

- Improvement of Basic Data (ex. Cross Sections & Branching Ratios of Photo-Nuclei Interactions): Nuclear Physics

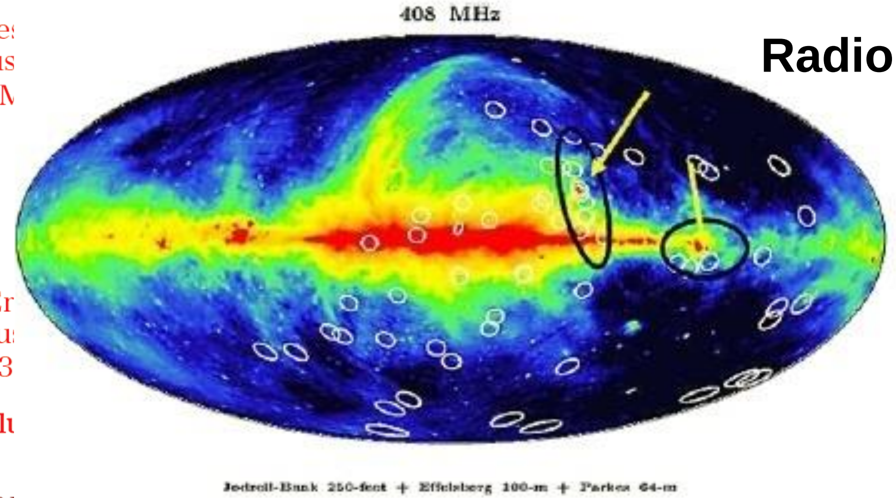
§　Simulations of Propagation of UHECRs: Astrophysics, Theory

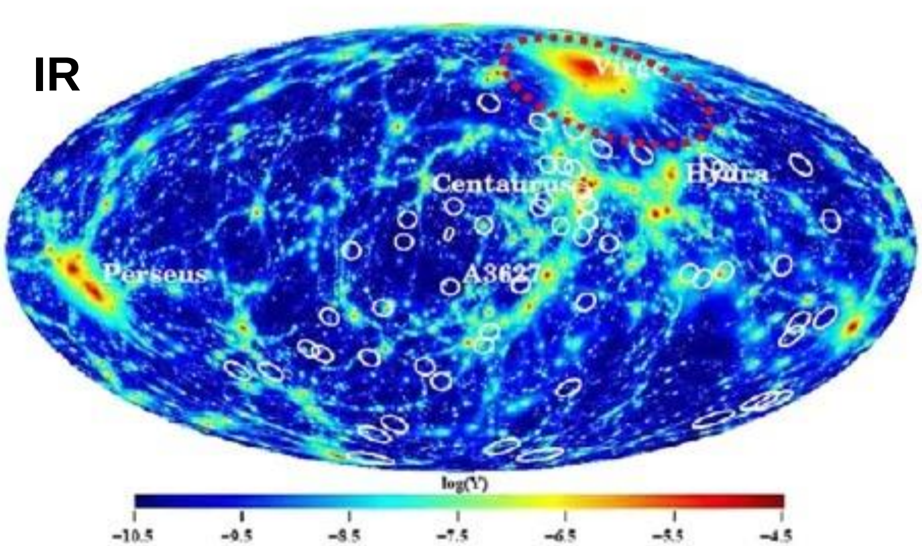
Ref.
Yoshiguchi, S.N. Tsubaki, Sato ApJ 586 (2003) 1211
Yoshiguchi, S.N. Sato *ApJ* 592 (2003) 311
Yoshiguchi, S.N. Sato *ApJ* 596 (2003) 1044
Yoshiguchi, S.N. Sato *ApJ 607* (2003) 840
Yoshiguchi, S.N. Sato *ApJ* 614 (2004) 43
Rouille d' Oefeuil, Allard+, S.N. A&A 567 (2014) 81

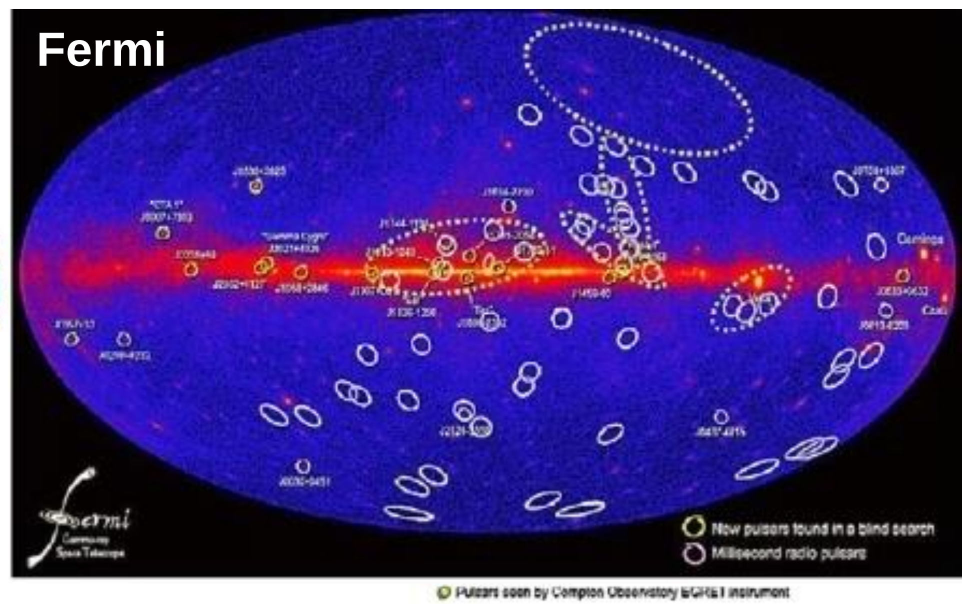
Which Distributions are Similar?



We must keep in mind that
B-Fields change the Distribution.

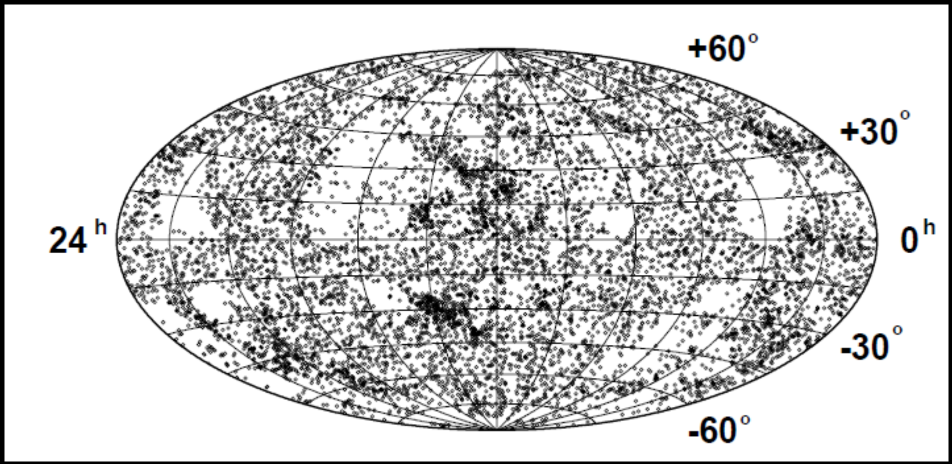






Simulations of Propagation of UHECRs

Ref. Yoshiguchi, S.N. Tsubaki, Sato 2003; Yoshiguchi, S.N. Sato 2003a,b,c,2004



Distribution of nearby Galaxies (from ORS galaxy Catalog)

Protons

$$p + \gamma_{\rm CMB} \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma_{\rm CMB} \rightarrow N + {\rm pions}$$

UHECRs are assumed to be Protons.

$$\langle B^2(k) \rangle \propto k^{n_{\rm H}} \text{ for } 2\pi/l_c \le k \le 2\pi/l_{\rm cut}$$

$$n_{\rm H} = -11/3, \quad l_{\rm cut} = 1/8 \times l_c$$

Gaussian random field with Zero mean and a power-law Spectrum for ICM.

$$B_x = -3\mu_G \sin\theta \cos\theta \cos\varphi / r^3,$$

$$B_y = -3\mu_G \sin\theta \cos\theta \sin\varphi / r^3,$$

$$B_z = \mu_G (1 - 3\cos^2\theta)/r^3,$$

$$\mu_G \sim 184.2 \ \mu{\rm G \ kpc}^3$$

Dipole field with random field For the Milky Way

Energy Spectrum and Auto-correlation function

Ref. Yoshiguchi, S.N. Tsubaki, Sato 2003; Yoshiguchi, S.N. Sato 2003a,b,c,2004

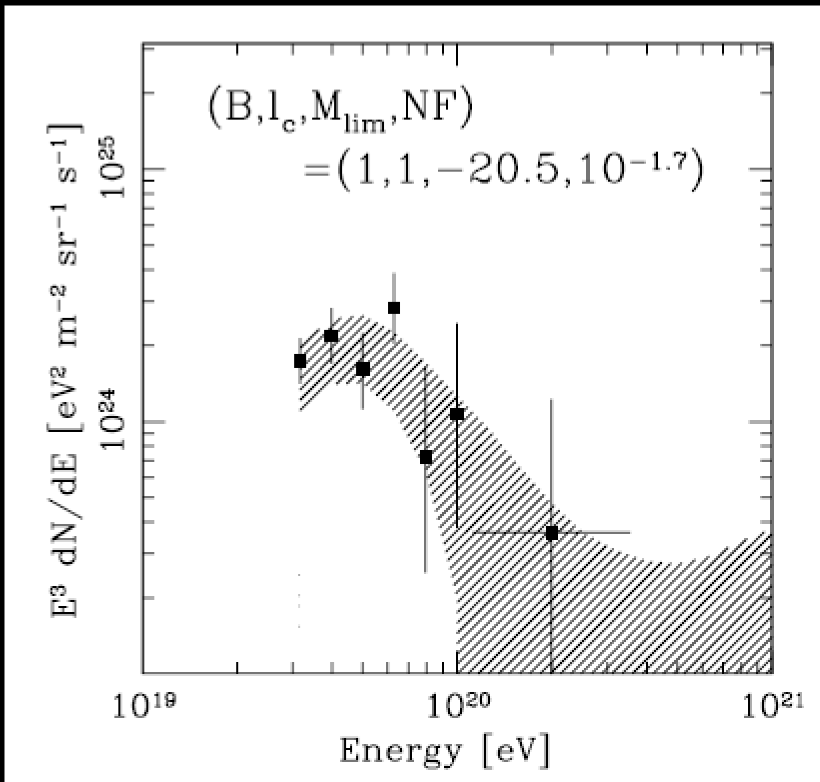
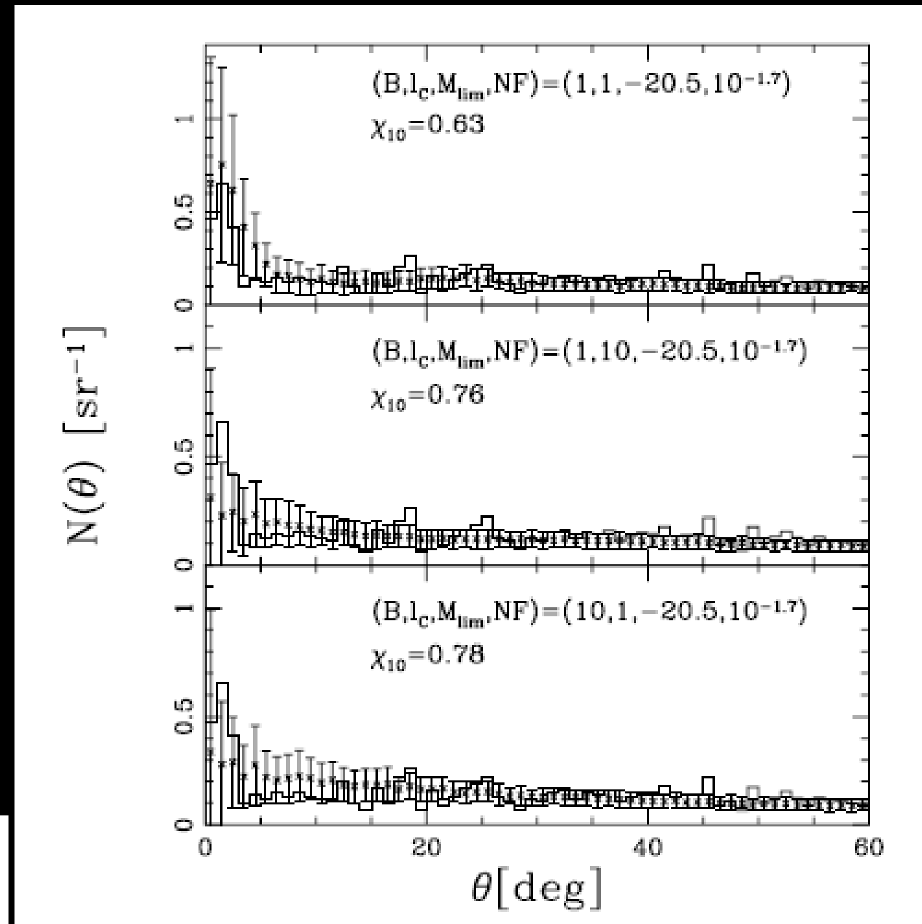


FIG. 22.—Energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ in the case of $(B, l_c, {\rm NF}) = (1, 1, -20.5, 10^{-1.7})$. NF represents the number fraction of selected UHECR sources to all ORS galaxies ($M_{\rm lim} < -20.5$). They are fitted to the data of the HiRes I detector (*squares and error bars*). The shaded regions represent 1 σ error due to the source selection from our ORS sample.



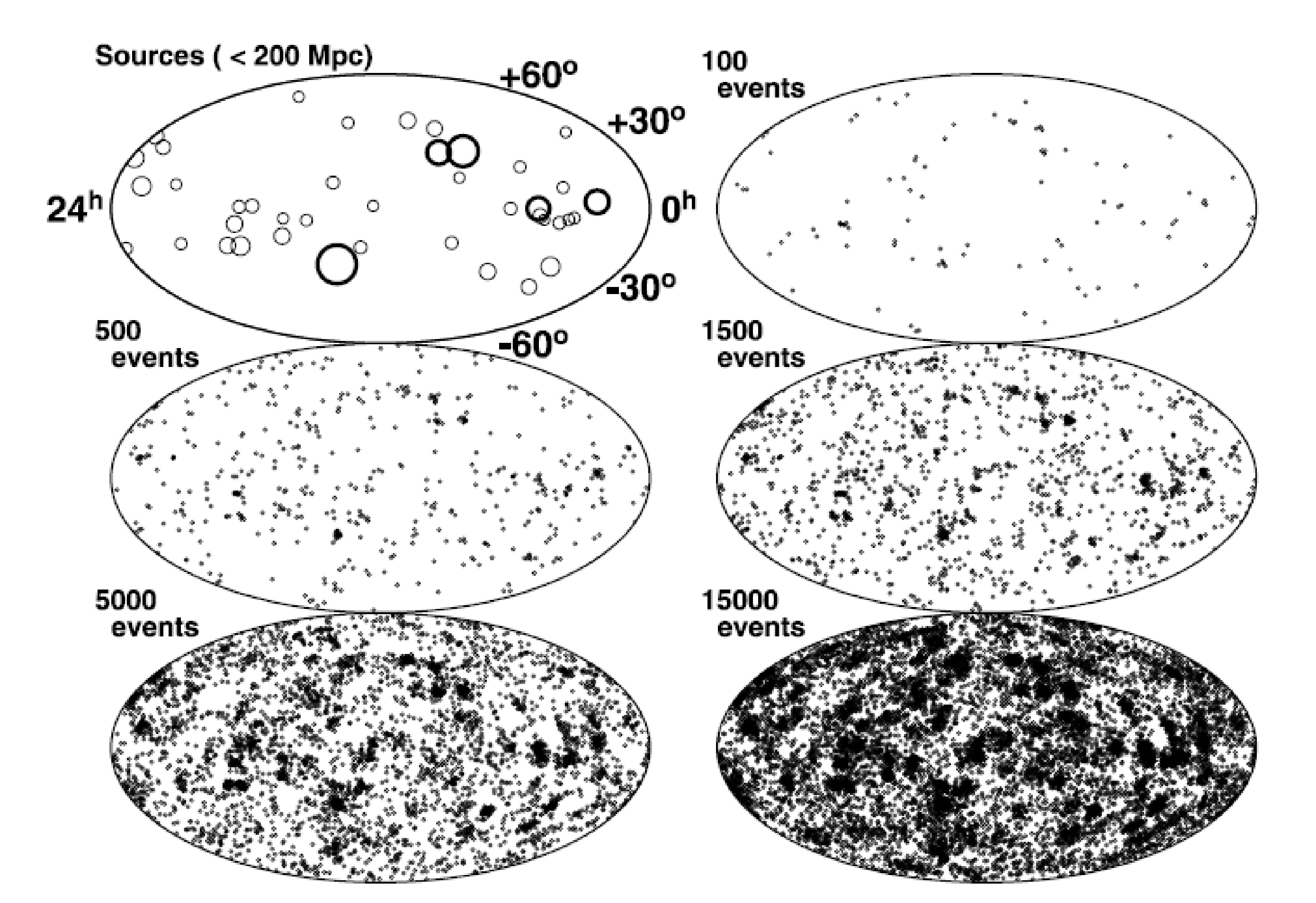
$$N(\theta) = \frac{1}{2\pi |\cos\theta - \cos(\theta + \Delta\theta)|} \sum_{\theta \le \phi \le \theta + \Delta\theta} 1 \ [{\rm sr}^{-1}],$$

Hatched region: Simulation.
Dots: Observations (HiRes)

Dots with error bars: Simulation.
Histgrams: Observations (AGASA)

An Example of Arrival Distribution of UHECRs

Yoshiguchi, S.N. Sato *ApJ* 592 (2003) 311



Arrival distribution
Will be correlated
With matter
distribution.

c.f.
102 events with
E>4*10^19eV are
Found by Auger
(Auger collabora-
Tion 2009).

FIG. 3.—Arrival directions of UHECRs above 4×10^{19} eV predicted by a specific source scenario when 1/50 of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ are selected as UHECR sources. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100 Mpc are shown with bold circles.

Important Players of This Game

- Observations as Normalization
  (Spectrum, Arrival Directions, Compositions)

Theoretical Future Predictions depend on Current Observations.

- Source Distributions/Properties
- B-Fields (EGMF/GMF)
- Composition of UHECRs (E/Z)

- Basic Data of Cross Sections & Branching Ratios of Photo-Nuclei Interactions

Future Collaboration with N. Globus

We are going to do latest, realistic Simulations of propagataion of UHECRs with Noemie Globus (NYU/ABBL).

Composition.
B-Fields.

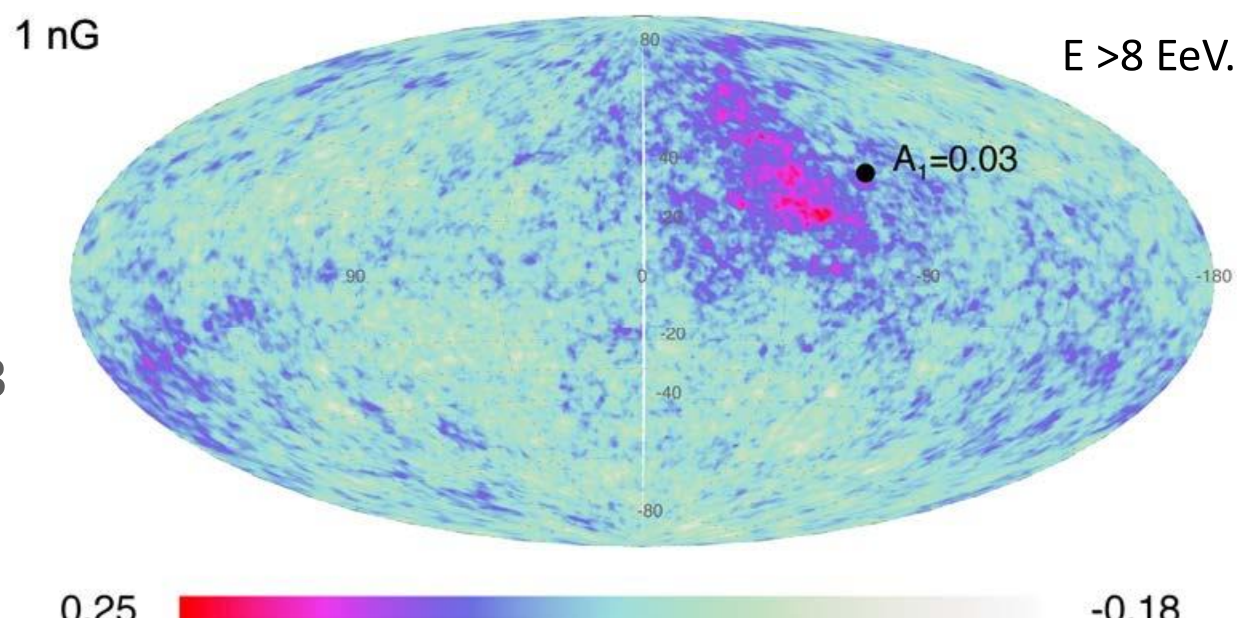
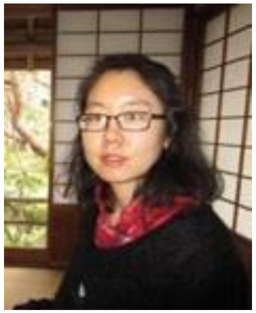


Figure from
Globus, Piran, + 2019
MNRAS 484, p.4167-4173

“The Possible Extragalactic Source of UHECRs at the Telescope Array Hotspot ”



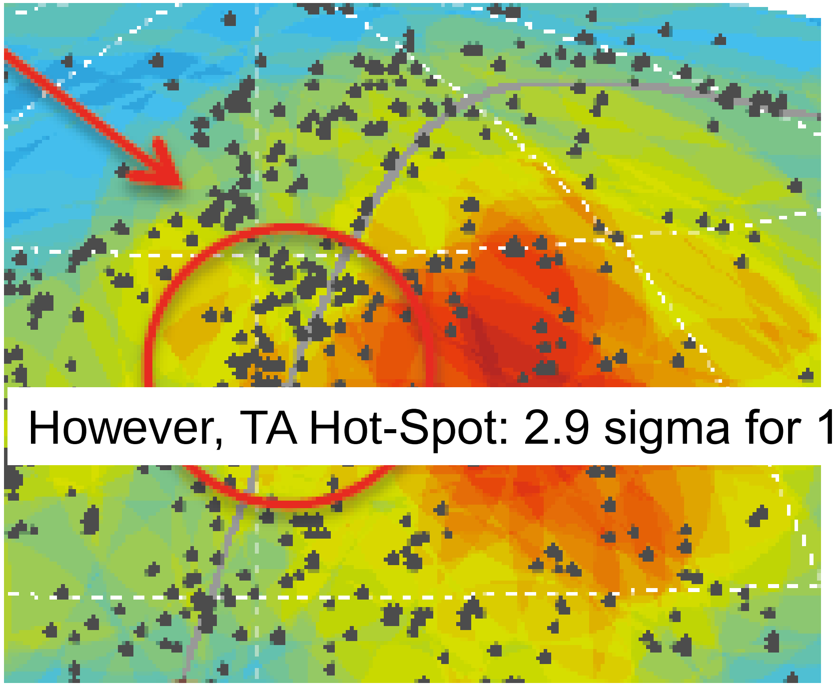
Hao-Ning He,[1,2] Alexander Kusenko,[1,3] Shigehiro Nagataki,[4] Bin-Bin Zhang,[5] Rui-Zhi Yang,[6,2] and Yi-Zhong Fan[2]

[1] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA*
[2] *Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*
[3] *Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
[4] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[5] *Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35899, USA*
[6] *Max-Planck-Institut für Kernphysik, P.O. Box 103980, 69029 Heidelberg, Germany*

Physical Review D, Volume 93, Issue 4, id.043011 (2016)

This study did not depend on numerical simulations. We discussed the TA hotspot phenomenologically.

Motivation & Method of This Study



However, TA Hot-Spot: 2.9 sigma for 11 years in 2020…

Kawata et al. @ ICRC 2015

Black Dots are nearby galaxies.
Grey line represents the Super-Galactic-Plane.

Is the Source of the Hot Spot in the Spot?

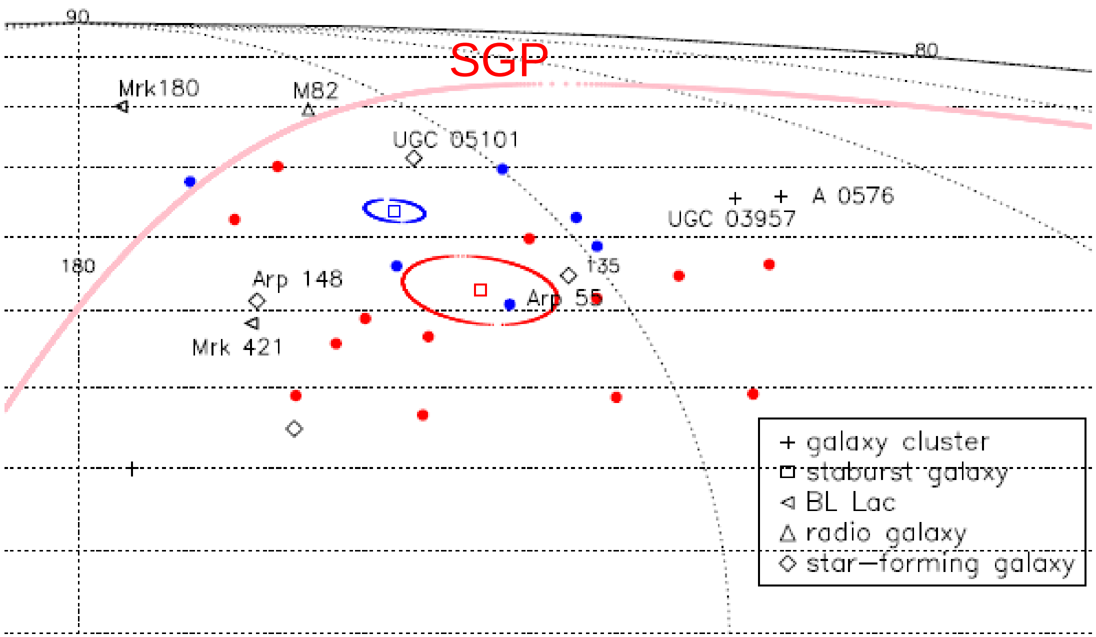
Or,

Is the Source away from the Spot due to B-Fields?

Before going to detailed numerical simulations,
We did some simple analysis, and found some
Very Interesting Implications.

Our First Analysis

- Data Sample: 72 Events with > 57EeV (5 years, TA-Collaboration ApJ 2014.)
- We analyzed the 19 events of the hot-spot.



Blue: Events with > 75EeV (High Rigidity).

Red: Events with < 75EeV (Low Rigidity).

Circles represent the mean Positions of the events.

The Source is at around The Super-Galactic-Plane?

Hao-Ning He,[1,2] Alexander Kusenko,[1,3] Shigehiro Nagataki,[4] Bin-Bin Zhang,[5] Rui-Zhi Yang,[6,2] and Yi-Zhong Fan[2]

Magnetic Bending Effects

Effect of Regular Field:

$$\delta_{\rm reg} \simeq 0.5^\circ Z \frac{100\,{\rm EeV}}{E} \frac{D_{\rm reg}}{1{\rm Mpc}} \frac{B_{{\rm reg},\perp}}{1{\rm nG}} = A_1 \times \frac{100\,{\rm EeV}}{E}$$

$$A_1 = 0.5^\circ Z \frac{D_{\rm reg}}{1{\rm Mpc}} \frac{B_{{\rm reg},\perp}}{1{\rm nG}}$$

$D_{\rm reg}$: Propagation length
In the regular B-field.

Effect of Random Field:

$$f(\delta_{\rm dif}, \delta_{\rm rms}) = \frac{1}{\delta_{\rm rms}\sqrt{2\pi}} exp\left(-\frac{\delta_{\rm dif}^2}{2\delta_{\rm rms}^2}\right)$$

Probability of Bending Angle: $\delta_{\rm dif}$

$$\delta_{\rm rms} \simeq 0.36^\circ Z \frac{100\,{\rm EeV}}{E} \left(\frac{D_{\rm dif}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}}$$

$$= A_2 \times \frac{100\,{\rm EeV}}{E}$$

$$A_2 = 0.36^\circ Z \left(\frac{D_{\rm dif}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \left(\frac{D_{\rm c}}{1{\rm Mpc}}\right)^{\frac{1}{2}} \frac{B_{\rm rms}}{1\ {\rm nG}}$$

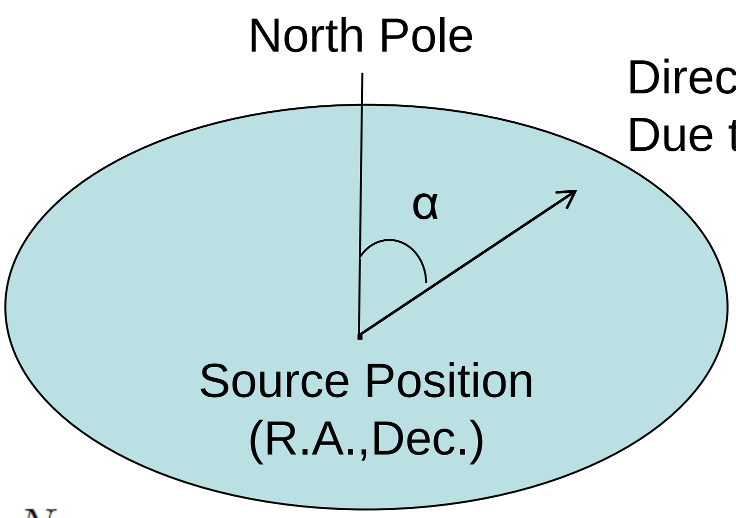
$D_{\rm dif}$: Propagation length
In the random B-field.

$D_{\rm c}$: Coherent length
of the random B-field.

Monte Carlo Fitting Engine

Probability for i-th UHECR arrives at the Earth from the observed direction
From the source at (R.A.,Dec.) with A1, A2, and α.

$$f_i(\delta_{\mathrm{reg},i}(\mathrm{R.A.}, \mathrm{Dec.}, \alpha, A_1), \delta_{\mathrm{rms},i}(A_2))$$



Direction of Shift of UHECR
Due to the Regular Field

We assumed that a single source
Is contributing to the TA Hot-Spot.

$$P \propto \prod_{i=0}^{N} f_i$$

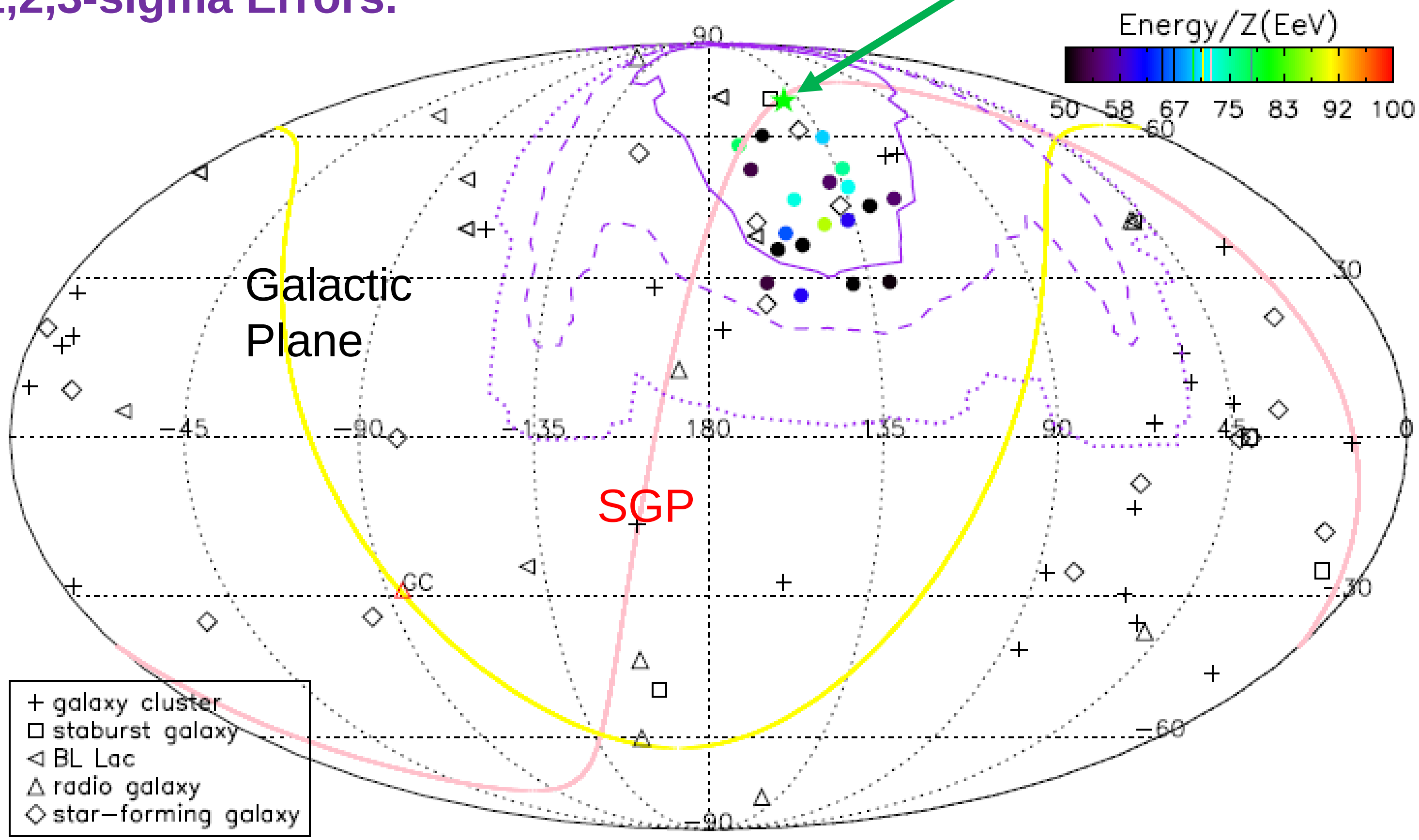
Total Probability.
N (=19) is the number of the events in the hot-spot.

→ By the Monte-Carlo likelyhood fitting, we can obtain the best values for (R.A.,Dec.,A1, A2, α) (Zhang et al.15; Feroz & Hobson 08).

The Source is on the SGP?

The most likely Source Position As a Result of Our Analysis.

Purple Lines are Source Positions With 1,2,3-sigma Errors.



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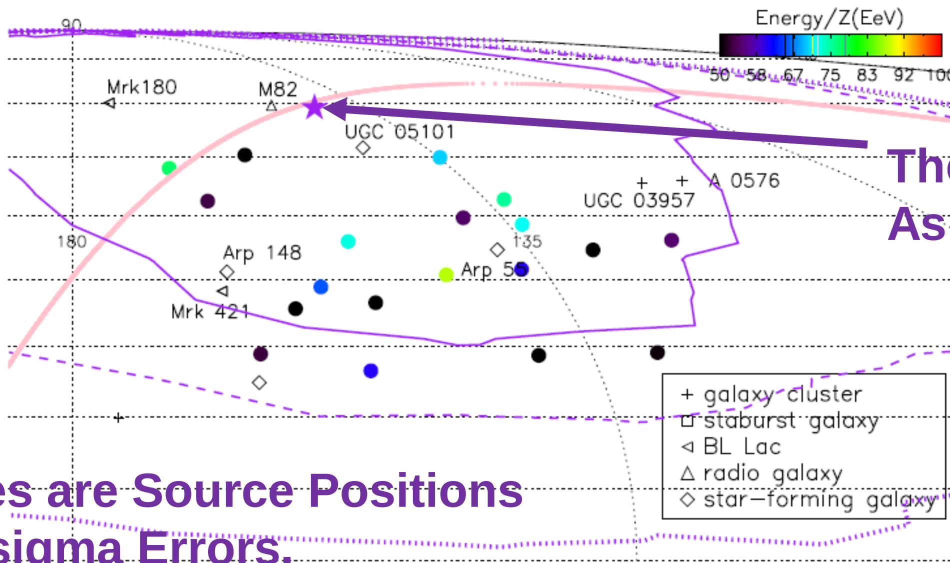
The Source is on the SGP?



The most likely Source Position As a Result of Our Analysis.

M82 is very Close from the most likely Source Position!

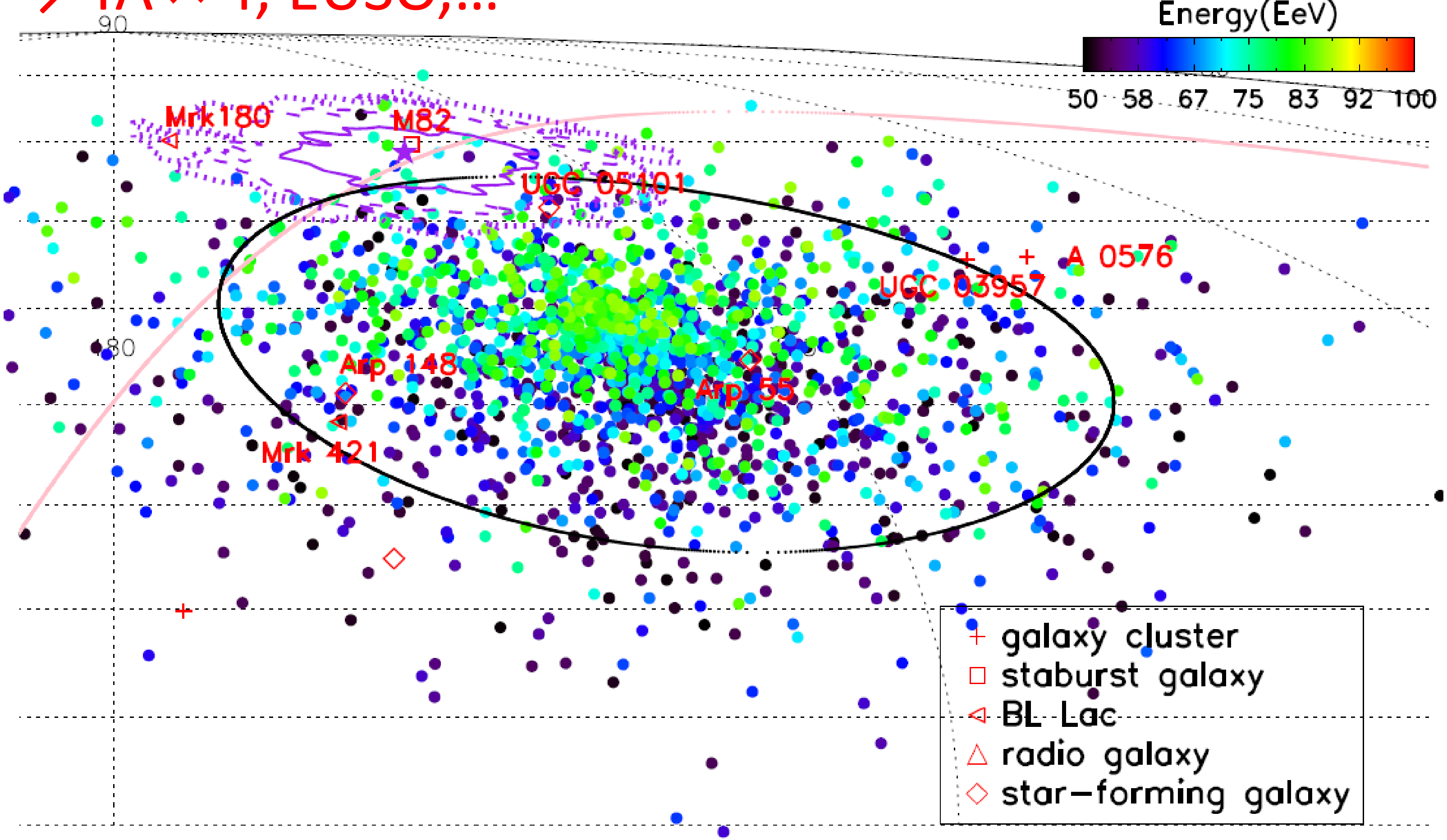
Purple Lines are Source Positions With 1,2,3-sigma Errors.

Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\mathrm{bes-fit}}$ (%)
best-fit	-	-	$17.4^{+17.0}_{11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	67.4
A 0576	galaxy cluster	169.0	17.0	9.4	63.4
Arp 55	star-forming Galaxy	162.7	1.9	9.7	55.3
Arp 148	star-forming Galaxy	143.3	10.5	10.0	41.8
Mrk 421	blazar	134	11.2	9.9	35.6

M82

Discussion - I

We can Identify the Source if we have 2000 Events.
→ TA × 4, EUSO,...



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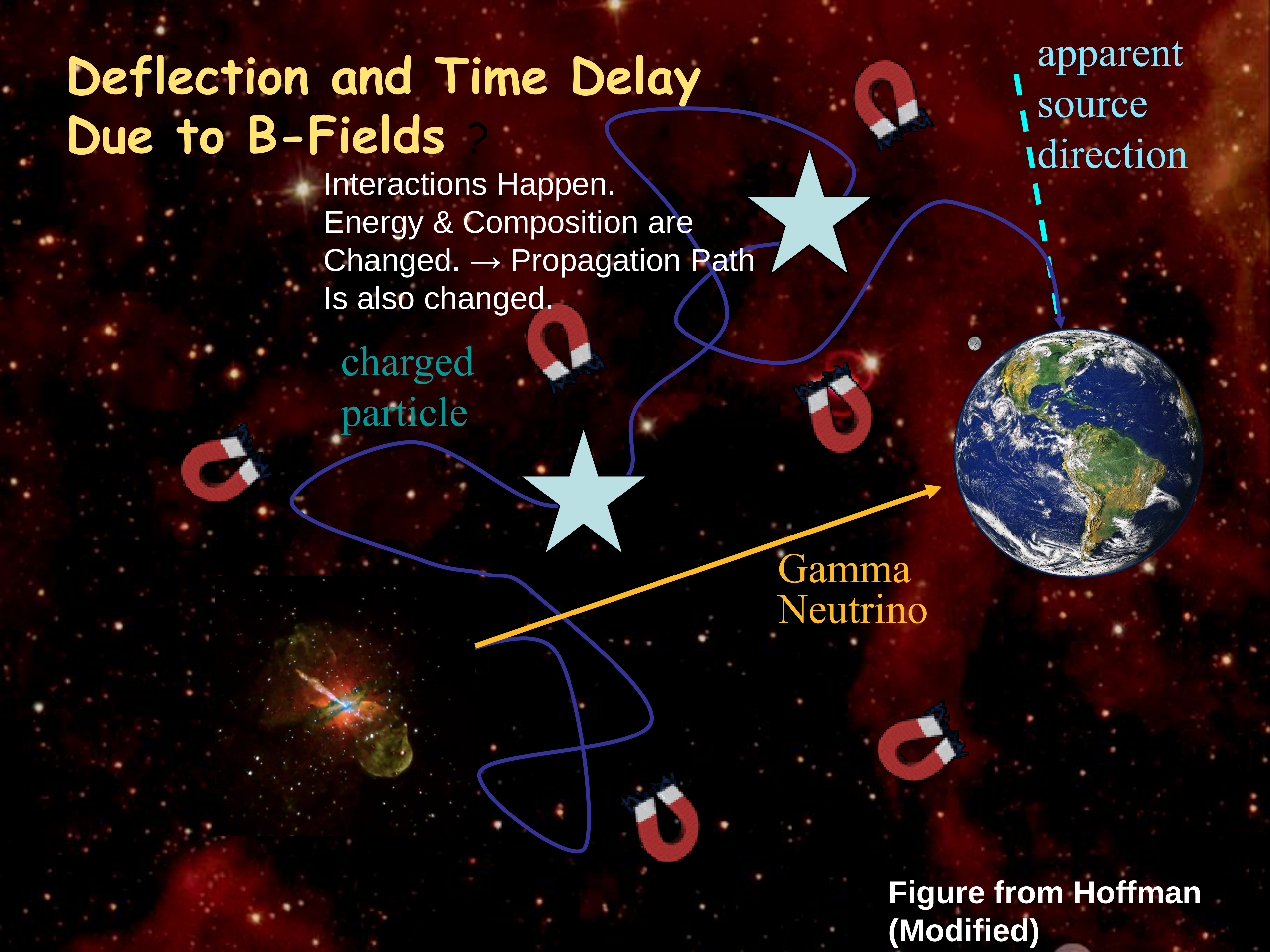
§ Improvement of Basic Data: UHECRs from Nuclear Physics Point of View

New Project “PANDORA”
Photo-Absorptions of Nuclei and Decay Observation for Reactions in Astrophysics


Deflection and Time Delay
Due to B-Fields ?
Interactions Happen.
Energy & Composition are
Changed. → Propagation Path
Is also changed.
charged
particle
apparent
source
direction
Gamma
Neutrino
Figure from Hoffman
(Modified)

PANDORAプロジェクト状況報告

Atsushi Tamii

Research Center for Nuclear Physics (RCNP)
Osaka University, Japan

r-EMU Informal Meeting, Aug 8, 2020 by Zoom

PANDORA Project: Organization

Since 2019

Nuclear Experiments

RCNP	*Osaka Univ.* A. Tamii, N. Kobayashi, T. Sudo, Z. Yang, T. Furuno, M. Murata, A. Inoue, H. Mori
ELI-NP	*ELI-NP* D. Balabanski, P.-A. Söderström, L. Capponi, T. Petruse, D. Nichita, Y. Xu
iThemba LABS	*iThemba LABS, Witswatersland Univ., Stellenbosh Univ.* L. Pellegri, R. Neveling, F.D. Smit, J.A.C. Bekker, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya
TU-Darmstadt	P. von Neumann-Cosel, N. Pietralla, J. Isaak

Nuclear Theory

AMD	M. Kimura, Y. Taniguchi, H. Motoki	**Antisymmetrized Molecular Dynamics**
NRFT	E. Litovinova, P. Ring, H. Wibowo	**Nuclear Relativistic Field Theory**
TALYS	S. Goriely, E. Khan	

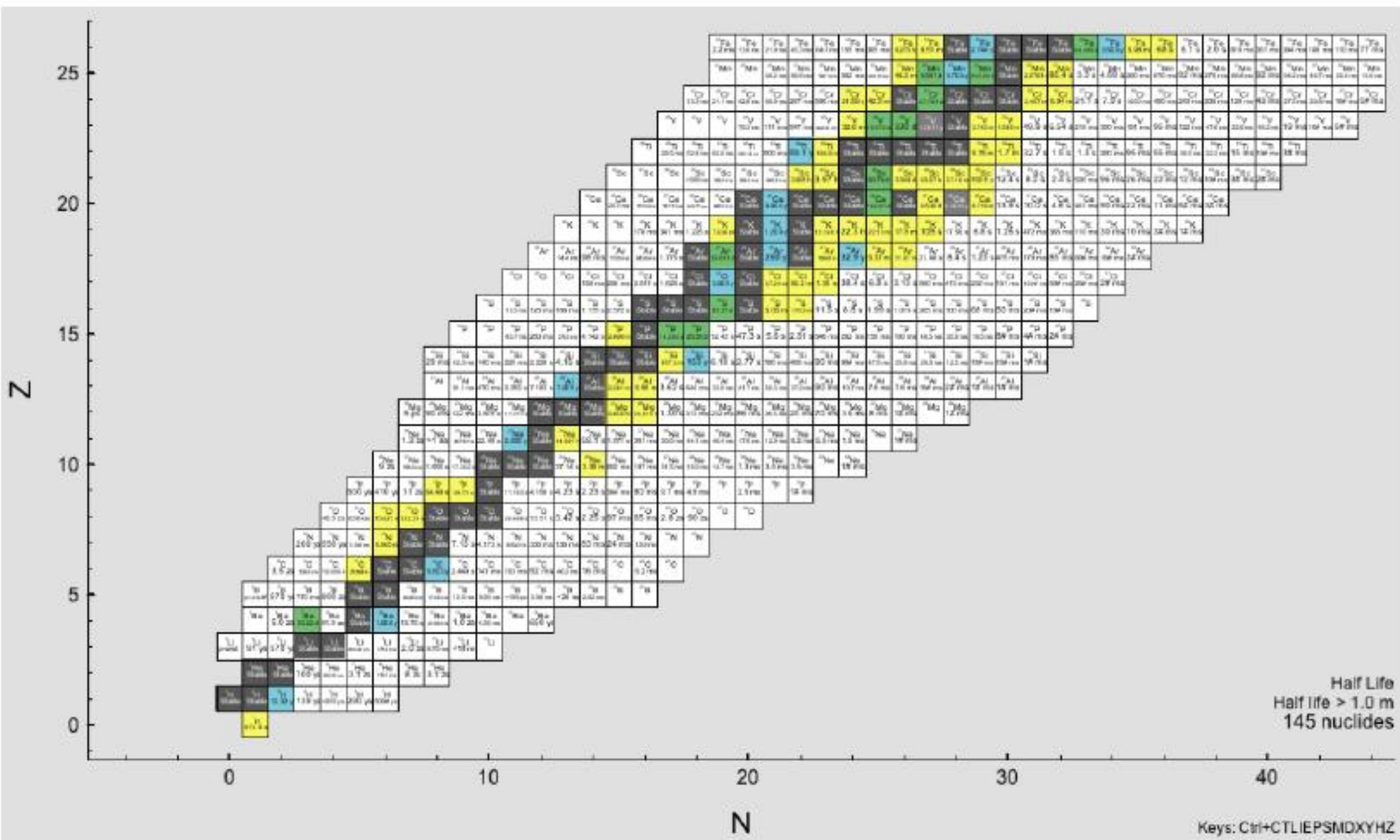
UHECR Theory

Propagation	D. Allard, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff
Production	S. Nagataki, J. Oliver, H. Haoning E. Kido

NC Neutrino Detection Y. Koshio, M. Sakuda, M.S. Reen

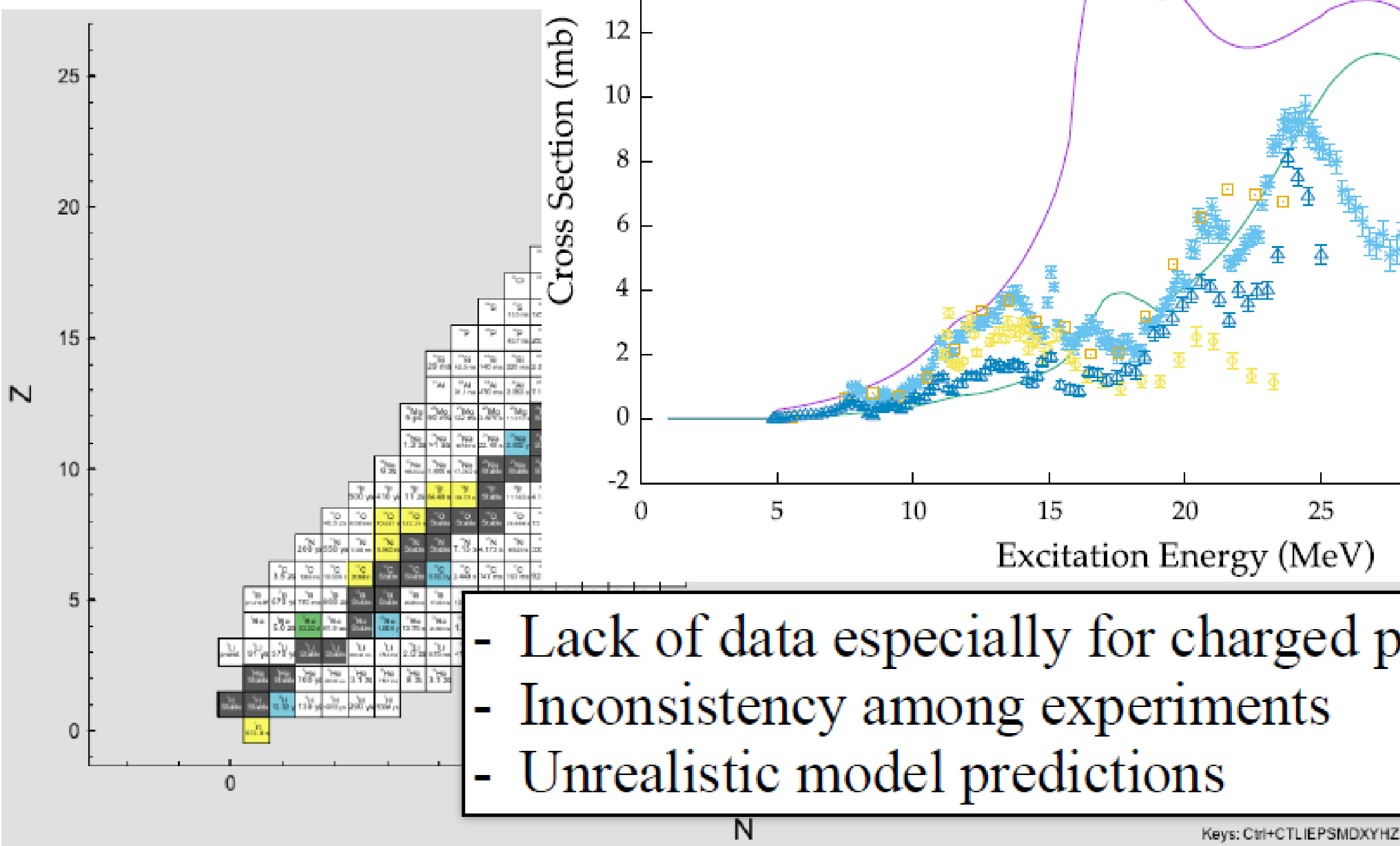
Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

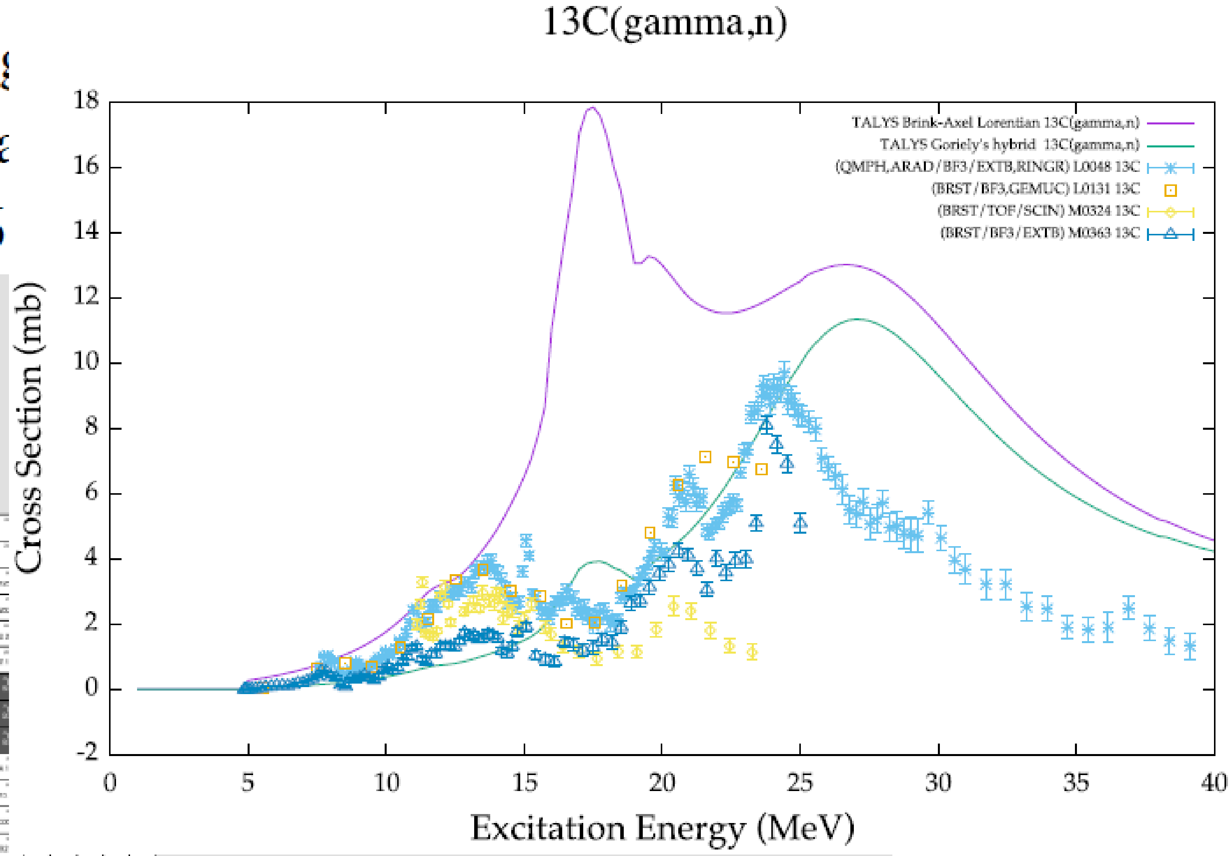
- photo-absorption (electric dipole) strength distribution
- n, p, α, γ decay branching ratios
- for stable nuclei from light to A~56



Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

- E1 excitation stren
- n, p, α, γ decay bra
- from light to A~56

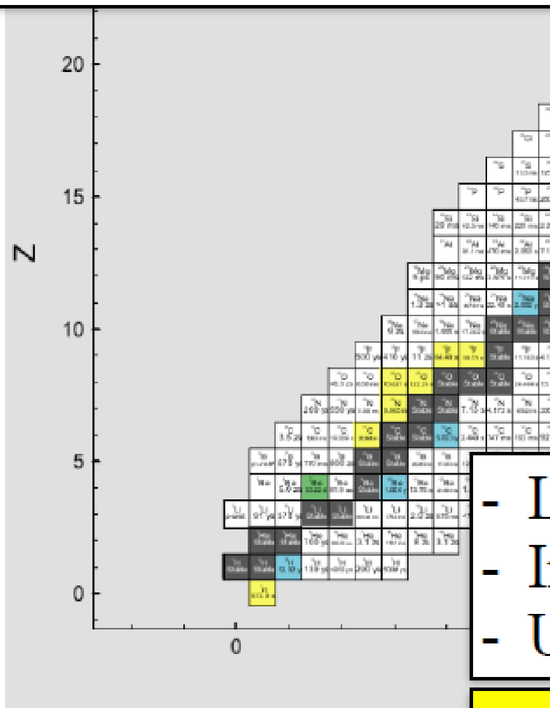


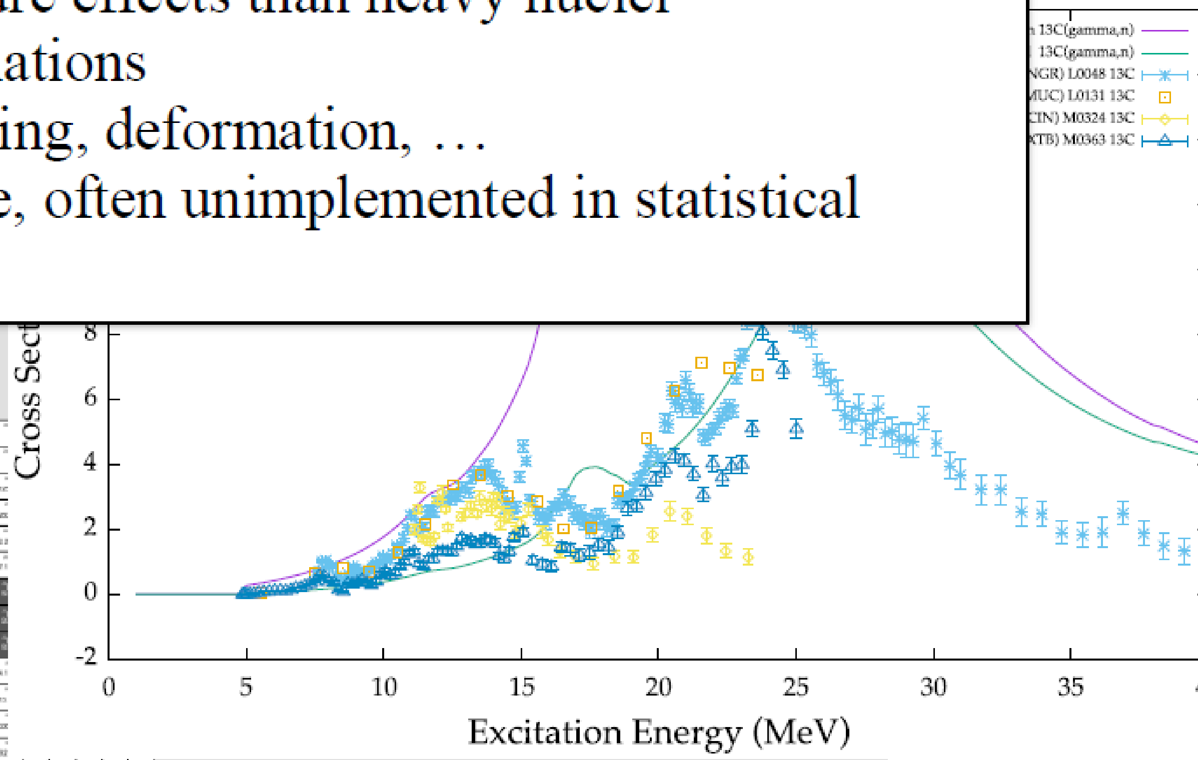


- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

difficulties in theoretical modeling of light-medium mass nuclei
- stronger shell structure effects than heavy nuclei
- many-nucleon correlations
  α-clustering, *np*-pairing, deformation, …
- isospin selection rule, often unimplemented in statistical calculations.





- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

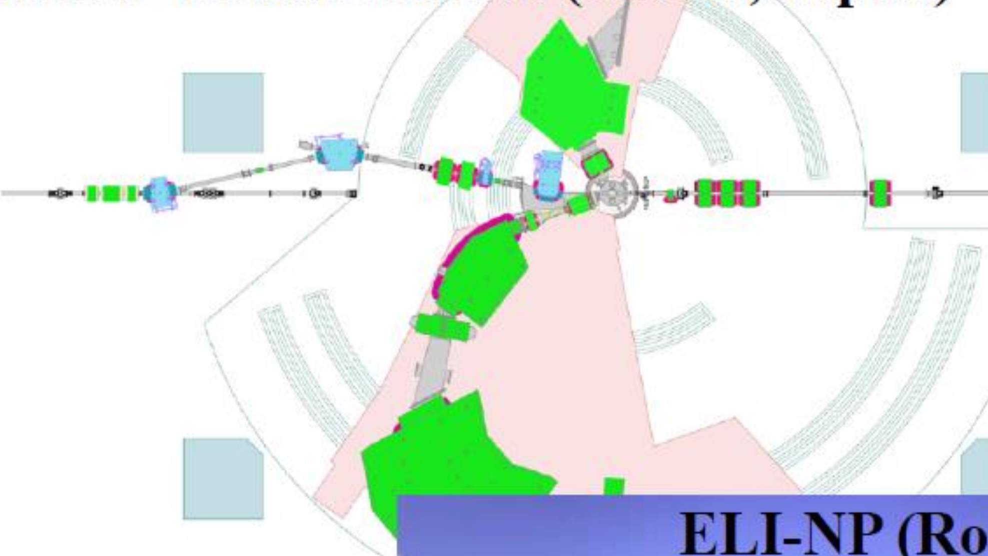
We need good systematic data and reliable models!

PANDORA Project

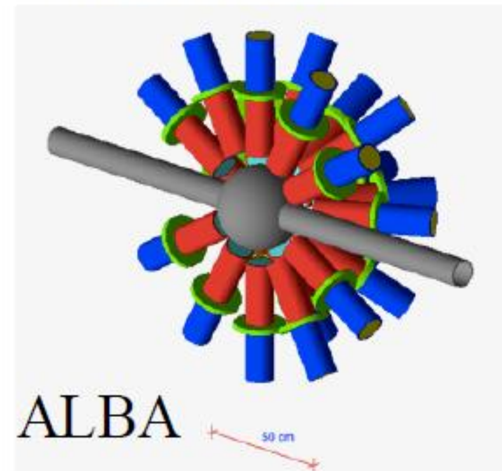
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Joint project among three experimental facilities with nuclear theories and astrophysical simulations

RCNP-Grand Raiden (Osaka, Japan)

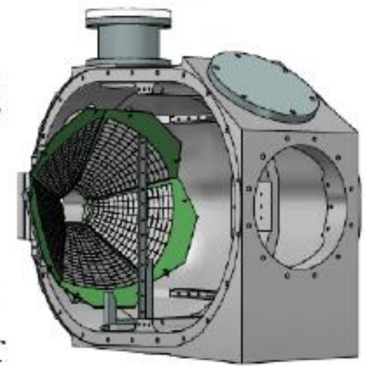


iThemba LABS South Africa



ELI-NP (Romania)

CAKE



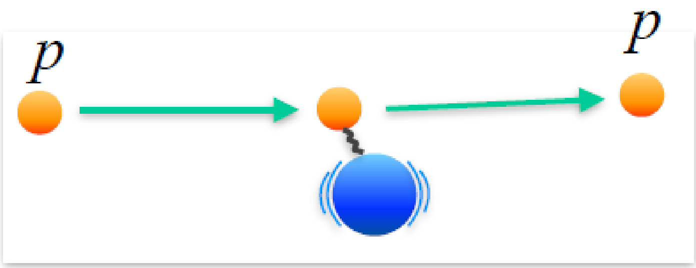
decay charge particle detector array

complementary experimental techniques

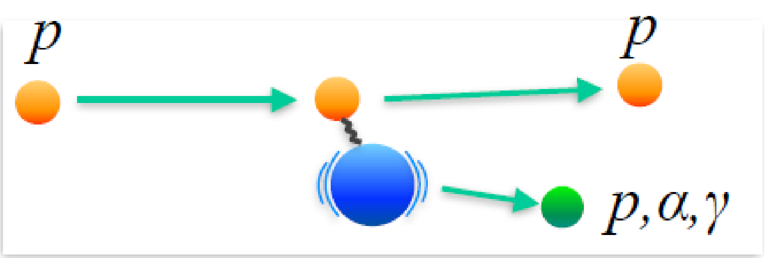
Probing Photo-Nuclear Response of Nuclei

Virtual photo excitation by proton scattering

- Missing mass method
  with proton Coulomb excitation

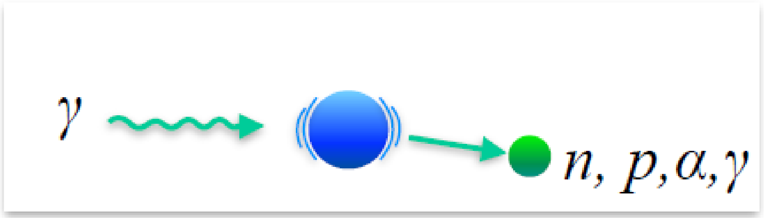


- better for total strength
  and strength distribution
  higher cross sections
  also applicable for p,α,γ decays



Real photo excitation

- Gamma-beam by laser-Compton
  scattering with an electron beam



- individual decay channels
  better for absolute normalization
  applicable also for *n* and *xn* decays in addition to p,α,γ

Input from & Feedback to Nuclear Theories

Recent advances and perspectives of cluster physics

M. Kimura (Hokkaido Univ.)

Model: Real-Time evolution method

◎ Model wave function (time-dependent wave packets)

○ Slater determinant of nucleon wave packets

$$\Phi(t) = \mathcal{A}\{\,\phi(\boldsymbol{Z}_1(t)), \ldots, \phi(\boldsymbol{Z}_A(t))\,\}$$

$$\phi(\boldsymbol{Z}_i(t)) = \exp\{\,-\nu(\boldsymbol{r} - \boldsymbol{Z}_i(t))^2\,\}\,(\alpha_i(t)\,|\uparrow\rangle + \beta_i(t)\,|\downarrow\rangle)$$

○ Dynamical variables of the model (time-dependent parameters)

$\boldsymbol{Z}_i(t)$: Centroids of wave packets (position and momentum)

$\alpha_i(t)\ \beta_i(t)$: Spin directions

◎ Hamiltonian

$$H = \sum_{i=1}^{A} t(i) - t_{cm} + \sum_{i<j}^{A} v(ij)$$

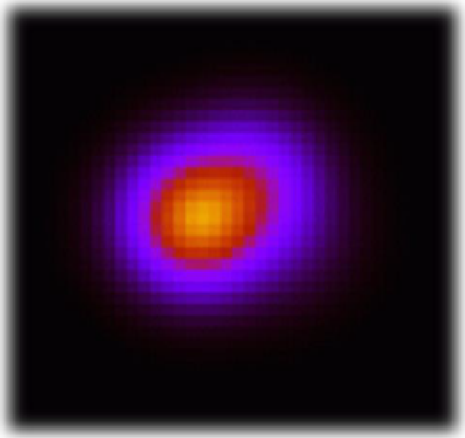
○ Microscopic Hamiltonian with effective/bara NN interactions

Model: Real-Time evolution method

◎ Time-dependent variational principle

$$\delta \int dt \frac{\langle \Phi(t) | i\hbar d/dt - H | \Phi(t) \rangle}{\langle \Phi(t) | \Phi(t) \rangle} = 0$$

^{6}He (6 nucleons)

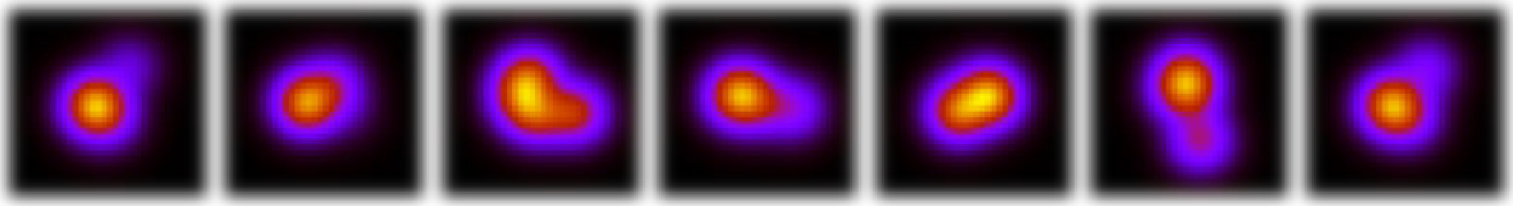


◎ Equation of Motion for nucleon wave packets

$$\Rightarrow \quad i\hbar \frac{d\boldsymbol{Z}_i(t)}{dt} = \sum_j C_{ij}^{-1} \frac{\partial \mathcal{H}}{\partial \boldsymbol{Z}_j^*(t)}$$

$$\mathcal{H} = \frac{\langle \Phi(t) | H | \Phi(t) \rangle}{\langle \Phi(t) | \Phi(t) \rangle}, \quad C_{ij} = \frac{\partial^2}{\partial \boldsymbol{Z}_i^* \partial \boldsymbol{Z}_j} \log \langle \Phi(t) | \Phi(t) \rangle$$

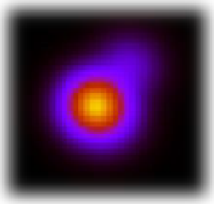
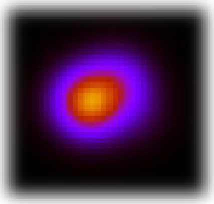
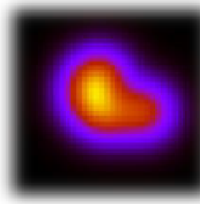
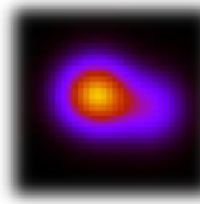
○ By solving EOM, we obtain ensemble of wave functions



t = 0 fm/c 100 fm/c 200 fm/c 300 fm/c 400 fm/c 500 fm/c 600 fm/c …

Model: Real-Time evolution method

◎ We superpose time dependent wave function and diagonalize the Hamiltonian

$\Psi^{J\pi} = f_1$  $+ f_2$  $+ f_3$  $+ f_4$  $\cdots$

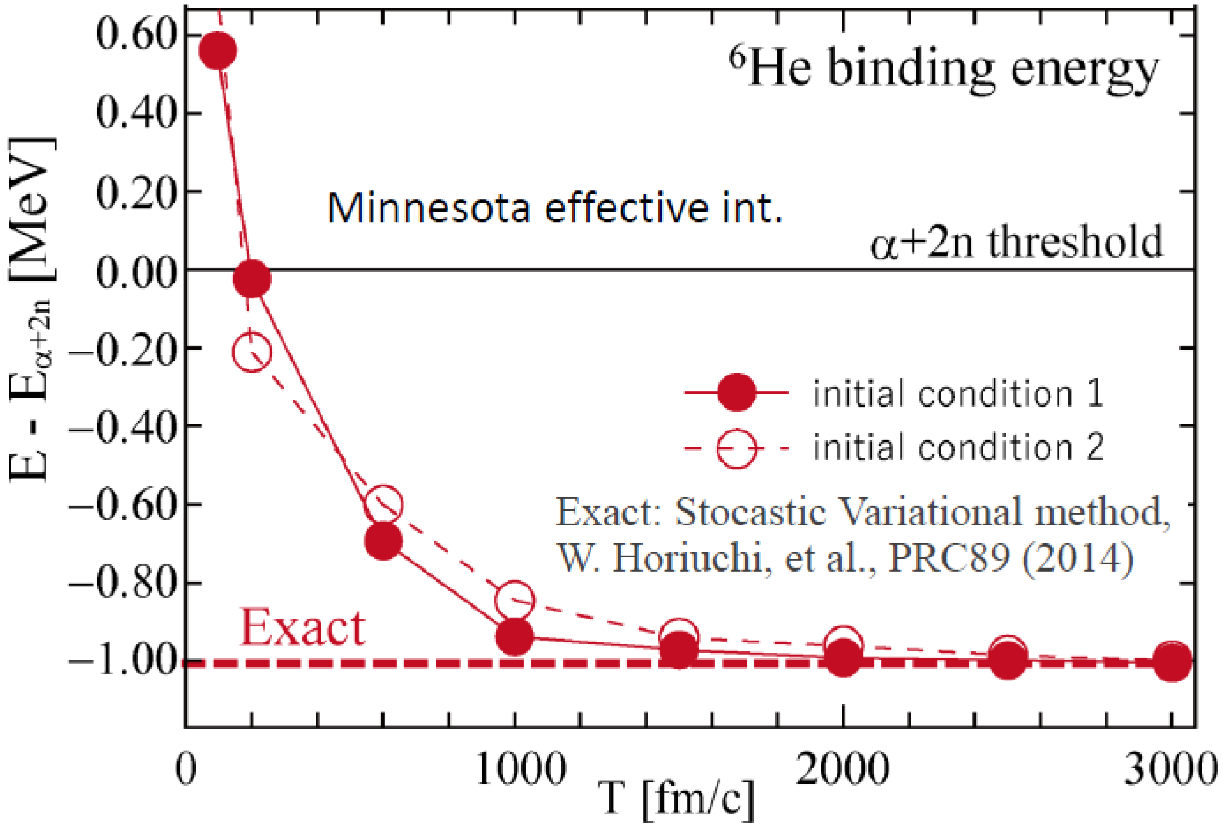
$$= \int_0^{T_{max}} dt\ f(t) \hat{P}^J_{MK} \Phi(t)$$

$f_1, f_2, f_3, f_4, \ldots$ are determined by the diagonalization of Hamiltonian

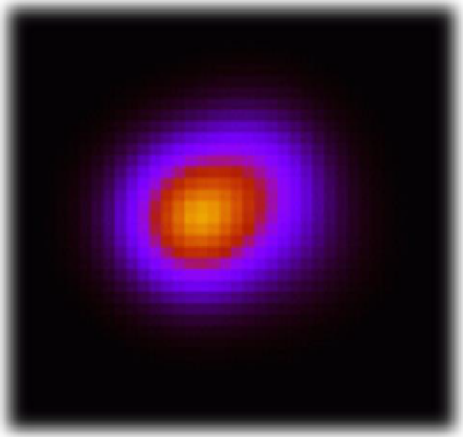
○ The result (eigen energy & wave function) should be converged after the long-time propagation

○ The result should not depend on the initial condition at t=0

Benchmark calculations for few-body systems



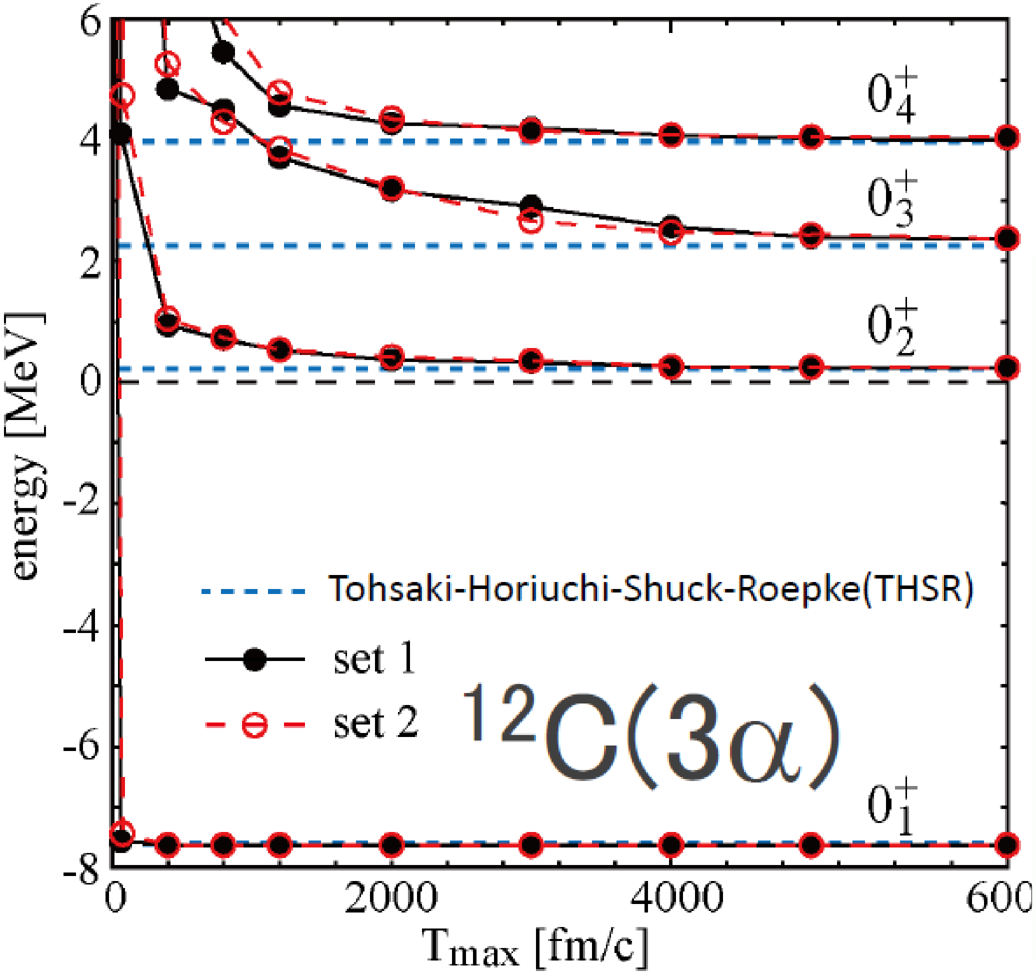
^{6}He (6 nucleons)



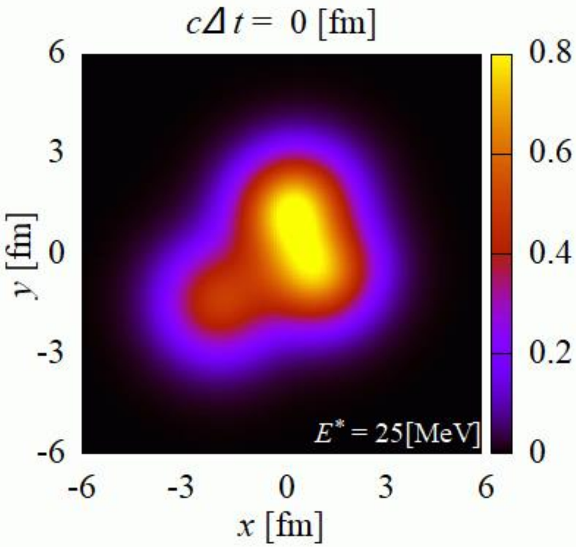
	S_{2n}	proton radii	neutron radii
REM	−1.01 MeV	1.83 fm	2.64 fm
Exact	−1.01 MeV	1.83 fm	2.65 fm

Benchmark calculations for ^{12}C (3α cluster system)

R. Imai, T. Tada and M.K., arXiv:1802.03523



$$\Psi^{J\pi} = \int_0^{T_{max}} dt \; f(t) \hat{P}^J_{MK} \Phi(t)$$



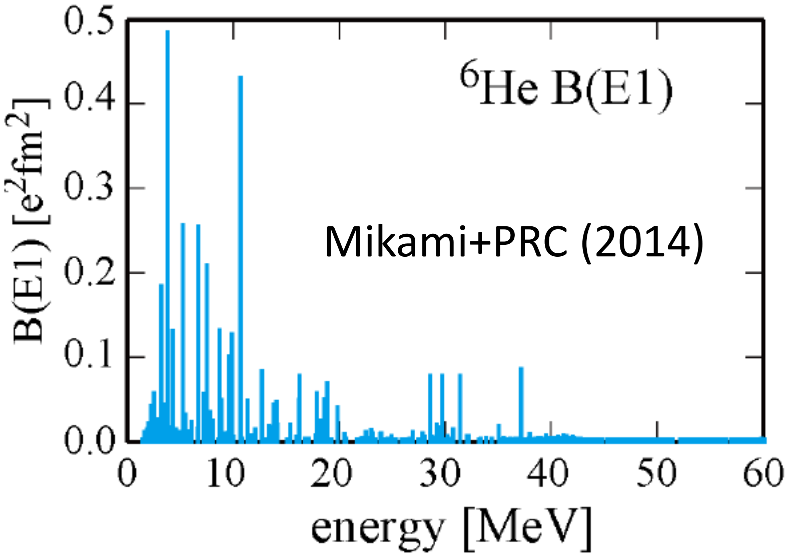
Cross Sections & Branching Ratios

Cross Sections
(Excitation)

$$B(E1;0_1^+ \to 1_n^-) = \sum_\mu |\langle \Psi_n^{1^-\mu} | \mathcal{M}_\mu(E1) | \Psi_1^{0^+0} \rangle|^2$$

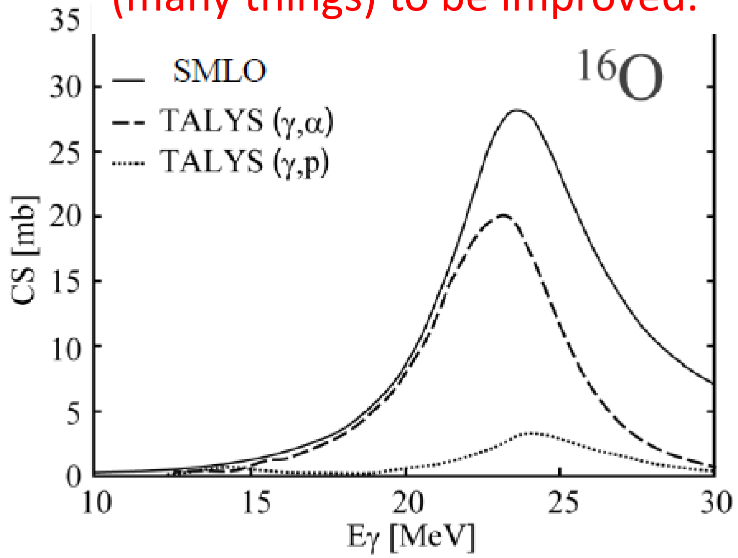
Branching Ratio
(On-Going)

$$\Gamma = 2P_\ell(a)\frac{\hbar^2}{2\mu a}|ay_\ell(a)|^2 \qquad ry_\ell(r) = r\sqrt{\frac{A!}{A_1!A_2!}}\langle Y_\ell(\hat{r})\phi_{A_1}\phi_{A_2}|\Psi\rangle$$



Cross Section for Excitation

TALYS Data contain something (many things) to be improved.



Cross Section + Branching Ratio

Summary: What can we do to identify the sources of UHECRs?

- More Observations. Higher Statistics: Astrophysics, Observations. →EUSO, TA4
- Simulations of Propagation of UHECRs and comparison with the observations: Astrophysics, Theory.
- Improvement of Basic Data (ex. Cross Sections & Branching Ratios of Photo-Nuclei Interactions): Nuclear Physics