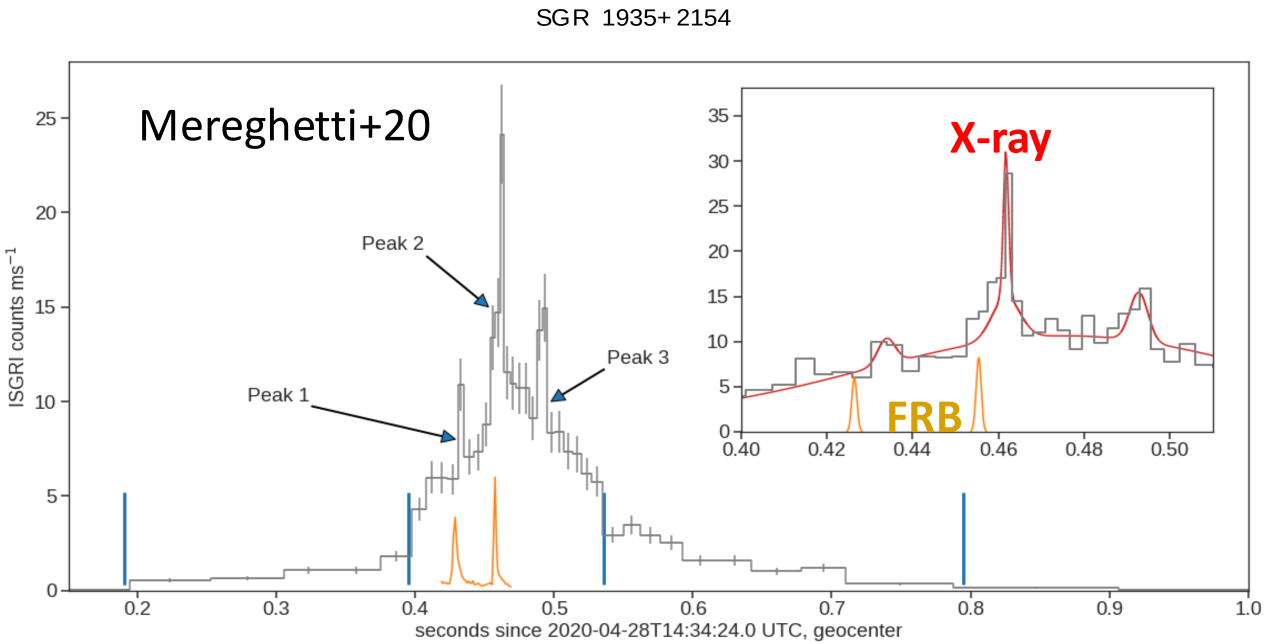
強磁場中性子星でのAmaterasu-like宇宙線加速の可能性

Jiro Shimoda & Tomoki Wada

空気シャワー研究会,
ICRR, 2025, March, 25



←Sample of Magnetar Burst SGR 1935+2154

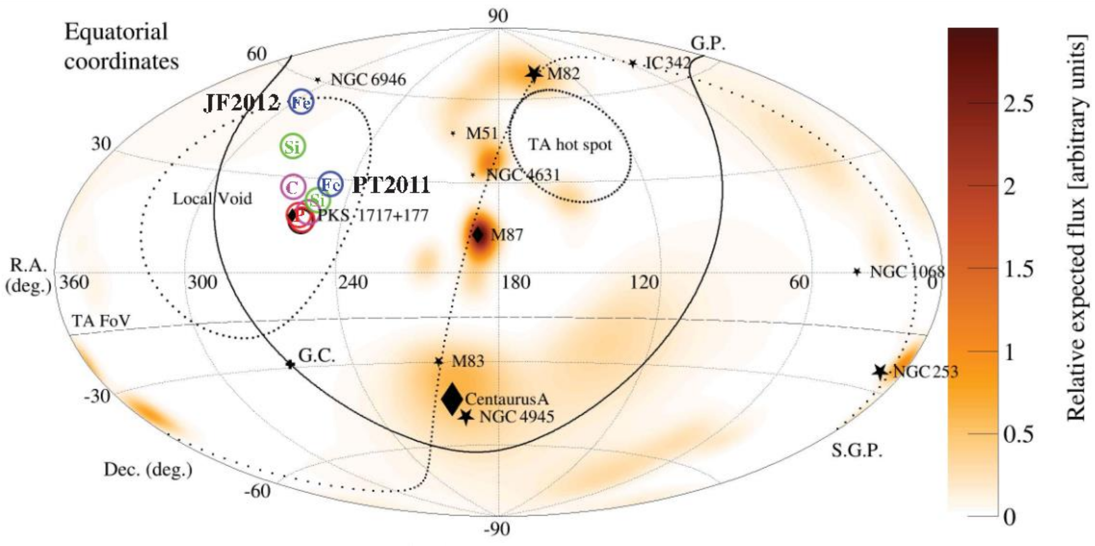
- Trigger Mechanism？
- Particle acceleration？

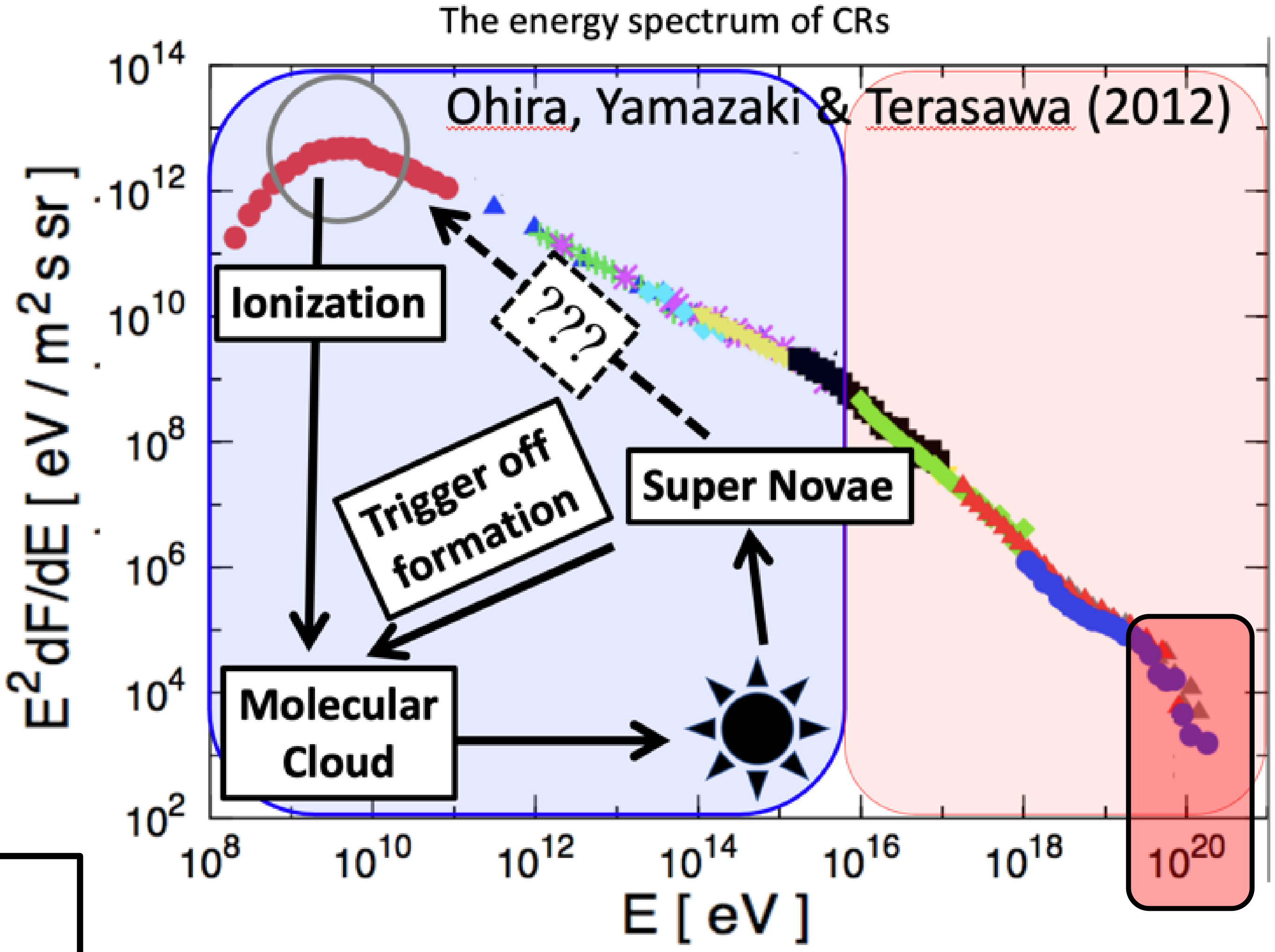
Highest Energy Cosmic Rays (>100 EeV)

TA collaboration (2023)

2021 May 27th 10:35:56 (UTC)

Amaterasu (the highest-energy CRs)





Energy~200 EeV ($2*10^{20}$ eV)!

m.f.p. ~ 1-10 Mpc (by photon)

The Origin & Acceleration Mechanism Remain a BIG MYSTERY.

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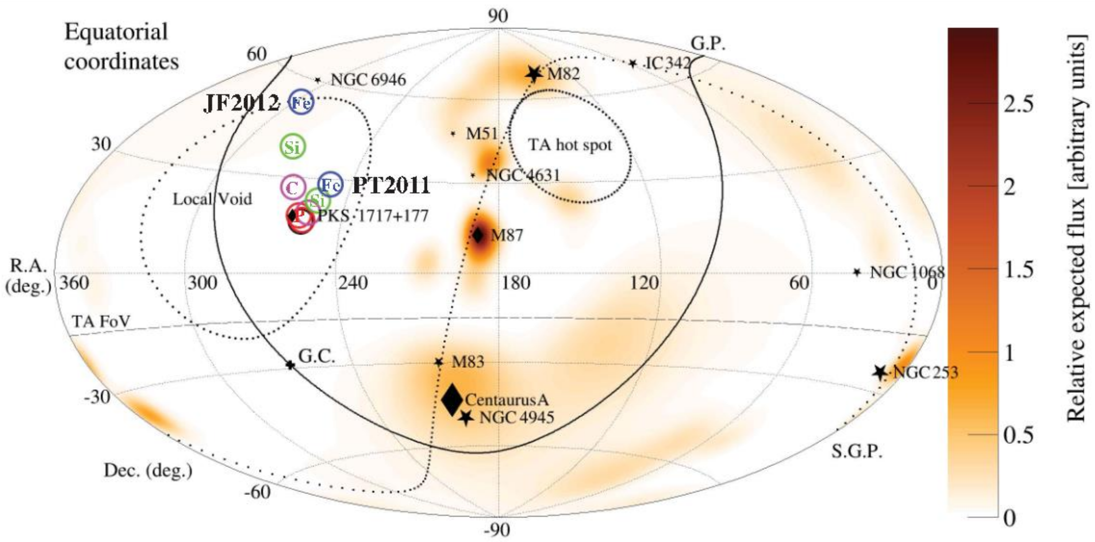
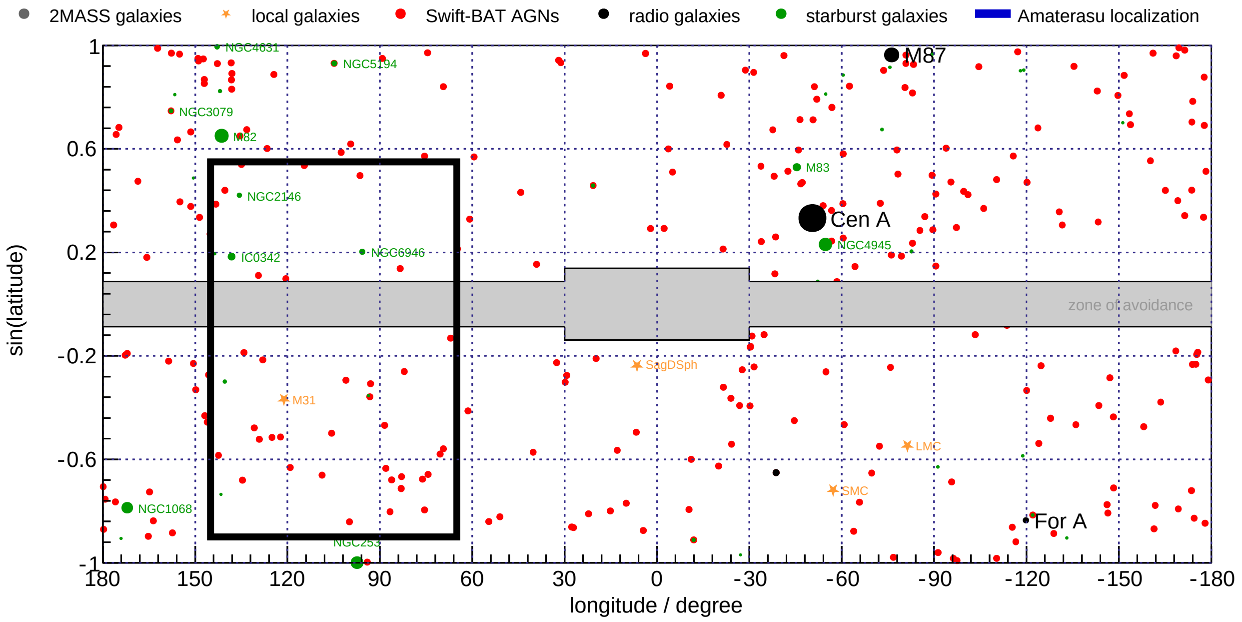


Source Candidates of Amaterasu



(a) Distribution of galaxies up to $D =$ 125 Mpc. The area zoomed in the lower panels (b)-(e) is indicated by a black rectangle.

Unger & Farrar (2024) state
no candidate among powerful radio galaxies.
They support the Transients Scenario.

Highest Energy Cosmic Rays (>100 EeV)

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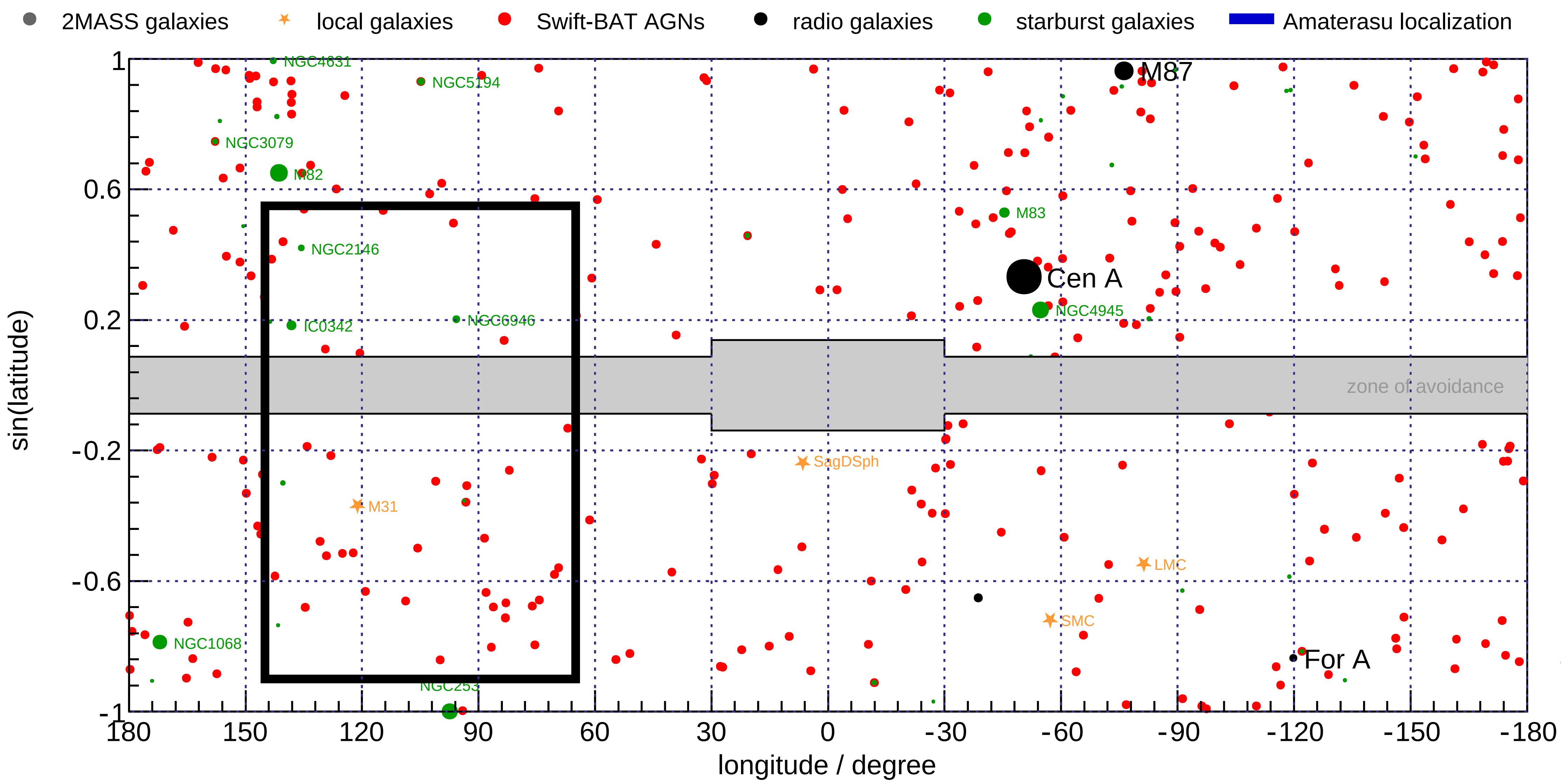

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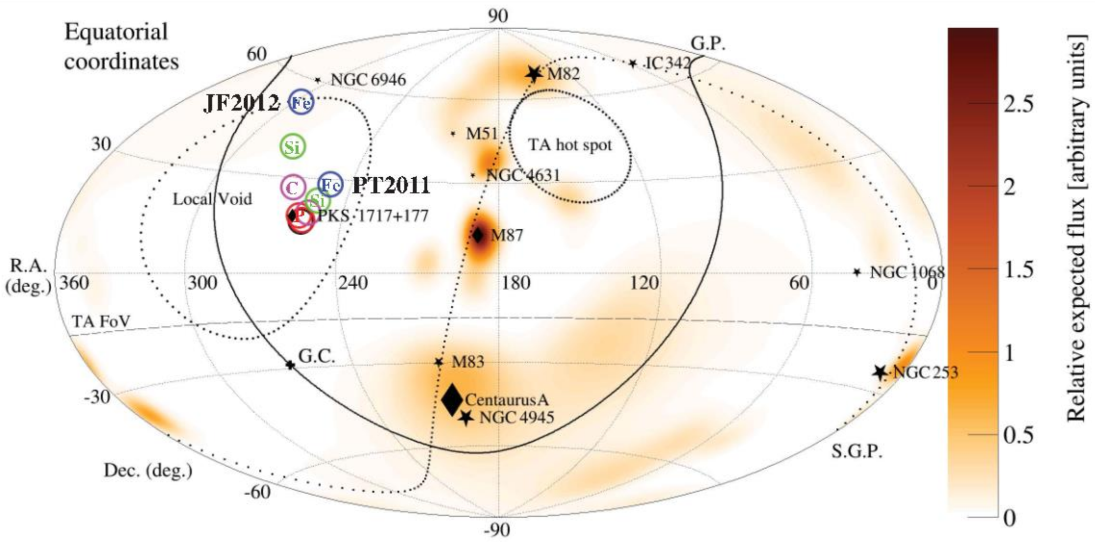

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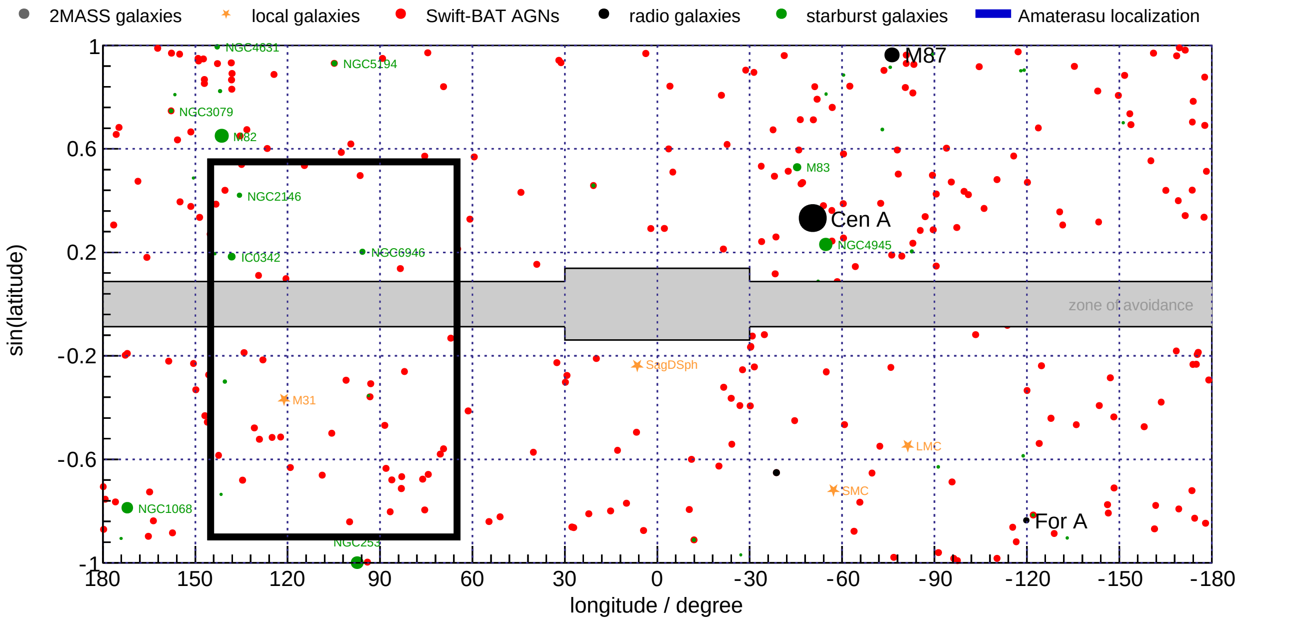

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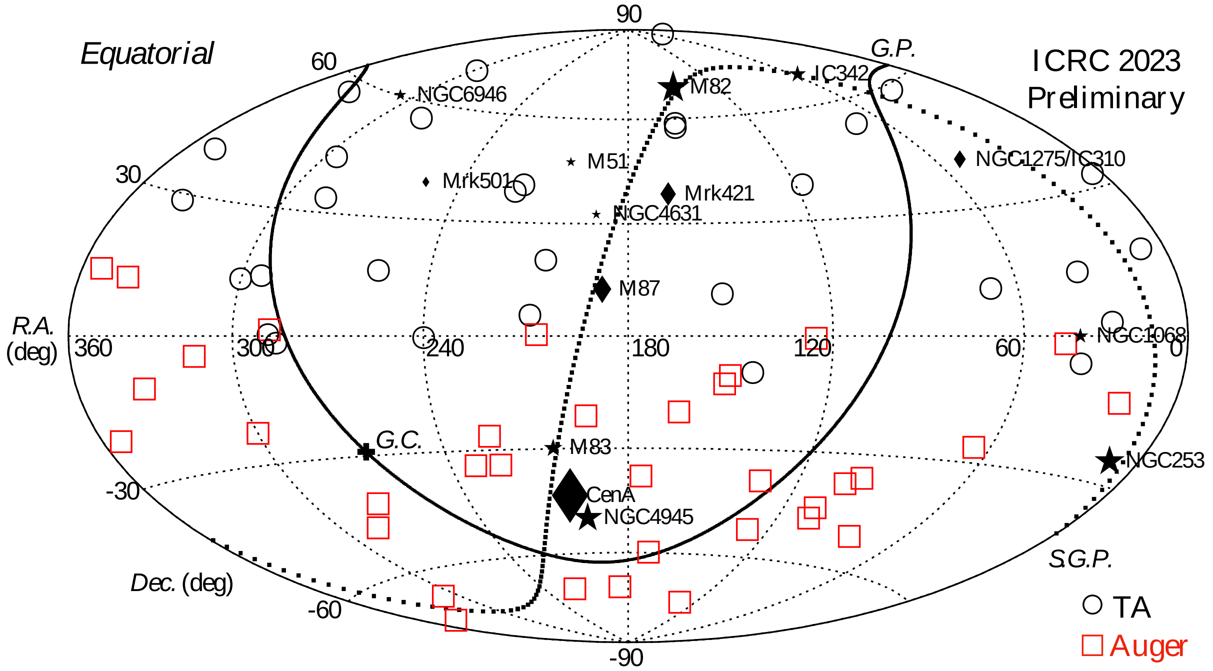
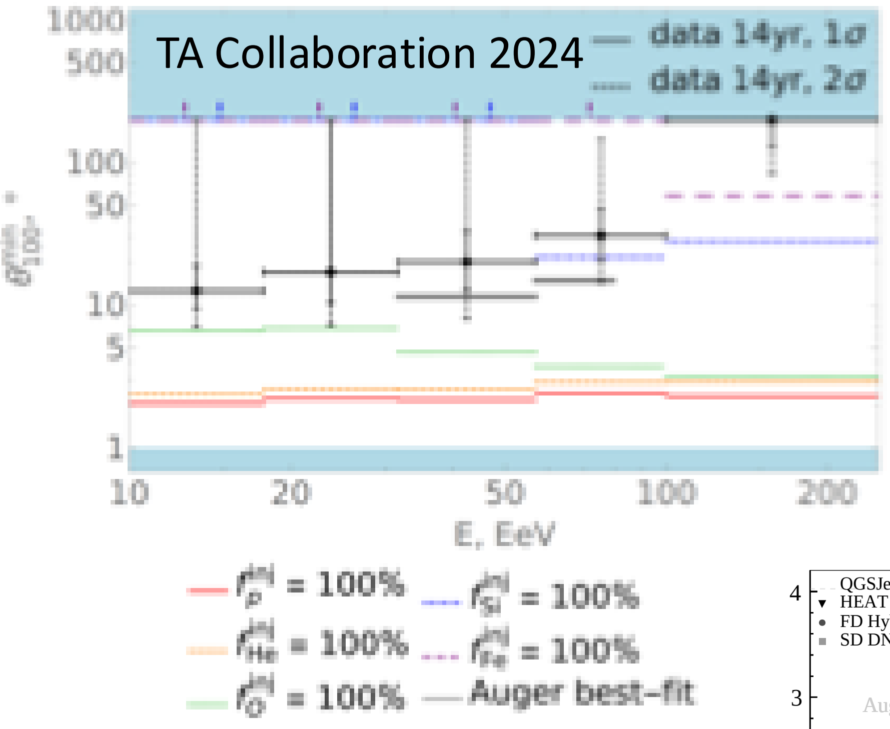
Observations of ~100 EeV Cosmic Rays

$r_g \sim 100\ \mathrm{kpc}\ Z^{-1}(\epsilon_i/100\ \mathrm{EeV})(B_{\mathrm{ISM}}/1\ \mu\mathrm{G})^{-1}$



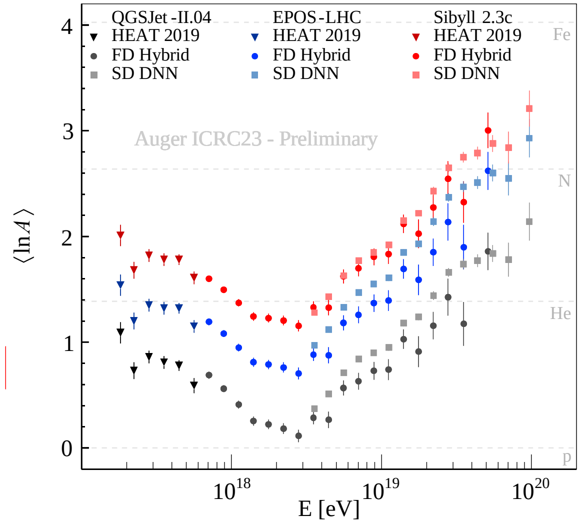
Arrival direction

→ Looks no hot spot (No hints)

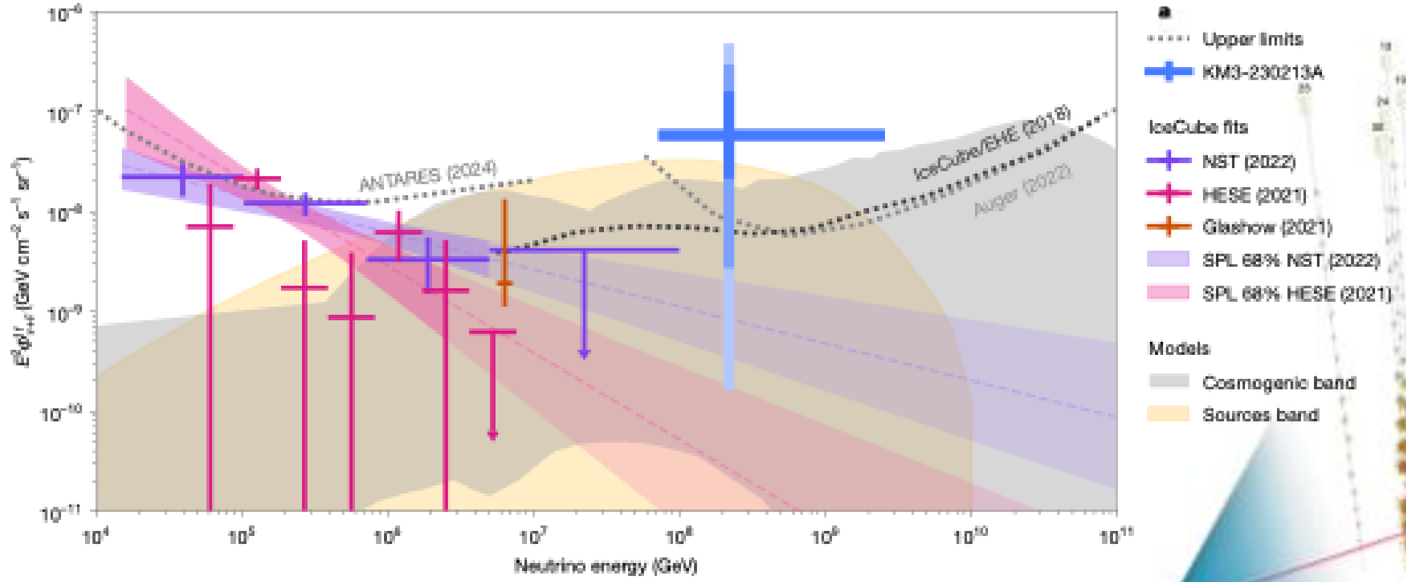


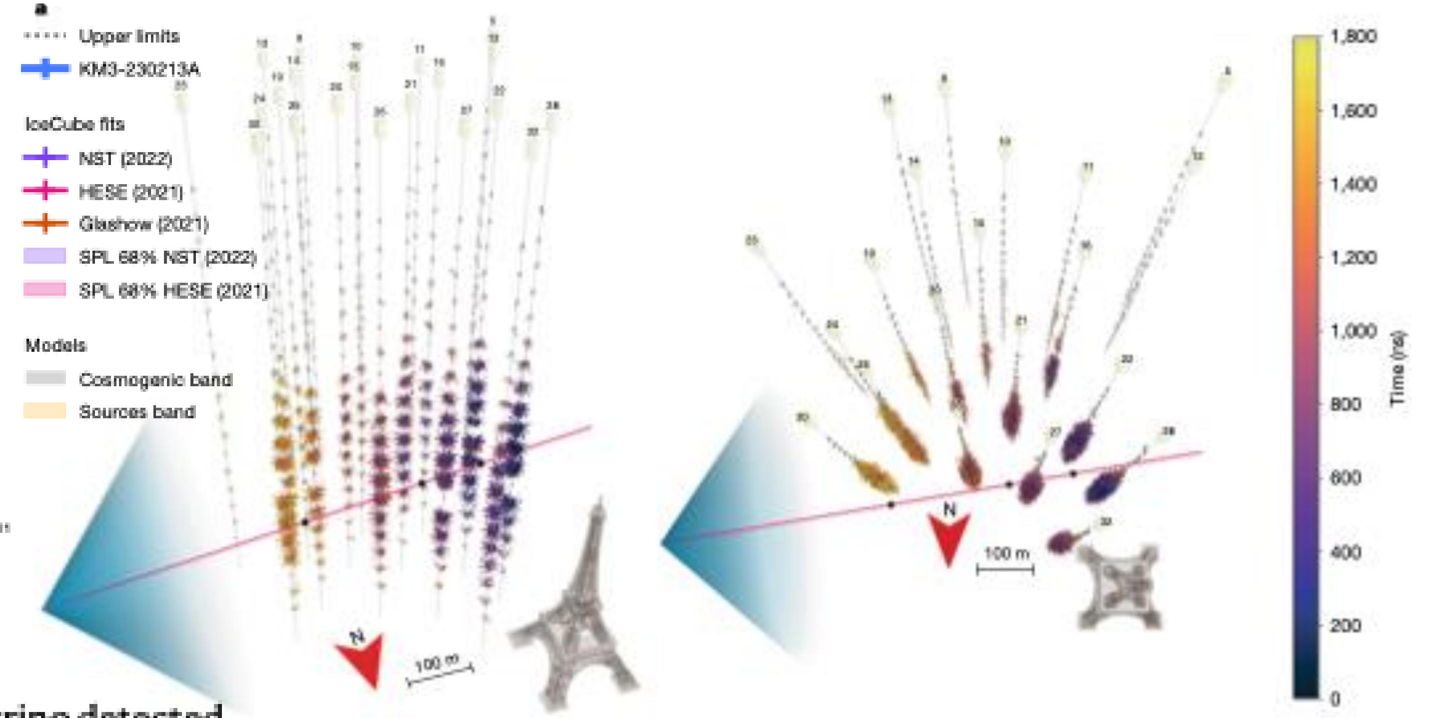
Composition

→ Heavy elements are likel

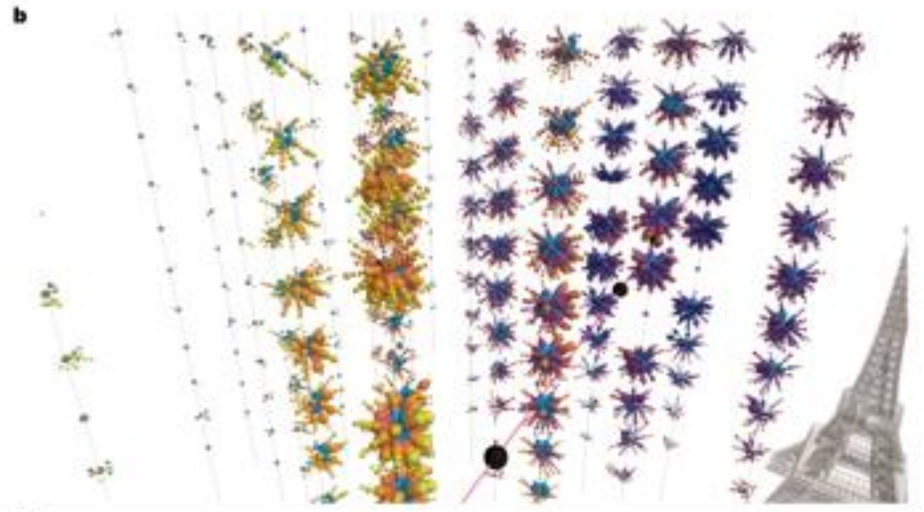


Recent News: KM3Net ~100 PeV Neutrino





However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[8], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

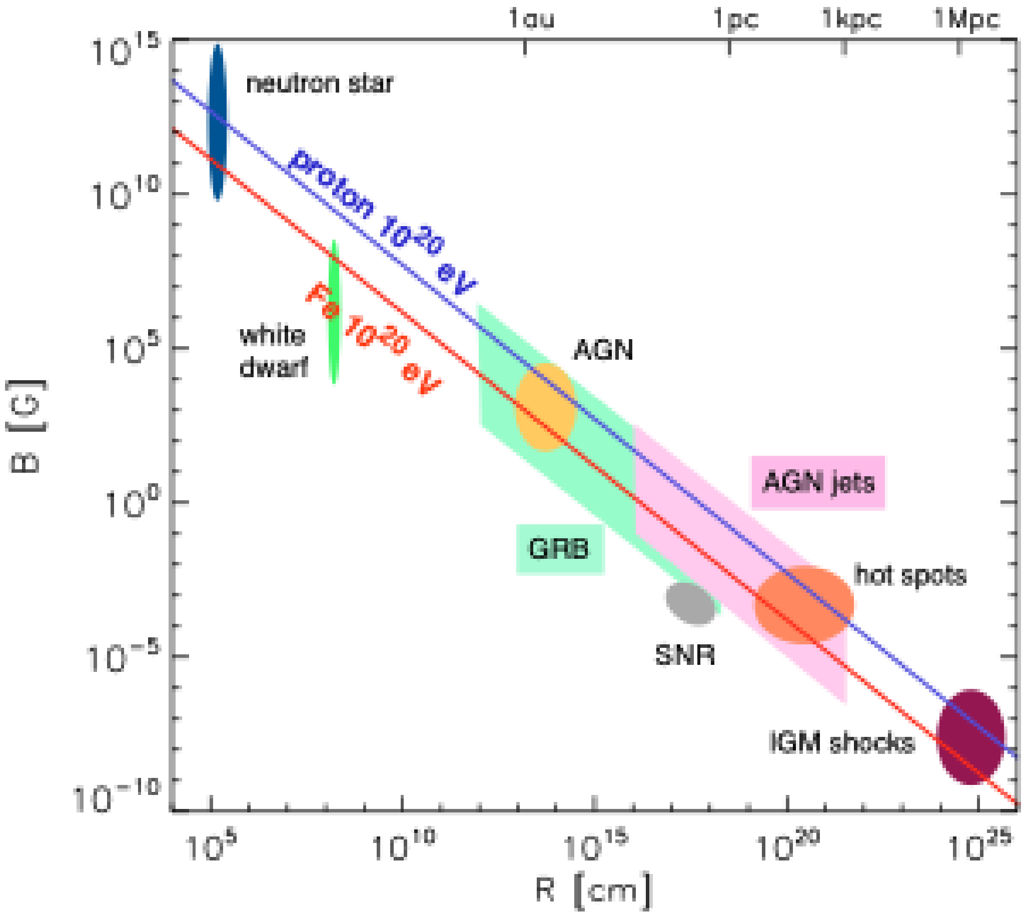


***Strange* source(s)？**

理論家：そんなとこに点打たれても．．．
まあ，ソースが近けりゃfluxは上げられるけど．

Neutron Stars (Magnetars) as a candidate of source

"Hillas diagram"
Ecr/qB ~ Object Size→Confine the CRs



Neutron Stars w/ B ~ 10^{15} G are one of the candidates.

How accelerates *nuclei* in a Neutron Star Transient Event is the main problem.
(see, also Arons 04, Kotera 11, Asano+06)

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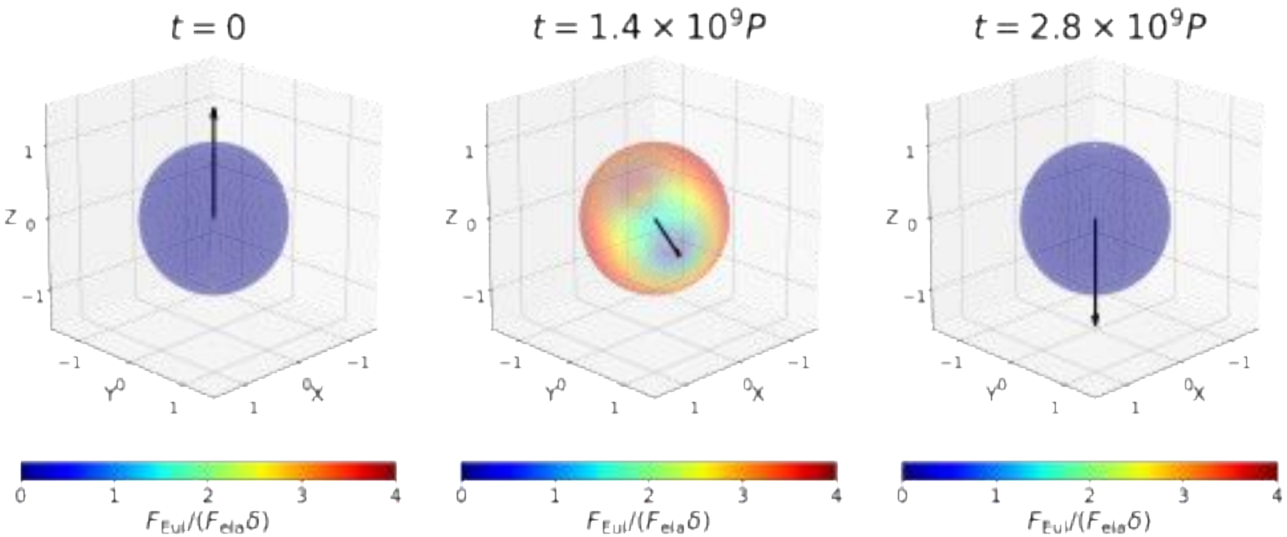
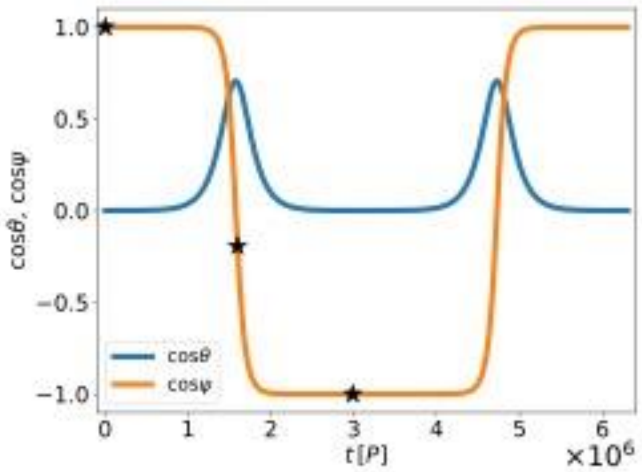
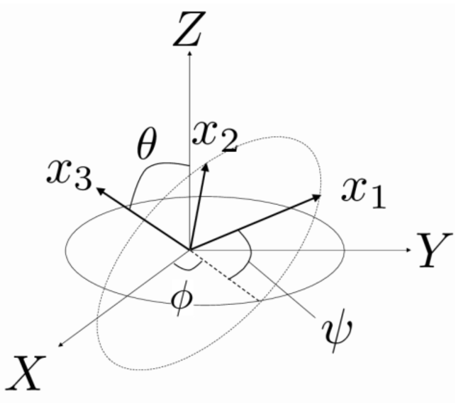
New Scenario for *Trigger* Mechanism of NS-transients







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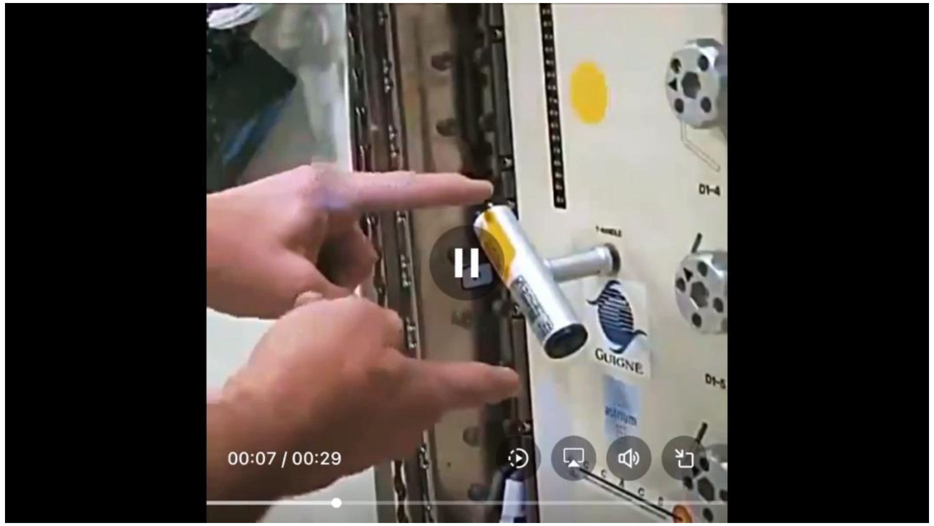

Known as the Dzhanibekov effect
as a solution of the Euler

なんか面白そうな動画→
見つけた.
和田くんに聞いてみよ.

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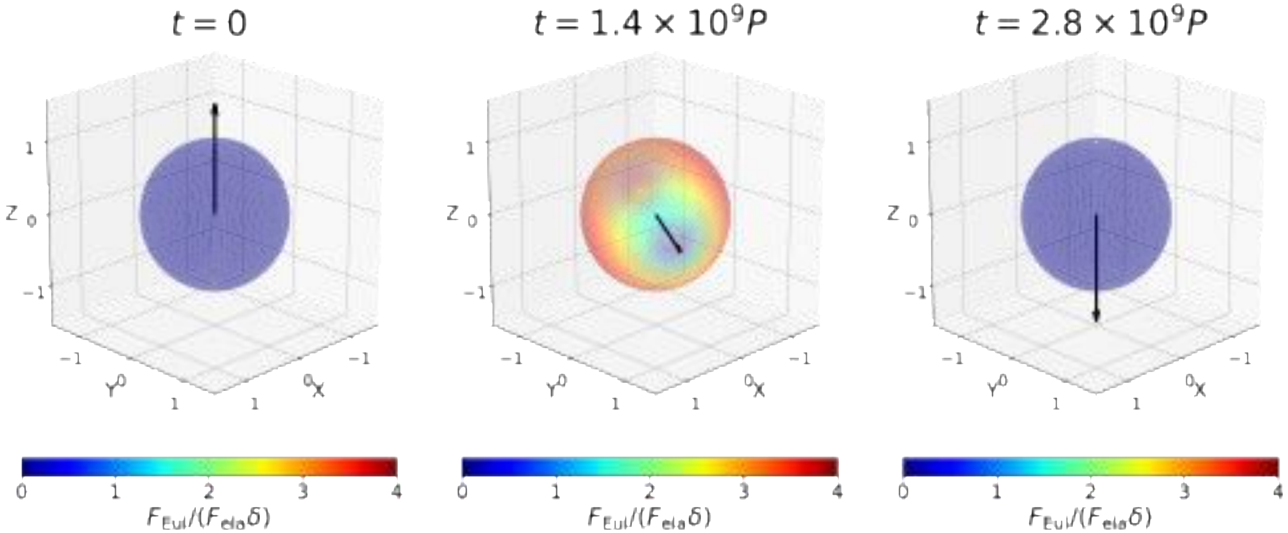

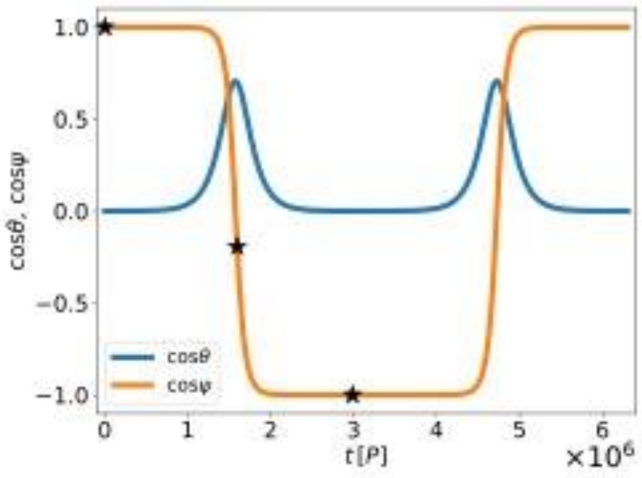

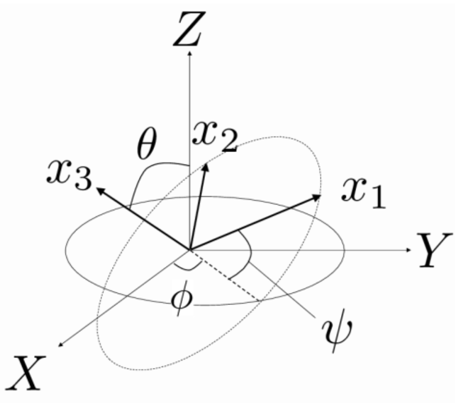

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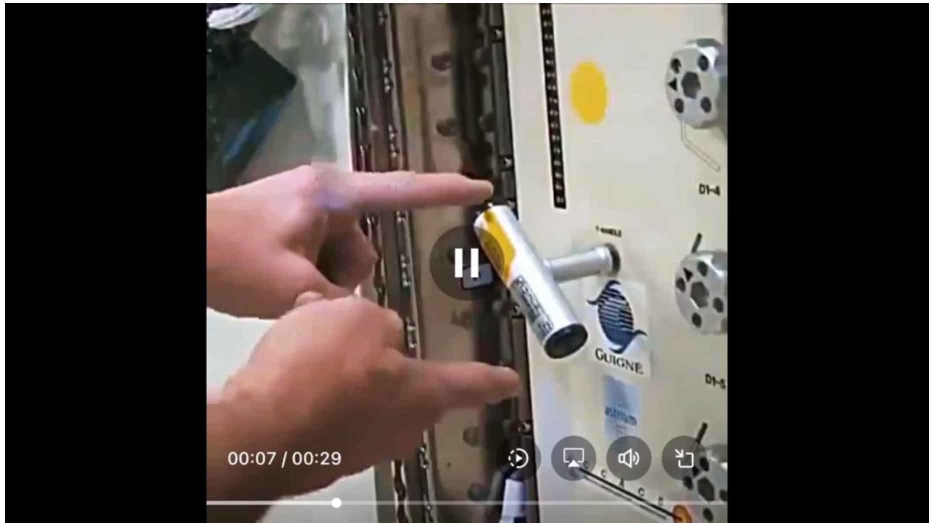

Known as the Dzhanibekov effect as a solution of the Euler ation.

ランダウの力学に書いてあり
ますねえ（京都弁）．
計算↑しました（１日で）

New Scenario for *Trigger* Mechanism of NS-transients

Known as the Dzhanibekov effect as a solution of the Euler equation.

$$\frac{d\Omega_1}{dt} + \frac{I_3 - I_2}{I_1}\Omega_2\Omega_3 = 0,$$

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$$\frac{d\Omega_3}{dt} + \frac{I_2 - I_1}{I_3}\Omega_1\Omega_2 = 0,$$

with the conservation laws of the energy

$$\frac{J_1{}^2}{I_1} + \frac{J_2{}^2}{I_2} + \frac{J_3{}^2}{I_3} = 2E,$$

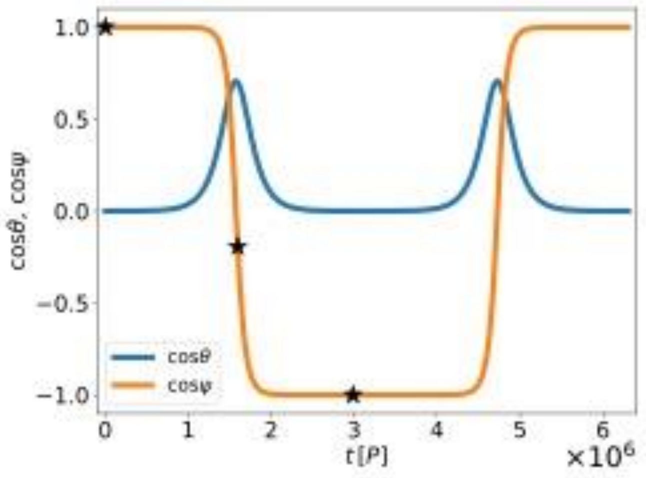
and the angular momentum

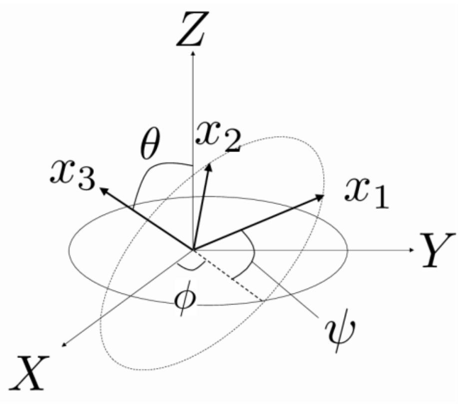
$$J_1{}^2 + J_2{}^2 + J_3{}^2 = J^2,$$

where $J_i = I_i\Omega_i$ is the components of the angular momentum vector, $J = |\boldsymbol{J}|$

$$2EI_1 < J^2 < 2EI_3$$

＊剛体を構成する質量要素が角運動量保存とエネルギー保存を満たしながら運動する時の「軌道」の一種.
角速度ベクトルΩ ≠ 角運動量ベクトルJ がポイント.





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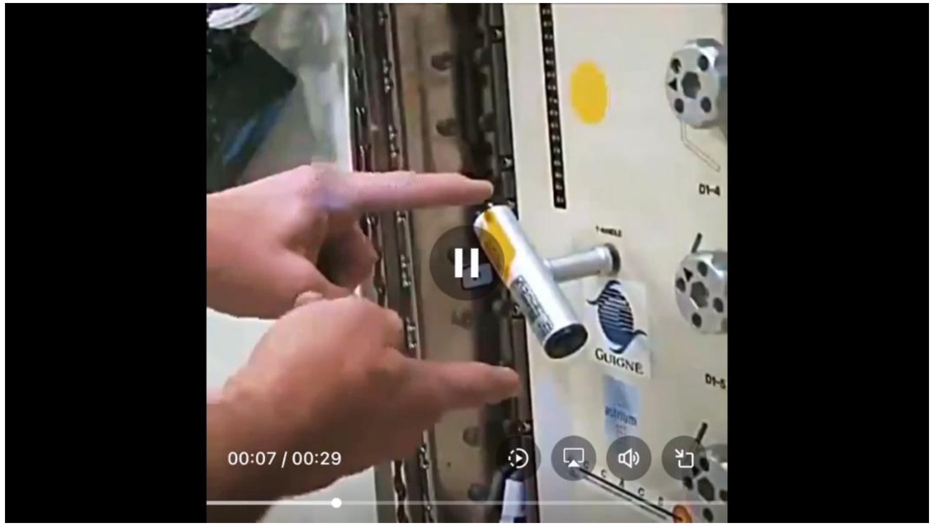

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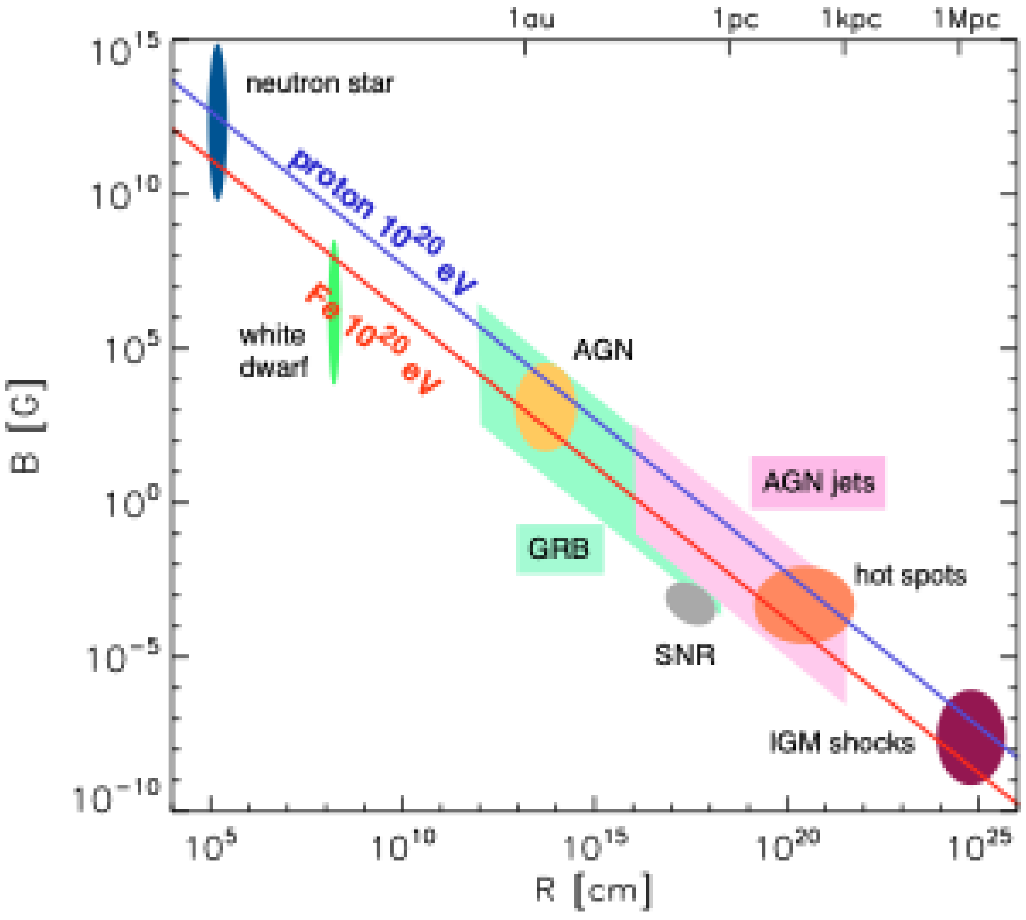

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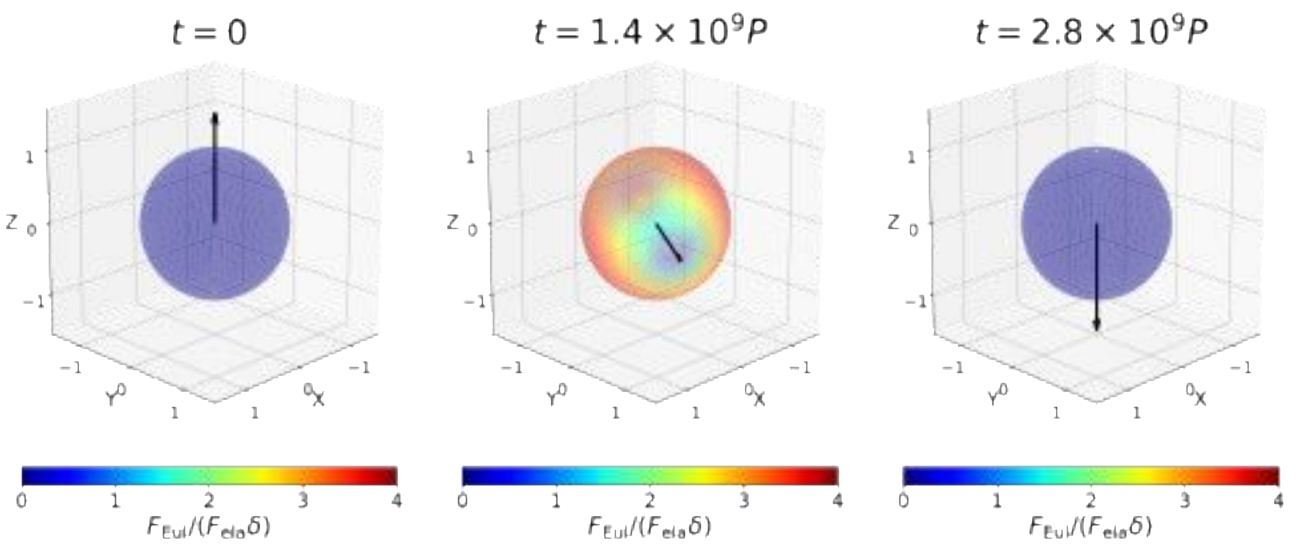

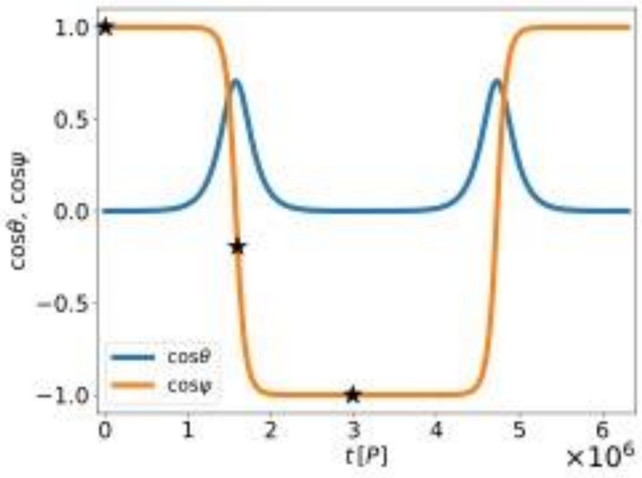

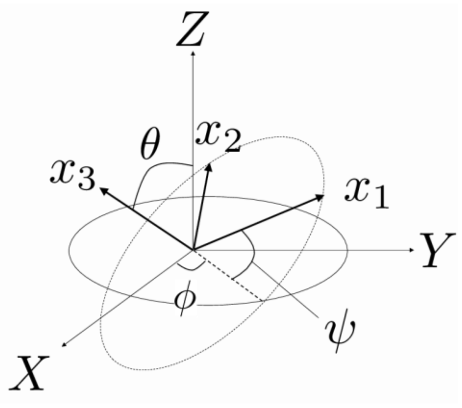

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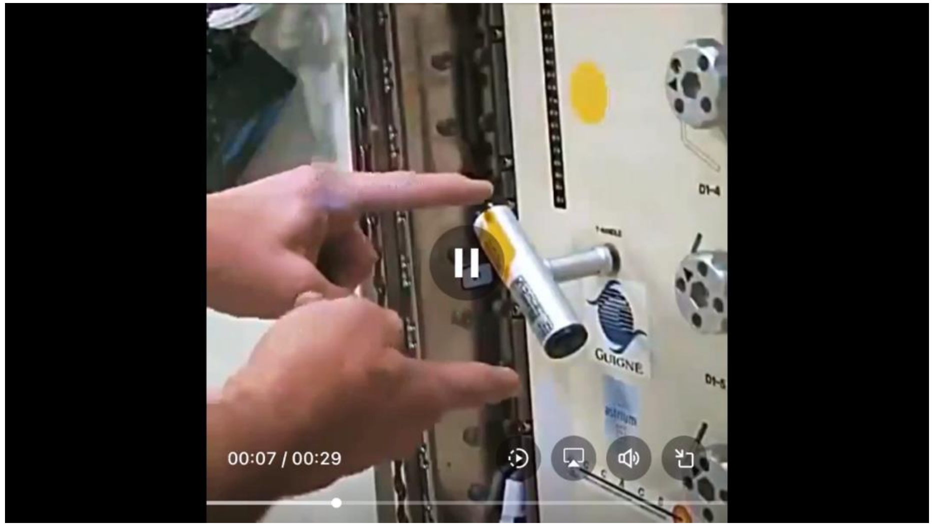

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この星，割れんの？

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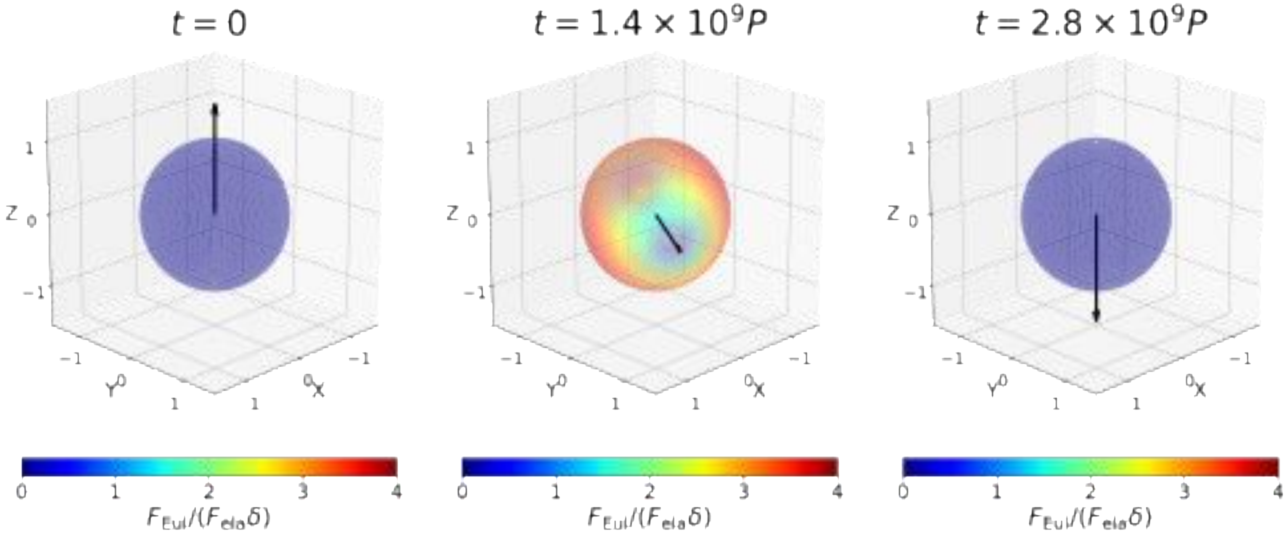

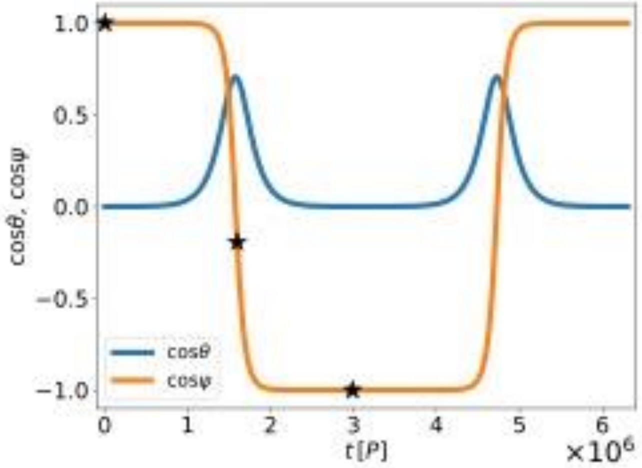

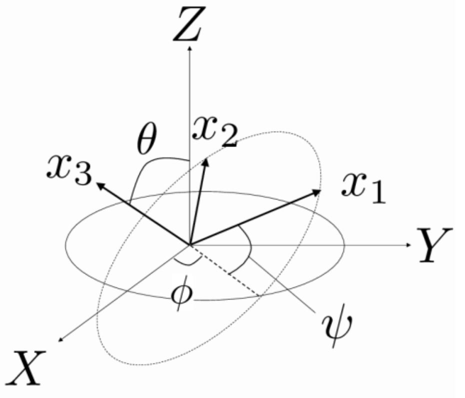

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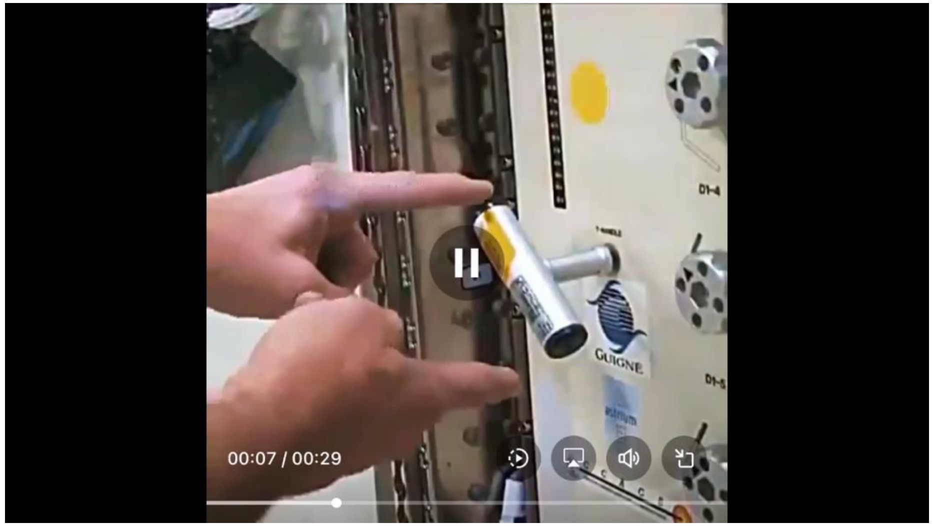

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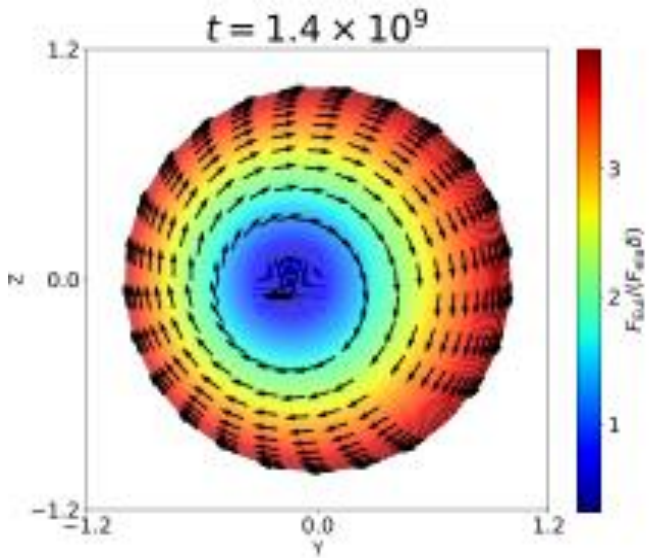
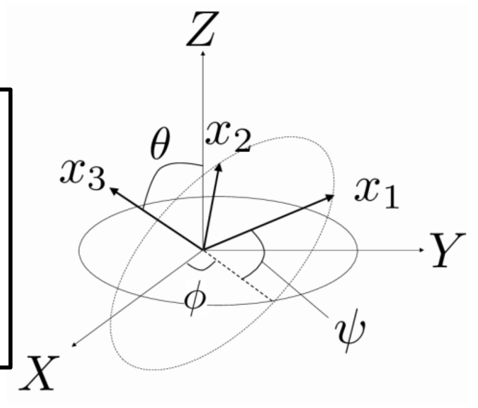
調べてみました（数日で）．
割れますねえ（京都弁）．

New Scenario for *Trigger* Mechanism of NS-transients

Euler force Direction & Strength from X-axis



The sudden motion of the spin axis induces the sudden rise of the Euler force (F_{Eul} =r * dΩ/dt).
→ Breaking the force balance among the Lorentz force and elastic force (Wada & Shimoda 24).



$$\frac{F_{\rm Eul}}{|F_{\rm Lor} - F_{\rm ela}|} \approx 4\,`_{3} R_{NS,6} P_{,0}^{-2} \sigma_{c,-2}^{-2} \left(\frac{\mu}{14}\right)^{-1} > 1$$

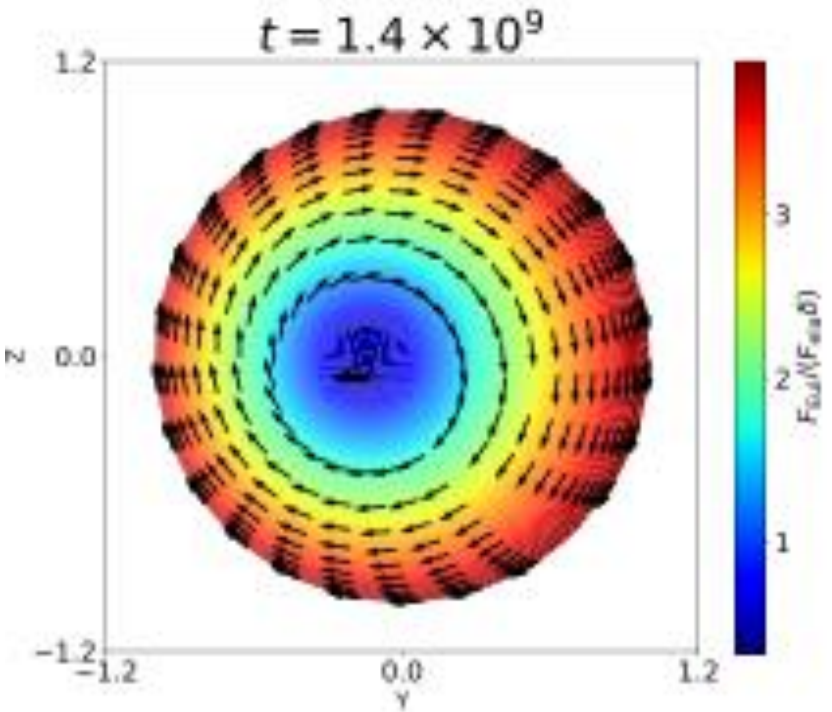
μ and σ give the ***stiffness*** of the rigid body (Ogata & Ichimaru 90, Chamel & Haensel 08, Kojima+21).

The shear of force with a length scale of $x > l \sim 10^3$ cm is large enough to induce the plastic flow.

→ We expect appearing “Cracks” at the NS outer crust.

Euler vs. Elastic

福島県ハイテクプラザの
youtube投稿動画より



Kinetic Energy of Euler force

vs.

Elastic energy

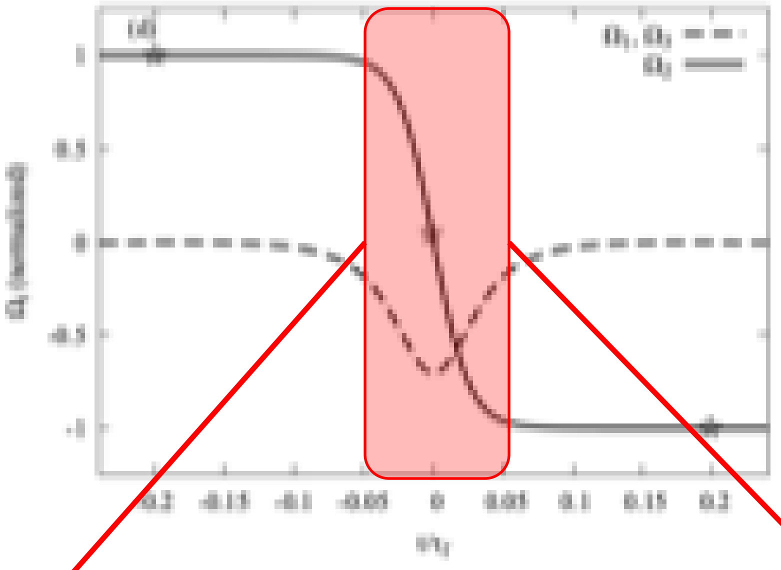
For Japanese students
ブリタニカ国際大百科事典より

・Plastic Flow（塑性流動）

一定限度をこえる応力を受けた物質に生じる不可逆的変形。

Parametrized by σ_c

What happens in the NS under the Dzhanibekov effect?



$$F_{\rm Eul} = |\boldsymbol{r} \times \dot{\boldsymbol{\Omega}}| \sim R_* \Omega^2 \delta$$

The waiting time for "flip"

$$\tau_{\rm f} \sim 200 \ {\rm yr} \ K_{,1} \delta_{,-9}{}^{-1} P_{,0},$$

$I_3 > I_2 > I_1$, where $I_2 = (2/5) M_* R_*{}^2$, $I_1 = (1-\delta) I_2$, and $I_3 = (1+\delta) I_2$.

Euler force appears

Work by Euler force

$$V \equiv \pi l^2 \mathcal{H}, \ \Delta \mathcal{P} = M F_{\rm Eul} \Delta \tau_{\rm f}$$

$$\Delta \tau_{\rm f} = 1.5 \times 10^{-3} \tau_{\rm f}$$

$$W_{\rm Eul} \sim \frac{\Delta \mathcal{P}^2}{2M} \sim \frac{M R_*{}^2 \Omega^4 \delta^2 \Delta \tau_{\rm f}{}^2}{2}$$

Elastic Potential Energy (*stiffness* of the crust material)

$$U_{\rm ela,c} = \mu \sigma_{\rm c}{}^2 V$$

$$\mu/\rho = 10^{14} \ {\rm cm}^2 \ {\rm s}^{-2} (A/56)^{-4/3} (Z/26)^2 \rho_A^{1/3}$$

$$\sigma_{\rm c} = 0.01$$

$$\rho = \rho_s \left(\frac{\mathcal{H}}{\mathcal{H}_s} \right)^{5/2} \quad H = -\rho(dr/d\rho)$$

What happens in the NS under the Dzhanibekov effect?

Euler vs. Stiffness

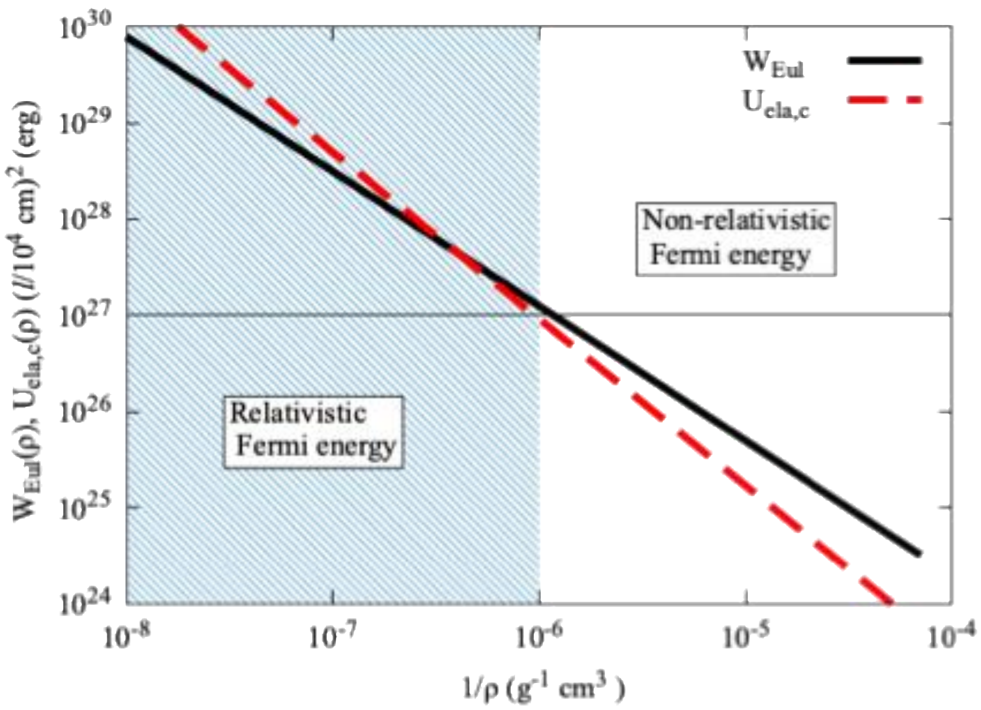
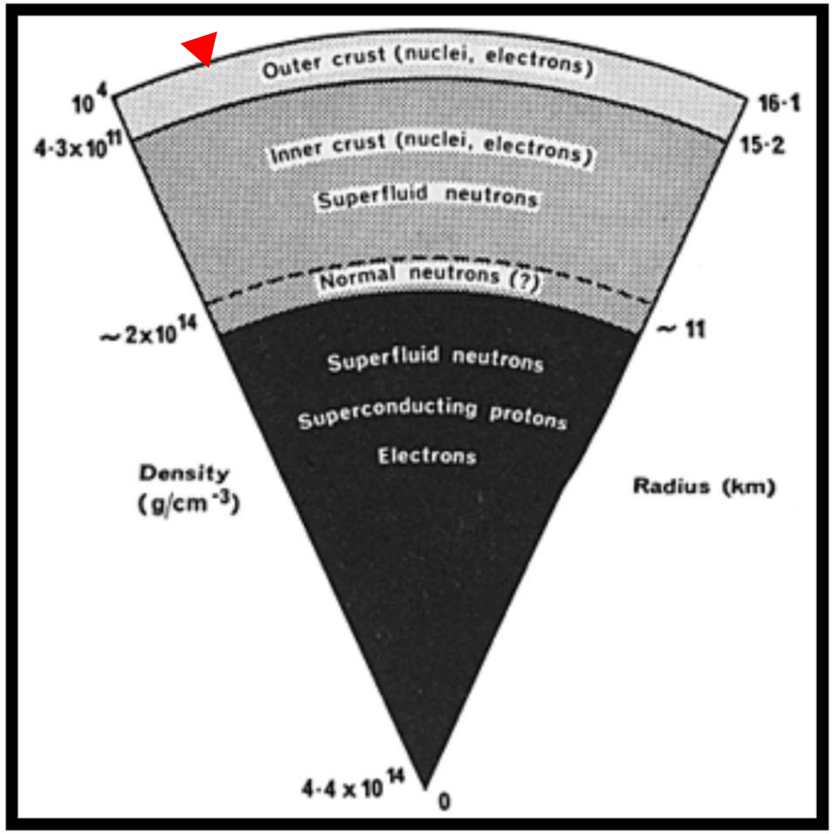


Fig. 2 Comparison of the total work of the Euler force (solid line) and the critical elastic energy (broken line). The hatched region indicates the region where the Fermi energy of electrons is relativistic ($\rho > 10^6$ g cm^{-3}). We adopt $R_* = 10^6$ cm, $\Delta\tau_f = 1.5 \times 10^{-3}\tau_f$, $\sigma_c = 0.01$, $l = 10^4$ cm, and $M = \rho V$.

The crust will be significantly affected within $\Delta\tau_f \sim 10^{-3}\ \tau_f \sim 3$ months δ_{-9}^{-1}

Cracks reaches at H ~ 63 cm

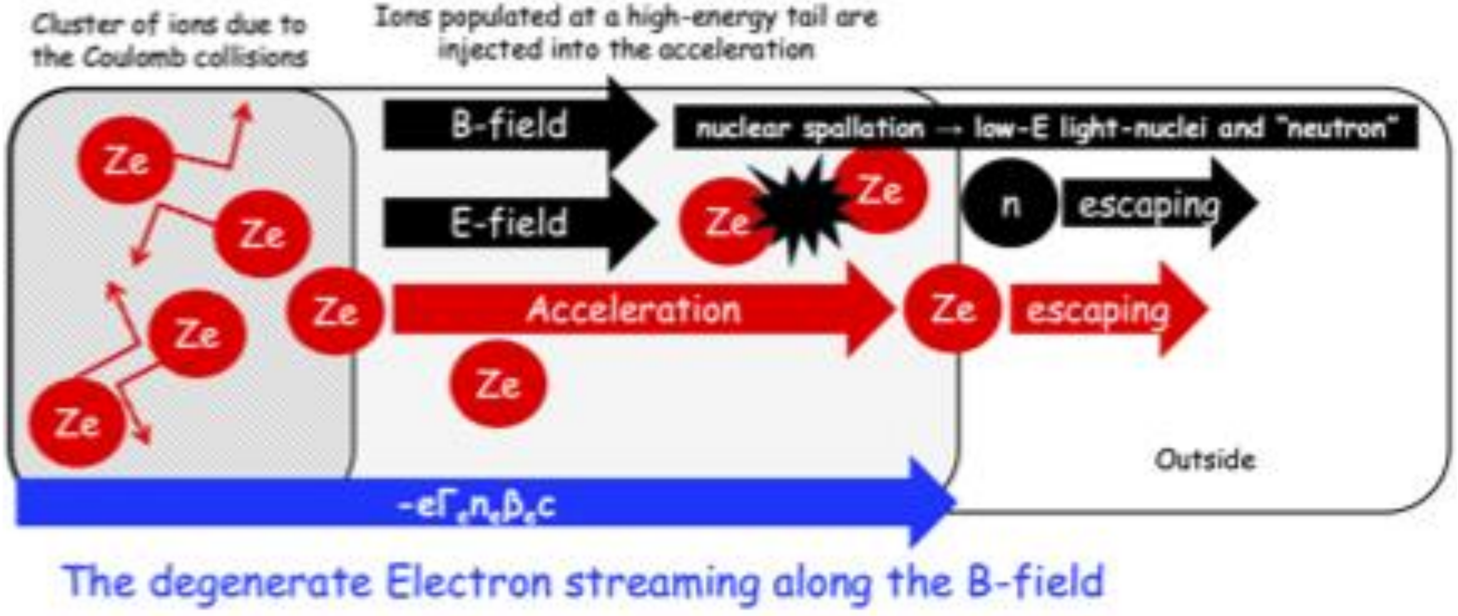


Euler force can deform the NS surface at

ρ < 1.0e6 g/cc (r < 60 cm)

(Outer crust)

At a Moment of Phenomenon (Shimoda&Wada 2025)



$$j_{\rm ret} = Ze\Gamma_{\rm i} n_{\rm i} \beta_{\rm i} c = -j_{\rm e}$$

$$j_{\rm e} = -e\Gamma_{\rm e} n_{\rm e} \beta_{\rm e} c$$

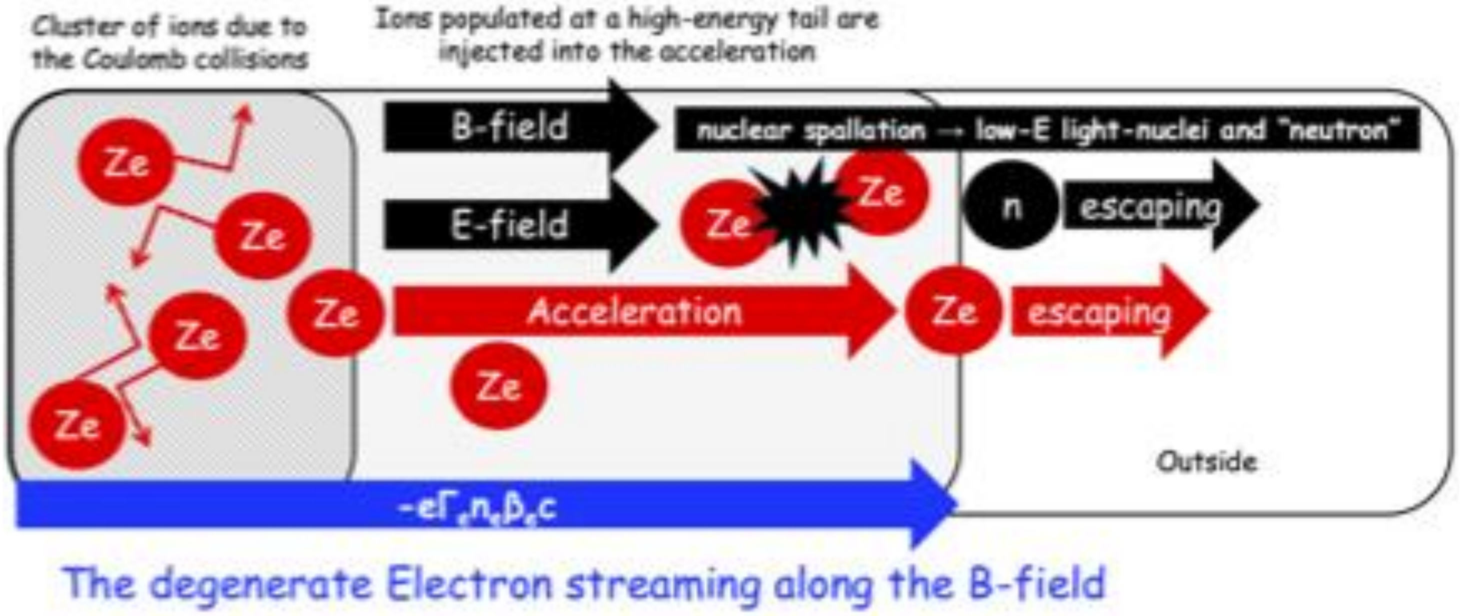
$$\Gamma_{\rm i} n_{\rm i} q_{\rm i} E \sim -m_{\rm i} \Gamma_{\rm i} n_{\rm i} \beta_{\rm i} c \Omega_{\rm C,ii} \text{ as (Ohm's law)} \qquad \Omega_{\rm C,ii} \sim 4\pi \Gamma_{\rm i} n_{\rm i} c \left(\frac{Z^2 e^2}{m_{\rm i} c^2}\right)^2 \left(\frac{T_{\rm i}}{m_{\rm i} c^2}\right)^{-3/2}$$

$$E_{\rm res} \sim -\frac{m_{\rm i}}{q_{\rm i}} \beta_{\rm i} c \Omega_{\rm C,ii}$$

$$ZeE_{\rm res} \sim 5.6 \times 10^{22} \ {\rm eV\ cm^{-1}} \ \rho_{\rm c}^{4/3} \ (Z/26)^{13/3} \ (A/56)^{-5/6} \ (T_{\rm i}/0.3 \ {\rm keV})^{-3/2}$$

Very strong Electric field is induced.

At a Moment of Phenomenon (Shimoda&Wada 2025)



Injection of Cold ions
→ kinetic energy of $T_{inj} \sim \eta T_i$
(η~5 is supposed)
→ $n_{inj} \sim n_i \exp(-\eta)$
Effective Energy Loss Process
→ Nuclear spallation reactions
→ $\sigma_A \sim \pi a_A^2$, $a_A \sim 4.59\text{e-}13$ cm $(A/56)^{1/3}$

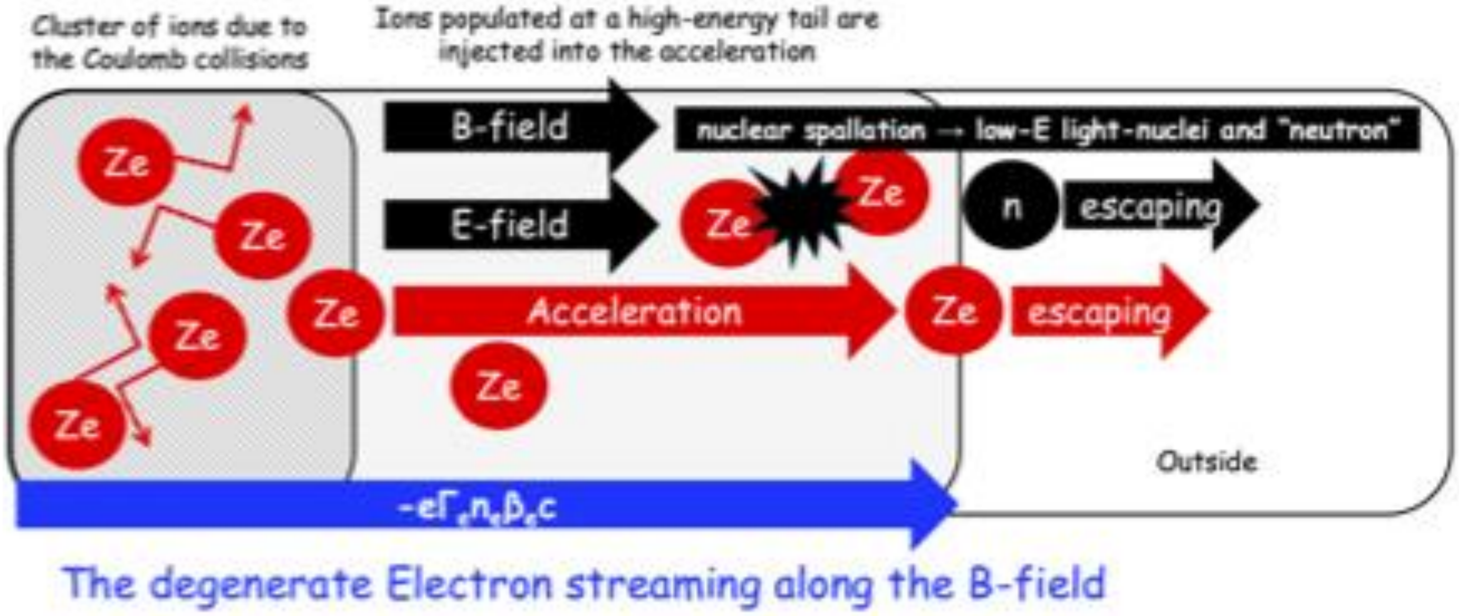
Estimated Maximum Energy of accelerated ions

$$\epsilon_{\rm i,max} \sim ZeE_{\rm res} l_{\rm mfp} \sim 1.2\ {\rm ZeV}\,{\rho_c}^{1/3} \left(\frac{Z}{26}\right)^{13/3} \left(\frac{A}{56}\right)^{-1/2} \left(\frac{T_{\rm i}}{0.3\ {\rm keV}}\right)^{-3/2}$$

$$l_{\rm mfp}/c \sim 7.0 \times 10^{-13}\ {\rm s} = 0.7\ {\rm ps}$$

Ions can be accelerated up to ~ ZeV=10^{21} eV scale within a time of ~ 1ps.

At a Moment of Phenomenon (Shimoda&Wada 2025)



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Effective Energy Loss Process

→ Nuclear spallation reactions

→ $\sigma_A \sim \pi a_A^2$, $a_A \sim 4.59\text{e-}13$ cm $(A/56)^{1/3}$

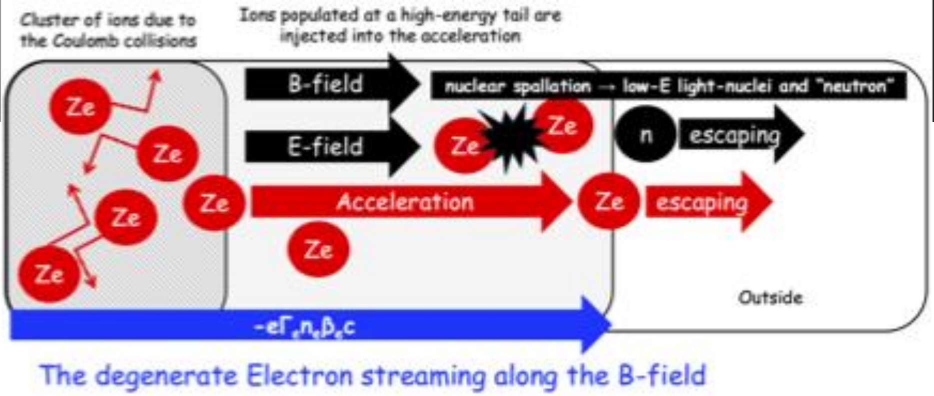
Estimated Maximum Energy of accelerated ions

$$\epsilon_{i,\max} \sim ZeE_{\rm res} l_{\rm mfp} \sim 1.2\ {\rm ZeV}\, {\rho_c}^{1/3} \left(\frac{Z}{26}\right)^{13/3} \left(\frac{A}{56}\right)^{-1/2} \left(\frac{T_i}{0.3\ {\rm keV}}\right)^{-3/2}$$

$$l_{\rm mfp}/c \sim 7.0 \times 10^{-13}\ {\rm s} = 0.7\ {\rm ps}$$

Instant ZeV-ion-acceleration in Upset Magnetar Origin Bursts

→ IZUMO Bursts



Discussion

Proper prediction of the IZUMO Bursts:

neutrinos w/energy of $E_\nu \sim 0.05$ ZeV/A ~ 100 PeV (10^{17} eV).

neutrons w/ energy of $E_n <$ ZeV/A ~ 20 EeV (10^{19} eV).

β-decay time of neutron $\tau_\beta \sim$ (10 min.)*$\gamma_n < 4\text{x}10^5$ yr (E_n/20 EeV)

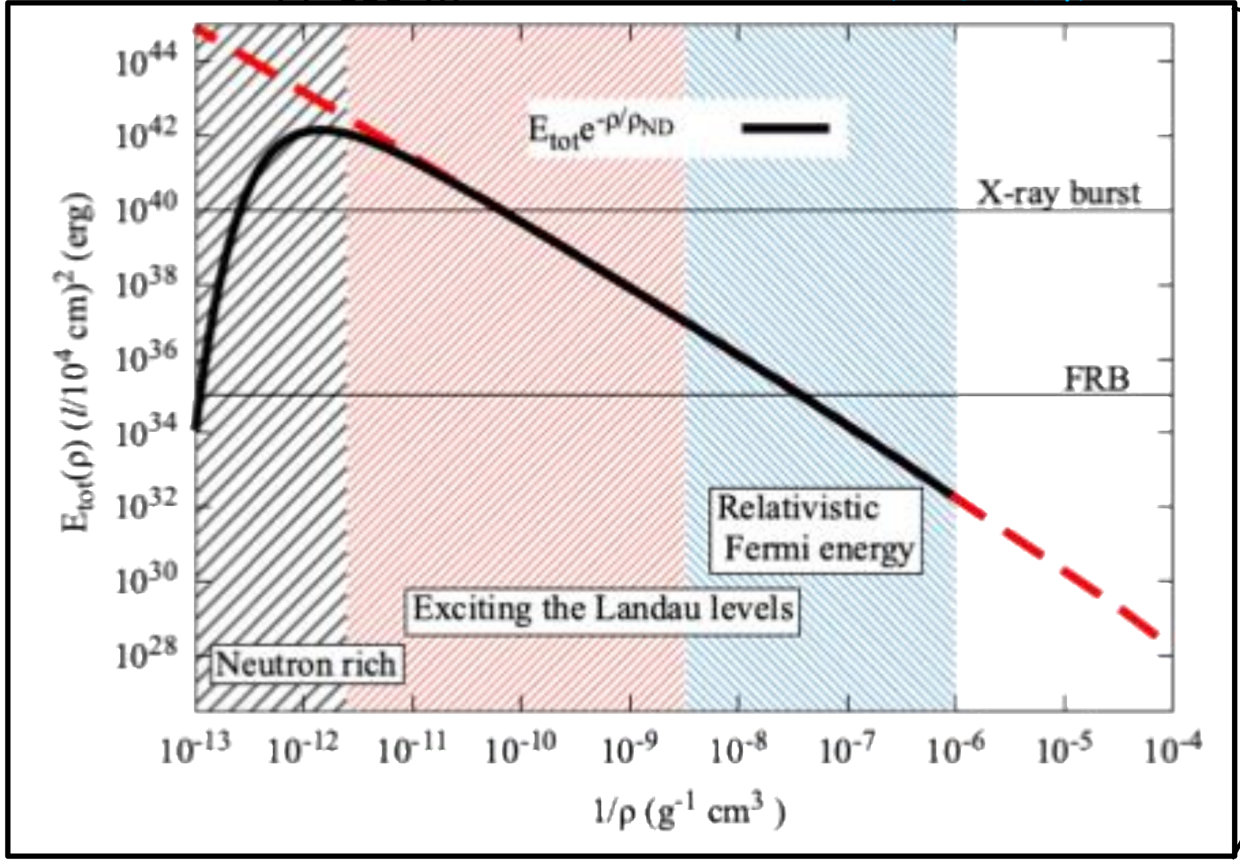
$\rightarrow c\tau_\beta <$ 120 kpc(E_n/20 EeV)

Ultrahigh-Energy CR *neutron* events @ the Earth can show time & position coincidences with NS-transient events from nearby galaxies.

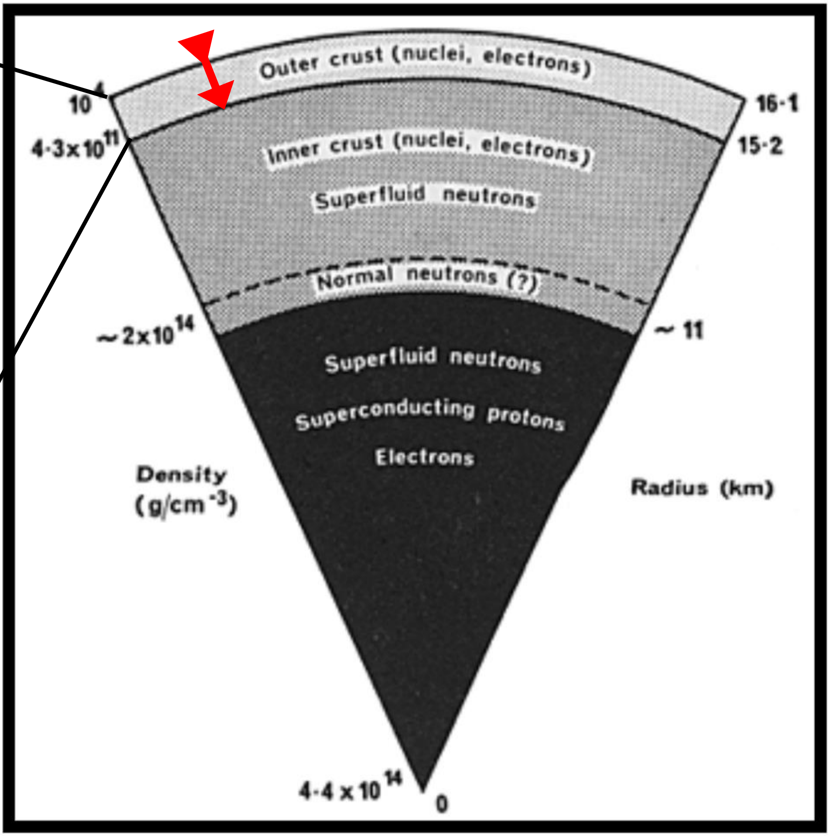
Neutrons do not *feel* the B-field unlike from the usual CR nuclei (idea provided by Prof. Takashi Sako @ ICRR TA group)

NS-transients observed by photons

H=110 m H=7 m H=63 cm



Cracked at H ~ 63 cm→ Develop



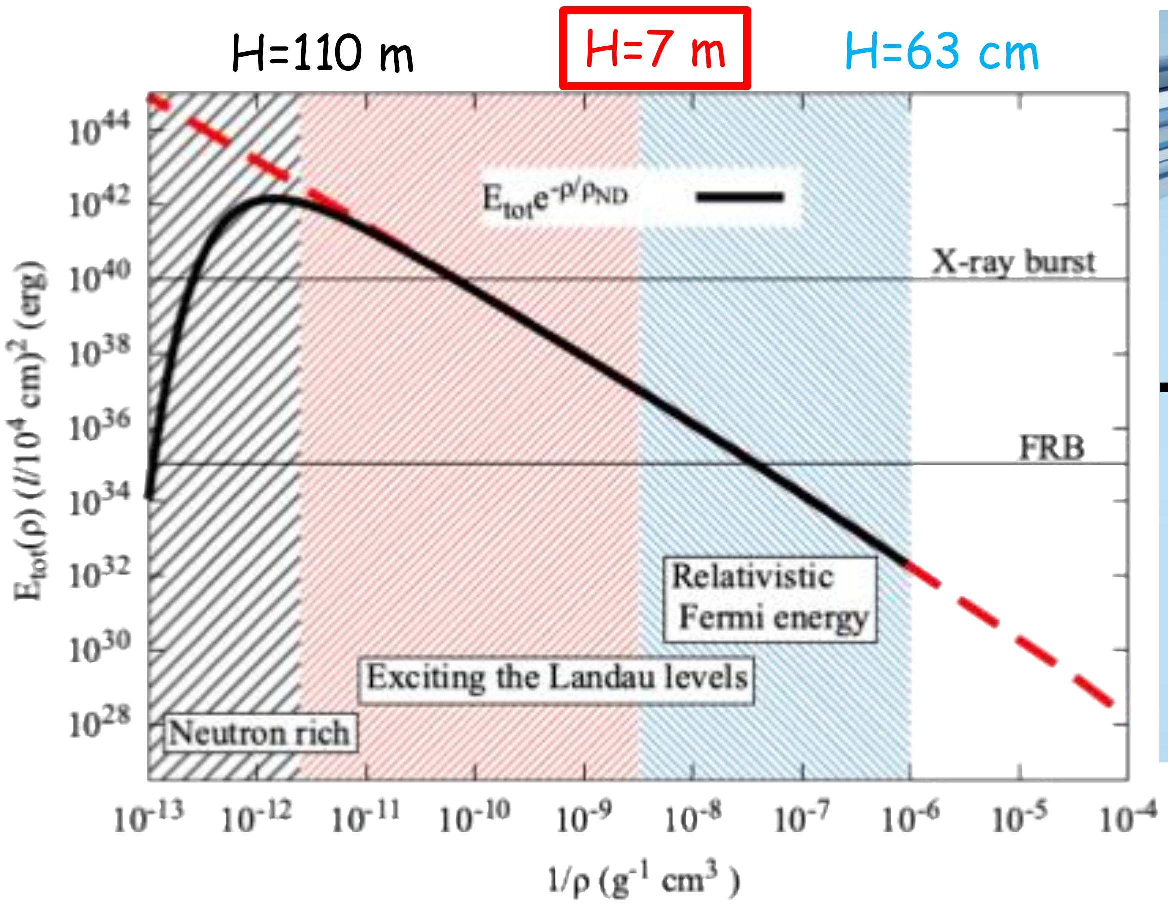
Electrons can occupy the Landau levels when

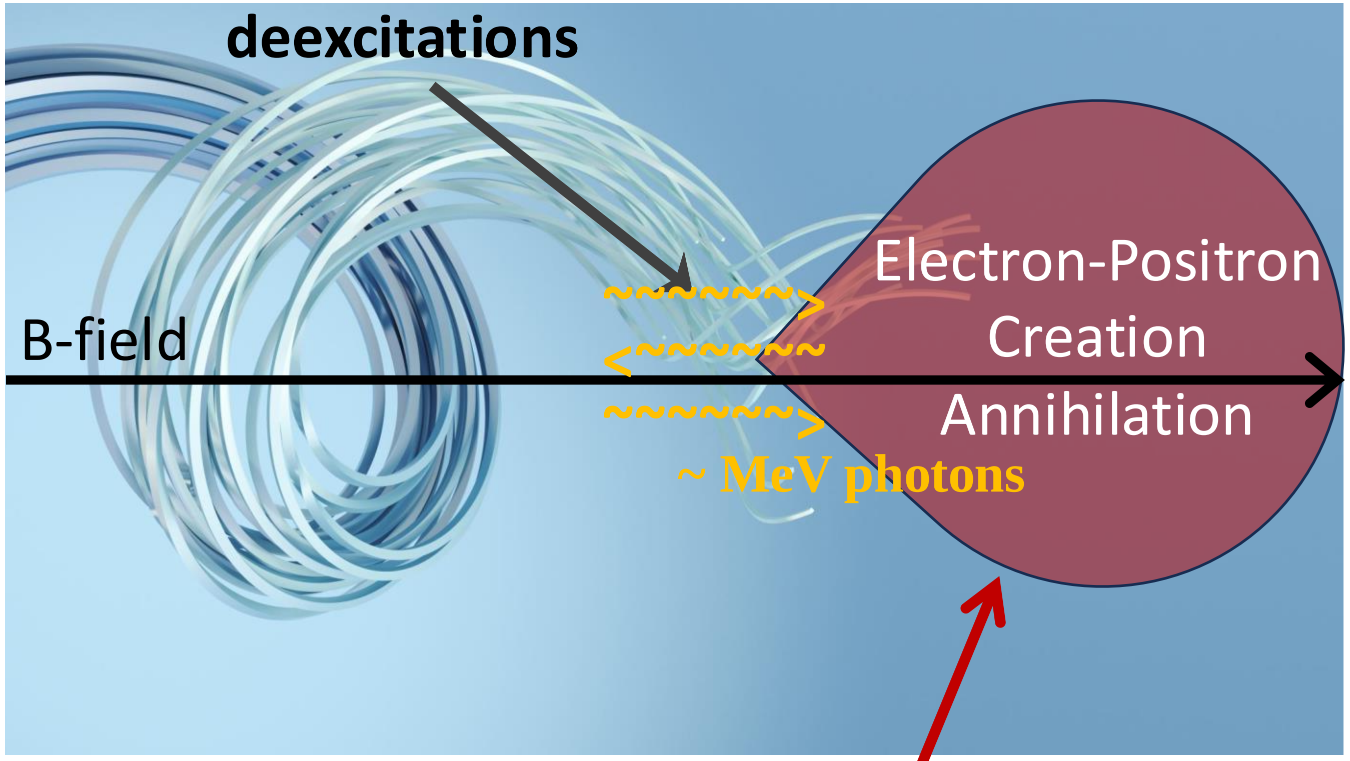
Fermi energy $\epsilon_{\mathrm{F,e}}(\rho) > \Delta\epsilon_{\mathrm{L,e}}^{(1-0)}(B)$ ~6 MeV 1st Landau Level

ρ > 1.0e8 g/cc (r = 4 m).

Fireball may be formed

NS-transients observed by photons





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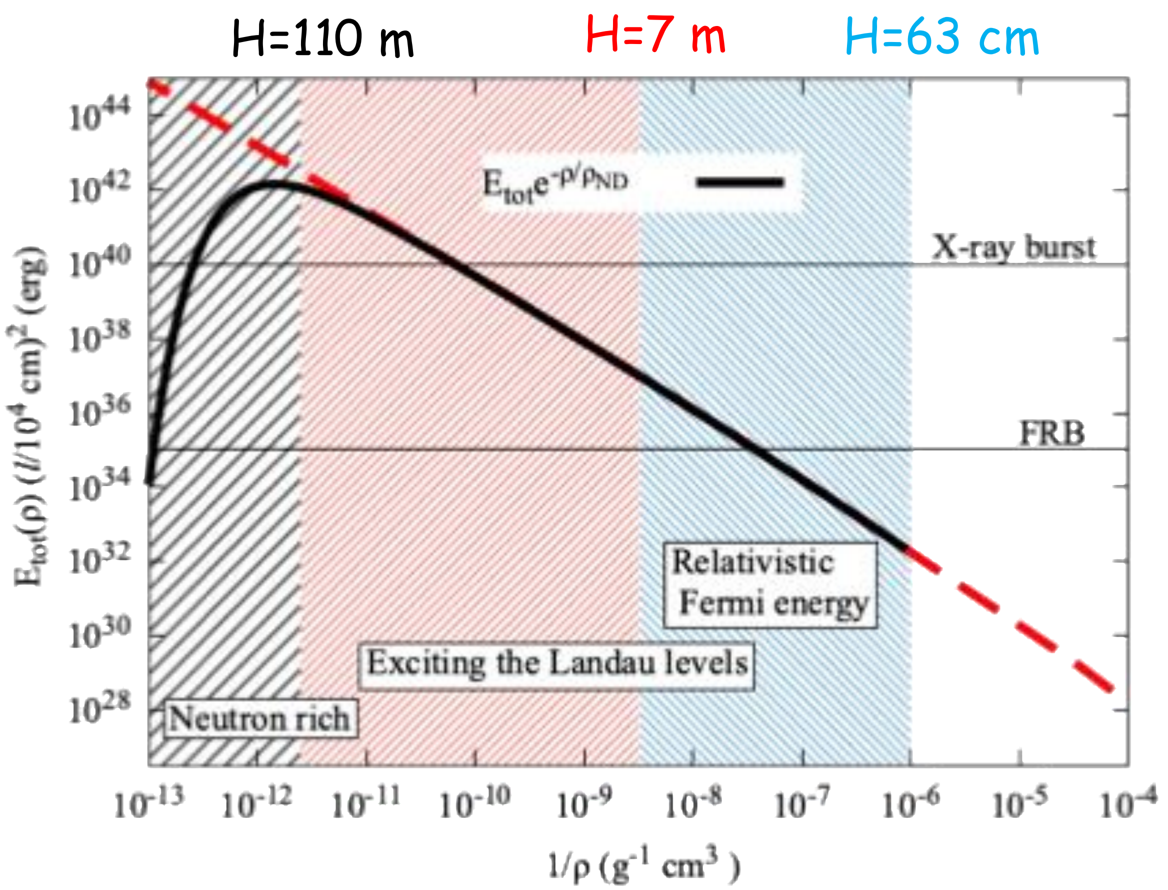
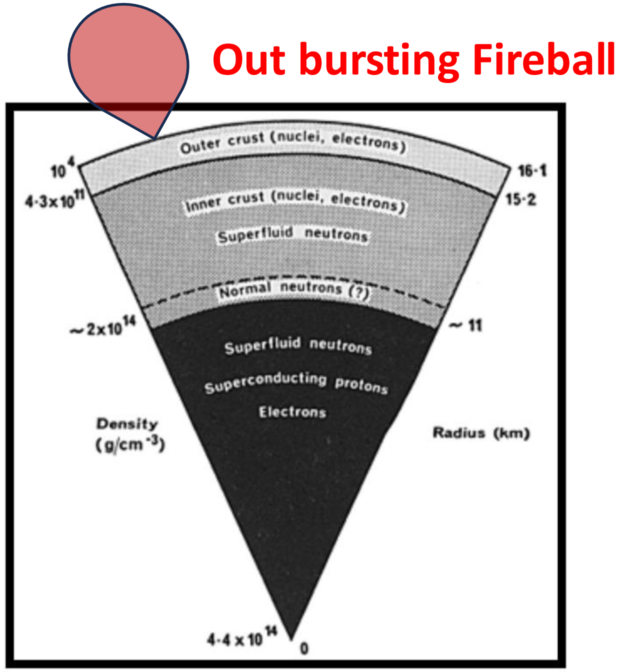
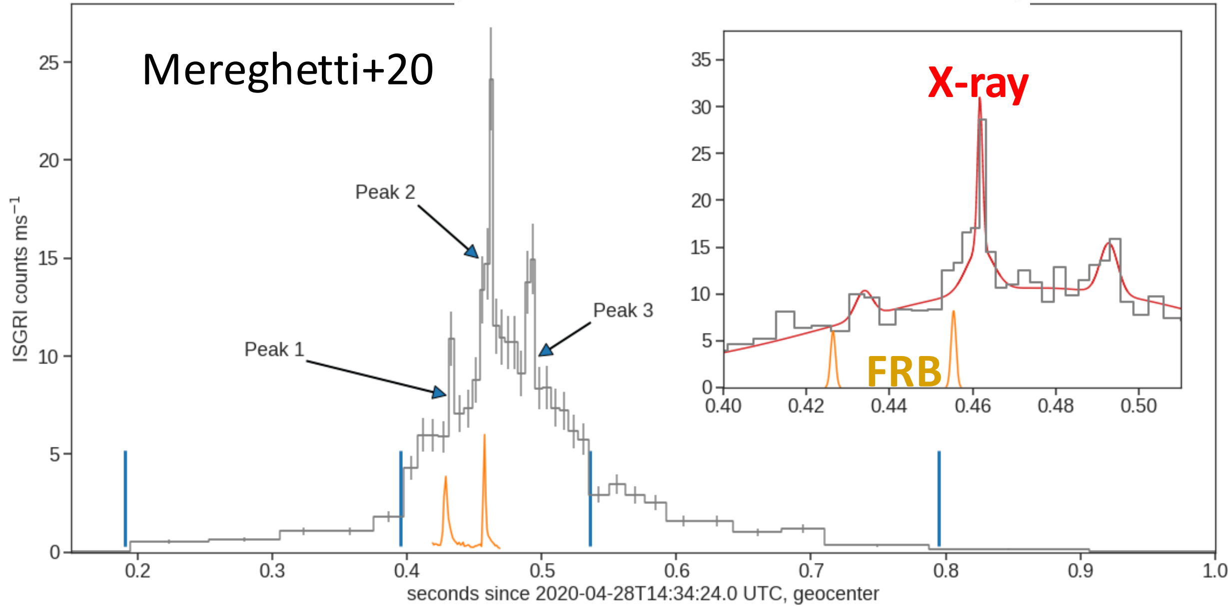
NS-transients observed by photons



Our scenario can explain the SGR 1935+2154 bursting events (Luminosity & ~100 keV Photons)

*FRB is still under debate.





Other Properties of SGR1935+2154 (Future works)

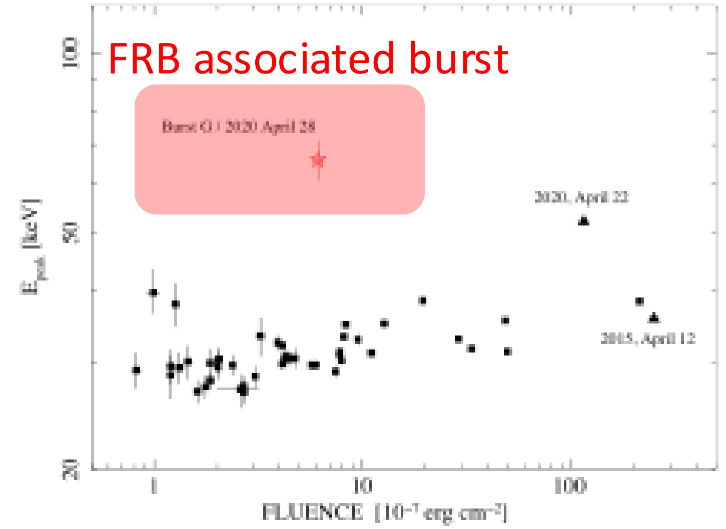
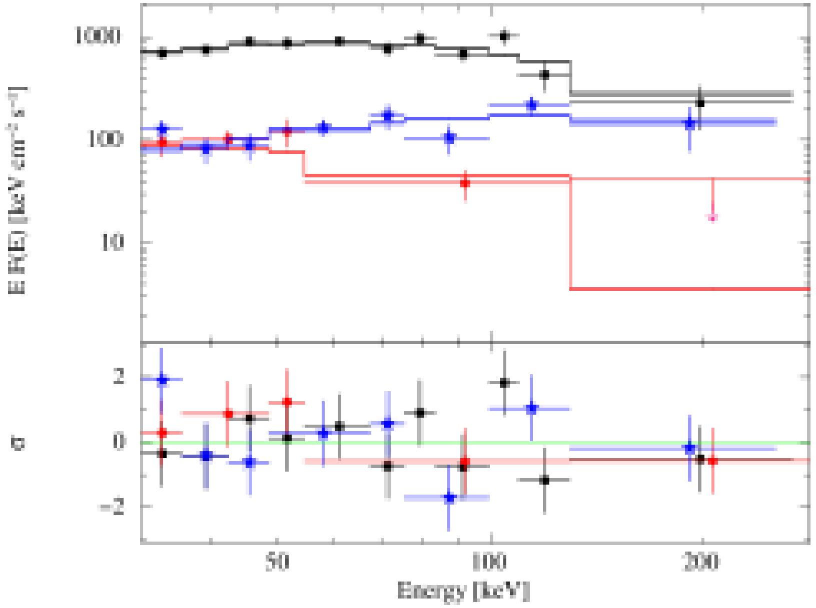
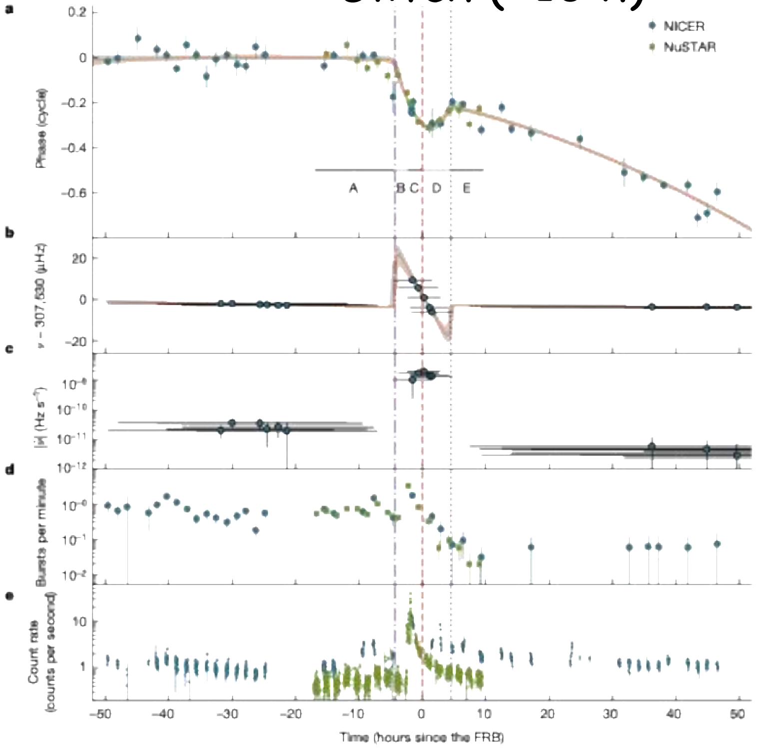


Figure 6. Peak energy vs. fluence for burst-G (red star) and other bursts from SGR 1935+2154 (squares from Lin et al. 2020a; triangles from Kozlova et al. 2016 and Ridnaia et al. 2020a).



Mereghetti+20

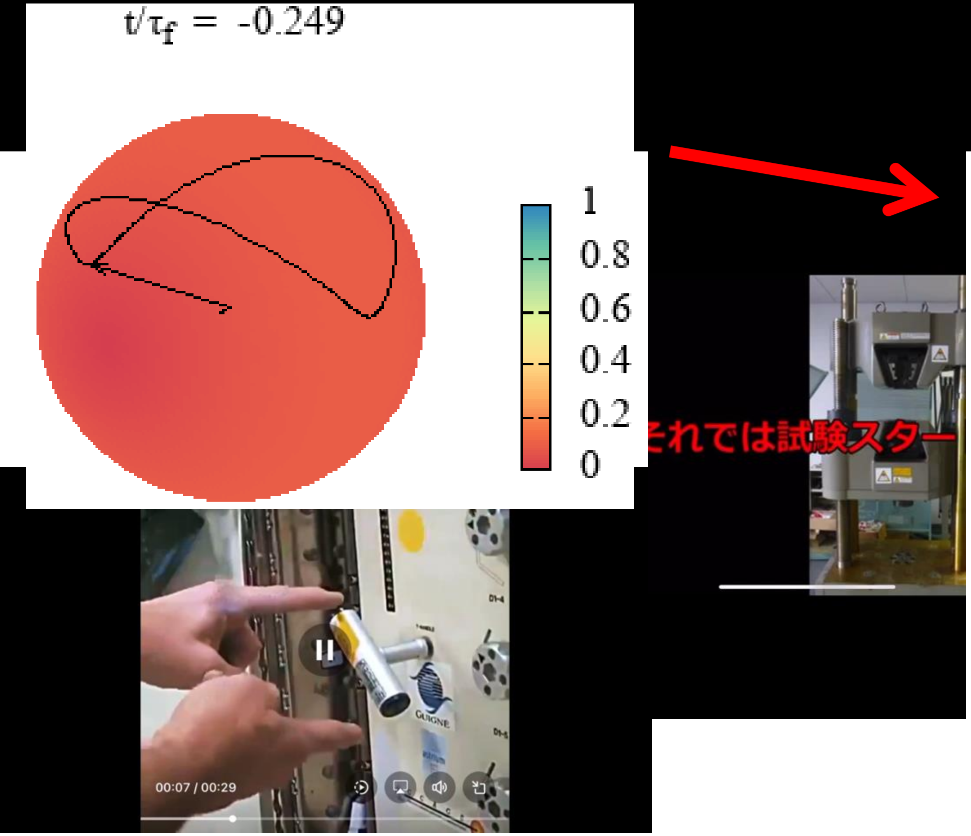
Glitch (~10 h)

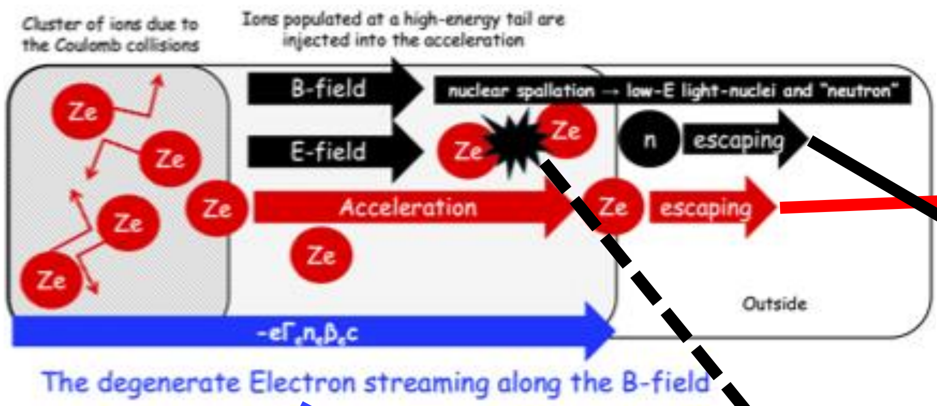


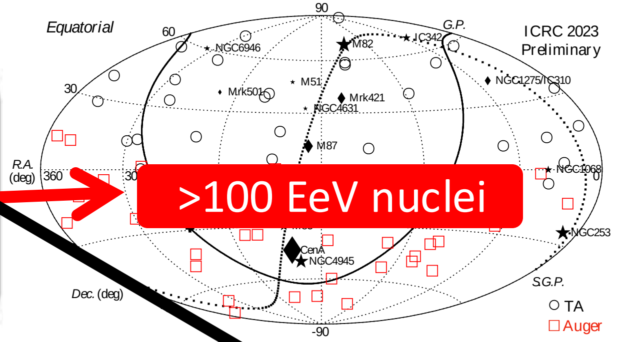
Hu+24

1. SGR 1935+2154 exhibits FRB-associated bursting activity at X-ray band (up to ~ 100 keV), called **the burst-G**.
2. Looks like an **exceptional case** → unusual mechanism?
3. The **glitch activity**, which can be interpreted by the change of Ω.
   → Does the Dzhanibekov effect reproduce it?

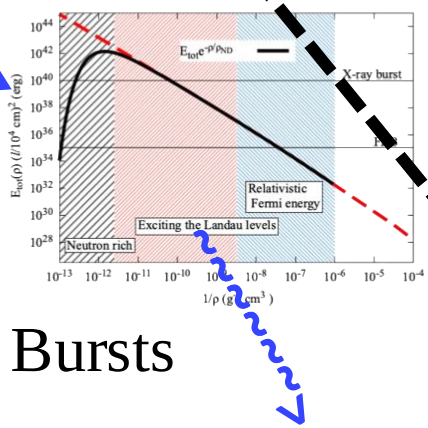
Summary

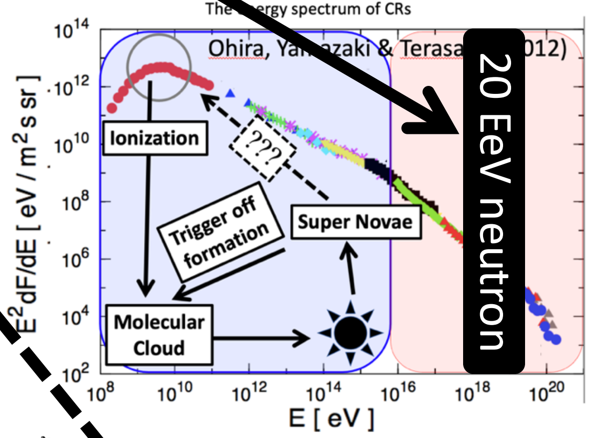






>100 EeV nuclei



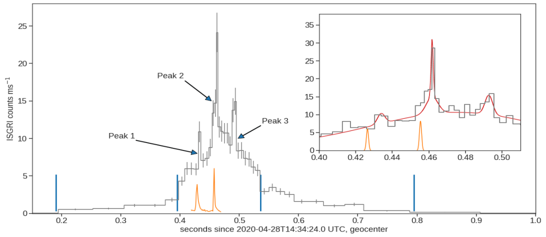


20 EeV neutron

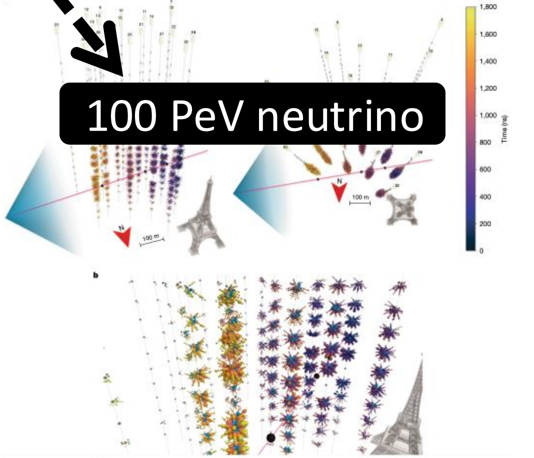
Instant ZeV-ion-acceleration in Upset Magnetar Origin Bursts
→ IZUMO Bursts

The *cracked* Area is ~ πl^2 ~ 3.0e8 cm^2 .
$\Delta\Omega$ang~$\pi l^2/(4\pi R_*^2)$~1.0e-6, H ~ 100 m/R_*~1.0e-2 (R_*/10 km)$^{-1}$
For the Earth…
ΔA_{Earth}~$4\pi R_{Earth}{}^2\Delta\Omega$ang~510 km^2 (出雲市~624 km^2)
H_{Earth} ~ R_{Earth} (H/R_*) ~ 63.71 km
出雲市（~ 624 km^2）が吹き飛んで深さ~60 kmの穴を作るくらい。
(Not So Drastic)

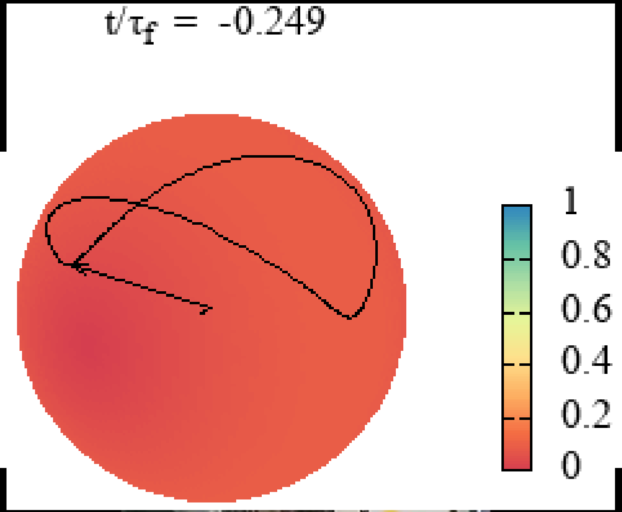
100 keV photon

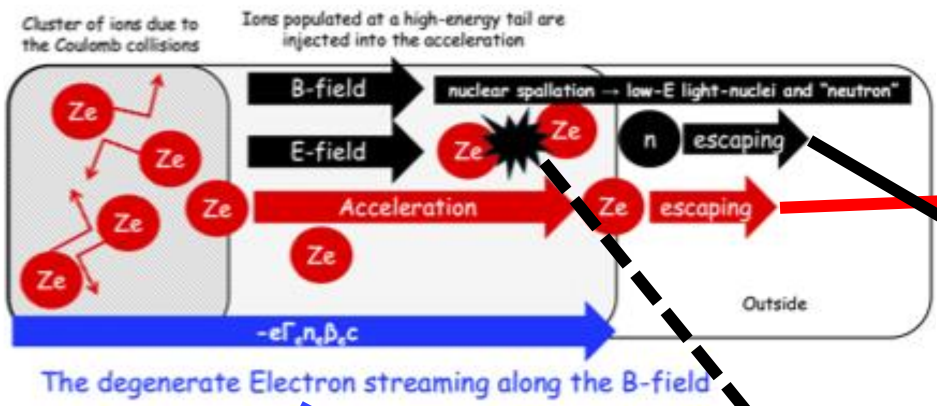


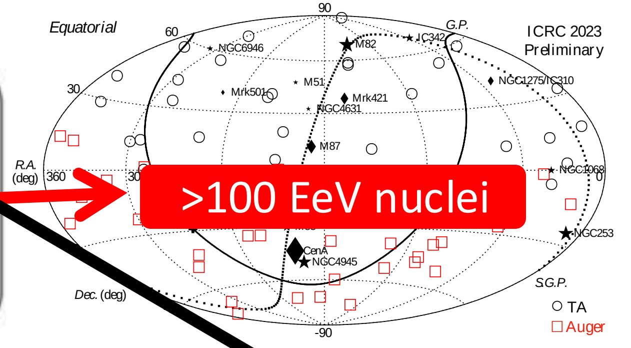
100 PeV neutrino

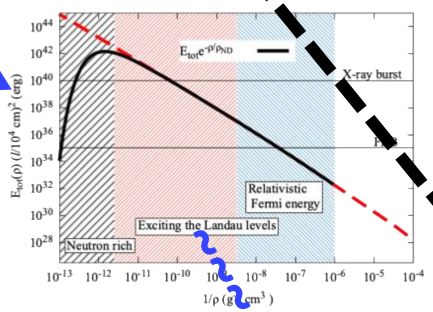


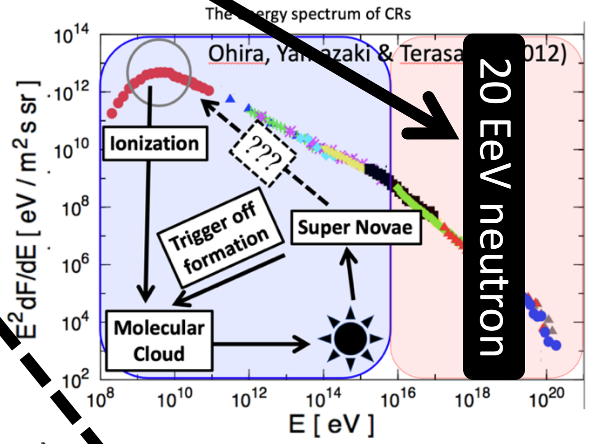
Summary

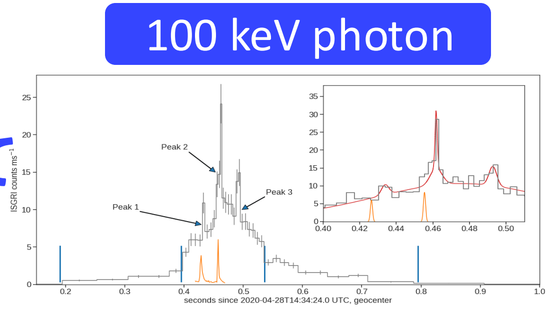


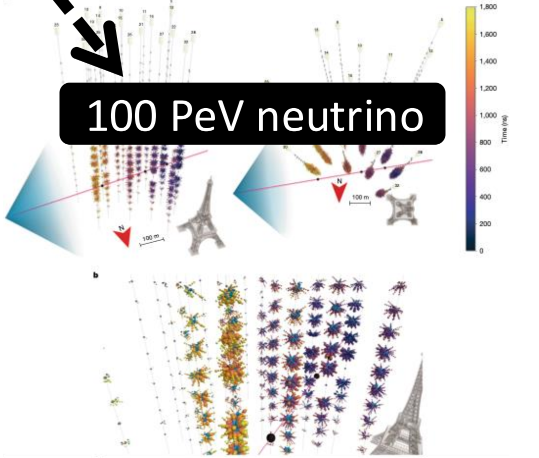






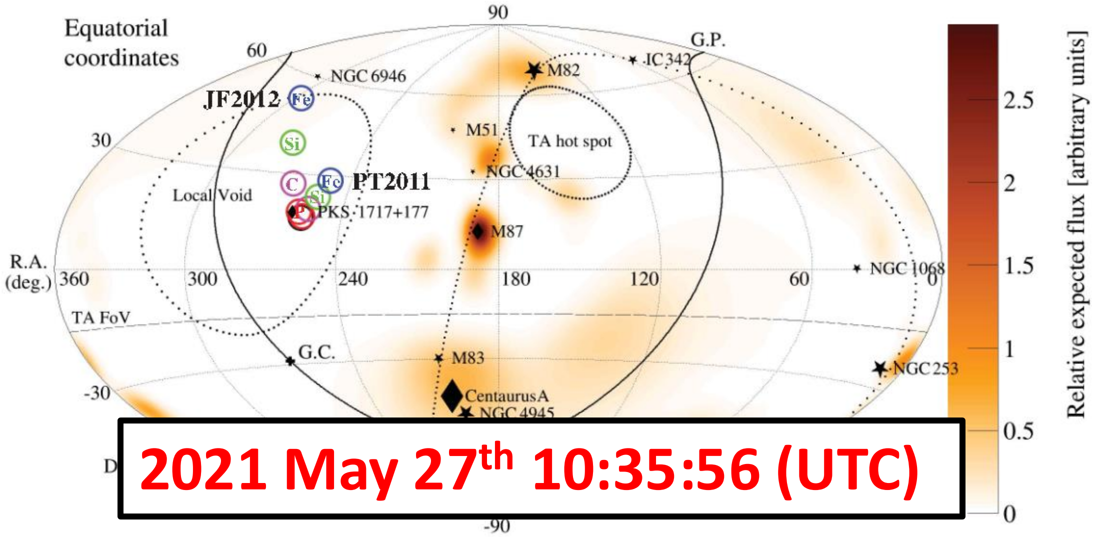






Chronos/JEDI project （次世代X線衛星計画）
旧称(?)は*FORCE*
こういう突発天体@X線→の観測を狙う衛星.
***20 EeV neutron*は~120 kpcしか飛ばない.**
こういう衛星が天の川銀河等をモニター観測してくれると，宇宙線+ニュートリノ+光子のマルチメッセンジャー天文学ができる.

Amaterasu & SGR 1935+2154



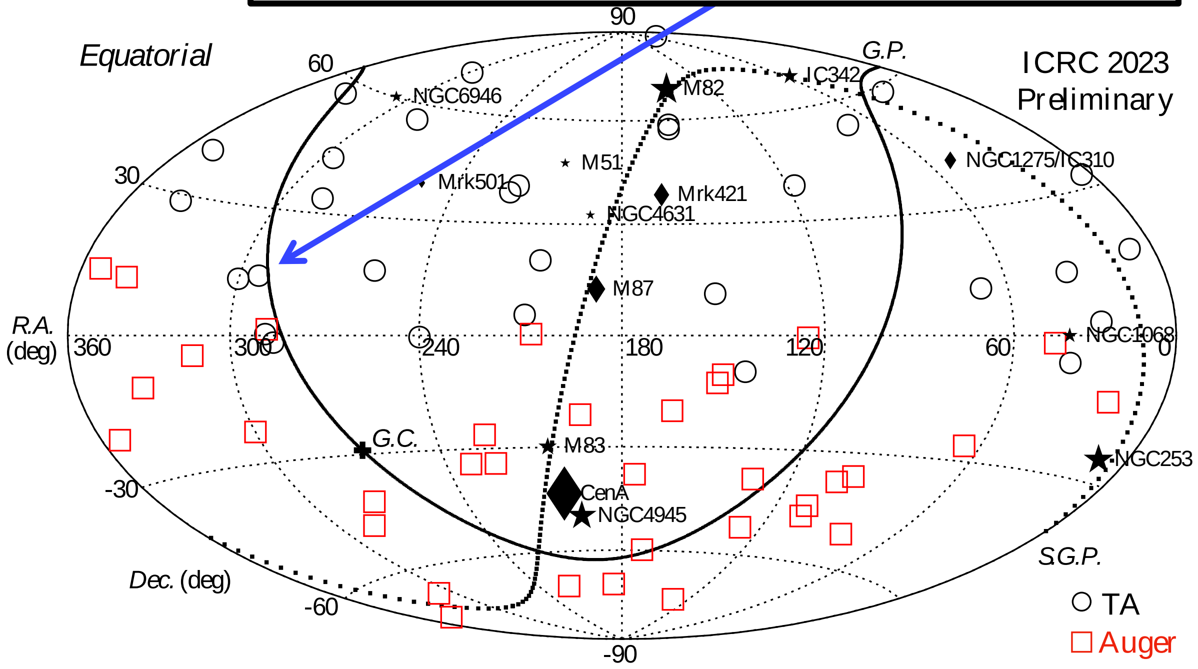
2021 May 27th 10:35:56 (UTC)

TA collaboration (2023)

Energy~200 EeV!
m.f.p ~ 1-10 Mpc (by photon)

$$r_g \sim 100\ \mathrm{kpc}\ Z^{-1}(\epsilon_i/100\ \mathrm{EeV})(B_{\mathrm{ISM}}/1\ \mu\mathrm{G})^{-1}$$

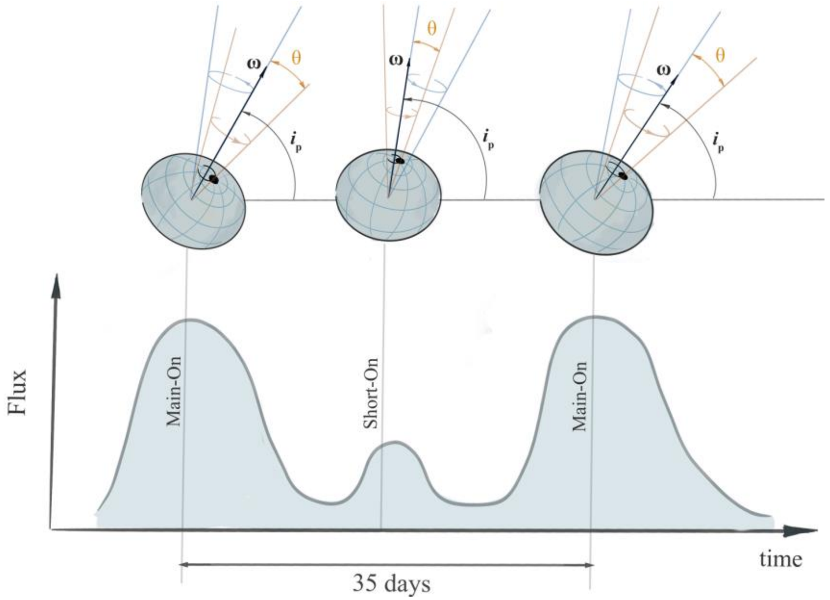
SGR 1935+2154
(RA, Dec)=(293.750, +21.911) deg
(l, b)=(57, 0.8) deg
2021 May 16th 20:15:08 (GMT)



Estimated Arrival directions for E > 100 EeV
(Fujii 2023)

The case of Her X-1
e.g., Shakura+98, Kolsenikov+20, Heyl+23

Heyl+23



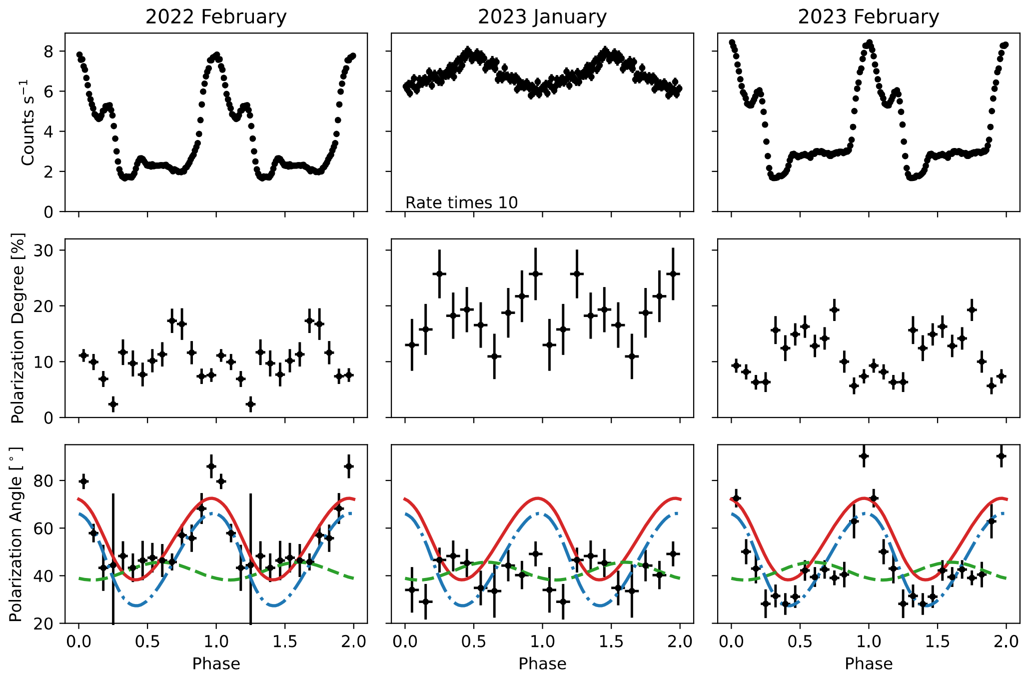
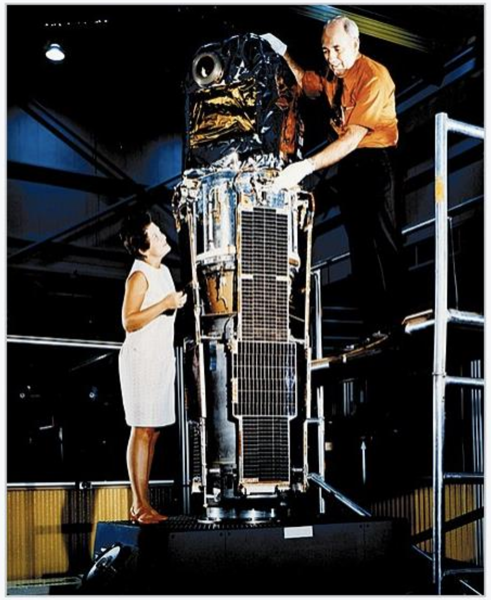


Figure 2: **IXPE Observations of Hercules X-1 as a Function of Spin Phase.** The top, middle



Uhuru (X-ray Explorer Satellite)

Wikipediaより

世界初とされるX線天文衛星*Uhuru*が1972年にHer X-1での
35日周期の変動を報告したとされる.
ShakuraグループはPrecessionシナリオ推しの模様.