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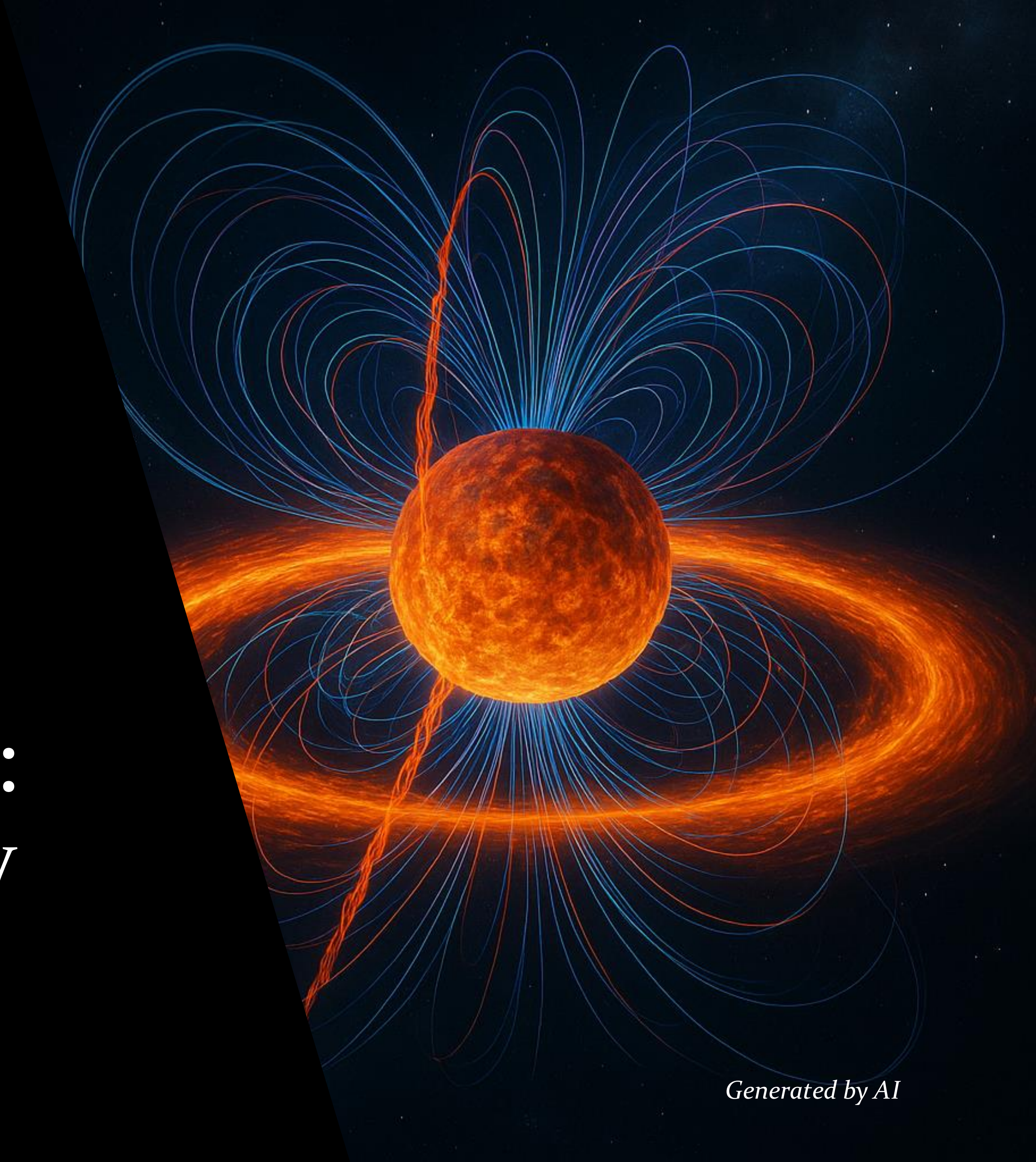
I - Strange quark star: magnetized and rapidly rotating configurations



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Brief history of strange star

- 1960 s, in Stanford Linear Accelerator Center SLAC a high-energy scattering examination.

  showed that protons and neutrons are composed of smaller particles.
- 1964, Gell–Mann & Zweig proposed the theory of quarks to explain these subatomic Particles.
- Bodmer (1971), Terazawa (1979), and Witten (1984) pointed out that the strange quark matter may be the stable state of matter (Energy per baryon ≤ ^{56}Fe).
- 1984, Farhi & Jaffe used the MIT bag model to study the stability of strange quark Matter.
- 1986, Alcock, et al. and Haensel & Zdunik, et al. independently, discussed the properties of

  strange stars.
- 1995, Weber discussed quark deconfinement in the core of neutron stars.

Some arguments…

- **SQS might exist after a super luminous explosion (Quark-Novae):**

  a) an increase in the core density due to spin-down of the proto-neutron star or the neutron star (NS)

  b) an increase in the core density following the accretion from the companion in binary NS

- **Certain properties of observed neutron stars may be better explained if the stars are actually strange quark stars e.g.**

  - Supernova remnant HESS J1731-347: M = 0.77$M_\odot$ and R = 10.4 km *(Doroshenko, et. al., 2022)*

  - Observational signatures of Quark-Novae, a promising candidate is Cassiopeia A

  (Ouyed, et al, 2015)

Arguments against SQS:

- **Lack of Strangeness in Neutron Star Mergers: Observations from neutron star mergers are consistent with the ordinary nuclear matter, not SQM.**

- **Although some studies suggest that glitches observed in pulsars could be attributed to SQS,**
  - **Glitches can arise from conventional mechanisms within neutron stars, such as superfluidity or interactions between the crust and the superfluid core.**

Some models:

- Rapidly rotating strange star is discussed by Gondek-Rosinska, et al. in 2000.
- Maximum rotational frequency of NS and SQS is studied by Haensel et al. in 2009.
- Deformation of a magnetized neutron star was studied by Mallick, et al. in 2014 and

Mastrano, et al. in 2015.

- A magnetized rotating neutron star is studied by Chatterjee et al. in 2015.

Our model and assumptions

1. **Equation of state:**
   - The density-dependent MIT bag model (*Burgio et al., 2002*)
   - Strange quark matter (SQM) contains up, down and strange quarks.
   - In magnetized model: Landau quantization effect

2. **Configurations:**
   - 28 models by varying the magnetic filed strength in range of [0 - 10^{18}]G
   - 12 Models with different rotational frequencies in range of [0 – 1300]Hz

- In each model we compute configurations with the central enthalpy in the range of [0.01 - 0.51] c^2, with the spacing of 0.001 c^2

LORENE library

- The LORENE library is a code based on C++ that uses the spectral method to solve PDEs.
- Space is separated into domains and mapped onto the specific coordinate system that can be re-adjusted to handle non-spherical shapes.
- *Et_magnetisation* class is used to compute to calculate hydrostatic configurations for uniformly (not differentially) rotating magnetized stars. *(located in the directory Lorene/Codes/Mag_eos_star)*
- EOS is provided as a table including the number density, central mass density, pressure, magnetic field and magnetization, etc.

Equation of state

$$P(\rho) = \rho \left(\frac{\partial \varepsilon_{\rm tot}}{\partial \rho} \right) - \varepsilon_{\rm tot}.$$

$$\varepsilon_{\rm tot} = \sum_{i,j=\pm} \varepsilon_i^{(j)} + \mathcal{B}_{\rm bag}(\rho),$$

$$\mathcal{B}_{\rm bag}(\rho) = \mathcal{B}_\infty + (\mathcal{B}_0 - \mathcal{B}_\infty) e^{-\alpha(\rho/\rho_0)^2}$$

$$\varepsilon_i^{(j)} = \frac{2B_D}{(2\pi)^2 \lambda^3} m_i c^2 \sum_{\nu=0}^{\nu_{\rm max}} g_\nu (1 + 2\nu B_D) \eta(x),$$

$$\eta(x) = \frac{1}{2}\left[x\sqrt{1+x^2} + ln(x\sqrt{1+x^2}) \right],$$

$$x = \frac{X_F^{(j)}}{(1+2\nu B_D)^{1/2}}$$

$$X_F^{(j)} = (\epsilon_F^{(j)2} - 1 - 2\nu B_D)^{1/2}.$$

$$B_{\rm D} = B/B_{\rm C}$$

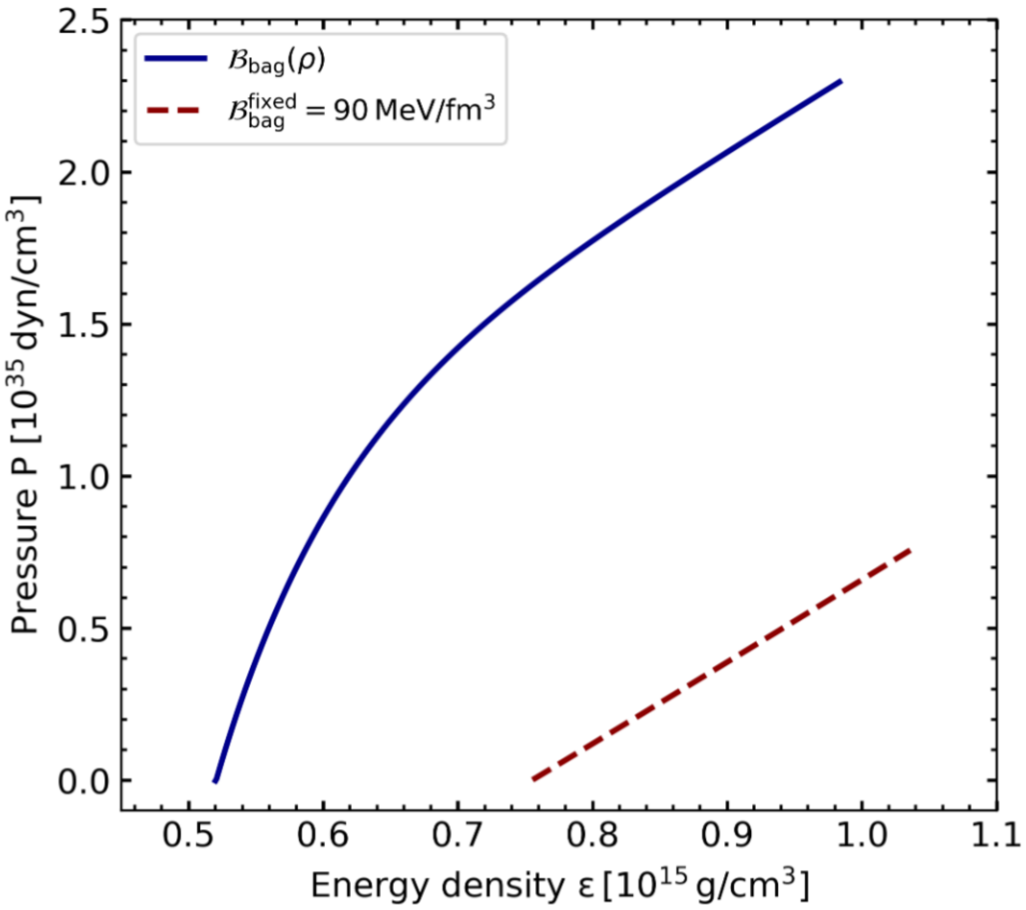
$$B_{\rm C} = m_i^2 c^3 / q_i \hbar$$

$$\nu_{\rm max} = \frac{\epsilon_{\rm Fmax}^2 - 1}{2 m_i c B_D}.$$

maximum Fermi energy

Degeneracy of of the ν-th Landau level

ρ is mass density and ρo = 0.17 fm3 is normal nuclear mass density, α = 0.17 and $B_0 = B_{bag}(0)$ =400 MeV/fm3. B_∞ = 8.99 MeV/fm³ is defined in such a way that the bag constant would be compatible with experimental data (CERN-SPS) *(Heinz & Jacob 2000; Burgio et al. 2002).*



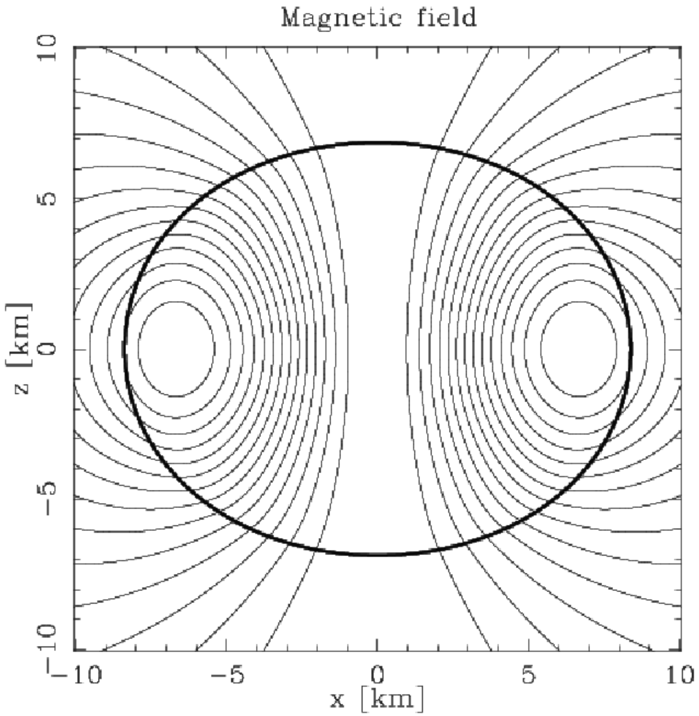
Model	a	ε_0 [10^{15} g/cm^3]	M_g^{max} [$M_\odot$]	f^{max} [kHz]
$\mathcal{B}_{bag}(\rho)$	1 - 0.260	0.5	2.35	1.3
$\mathcal{B}_{bag}^{fixed}$	0.253	0.75	1.32	2.4
SS1	0.463	1.15	2.04	2.6
SS2	0.455	1.33	1.88	2.8

Gondek-Rosińska et al. (2000),

Stellar structure

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu + Pg^{\mu\nu} + \frac{\mathcal{M}}{B}\Big[b^\mu b^\nu - (b\cdot b)(u^\mu u^\nu + g^{\mu\nu})\Big] + \frac{1}{\mu_0}\Big[-b^\mu b^\nu + (b\cdot b)(u^\mu u^\nu + \frac{1}{2}g^{\mu\nu})\Big]$$

$$ds^2 = -N^2dt^2 + A^2(dr^2 + r^2d\theta^2) + \lambda^2 r^2\sin^2(\theta)(d\phi - N^\phi dt)^2$$



$$\Delta_3 = 4\pi A^2(E^T + S^r_r + S^\theta_\theta + S^\phi_\phi) + \frac{\lambda^2 r^2\sin^2(\theta)}{2N^2}\delta N^\phi \delta N^\phi - \delta\nu\delta(\nu + \beta) \quad (17)$$

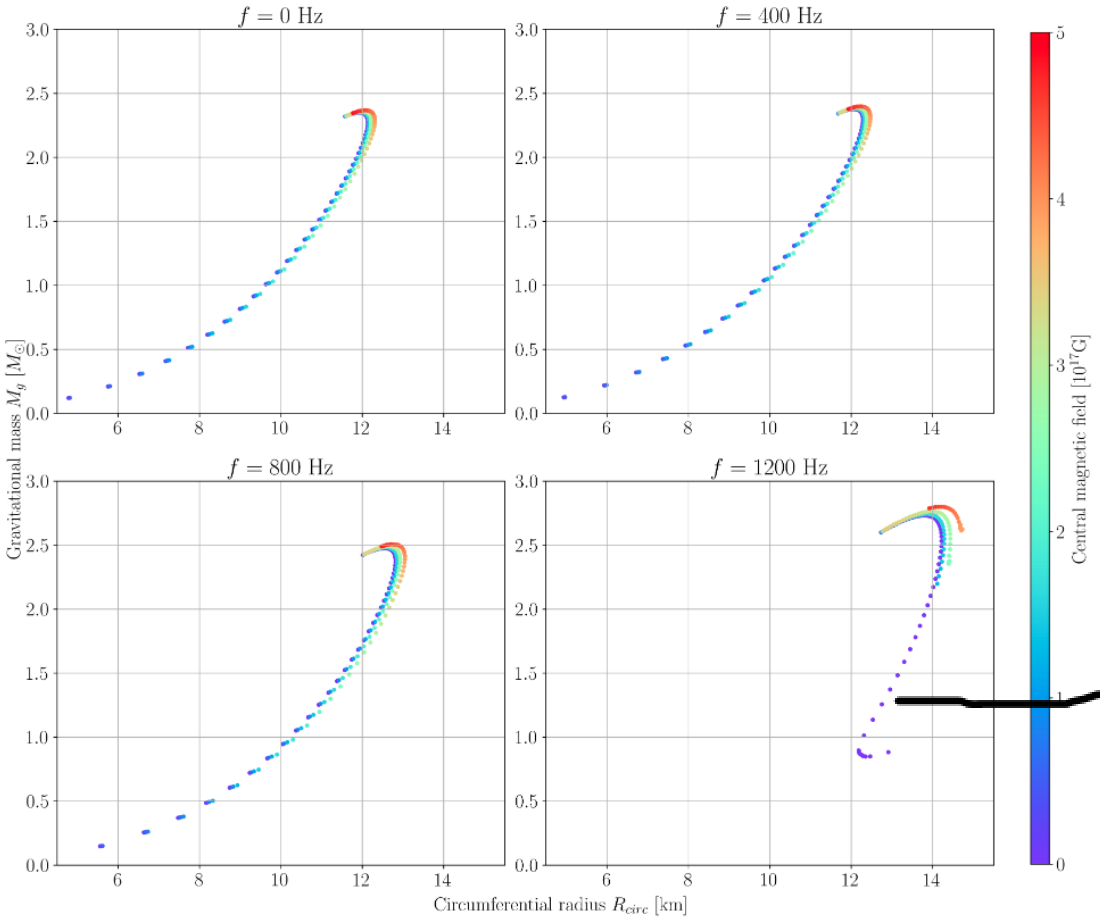
$$\Delta_2[\alpha + \nu] = 8\pi A^2 S^\phi_\phi + \frac{3\lambda^2 r^2\sin^2(\theta)}{4N^2}\delta N^\phi \delta N^\phi - \delta\nu\delta\nu \quad (18)$$

$$\Delta_2[(N\lambda - 1)r\sin(\theta)] = 8\pi N A^2\lambda r\sin(\theta)(S^r_r + S^\theta_\theta) \quad (19)$$

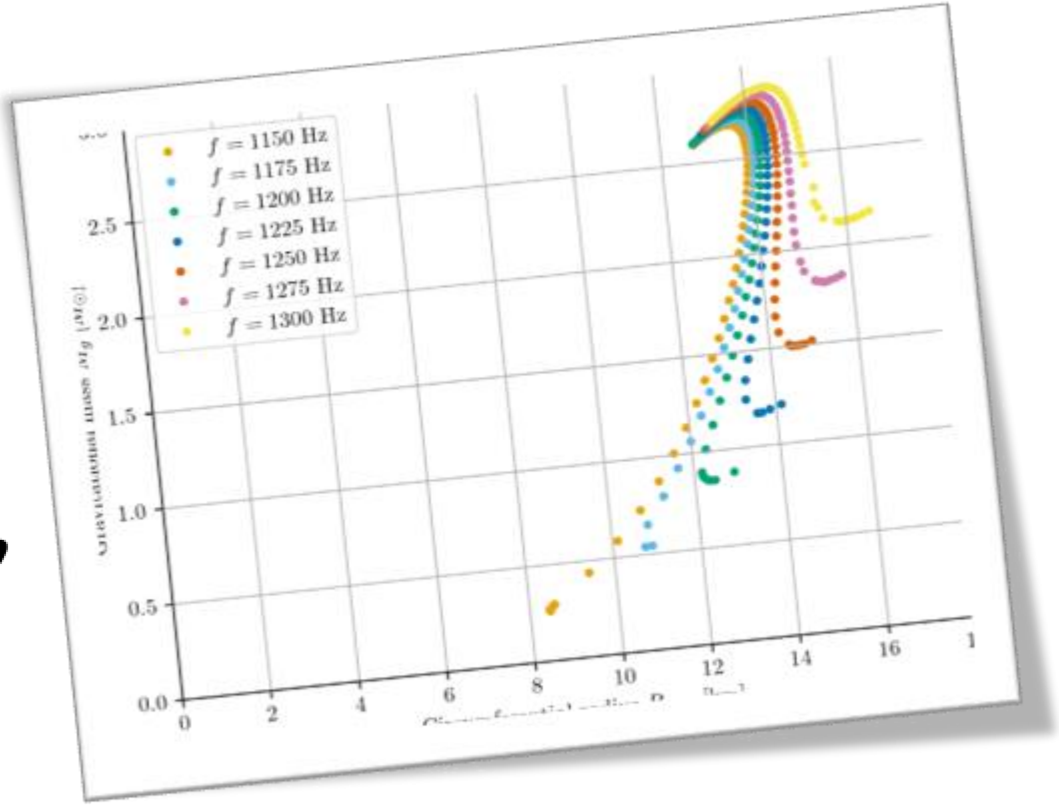
and

$$\left[\Delta_3 - \frac{1}{r^2\sin^2(\theta)}\right](N^\phi r\sin(\theta)) = -16\pi\frac{NA^2}{\lambda^2}\frac{J^\phi}{r\sin(\theta)} + r\sin(\theta)\delta N^\phi \delta(\nu - 3\beta), \quad (20)$$

MASS-RADIUS



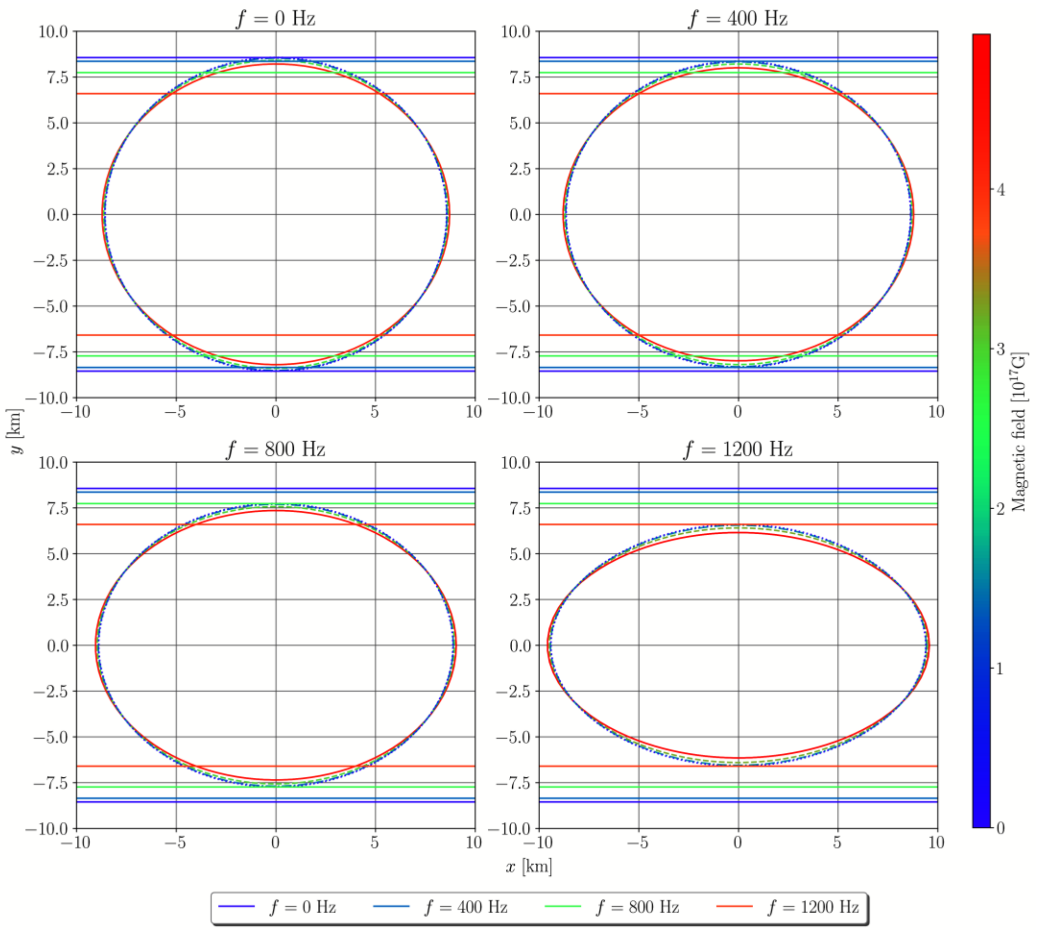
$f = 0$ Hz
$f = 400$ Hz
$f = 800$ Hz
$f = 1200$ Hz
Gravitational mass M_g [$M_\odot$]
Circumferential radius R_{circ} [km]
Central magnetic field [10^{17}G]

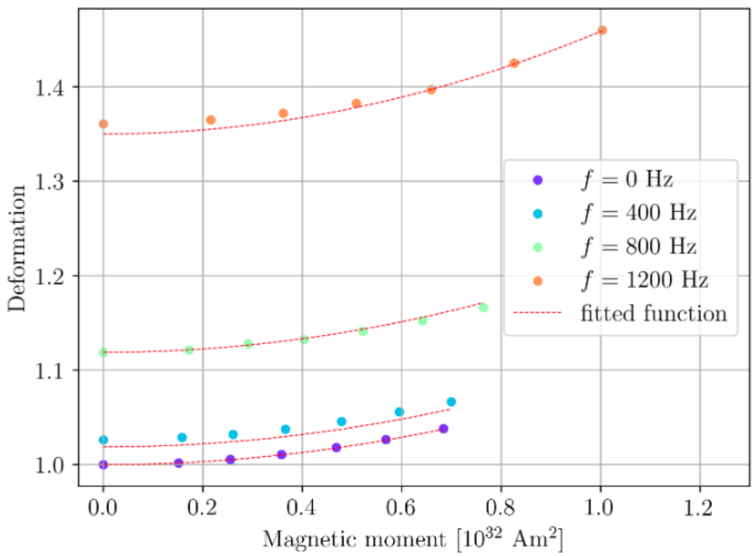


$f = 1150$ Hz
$f = 1175$ Hz
$f = 1200$ Hz
$f = 1225$ Hz
$f = 1250$ Hz
$f = 1275$ Hz
$f = 1300$ Hz

f (Hz)	B_c (10^{17} G)	$M_g(M_\odot)$	$M_b(M_\odot)$	R_{circ} (km)	a	$\|E_{EB}\|/A$ (MeV)
0	0	2.35	2.92	11.92	1	184
	1.05	2.35	2.92	11.9	1.0	184
	2.43	2.36	2.93	11.97	1.01	184
	3.10	2.36	2.94	12.03	1.02	184
	3.84	2.36	2.94	12.03	1.03	184
	4.51	2.37	2.95	12.09	1.04	183
	5.11	2.37	2.95	12.21	1.05	183
400	0	2.38	2.96	12.05	1.03	184
	1.03	2.38	2.95	12.1	1.03	184
	1.74	2.38	2.96	12.1	1.03	184
	3.12	2.39	2.97	12.15	1.05	183
	3.78	2.39	.98	12.22	1.06	183
	4.5	2.40	2.98	12.22	1.07	183
	5.15	2.40	2.99	12.34	1.08	182
800	0	2.48	3.07	12.54	1.11	182
	1.05	2.48	3.10	12.55	1.12	182
	2.45	2.49	3.10	12.59	1.13	182
	3.87	2.5	3.10	12.65	1.15	182
	4.6	2.51	3.11	12.70	1.16	182
	5.11	2.51	3.11	12.93	1.20	180
1200	0	2.73	3.38	13.08	1.36	179
	1.04	2.73	3.38	13.84	1.36	179
	2.44	2.75	3.40	13.90	1.38	179
	3.83	2.78	3.43	14.10	1.43	178
	4.51	2.80	3.46	14.21	1.46	177
	4.97	2.80	3.43	14.6	1.55	171

SHAPE (DEFORMATION)

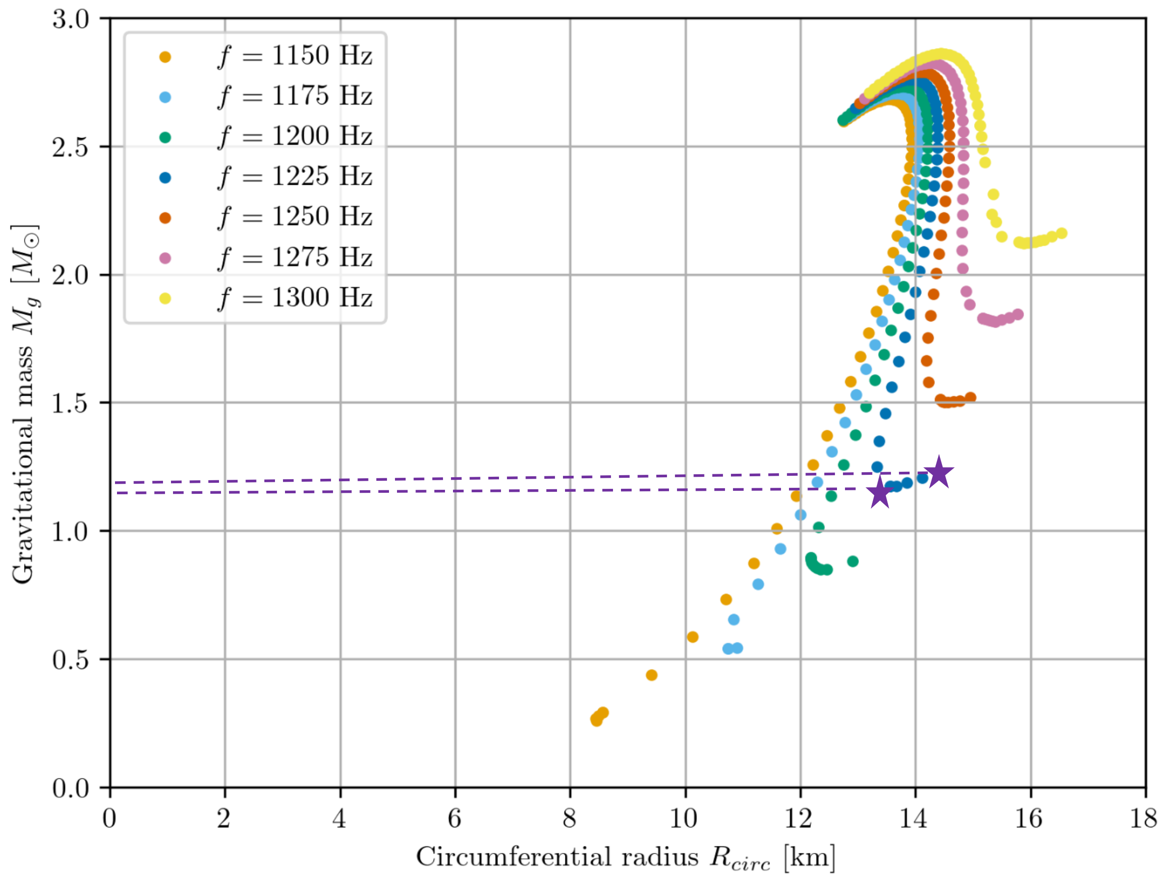


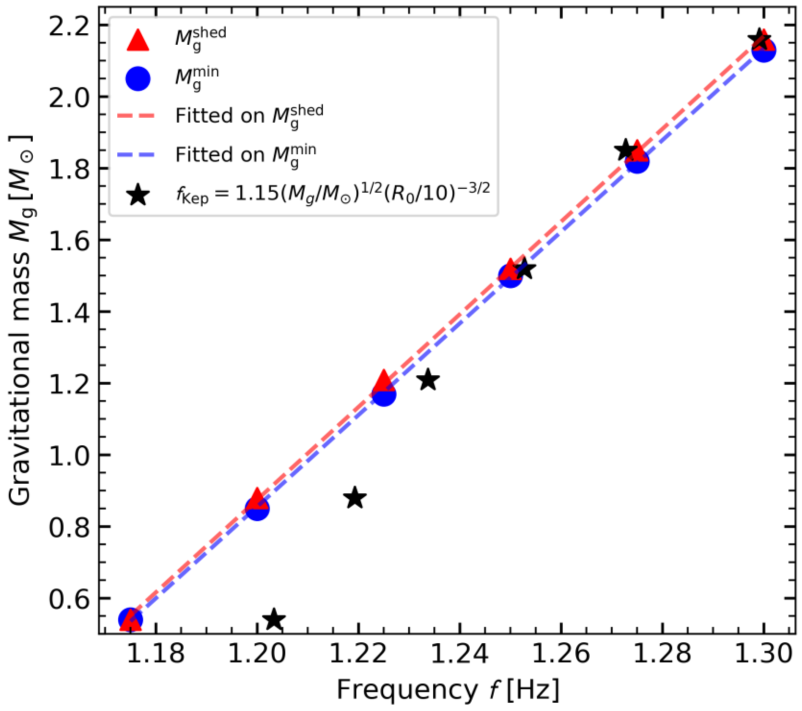


$$\frac{a(\mu, f)}{a(0,0)} \simeq (1 + \tilde{a}\mu^2)(1 + \tilde{b} f^{\tilde{c}})$$

The maximum deformation parameter
a = 1.55 corresponds to
magnetized rotating SQS with
$B_c \simeq 5 \times 10^{17}$ G and f = 1200 Hz.

Rapidly (uniformly) rotating star



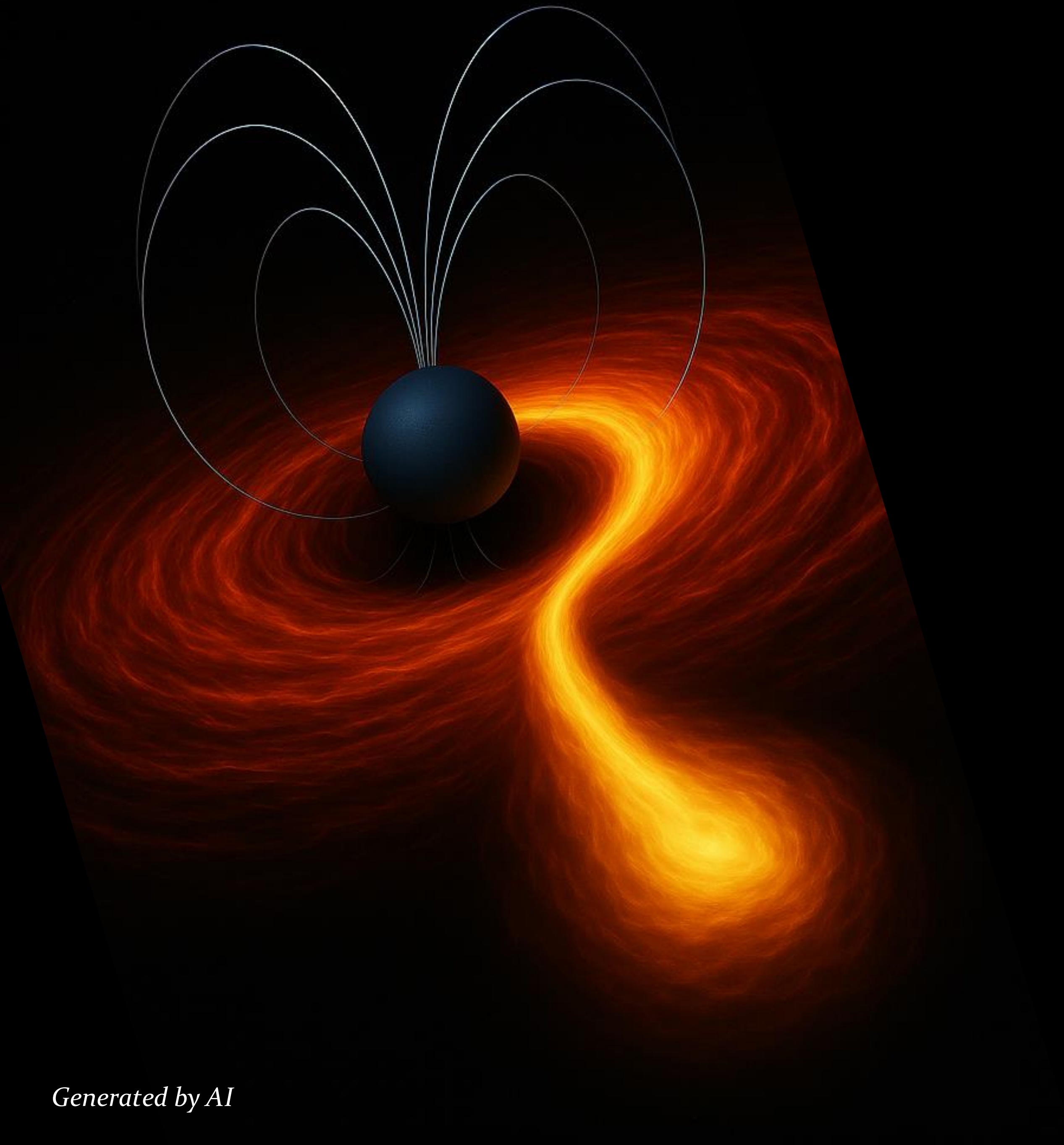


$$f_{\rm Kep} = 1.15 \left(\frac{M_{\rm g}}{M_\odot}\right)^{1/2} \left(\frac{R_0}{10}\right)^{-3/2} \ \text{kHz}$$

Haensel et al. (2009).

Conclusions

- Strange quark matter with density-dependent MIT bag model may explain the mass and rotational frequency of detected compacts
- Relation between the rotational frequency, magnetic field and deformation parameter and maximum gravitational mass.
- Maximum gravitational mass and deformation parameter for magnetized spinning star are about **2.8** solar mass and **1.55**.
- Keplerian configuration with the mass in the range of **0.6 - 2.2** solar mass and frequency of **1175 – 1300** Hz.



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II Accretion onto magnetized compacts: neutron star, black hole, exotic object??

Neutron star-ultraluminous X-ray sources (NS-ULXs)

- **ULXs: Non-nuclear** extra-galactic sources that emit X-rays at luminosities **exceeding 10^{39} erg s^{-1}**, above the **critical Eddington luminosity** for a compact object with a mass less than 10 solar mass.
    - Super-Eddington accretion onto stellar mass objects (neutron stars and black holes),
    - Supper-Eddington radiation in the radii between magnetosphere and spherization radius,

$$L \simeq L_{Edd}\,[1 + \ln \dot{M} / \dot{M}_{Edd}],$$ *(Shakura & Sunyaev, 1973).*

    - Radiation pressure causes the **outflow** and resulting **beaming** *(King et al. 2001).*
    - *King. et.al, 2001:* ULXs powered by **extremely high accretion rate** onto compact objects in high-mass X-ray binaries **(HMXBs)** in a transient stage.

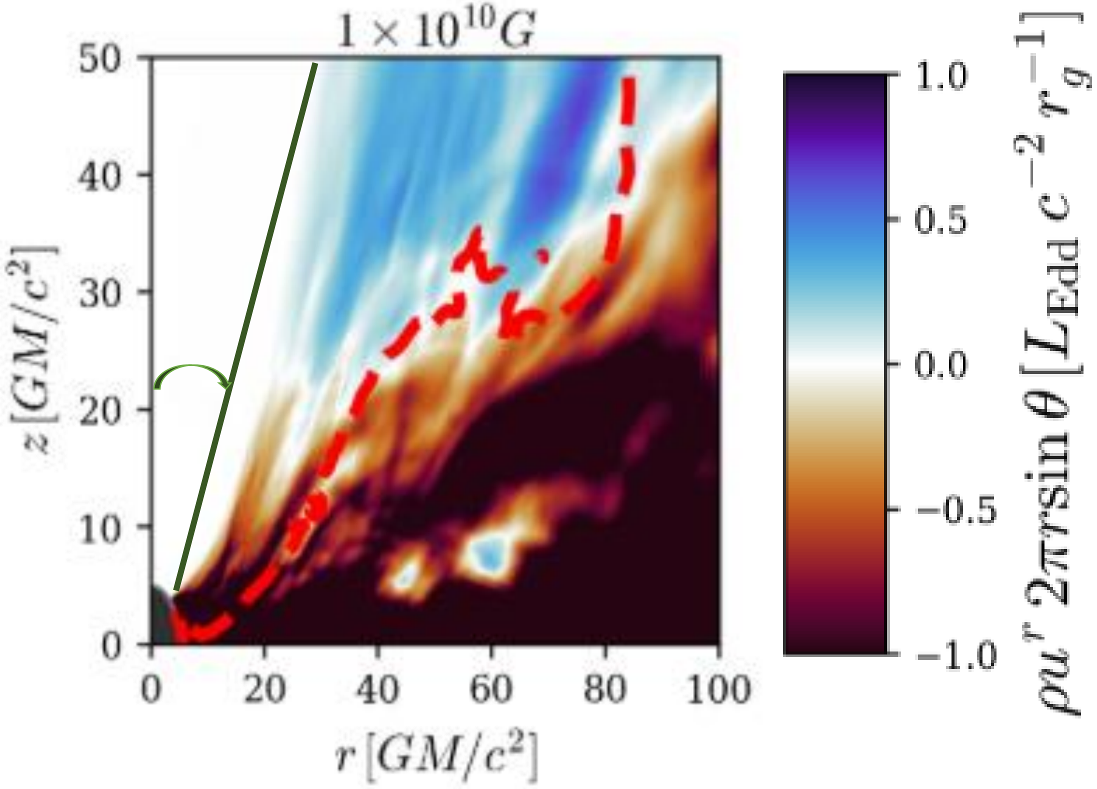
Beaming emission

- **KLK model** (studied by King, Lasota & Kluźniak, 2017; King & Lasota, 2019, 2020):
  - ✓ The compact object emits its radiation within a fraction b of the unit sphere, causing the luminosity to be overestimated by a factor of 1/b
  - ✓ when b<<1 then the inferred isotropic luminosity, $L_{iso} \sim L/b$

$$L_{iso} = 4\pi d^2 F^r_{rad}$$

F^r_{rad}: radiation flux in optically thin cone-like region

d: distance between source and detector

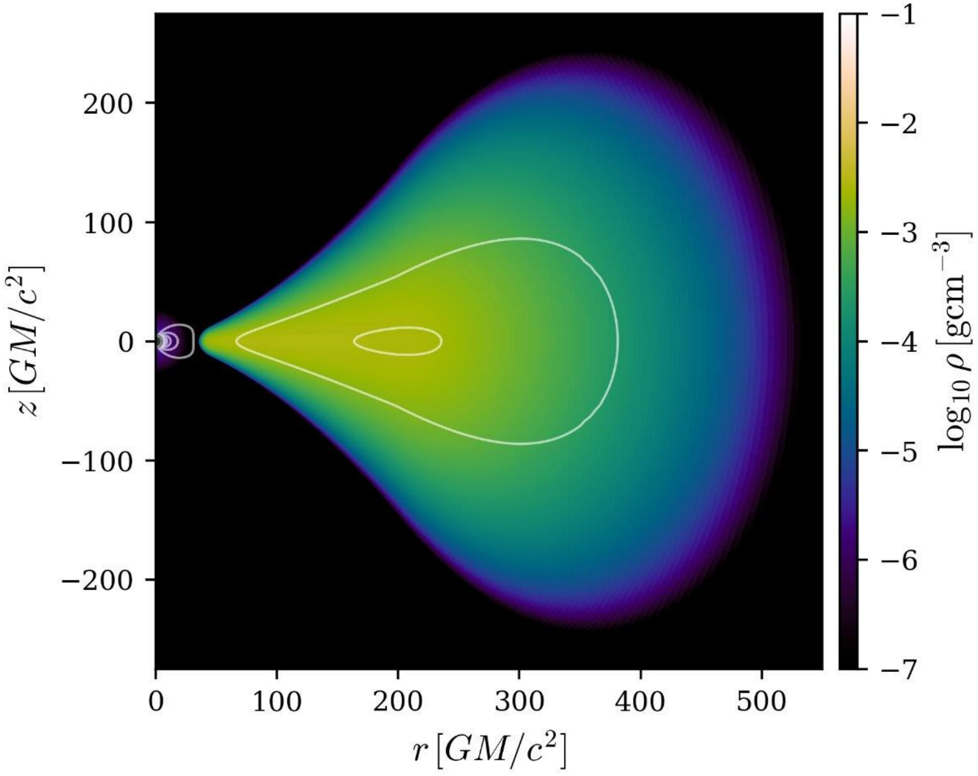


Simulation details

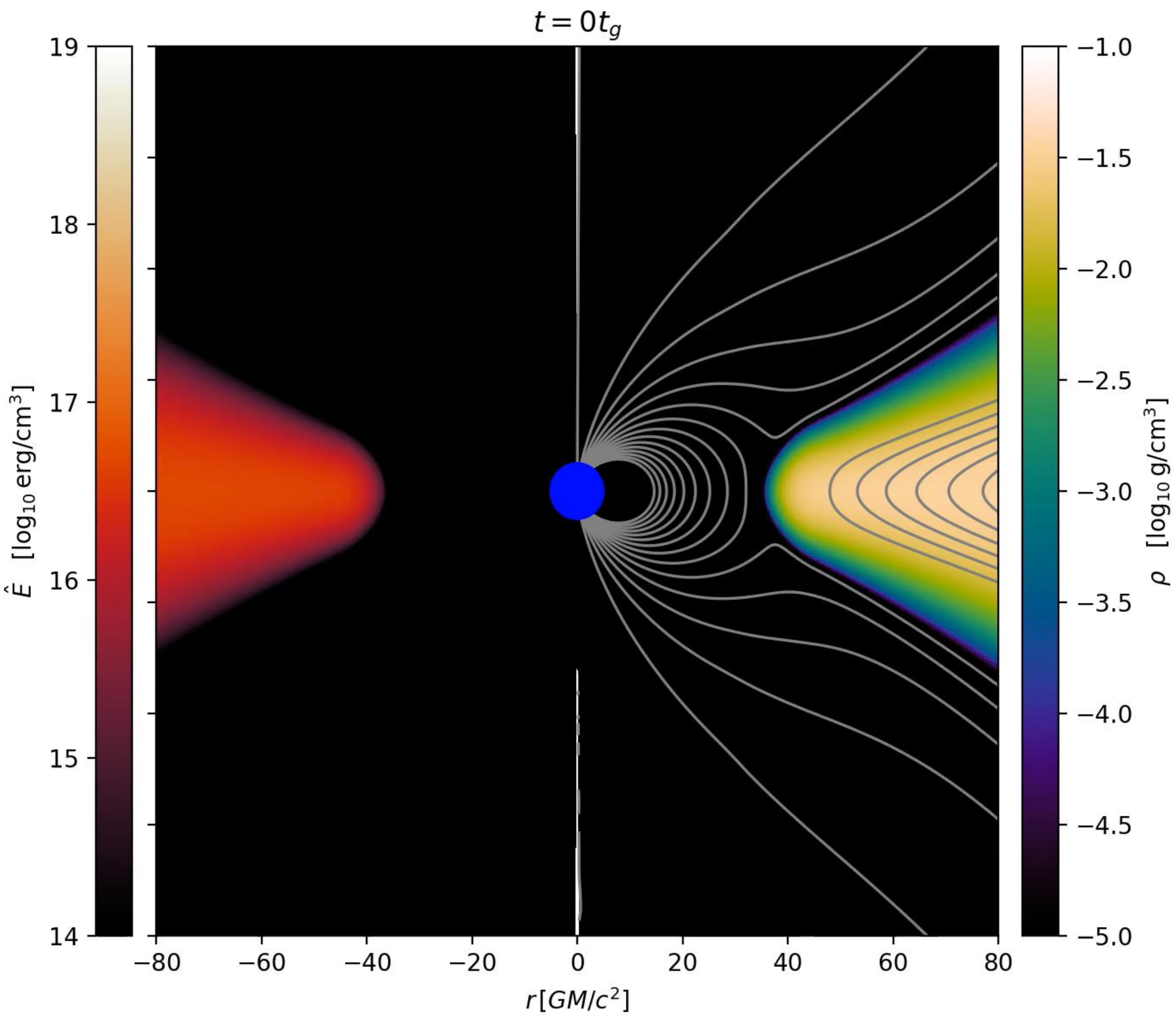
- General relativistic radiative magnetohydrodynamic (GRRMHD) code, KORAL.
- Conservation of mass ne energy-momentum tensor:

$$\nabla_\mu(\rho u^\mu) = 0 \quad \& \quad \nabla_\mu(T^\mu{}_\nu + R^\mu{}_\nu) = 0$$

- Neutron star: mass 1.4 $M_\odot$ and radius $5r_g$ ($r_g = GM/c^2$) with dipole magnetic field
- Torus: Equilibrium torus with loop magnetic field with $\beta = (P_{gas}+P_{rad})/P_{mag} = 10$
- Resolution: $N_r \times N_\theta \times N_\varphi = 512 \times 510 \times 1$ with logarithmic spacing in r direction
- Schwarzschild metric
- Boundary condition: energy reflective surface for the neutron star with albedo 0.75



200
100
0
−100
−200
$z\,[GM/c^2]$
0
100
200
300
400
500
$r\,[GM/c^2]$
−1
−2
−3
−4
−5
−6
−7
$\log_{10}\rho\,[\mathrm{gcm}^{-3}]$

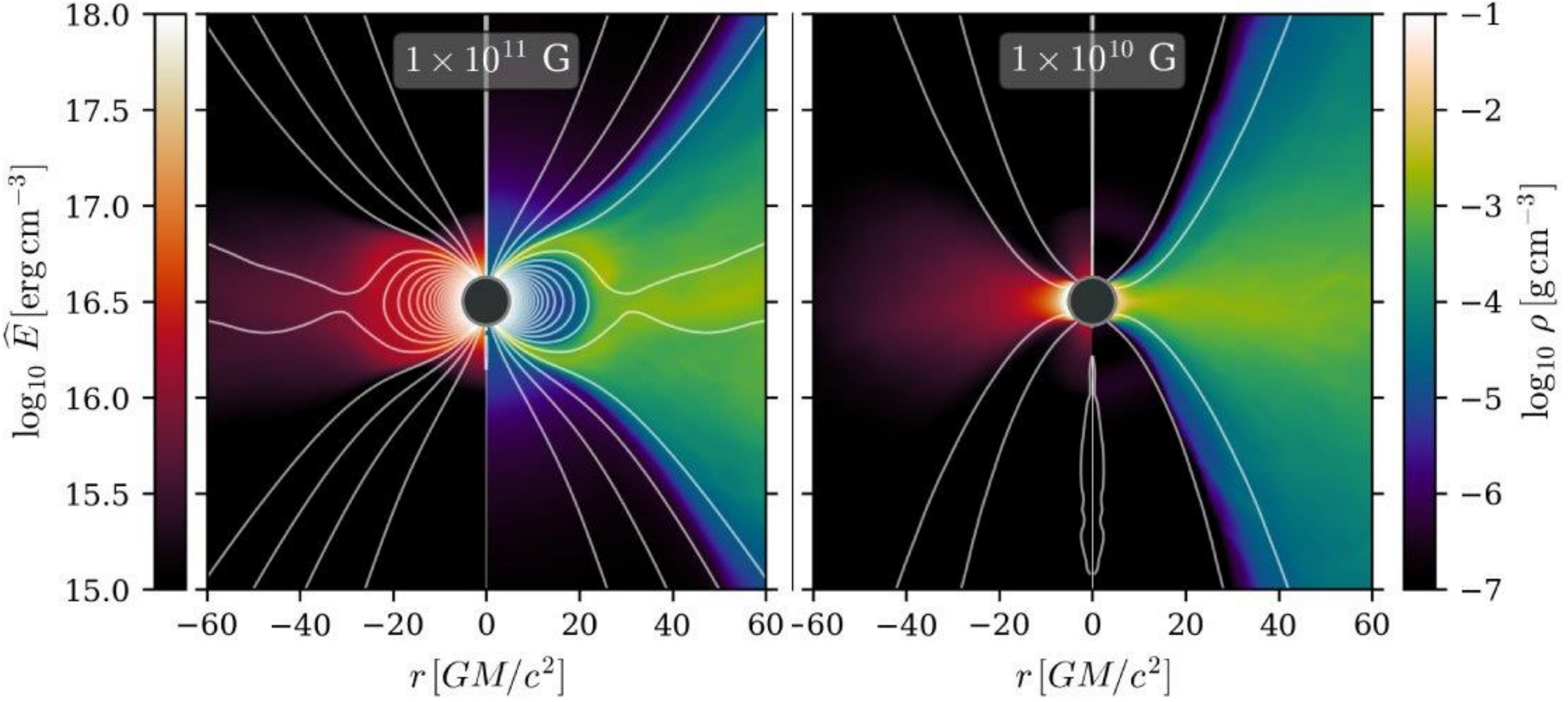


$t = 0t_g$
19
18
17
16
15
14
$\hat{E}$ [$\log_{10}$ erg/cm^3]
−80
−60
−40
−20
0
20
40
60
80
$r[GM/c^2]$
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
ρ [$\log_{10}$ g/cm^3]

MODELS

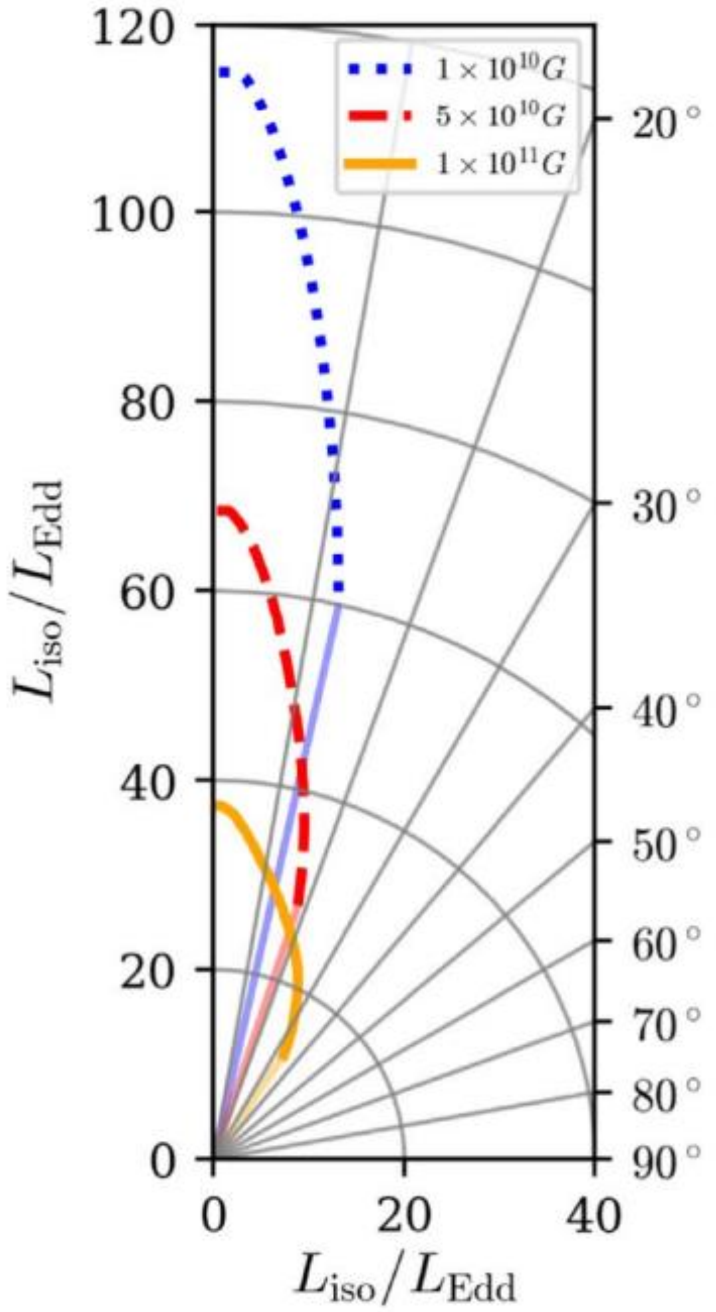
B [G]	$\dot{M}$ [L_{Edd} c^{-2}]	$\dot{M}_{out}$ [L_{Edd} c^{-2}]	L/L_{Edd}	b_{min}	L_{iso}/L_{Edd}	R_A/r_g
1×10^{10}	257	325	2.10	0.016	115	5.25
2×10^{10}	320	317	1.97	0.020	100	6.85
3×10^{10}	345	250	1.90	0.023	90	10.15
5×10^{10}	355	150	1.55	0.026	68	13.30
7×10^{10}	430	190	1.50	0.045	45	15.85
1×10^{11}	490	80	1.49	0.083	39	17.39

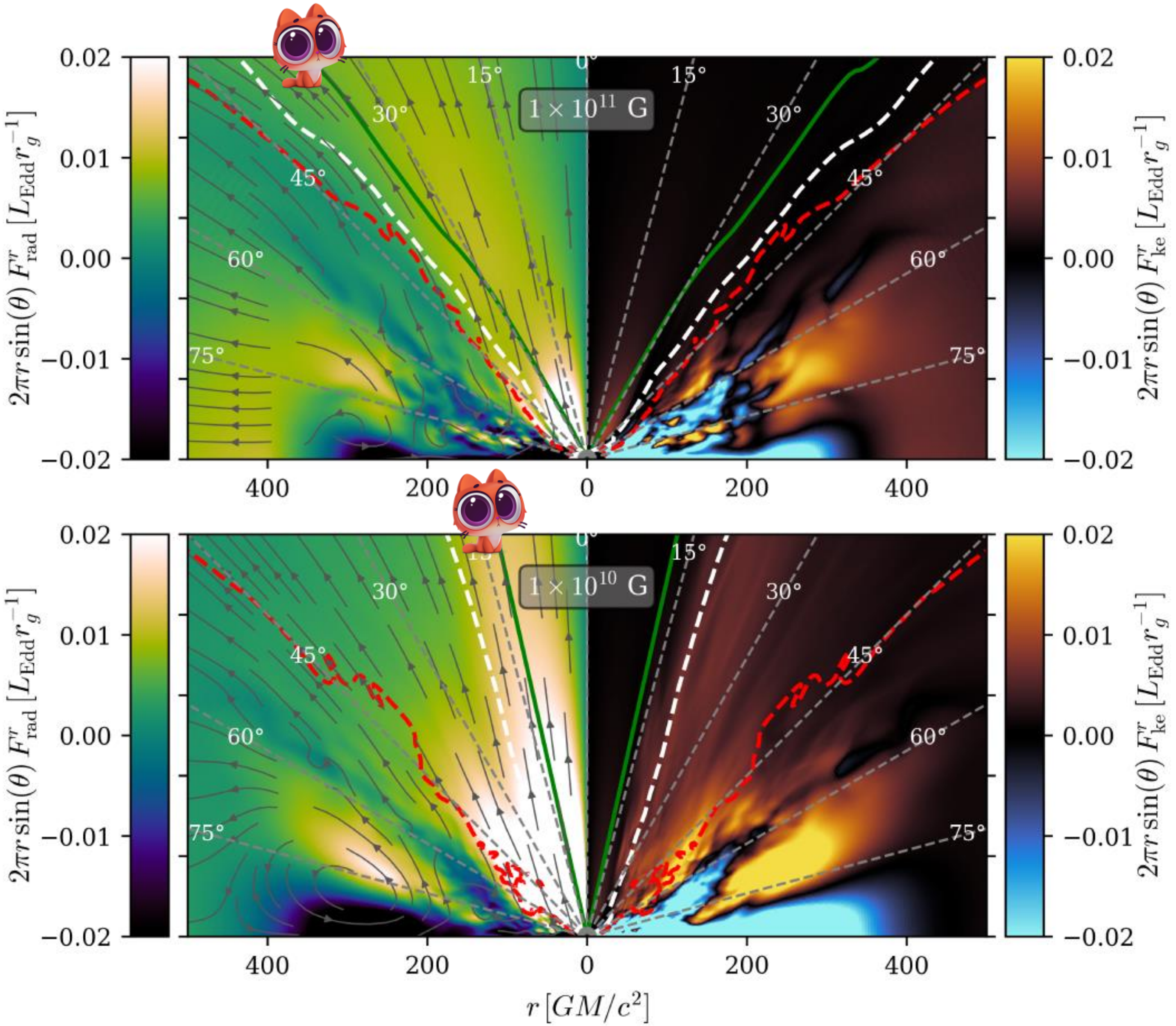
3×10^{10}	144	30	1.14	0.050	40	11.85
3×10^{10}	1000	3600	2.5	0.010	185	8.10



1×10^{11} G
1×10^{10} G
18.0
17.5
17.0
16.5
16.0
15.5
15.0
$\log_{10} \widehat{E} \, [\mathrm{erg\,cm^{-3}}]$
−1
−2
−3
−4
−5
−6
−7
$\log_{10} \rho \, [\mathrm{g\,cm^{-3}}]$
−60
−40
−20
0
20
40
60
$r \, [GM/c^2]$

BEAMING AND APPARENT LUMINOSITY



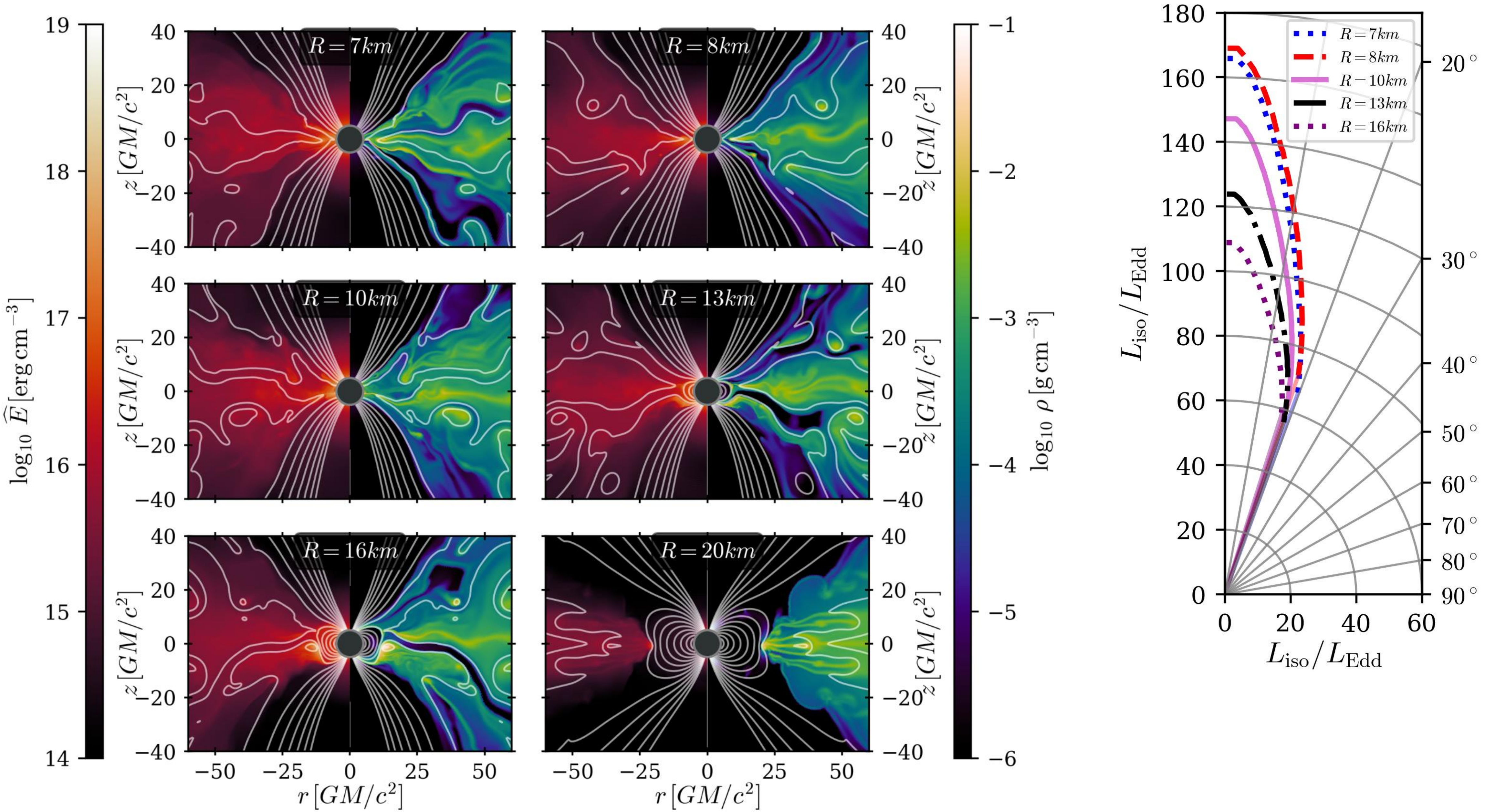


Inside out

- The mass-gap between neutron star and black hole: Neutron star, small black hole, or any exotic object?
- EOS of the compact accretor in NS-ULXs?
- How the compactness impacts the luminosity of ULXs?
- …

Compactness

Model	R-NS (r_g)	R-dipole (r_g)	Dipole at R-dipole (10^{10} G)	Dipole at R-NS (10^{10} G)
NS1	2.3	NS radius	0.17	3
NS2	2.5	NS radius	0.2	3
NS3	3.1	NS radius	0.4	3
NS4	4.0	NS radius	0.9	3
NS5	5.0	NS radius	1.7	3
NS6	2.3	6	1	18
NS7	2.5	6	1	14
NS8	3.1	6	1	7.3
NS9	4.0	6	1	3.4
NS10	5.0	6	1	1.7



R = 7km
R = 8km
R = 10km
R = 13km
R = 16km
R = 20km
$\log_{10}\,\widehat{E}\,[\mathrm{erg\,cm^{-3}}]$
$\log_{10}\,\rho\,[\mathrm{g\,cm^{-3}}]$
$z\,[GM/c^2]$
$r\,[GM/c^2]$
$L_{\rm iso}/L_{\rm Edd}$
20°
30°
40°
50°
60°
70°
80°
90°