Braking index of Young Neutron Stars

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Acknowledgements

FAPERJ

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Some advertising....

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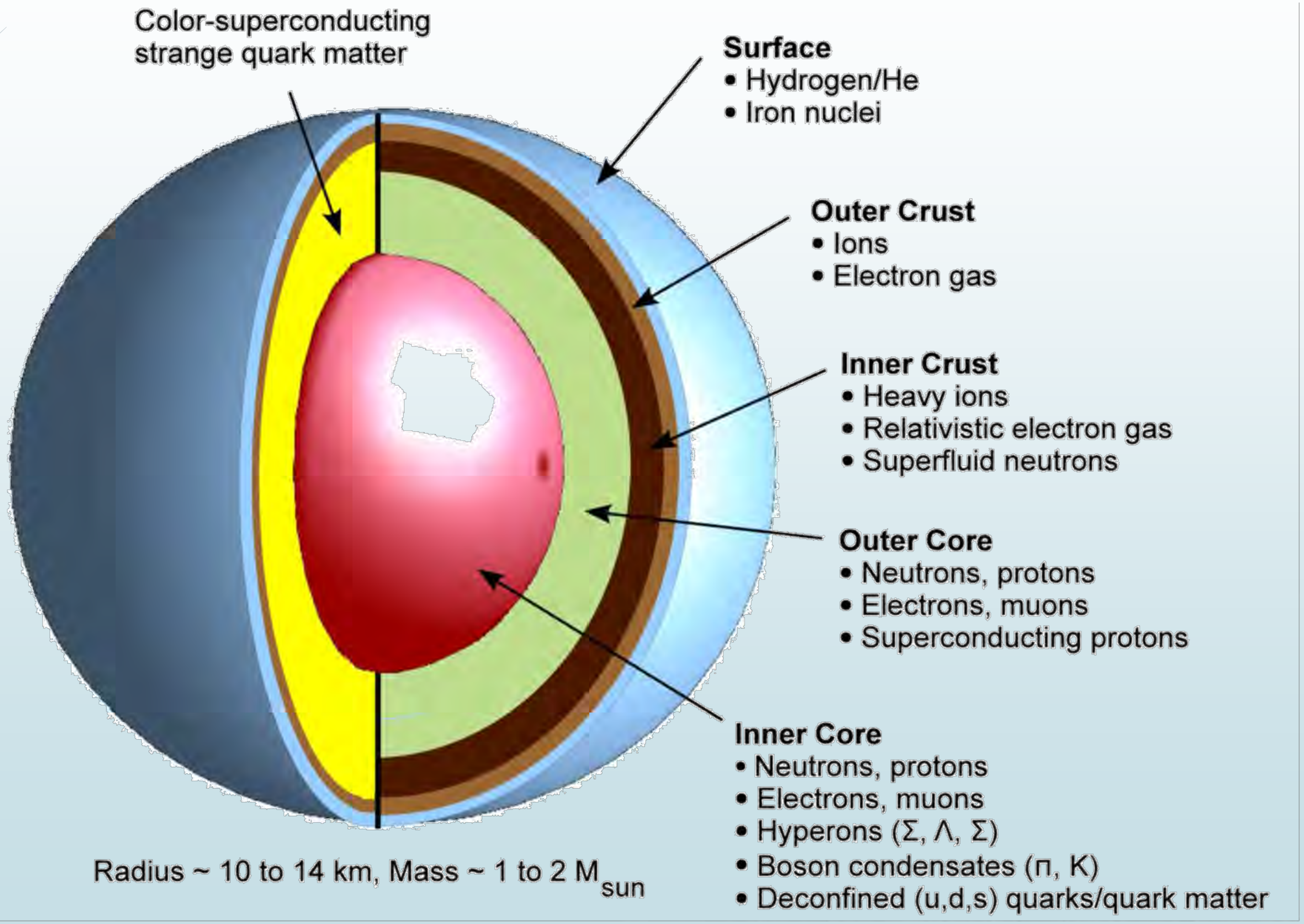
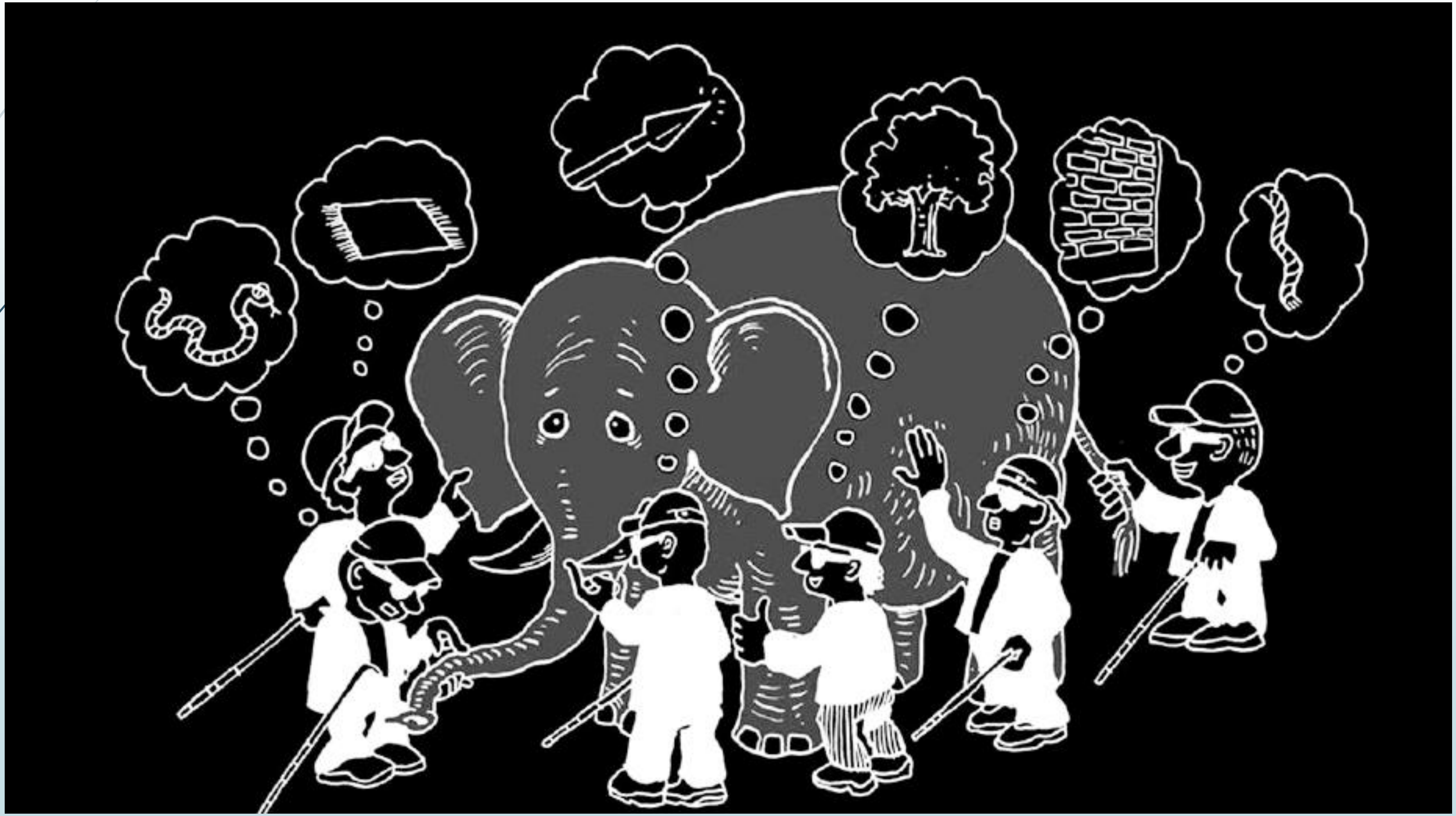
The microscopic "Zoo"



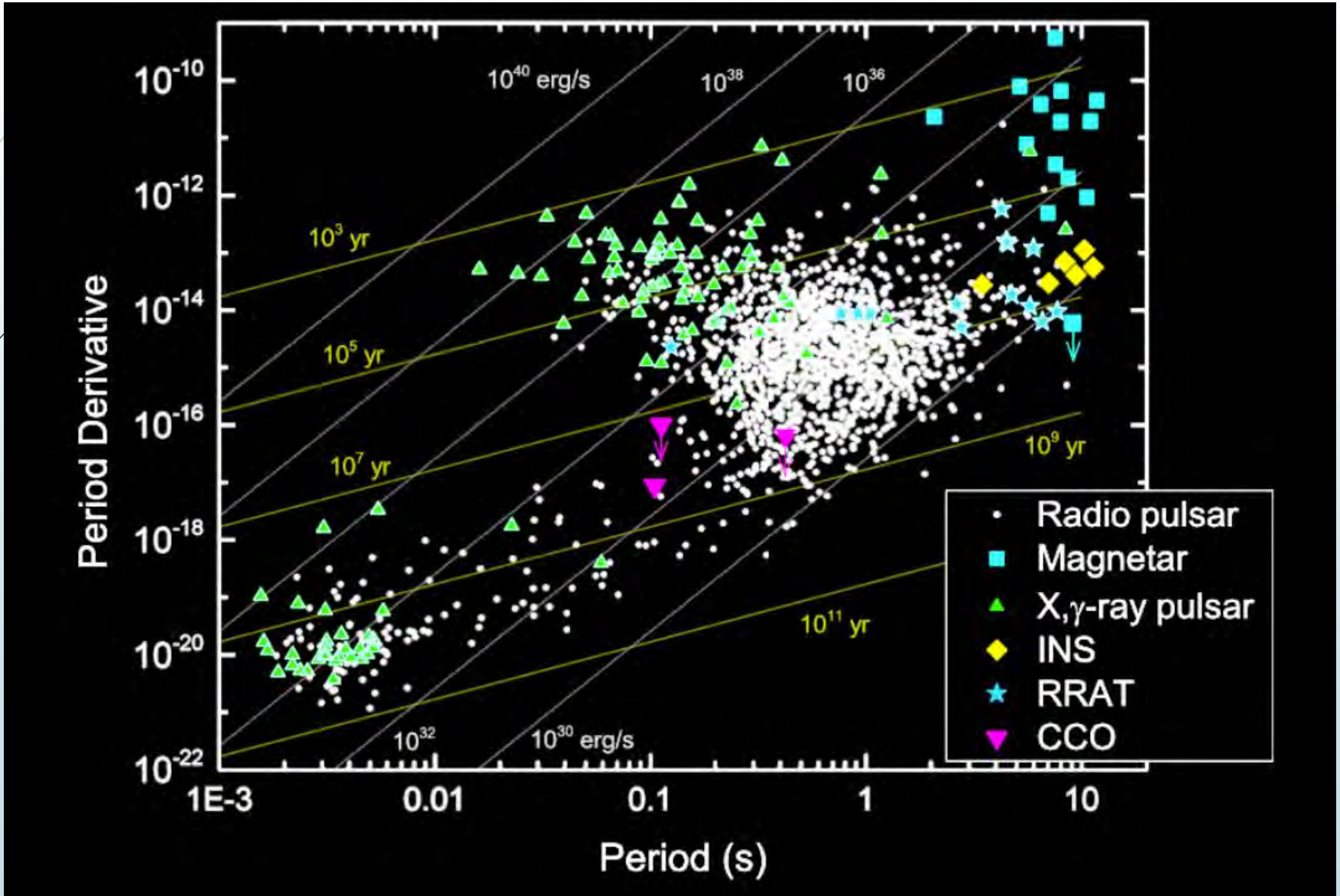
Weber, Hamil, Mimura and Negreiros (2011)

Neutron Stars Zoo

Neutron Star Diversity



Neutron Star Population



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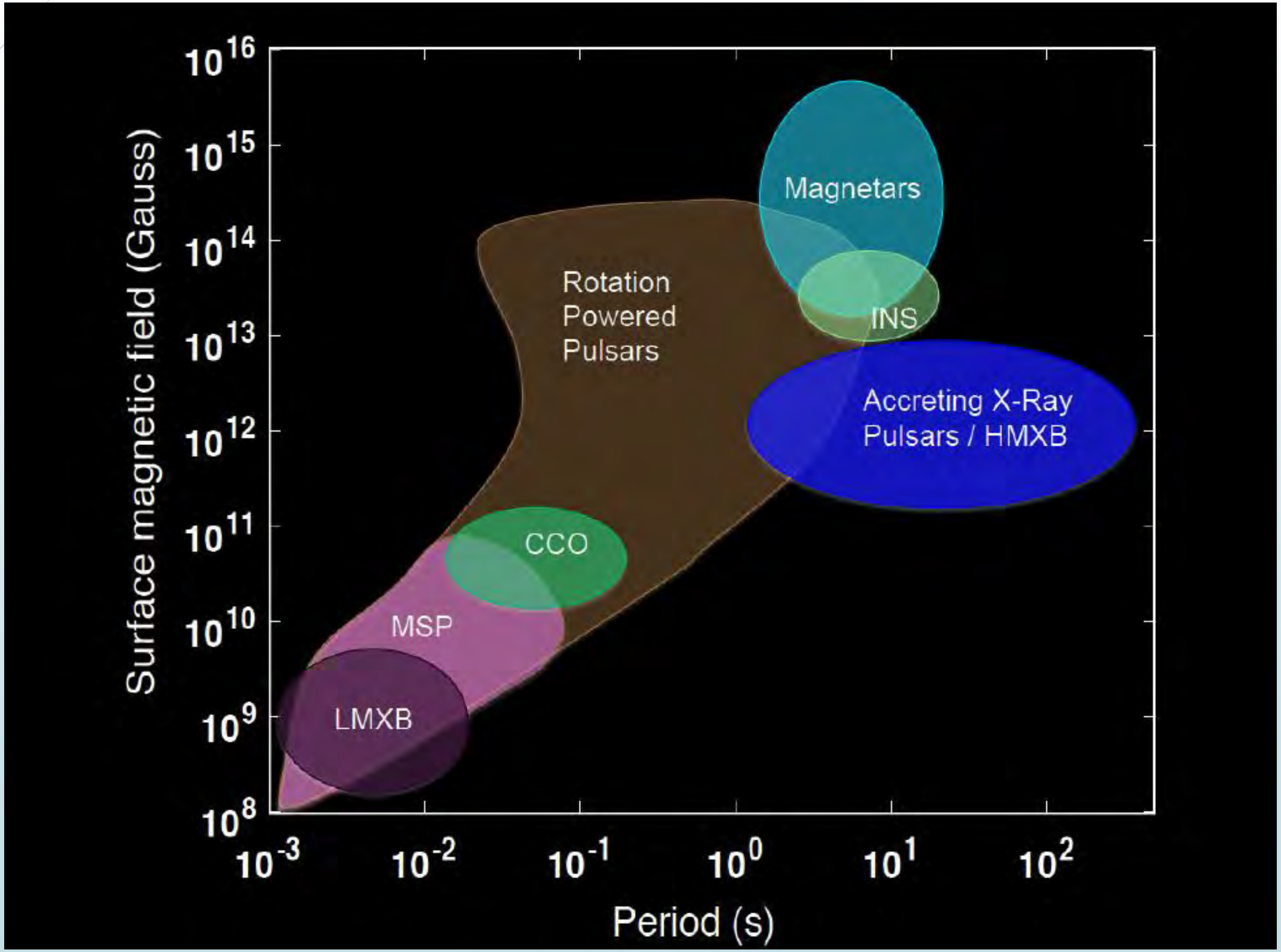

Magnetic Braking Model

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = -C\Omega^{n+1}$$

- For magnetic dipole radiation (n =3)

$$-\frac{dE}{dt} = -\frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = \frac{2}{3}R^6 B^2 \Omega^4 \sin^2 \alpha$$

- Characteristic age

$$\tau = \frac{\Omega}{(n-1)\dot{\Omega}}\left[\left(\frac{\Omega}{\Omega_0}\right)^{n-1} - 1\right] = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$

Observed Data

Pulsar name	Supernova remnant	Period P(s)	Period derivative $\dot{P}$(s s^{-1})	Characteristic age τ(yr)	Age t(yr)	Braking index n_{obs}	References
B0531+21	Crab	0.0331	4.23×10^{-13}	1240	960	2.51(1)	Lyne et al. 1988
J05376910	N157B	0.0161	5.18×10^{-14}	4930	2000^{+3000}_{-1000}	-1.5(1)	Middleditch et al. 2006
B0540-69	0540-69.3	0.0505	4.79×10^{-13}	1670	1000^{+660}_{-240}	2.140(9)	Nagase et al. 1990
B083345	Vela	0.0893	1.25×10^{-13}	11300	11000^{+5000}_{-5600}	1.4(2)	Lyne et al. 1996
J11196127	G292.2-0.5	0.408	4.02×10^{-12}	1610	7100^{+500}_{-2900}	2.684(2)	Weltevrede et at. 2011
B150958	G320.4-1.2	0.151	1.54×10^{-12}	1550	< 21000	2.839(3)	Kaspi et al. 1994
J18460258	Kesteven 75	0.325	7.08×10^{-12}	729	1000^{+3300}_{-100}	2.65(1)	Livingstone et al. 2007
J17343333	G354.8-0.8	1.17	2.28×10^{-12}	8120	> 1300	0.9(2)	Espinoza et al. 2011

Deviations from the standard oblique rotator model

- Multipolar electromagnetic radiation ($n \geq 5$)
- Quadrupolar gravitational radiation ($n = 5$)
- Decay of the magnetic field, $n > 3$
- Radial deformation of the magnetic field lines, $1 \leq n \geq 3$,
- Relativistic winds $n < 3$,
- Growth of an intense magnetic field submerged on neutron star crust in the hypercritical accretion phase, which re-emerge by ohmic diffusion, $n < 3$ (Muslimov & Page 1996, Bernal et al. 2010, 2013, Pons et al. 2012)
- Changes in the moment of inertia of the neutron star, $n < 3$ (Glendenning 2003, F. Weber 2010)

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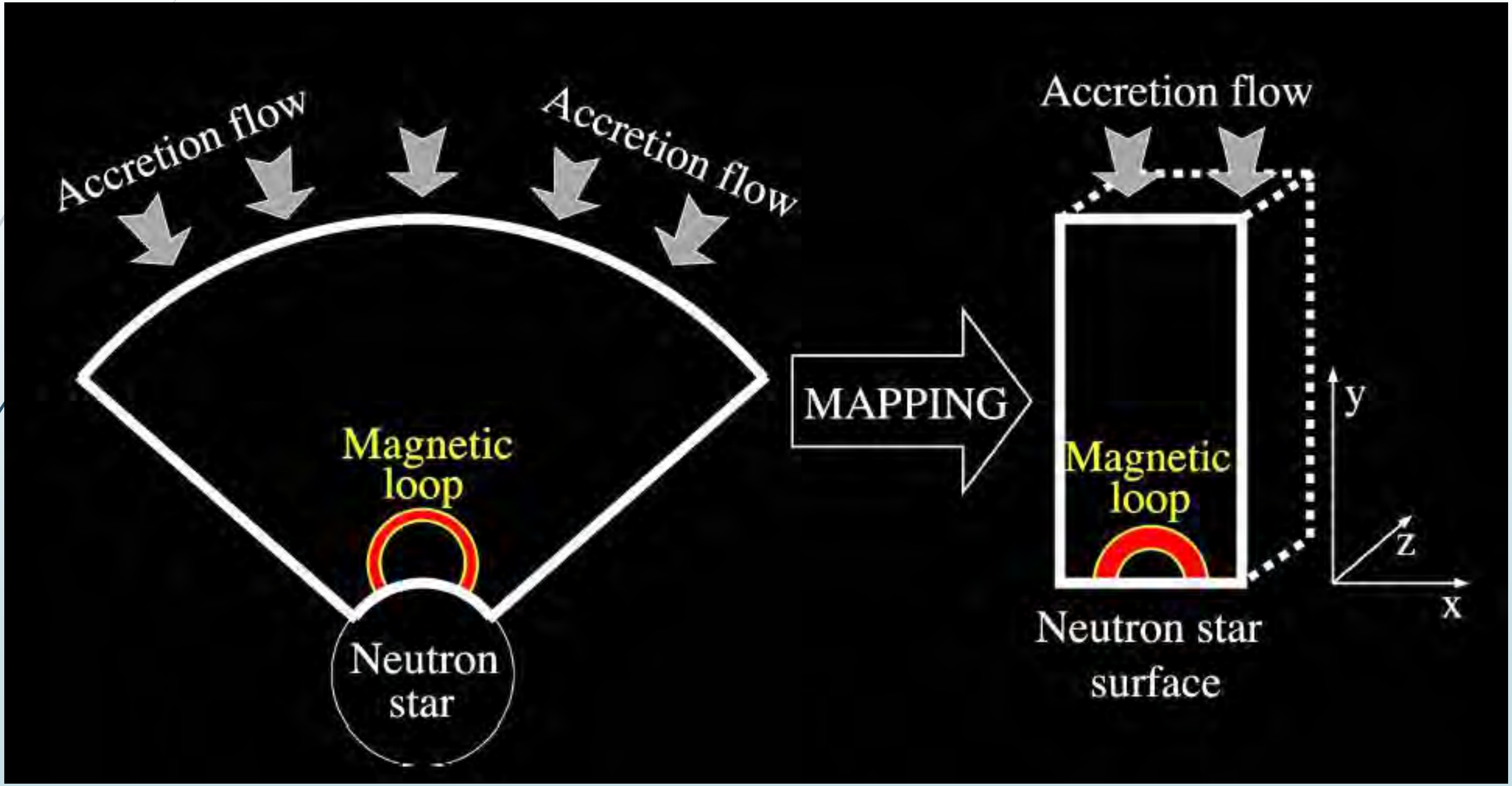
THE GROWTH OF THE MAGNETIC FIELD

- A newborn neutron star may be exposed to a hyper accretion phase few moments after the supernova explosion that originated it.
- In the core-collapse scenario, the shock wave sweeps the outer layers of the progenitor until it encounters a discontinuity in density. At this point, a reverse shock is generated leading to a fallback episode which allows to deposite large amounts of material on the stellar surface.
- The magnetic field can be <u>submerged</u> on the new crust of the neutron star during such phase.
- Following these ideas it is possible to study the growth of the magnetic field, when it re-emerge from the neutron star crust, and to follow its consequences on the pulsar <u>spindown</u>

Hyper-Accretion Simulations



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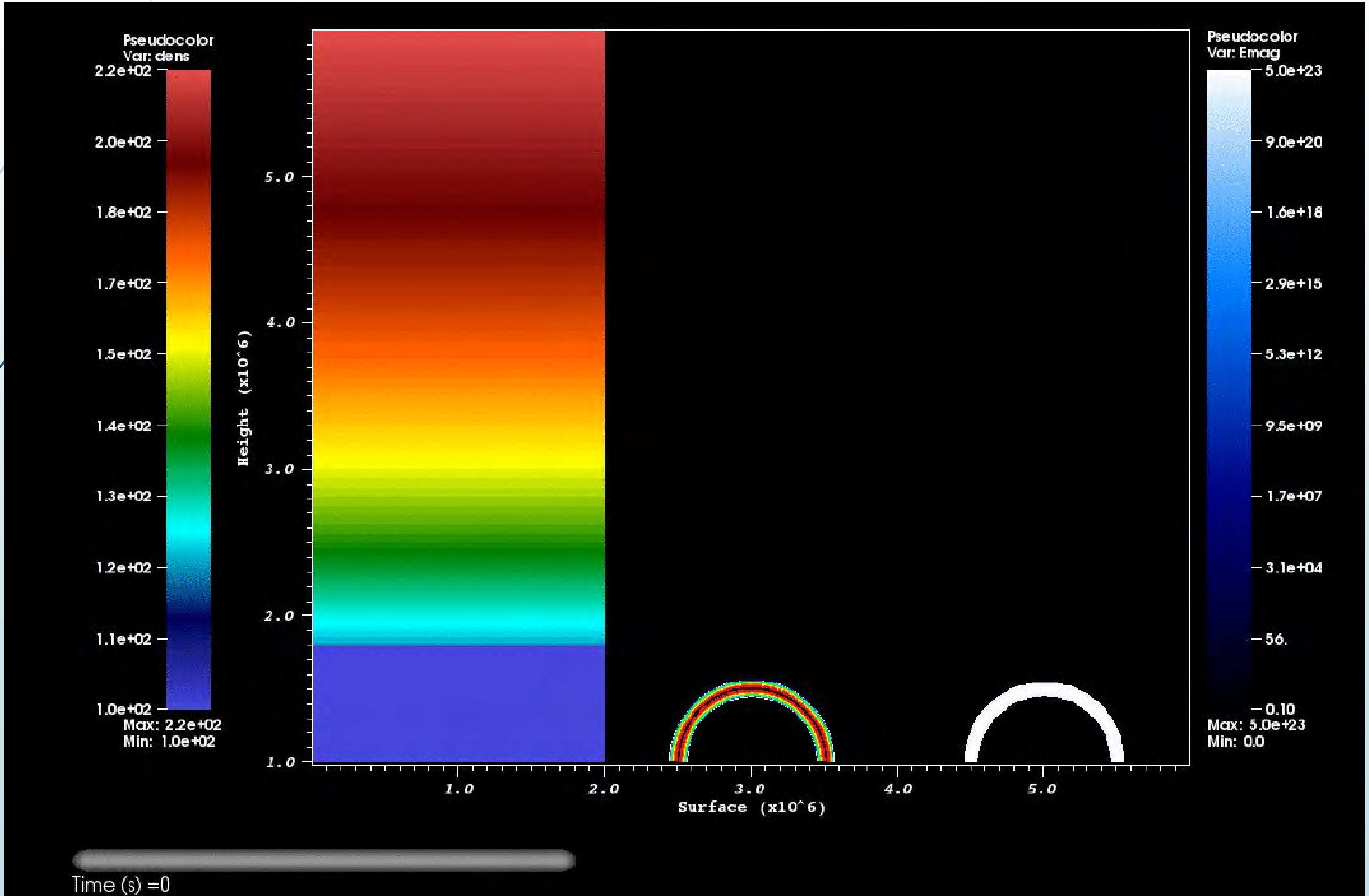

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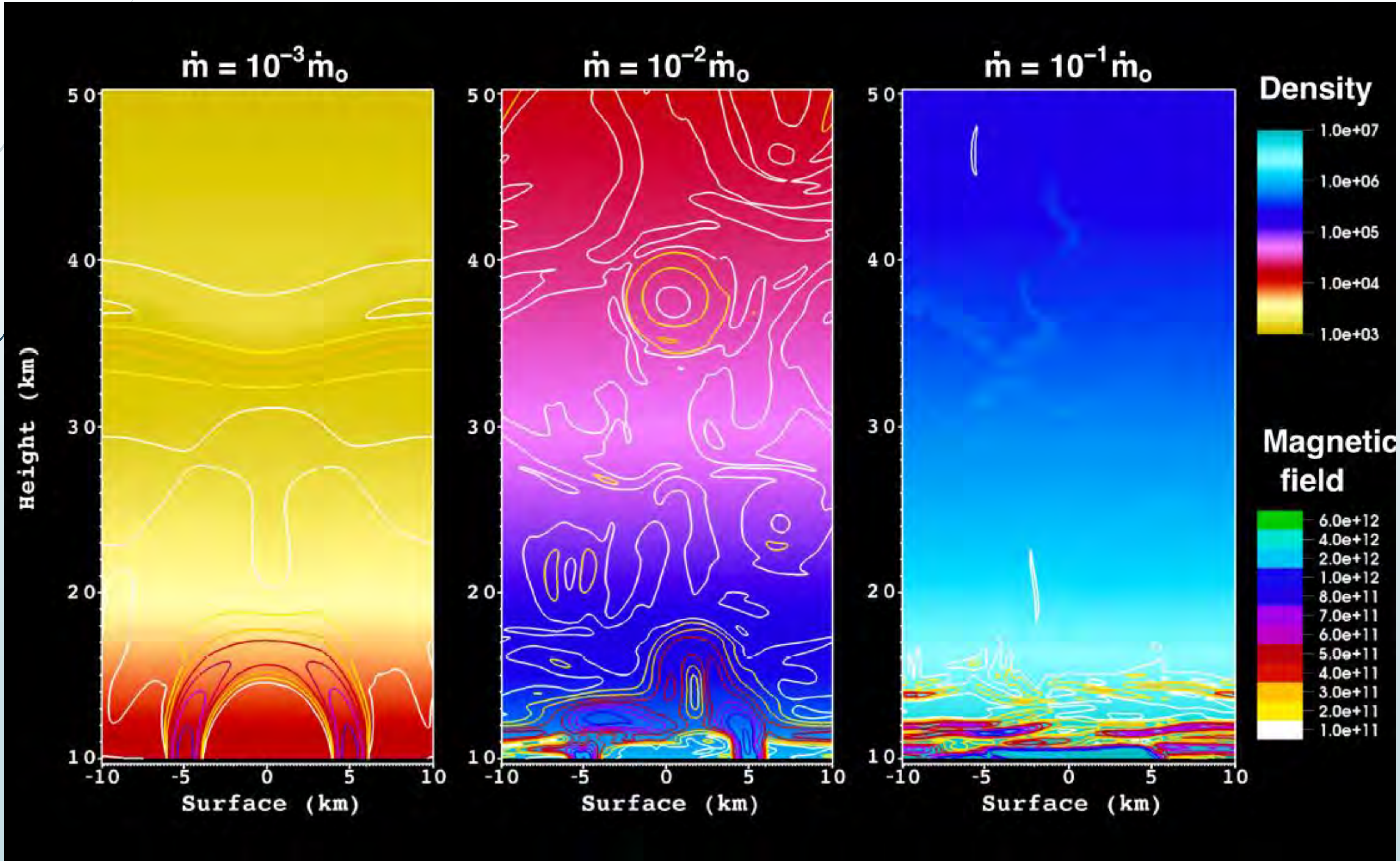


THE GROWTH OF THE MAGNETIC FIELD

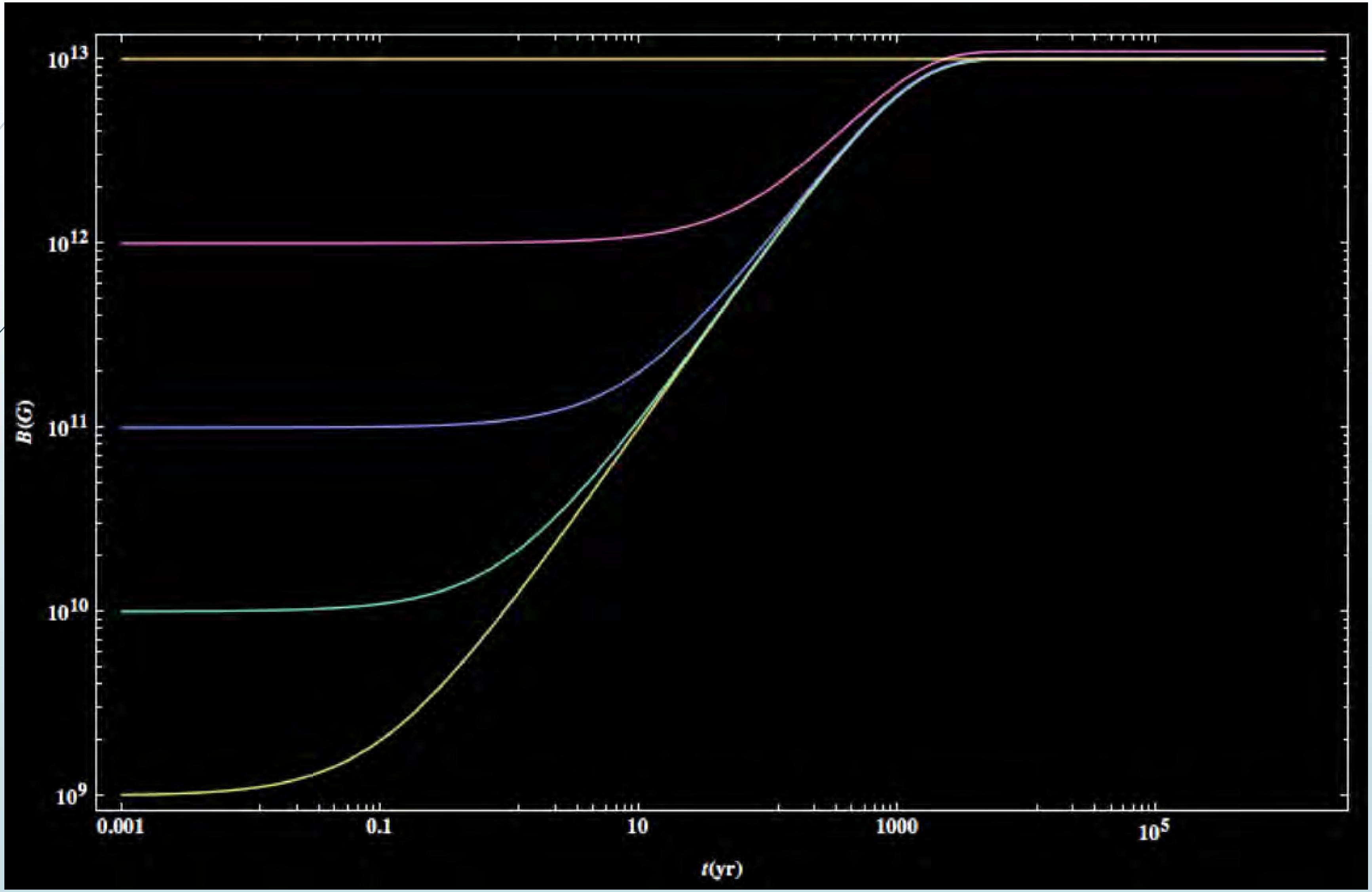
$$\dot{\Omega} = -k(t)\Omega^n, \quad k(t) = kf(t)$$

$$\tau = \frac{1}{f(t)}\left[\tau_0 + \int_0^t f(t)dt\right]$$

$$n = n_* + \frac{\dot{f}(t)}{f(t)}\frac{\Omega}{\dot{\Omega}} = n_* - \frac{\dot{f}(t)}{f(t)}\frac{P}{\dot{P}}$$

$$f(t) = \epsilon + \left[1 - \exp\left(-\frac{t}{\tau_B}\right)\right]$$

THE GROWTH OF THE MAGNETIC FIELD



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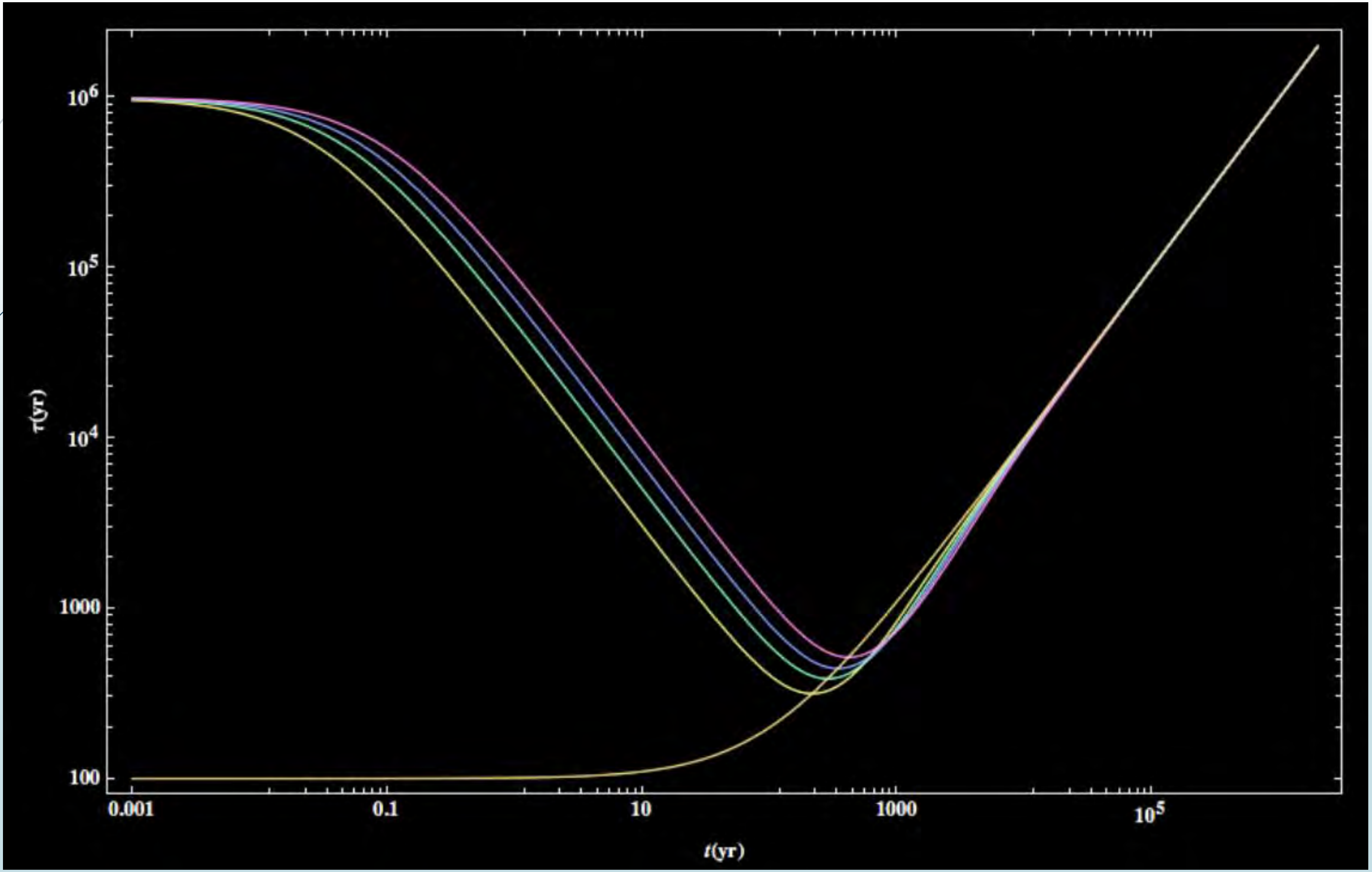
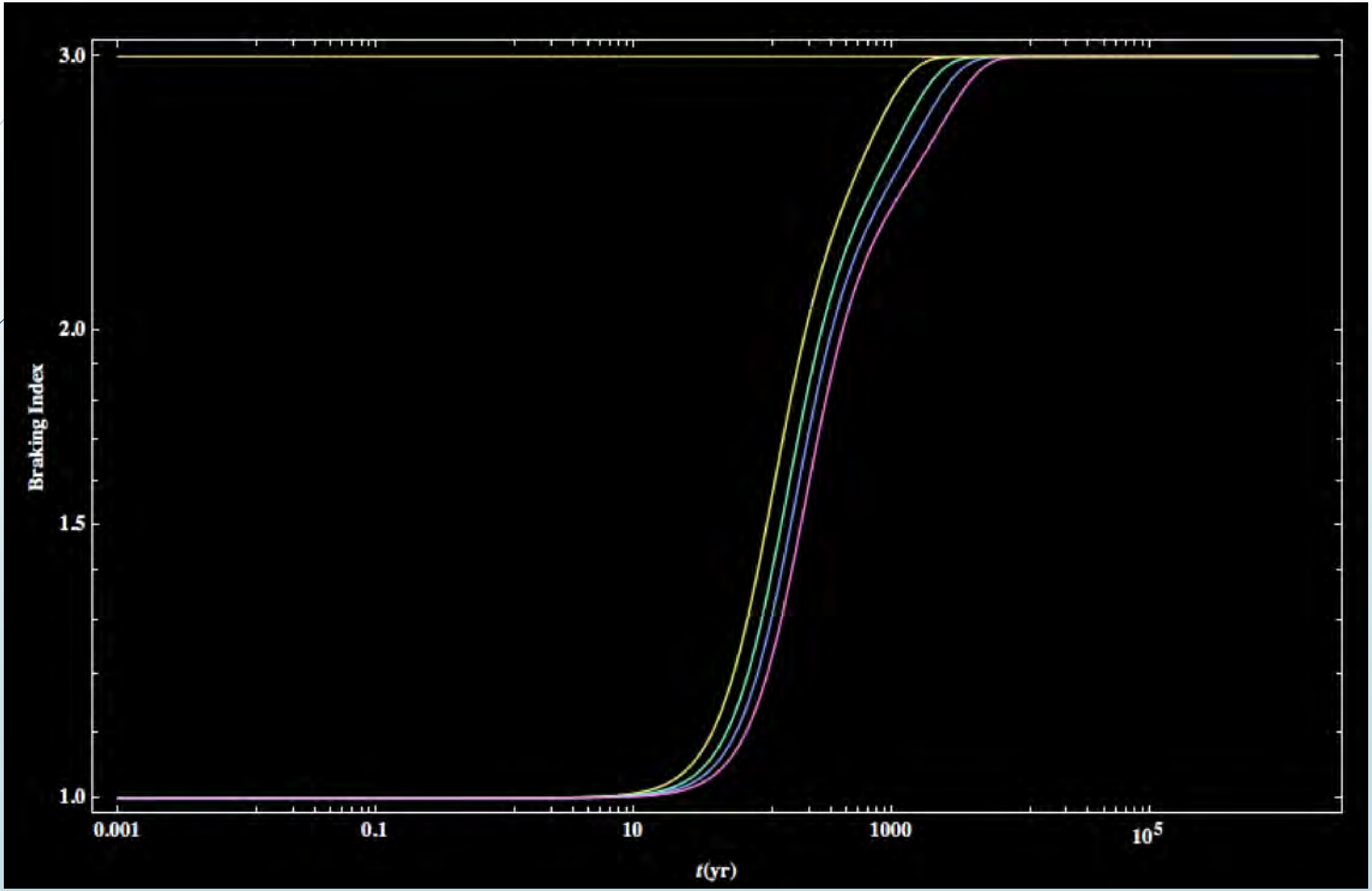


Braking Index



Changes in the Moment of Inertia

- Superfluid Decoupling*

$$\frac{d}{dt}(I\Omega) = -\beta\Omega^3 - N_{\rm pin} - N_{\rm mf}$$

$$\frac{d}{dt}(I_{\rm sf}\Omega_{\rm sf}) = N_{\rm pin} + N_{\rm mf},$$

* Ho and Anderson, 2012

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Mutual friction

Vortex Pinning

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Moment of Inertia of unpaired matter

Moment of Inertia of SF matter

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Mutual friction

Vortex Pinning

Moment of Inertia of unpaired matter

Moment of Inertia of SF matter

- Considering the case in which pinning leads to: $\Omega_{sf} = 0$ *

$$\frac{d\Omega}{dt} = (\Omega_{\rm sf} - \Omega)\frac{1}{I}\frac{dI}{dt} - \beta\frac{\Omega^3}{I}$$

* Ho and Anderson, 2012

Changes in the Moment of Inertia

- To keep track of the moment of inertia changes, one need to investigate the thermal evolution.

$$\frac{\partial(Le^{2\phi})}{\partial m} = -\frac{1}{\epsilon\sqrt{1-2m/r}}\left(\epsilon_\nu e^{2\phi} + c_v \frac{\partial(Te^{\phi})}{\partial t}\right)$$

$$\frac{\partial(Te^{\phi})}{\partial m} = -\frac{(le^{-\phi})}{16\pi^2 r^4 \kappa\epsilon\sqrt{1-2m/r}},$$

Changes in the Moment of Inertia

- While in their work, Ho and Anderson only considered neutron (3P2) pairing on a npe neutron star, we consider a more complex scenario.

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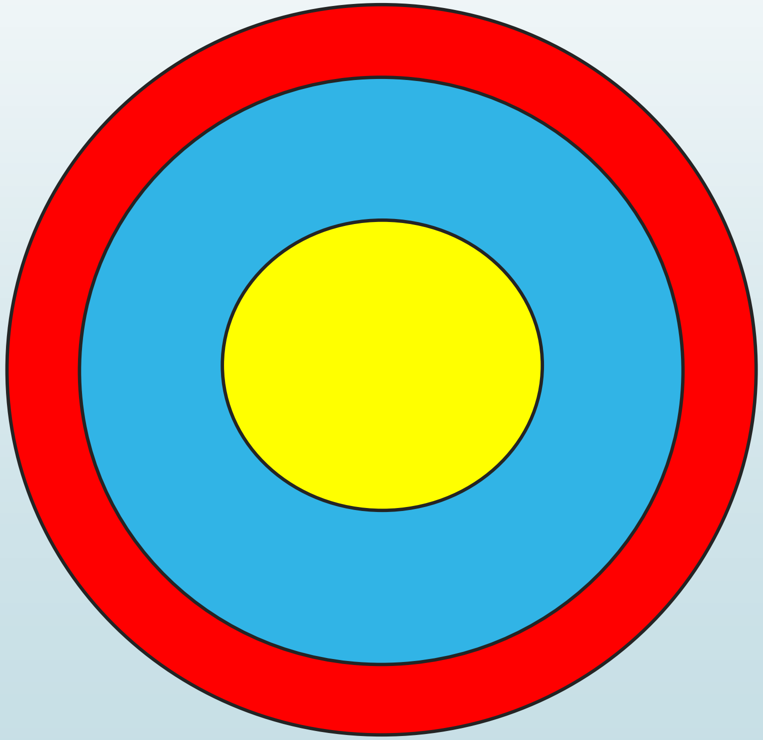

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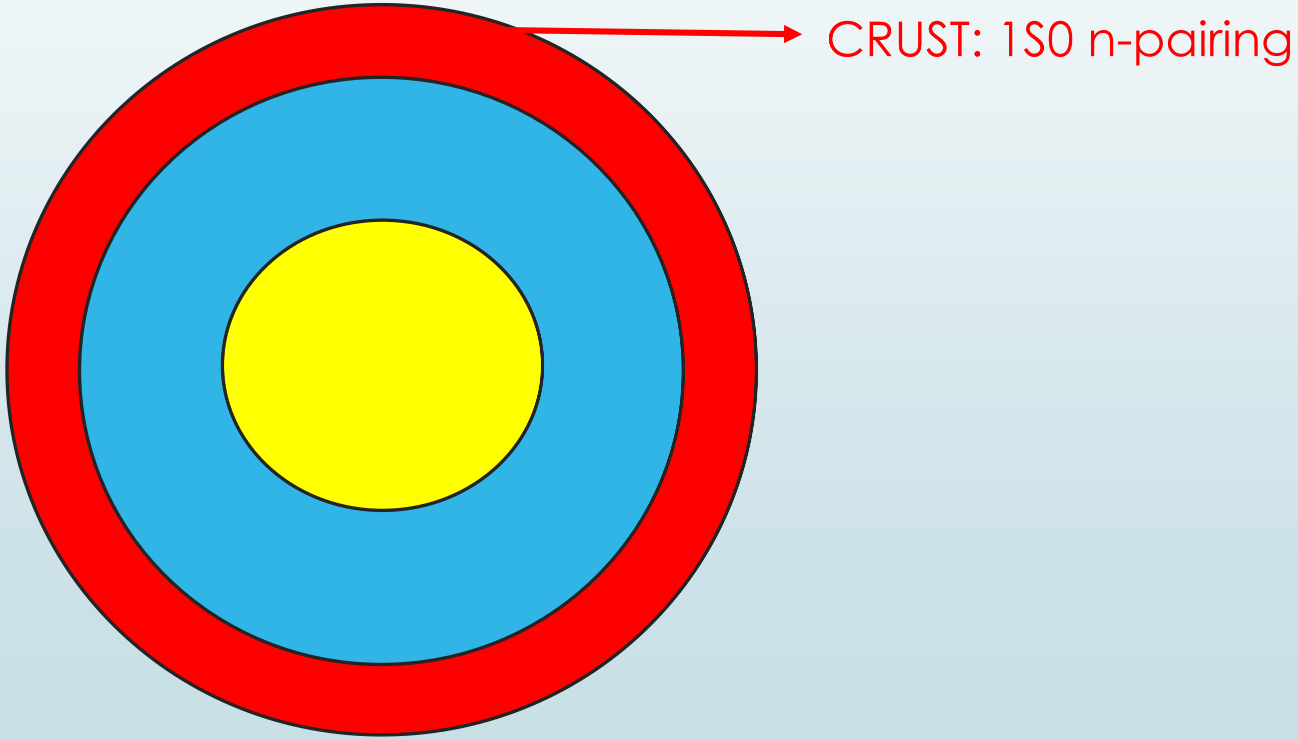

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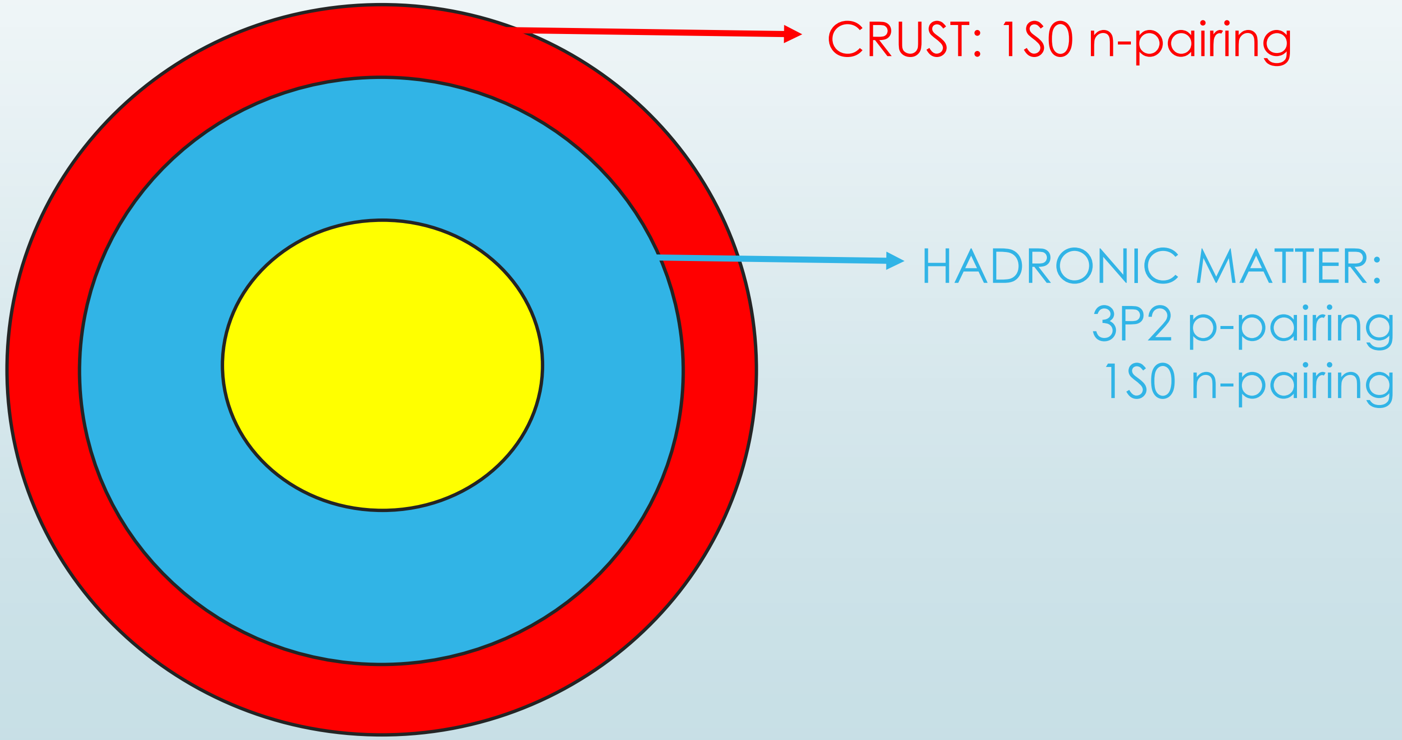

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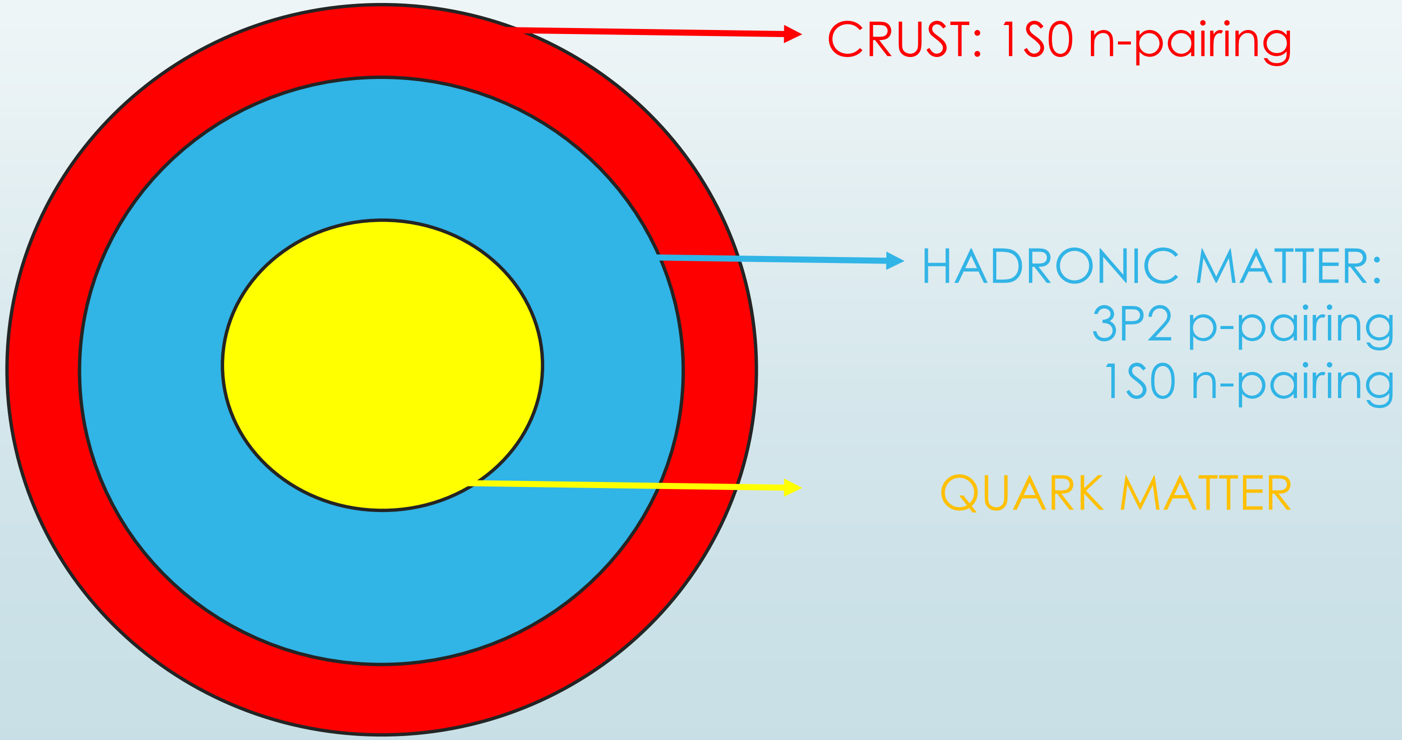

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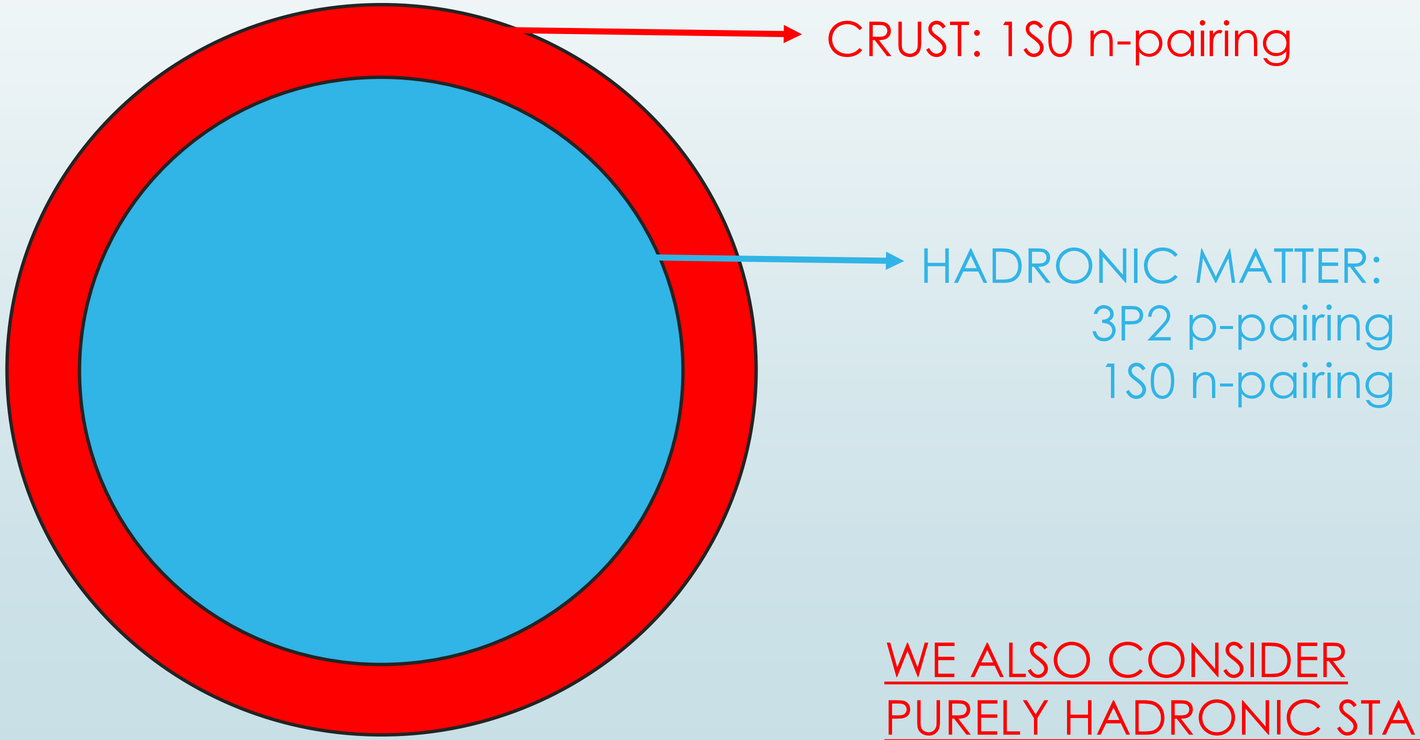
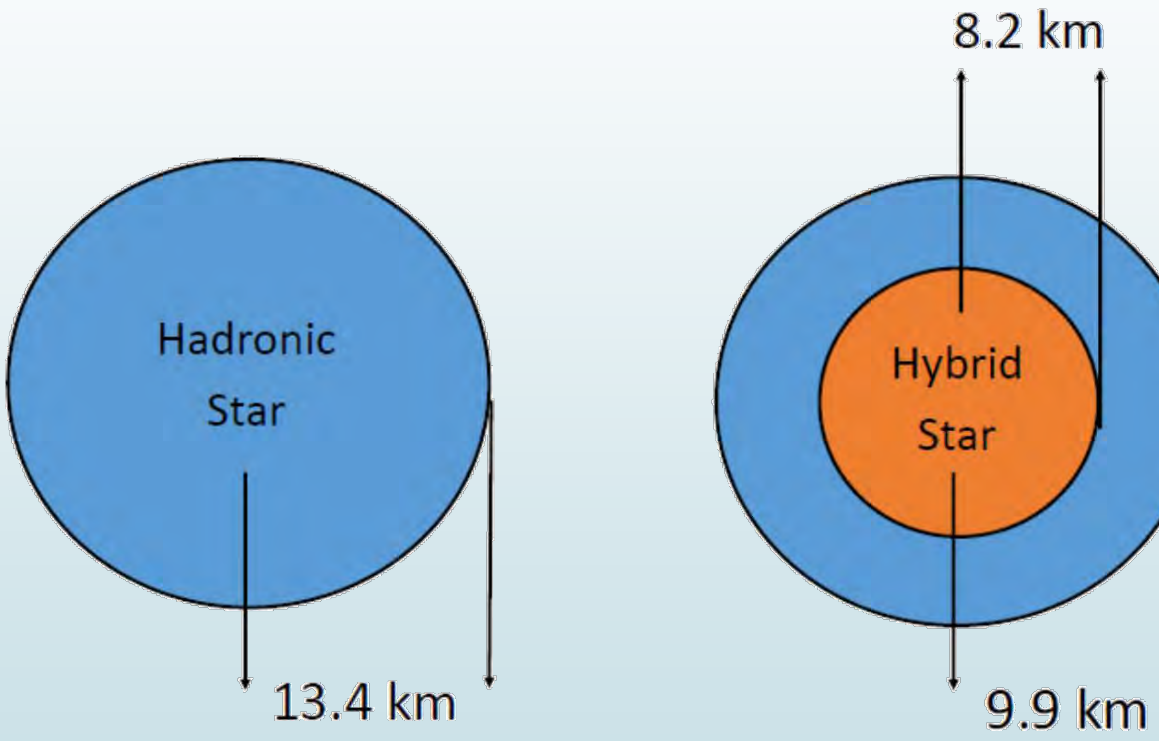


WE ALSO CONSIDER
PURELY HADRONIC STARS !

Changes in the Moment of Inertia

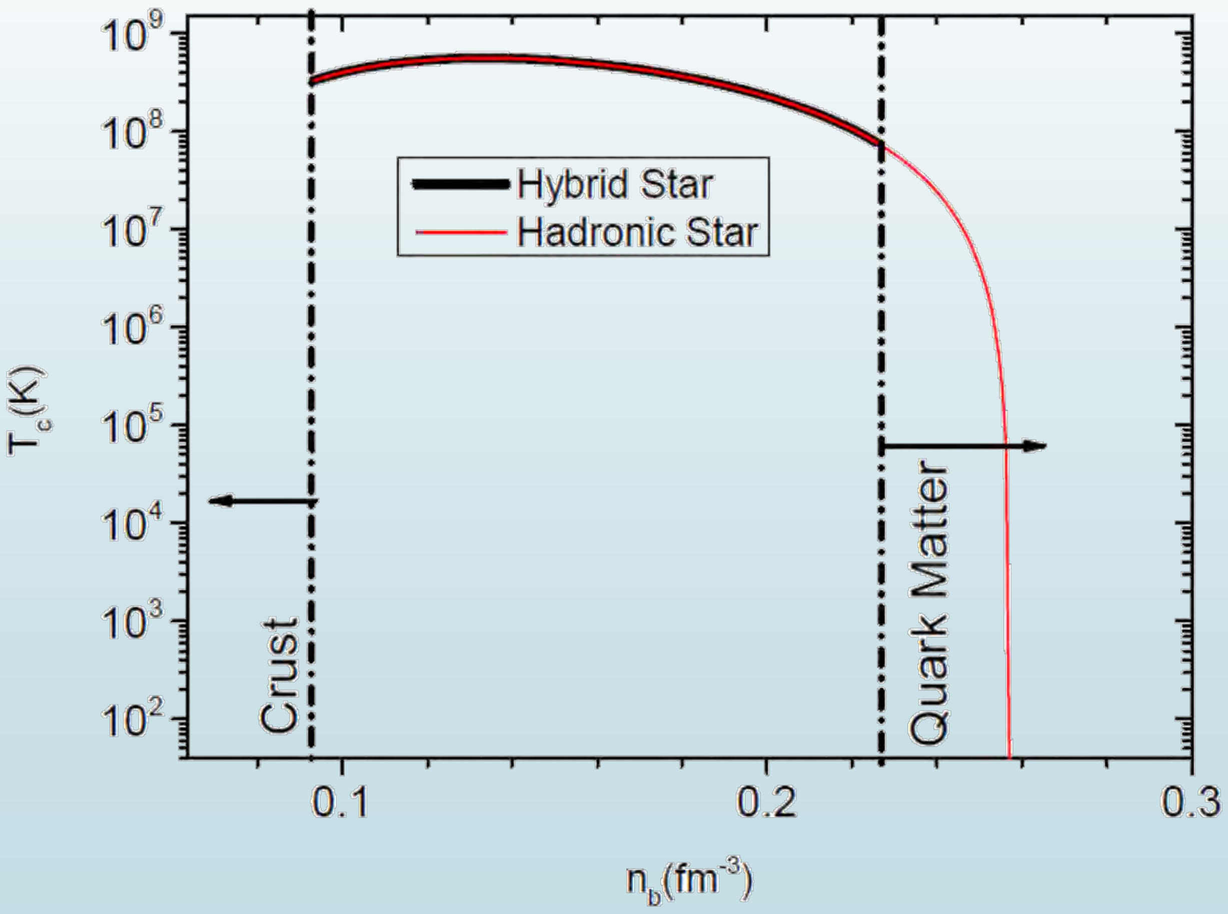
- Two neutron star modelos studied



Mass = 1.55 Msun

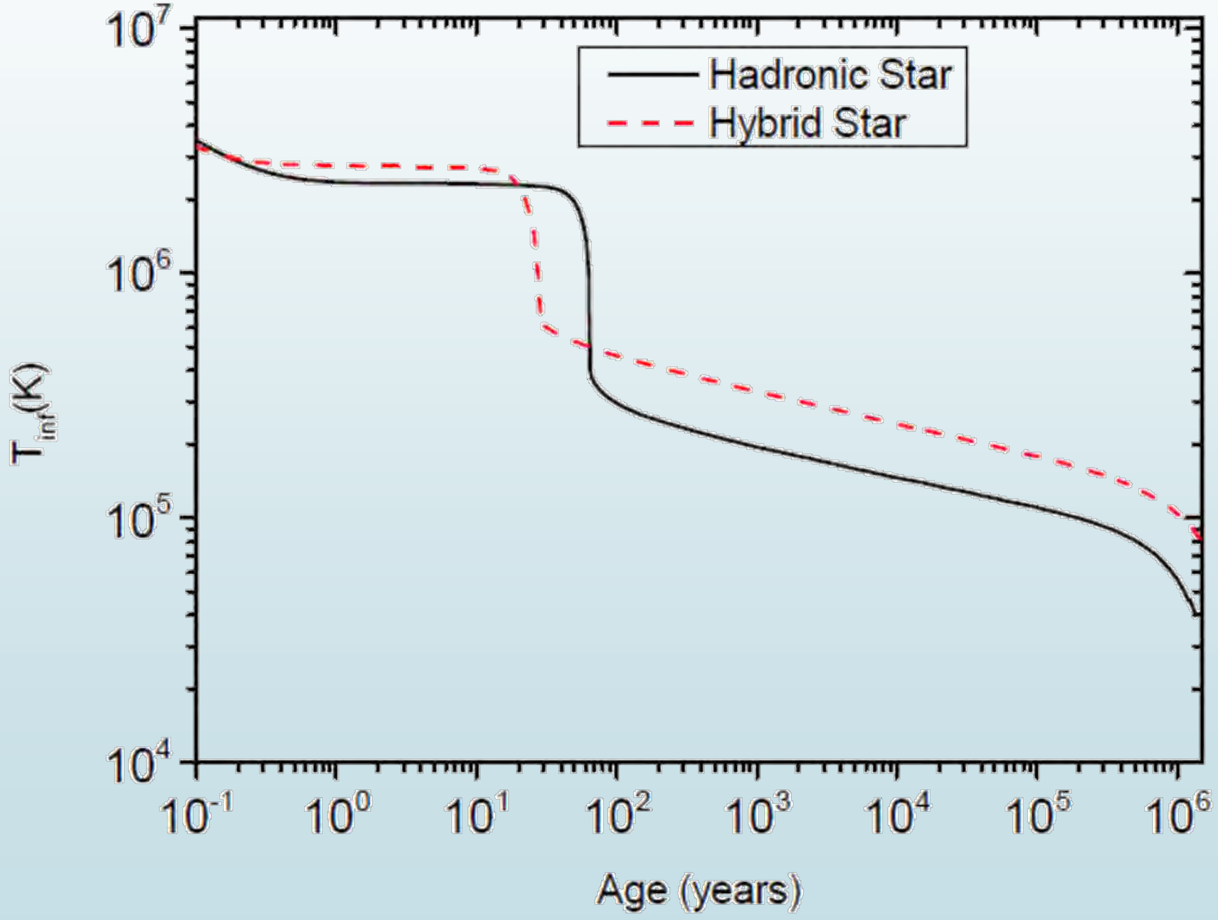
Superfluidity model

- Superfluidity model adopted



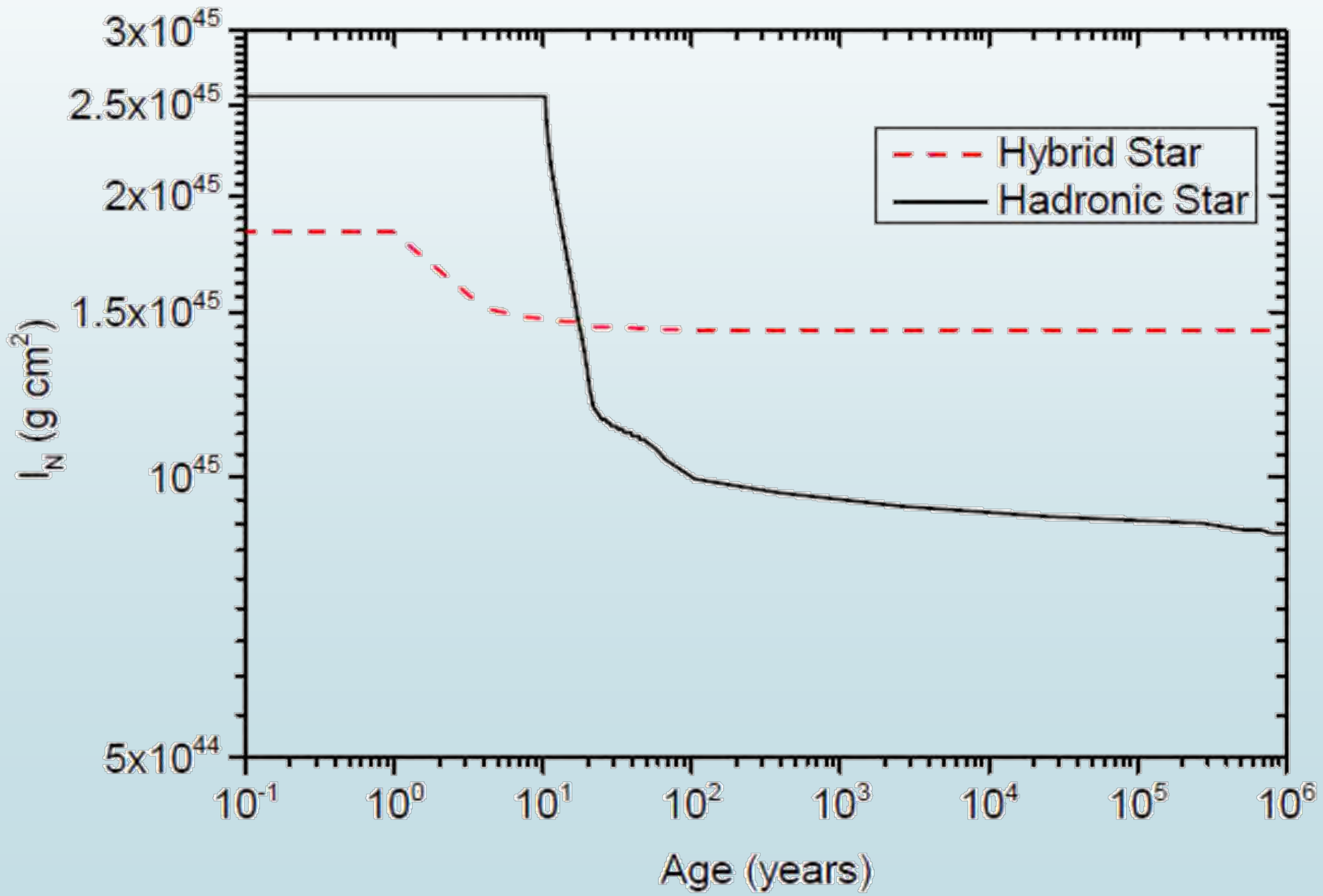
Thermal Evolution

- Collins of thestudied stars under current superfluidity model



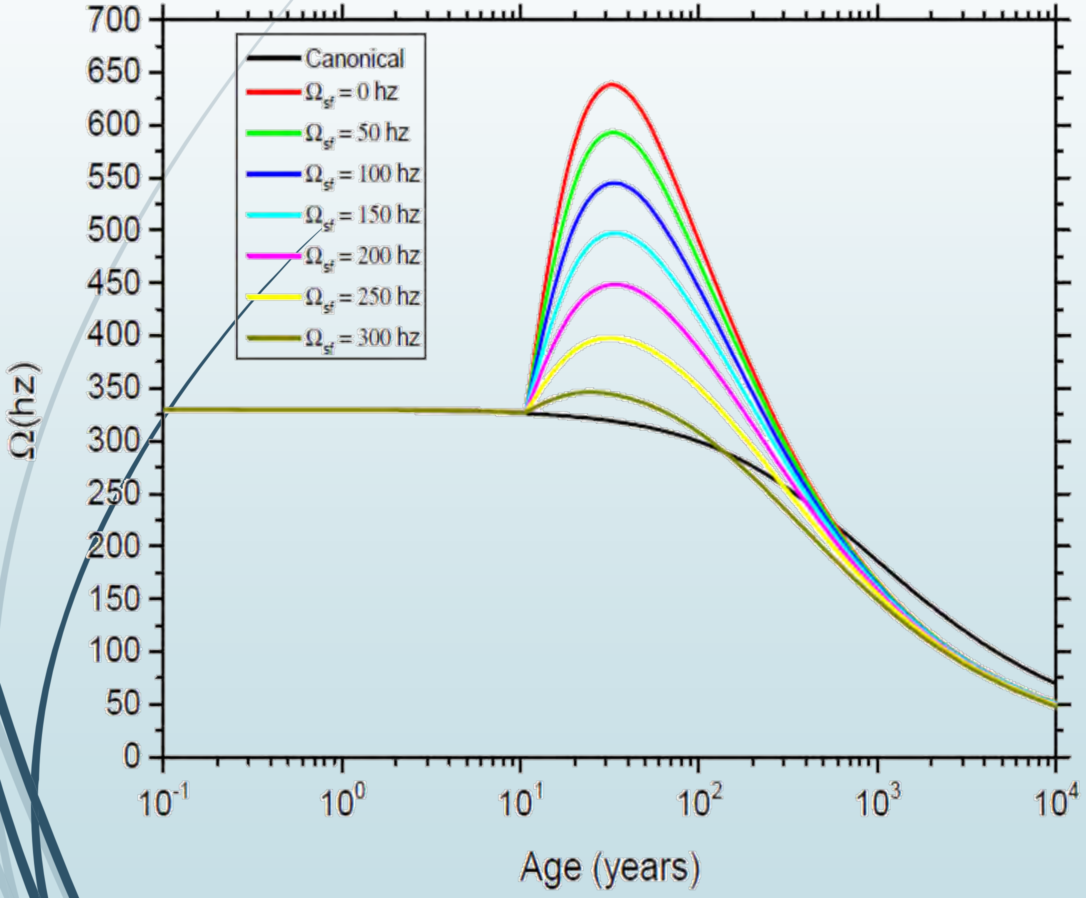
Moment of Inertia Evolution

- Coupled momen inertia evolution

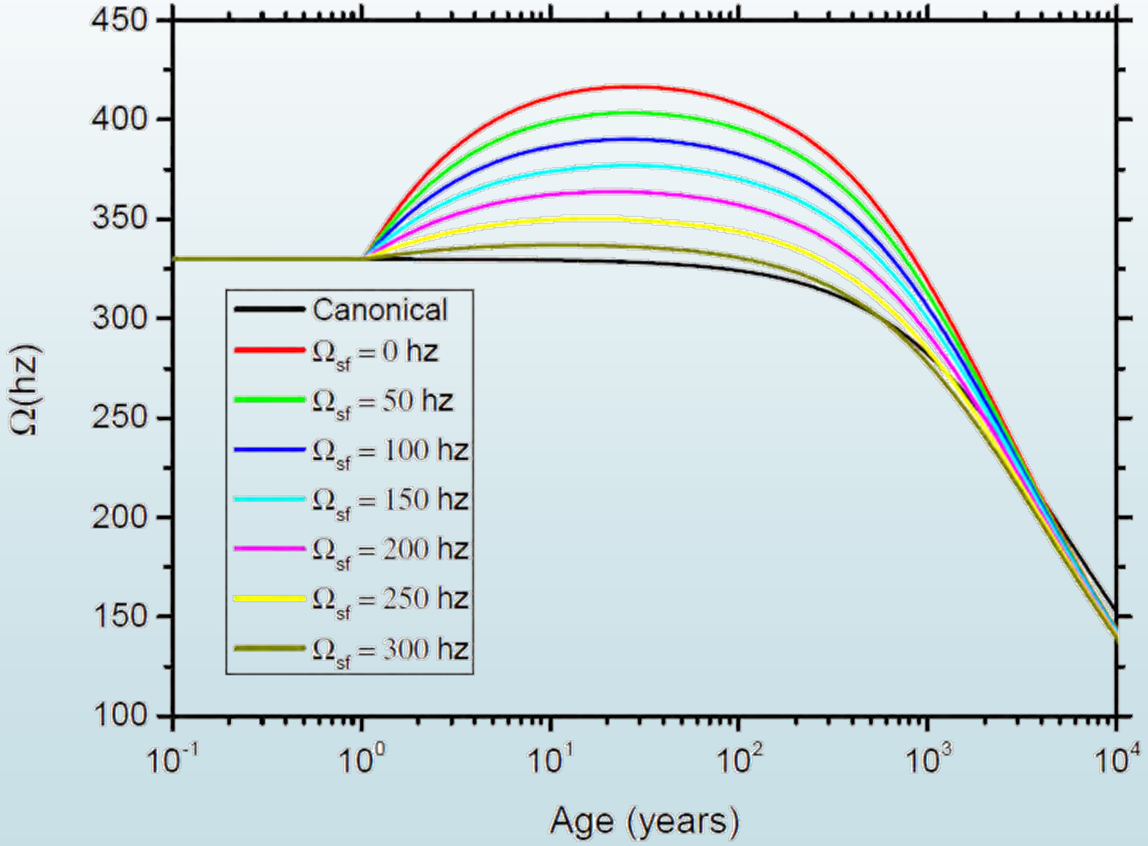


Spin Evolution

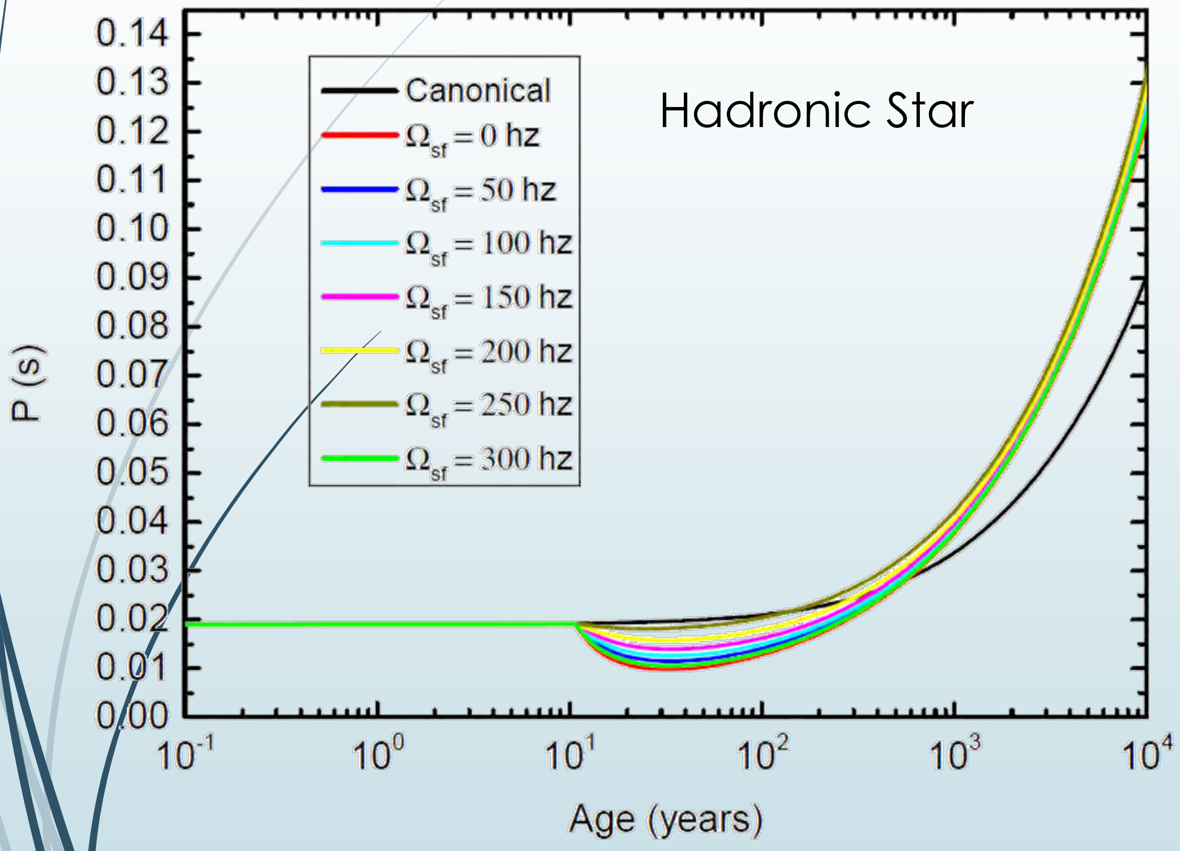
Hadronic Star

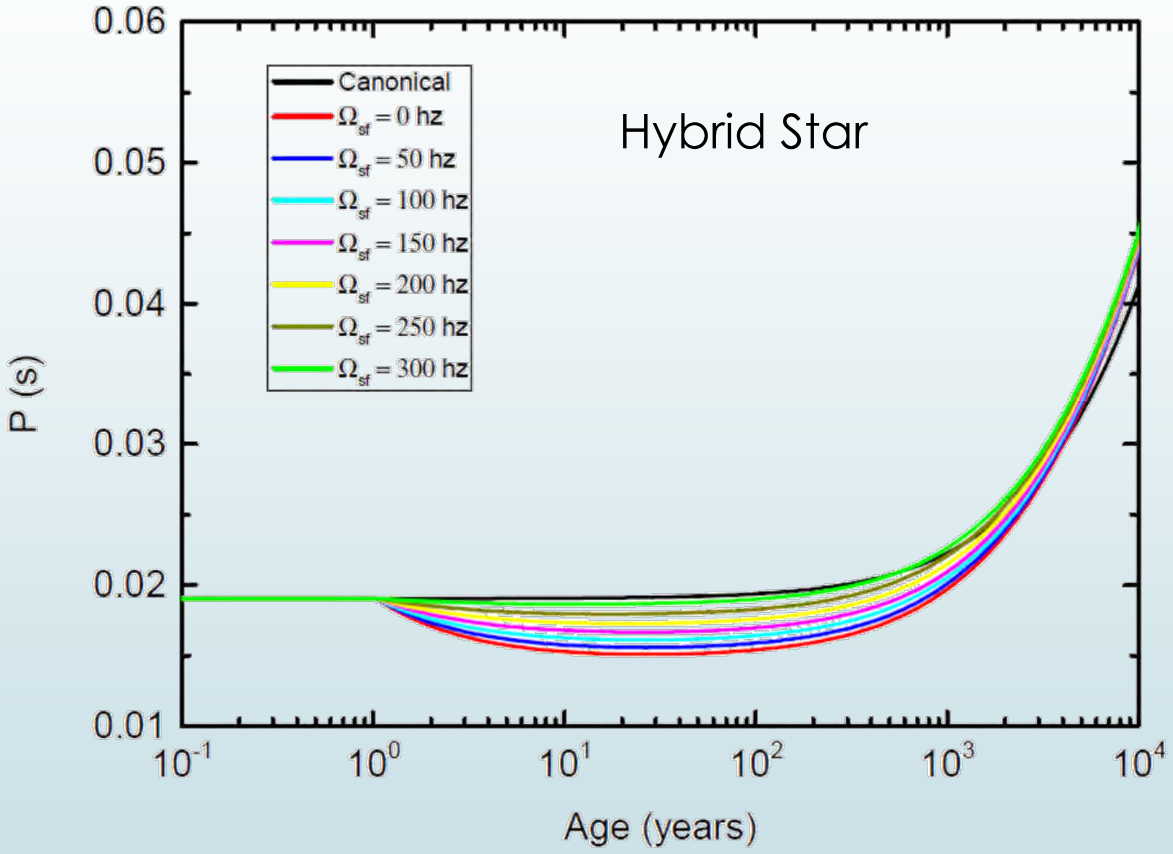


Hybrid Star

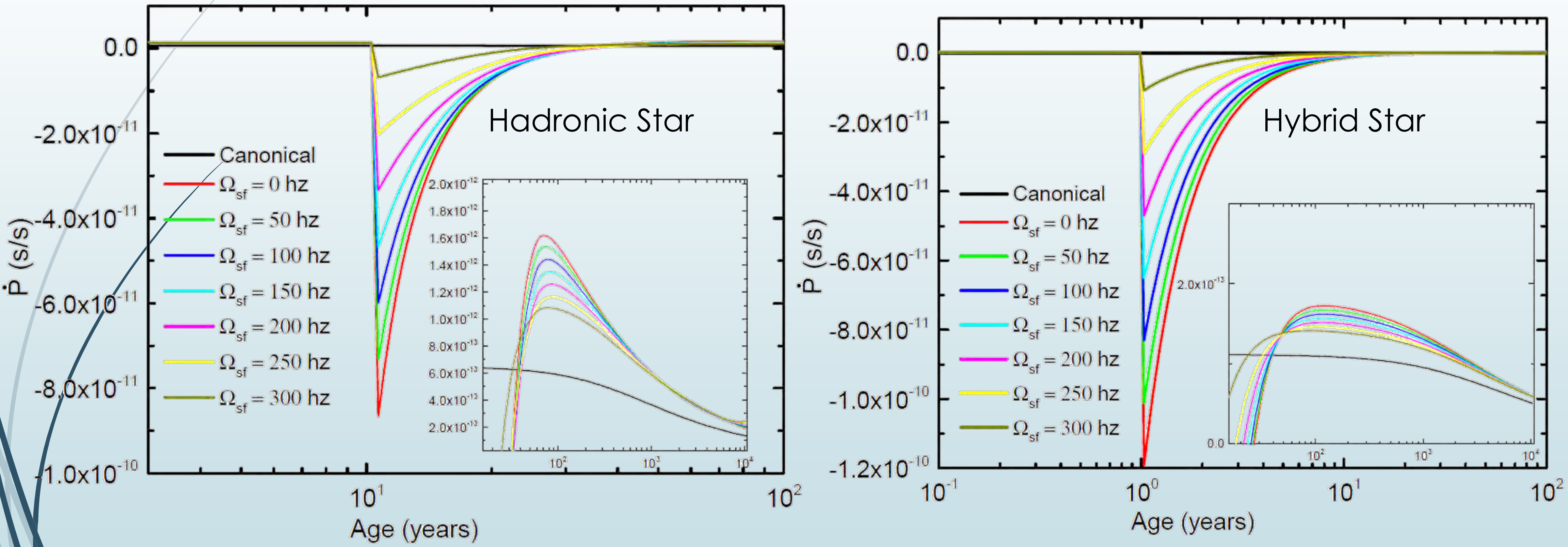


Spin Evolution

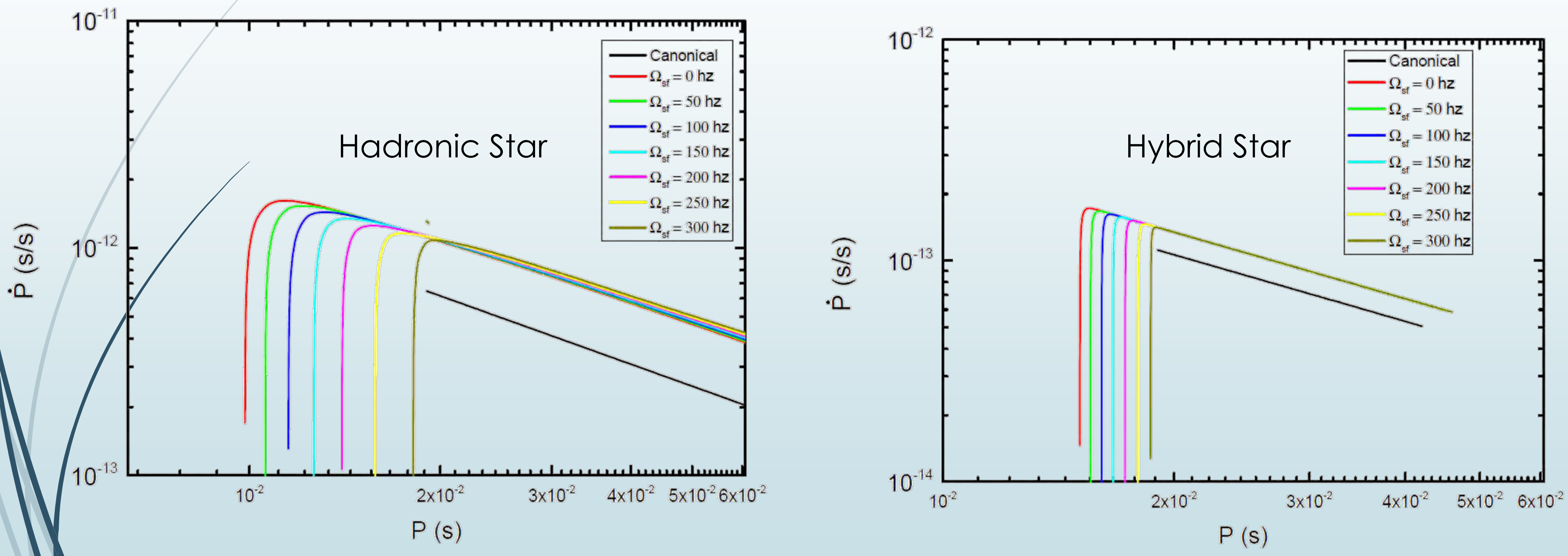




Pdot evolution

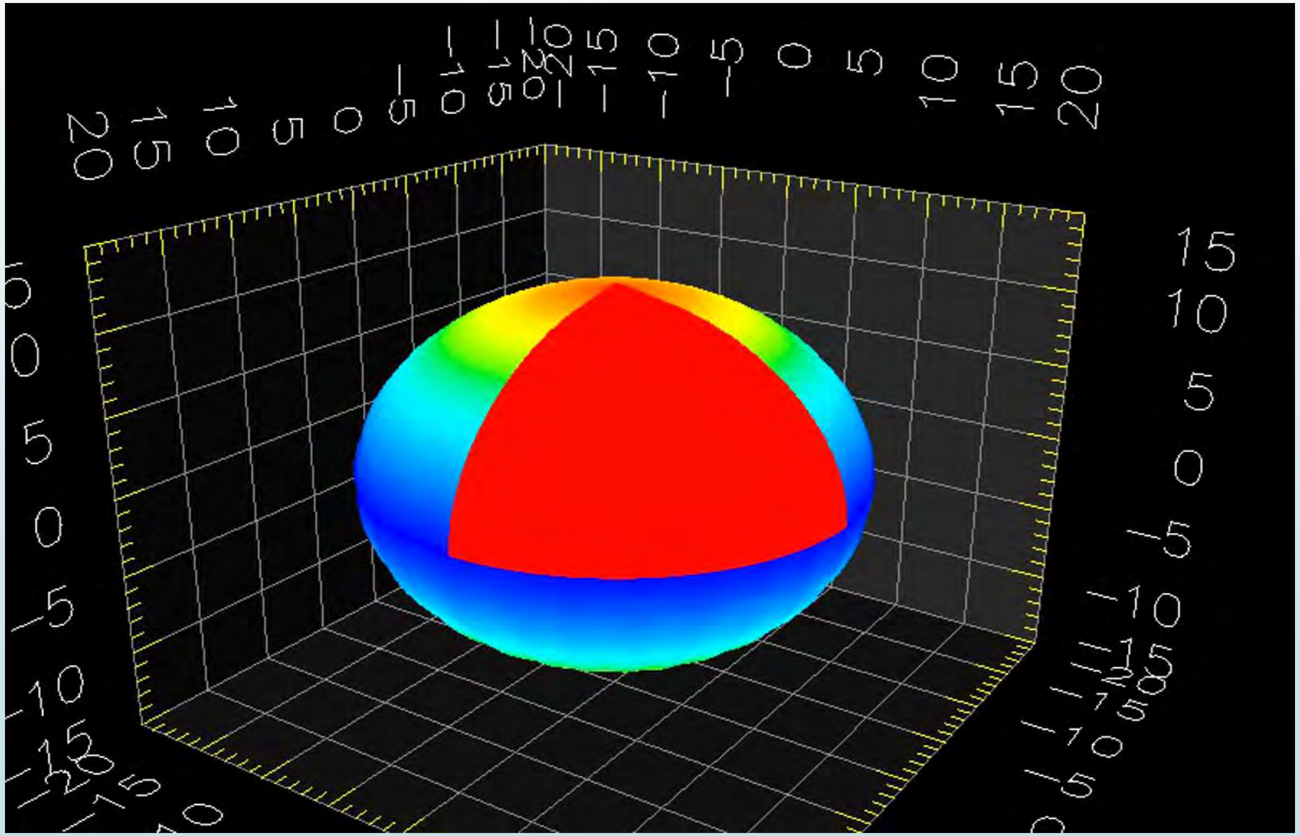


P-Pdot diagram



Next Steps

- Include rotation and magnetic field effects

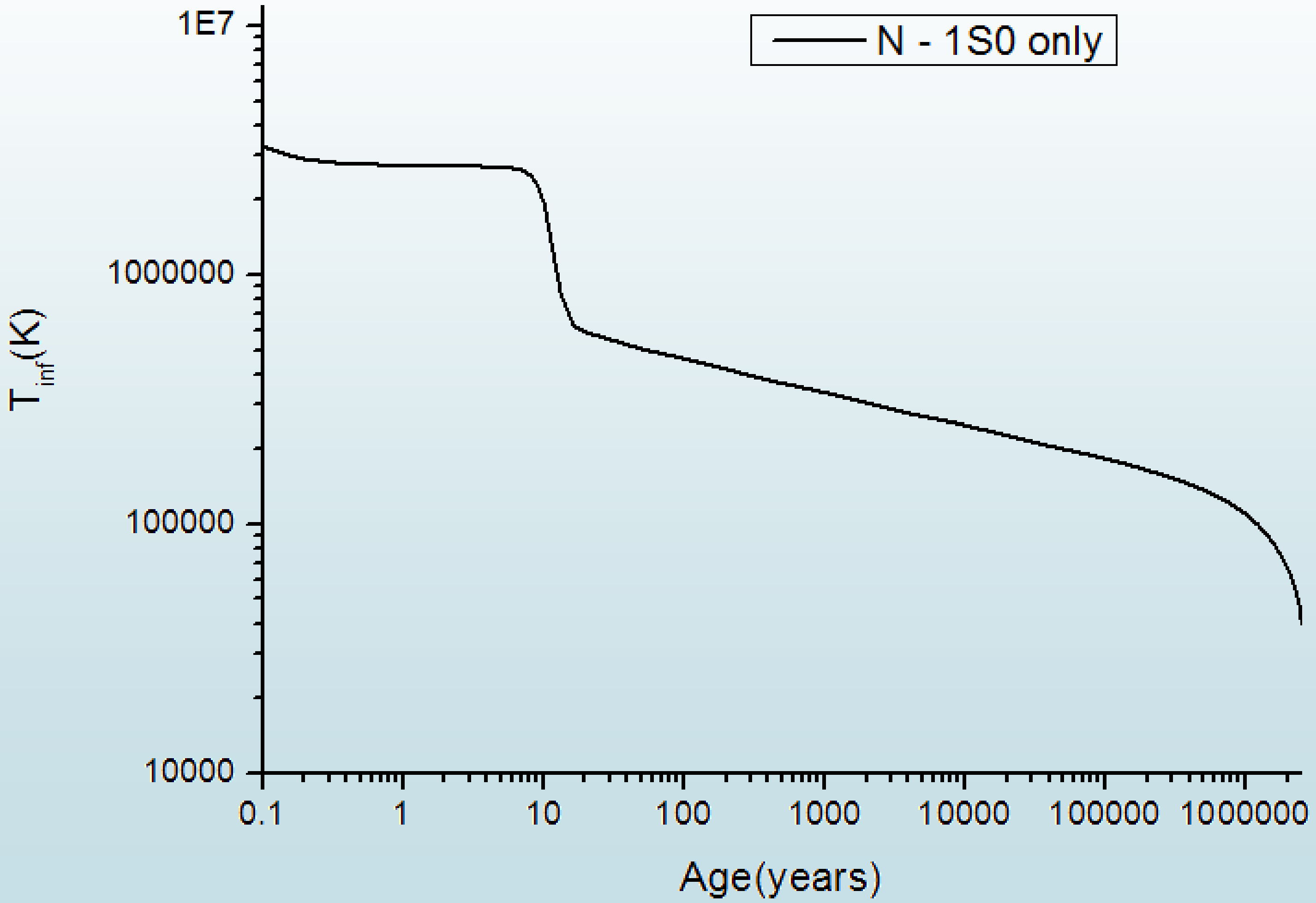


Negreiros, Schramm and Weber, Phys.Rev. D85 (2012) 104019

Conclusions

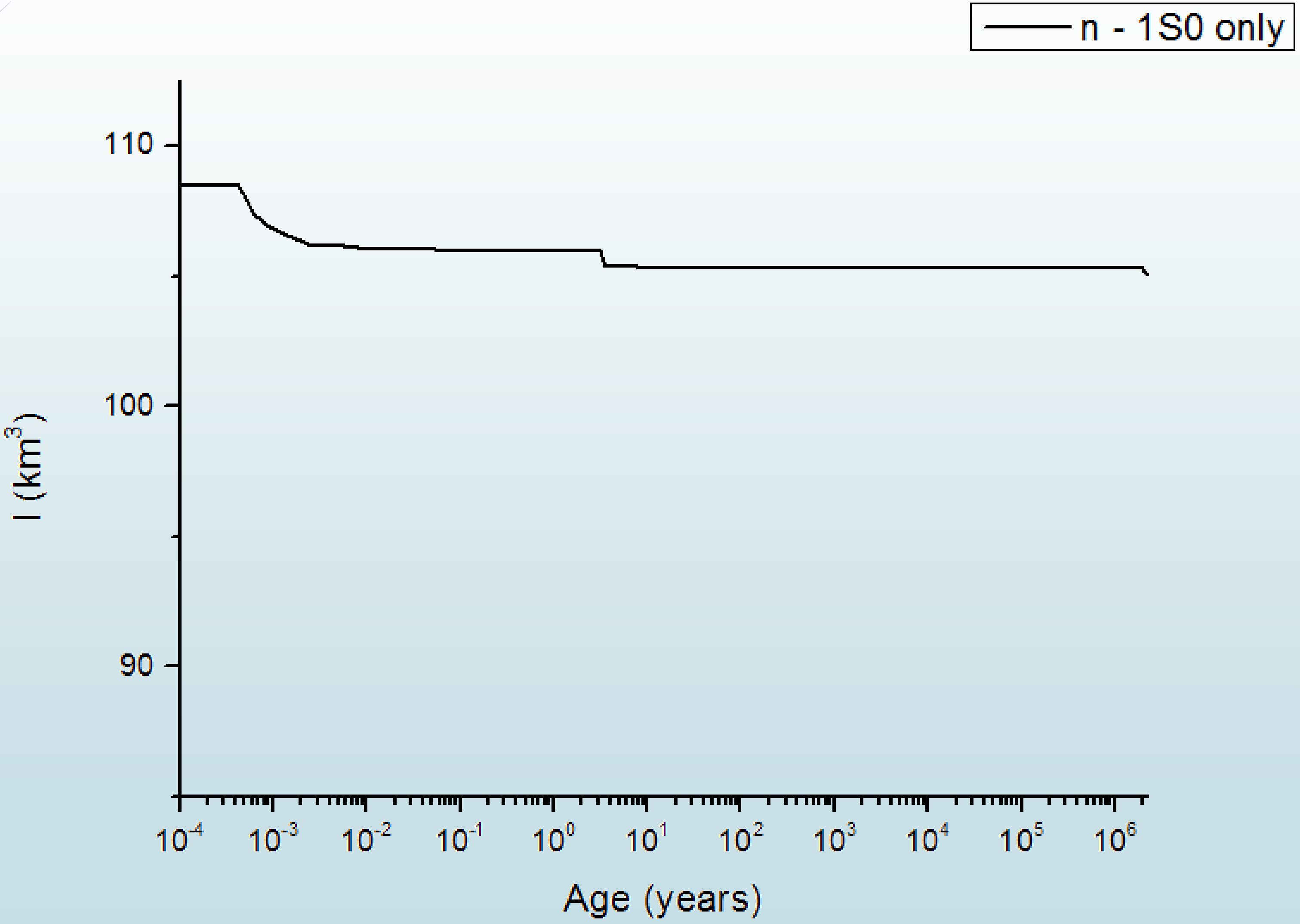
- Submerged magnetic fields may explain the existence of braking índices smaller than one.
- Superfluidity effects may also play a role in the spin-evolution of the object.
- Observation of spin properties may be used to constrain the inner composition.
- Need to explore further pairing patterns and microscopic models.

Cooling



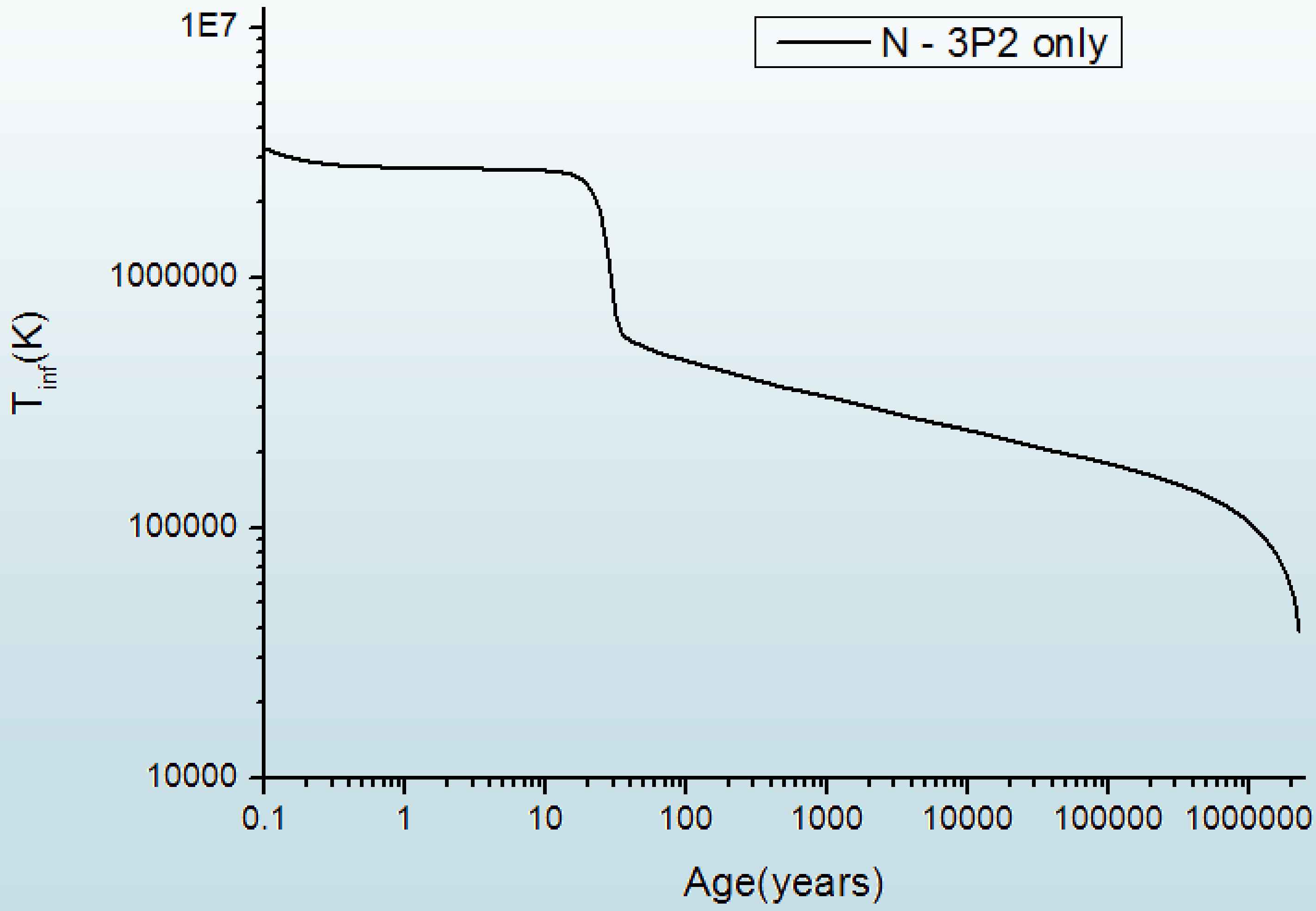
N - 1S0 only
1E7
1000000
100000
10000
T_{inf}(K)
0.1
1
10
100
1000
10000
100000
1000000
Age(years)

Cooling



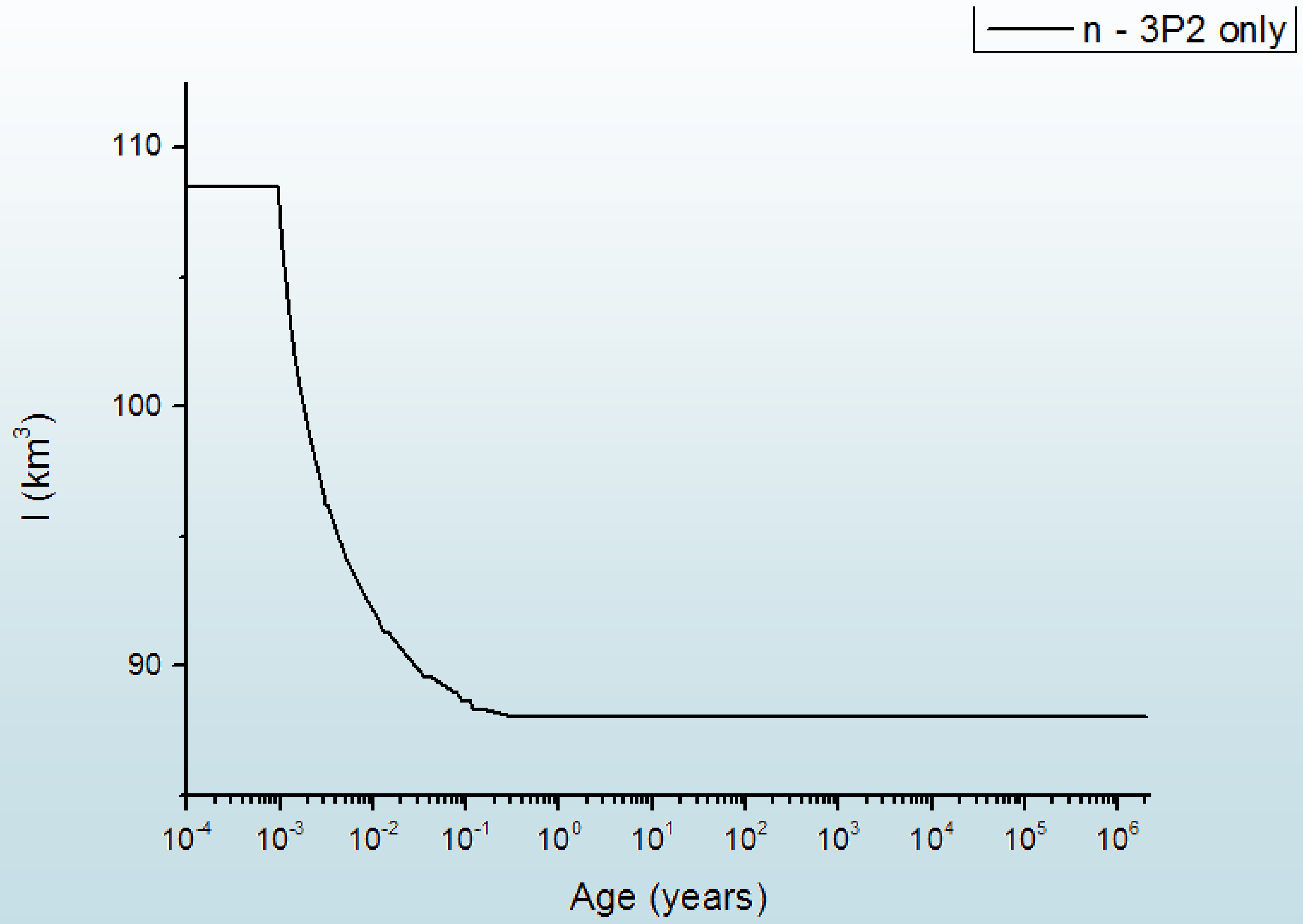
n - 1S0 only
110
100
90
I (km^3)
10^-4 10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6
Age (years)

Cooling



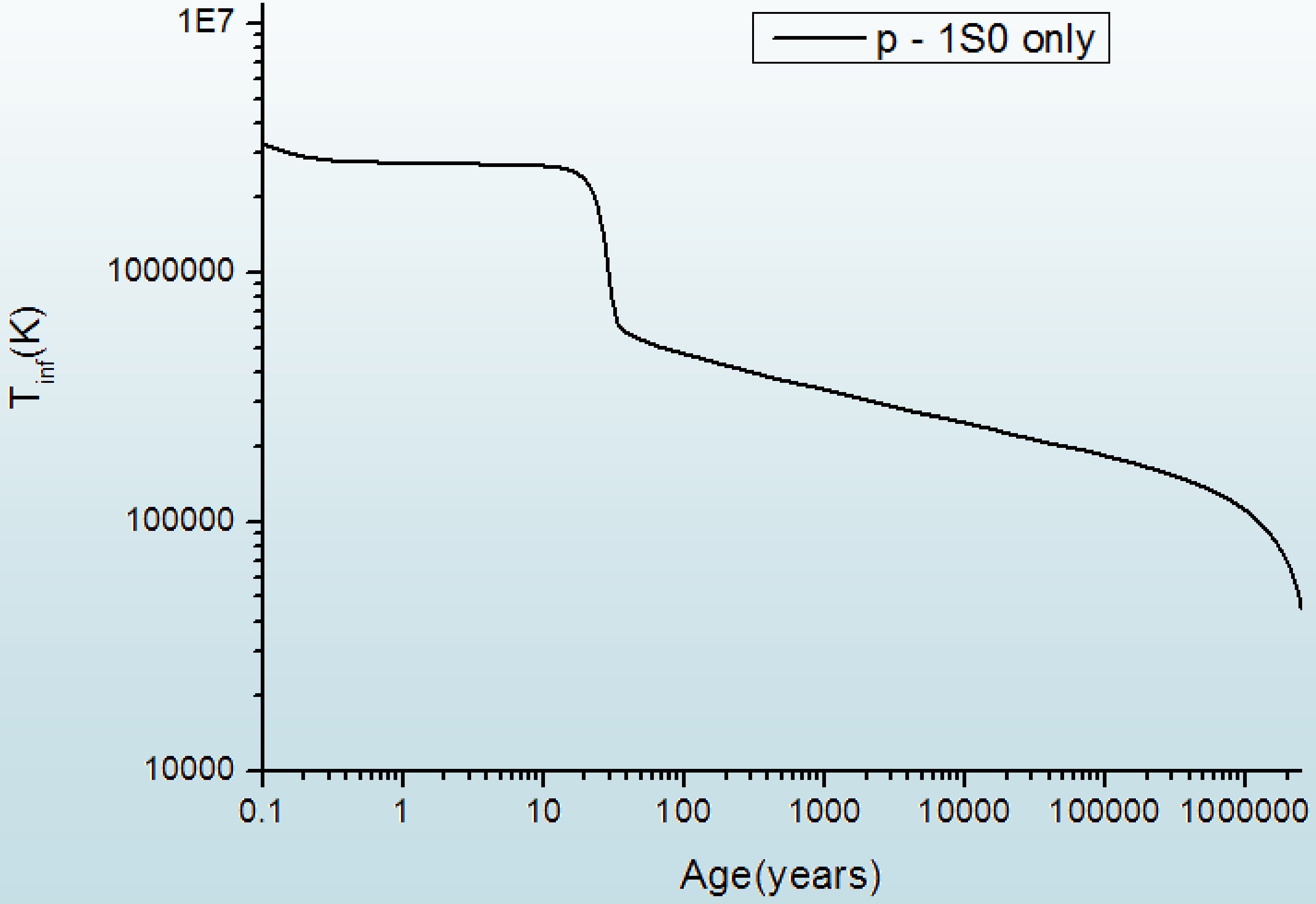
N - 3P2 only
1E7
1000000
100000
10000
T_{inf}(K)
0.1
1
10
100
1000
10000
100000
1000000
Age(years)

Cooling



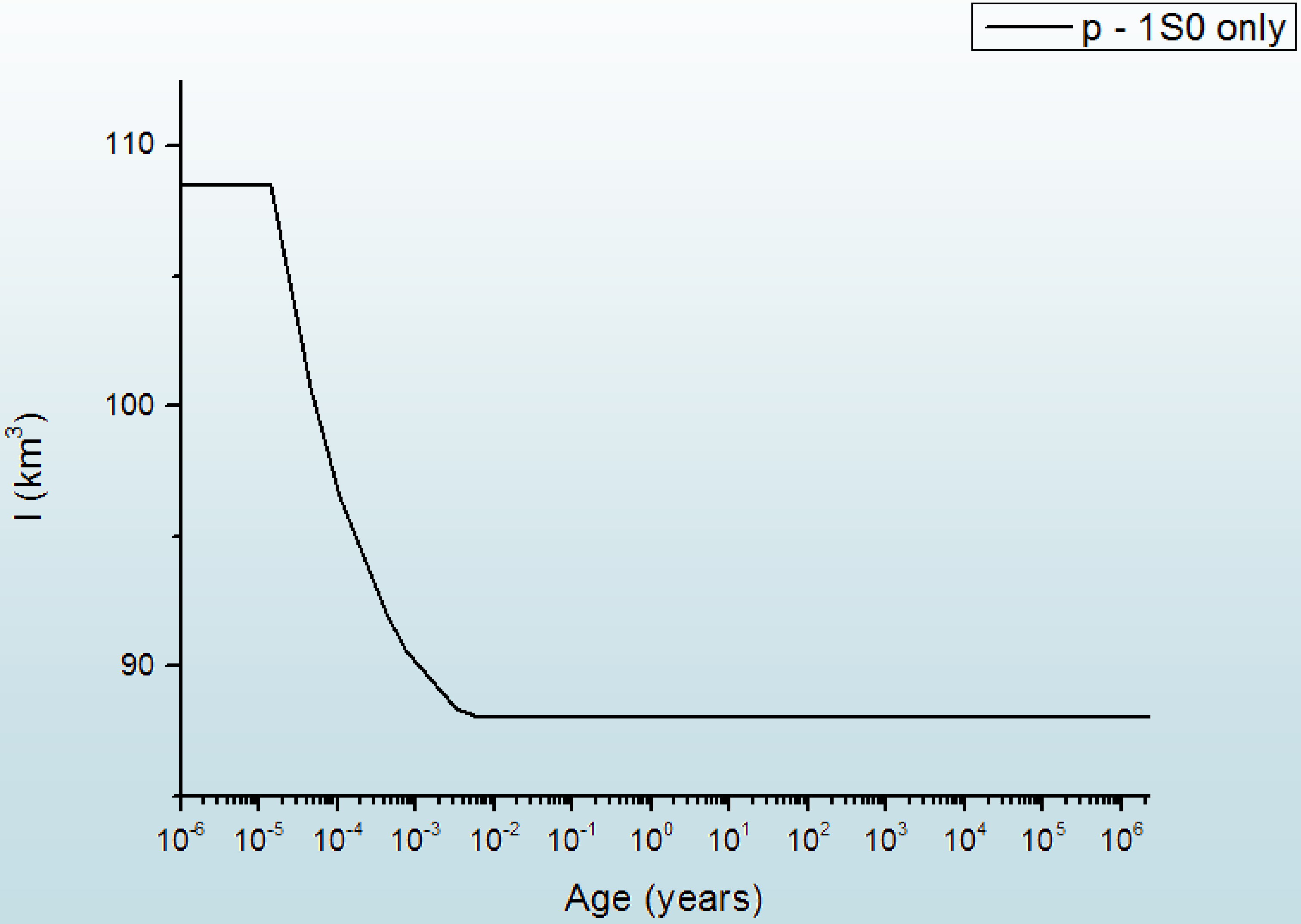
n - 3P2 only
110
100
90
I (km^3)
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Age (years)

Cooling



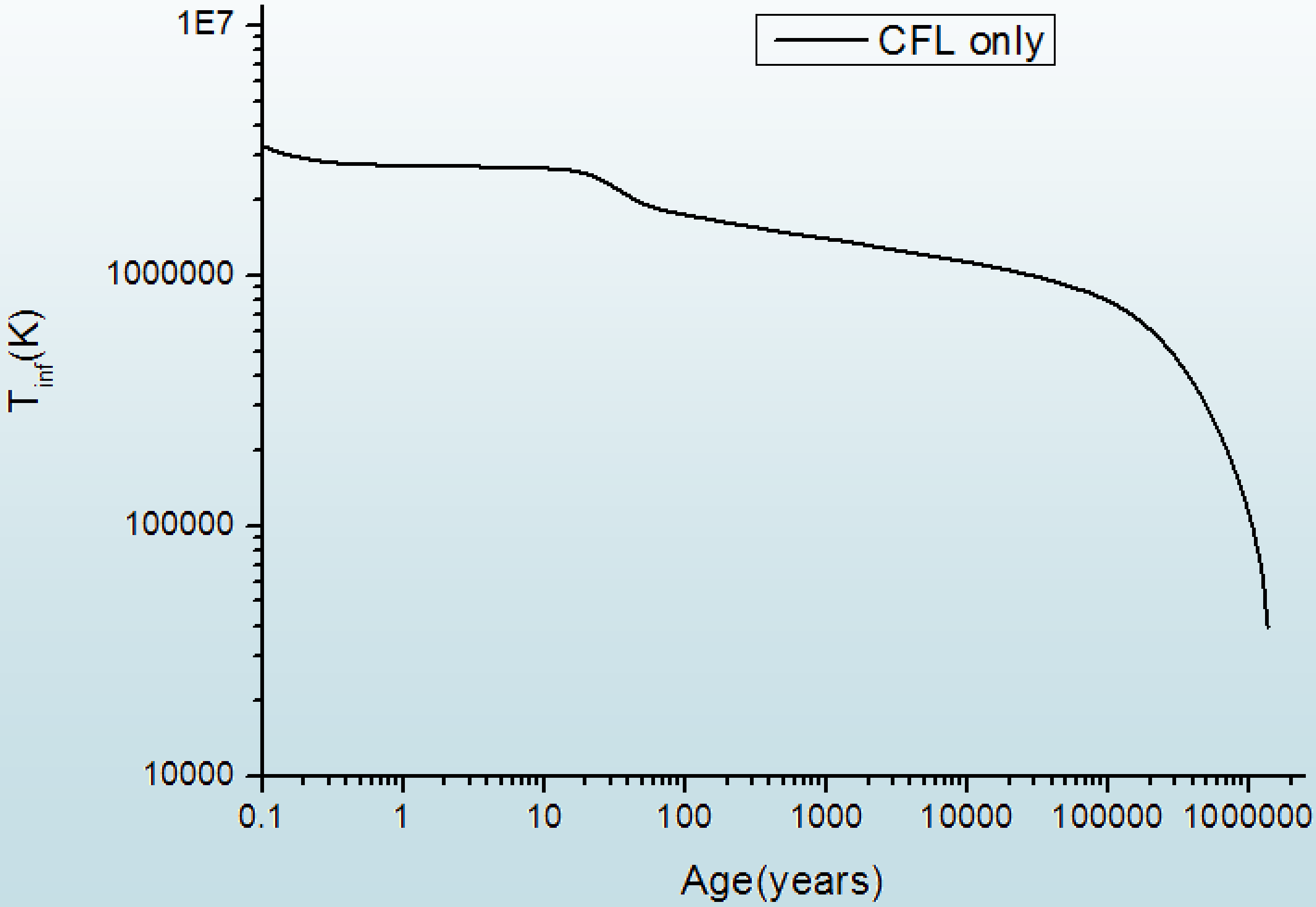
p - 1S0 only
1E7
1000000
100000
10000
T_inf(K)
0.1
1
10
100
1000
10000
100000
1000000
Age(years)

Cooling



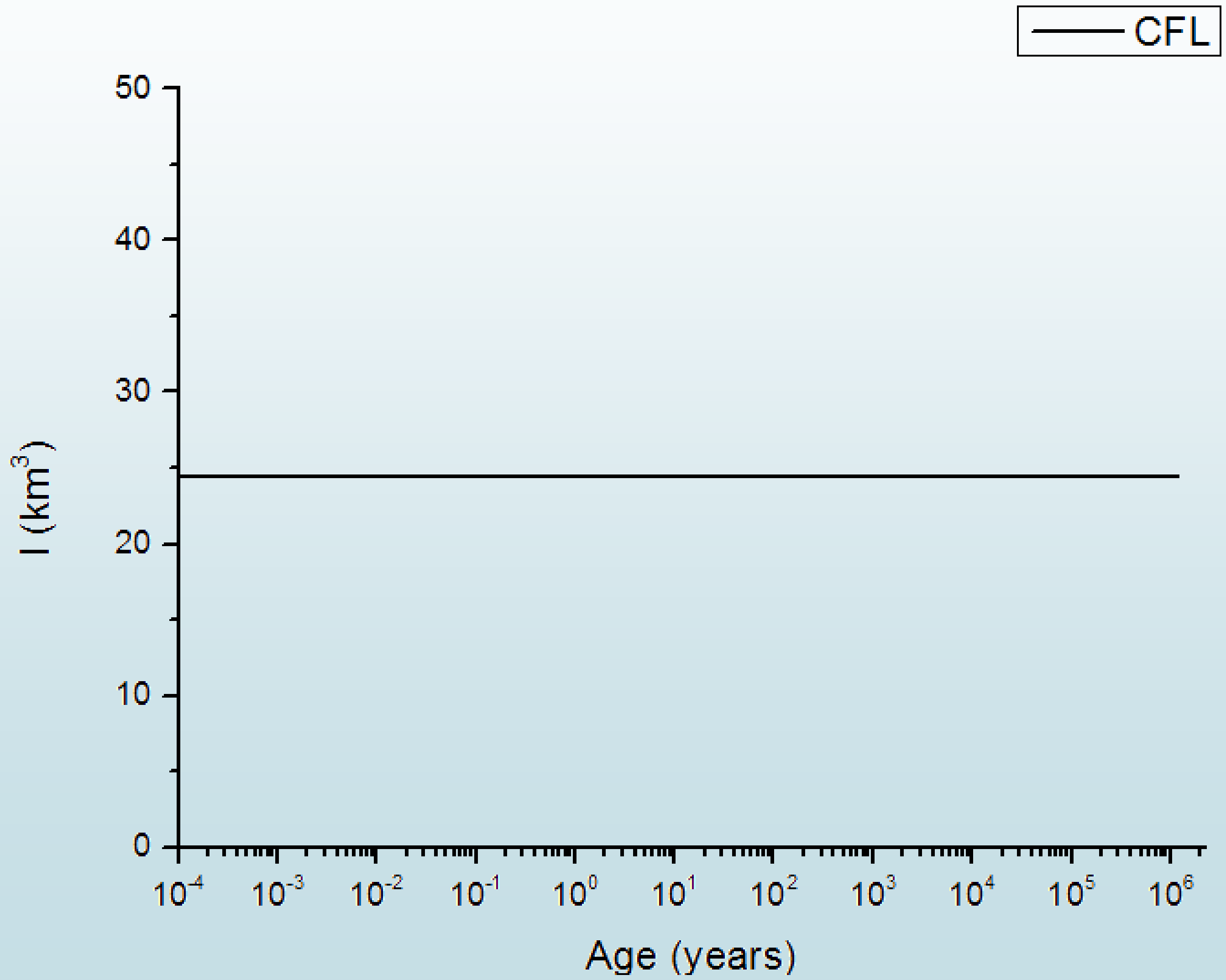
p - 1S0 only
110
100
90
I (km3)
10-6
10-5
10-4
10-3
10-2
10-1
100
101
102
103
104
105
106
Age (years)

Cooling



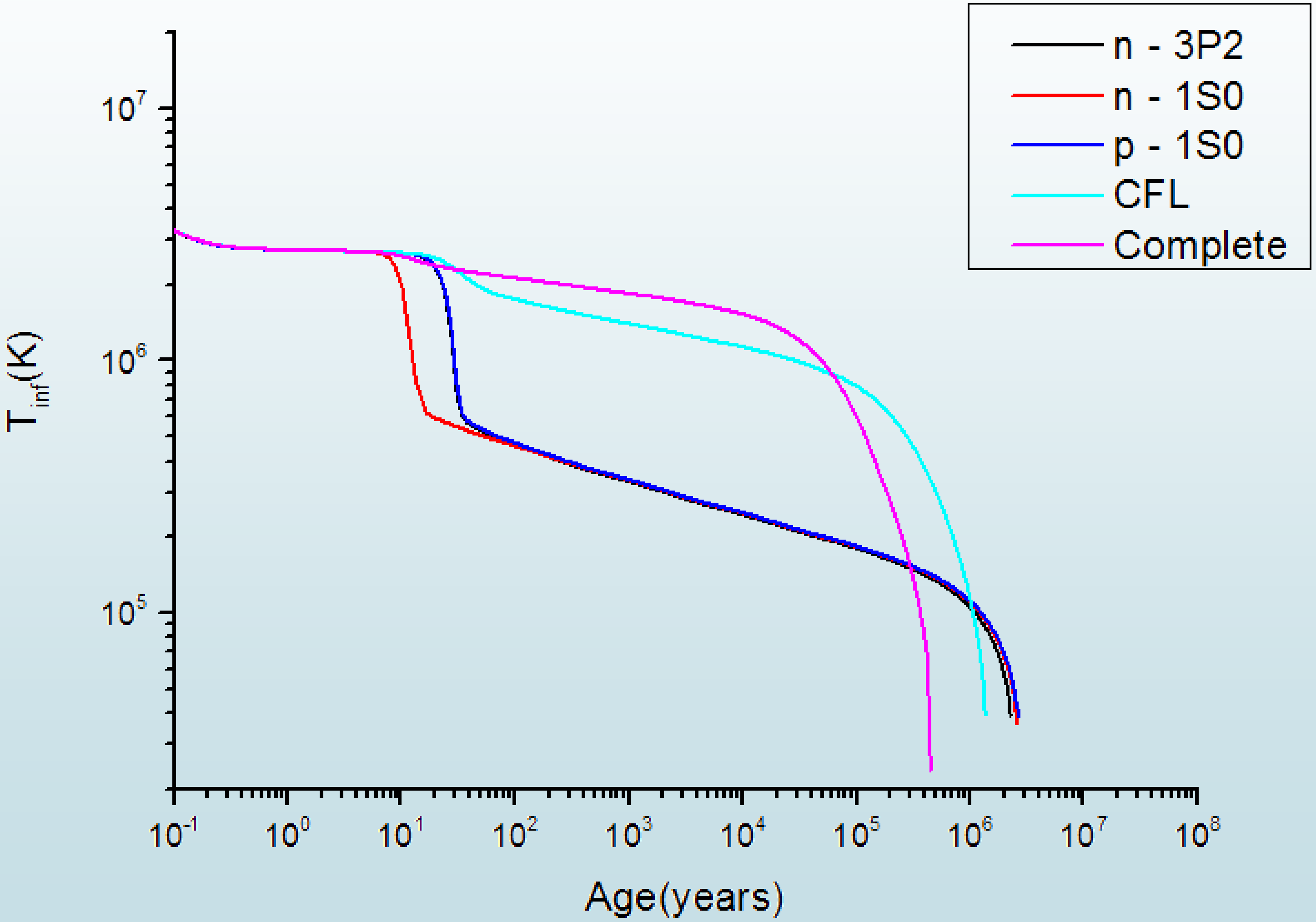
CFL only
1E7
1000000
100000
10000
T_{inf}(K)
0.1
1
10
100
1000
10000
100000
1000000
Age(years)

Cooling



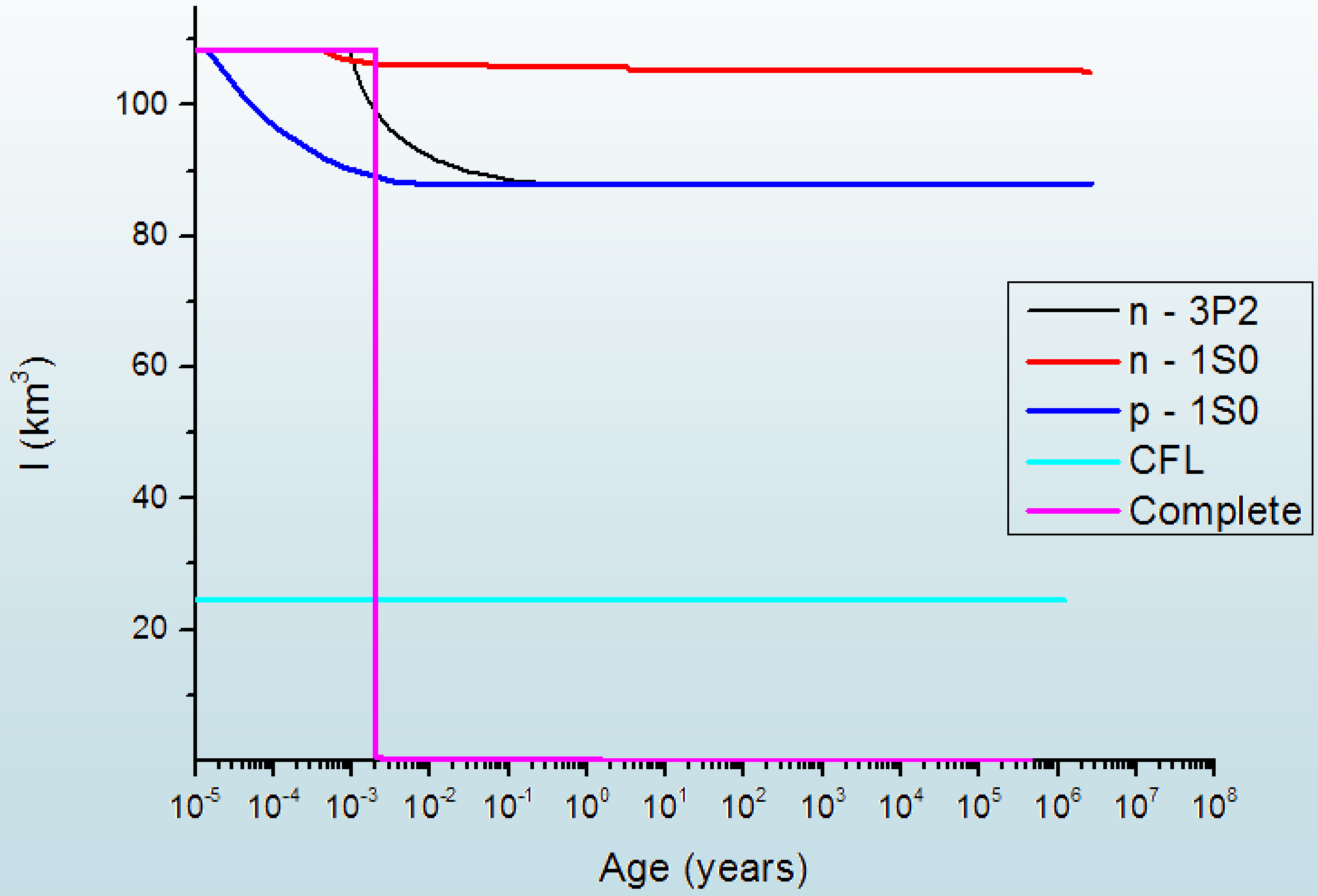
CFL
50
40
30
20
10
0
I (km^3)
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Age (years)

Cooling



n - 3P2
n - 1S0
p - 1S0
CFL
Complete
10^7
10^6
10^5
T_{inf}(K)
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
Age(years)

Momet of Inertia



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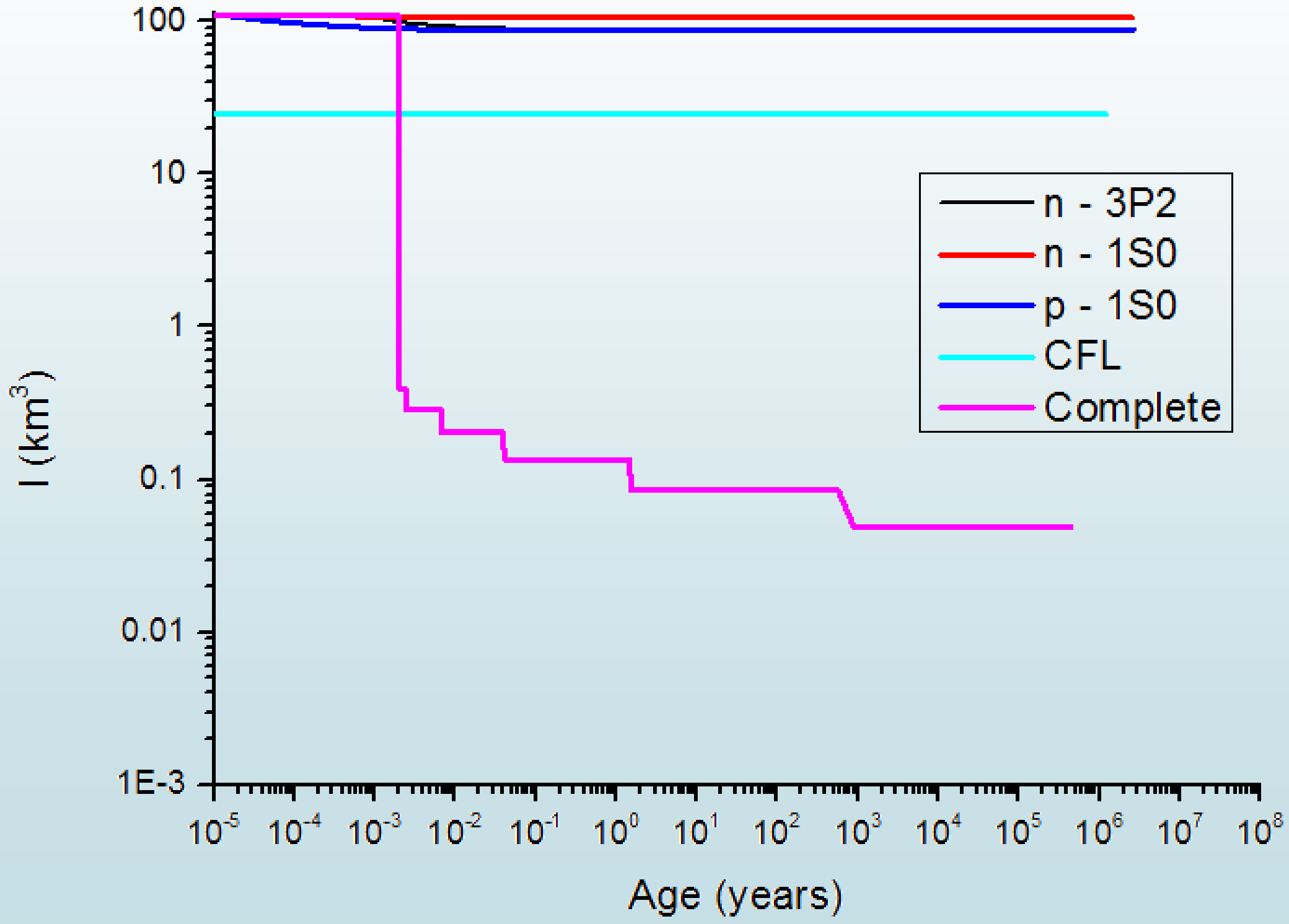
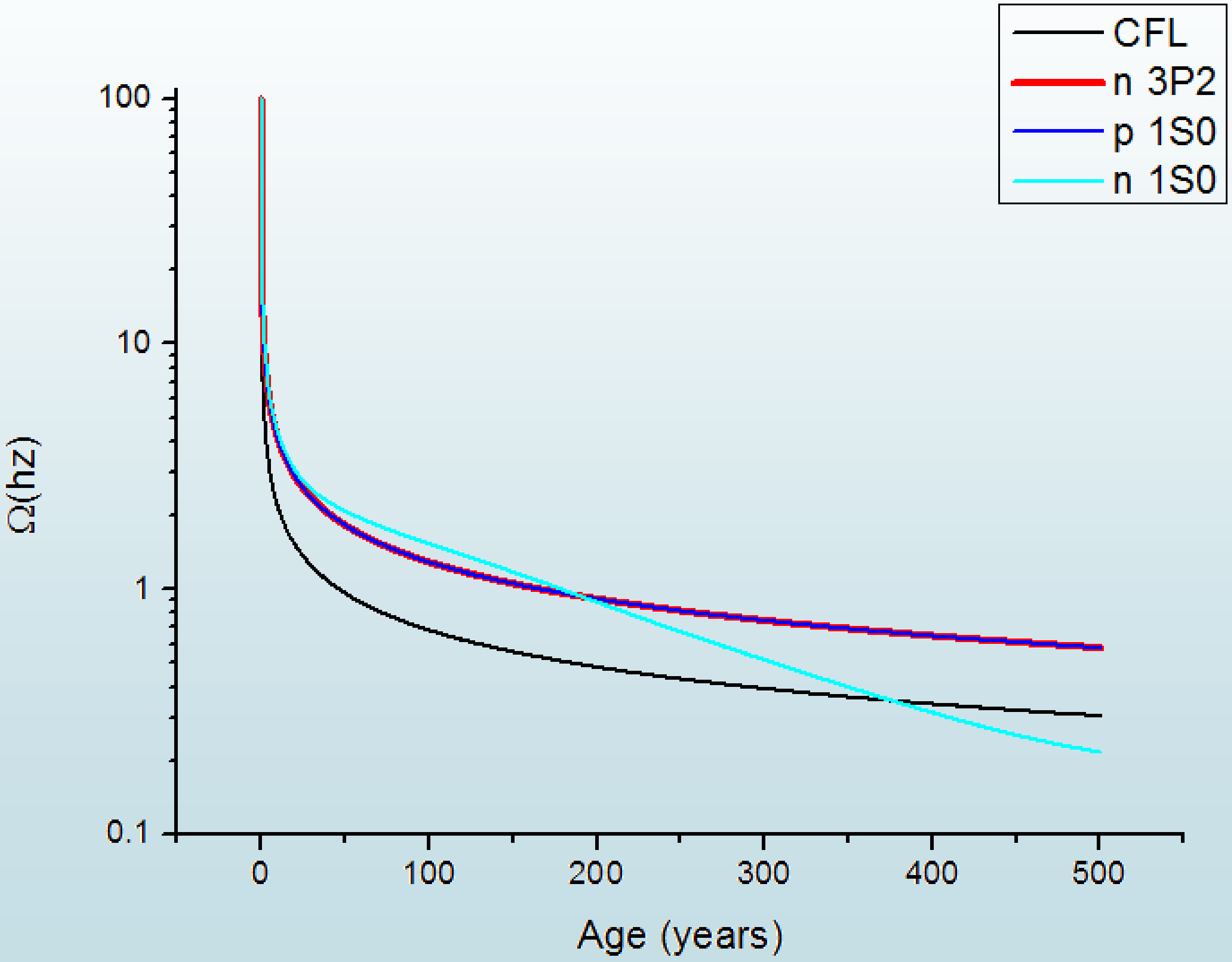


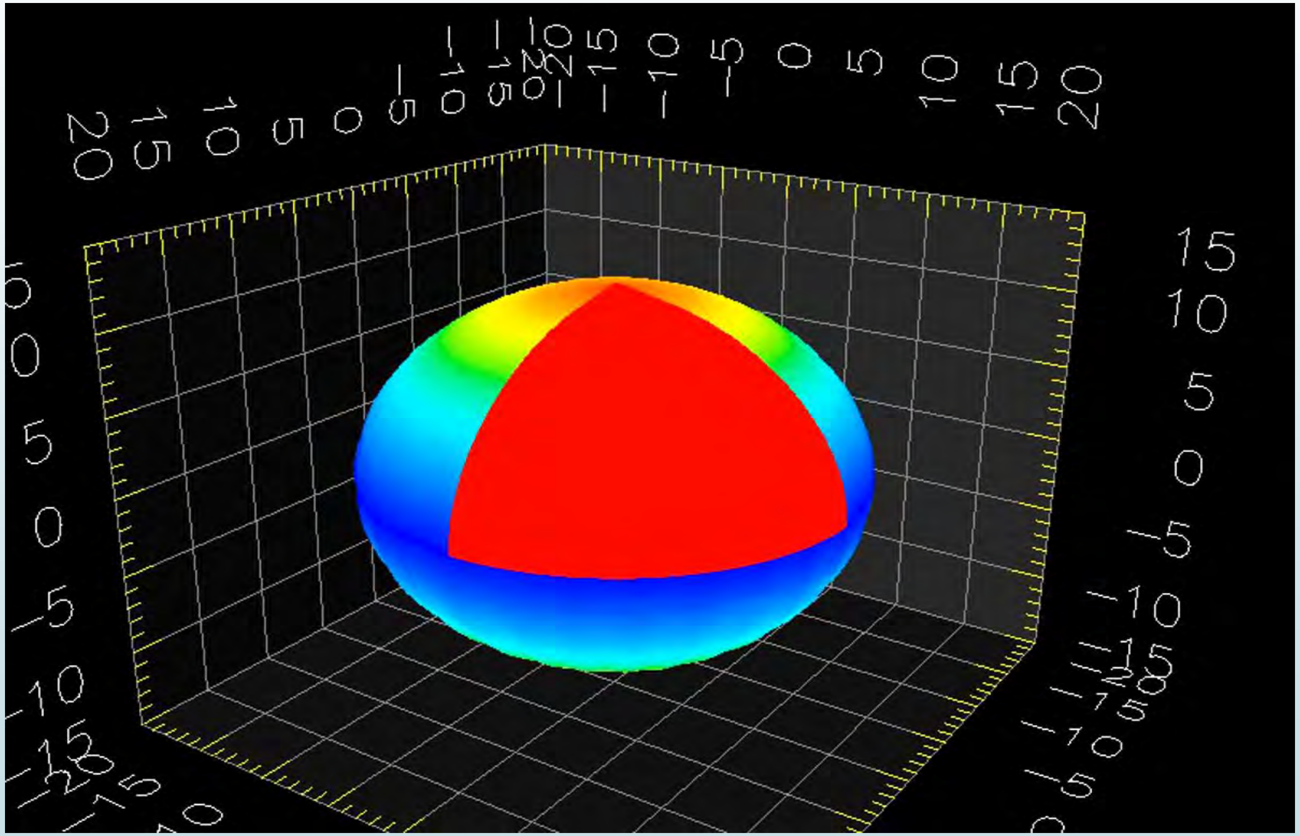
Frequency



CFL
n 3P2
p 1S0
n 1S0
100
10
1
0.1
Ω(hz)
0
100
200
300
400
500
Age (years)

Next Steps

- <u>Include rotation and magnetic field effects</u>



Conclusions and outlook

- There is something missing in the traditional Braking model....
- One can hope to explain the observed data by either changes in the magnetic field or the moment of inertia of the star.
- We believe that the most likely scenario involves a growing magnetic field together with changes in the moment of inertia.
- Changes in the moment of inertia may be triggered by cooling and/or spin evolution.
- Next: Include a self-consistente spin-magneto-hydro-thermal evolution.