中性子星の磁場はどう決まっているのか？
を
クラスト形成時間から考えてみる

諏訪雄大
（東大総合文化 ＆ 京大基研）

Back to NS workshop in 2017

Asia/Tokyo English Login

～中性子星の観測と理論～　研究活性化ワークショップ 2017

23-25 November 2017
Asia/Tokyo timezone

- Overview
- Timetable(with slide)
- Registration
- Participant List

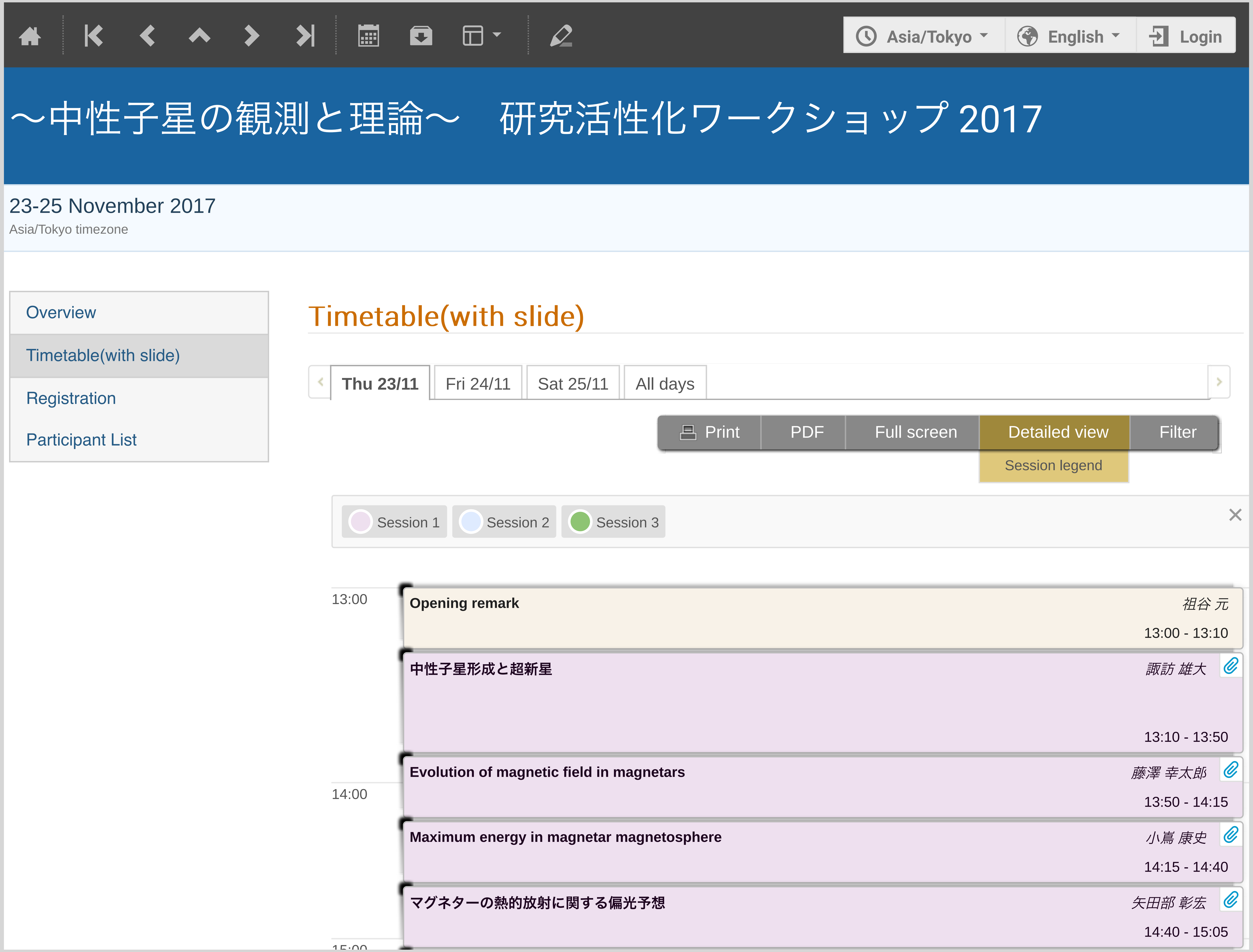
Overview

https://indico2.riken.jp/event/2545/page/94-overview

第７回DTAシンポジウム:
～中性子星の観測と理論～
研究活性化ワークショップ 2017

多くの皆様にご参加いただき、ありがとうございました！

Back to NS workshop in 2017



Back to NS workshop in 2017

[🔗Link to slides]

中性子星形成と超新星

諏訪雄大

（京都大学 基礎物理学研究所 重力物理学研究センター）

CGP

YITP

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Agenda

Observable of NS:

1. **mass**
2. **spin**
3. **magnetic fields**

Can we calculate them w/ supernova simulations?

23/11/2017 諏訪雄大 @ 〜中性子星の観測と理論〜研究活性化ワークショップ 5 /36

Back to NS workshop in 2017

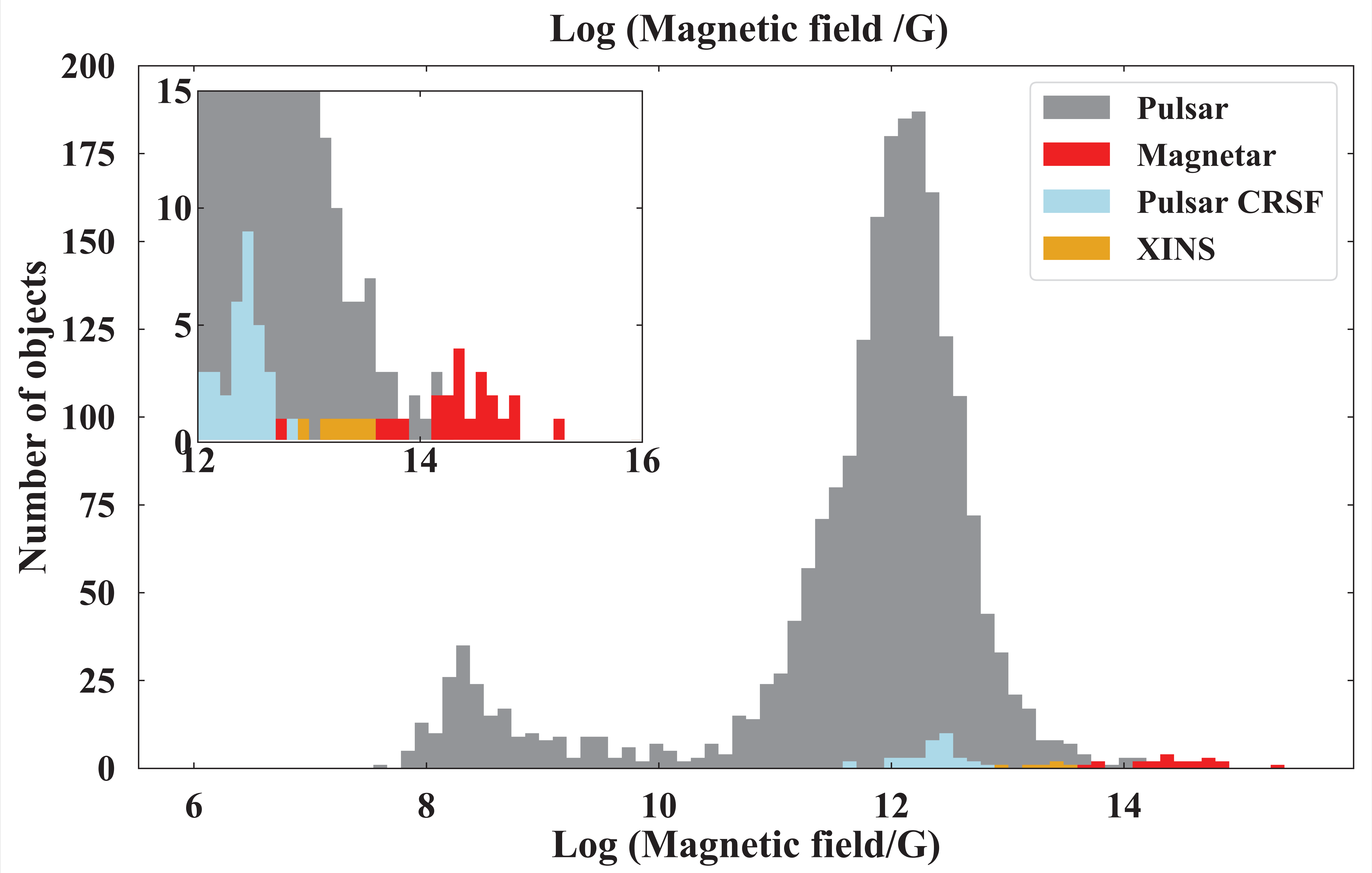
[🔗Link to slides]

Summary

Can we calculate them w/ supernova simulations?

1. **mass**
   - *yes w/ stellar evolution*
   - Si/Si-O interface at collapse is important
2. **spin**
   - *probably yes w/ stellar evolution*
   - post-explosion evolution is important
3. **magnetic fields**
   - *no, origin is highly uncertain*
   - crust formation might be important

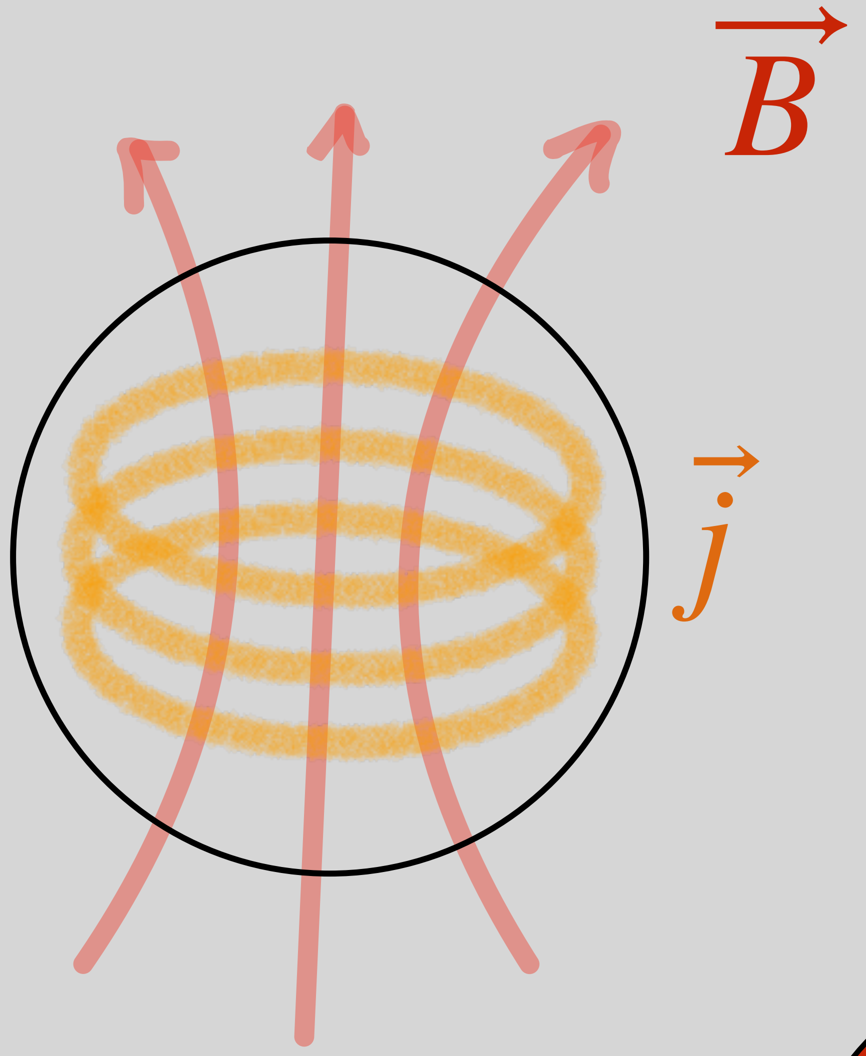
Magnetic fields of NSs



Enoto, Kisaka, Shibata (2019)

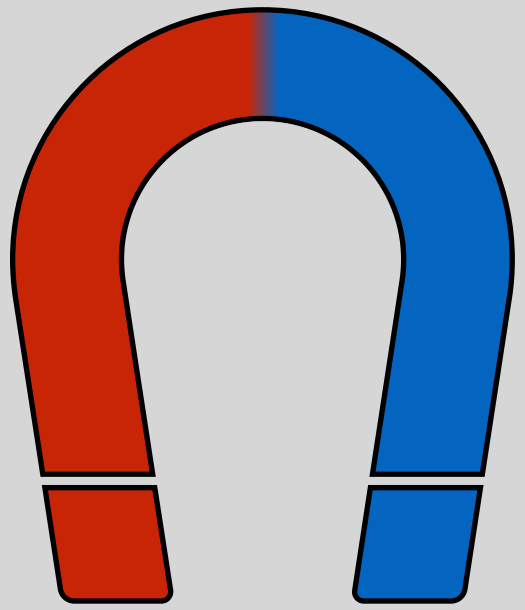
Origin of dichotomy between magnetars and radio pulsars

- **Two different physical processes to sustain magnetic fields**
  - magnetic induction by electric current
  - remanent (residual) magnetization left behind after magnetic-field decay



- **Magnetar**
  - strong internal current ?
  - dynamo ? fossil ?

- **Radio pulsar**
  - remanent fields in crust of NS ?



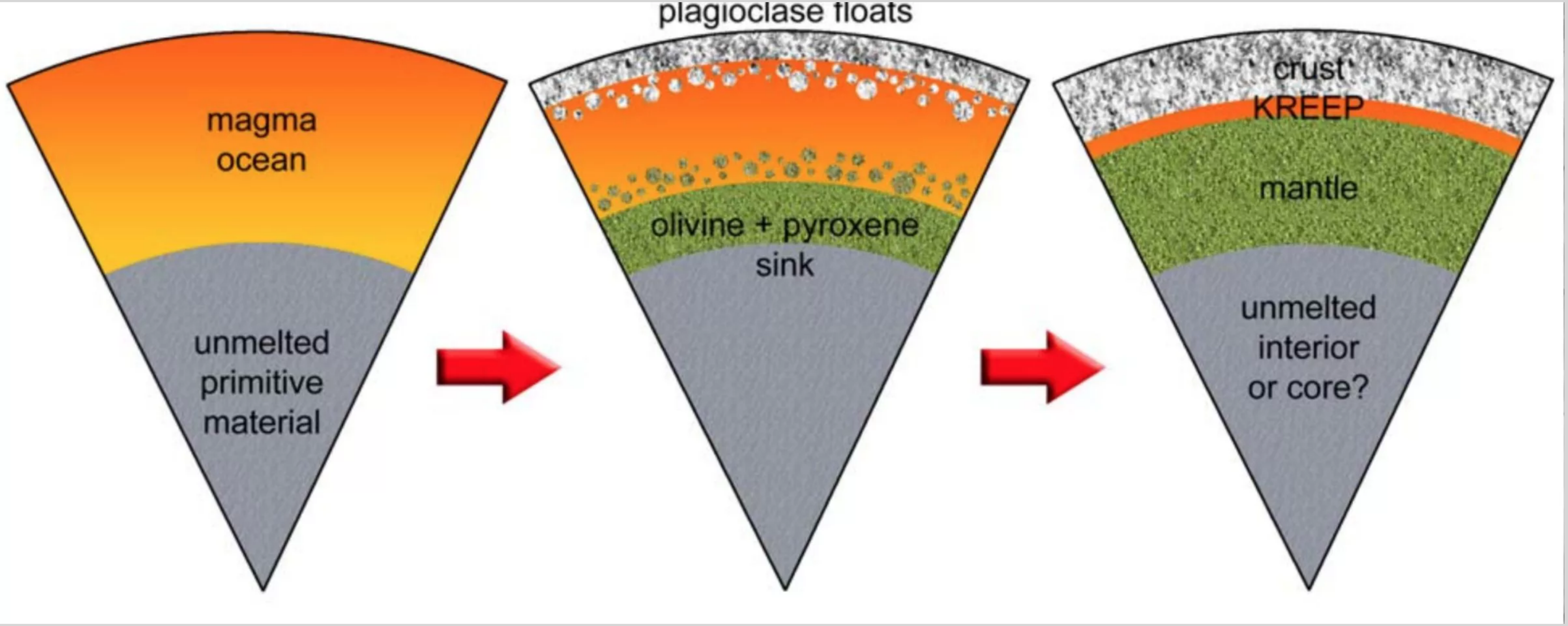
Origins of magnetic fields of planets & satellites

Stevenson (2010)

	B (G)	origin
Mercury	2×10^{-3}	?
Venus	$<10^{-4}$	remanence
Earth	0.5	core dynamo
Moon	10^{-5}-10^{-3} (patchy)	remanence
Mars	10^{-5}-1 (patchy)	strong remanence
Jupiter	4.2	dynamo
Saturn	0.2	dynamo

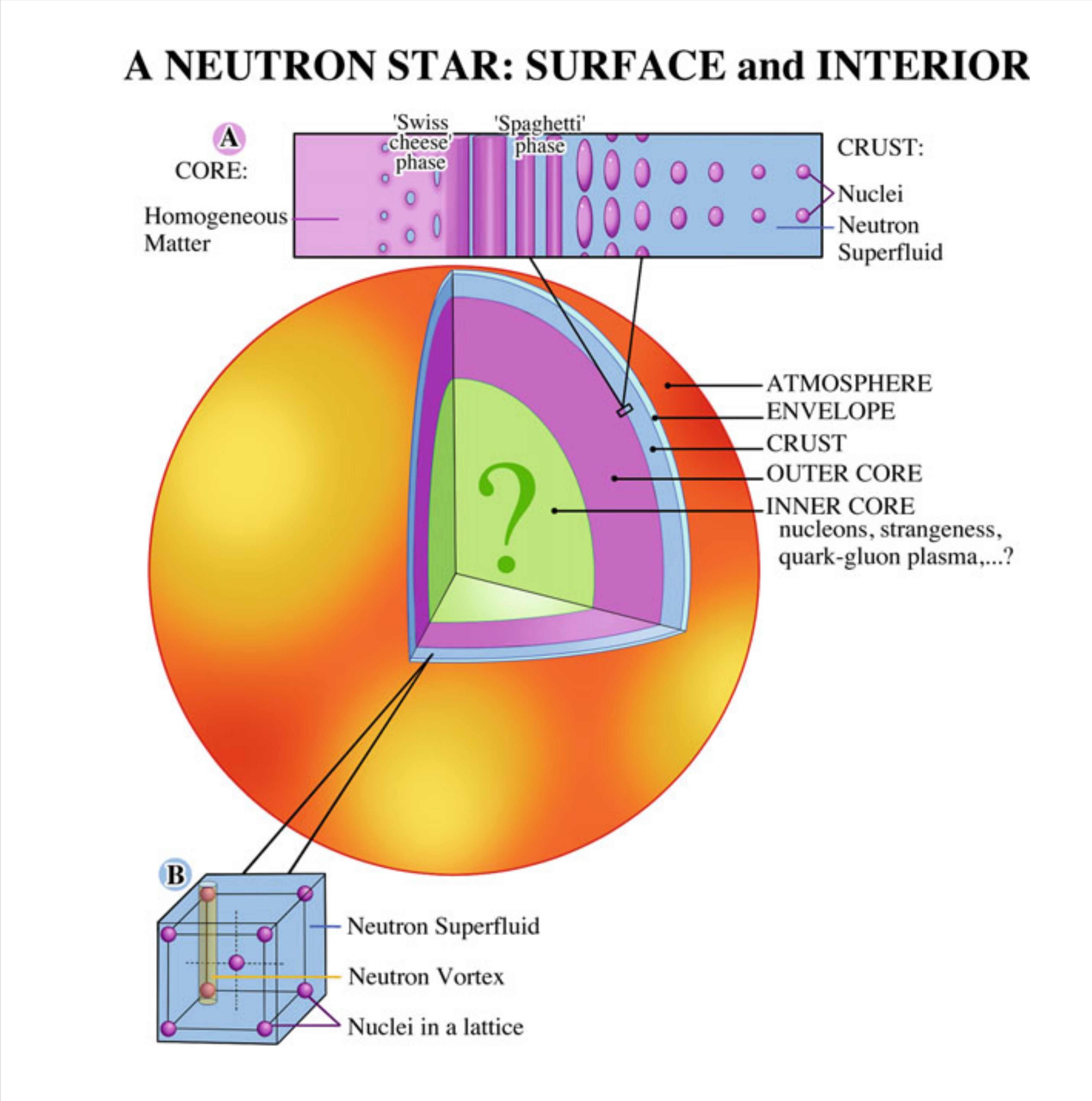
	B (G)	origin
Uranus	0.2	dynamo
Neptune	0.2	dynamo
Io	$<10^{-2}$	complex
Europa	10^{-3}	Induction response
Ganymede	2×10^{-2}	likely dynamo
Callisto	4×10^{-5}	Induction responce
Titan	$<10^{-3}$	need more data

Lunar crust formation



https://www.planetary.org/space-images/lunar-crust-formation

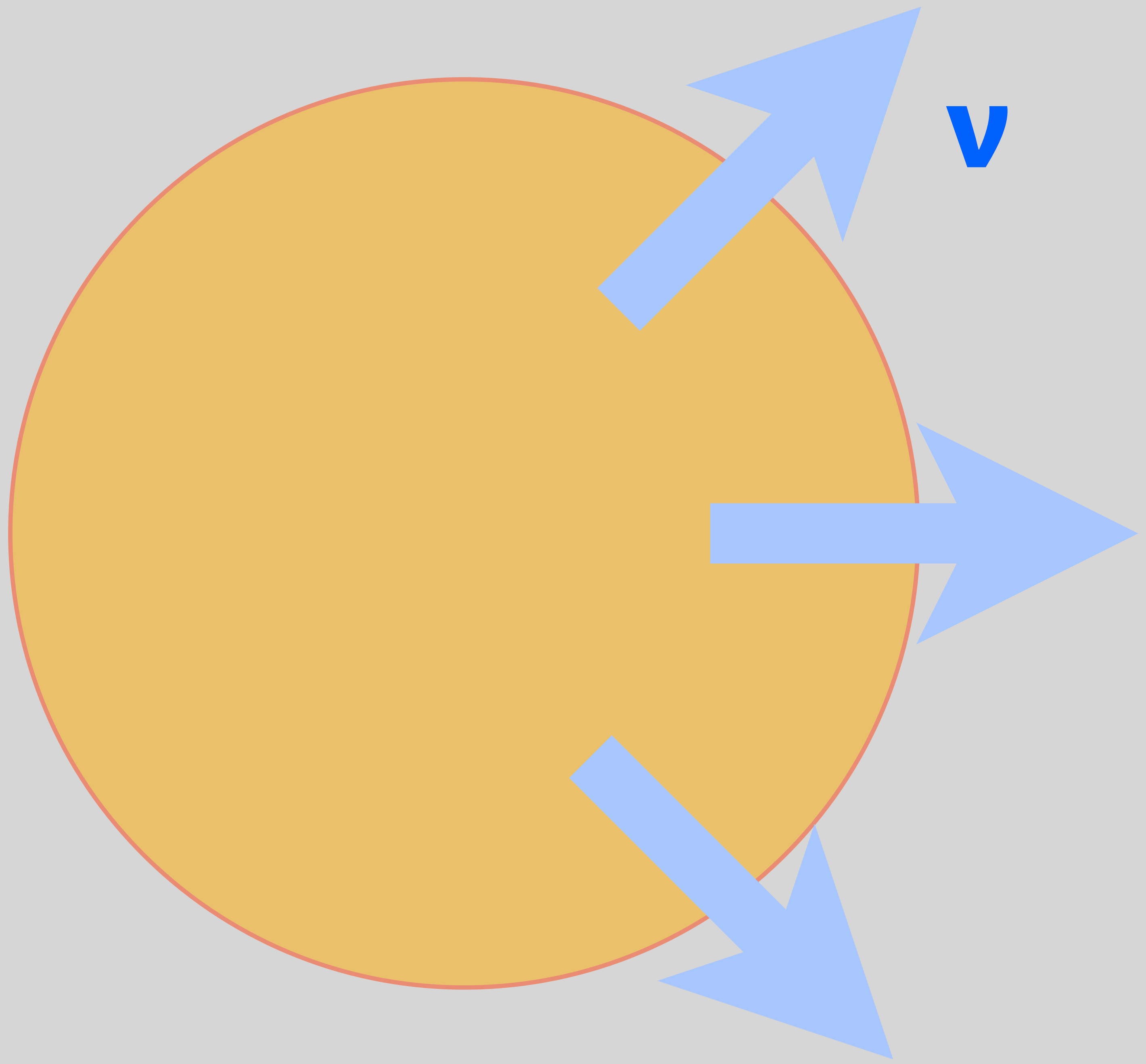
Neutron stars also have crust

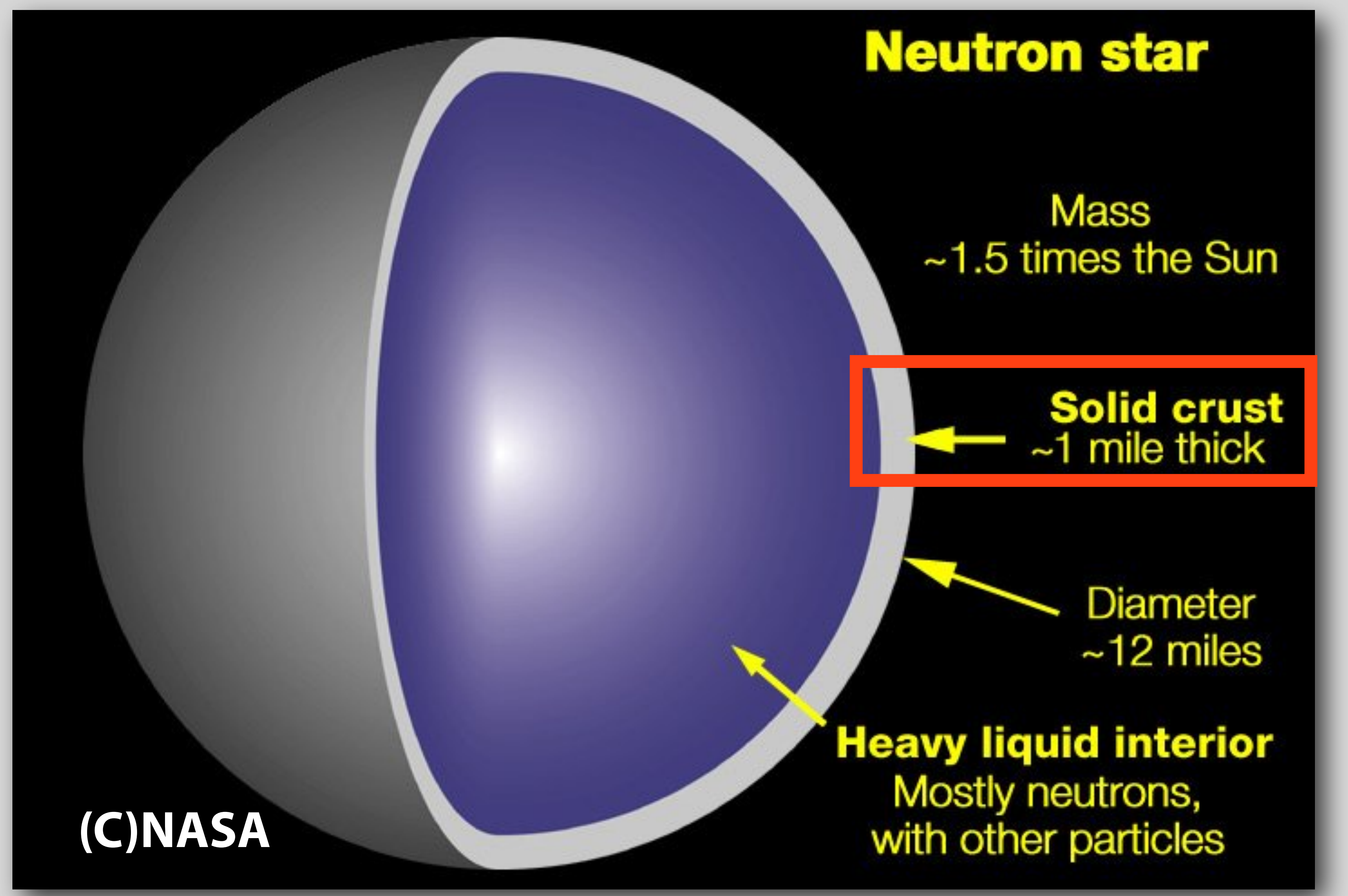


Obertelli and Sagawa (2021)

Crust formation

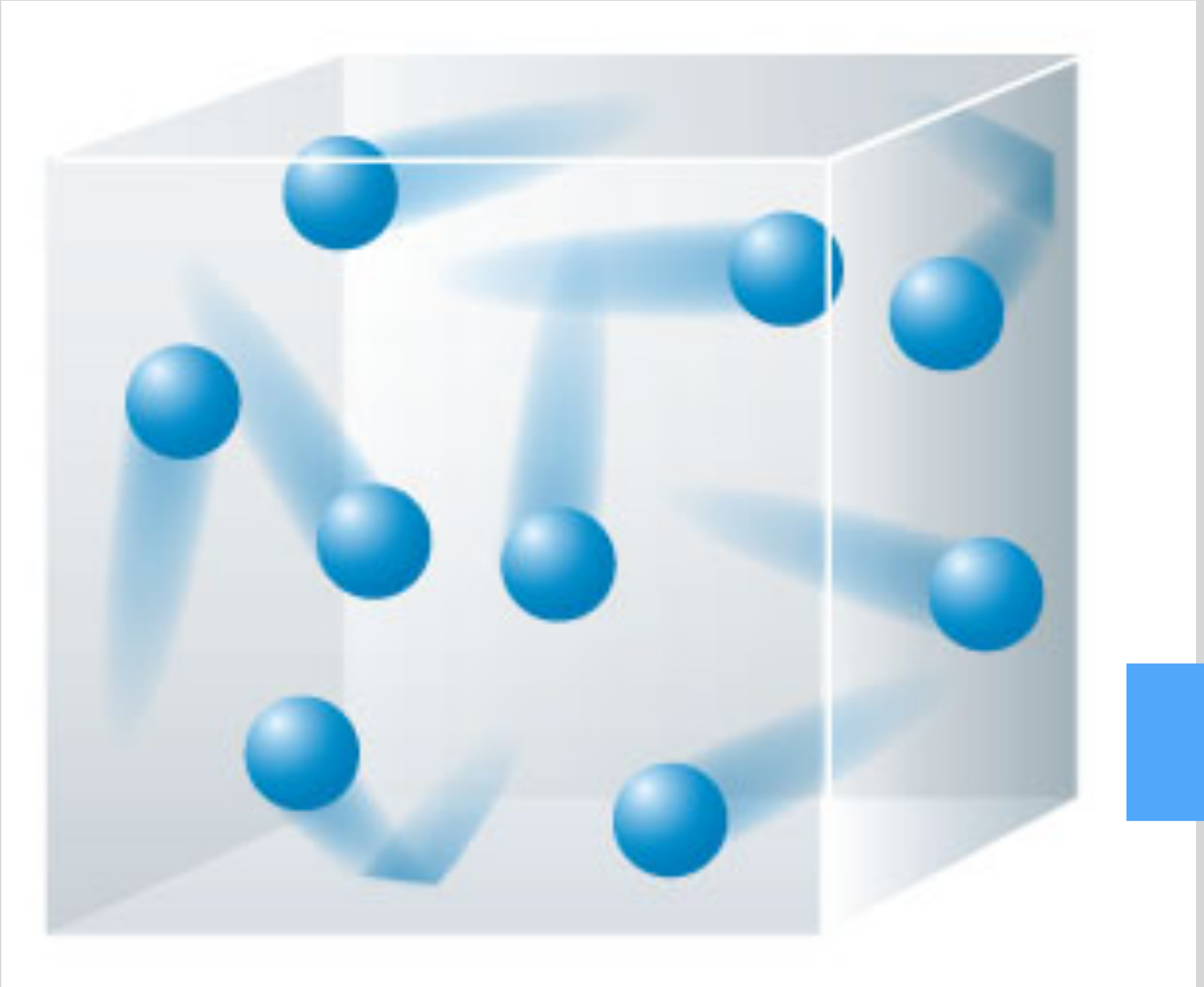
- NS crust forms as it cools down by neutrino emission. WHEN?
- Is building up of magnetic fields faster than crust formation?

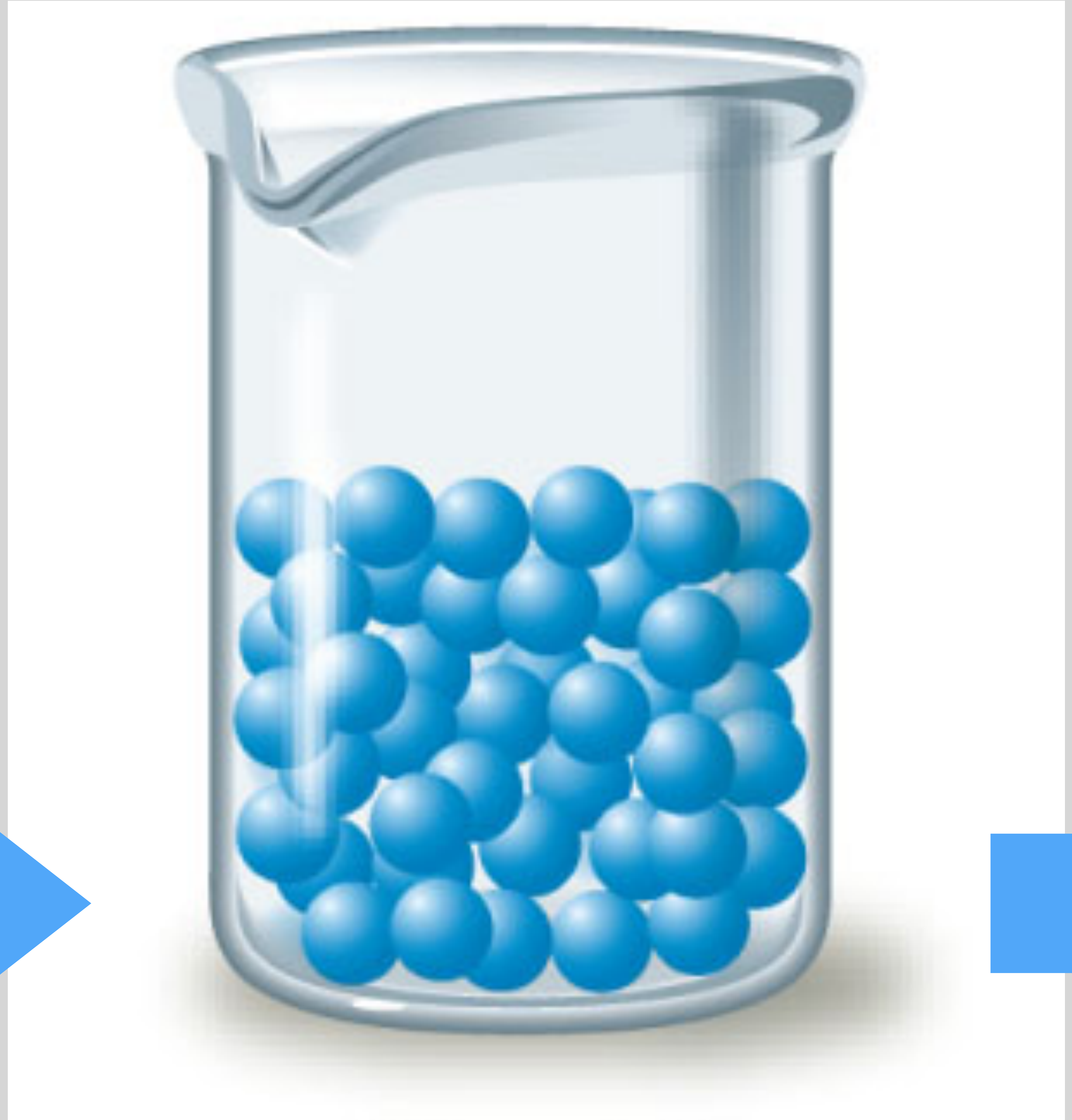


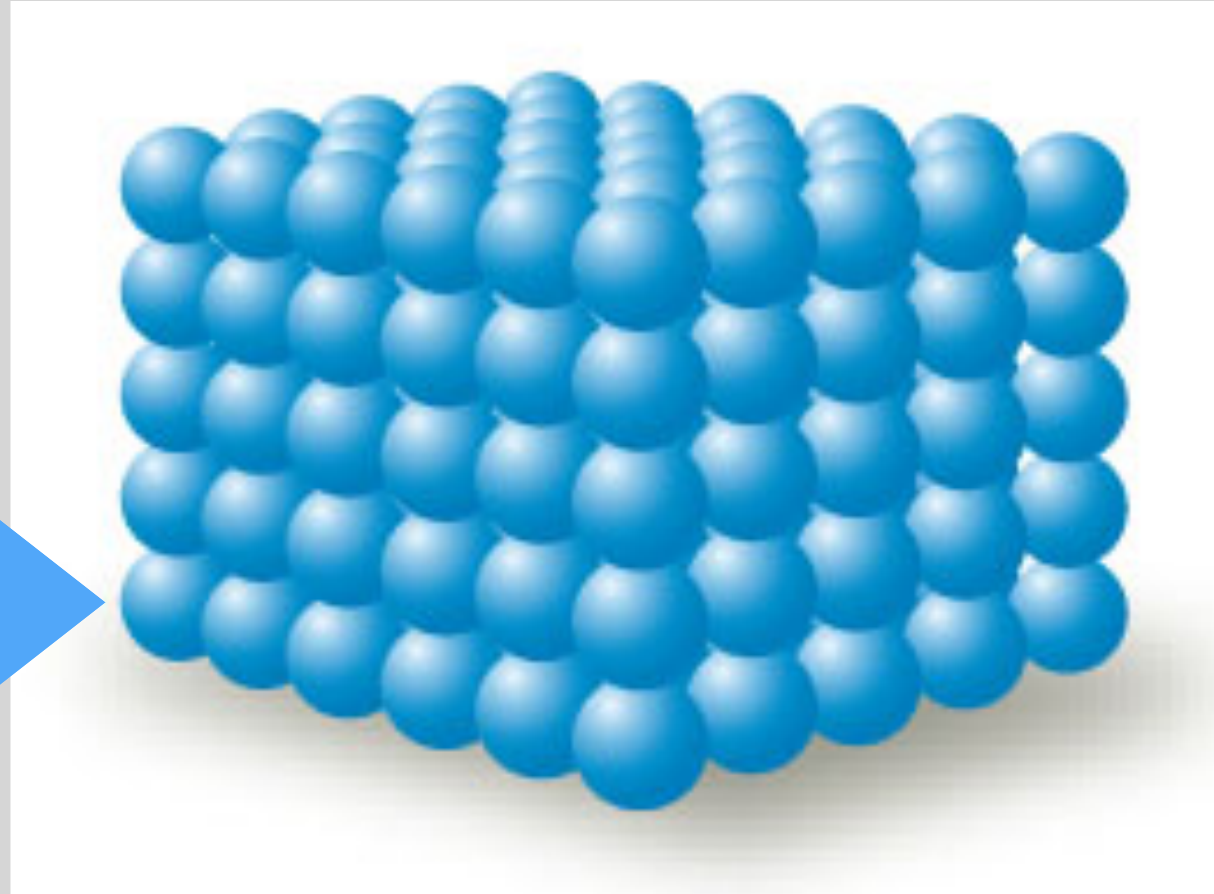


Crust formation = crystallization = phase transition

gas **liquid** **solid**



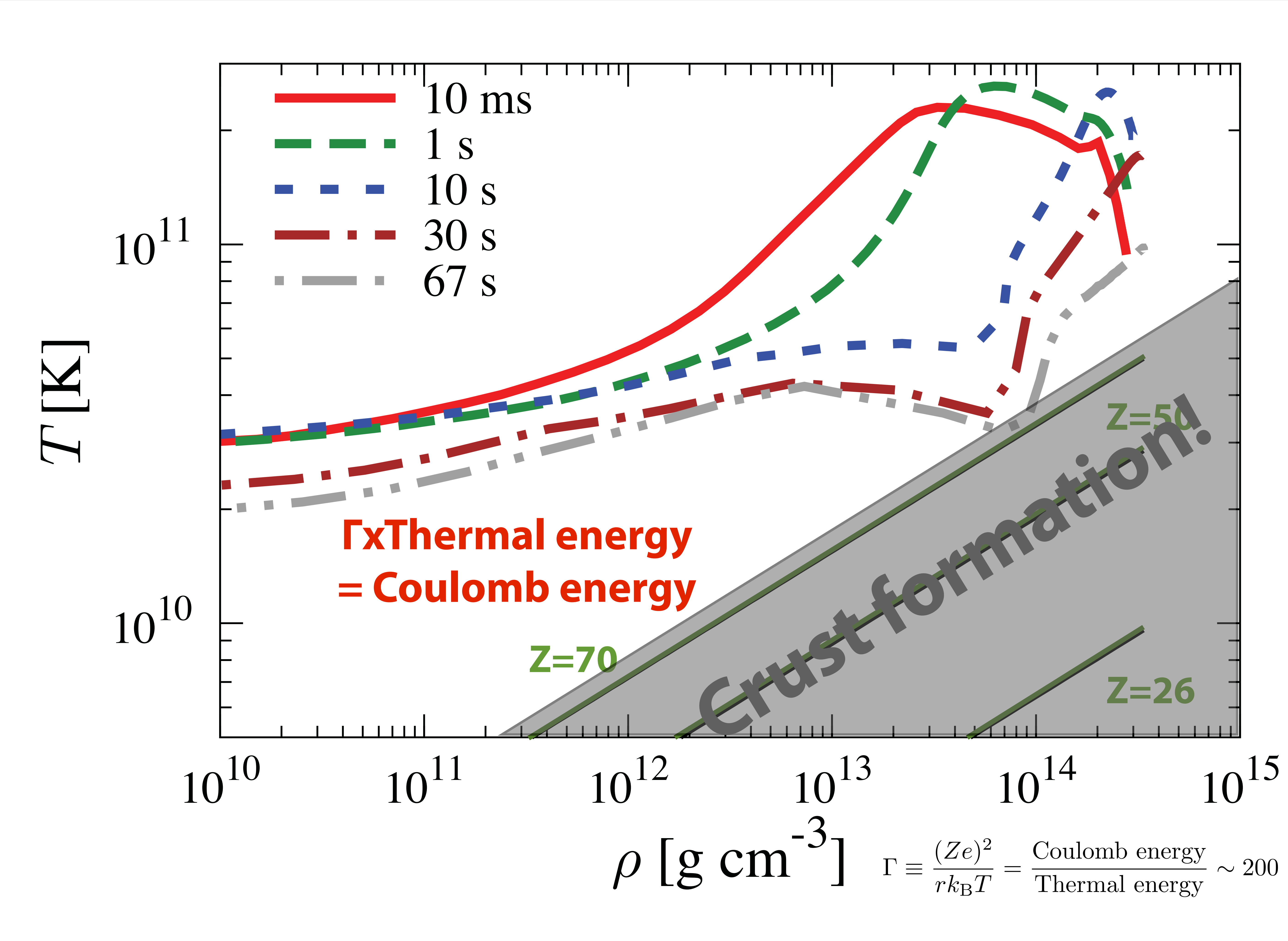


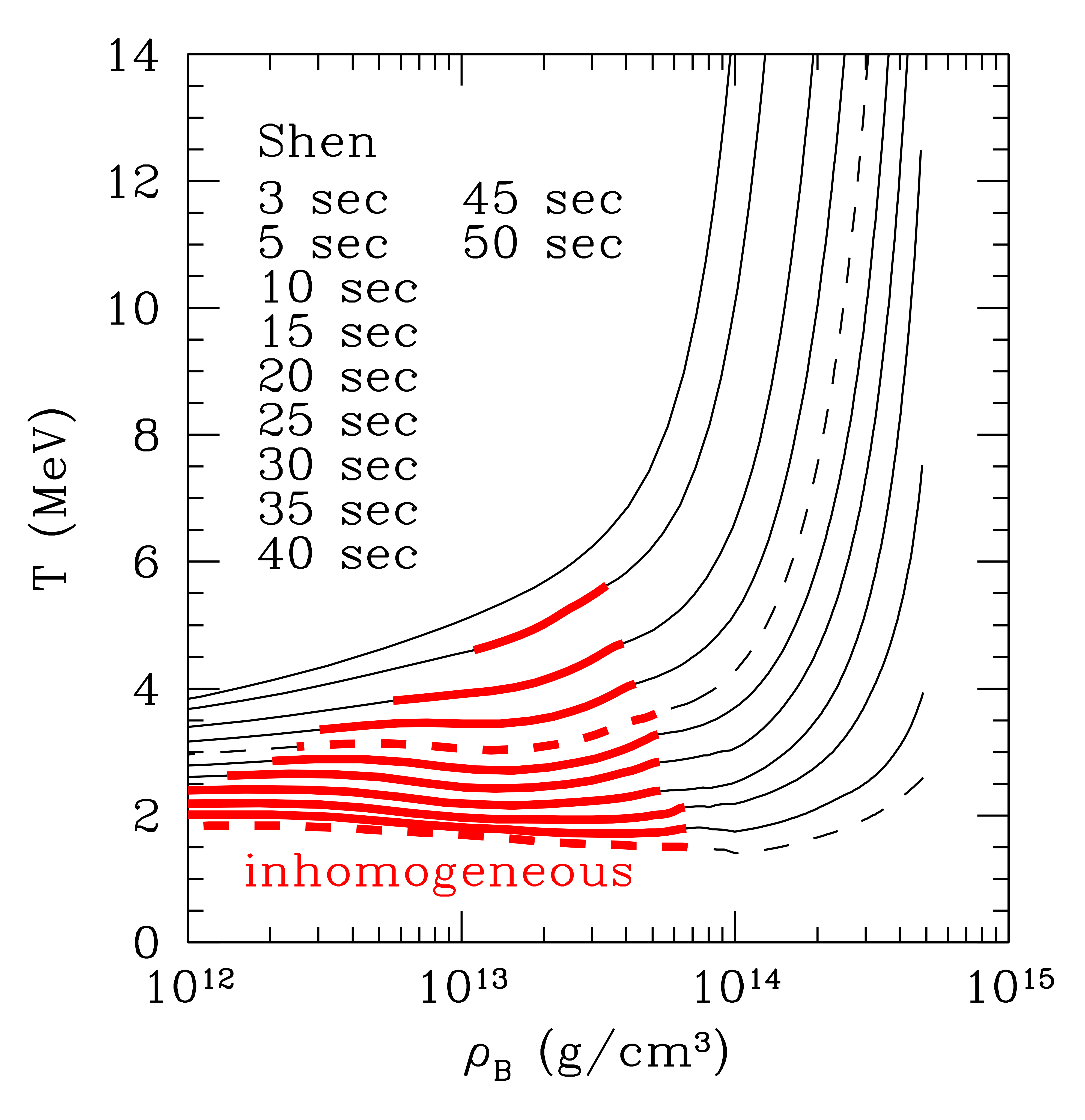


cool down **cool down**

https://laney.edu/huisunkim/wp-content/uploads/sites/407/2017/08/30A-Ch12-Liquids-Solids-Intermol-Forces.pdf

Numerical simulation of (close-to) crust formation of NSs





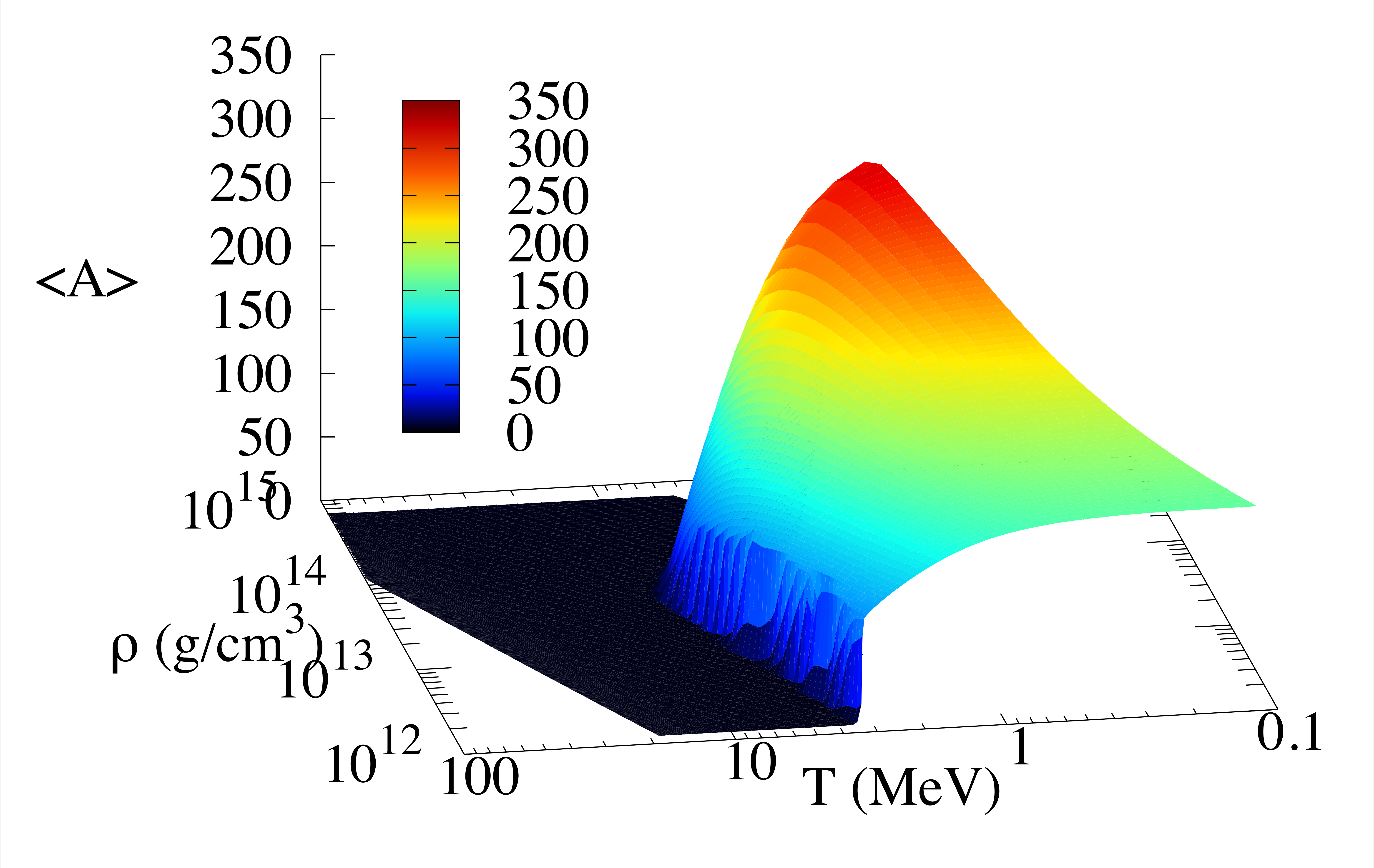
Suwa (2014)

Nakazato+ (2018)

What do we need?

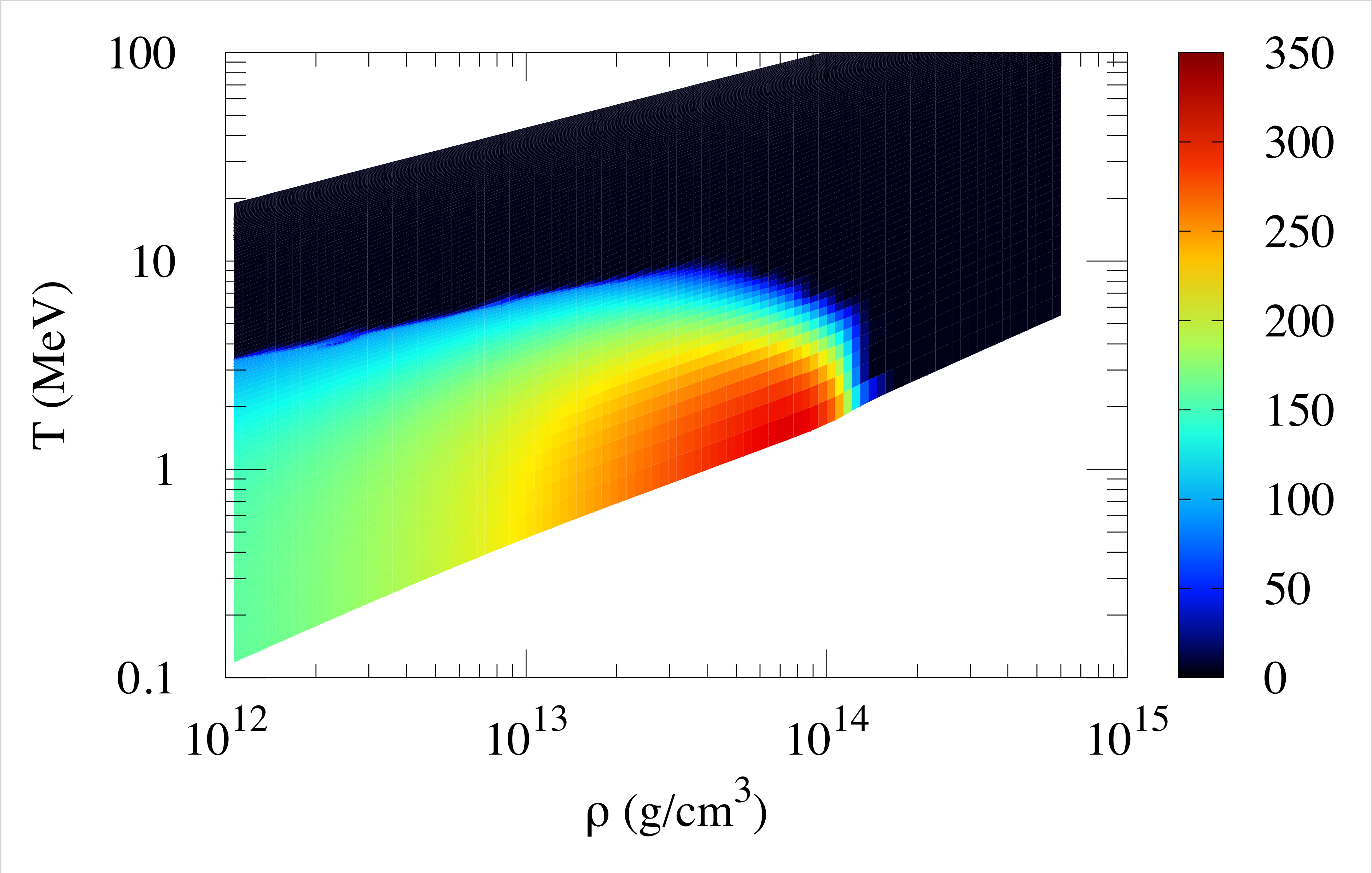
- **Long-term simulations of PNS cooling**
  (Nakazato+ 2013, Mori+ 2021, etc.)
  - but, **need a better neutrino transfer** than diffusion-based/truncated momentum methods
  - approx. methods have considerable errors around decoupling
  - S_N? Monte-Carlo? variable Eddington method? any suggestion?
- **Multicomponent nuclear EOS**
  (Hempel+ 2010, Furusawa+ 2011, etc.)
  - phase transition btw. uniform and non-uniform matter? nuclear pasta?
- **Better understanding of crust formation**
  (Sonoda+ 2007, etc.)
  - (Q)MD simulations? any other modern way?

Simulations crush due to emergence of heavy nuclei before crust formation



coherent scattering of neutrinos

$$\sigma_\nu \propto \langle A^2 \rangle$$



Finding a solution of neutrino transport fails → change the mind

Analytic solutions for neutrino emission

[Suwa, Harada, Nakazato, Sumiyoshi, PTEP, 2021, 0130E01 (2021)]

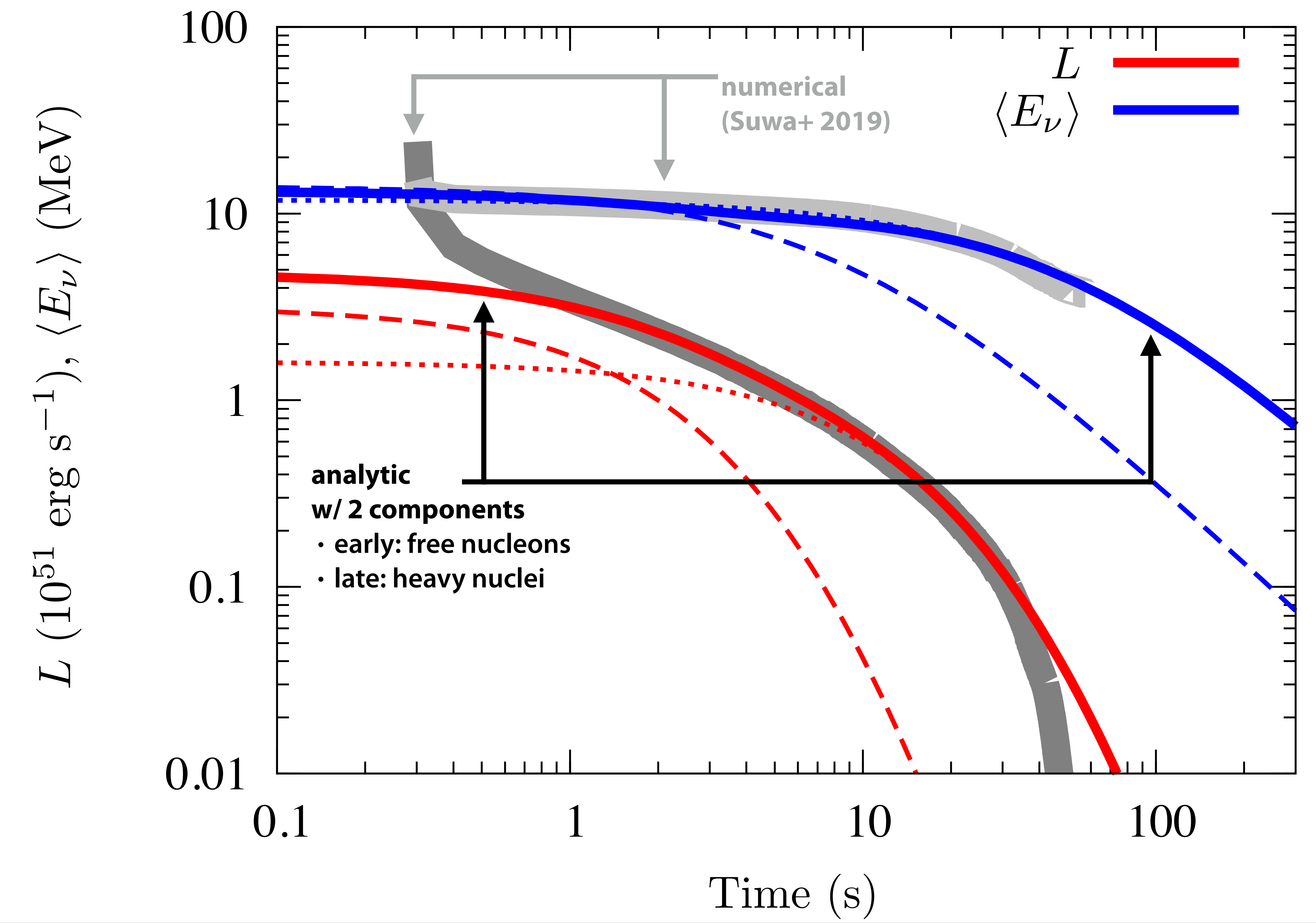
- **Solve neutrino transport eq. analytically**
  - **Neutrino luminosity**

$$L = 3.3 \times 10^{51}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\mathrm{PNS}}}{1.4 M_\odot}\right)^{6} \left(\frac{R_{\mathrm{PNS}}}{10\,\mathrm{km}}\right)^{-6} \left(\frac{g\beta}{3}\right)^{4} \left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-6}$$

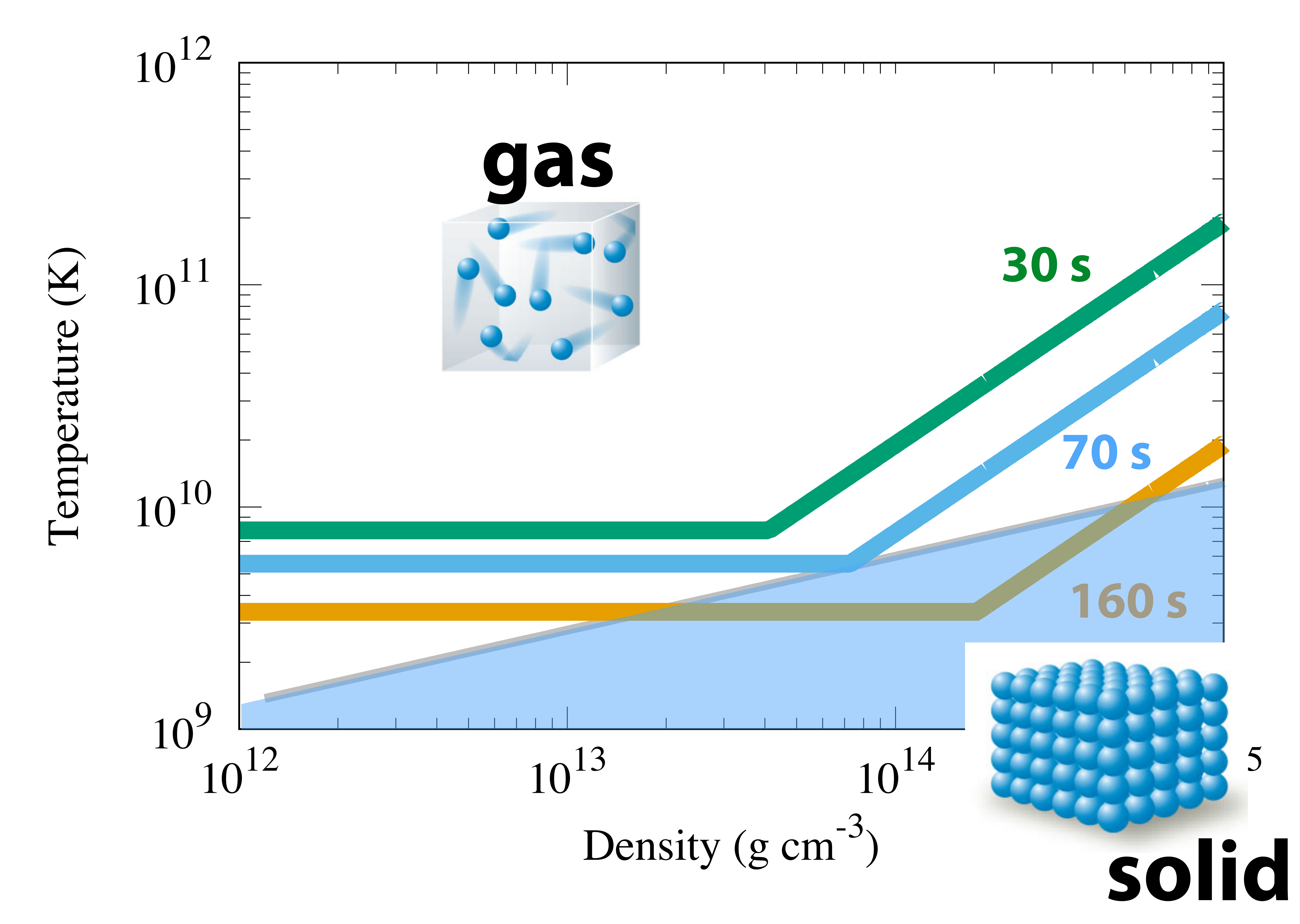
  - **Neutrino average energy**

$$\langle E_\nu \rangle = 16\,\mathrm{MeV} \left(\frac{M_{\mathrm{PNS}}}{1.4 M_\odot}\right)^{3/2} \left(\frac{R_{\mathrm{PNS}}}{10\,\mathrm{km}}\right)^{-2} \left(\frac{g\beta}{3}\right) \left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2}$$

  - **two-component model**
    - **early cooling phase** (β=3, free p and n)
    - **late cooling phase** (β=O(10), heavy nuclei)



Evolution in ρ-T plane

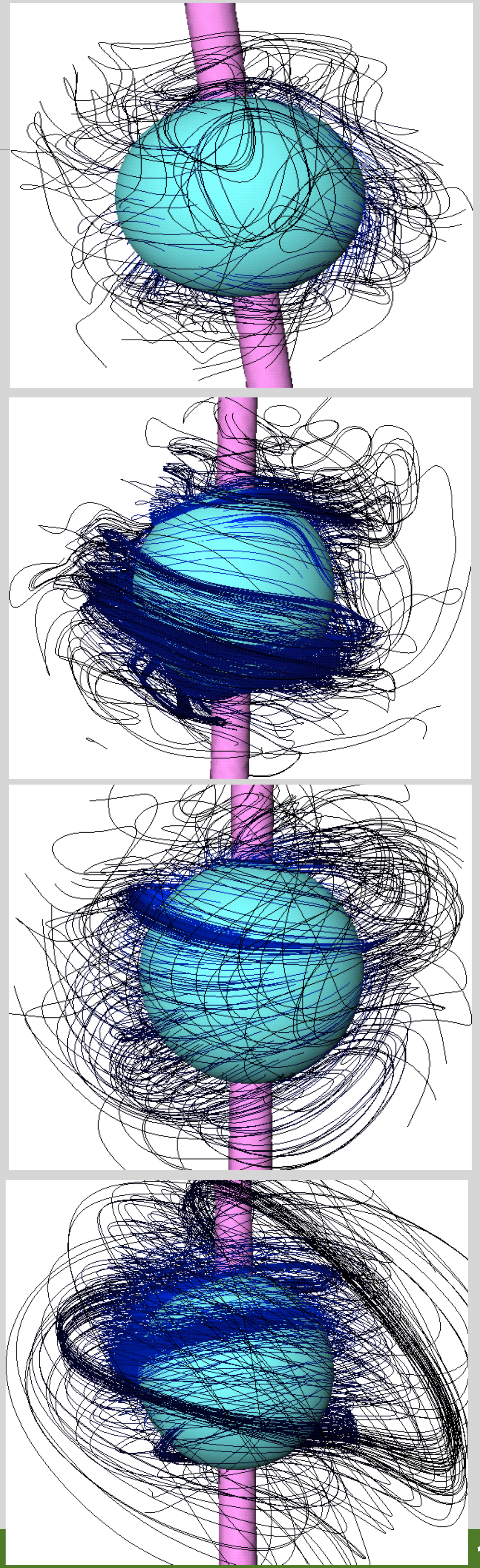


NS crust forms at ~100 s after SN

Relaxation time scales

- **Turbulent B-fields would be relaxed to some equilibrium configuration** (Braithwaite & Cantiello 2013)
  - $t_{equil} \sim t_{Alfven}^2/P \sim 10\ \mathrm{s}\ (B_{equil}/10^{15}\mathrm{G})^{-2}(P/1\mathrm{ms})^{-1}$

	B (G)	P (ms)	t_{equil}
magnetar	10^{15}	10^{3}	0.01 s
ms-magnetar	10^{15}	1	10 s
pulsar	10^{12}	30	3 days
CCO	10^{10}	300	1000 years



Braithwaite & Nordlund (2006)

Summary

* **Origin of dichotomy of magnetic fields in neutron stars remains puzzling**
* **An idea**
  * Magnetars have strong magnetic fields, sustained by ***internal currents originating from dynamos***
  * Radio pulsars have weaker magnetic fields, which are ***remnant fields embedded in the neutron-star crust***

* **Impacts of crust formation**
  * Two different timescales, *crust formation* and *relaxation of turbulent motion*
  * If crust forms earlier than relaxation → *radio pulsars*
  * If crust forms later than relaxation → *magnetars*