NS 1987A: A New Probe of Crustal Superfluidity with Lynx

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Dohi et al. 2023 ApJ 949 97

Dohi et al. under review

N3AS Annual Meeting @ UC Berkeley

NS 1987A and Possible Detection by Lynx

Dohi et al. 2023 ApJ 949 97

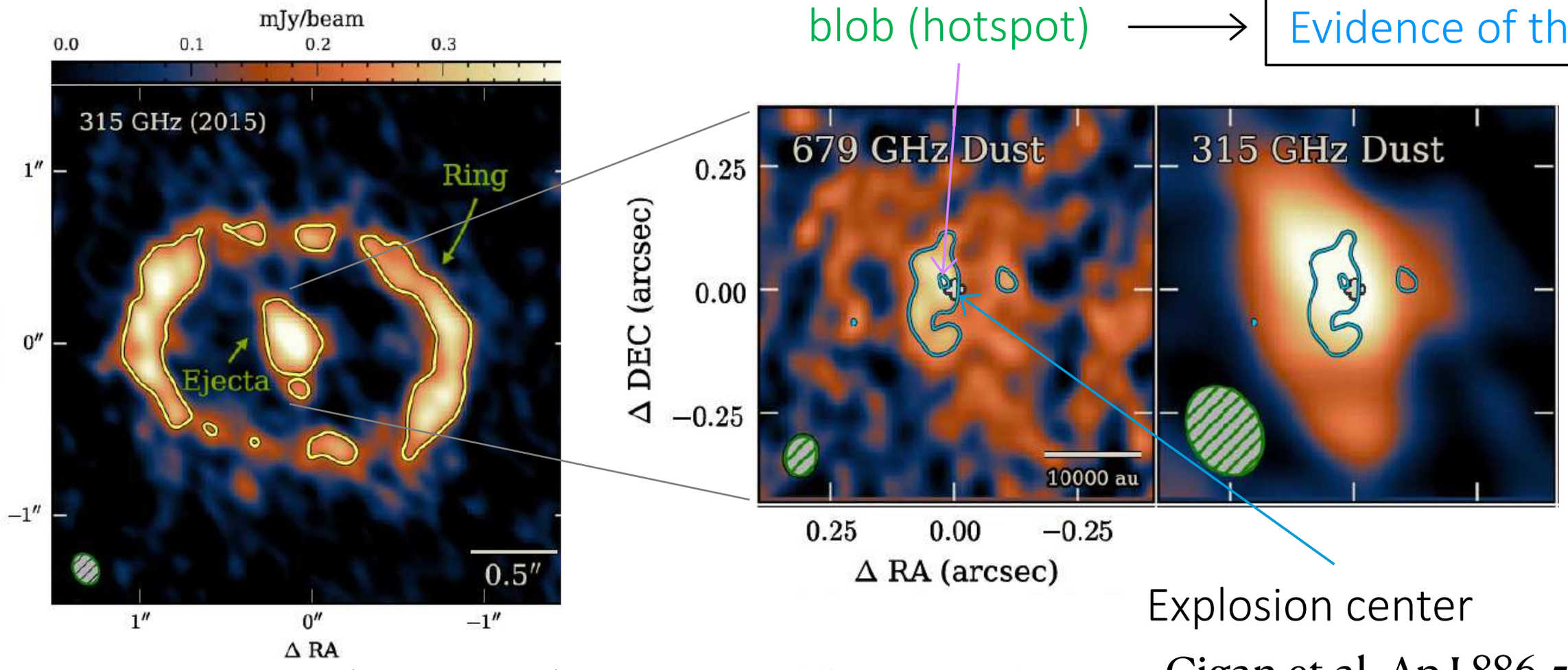
SN 1987A

https://public.nrao.edu/news/alma-finds-possible-sign-of-neutron-star-in-supernova-1987a/

- The CCO is believed to be a neutron star (what we called “NS 1987A”) from several observations such as SN ν detection, SN light curves.

First Direct Evidence of NS 1987A ?!
Blob in SN 1987A observed by ALMA

blob (hotspot) ⟶ Evidence of the NS?



Explosion center

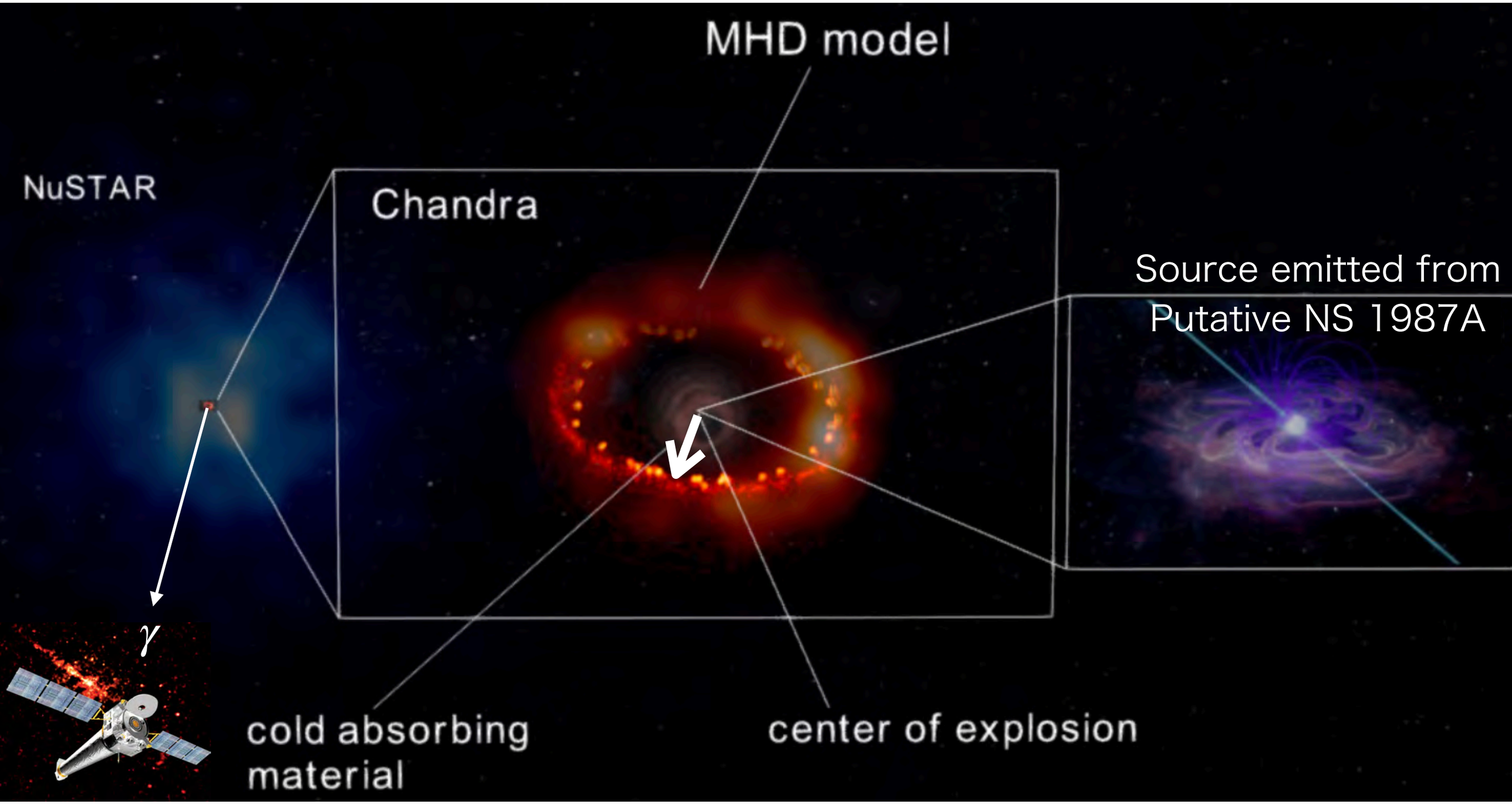
Cigan et al. ApJ 886 51 (2019)

Page et al. ApJ 898 125 (2020)

- Luminosity: $(26-90)\,L_\odot \sim 10^{35}$ erg s^{-1}
- The powerful origin of the blob is (See also Fransson et al. 2024 for JWST obs.)
  - Non-thermal emission due to pulsar spin-down (PWN87A scenario)

    Greco+AD et al. 2021 ApJ 908 L45; 2022 ApJ 931 132
  - Thermal emission (NS87A scenario) AD et al. 2023 ApJ 949 97

Image of X-ray detection



https://airandspace.si.edu/multimedia-gallery/nasa-photohjpg
(©Smithsonian Instituion)

https://skfb.ly/6XZIU (© S. Orlando)

Next-generation X-ray astronomy satellite: Lynx

- Chandra: X-ray satellites with the highest spatial resolution now
- Lynx: High-resolution X-ray satellites which will be launched in 2036 at the earliest.
- The difference between Chandra and Lynx is the number of mirrors, which increase the effective area.

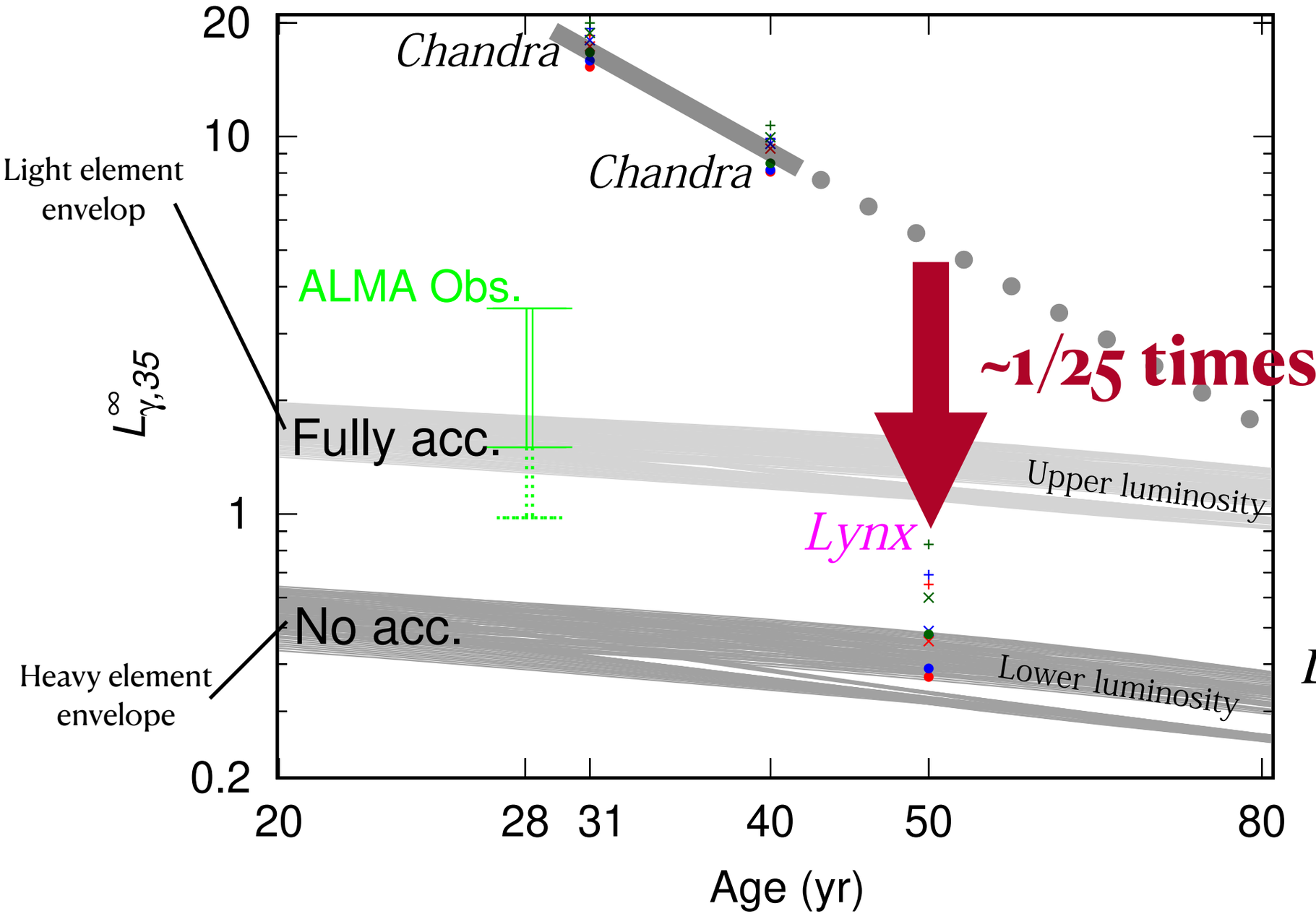
	Effective area @ 1 keV, 6 keV	On-axis angular resolution (HPD)	Off-axis angular resolution @ 10' radius (HPD)
Lynx - design reference mission Silicon meta-shell	2 m^2, 0.2 m^2	0.5"	~1"
Chandra Direct fabricated, full-shell zerodur	0.08 m^2, 0.03 m^2	0.5"	~8"

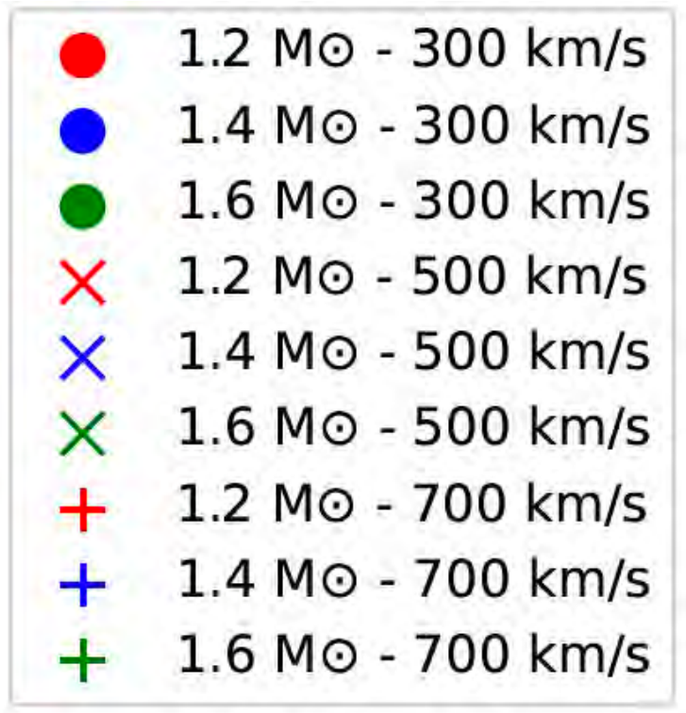
25 times !!

(Gaskin et al 2019, JATIS 5, 021001)

(Taken from NASA's homepage)

Possible Detection of NS 1987A by Lynx

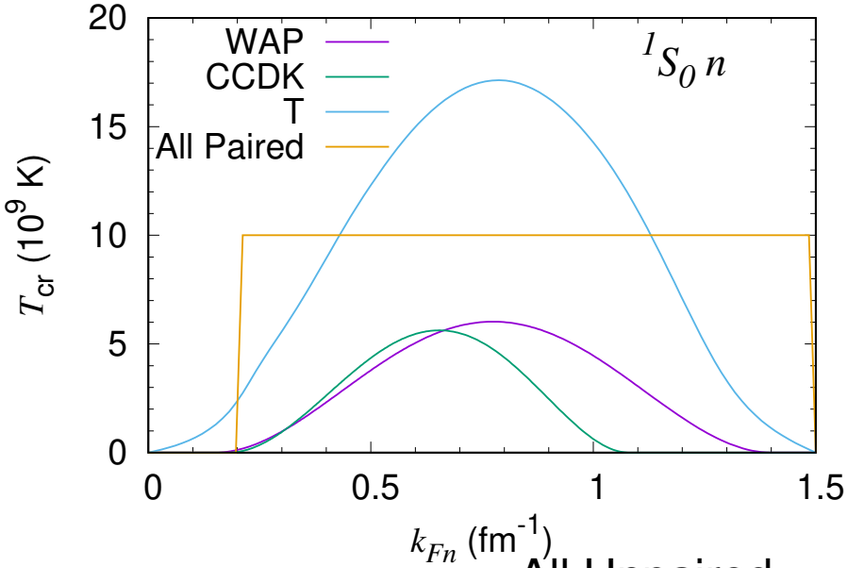


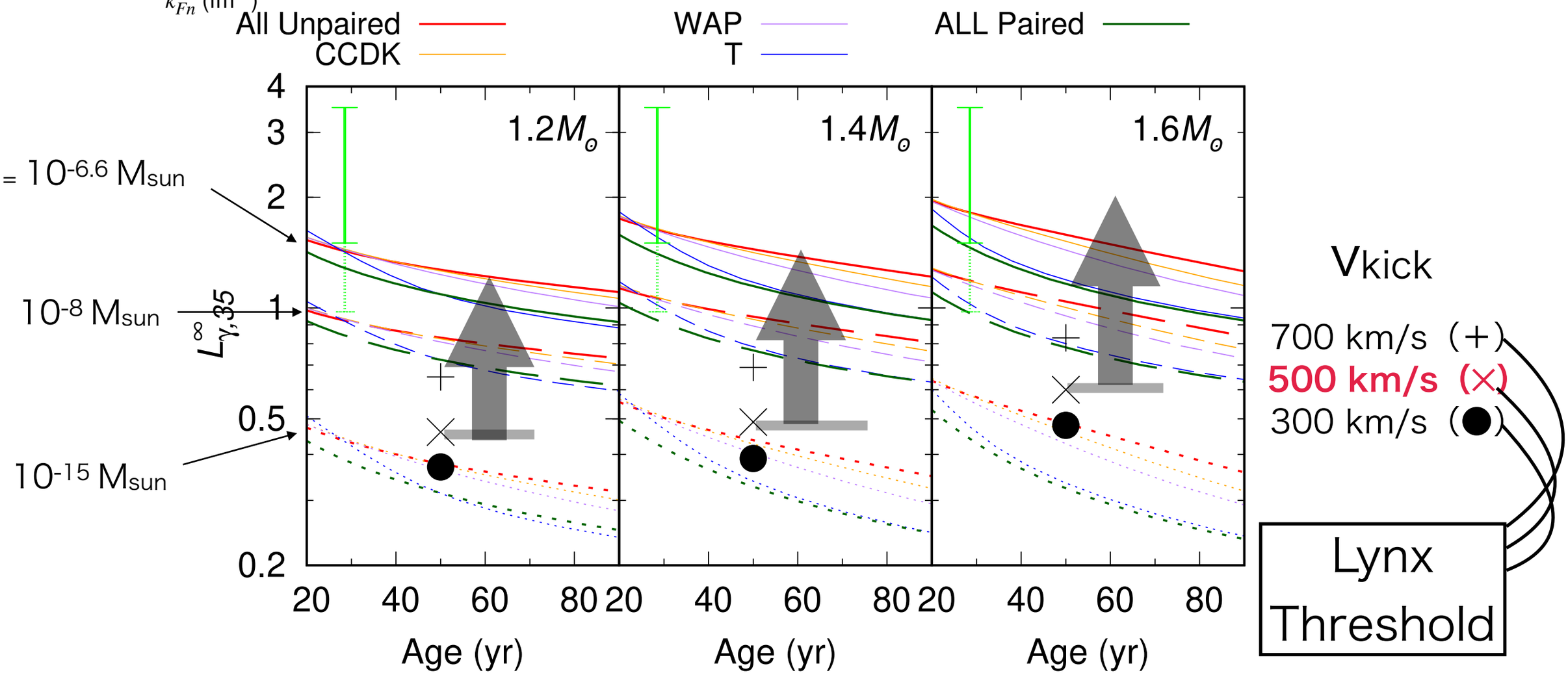


$L^{\infty}_{\gamma,35}$: Redshifted luminosity
In units of 10^{35} erg/s

In t = 50 yr (2037), the luminosity is comparable with Lynx sensitivity limit → Possible detection of NS 1987A by Lynx

Detection Scenario for NS 1987A by Lynx





- Heavy envelope, i.e., many light elements the NS 1987A is favored. Similar constraints of ALMA obs.

When is the NS 1987A found by Lynx ?

Dohi et al. under review in ApJ

Extension of Dohi et al. 2023

- Dohi+2023 discussed the non-detection/detection at $t = 50$ yr, but people must have an interest of **when the NS 1987A is detected**.
- Qualitatively, if time goes, detection should be realized because:

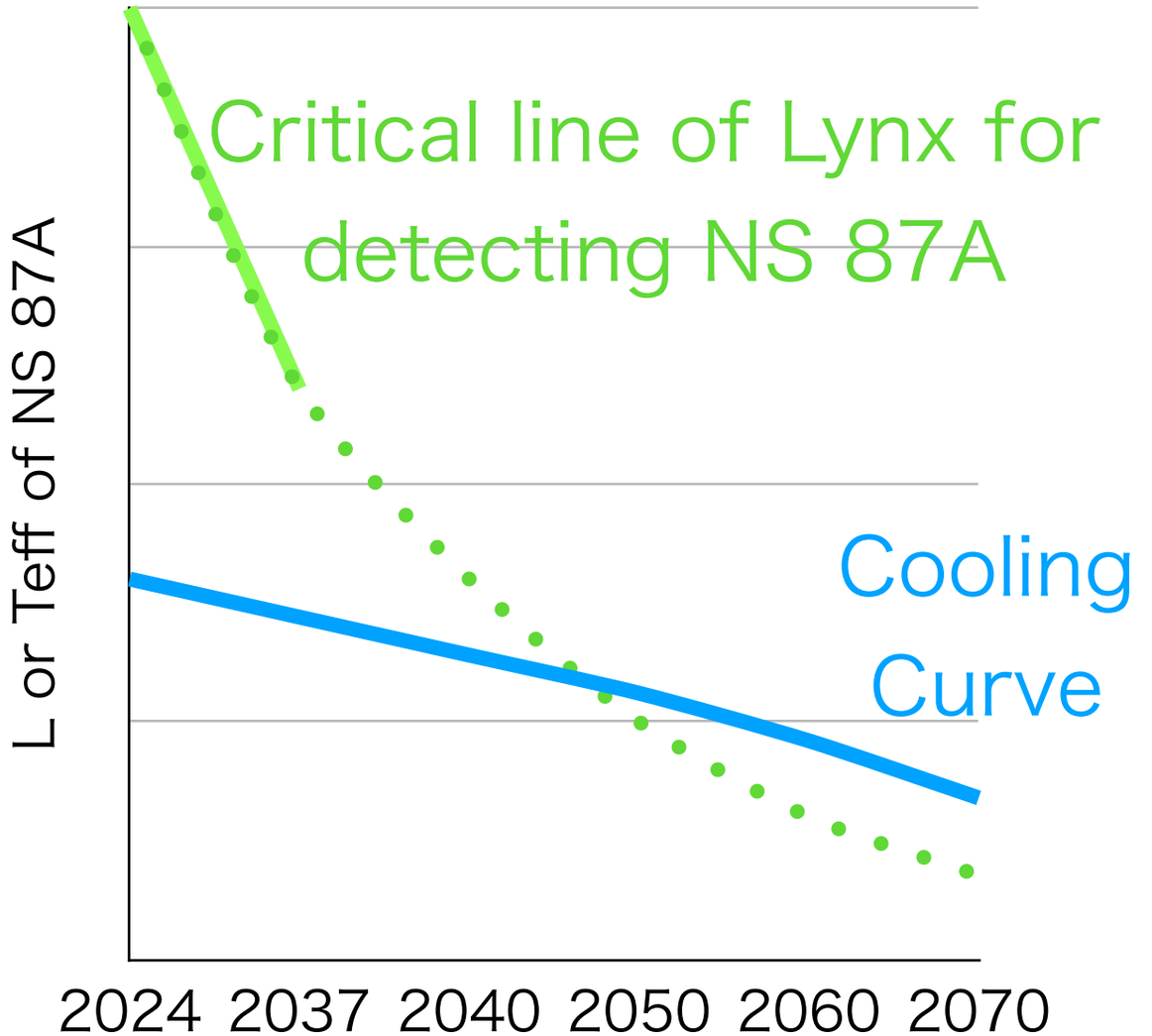
1. ejecta becomes sparse ($\rho_{\rm ejecta} \propto t^{-3} \Leftrightarrow L_{\rm Lynx} \propto t^{-3}$)

2. ν cooling results in $L_\gamma \propto t^{-\alpha}$ with

$\alpha = 1/3 - 1/2$ (Page+04) $<< 3$

- Our strategy: Based on Lynx data in 2037, we make Lynx critical lines compared with various cooling models.

—> What physics do we know when NS 1987A is detected?



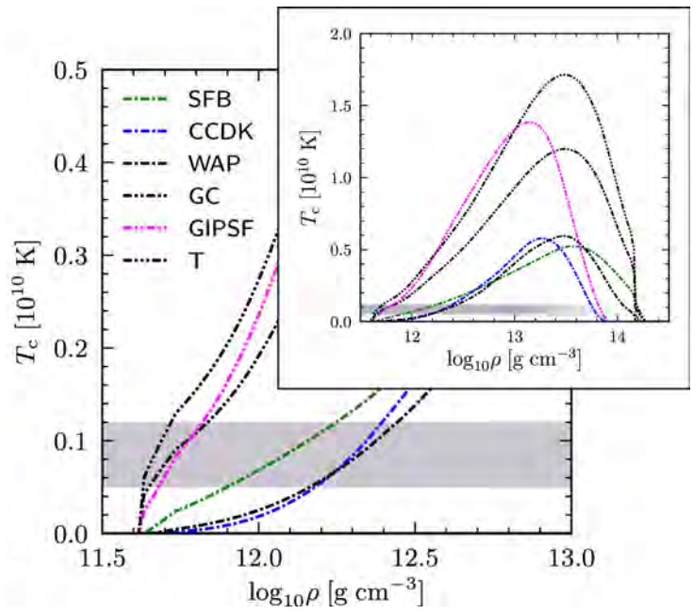
Physics that can be probed from NS 1987A

Potekhin, Chabrier, D.G. Yakovlev 1997 A&A 323 (1997) 415

1. Envelope mass $\eta = g_{s,14} M_{\rm env}/M_{\rm NS}$ $10^{-15} - 10^{-6.6}$

2. Crust Superfluidity (SF) ???

—> Taking same SF models of Page+20:



3. NS mass $M_{\rm NS}$ [$M_\odot$] 1.18-1.62

Utorbin et al 2019 A&A 624, 16

Ertl et al 2020 ApJ 890, 45

4. Core Physics ???

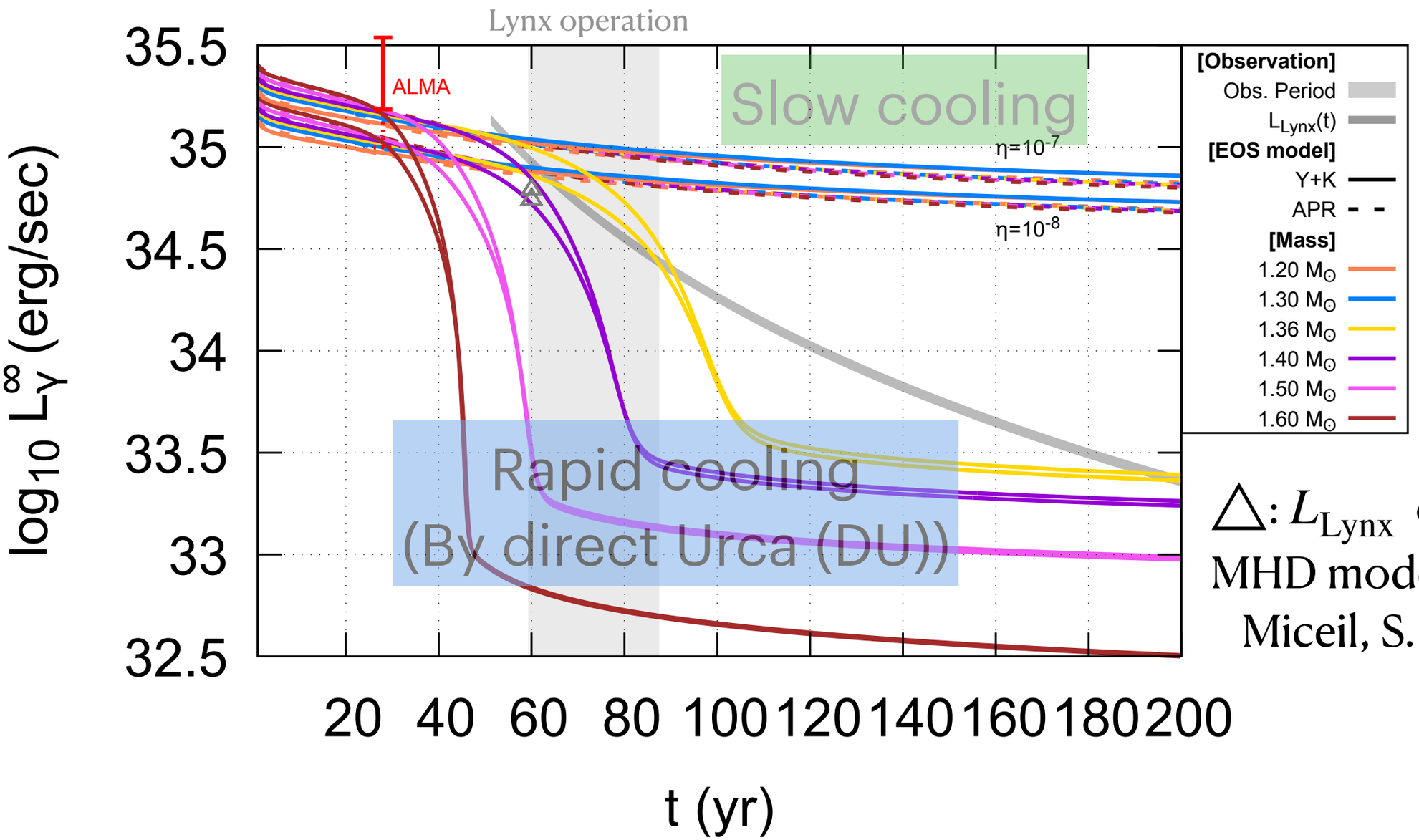
In particular, whether the direct Urca (DU) process occurs or not (i.e., $n \to p + e + \bar{\nu}_e$, $p + e \to n + \nu_e$ that occur for $Y_{p,\rm Center} \gtrsim 1/9$)

Boguta 1981, Lattimer et al. 1991

—> Taking APR, and Y+K EOS (Muto 2025 PRC 111, 045802), which have $M_{\rm DU}/M_\odot = 1.96$ and 1.31(possible).

Model dependence on the future detection of NS 87A

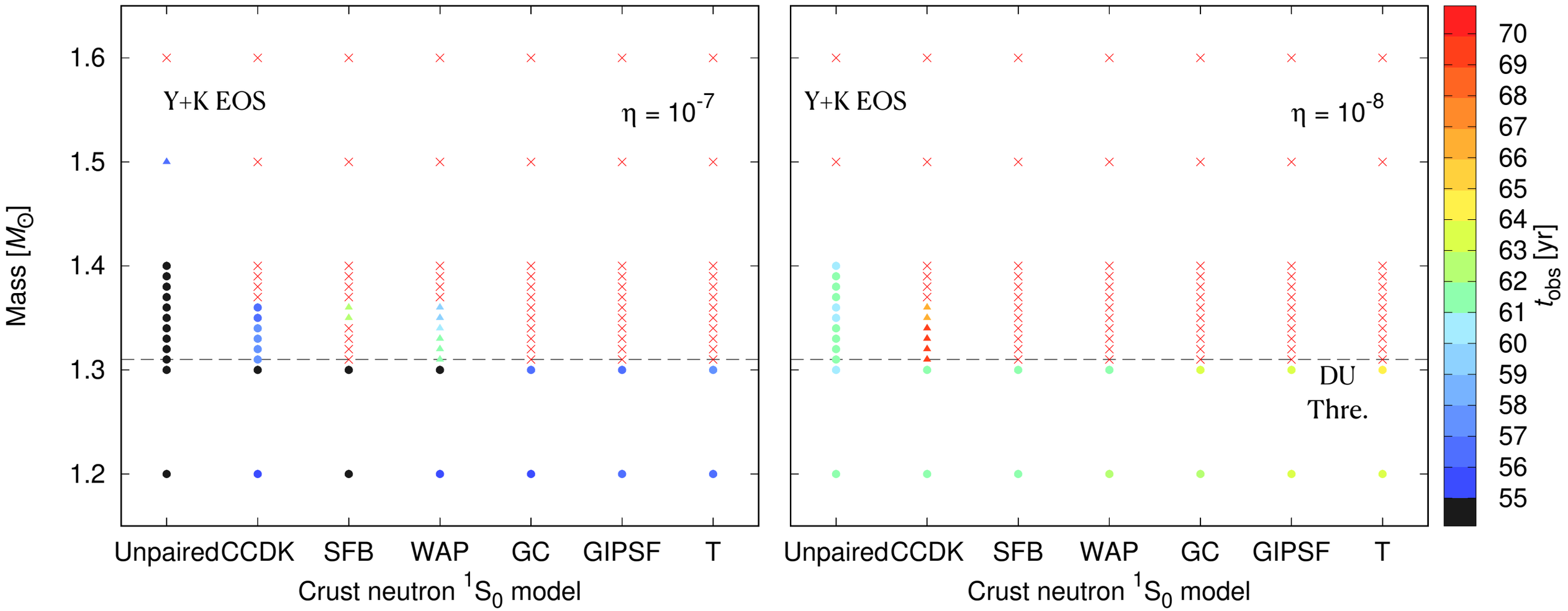
w/o superfluidity



△: $L_{\rm Lynx}$ obtained from 3D MHD model by E. Greco, M. Miceil, S. Orlando (INAF)

- Slow cooling case : $t_{\rm obs} \lesssim 60$ yr, fast cooling case: more pessimistic

Impact of DU/crust SF on detectable age



* Note that in APR case, all model show detection, so not shown.

● detection

▲ shooting star

× non-detection

Uniqueness of NS 87A as a probe of crust

- Effective cooling timescale (Lattimer+94)

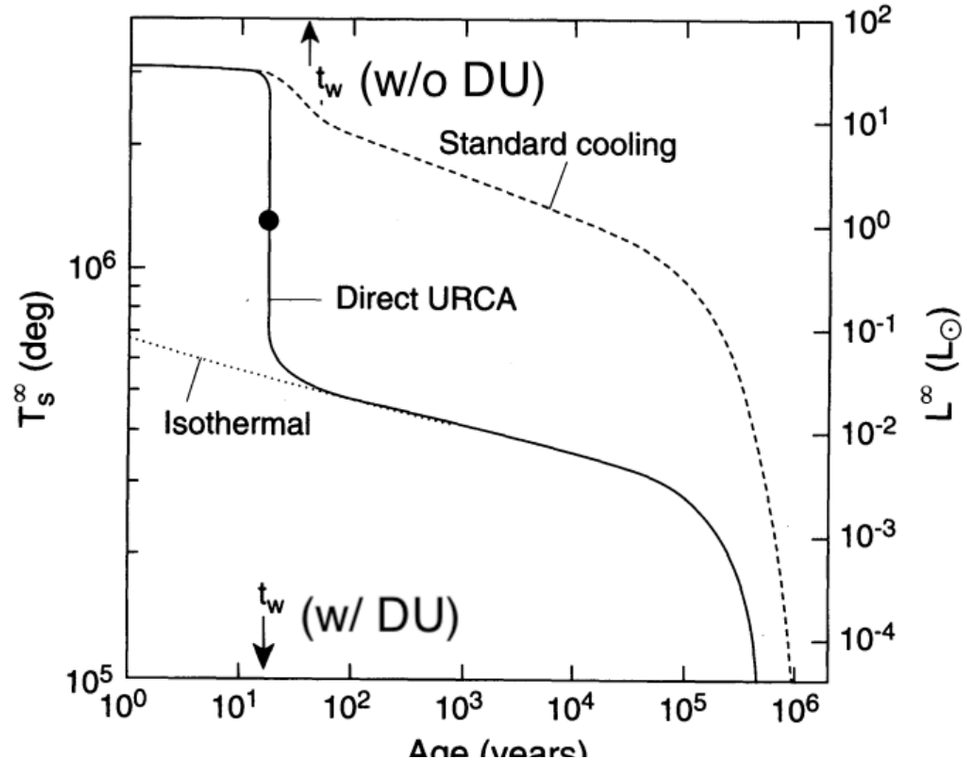
$$t_w \equiv t \ \text{for max} \left| \frac{d \ln(L_\gamma)}{d \ln(t)} \right|$$

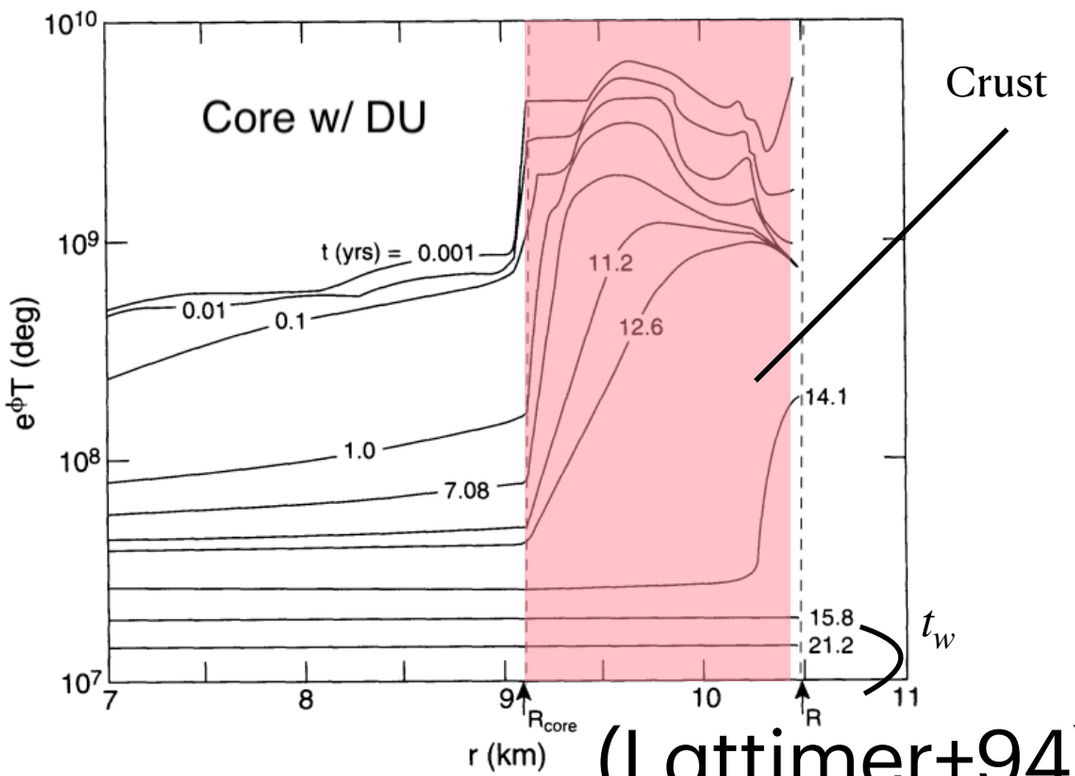
- NS87A may Not be isothermal due to its youth, which is a unique.

- When NS 87A is detected at $t = t_{\rm obs}$:

For $t_{\rm obs} \gtrsim t_w$, NS87A is isothermal, and could be a probe to NS core.

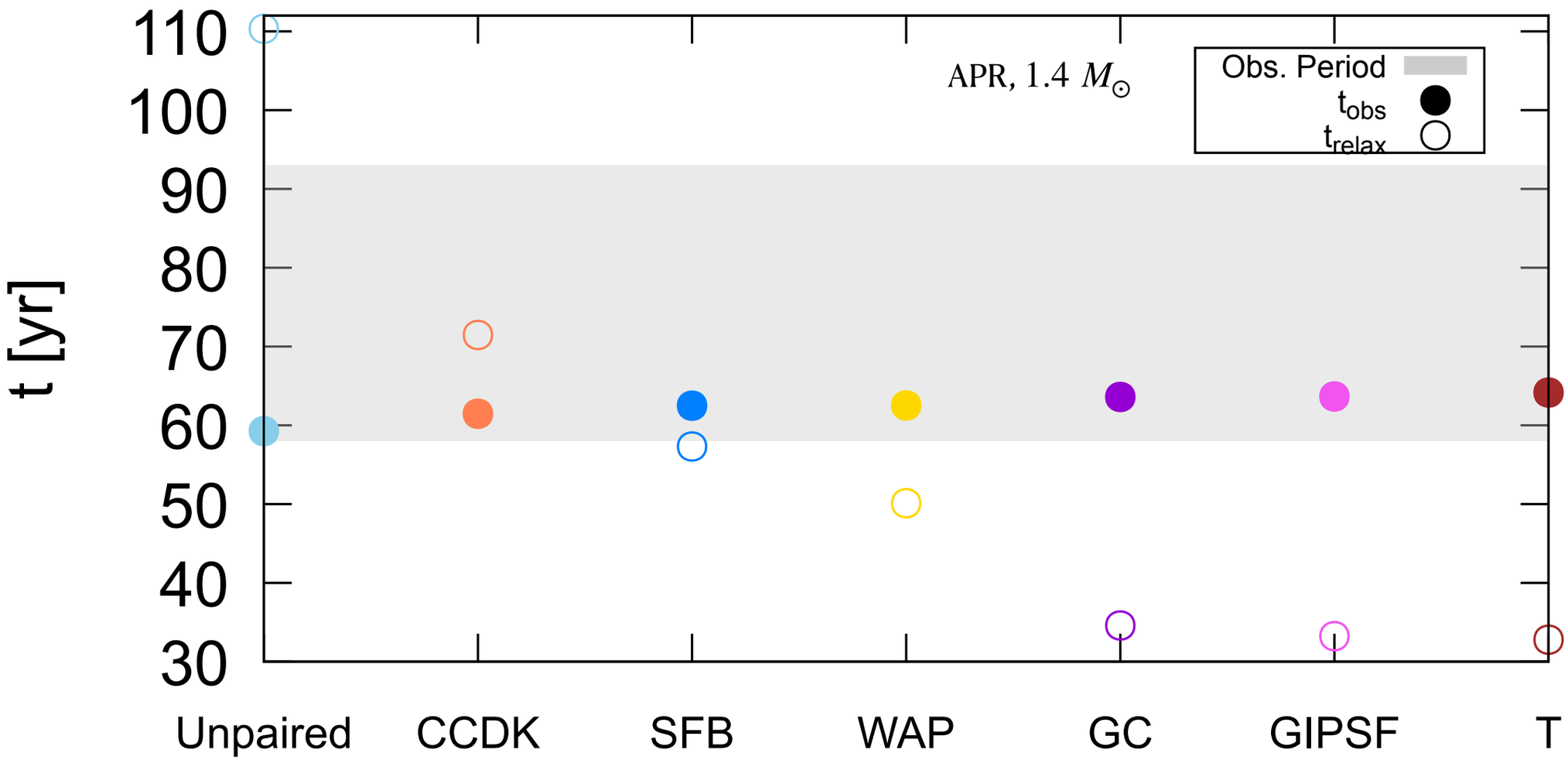
For $t_{\rm obs} < t_w$, crust is hotter than core, which enables us to probe the crust.





(Lattimer+94)

$t_{\rm obs}$ v.s. $t_{\rm relax}$: Crust SF model Dept.



Weaker ← Crust neutron $^1S_0$ model → Stronger

$t_{\rm obs}$: Almost $\sim$ 60 yr

$t_{\rm relax}$: Smaller with stronger crust SF

—> **NS 87A could be a unique probe to crust with weak neutron SF!**

Conclusion

Conclusion

- ALMA/JWST observations indicate heating source associated with NS 1987A, which can be detected by high-resolution X-ray satellite such as Lynx.

- When the NS1987A is detected depends on neutron-star physics, such as superfluidity and rapid cooling.

- Rapid cooling: making detection impossible, depending on core superfluid models.

- If crust superfluidity is weak, NS 87A is a probe for crust physics. Otherwise, it is a probe for core.

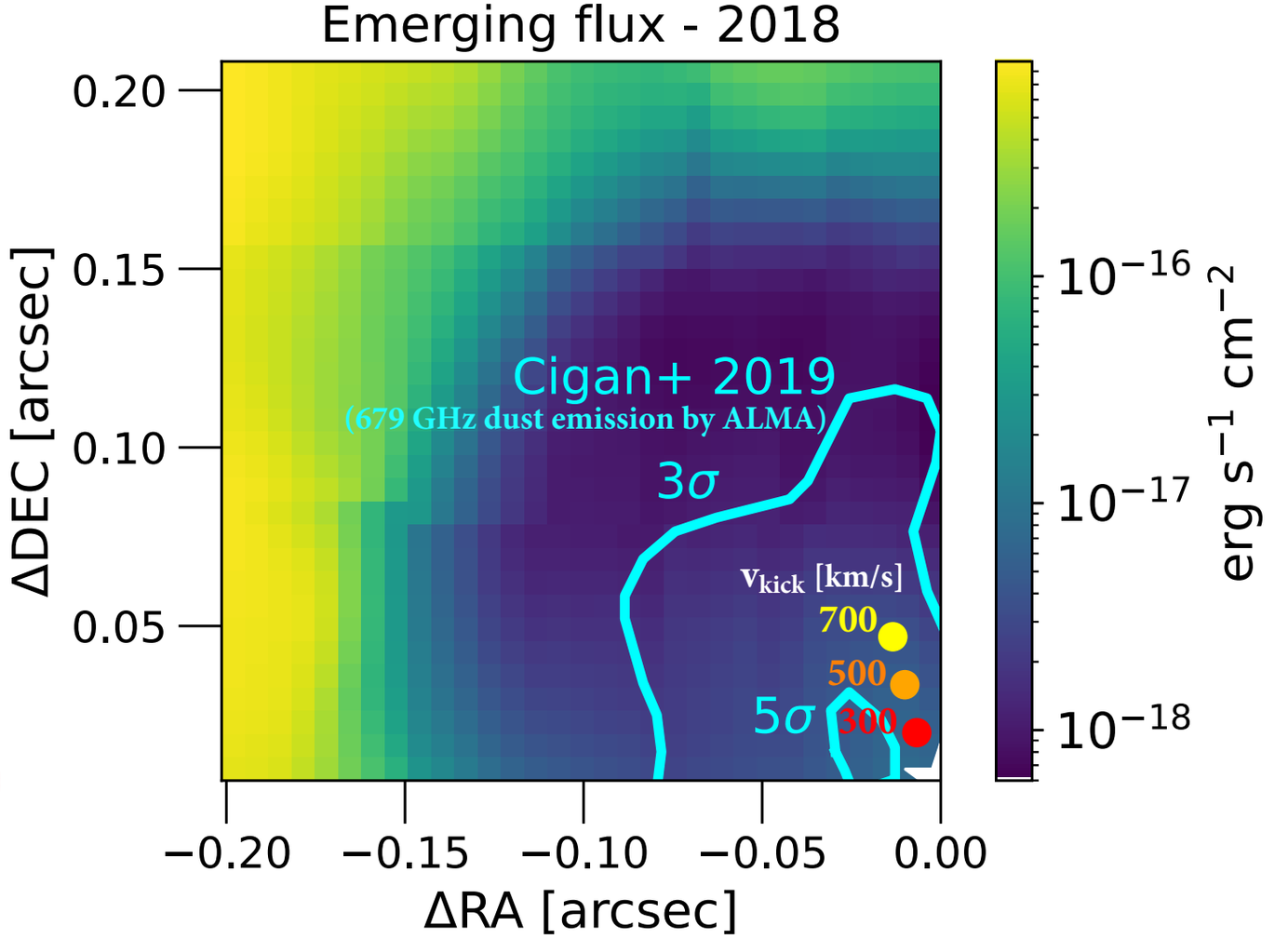
Standard Model of SN 1987A + Black-Body (BB)

- Standard Model + BB components, which are affected by the absorption of ejecta

→ 3DMHD Model for 87A up to 50 yrs

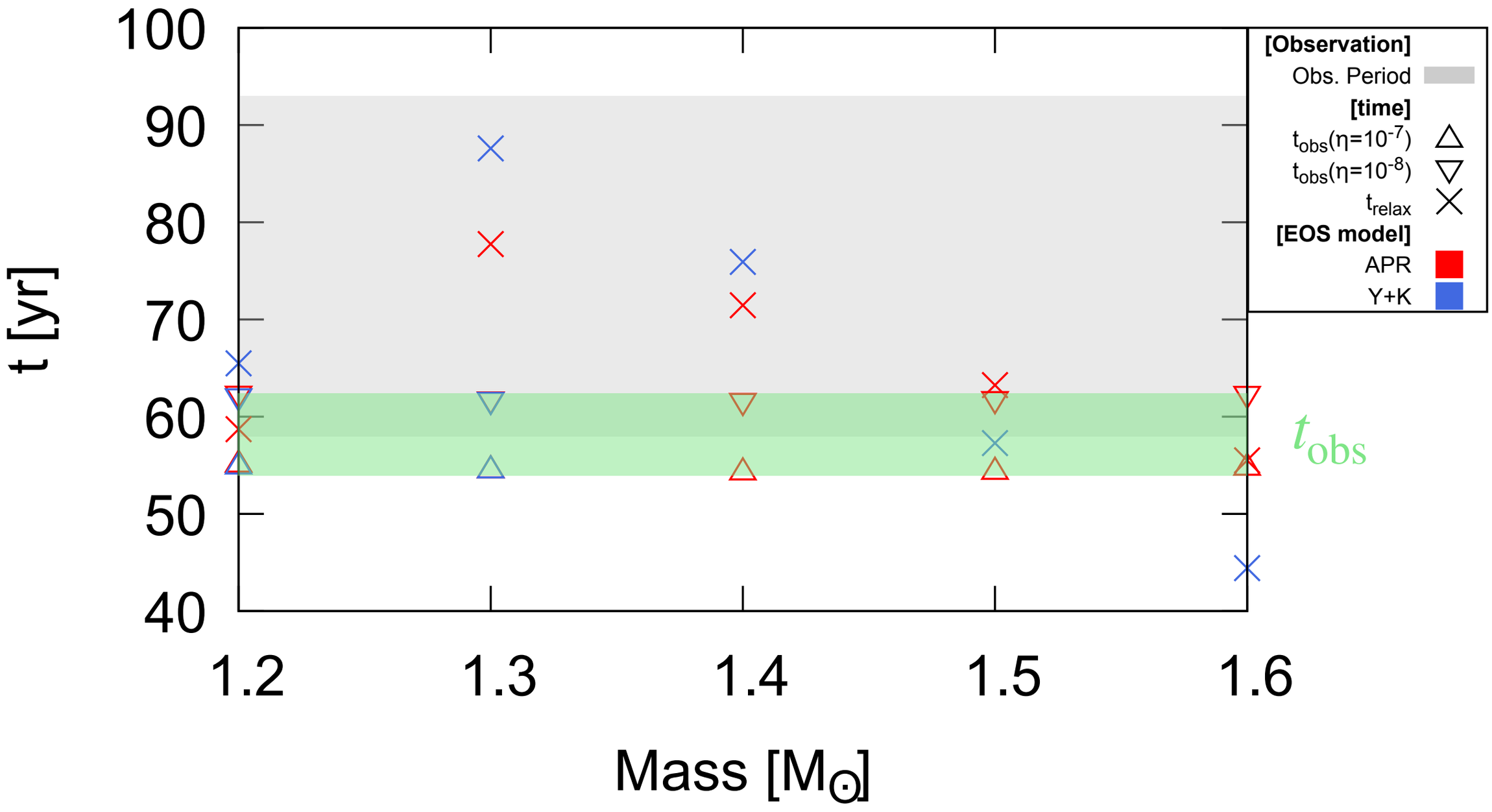
Orlando et al. 2020 A&A 636 A22

- The position of CCO is consistent with ALMA obs. (Cigan+19)
- Thermal X-ray radiation is more absorbed for higher kick velocity ($v_{\rm kick}$)



$t_{\rm obs}$ v.s. $t_{\rm relax}$: EOS and mass Dept.

Neutron SF model: CCDK



- In most case, $t_{\rm obs} < t_{\rm relax}$: The only core physics can be probed.
- $M_{\rm NS} > 1.3\ M_\odot$ with Y+K EOS: At least $t_{\rm obs} > 100$ yr (non-detection)