On the Thermal Emission Scenario to Find NS 1987A by Lynx

Akira Dohi（RIKEN ABBL/iTHEMS）

ApJ 949 97 (2023)

Collaborators

E Greco(GRAPPA), S. Nagataki（RIKEN/OIST）, M. Ono（Academia Sinica）

M. Miceil (INAF), S. Orlando (INAF), B. Olmi (INAF)

Joint RIKEN/N3AS Workshop on Multi-Messenger Astrophysics, 2023/11/26

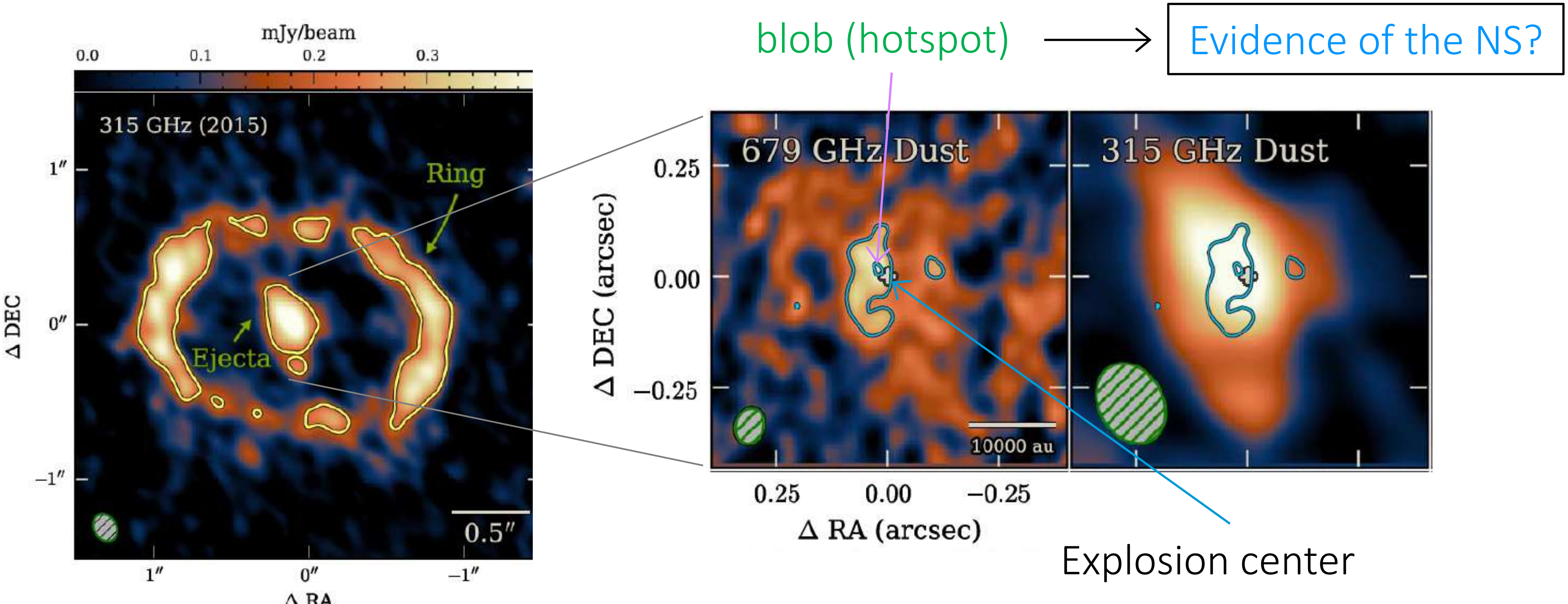
Possibility of NS 1987A

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

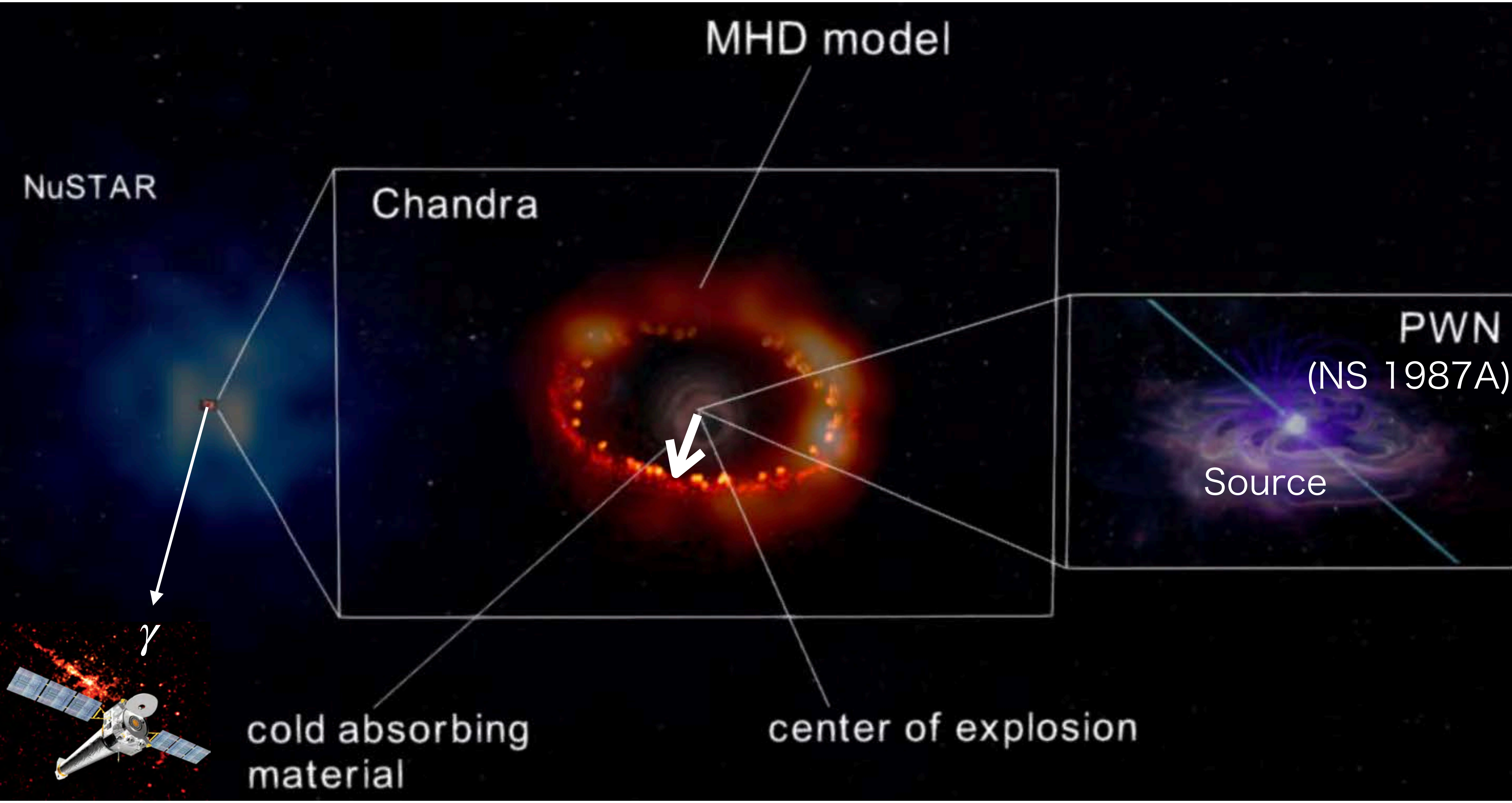


Cigan et al. ApJ 886 51 (2019)
Page et al. ApJ 898 125 (2020)

- Luminosity: $L_{\mathrm{bol,obs}} = (26 - 90)\, L_{\odot}$
- The powerful origin of the blob is
  - 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

PWN87A Scenario

Image for detecting radiation from NS 1987A



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

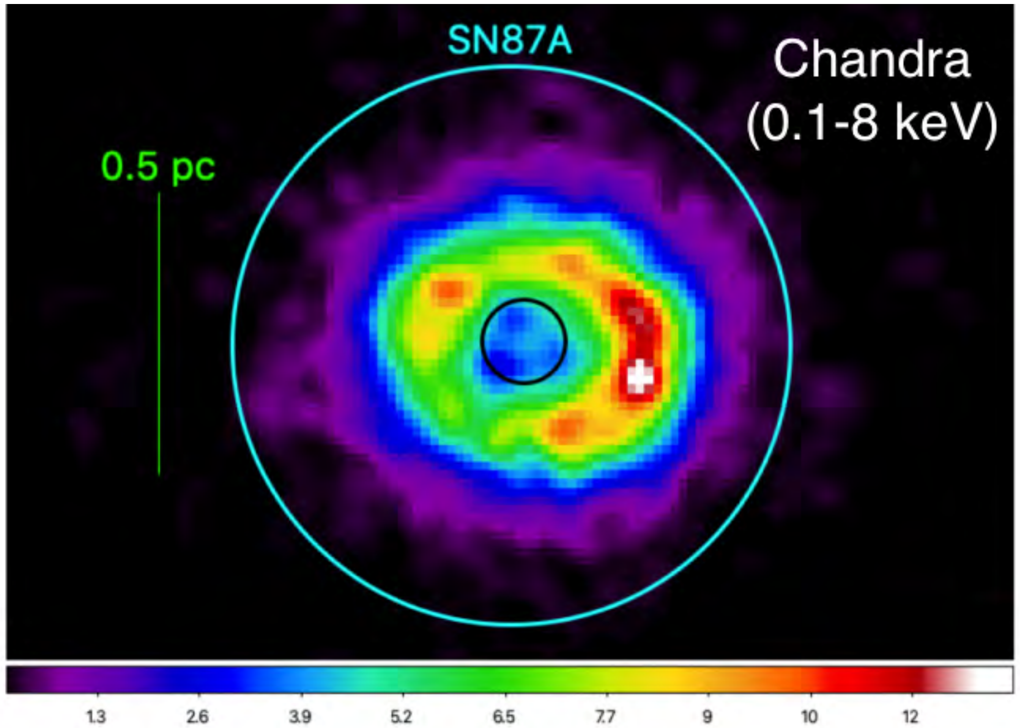
https://skfb.ly/6XZIU (© S. Orlando)

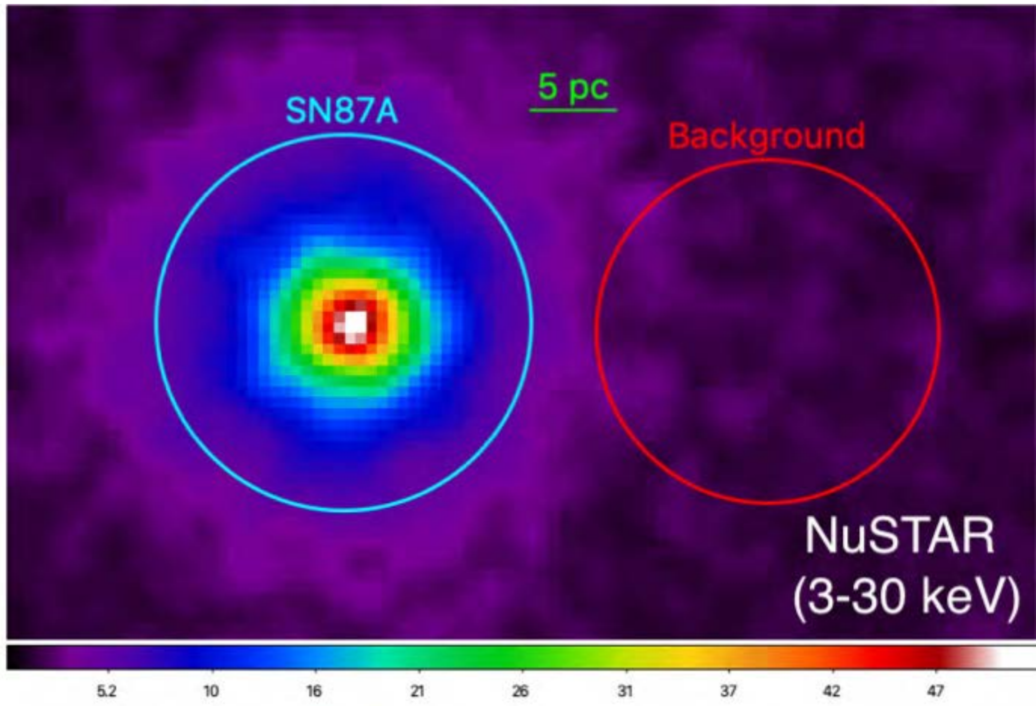
Standard Model of SNR 1987A + Power-Law (PL)

- Spectrum: Chandra ACIS-S, NuSTAR, XMM-Newton
- Standard Model：Interstellar absorption + two-component plasma
- We add a PL component as the non-thermal radiation.

To consider the absorption of ejecta, elements profiles are needed → 3DMHD Model for 87A

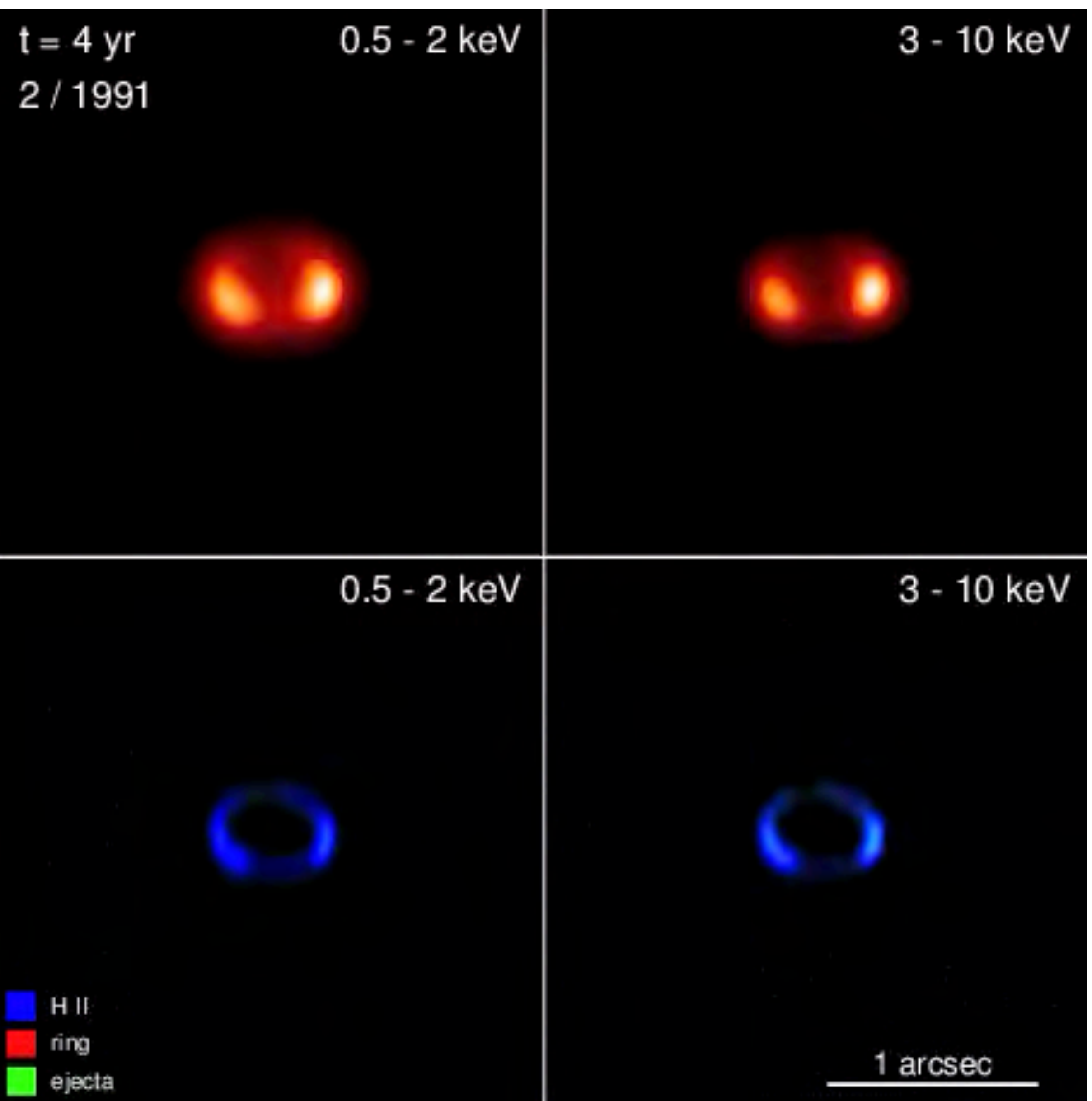
Orlando et al. 2020 A&A 636 A22

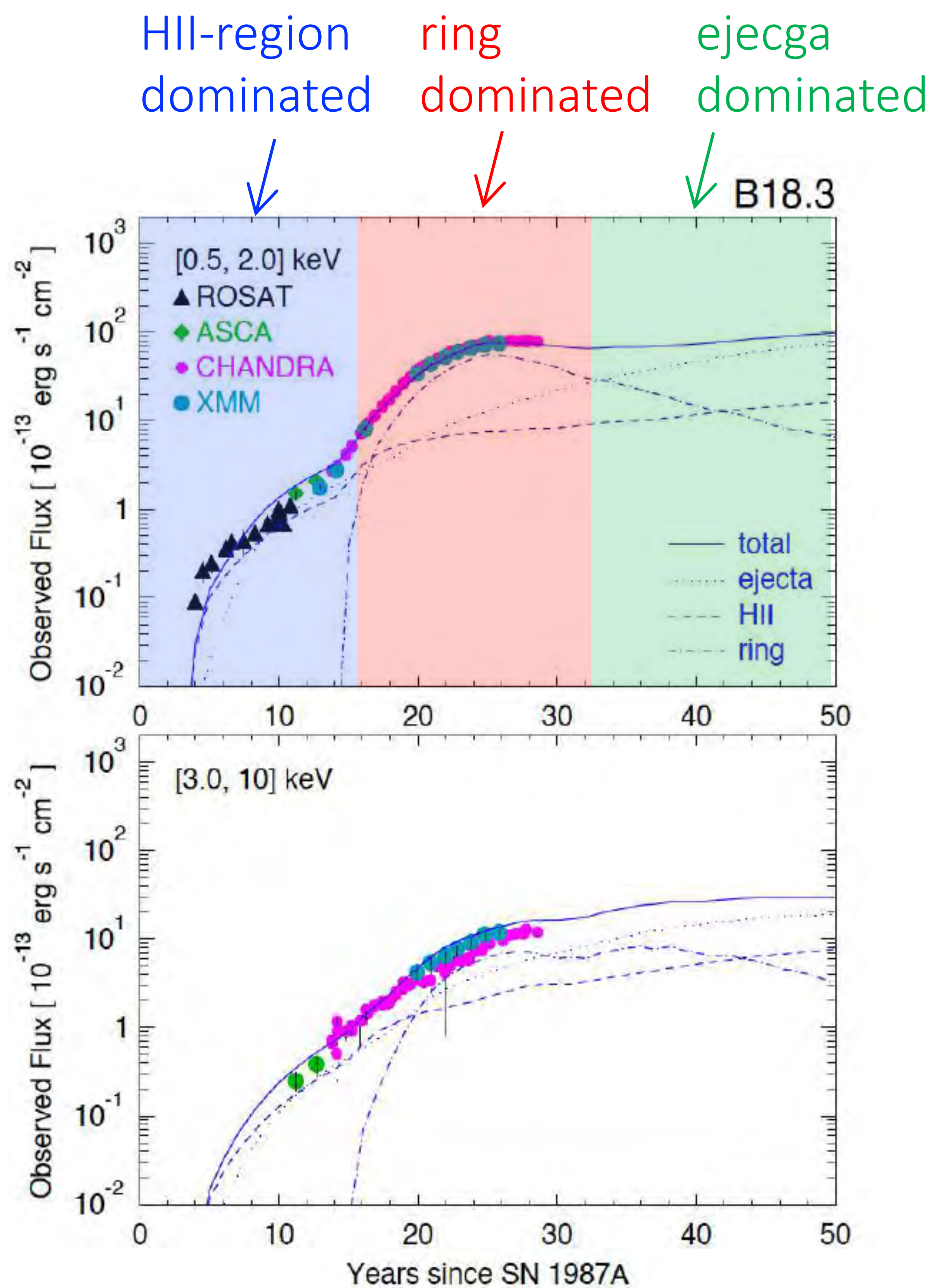




3D MHD Model of 87A up to 50 yrs
(Orlando et al., 2020, Ono et al., 2020)

- Binary merger progenitor model B18.3 ($14M_{\odot}$+$9M_{\odot}$, Urushibata+18)
- Consistent with SN 87A obs.





Spectral Fitting

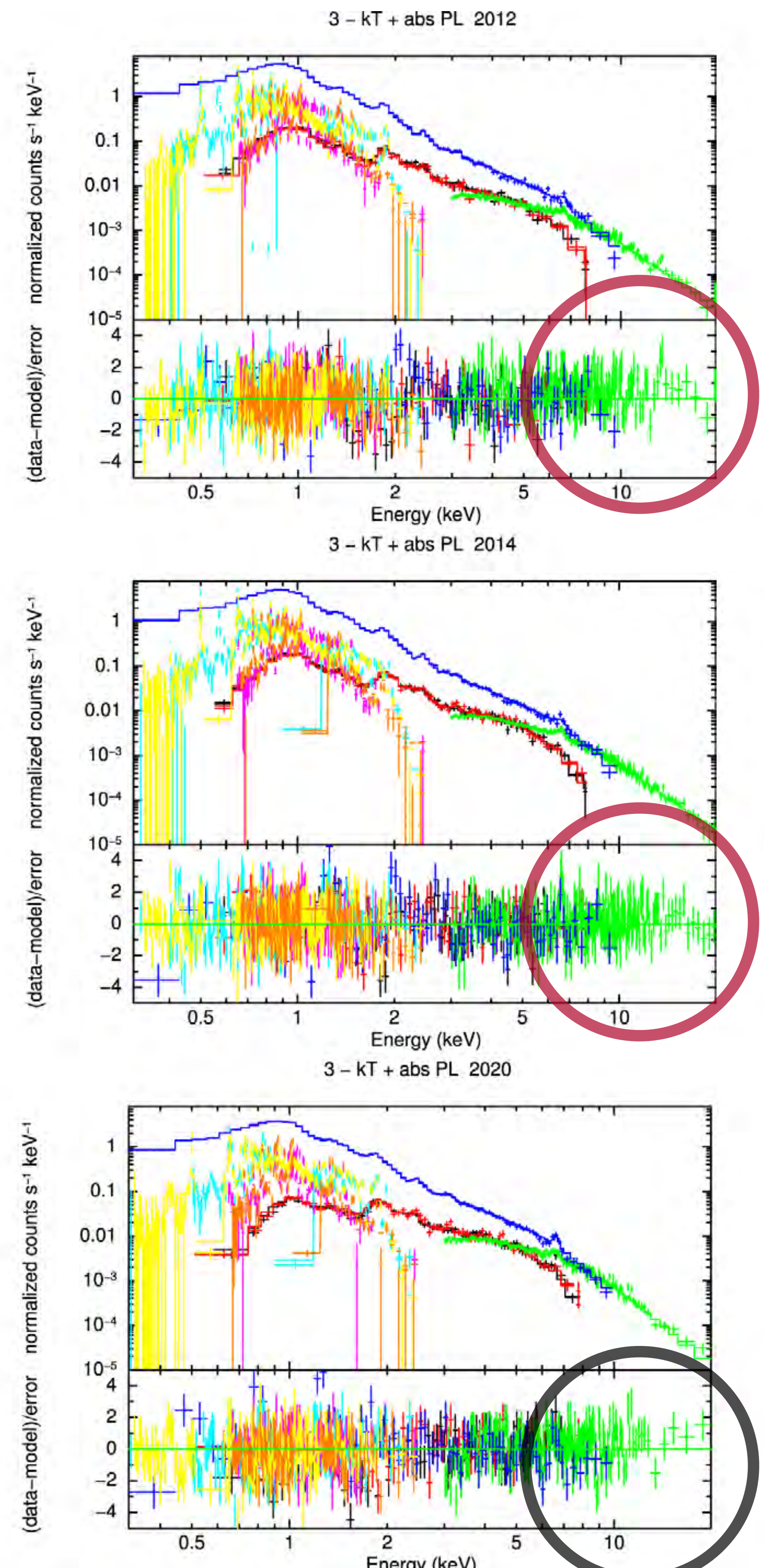
- Data：Chandra/ACIS-S, XMM-Newton/ pn, RGS, and NuSTAR/FPMA,B
- PL components can explain NuSTAR obs.
- In 2020, it seems to be consistent even without PL component. No distinct feature of PWN.

(See also Alp et al. 2021, 2022)

—>Assuming regular syncrotron radiation, it may not match with the sparseness of ejecta due to free expansion of SNR !?

—> Other scenarios with non-steady radiation such as thermal emission from NS 1987A?

w/o **PL comp.** (inc. MHD)



NS 87A Scenario

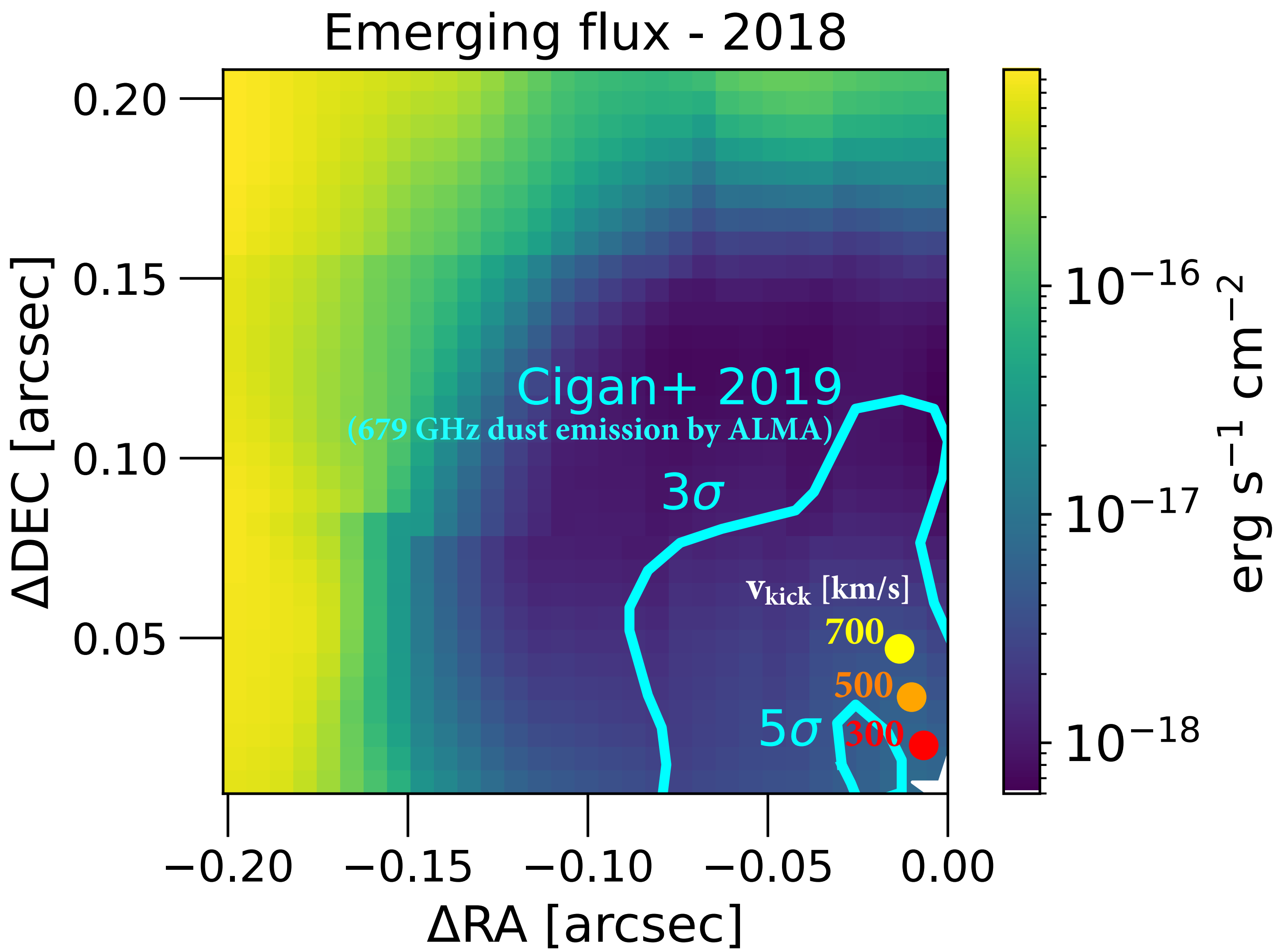
Standard Model of SN 1987A + Black-Body (BB)

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

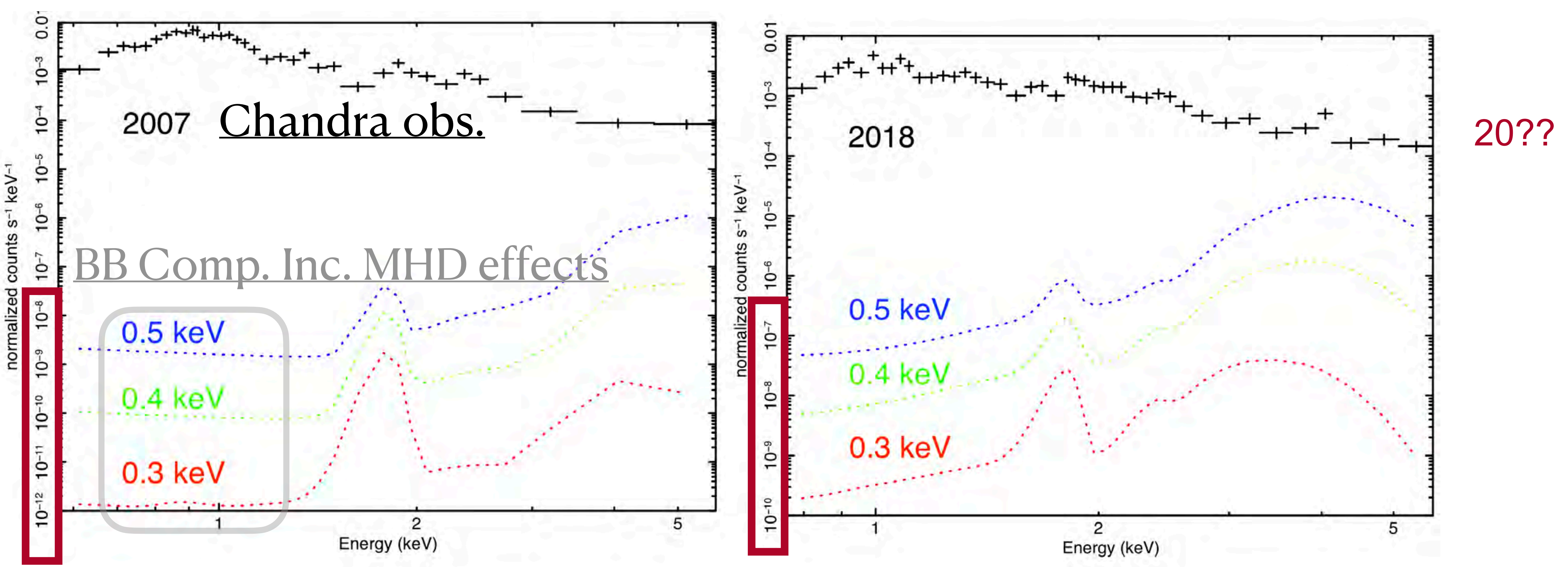
→ 3DMHD Model for 87A up to 50 yrs

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 ($v_{\rm kick}$)



The importance of sparseness of ejecta



- If time goes, BB components become active because the ejecta density is decreased ($\rho_{\rm ejecta} \propto t^{-3}$)

—> We may directly see thermal emission somedays (but still difficult to reach the flux observed by Chandra···).

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)

Setup for calculating X-ray Sensitivity Limits

- We calculate X-ray sensitivity limits to detect thermal emission from NS 1987A in 2018, 2027, and 2037, with use of 3D MHD ejecta profiles.
- Parameters for sensitivity limits:
  - Kick velocity $v_{\rm kick}$: 300, 500, 700km/s
  - Sensitivity of X-ray detectors: Chandra (-2027), Lynx (2037)
  - Gravitational Redshift $1+z=(1-2M_{\rm NS}/R_{\rm NS})^{-1/2}$: 1.2 - 1.3
  - Exposure time (2027,37): $t_{\rm exp}=1\ {\rm Ms}$

(see the case of $t_{\rm exp}=0.2\ {\rm Ms}$ in AD et al. 2023 ApJ 949 97)

- To check the validity, we need to compare the obtained sensitivity limits with theoretical models of NS luminosity.

Theory of 1D NS luminosity and Setup

- NS cools down mainly by the ν losses.

See e.g., Page et al. 2004 ApJS 155, 623

- To calculate the luminosity of isolated NSs with $t \sim O(10\ \mathrm{yr})$,

we utilize the public cooling code, NSCool

developed by Dany Page (1989, 2016)

Parameters of young NSs

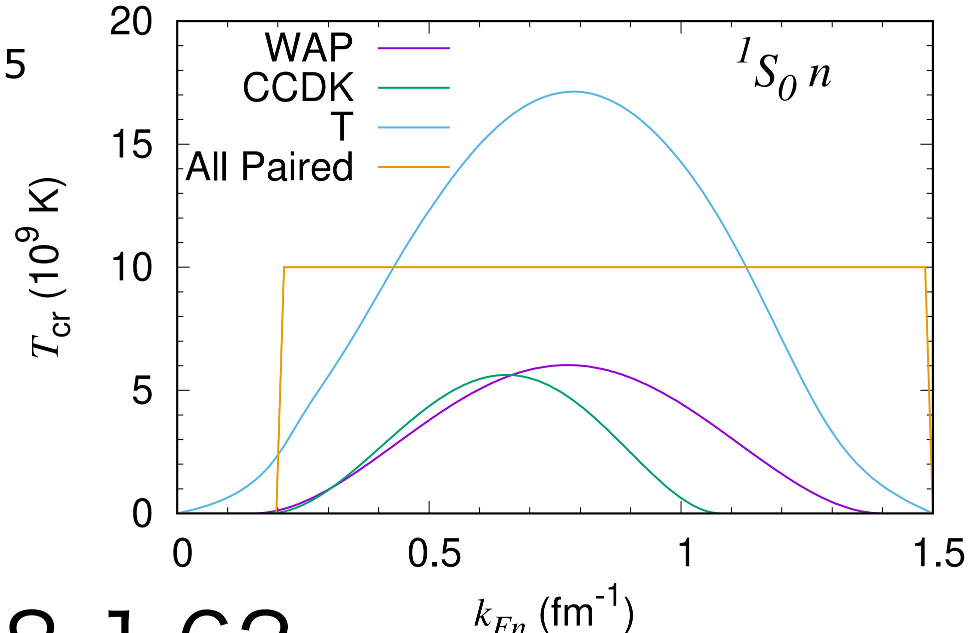
1. Envelope mass M_{env} / M_{NS} $10^{-15} - 10^{-6.6}$

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

2. Crust Superfluidity (SF)

w/o SF + four models

Based on Ho et al 2015, Phys. Rev. C 91, 015806



3. NS mass M_{NS} [M_{sun}] 1.18-1.62

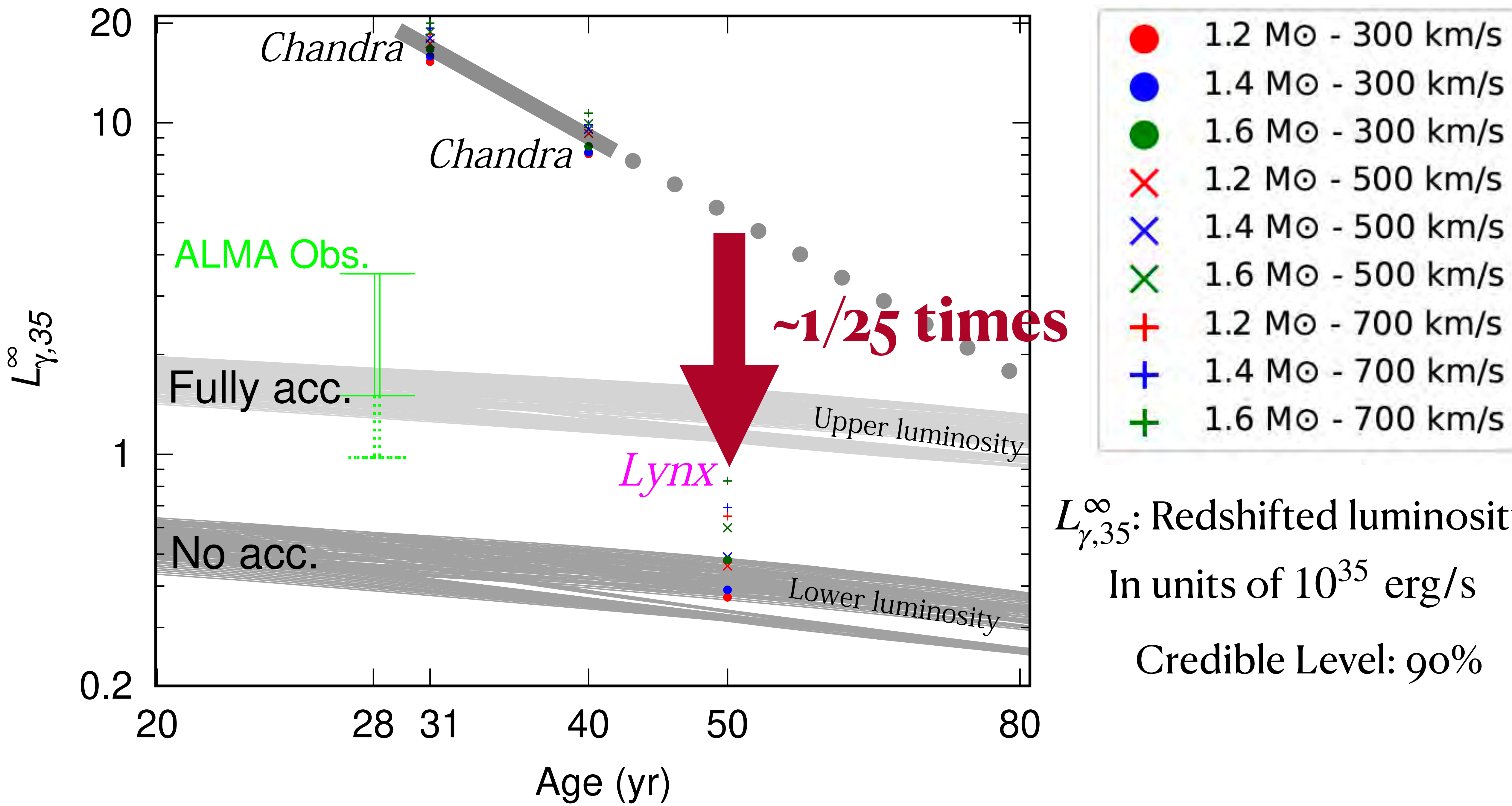
Utorbin et al 2019 A&A 624, 16
Ertl et al 2020 ApJ 890, 45

4. EOS APR (fixed)

Akmal, Pandharipande, Ravenhall 1998 Phys. Rev. C 58, 1804

NS 87A Scenario: Results

Possible Detection of NS 1987A by Lynx



$L^{\infty}_{\gamma,35}$: Redshifted luminosity

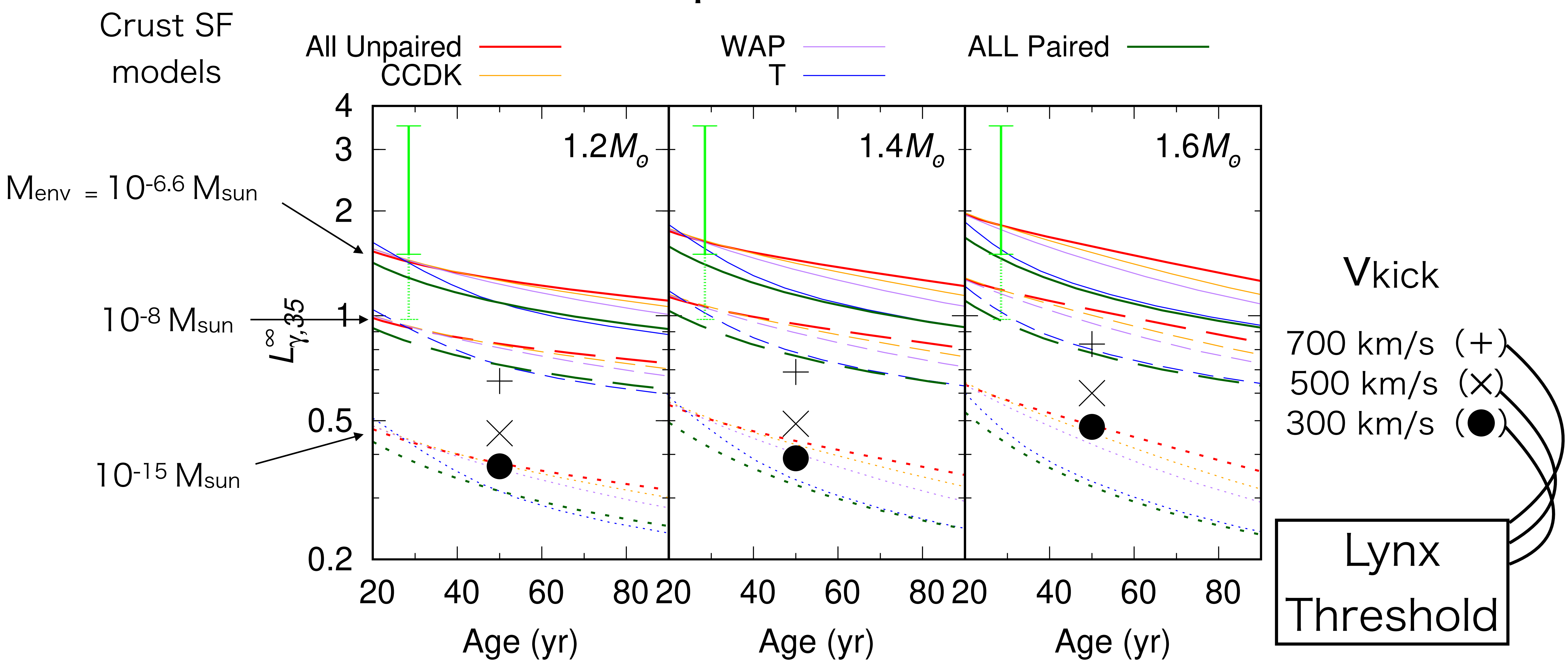
In units of 10^{35} erg/s

Credible Level: 90%

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

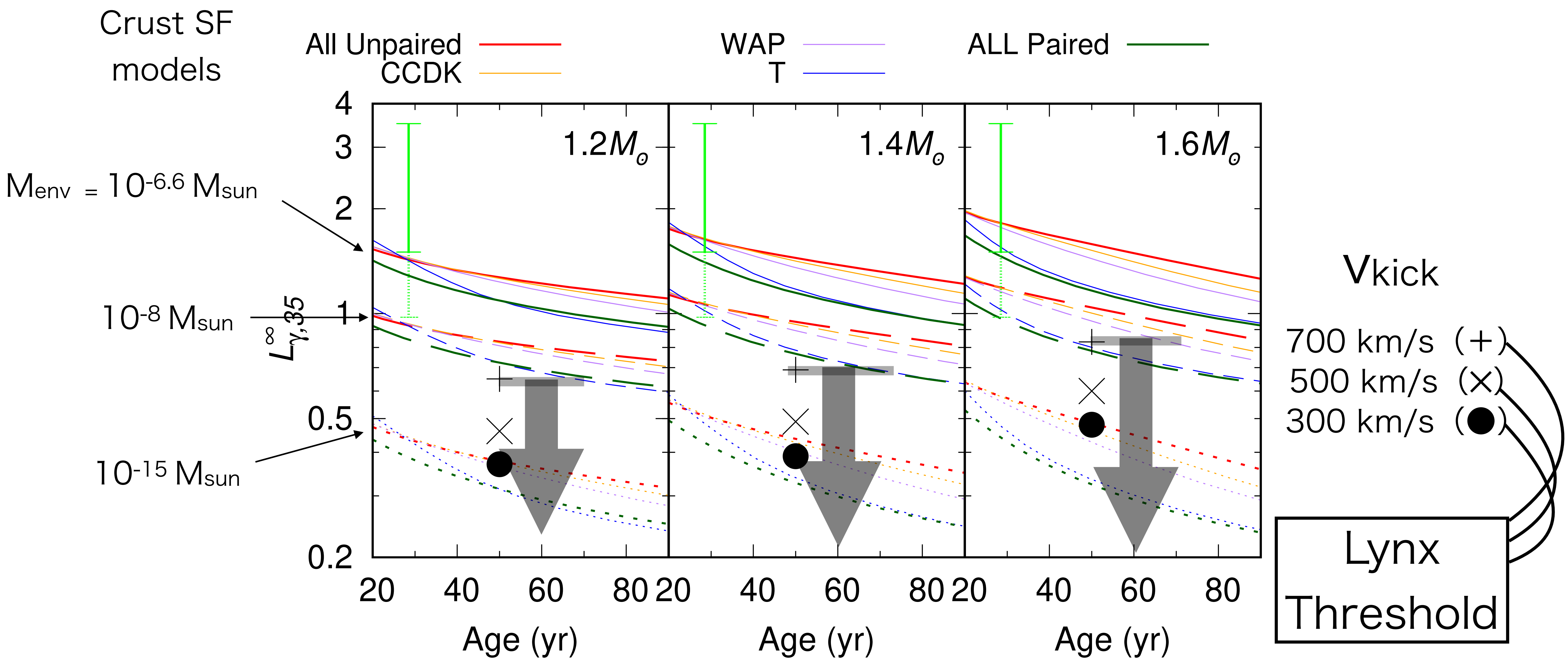
Possible Detection of NS 1987A by Lynx

～Model Dependence～



- ALMA: high M_{env} (depending on ^{44}Ti decay heating)
- Lynx: Two scenarios of non-detection and detection

Non-Detection Scenario for NS 1987A by Lynx

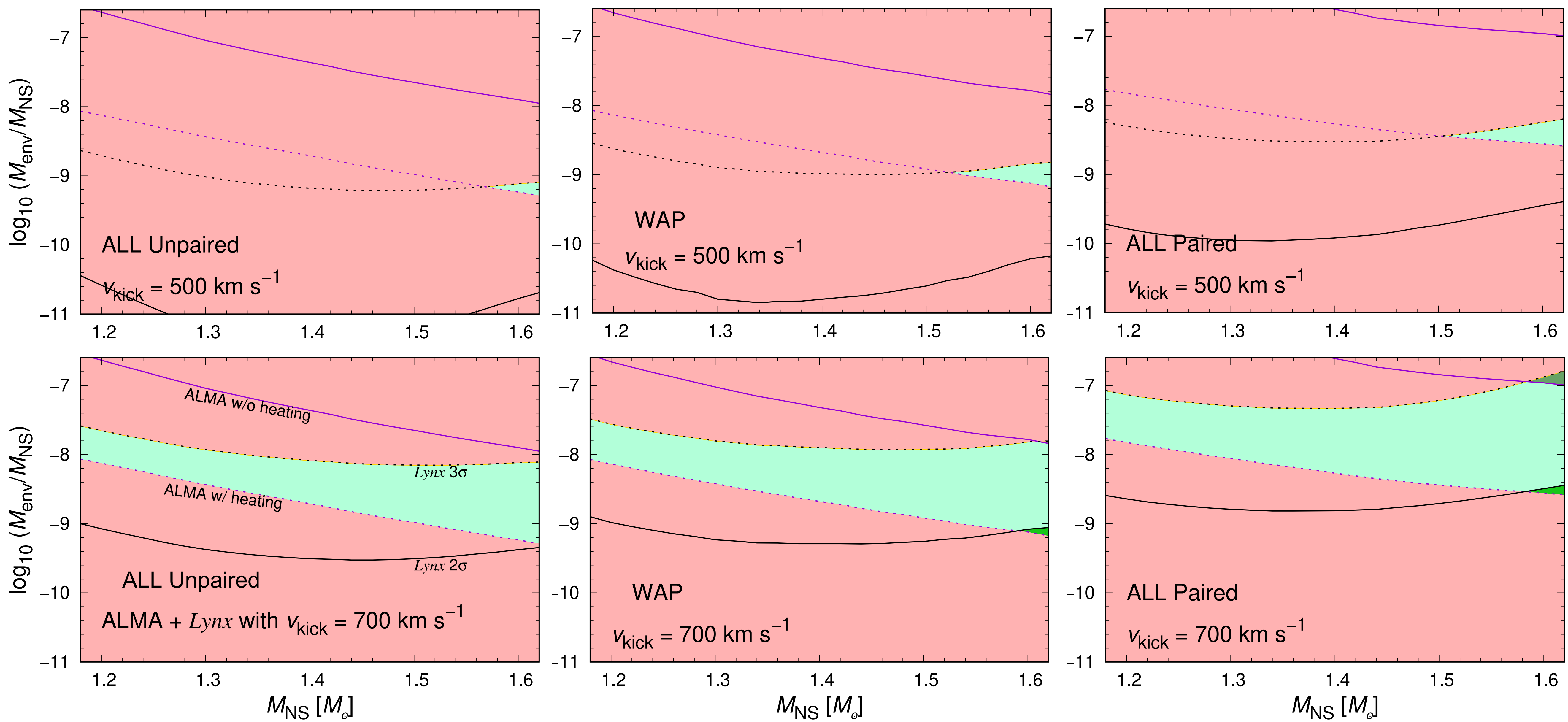


- Many models are excluded due to ALMA obs.
- However, if there is any rapid cooling at $t \sim 40$ yr (maybe derived from crust physics), non-detection scenario holds.

Non-Detection Scenario for NS 1987A by Lynx

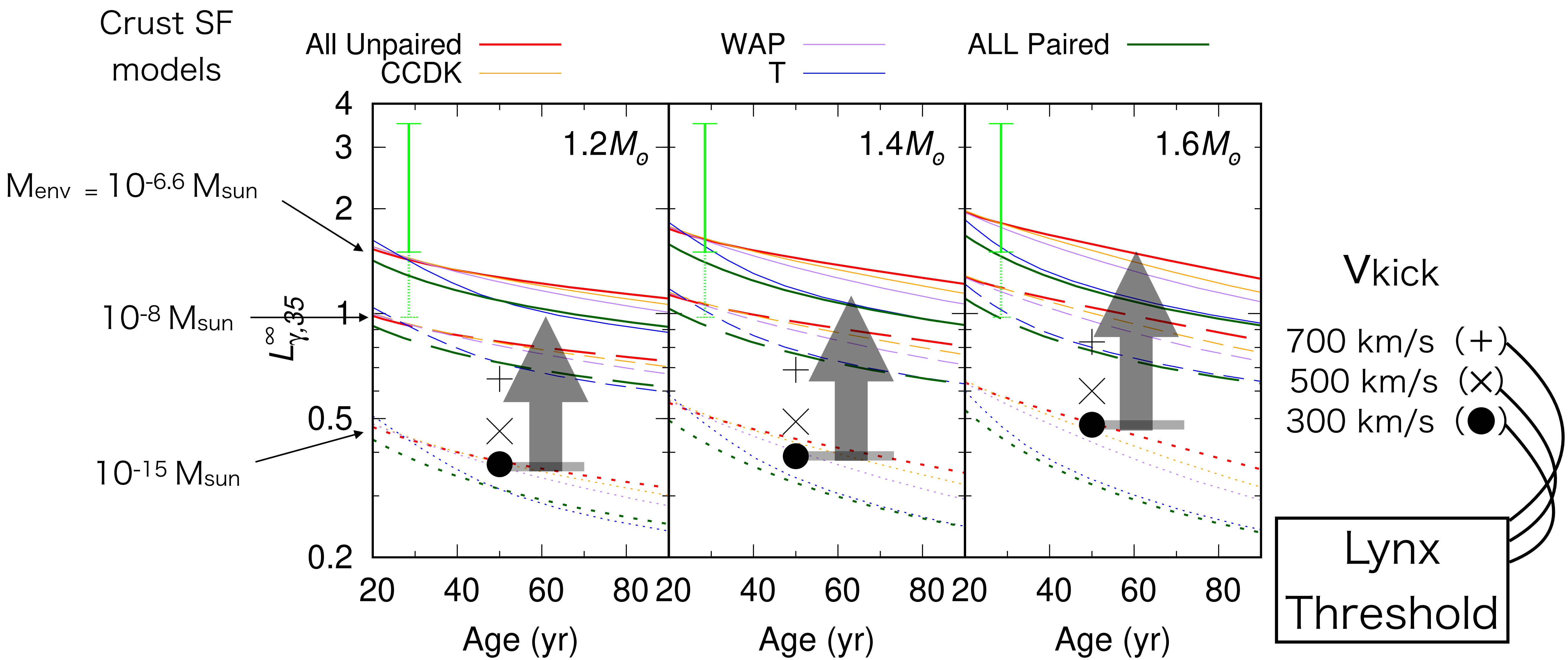
* Note that all models with $v_{\rm kick} = 300$ km/s are excluded.

SF: Not included Weak Strong



$v_{\rm kick} \sim 700$ km/s (Roughly upper limits of ALMA obs.)

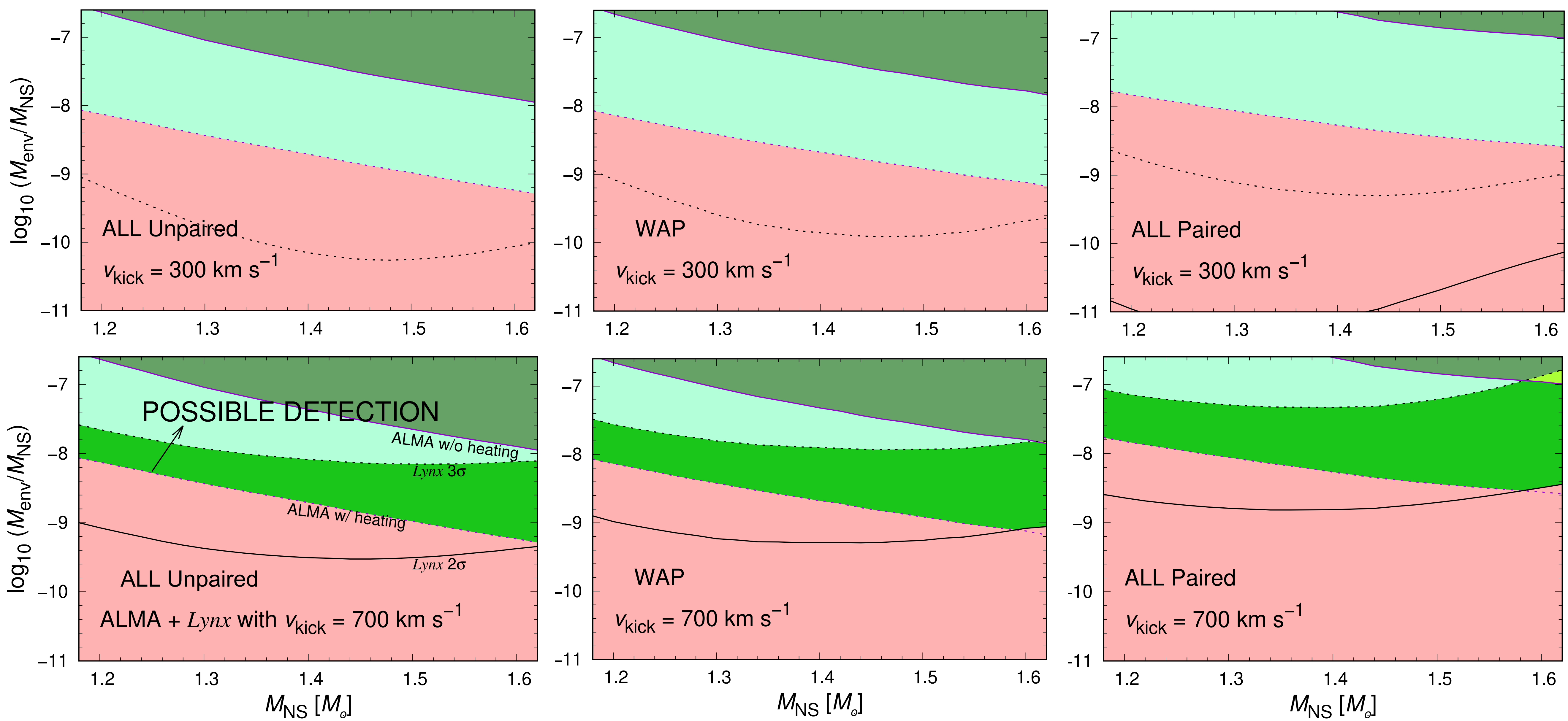
Detection Scenario for NS 1987A by Lynx



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

Detection Scenario for NS 1987A by Lynx

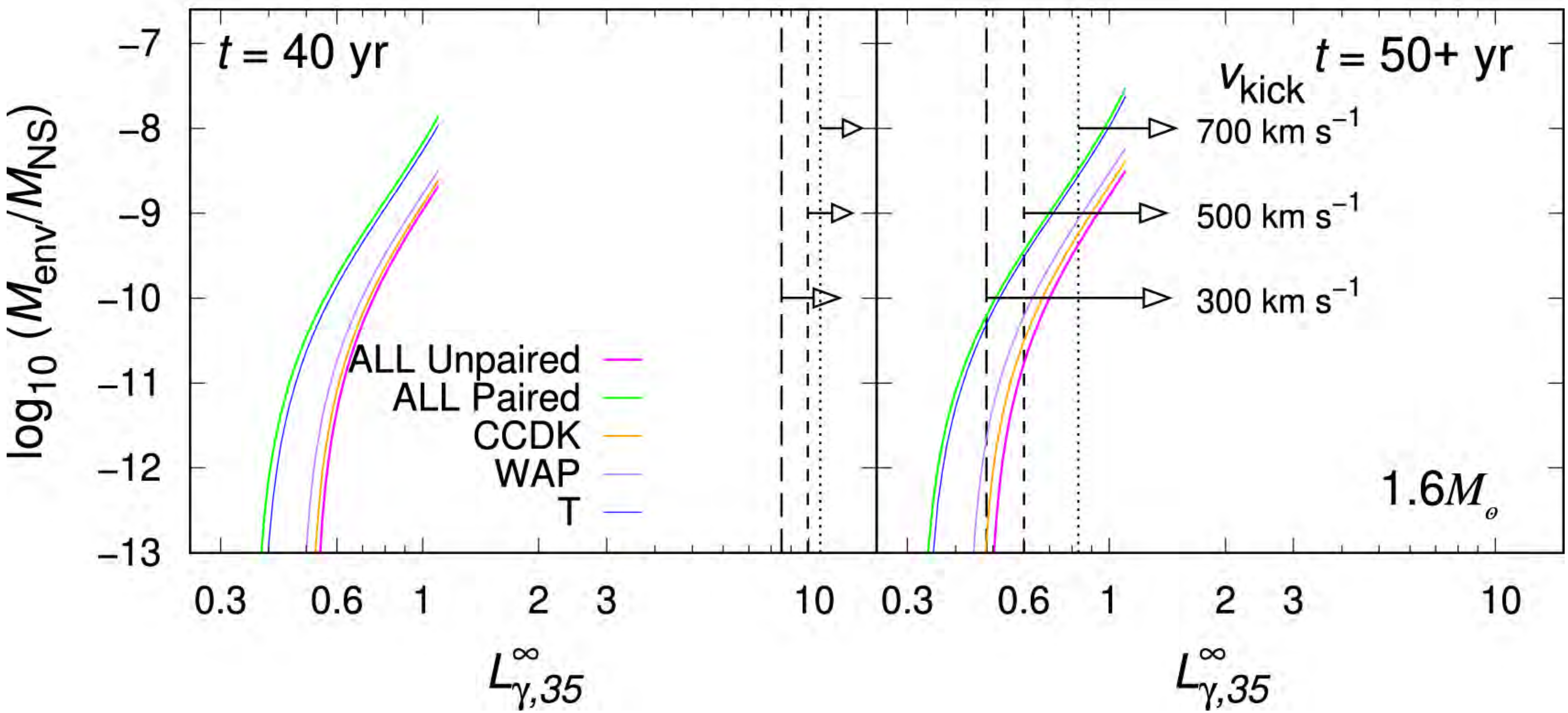
SF: Not included Weak Strong



Not v_{kick} dependence so much (ALMA obs. Is dominant)

Possibility to detect NS 1987A by Lynx

* Note that our results are similar even if the launched date is delayed.



- Smaller v_{kick} is better for the detection.
- If the envelope mass is higher, or crust SF is weaker, the detectability becomes higher.

Conclusion

Conclusion

- Motivated by the recent ALMA observations, we examine heating sources associated to NS 1987A:

- PWN87A Scenario：It is likely in 2012 and 2014.

- NS87A Scenario：Although it is hard to detect thermal emission now, Lynx could detect NS 1987A in the 2040s if exotic cooling process working at $t \sim 40~\mathrm{yr}$ is absent.

- Future work: Investigation of impact of possible crust physics on the NS 1987A