Nuclear Physics of Accreting Neutron Stars

Hendrik Schatz, Rahul Jain*

September 22, 2023

17th International Symposium on Nuclei in the Cosmos (NIC XVII)

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and used resources of the Facility for Rare Isotope Beams (FRIB), which is a DOE Office of Science User Facility, under Award Number DE-SC0000661.

X-ray from the Space

PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

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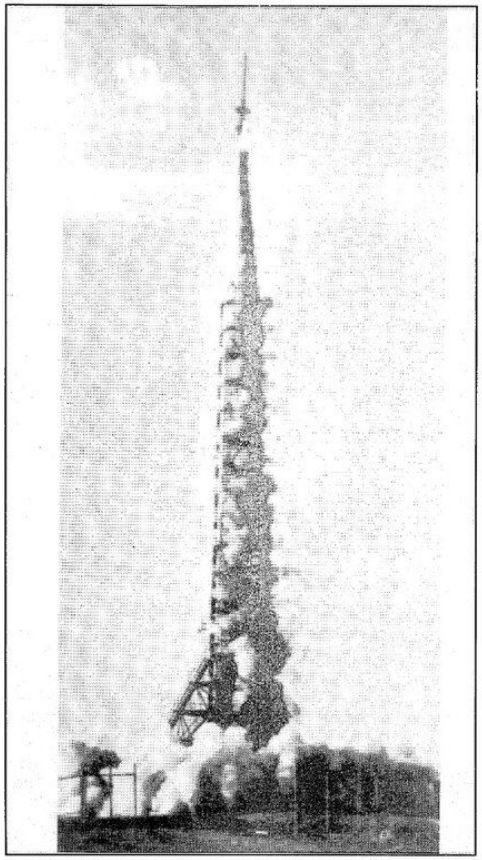
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received October 12, 1962)



Aerobee Rocket Launch, 1949
Holloman Air Force Base Archives

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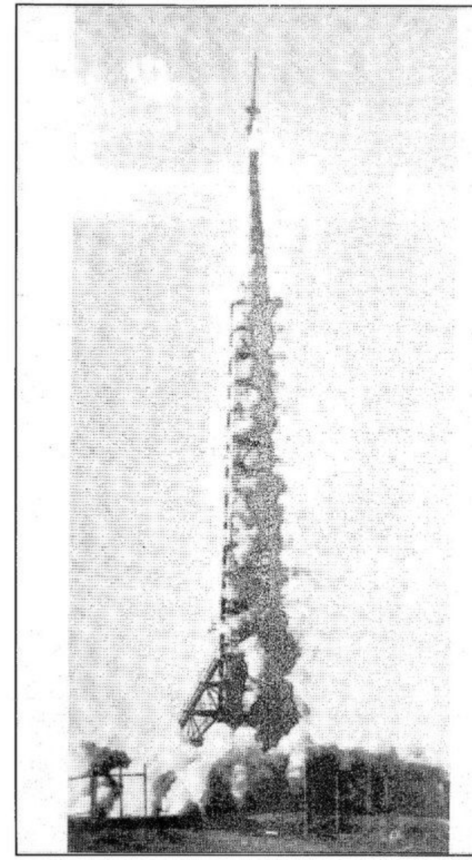

Aerobee Rocket Launch, 1949
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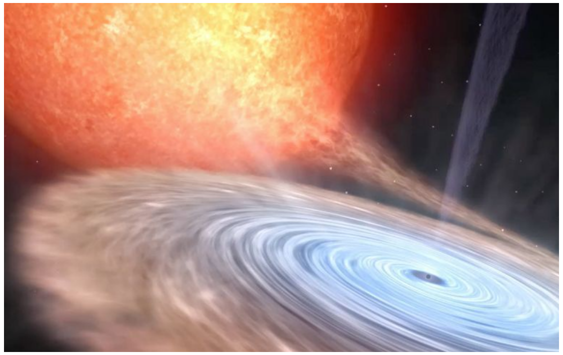
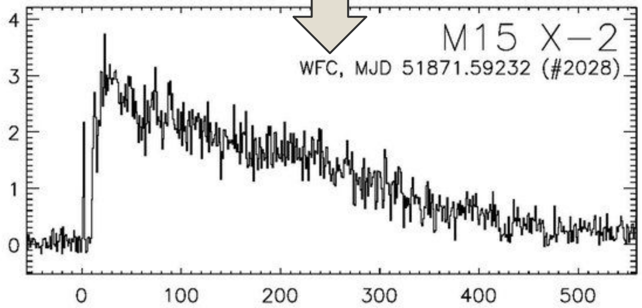
Accreting Neutron Stars Observables

Accretion Outburst





Galloway et al., ApJS (2020)

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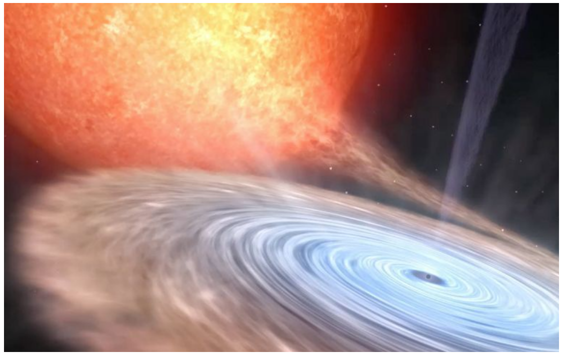
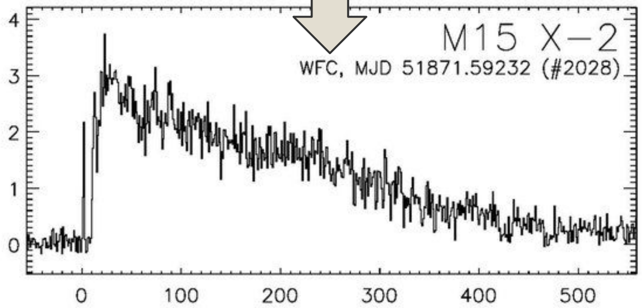
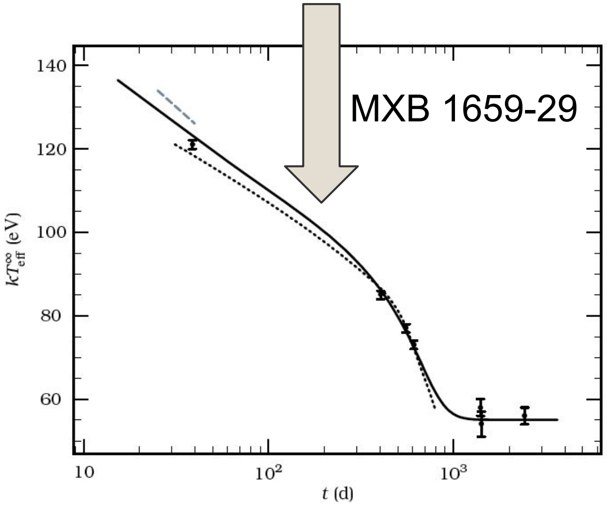




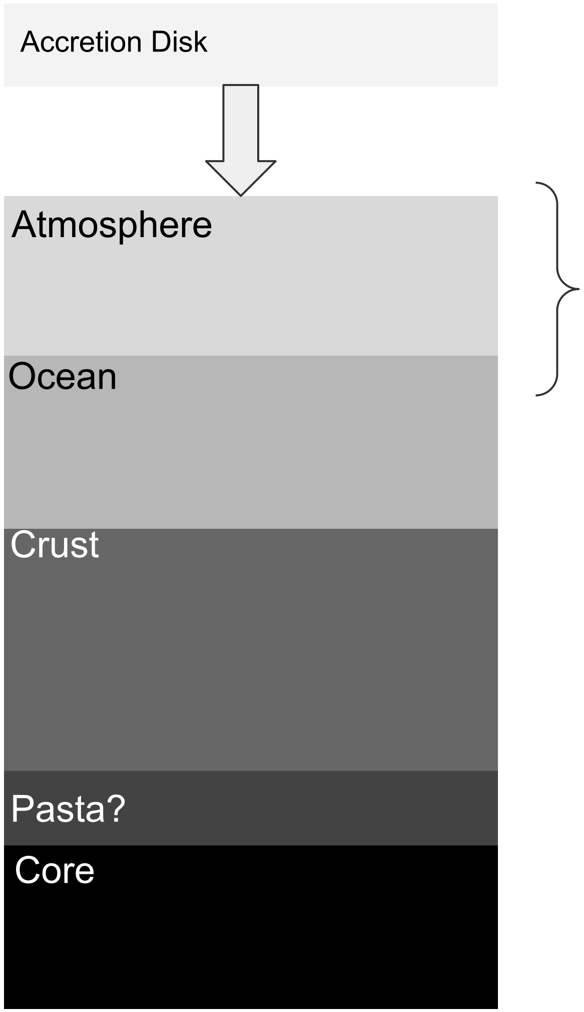
Galloway et al., ApJS (2020)

Quiescence

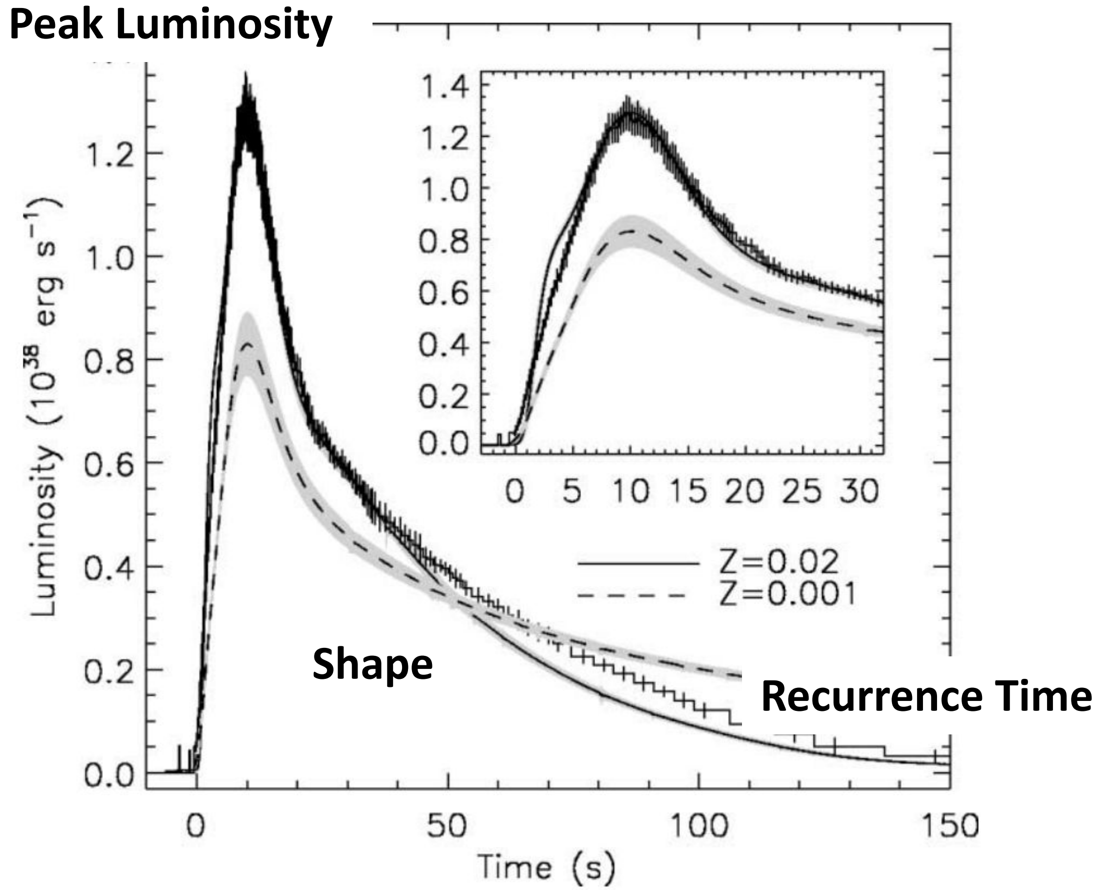


Brown and Cumming, ApJ (2009)

Prompt Observables

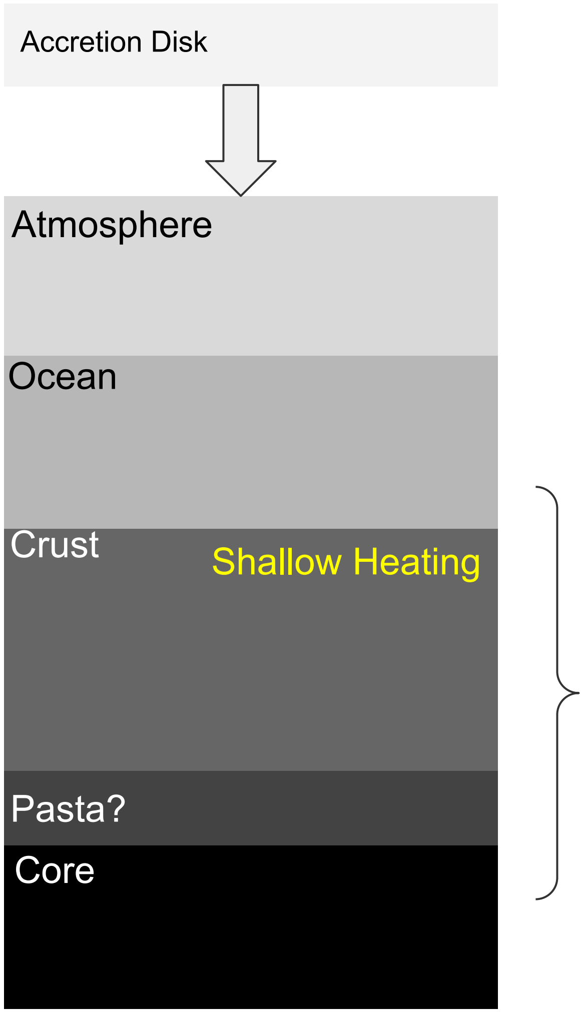


Light Curves

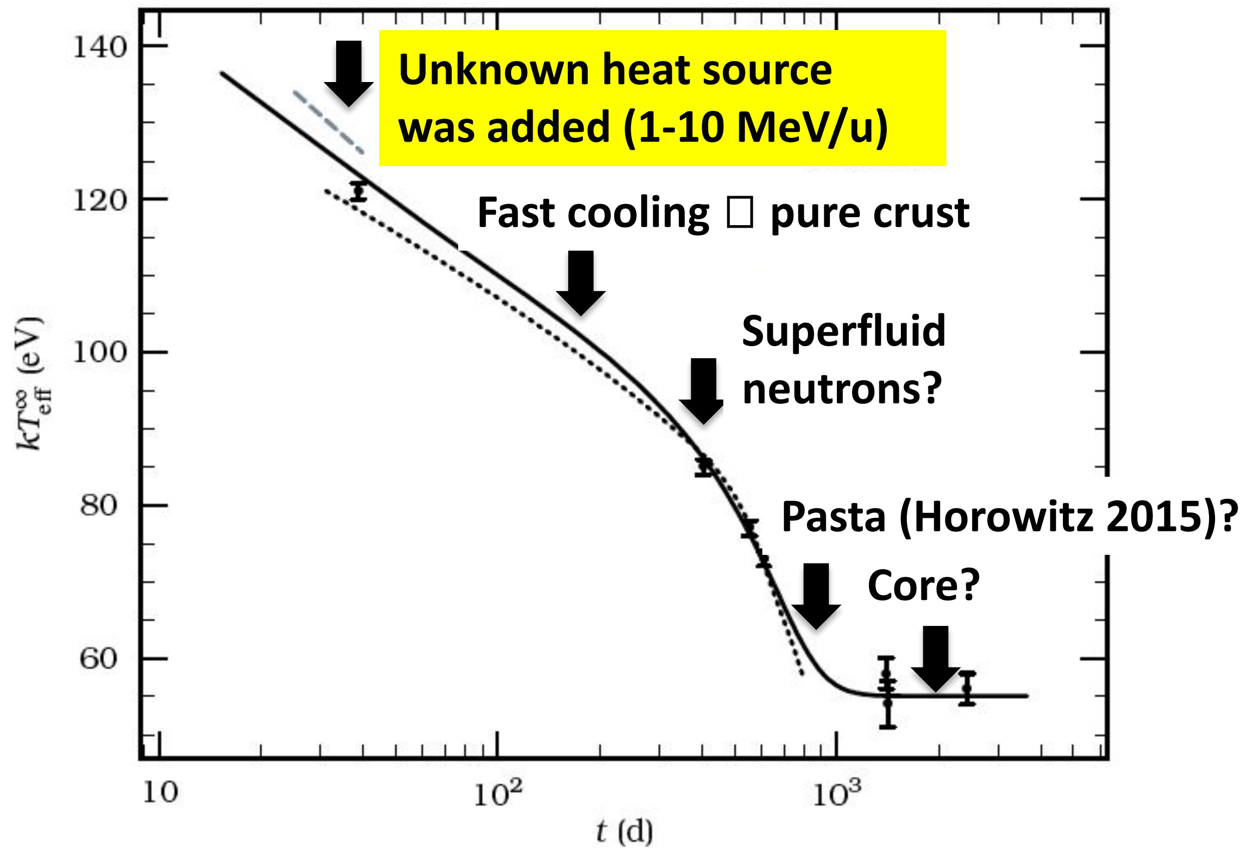


A. Heger et al., ApJ (2007)

Delayed Observables

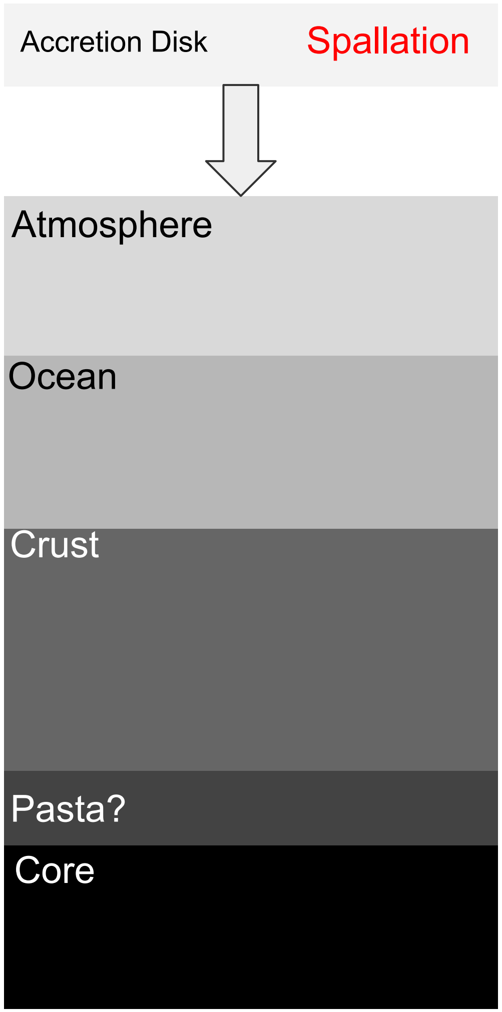


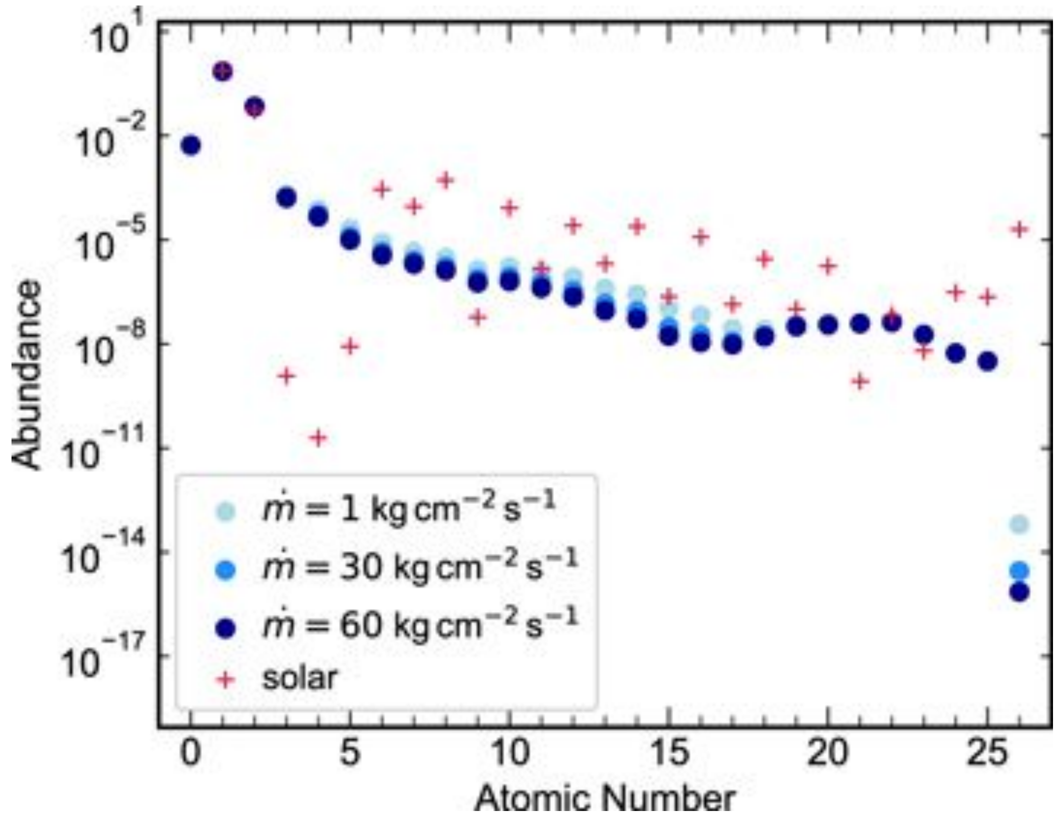
Cooling Curves



Brown and Cumming, ApJ (2009)

Spallation





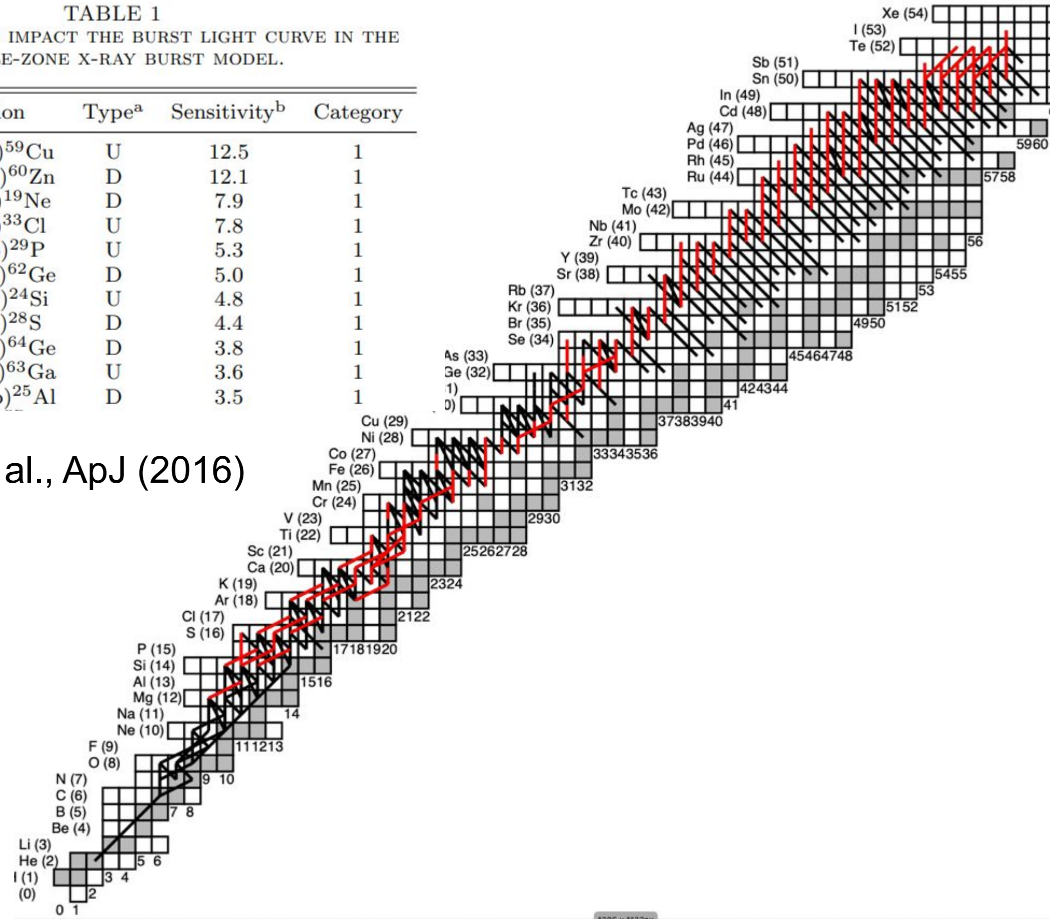
J. S. Randhawa et al. ApJ (2019)

X-ray bursts

TABLE 1
REACTIONS THAT IMPACT THE BURST LIGHT CURVE IN THE SINGLE-ZONE X-RAY BURST MODEL.

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{56}Ni(α,p)^{59}Cu	U	12.5	1
2	^{59}Cu(p,γ)^{60}Zn	D	12.1	1
3	^{15}O(α,γ)^{19}Ne	D	7.9	1
4	^{30}S(α,p)^{33}Cl	U	7.8	1
5	^{26}Si(α,p)^{29}P	U	5.3	1
6	^{61}Ga(p,γ)^{62}Ge	D	5.0	1
7	^{23}Al(p,γ)^{24}Si	U	4.8	1
8	^{27}P(p,γ)^{28}S	D	4.4	1
9	^{63}Ga(p,γ)^{64}Ge	D	3.8	1
10	^{60}Zn(α,p)^{63}Ga	U	3.6	1
11	^{22}Mg(α,p)^{25}Al	D	3.5	1

R. H. Cyburt et al., ApJ (2016)



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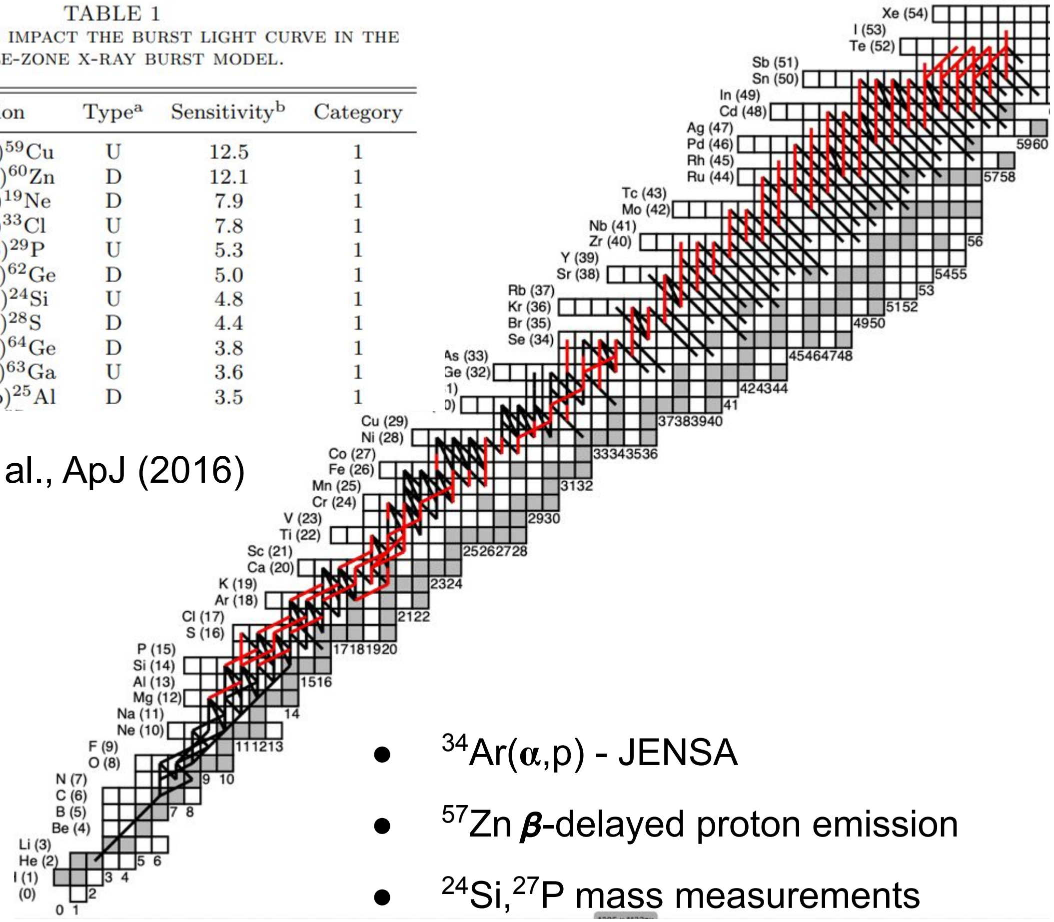
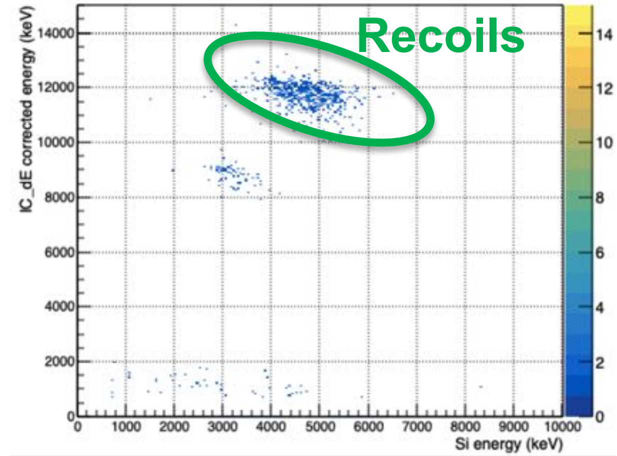
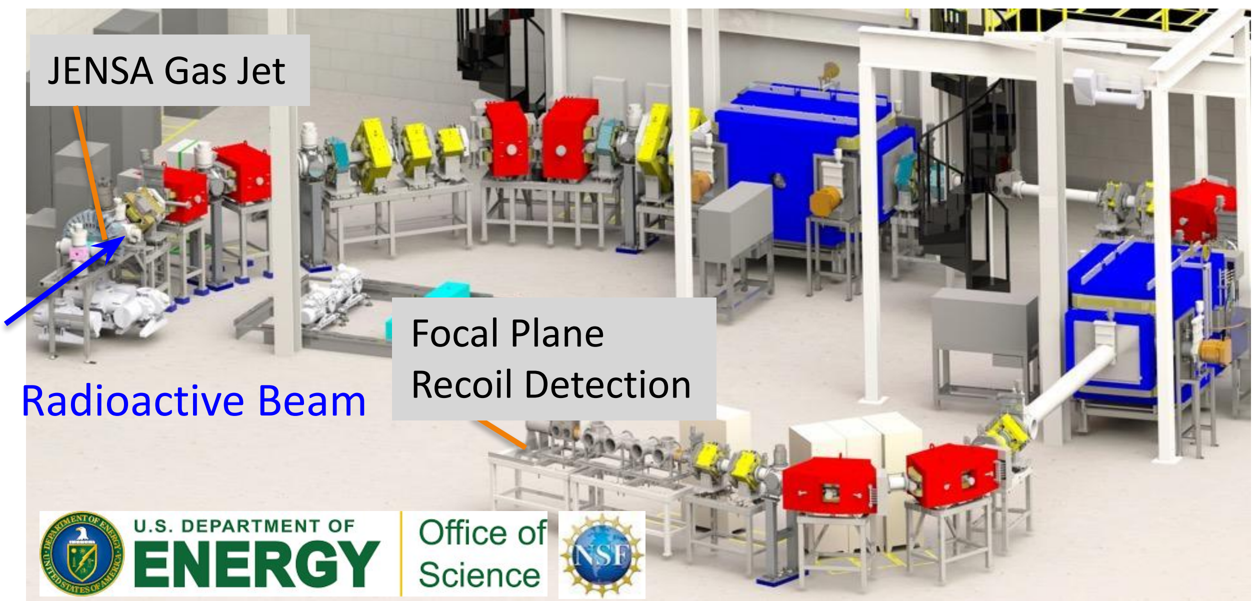


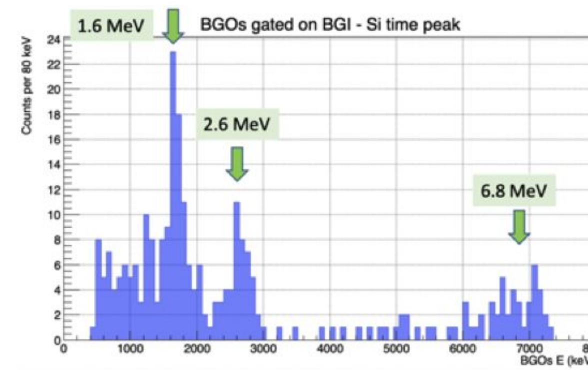
- $^{34}Ar(\alpha,p)$ - JENSA
- ^{57}Zn ***β***-delayed proton emission
- ^{24}Si,^{27}P mass measurements

SECAR

Lead
G. Berg, M. Couder, Notre Dame
F. Montes, H. Schatz, MSU
J. Blackmon, LSU
K. Chipps, M. Smith, ORNL
U. Greife, CSM

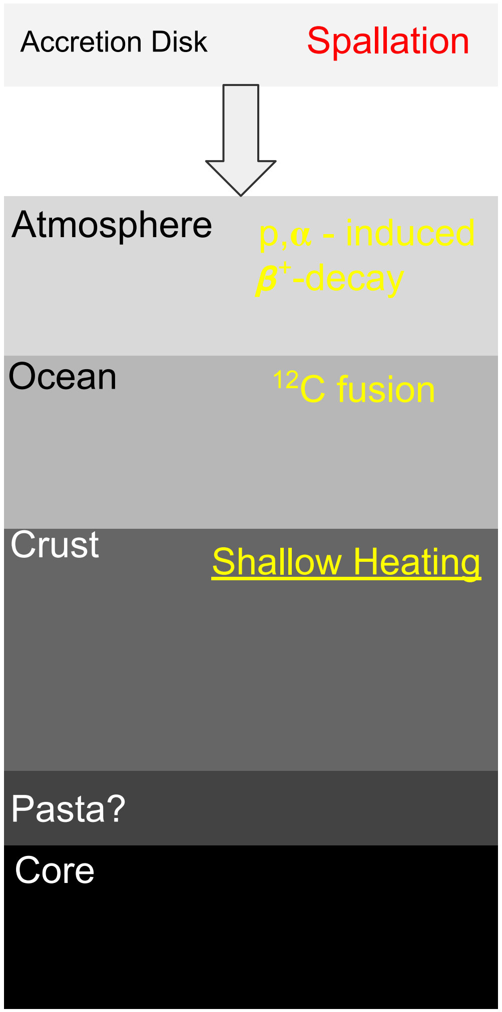


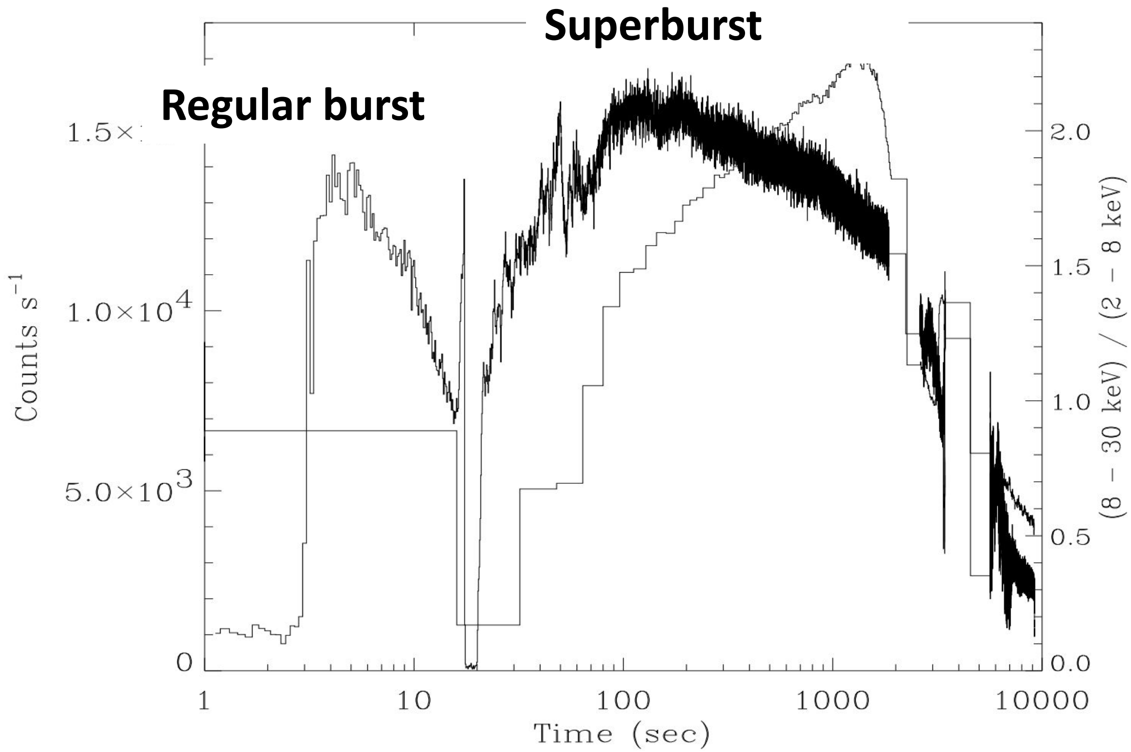




First recoil detection from $^{16}O(\alpha,\gamma)^{20}Ne$ concludes construction
□ Scientific commissioning ongoing

Superbursts



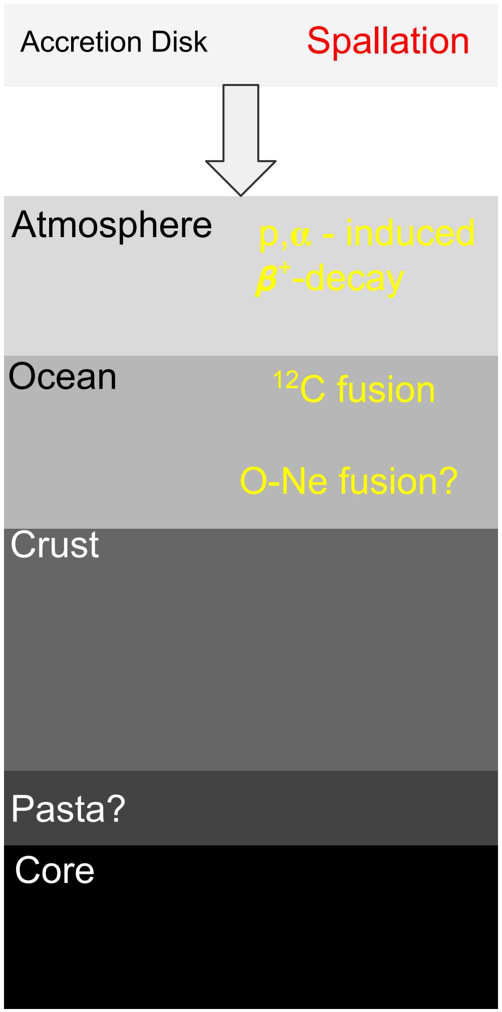


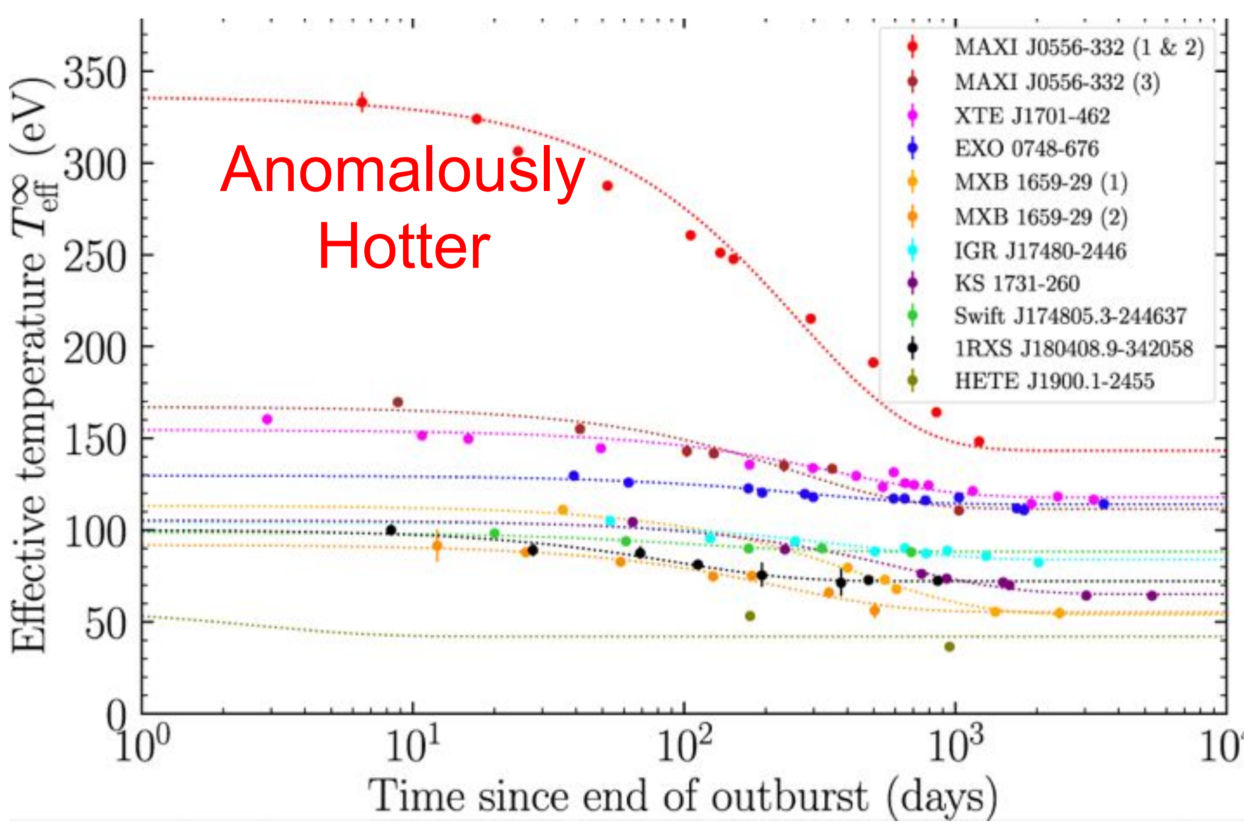
Strohmayer and Brown, ApJ (2002)

Ignition mechanism - unknown?

Britt, Grace, Jain et al. (in prep)

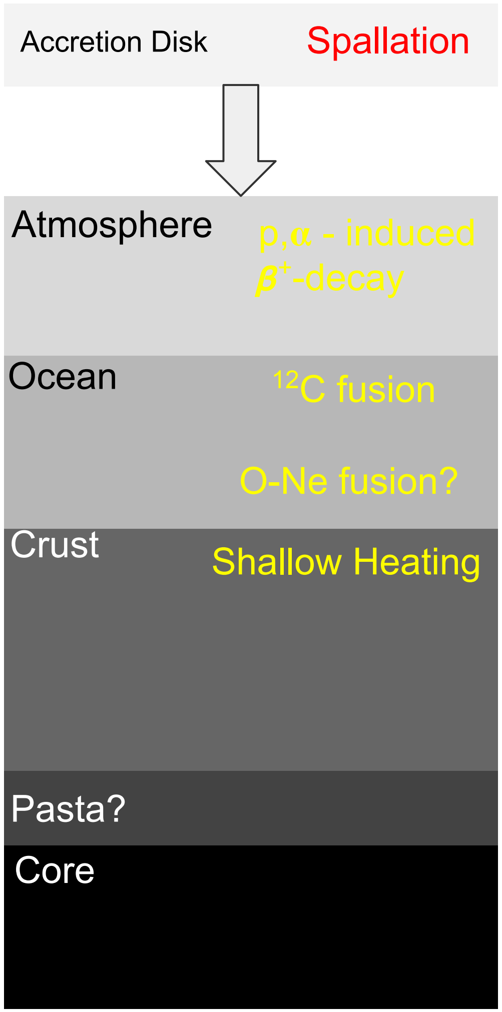
Hyperbursts

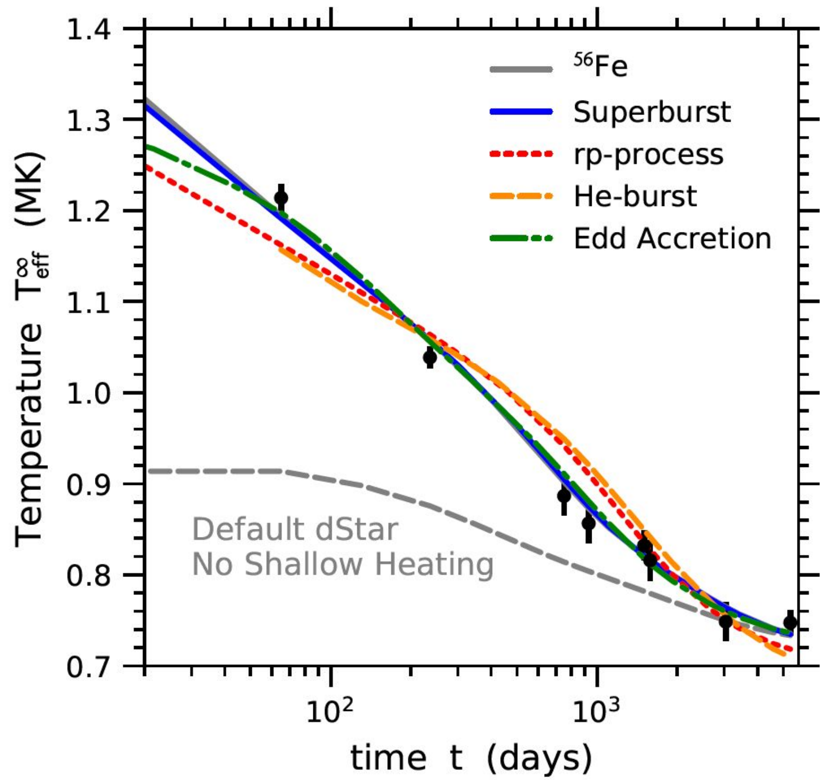




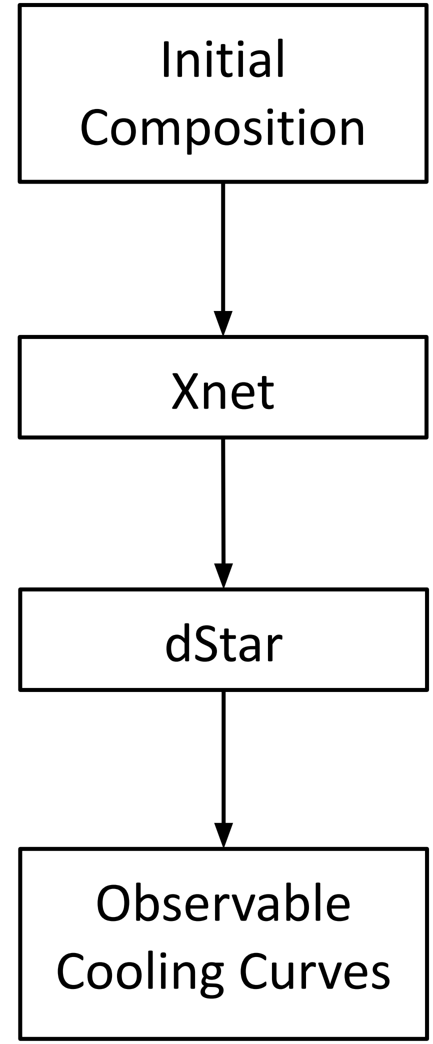
Page et al., ApJ (2022)

Shallow Heating

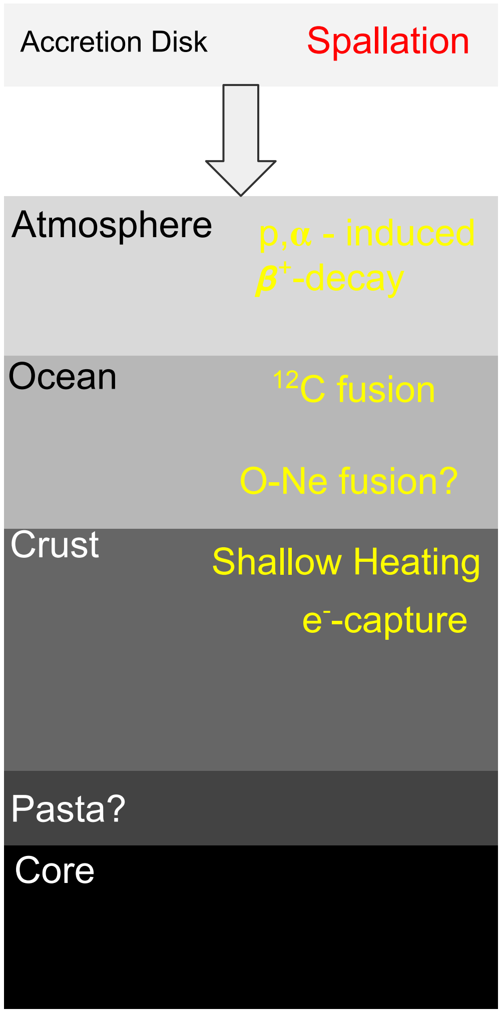




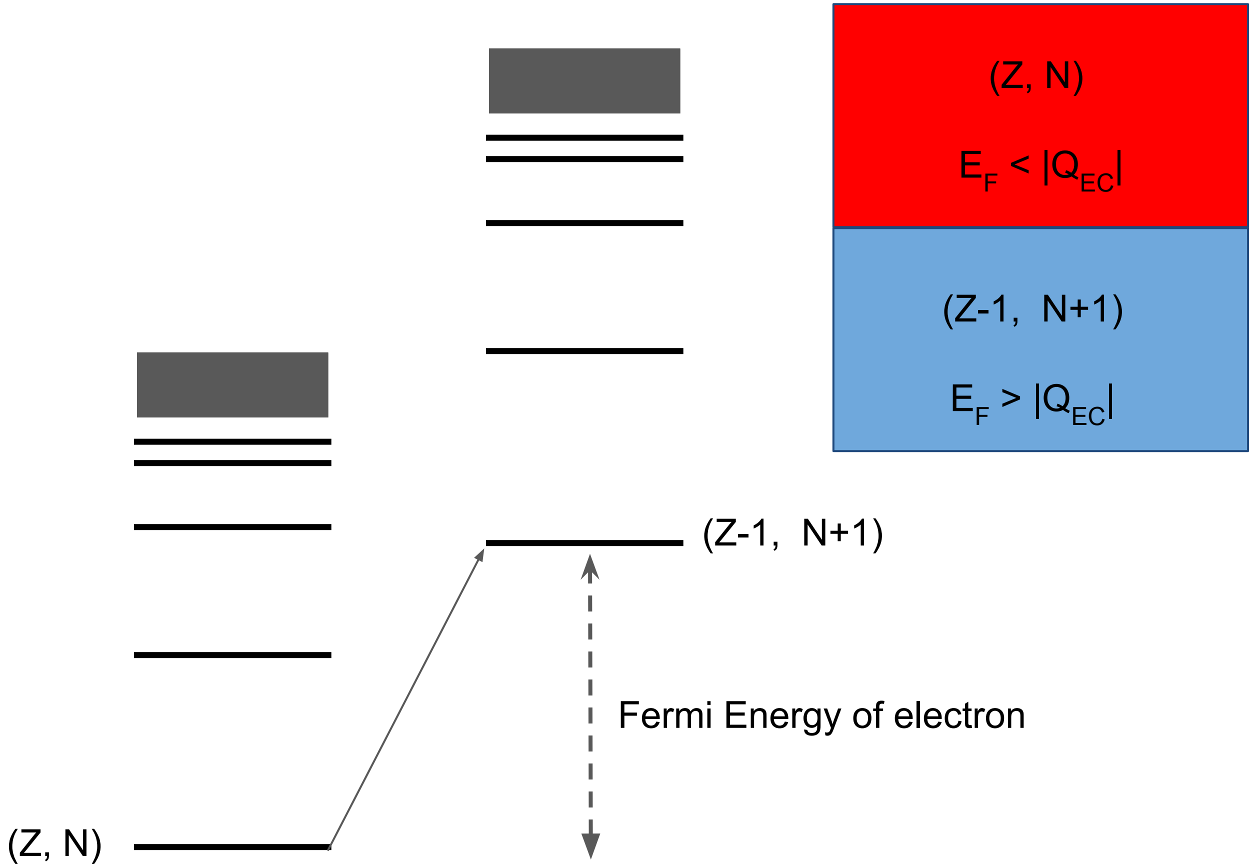
Jain et al., (in prep)



e⁻ Captures



Accretion Disk
Spallation
Atmosphere
p,α - induced
β⁺-decay
Ocean
¹²C fusion
O-Ne fusion?
Crust
Shallow Heating
e⁻-capture
Pasta?
Core



(Z, N)
(Z-1, N+1)
Fermi Energy of electron
(Z, N)
E_F < |Q_EC|
(Z-1, N+1)
E_F > |Q_EC|

Urca cooling

Accretion Disk — Spallation

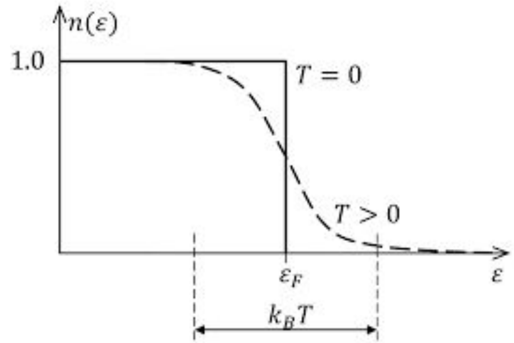
Atmosphere — p,α - induced β^+-decay

Ocean — ^{12}C fusion; O-Ne fusion?

Crust — Shallow Heating; e^--capture/β^--decay

Pasta?

Core



(Z, N)

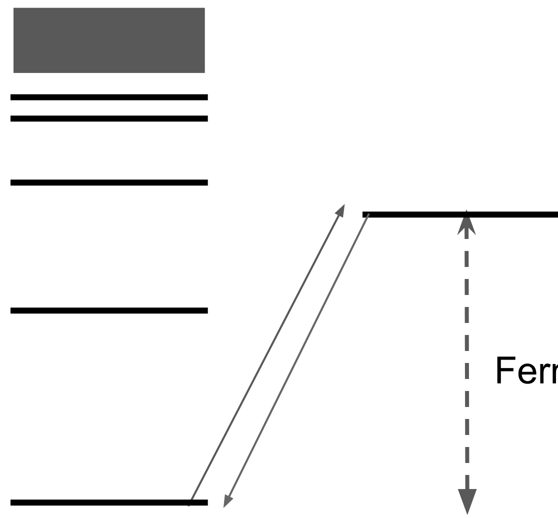
$E_F < |Q_{EC}|$

Urca Cooling Layer

$E_F \sim |Q_{EC}|$ ($k_B T$)

(Z-1, N+1)

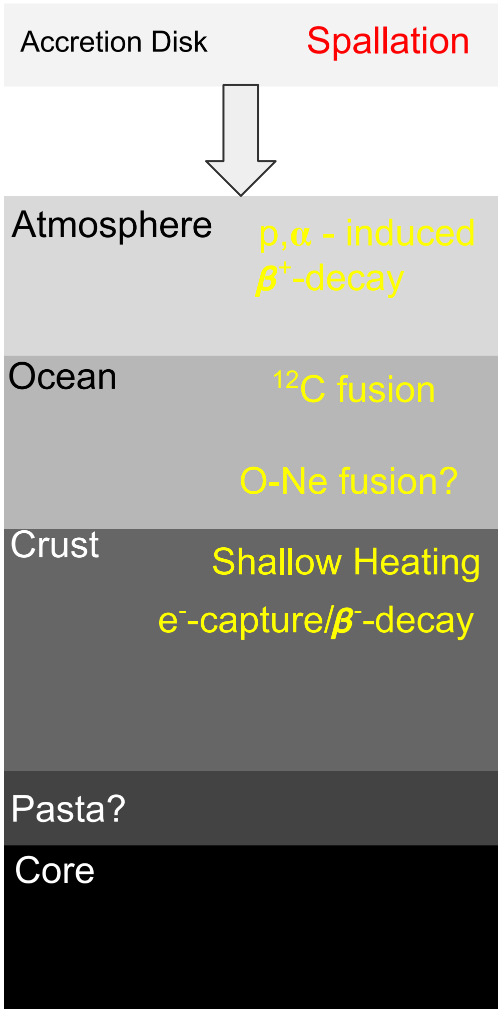
$E_F > |Q_{EC}|$

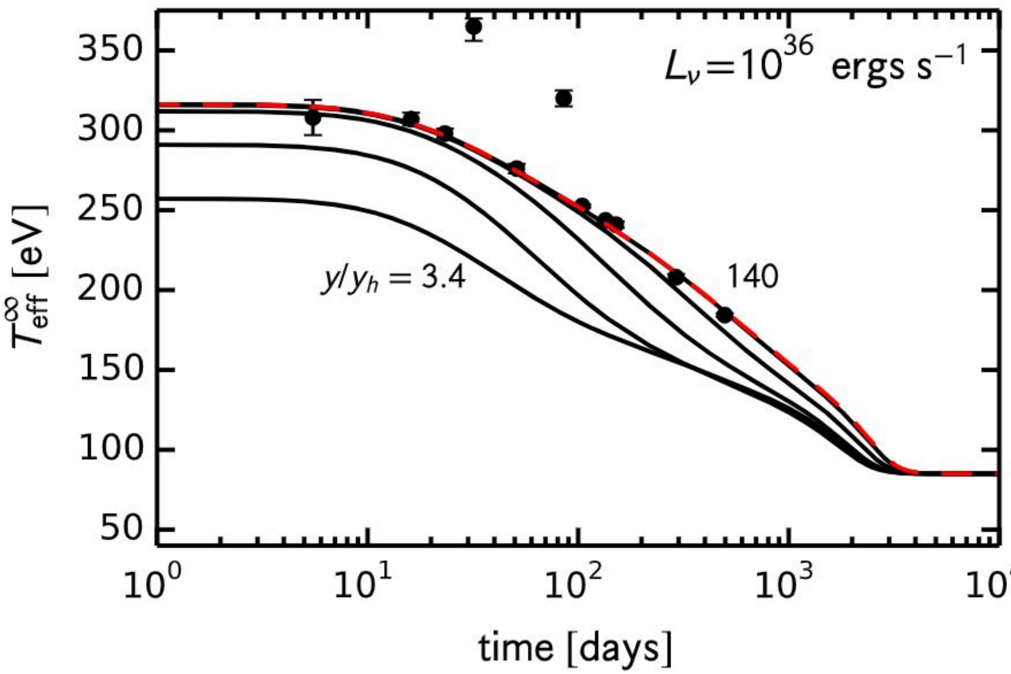


Fermi Energy of electron

H. Schatz et al., Nature (2014)

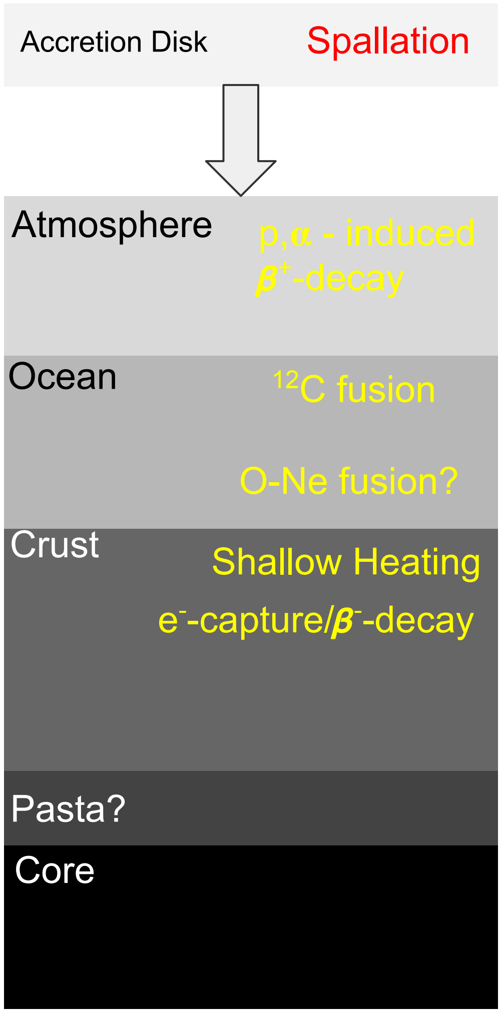
Urca cooling

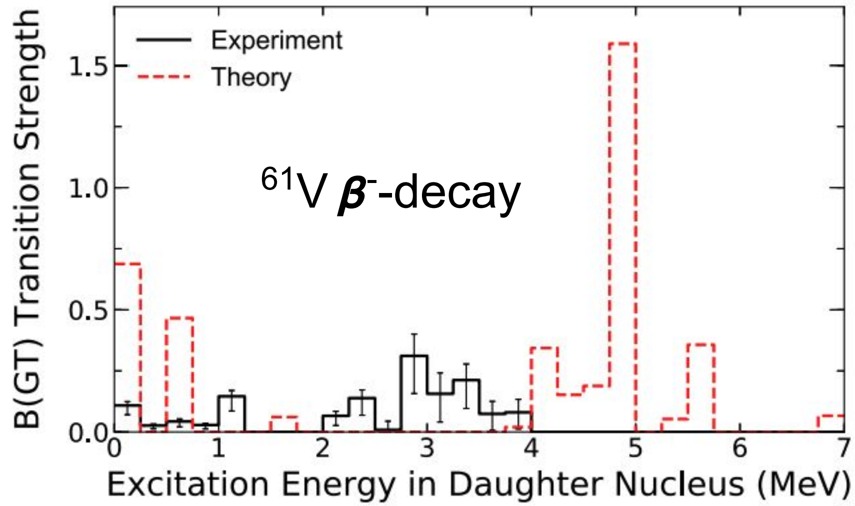


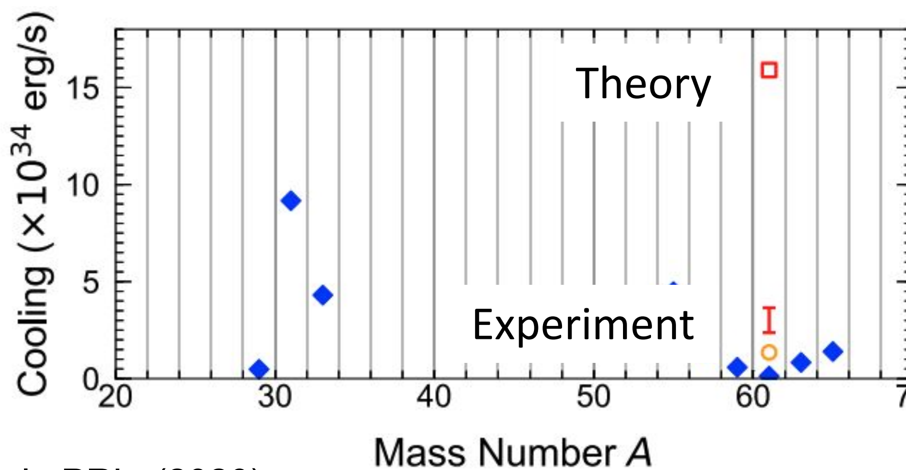


A. Deibel et al., ApJ 2016

Urca cooling

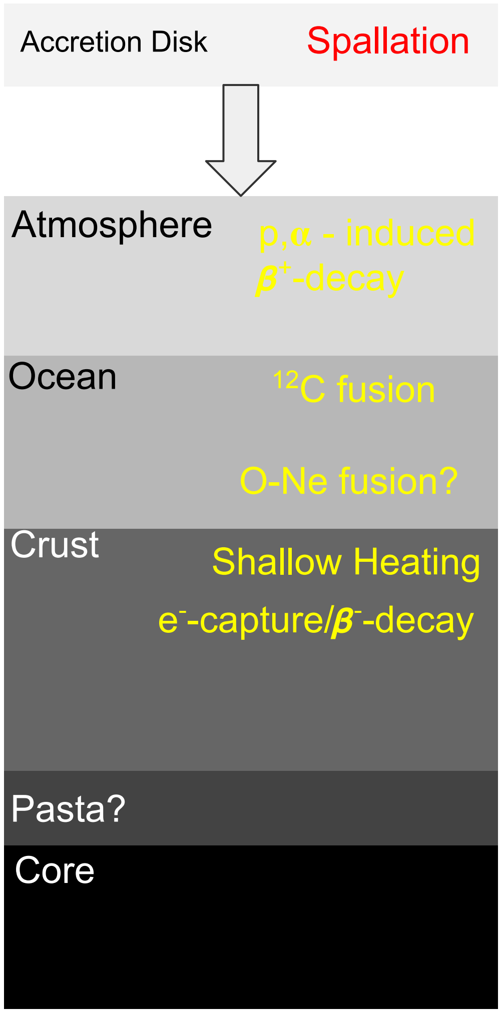


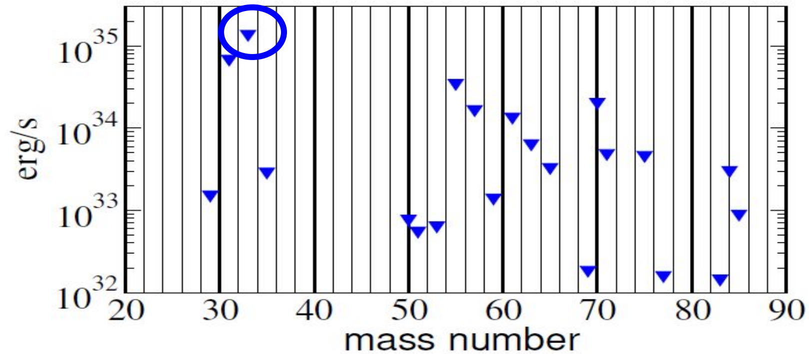


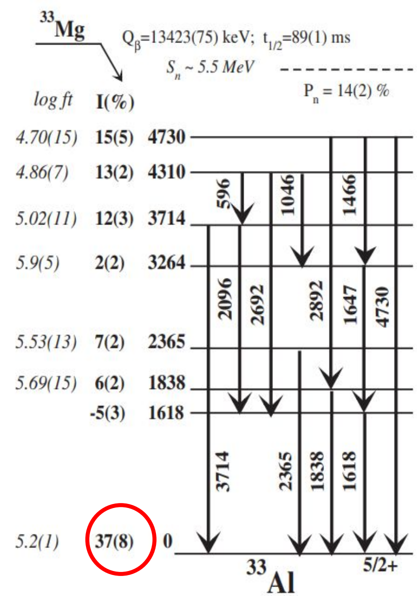


W.-J. Ong et al., PRL, (2020)

Urca cooling



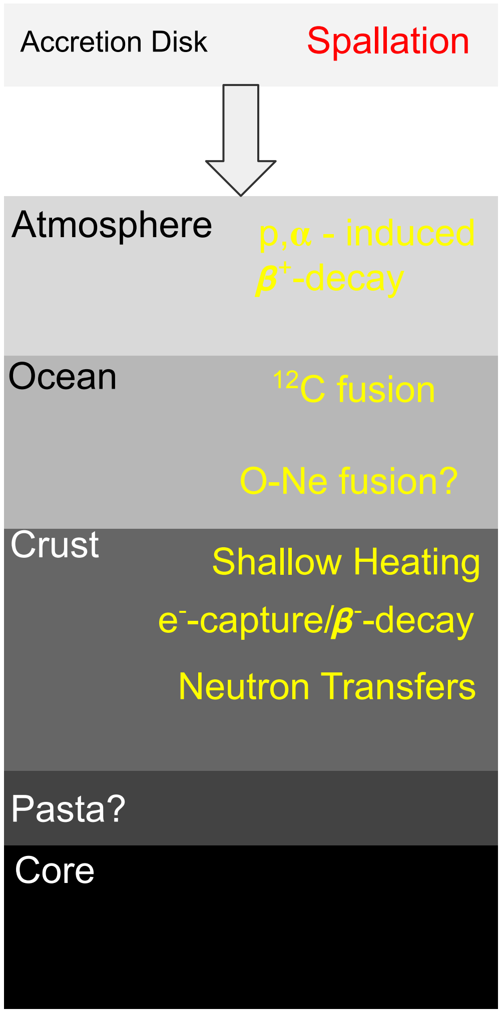




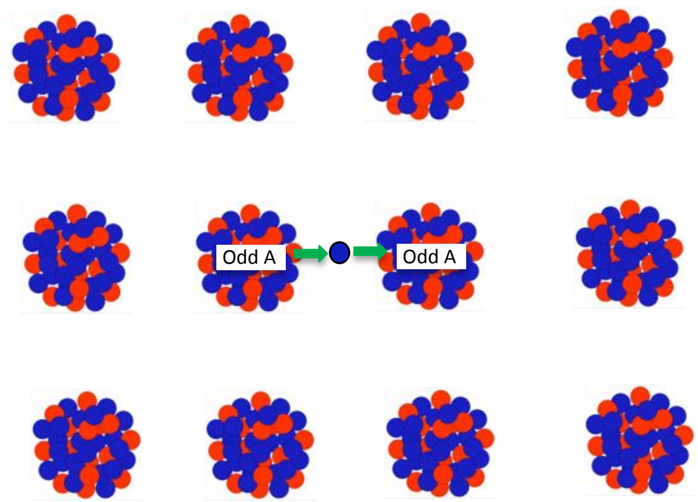
^{33}Mg β^--decay

Ph.D. Thesis, R. Jain

Neutron Transfer Reactions



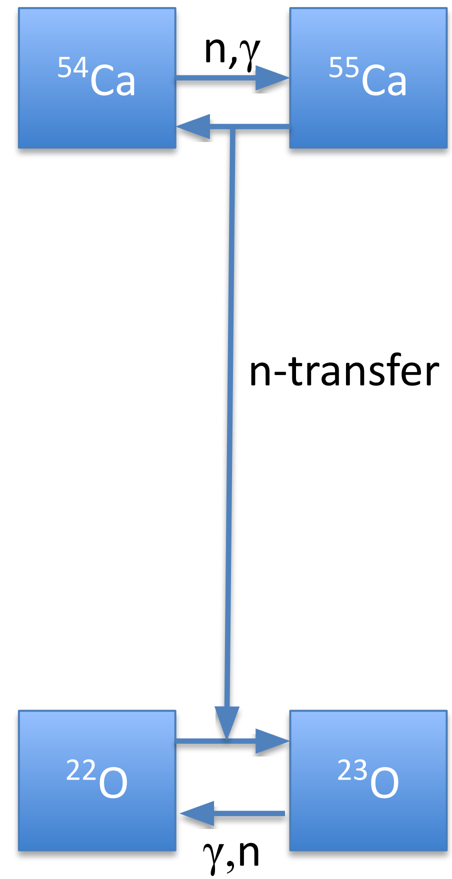
New Type of Crust Reaction:
Neutron Transfer Reactions
Proposed to destroy odd A nuclei
(Chugunov 2019)



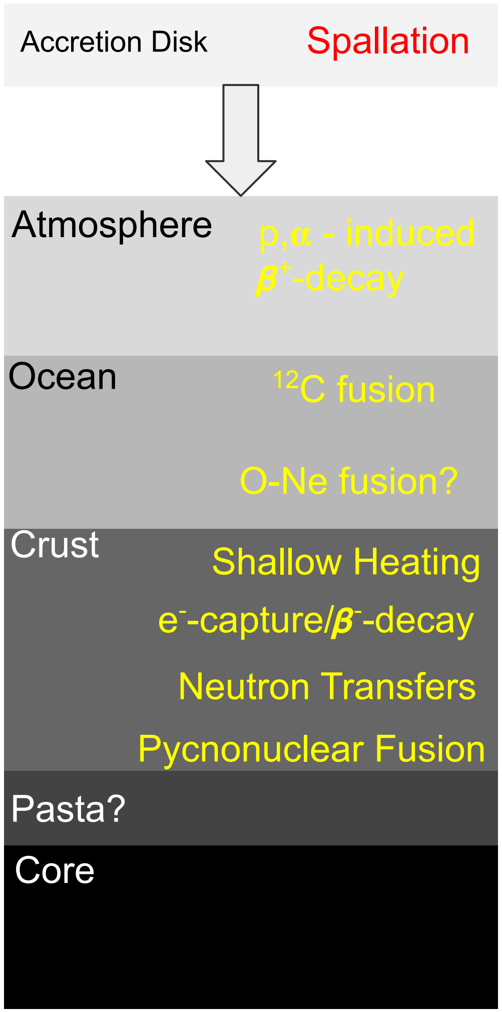
☐ So no Urca Cooling?

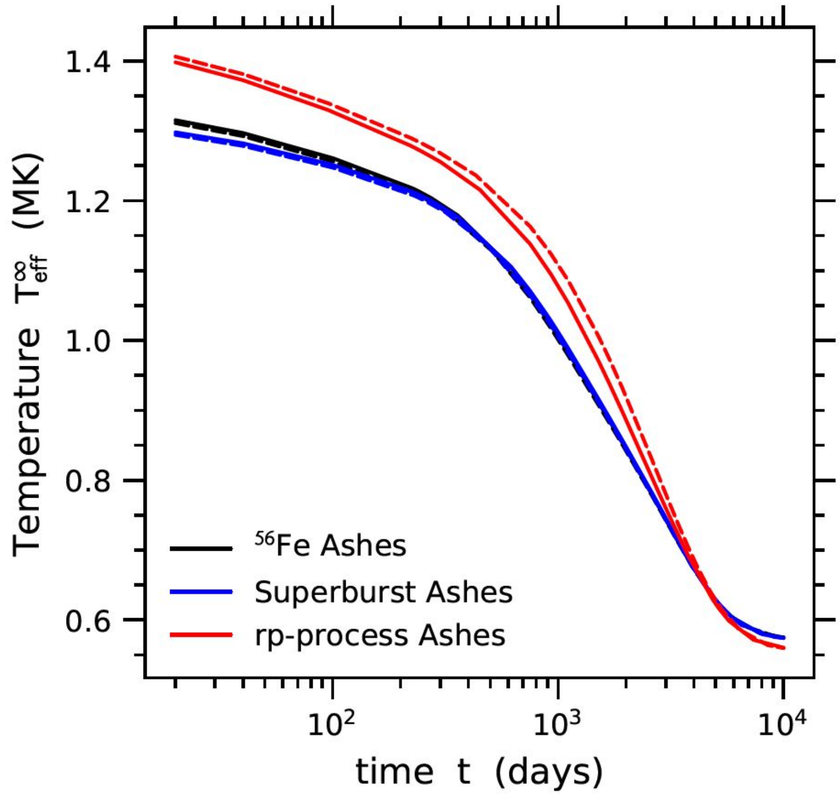
H. Schatz et al., ApJ (2022)

Example:

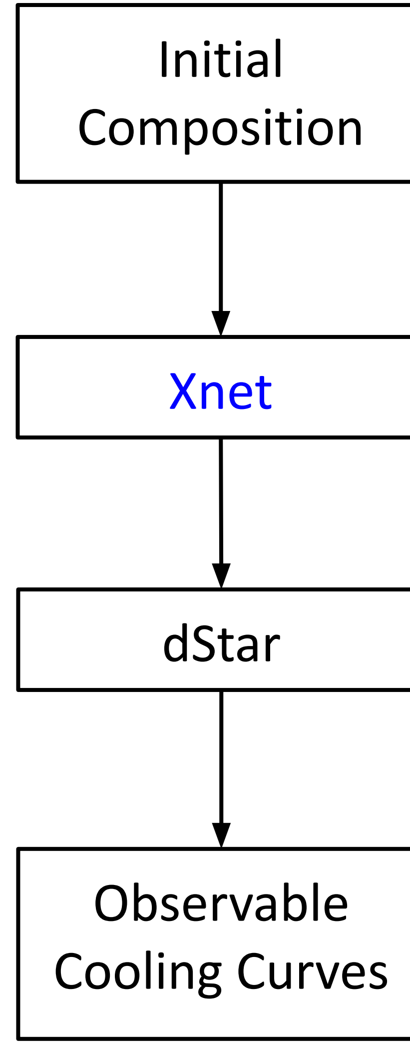


Pycnonuclear Fusion





R. Jain et al., ApJ (2023)



Nuclear Pasta?

Accretion Disk — Spallation

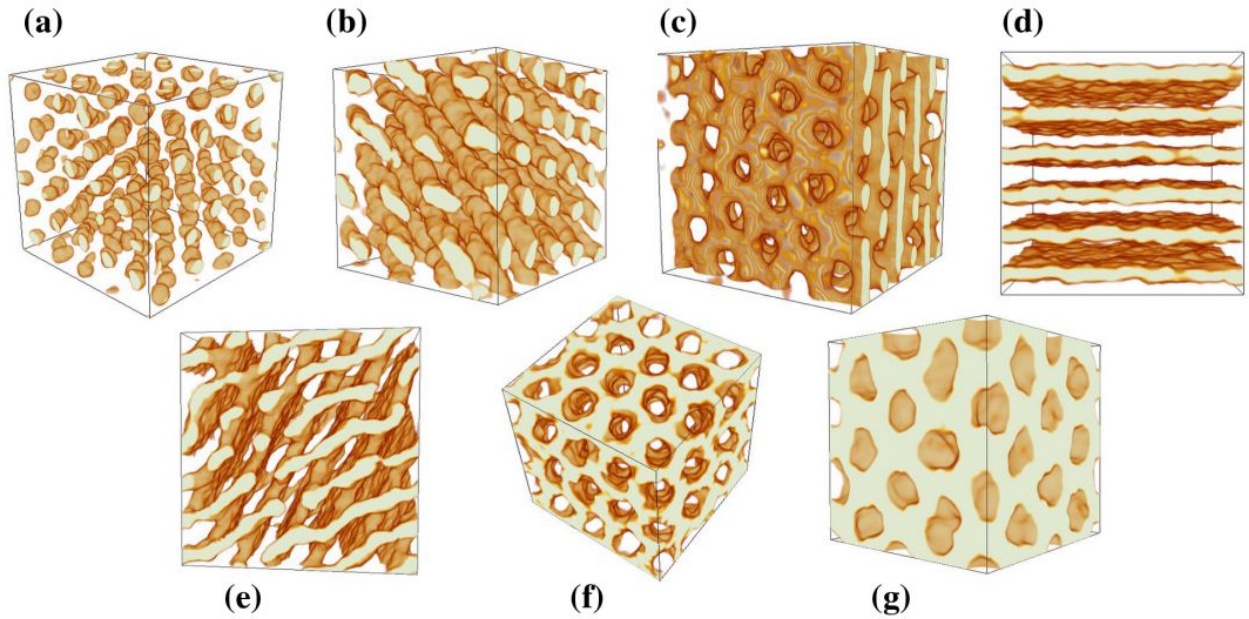
Atmosphere — p,α - induced β^+-decay

Ocean — ^{12}C fusion; O-Ne fusion?

Crust — Shallow Heating; e^--capture/β^--decay; Neutron Transfers; Pycnonuclear Fusion

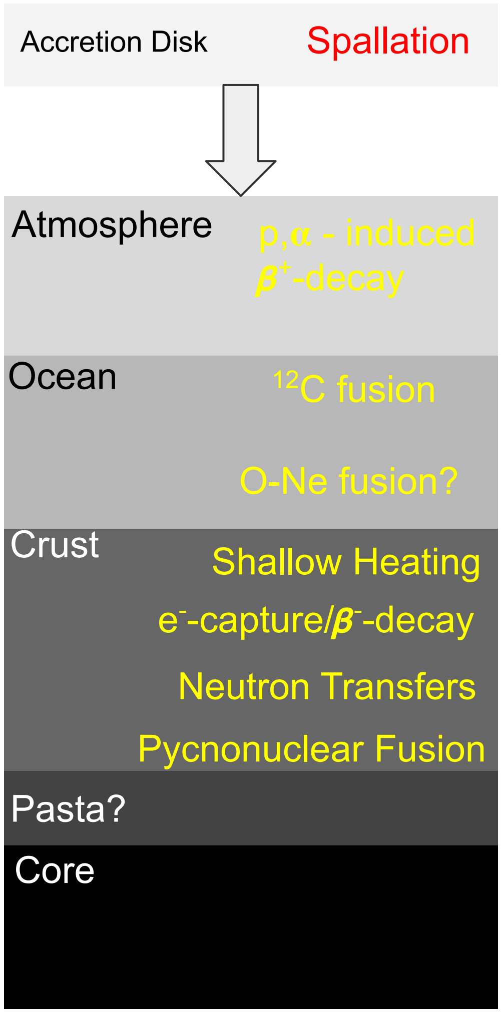
Pasta?

Core

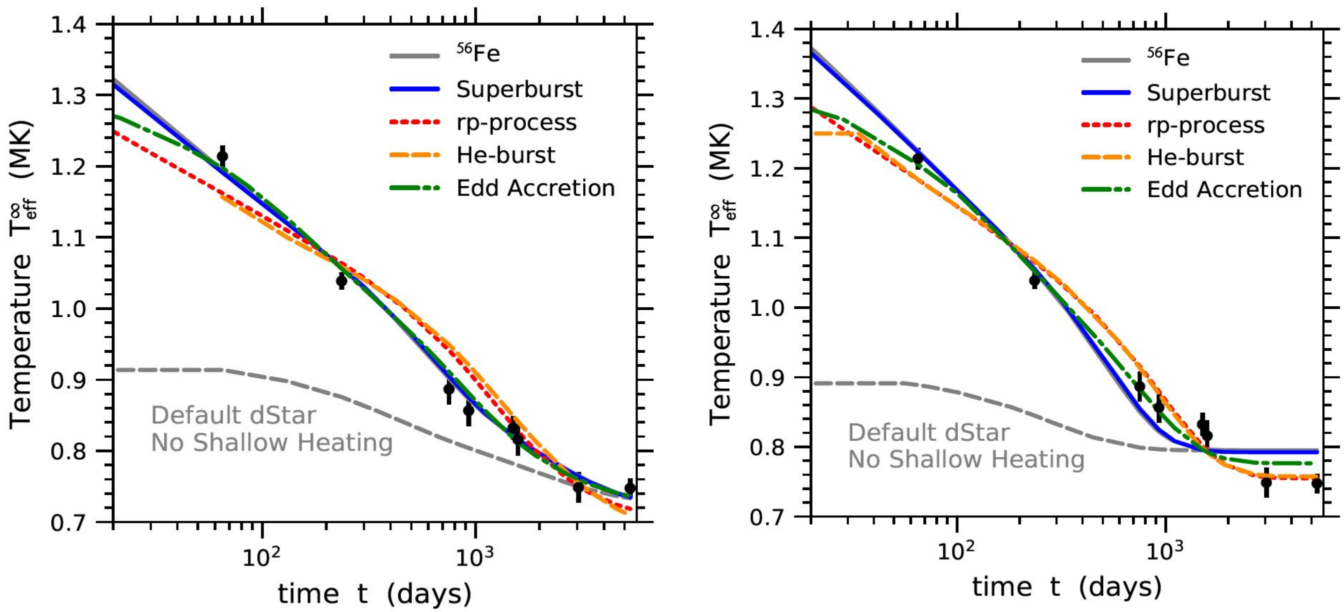


Caplan and Horowitz, Rev. Mod. Phys. (2017)

Nuclear Pasta?



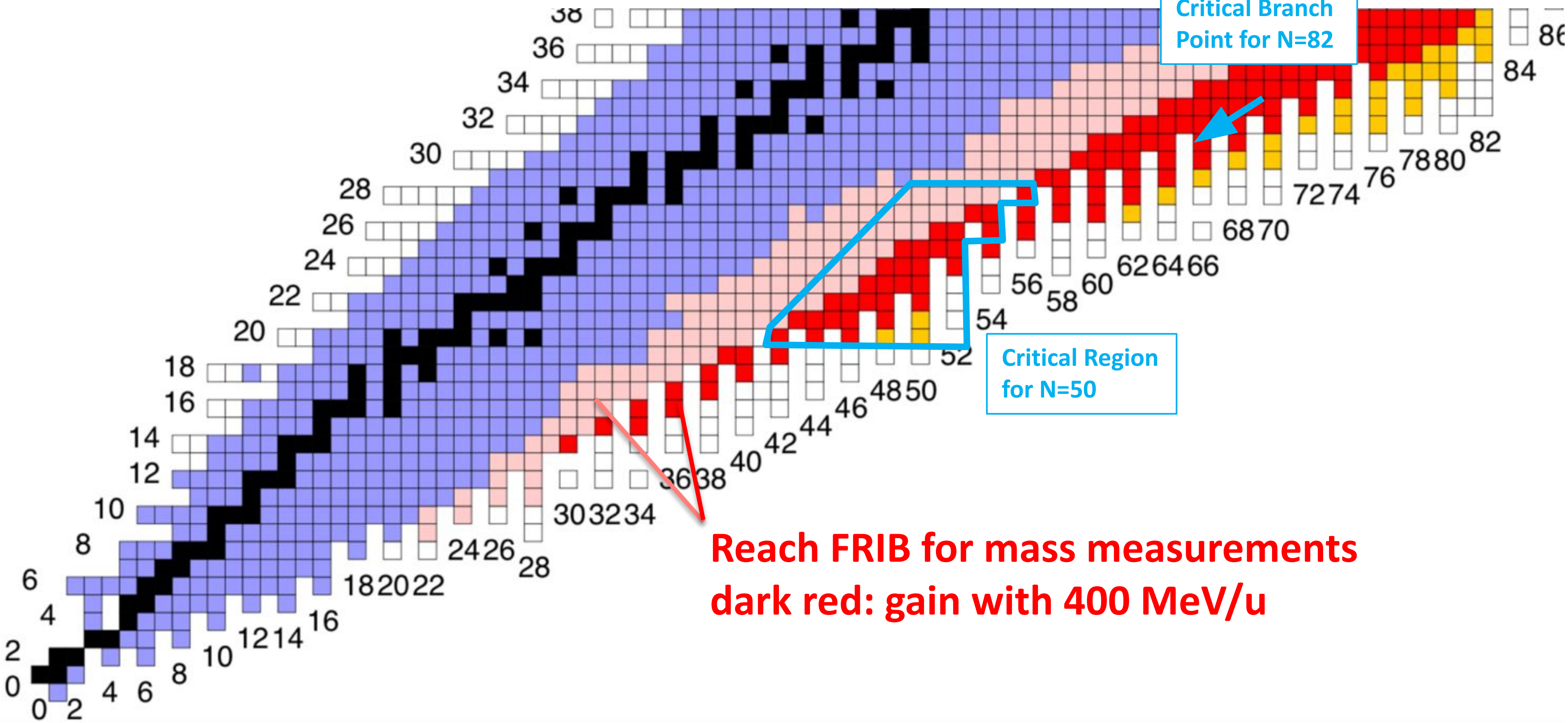
KS 1731-260



R. Jain et al., (in prep)

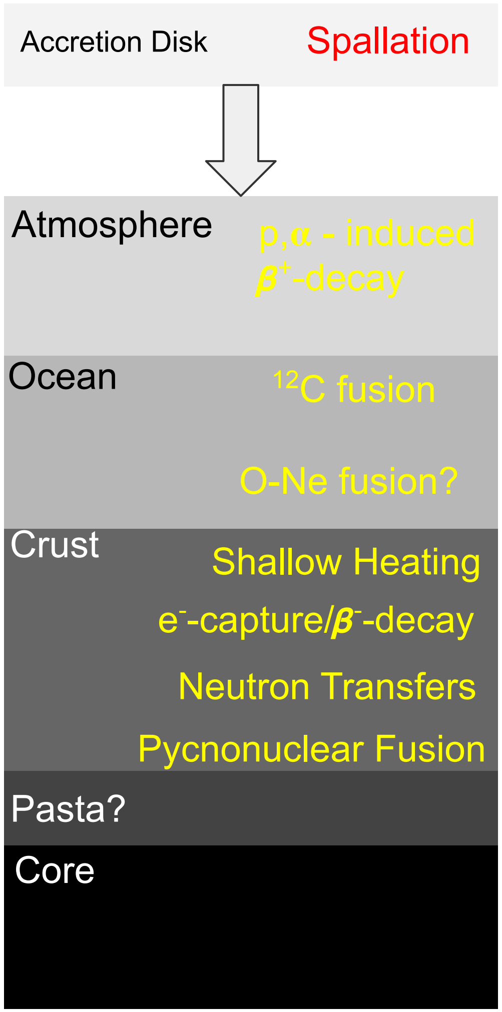
FRIB Outlook

Known masses



Reach FRIB for mass measurements
dark red: gain with 400 MeV/u

Summary



- Accreting Neutron Stars are interesting dynamical systems to test our knowledge of nuclear physics.
- Sensitive to both neutron and proton rich side of the valley of stability.
- Lots of uncertainties still exist!
- Many theoretical as well as experimental efforts forthcoming. Stay tuned.