The Thermal State of KS 1731−260 after 14.5 years in Quiescence

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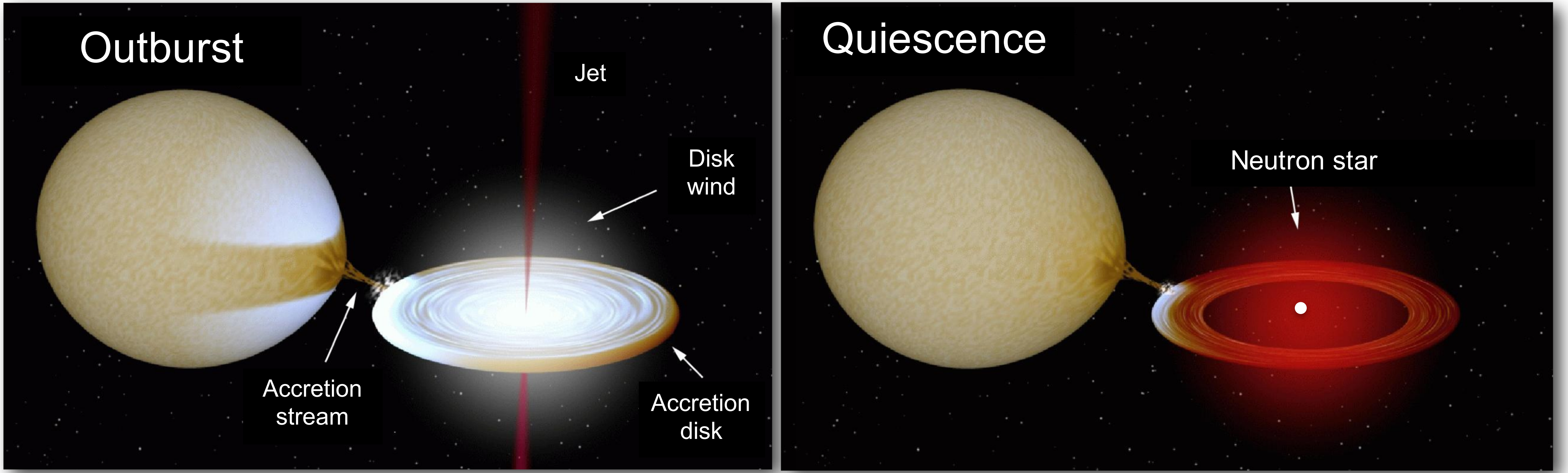
Low Mass X-ray Binary



Credit: R. Hynes

Deep crustal heating

- During outburst:
  - Electron capture
    - Releases ~0.5 MeV/nucleon
  - Pycnonuclear fusion
    - Releases ~1.5 MeV/nucleon

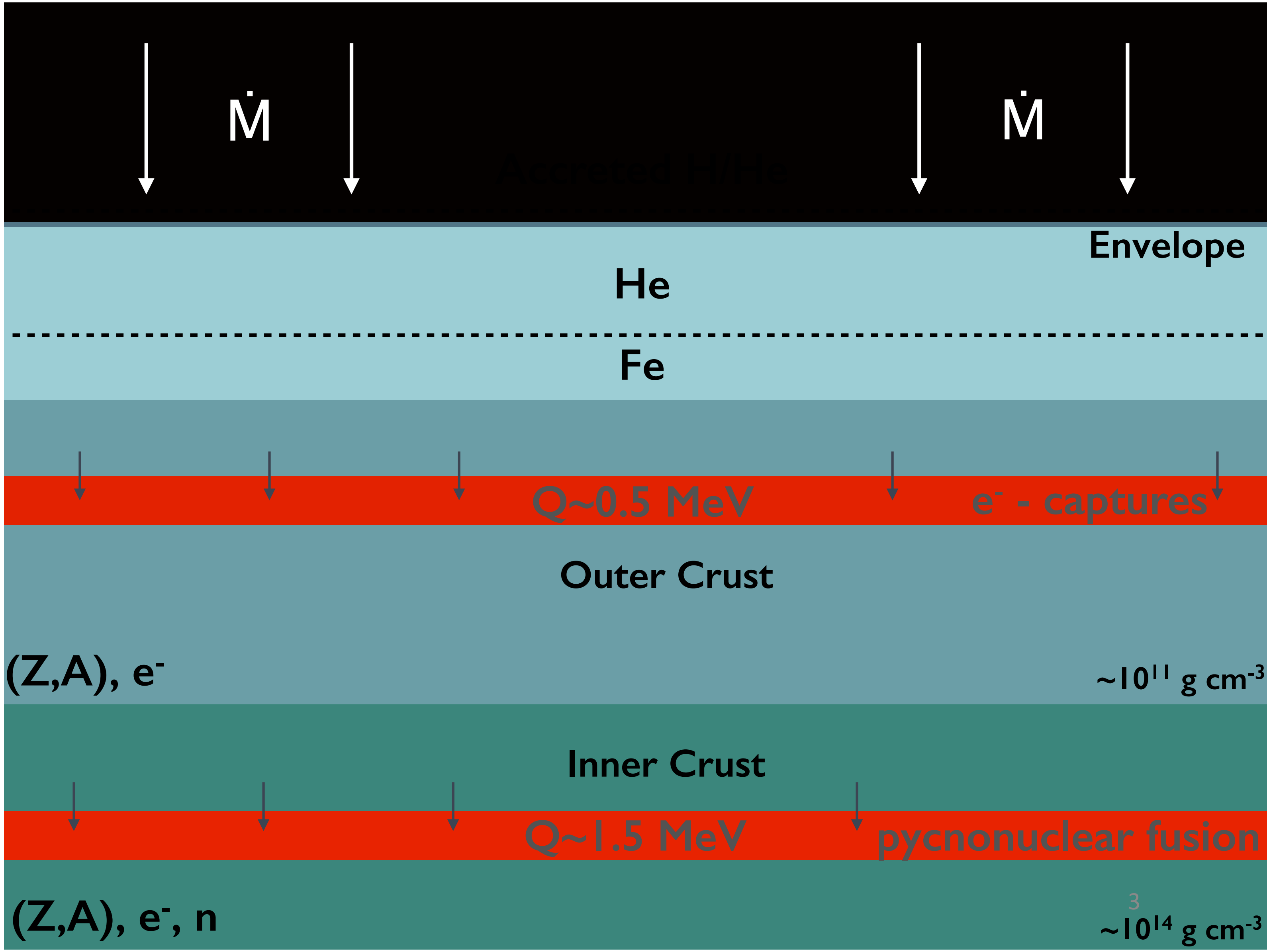
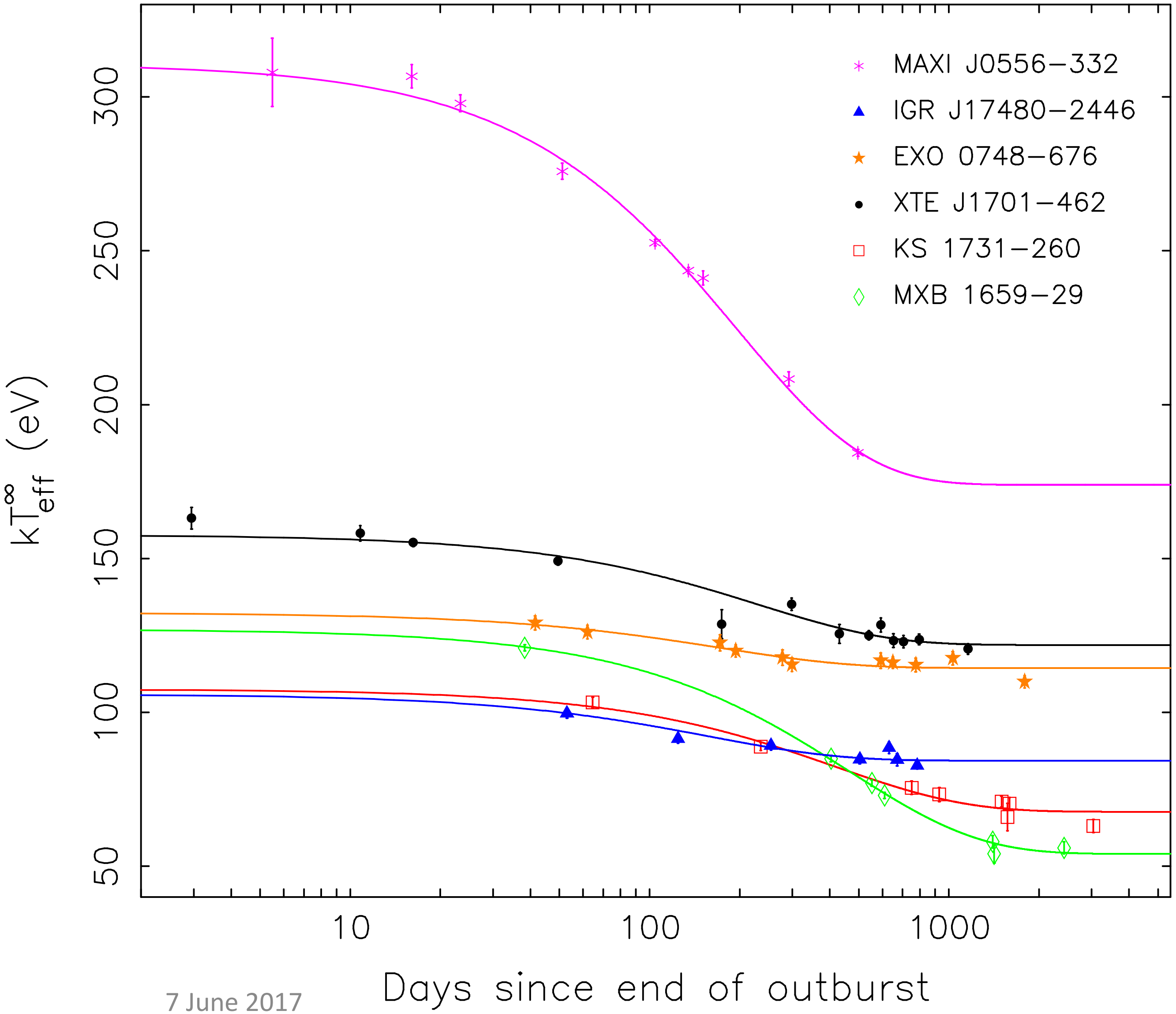


Image courtesy of Alex Deibel

Crustal cooling

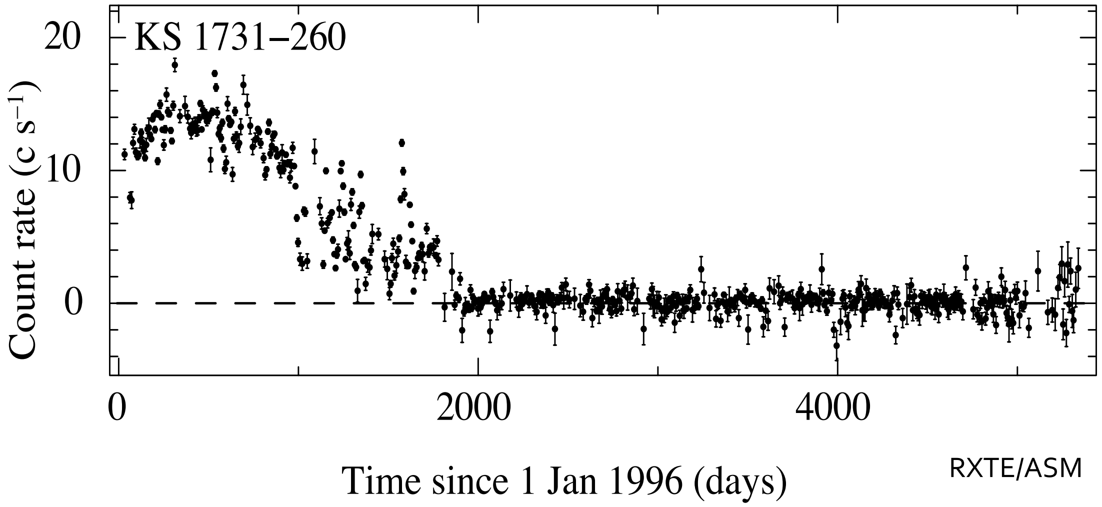


- Eight observed sources
- Similarly shaped cooling curves
- Variations in:
  - Outburst timescales
  - Initial quiescent temperatures
  - Cooling timescales

Homan et al. (2014)

KS 1731-260: A Brief History

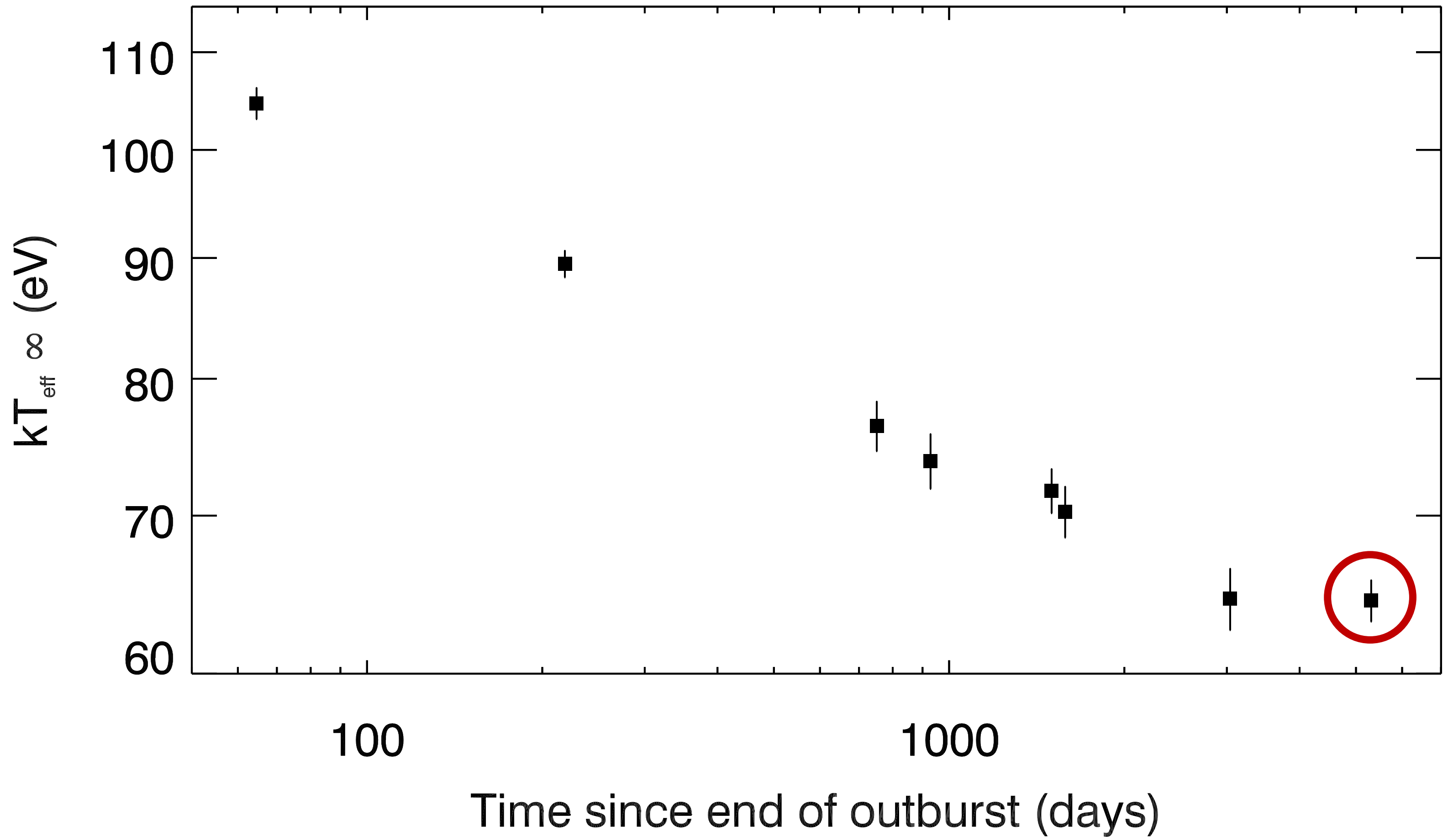
- Transient NS LMXB discovered in outburst by *Mir-Kvant* in August 1989 (also observed in October 1988)



- Returned to quiescence in early 2001
- Since returning to quiescence, 2 *XMM-Newton* (XMM) and 7 *Chandra* (CXO) observations (March 2001 - August 2015)
- Longest cooling baseline of any source to date
- Newest observation: Has crustal cooling stopped?

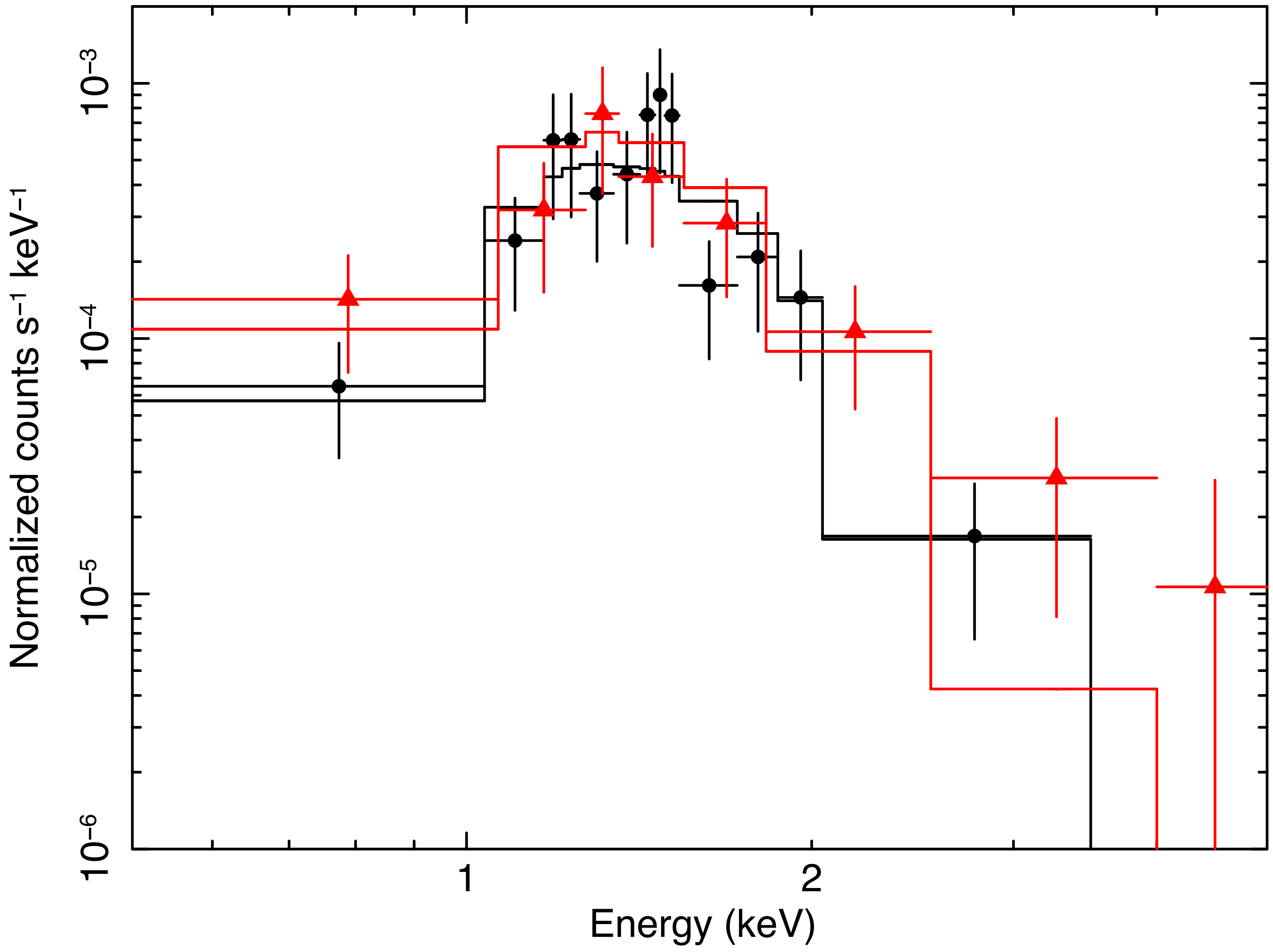
Newest Observation

RM et al. 2016
arXiv:1608.03880
ApJ



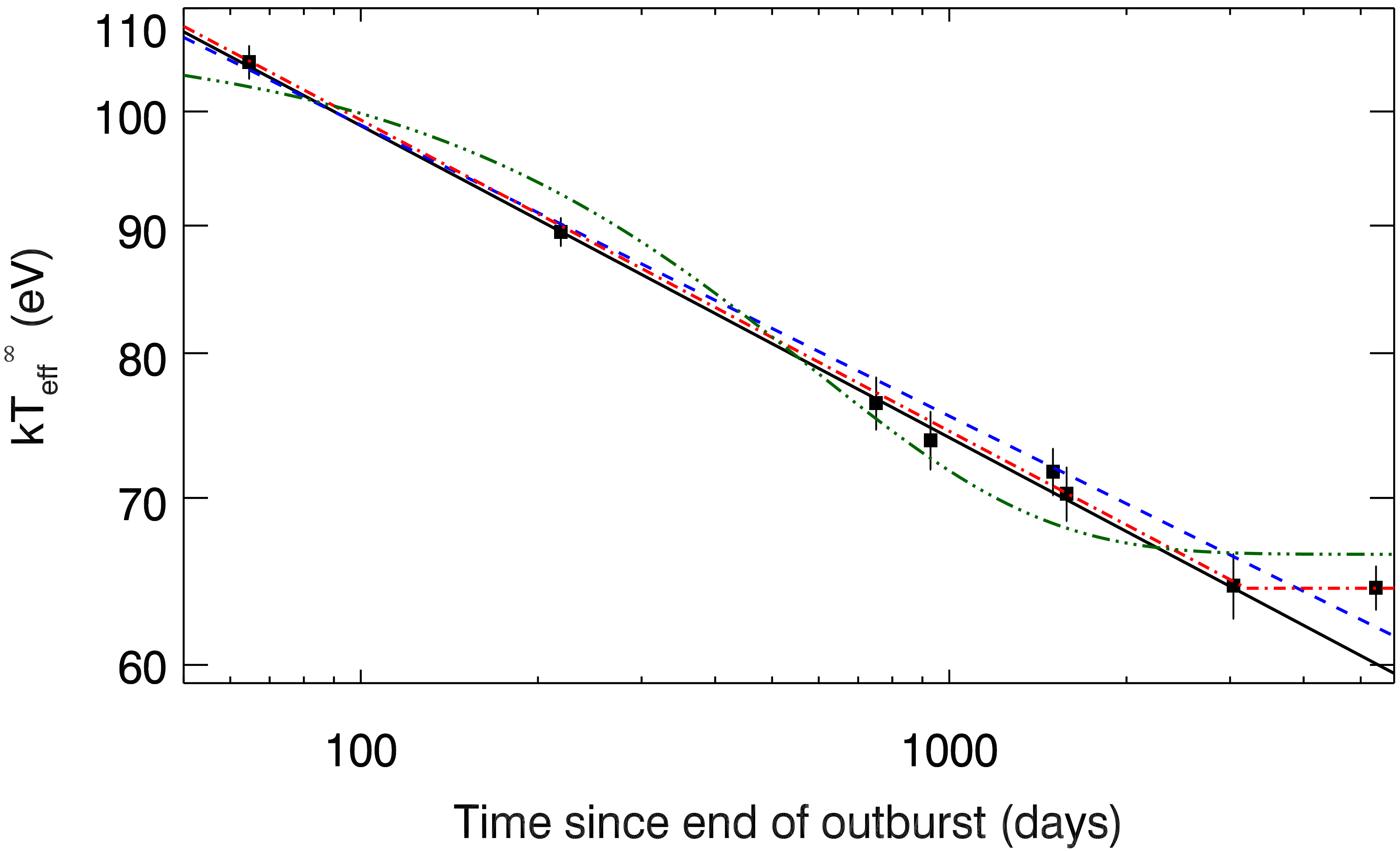
- 150 ks CXO observation, three separate pointings
  - 66 ks 2015 Aug 6/7
  - 20 ks 2015 Aug 8
  - 64 ks 2015 Aug 9
- Fit with XSPEC using `phabs*nsa` model
- **kT^{∞}_{eff} = 64.4 ± 1.2 eV**

Spectra Comparison



- X-ray spectra
  - May 2009 (**triangles**) versus August 2015 (**circles**)
- **2009: kT^{∞}_{eff} = 64.5 ± 1.8 eV**
- **2015: kT^{∞}_{eff} = 64.4 ± 1.2 eV**
- Consistent within 1σ
  - Crust/core thermal equilibrium reached?

Empirical Models



- **Exponential decay:** not a good fit
- **Power law:** χ^2=7.74 (dof=6)
- **Broken power law:** χ^2=1.26 (dof=5)
- **Extrapolated power law**: newest observation deviates at **3.5σ level**
  - Cooling has stopped?

Physical Models – The "Simple" One

- Model thermal evolution of NS using open-source code, **`dStar`**[1]
- Prior to modeling cooling, simulate 12.5 years of constant accretion at the rate $\dot{M} = 10^{17}$ g s^{-1} (Galloway et al. 2008)
- Modeled with and without a low thermal conductivity layer, which is consistent with nuclear pasta.
- Varied parameters:
  - Core temperature (T_c)
  - Impurity parameter
    - $Q_{\rm imp} \equiv n_{\rm ion}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2$
  - Additional shallow heating (Q_{sh})

Fixed parameters:

Crust composition (Haensel & Zdunik 1990)

Light element column depth – 10^4 g cm^{-2}

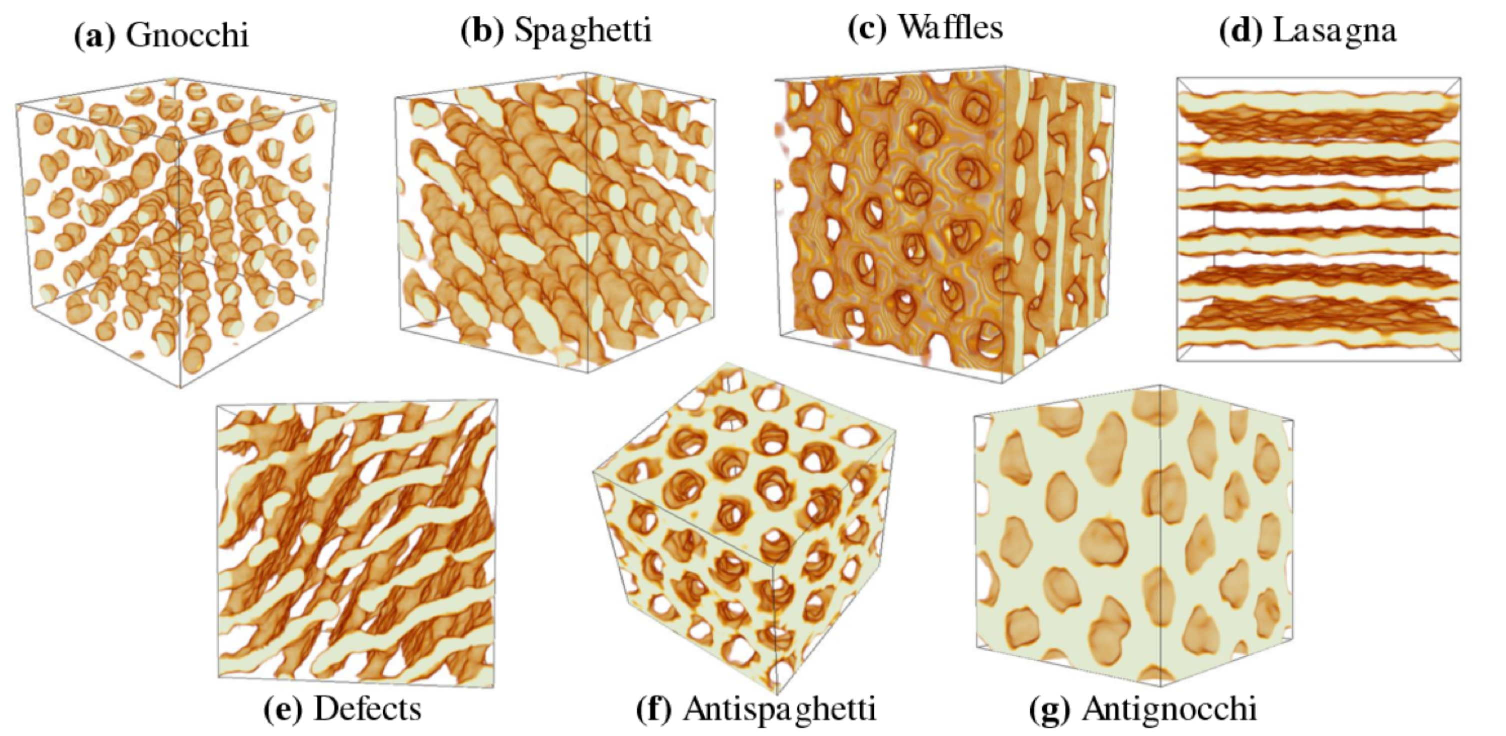
Crust-core transition density – 8.13×10^{13} g cm

Canonical mass and radius ($M=1.4M_\odot$, R=10 km)

Superfluid critical temperature in the crust (Schwenk et al. 2003)

[1] Brown 2015 – https://github.com/nworbde/dStar

Nuclear Pasta



Nuclear pasta configurations produced in molecular dynamics simulations with 51,200 nucleons
Schneider et al. (2013, 2014); Horowitz et al. (2015)

- Nuclear pasta is the result of distorted nuclei at high densities
- Presence of a pasta phase requires a greater temperature gradient to carry a thermal flux

Physical Models – The "Pasta" One

- Model thermal evolution of NS using open-source code, **`dStar`**[1]
- Prior to modeling cooling, simulate 12.5 years of constant accretion at the rate $\dot{M}=10^{17}$ g s^{-1} (Galloway et al. 2008)
- Modeled with and without a low thermal conductivity layer, which is consistent with nuclear pasta.

- Varied parameters:
  - **Impurity parameter of pasta layer ($Q_{imp,pasta}$)**
  - **Transition density to the pasta phase (ρ_{pasta})**
  - Core temperature (Tc)
  - Impurity parameter
  - Additional shallow heating (Qsh)

Fixed parameters:

Crust composition (Haensel & Zdunik 1990)
Light element column depth – 10^4 g cm^{-2}
Crust-core transition density – 8.13×10^{13} g cm
Canonical mass and radius ($M=1.4M_{\odot}$, R=10 km)
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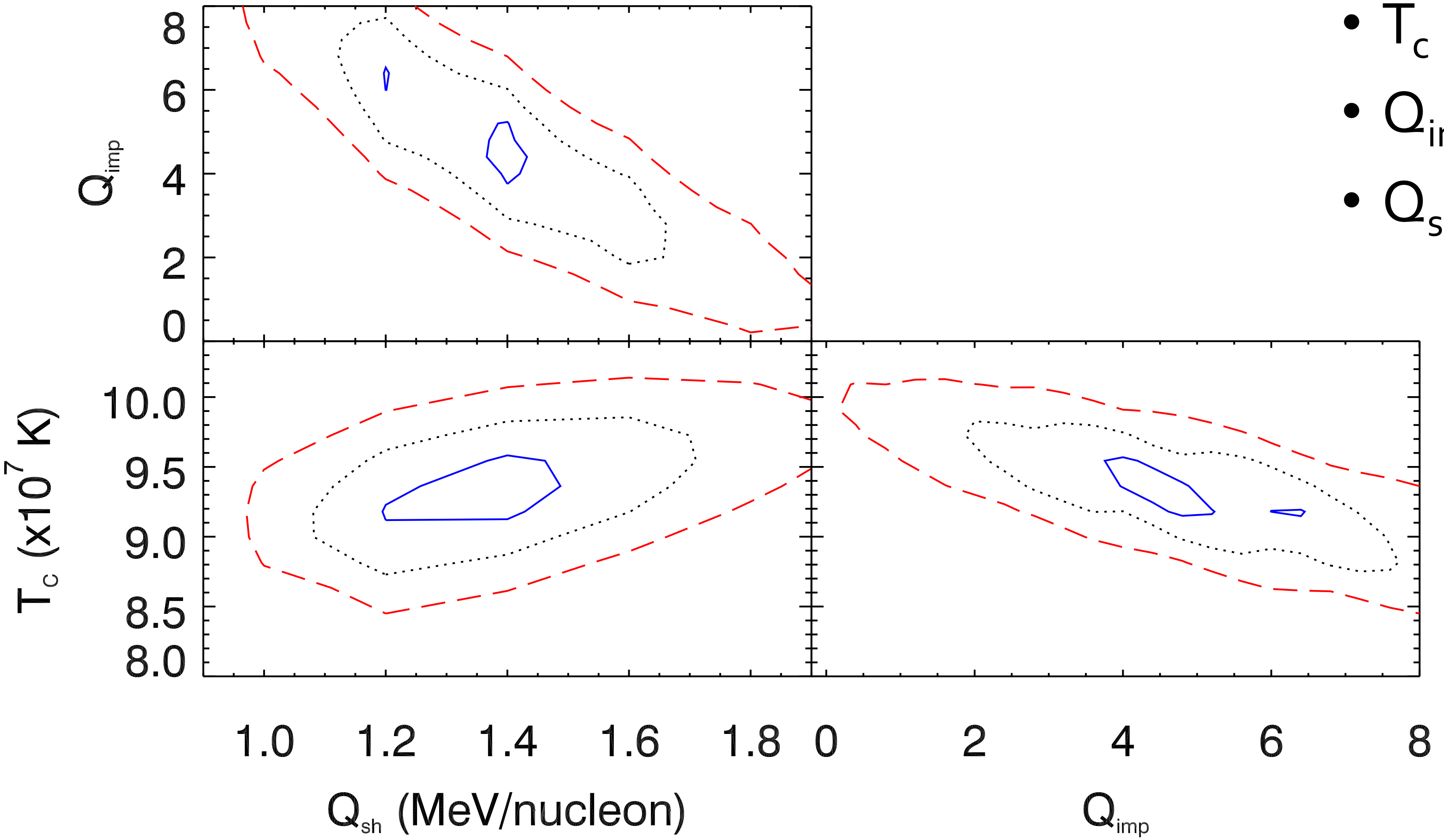
Parameter Space

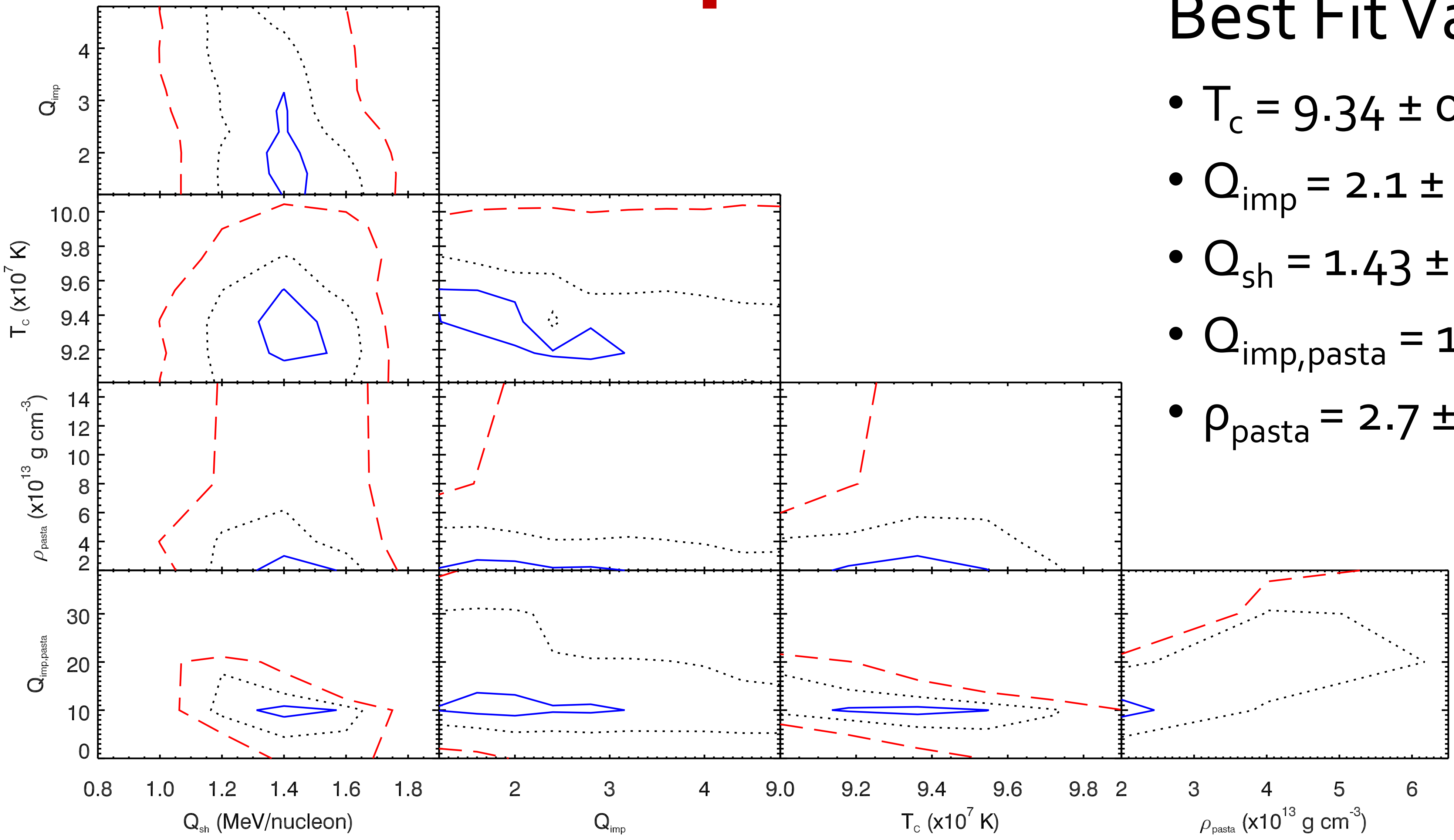


Best Fit Values:

- $T_c = 9.35 \pm 0.25 \times 10^7$ K
- $Q_{imp} = 4.42^{+2.2}_{-0.5}$
- $Q_{sh} = 1.36 \pm 0.18$ MeV/nucleon

1σ – solid line
2σ – dotted line
3σ – dashed line

Parameter Space

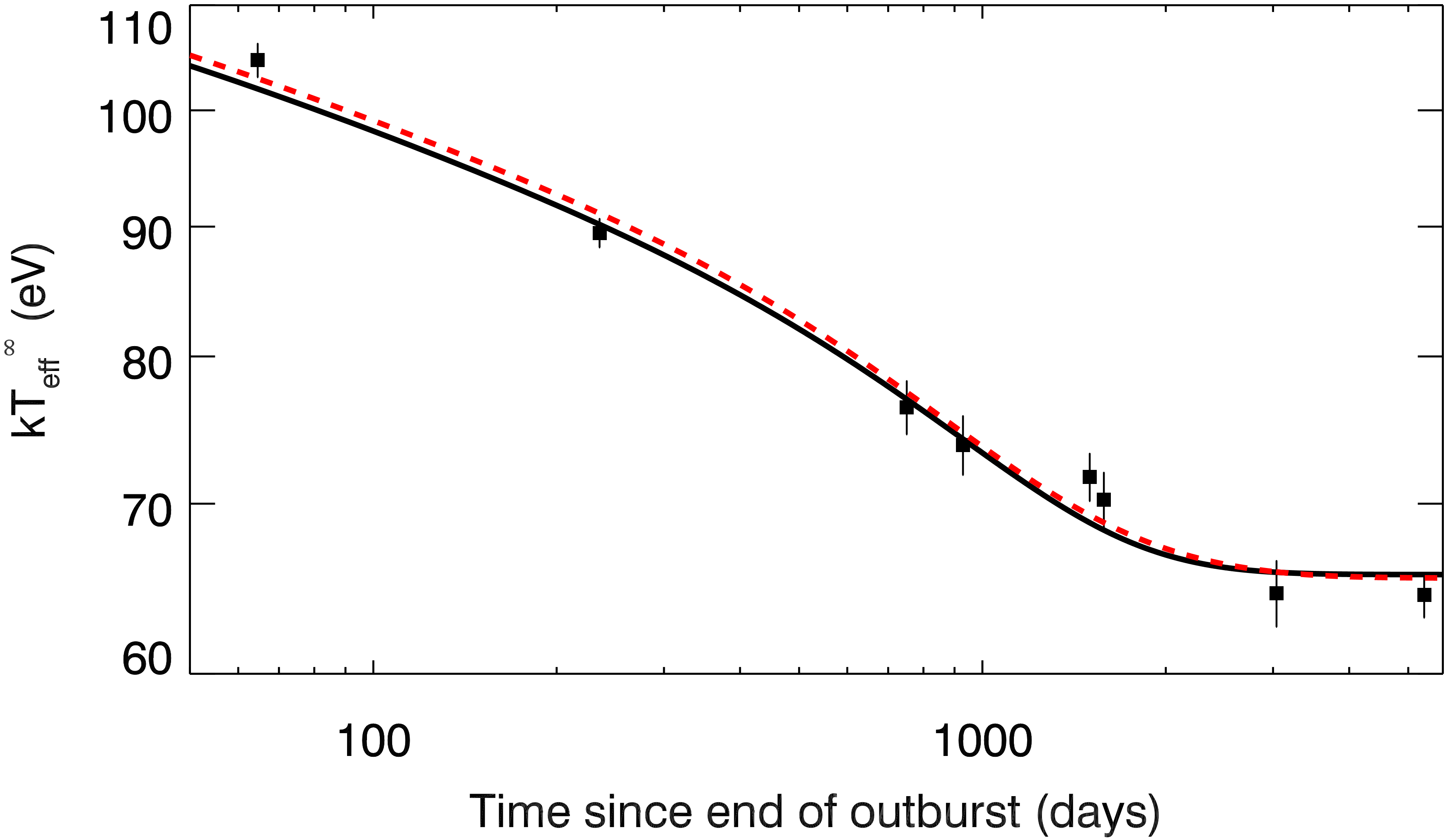


Best Fit Values:

- $T_c = 9.34 \pm 0.21 \times 10^7$ K
- $Q_{imp} = 2.1 \pm 1.0$
- $Q_{sh} = 1.43 \pm 0.15$ MeV/nucleon
- $Q_{imp,pasta} = 12.4 \pm 5.1$
- $\rho_{pasta} = 2.7 \pm 0.8 \times 10^{13}$ g cm^{-3}

1σ – solid line
2σ – dotted line
3σ – dashed line

Best Fit Models



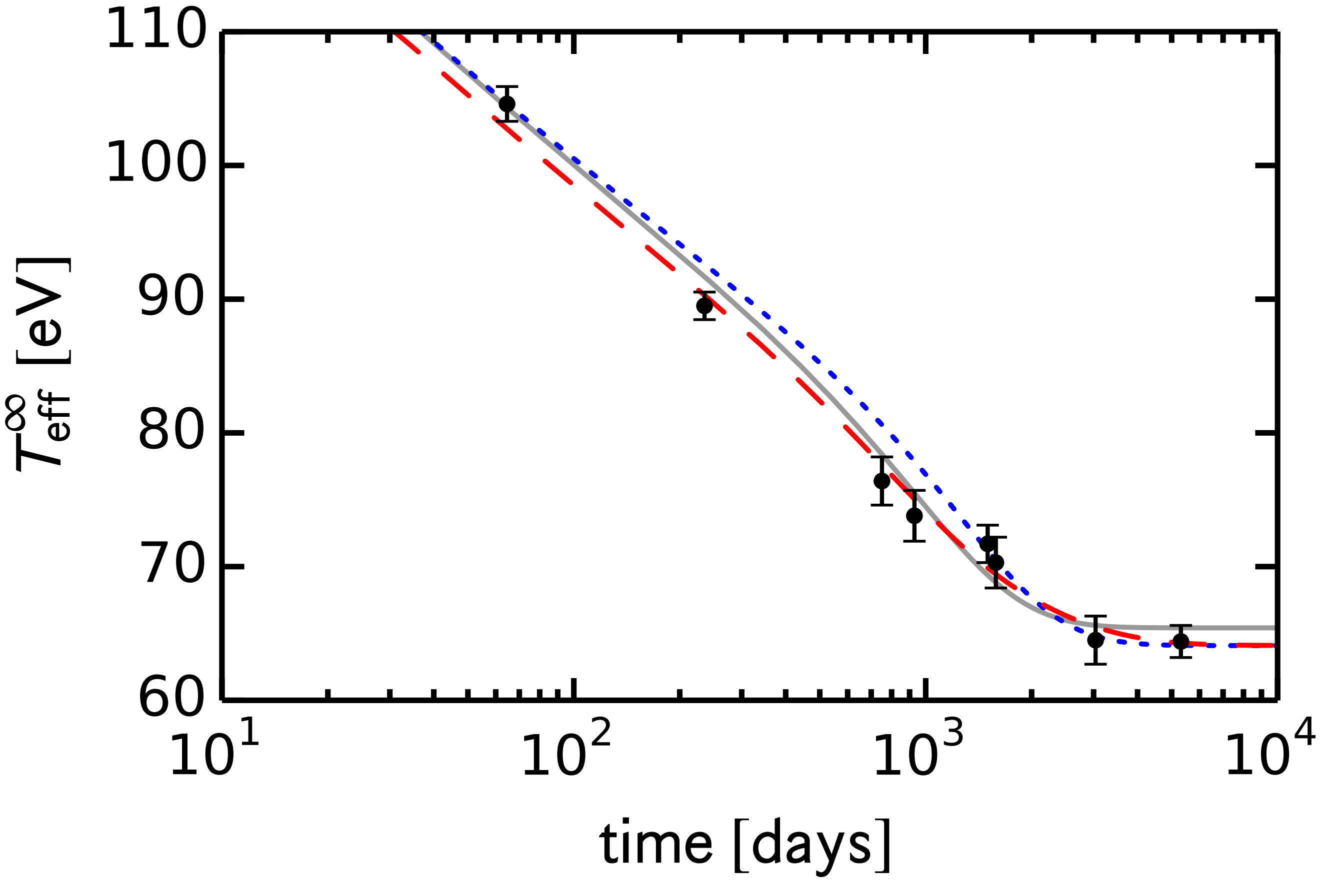
- No Pasta – **solid**
  - Reduced χ^2=2.00 (dof=5)
- With Pasta – **dashed**
  - Reduced χ^2=3.23 (dof=3)

Conclusions

- Newest *Chandra* observation gives $kT^{\infty}_{eff} = 64.4 \pm 1.2$ eV
  - Within 1σ of previous Chandra observation (2009)
  - Cooling has stopped?
- First time a full exploration of parameter space has been conducted
- Data fit equally well with or without a low thermal conductivity layer

Conclusions

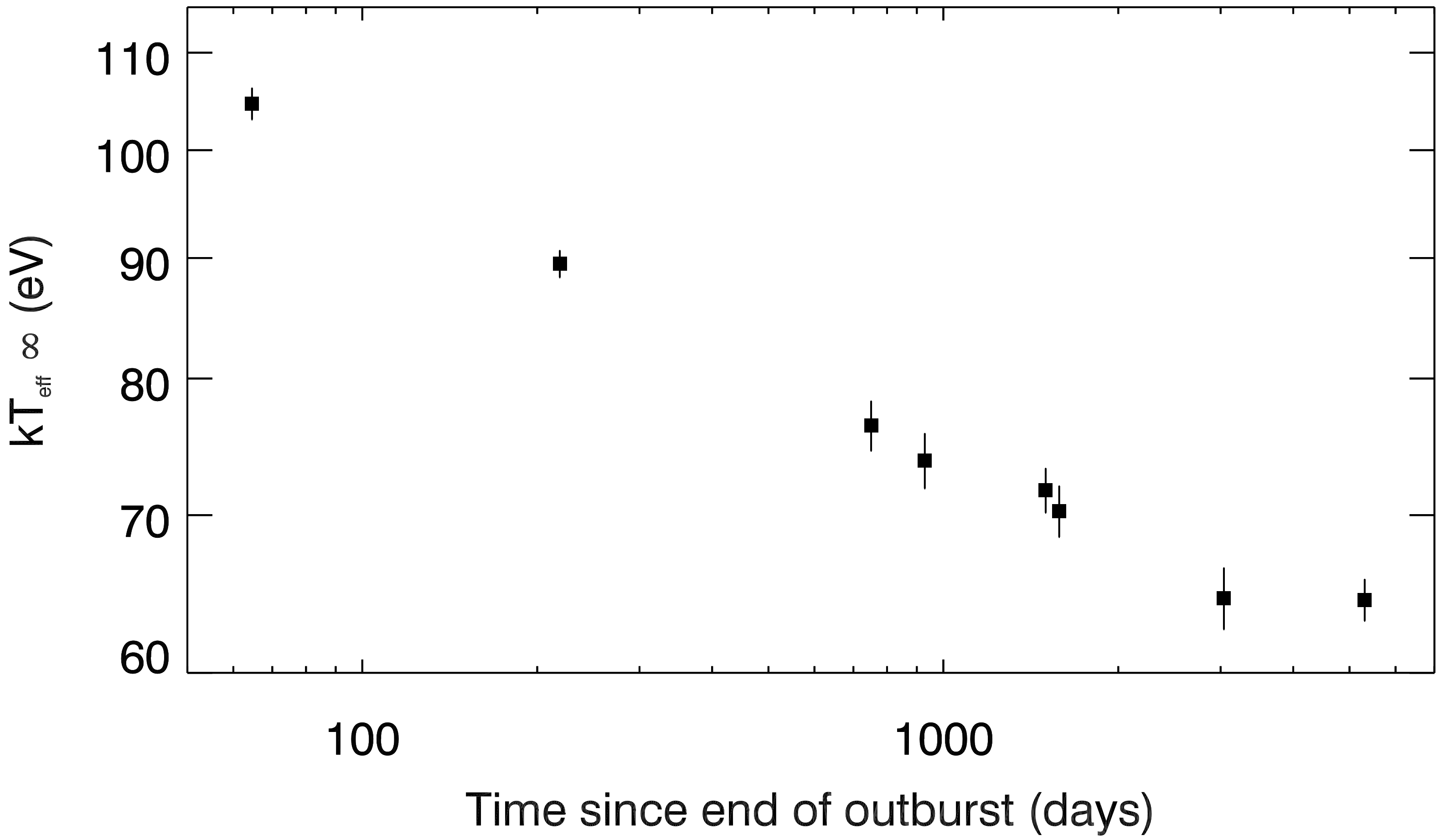
- Does superfluid critical temperature influence cooling curve?
  - (Yes. Deibel et al. 2016 arXiv:1609.07155)



Deibel et al. (2016)

Future Work

- Need another observation to verify cooling has stopped



Acknowledgements

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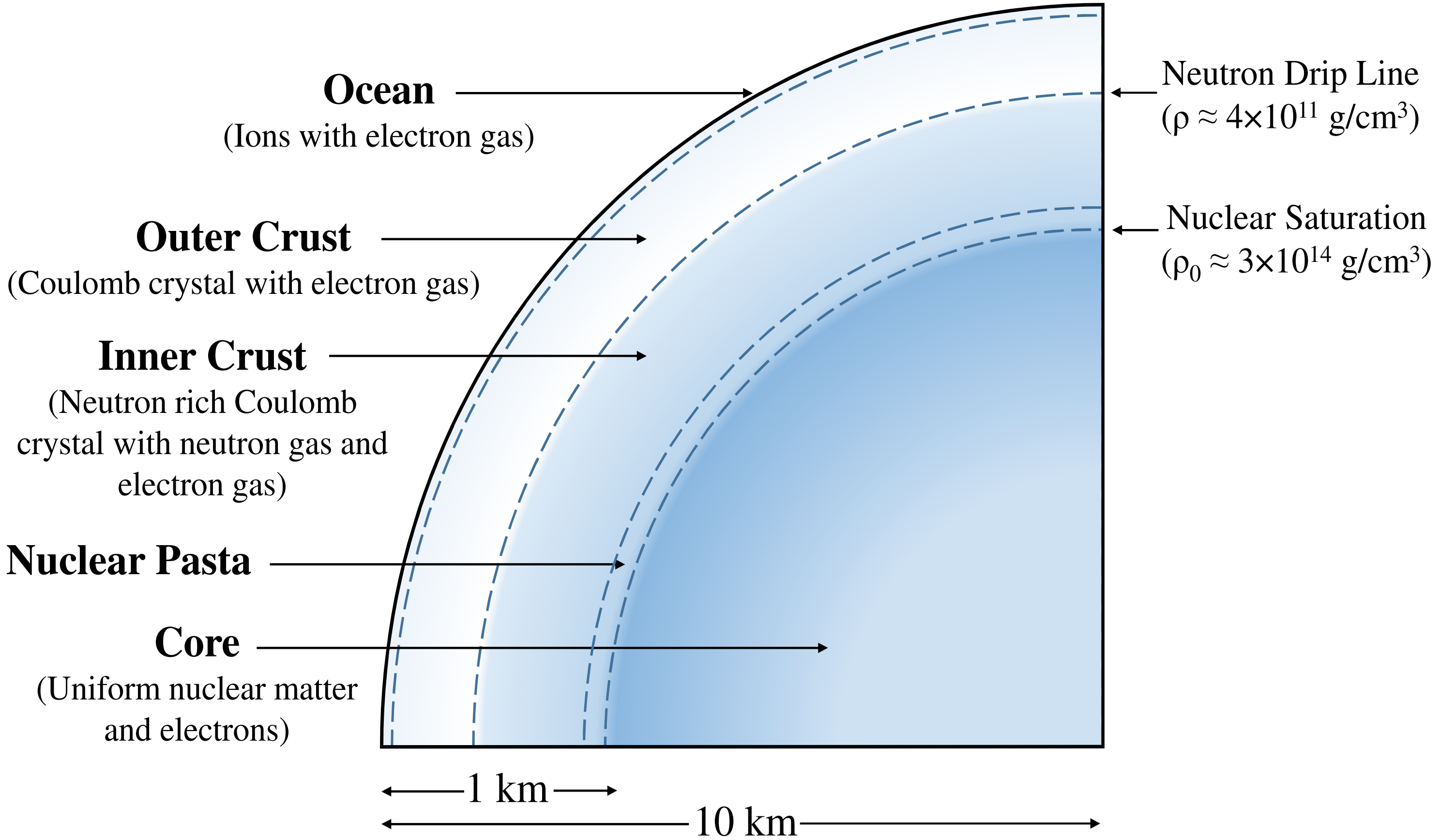
Thank you!
Questions?

Backup Slides

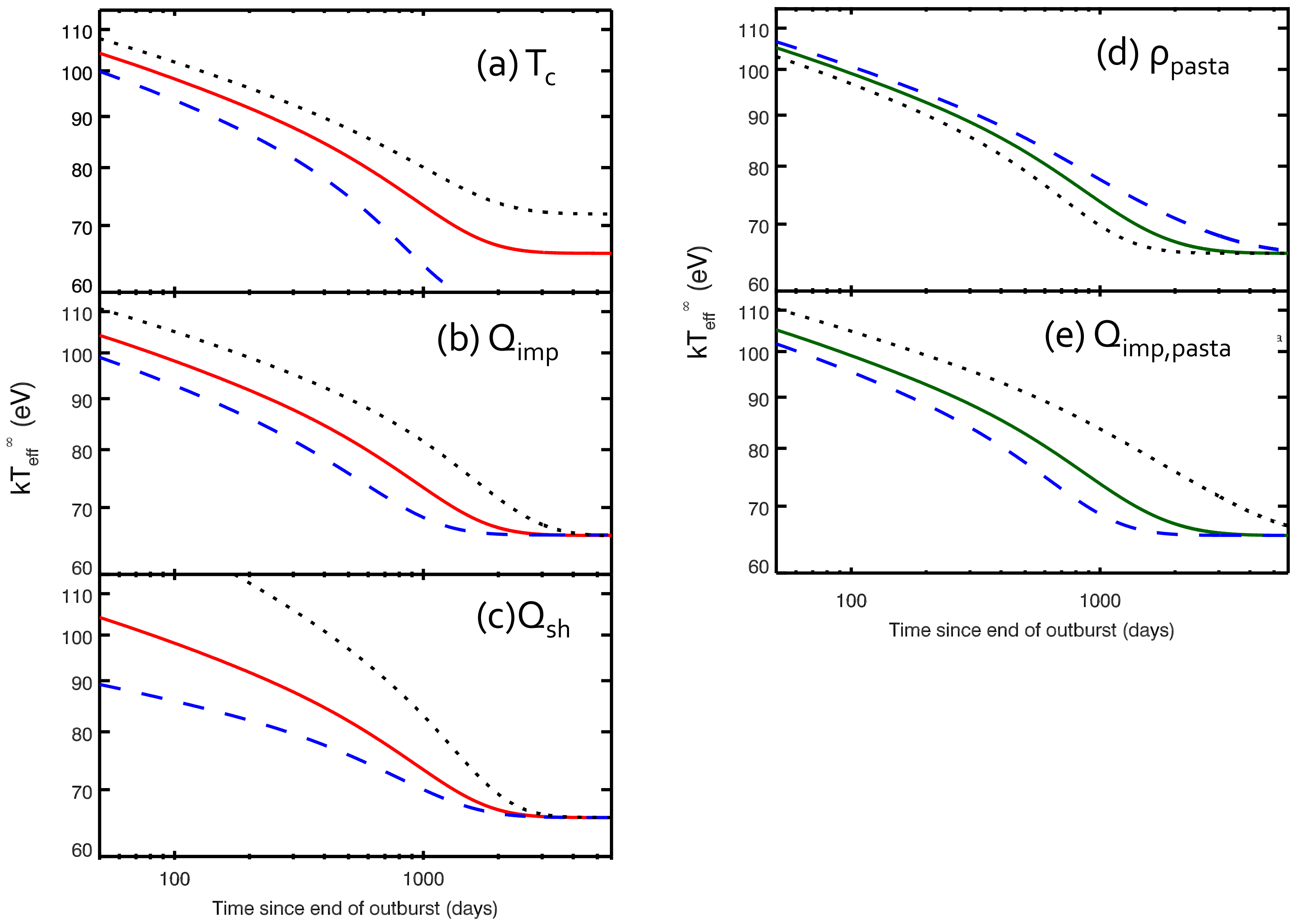
Neutron star structure

- Inner Crust
  - Few hundred meters
  - Superfluid
  - At $\rho \sim 10^{14}$ g cm^{-3}, Coulomb repulsion begins to distort nuclei
    - Nuclear pasta!



Caplan and Horowitz (2016)

Parameter Influences



- **Solid lines** – best fit model
- **Dashed lines** – lower parameter value
- **Dotted lines** – higher parameter value