Relativistic Plasma Screening Effects on Pulsational Pair-Instability Supernova, ~~Magnetars, Other Sites~~

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Screening and Weak Interactions in High-T, High-B Plasmas

Outline

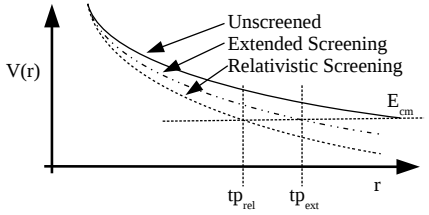
Published Preprints

- arXiv:2009.10925 - ApJ 904, 29 (2020)
- arXiv:2006.14148 - ApJ 898, 163 (2020)
- arXiv:2002.08636 - PRD 101, 083010 (2020)
- arXiv:1603.03137 - PRC 93, 045804 (2016)

Review: Nuclear Screening - Old Physics With New Applications

Plasmas Characterized by Debye Length: Shorter Debye Length = More Screening

Small shift in potential $\rightarrow$ big shift in r_{tp}

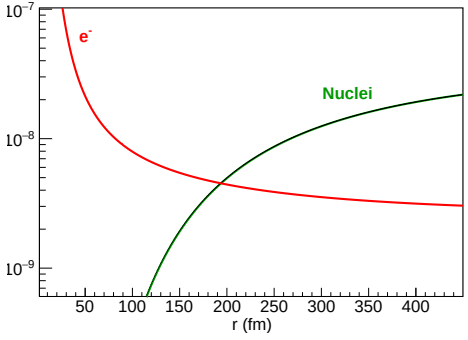


Weak Screening Length (Debye Length):

$$\phi_{scr}(r) = \frac{Ze}{r} e^{-\frac{r}{\lambda}}$$

$$\lambda \propto \frac{\partial n}{\partial \phi}$$

Charge Density vs. Radius



More charge means more enhanced screening, **regardless of the sign of the charge.**

For High Temperature in Plasma....

Everything starts with the charge density, n. (Electron charge densities shown.)

Classical Screening: MB Distribution

$$n = -Zn_z e \exp\left[-\frac{e\phi}{kT}\right]$$

Relativistic Screening: High-Temperature: Fermi-Dirac Screening

$$n = -\frac{e}{4\pi}\int_0^\infty d^3p\left[\frac{1}{e^{(E-\mu-e\phi)/T}+1} - \frac{1}{e^{(E+\mu+e\phi)/T}+1}\right]$$

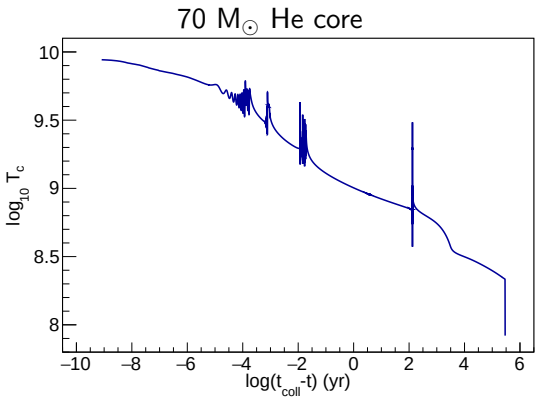
With B-Fields: Landau Levels

$$n = -\frac{eB}{2\pi^2}\sum_{\nu=0}^{\infty} g_\nu \int_0^\infty dp_z \left(\left[\exp\left(\frac{\sqrt{p_z^2+m_e^2+2\nu eB}-\mu-e\phi}{T}\right)+1\right]^{-1}\right) - n_+$$

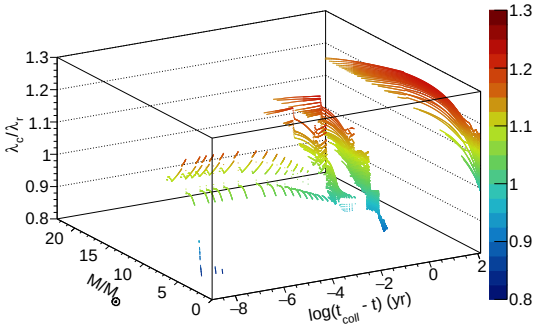
All of these change the Fermi-distribution, Pauli blocking factor, and λ_D.

Applicability of Relativistic Screening to PPISN

Ratio of Screening Lengths: MESA Time Steps Larger $\lambda_c/\lambda_r \rightarrow$ More Enhanced Rates



Each dot is a mass element at a time step.
Only kT>150 keV shown.

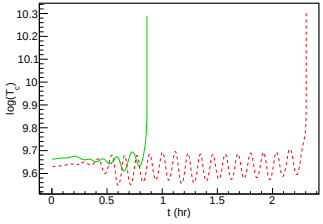


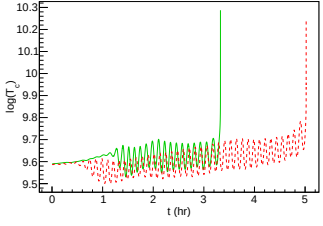
MESA simulations adapted from Marchant et al. (2019).

Pulse Morphology: First Pulse

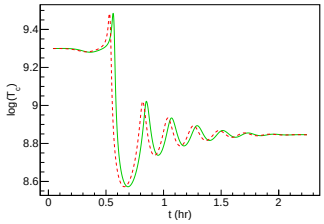
First Pulse: 44, 44.5, 70, 76, 89, 89.02 $M_\odot$, Increased Heating, ^{16}O Burning

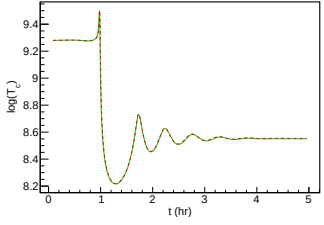
DC-PPISN Boundary



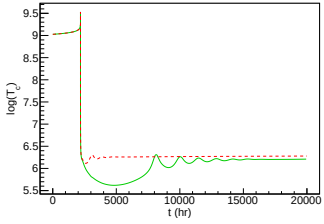


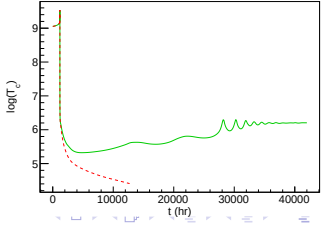
"Intermediate" M_{prog}





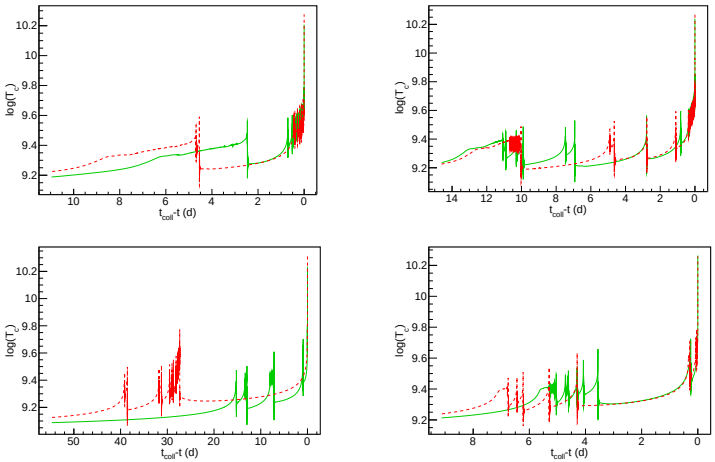
PPISN-PISN Boundary





Pulse Morphology: Last Pulse

Final Pulse: 52, 58, 64, 70 $M_\odot$ He Core - Small Changes in Overall System Stability



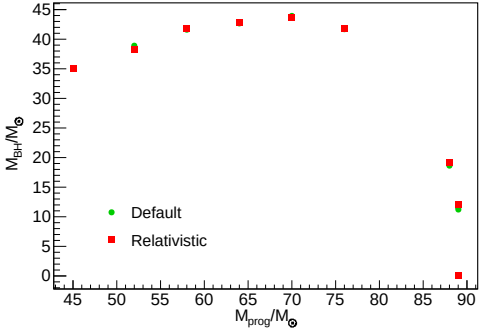
Instabilities

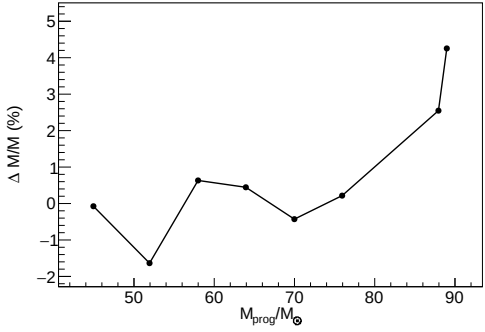
- Some changes in overall pulse morphology.
- NOTE: $t_c - t$: all final points set to zero.
- Pulsational phase can have slight increase in heating.
- System instability affects T_c where system leaves pulsational period.

Famiano et al. (submitted)

Black Hole Masses

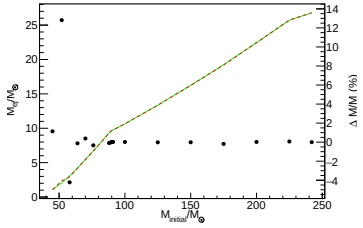
Small change in BH mass and **slight** shift in PPISN-PISN boundary. However, overall change is likely not greater than numerical uncertainties of model.

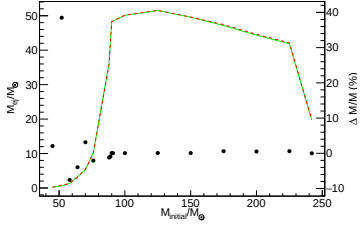




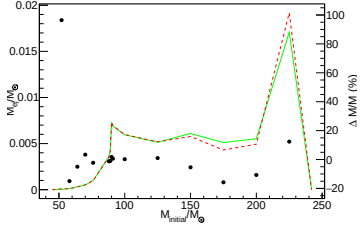
Nucleosynthesis and Ejecta

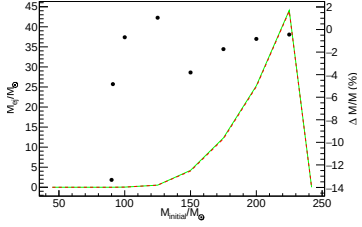
PPISN: Winds (top: ^{12}C, bottom: ^{16}O)





PISN: Explosion (Top ^{56}Fe, bottom: ^{56}Ni)





Ejected Mass

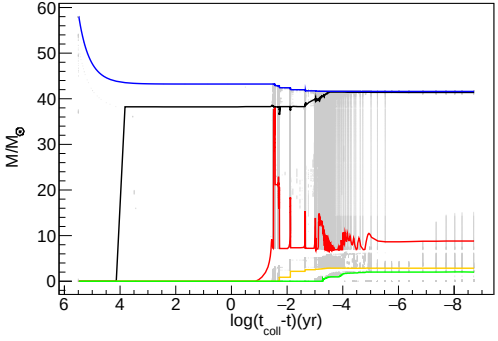
- Light elements: "Large" differences in pulsational ejections
- Little difference in PISN: Entire mass of star is ejected.
- Fe-group elements: Some difference in PISN ejection: Core burning.

Stellar Evolution

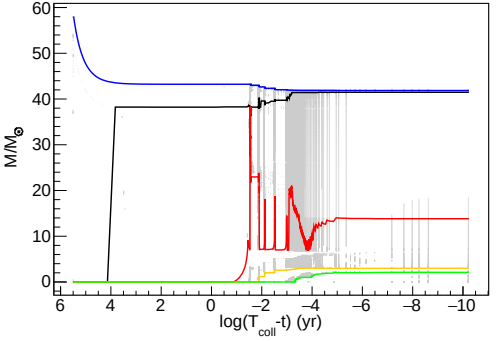
Kippenhahn Diagram: 58 $M_\odot$ He Core, Surfaces defined where $X<10^{-2}$.

He, C, O, Si

Note large convective region at pulsation. C/O boundary more extreme changes.



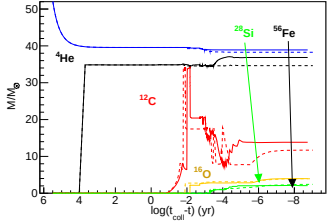
Classical screening.

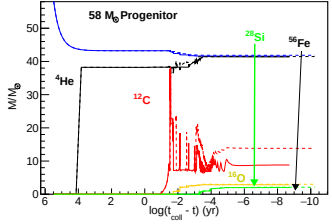


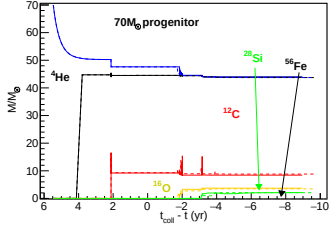
Relativistic screening.

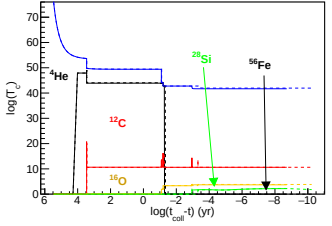
Stellar Evolution

Kippenhahn Diagrams: 52, 58, 70, 76 $M_\odot$ He Core









Compare Diagrams

- Solid: Default, Dashed: Relativistic
- Mass loss (blue line) may differ slightly. Wind sensitivity for He shell.
- Differences in pulse periods (hot T)
- Largest sensitivity for C/O boundary in lighter stars.

Conclusions

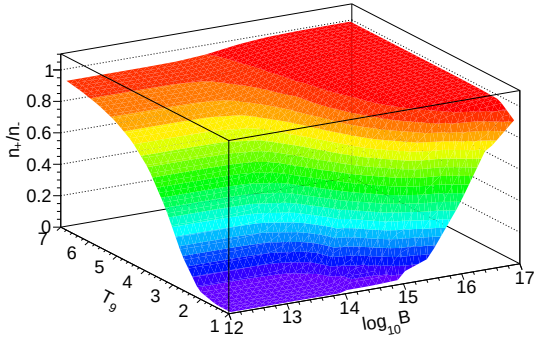
Conclusions

- Very little sensitivity of final black hole mass to screening model.
- Have not addressed strong screening yet. (Default screening in the core.)
- Some changes in ejected mass from increased heating, changes to core boundaries.
- Reduce temperature range of numerical model.
- Currently working on high B-fields in n-star and PNS cooling. Relevance to "lower" BH mass gap?
- Advertisement: Other sites include collapsar nucleosynthesis, BBN, magnetar surfaces. Weak rates and screening at high-B.

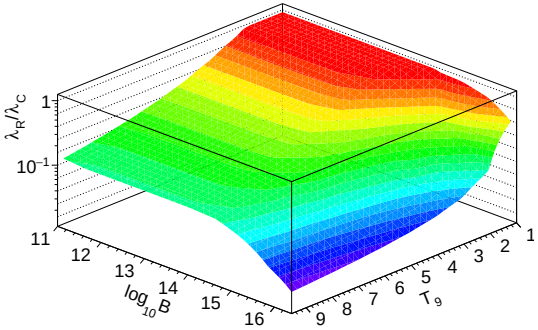
Work supported by NSF PHY-1204486 and PHY-1712832, NASA Grant #80NSSC20K0498 an NAOJ Visiting Professorship, and the Fulbright Program

Are Relativistic Effects Important?

Positron-Electron Ratios and Screening Length Ratios: More Charge → More Screening



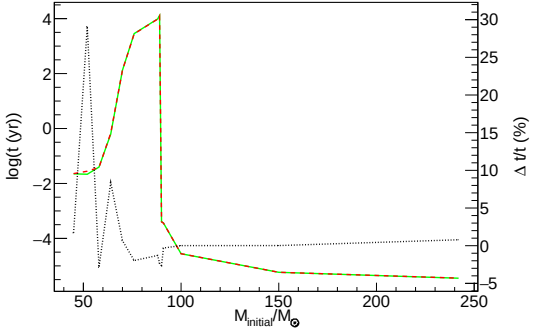
Positron/electron ratio vs. T_9 and B.
$\rho = 10^6$ g cm^3, $Y_e = 0.5$.
Chemical potential changes.
Famiano et al., ApJ (2020)



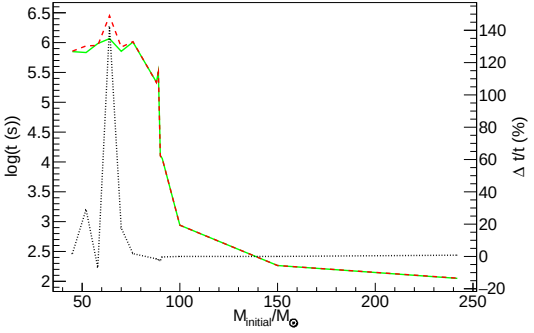
λ_R/λ_C vs. T_9 and B
(Note: just showing electron screening length only.)
Shorter screening length →Stronger Screening

Collapse Time

Overall trends reflect instabilities in models.



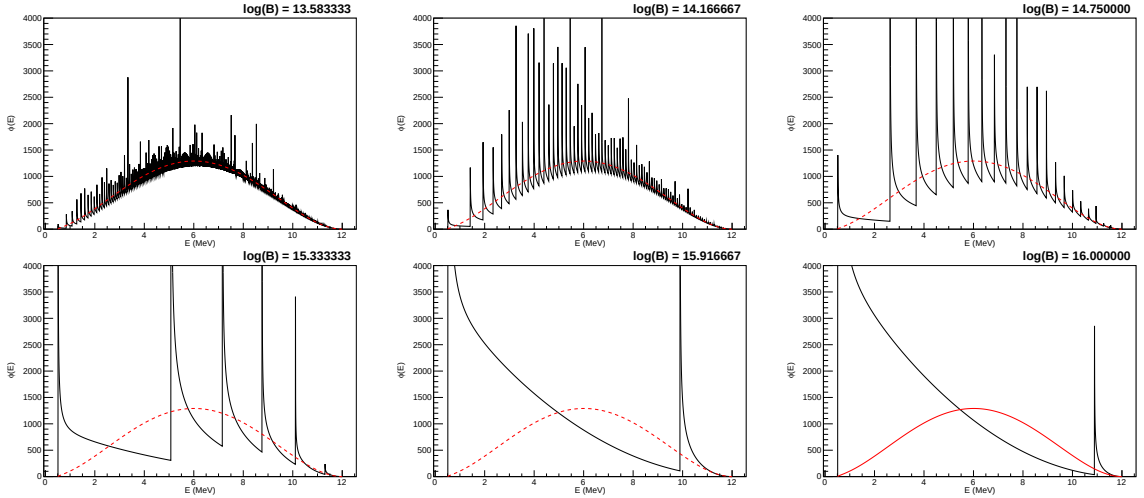
Total time from first pulse to collapse/explosion.



Total time at kT $>$ 150 keV.

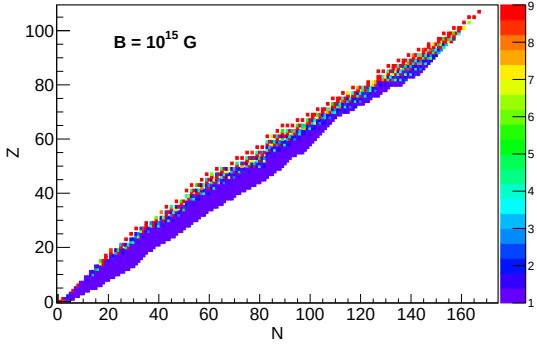
Beta-Decay Integrands

Electron Spectrum of β Decay for Q=12 MeV: Fermi Function and Pauli Blocking in Weak Interactions

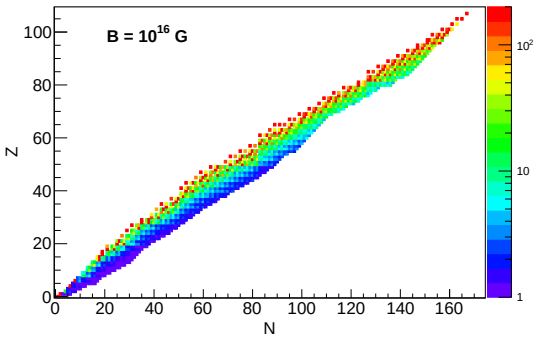


β^--Decay Ratios in Collapsar Environment

$\rho = 10^6 gcm^{-3}$, $Y_e = 0.5$, Fermi Theory....



$eB \lesssim Q$: Little change.

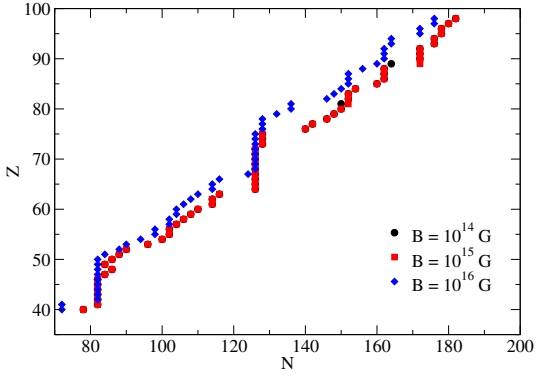


$eB \gtrsim Q$: More significant change.

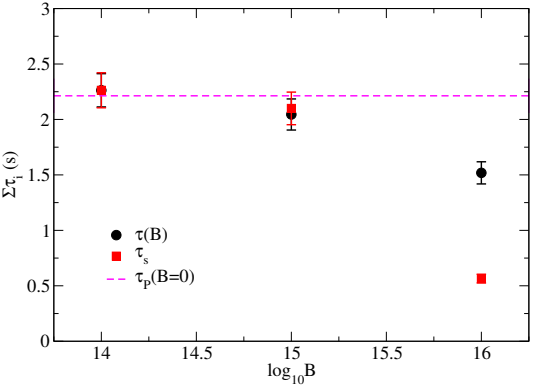
Increased Decay Rates Shift the r-Process Path (Collapsar Model)

Faster Decay Rates, Shift in Path, Also Fission Cycling Time Changes

r-Process Path When $Y_{Cf} > 10^{-20}$



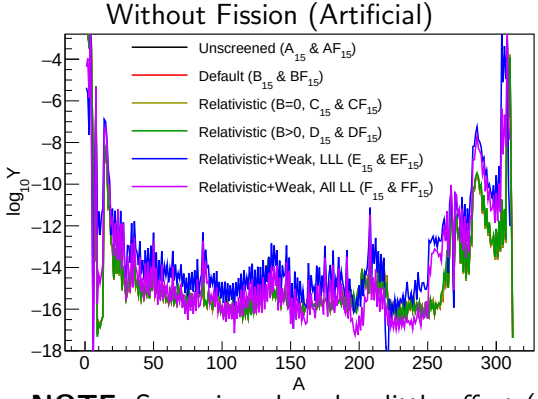
Fission Cycling Time

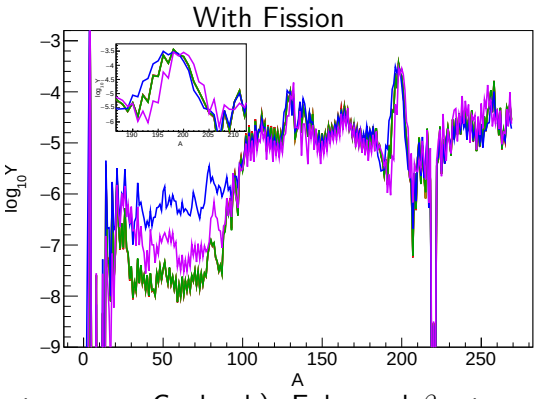


Famiano et al., ApJ (2020), Nakamura et al., A&A (2015)

Collapsar Nucleosynthesis

r-Process Abundance Distribution, B = 10^{15} G





NOTE: Screening alone has little effect (n-capture = no Coulomb). Enhanced β rates has a noticeable effect, including shift in peaks. Fission is necessary!

Characterizing a Collapsar r-Process Site by Field and Fission

Galactic Chemical Evolution?

Sr/X Ratios

$$R \equiv \frac{(Y_{Sr}/Y_X)_B}{(Y_{Sr}/Y_X)_{B=0}}$$

- How do ratios change with B.
- Shifts can be dramatic as abundance peaks shift (e.g., Dy).
- Also heavily dependent on fission model.
- Can be used to characterize a single-site r-process?