Hadronic-to-Quark-Matter Conversion in Neutron Stars

Recent Developments
and
Astrophysical Implications

Rachid Ouyed (Univ. of. Calgary)

CSQCDV, GSSI & LNGS, May 26, 2015

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Content

Simulation of the ……………… Hadronic → Quark matter transition

5 minutes

What has been done, what we have learned

A consensus ?

Quark-Nova (QN) simulations: *a numerical challenge*

15 minutes

Burn-UD in 1D

Burn-UD in 2D & 3D

The Hyrdro-Neutrino intimacy

Burn-UD

Quark-Novae (QNe) in Astrophysics : *predictions, predictions, predictions*

15 minutes

Implications to Nuclear Astrophysics

Neutrino signal? *contribution to core-collapse SNe?*

GW signal?

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Early Work:

Baym et al. (1985)
Alcock et al. (1986)

Olinto (PLB 192, 71 (1987)): 1D Reactive-Diffusive
Diffusion of massless strange quarks across a *zero-width* interface

Rapid (0.1ms) conversion

Compression shock Prior to deflagration

Horvath & Benvenuto (1988), Cho (1984), Lugones (2002), Drago et al., ApJ 659, 1519 (2007)

Strong deflagration

Hydrodynamics with jump conditions

Recent Efforts/Simulations: *not all cited/referenced*

Group	2-step conv.	Weak deflag	Strong deflag	Detonation	Key idea
Olinto et al.		x			*Diffusion of seed gives combustion*
Heiselberg et		x			*Diffusion of seed gives combustion*
Olesen et al.		x			*Diffusion of seed gives combustion*
Benvenuto …				x	*Deconfinement leads to shock induced detonation*
Niebergal …			x		***Hydrodynamics and microphysics***
Herzog et al.			x		*Macroscopic Hydro instabilities*
Bhattacharry	x			x	*Advocate for 2 step conversion*
Mishustin …				x	*Front velocity depends on hadronic matter velocity*
Cho et al.				x	
Tokareva et al				x	*All combustion modes are possible*
Lugones et al.	x			x	
Drago et al.			x		*Mixed phase*
Furusawa …	x			x	*Strong detonation in exothermic and endothermic regimes*

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- *If one uses ONLY jump conditions, one is assuming that only fluid pressure differences matter.*

- *NEUTRINOS change the temperature profile at the interface and ALTER the jump conditions quite a bit !*

- *Non-premixed (i.e. diffusion-driven not heat-riven).*

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The Burn-UD code:

Latest upgrade

In pre-mixed, oxidant and fuel are mixed and they react when the mixture becomes hot enough.

Flame propagation is mostly controlled by heat transfer!

Heat is relatively fast and efficient.

Non Pre-mixed combustion is chemically driven and diffusion combustion is hydrodynamic. I.e. flame driven by diffusion, so hydrodynamics needed.

Even if temperature rises, there won't be combustion until fuel and oxidant mix in an interface. Mixing happens through diffusion and is ***way slower*** than heat transfer.

Rate/Hydro Equations

Reactive-Diffusive Hydrodynamics

reactions + diffusion + fluids
=
combustion

$$
\begin{aligned}
\frac{\partial n_i}{\partial t} &= -\nabla \cdot (n_i v - \mathcal{D}\nabla n_i) + \mathcal{R}_i \\
\frac{\partial n_{\rm total}}{\partial t} &= -\nabla \cdot (n_{\rm total} v - \mathcal{D}\nabla n_{\rm total}) \\
\frac{\partial h v}{\partial t} &= -\nabla (h v \cdot v) - \nabla P \\
\frac{\partial s}{\partial t} &= -\nabla \cdot (s v) \boxed{- \frac{1}{T}\sum_i \mu_i \frac{\partial n_i}{\partial t}}
\end{aligned}
$$

Strangeness as a Catalyst

$$
\begin{aligned}
d &\rightarrow u + e^- + \bar{\nu}_e \\
u + e^- &\rightarrow d + \nu_e \\
s &\rightarrow u + e^- + \bar{\nu}_e \\
u + e^- &\rightarrow s + \nu_e \\
d + u &\leftrightarrow u + s\ .
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_1 - \Gamma_2 &= \frac{34}{5\pi} G_F^2 \cos^2\theta_C p_F(d)\, p_F(u)\, T^4 (\mu_d - \mu_u - \mu_e)^2 \\
\Gamma_3 - \Gamma_4 &= \frac{17}{40\pi} G_F^2 \sin^2\theta_C \mu_s m_s^2 T^4 (\mu_s - \mu_u - \mu_e) \\
\Gamma_5 &= \frac{16}{5\pi^5} G_F^2 \cos^2\theta_C \sin^2\theta_C \\
&\times\ p_F^2(u)\, p_F(d)\, p_F^2(s)\, \Delta\mu \left[\Delta\mu^2 + (4\pi T)^2\right]\ .
\end{aligned}
$$

Niebergal, Ouyed, & Jaikumar, PRC Rapid Comm. 82, 062801 (2010)

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Burn-UD in a nutshell

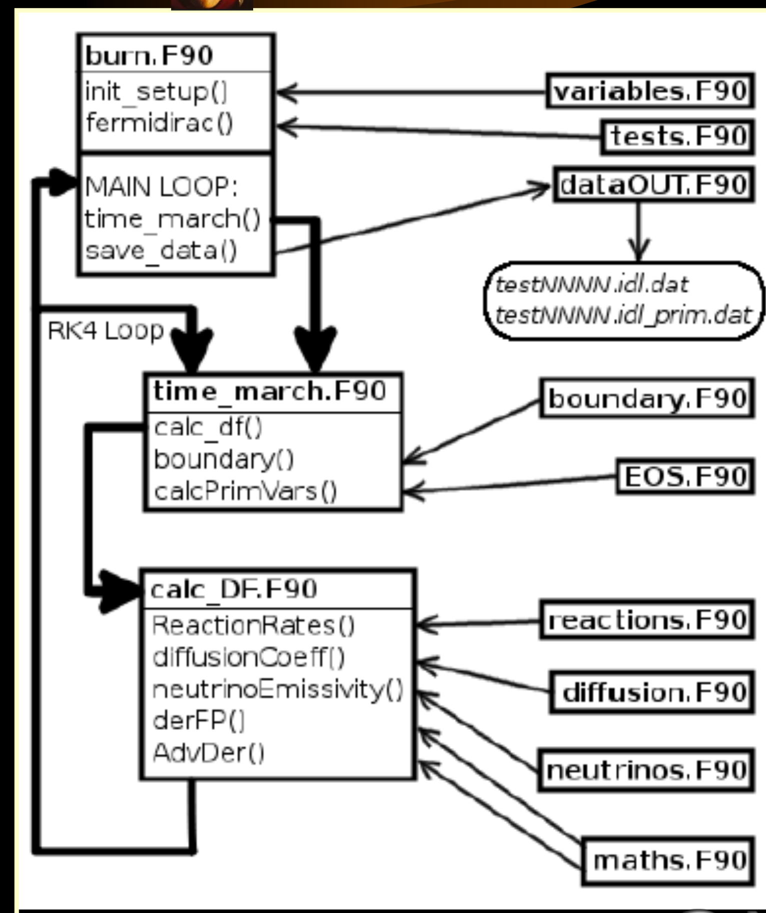
(Niebergal's PhD Thesis)

Solves the equations of hydrodynamical combustion to SQM.

Equations solved explicitly in time using an RK4 scheme.

Spatial derivatives are treated separately, as per the method of lines.

The spatial derivatives include (compressible) advection - which is treated with a third-order upwinded, flux-limited, finite-volume scheme - as well as diffusion and pressure terms, which are solved via a second-order, non-upwinded scheme, and treated separately from the advection terms (ie. not flux-limited).



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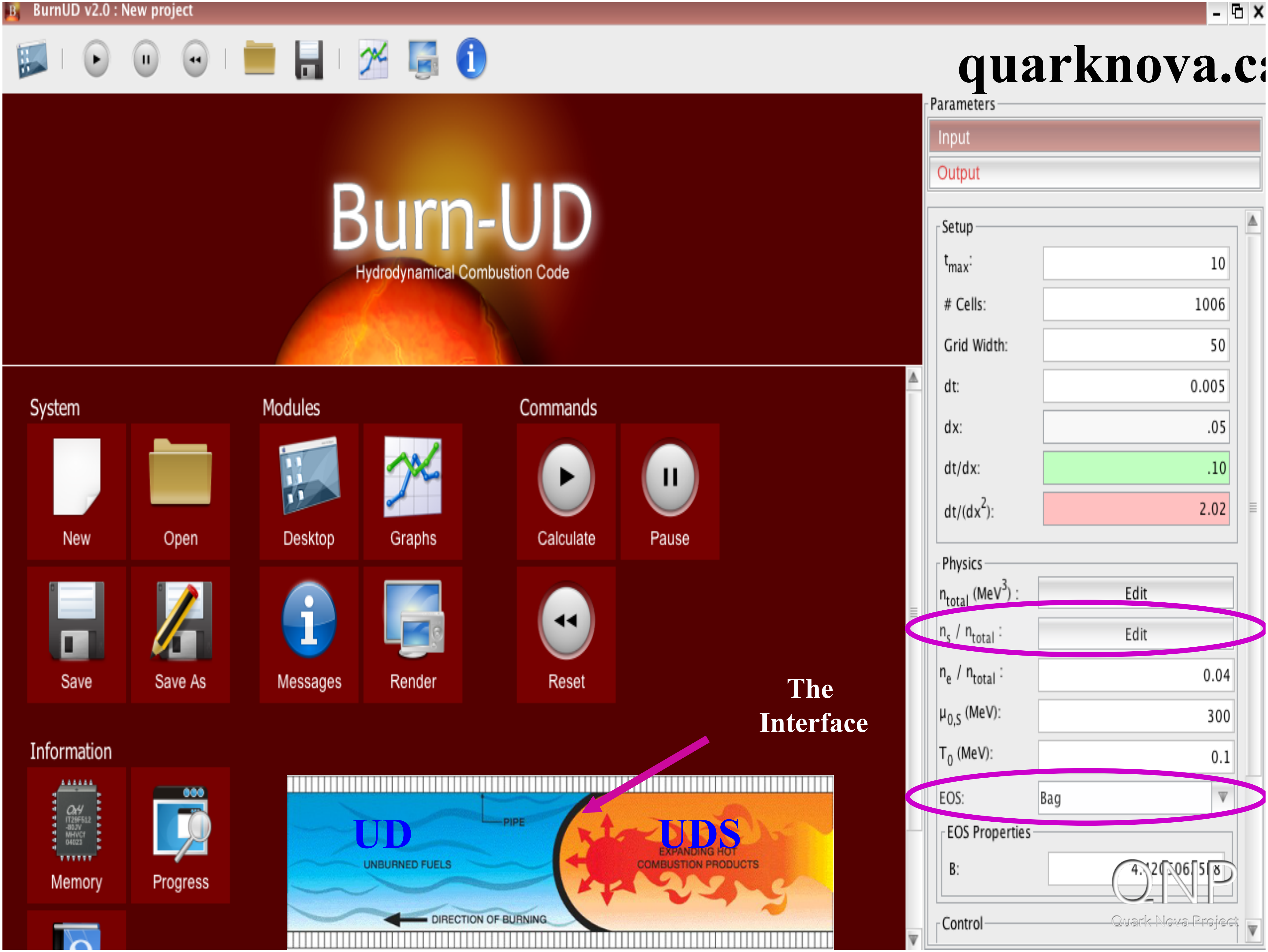

BurnUD v2.0 : New project
quarknova.ca
Burn-UD
Hydrodynamical Combustion Code
System
New
Open
Save
Save As
Modules
Desktop
Graphs
Messages
Render
Commands
Calculate
Pause
Reset
Information
Memory
Progress
Parameters
Input
Output
Setup
t_{max}: 10
Cells: 1006
Grid Width: 50
dt: 0.005
dx: .05
dt/dx: .10
$dt/(dx^2)$: 2.02
Physics
n_{total} (MeV^3) : Edit
n_s / n_{total} : Edit
n_e / n_{total} : 0.04
$\mu_{0,S}$ (MeV): 300
T_0 (MeV): 0.1
EOS: Bag
EOS Properties
B:
Control
The Interface
UD
UNBURNED FUELS
PIPE
UDS
EXPANDING HOT COMBUSTION PRODUCTS
DIRECTION OF BURNING
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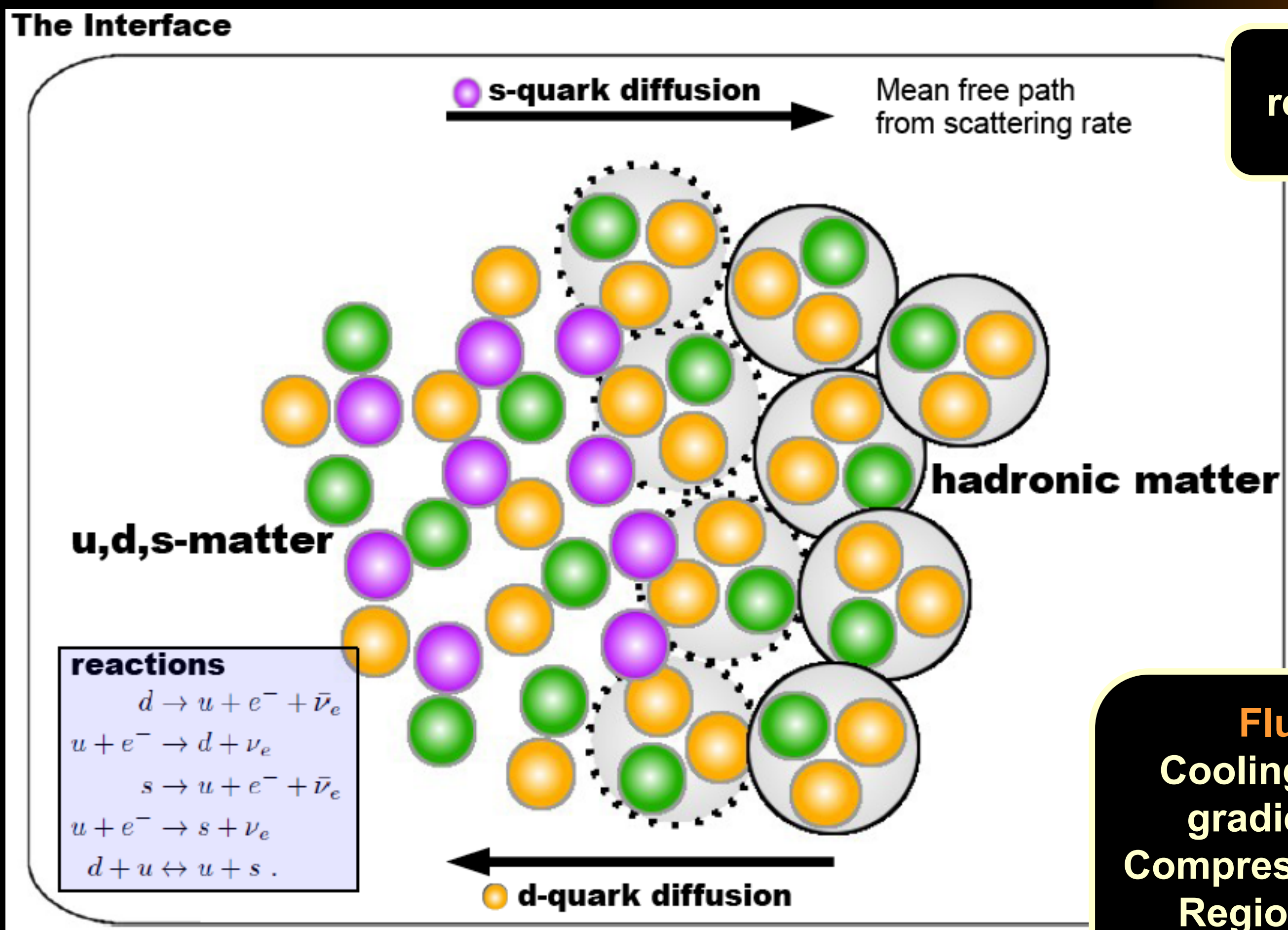
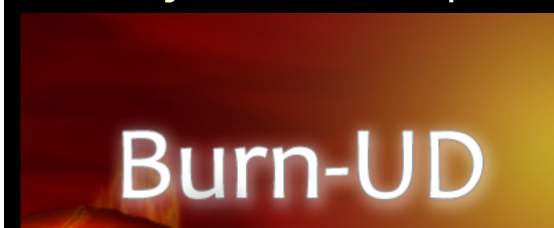
Burn-UD: A reactive-diffusive hydro code (1D-2D-3D)



Interface: interplay between reactions and diffusion defines $v_{interface}$

- Burn Hadrons -> SQM
- Study conversion speeds



Fluid dynamic treatment:
Cooling of ash results in pressure gradients in&around interface. Compression&rarefaction in burning Region (enhanced or quenched combustion) … instabilities

See Ouyed (2013) for a review

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Scratching our heads:

(1) Transition in the PNS (**T** ~ 50 MeV and **Ye** ~0.3)? Transition well after the birth of the neutron star, **(T** ~ 50 keV, **Ye** ~ 0.01)? Are neutrinos free-streaming through the envelope or trapped near the conversion front.

(2) How much energy is deposited by neutrinos in the surrounding unconverted matter? (neutrino energy, temperature, density, **Ye** , the electron fraction of the untransformed neutron star).

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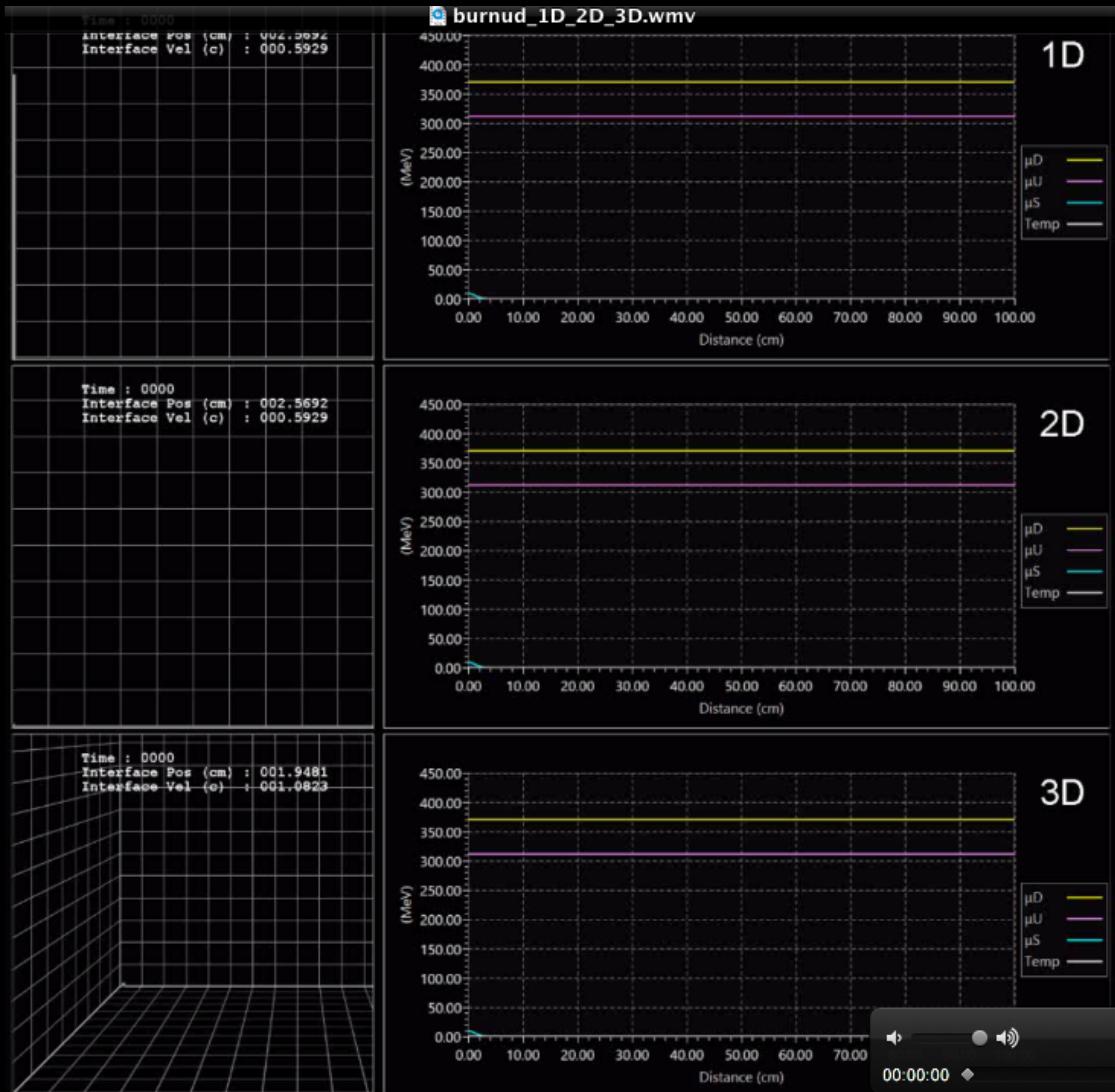

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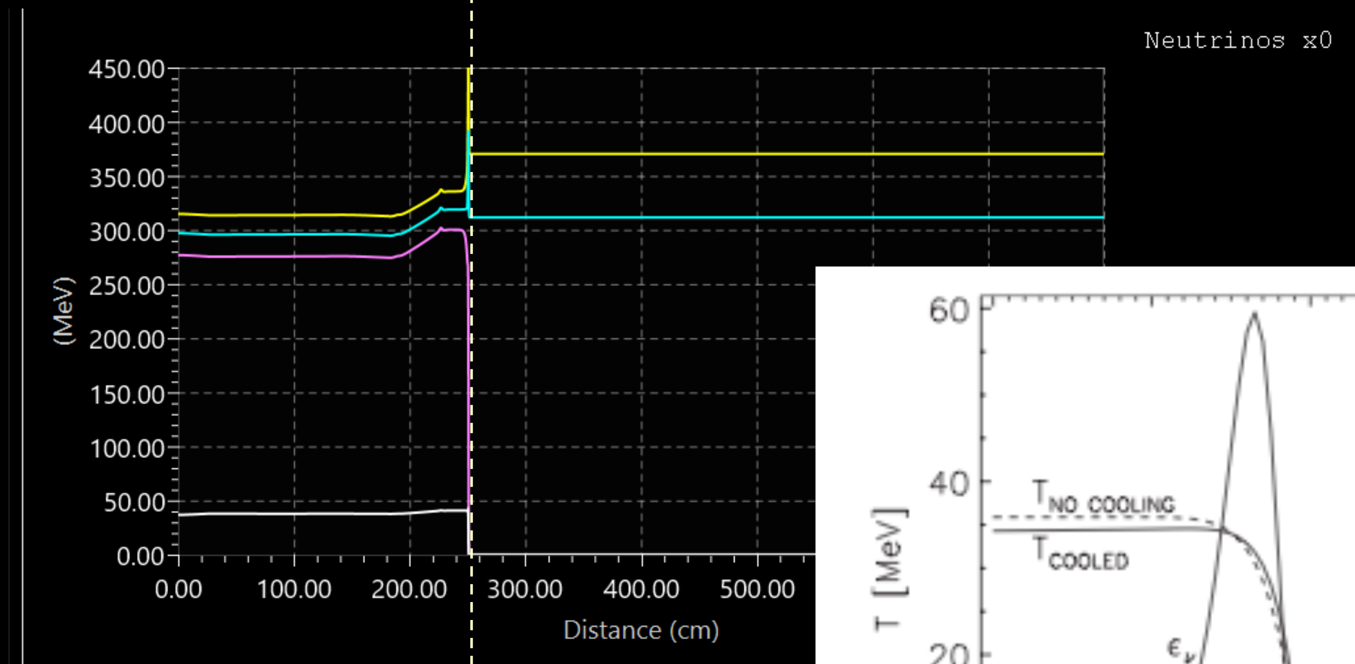
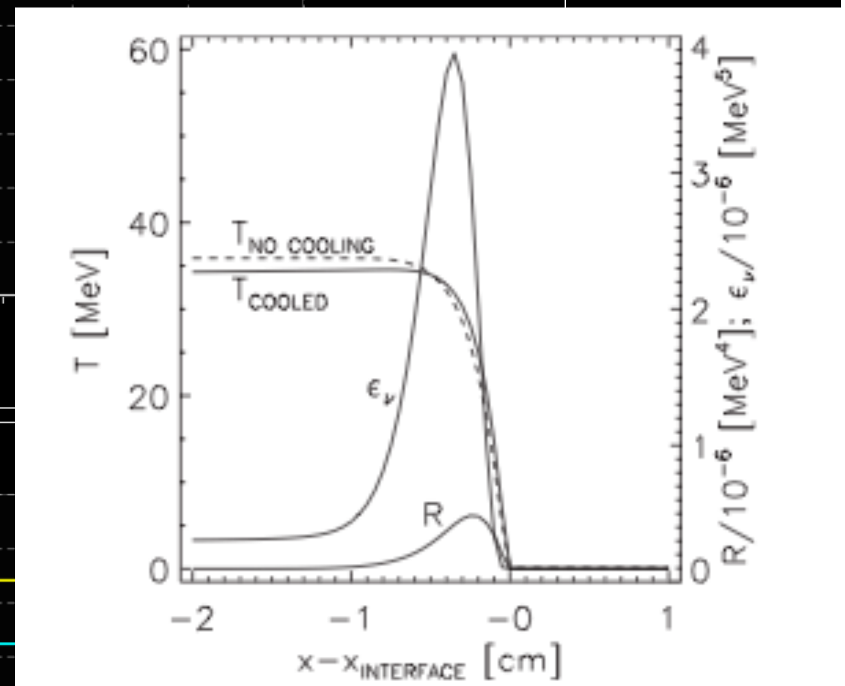
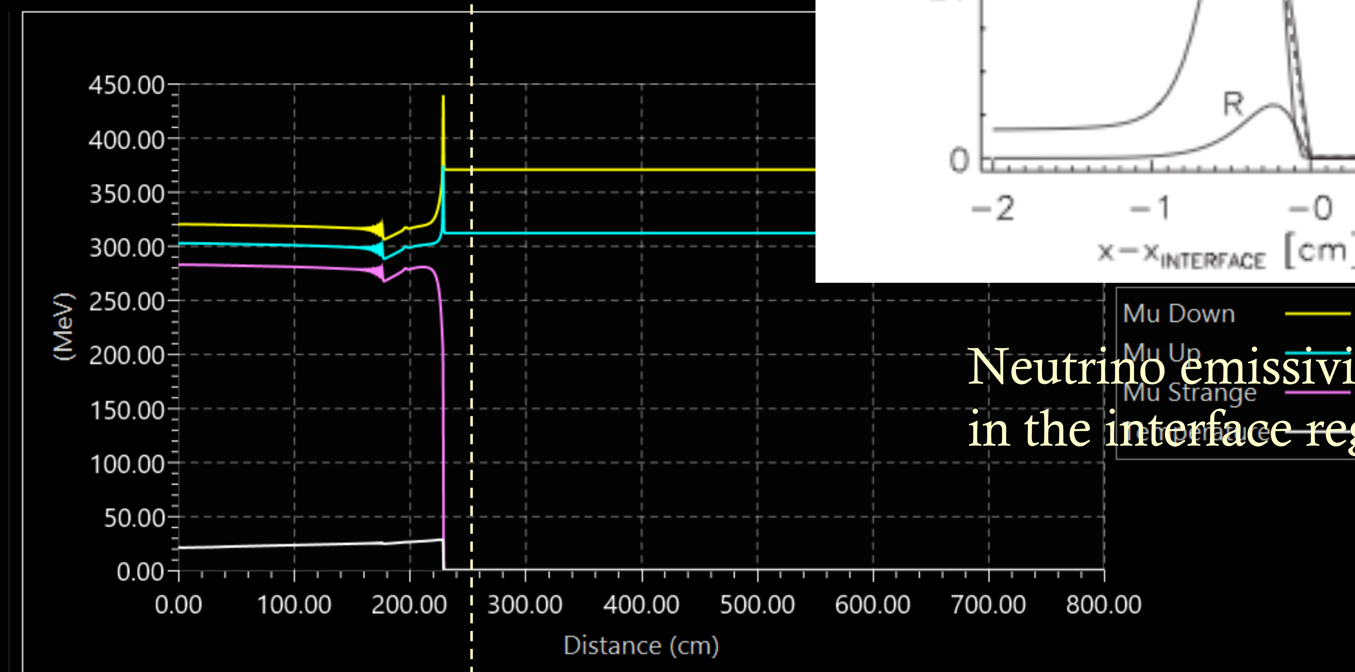
With / without Neutrinos







Neutrino emissivity peaks
in the interface region

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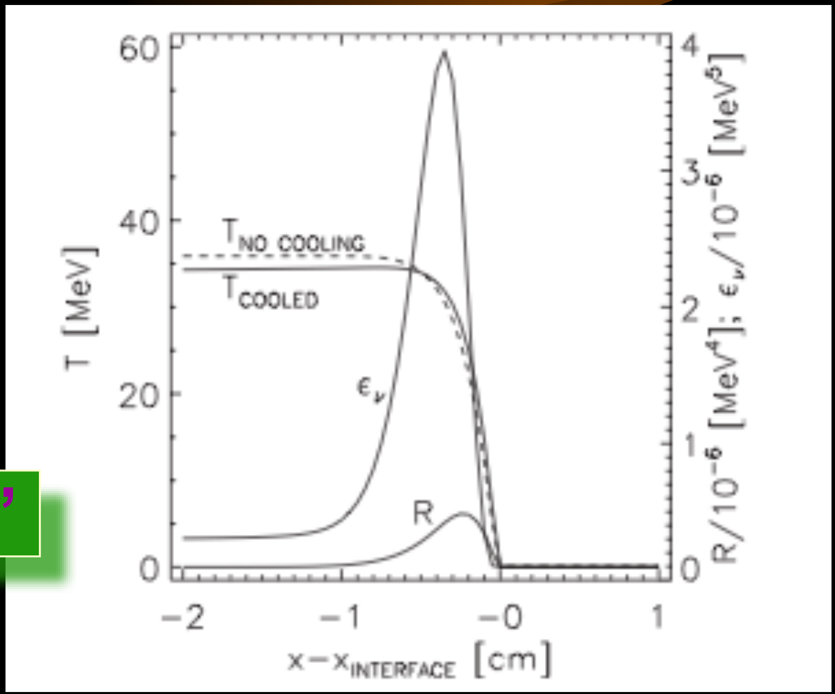
Contained uds core ?

Neutrino Cooling

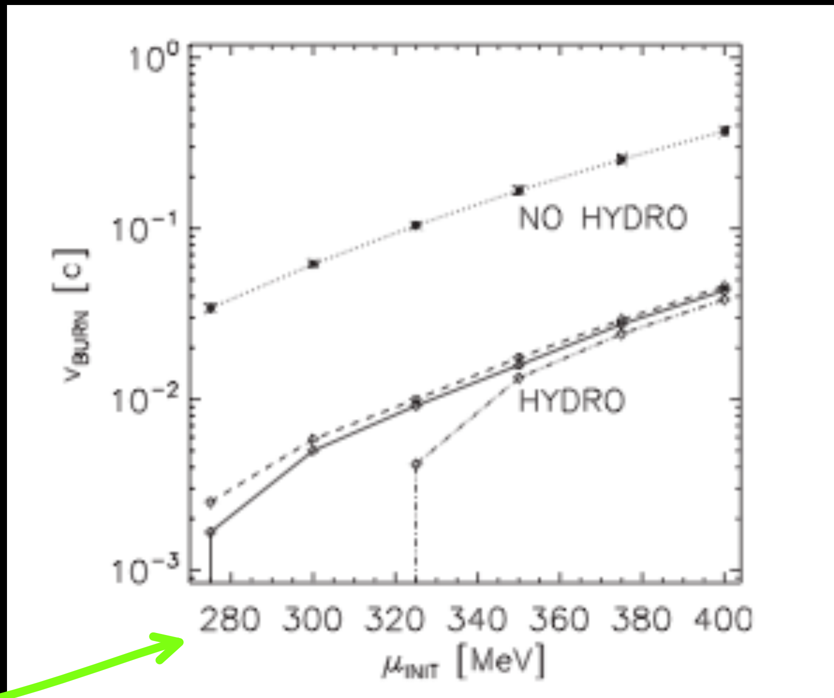
- Cooling leads to pressure drop behind the interface.
- P goes as T^4
- Backpressure can halt parts of the interface at lower densities, but burning continues.
- wrinkles the interface.

"Cavitation"



Neutrino emissivity peaks in the interface region

Halting of the interface



~ 1 km uds core

"Contained" Quark-Nova!

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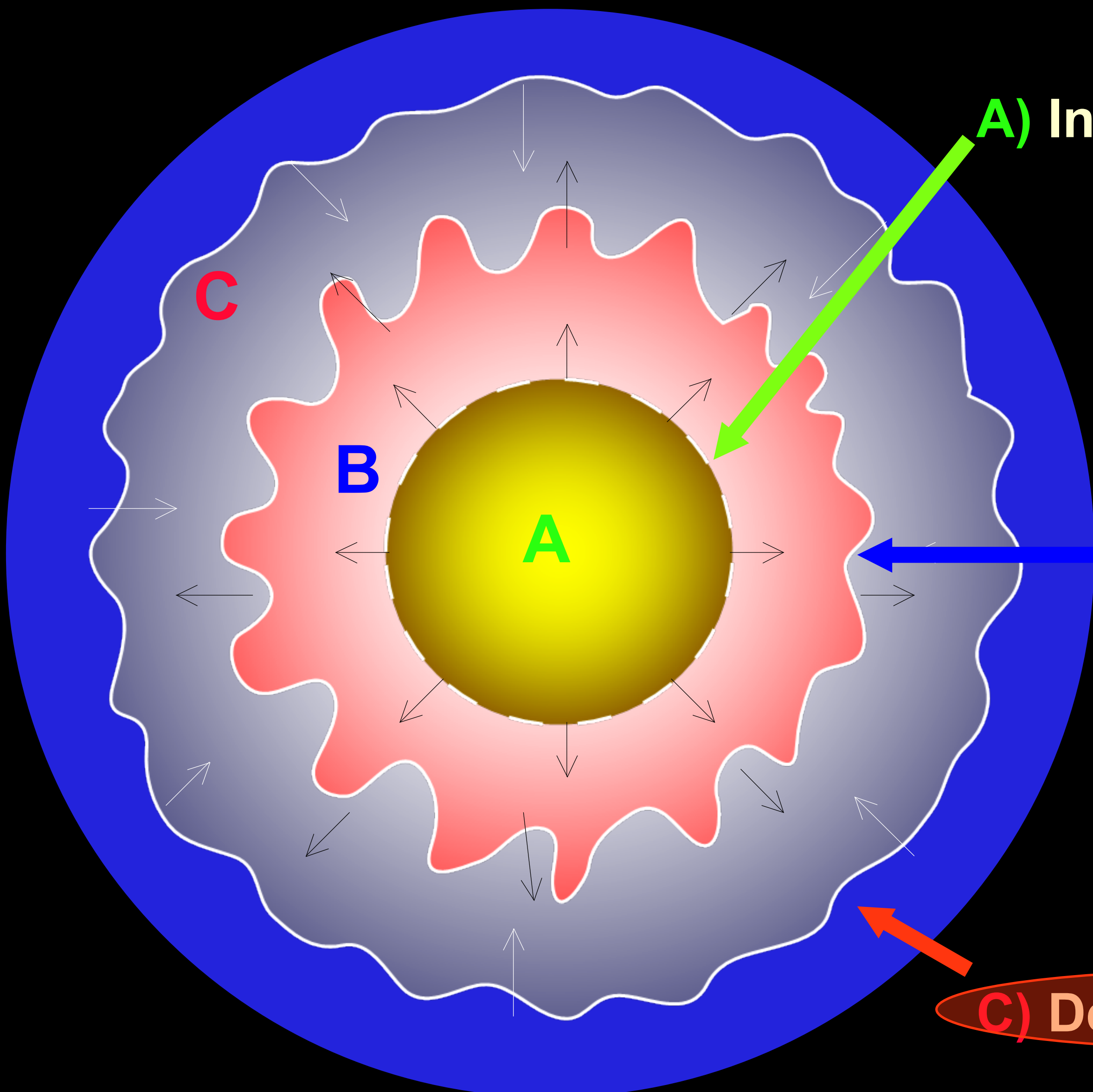
Explosive Transition

Parent Neutron Star



A) Initial laminar burning
-> fast

B) Gravitational Instabilities
-> Rayleigh-Taylor, etc.
-> Detonation?

C) Deleptonization
-> Interface halts!
-> 2nd Core collapse?!
-> Quark-Nova

Deleptonization instability ?

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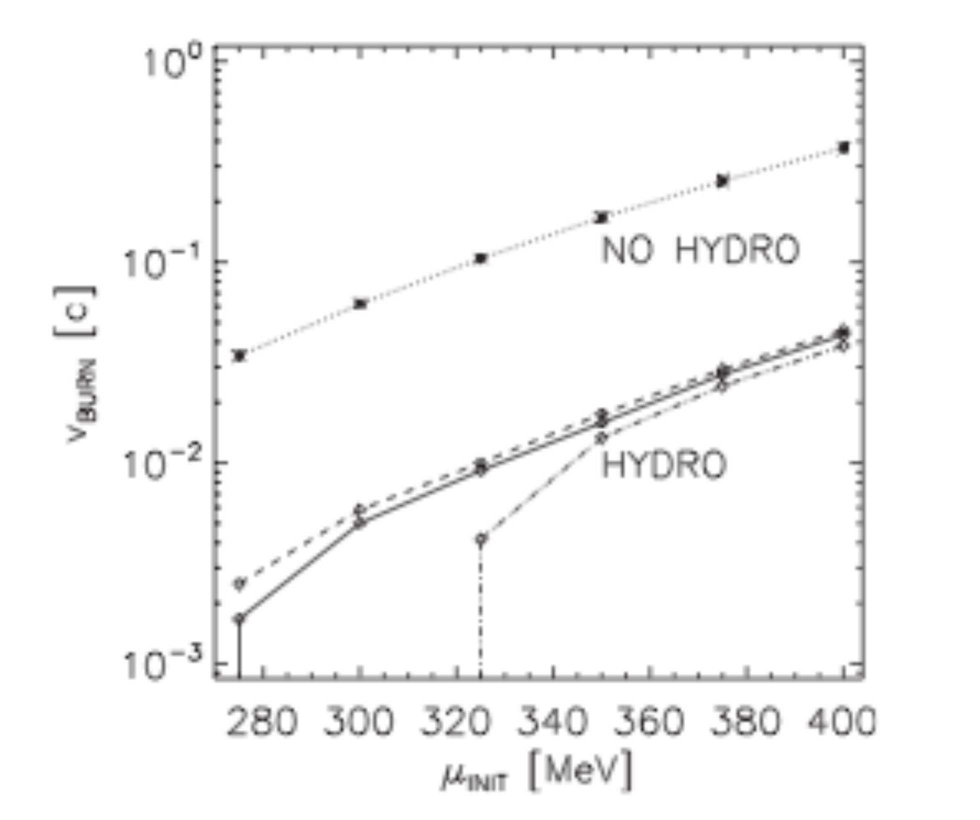
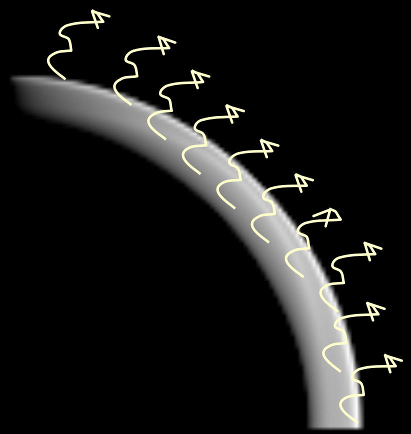
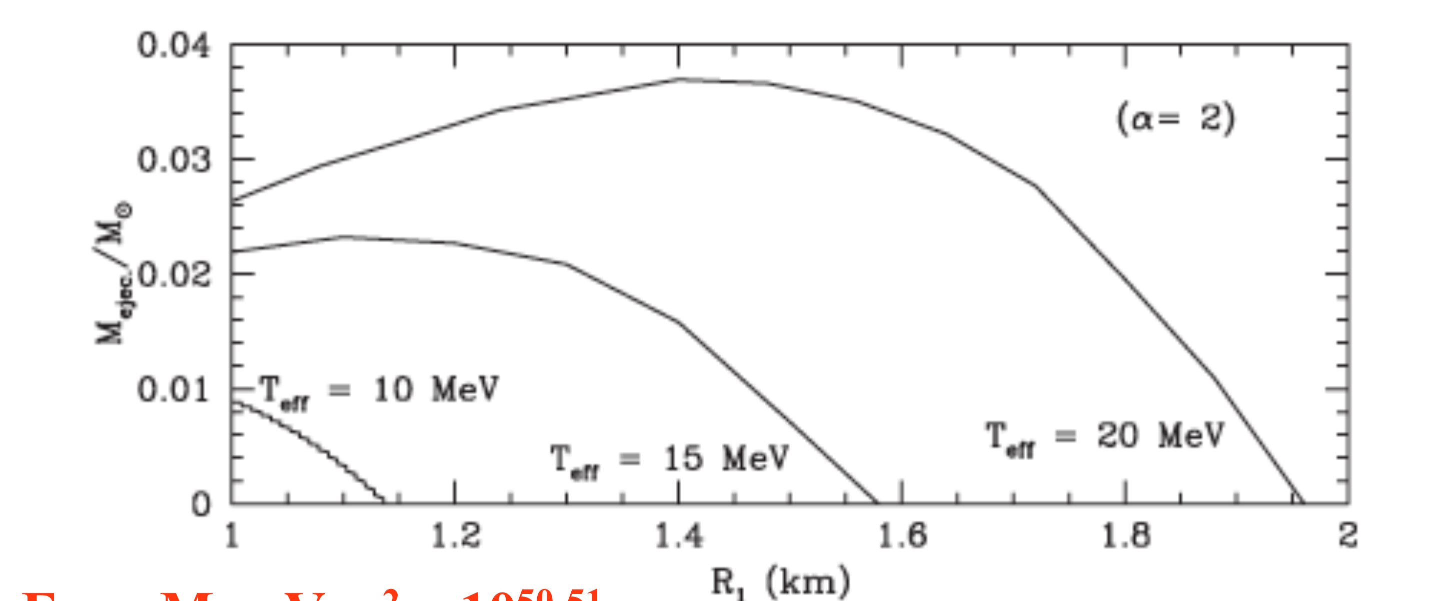
Astrophysical Implications



"Contained Quark Nova"



Keranen, Ouyed, Jaikumar 2005



$E_{eje.} \sim M_{eje.} V_{eje.}^2 \sim 10^{50-51}$ ergs

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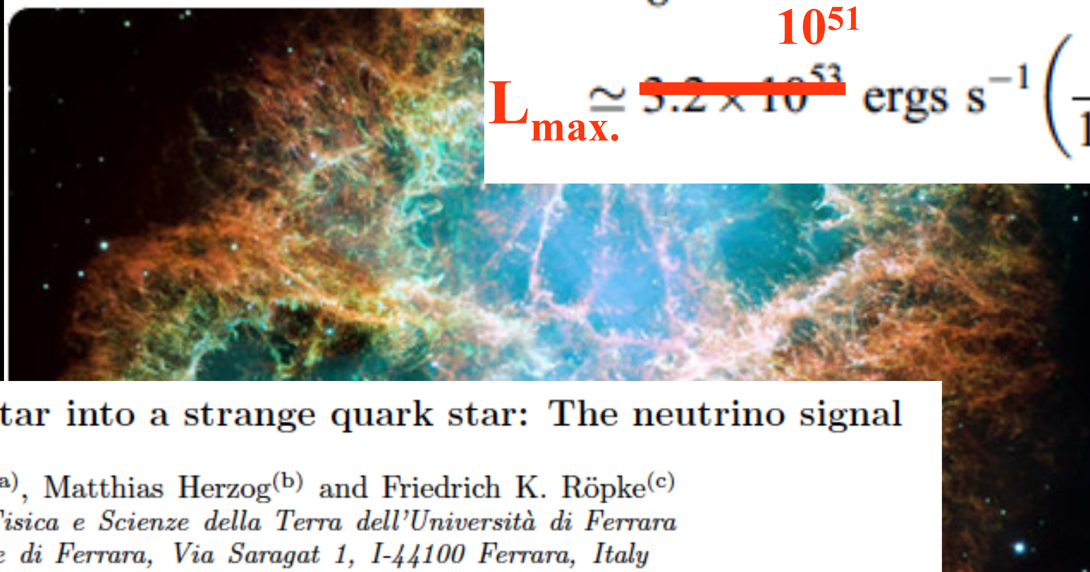
Neutrino Signal?

Helium and Lead Observatory
Astronomically patient

Home Page | Ab



$$L_\nu = \frac{7}{8} N_\nu 4\pi R^2 \sigma T_\nu^4$$

used up in mass-ejection

R=1 km

$$L_{max.} \simeq \cancel{3.2\times 10^{53}}\ 10^{51} \text{ ergs s}^{-1} \left(\frac{R}{10\text{ km}}\right)^2 \left(\frac{kT_{\rm eff}}{10\text{ MeV}}\right)^4$$

Combustion of a neutron star into a strange quark star: The neutrino signal

Giuseppe Pagliara[a], Matthias Herzog[b] and Friedrich K. Röpke[c]
[a] *Dipartimento di Fisica e Scienze della Terra dell'Università di Ferrara and INFN Sezione di Ferrara, Via Saragat 1, I-44100 Ferrara, Italy*
[b] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741 Garching, Germany and*
[c] *Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil Fischer-Strasse 31, D-97074 Würzburg, Germany*

There are strong indications that the process of conversion of a neutron star into a strange quark star proceeds as a strong deflagration implying that in a few milliseconds almost the whole star is converted. Starting from the three-dimensional hydrodynamic simulations of the combustion process which provide the temperature profiles inside the newly born strange star, we calculate for the first time the neutrino signal that is to be expected if such a conversion process takes place. The neutrino emission is characterized by a luminosity and a duration that is typical for the signal expected from protoneutron stars and represents therefore a powerful source of neutrinos which could be possibly directly detected in case of events occurring close to our Galaxy. We discuss moreover possible connections between the birth of strange stars and explosive phenomena such as supernovae and gamma-ray-bursts.

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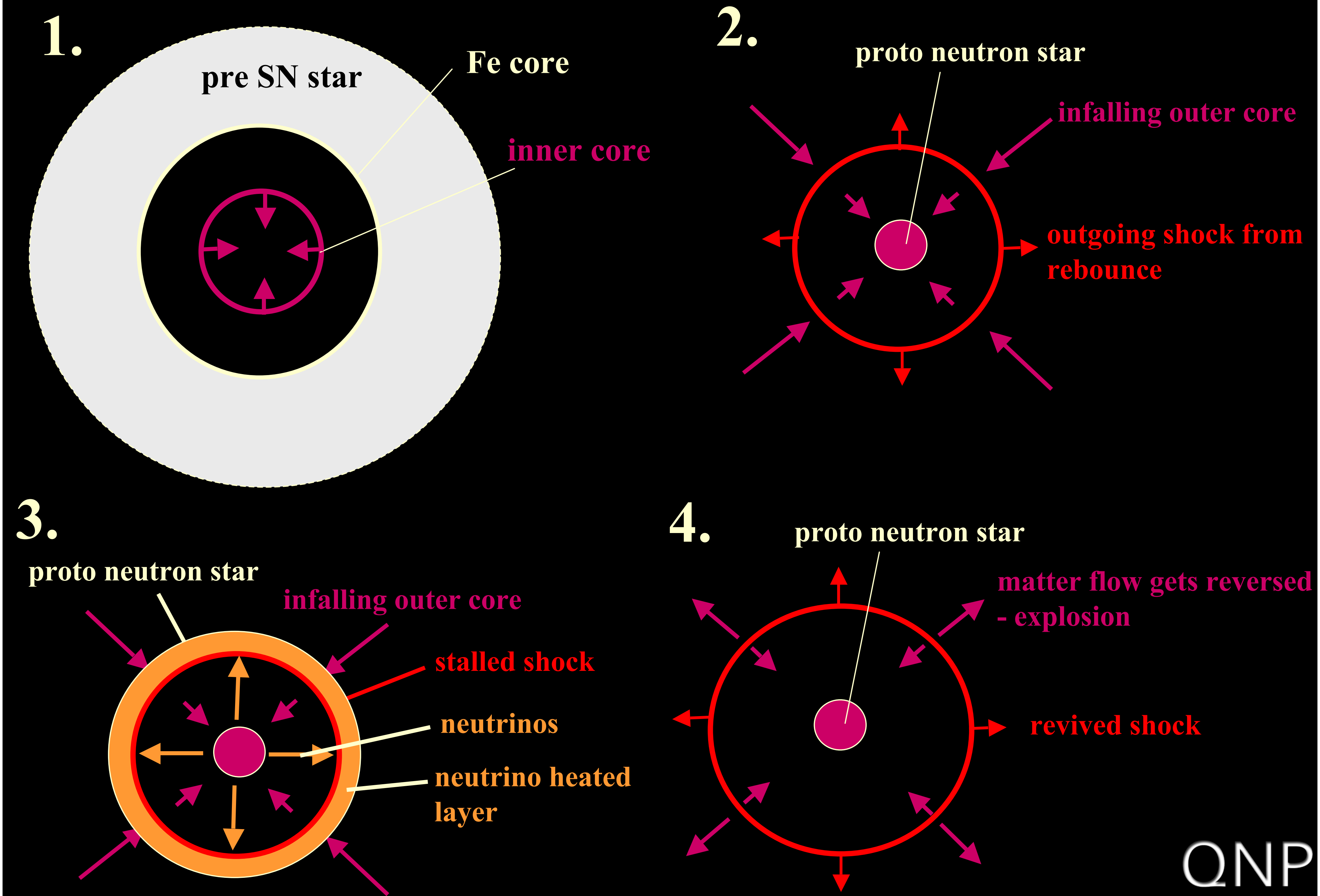
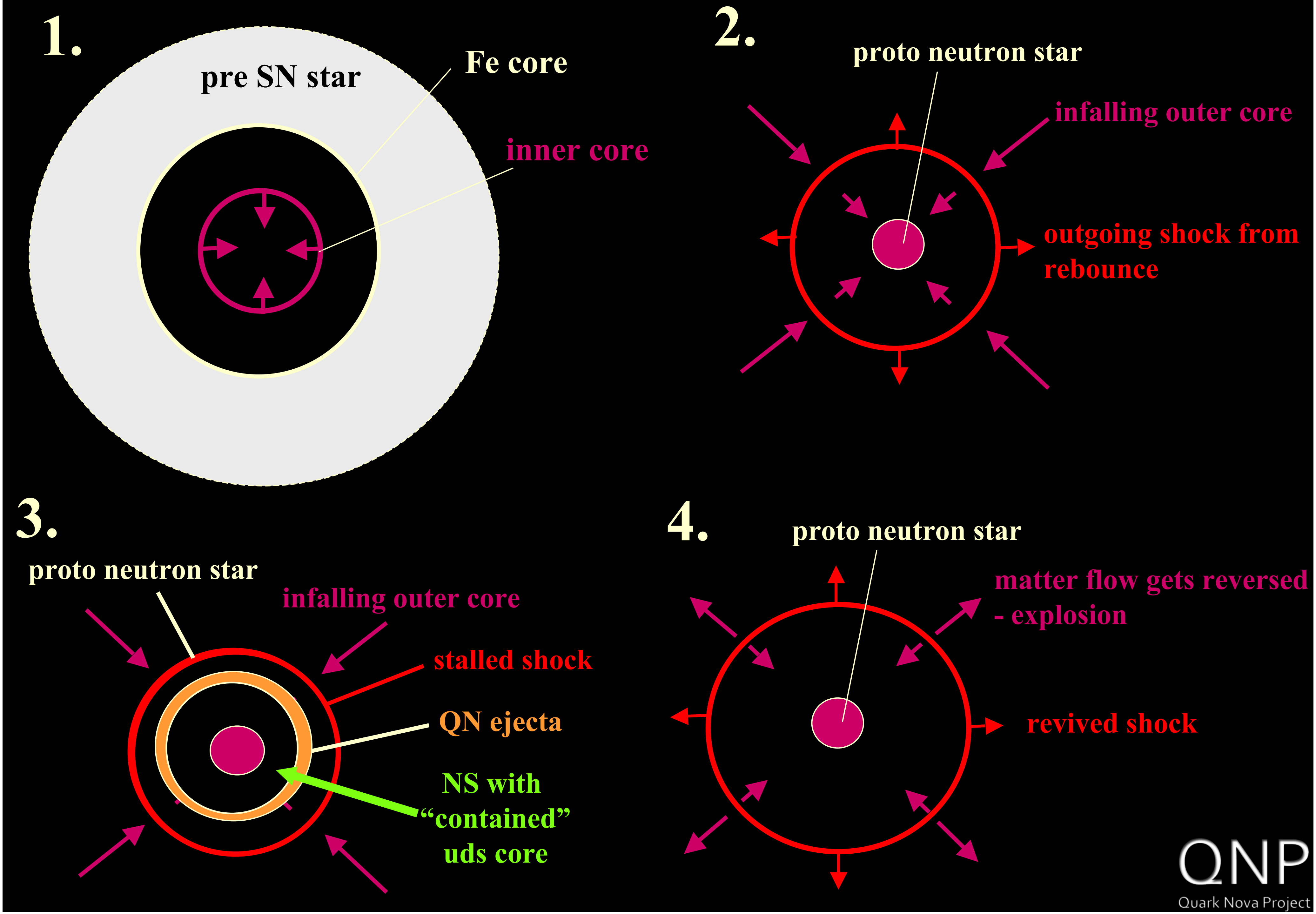
Super-Novae as contained Quark-Novae?

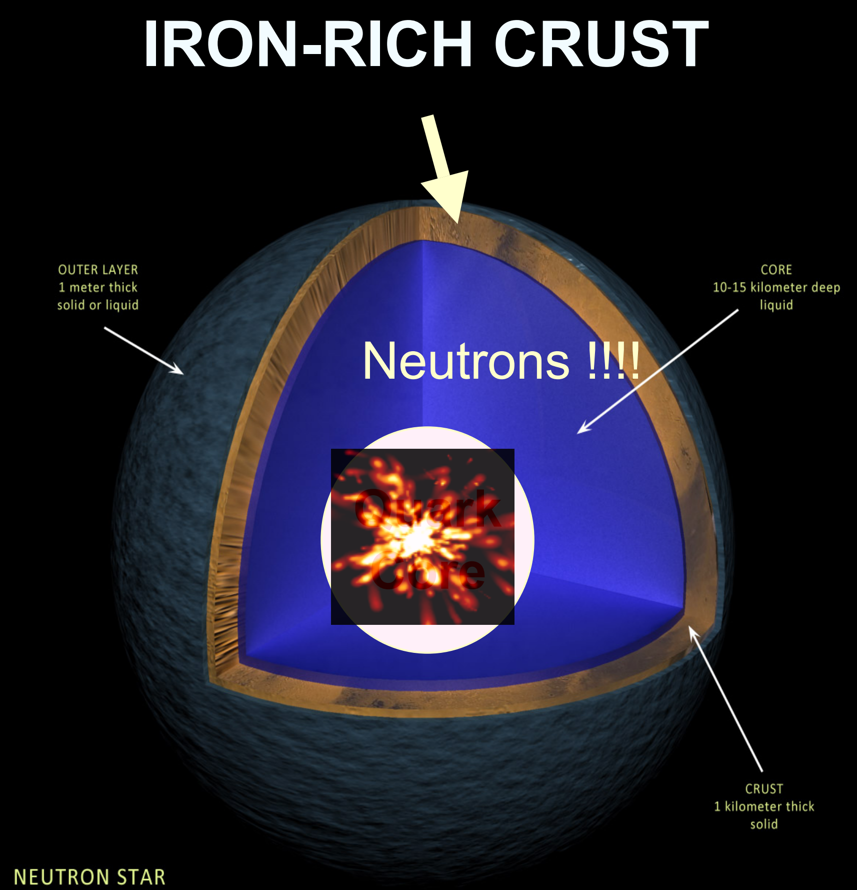
core collapse supernova mechanism

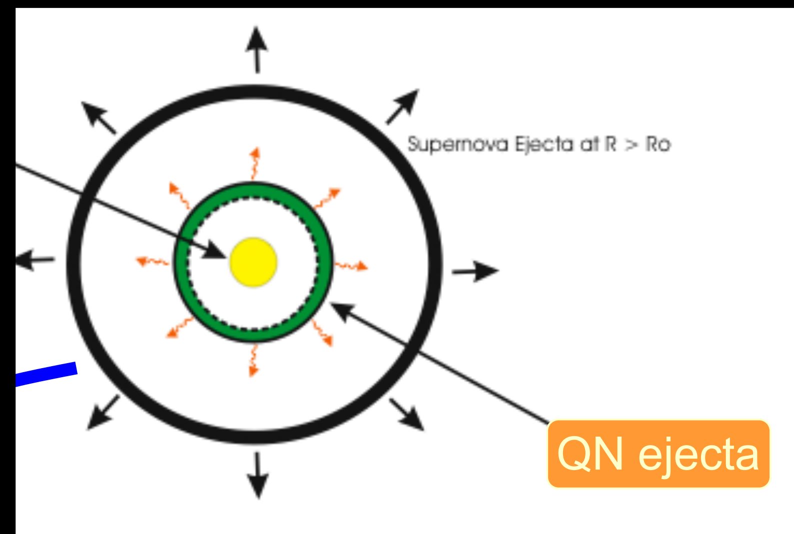


core collapse supernova mechanism



QN as an r-process site : SITE FOR HEAVY ELEMENTS FORMATION





Jaikumar et al. 2007
Charignon et al. 2012
Kostka et al. 2014
Kostka et al. 2015

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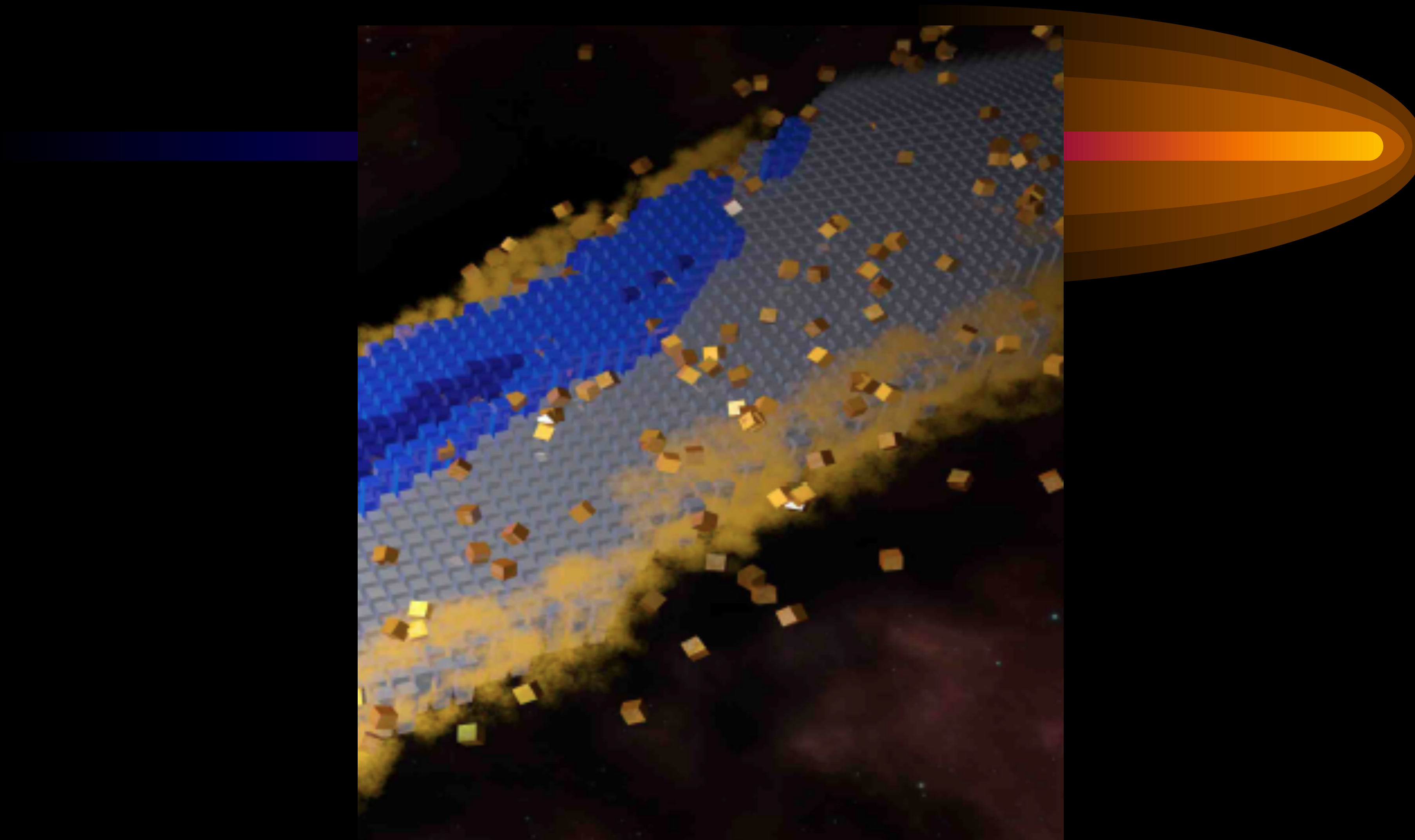

[Kostka et al. 2014a&b]

r-Java

r-process code for Java

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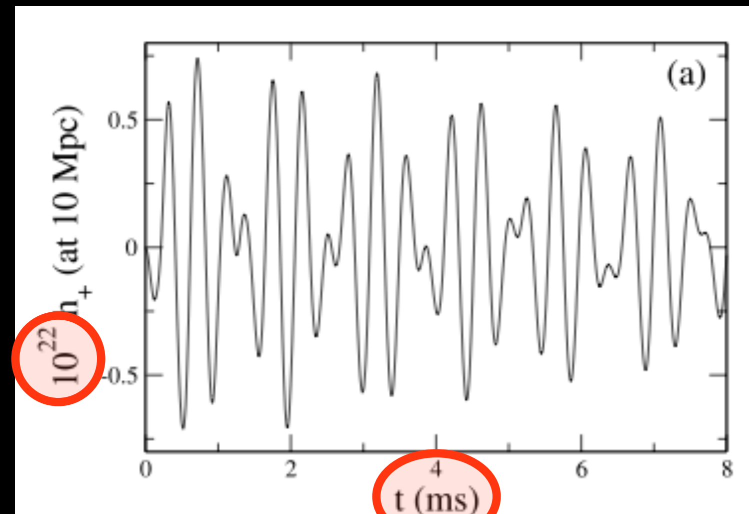
Gravitational waves from collapsing NS to a hybrid star

Earlier work by Lin et al. (ApJ 639, 382 (2006))

- Phase-transition induced collapse with ***mixed phase*** of hadrons+quarks in the center



Gravitational waves from SQM burning
(non-axisymmetric expanding interface!)

(Staff et al. 2012, ApJ, 751, 24))

- Signal emitted due to the combustion process
  Starts with non-premixed fluids and quark front advances at speeds determined by previous simulation

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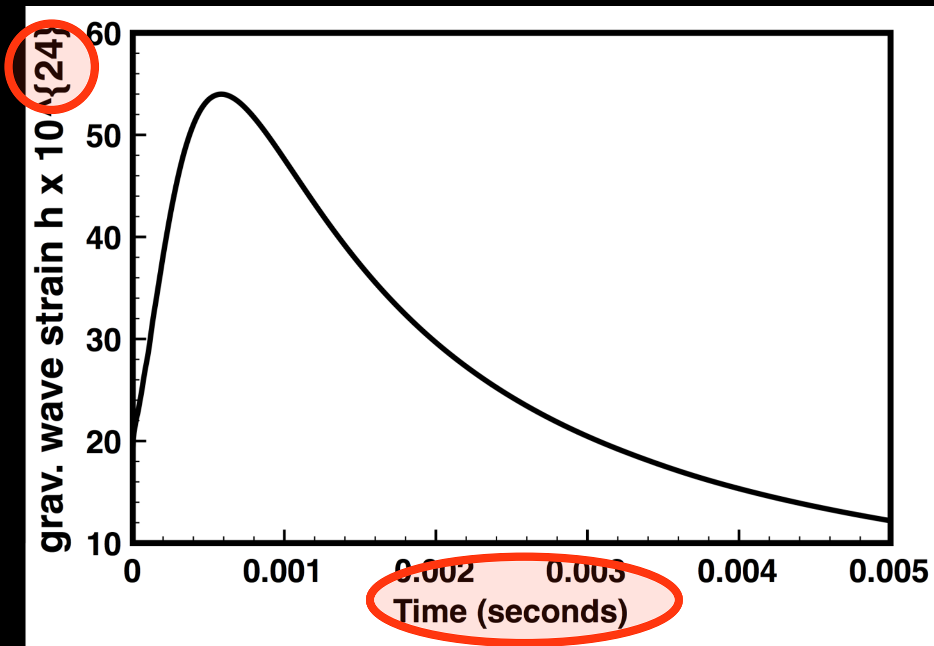
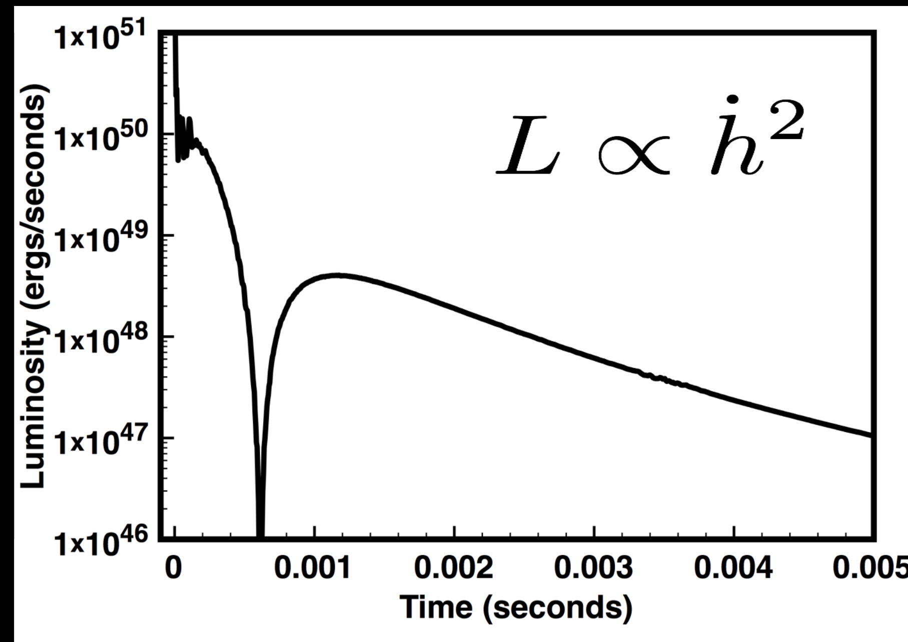
GW Luminosity: *GW Double-hump* (Staff et al. 2012, ApJ, 751, 24)





Peak comes from competing effects of increasing mass flow and decreasing density gradient – duration of signal is set by conversion time (millsecs.)

Integrated luminosity ~ 10^{46}-10^{48} ergs (0.01% of binding energy of neutron star)

Signal could be significant for a Galactic event

>> GW from SNe

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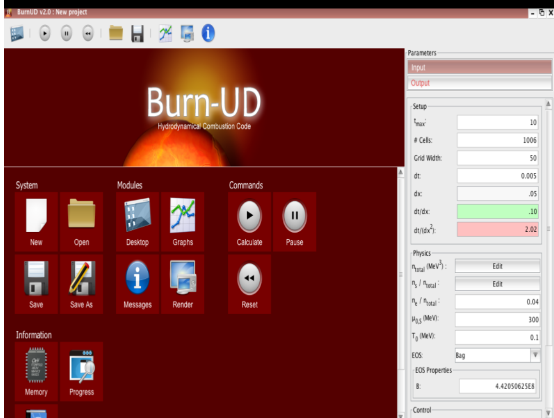
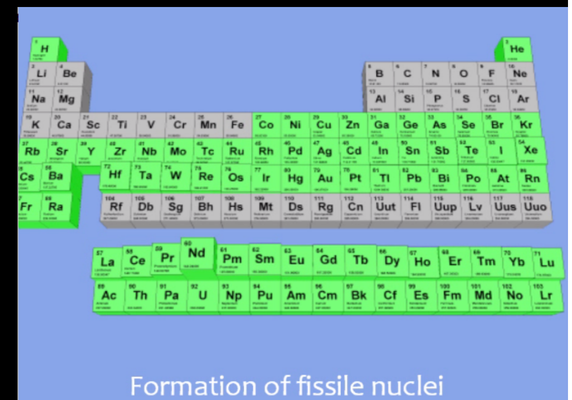


Public Domain Codes



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quarknova.ca