The Burn-UD code

The Physics and the Astrophysics

Rachid Ouyed (Uni. of. Calgary)

CSQCD-IV (Prerow, Sept. 26-29, 2014)

Content

Simulation of the Hadronic → UDS transtion (the QN) :

The EoS

The s-quark seed/mass

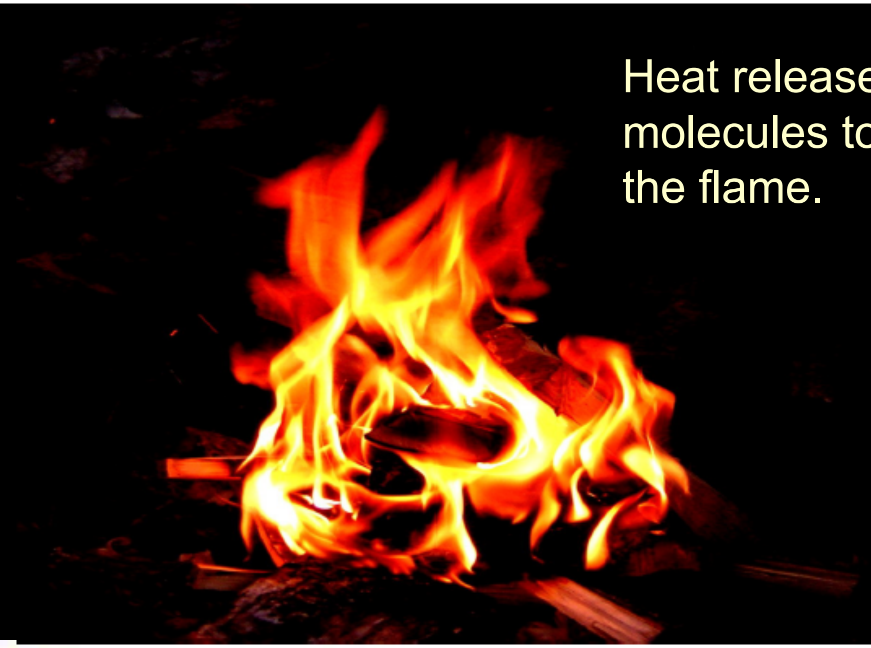
Astrophysical Implications

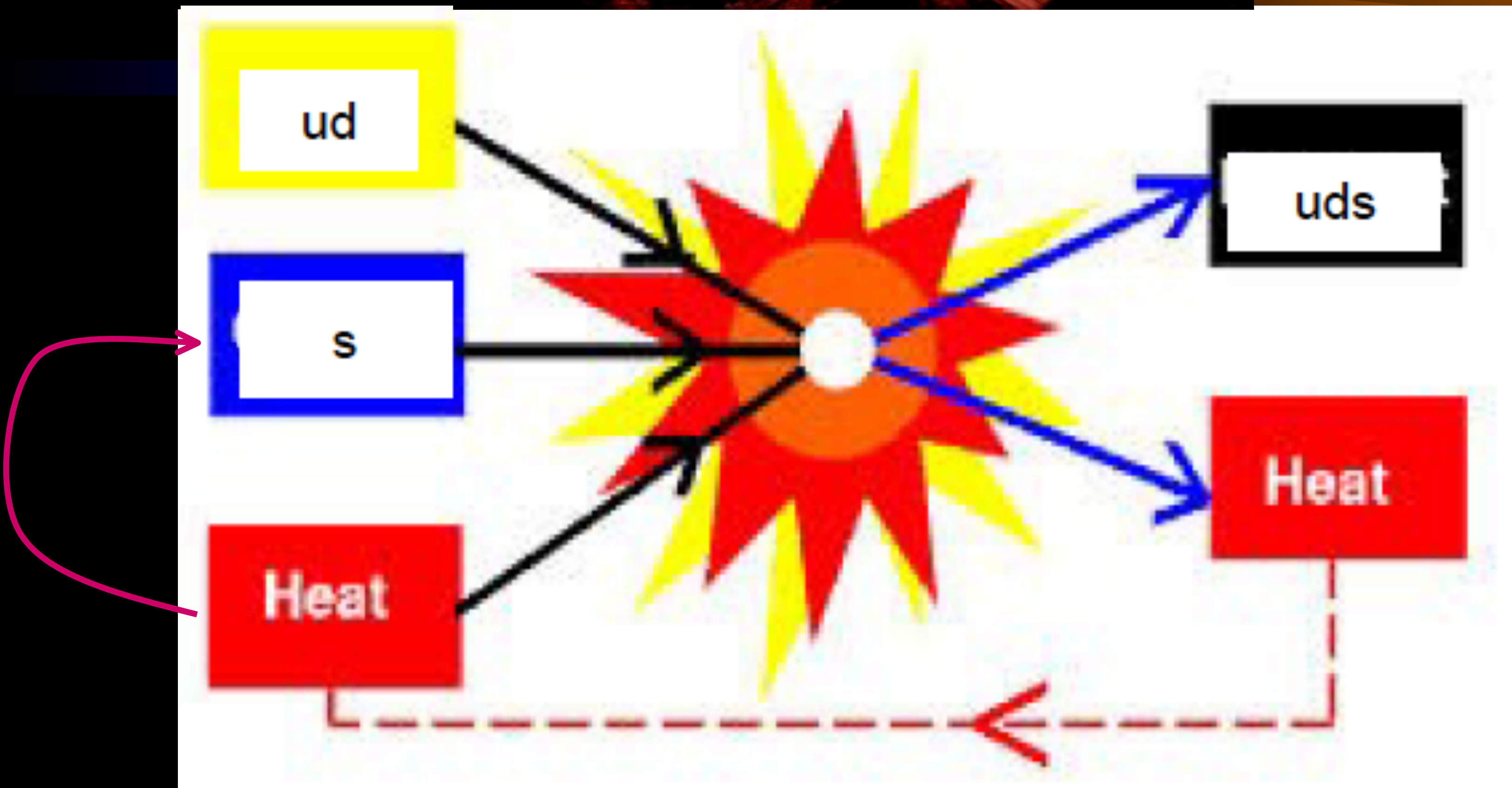
Super-luminous SNe

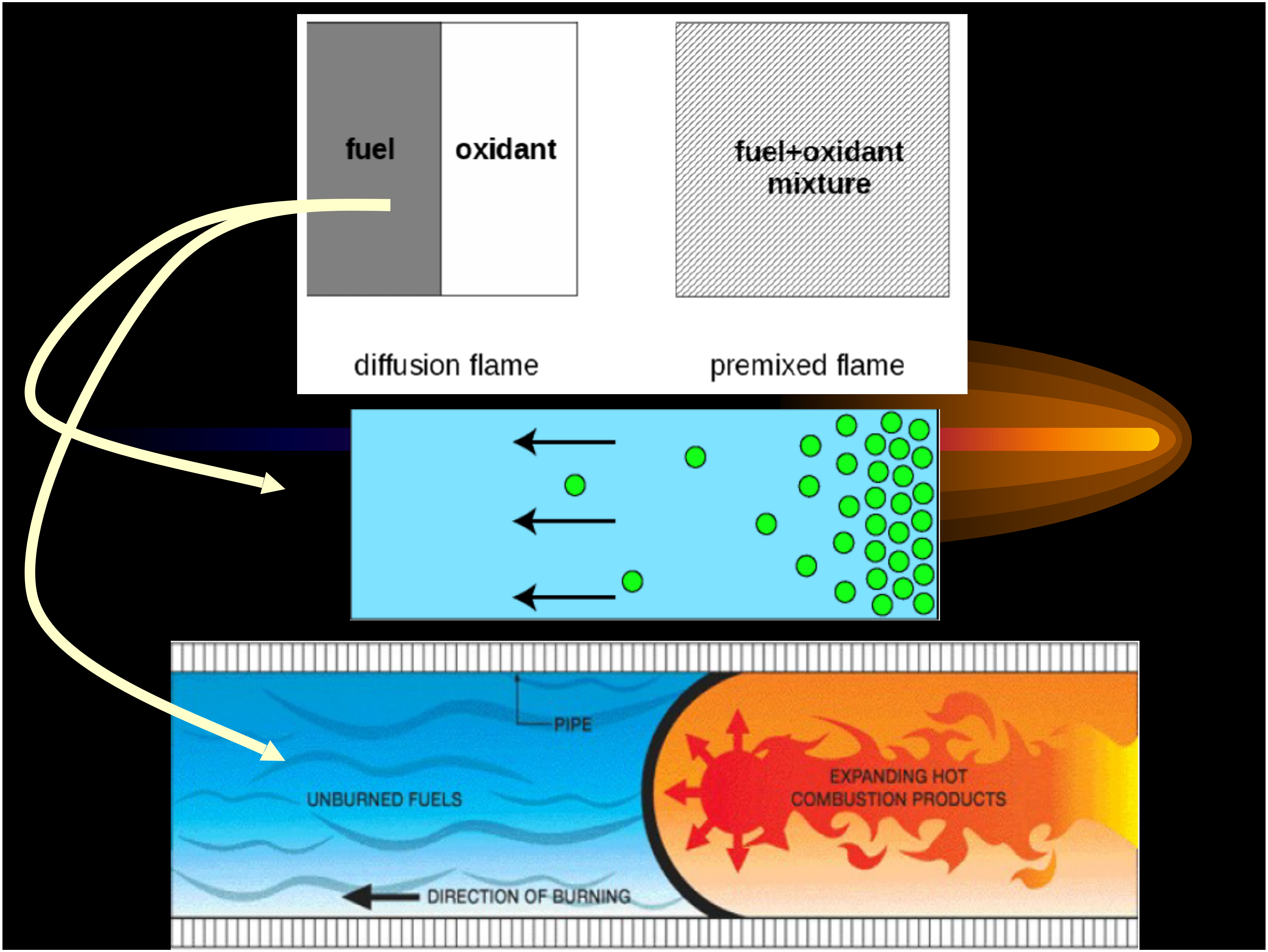
^{44}Ti and ^{sub}Fe

Dark Energy

Heat released excites electrons in molecules to release light, hence the flame.






fuel
oxidant
fuel+oxidant mixture
diffusion flame
premixed flame
PIPE
UNBURNED FUELS
EXPANDING HOT COMBUSTION PRODUCTS
DIRECTION OF BURNING

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

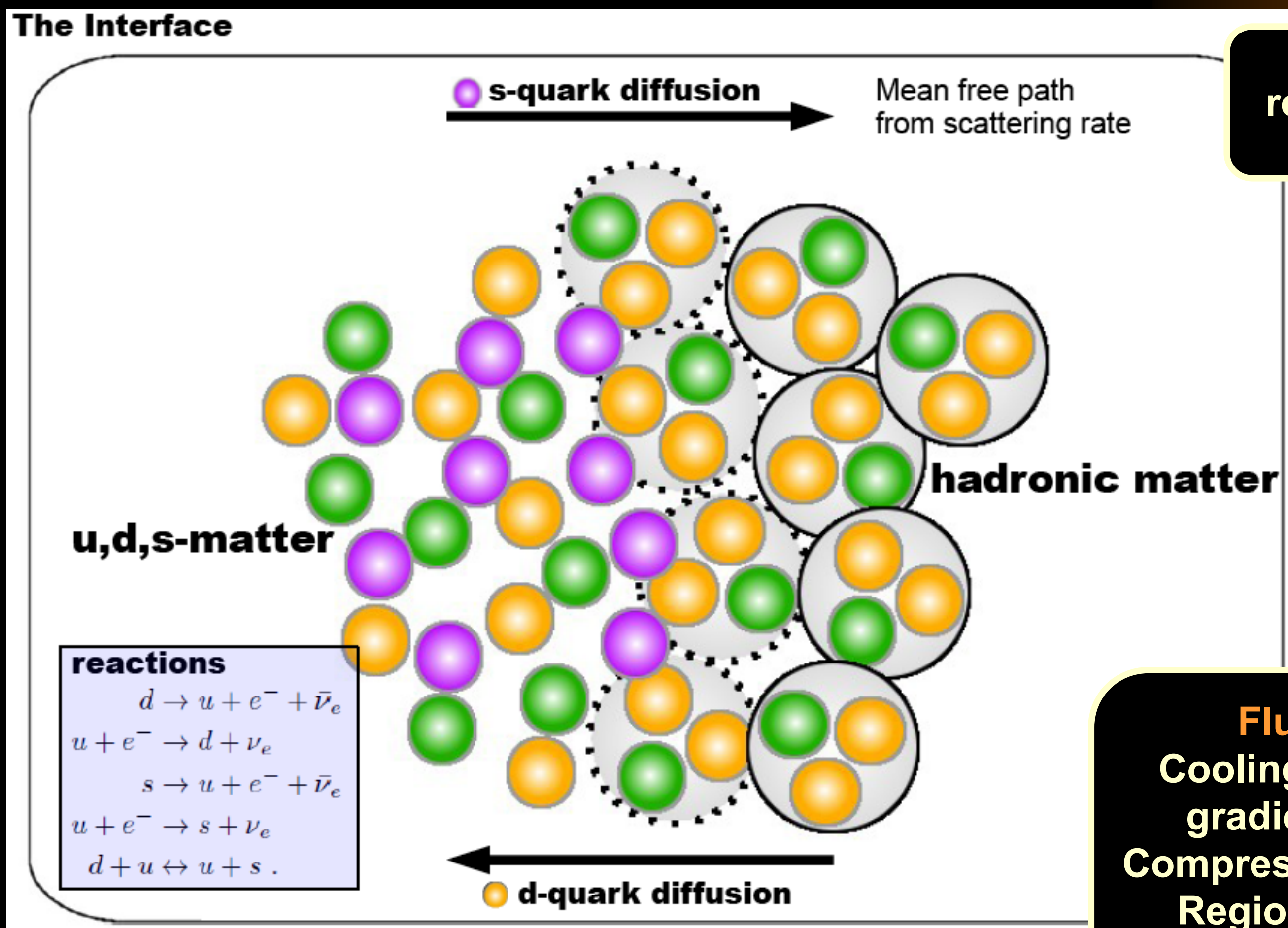
In pre-mixed, oxidant and fuel are mixed and they react when the mixture becomes hot enough.

Flame propagation is mostly controlled by heat transfer!

Heat is relatively fast and efficient.

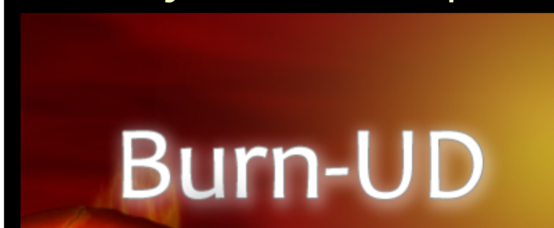
Even if temperature rises, there won't be combustion until fuel and oxidant mix in an interface. Mixing happens through diffusion and is way slower than heat transfer.

Burn-UD: A reactive-diffusive hydro code (1D)



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

Rate Equations

Burn-UD

Reactive-Diffusive Hydrodynamics

reactions + diffusion + fluids
=
combustion

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

Neutrino Cooling

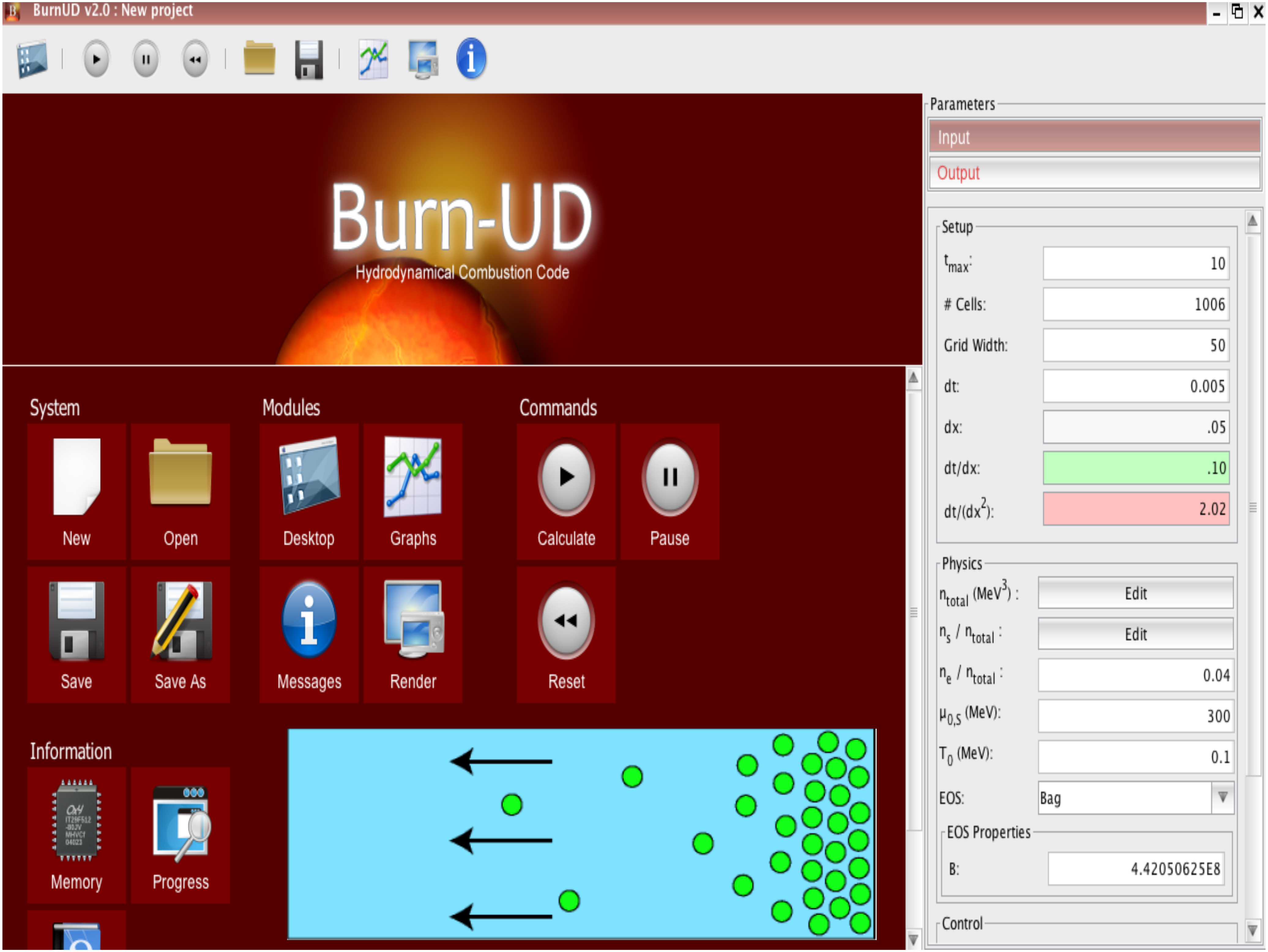
Rates for production of neutrinos can be found in the literature (eg. Iwamoto 1982).

Strangeness as a Catalyst

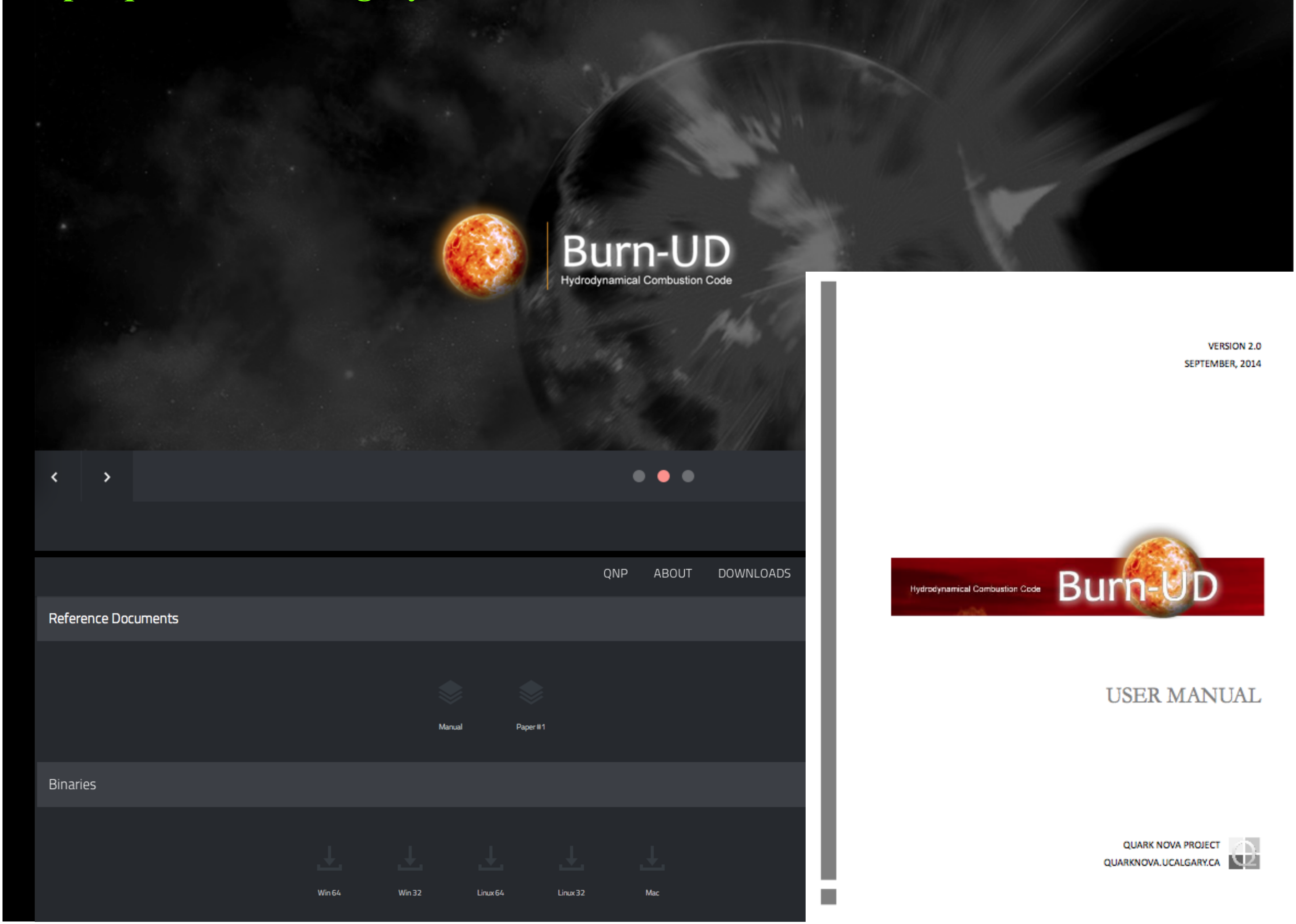
$$\begin{aligned}
d &\rightarrow u + e^- + \bar{\nu}_e \\
u + e^- &\rightarrow d + \nu_e \\
s &\rightarrow u + e^- + \bar{\nu}_e \\
u + e^- &\rightarrow s + \nu_e \\
d + u &\leftrightarrow u + s\ .
\end{aligned}$$

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

B. Niebergal, R. Ouyed, PJ, PRC Rapid Comm. 82, 062801 (2010)


BurnUD v2.0 : New project
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
tmax:
10
Cells:
1006
Grid Width:
50
dt:
0.005
dx:
.05
dt/dx:
.10
dt/(dx2):
2.02
Physics
ntotal (MeV3) :
Edit
ns / ntotal :
Edit
ne / ntotal :
0.04
μ0,S (MeV):
300
T0 (MeV):
0.1
EOS:
Bag
EOS Properties
B:
4.42050625E8
Control

http://quarknova.ucalgary.ca/BurnUD/



The EoS

MIT BAG (B)

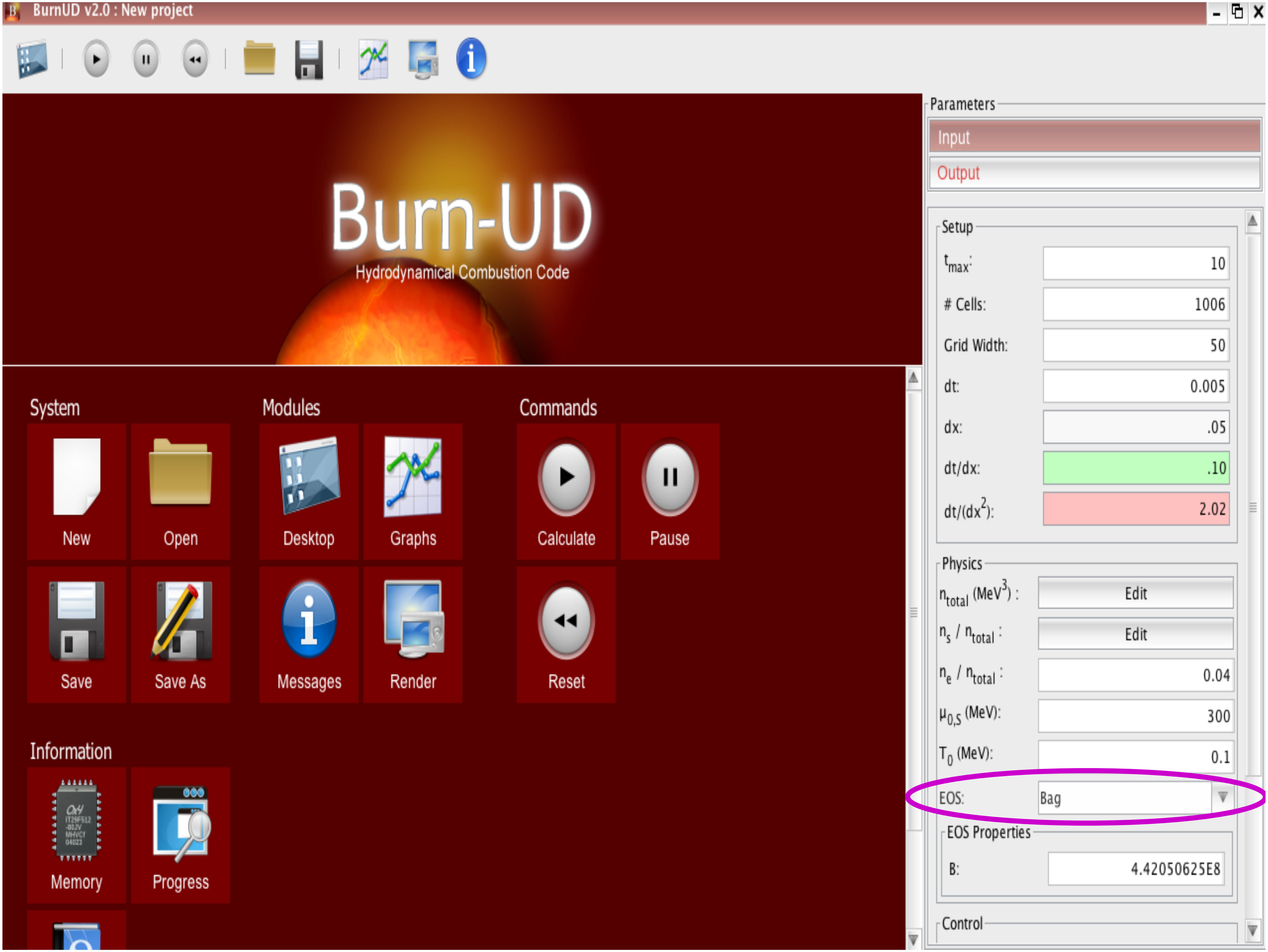
+ **CFL**

Color Superconductivity

The MIT BAG EoS used in BURNUD is an approximation in the limit :

$$m_s = m_u = m_d = 0$$

$$P = \frac{19}{36}\pi^2 T^4 + \frac{T^2}{2}\sum_i \mu_i^2 + \frac{1}{4\pi^2}\sum_i \mu_i^4 - B$$


BurnUD v2.0 : New project
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
tmax: 10
Cells: 1006
Grid Width: 50
dt: 0.005
dx: .05
dt/dx: .10
dt/(dx2): 2.02
Physics
ntotal (MeV3) : Edit
ns / ntotal : Edit
ne / ntotal : 0.04
μ0,S (MeV): 300
T0 (MeV): 0.1
EOS: Bag
EOS Properties
B: 4.42050625E8
Control

CFL is added to BURNUD through the following prescription:

$$\Delta_0 = 100 \text{ MeV}$$

$$T_c = 2^{1/3} \times 0.57\Delta_0$$

$$\Delta = 2^{-1/3}\Delta_0\sqrt{1-\left(T/T_c\right)^2}$$

$$P = P_{\text{non-CFL}} + \frac{3\Delta^2\mu^2}{\pi^2}$$

$$h = 4(P+B) - 2 \times \frac{3\Delta^2\mu^2}{\pi^2}$$

$$\mu_u - \mu_s < \Delta$$

$$T < T_c$$

Palluci & Horvarth assume equilibrium.

Yeah, except the difference between chemical potentials being within the gap energy. Note that pairing is still "allowed" if the Fermi momenta of the quarks have a difference within Delta. We had to add that because in the simulation, the chemical potentials are never exactly the same.

CFL is added to BURNUD through the following prescription:

$$\Delta_0 = 100 \text{ MeV}$$

$$T_c = 2^{1/3} \times 0.57\Delta_0$$

$$\Delta = 2^{-1/3}\Delta_0 \sqrt{1 - (T/T_c)^2}$$

$$P = P_{\text{non-CFL}} + \frac{3\Delta^2\mu^2}{\pi^2}$$

$$h = 4(P+B) - 2 \times \frac{3\Delta^2\mu^2}{\pi^2}$$

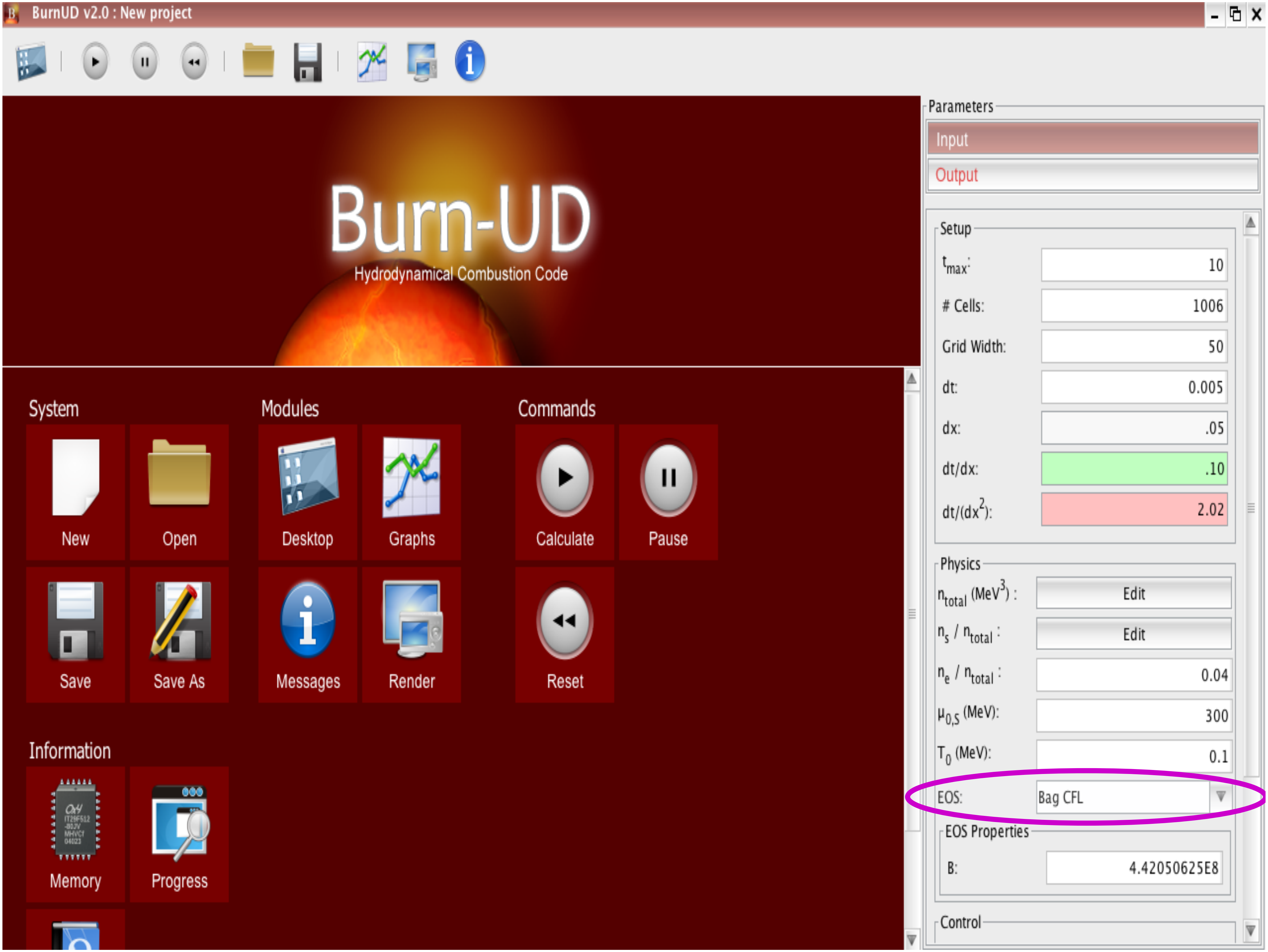
$$\boxed{\mu_u - \mu_s < \Delta \qquad T < T_c}$$

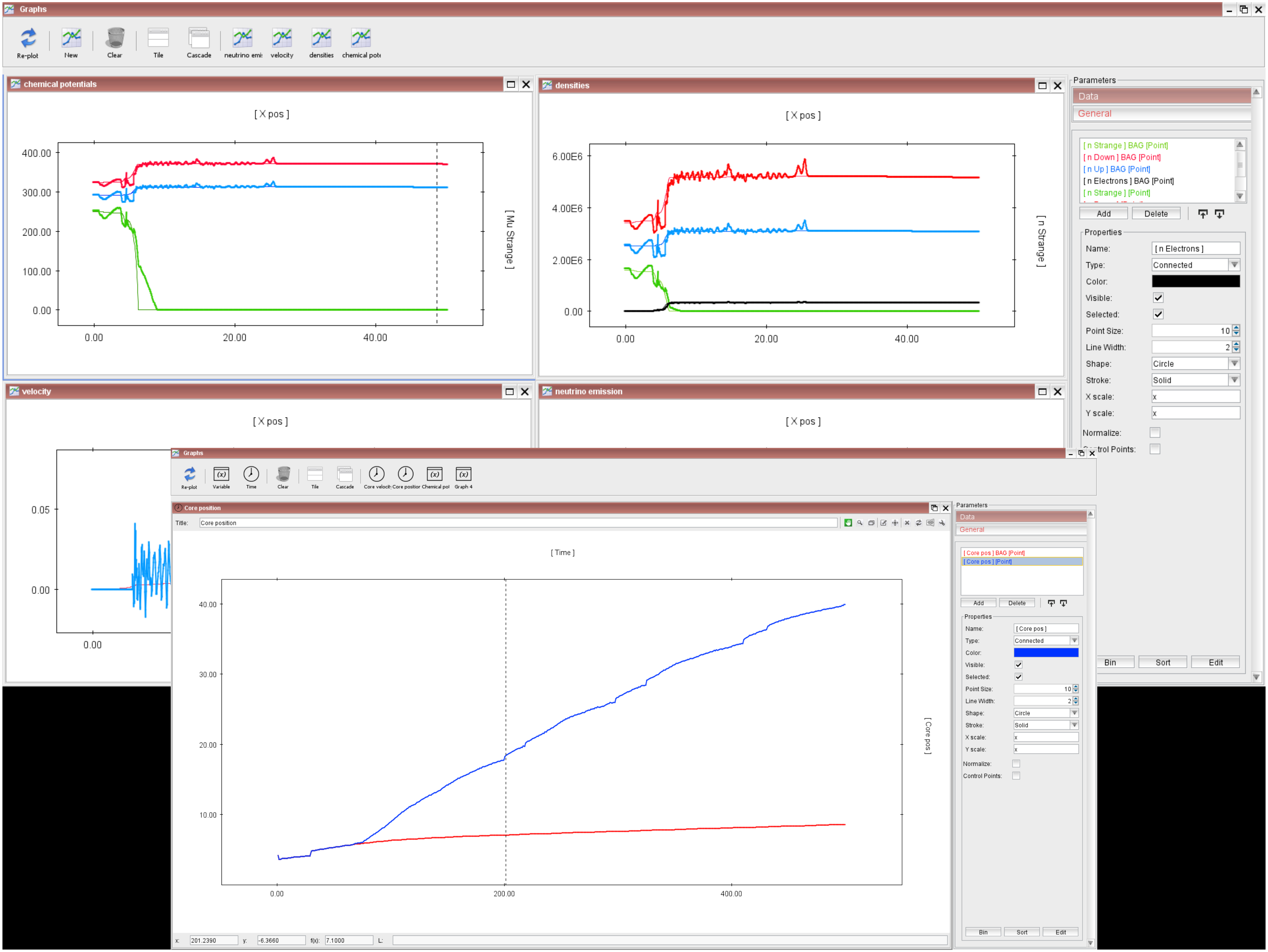
$$s = s_{non-cfl} - 3 \times 2^{1/3}\left(\frac{\Delta_0\mu_B}{\pi T_c}\right)^2 T$$

$$\mu_B = \frac{\mu_u + \mu_d + \mu_s}{3}$$

Because these 2 conditions need to be met, CFL effect can't just be absorbed into an effective bag constant in a combustion simulation!

Also, Delta depends on temperature !!


BurnUD v2.0 : New project
Burn-UD
Hydrodynamical Combustion Code
System
Modules
Commands
New
Open
Desktop
Graphs
Calculate
Pause
Save
Save As
Messages
Render
Reset
Information
Memory
Progress
Parameters
Input
Output
Setup
tmax: 10
Cells: 1006
Grid Width: 50
dt: 0.005
dx: .05
dt/dx: .10
dt/(dx2): 2.02
Physics
ntotal (MeV3) : Edit
ns / ntotal : Edit
ne / ntotal : 0.04
μ0,S (MeV): 300
T0 (MeV): 0.1
EOS: Bag CFL
EOS Properties
B: 4.42050625E8
Control


Graphs
Re-plot
New
Clear
Tile
Cascade
neutrino emi:
velocity
densities
chemical pote
chemical potentials
[X pos]
[Mu Strange]
densities
[n Strange]
Parameters
Data
General
[n Strange] BAG [Point]
[n Down] BAG [Point]
[n Up] BAG [Point]
[n Electrons] BAG [Point]
[n Strange] [Point]
Add
Delete
Properties
Name:
[n Electrons]
Type:
Connected
Color:
Visible:
Selected:
Point Size:
Line Width:
Shape:
Circle
Stroke:
Solid
X scale:
Y scale:
Normalize:
Control Points:
Bin
Sort
Edit
velocity
neutrino emission
Variable
Time
Core velocit
Core positior
Chemical pol
Graph 4
Core position
Title:
[Time]
[Core pos]
[Core pos] BAG [Point]
[Core pos] [Point]
x:
201.2390
y:
-6.3660
f(x):
7.1000
L:

Currently implementing:

(i) MIT with dynamic B

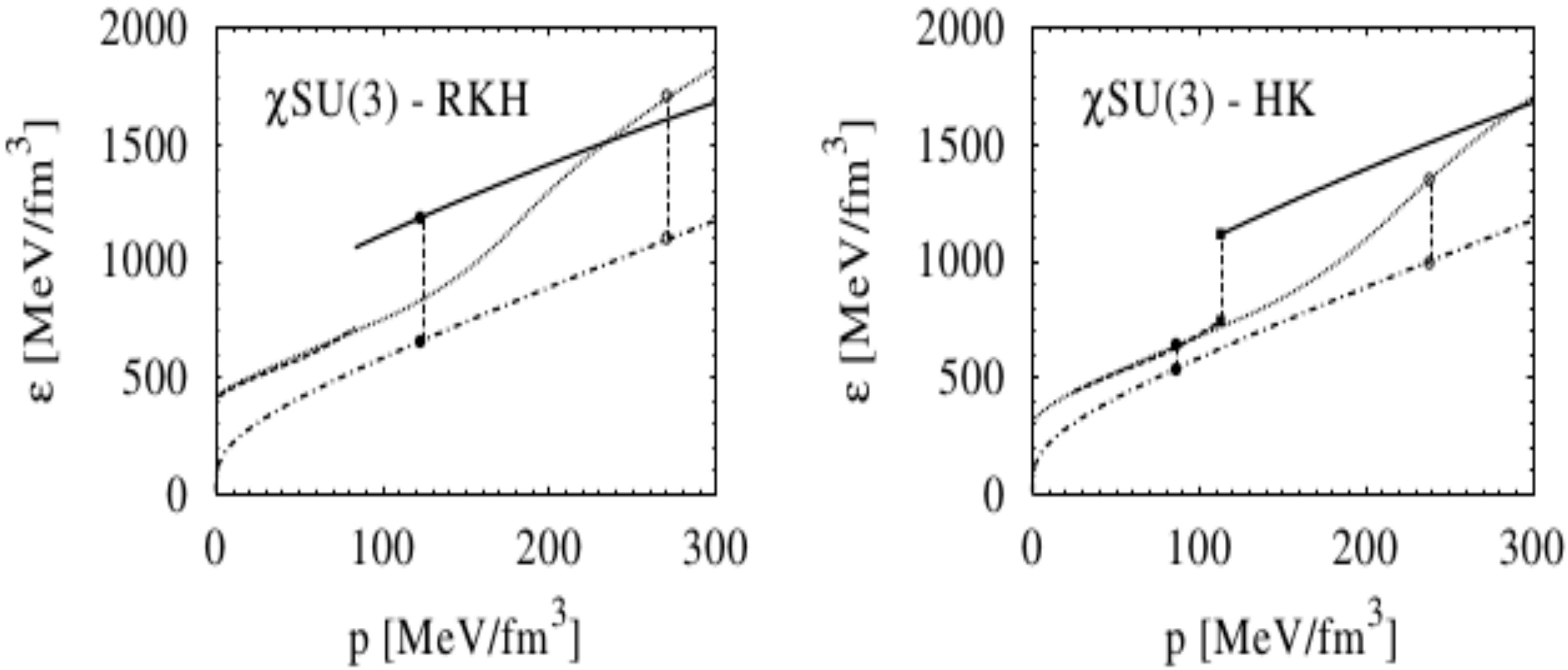
(ii) NJL

Nambu-Jonas-Lascinio model is more consistent (includes chiral symmetry breaking).

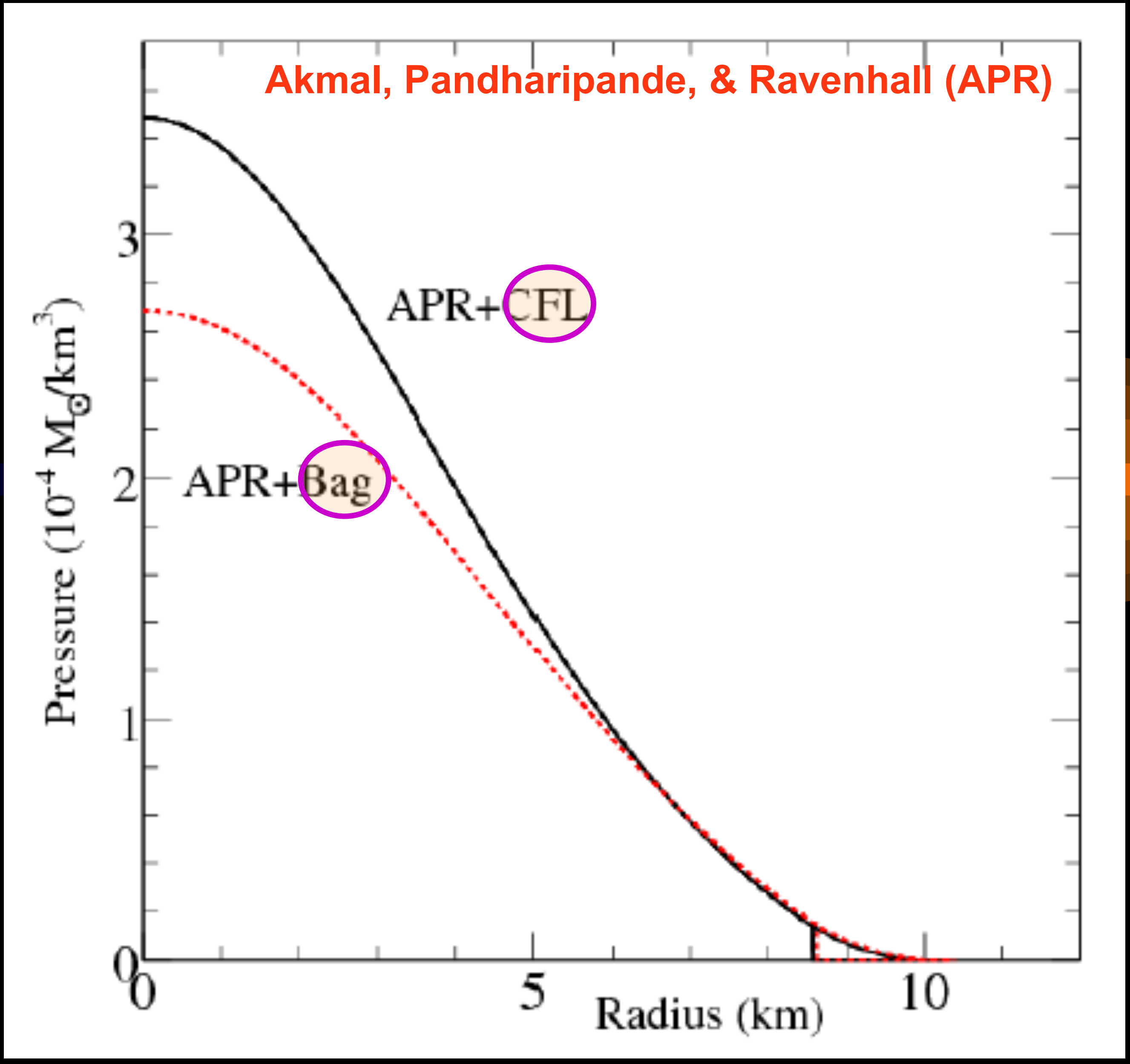
(iii)   APR + CFL

Also, in the NJL model, CFL is not necessarily a lower energy state than non-CFL uds matter, because in the NJL model, CFL state have always a large amount of massive s-quarks, while non-CFL matter has few massive s-quarks until higher pressures. In contrast, in the MIT Bag picture CFL is implemented by subtracting a gap factor from the energy density, which always lowers the energy.

Buballa 2005



Solid line = CFL.
Dotted line = non-CFL quark matter.
Dotted and dashed line= hadronic matter.



Akmal, Pandharipande, & Ravenhall (APR)
APR+CFL
APR+Bag
Pressure (10^{-4} $M_\odot$/km^3)
Radius (km)
0
1
2
3
0
5
10

s-quark Mass

- The assembly of massive strange quarks would suck up more energy, which would probably slow down the burning front.

- Including quark masses leads, for example, at a given **B** to an energy per baryon which is about 20 MeV higher

BURNUD depends on the mass of strange quark through the weak-reaction rate equations.

$$\Gamma_1 - \Gamma_2 = \frac{34}{5\pi} G_F^2 \cos^2\theta_C p_F(d)\, p_F(u)\, T^4 (\mu_d - \mu_u - \mu_e)^2$$

$$\Gamma_3 - \Gamma_4 = \frac{17}{40\pi} G_F^2 \sin^2\theta_C \mu_s \boxed{m_s^2} T^4 (\mu_s - \mu_u - \mu_e)$$

$$\Gamma_5 = \frac{16}{5\pi^5} G_F^2 \cos^2\theta_C \sin^2\theta_C \times p_F^2(u)\, p_F(d) \boxed{p_F^2(s)} \Delta\mu \left[\Delta\mu^2 + (4\pi T)^2\right] ,$$

$$\boxed{p_{F_s} = \sqrt{\mu_s^2 - m_s^2}}$$

A more consistent MIT Bag EoS with non-zero strange mass would be non-analytic.

$$\Omega_i = \mp T \int_0^\infty dk g_i \frac{k^2}{2\pi^2} \ln \left[1 \pm \exp\left(- \frac{\epsilon_i(k) - \mu_i}{T} \right) \right]$$

Thermodynamic Potential (NEGATIVE Pressure)

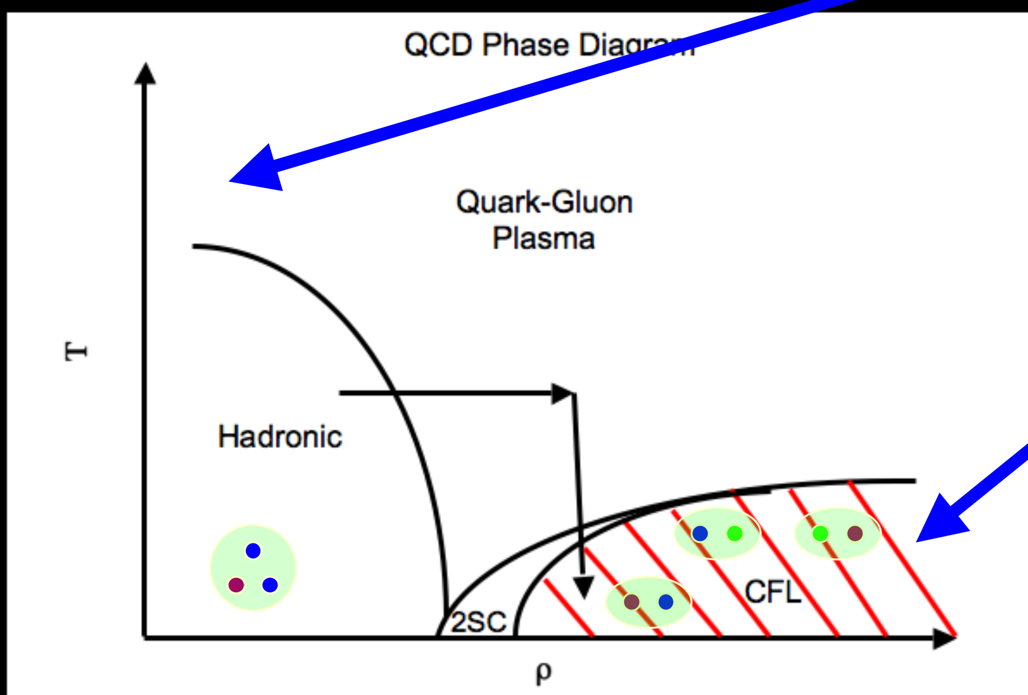
We will implement this more consistent EoS in future versions.

RHIC Regime

quarknova.ucalgary.ca

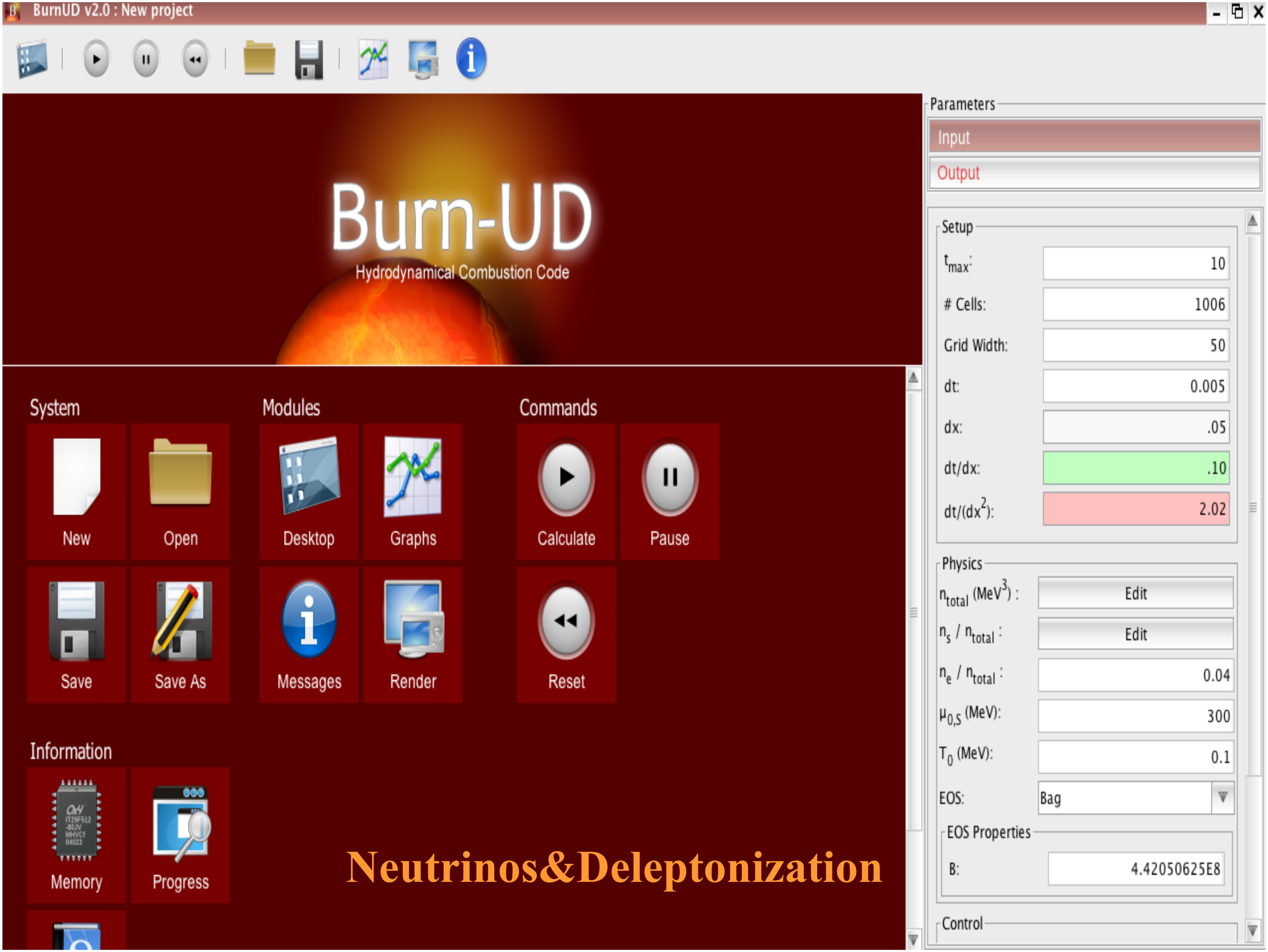
Non-ideal effects:
Viscosity & Thermal Conduction
Gluon-Gluon interactions

RHIC



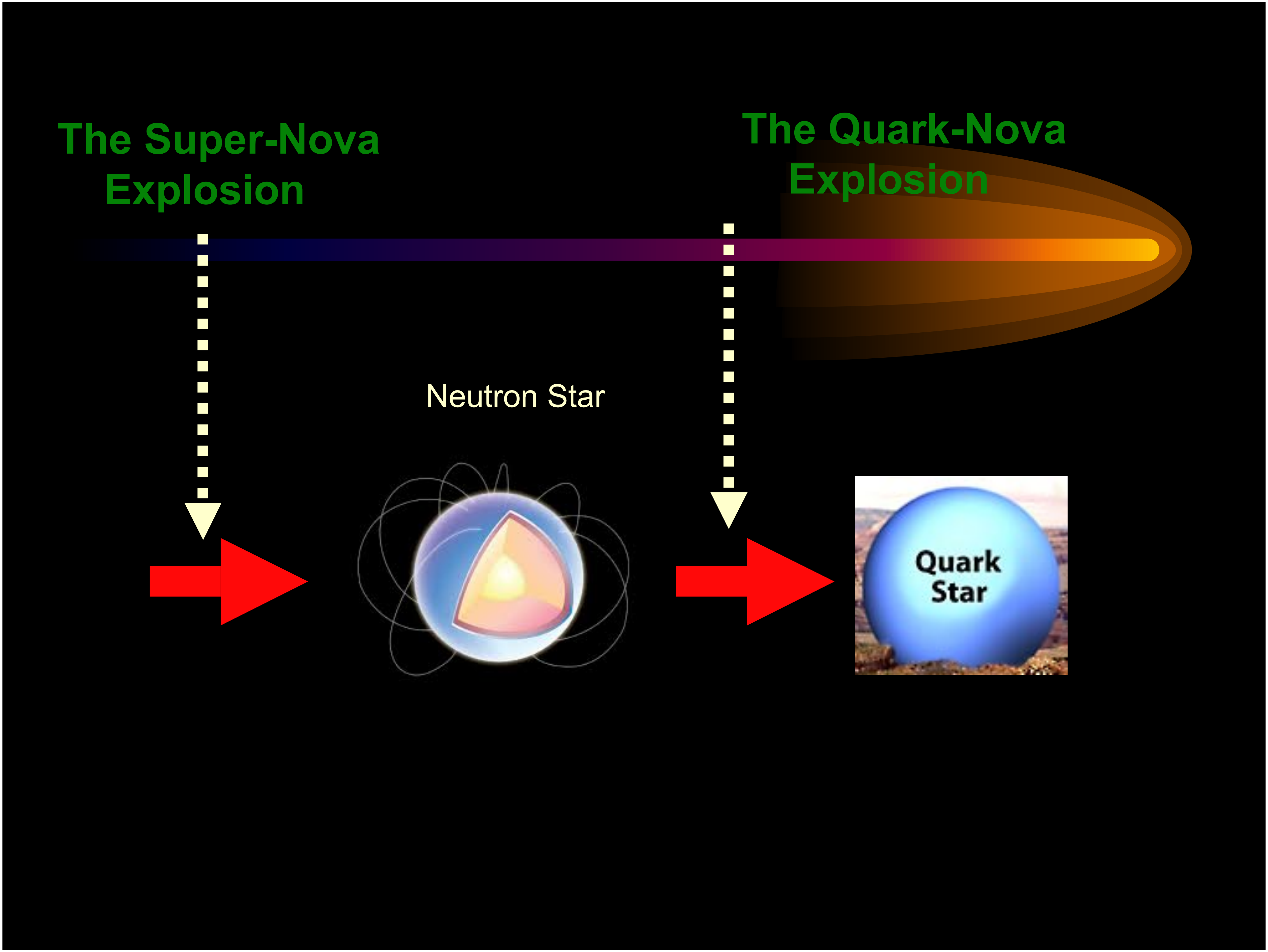
ASTRO

2D version (being tested !):
De-leptonization Instability suggests
Quark-Nova



BurnUD v2.0 : New project
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: 4.42050625E8
Control
Neutrinos&Deleptonization

Astrophysical Implications

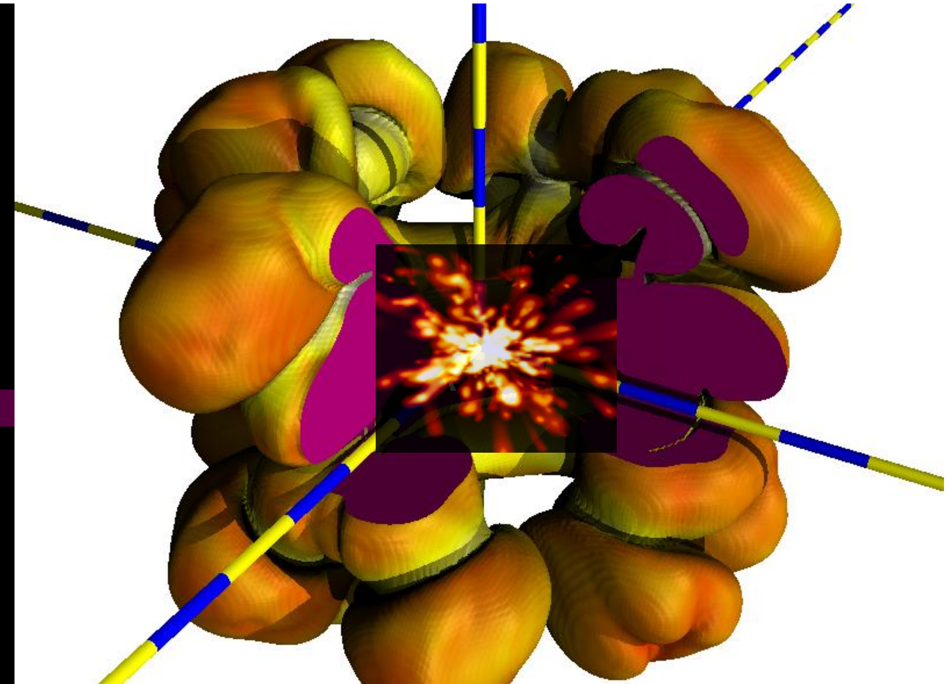

The Super-Nova Explosion
The Quark-Nova Explosion
Neutron Star
Quark Star

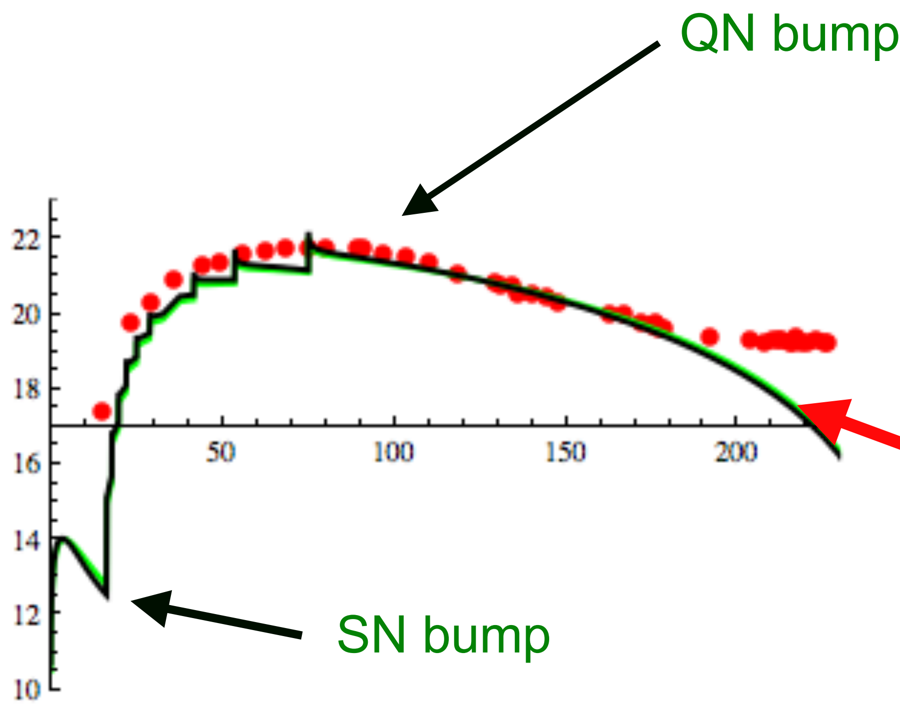
PREDICTIONS:

double-humped light-curve

```
Range → {{0.0, 230}, {10, 23}}, AxesOrigin → {0.0, 17.}];

)]
```



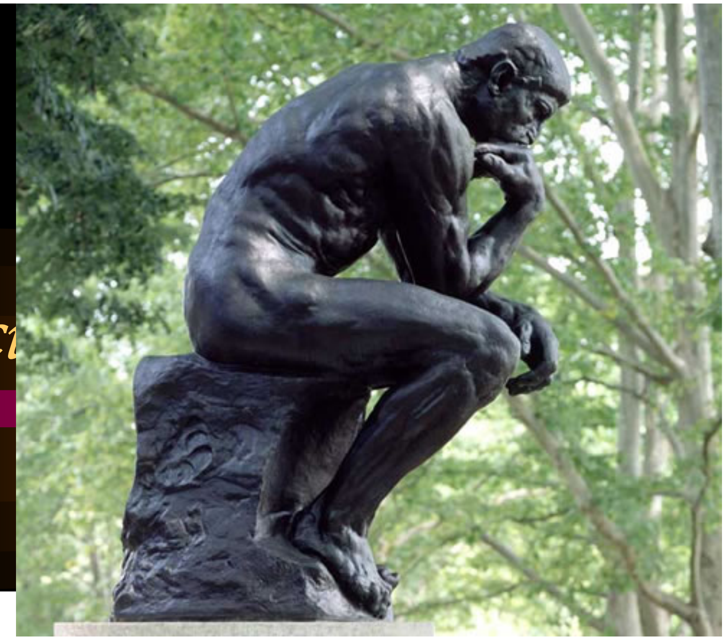


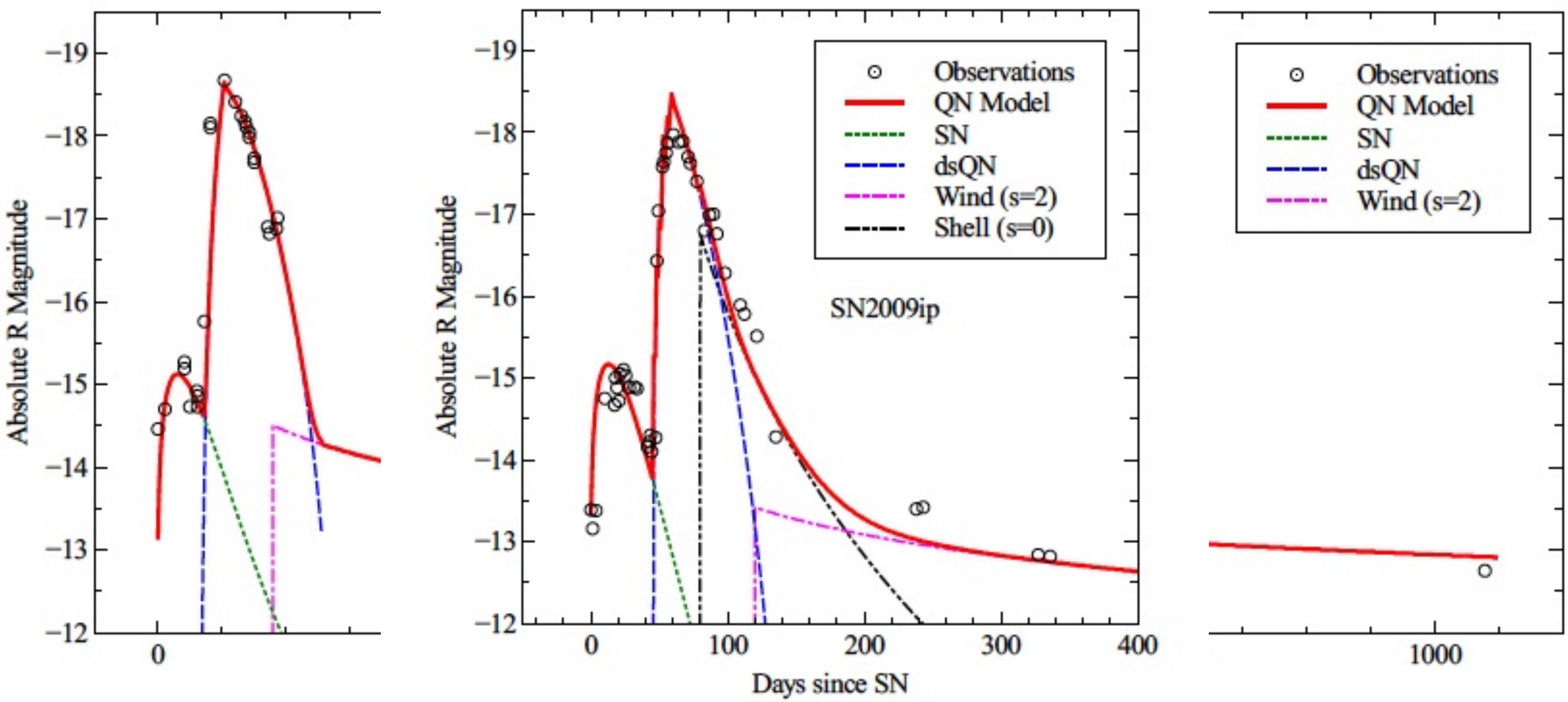
Mass = $\boxed{20\text{-}40}$ Solar Masses

Delay = a few days

Quark-Nova Fit

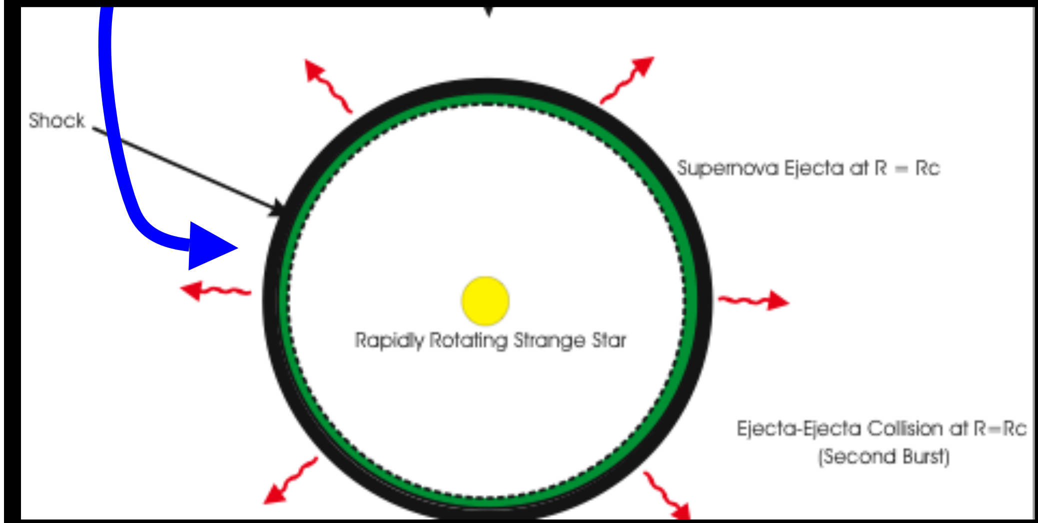
PREDICTIONS: *double-humped light-c*





Collision between the QN neutrons & SN-ejecta

Spallation in QNe



spall

Ouyed et al. PRL (2011); Ouyed et al. Rev. Mex (2012); Ouyed et al. PRC (2014)

PRL **107,** 151103 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

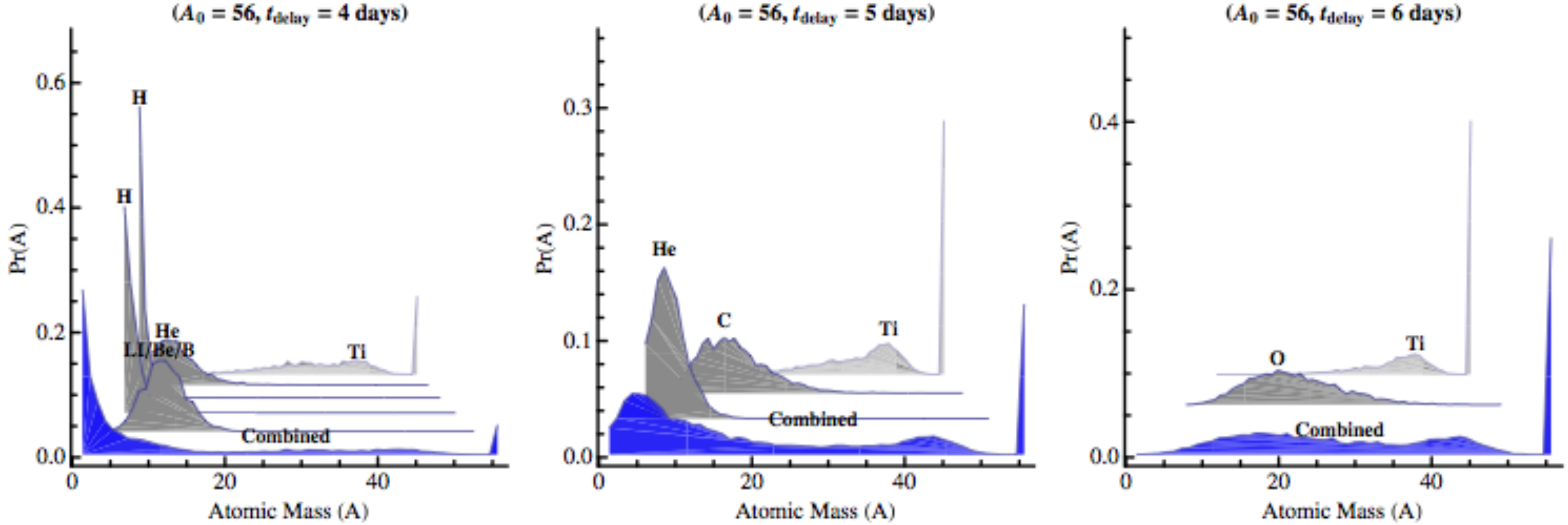
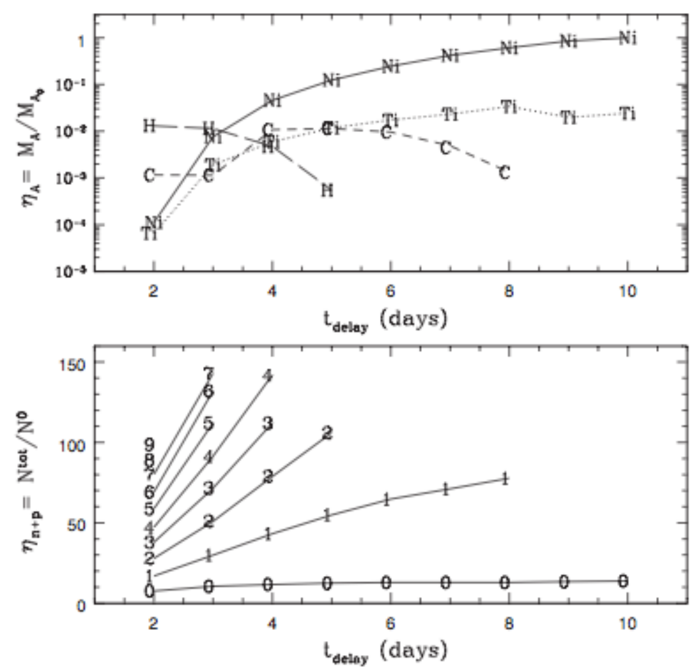


FIG. 1 (color online). Spallation products in successive layers (back to front) from ^{56}Ni for $t_{delay} = 4, 5, 6$ days. The overall distribution is shown in the front layer labeled "combined."

^{56}Ni depletion
^{44}Ti formation
^{sub}Fe formation



Ouyed et al. PRL (2011); Ouyed et al. PRC (2014)

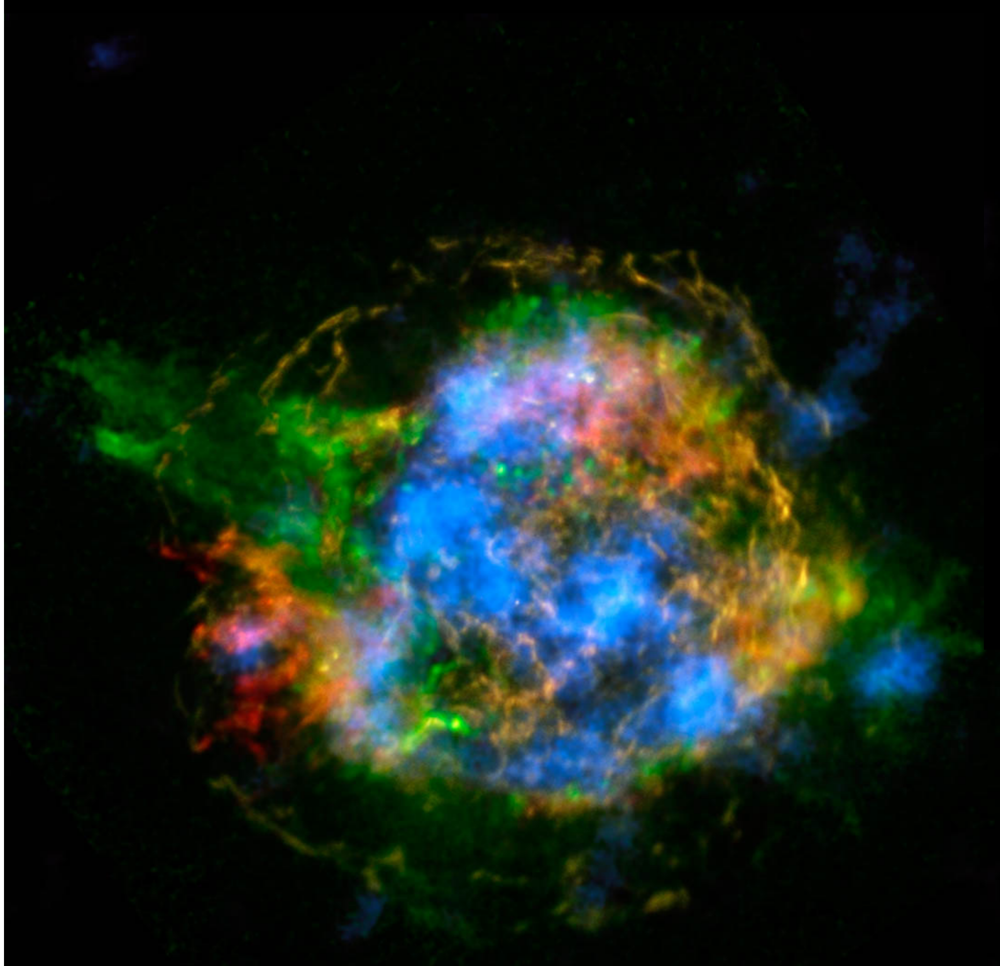
PREDICTIONS

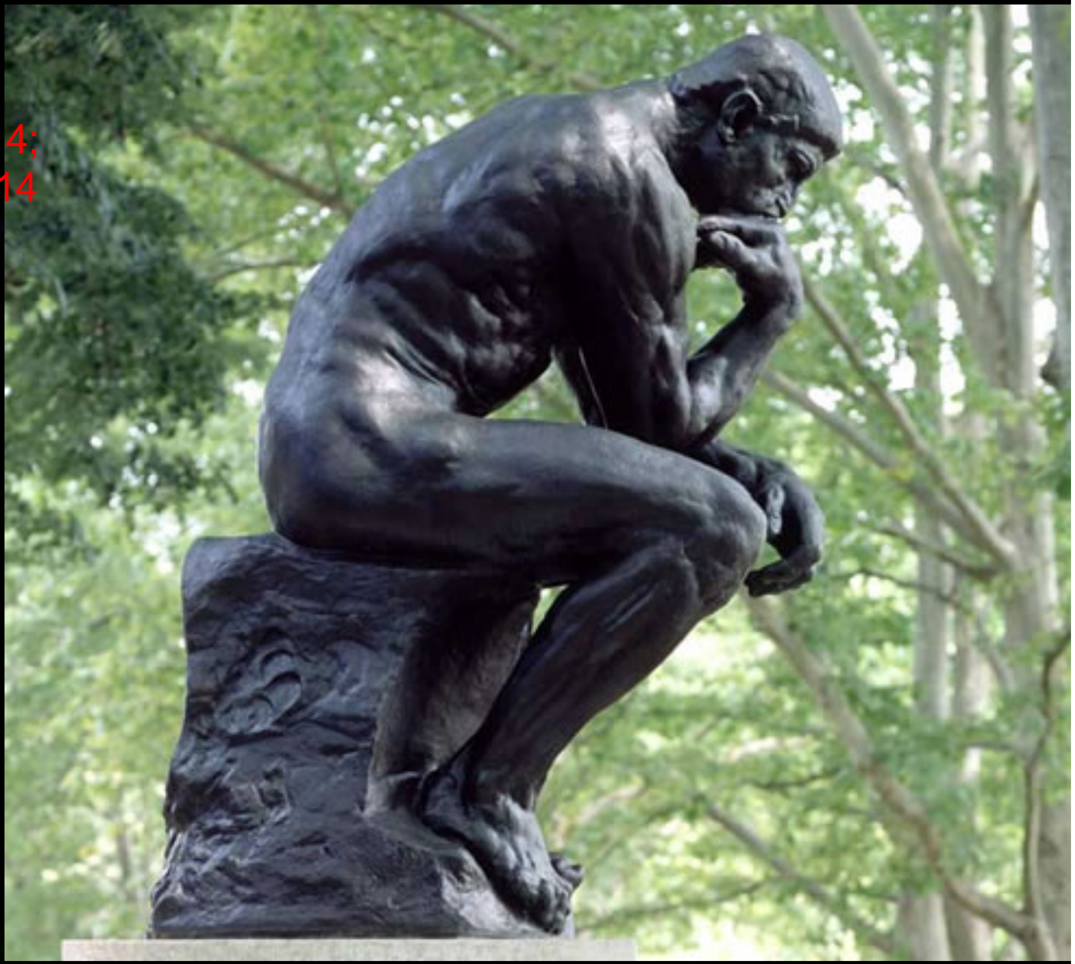
QN n-spallation → ★ Sub-luminous SN

QN n-spallation → ★ ^{44}Ti and ^{56}Ni *not co-spatial*

Fe and ^{44}Ti not co-spatial in Cas A

Grefenstette et al., Naure 2014;
Laming, Nature 2014

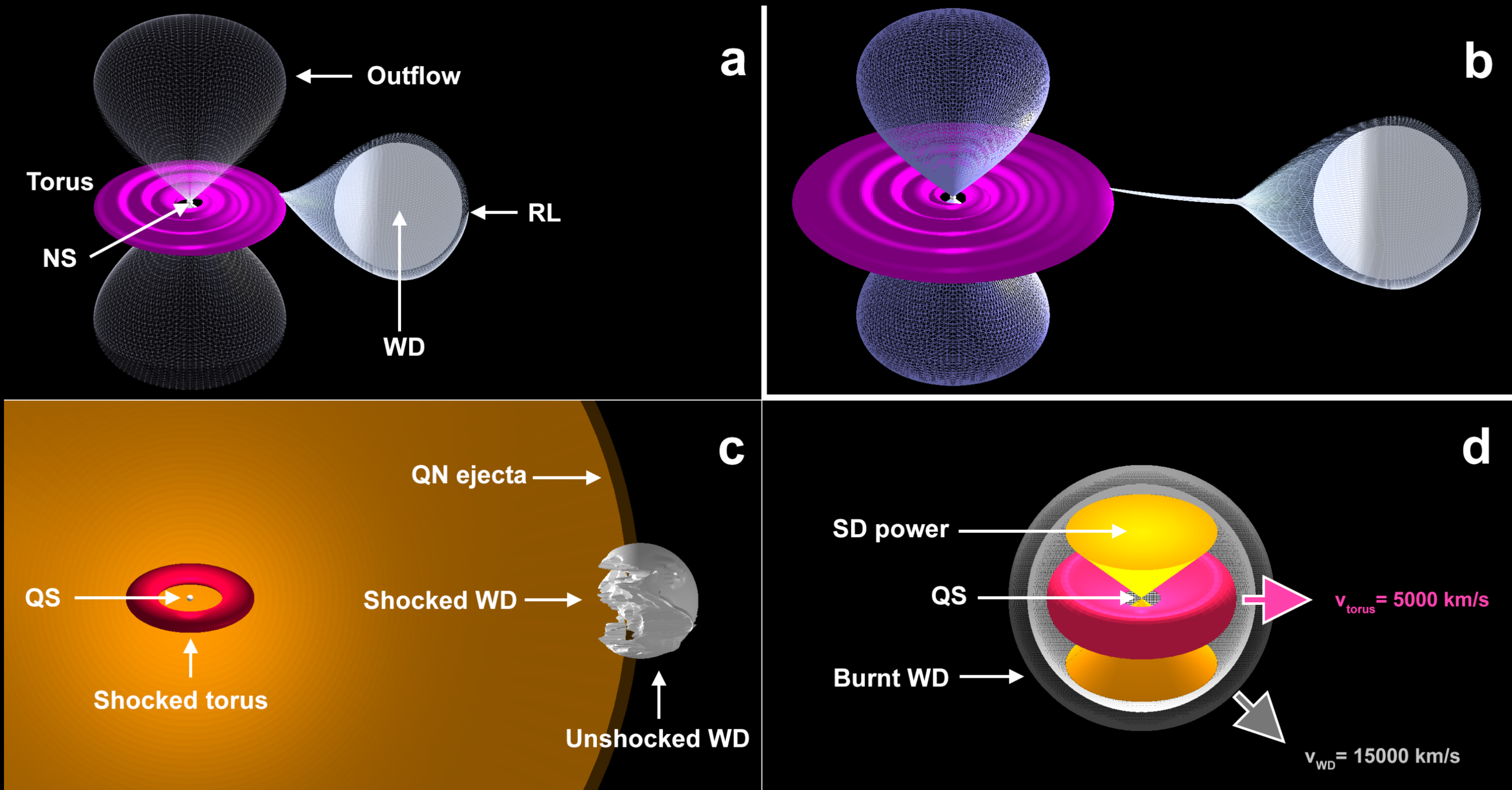




Cas A is a Sub-luminous SN !

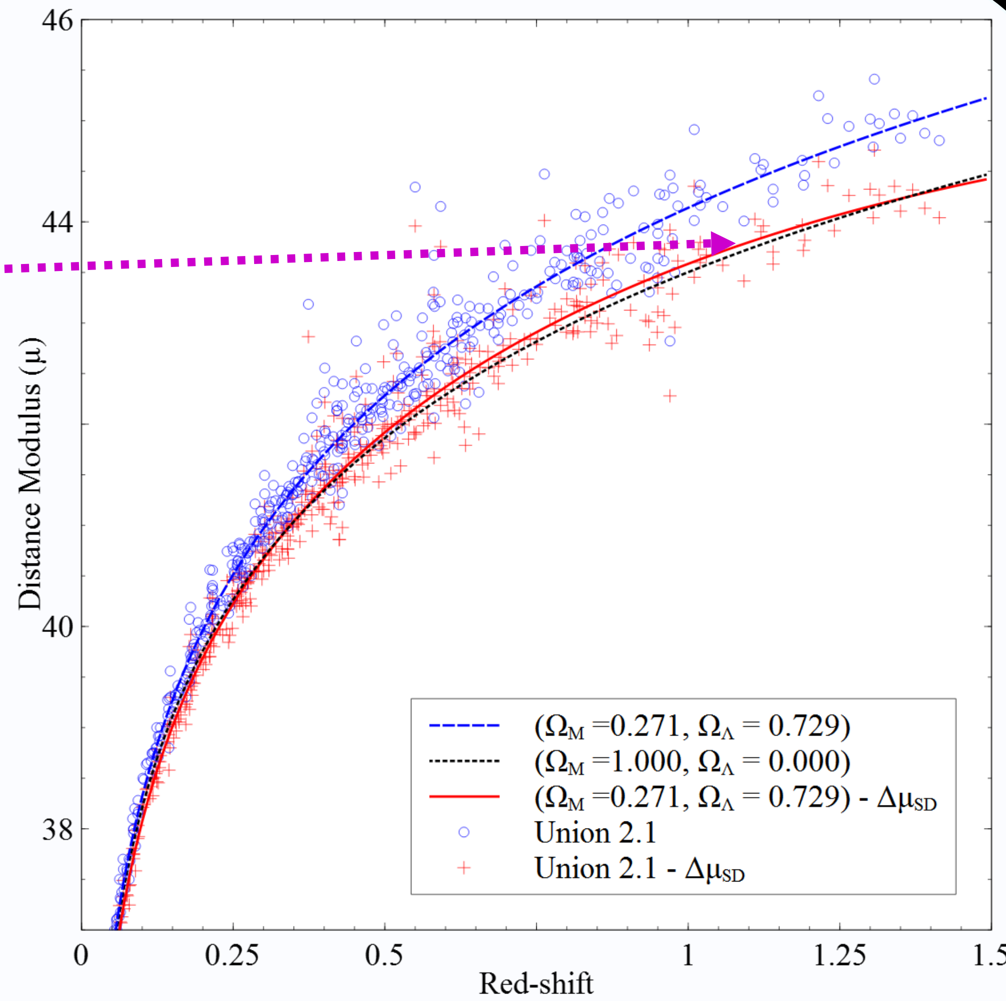
Dark Energy ?

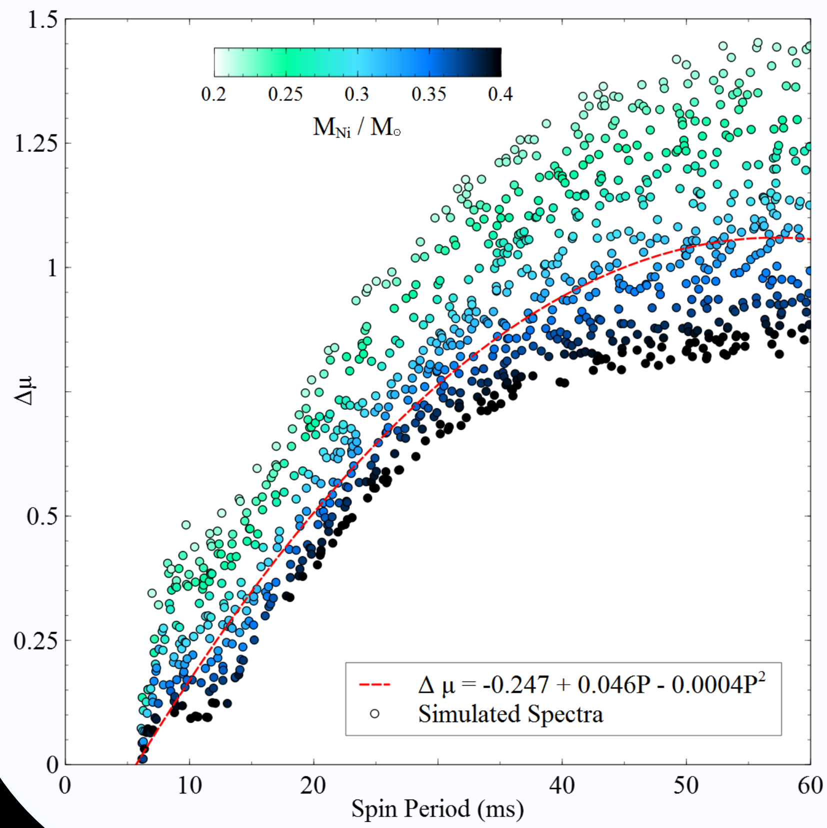
The Quark Star (an additional **power source**)



Ouyed et al. (2014)

The Quark Star spin-down power gets rid of DE !





Ouyed et al. (2014)

Burn-UD

ThaNK YOU!

quarknova.ucalgary.ca