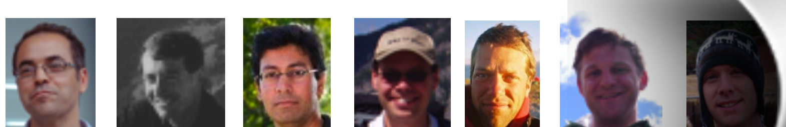
Emergence of Quark Phase in Neutron Stars & Observational Signatures

Rachid Ouyed

University of Calgary, Alberta, Canada

CSQCDIII, Guaruja, Dec. 12-15, 2012

- Group:



quarknova.ucalgary.ca

OUTLINE

<u>Strange Quark Matter (SQM)</u>

- Hypothesis
- Reactive Diffusive Hydrodynamics
- Simulation Results (1D)
- Current Efforts and Future Avenues

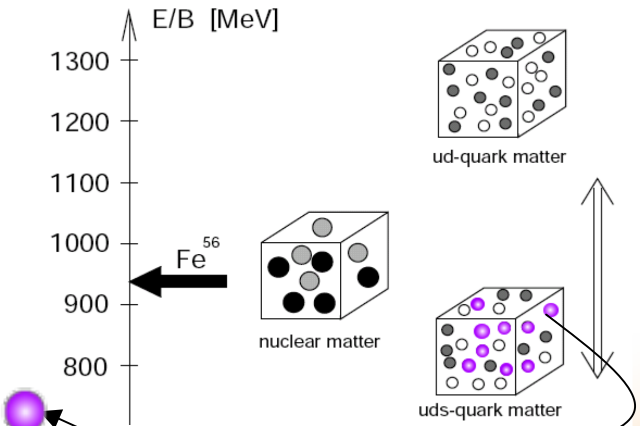
- Burn Hadrons -> SQM
- Study conversion speeds

<u>Observational Signatures</u>

- The "double-humped" SNe (Type II QNe)
- The nuclear/spallation proxies
- QNe in Binaries (Type Ia QNe / GRBs)
- Gravitational Waves from QNe

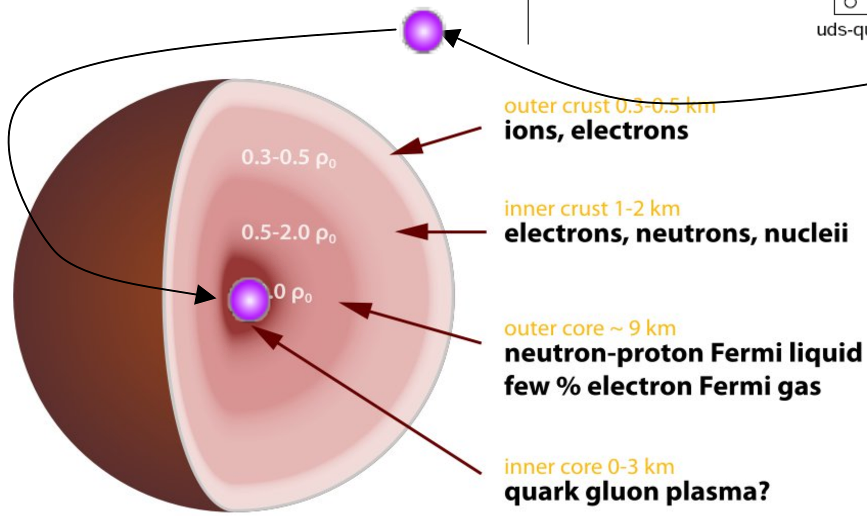
Combustion of Neutron matter to Quarks

Fig: F. Weber,
Prog. Part. Nucl. Phys.
54, 193 (2005)



$$\bar{\mu}_{(\mathrm{uds})} \approx 0.89\bar{\mu}_{(\mathrm{ud})}$$

Bodmer-Terazawa-Witten conjecture



Contamination Scenarios

- lambda clustering
- neutrino sparking
- outside strangelet

Bombaci et al. (2004)

- First order Transition
- Quantum Nucleation
- Prob. exp. sensitive to P

Some previous works

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

$$v = \dot{x} \sim \sqrt{\frac{D}{\tau}} \approx 10 - 100 \text{ km/s}$$

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

$$v \sim (0.1 - 0.2)c$$

Burn-UD in a nutshell

Burn-UD

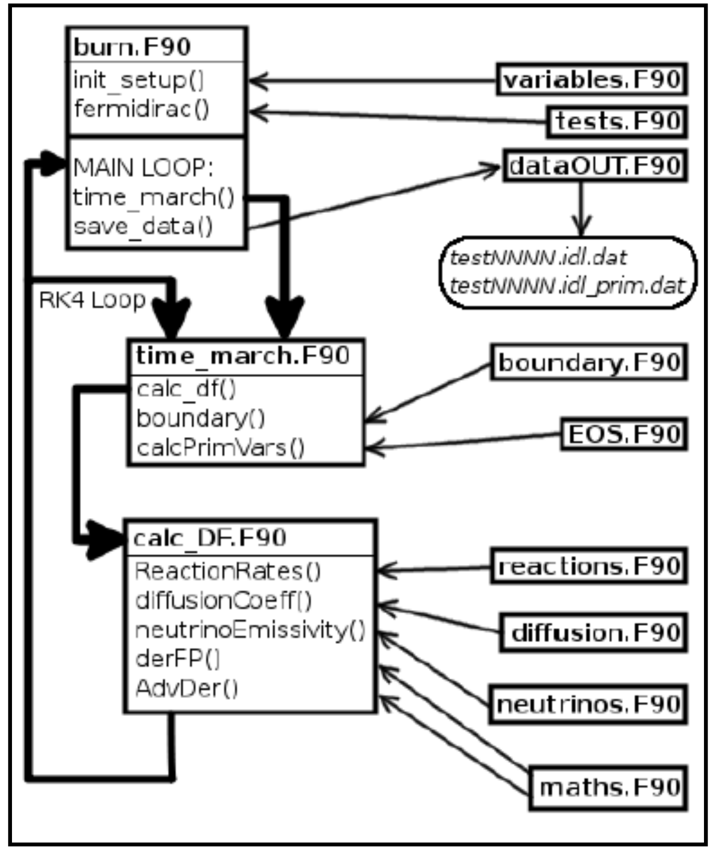
(Niebergal's PhD Thesis)

Solves the equations of hydrodynamical combustion to SQM.

Equations solved explicitly in time using a 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).



Rate Equations

Burn-UD

Reactive-Diffusive Hydrodynamics

reactions + diffusion + fluids
=
combustion

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

Neutrino Cooling

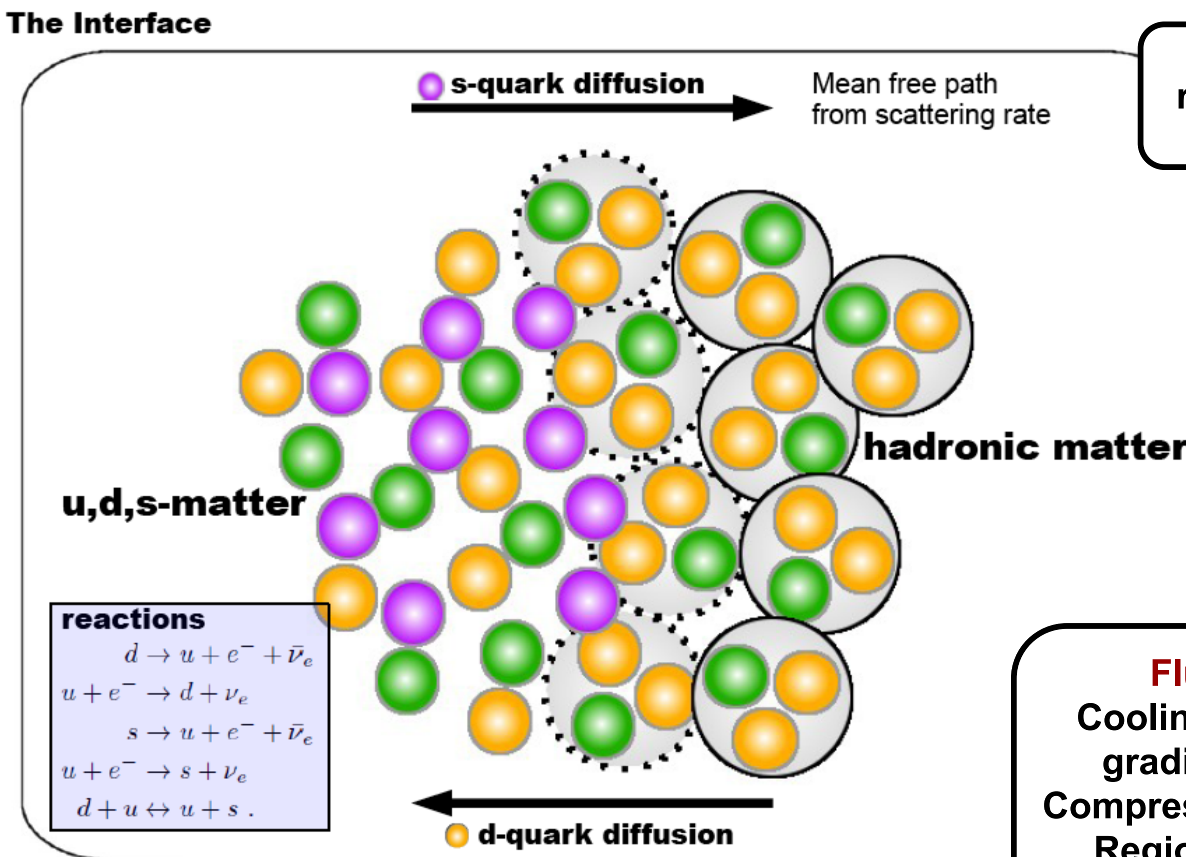
Rates for production of neutrinos can be found in the literature (eg. Iwamoto 1982).

Strangeness as a Catalyst

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

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

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

Burn-UD

Major Findings

Burn-UD

1) V_{burn} = 0.002 to 0.04c
- Much faster than analytic estimates

2) Neutrino cooling is essential
- Must be included in jump conditions

3) New kind of instability
- halts SQM growth

Cancer contained

4) Transition will be explosive (Quark-Nova)

Deleptonization instability

A snapshot during the simulation of the:

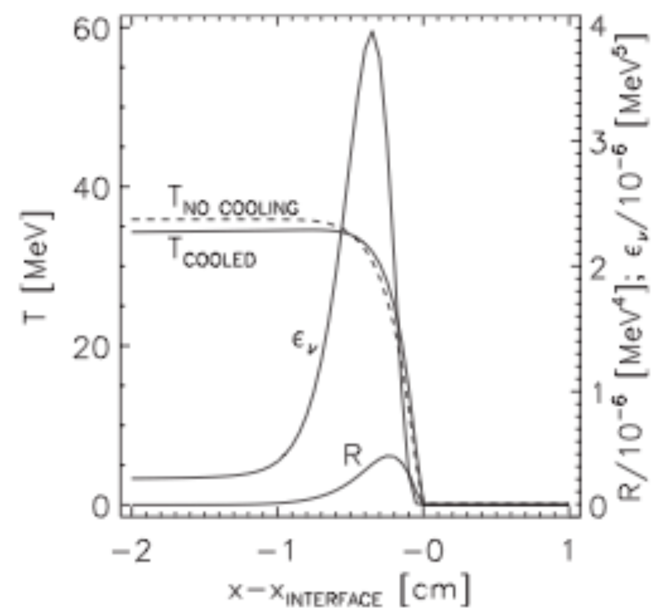
(i) temperature (T);
(ii) reaction rate (R),
(iii) and neutrino **emissivity**,

throughout the burning interface.

T is shown with (solid line) and without (dashed line) neutrino cooling, where the difference between the two is the variable

[C = T -T_cooled]

that serves as the measure of cooling.



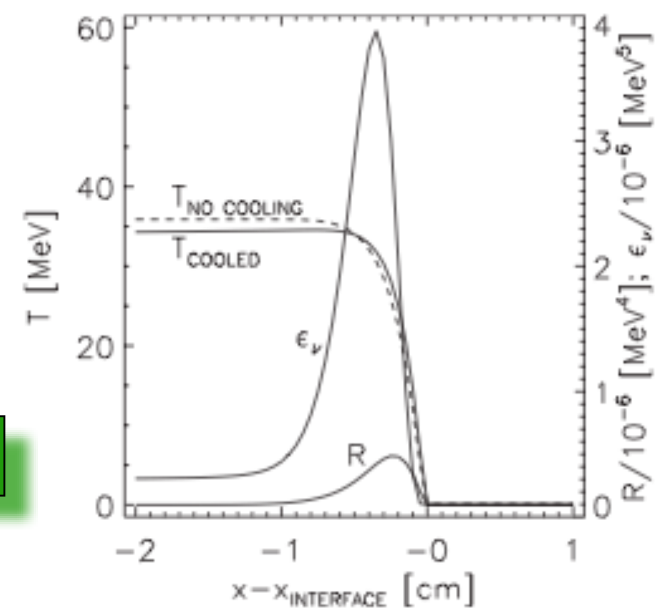
Neutrino emissivity peaks in the interface region

Deleptonization instability

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"

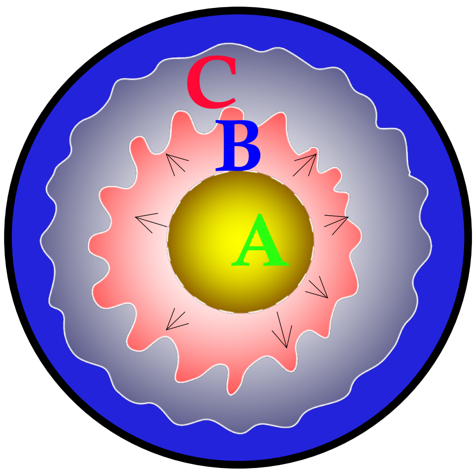


Neutrino emissivity peaks in the interface region

Deleptonization instability

- burning rate increases due to wrinkling.
- cooling increases wrinkling.

A “Quark-Nova” in 2D



Parent
Neutron
Star

A) Initial laminar burning -> fast

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

C) Deleptonization
-> Interface halts!
-> 2nd Core collapse..
->Black-Hole?

Quark-Nova ?

Ongoing…

1. Going to 3-Dimensional (3D) simulations.

2. Adding turbulence and study of neutrino cooling effects in 3D

2. Coupling to oscillation modes of the star

3. RHIC regime

4. Neutrinos signals in RHIC&ASTRO regimes (*conversion*+*deleptonization*)

Multi-D simulations:

Wrinkling instability of Interface versus diffusive stabilization

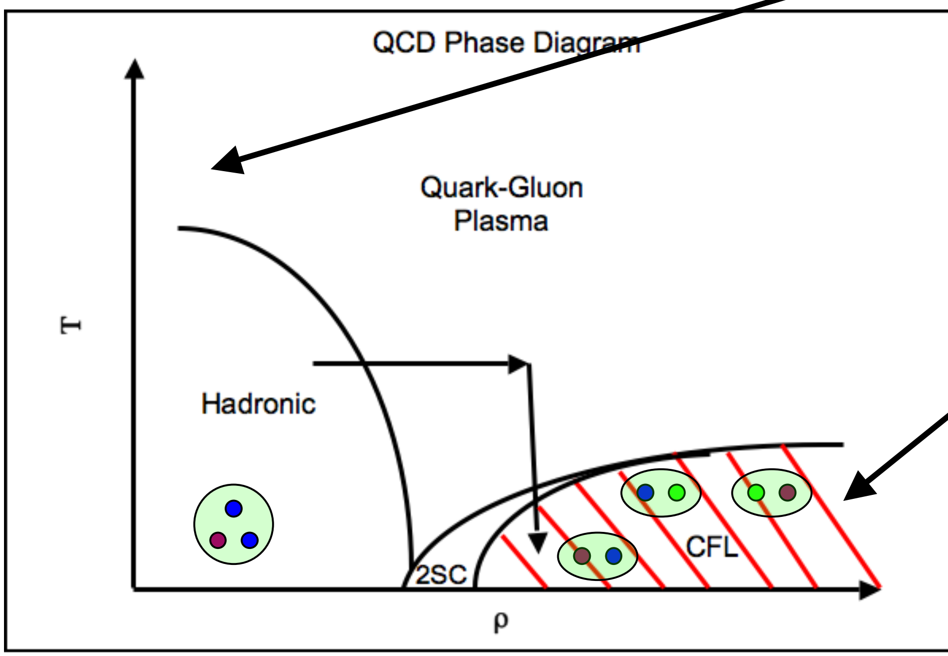
Equation of State :

Mixed Phases, Color Superconductor..

RHIC Regime

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

RHIC



ASTRO

Color Superconductivity

Astrophysical Implications/Applications

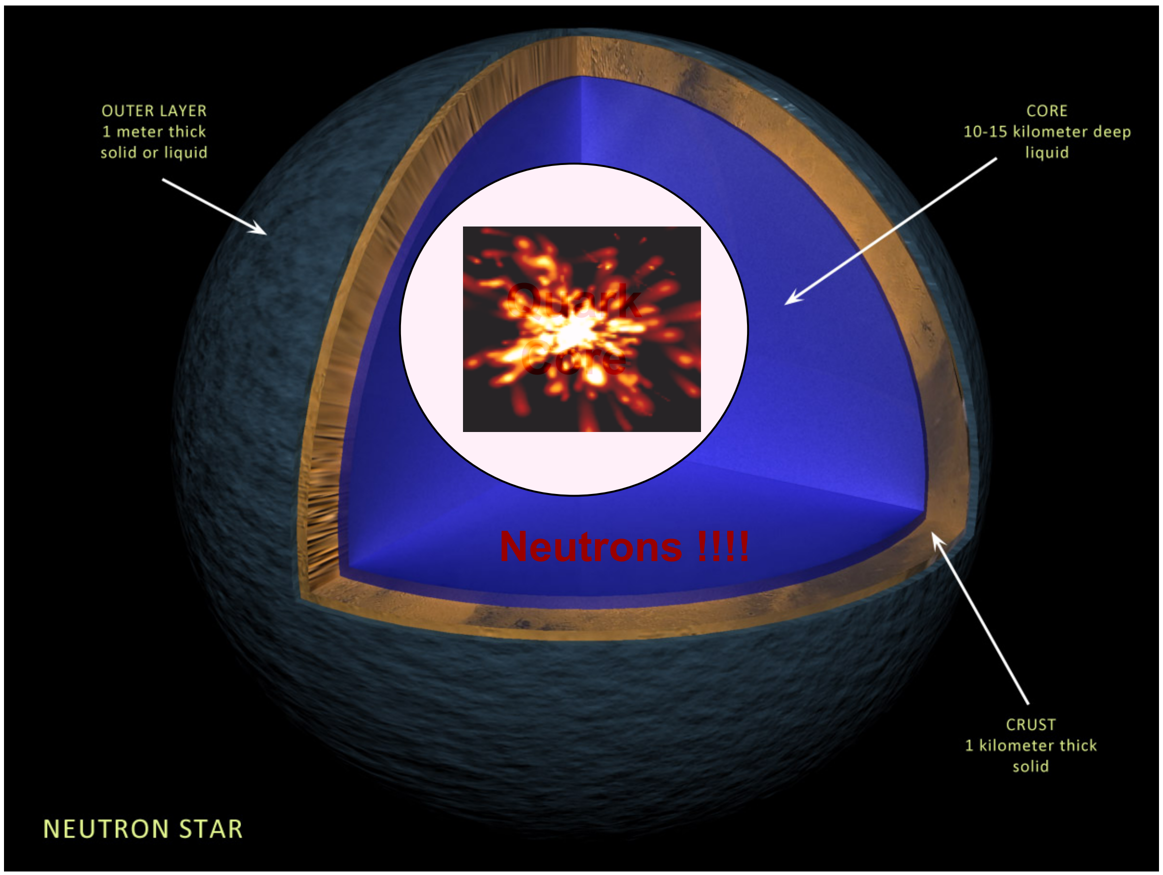
If detonation can be achieved, binding energy release is huge and fast ~ 10^{52} ergs

The Quark-Nova

Implications to

Explosive Astrophysics
&
Nucleo-Synthesis

Quark-Nova: **Novel r-process site**

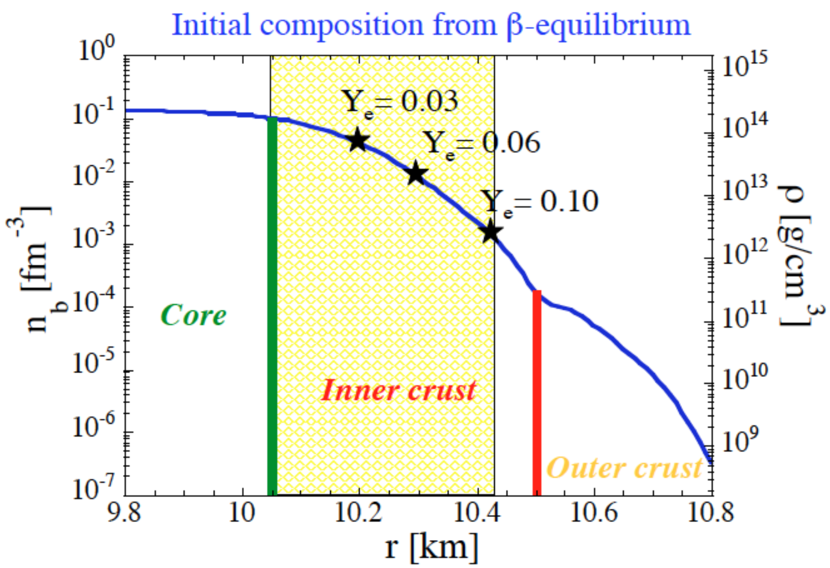


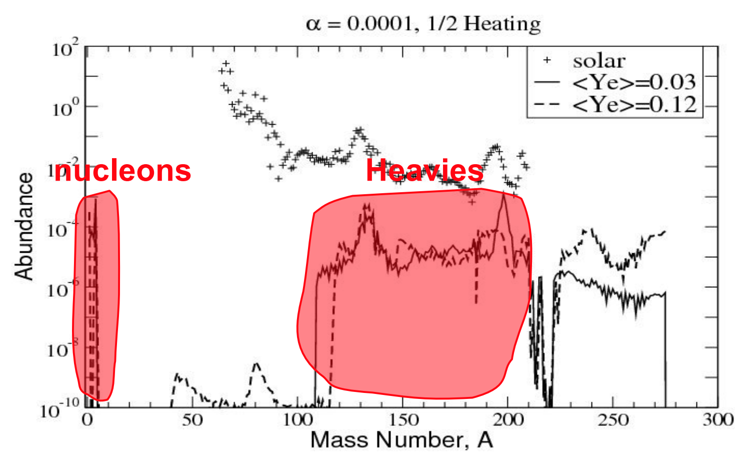
Quark-Nova: **Novel r-process site**

(Jaikumar et al. 2007, A&A, 471, 227; Charignon et al. 2011, 531, A79)

Ye << 1: Fast expansion reduces positron capture

From a single Quark-Nova



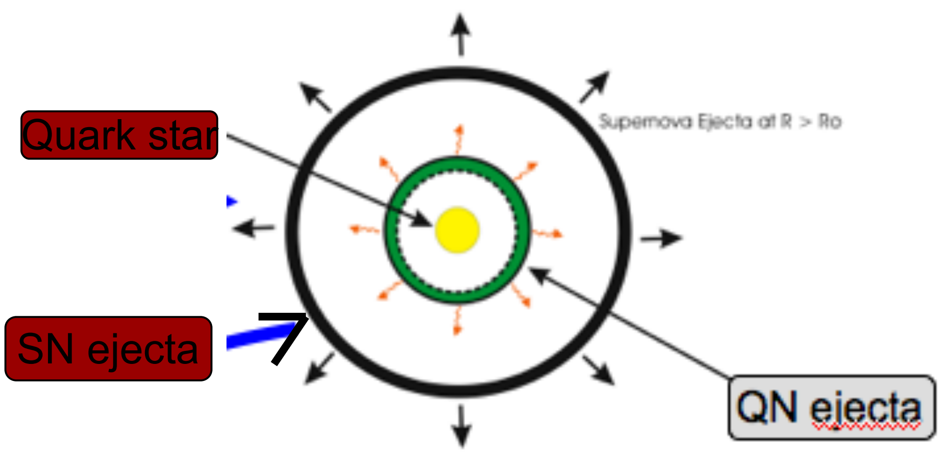


Quark-Nova: **Novel r-process site**

1 QN per 100 SNe

Play Animation

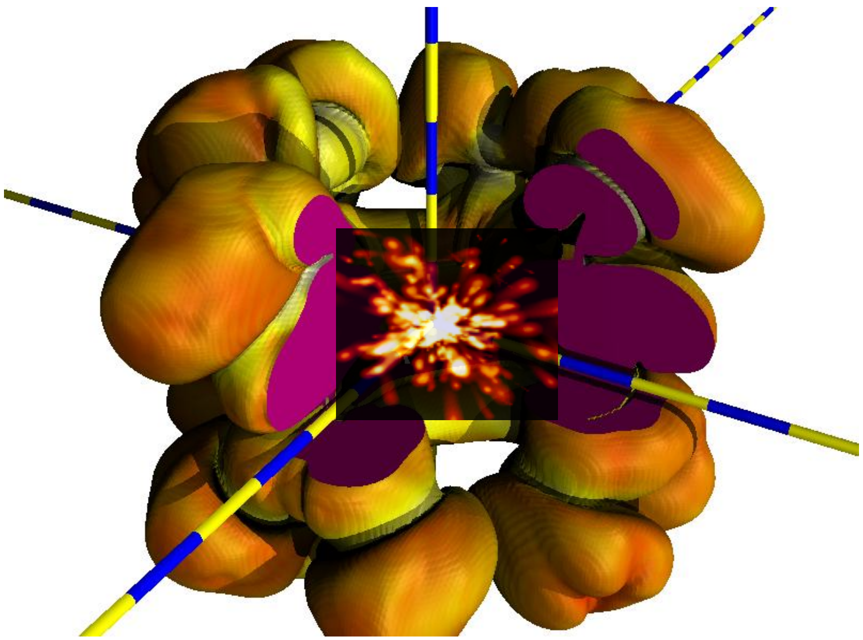
QN ejecta: **Properties**



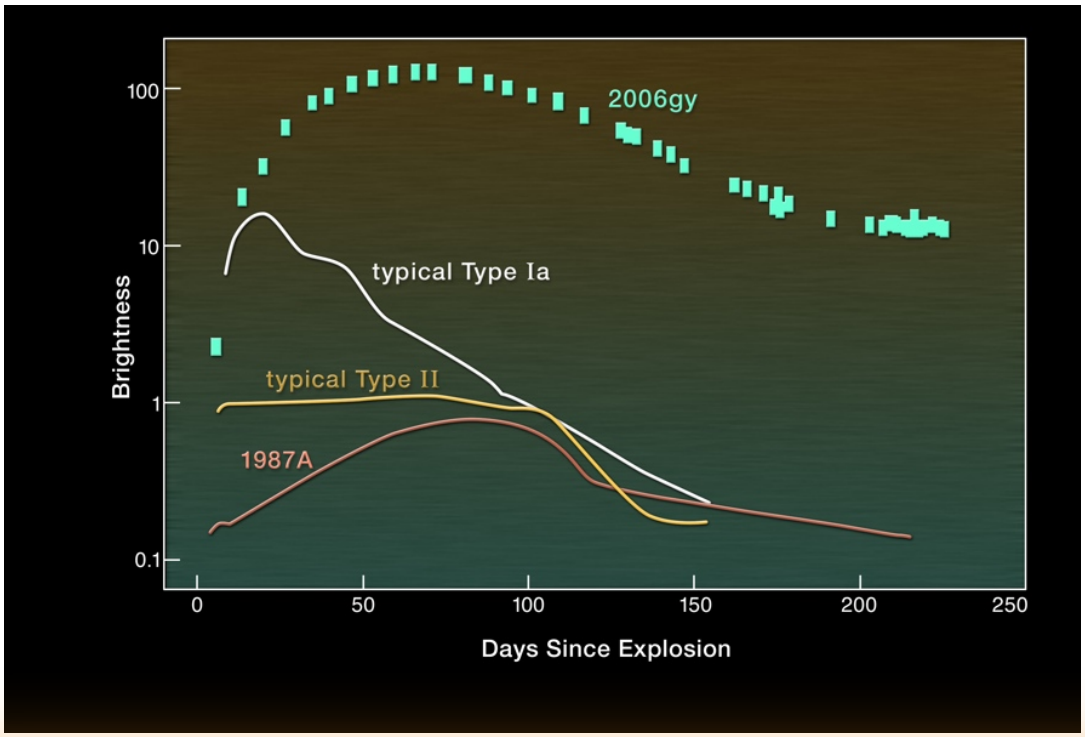
- Momentum
- 10^{52} erg in Energy
- Relativistic neutrons (E_n ~ 10-100 GeV)
- Relativistic A-rich Chunks

Dual-Shock Quark Nova

Time delay between SN and QN is key !



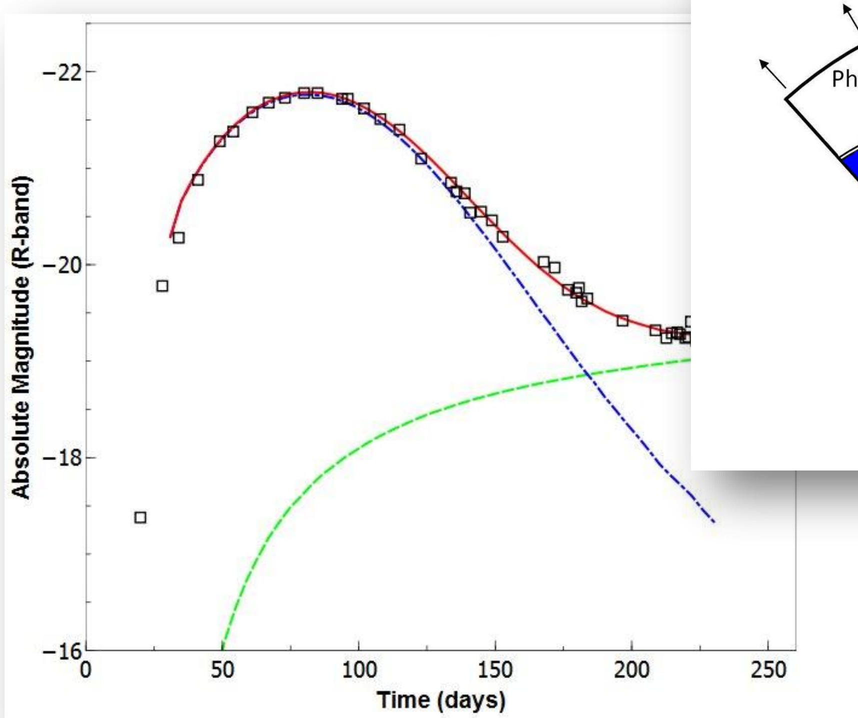
Superluminous Super-Novae

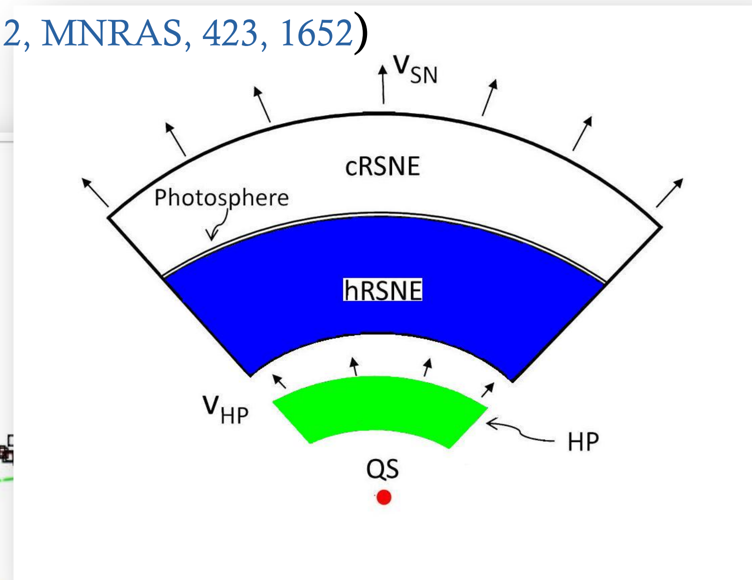


100 times brighter than a normal Supernova !

Superluminous Super-Novae

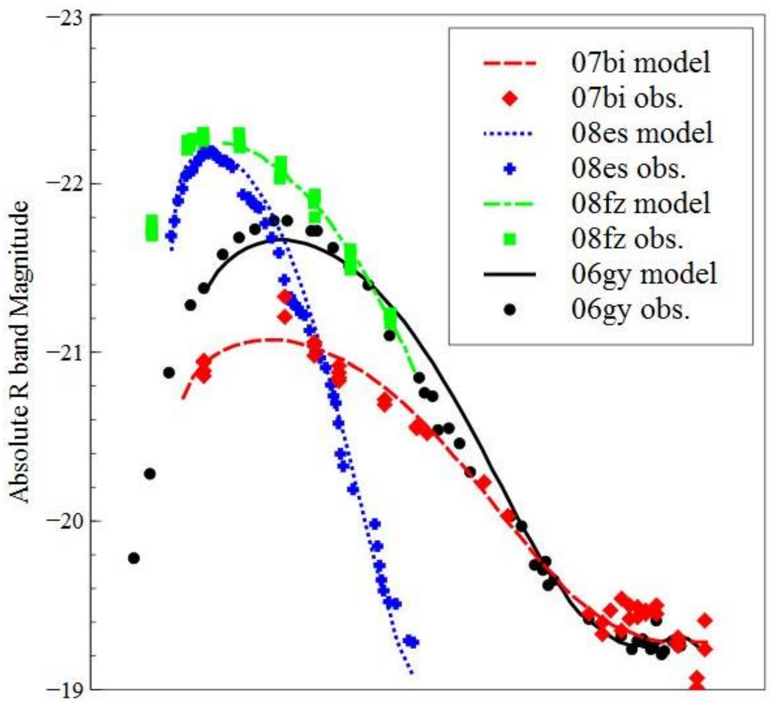
(Leahy&Ouyed 2008, MNRAS, 387, 1193; Ouyed et al. 2012, MNRAS, 423, 1652)





M_{ejec} = 30M_{sun}
V_{SN} = 4000 km/s
t_{delay} = 10 days

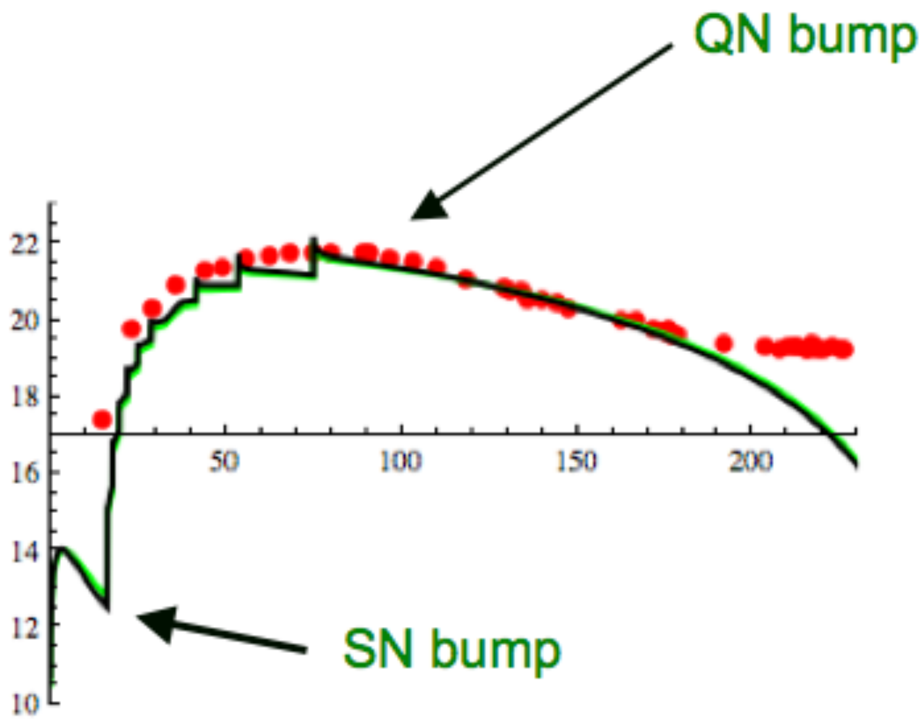
Superluminous Super-Novae: Since CSQCDII

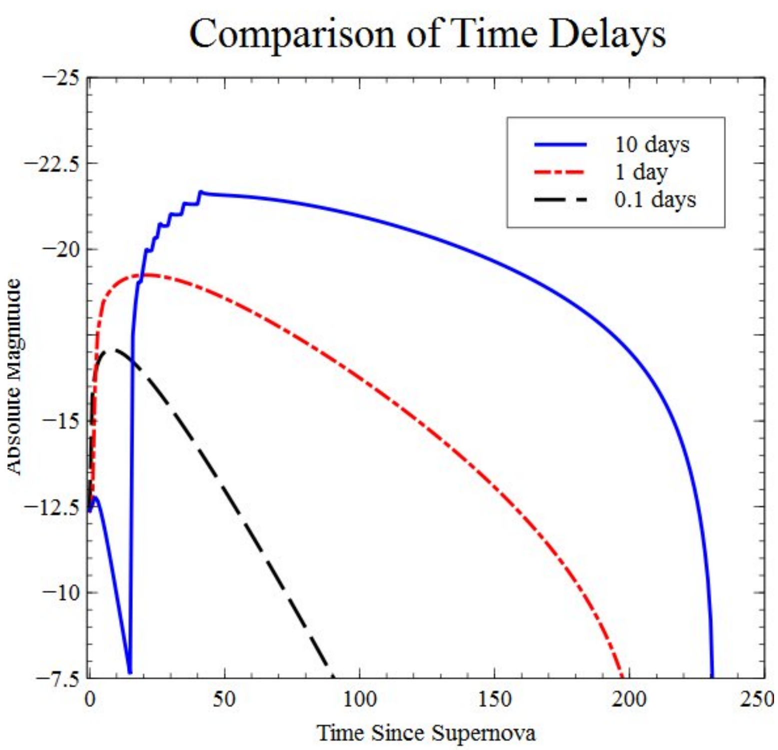


SLSNe	t_{delay} (days)
SN 2006gy	15.2
SN 2007bi	12
SN 2008es	10.5
SN 2008fz	16.5

Fits to SLSNe using 20 $M_{\odot}$ progenitor model. The observed light curves of four SLSNe (SN 2006gy – black circles, SN 2007bi – red diamonds, SN 2008es – blue plusses and SN 2008fz – green squares) are fit using dsQN models which all contain a progenitor mass of 20 $M_{\odot}$ ($M_{\odot}$ and $M_{\odot}$).

The Double-hump !





The Double-hump : **Since CSQCDII** !

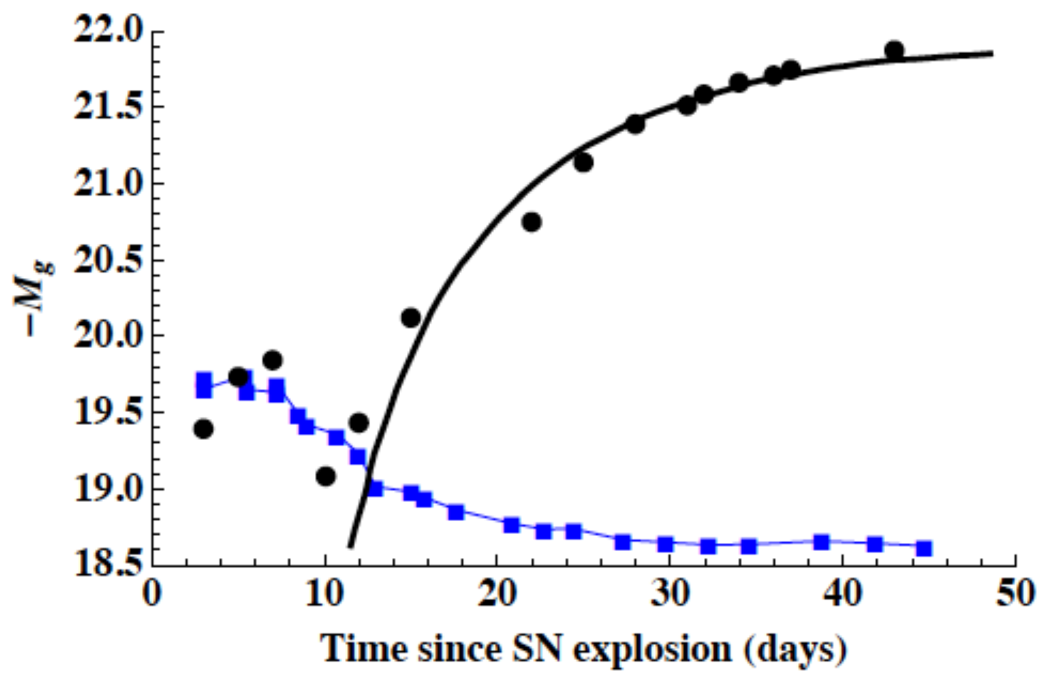
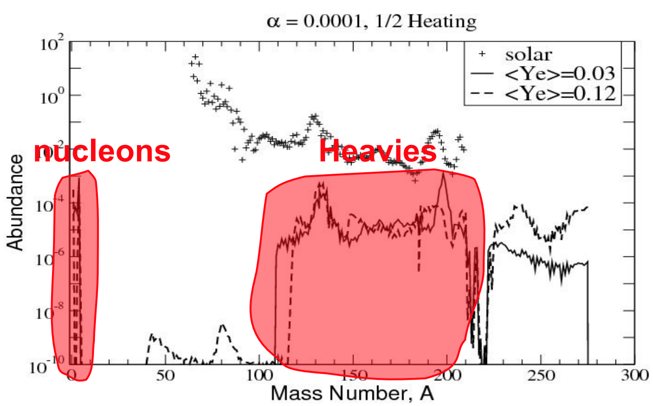


FIG. 1.— SN2006oz g-band absolute magnitude light curve (solid circles). The dsQN model is calculated for $M_{\rm ejecta} = 20 M_\odot$ and $t_{\rm delay}$ = 6.5 days (see text for other parameters). The proto-type SN light curve (connected squares) is a scaled version of that observed for SN1999em (see text).

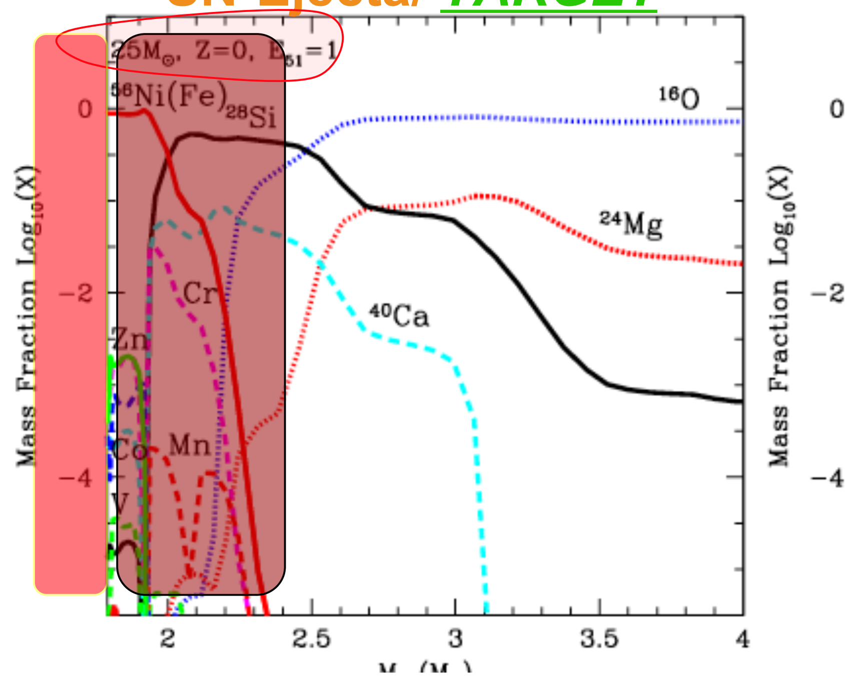
SN-QN collision: Spallation

QN-Ejecta/ ***BEAM***



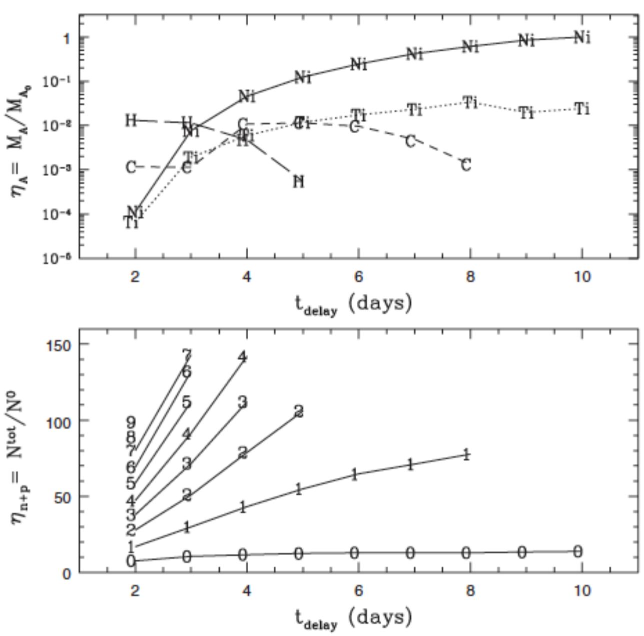
t_{delay}

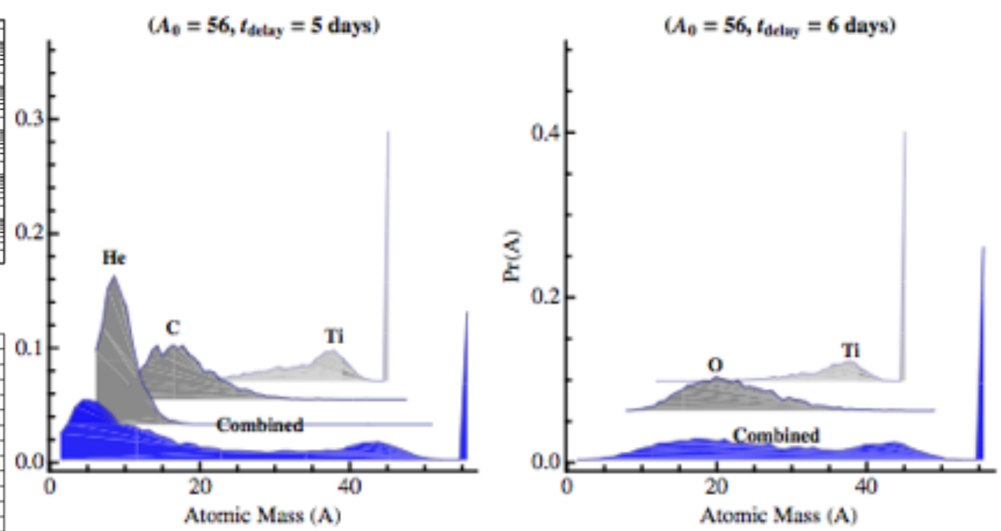
SN-Ejecta/ ***TARGET***



SN-QN collision: **Spallation**

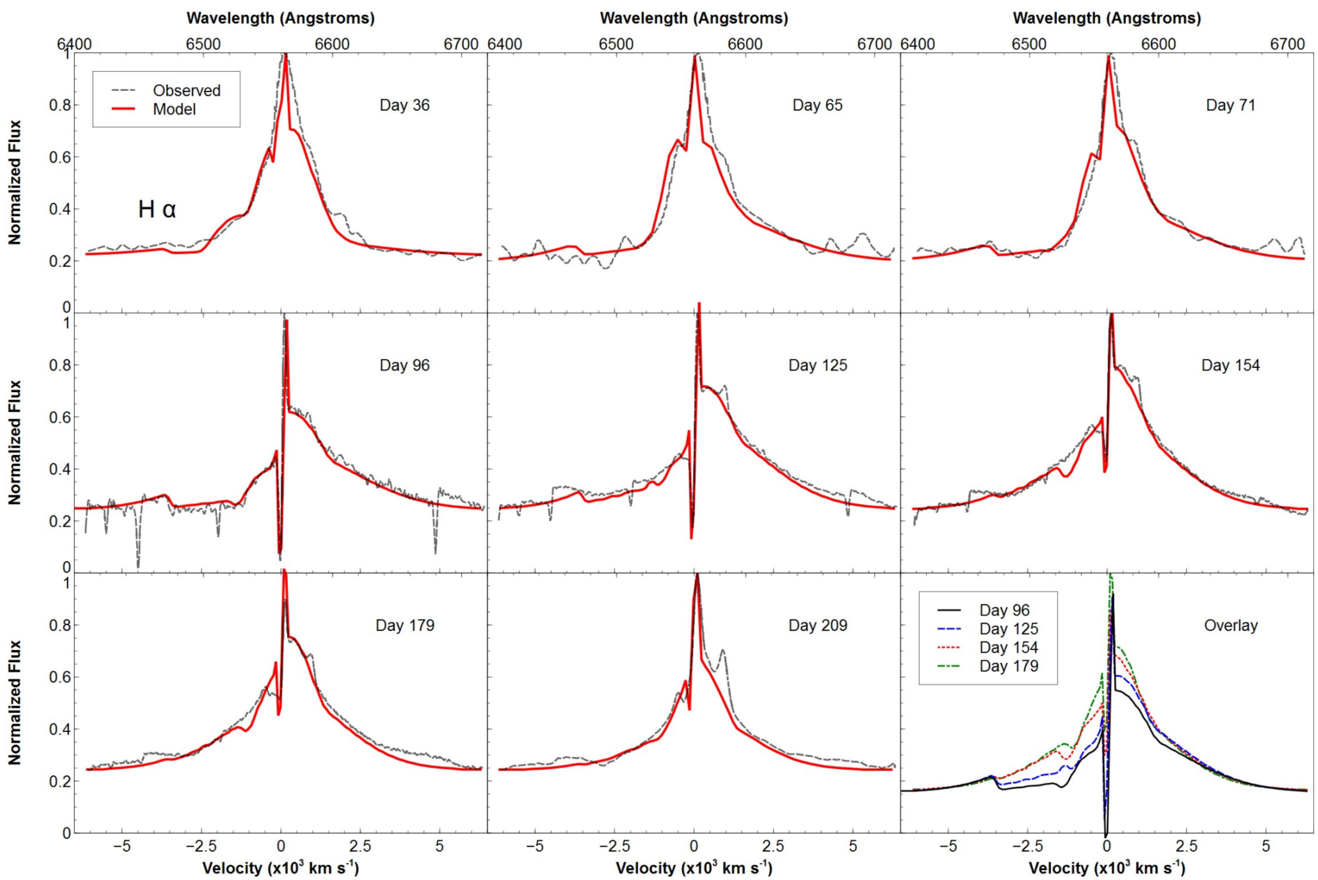
(Ouyed et al. 2011, PRL, 107, 151103; Ouyed 2012, MNRAS, 9)



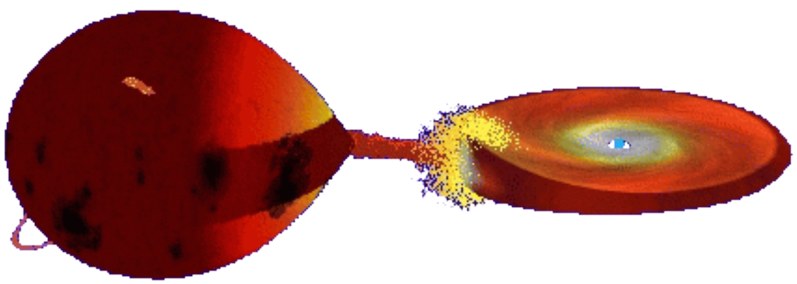


successive layers (back to front) from ^{56}Ni for t_{delay} = 4, 5, 6 days. The overall "combined."

SN-QN collision: Spectral Fits



Quark-Novae in Binaries: Type-Ia QNe



A Neutron Star accreting from a :

a. Carbon-Oxygen White Dwarf

b. Helium White Dwarf

Quark-Novae in Binaries: **Type-Ia QNe**

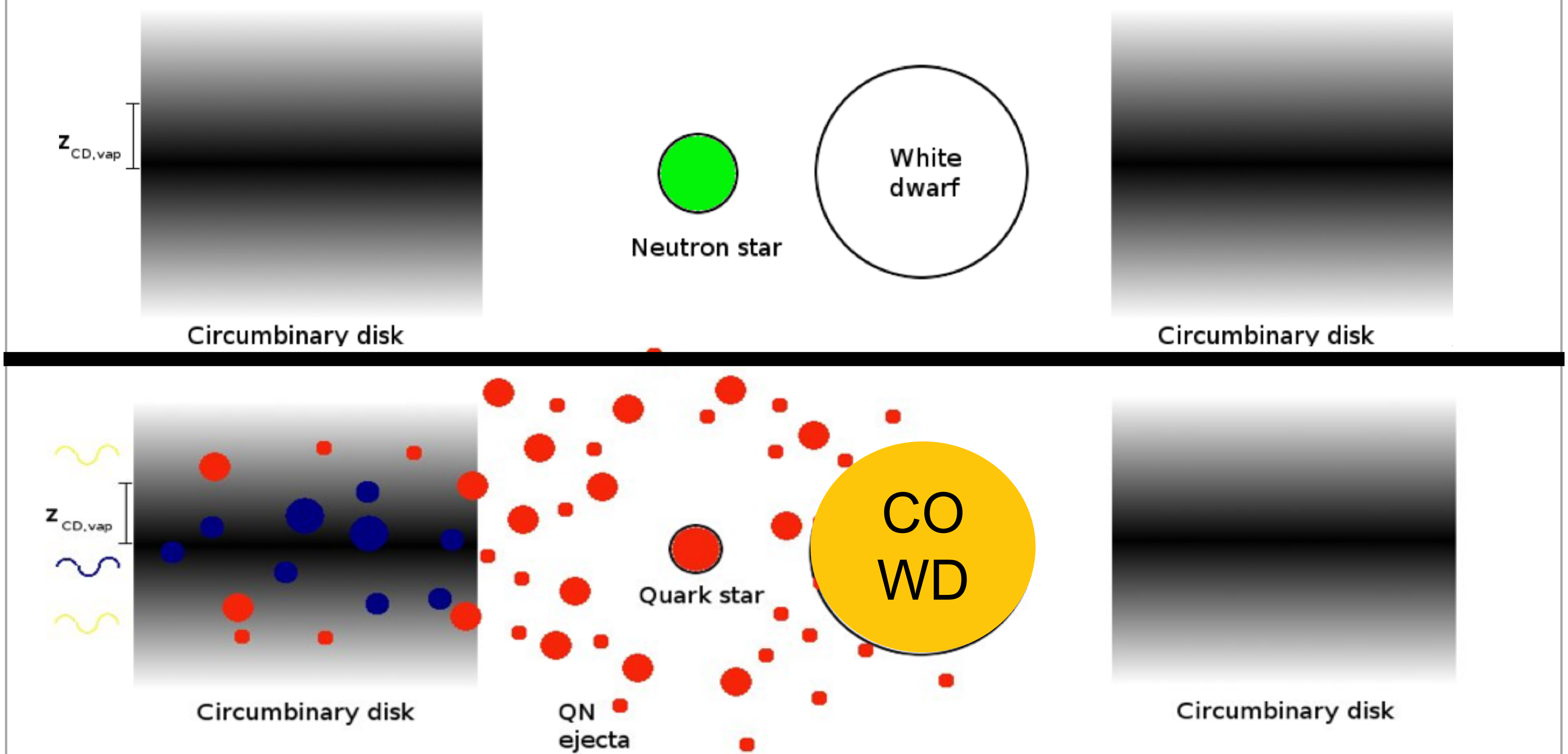
Play Animation

$$\rho_{\rm QNE} \sim 1.8 \times 10^6 \ {\rm g\ cm^{-3}} \times \frac{\rho_{0,14}\Delta r_{0,4}}{a_9^{9/4} M_{\rm QN,-3}^{1/4}}$$

$$T_{\rm SWD} \sim 9.5 \times 10^9 \ {\rm K} \ \frac{E^{\rm KE}_{\rm QN,52}}{a_9^2} \frac{f(M_{\rm WD})/0.68}{\mu_{\rm WD,2}^{7/3} M_{\rm WD,0.6}^{5/3}}$$

Type Ia Quark-Novae

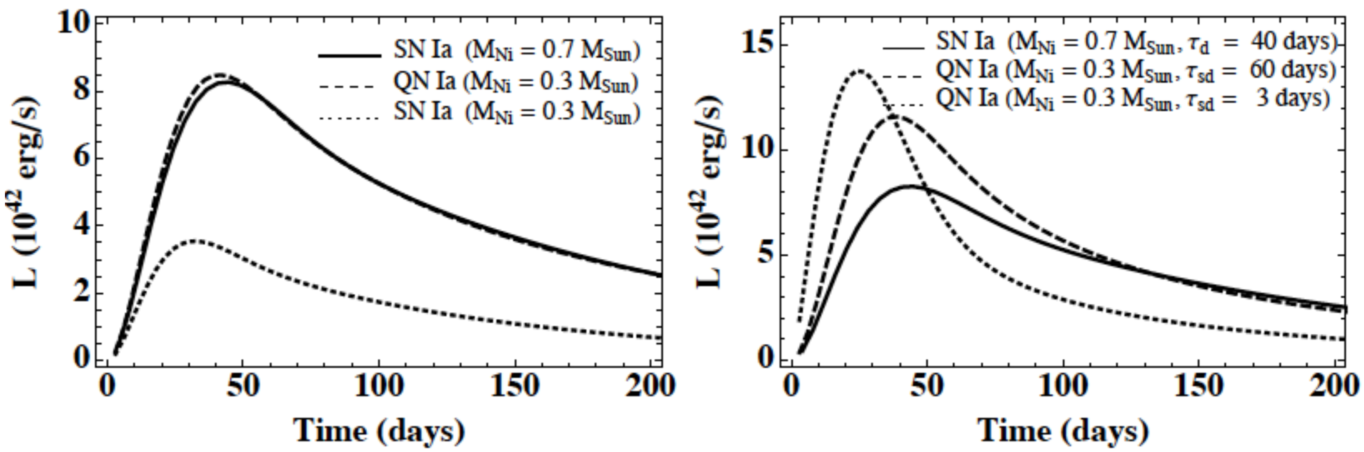
(Ouyed et al. 2011, ApJ, 729, 60; Ouyed et al. 2011, ApJ, 743, 116)



Type Ia Quark-Novae

(Ouyed, R. & Staff, J. 2012, RAA)

Quark-Novae in NS-WD Binaries: spin-down powered Type Ia Supernovae ? 11



Detonation of a CO WD.
Resulting light-curve does NOT obey the Phillips relationship!

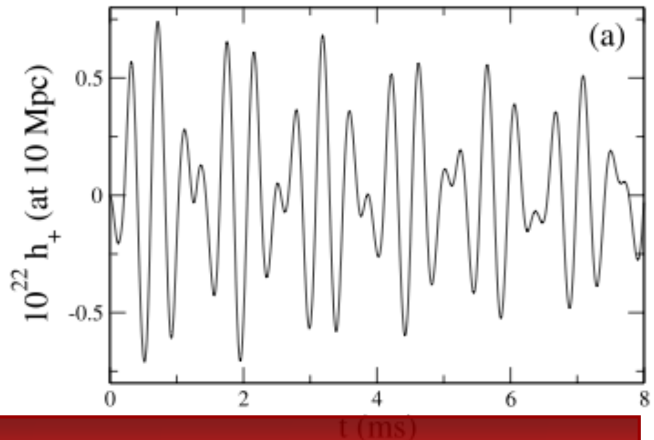
Astrophysical Applications: **Current Efforts**

Quark matter in Neutron Stars:
Quark-Novae:
Gamma-Ray Bursts
Neutrino Burst
Gravitational Waves:
Nucleosynthesis:

Gravitational waves from SQM burning

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

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

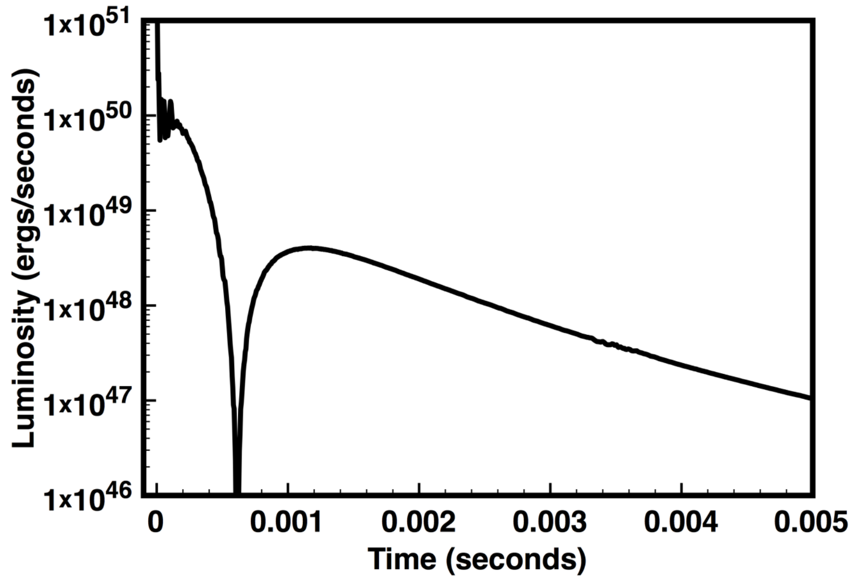


Present work by Jaikumar et al. (ApJ 751, 24 (2012))

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

GW Luminosity: **GW Double-hump**

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



$$L \propto \dot{h}^2$$

$$h(t) = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\theta\frac{A_{20}^{E2}(t)}{D}$$ *(GW strain)*

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

Obrigado!

quarknova.ucalgary.ca