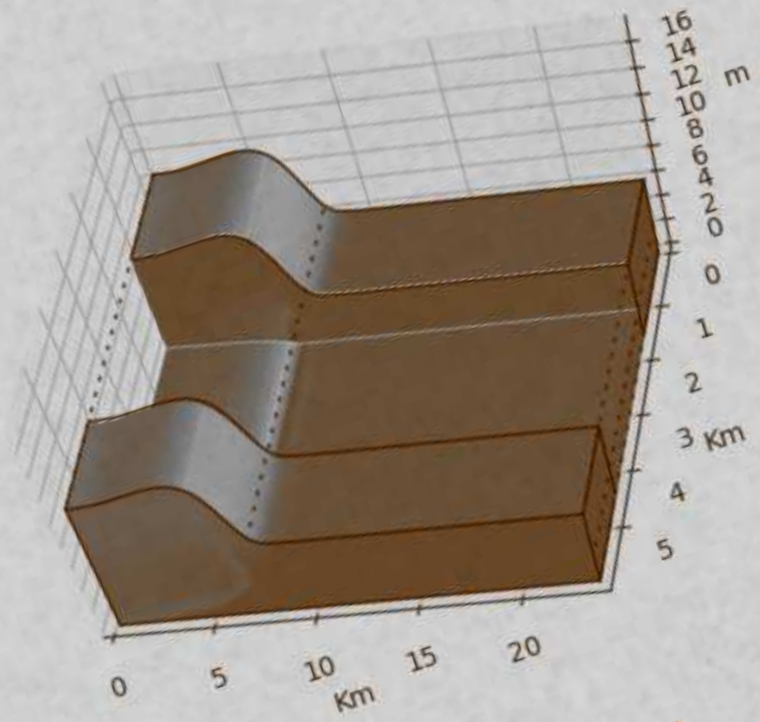
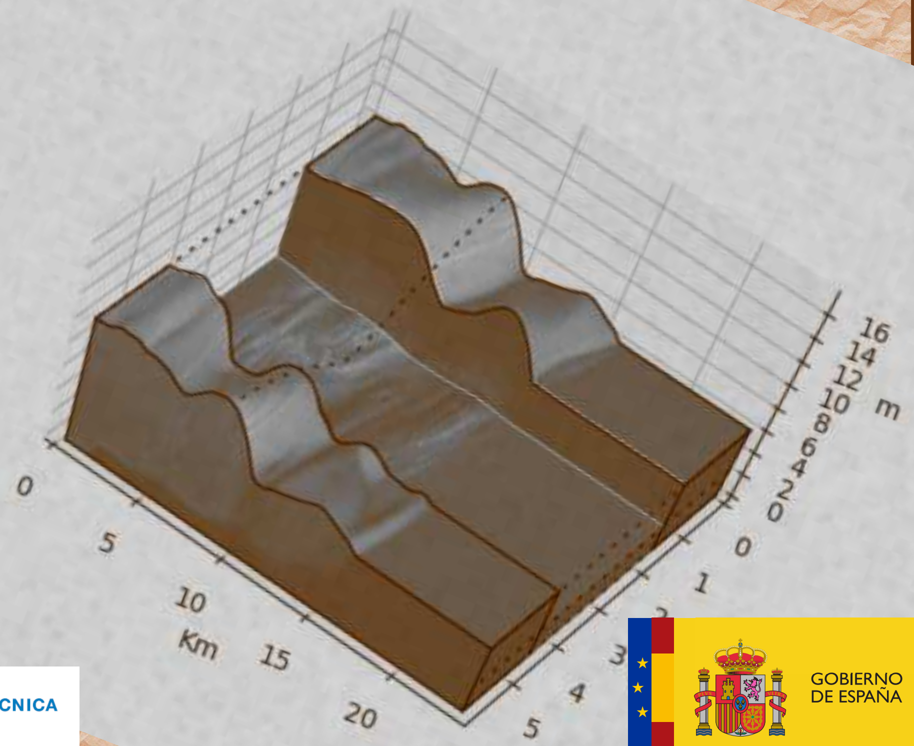
Yuri Cavecchi

MHD Simulations of Type I Bursts

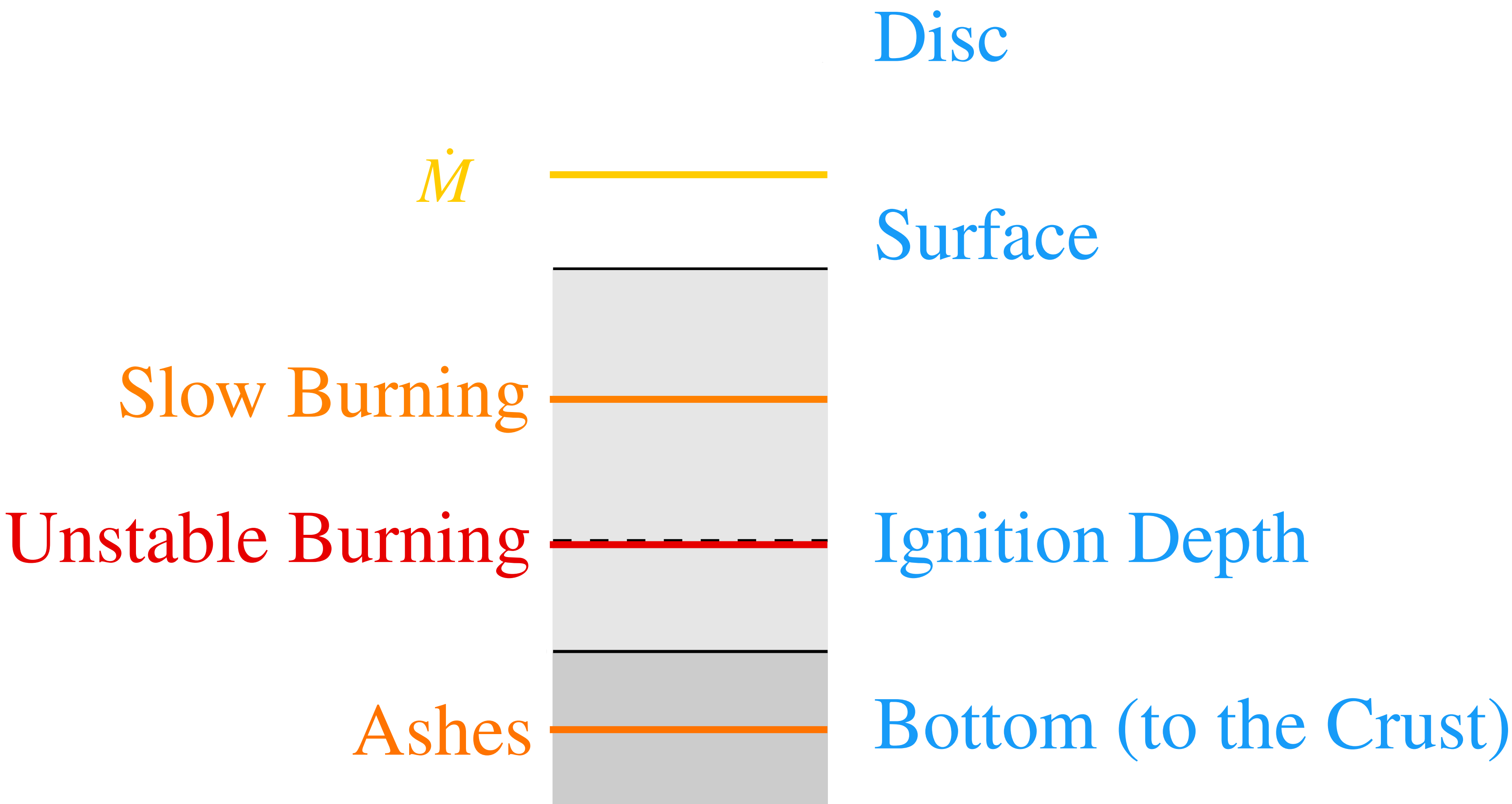




UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

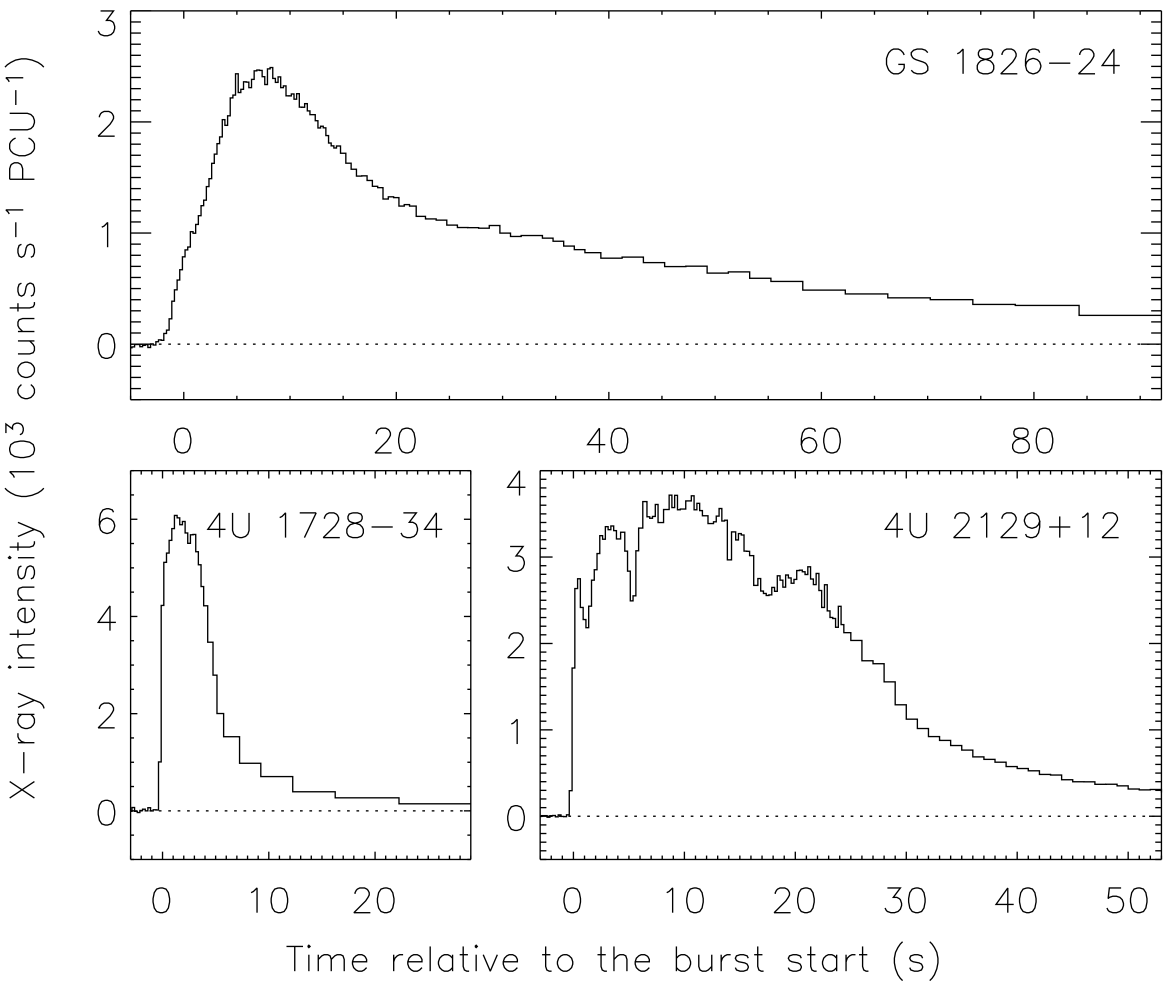
GOBIERNO DE ESPAÑA

Type I Burst: Nuclear Burning in Low Mass X-ray Binaries



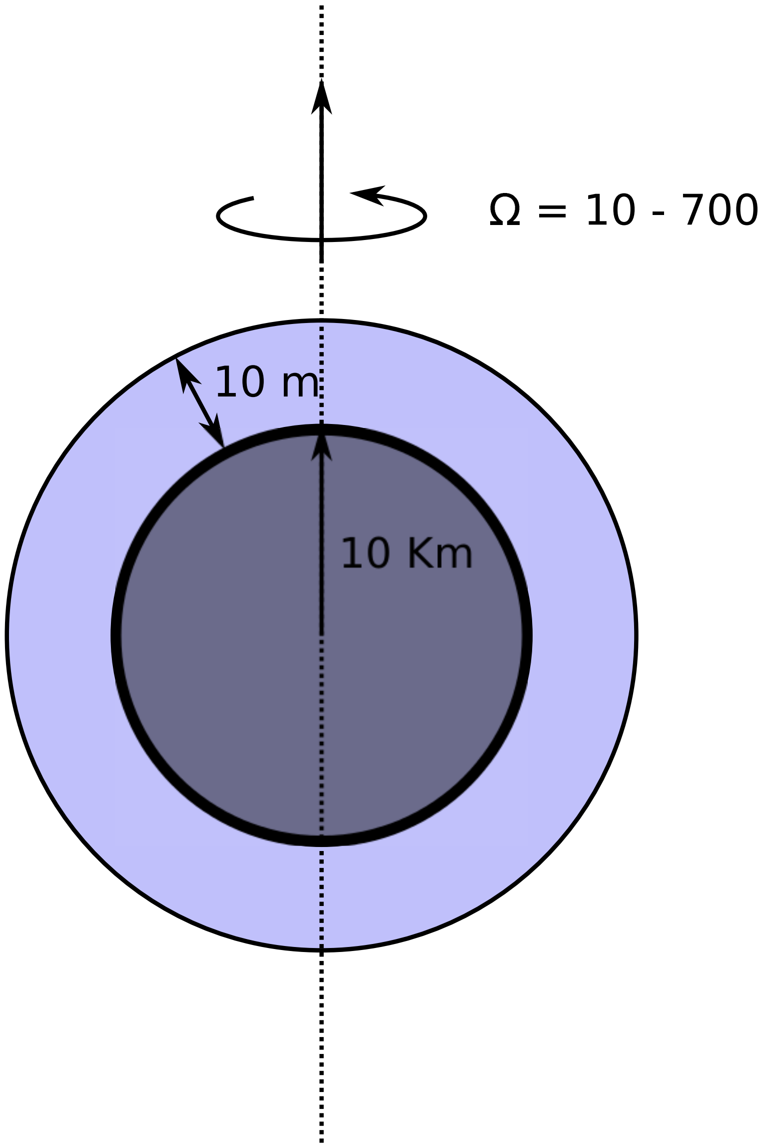
(Piro & Bildsten, 2007)

Type I Bursts



(Galloway et al., 2008)

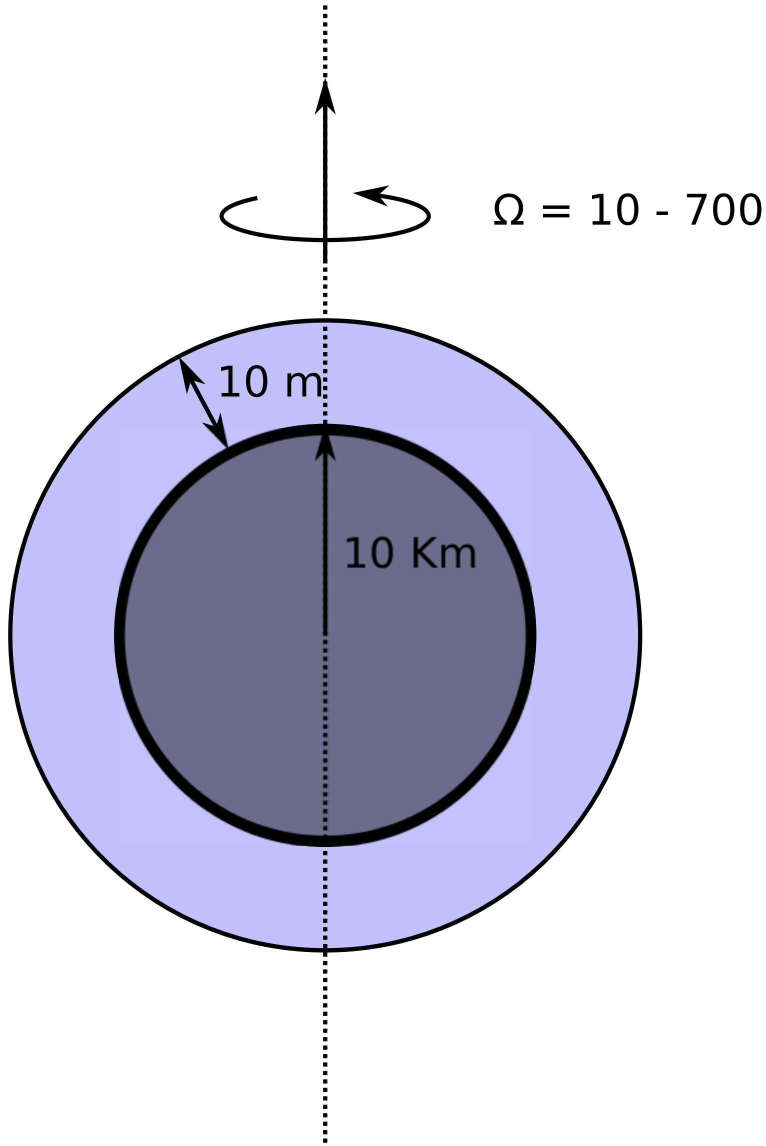
Problems 1: Largely Different Time and Length Scales



- Burning layer height $\sim 10^3$ cm
- Burning layer width $\sim 10^6$ cm
- Stars are spinning fast ($\Omega \sim 500$ Hz, $P \sim 2 \times 10^{-3}$ sec)
- Vertical sound crossing time $\tau_c \sim 10^{-6}$ sec

Problems 2: What we Need to Obtain

- Rise time is ~ 1-10 sec (**fast**: $v \sim 10^6 - 10^5$ cm/sec)
- Remember burning is **fast**, but **not** a **detonation**
- Coriolis force is dynamically important



Problems 3: Too Much Physics to Follow

- Trade off between accuracy and wall clock time
- Microphysics:

  Detailed nuclear reactions

  Conductivity

  Interaction with the crust and core (flux, oscillations)
- Macrophysics – Fluid Dynamics:

  Vertical motion → convection, heat transport, composition

  Motion along the surface → lightcurves (important for EOS)

Problems 3: Too Much Physics to Follow

- Trade off between accuracy and wall clock time
- Microphysics:

  Detailed nuclear reactions

  Conductivity

  Interaction with the crust and core (flux, oscillations)
- Macrophysics – Fluid Dynamics:

  Vertical motion → convection, heat transport, composition

  Motion along the surface → lightcurves (important for EOS)

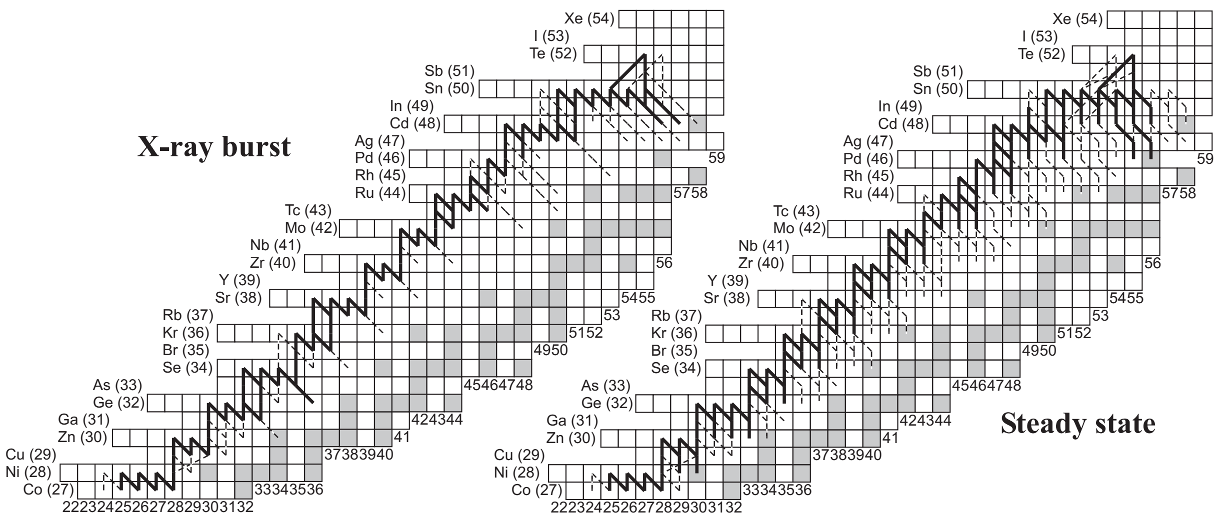
Microphysics

- First results came from 1 zone or 1D semianalytycal models

  (Fujimoto, Schatz, Thielemann, Bildsten, Brown, Cumming, Cyburt)

- Expanded upon by fully resolved, time dependent 1D simulations

  (`KEPLER` - Woosley, Heger, Keek; `MESA` - Paxton et al., Meisel, Brown; custom codes - Dohi et al.)



(Schatz, 2001)

Microphysics

- Different regimes depending on $\dot{m}$

$\dot{M}/\dot{M}_{\rm Edd} < 0.1\%$: H flashes, burn He

$0.1\% < \dot{M}/\dot{M}_{\rm Edd} < 0.4\%$: H/He flashes, burn He

$0.4\% < \dot{M}/\dot{M}_{\rm Edd} < 8\%$: pure He flashes

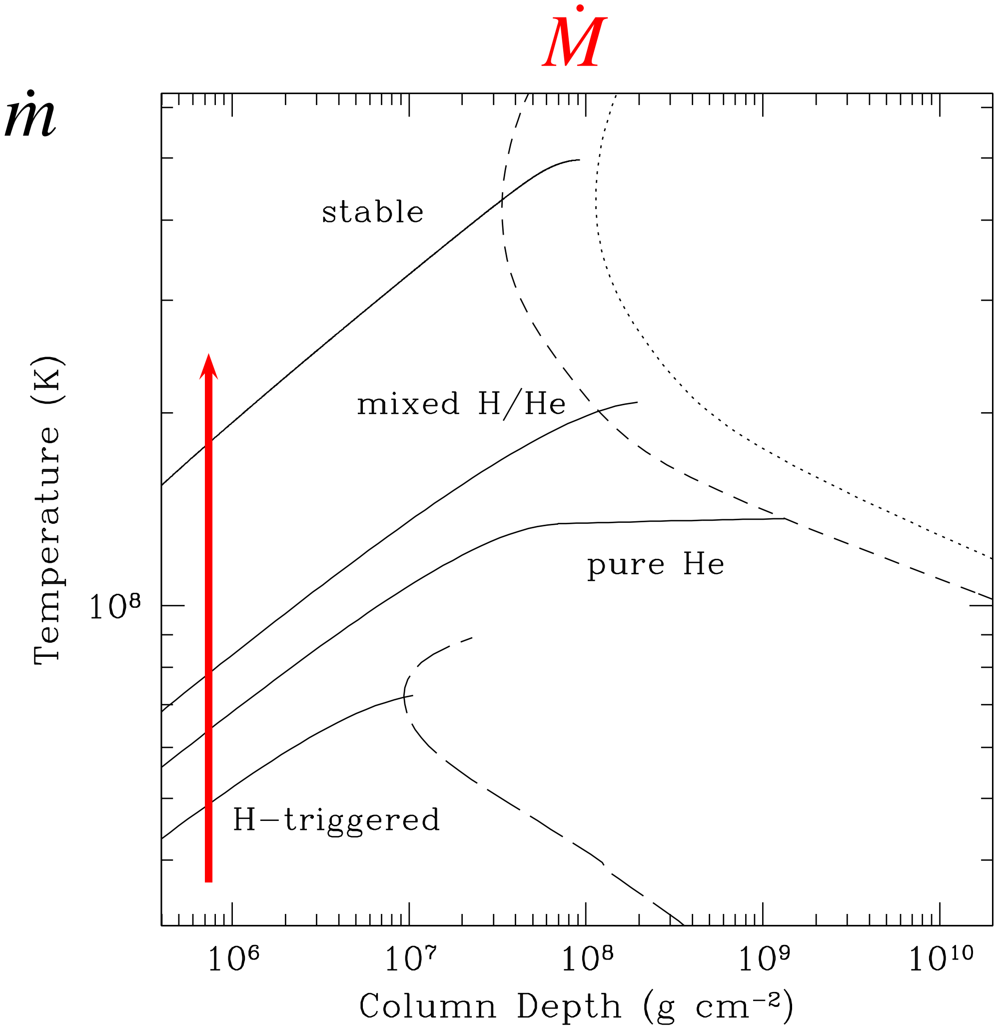
$8\% < \dot{M}/\dot{M}_{\rm Edd} < 11\%$: stable

$11\% < \dot{M}/\dot{M}_{\rm Edd} < 100\%$: H/He flashes

Long Bursts (deep, thick layers of He)

Superbursts (deeper, C)

(e.g. Fujimomto et al., 1981, Bildsten, 1998, Keek & Heger, 20** …)

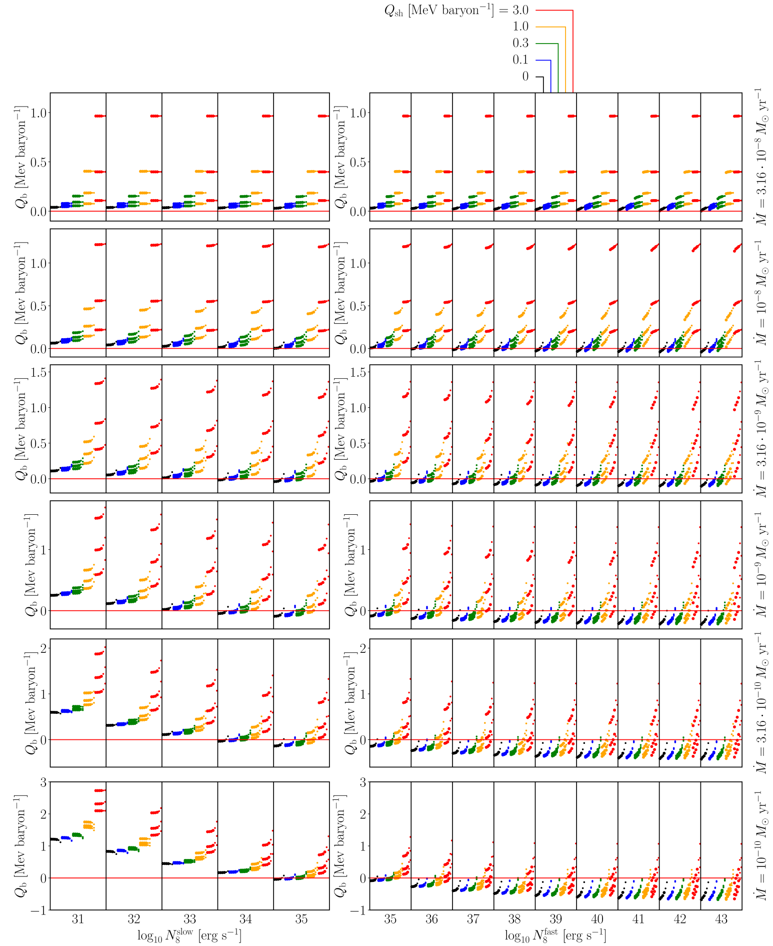


(Cumming, 2004)

Microphysics

- Bursts constrain reaction rates
- Produce heavy(er) elements which proceed to crust
- A window on crust and core
  mainly heat exchange (Brown, 2004),
  but incompatible with strong cooling in the crust
  (Cumming et al., 2006) → Shallow heating problem
  (Brown and Cumming, 2009)

Flux



(Nava-Callejas et al., 2025 Sub.)

Problems 3: Too Much Physics to Follow

- Trade off between accuracy and wall clock time
- Microphysics:

  Detailed nuclear reactions

  Conductivity

  Interaction with the crust and core (flux, oscillations)
- Macrophysics – Fluid Dynamics:

  Vertical motion → convection, heat transport, composition

  Motion along the surface → lightcurves (important for EOS)

Fluid Dynamics

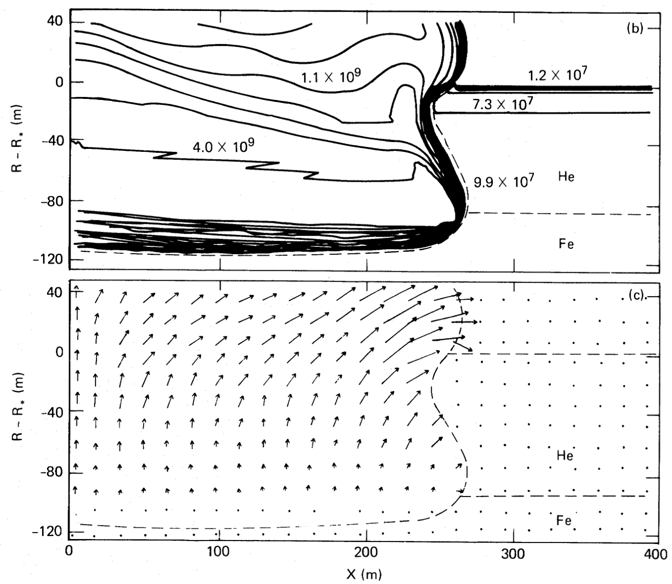
- Early works explored the ignition in 2D, but obtained detonations

- Spitkovsky et al., 2002 were the first to propose a mechanism for a fast deflagration, fluid dynamics helping conduction

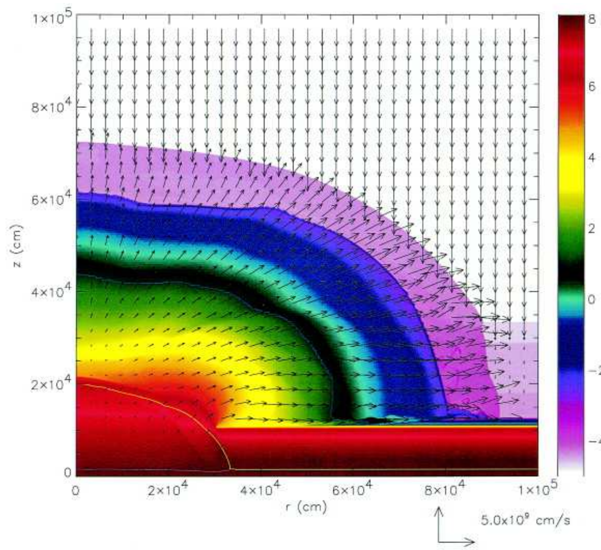
(∼ semi-analytically, see also Frixwell & Woosley, 1982b)

T

$\vec{v}$



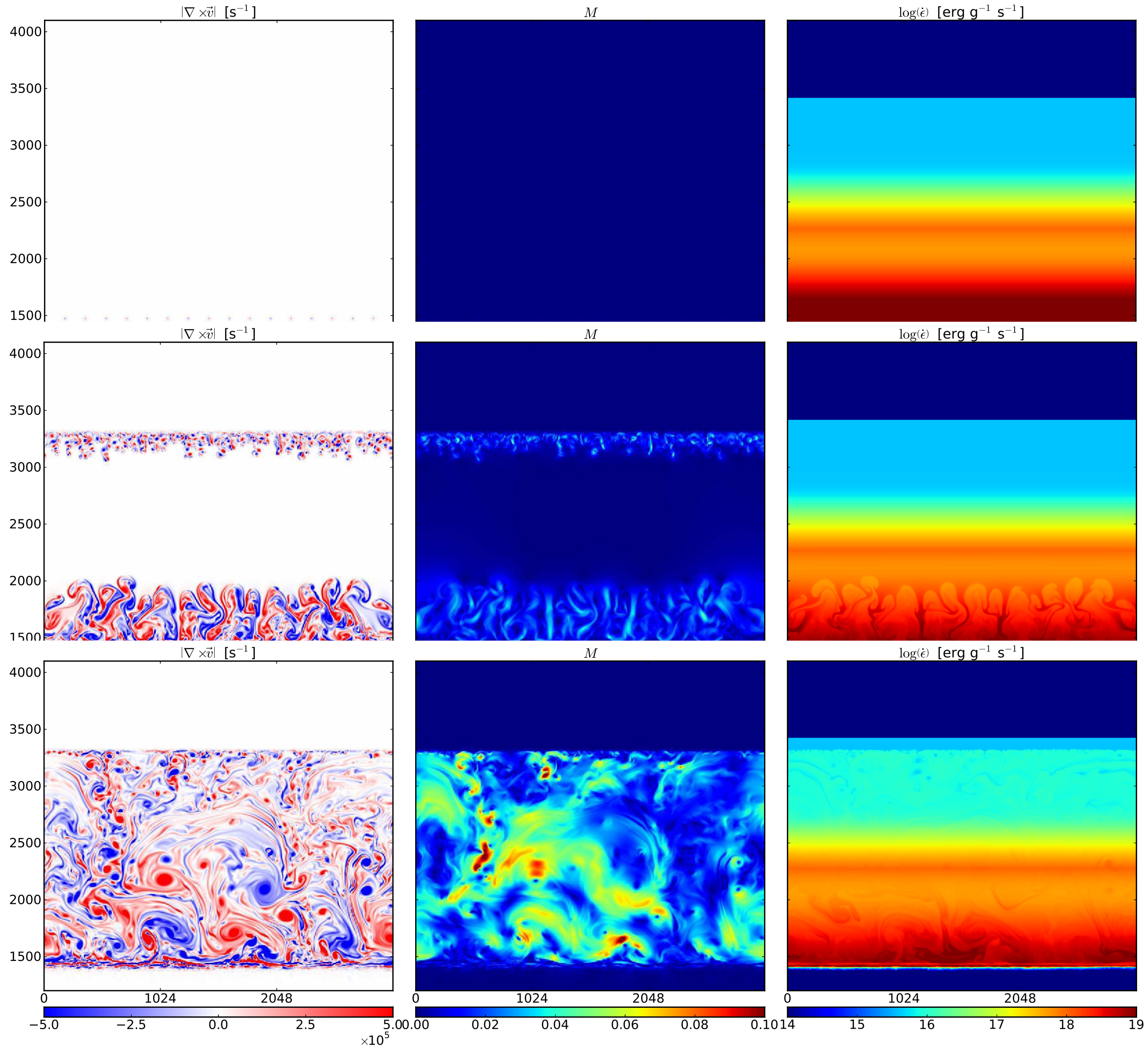
(Frixwell & Woosley, 1982a - for GRBs)



$\rho, \vec{v}$

(Zingale et al., 2001)

Fluid Dynamics - Ignition and Convection



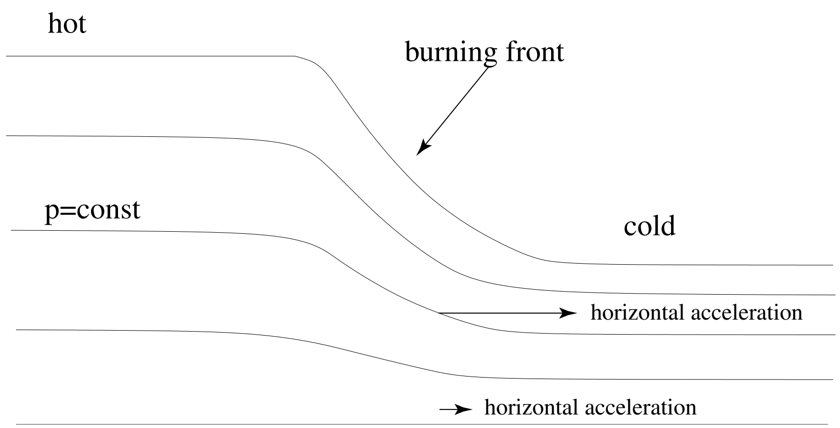
(Malone et al., 2014)

Fluid Dynamics

- Early works explored the ignition in 2D, but obtained detonations

- Spitkovsky et al., 2002 were the first to propose a mechanism for a fast deflagration, fluid dynamics helping conduction

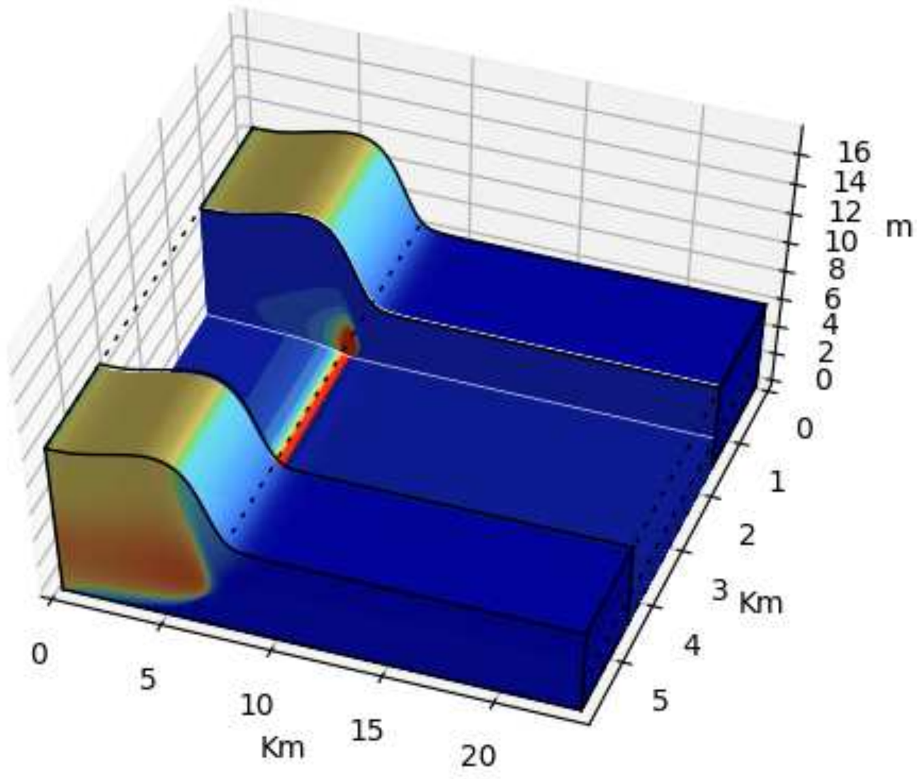
(~ semi-analytically, see also Frixwell & Woosley, 1982b)



(Spitkovsky et al., 2002)

Fluid Dynamics - Propagation

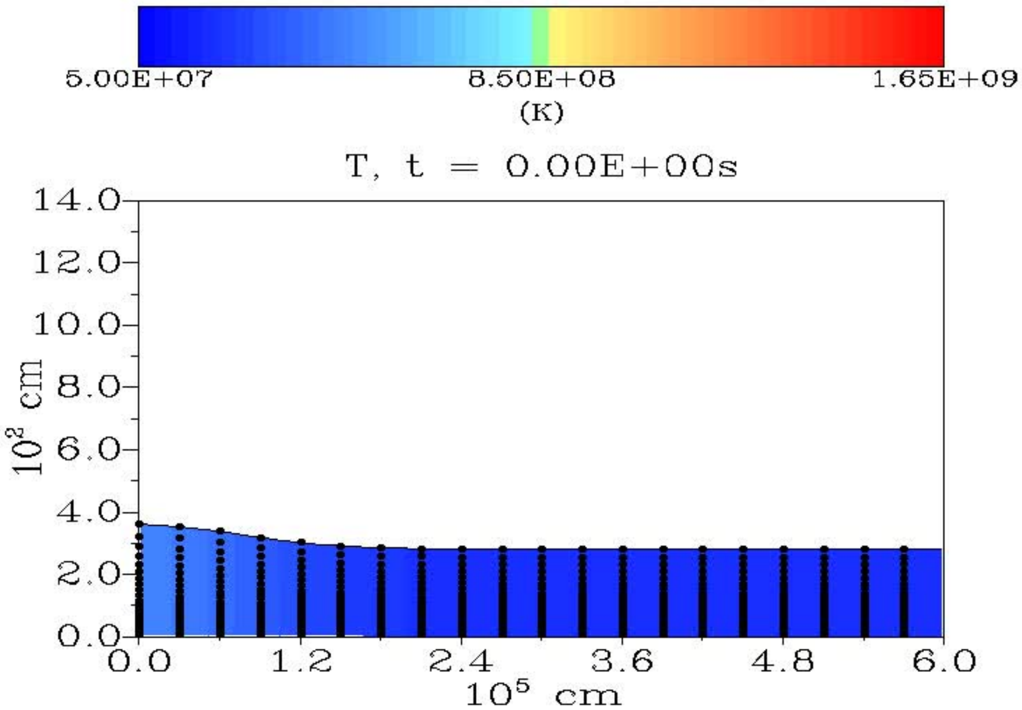
Equator



Pole

(Cavecchi & Spitkovsky, 2019)

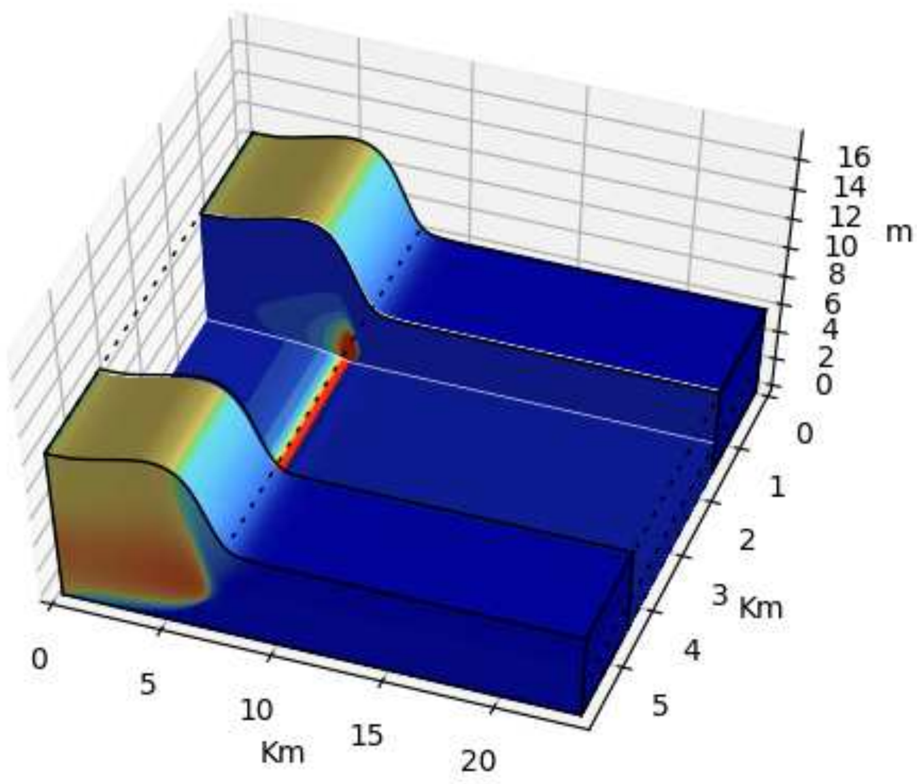
Fluid Dynamics - Basic Propagation Mechanism



(Cavecchi et al., 2013)

Coriolis force
Conduction

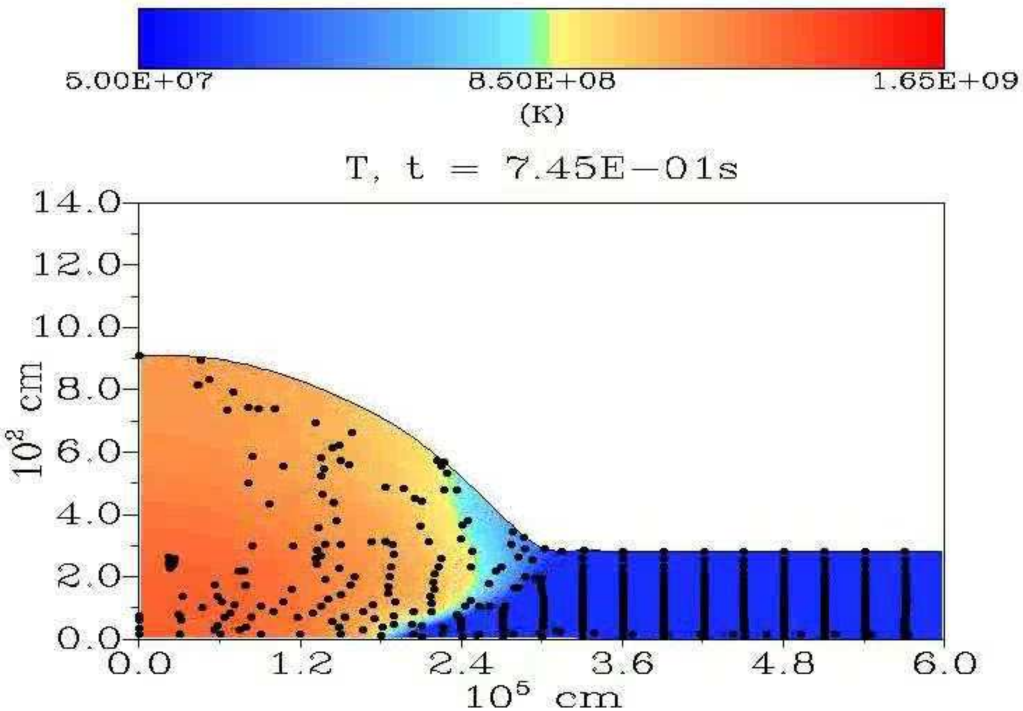
Equator



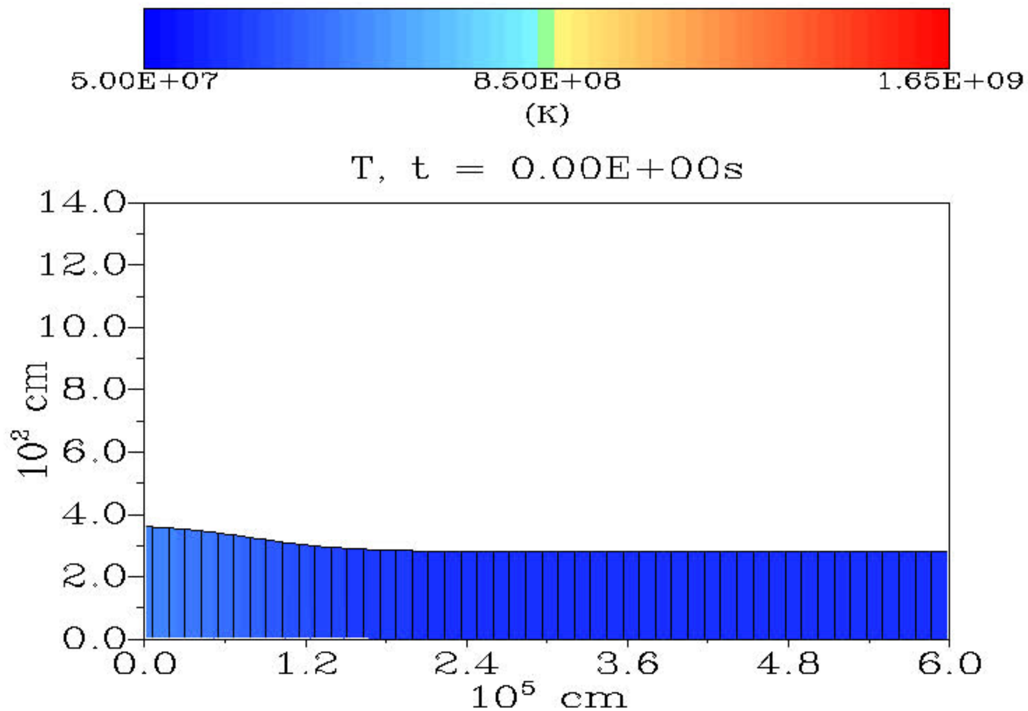
Pole

(Cavecchi & Spitkovsky, 2019)

Fluid Dynamics - Propagation and Instabilities



(Cavecchi et al., 2013)

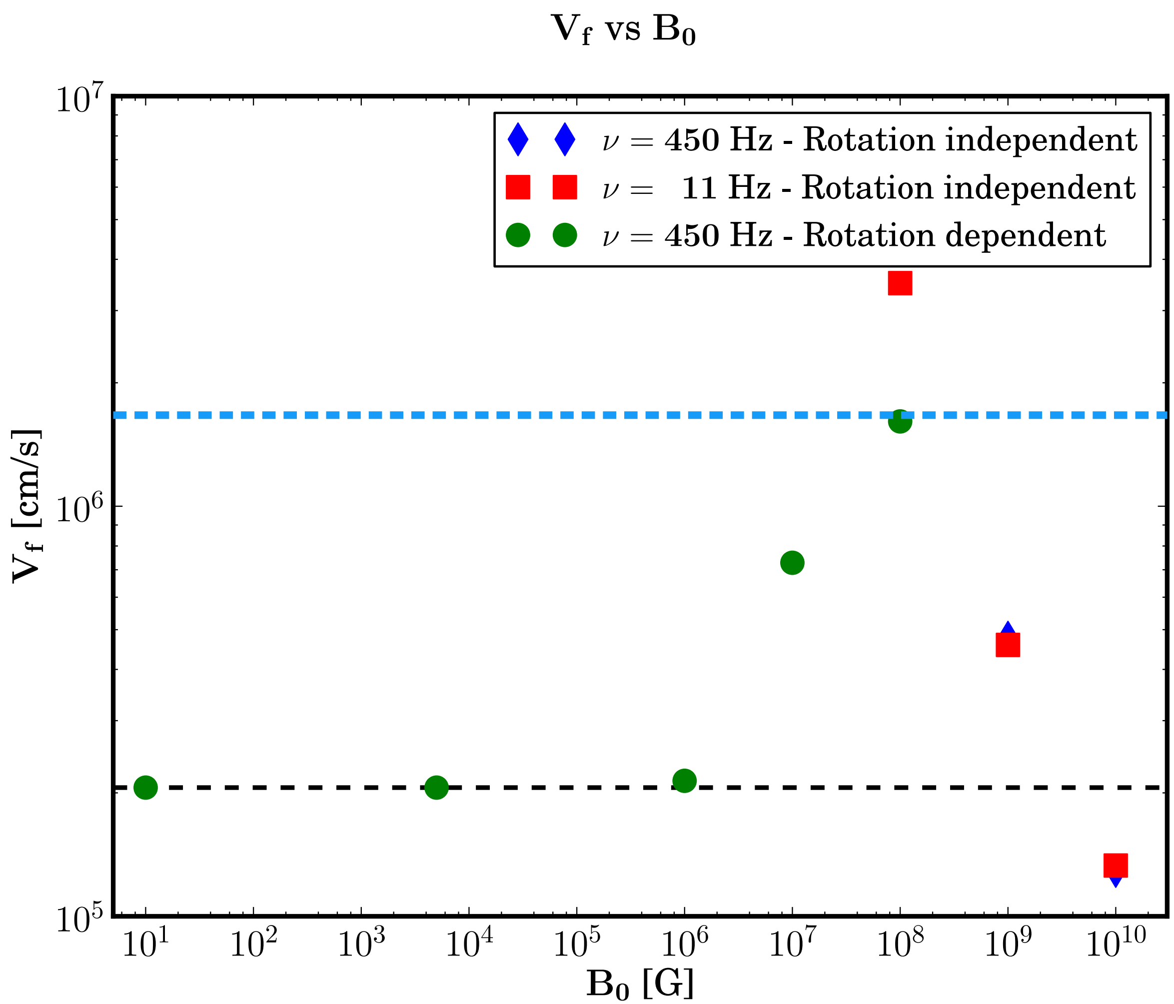


(Cavecchi et al., 2016)

Coriolis force plus Magnetic field

Conduction

Fluid Dynamics

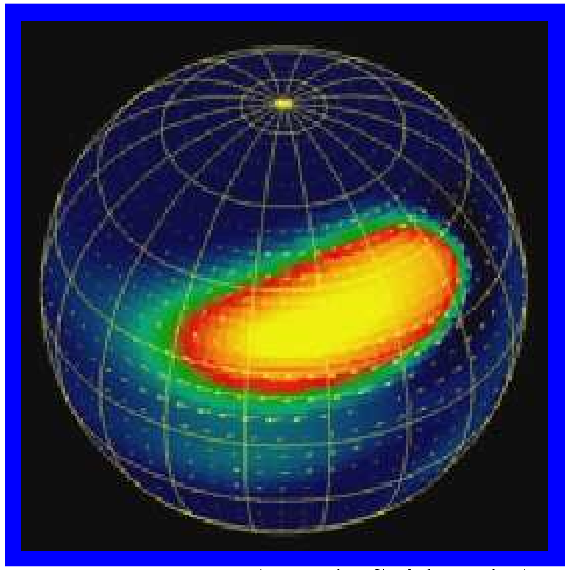


(Cavecchi et al., 2016)

Burst Oscillations and the Neutron Star Equation of State

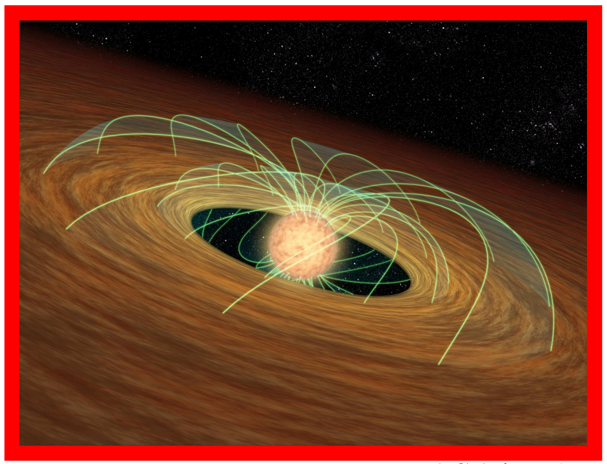
- Inhomogeneities in the emission modulate the lightcurves
- The profiles depend on the pattern (fluid dynamics) and on general relativistic effects, hence on the star equation of state

(e.g. Watts 2012 for a review)



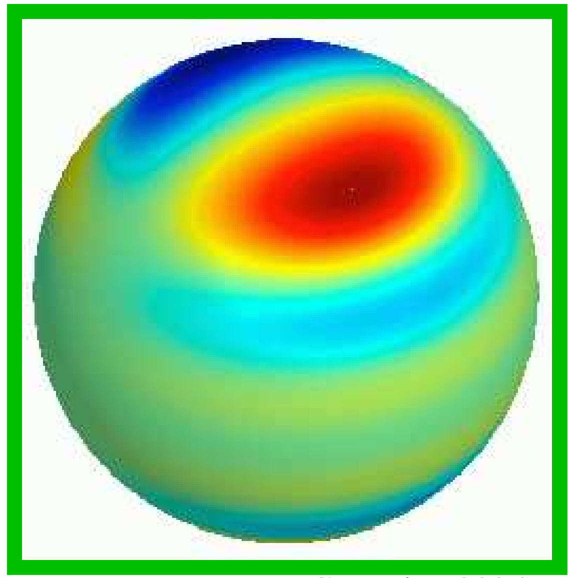
(Anatoly Spitkovsky)

(Strohmayer et al., 1996; Spitkovsky et al., 2002)



(NASA/JPL)

(Cavecchi et al., 2011; Cavecchi & Patruno, 2022)



(Cumming 2005)

(Heyl, 2004 . . .)

Local Conditions and the Burst Rate

- The burst rate as a function of the global accretion rate initially follows 1D predictions, but suddenly decreases and the burst are quenched earlier than expected

Local conditions?

(e.g. Bildsten, 1998; Cooper & Narayan, 2007; Cavecchi et al., 2017, 2020; Nattila et al., 2024)

Extra heating from boundary/spreading layer?

(e.g. Inogamov & Sunyaev, 1999, 2010)

Instabilities? (e.g. Piro & bildsten, 2007; Keek et al., 2009)

Heating from the crust or thermal inertia?

(e.g. Brown, 2004; Cumming et al., 2004, Nava-Callejas, 2025 Sub.; Johnston, 2018)

Correction to reaction rates? (e.g. Keek et al., 2014)

Conclusions

- All the physical ingredients available play an important role
- Reactions determine energetics, time scales and burst rate
- Conductivity and crust/core physics are important for the burst rate and stabilization
- The MHD of the fluid determines macro scale effects such as rise time and oscillations, but it is also related to the ignition conditions and burst rate (link to accretion too)
- Both “micro” and “macro” physics intimately interplay, so we need effective ways to combine them