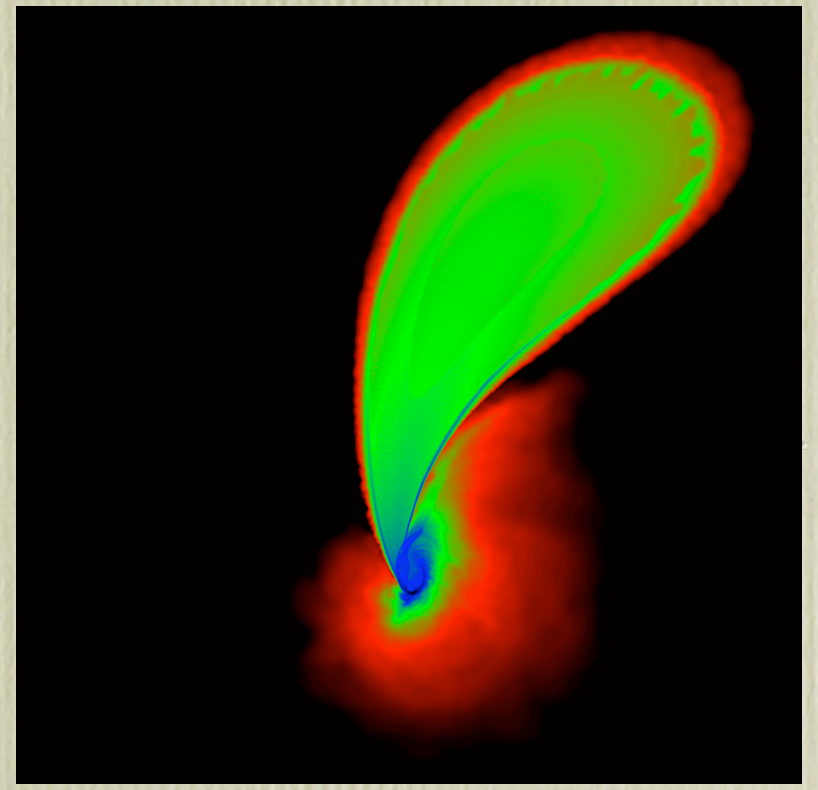
Santa Barbara, Feb 12, 2009

Tidal crushing of white dwarfs by Intermediate-mass black holes



Literature

- ApJ 679, 1385 (2008)
- 2008arXiv0808.2143
- 2008arXiv0811.2129

Stephan Rosswog
Jacobs UniversityBremen,Germany

Collaborators: Enrico Ramirez-Ruiz, Santa Cruz, USA
Raph Hix, Oak Ridge, USA
Dan Kasen, Santa Cruz, USA

I. Motivation

- IF IMBH do exist:

how would they reveal their existence?

I. Motivation

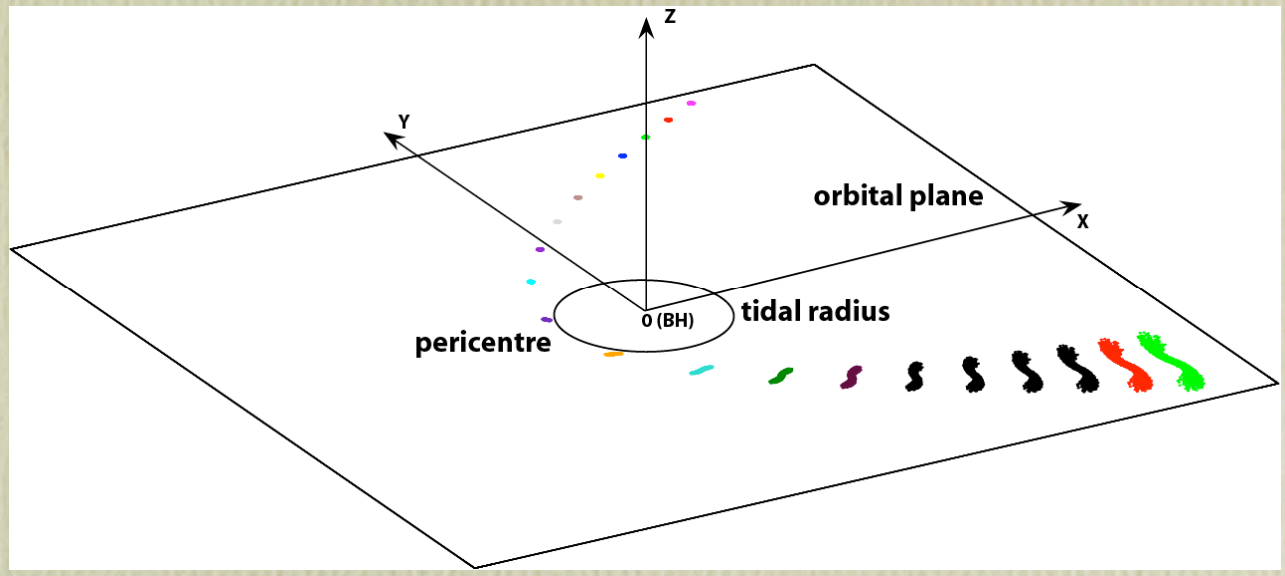
- IF IMBH do exist:

how would they reveal their existence?

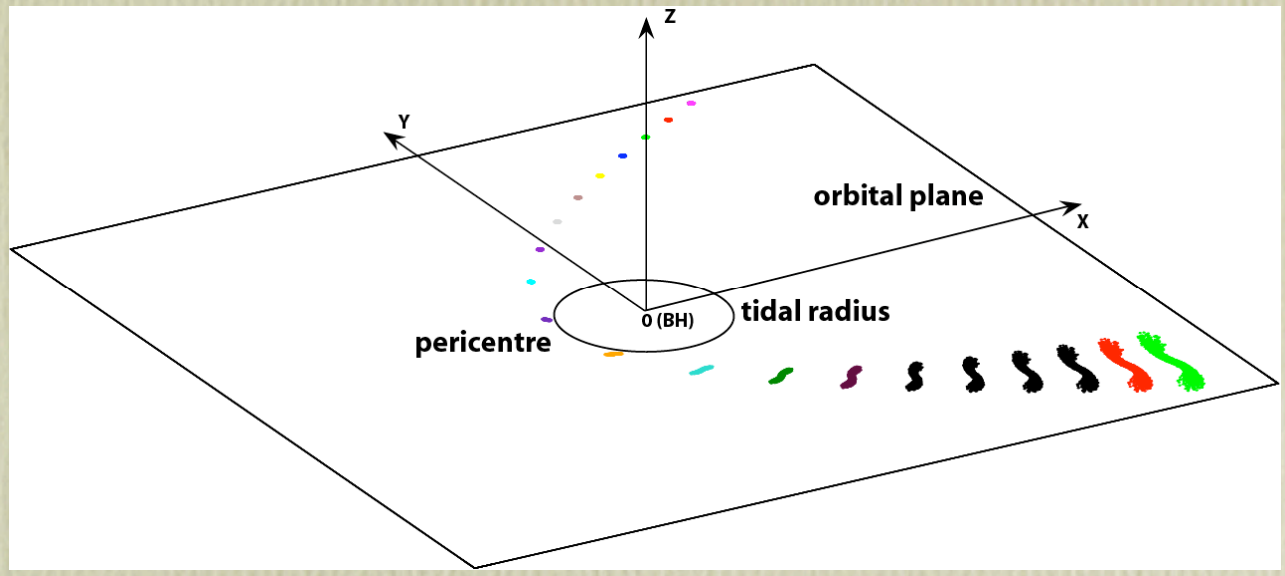
→ Tidal disruptions of white dwarfs offer a complementary way to probe their existence

II. tidal disruption basics

II. tidal disruption basics

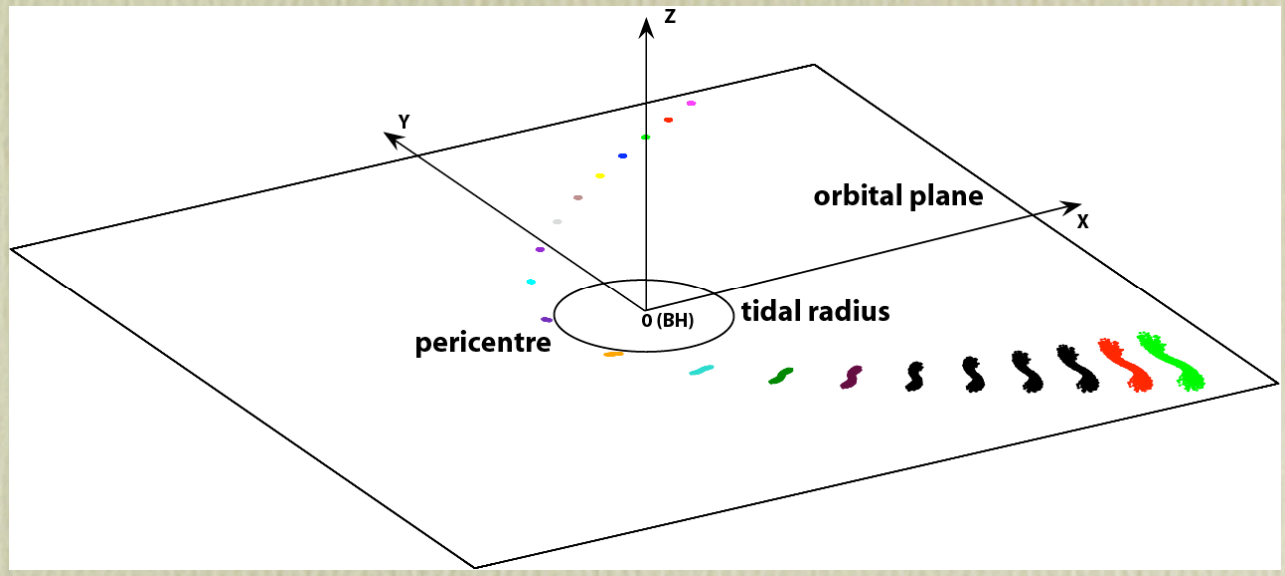


II. tidal disruption basics



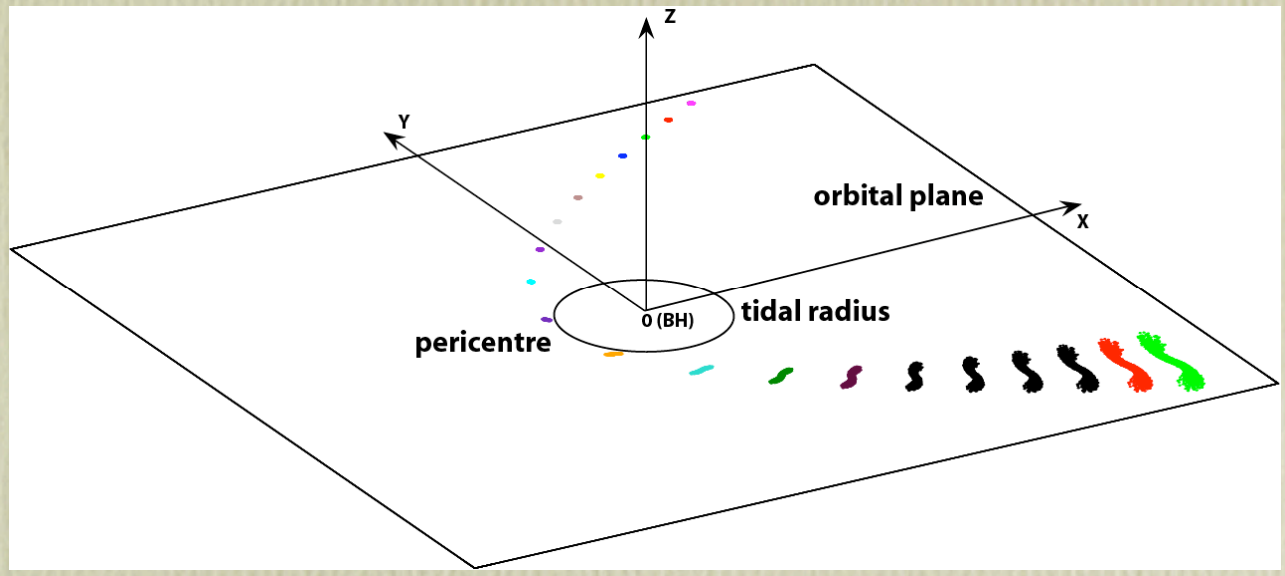
- star becomes disrupted at tidal radius:

II. tidal disruption basics



- star becomes disrupted at tidal radius: $R_{\rm t} \approx \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} R_*$

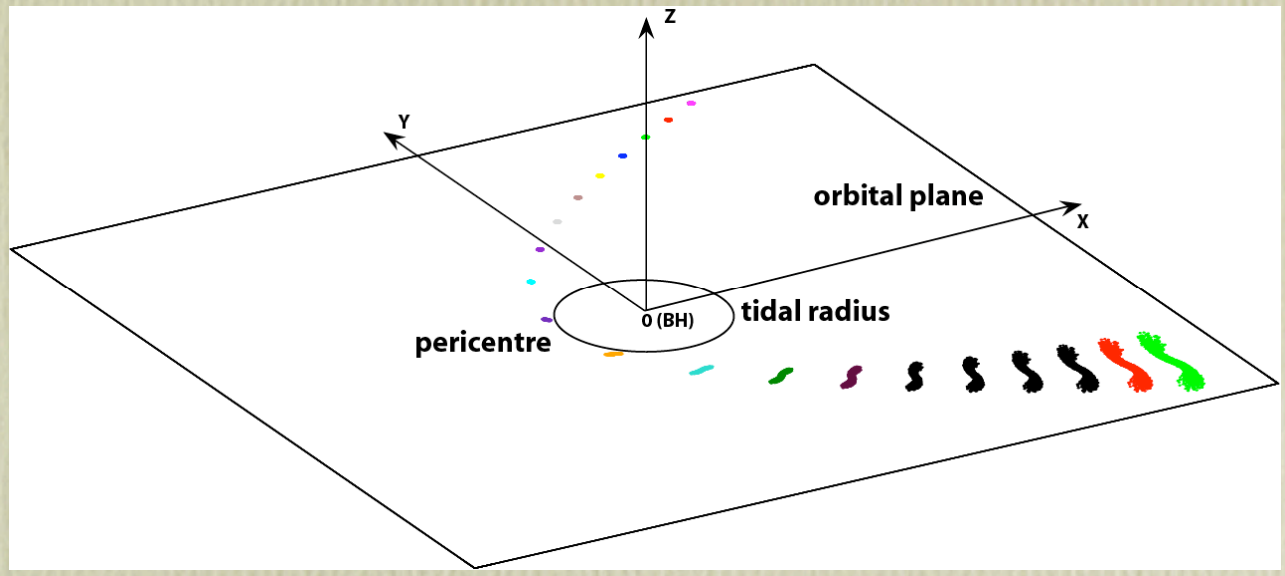
II. tidal disruption basics



- star becomes disrupted at tidal radius: $R_{\rm t} \approx \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} R_*$

  - for solar-type stars: $R_{\rm t,MS} = 20\, R_{S,10^6 {\rm M}_\odot}\, M_{\rm BH,10^6 M_\odot}^{1/3} \left(\frac{R_{\rm MS}}{R_\odot}\right) \left(\frac{M_\odot}{M_{\rm MS}}\right)^{1/3}$

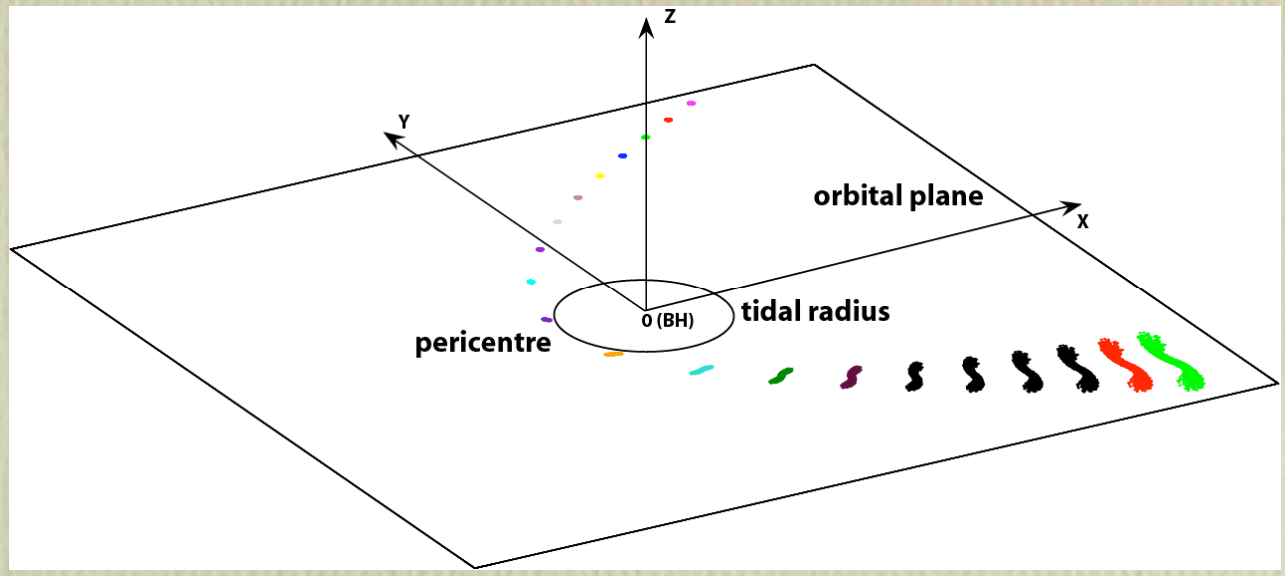
II. tidal disruption basics



- star becomes disrupted at tidal radius: $R_{\rm t} \approx \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} R_*$

  - for solar-type stars: $R_{\rm t,MS} = 20\, R_{S,10^6{\rm M}_\odot}\, M_{\rm BH,10^6{\rm M}_\odot}^{1/3} \left(\frac{R_{\rm MS}}{R_\odot}\right) \left(\frac{M_\odot}{M_{\rm MS}}\right)^{1/3}$
  - for white dwarfs: $R_{\rm t,WD} = 0.3\, R_{S,10^6{\rm M}_\odot}\, M_{\rm BH,10^6{\rm M}_\odot}^{1/3} \left(\frac{R_{\rm WD}}{10^9{\rm cm}}\right) \left(\frac{0.6 M_\odot}{M_{\rm WD}}\right)^{1/3}$

II. tidal disruption basics



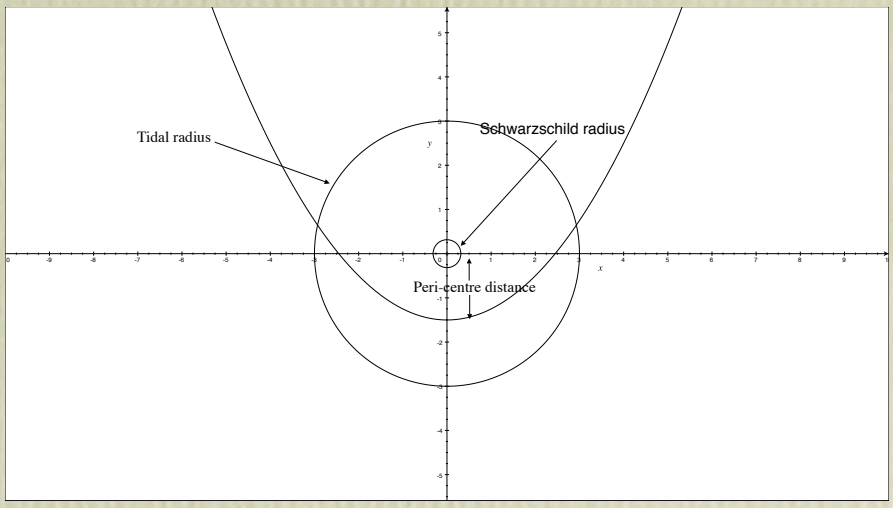
- star becomes disrupted at tidal radius: $R_{\rm t} \approx \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} R_*$

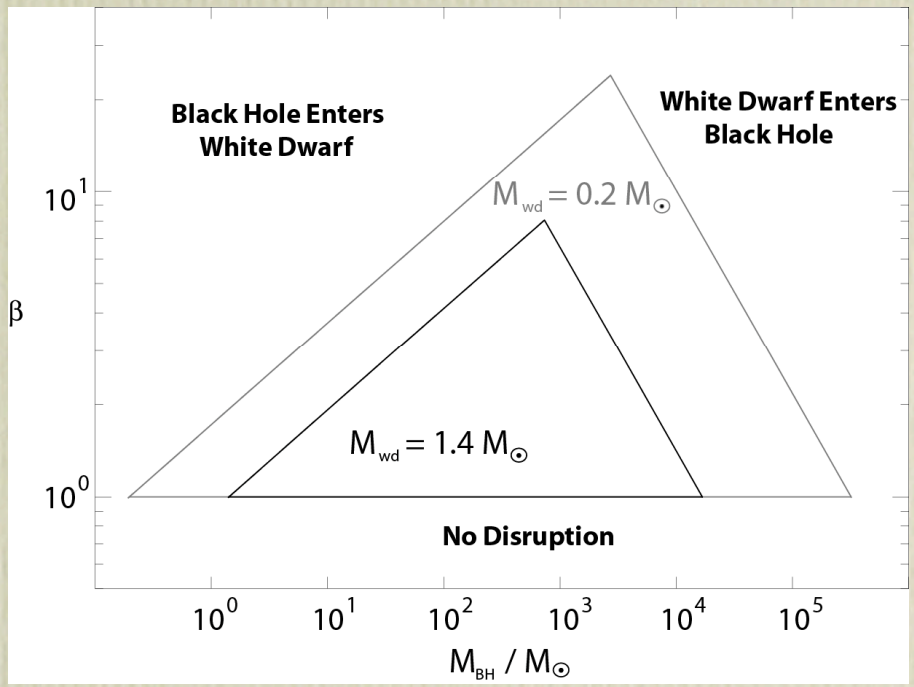
  - for solar-type stars: $R_{\rm t,MS} = 20\, R_{S,10^6{\rm M}_\odot}\, M_{\rm BH,10^6{\rm M}_\odot}^{1/3} \left(\frac{R_{\rm MS}}{R_\odot}\right) \left(\frac{M_\odot}{M_{\rm MS}}\right)^{1/3}$
  - for white dwarfs: $R_{\rm t,WD} = 0.3\, R_{S,10^6{\rm M}_\odot}\, M_{\rm BH,10^6{\rm M}_\odot}^{1/3} \left(\frac{R_{\rm WD}}{10^9{\rm cm}}\right) \left(\frac{0.6 M_\odot}{M_{\rm WD}}\right)^{1/3}$

⇒ white dwarf disruption only for moderate mass black holes !!

II. Disruption basics

- consider parabolic orbits
- measure encounter strength by "penetration factor" $\beta = \frac{R_{\rm t}}{R_{\rm peri}}$
- astrophysical relevance of white dwarf disruptions
- ideally: deep inside tidal radius but still safe distance from BH





What do we want to know?

- (How frequent do white dwarf tidal disruptions occur?)
- How much material becomes ejected into the cluster?
- What are the nucleosynthetic yields?
- Can tidal compression trigger nuclear reactions to cause a thermonuclear explosion?
- For all white dwarf masses?

III. Simulations of IMBH WD disruptions

III.1 Input physics and methods

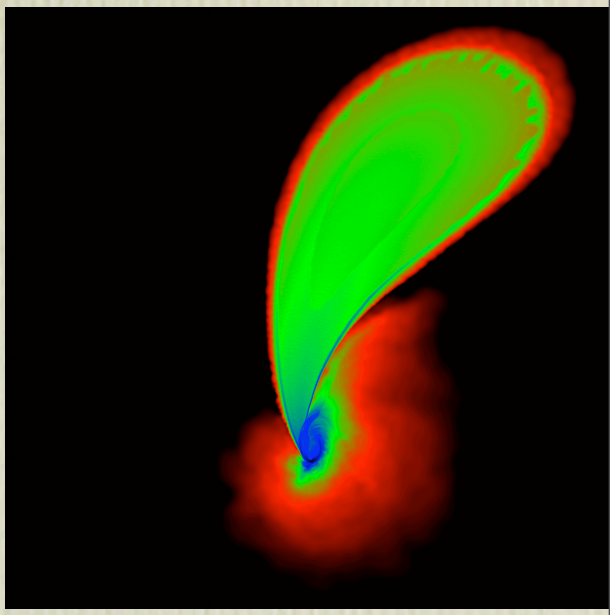
- Smoothed Particle Hydrodynamics (SPH):
  - fully Lagrangian ⇒ highly adaptive
  - derivable from Lagrangian: exact conservation of mass, energy, linear and angular momentum even in discrete form
  - no problems with voids
- gravity:
  - black hole: relativist. pseudo potential (Paczynski&Wiita 1980)
  - stellar fluid: self-gravity via binary tree (Benz et al. 1990)

III.1 Input physics and methods

- equation of state: "Helmholtz-EOS"
  - allows to freely specify nuclear composition
  - completely general electron-positron EOS (tabulated)
  - thermodynamic consistent interpolation (Timmes & Swesty 2000)
- time integration:
  - hydrodynamics:

    orders of magnitude between time steps

    ⇒ individual time steps



III.1 Input physics and methods

- nuclear burning:
  - "Quasi-equilibrium reduced alpha-network" (Hix et al. 1998)
  - collect individual nuclei into 7 groups
  - accurate energy generation

    $\Rightarrow$ each SPH particle knows its nuclear composition

  - $\tau_{\mathrm{nuclear}} \ll \tau_{\mathrm{hydro}} \Rightarrow$ integrate separately

    hydro explicitly & nuclear network implicitly

Performed simulations

- explored parameter space:

  (0.2 ... 1.2) $M_\odot$ x (100 ... 5000) $M_\odot$ x various β

  WD-mass BH-mass pen.factor

- all white dwarfs initially on parabolic orbits
- performed more than 20 simulations
- numerical resolution: 500 000 - 5 000 000 SPH-particles
- illustrated by: 0.2 $M_\odot$ WD & 1000 $M_\odot$ BH, β= 12

III.2 Examples

1. Marginal disruption $\beta = 0.9$

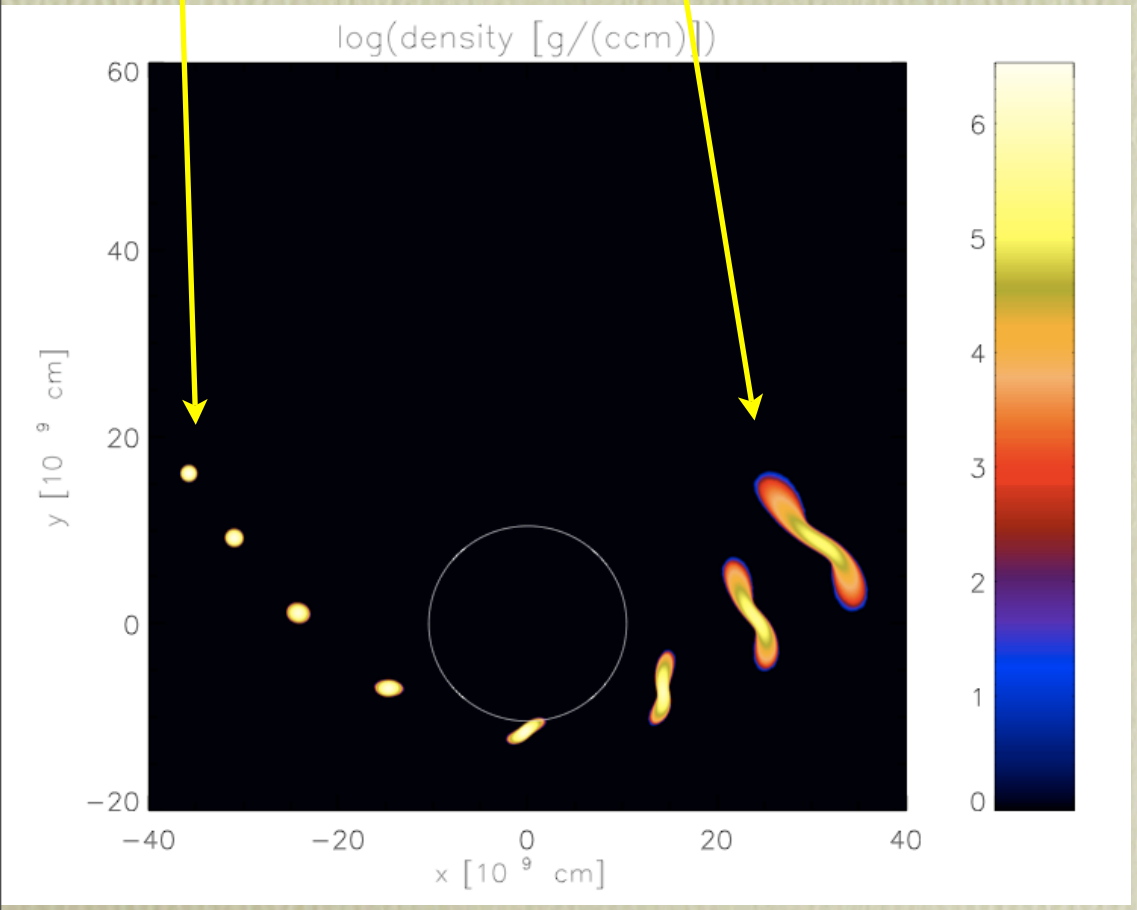
(WD: 0.6 $M_\odot$, C/O; BH: 1000$M_\odot$)

III.2 Examples

1. Marginal disruption $\beta = 0.9$

(WD: 0.6 $M_\odot$, C/O; BH: 1000$M_\odot$)

t= 0.34 s t= 24.01 s

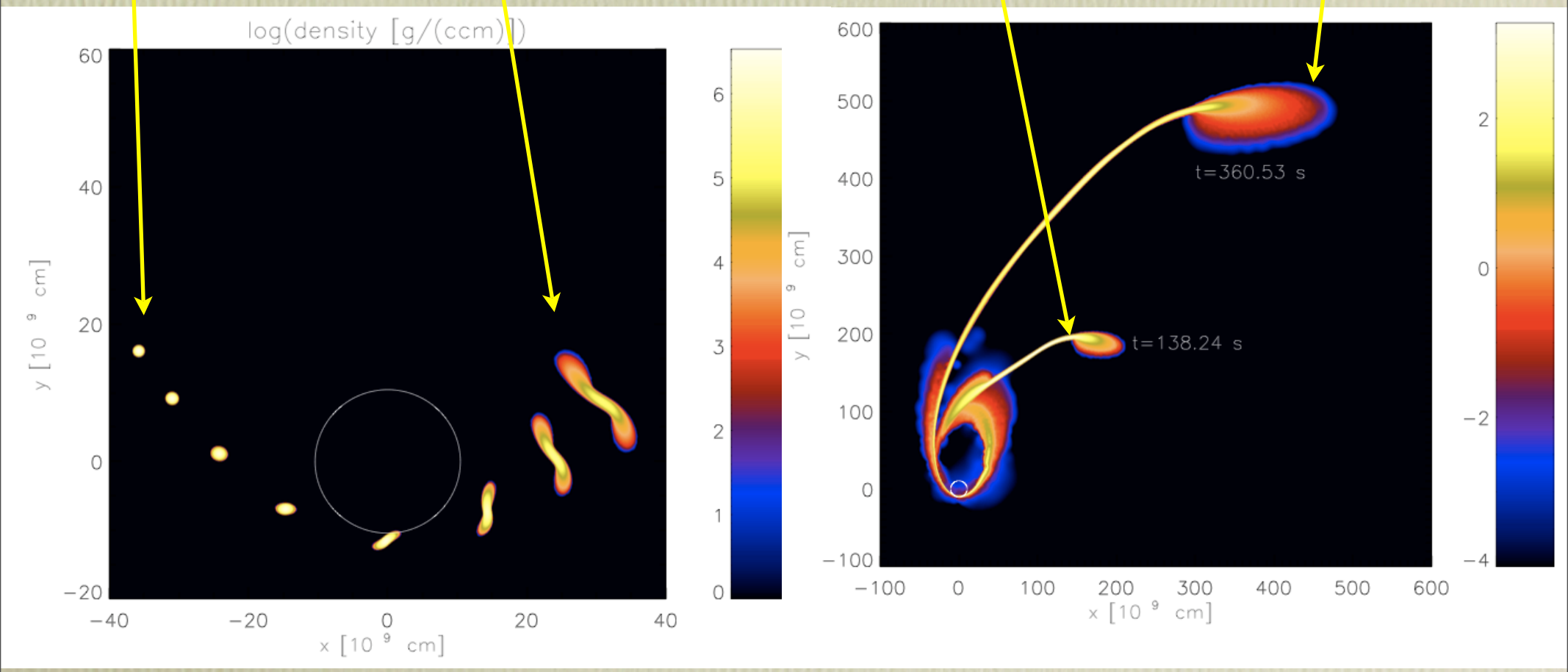


III.2 Examples

1. Marginal disruption $\beta = 0.9$

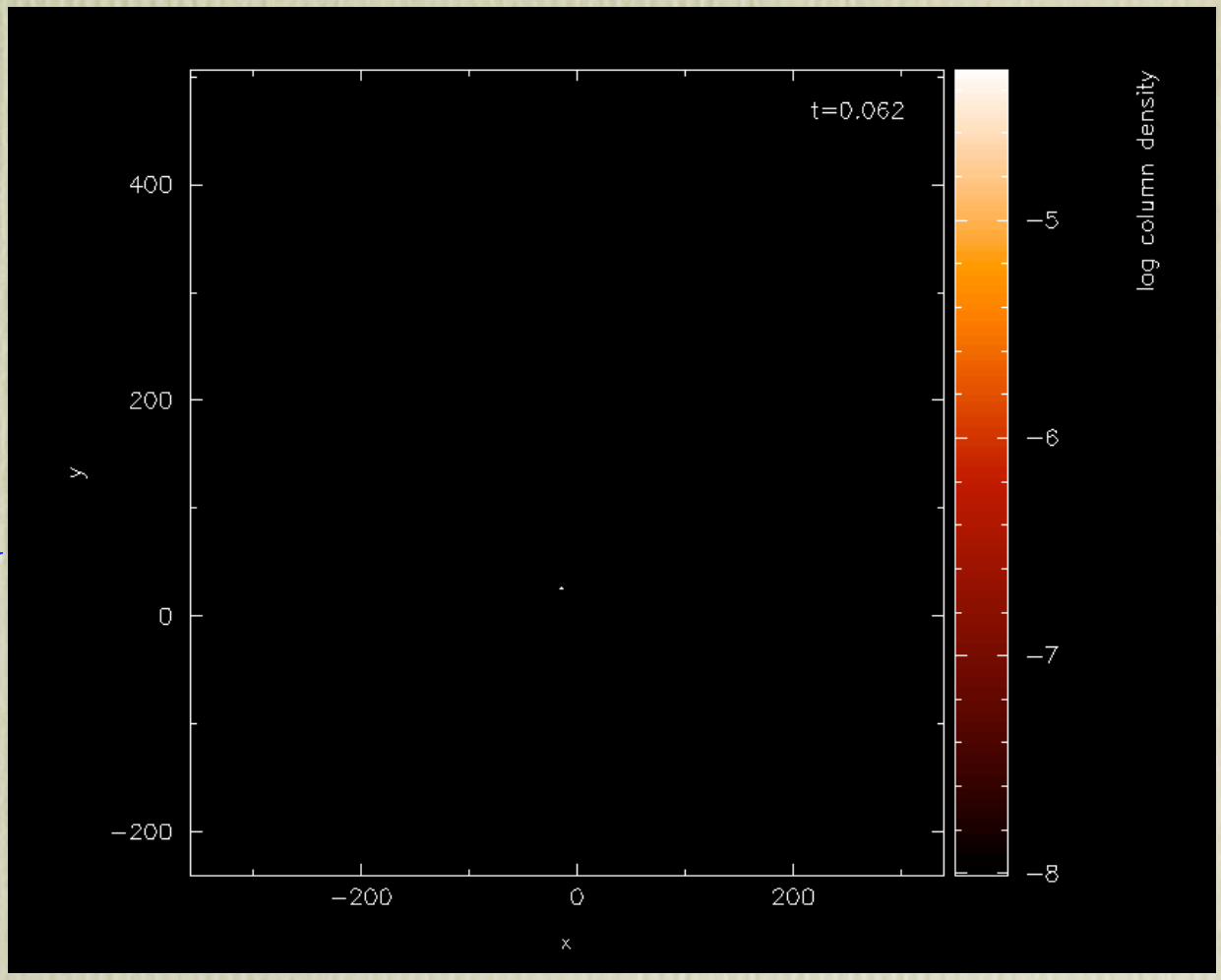
(WD: 0.6 $M_\odot$, C/O; BH: 1000$M_\odot$)

t= 0.34 s t= 24.01 s t= 138.24 s t= 360.53 s



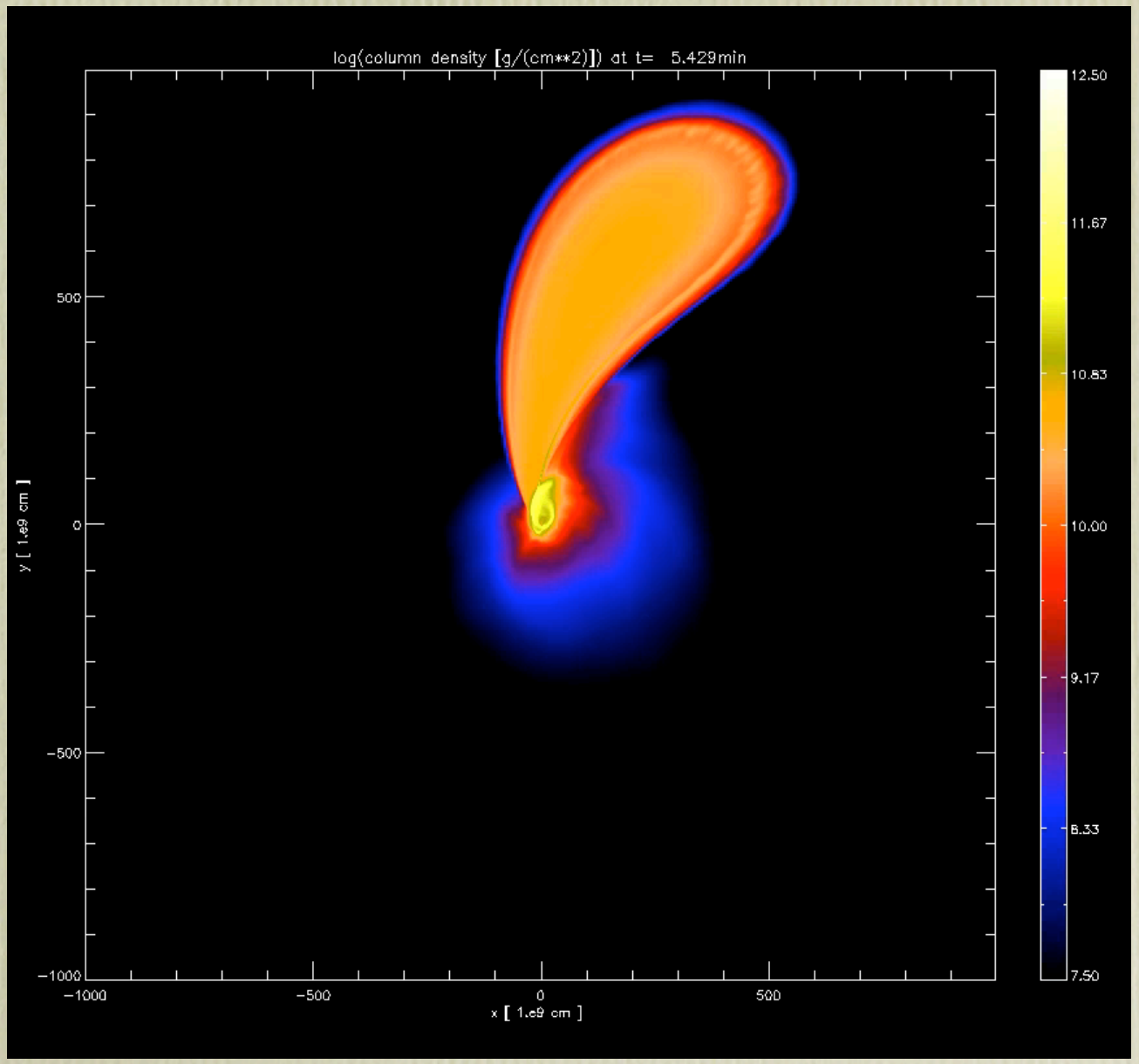
III.2 Examples: 2. Very strong encounter with low-mass WD

- white dwarf 0.2 $M_\odot$
- in. composition: pure He
- black hole: 1000 $M_\odot$
- pen. factor= 12
- simul. time: ~ 5.5 min.
- colour-coded: column density
- units: time 2.74 s
  length 10^9 cm
- ca. 4 000 000 SPH particles



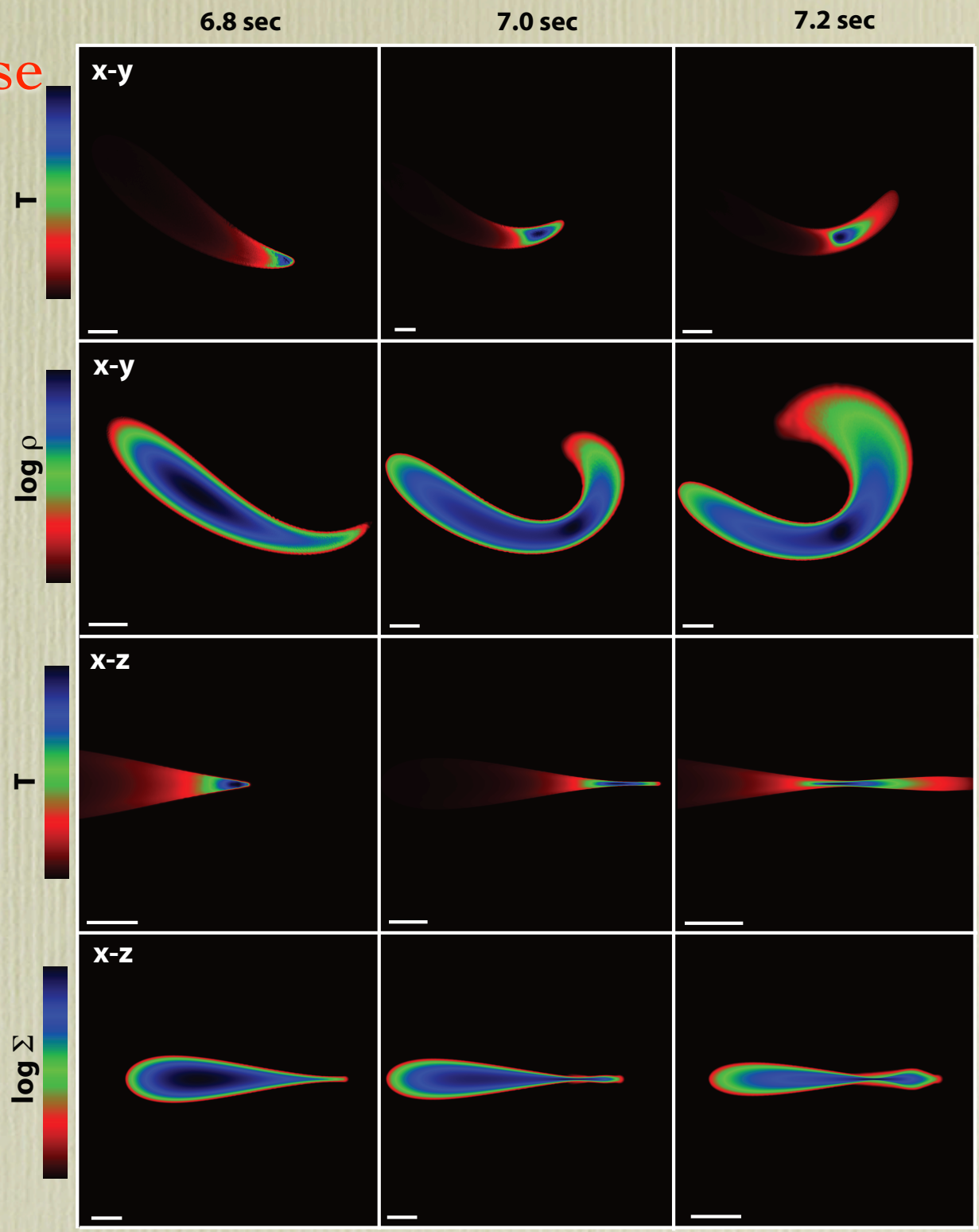
III.2 Example

Remnant geometry



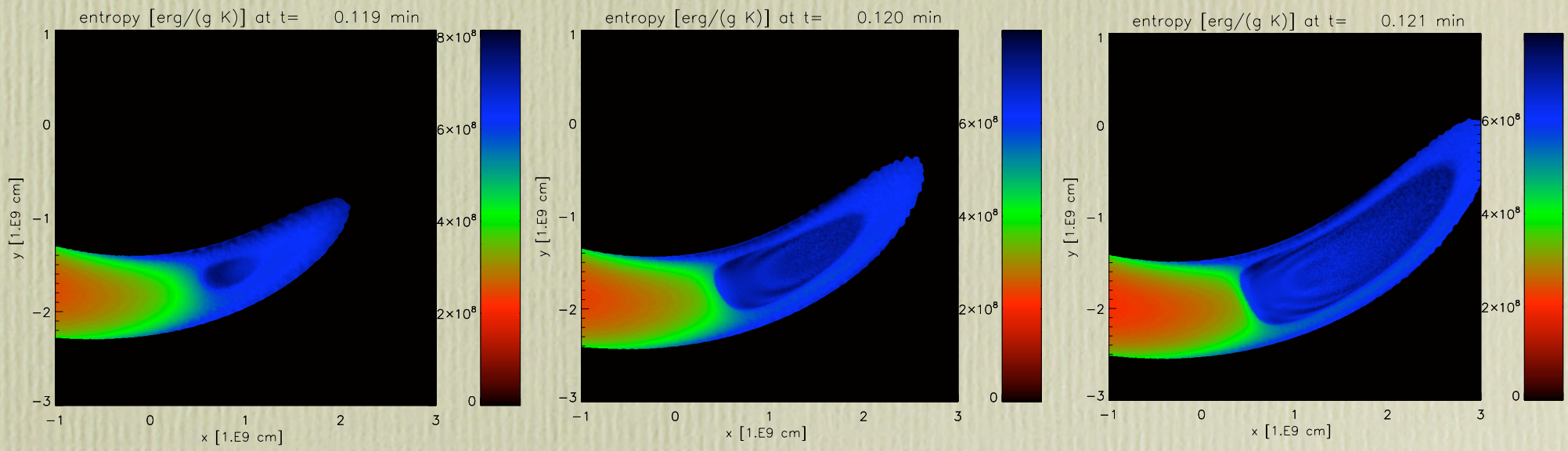
III.3 Compression phase

- cut XY-plane
- cut XZ-plane



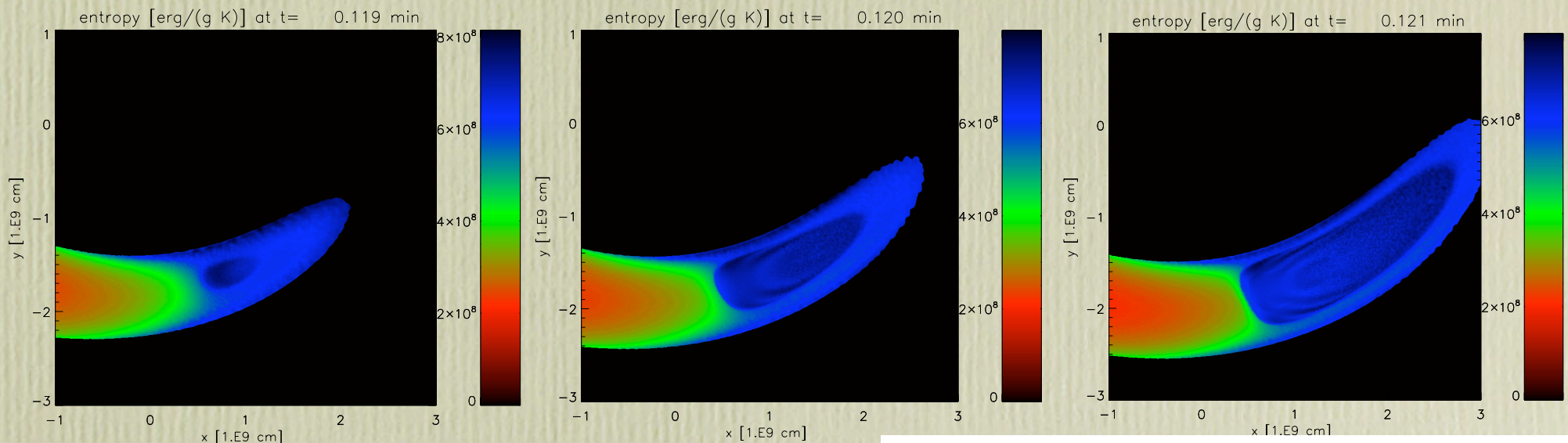
III.3 Compression phase

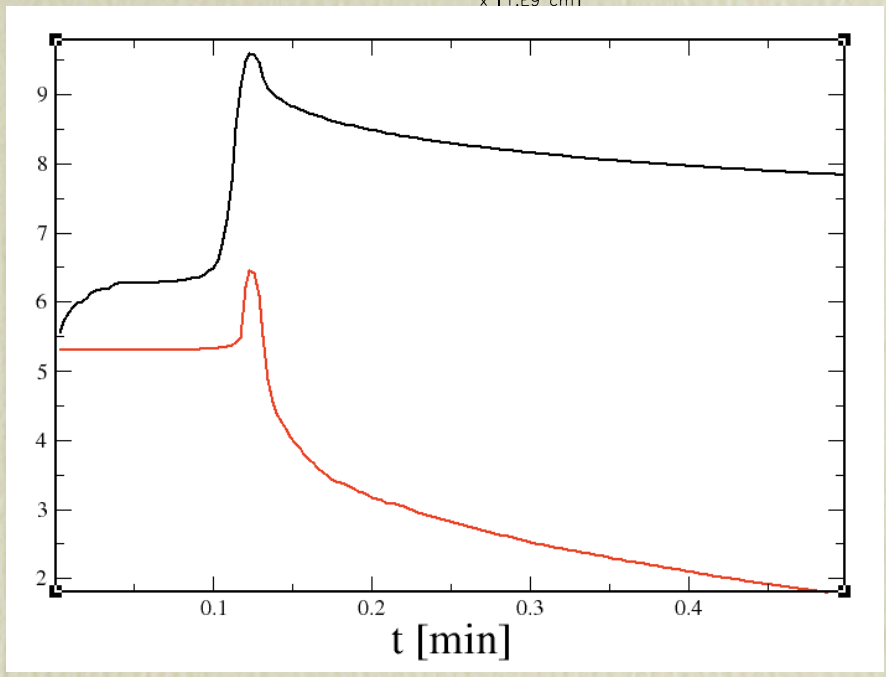
- Entropy evolution during passage: shock heating



III.3 Compression phase

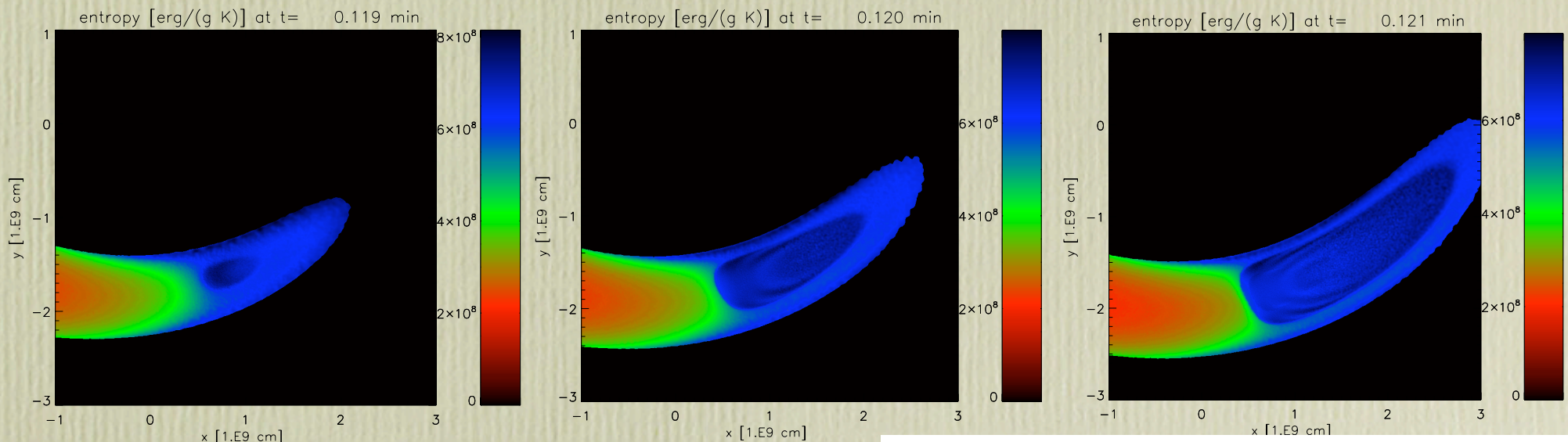
- Entropy evolution during passage: shock heating



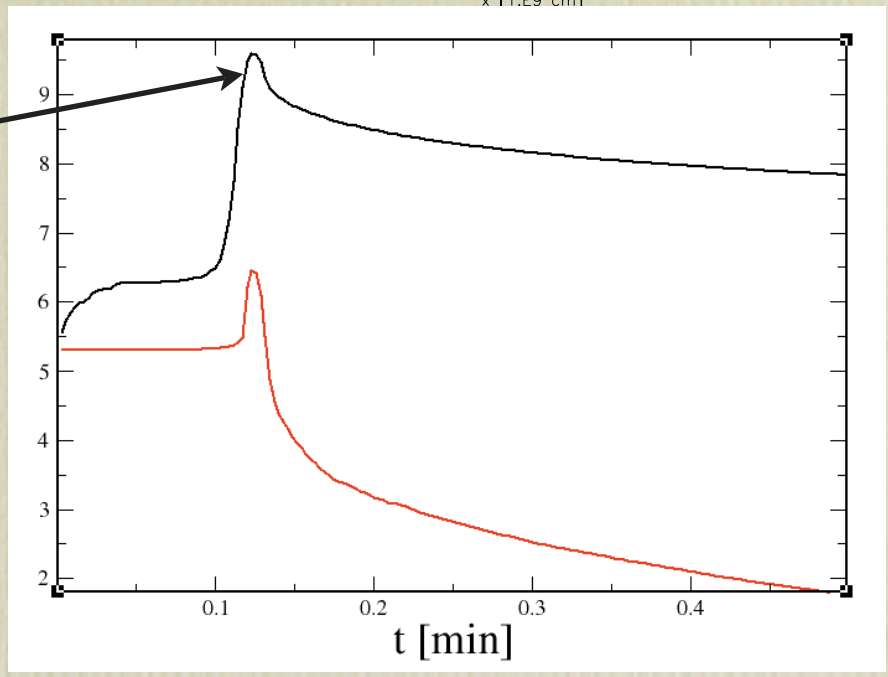


III.3 Compression phase

- Entropy evolution during passage: shock heating

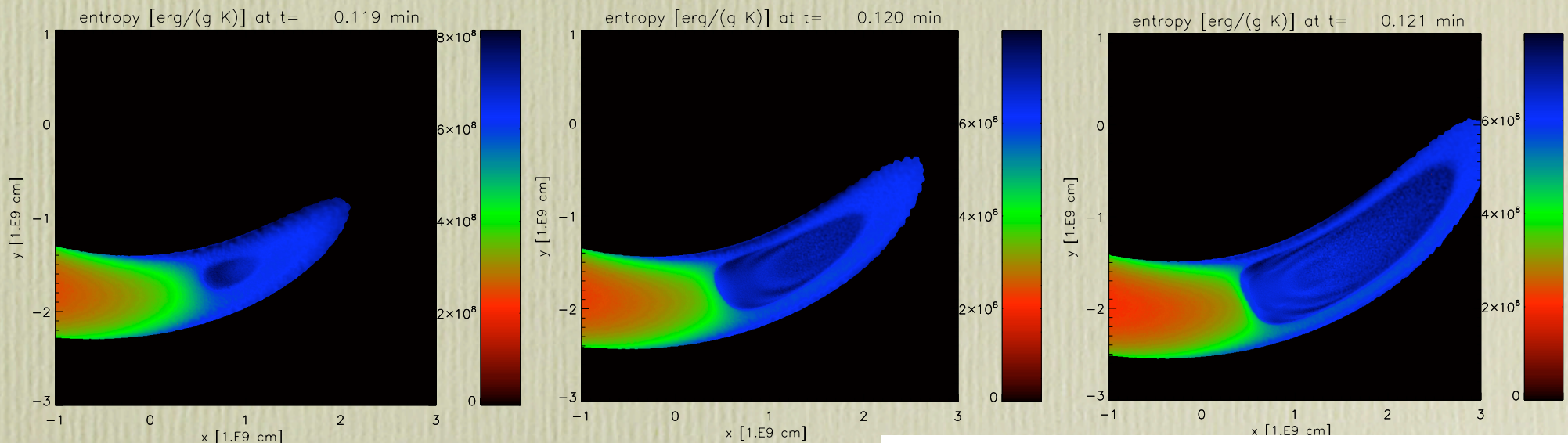


$$\log\left(T_{\max}[K]\right)$$



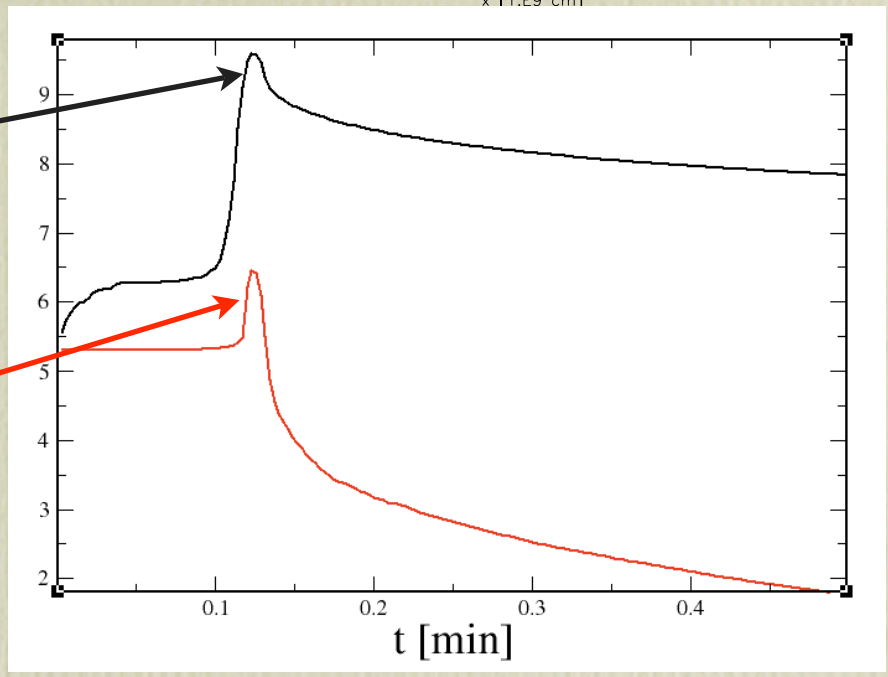
III.3 Compression phase

- Entropy evolution during passage: shock heating



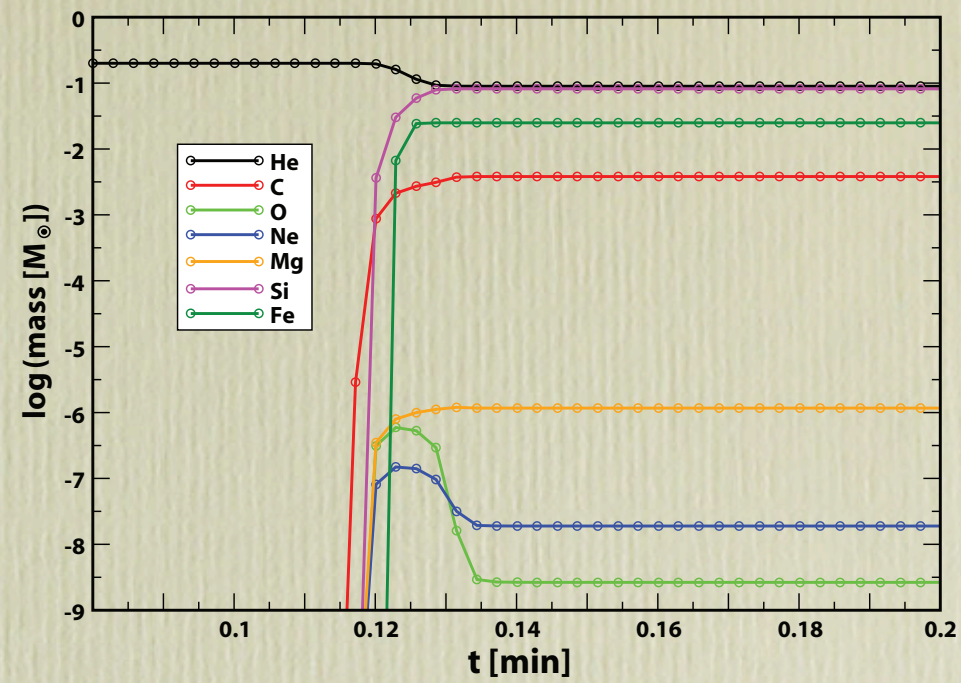
$\log\left(T_{\max}[K]\right)$

$\log\left(\rho_{\max}[\mathrm{g/cm^3}]\right)$



III.4 Nucleosynthesis $(0.2\ M_\odot\ \mathrm{WD},\quad 1000\ M_\odot\ \mathrm{BH},\quad \beta = 12)$

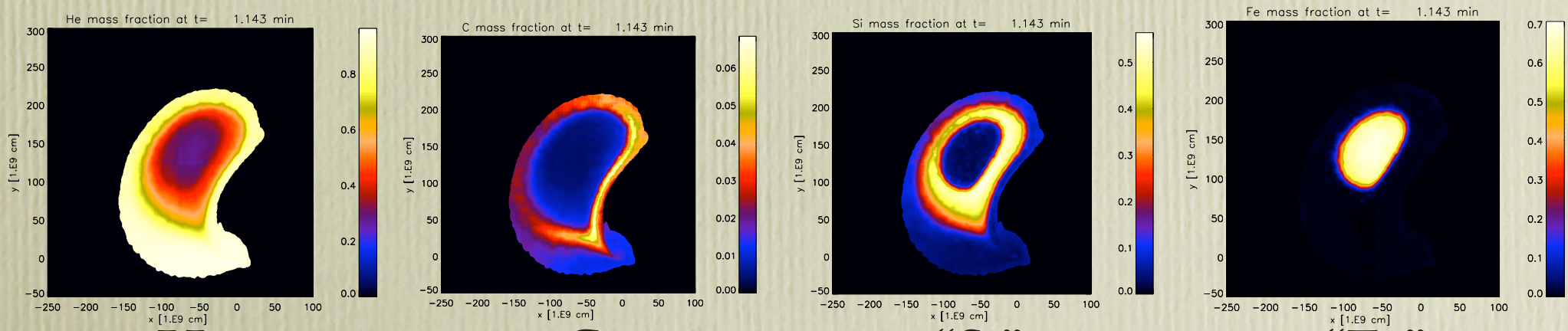
- nuclear evolution:



- nuclear energy release:

  $2.5\ 10^{50}$ erg (> E_{grav}= $1.3\ 10^{49}$ erg)

- element distribution:



He C "Si" "Fe"

$0.03\ M_\odot$ "Fe"

III.4 Nucleosynthesis / thermonuclear explosion

- the compression near the black hole takes

$$\Delta t_{\rm comp} \sim \frac{R_{\rm WD}}{v_{\rm P}} \quad v_{\rm P} \sim c(R_{\rm g}/R_{\rm T}) \sim 5 \times 10^9 \ {\rm cm/s}$$

$$\propto \beta^{-1/2} \ R_{\rm WD}^{3/2} \ M_{\rm WD}^{-1/6} \ M_{\rm BH}^{-1/3}$$

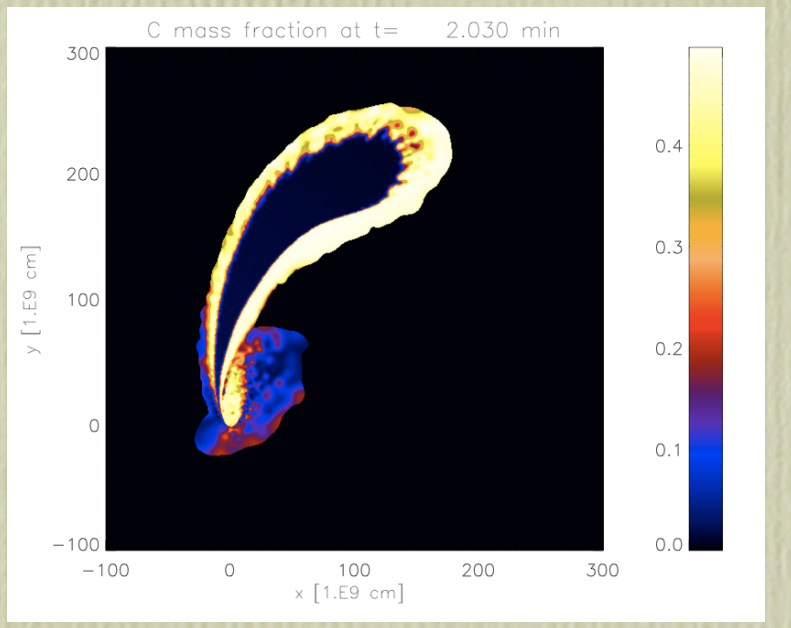
$$\sim 0.2 \ {\rm s} \ \text{ for } \ 0.6{\rm M}_\odot \ \text{WD and } 1000{\rm M}_\odot \ BH$$

- to release substantial amount of nuclear energy ($E_{\rm burn} \sim E_{\rm grav,WD}$) ideally:

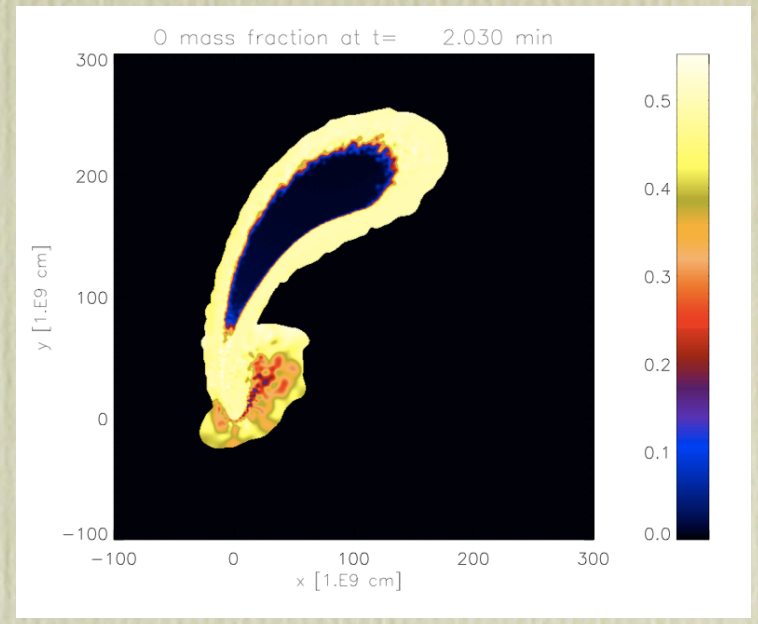
$$\tau_{\rm burn} \ll \Delta t_{\rm comp} \ll \tau_{\rm dyn,WD} \approx \sqrt{\frac{1}{G\bar{\rho}}}$$

- not much time for burning, very large temperatures required

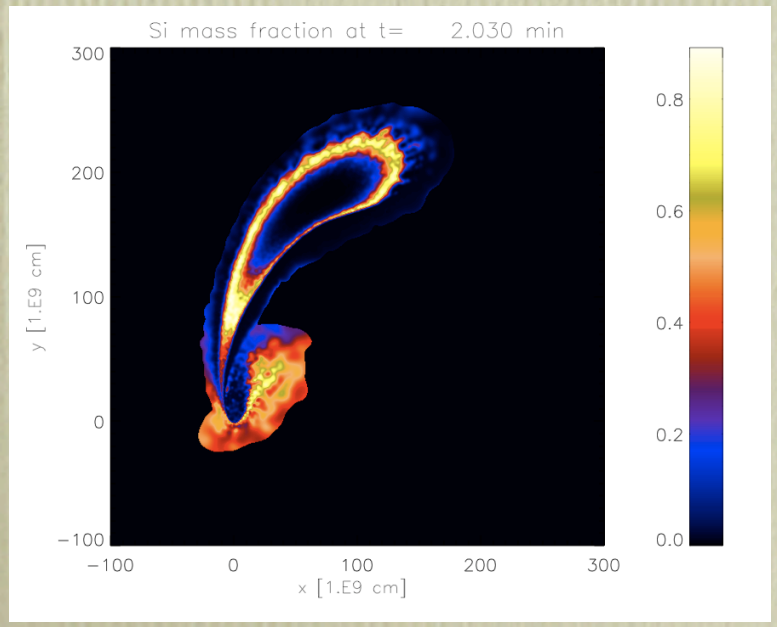
another example: WD : $0.6\ M_\odot$, C/O, BH : $500\ M_\odot$, $\beta = 5$



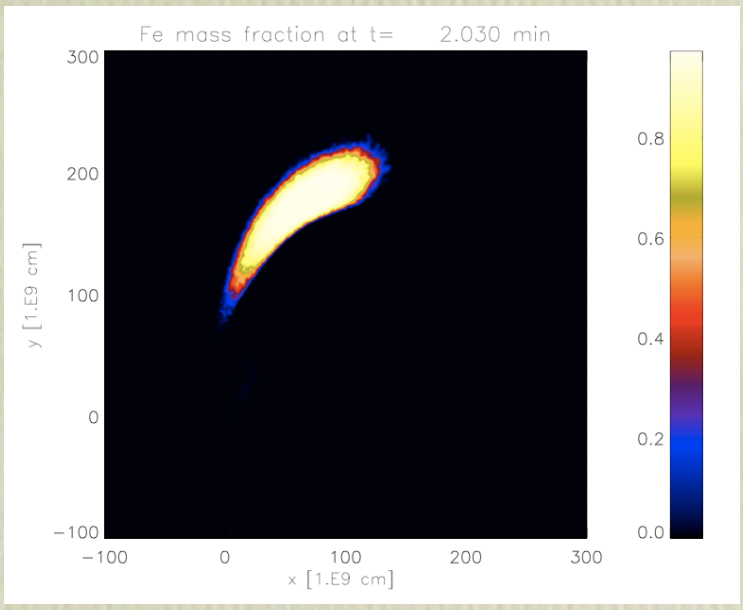
C



O



"Si"



"Fe"

$0.18\ M_\odot$

- Do we always get an explosion?

- Do we always get an explosion?
  - NO, only for penetration factors $\beta \equiv \frac{R_{\rm t}}{R_{\rm peri}} \geq 3$

- Do we always get an explosion?
  - NO, only for penetration factors $\beta \equiv \frac{R_{\rm t}}{R_{\rm peri}} \geq 3$

- Can we explode all types of white dwarfs?

- Do we always get an explosion?
  - NO, only for penetration factors $\beta \equiv \frac{R_{\rm t}}{R_{\rm peri}} \geq 3$
- Can we explode all types of white dwarfs?
  - YES, we can ..., examples from 0.2 ... 1.2 $\mathrm{M}_\odot$

III.5 Rates

- stellar disruption rate per globular cluster

$$R_{*,GC} \sim 10^{-7}\mathrm{yr}^{-1}\, M_{\mathrm{bh},3}^{4/3} \left(\frac{n_*}{10^6\mathrm{pc}^{-3}}\right)\left(\frac{10\ \mathrm{kms}^{-1}}{\sigma}\right)\left(\frac{r_{\mathrm{min}}}{r_{\mathrm{t}}}\right)$$

- WD fraction of disrupted stars: 10 % (Baumgardt et al. 2004)

- expl. rate per galaxy: $R_{\mathrm{WD,gal}} \sim 10^{-5}\mathrm{yr}^{-1} \left(\frac{R_{\mathrm{WD,GC}}}{10^{-8}\ \mathrm{yr}^{-1}}\right)\left(\frac{f_{\mathrm{bh}} N_{\mathrm{GC}}}{10^3}\right)$

III.5 Rates

- stellar disruption rate per globular cluster

$$R_{*,GC} \sim 10^{-7}\mathrm{yr}^{-1}\, M_{\mathrm{bh},3}^{4/3} \left(\frac{n_*}{10^6\mathrm{pc}^{-3}}\right)\left(\frac{10\ \mathrm{kms}^{-1}}{\sigma}\right)\left(\frac{r_{\mathrm{min}}}{r_{\mathrm{t}}}\right)$$

- WD fraction of disrupted stars: 10 % (Baumgardt et al. 2004)

- expl. rate per galaxy: $R_{\mathrm{WD,gal}} \sim 10^{-5}\mathrm{yr}^{-1} \left(\frac{R_{\mathrm{WD,GC}}}{10^{-8}\ \mathrm{yr}^{-1}}\right)\left(\frac{f_{\mathrm{bh}} N_{\mathrm{GC}}}{10^3}\right)$

→ few permille of type Ia supernova rate

III.5 Rates

- stellar disruption rate per globular cluster

$$R_{*,GC} \sim 10^{-7}\mathrm{yr}^{-1}\, M_{\mathrm{bh},3}^{4/3} \left(\frac{n_*}{10^6\mathrm{pc}^{-3}}\right)\left(\frac{10\ \mathrm{kms}^{-1}}{\sigma}\right)\left(\frac{r_{\mathrm{min}}}{r_{\mathrm{t}}}\right)$$

- WD fraction of disrupted stars: 10 % (Baumgardt et al. 2004)

- expl. rate per galaxy: $R_{\mathrm{WD,gal}} \sim 10^{-5}\mathrm{yr}^{-1} \left(\frac{R_{\mathrm{WD,GC}}}{10^{-8}\ \mathrm{yr}^{-1}}\right)\left(\frac{f_{\mathrm{bh}} N_{\mathrm{GC}}}{10^3}\right)$

→ few permille of type Ia supernova rate

→ future supernova surveys should see some of them

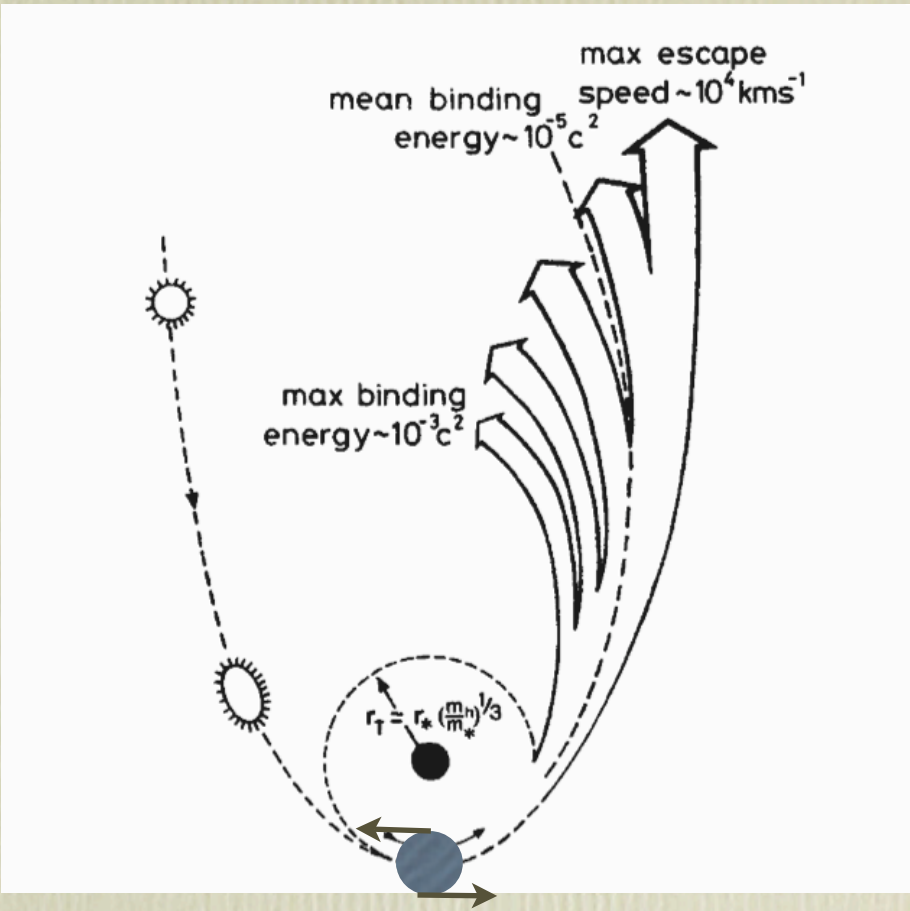
Comparison with "standard" type Ia supernovae

"standard" type Ia supernova	tidal WD-ignition
• mass: "Chandrasekhar", $1.4\ M_\odot$	• full WD mass range
• composition: Carbon/Oxygen	• from He to C/O ...
• rate: $R_{Ia} \approx 2.5 \cdot 10^4\ (\text{year})^{-1}\text{Gpc}^{-3}$	• few permille of R_{Ia}
• geometry: "spherical"	• "pancake"
• accompanying signal:	• shock breakout+ X-ray flare

III.6 Accretion: "fan" and disk formation

- at peri-centre:

  large spread of specific energies across stellar radius, $\Delta\epsilon$



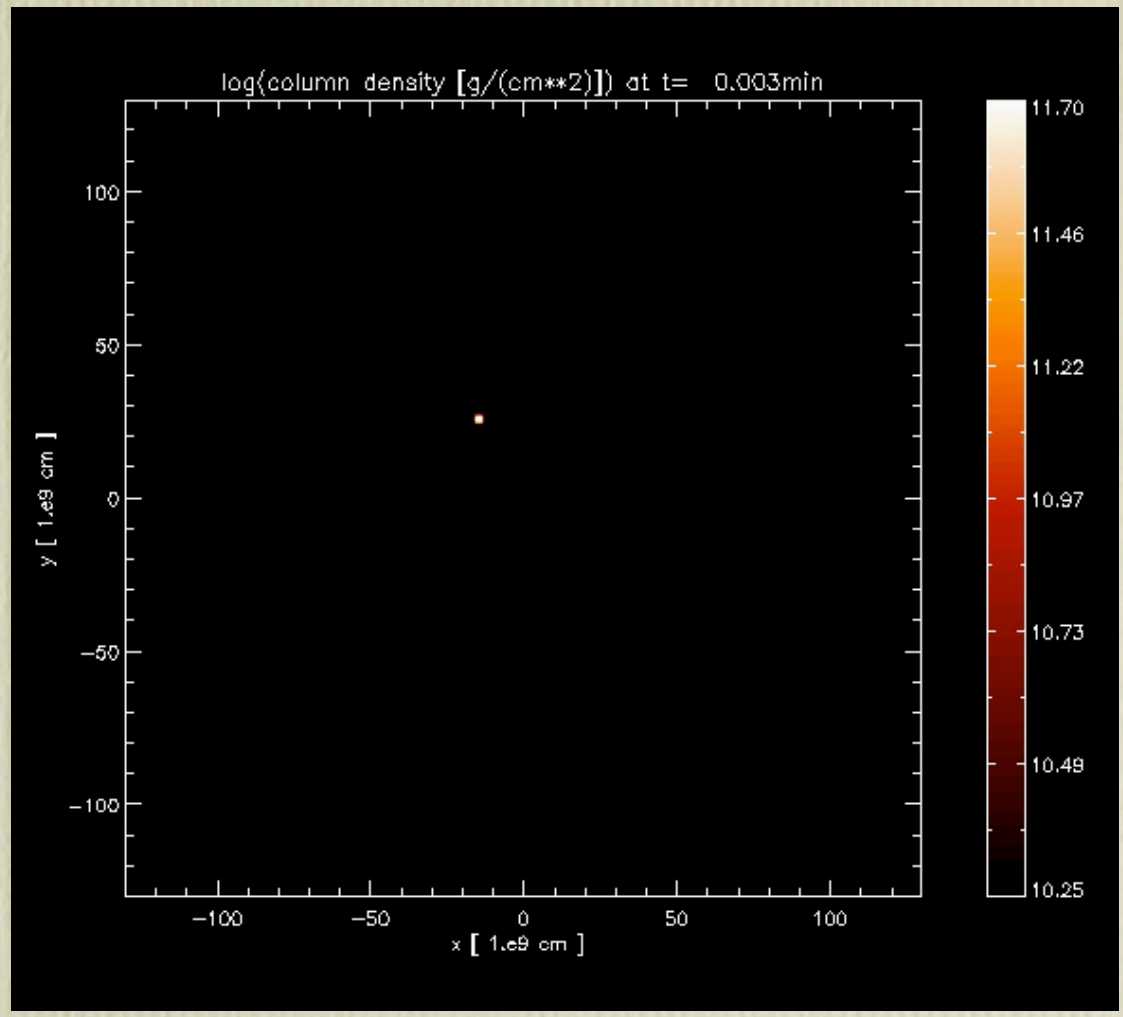
(Rees 1988)

→ large spread of apo-centre distances, "expansion" fan

$$\frac{\Delta\epsilon}{\epsilon_{\rm grav,WD}} \sim \left(\frac{M_{\rm BH}}{M_{\rm WD}}\right)\left(\frac{R_{\rm WD}}{R_{\rm peri}}\right)^2 \sim 50$$

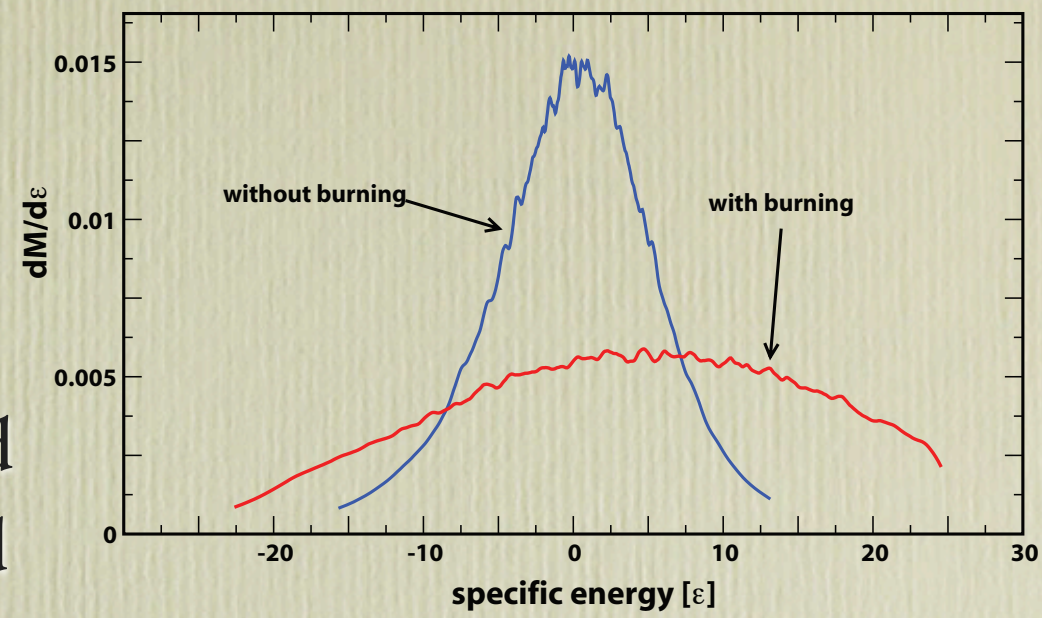
III.6 Accretion

- pericentre acts as "nozzle"
- strong sensitivity to exact orbit: "expansion fan"
- circularization via angular momentum redistribution shock



III.6 Accretion

- influence of burning



without burning: 50% ejected
with burning: 65% ejected

- initial accretion rate: $\dot{M} \sim 10^2 \, \frac{M_\odot}{\mathrm{yr}}$
- later drop off: $\dot{M} \propto t^{-5/3}$
- expected X-ray flare: $L_X \sim L_{\mathrm{edd}} \sim 10^{41} \mathrm{erg/s}$
- duration: several months

IV. Summary

- tidal compression can induce a thermonuclear explosion (for pen. factors > 3)
- estimated rates: few 10^{-3} of SN Ia rate

  (LSST: >250 000 type Ia per year)
- ~ 30 % of the star is accreted onto the hole and produces a X-ray flare
- underluminous thermonuclear explosion plus soft X-ray flare ($L_X \sim L_{Edd} \approx 10^{41}$erg/s $M_{BH,3}$) would be compelling evidence for existence of IMBH