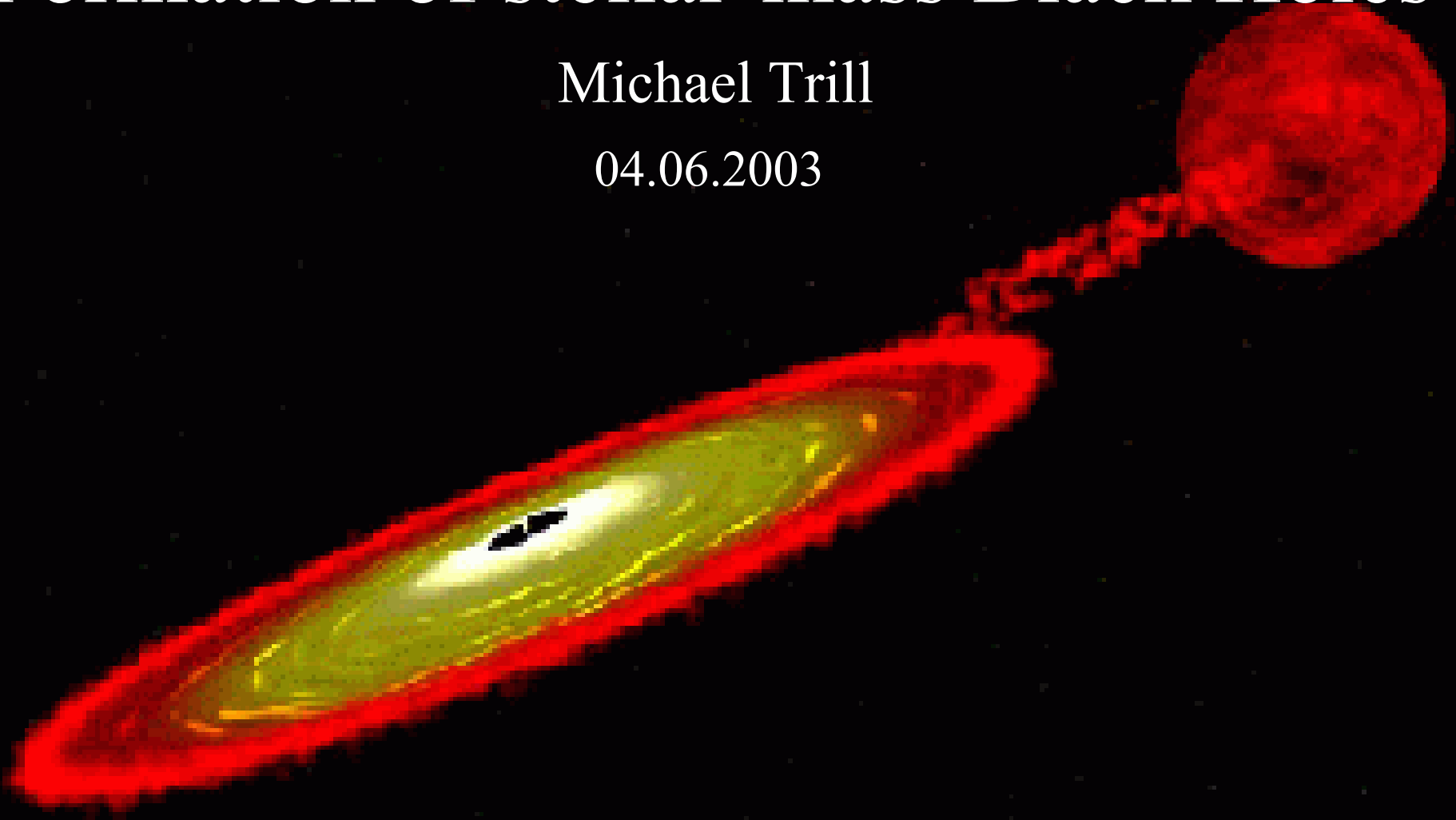


# Formation of stellar-mass Black Holes

Michael Trill

04.06.2003

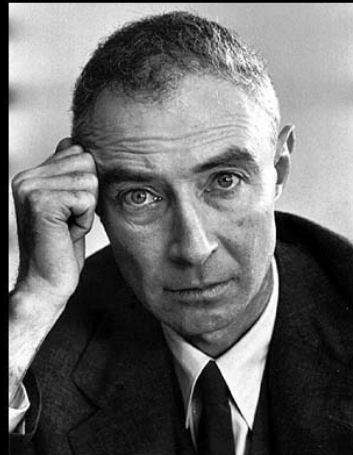


# Overview

- Introduction
  - Historical note
  - What are stellar-mass BH's?
- Formation of BH
  - Gravitational collapse
  - Merger
- Details
  - Accreting matter towards a BH
  - Zero metallicity: Pop III stars
  - Uncertainties in the evolution of binaries and massive stars
- Summary

## Historical note

Robert Oppenheimer & Hartland Snyder 1939:  
stellar-mass black holes could form from the  
collapse of massive stars



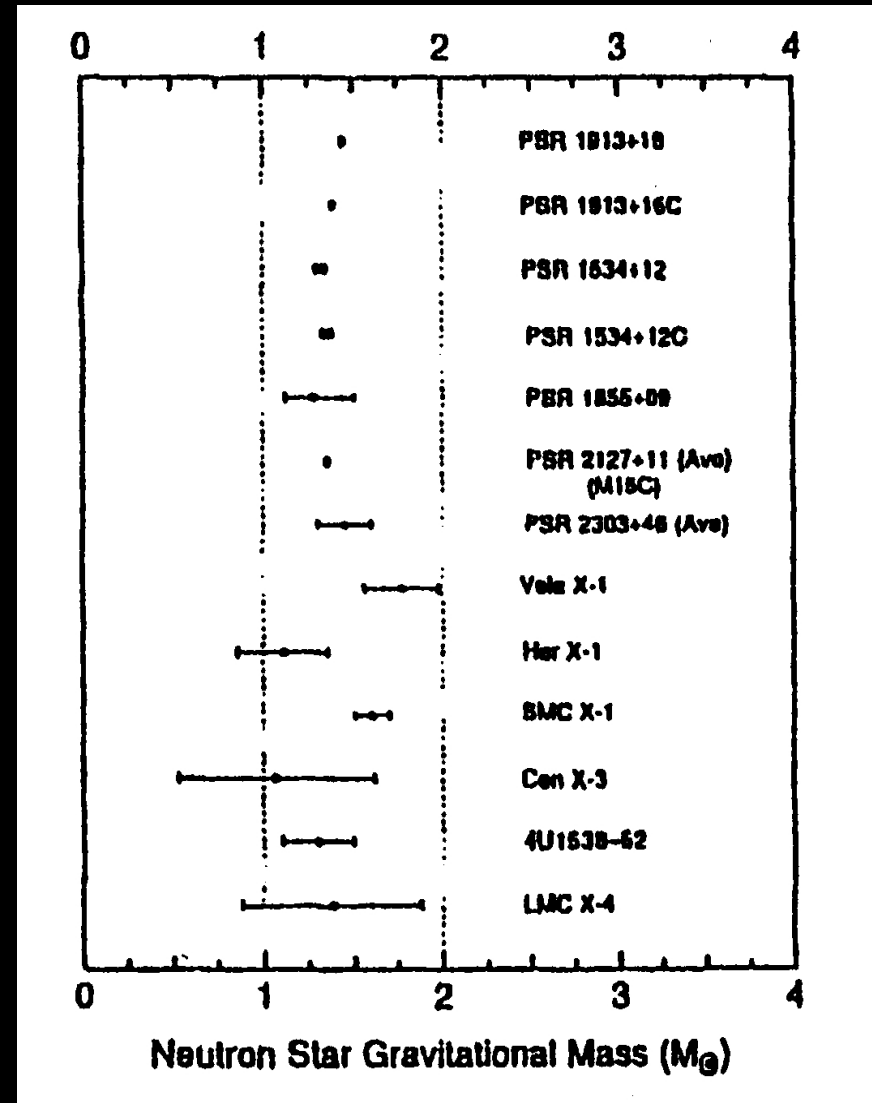
Robert Oppenheimer



Hartland Snyder

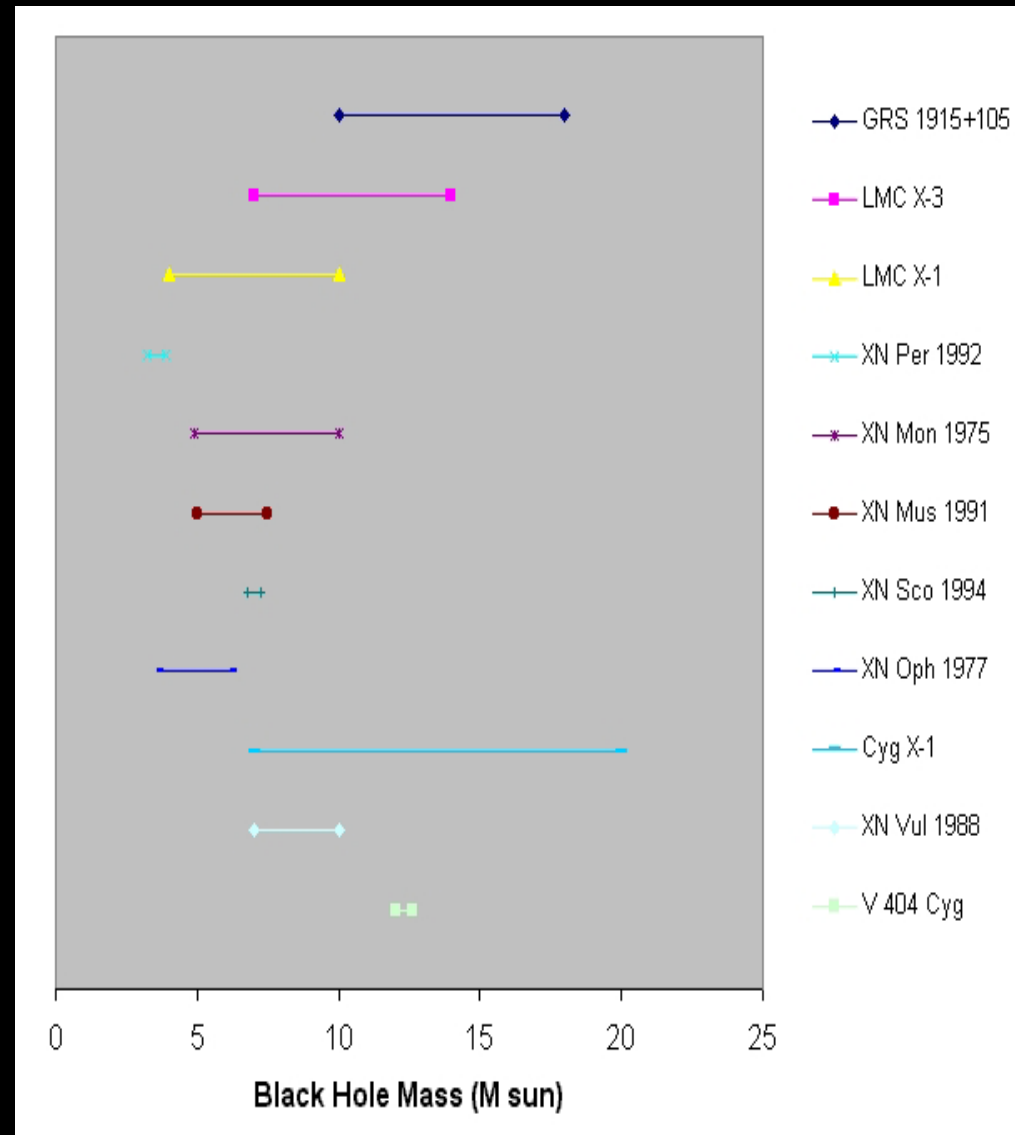
# Determining masses of compact stars

- binary stars: observation
  - => mass function
  - => lower limit of  $M_{\text{compact-star}}$
- for neutron star masses
  - $\sim 1 M_{\odot} < M_{\text{NS}} < \sim 2 M_{\odot}$



# Masses of BH candidates

- ... 17 BH-candidates in the range of 3-20  $M_{\odot}$



# What are stellar-mass BH's?

- these 17 compact components of binaries are *observable* “stellar-mass” Black Holes
- compare: supermassive BH's in centers of galaxies,  $M_{\text{BH}} > 10^6 M_{\odot}$

# The two possibilities of the formation of stellar-mass BH

1. Gravitational collapse

2. Merger ,  $\text{NS} + \text{NS} \rightarrow \text{BH}$

# 1. Gravitational collapse

# Stellar evolution towards gravitational collapse

- what progenitor stars are able to form iron cores?
  - > massive star  $> 8-10 M_{\odot}$
- through the stellar stages live: hydrodyn. equilibrium states  
gravitation = thermal pressure + electron degeneracy
- nucleons of iron at maximum in binding state
  - >nuclear fuel is used up
  - > just gravitation, no equilibrium state

# The gravitational collapse

- gravitational collapse: runaway process  
central collapse happens in ms

# What happens ? first just gravitation

- > • grav. contraction of iron core
  - > higher temperature ( $10^{10}$  K), density & pressure
- > • neutrino loss
  - > energy loss
  - electron capture produces neutrons
    - > reduces electron degeneracy pressure
  - photodissociation of iron into alpha particles
    - > endothermic reaction
    - > lower temperature
- > • grav. contraction of iron core ...  
.... and so on , until

... we reaches nuclear densities

-> neutrinos cannot escape

- nuclear forces and neutron degeneracy  
pressure halt the collapse

- formation of a proto-neutron star

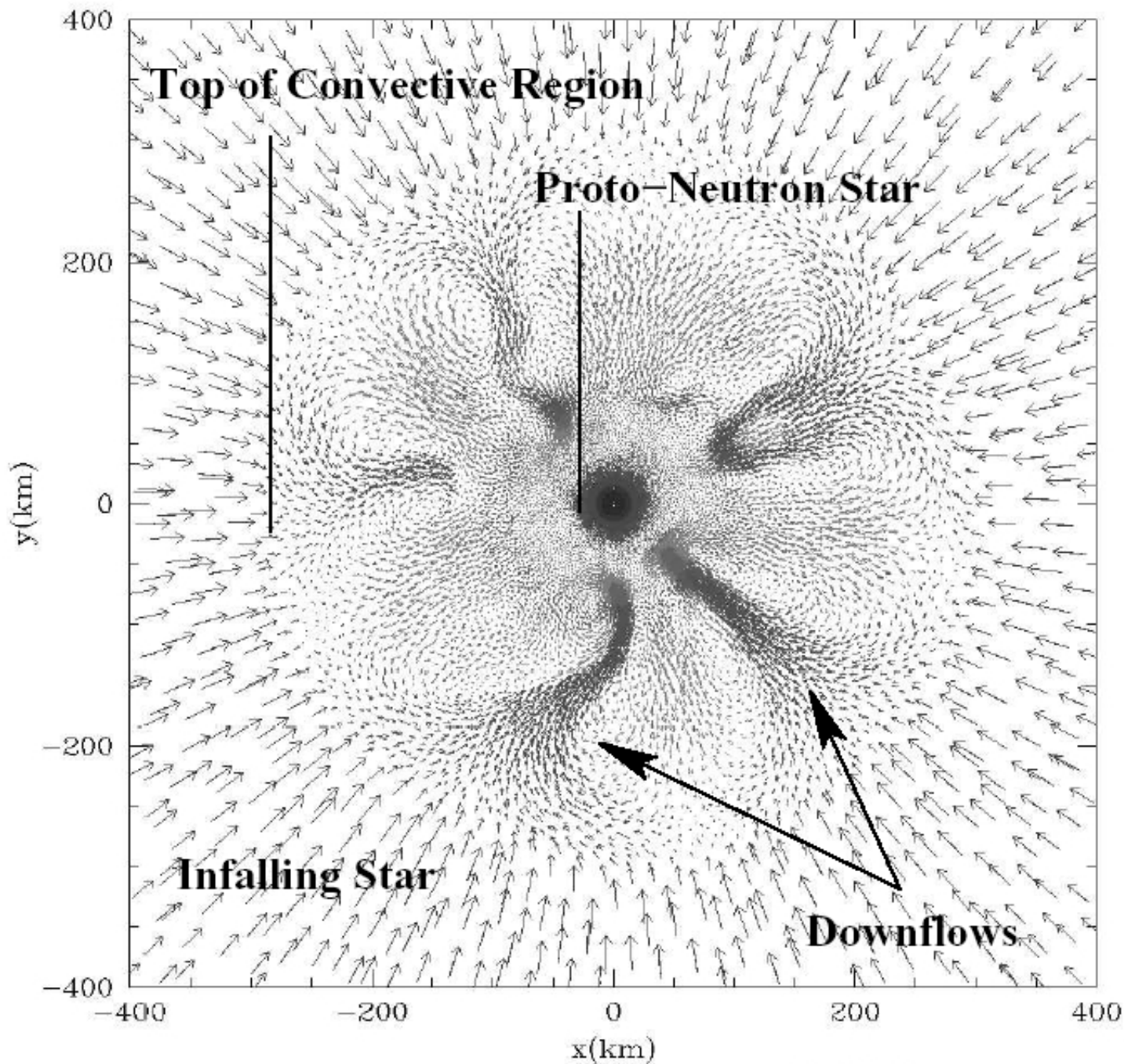
- outer iron core falling in slowly

# For not too massive proto-neutron stars :

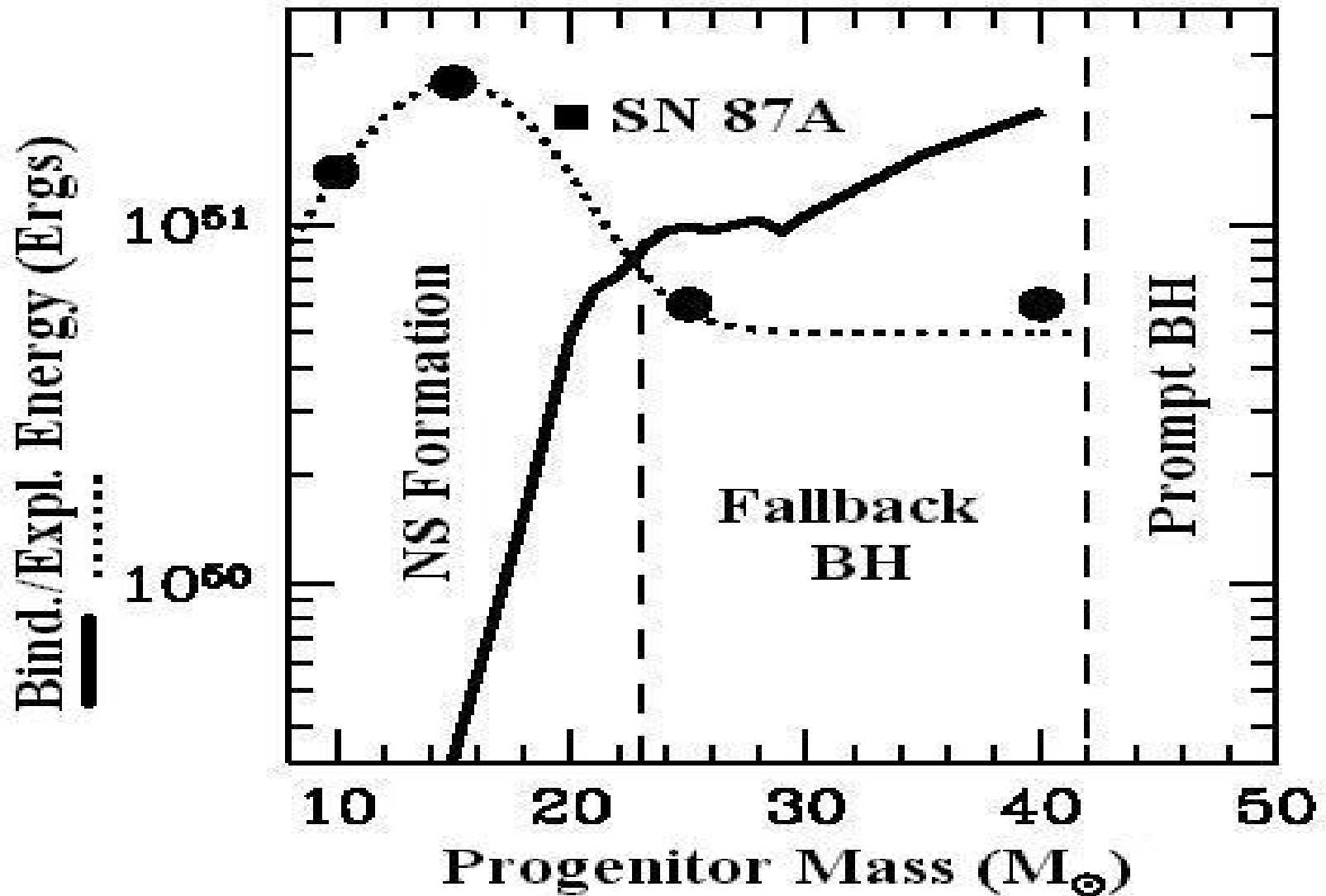
- inner neutron core cannot be compressed any more
  - material from outside collide onto compact neutron core but then bounce of the core launches a shock wave back through the star
- > outward motion

- but still infalling material
  - > ram pressure from inward motion
  - > convection region, shock is stalled
- neutrinos from inside and heat of accretion (downflows inwards) revive the shock
- convection region overcome ram pressure
  - > Supernova is launched

Picture of slice of a 3D simulation (Fryer)



# Three regimes of compact object formation :



# Core collapse calculation (Fryer et al. 2003)

- simulation just gives trends in explosion energy and remanent mass
- 2D smooth-particle hydrodynamic simulation with 13.000-16.000 particles
- close binary,  $60 M_{\odot}$  primary progenitor and  $34 M_{\odot}$  companion with initial orbit period of 20 d
- equation of state is patchwork of series codes
- iron core masses at collapse from:
  - same primary progenitor with different wind loss rates at Wolf-Rayet stage (1s1 highest rate,...,1s6 lowest rate, later on)
  - or
  - different progenitors masses

## RESULTS FROM THE CORE-COLLAPSE CALCULATIONS

Model <sup>a</sup>	$M_{\text{Fe core}}^b$ ( $M_{\odot}$ )	$E_{\text{exp}}^c$ ( $10^{51}$ ergs)	$t_{\text{exp}}^d$ (ms)	$\text{KE}_{\infty}^e$ ( $10^{51}$ ergs)	$M_{\text{remnant}}^f$ ( $M_{\odot}$ )
1s1 .....	1.321	1.45	150	0.7	1.35
1s2 .....	1.352	2.36	160	1.3	1.17
1s3 .....	1.590	1.60	180	1.0	2.11
1s4 .....	1.750	0.3	180	0.15	5.2
1s6 .....	1.497	0	...	0	10.7

<sup>a</sup> See Table 1.

<sup>b</sup> Mass of the iron core at collapse.

<sup>c</sup> Amount of energy injected in the star by neutrinos. A portion of this energy will unbind the star, a portion will go into the velocity of the ejecta, and some will fall back onto the neutron star.

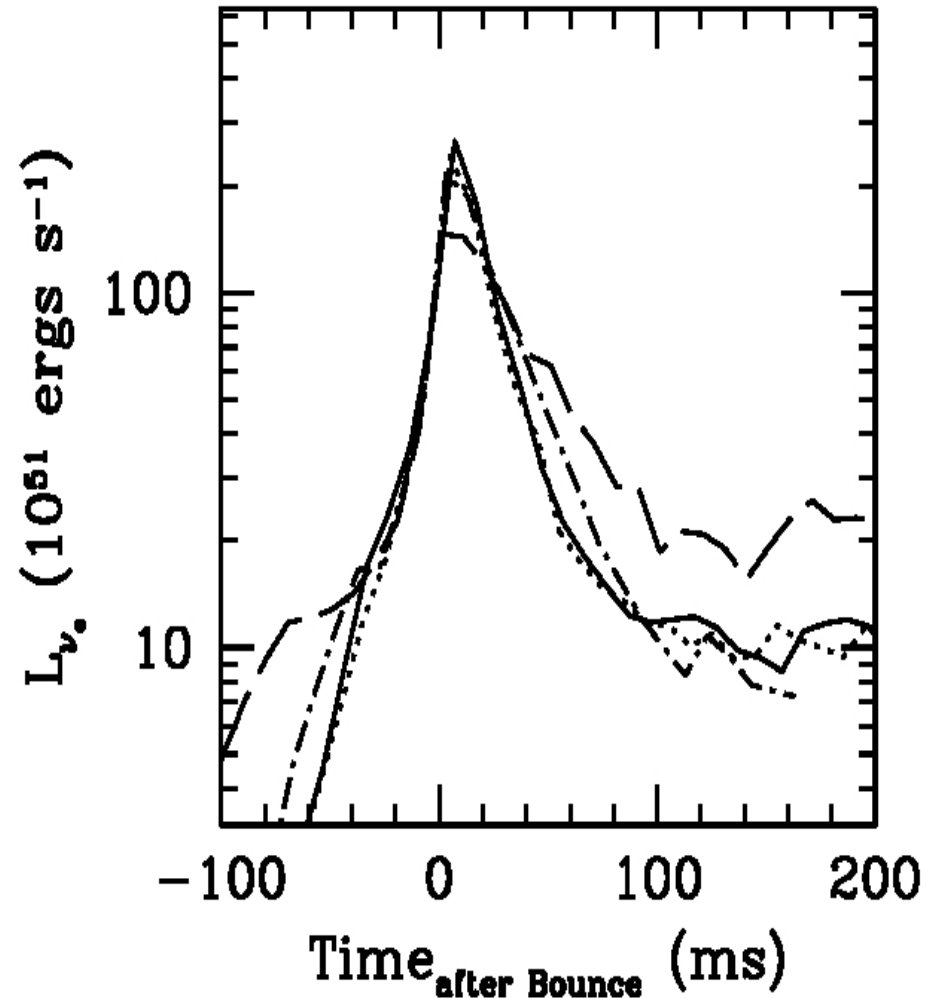
<sup>d</sup> Time it takes for the shock to be pushed beyond 1000 km.

<sup>e</sup> Kinetic energy of the ejecta 1 yr after explosion.

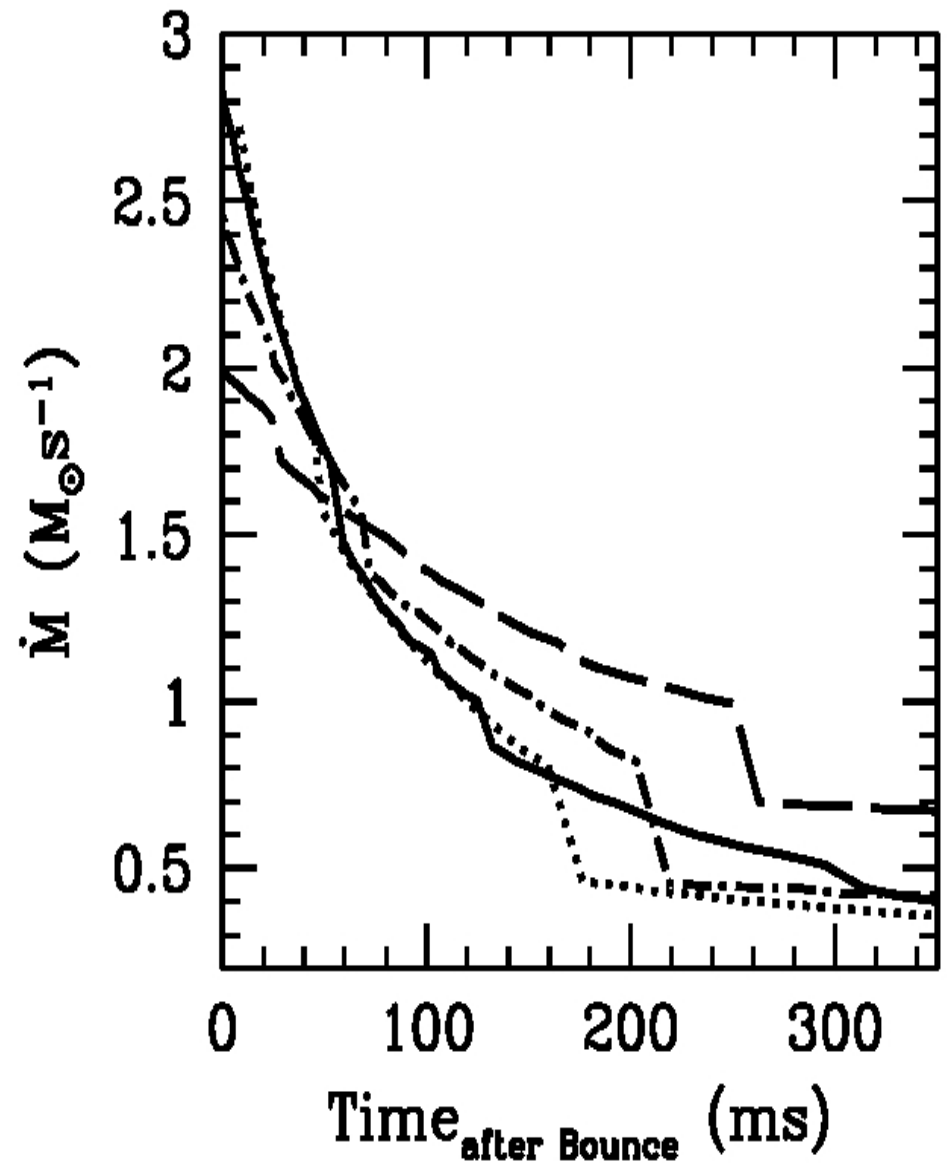
<sup>f</sup> Mass of the compact remnant after fallback.

# Neutrino luminosity

- electron neutrino luminosity as a function of time after bounce
- model 1s1 (solid line),  
1s2 (dotted line),  
1s4 (dashed line),  
1s6 (dot-dashed line)
- $L_{\nu_e}$  determines the energy deposited in the convection region
- model 1s4 emits nearly twice as many  $\nu_e$  100 ms after bounce  
-> explosion compared with 1s6 (no explosion)



- accretion rate vs. time after bounce for the different models
- 1s1 (solid line), 1s2 (dotted line), 1s4 (dashed line), 1s6 (dot-dashed line)
- accretion rates do not differ significantly for any of the progenitor.
- simply following the accretion rate, model 1s1 should have the strongest explosion, followed by models 1s2, 1s6, 1s4.
- but shock pressure is better diagnostic for explosion energy

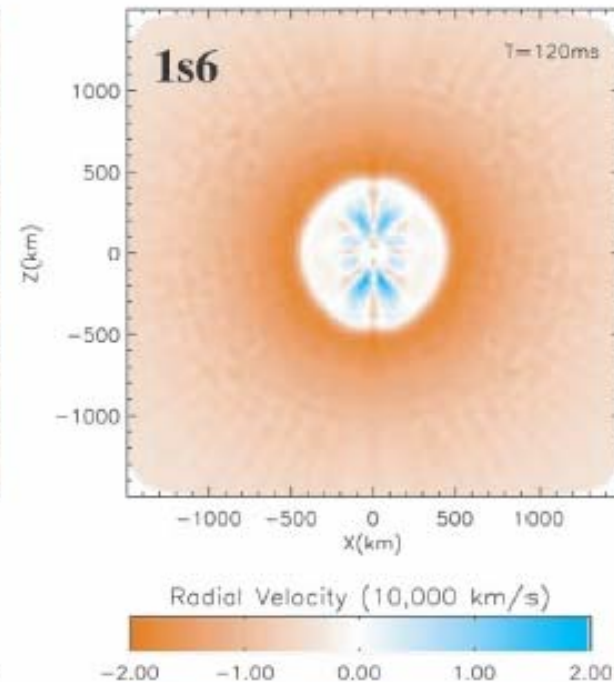
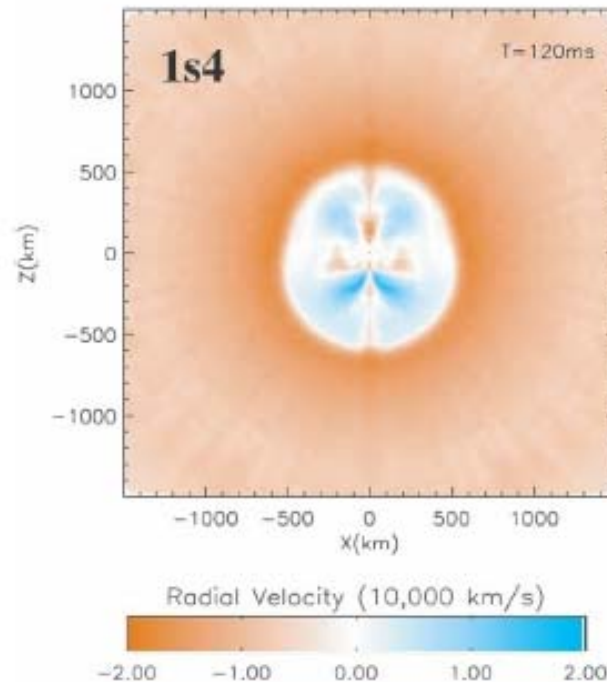
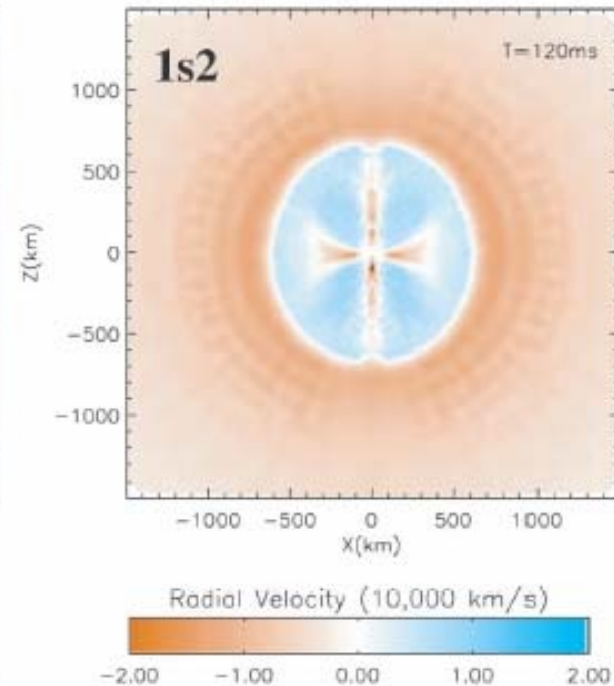
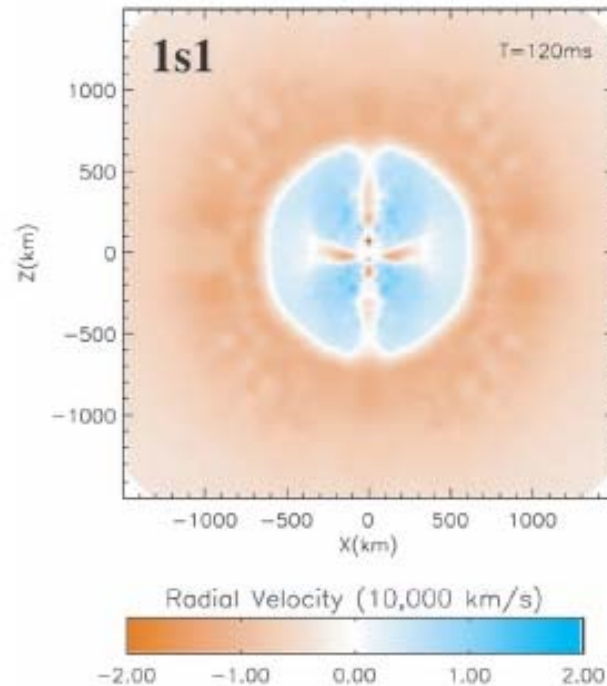


- snapshots of the core collapse of models 120 ms after bounce

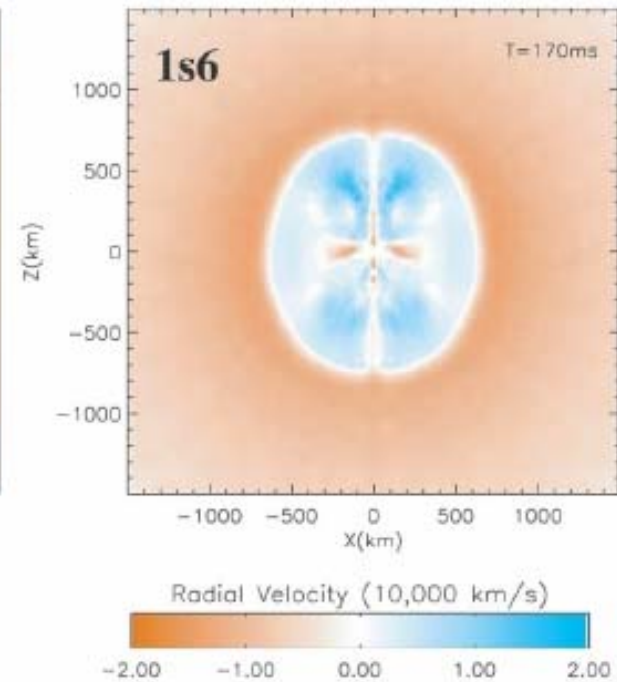
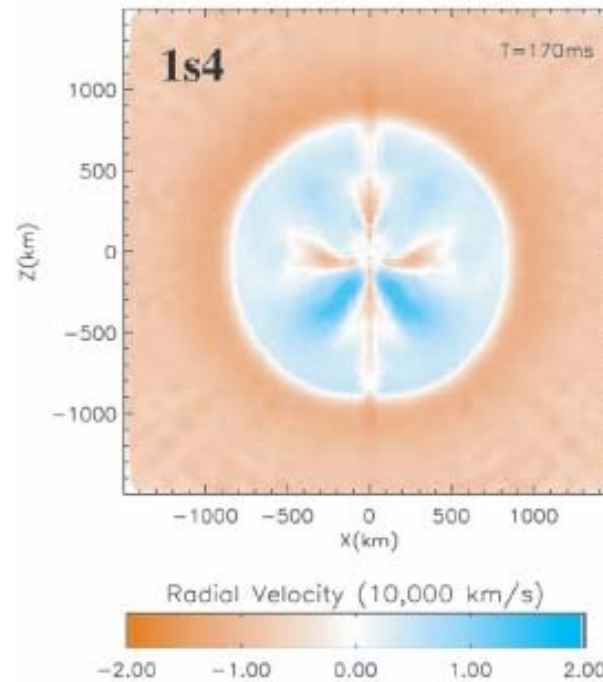
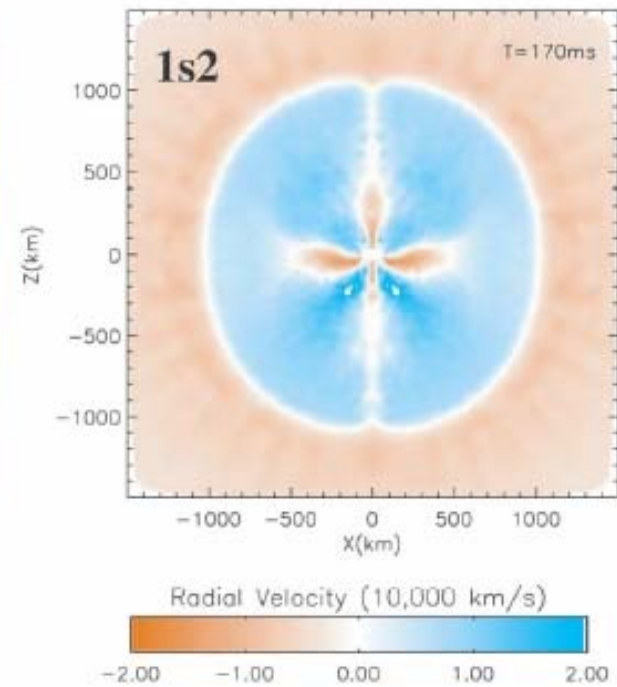
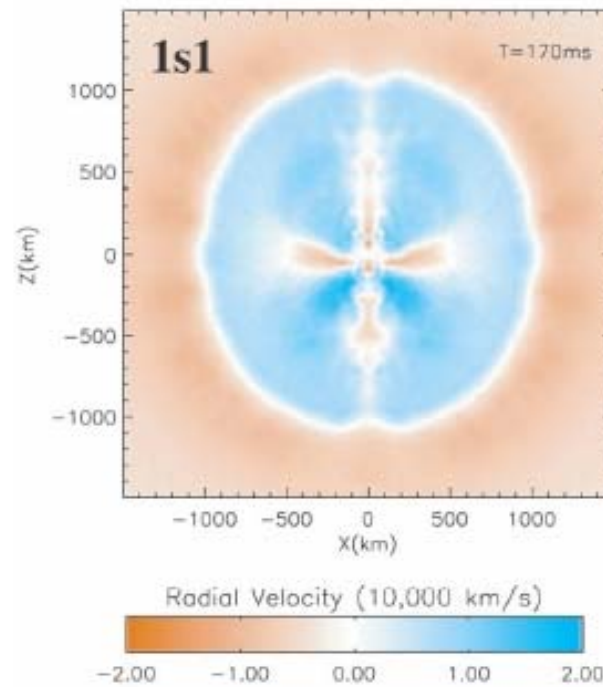
1s1 (top left),  
1s2 (top right),  
1s4 (bottom left), and  
1s6 (bottom right)

- colour denotes radial velocity, and the position of the accretion shock can be easily be determined for each model.

- for models 1s1 and 1s2, the shock is at roughly 650 km, the shocks of models 1s4 and 1s6 are below 500 and 400 km.



- same pictures  
170 ms after bounce
- in all the models shock has moved outward over the past 50 ms .
- for models 1s1 and 1s2, shock is at roughly 1000 km and expanding rapidly.
- model 1s4 also seems to be exploding. Shock of model 1s6 has stalled at 650 km without explosion



# Black hole kicks

- BH can receive kicks
- kicks are produced by a-/symmetric SN  
(collapse->NS->SN->kick->fall-back->BH)
- binary system kicks:
  - system kick velocity varying from 10 to 60 km/s, but also higher  
(Prodsiadlowski, Nova Scorpii)
- kicks, that separate the binary system: (in principle: binary -> 2 SN possible)
  - difficult to receive a kick distribution for single BH, but kick velocity probably in the same order of single NS ( $v_{\max} \sim 1000$  km/s, Freyer, BH formation from stellar collapse) )

# Formation rates

- 5-40% of all collapsing stars form black holes

->  $5 \cdot 10^6$  -  $4 \cdot 10^7$  black holes in our galaxy

(Fryer & Kalogera 2001)

# 2. Merger

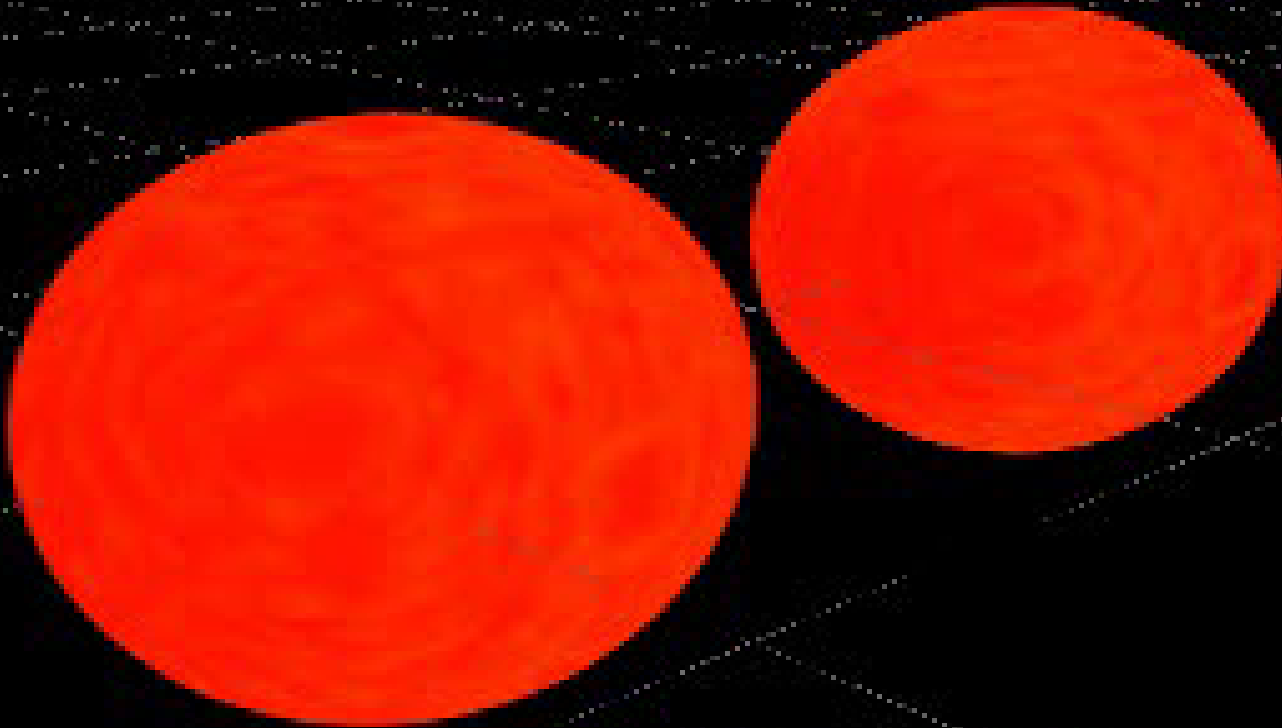
# NS Merger: NS + NS $\rightarrow$ BH

- double binary pulsar PSR 1510-54 +16 found 1974
- general relativity : grav. waves are emitted from NS binary
  - $\rightarrow$  energy loss decrease of the period  $\rightarrow$  merger
- observation of decrease of period in good agreement with GR
- NS-NS merger : good candidat for gamma-ray-bursts

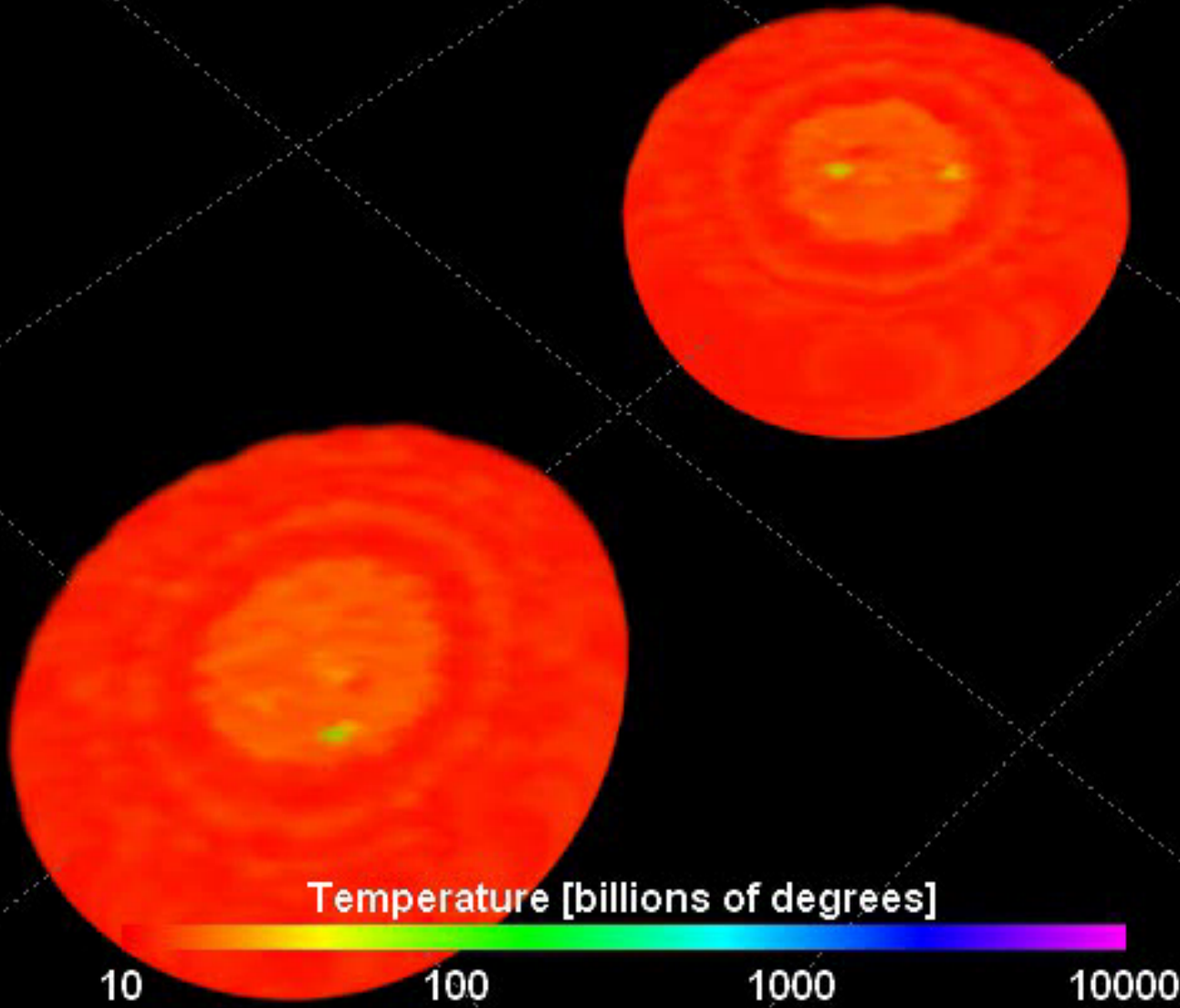
## 2 stages of merger: masspoint and hydrodynamic phase

((Ruffert (1996), Shibata (1992), Rasio (1992))

- first phase: good approximation of the situation by stucturless masspoints distance between NS  $a \gg R$  radius of NS
- second phase : beginns, when size and inner structure of object gets important and tidal forces beginn to deform the NS



At the start of the simulation the two stars (each  $1.4 M_{\odot}$ , but less than 30 km diam.) are less than 10 km apart, and moving at around  $0.2 c$ . As the two stars spiral together they become deformed, and finally touch. As they merge the matter reaches unimaginable temperatures ( $10^{11}$  K). A few percent of the matter is ejected in the form of spiral arms, which cool rapidly. The whole merger process takes only a few ms, and in this short time shines brighter than the rest of the universe put together. The grid in the movies has a spacing of 30 km intervals.



Temperature [billions of degrees]

10 100 1000 10000

The second movie shows a cut-away of the merger, focusing on the two central stars. It shows the formation of two "hot spots" in the merged object (coloured purple) where temperatures reach 10 thousand million degrees.

# Details

# BH formation by accreting matter of NS

- possibilities of accretion: - common-envelope evolution  
- fall-back matter of SN
- Eddington limit of accretion exceeded, high pressure
  - > neutrinos radiate released gravitational energy
  - > Hypercritical mode of accretion (advection dominated),
  - > enormous accretion rates possible
  - > BH formation / gamma-ray burst?
- fate of NS depends on outflows/jets  
outflows/jets low -> BH, otherwise NS  
but mass lost uncertain

# Zero metallicity: Pop III stars

(massive primordial stars)

- lacking metals (  $Z=0$  ), these stars reach their late evolutionary stages without appreciable mass loss
  - Pop III stars of the range of 20 - 130  $M_{\odot}$  might have been the first stars that formed high mass stellar BH in the early universe
- Why?
- recently extrem metal-poor (EMP) star / iron-deficient star  
HE 0170-5240 has been found
  - EMP stars might have formed of the ejecta of supernova of these POP III stars because of the good agreement with the pattern of elemental abundance of the EMP stars with the nucleosynthesis that occurs of the POP III when they become supernova

# Uncertainties in the evolution of binaries and massive stars

- relationship between progenitor mass and remanent mass in binaries uncertain because binary evolution much more complicated:
  - big mass losses from massive progenitors because of wind loss rates during Wolf-Rayet stage (metallicity) but rates are very uncertain at the moment cannot be obtained from basic physics
  - common evolution (Roch lobe overflow, the lack of hydrogen-envelope, different temporal interactions for different starting conditions)
- single stars: BH form above progenitor of 20-25  $M_{\odot}$  but not observable -> no information

# Summary

- stellar-mass black holes can form from supernovae core collapse either directly or by fall-back to the proto-neutron star, depending on different mass limits.
- uncertainties in stellar wind mass loss of the progenitors may change the current results significantly.
- a lot of further research have to be done, to get more precise results

# End

- Web sites NS merger

<http://www.ukaff.ac.uk/movies/nsmerger/>

[http://www.e12.physik.tu-muenchen.de/~teberl/da/da\\_html/node30.html](http://www.e12.physik.tu-muenchen.de/~teberl/da/da_html/node30.html)

- Main papers:

-C.L.Fryer 2002, Black hole Formation from Stellar Collapse

-C.L.Freyer, H.Heger, N.Langer, S.Wellstein , The Limiting Stellar Initial Mass For Blach Hole Formation In Close Binary Systems, The Astrophysicla Journal, 578:335-347, 2002 October 10

-P.Podsiadlowski, K. Nomoto, K. Maeda, T.Nakamura, P.Mazzali, B.Schmidt, Formation Of The Blach Hole in Nova Scorpii, The Astrophysicla Journal, 567, 491-502, 2002 March 1

-H.Umeda & K. Nomoto, First-generation black-hole-forming supernovae and the metal abundance pattern of very iron-poor star, NATURE, Vol 422, 871-872, 24 APRIL 2003