Connection between Gamma-Ray Bursts and Extremely Metal-Poor Stars

Nozomu Tominaga

(Univ. of Tokyo & KITP)

Collaborators:
K. Maeda, H. Umeda,
K. Nomoto, M. Tanaka,
T. Suzuki (U. Tokyo),
N. Iwamoto(JAEA),
P. A. Mazzali(MPA)

ApJ, 657, L77 (2007)

and coming papers

Extremely Metal-Poor stars

Metal-Poor Stars

Mega Metal-Poor (MMP):	$[Fe/H] < -6$
Hyper Metal-Poor (HMP):	$[Fe/H] < -5$
Ultra Metal-Poor (UMP):	$[Fe/H] < -4$
Extremely Metal-Poor (EMP) :	$[Fe/H] < -3$
Very Metal-Poor (VMP):	$[Fe/H] < -2$
Metal Poor (MP) :	$[Fe/H] < -1$
Solar:	$[Fe/H] \sim 0$
Super Metal Rich (SMR):	$[Fe/H] > +0.5$

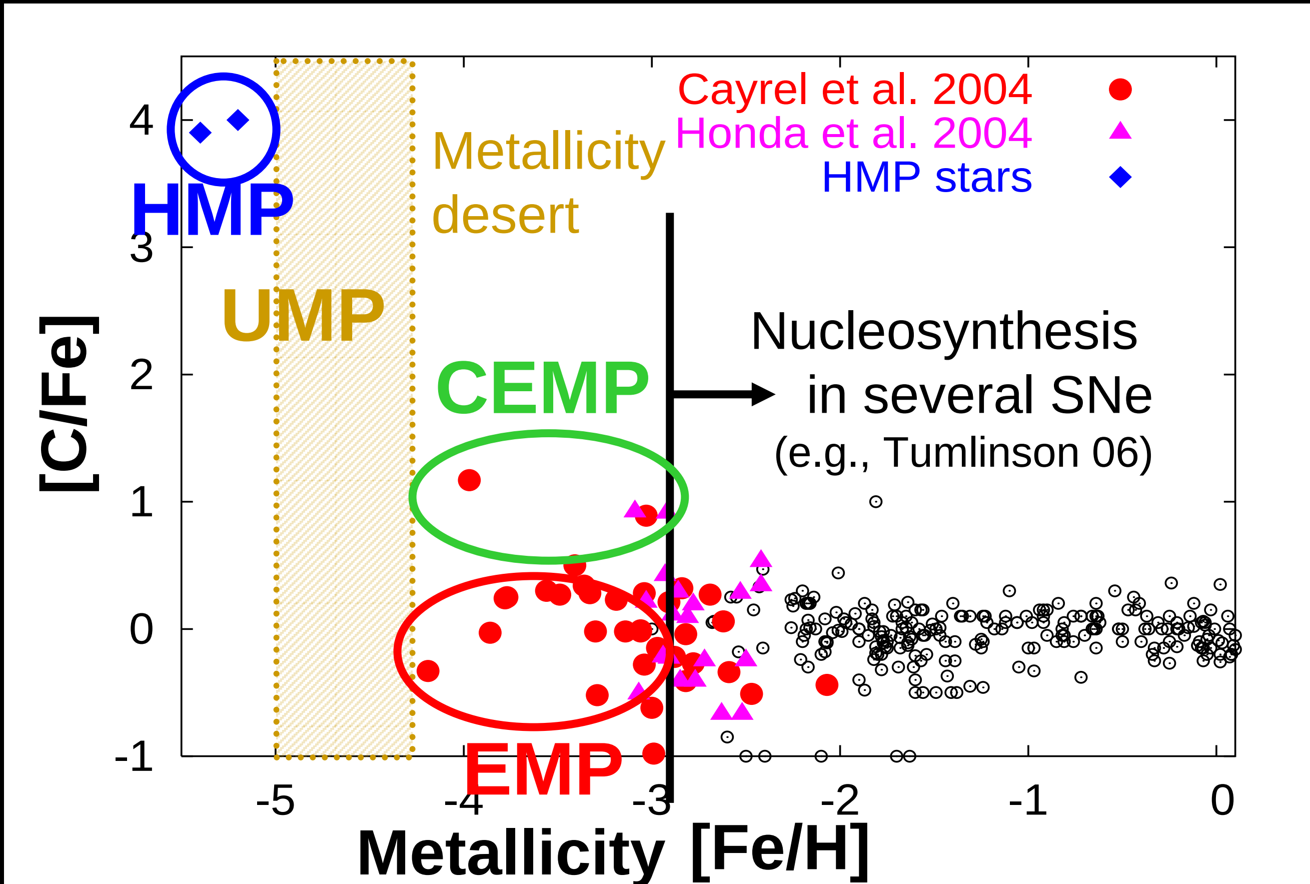
$[Fe/H]=\log(Fe/H)-\log(Fe/H)_{\odot}$

(Beers & Christlieb 05)

[C/Fe] *in Metal-Poor Stars*

EMP stars reflect nucleosynthesis in a single Pop III SN.

Good indicators for SN nucleosynthesis.



[Fe/H] ⇩

[C/Fe] ⇧

Abundance ratios of EMP stars

CEMP stars
(Depagne et al. 02)

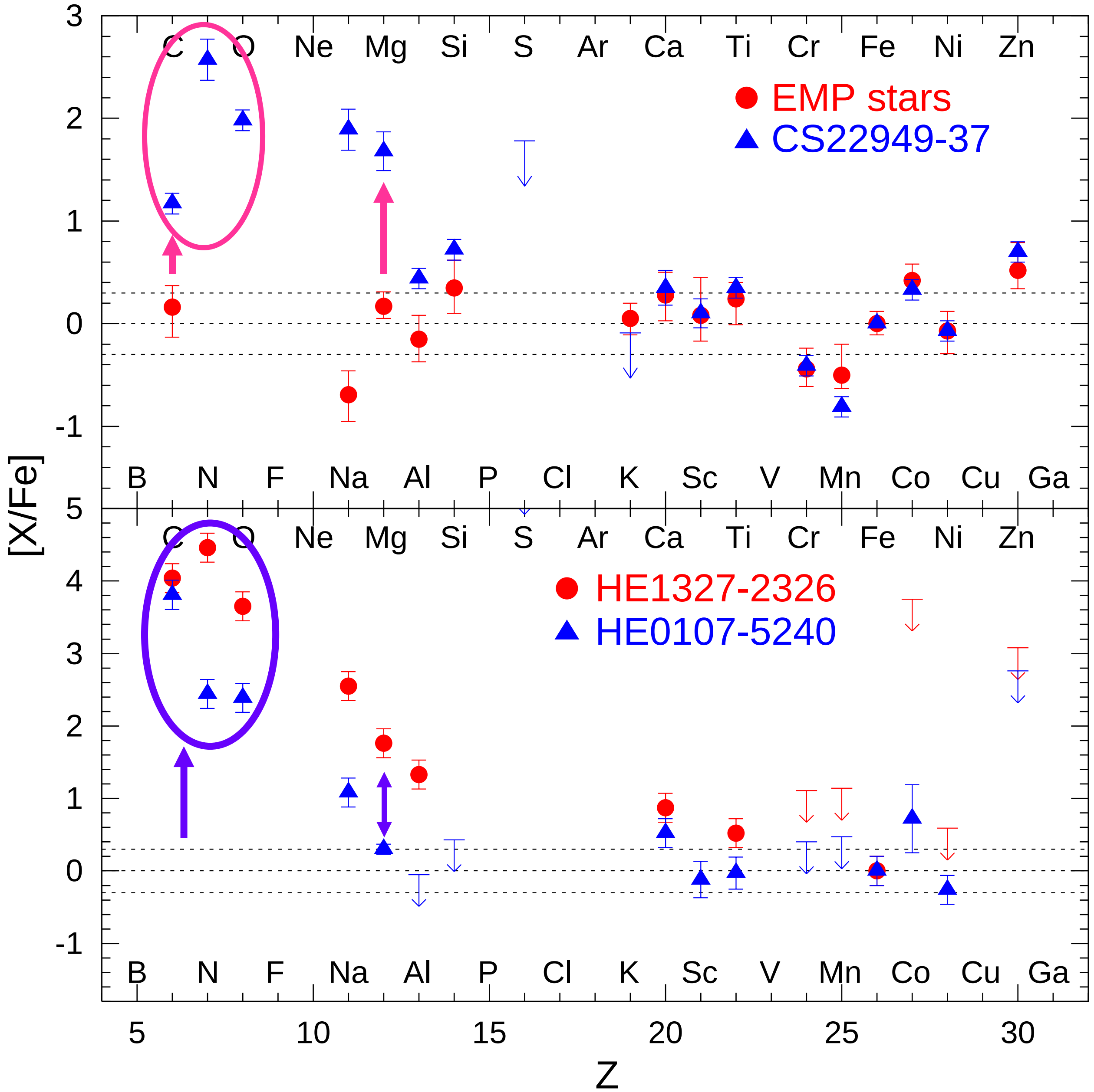
[(C,Mg)/Fe]>1

EMP stars
(Cayrel et al. 04)

[C/Fe]~0

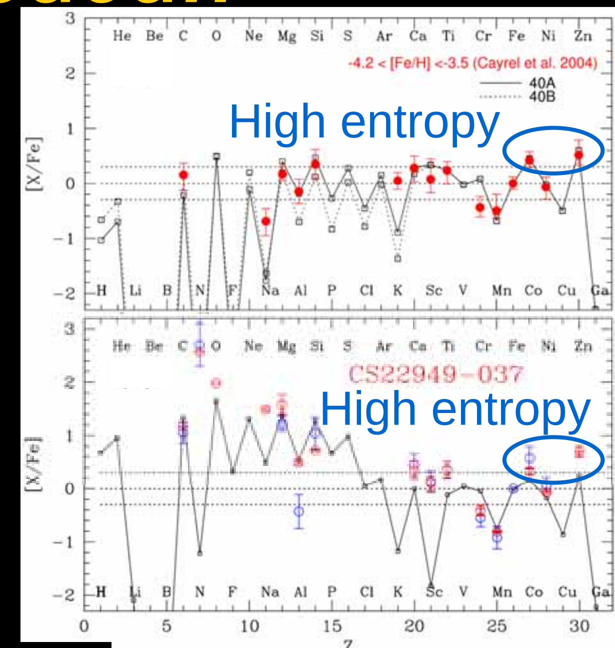
HMP stars
(Christlieb et al. 02)
(Frebel et al. 05)

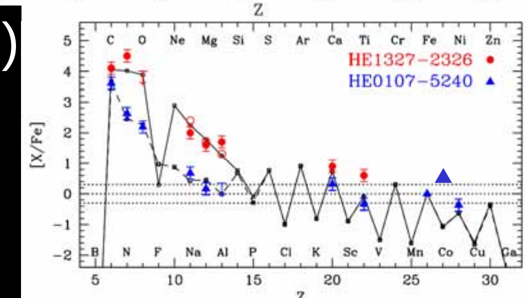
[C/Fe]~4
[Mg/Fe]~0-2



1D models with mixing and fallback succeeded!!

- EMP stars (e.g., NT, Umeda, & Nomoto 07)
  - HNe [M(^{56}Ni)~0.1M$_{\odot}$]
- CEMP stars (e.g., Umeda & Nomoto 05)
  - Faint HNe [M(^{56}Ni)~10^{-3}M$_{\odot}$]
- HMP stars (e.g., Iwamoto, Umeda, NT, et al. 05)
  - Faint SNe [M(^{56}Ni)~10^{-5}M$_{\odot}$]

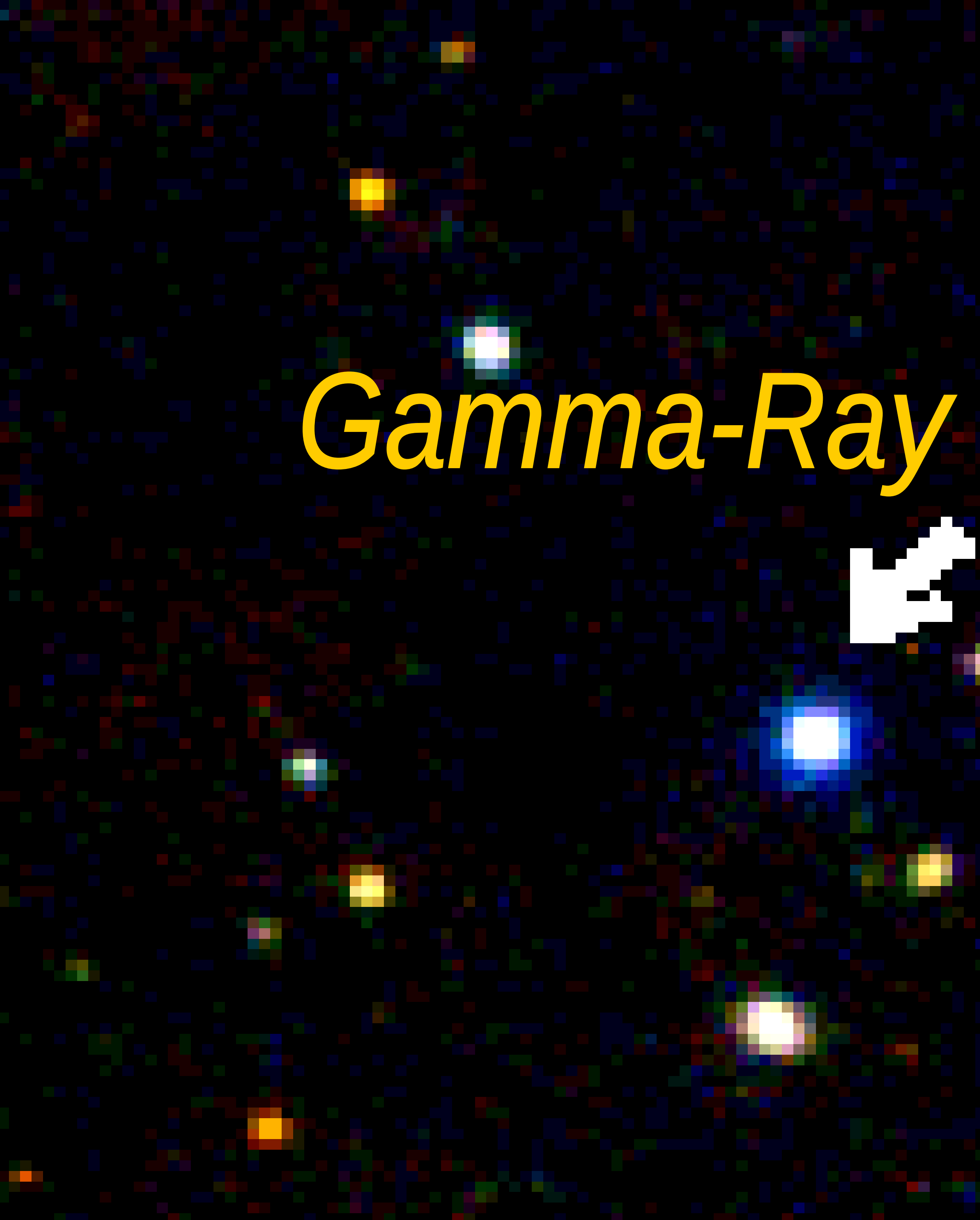


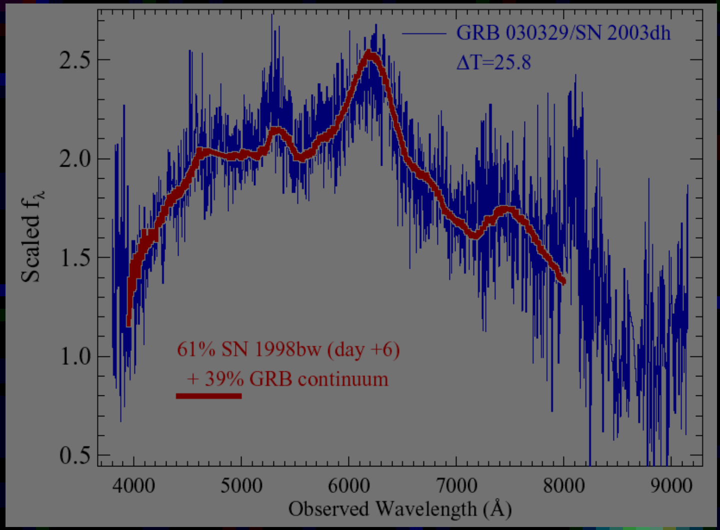


Bessell & Christlieb 05

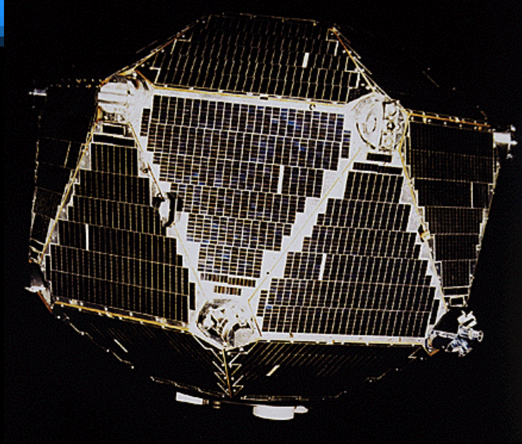
•[Co/Fe] in HE0107-5240
•What causes the differences?

Gamma-Ray Bursts

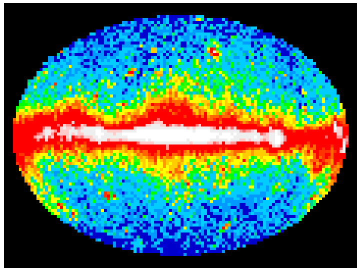


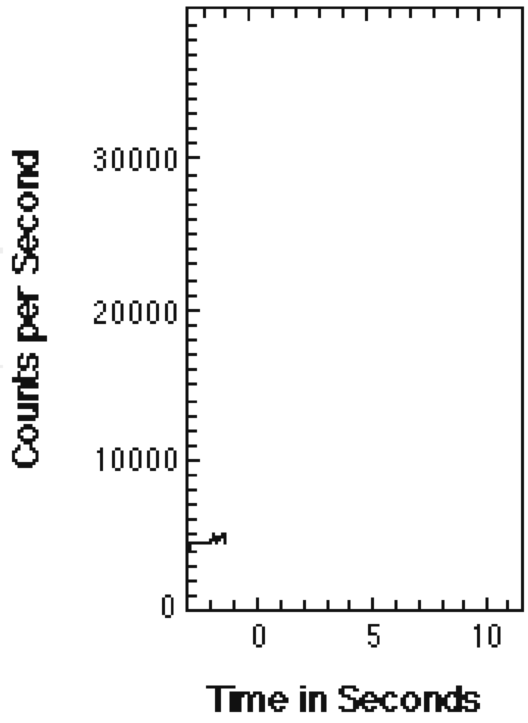


Gamma-Ray Bursts (GRBs)



1960’ Vela Satellite





THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed betw 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less t 0.1 s to ~30 s, and time-integrated flux densities from ~10^{-5} ergs cm^{-2} to ~2×10^{-4} cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directi information eliminates the Earth and Sun as sources.

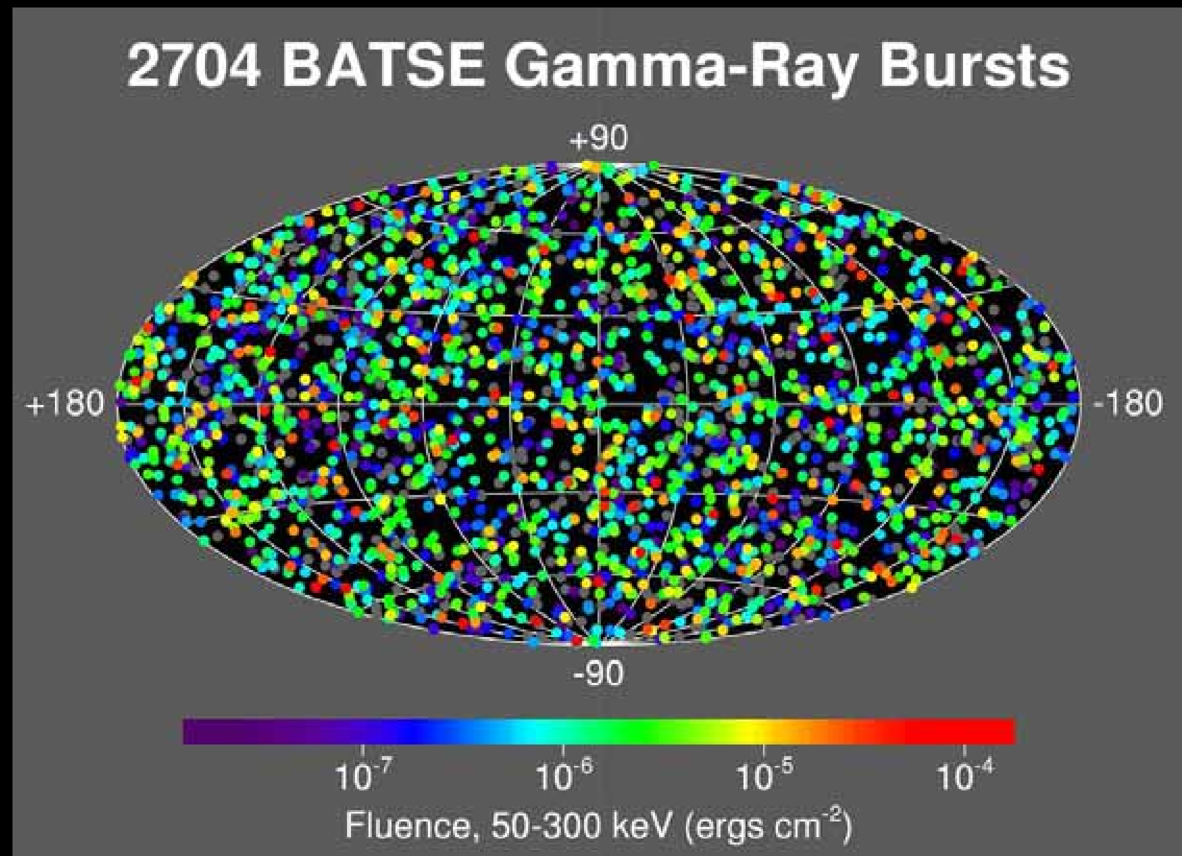
Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

On several occasions in the past we have searched the records of data from ea *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance supernovae. These searches proved uniformly fruitless. Specific predictions of gam ray emission during the initial stages of the development of supernovae have si been made by Colgate (1968). Also, more recent Vela spacecraft are equipped v much improved instrumentation. This encouraged a more general search, not

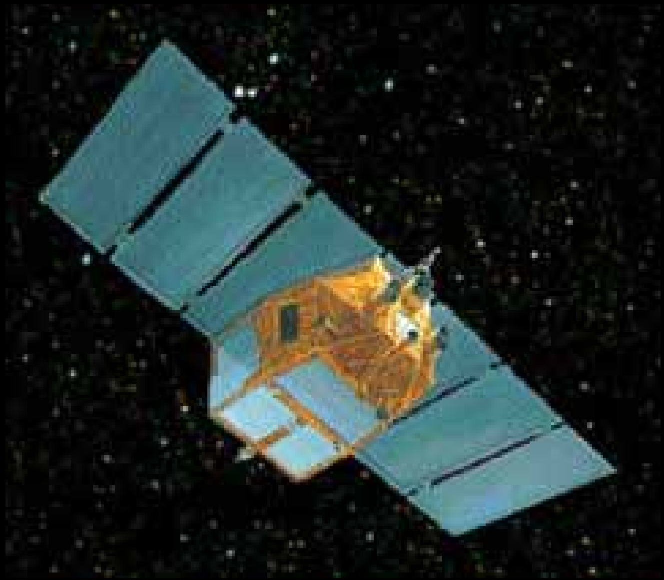
What is GRB ? (1)

CGRO (1991~2000)

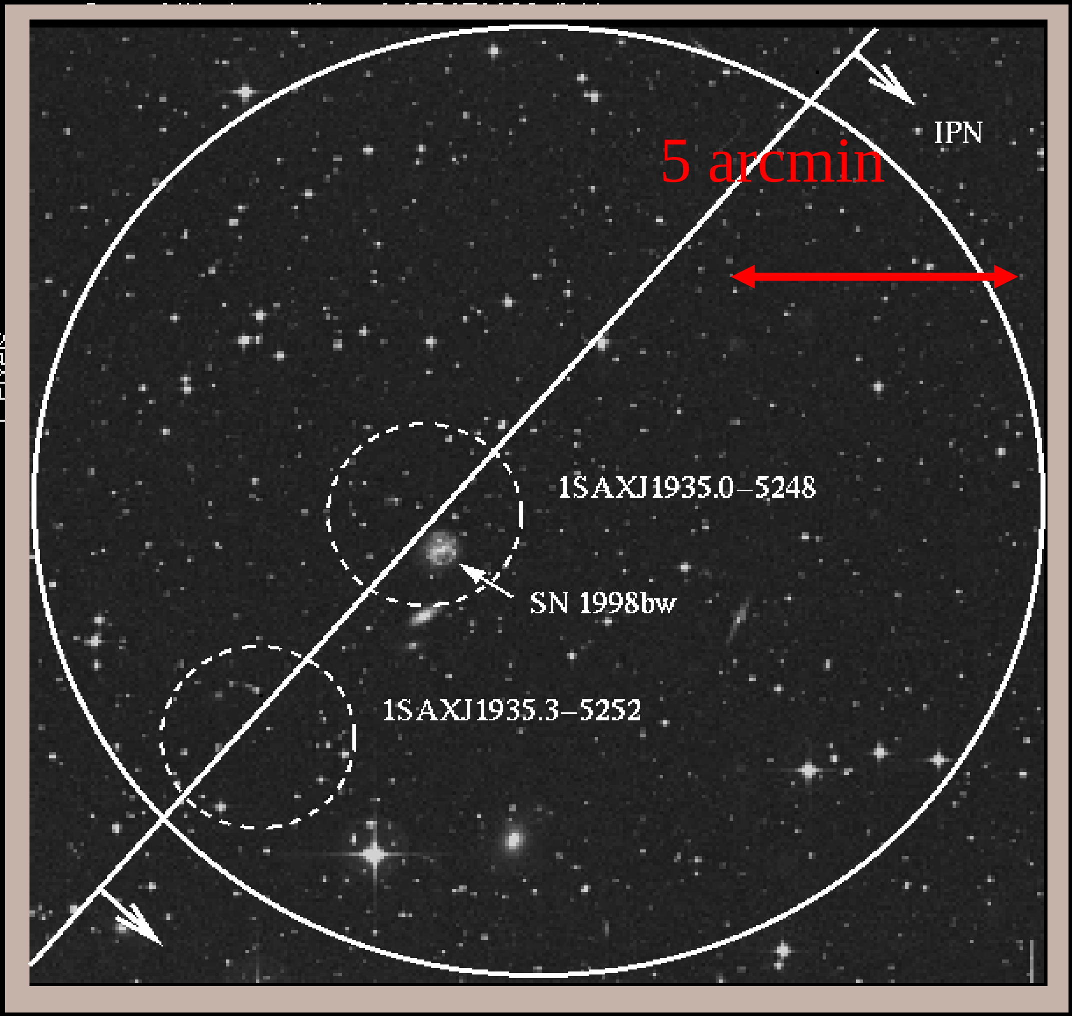


(CGRO BATSE group, 2001)

What is GRB ? (2)

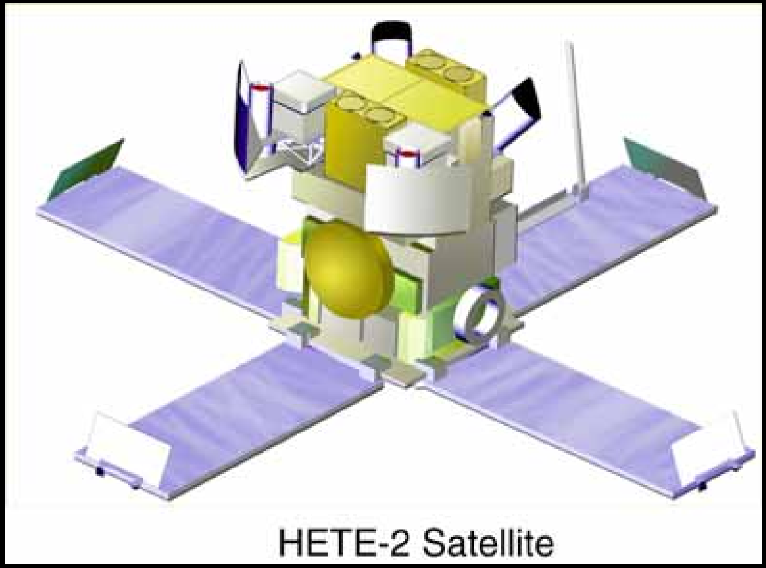


BeppoSAX
(1996~2003)

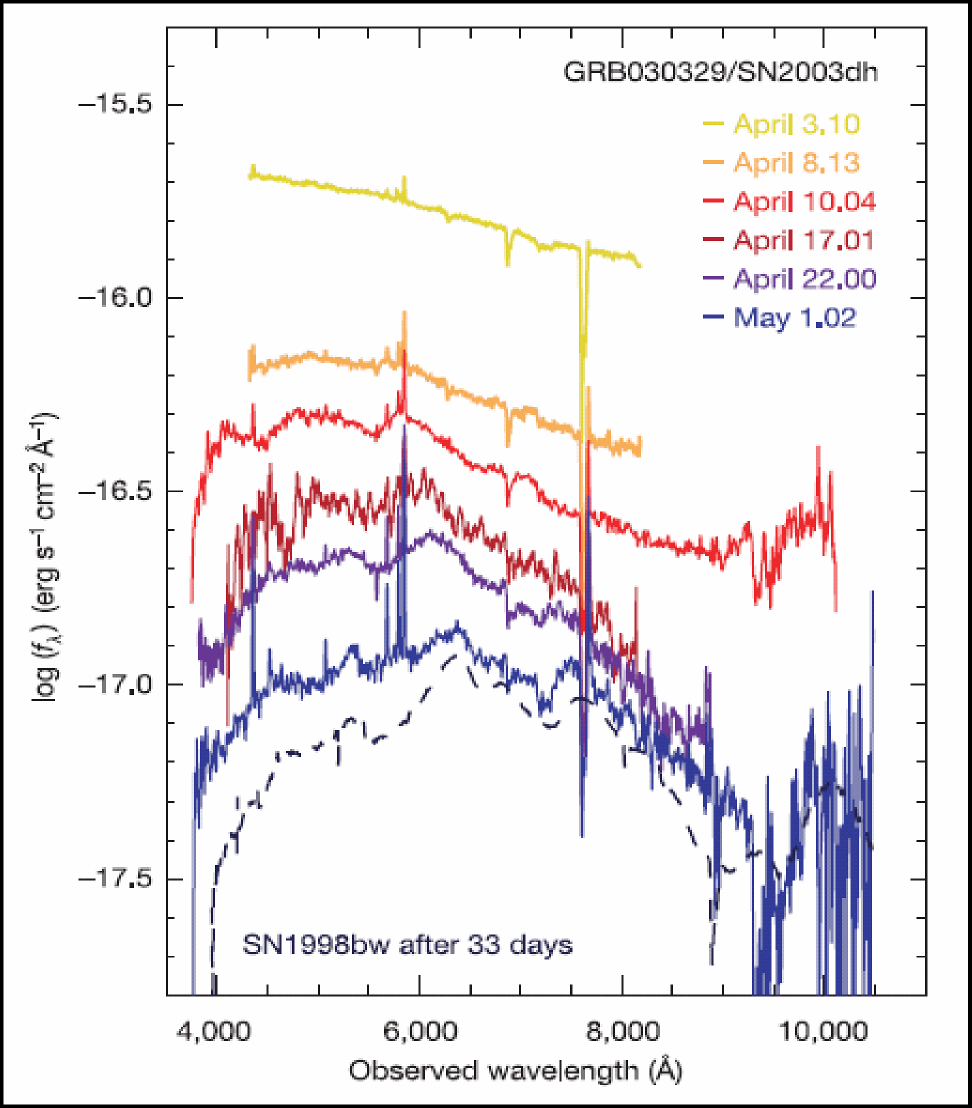


Galama et al. (1998, 1999)

GRB – SN Connection

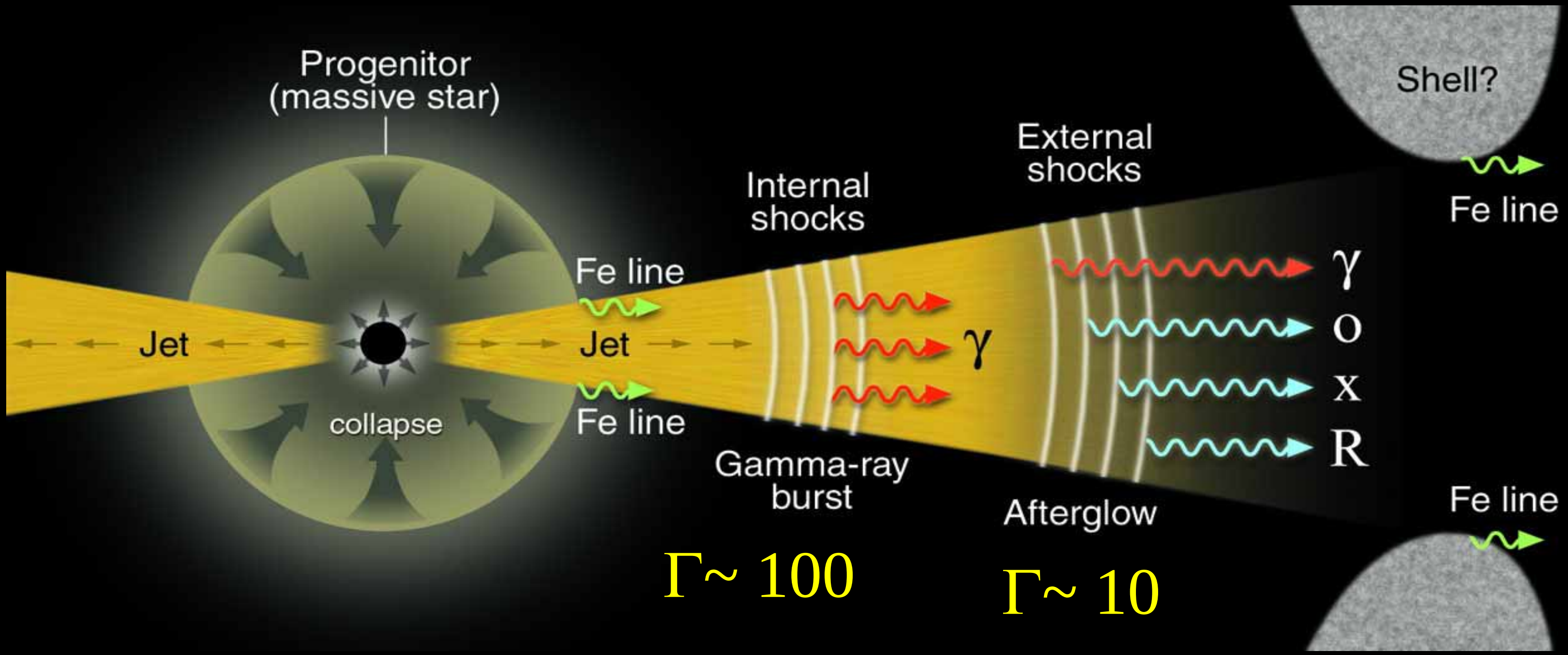


HETE-2 (2000~)



(Hjorth et al. 2003)

Long GRBs with HNe

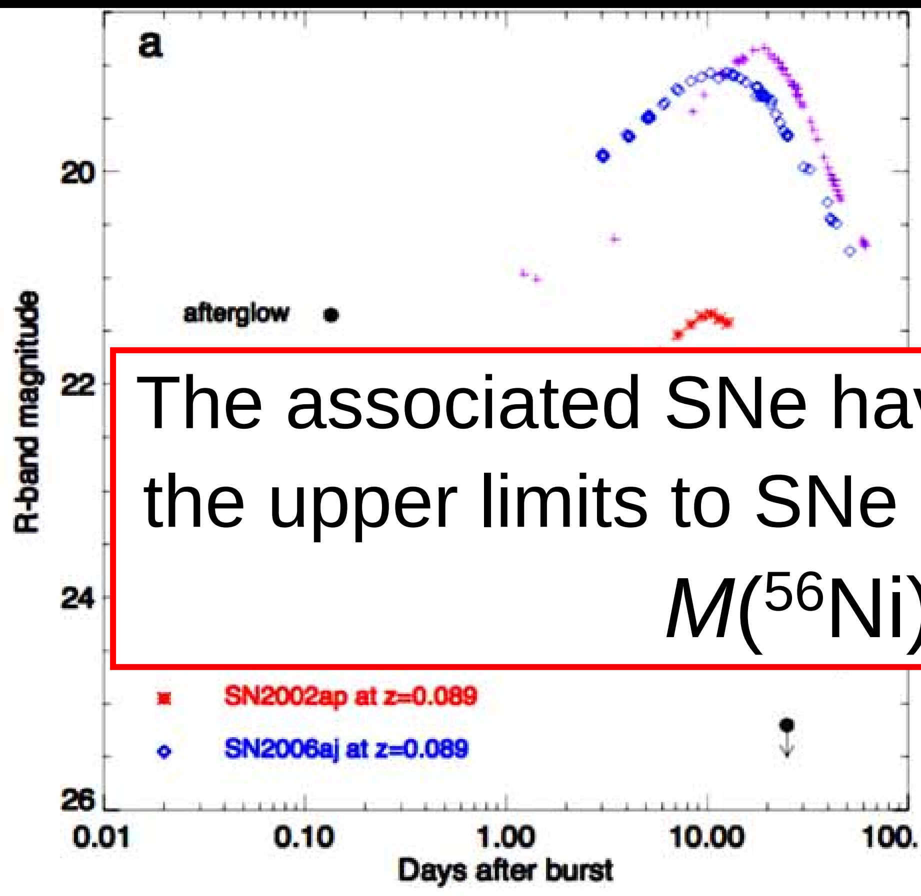


The luminosities are very high.
$M(^{56}\mathrm{Ni}) > 0.3 M_\odot$

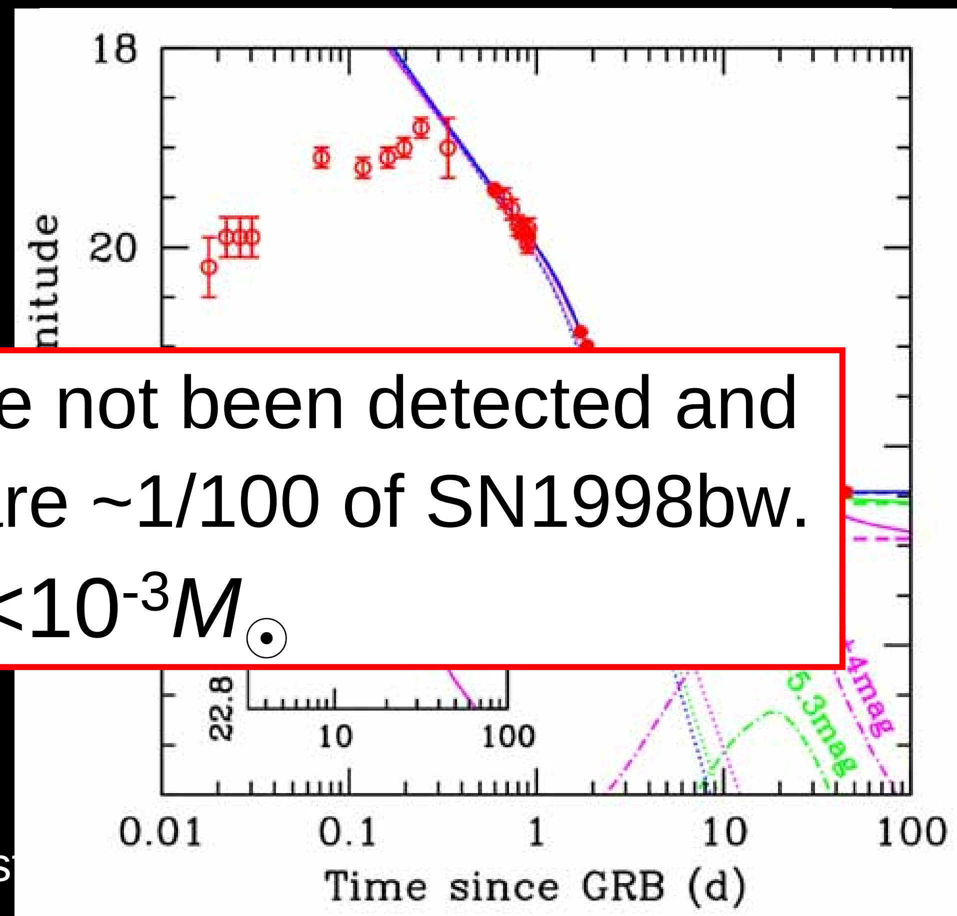
GRB 060505 & GRB 060614

Della Valle et al. 06, Gal-Yam et al. 06, Fynbo et al. 06, Gehrels et al. 06

GRB 060505 at z=0.089



GRB 060614 at z=0.125



The associated SNe have not been detected and the upper limits to SNe are ~1/100 of SN1998bw.

$M(^{56}\mathrm{Ni})<10^{-3}M_{\odot}$

Why the SNe were not detected?

- Chance superposition?
  - Schaefer & Xiao 06, Cobb et al. 06
- Short GRBs with long tails?
  - t_{lag}: Gehrels et al. 06
  - King et al. 07 (WD-BH merger?)
- Long GRBs with faint SNe?
  - NT et al. 07

Long GRBs with faint SNe?

- Faint SNe are Type II SNe.

(Detected by bright plateau.)

  - SN 1994W (Sollerman et al. 98)

    $M(^{56}\mathrm{Ni}) < 2.6 \times 10^{-3} M_\odot$

  - SN 1997D (Turrato et al. 98)

    $10^{-3} M_\odot < M(^{56}\mathrm{Ni}) < 10^{-2} M_\odot$

The explosion energies are small ($E < 10^{51}$ ergs).

Can small $M(^{56}\mathrm{Ni})$ be compatible with the formation of energetic GRBs?

Summary of introduction

- Metal-Poor stars
  - [Co/Fe] in HE0107-5240.
  - What causes the differences among the EMP, CEMP, HMP stars?
- GRBs
  - Are no-SN GRBs the deaths of massive stars as GRB-HNe?

To answer them, relativistic hydrodynamical and nucleosynthesis calculations are required.

Special relativistic hydrodynamics

ρ, v_1, v_2, v_3, e

↓

D, S^1, S^2, S^3, τ

$$\Gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$: Lorentz factor

$$D = \rho\Gamma$$: Density

$$S^i = \rho h \Gamma^2 v^i$$: Momentum density

$$\tau = \rho h \Gamma^2 - p - \rho\Gamma$$: Energy density

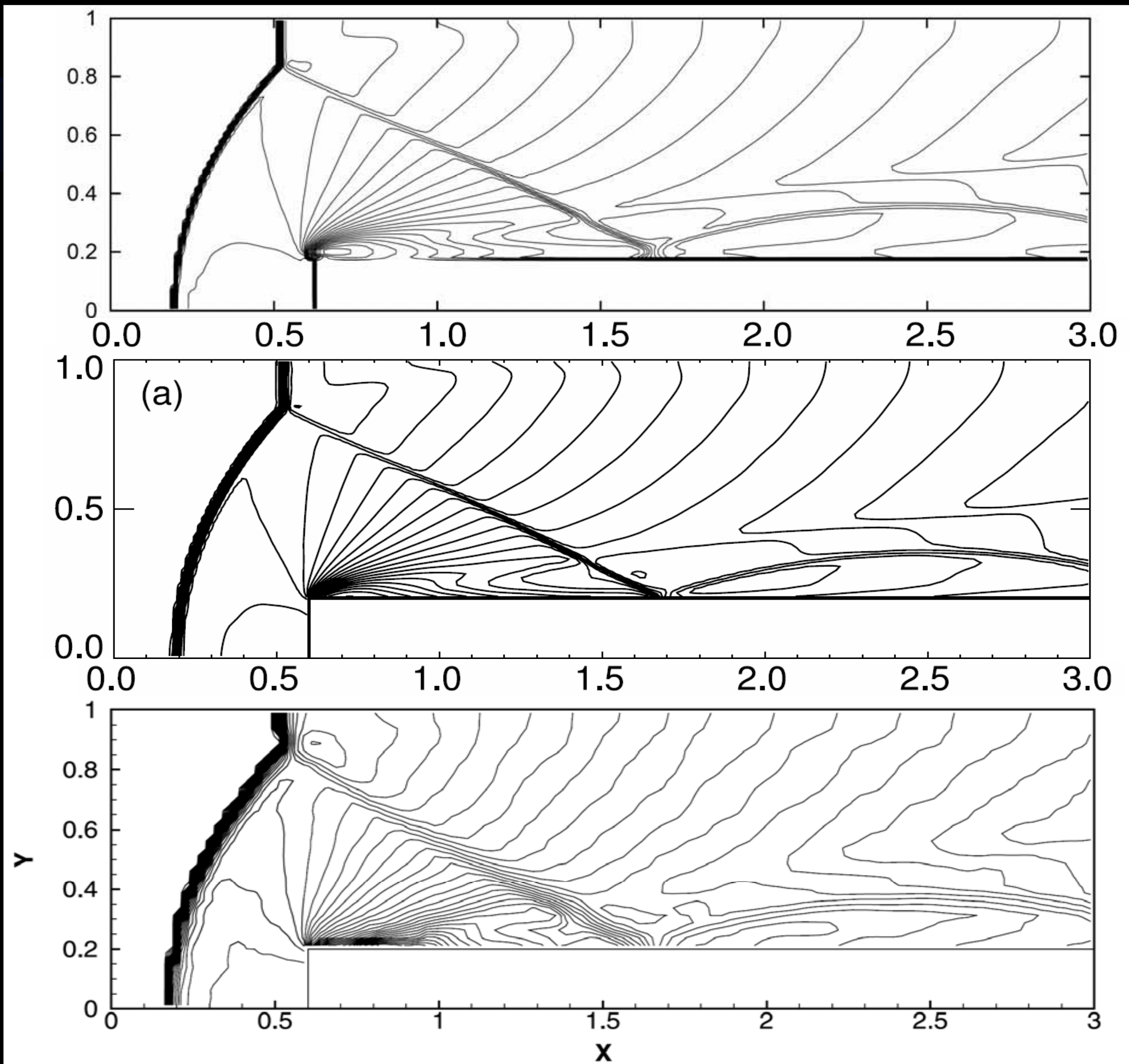
$$\frac{\partial D}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(D v^j\right) = 0$$ Eq. of continuity

$$\frac{\partial S^i}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(S^i v^j + \delta^{ij} p\right) = 0$$ Momentum conservation law

$$\frac{\partial \tau}{\partial t} + \sum_{j=1}^{3} \frac{\partial}{\partial x^j}\left(S^j - D v^j\right) = 0$$ Energy conservation law

Marti & Müller 1994

Code test (Emery step) *Emery 1968*

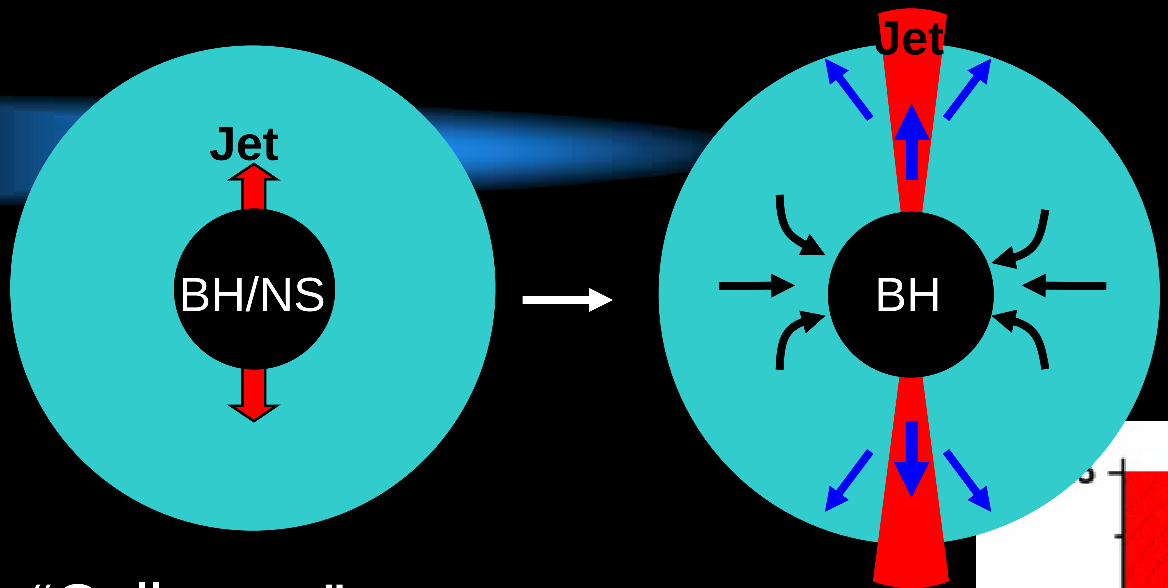


NT et al. 07 in prep.

Zhang & MacFadyen 06

Mizuta et al. 06

Jet-induced explosion



cf. "Collapsar"(e.g., MacFadyen et al. 01)

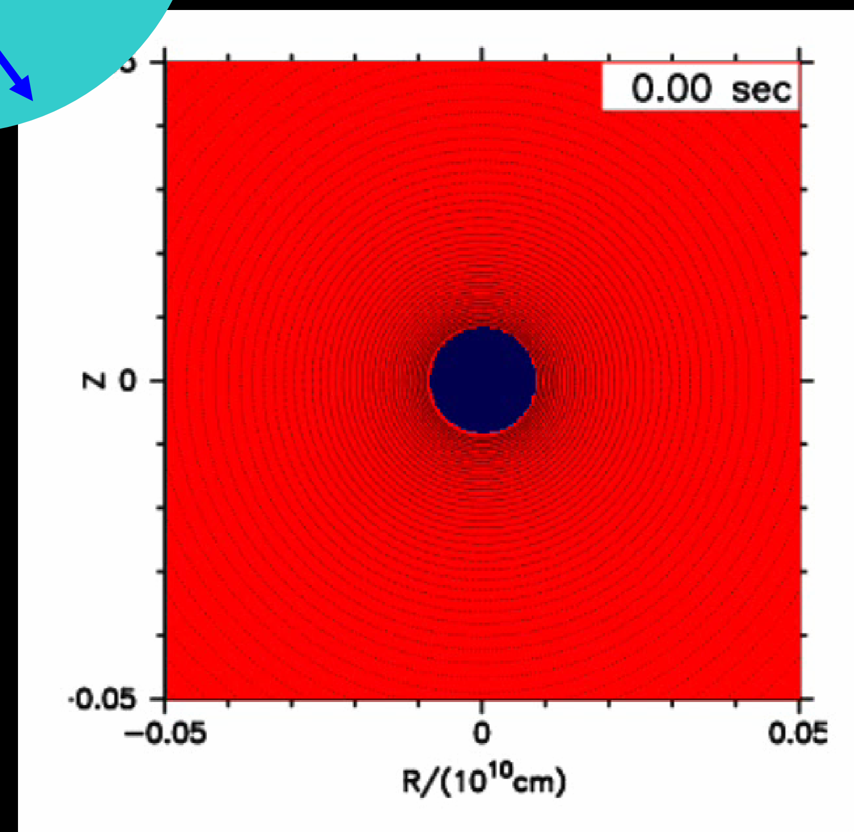
Magnetorotational Supernovae

(e.g., Moiseenko et al. 06)

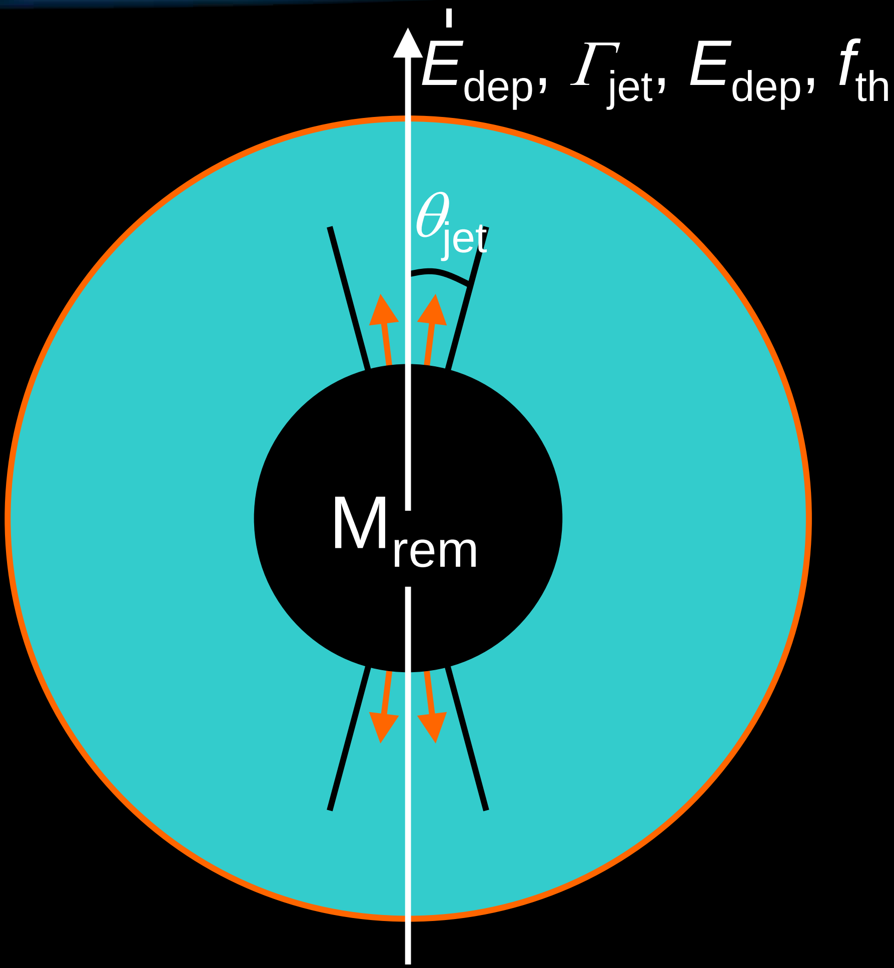
$\dot{E}_{\mathrm{dep}}$:
Energy deposition rate
(Rotation, ***B*** etc.)

Same mass and explosion energy

$40M_{\odot}$ 1.5×10^{52}erg



Jet parameters



$\dot{E}_{dep}$:
Energy deposition rate

Progenitor: Z=0, M_{MS}=40$M_{\odot}$

Total deposited enegy:

E_{dep}=1.5x10^{52}erg

Initial remnant mass:

M_{rem}=1.4$M_{\odot}$

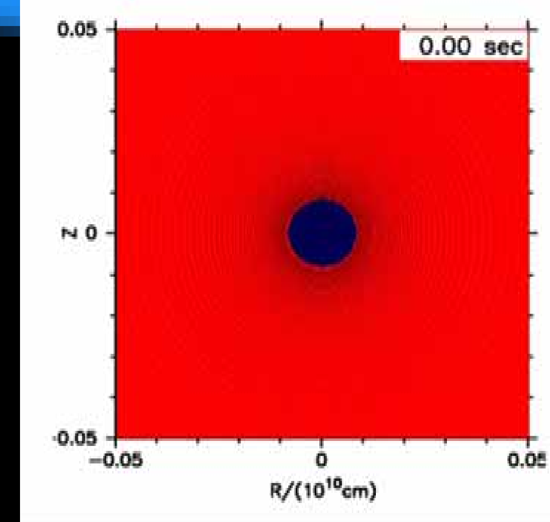
Initial opening angle: θ_{jet}=15^{o}

Initial velocity: Γ_{jet}=100

Ratio of thermal to total deposited energies:

f_{th}=E_{th}/ E_{dep}=10^{-3}

Sites of ^{56}*Ni production*

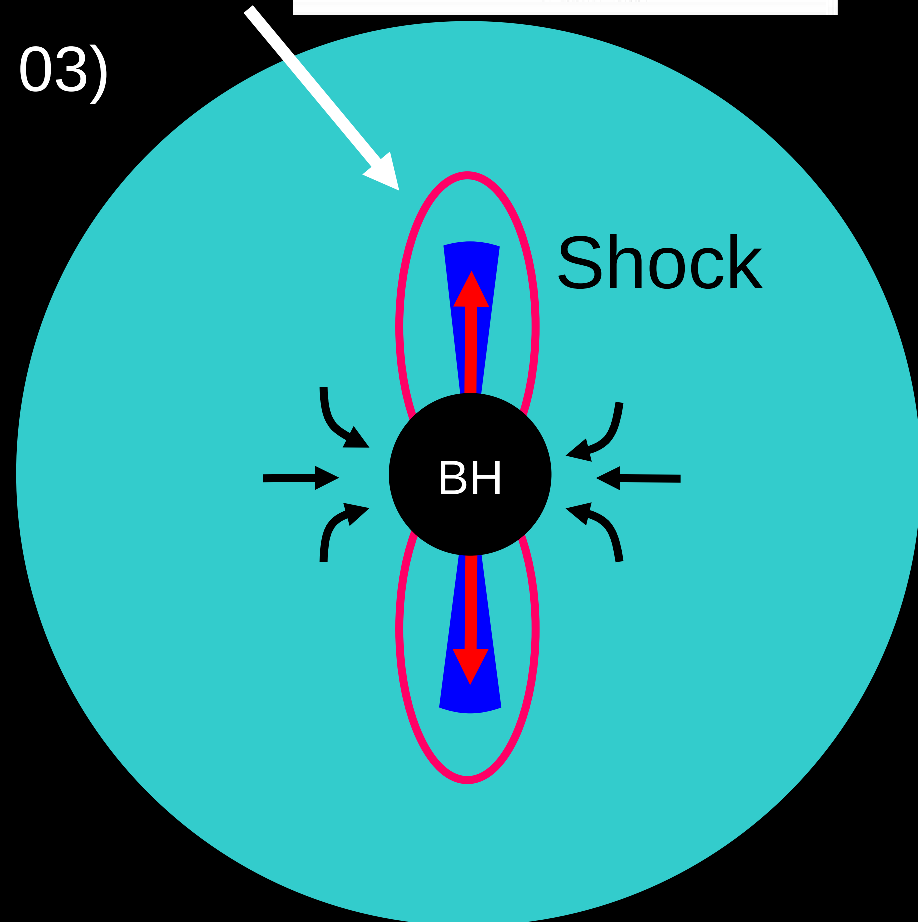


- Explosive nucleosynthesis
  (e.g. Maeda & Nomoto 03)

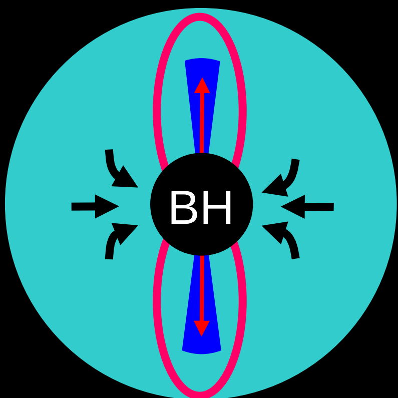
- Jet

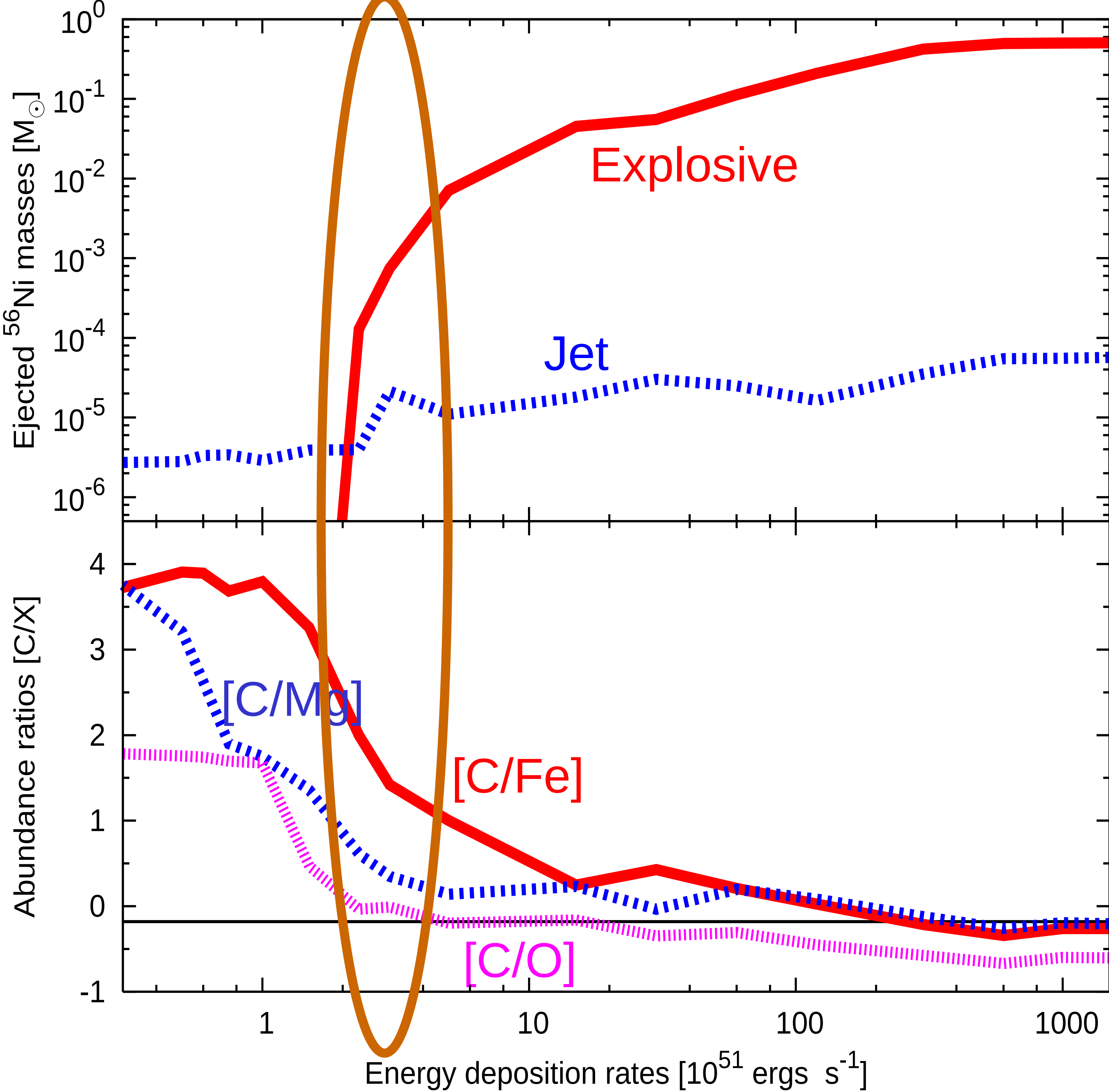
$$M_{jet} \sim E_{dep}/c^2/\Gamma_{max}$$
$$\sim 10^{-4} M_{\odot}$$

(E_{dep} =1.5x10^{52}ergs, Γ_{max}=100)

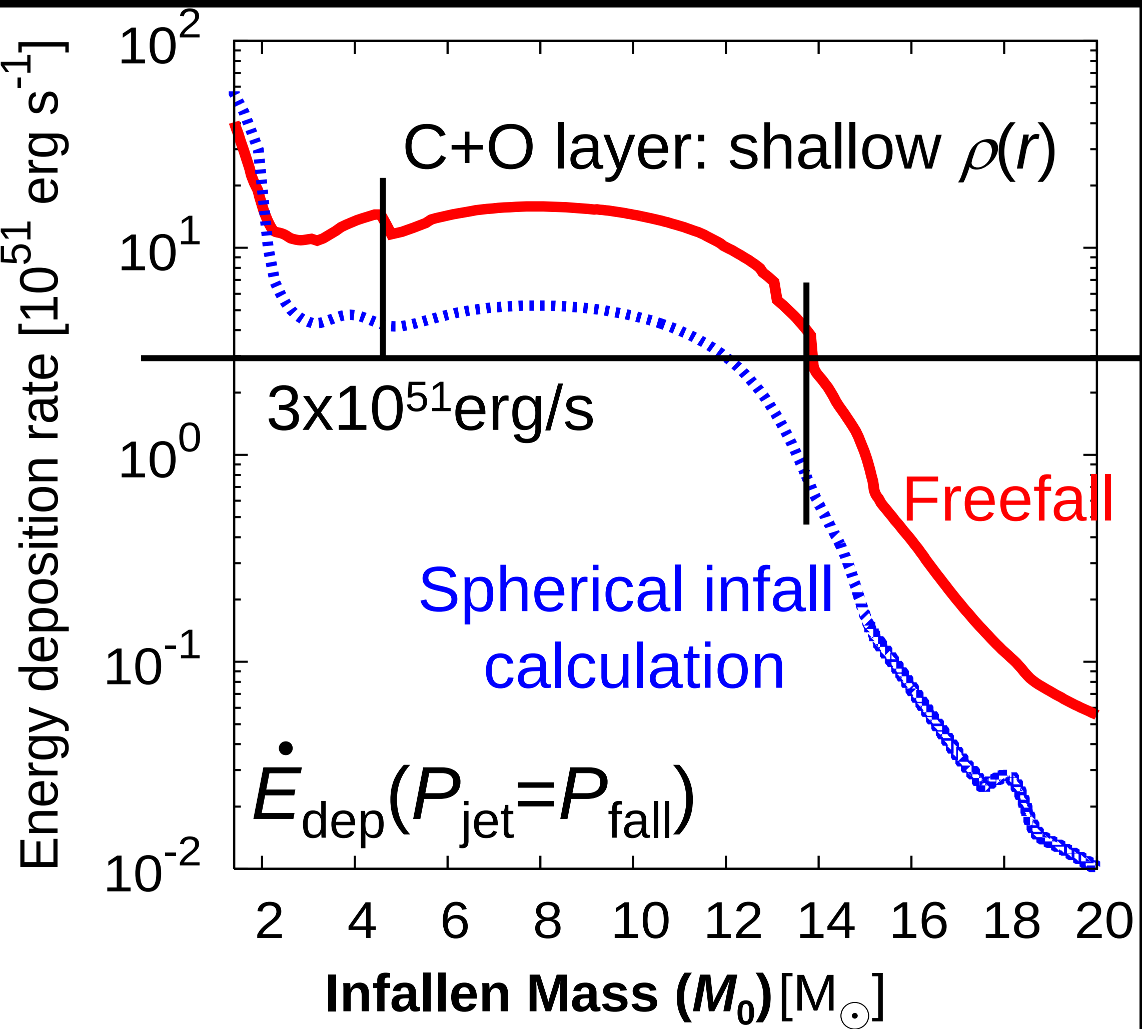


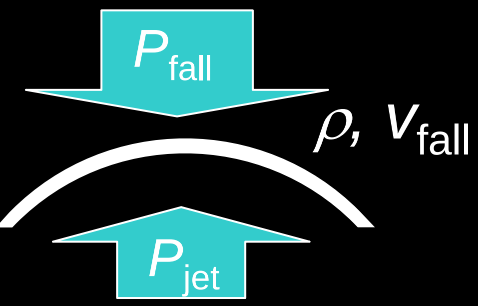
Results


BH


Ejected ^{56}Ni masses [$M_\odot$]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Explosive
Jet
Abundance ratios [C/X]
4
3
2
1
0
-1
[C/Mg]
[C/Fe]
[C/O]
1
10
100
1000
Energy deposition rates [10^{51} ergs s^{-1}]

$\dot{E}_{dep}$: *initiation of the jet injection*





In order to initiate the jet injection,

$$P_{jet} > P_{fall}$$

$$P_{fall} \propto \rho \, v_{fall}^2 \propto \rho_0 \, r_0^{3/2} M_0$$

Freefall

Fryer & Meszaros 03

Maeda & NT 07

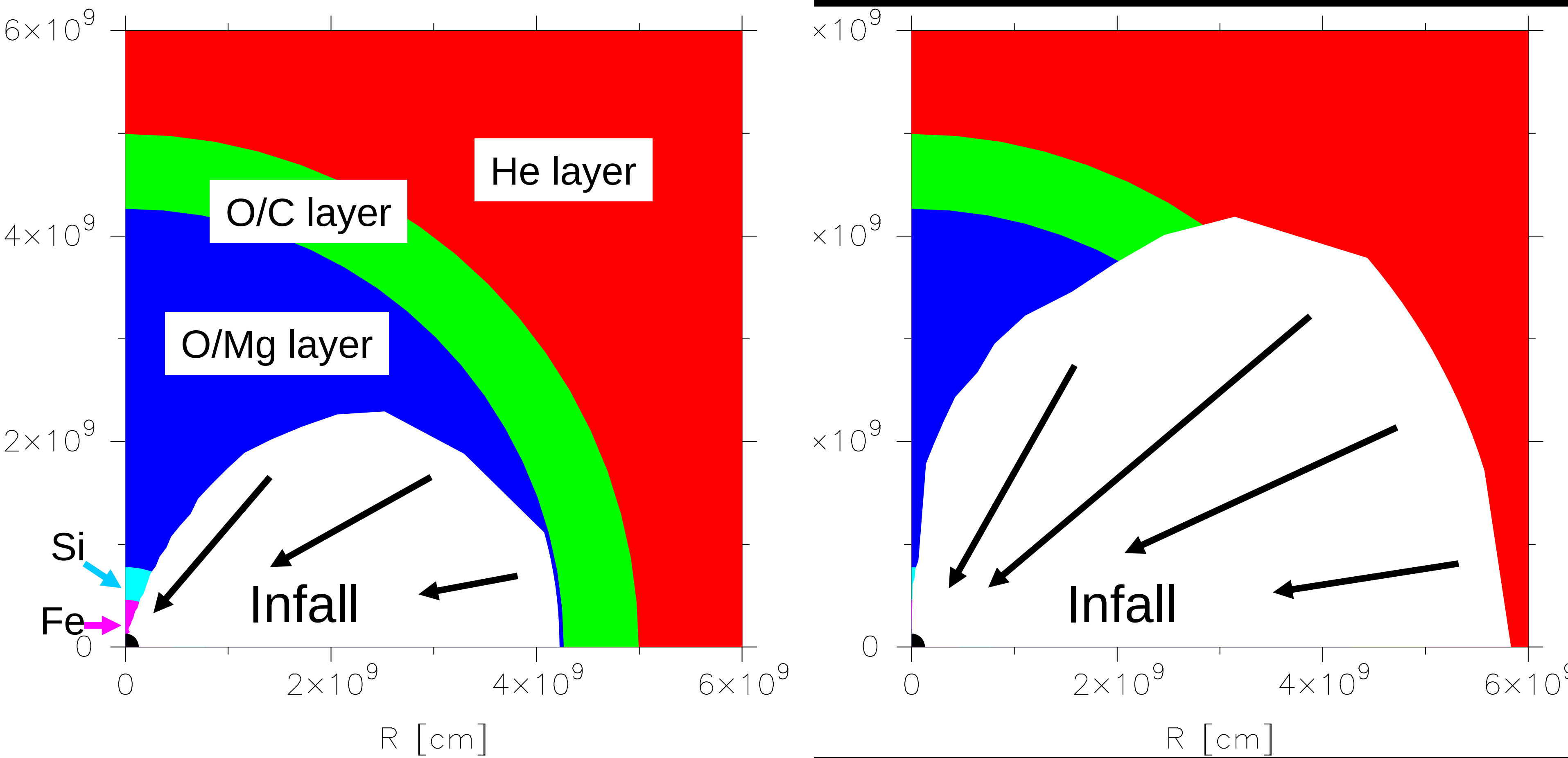
NT et al. 07

Dependence: $\dot{E}_{dep}$

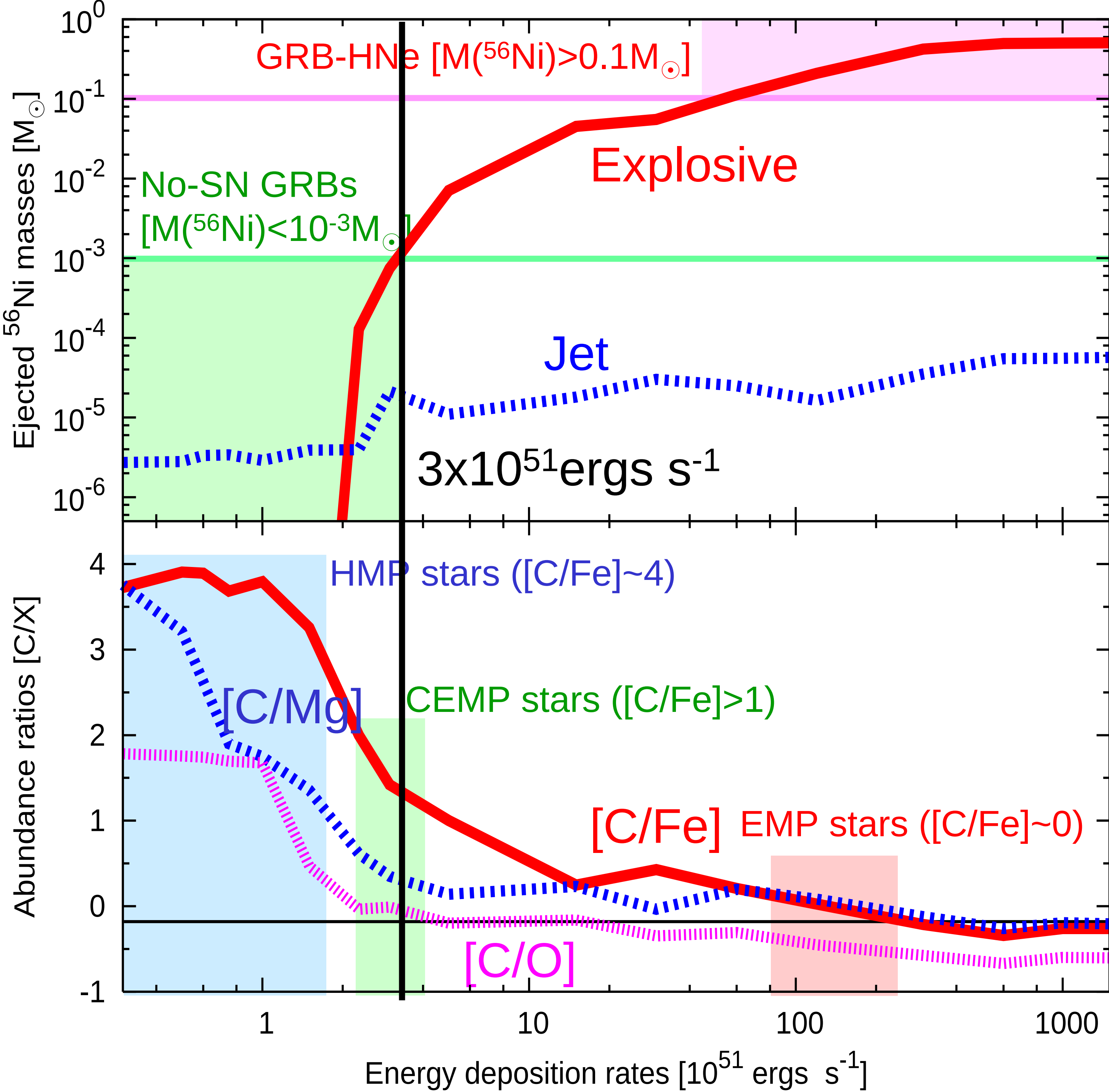
$\dot{E}_{dep}$ ↓ : Infall ↑

$M(^{56}\mathrm{Ni})$ ↓

Smaller $\dot{E}_{dep}$



Results



GRB-HNe [M(56Ni)>0.1M☉]
Explosive
No-SN GRBs
[M(56Ni)<10-3M☉]
Jet
3x10^51ergs s^-1
Ejected 56Ni masses [M☉]
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
HMP stars ([C/Fe]~4)
[C/Mg]
CEMP stars ([C/Fe]>1)
[C/Fe]
EMP stars ([C/Fe]~0)
[C/O]
Abundance ratios [C/X]
4
3
2
1
0
-1
1
10
100
1000
Energy deposition rates [10^51 ergs s^-1]

CEMP stars

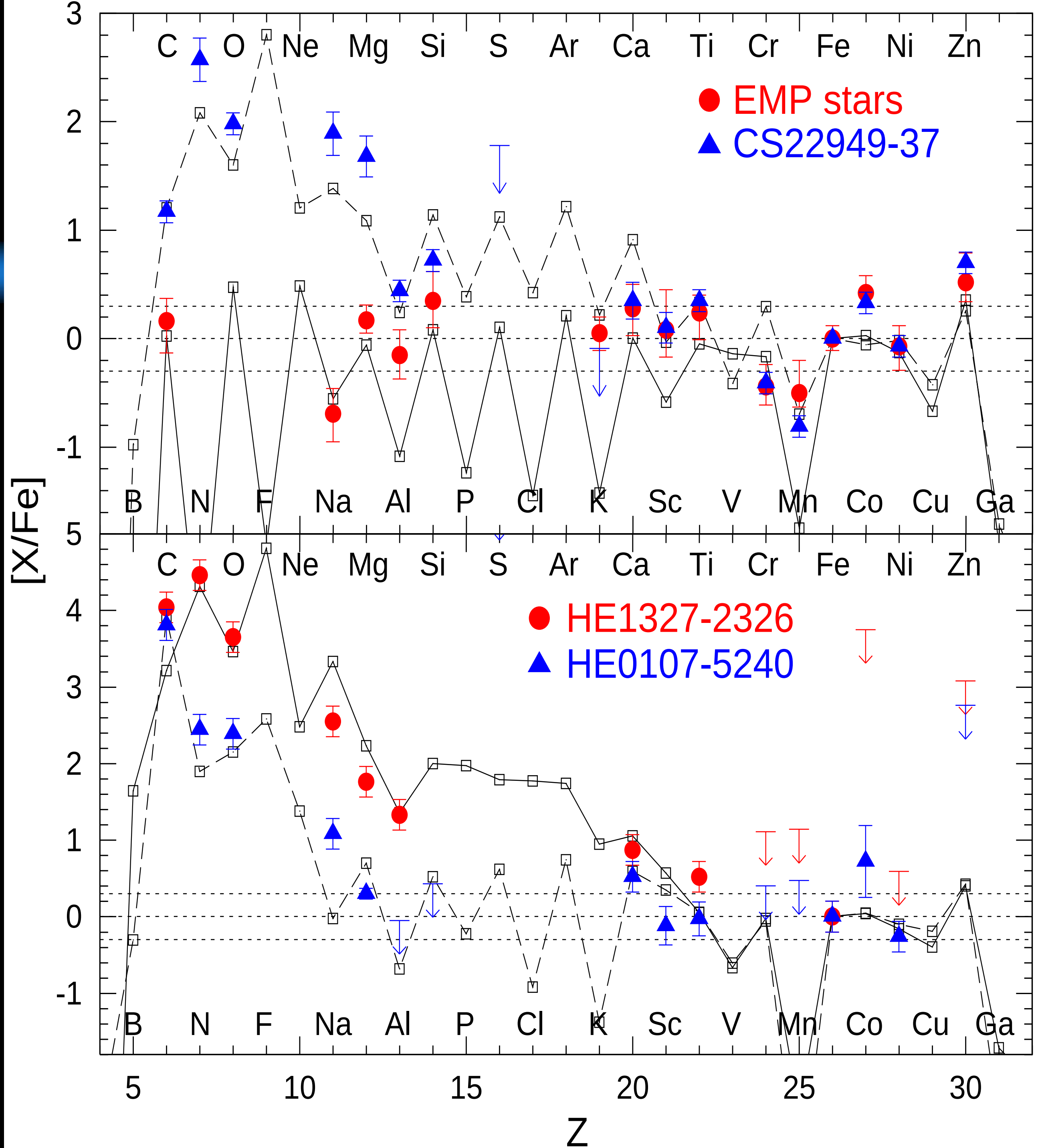
M(^{56}Ni)~8x10^{-4}M$_\odot$

EMP stars

M(^{56}Ni)~0.2M$_\odot$

HMP stars

M(^{56}Ni)~3-4x10^{-6}M$_\odot$

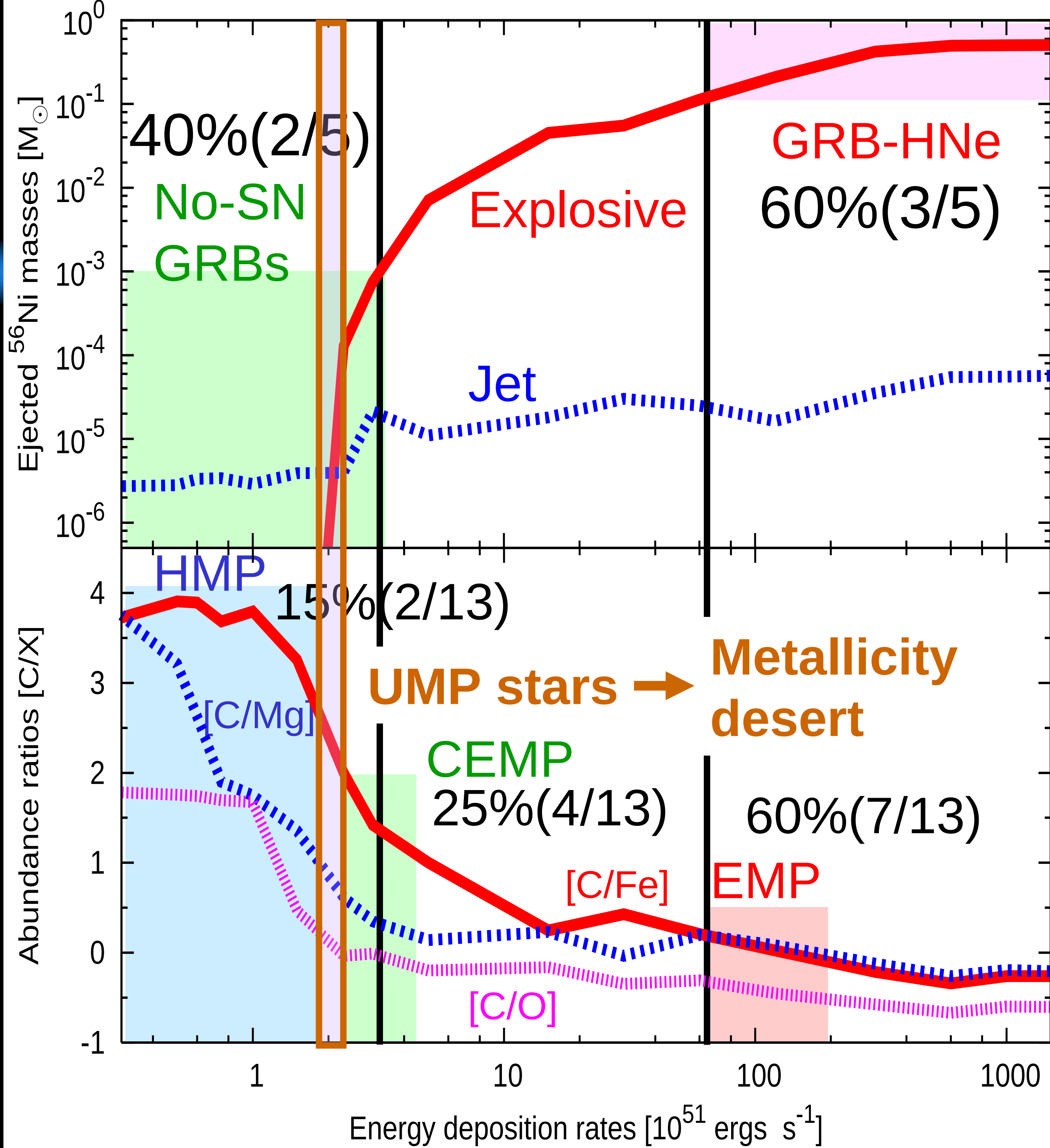


Counts

5 nearby GRBs
- 3 GRB-HNe
- 2 no-SN GRBs
- (excluding XRF060218)

For [Fe/H]<-3.5

13 metal-poor stars
- 7 EMP stars
- 4 CEMP stars
- 2 HMP stars



Summary

BH-forming SNe with relativistic jets

GRBs		**Metal-poor stars**
GRB-HNe	———	EMP stars
No-SN GRBs	———	CEMP stars HMP stars

Larger ↑ $\dot{E}_{\rm dep}$ Smaller

Some of Pop III SNe were induced by relativistic jets as GRB jets.