DECIPHERING THE VIOLENT UNIVERSE

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Ultra-stripped Type Ic supernovae generating double neutron stars

Credit: Nasa/JPL-Caltech

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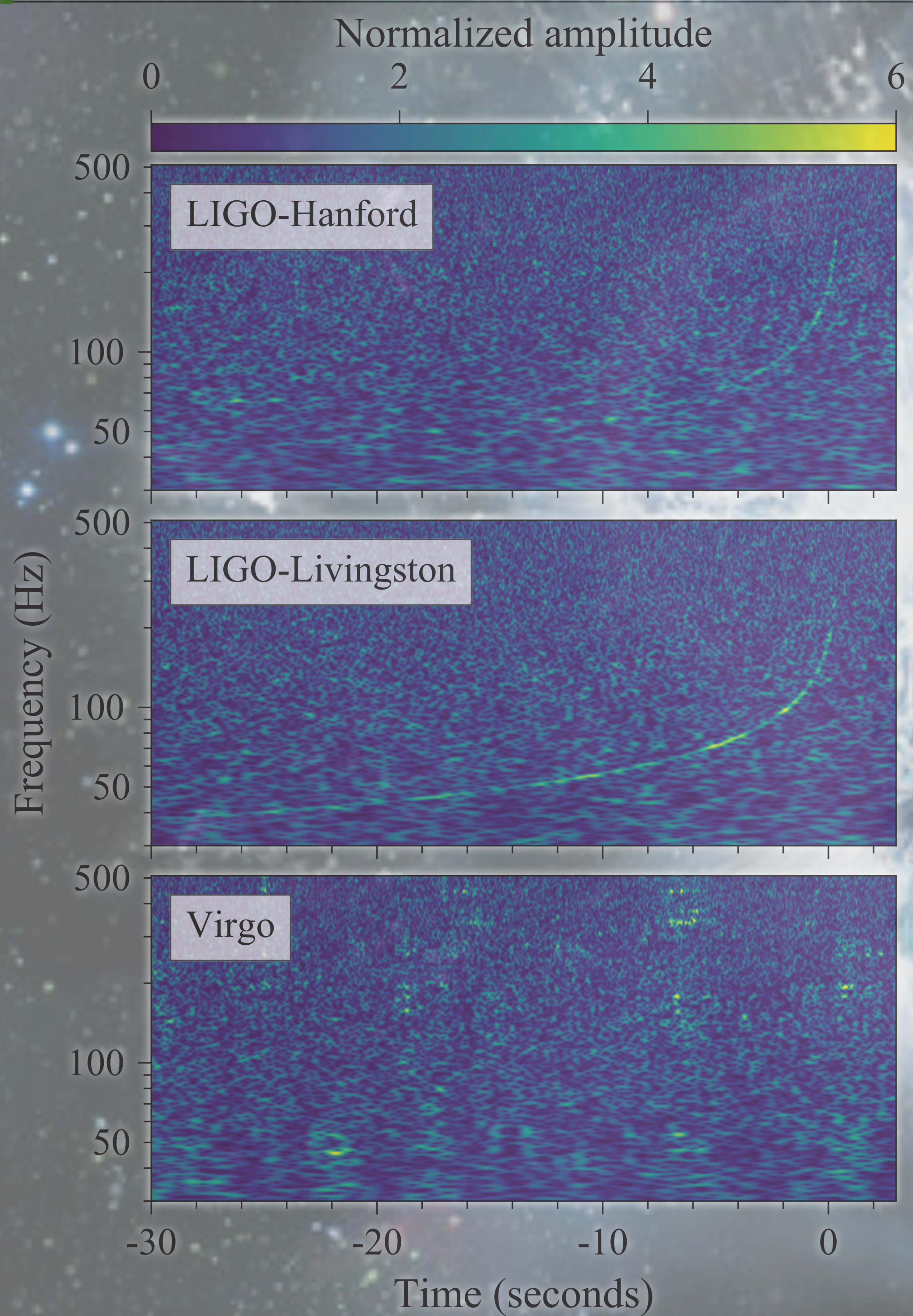
GW170817: Death of neutron stars



LIGO-Virgo, PRL **119**, 161101 (2017)

primary M_{NS}=1.36-1.60$M_\odot$ (low-spin)

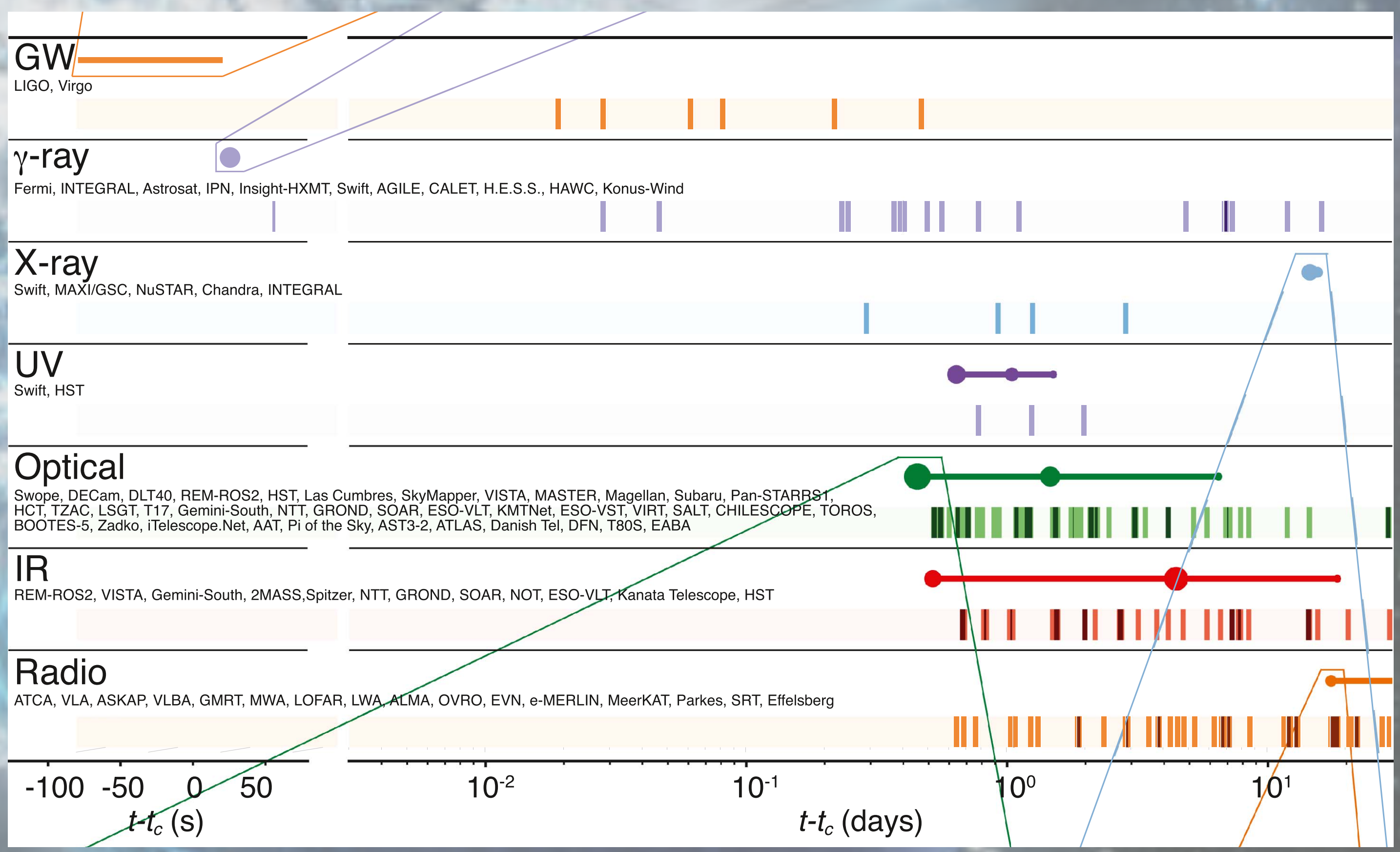
secondary M_{NS}=1.17-1.36$M_\odot$ (low-spin)

Event rate=1540^{+3200}_{-1220} Gpc^{-3} yr^{-1}

(~ 1% of SN rate)

see also many talks on Friday

LIGO-Virgo, ApJL, 848, L12 (2017)



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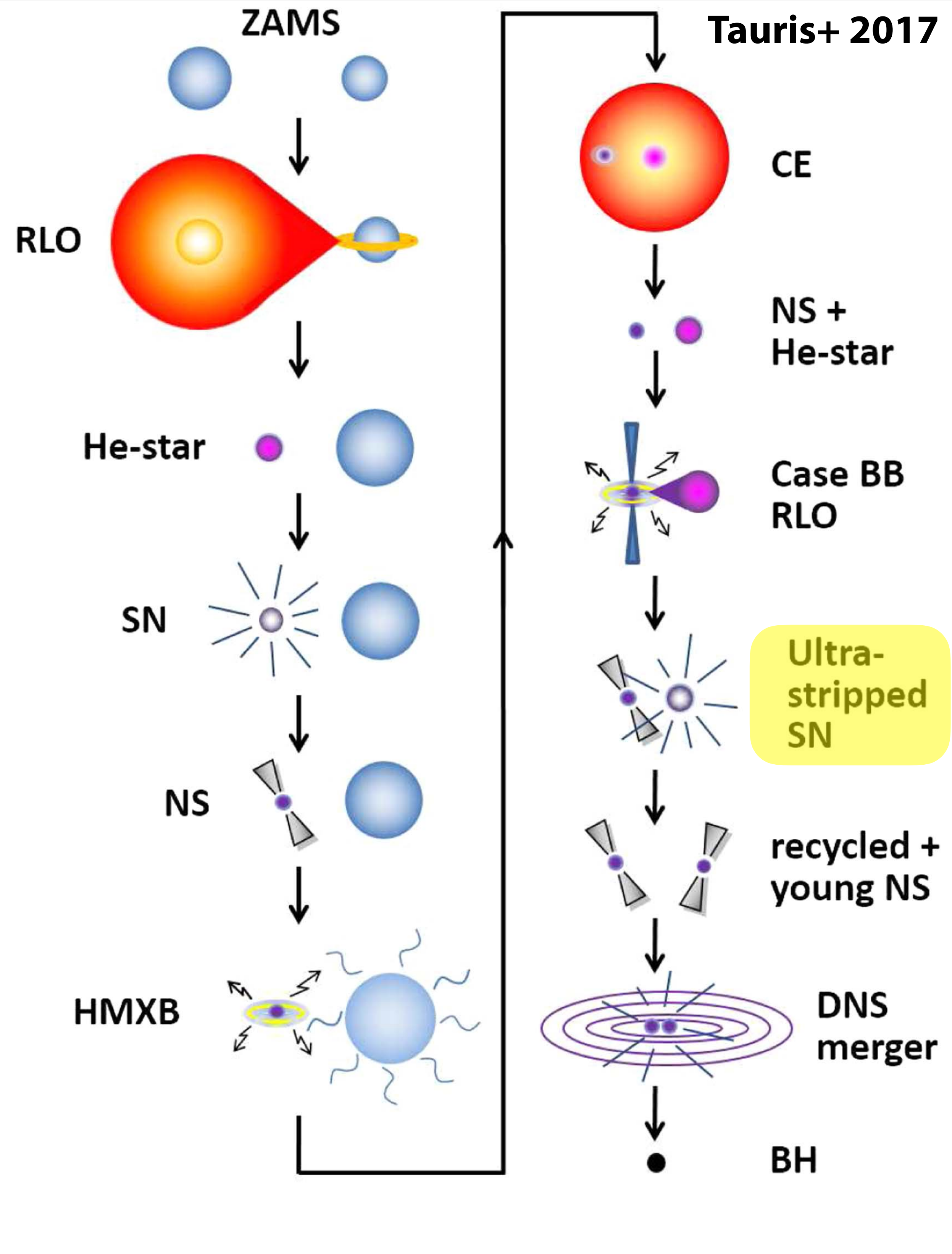
2017 is memorial year for NS

- **0 year from GW170817 observation *(NS death)*** [LIGO-Virgo]
- **30 years from SN1987A observation *(possible NS birth)*** [Kamiokande+]
- **50 years from pulsar discovery *(NS confirmation)*** [Hewish-Bell]
- 43 years from discovery of binary neutron stars [Hulse-Taylor]
- 83 years from theoretical prediction of neutron star [Baade-Zwicky]
- 85 years from discovery of neutron [Chadwick]
- 97 years from theoretical prediction of neutron [Rutherford]

Binary evolutions



- **Until double NSs form,**
- **There are *two* SNe**
  - first one may be usual (type-Ibc or type II)
  - second one explodes after close binary interactions, e.g. common envelope phase (if they are close enough)

- **How does a second SN look like? Is there any difference from normal SNe?**

Ultra-stripped supernovae?

$M_{total} \sim 10 M_\odot$ $M_{CO} \sim 3 M_\odot$

type II SN

$M_{ej} \sim 10 M_\odot$

$M_{total} \sim 5 M_\odot$ $M_{CO} \sim 3 M_\odot$

type Ibc SN

$M_{ej} \sim 3 M_\odot$

$M_{total} \sim M_{CO} \sim 1.5 M_\odot$

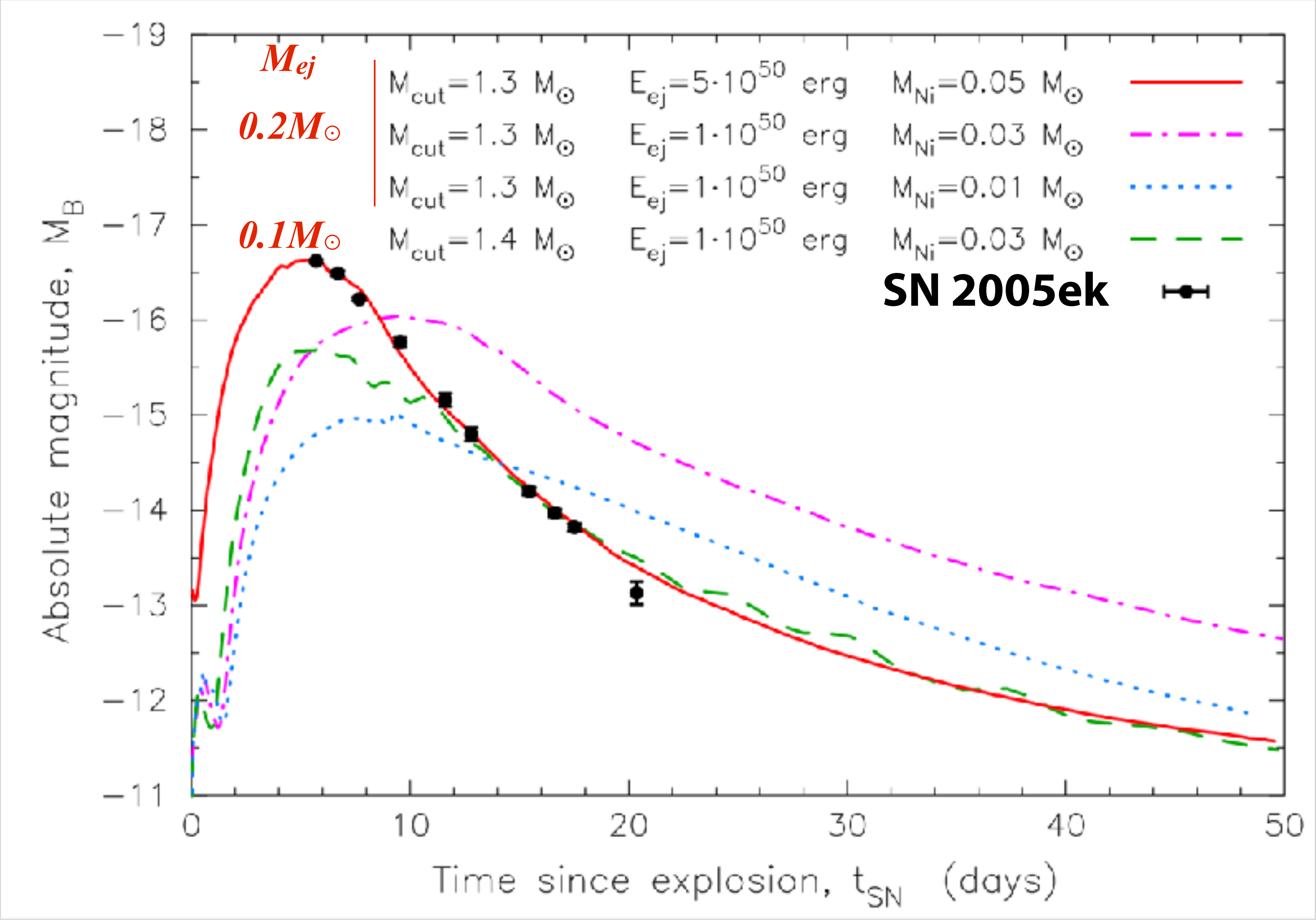
ultra-stripped SN

$M_{ej} \sim 0.1 M_\odot$

see also talks by Fox, Szalai

Small ejecta mass

Tauris+ 2013



see also posters by De, Moriya

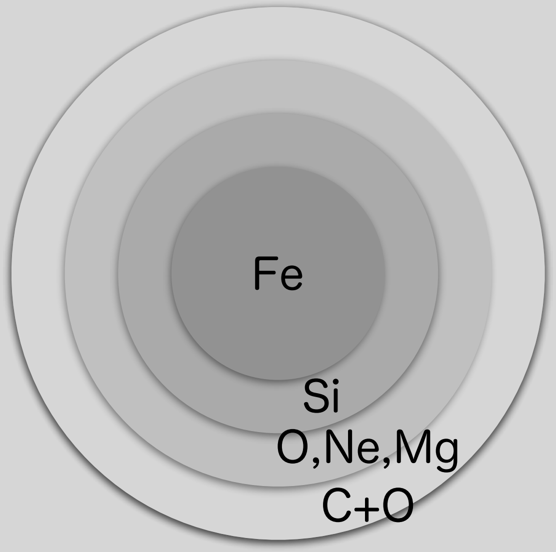
Stellar evolution calculations-1: setups

- **Stellar evolution code for massive stars**

(Umeda, Yoshida, Takahashi 2012; Takahashi, Yoshida, Umeda 2013; Yoshida, Okita, Umeda 2014)

$$\frac{\partial P}{\partial M_r} = -\frac{GM_r}{4\pi r^4} - \frac{1}{4\pi r^4}\frac{\partial^2 r}{\partial t^2},$$
$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho},$$
$$\frac{\partial \ln T}{\partial \ln P} = \min(\nabla_{\rm ad}, \nabla_{\rm rad}),$$
$$\frac{\partial L_r}{\partial M_r} = \epsilon_{\rm nucl} - \epsilon_\nu + \epsilon_{\rm grav}.$$

- **Nucleosynthesis and energy generation**
  - network with ~300 species

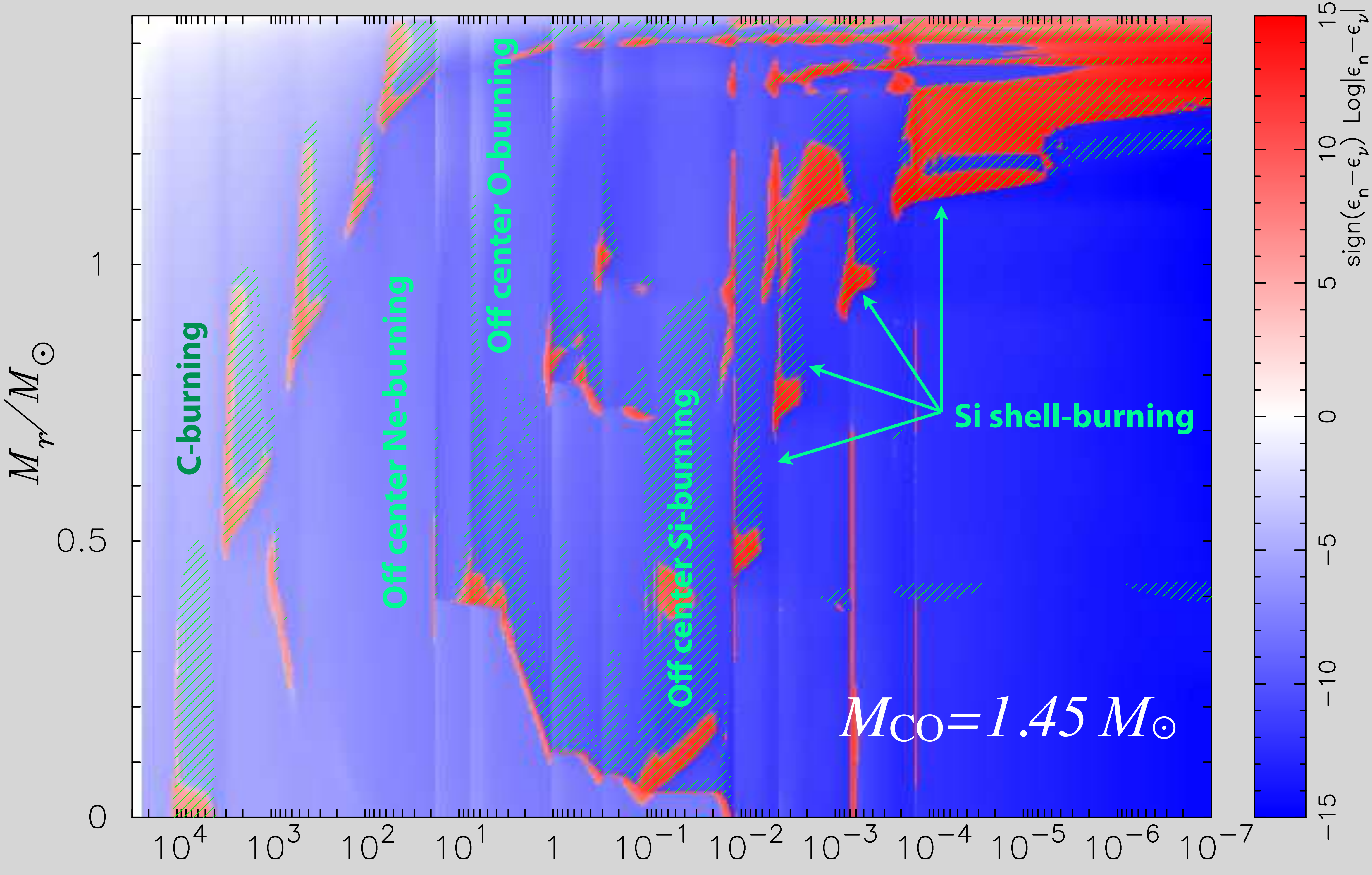


- **Initial condition**
  - bare CO cores (mimicking mass loss)
  - composition: central abundance of massive stars just after He burning
  - $X_{\rm C}({\rm C})$ = 0.33 - 0.36
  - $M_{\rm CO}$=1.45, 1.5, 1.6, 1.8 and 2.0 $M_\odot$

see also talks by Cantiello, Heger

Stellar evolution calculations-2: results

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]



Time before core collapse (year)

Explosion simulations-1: setups

* 2D (axial symmetry) (ZEUS-2D; Stone & Norman 92)

* MPI+OpenMP hybrid parallelized

* Hydrodynamics+spectral neutrino transfer (*neutrino-radiation hydrodynamics*)

See
Suwa et al., PASJ, **62**, L49 (2010)
Suwa et al., ApJ, **738**, 165 (2011)
Suwa et al., ApJ, **764**, 99 (2013)
Suwa, PASJ, **66**, L1 (2014)
Suwa et al., MNRAS, 454, 3073(2015)
Suwa et al., ApJ, **816**, 43 (2016)
for more details

hydrodynamics

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

$$\frac{\partial e^*}{\partial t} + \nabla \cdot [(e^* + P)\mathbf{v}] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_\nu,$$

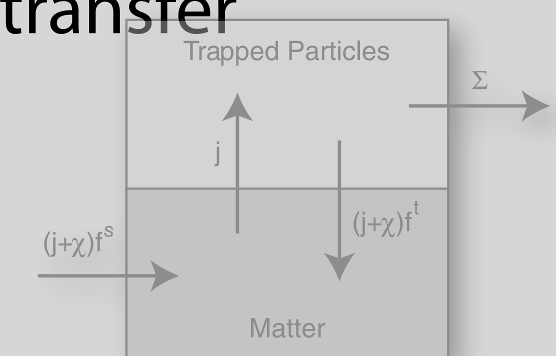
$$\triangle \Phi = 4\pi G \rho,$$

ν transfer

$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right] E \frac{\partial f}{\partial E} = j(1-f) - \chi f + \frac{E^2}{c(hc)^3} \times \left[(1-f)\int R f' d\mu' - f \int R (1-f') d\mu'\right].$$

* Isotropic diffusion source approximation (*IDSA*) for neutrino transfer (Liebendörfer+ 09)

* ***Ray-by-ray plus*** approximation for multi-D transfer (Buras+ 06)

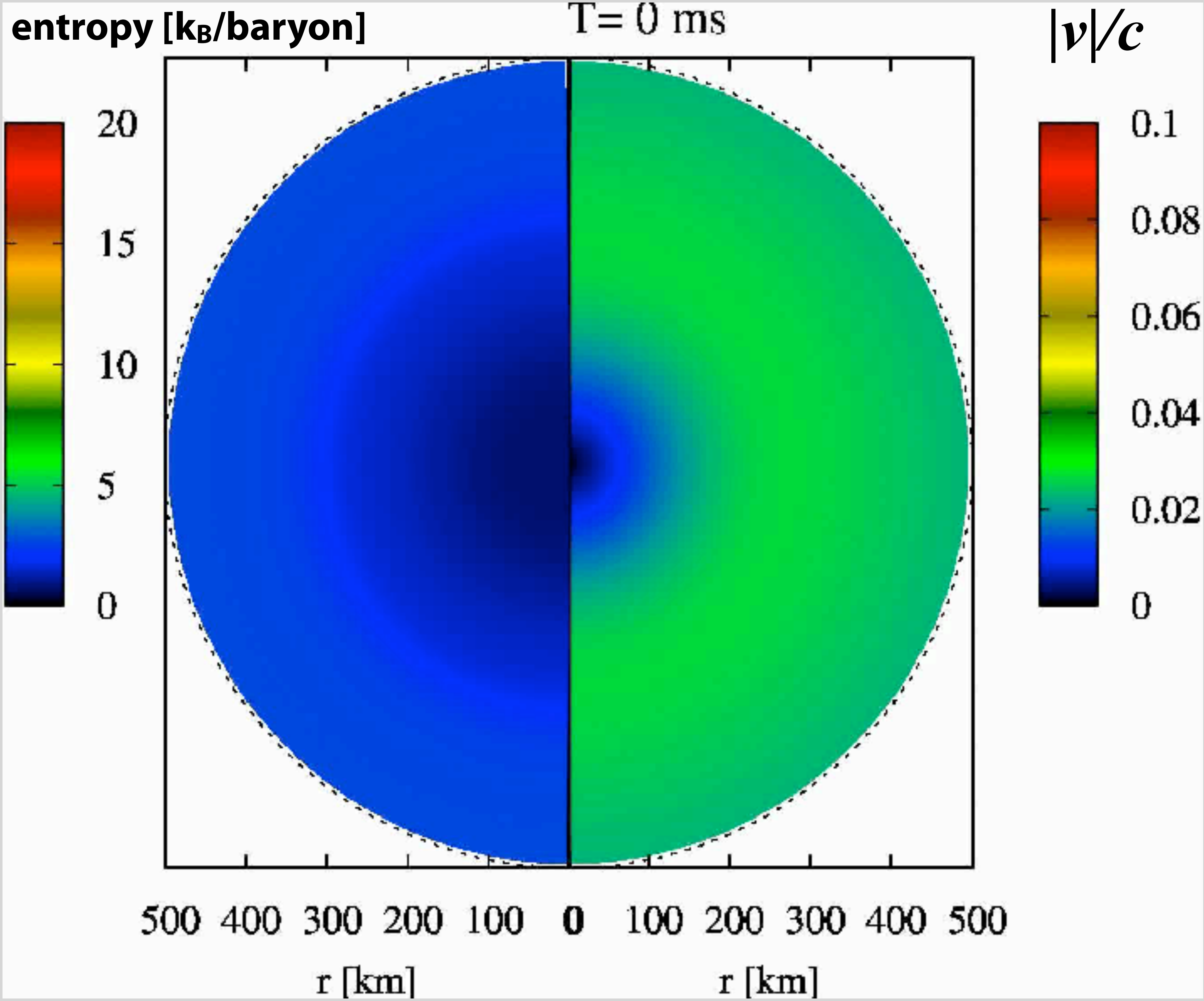


* EOS: Lattimer-Swesty (K=180,**220**,375MeV) / H. Shen

see also poster by Takiwaki

Explosion simulations-2: movie

M_{CO}=1.45 $M_\odot$



see also talk by Murphy

Explosion simulations-3: results

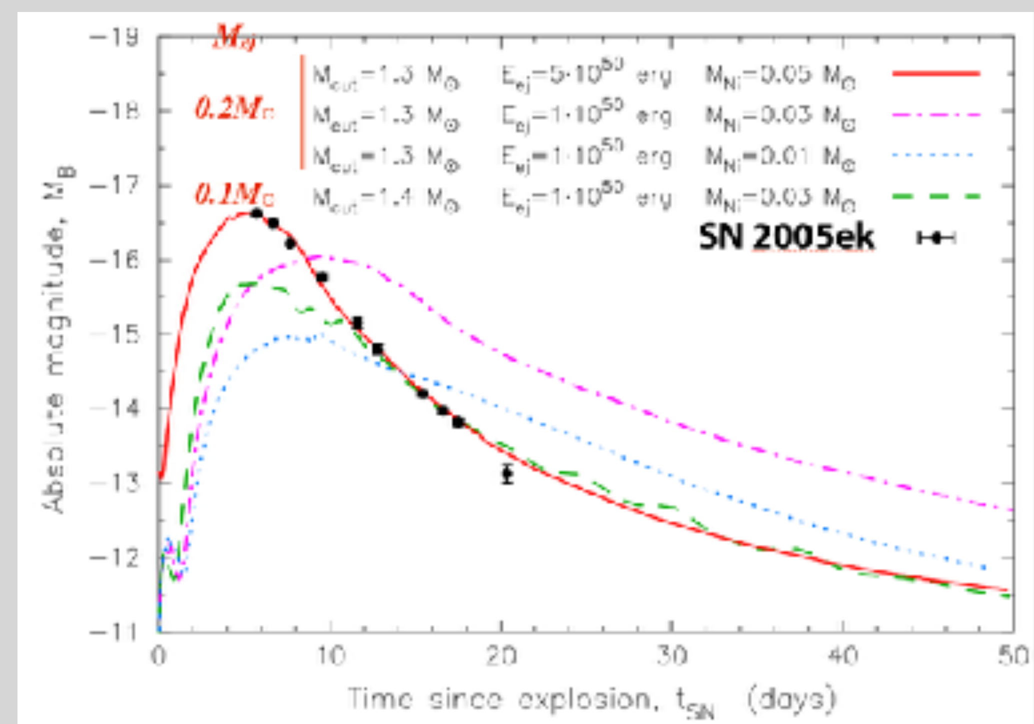
[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]

Model	$t_{\rm final}$ [a] (ms)	$R_{\rm sh}$ [b] (km)	$E_{\rm exp}$ [c] (B)	$M_{\rm NS,\,baryon}$ [d] ($\rm M_\odot$)	$M_{\rm NS,\,grav}$ [e] ($\rm M_\odot$)	$M_{\rm ej}$ [f] ($10^{-1}\,\rm M_\odot$)	$M_{\rm Ni}$ [g] ($10^{-2}\,\rm M_\odot$)	$v_{\rm kick}$ [h] ($\rm km\,s^{-1}$)
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20[i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

* **ALL models explode**
* **Final NS mass ~1.35-$1.6M_\odot$ (baryonic)**

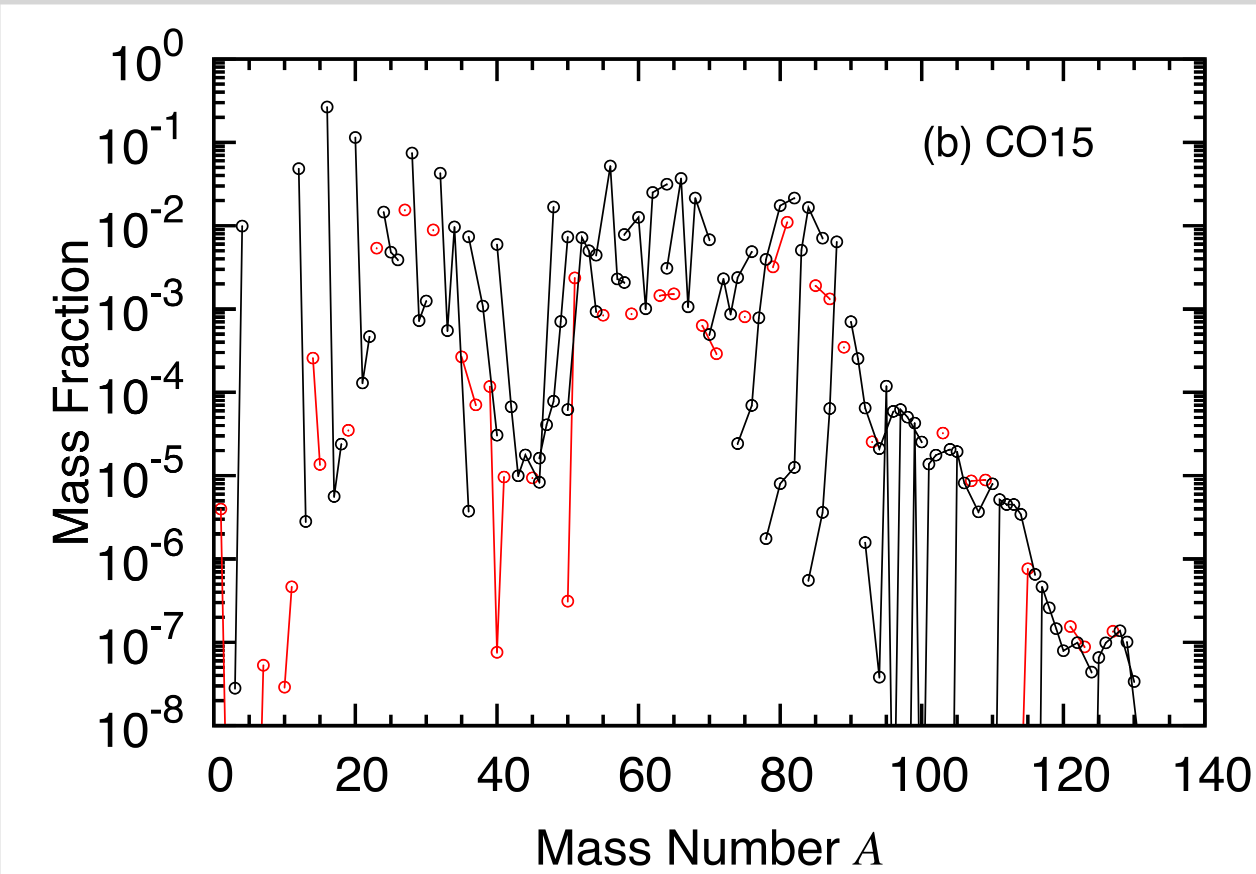
  ~1.24-$1.44M_\odot$ (gravitational)
* **Ejecta mass=M_{CO}-M_{NS} ~ $O(0.1)M_\odot$**
* **Explosion energy ~$O(10^{50})$ erg**
* **Ni mass ~$O(10^{-2})M_\odot$**

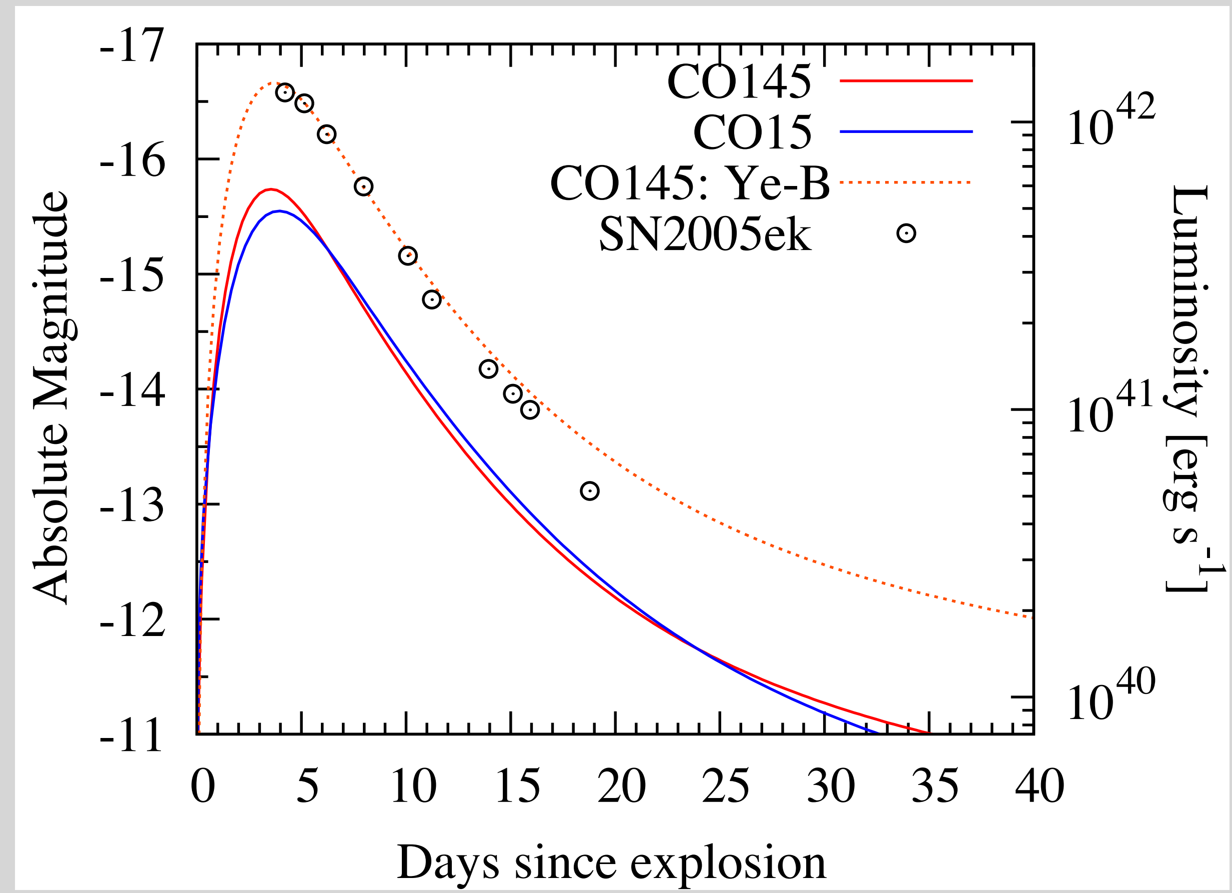
Tauris+ 2013



Nucleosynthesis yields and light curves

[Yoshida, Suwa, Umeda, Shibata, Takahashi, MNRAS, **471**, 4275 (2017)]





NB) This is one-zone model based on Arnett (1982).
Detailed radiation transfer calculations will be done.

Implications

- **small kick velocity due to small ejecta mass**

- **small eccentricity (e~0.1), compatible with binary pulsars J0737-3039 (e=0.088 now and ~0.11 at birth of second NS)**

  Piran & Shaviv 05

- **event rate (~0.1-1% of core-collapse SN)**
  - **SN surveys (e.g., HSC, PTF, Pan-STARRS, and LSST) will give constraint on ultra-stripped SN rate** Tauris+13, 15, Drout+ 13, 14
  - **Is it compatible to DNS merger rate(, which will be more precise in LIGO-Virgo O3 run)?**

Summary

* **Ultra-stripped SN might be second explosion in close binary forming double NSs**
* **To test this conjecture, we performed**
  * stellar evolution calculations of bare C/O cores
  * hydrodynamics simulations for neutrino-driven explosions
* **Compatible with parameters explaining observations**
  * $E_{\rm exp}=O(10^{50})$ erg
  * $M_{\rm ej}\sim O(0.1)\ M_\odot$
  * $M_{\rm Ni}\sim O(10^{-2}) M_\odot$
  * $M_{NS}\sim 1.2\text{-}1.4 M_\odot$ (gravitational)

Drout+ 13, Tauris+13

See
Suwa, Yoshida, Shibata, Umeda, Takahashi MNRAS, 454, 3073 (2015)
Yoshida, Suwa, Umeda, Shibata, Takahashi MNRAS, 471, 4275 (2017)
for more details