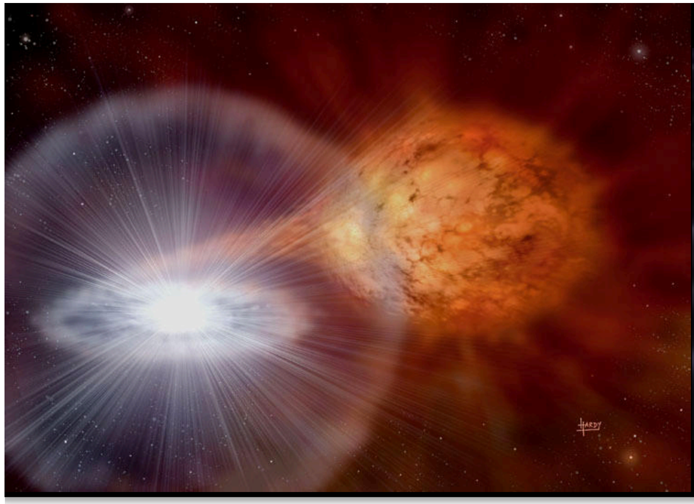

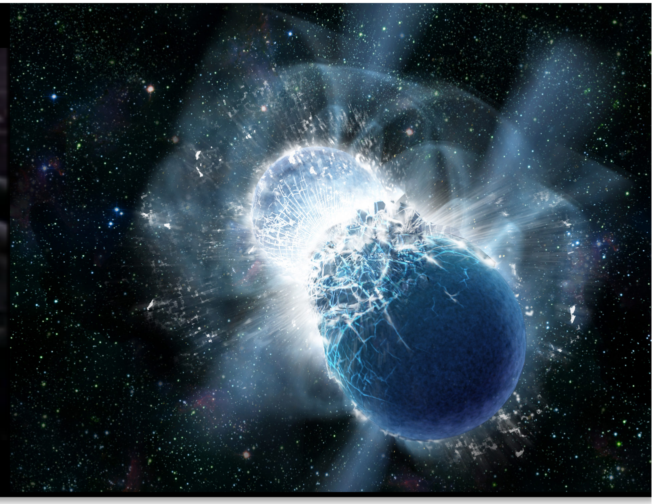

Radiative-transfer code-comparison study: Benchmark Type Ia Supernova models

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SRitp Workshop: Radiation Transfer and Explosive Thermonuclear Burning in Supernovae – 18 June 2018

Benchmarks are the latest fashion!

arXiv.org > astro-ph > arXiv:1806.04175

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Astrophysics > High Energy Astrophysical Phenomena

Global Comparison of Core-Collapse Supernova Simulations in Spherical Symmetry

Evan O'Connor, Robert Bollig, Adam Burrows, Sean Couch, Tobias Fischer, Hans-Thomas Janka, Kei Kotake, Eric J. Lentz, Matthias Liebendörfer, O. E. Bronson Messer, Anthony Mezzacappa, Tomoya Takiwaki, David Vartanyan

(Submitted on 11 Jun 2018)

We present a comparison between several simulation codes designed to study the core-collapse supernova mechanism. We pay close attention to controlling the initial conditions and input physics in order to ensure a meaningful and informative comparison. Our goal is three-fold. First, we aim to demonstrate the current level of agreement between various groups studying the core-collapse supernova central engine. Second, we desire to form a strong basis for future simulation codes and methods to compare to. Lastly, we want this work to be a stepping stone for future work exploring more complex simulations of core-collapse supernovae, i.e., simulations in multiple dimensions and simulations with modern neutrino and nuclear physics. We compare the early (first ~500ms after core bounce) spherically-symmetric evolution of a 20 solar mass progenitor star from six different core-collapse supernovae codes: 3DnSNe-IDSA, AGILE-BOLTZTRAN, FLASH, F{\sc{ornax}}, GR1D, and PROMETHEUS-VERTEX. Given the diversity of neutrino transport and hydrodynamic methods employed, we find excellent agreement in many critical quantities, including the shock radius evolution and the amount of neutrino heating. Our results provide an excellent starting point from which to extend this comparison to higher dimensions and compare the development of hydrodynamic instabilities that are crucial to the supernova explosion mechanism, such as turbulence and convection.

Comments: 24 pages, 7 figures, J. Phys. G focus issue on core-collapse supernovae. This document was written collaboratively on Authorea, comments welcome at this https URL

How it all started…

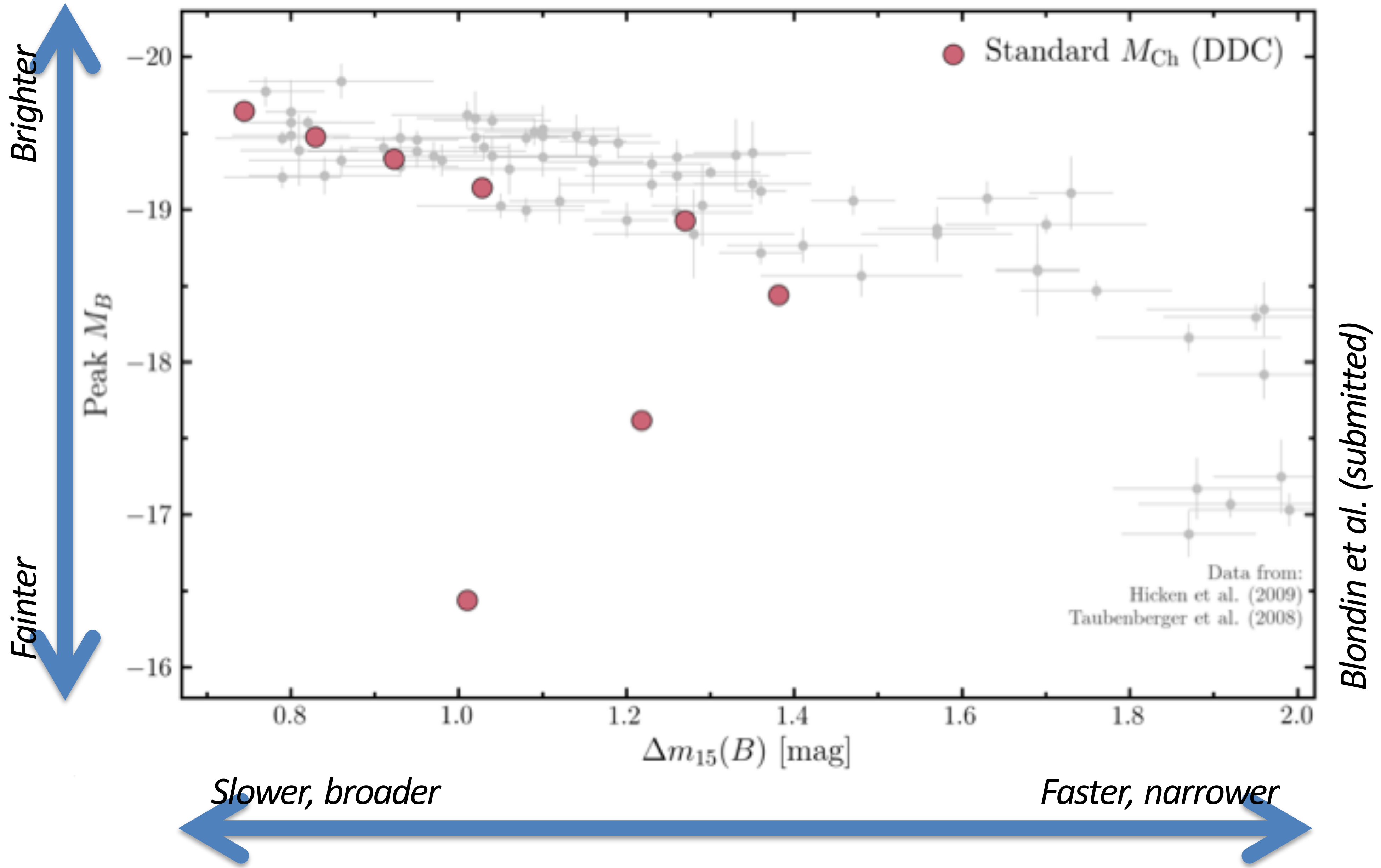
7. Session: Thermonuclear supernova progenitors and explosions

Chair: M. Tanaka

9:00–9:30 The case for multiple progenitor channels for Type Ia supernovae from radiative-transfer simulations – S. Blondin (INVITED)

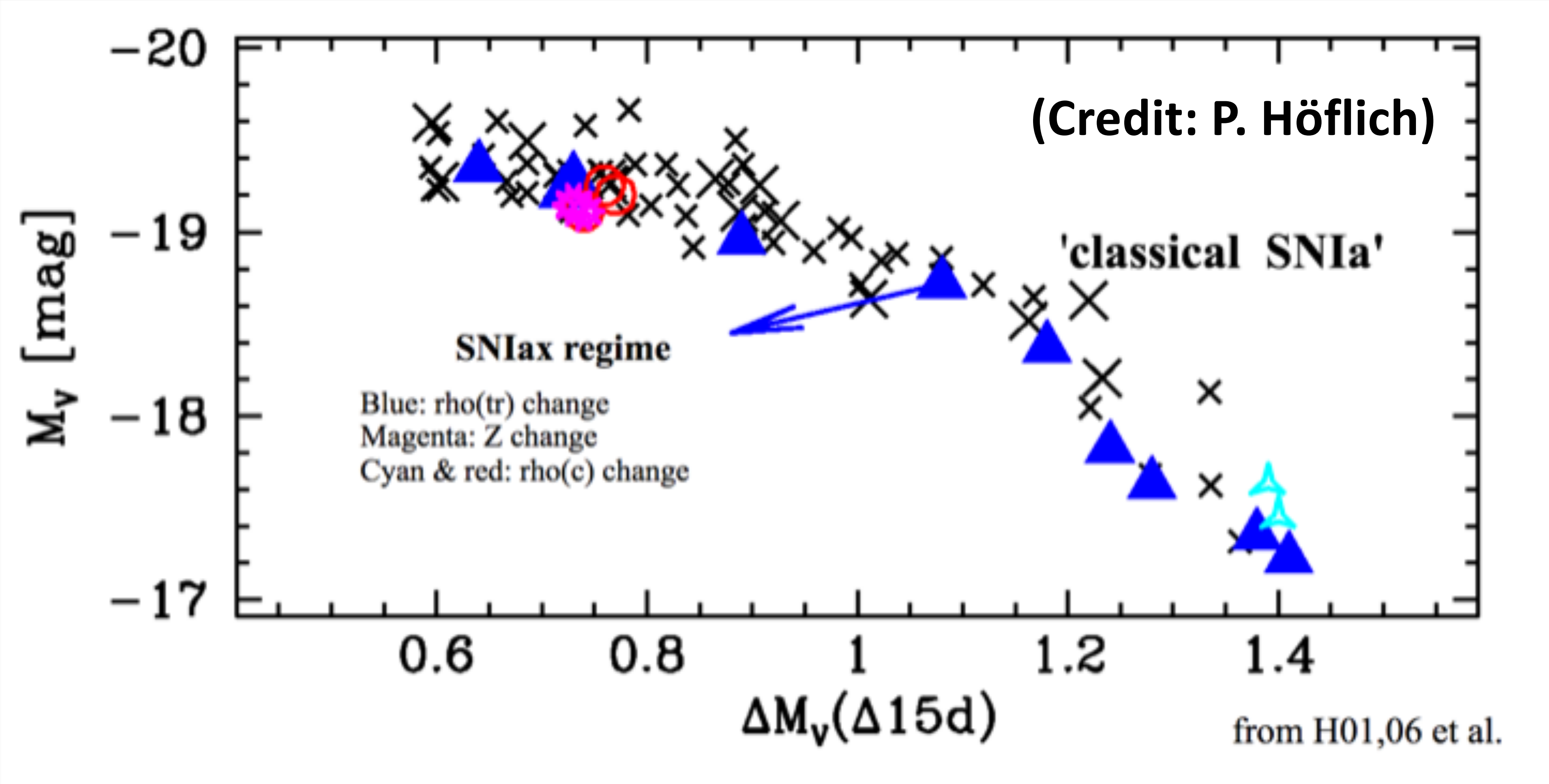
9:30–9:45 Type Ia Supernovae in a New Light: Probing the Signatures of the Progenitors and Progenitor Systems – P. Hoeflich

The Width-Luminosity Relation (WLR)



Comparison with Observations (x Suntzeff et al. 2001,Phillips et al. 2001)

The brightness decline relation and colors (Hoeflich et al. 1996, Mazzali et al. 2001, Kasen et al. 2009)
Ref. M(WD)=M(Ch), rho(c)=2E9g/ccm Z=solar, M(MS)=5Mo (WD structures from Dominguez et al. 2002)



- rho(tr) dominates the dm15 relation
- secondary parameter: M(MS), Z, rho(c) introduce spread in dm(15)
- Other indicators (IR-line profiles, expansion velocity)
- Variable mixing introduce a wider dispersion in the dm15 relation

Mixing suppressed: B-field (H.et al. 04, Penney & H., 12, Fesen etal. 07/15, Remming et al. 2014, Hiskov et al.15/16)

The long path to convergence

Aug 2016: discussion with Boaz Katz on setting up SN Ia RT code-comparison study

Feb 2017: proposal for SRitp workshop (approved Jun 2017)

Dec 2017: sketch out benchmark study with Boaz

1. analytical toy model (public script)
2. models previously run with CMFGEN

(**Jan 2018:** move to Chile…)

Apr 2018: 1st version of python code to generate toy models

May 2018: agreement on final setup

https://docs.google.com/document/d/1YQkv4vq45z-KGbKG1MhLRivSP6RmEite7nN-UZ0H-3M/

Model	Mtot [Msun]	Ekin [10^{51} erg]	M(IGE) [Msun]	M(^{56}Ni) [Msun]	M(IME) [Msun]	dM(IGE) [Msun]	dM(^{56}Ni) [Msun]	X(Ti)
High ^{56}Ni[(1)]	1.0	1.0	0.1	0.6	0.3	0.05	0.2	1e-5
Low ^{56}Ni[(2)]	1.0	1.0	0.1	0.1	0.8	0.05	0.05	1e-5

Of People and Codes…

Code	RT Method	Non-LTE	d/dt	People
ARTIS	MC	soon!	yes	Kromer, Sim, Shingles
CMFGEN	RTE	yes	yes	Hillier, Dessart, Blondin
HYDRA	RTE	yes	no	Höflich
JEKYLL	MC	yes	no	Ergon
PHOENIX	RTE	yes	yes	Baron
SEDONA	MC	soon!	yes	Kasen, Roth
SUMO	MC	yes	no	Jerkstrand
STELLA	Rad-Hydro	no	yes	Blinnikov, Kozyreva
TARDIS	MC	no	no	Kerzendorf
URILIGHT	MC	no	yes	Wygoda, Katz
VULCAN	Rad-Hydro	no	yes	Livne, Waldman

Toy model (1D)

- Ejecta defined by **total mass** (M_{tot}), **kinetic energy** (E_{kin})
- **Density profile** is exponential (Jeffery 1999) or broken power-law (Kasen 2010)

$$\rho(v) = \rho_0 e^{-v/v_e} \text{ with } \rho_0 = \frac{M_{tot}}{8\pi v_e^3 t^3} ; v_e = \sqrt{\frac{E_{kin}}{6M_{tot}}}$$

$$\rho(v) = \begin{cases} \rho_0 \left(\frac{v}{v_t}\right)^{-\delta} & v \leq v_t \\ \rho_0 \left(\frac{v}{v_t}\right)^{-n} & v > v_t \end{cases}$$

- Ejecta divided into **N zones** with fixed Δ*v* ; $M_{zone} = \rho_{ave} V_{zone}$ (asuming $R_{zone} = v_{zone} t_{exp}$)
- Four distinct **chemical zones**: stable IGE, ^{56}Ni(+Ti), IME(+Ti), unburnt C/O (zones connected with smooth analytical function over mass range Δ*M*)
- Ejecta **evolved to t_{end}** days assuming radiation-dominated gas, local ^{56}Ni decay energy deposition, and no diffusion. **Temperature** solved for **analytically** (Katz 2013)

Jeffery (1999)

3.3. *A Parameterized SN Ia Model*

In order to determine the optically thin $\bar{\tau}$ (our choice for $\tau_{\rm ch}$ for SNe Ia and other low-mass/rapidly-expanding supernovae) and relate real time t and reduced time x, we need a structural supernova model. In this section we will specify a simple parameterized structural model for SNe Ia.

Spherically symmetric hydrodynamic calculations of SN Ia explosions often (but not always) produce models with density profiles that are very exponential (i.e., inverse exponential) with velocity after homologous expansion has set in. For example, the well regarded Chandrasekhar mass SN Ia models W7 (Nomoto, Thielemann, & Yokoi 1984; Thielemann, Nomoto, & Yokoi 1986), DD4 (Woosley & Weaver 1994), and M36 (Höflich 1995, Fig. 10, but note that the density is mislabeled as energy deposition) are quite exponential with equivalent-exponential model e-folding velocities (see Appendix A, eq. [A10]) of about $2700\,{\rm km\,s^{-1}}$, $2750\,{\rm km\,s^{-1}}$, and $3000\,{\rm km\,s^{-1}}$, respectively. Such nearly-exponential density profile models have been quite successful in reproducing SN Ia spectra (e.g., Jeffery et al. 1992; Kirshner et al. 1993; Höflich 1995; Nugent et al. 1995). Therefore we will assume a spherically-symmetric, exponential density profile model (i.e., an exponential model for brevity) for our homologous epoch, parameterized SN Ia model. In Appendix A, we present a number of useful analytic results for exponential models and give a prescription for exactly exponential models (equivalent-exponential models) that can approximately replace nearly exponential hydrodynamic explosion models.

The density profile of an exponential model (for the homologous epoch) is given by

$$\rho(v,t) = \rho_{\rm ce,0}\left(\frac{t_0}{t}\right)^3 \exp\left(-v/v_e\right) = \rho_{\rm ce,0}\left(\frac{t_0}{t}\right)^3 \exp\left(-z\right) , \qquad (20)$$

where $\rho_{\rm ce,0}$ is the central density at fiducial time t_0, v is the radial velocity, v_e is the e-folding velocity, and z is radial velocity or radial position in velocity space in units of v_e. Substituting for density from equation (20) into equation (8) and assuming the opacity κ is constant, we find for an exponential model that the γ-ray optical depth from an emission point z to the surface (which is at infinity) is

$$\tau = \tau_{\rm ce,0}\left(\frac{t_0}{t}\right)^2 \int_0^\infty dz_s \exp\left(-z'\right) , \qquad (21)$$

where $\tau_{\rm ce,0}$ is the radial optical depth to the center at the fiducial time t_0 (see eq. [A16] in Appendix A for the expression), z_s is beam path velocity length in units of the e-folding velocity, and

$$z' = \sqrt{z^2 + z_s^2 + 2zz_s\mu} . \qquad (22)$$

The μ is the cosine of the angle at the emission point between the outward radial direction and the beam propagation direction. For a beam in the outward radial direction, $\mu = 1$ and the optical depth expression reduces to

$$\tau_r = \tau_{\rm ce,0}\left(\frac{t_0}{t}\right)^2 \exp\left(-z\right) . \qquad (23)$$

Python script demo

https://goo.gl/zNx6NF

Default:

```
python mk_snia_toy_model.py
```

High ^{56}Ni-mass model:

```
python mk_snia_toy_model.py --mtot 1.0 --ekin 1.0 --dvel 500.0 --tend 2.0 --
mige 0.1 --dmige 0.05 --mni56 0.6 --dmni56 0.2 --mime 0.3 --xfracti 1e-5 --fout
snia_toy_m1e1nip6.dat
```

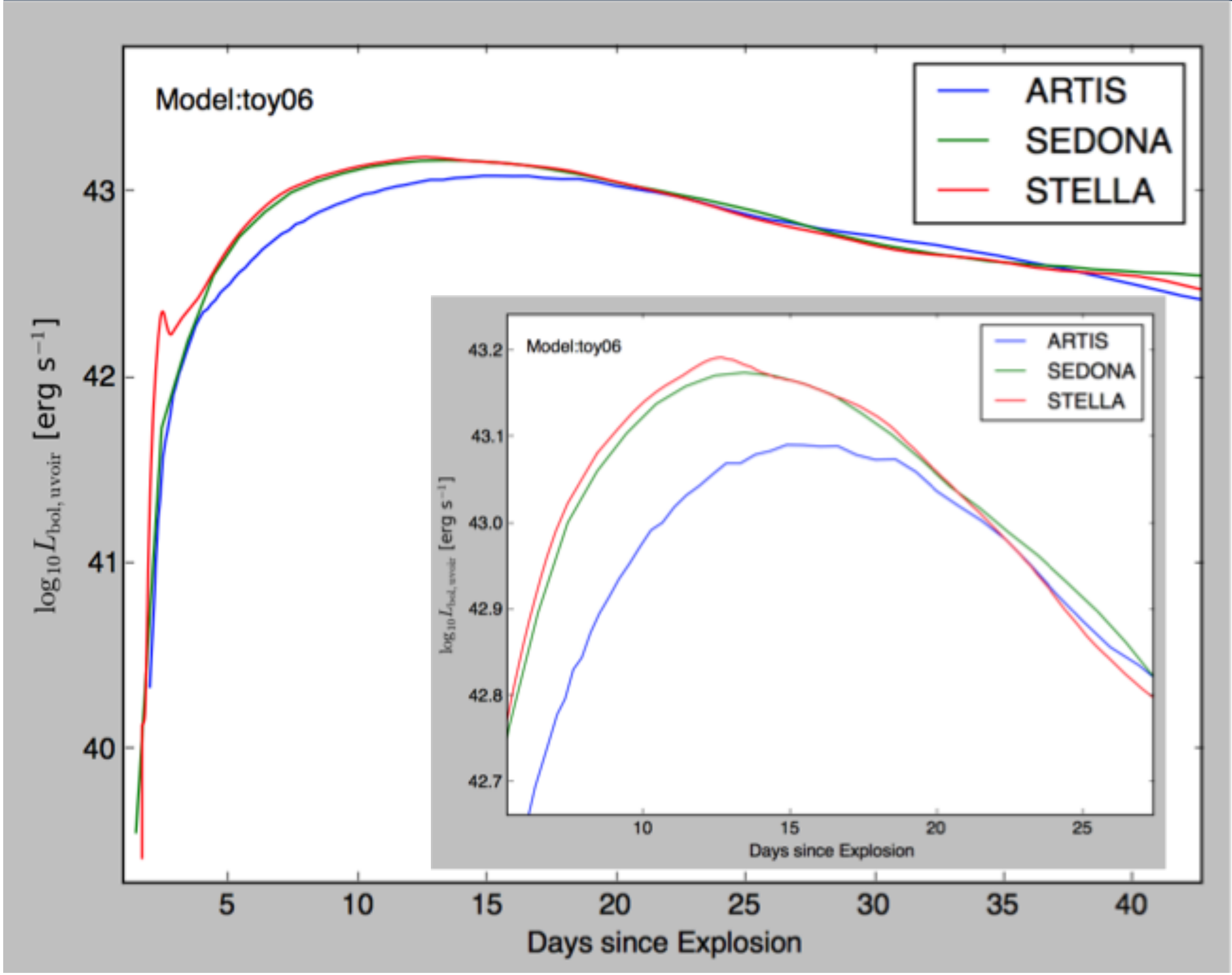
Low ^{56}Ni-mass model:

```
python mk_snia_toy_model.py --mtot 1.0 --ekin 1.0 --dvel 500.0 --tend 2.0 --
mige 0.1 --dmige 0.05 --mni56 0.1 --dmni56 0.05 --mime 0.8 --xfracti 1e-5 --
fout snia_toy_m1e1nip1.dat
```

Setup:

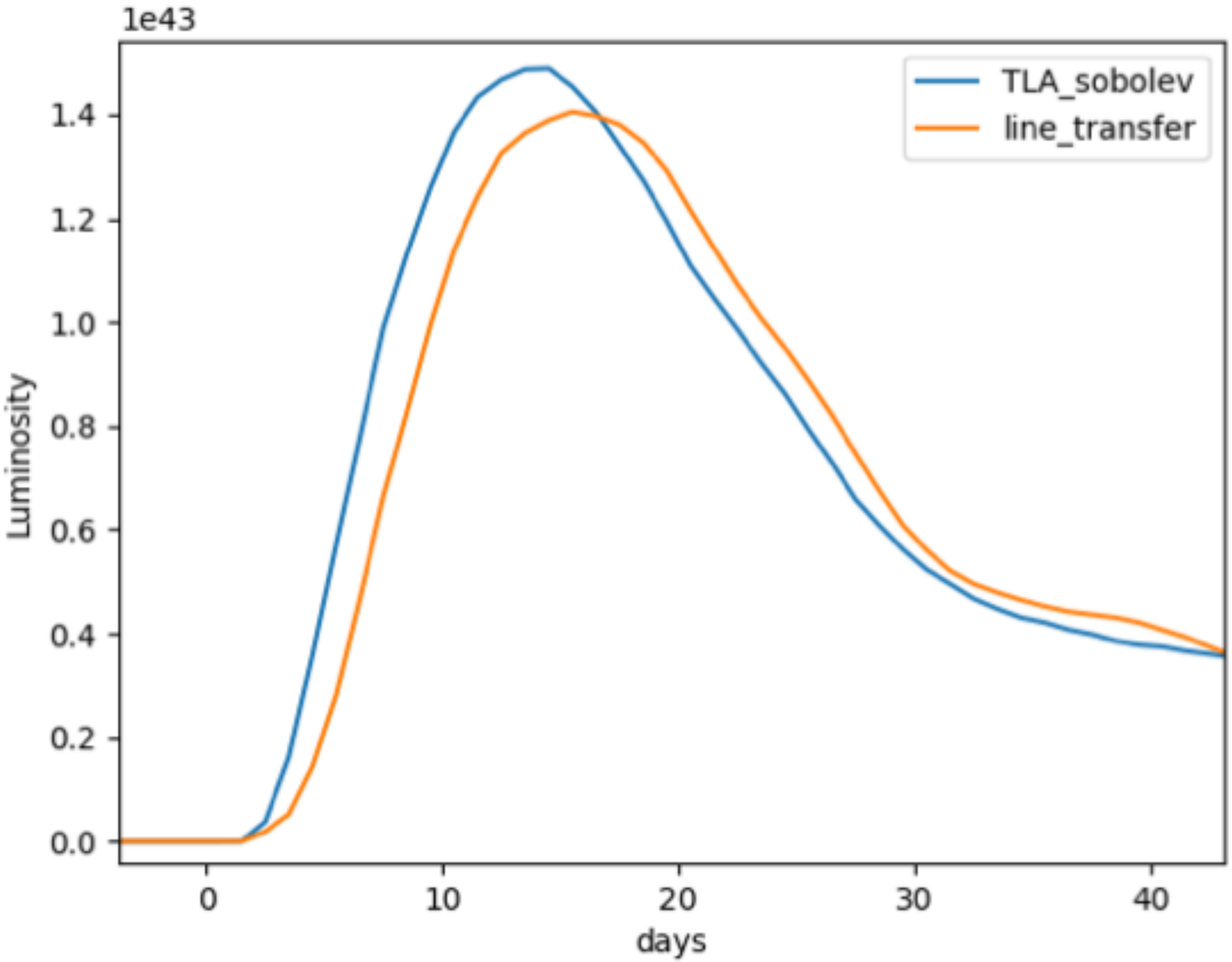
https://docs.google.com/document/d/1YOky4vq45z-KGbKG1MhLRjvSP6RmEite7nN-UZ0H-3M/

Results



Model:toy06
ARTIS
SEDONA
STELLA
43
42
41
40
5
10
15
20
25
30
35
40
Days since Explosion
$\log_{10} L_{\rm bol,\,uvoir}$ [erg s^{-1}]
43.2
43.1
43.0
42.9
42.8
42.7

Results



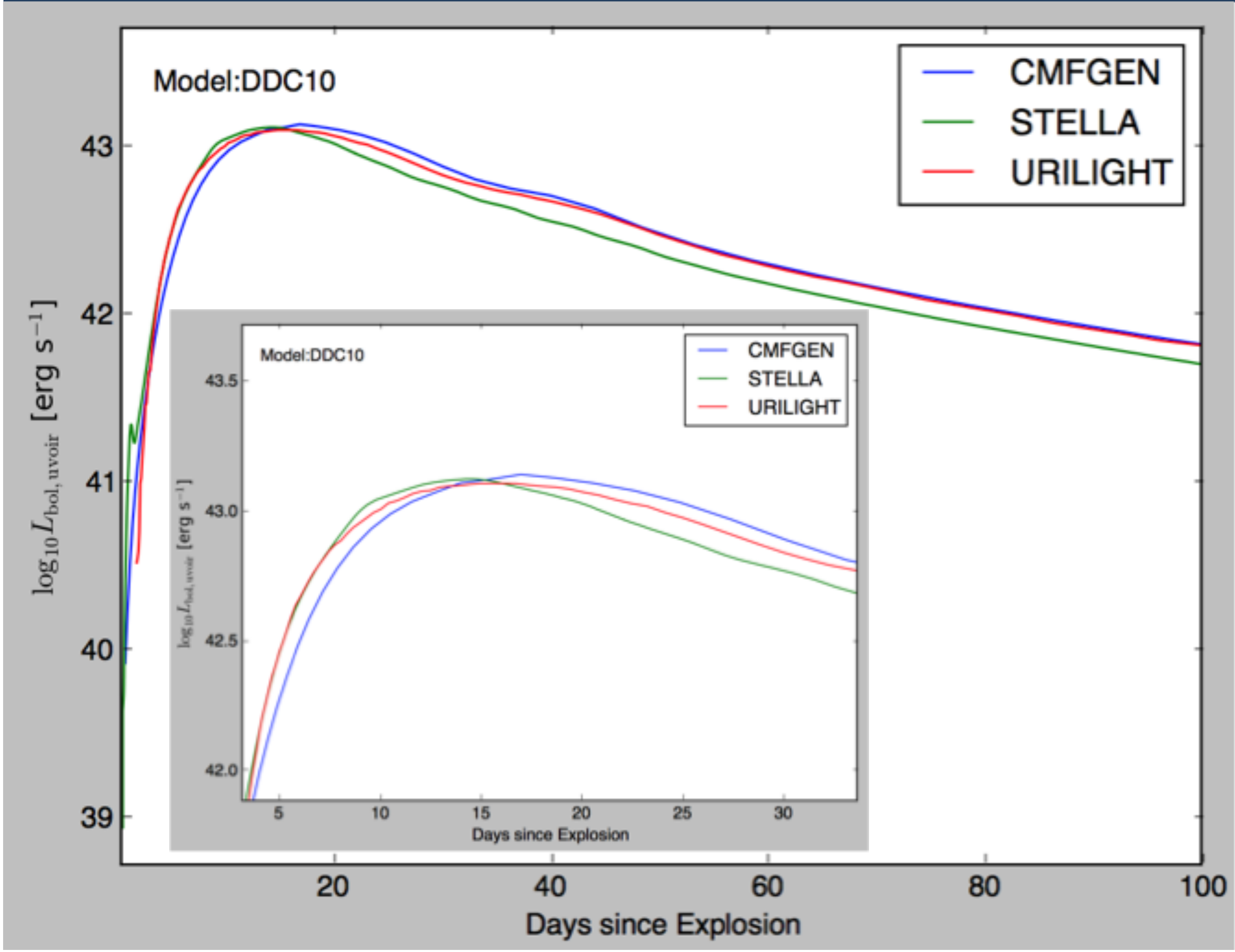
1e43
TLA_sobolev
line_transfer
Luminosity
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
days

CMFGEN models

MODEL	M_{tot}	$M(^{56}Ni)$	t_{start}
DDC10	1.4	0.62	0.976
DDC25	1.4	0.12	1.3
SCH5p5	1.08	0.63	1.0
SCH2p0	0.90	0.12	1.0

- converged CMFGEN solution provided at t_{start}
- Input provided in single file `SN_HYDRO_DATA` containing usual hydro variables + mass fractions (including isotopic mass fractions for radioactive chains)
- radioactive nuclear data provided in file `NUC_DECAY_DATA`

Results



Model:DDC10
CMFGEN
STELLA
URILIGHT
43
42
41
40
39
20
40
60
80
100
Days since Explosion
Model:DDC10
CMFGEN
STELLA
URILIGHT
43.5
43.0
42.5
42.0
5
10
15
20
25
30
Days since Explosion

Workshop Plans

1. **Plans for workshop**

   - All participants attempt at least high-^{56}Ni-mass toy model + DDC10
   - Agree on common inputs/methods. E.g. atomic data (line list) etc. Agree on what is it we should compare beyond LCs/spectra – **dedicated afternoon session on Wednesday!**
   - Have each group present code basics (+ some mini tutorial on its use? – this requires PUBLIC codes)

2. **Post-workshop plans**

   - Collect results + write summary paper?
   - Plan for more models? Same models but more tests (e.g. varying atomic data etc.)
   - Etc.