Mixing of Supernovae



Ke-Jung (Ken) Chen
ASIAA
EAMA, December 10th 2025

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The ASIAA Explosion Group at EAMA 11



- Po-Sheng Ou: Mass loss of massive stars and their CSM (AS-18P, DI-5P)
- Sung-Han Tsai: Binary Stars and their feedback (AS-6C, AS-10P, CS-12P)
- Wun-Yi Chen: Supernovae shock breakout (HE-6C)
- Pei-Cheng Tung: Dwarf Galaxies and SNRs (GF-17C)

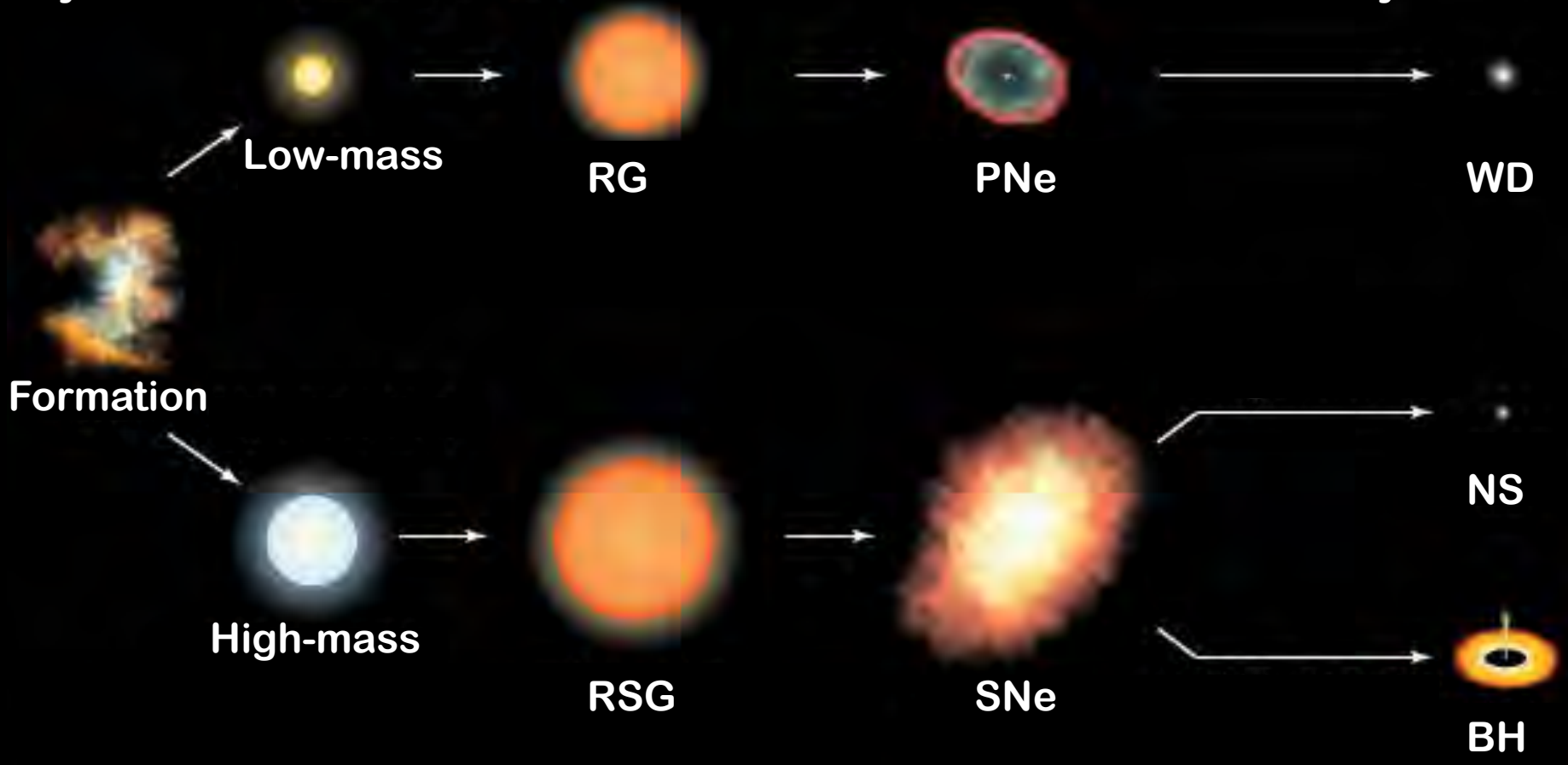


Po-Sheng Ou
Why stars turn red?

A Stellar Tale



Sung-Han Tsai
Binary Stars



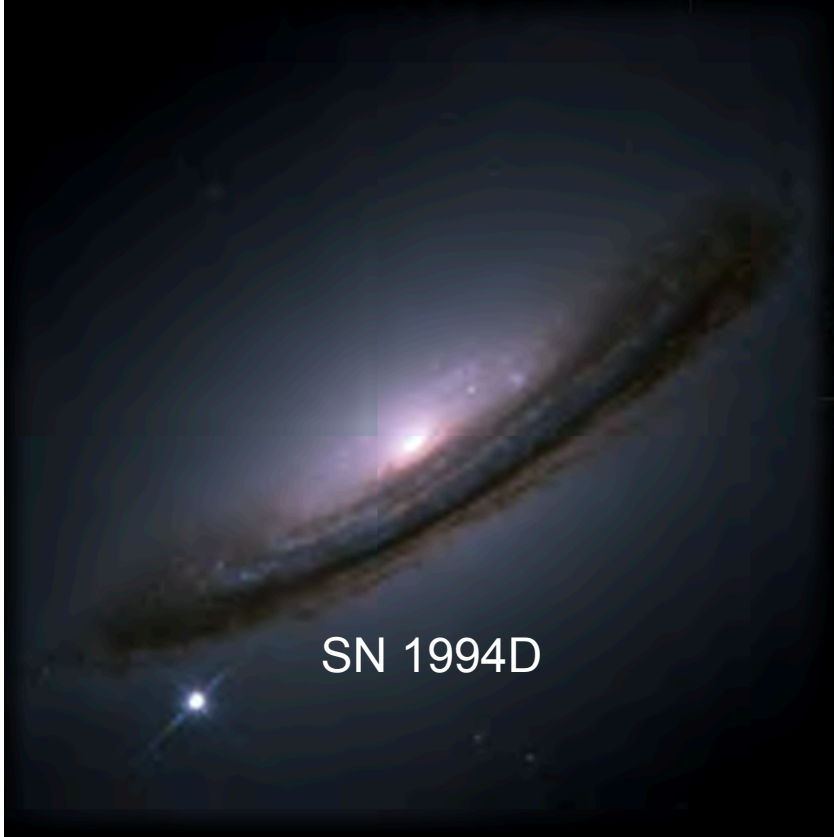
When Massive Stars Die, How Do They Explode?



Stan Woosley

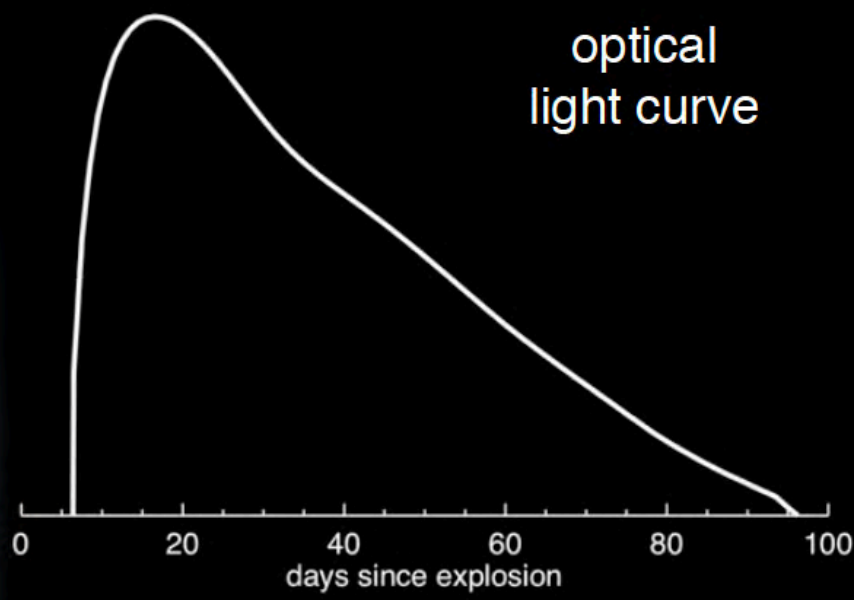
Neutron Star + Neutrinos	Neutron Star + Rotation	Black Hole + Rotation
Colgate and White (1966)	Hoyle (1946)	Bodenheimer and Woosley (1983)
Arnett	Fowler and Hoyle (1964)	Woosley (1993)
Wilson	LeBlanc and Wilson (1970)	MacFadyen and Woosley (1999)
Bethe	Ostriker and Gunn (1971)	Narayan (2004)
Janka	Bisnovatyi-Kogan (1971)	
Herant	Meier	
Burrows	Wheeler	
Fryer	Usov	*All of the above?*
Mezzacappa	Thompson	
etc.	etc	
10	20	35 $M_\odot$

supernovae and the transient universe

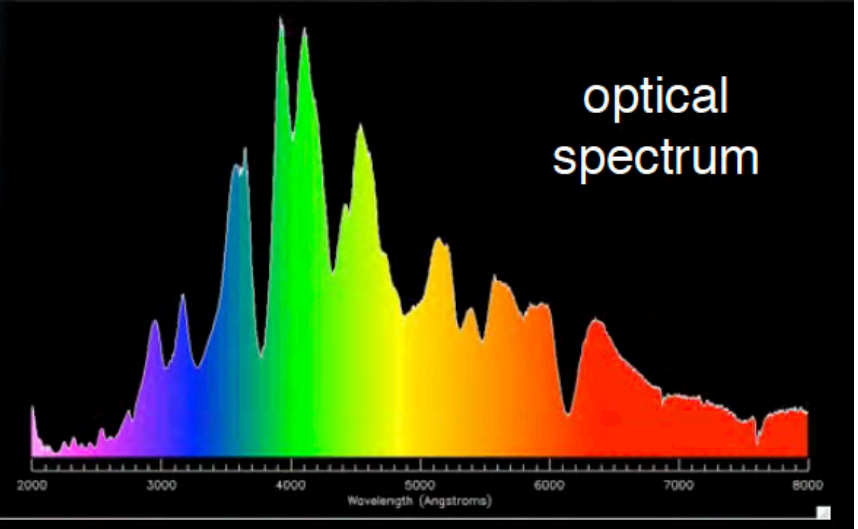


SN 1994D

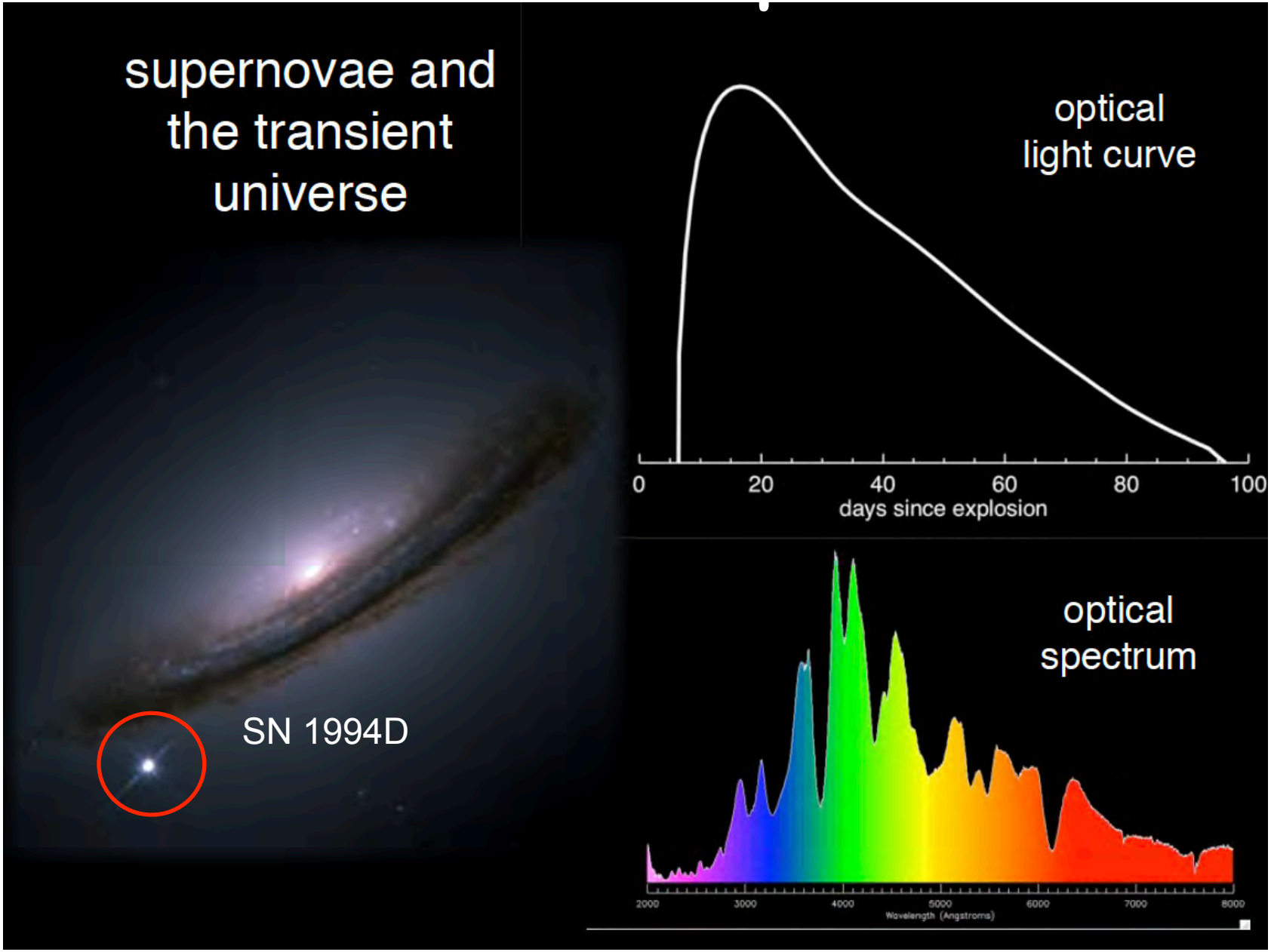
optical light curve



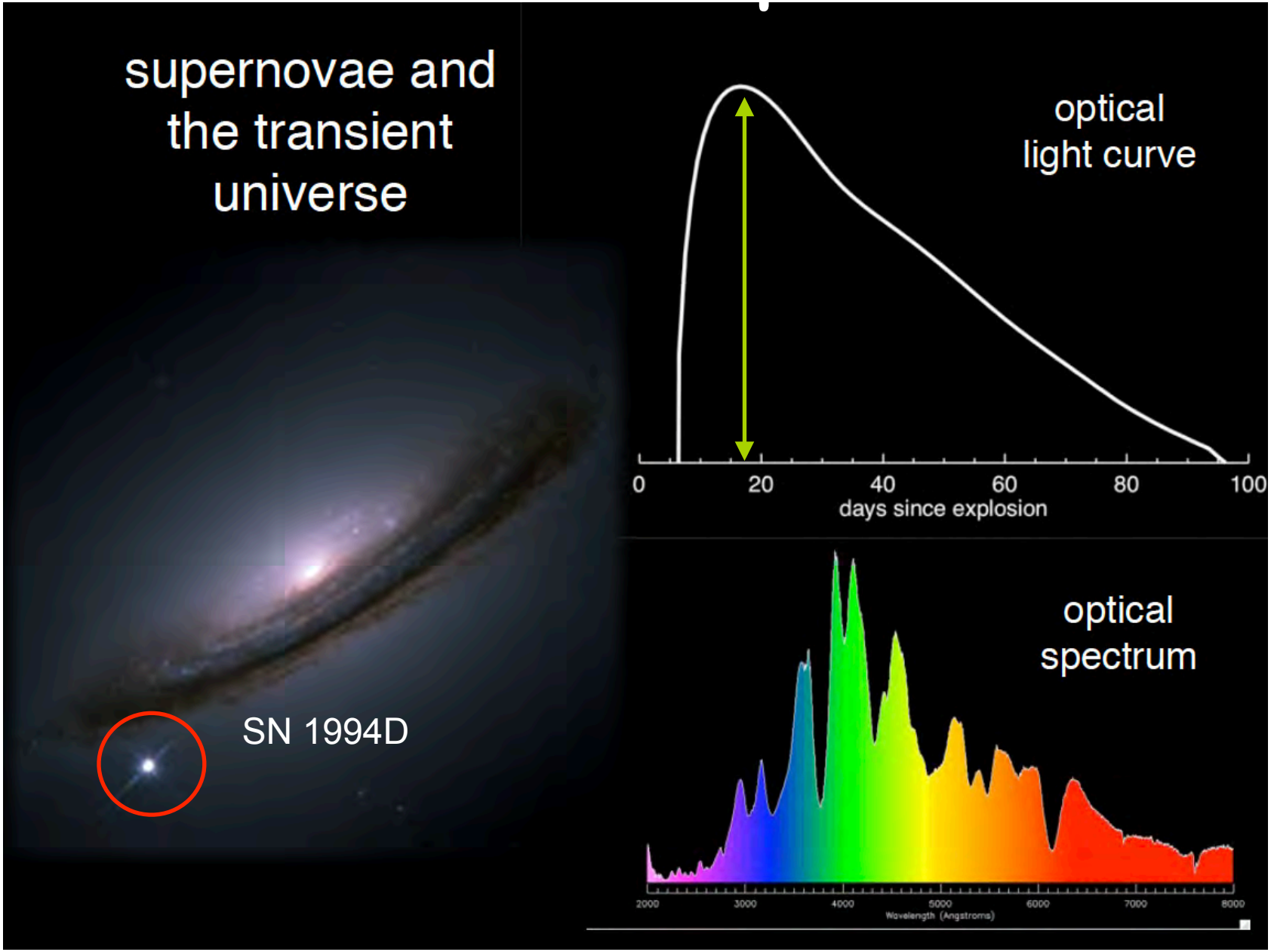
optical spectrum



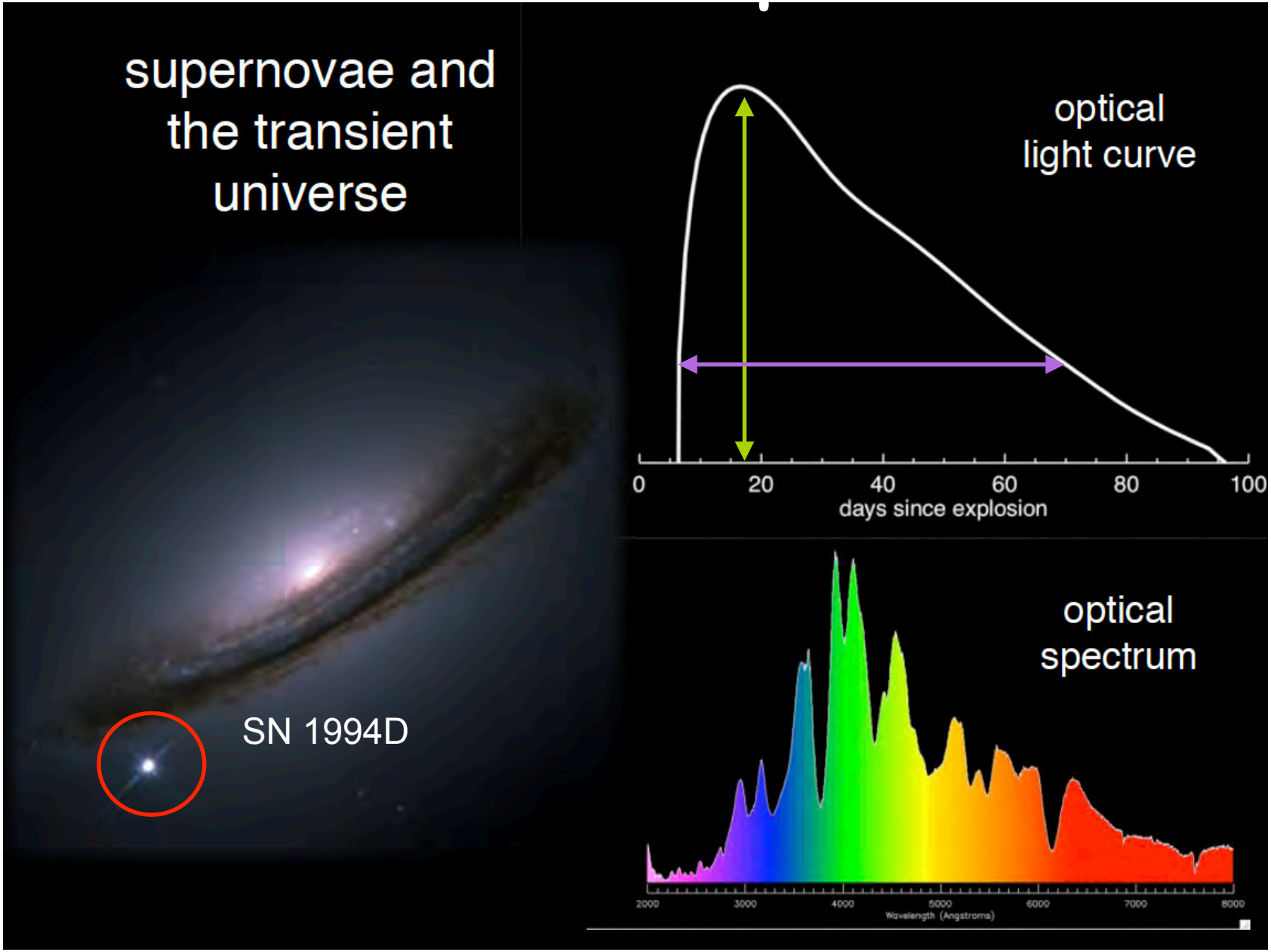
supernovae and the transient universe

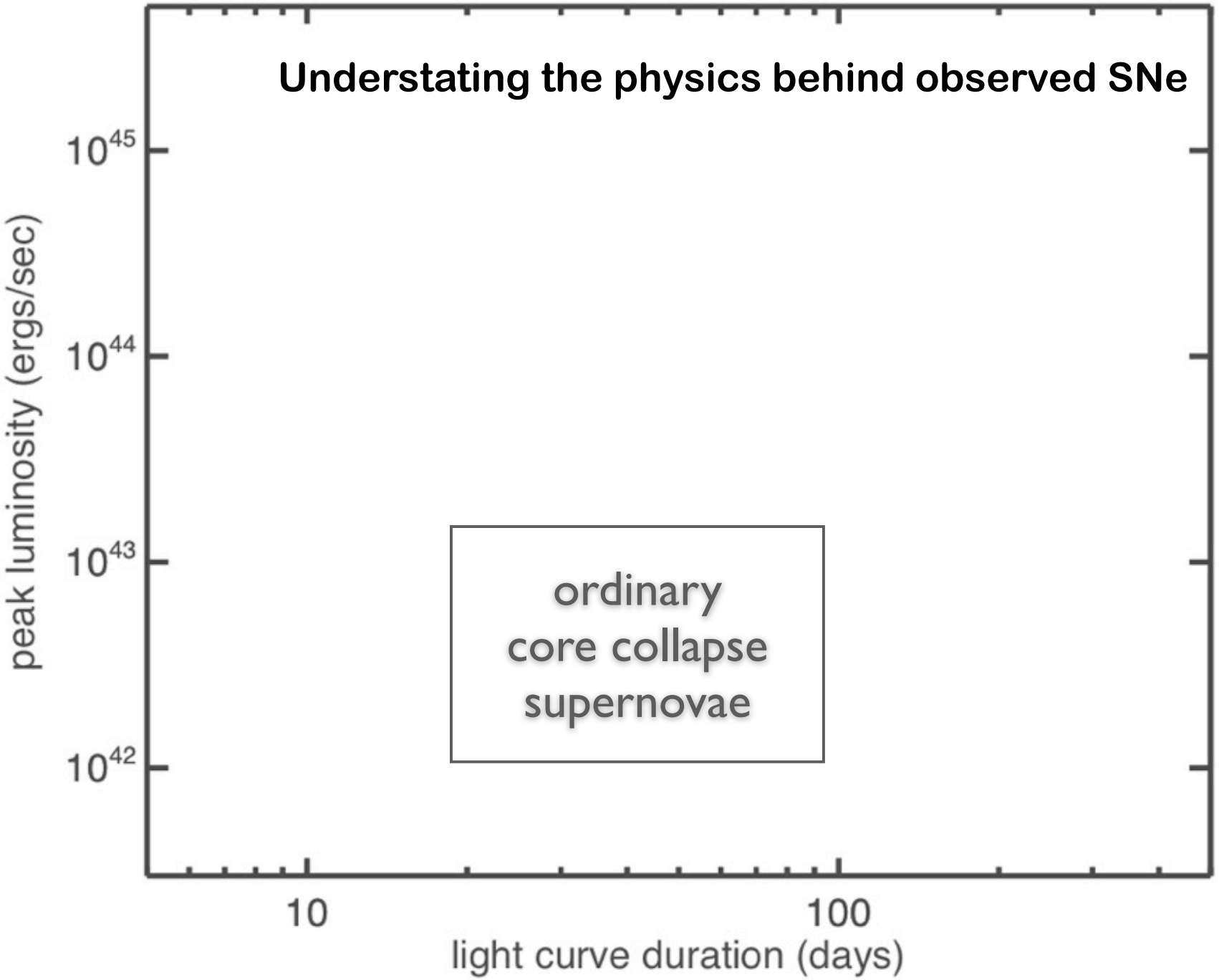


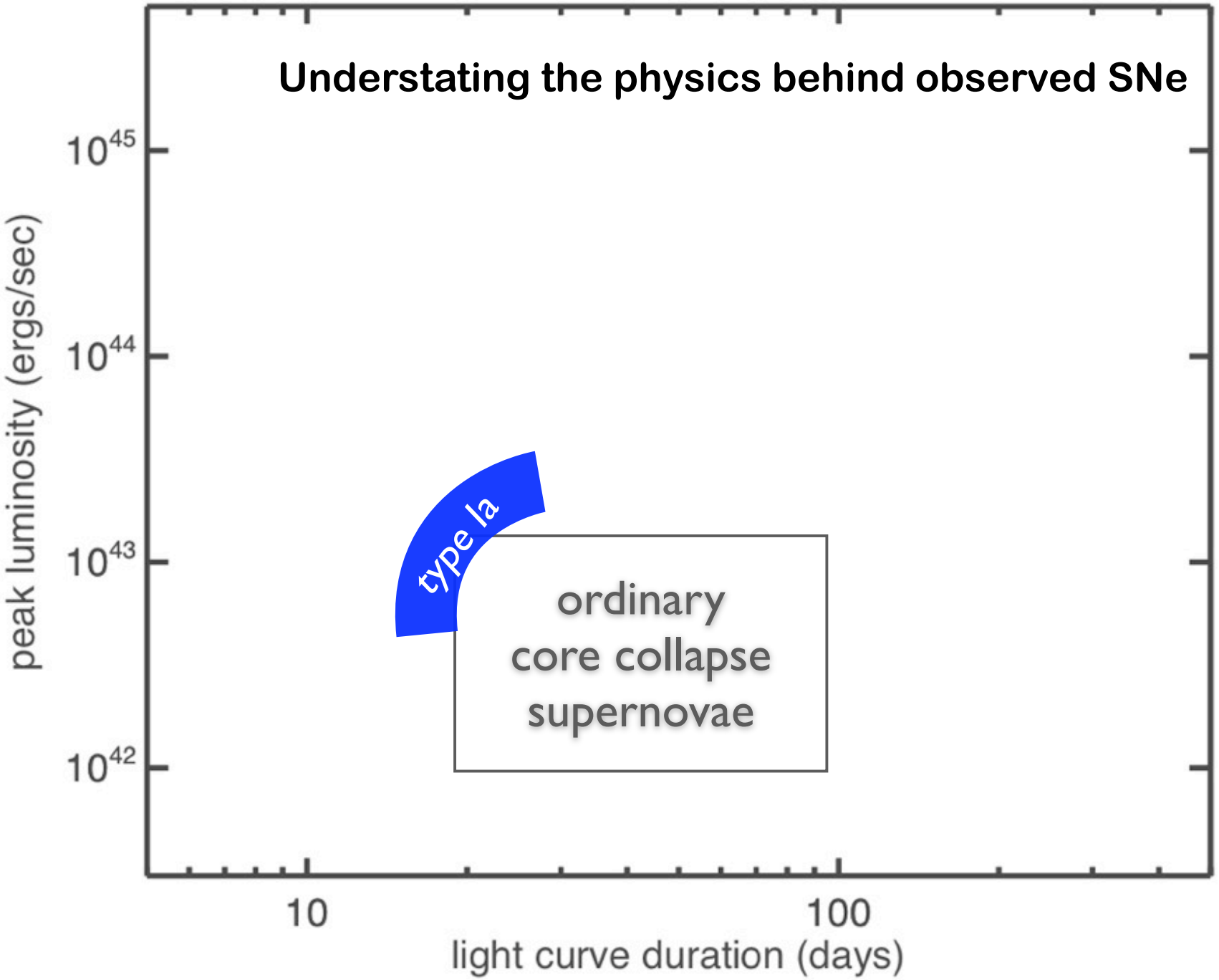
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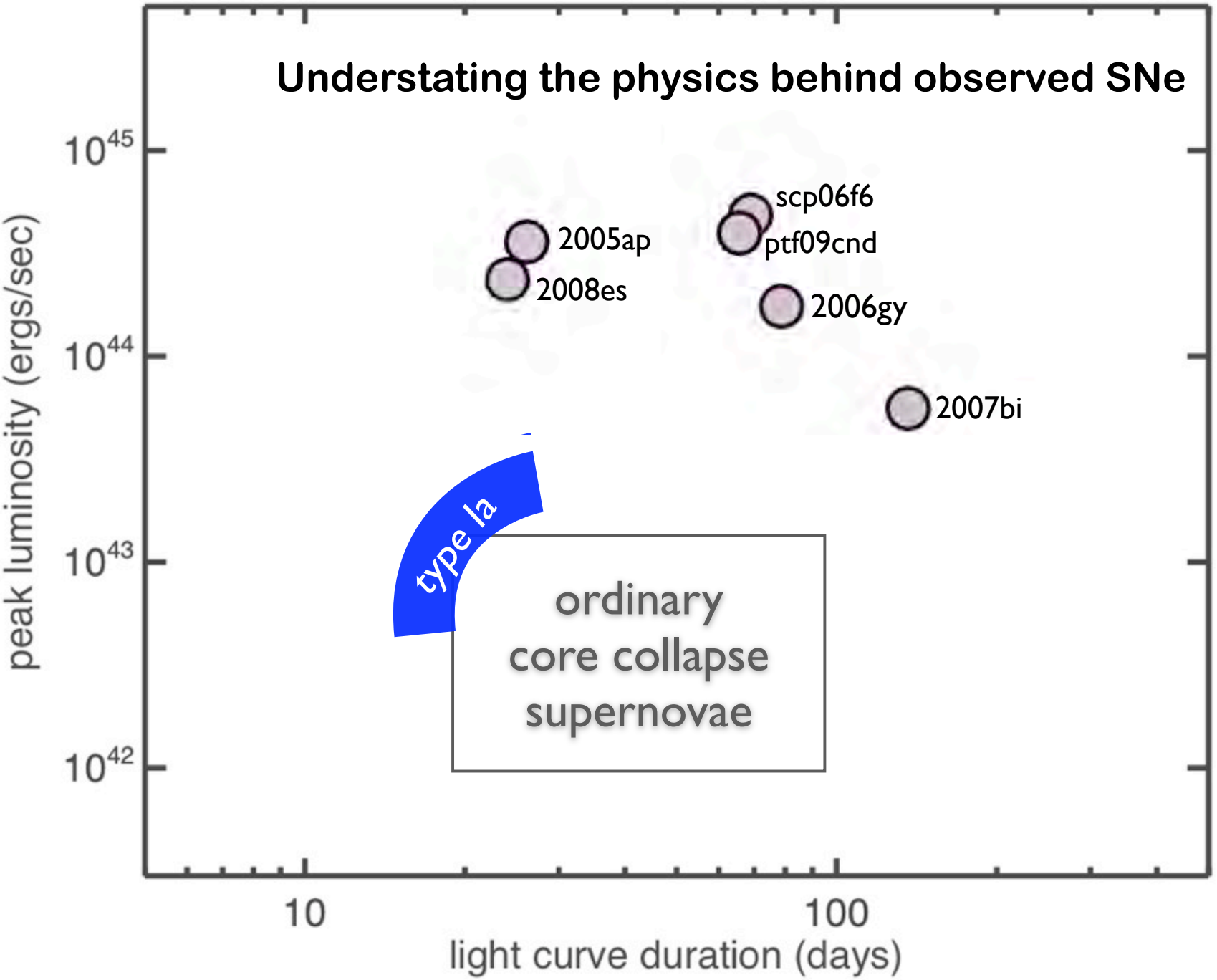


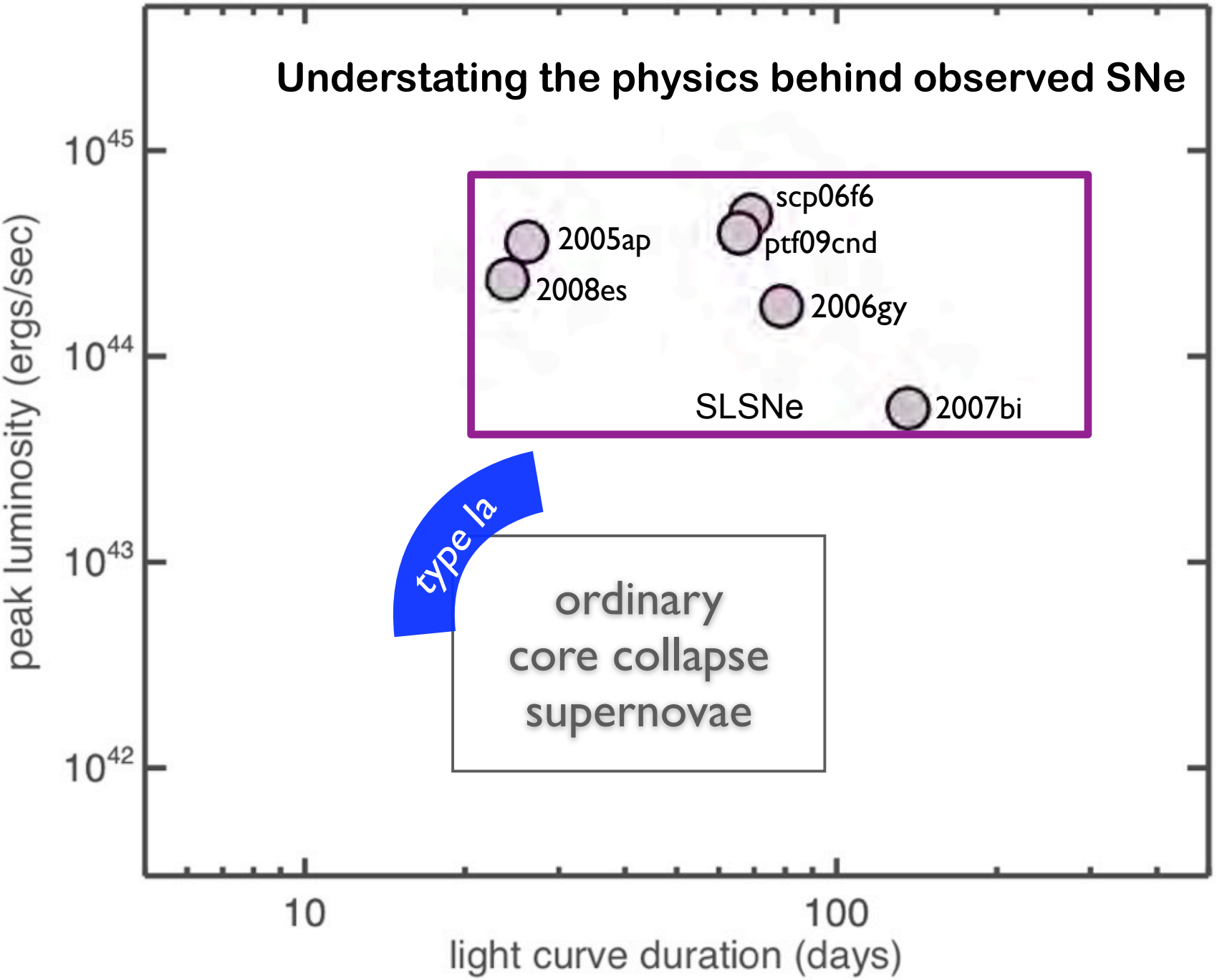
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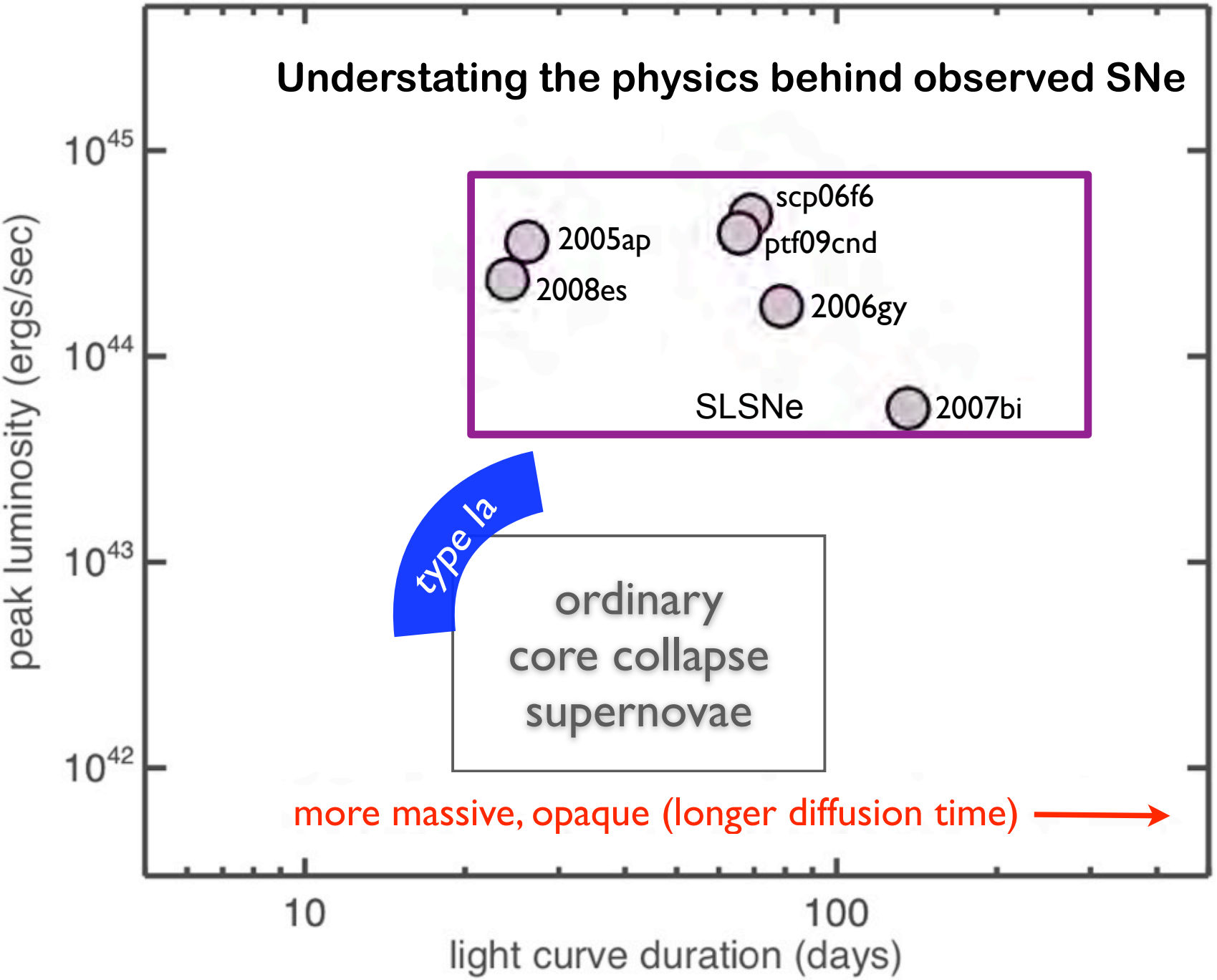


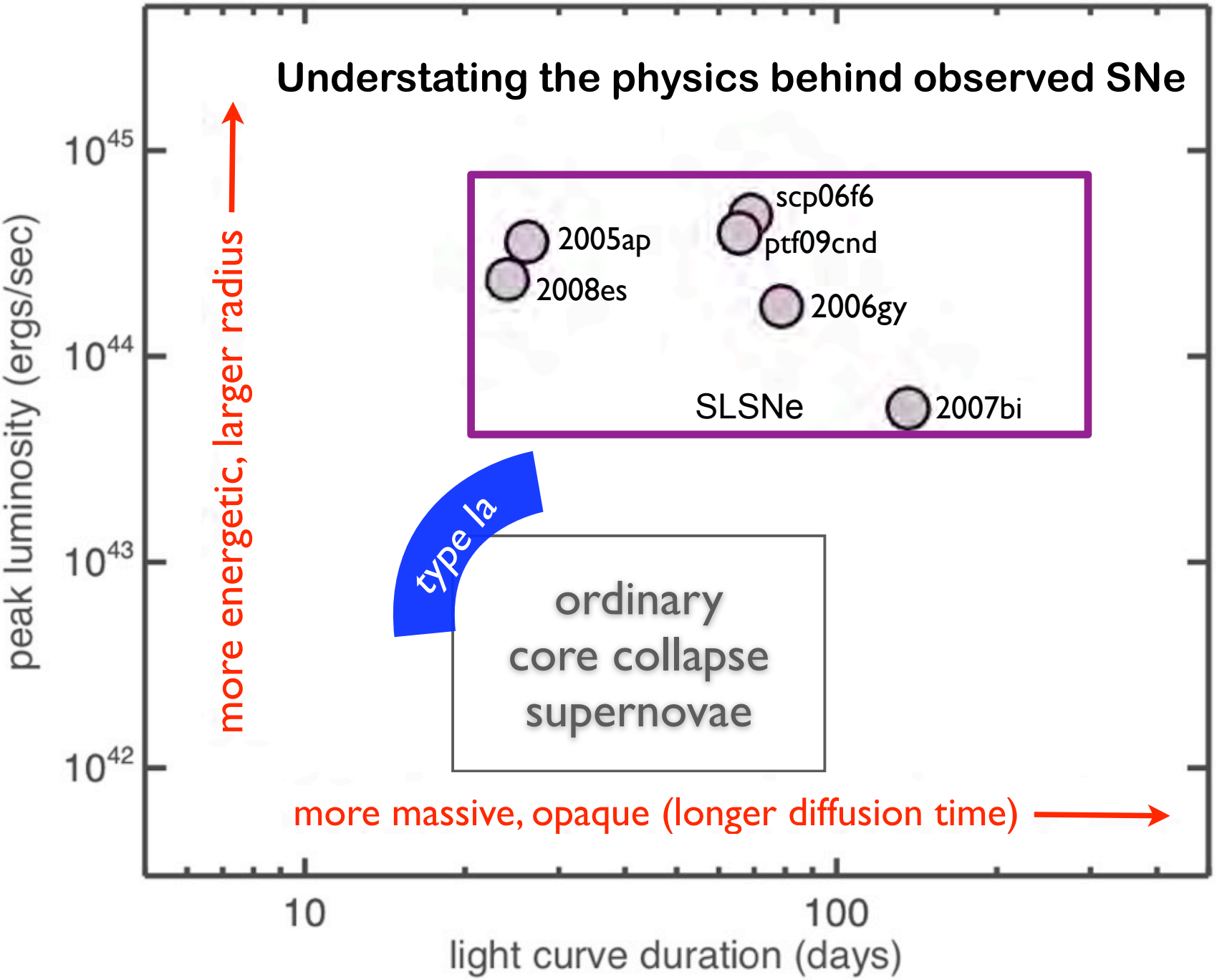

Understating the physics behind observed SNe
peak luminosity (ergs/sec)
10^{45}
10^{44}
10^{43}
10^{42}
ordinary
core collapse
supernovae
10
100
light curve duration (days)


Understating the physics behind observed SNe
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10^{45}
10^{44}
10^{43}
10^{42}
type Ia
ordinary
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10
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Understating the physics behind observed SNe
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2008es
scp06f6
ptf09cnd
2006gy
2007bi
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ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
10
100
light curve duration (days)


Understating the physics behind observed SNe
peak luminosity (ergs/sec)
10^{45}
10^{44}
10^{43}
10^{42}
more energetic, larger radius
2005ap
2008es
scp06f6
ptf09cnd
2006gy
SLSNe
2007bi
type Ia
ordinary
core collapse
supernovae
more massive, opaque (longer diffusion time)
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100
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Realistic 1D Stellar and SN Models ?



Physicists' view of everything



Massive Stars

Realistic 1D Stellar and SN Models ?

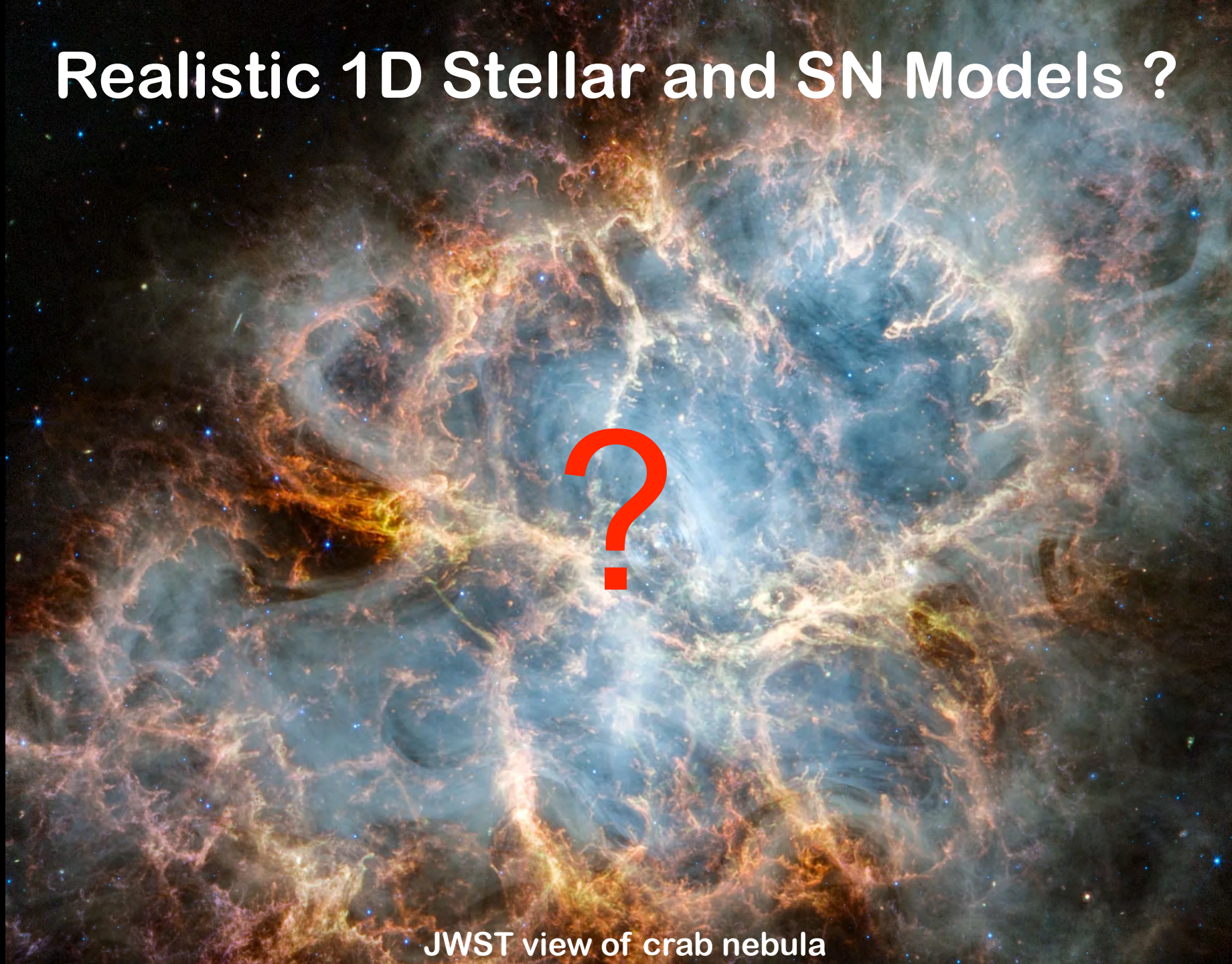


Physicists' view of everything



Massive Stars

Realistic 1D Stellar and SN Models ?



JWST view of crab nebula

What can we learn from Mixing?

Physics of Mixing in SNe and SNRs

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Physics of Mixing in SNe and SNRs

- Convective stellar structure

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Physics of Mixing in SNe and SNRs

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- Core collapse and neutrino heating

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Physics of Mixing in SNe and SNRs

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- Jet launching (B-field+rotation)

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- Explosive burning

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Physics of Mixing in SNe and SNRs

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- Jet launching (B-field+rotation)
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- Reverse shock

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- Decay of radiative isotopes

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Physics of Mixing in SNe and SNRs

- Convective stellar structure
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- Plasma and Radiative instabilities

What can we learn from Mixing?

Physics of Mixing in SNe and SNRs

- Convective stellar structure
- Core collapse and neutrino heating
- Jet launching (B-field+rotation)
- Explosive burning
- Reverse shock
- Decay of radiative isotopes
- Plasma and Radiative instabilities
- Colliding with CSM and ISM

Mixing of Core-Collaspe SNe

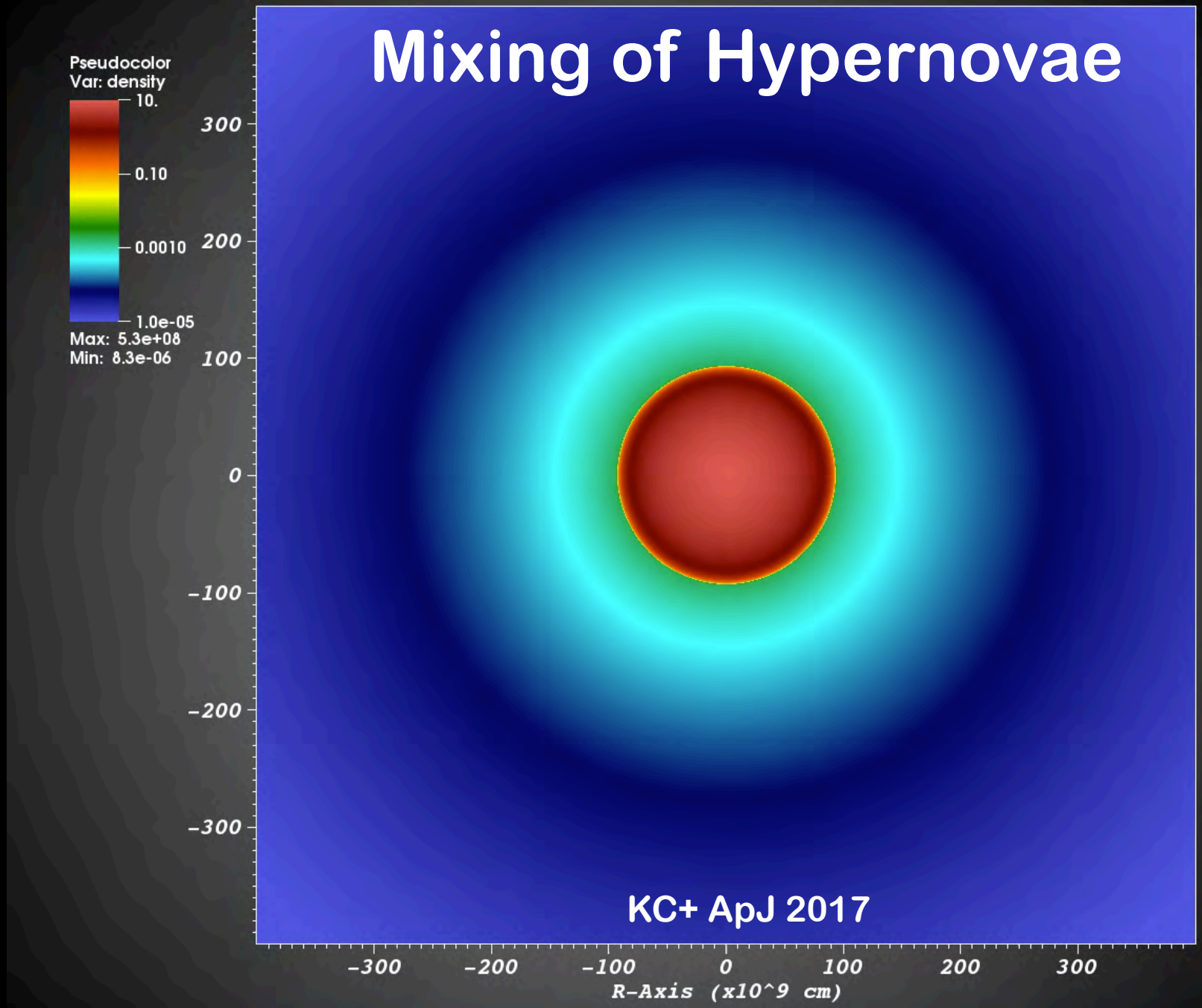


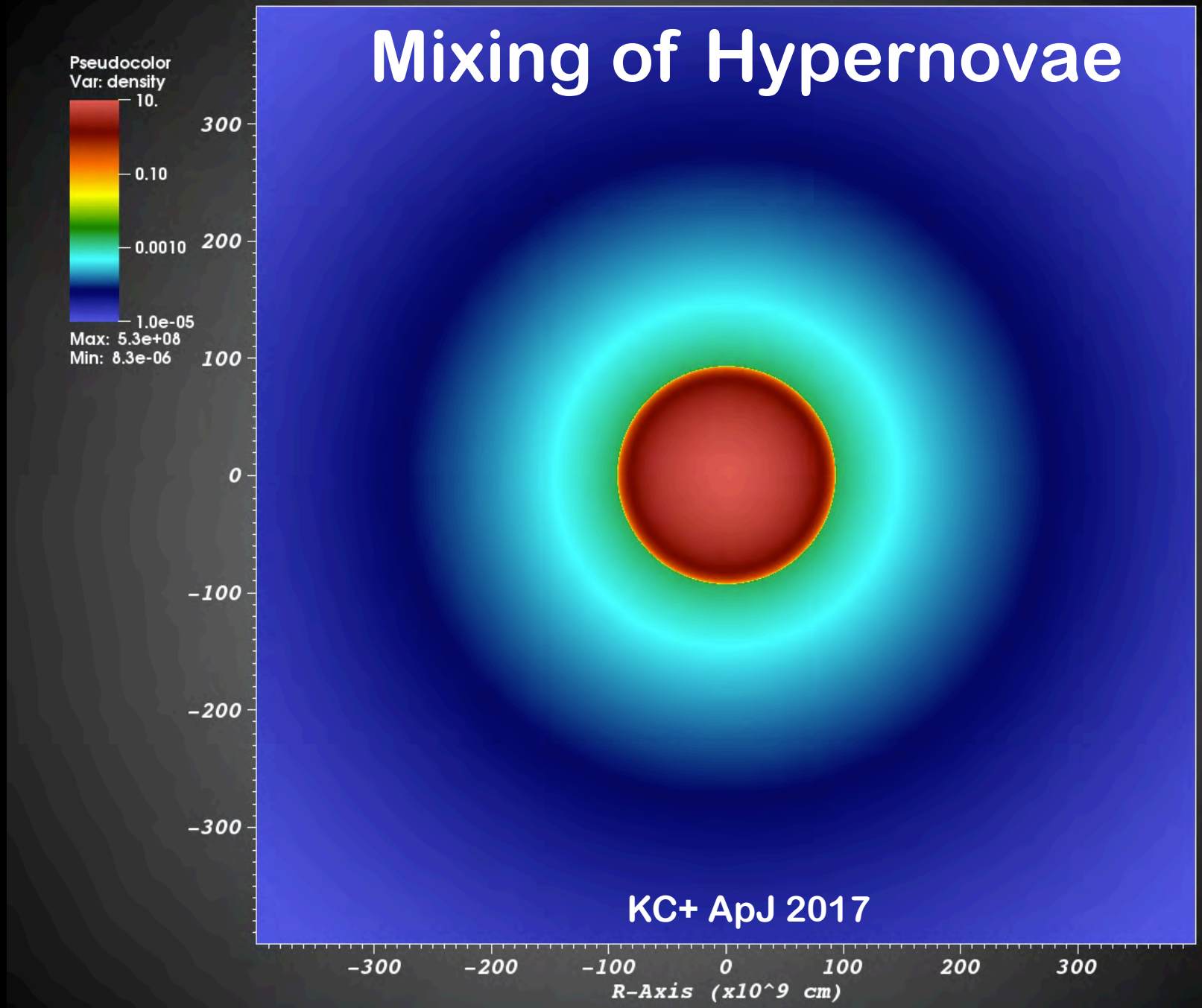
Nordhaus+ 2010

Mixing of Core-Collaspe SNe

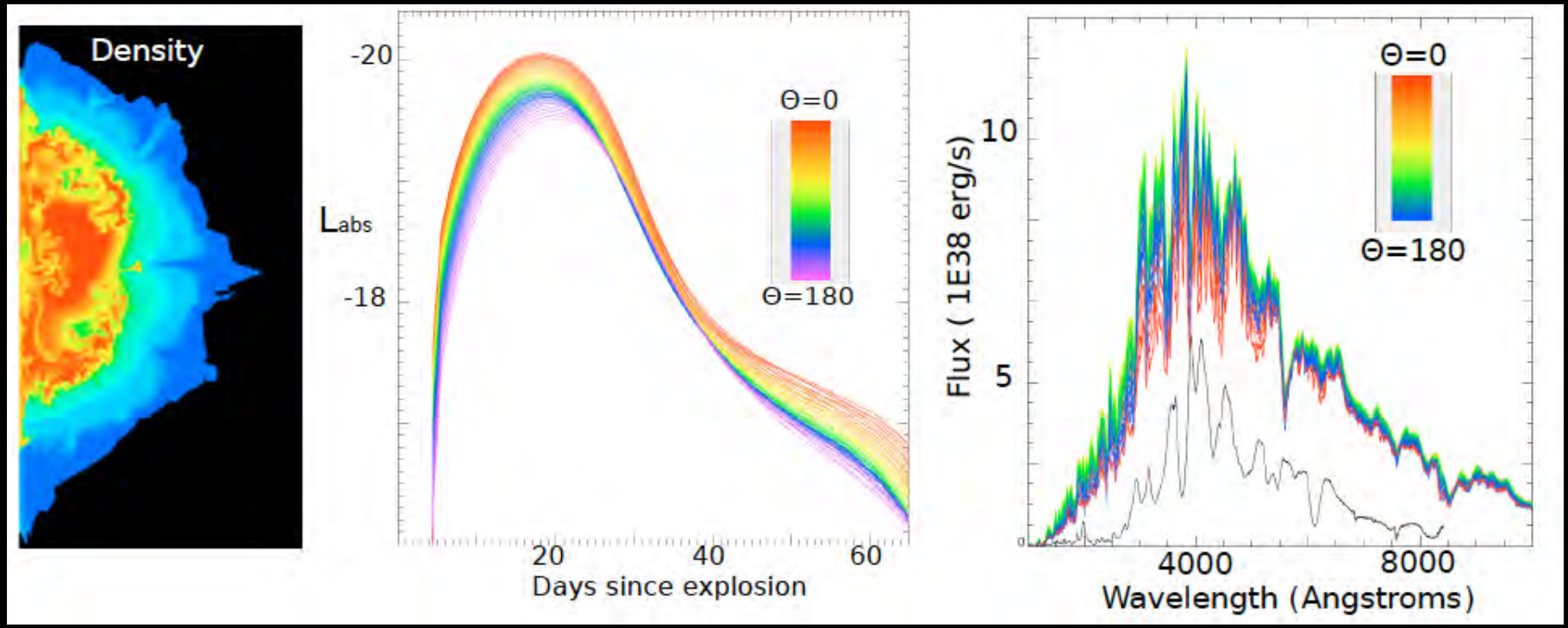


Nordhaus+ 2010


Mixing of Hypernovae
Pseudocolor
Var: density
10.
0.10
0.0010
1.0e-05
Max: 5.3e+08
Min: 8.3e-06
300
200
100
0
-100
-200
-300
KC+ ApJ 2017
-300
-200
-100
0
100
200
300
R-Axis (x10^9 cm)


Mixing of Hypernovae
Pseudocolor
Var: density
10.
0.10
0.0010
1.0e-05
Max: 5.3e+08
Min: 8.3e-06
300
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KC+ ApJ 2017
-300
-200
-100
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100
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300
R-Axis (x10^9 cm)

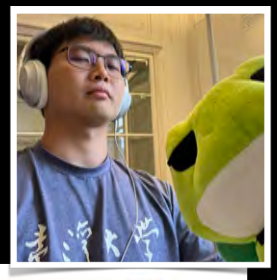
Impact of Mixing on SN Observational Signatures



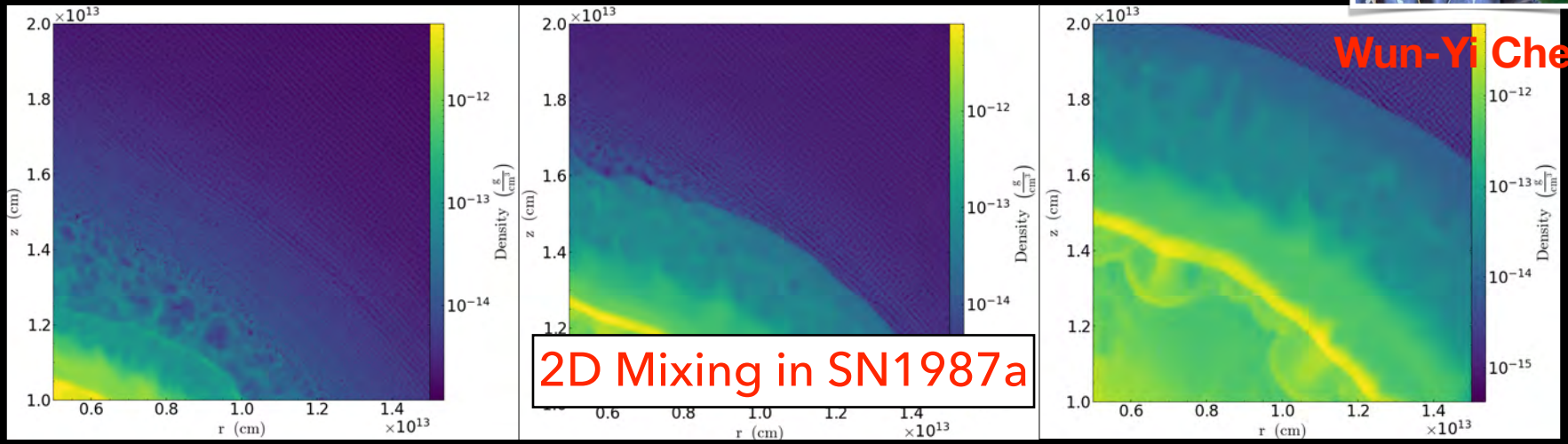
A Type Ia Example from Kasen+ 2008

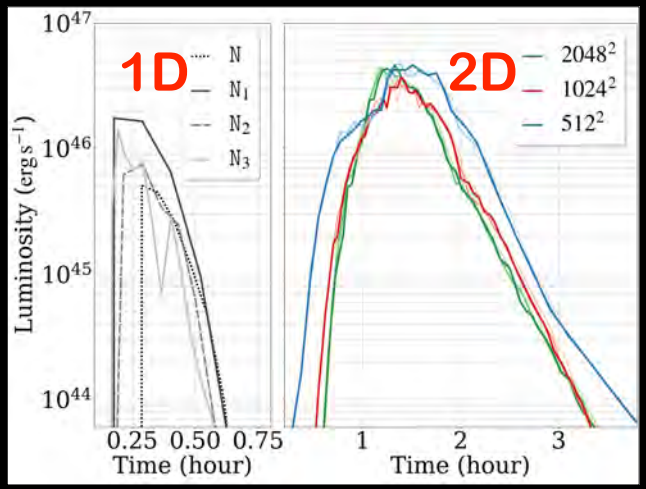
Mixing on Breakout Signatures

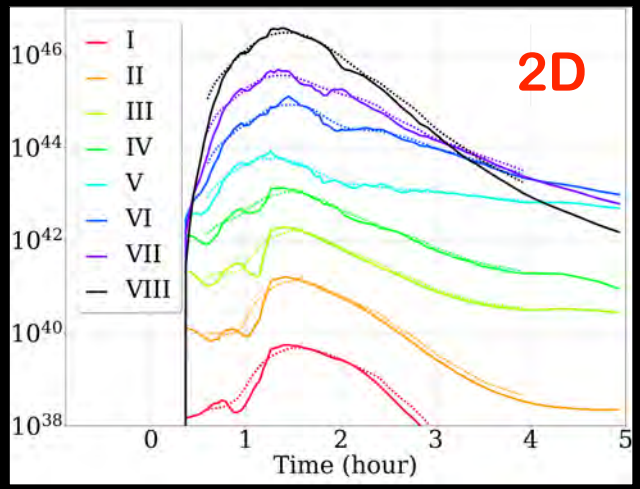
New 2D radiation transport simulations with CASTRO

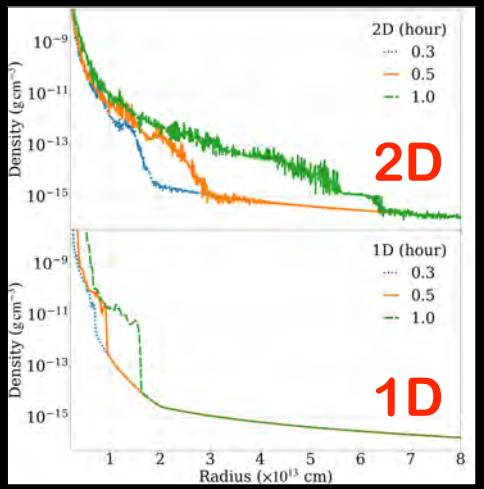


Wun-Yi Chen









Chen W.-Y., KC, Ono, 2024, ApJ, 976, 147.

Low Energy SNe



12 M⊙ < M* < 60 M⊙

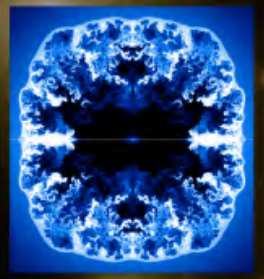
Trigger: iron core collapse

Dynamite: G-energy and neutrino

Characteristics:
1. 10,000+ fainter than normal SN
2. Almost no Ni ejecta
3. Strong mixing during fallback

Chen+ MNRAS 467 4731 (2017)

Magnetar-powered SNe



30 M⊙ < M* < 45 M⊙

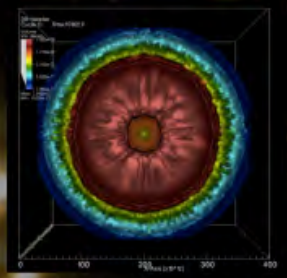
Trigger: iron core collapse

Dynamite: magnetar energy

Characteristics:
1. Luminous SN or GRB
2. < 0.1 M⊙ Ni
3. Radiation breakout at early on

Chen+ ApJ 832 73 (2016)

Pulsational Pair-Instability SNe



80 M⊙ < M* < 140 M⊙

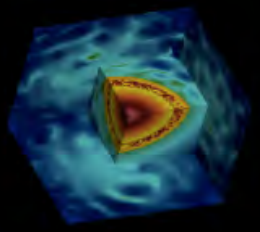
Trigger: e+/e- creation instability

Dynamite: explosive C/O burning

Characteristics:
1. Several eruptions
2. Multi-SNe (one superluminous)
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Chen+ ApJ 792 28 (2014)

Pair-Instability SNe



140 M⊙ < M* < 250 M⊙

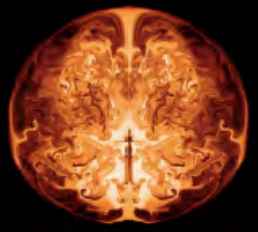
Trigger: e+/e- creation instability

Dynamite: explosive O/Si energy

Characteristics:
1. faint or superluminous SN
2. 0.2 to 30 M⊙ Ni
3. Mixing by reverse shock or burning

Chen+ ApJ 792 44 (2014)

GR Instability SNe



54,000 M⊙ < M* < 56,000 M⊙

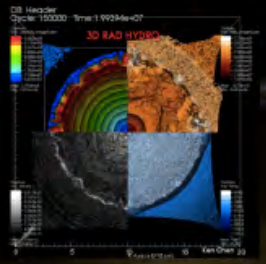
Trigger: GR instability

Dynamite: explosive He burning

Characteristics:
1. Energetic explosion ~ 1E55 erg
2. No Ni and no superluminous
3. Mixing by burning

Chen+ ApJ 790 162 (2014)

Radhydro models of Exotic SNe



30 M⊙ < M* < 140 M⊙

To advance the state of the art in synthetic light curves and spectra for SNe of massive stars, We perform multidimensional radiation hydrodynamics simulations to obtain their light curves and use time-dependent monte carlo radiative transfer calculations to retrieve the detailed spectra that can be directly compared to actual data..

KC+ ApJ 955 39 (2023)

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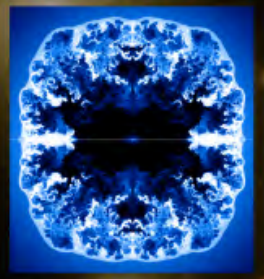
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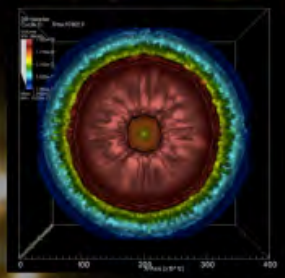
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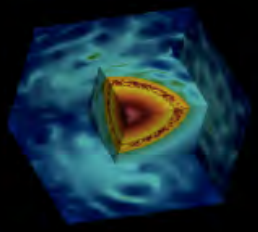
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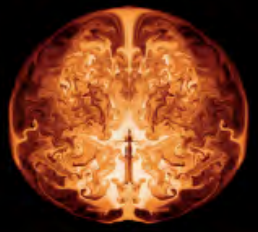
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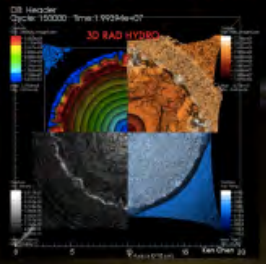
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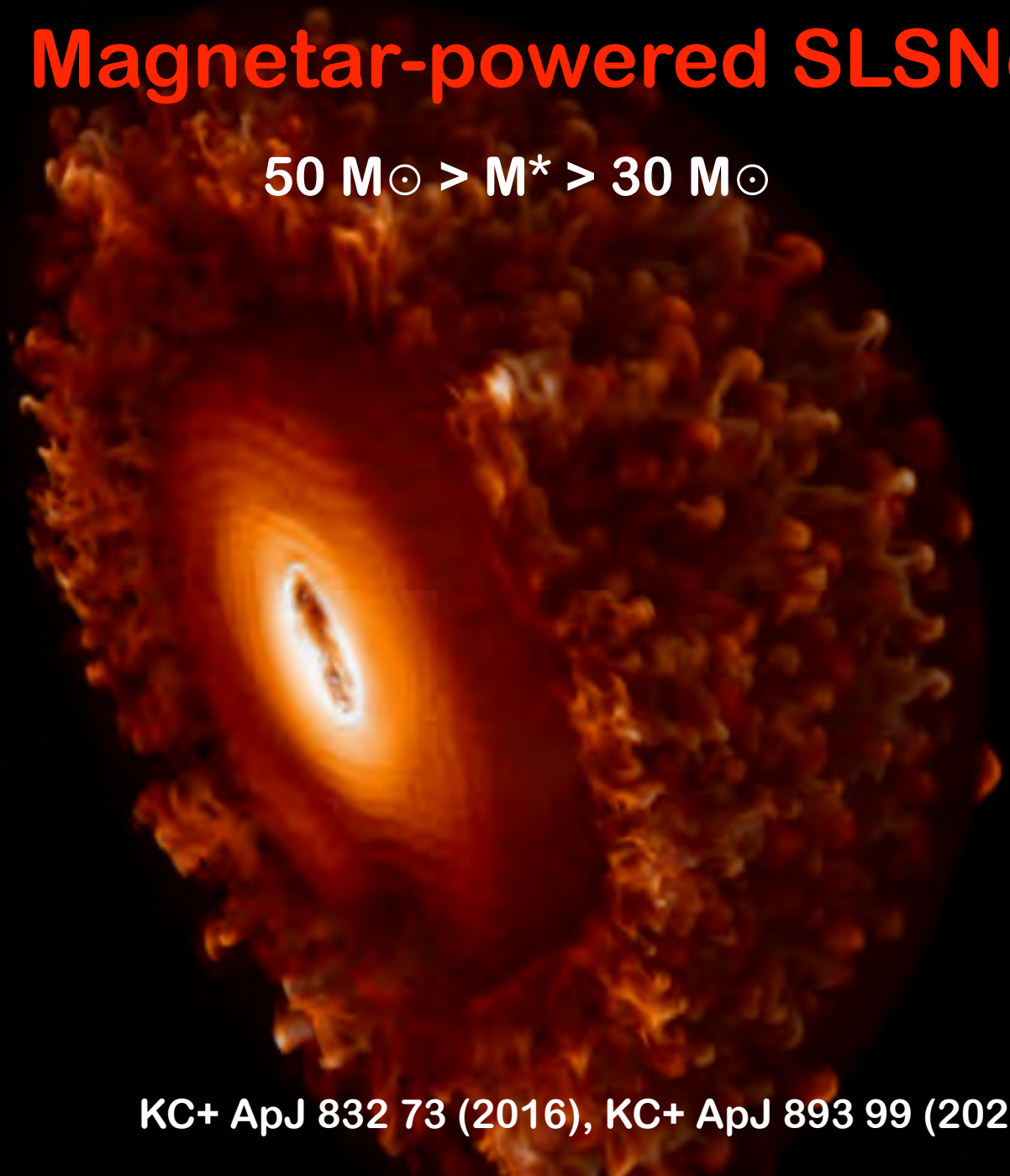
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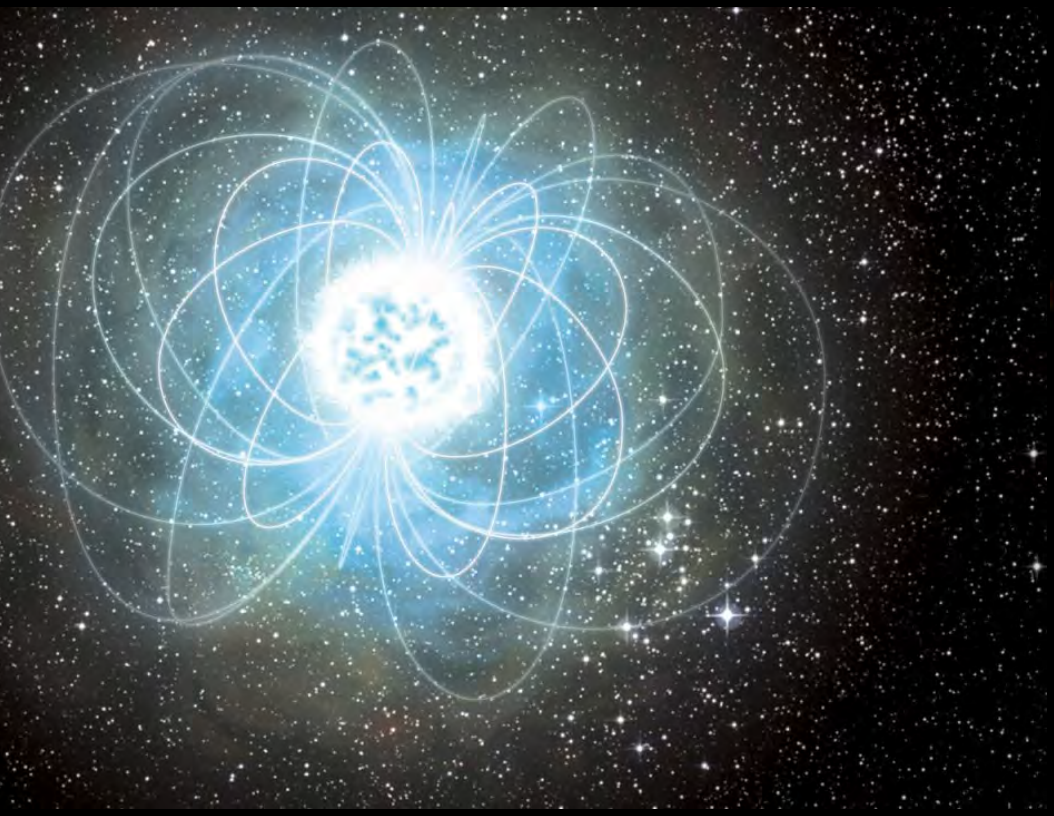
50 M⊙ > M* > 30 M⊙



KC+ ApJ 832 73 (2016), KC+ ApJ 893 99 (2020)

How magnetic field and rotation help to power SLSNe?

Original Ideas from Maeda, Kasen, Bildsten, Woosley

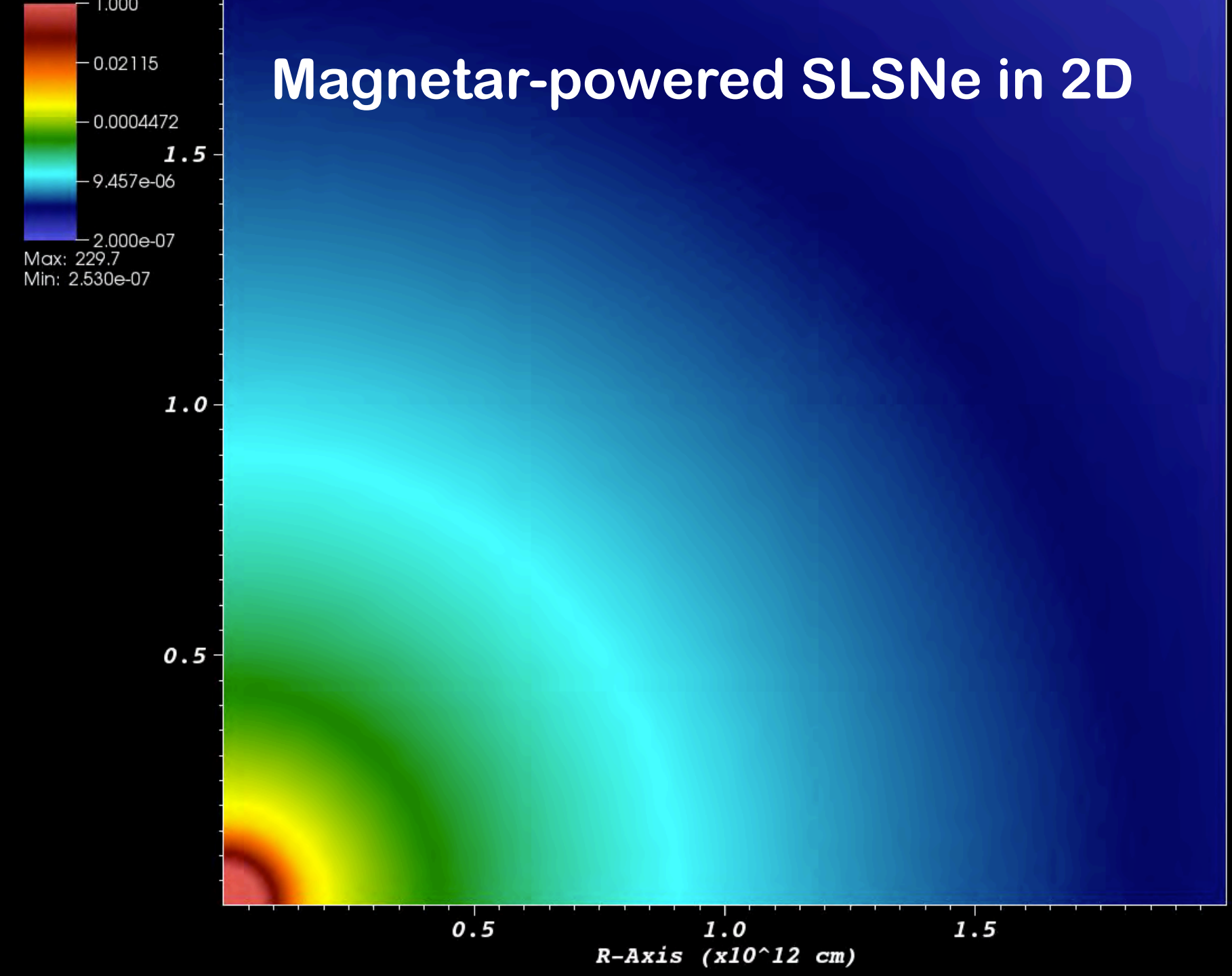


$$E = \frac{1}{2} I \omega^2 \approx 2 \times 10^{52} P_{ms}^{-2} \quad \text{erg}.$$

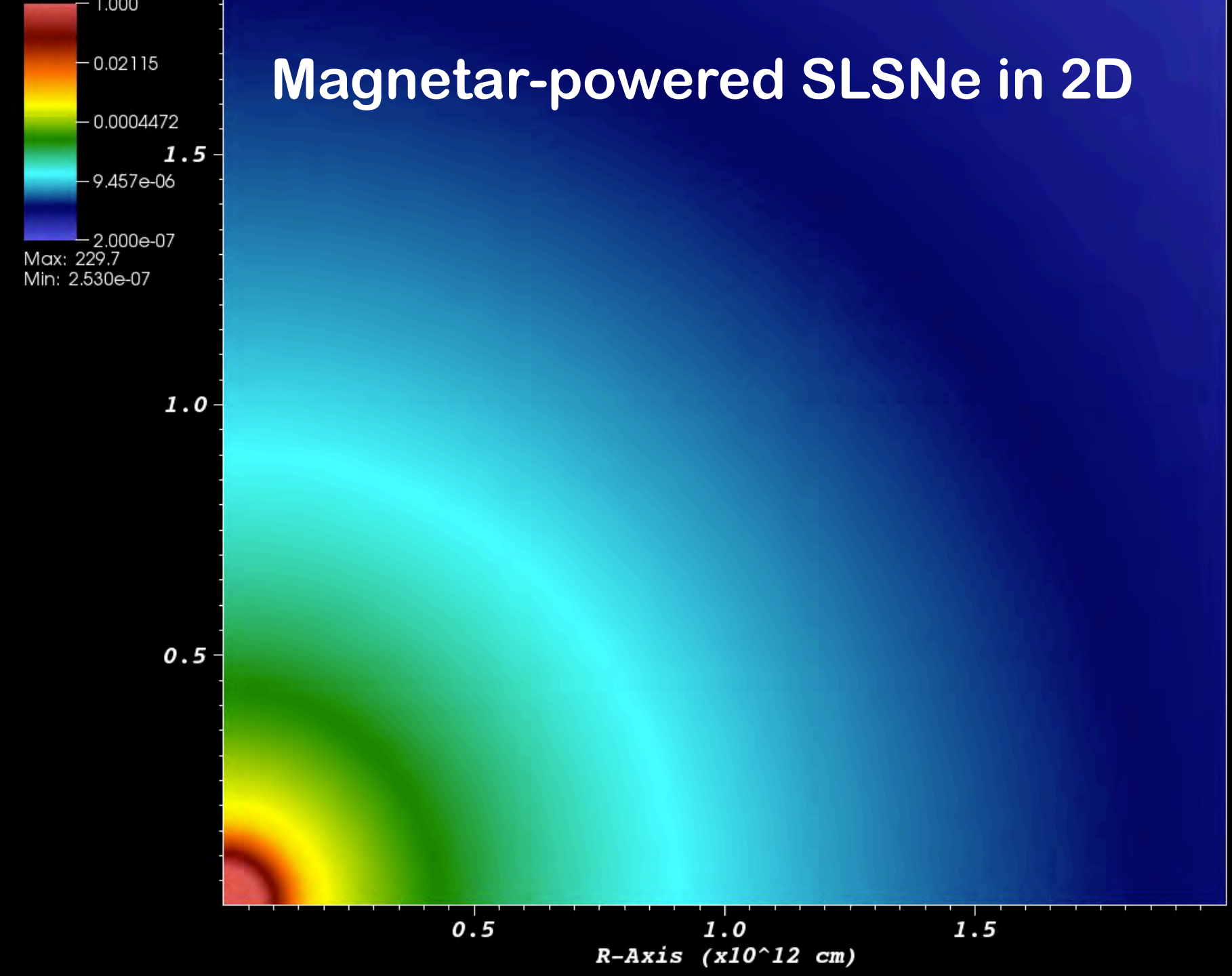
$$L_m = -\frac{32\pi^4}{3c^2} (B R_{ns}^3 \sin\alpha)^2 P^{-4}$$
$$\approx -1.0 \times 10^{49} B_{15}^2 P_{ms}^{-4} \quad \text{erg s}^{-1}$$

$$P(t) \approx (1 + t/t_m)^{1/2} P_0 \text{ ms},$$
$$L(t) \approx (1 + t/t_m)^{-2} E_0 t_m^{-1} \text{ erg s}^{-1},$$
$$E(t) \approx (1 + t/t_m)^{-1} E_0 \text{ erg},$$

where $P_0 = P_{ms}(0)$, $E_0 = E(P_0)$ and $t_m \approx 2 \times 10^3 P_{ms}^2 B_{15}^{-2}$

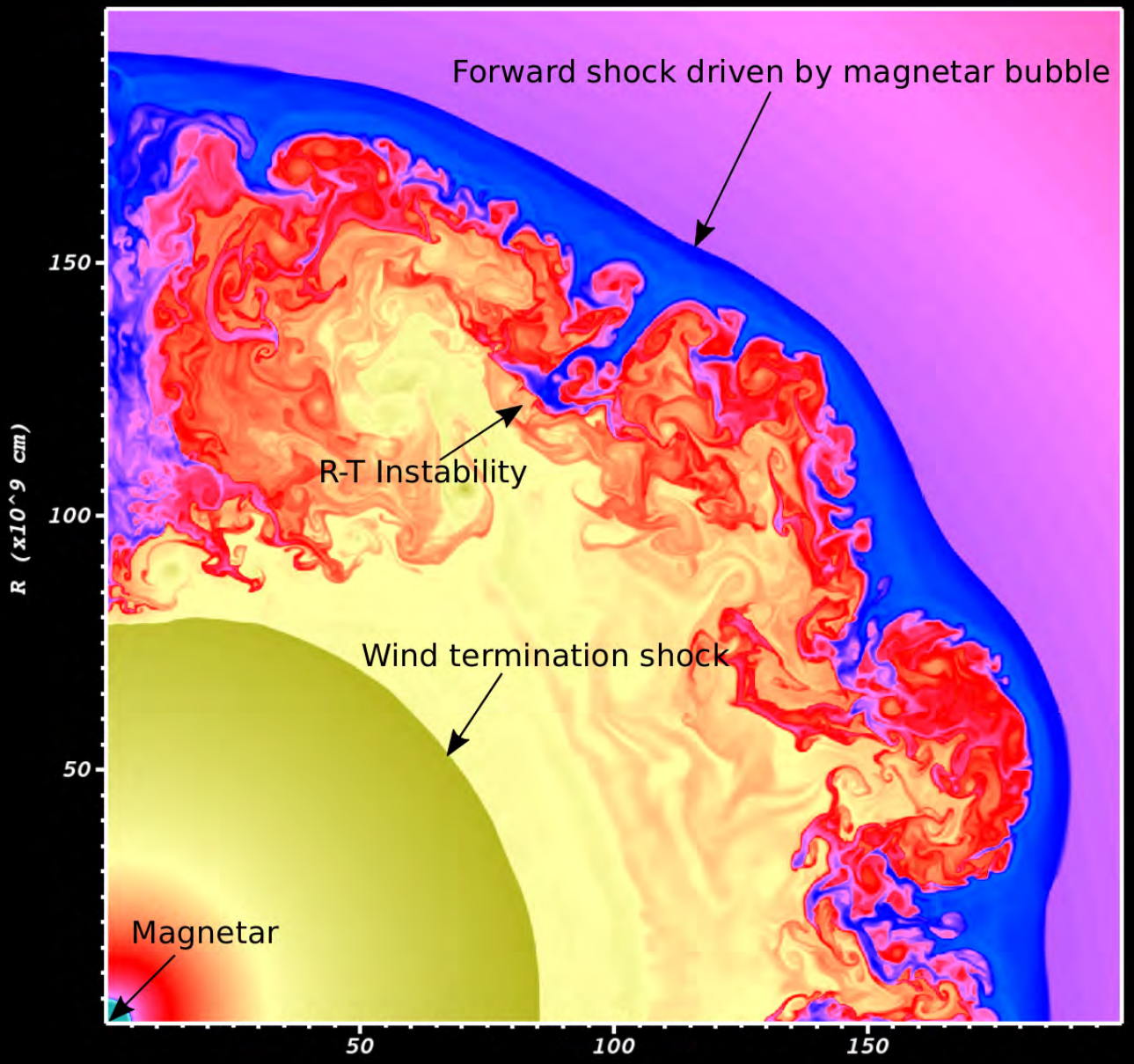


Magnetar-powered SLSNe in 2D



Magnetar-powered SLSNe in 2D

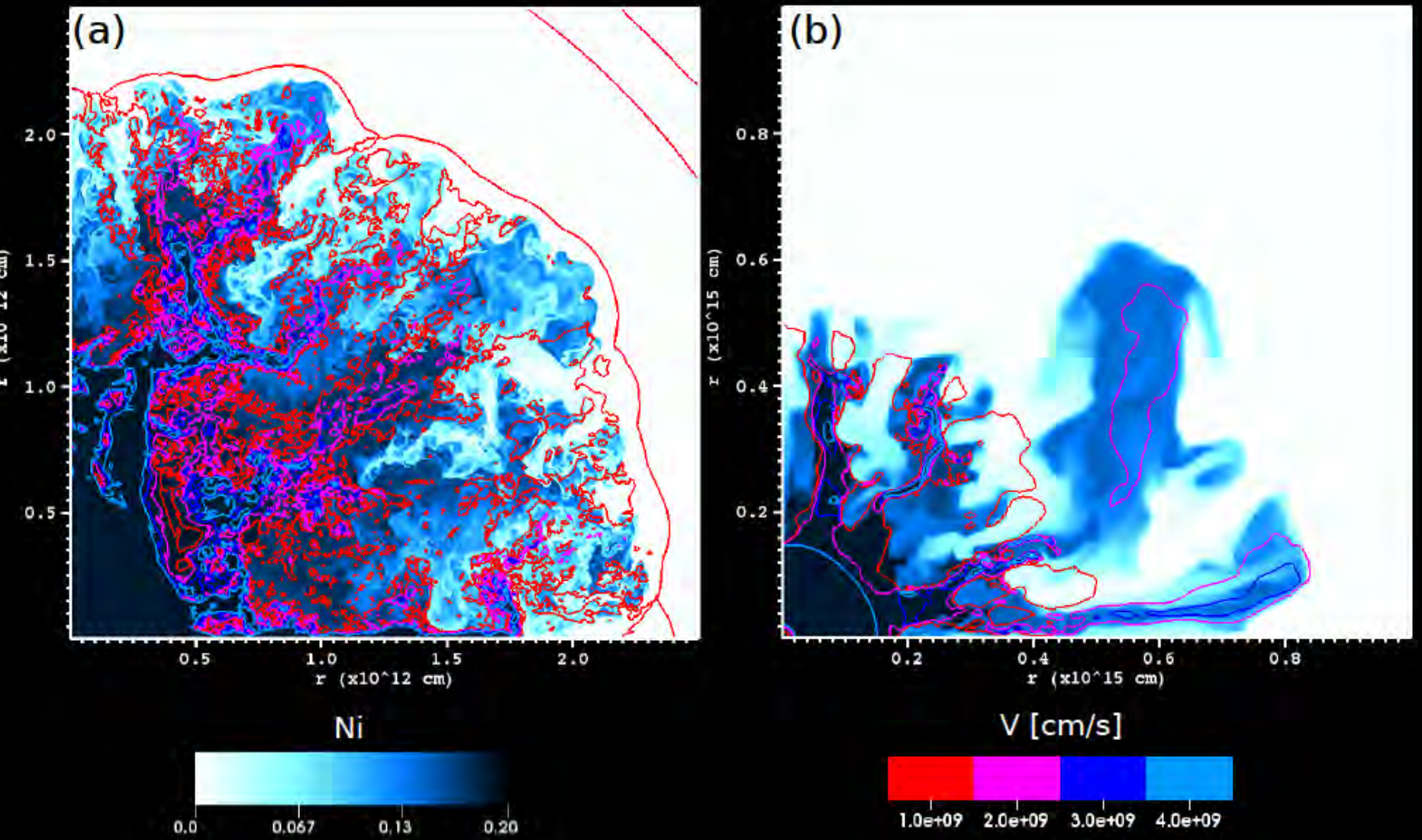
Mixing Structure



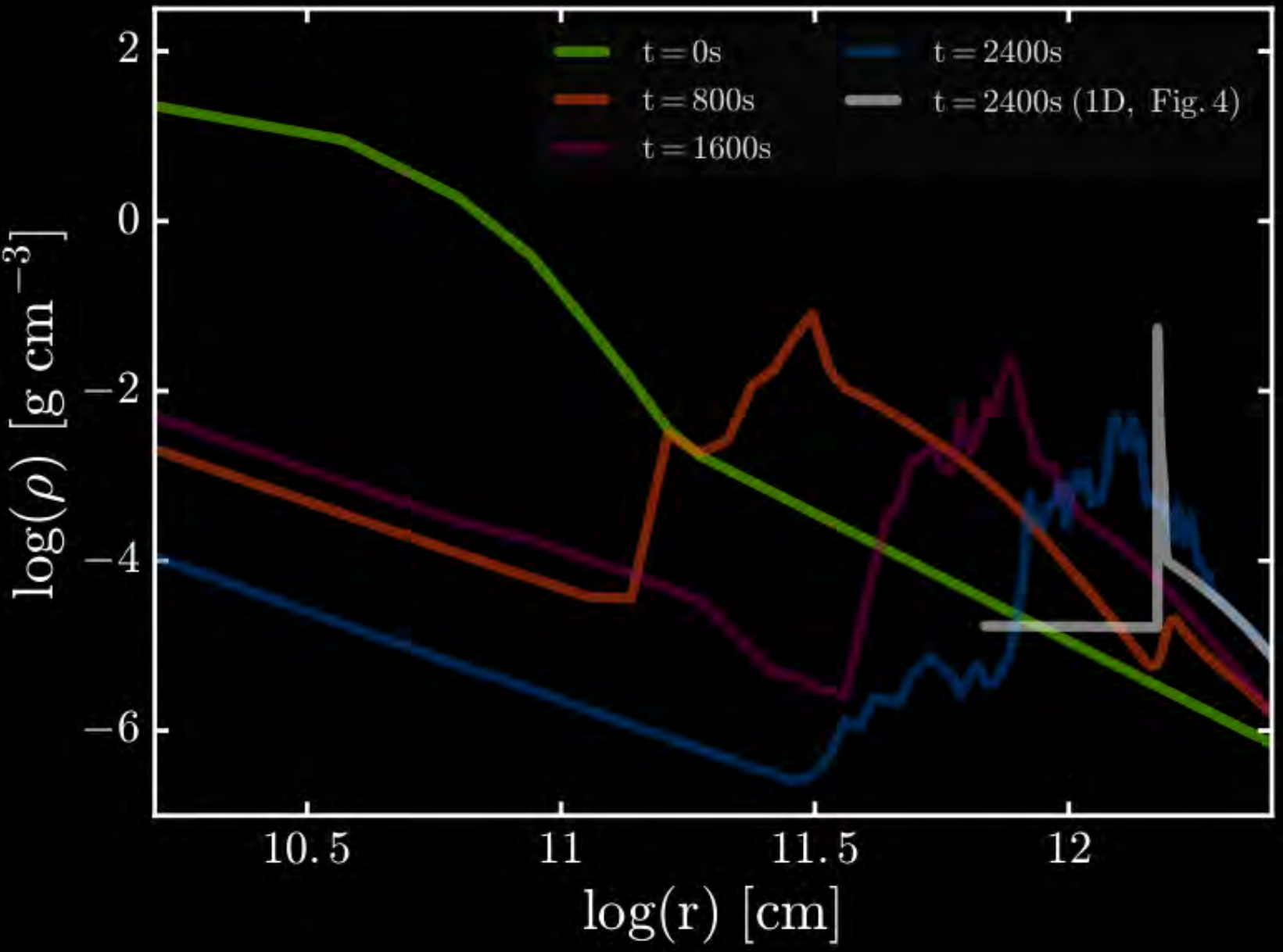
Radiation Breakout

P = 1 ms, B = 4E14 G

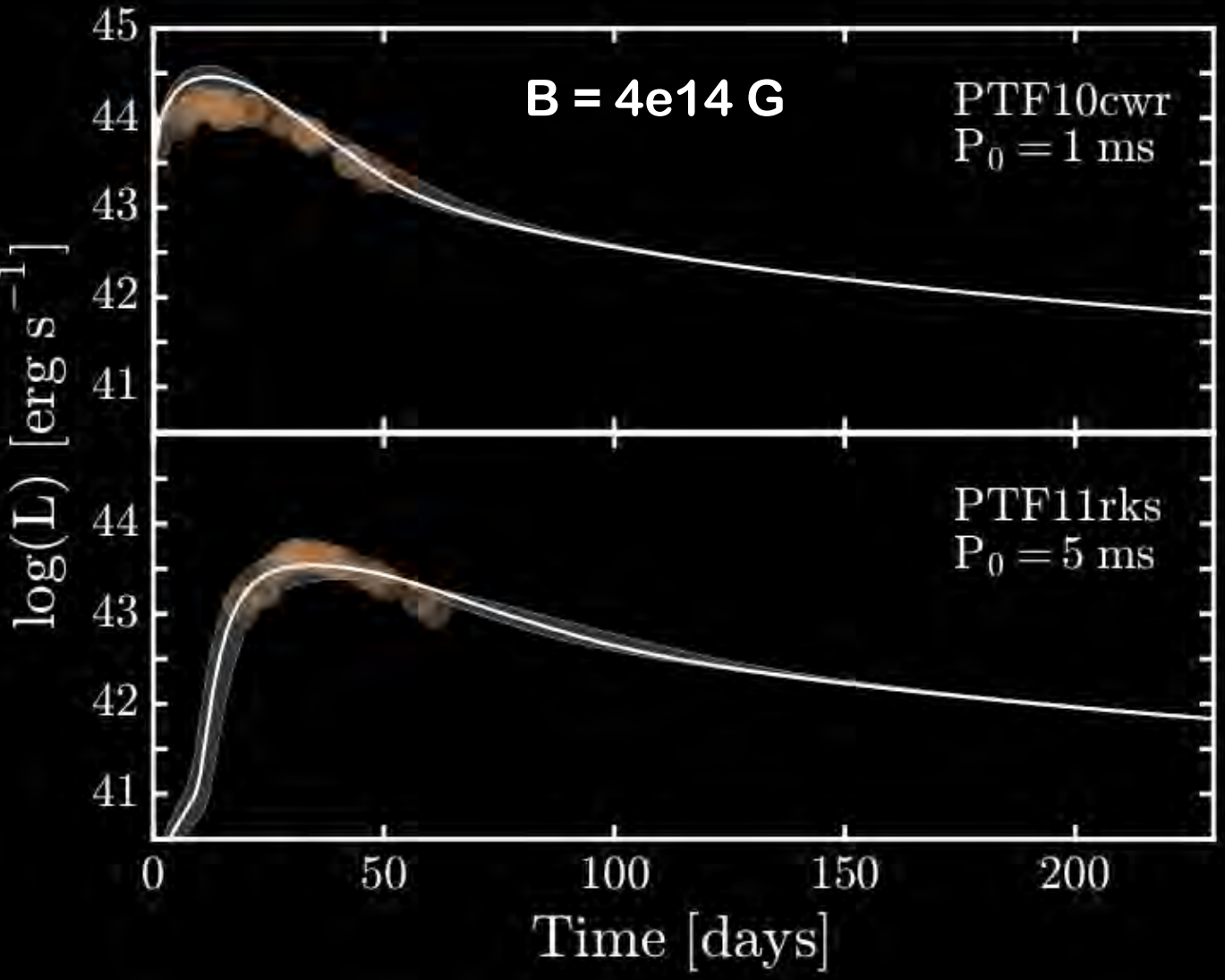
P = 5 ms, B = 4E14 G



1D vs 2D

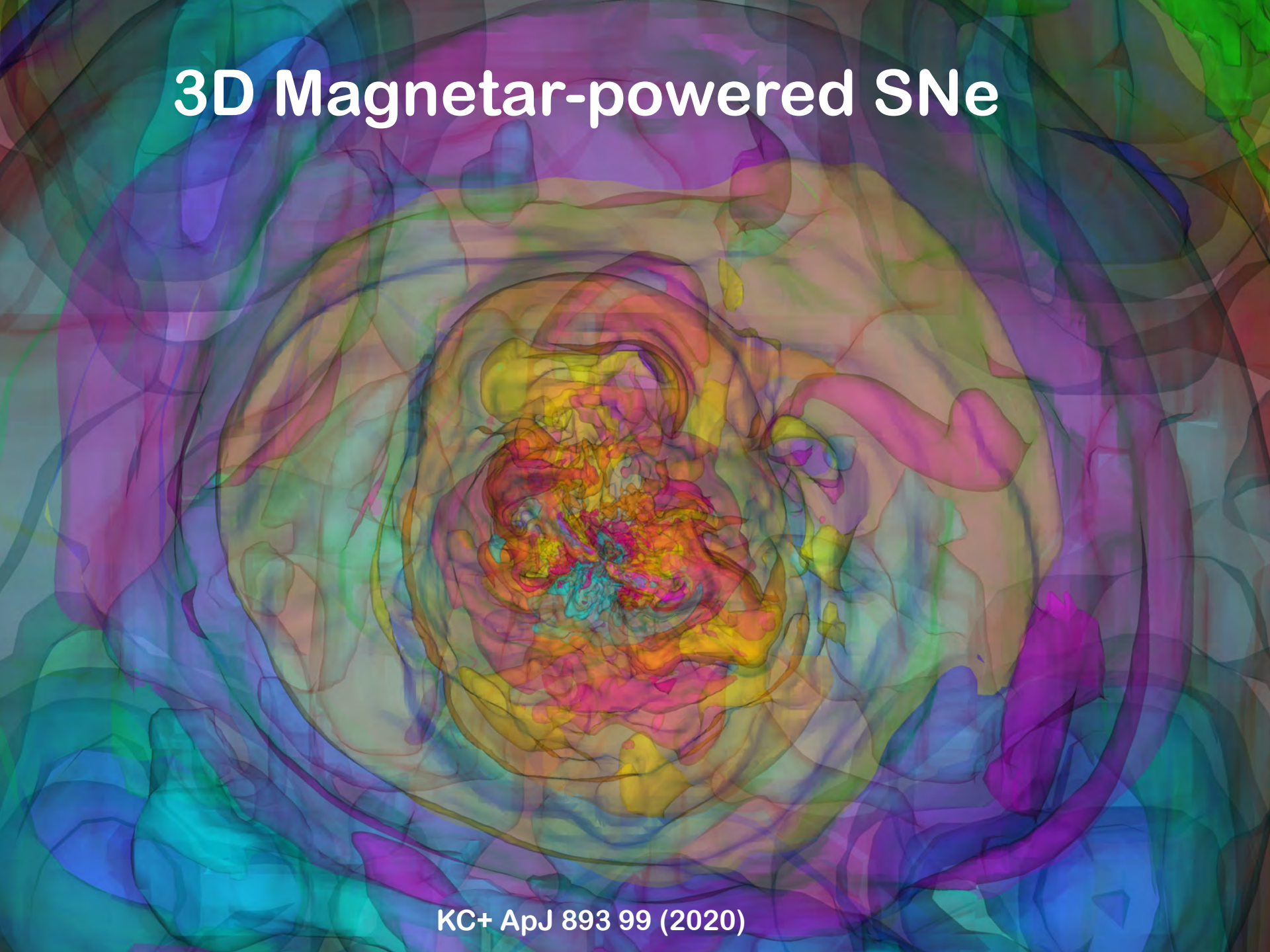

t = 0s
t = 800s
t = 1600s
t = 2400s
t = 2400s (1D, Fig. 4)
2
0
−2
−4
−6
log(ρ) [g cm⁻³]
10.5
11
11.5
12
log(r) [cm]

Superluminous SNe by Magnetar

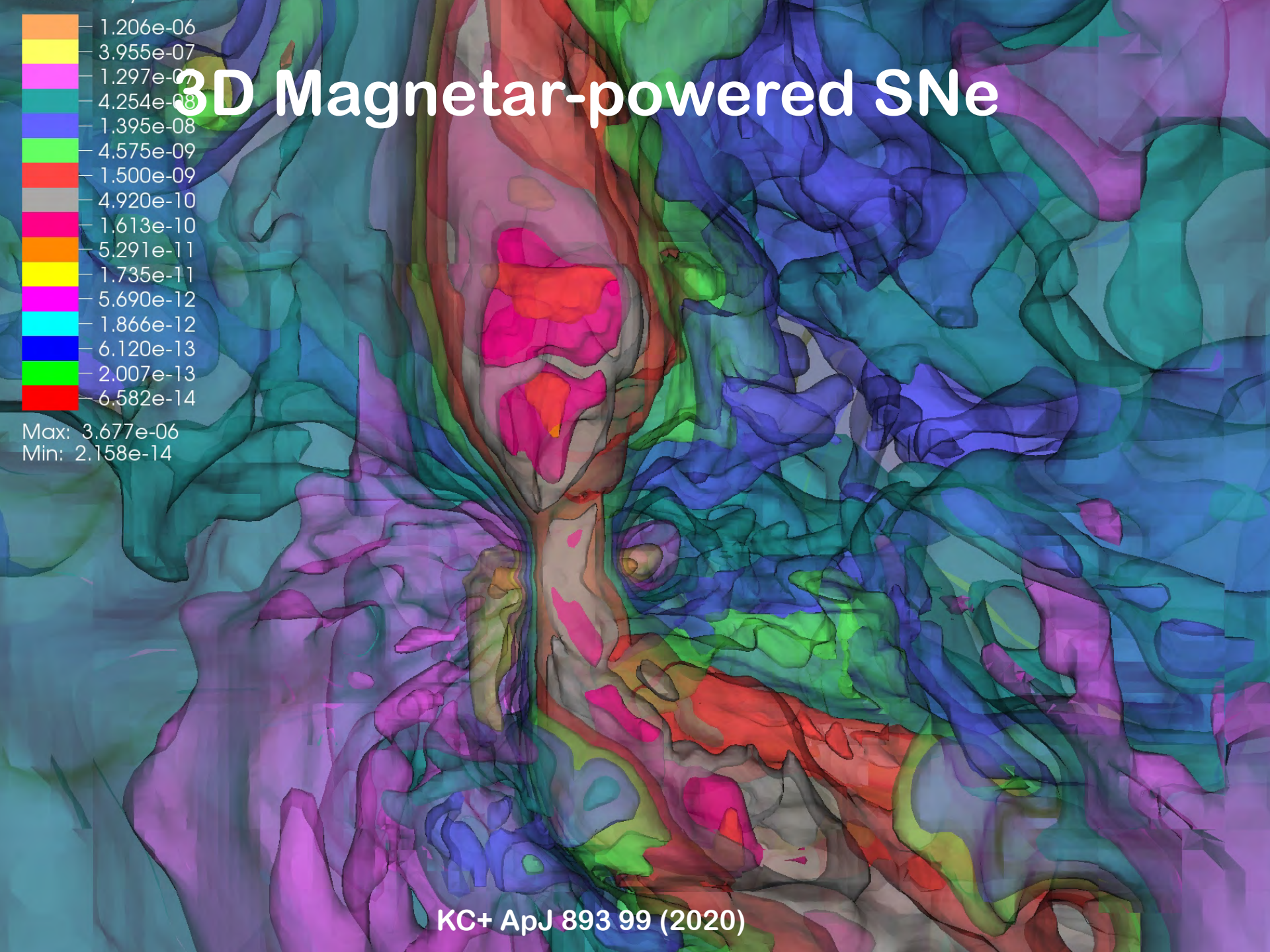


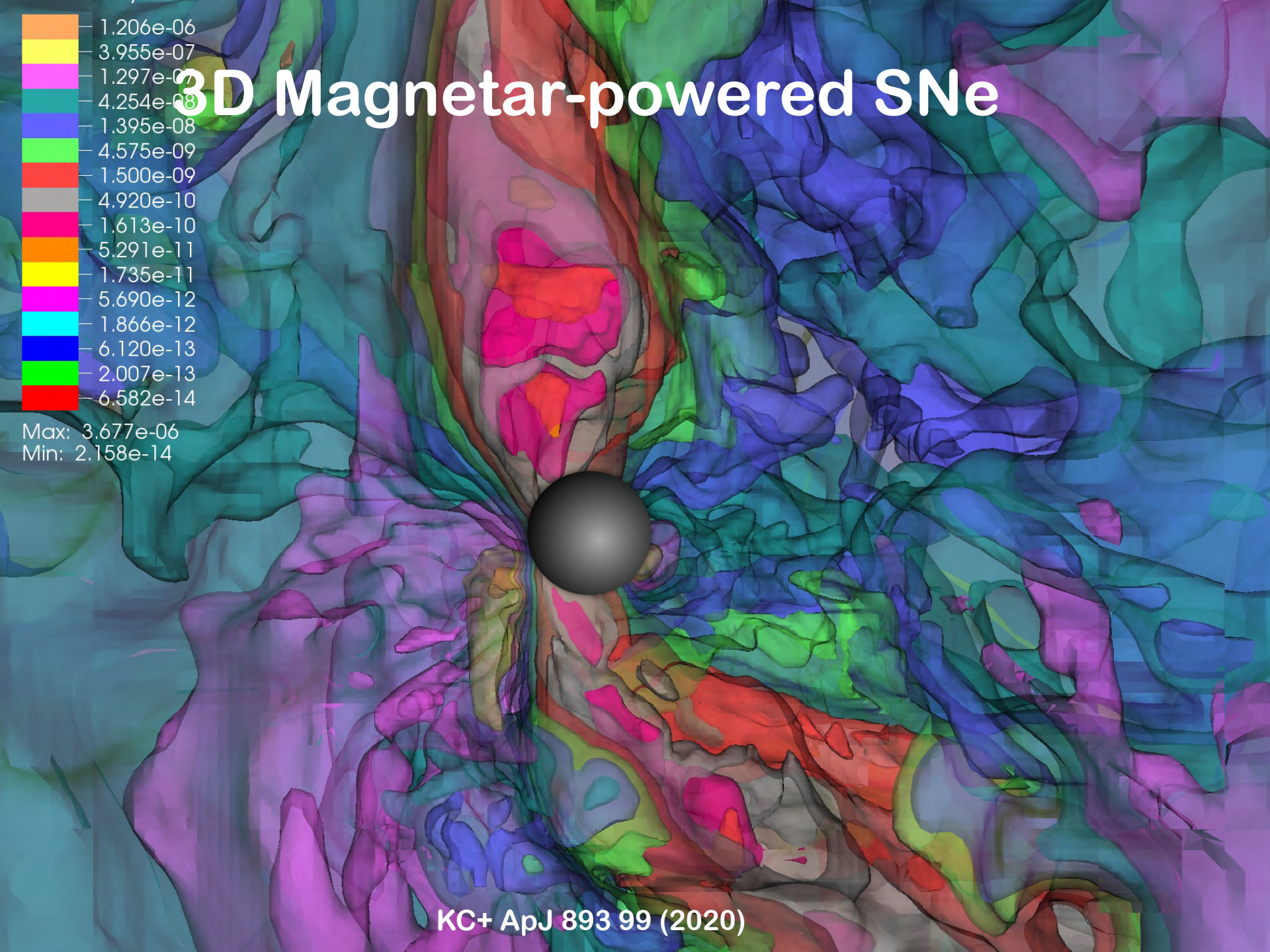
KC+ ApJ 832 73 (2016)

3D Magnetar-powered SNe



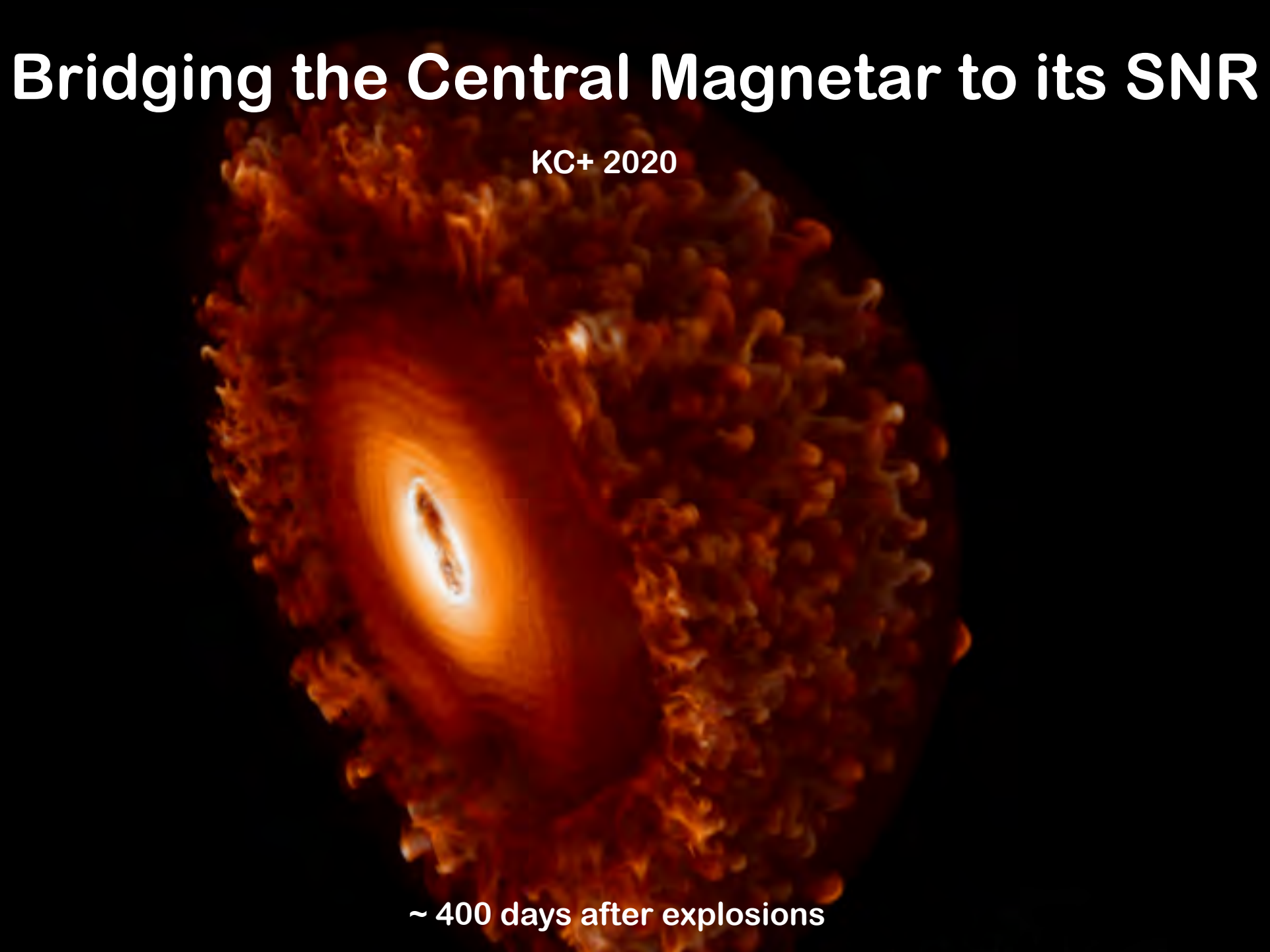
KC+ ApJ 893 99 (2020)


1.206e-06
3.955e-07
1.297e-07
4.254e-08
1.395e-08
4.575e-09
1.500e-09
4.920e-10
1.613e-10
5.291e-11
1.735e-11
5.690e-12
1.866e-12
6.120e-13
2.007e-13
6.582e-14
Max: 3.677e-06
Min: 2.158e-14
3D Magnetar-powered SNe
KC+ ApJ 893 99 (2020)


1.206e-06
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KC+ ApJ 893 99 (2020)

Bridging the Central Magnetar to its SNR

KC+ 2020

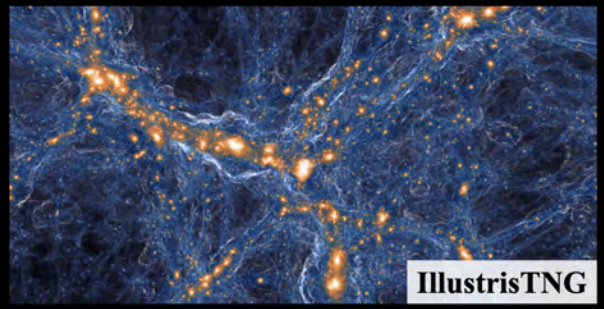


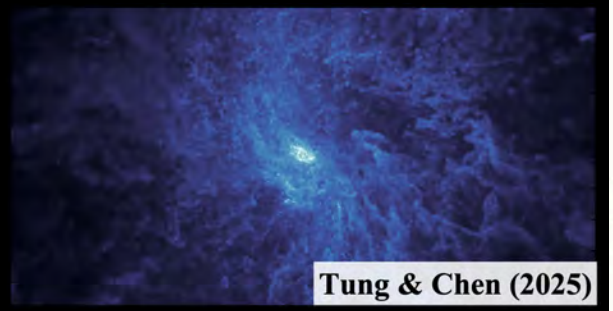
~ 400 days after explosions

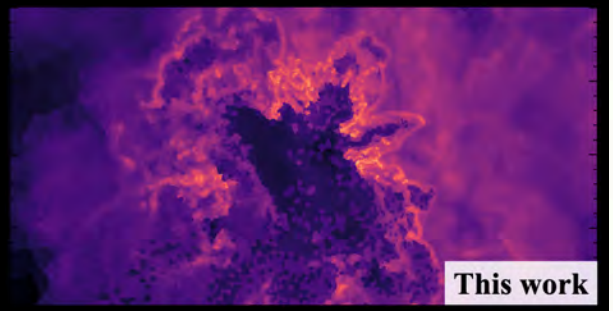
Mixing of SNRs in realistic ISM

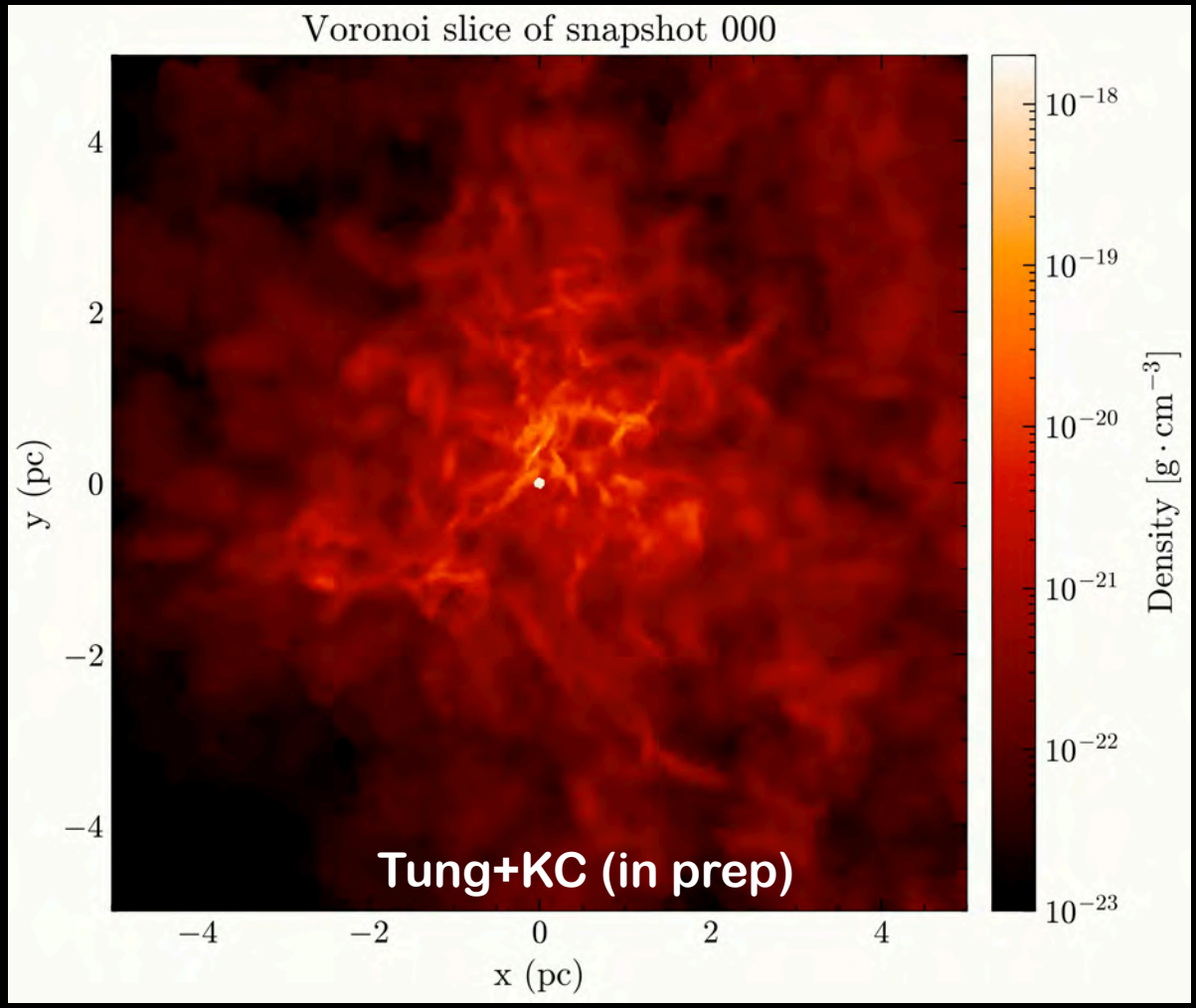


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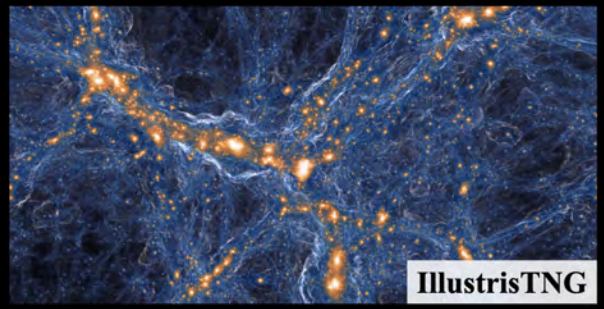


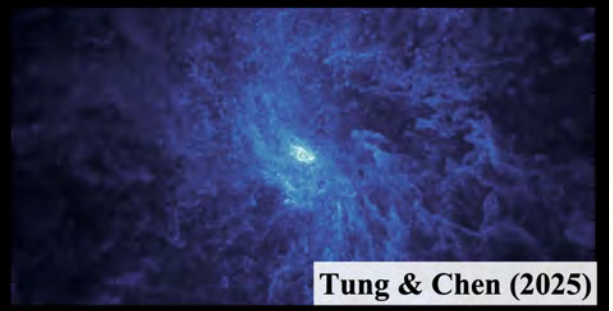


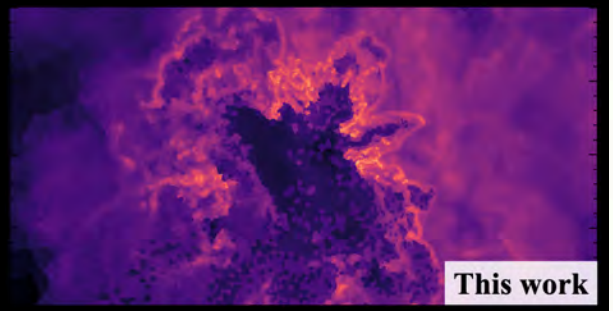
Mixing of SNRs in realistic ISM

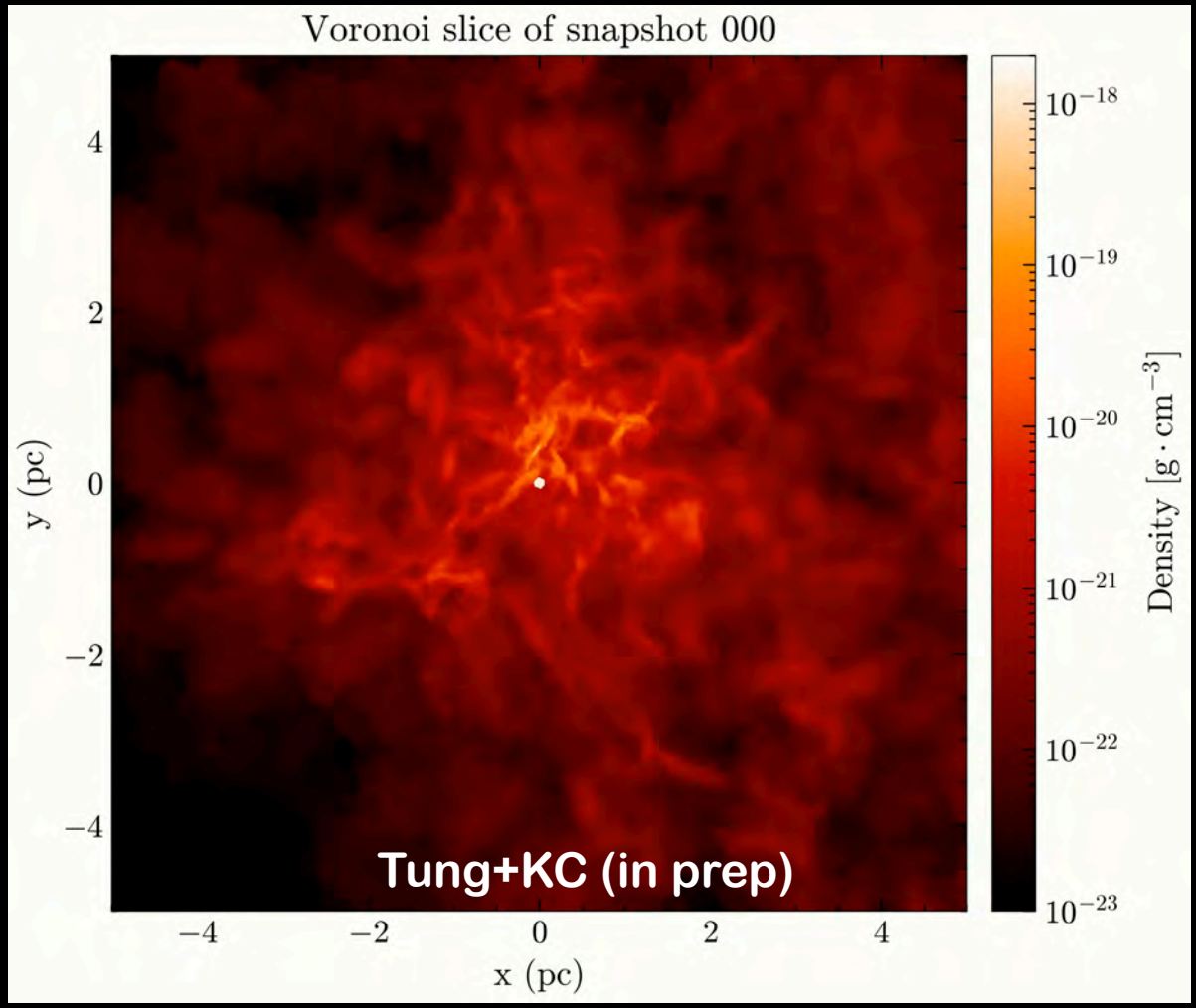


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- Violent mixing occurs at phases of explosions
- Drivers of mixing contain rich physics
- Mixing physics in 1D SN light curves and spectra completely missing
- Multi-D rad-hydro+Micro-physics simulations are powerful tools to model the mixing and signatures properly.