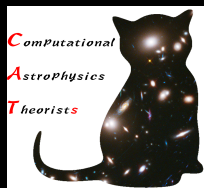


Magnetar-Powered Supernovae



Ke-Jung (Ken) Chen
ASIAA/HITS
ASIOP, March 27th 2026





中央研究院 天文及天文物理研究所

ACADEMIA SINICA
Institute of Astronomy and Astrophysics



ASIAA has approximately **200 staff, including 35 faculty members**. ASIAA has access to forefront observing facilities including **ALMA, SMA, JCMT, CFHT, and Subaru Telescope**. We are partners in the **Subaru Hyper Suprime-Cam (HSC) and Prime Focus Spectrograph (PFS)** projects, and are an associate member of the **SDSS-IV, LSST Surveys**. We recently became a member of **GMT**.

Theoretical and computational astrophysics is pursued in our theoretical group, originally established by Frank Shu. We aim to develop numerical simulators to bridge observations and theories in fluid dynamics, astrochemistry, and radiative transfer.

The Explosion Group at ASIAA



Recent work (2024-2026) from our group

(Topics Including the first stars and galaxies, massive stars, supernovae, black holes, and galaxy evolution)

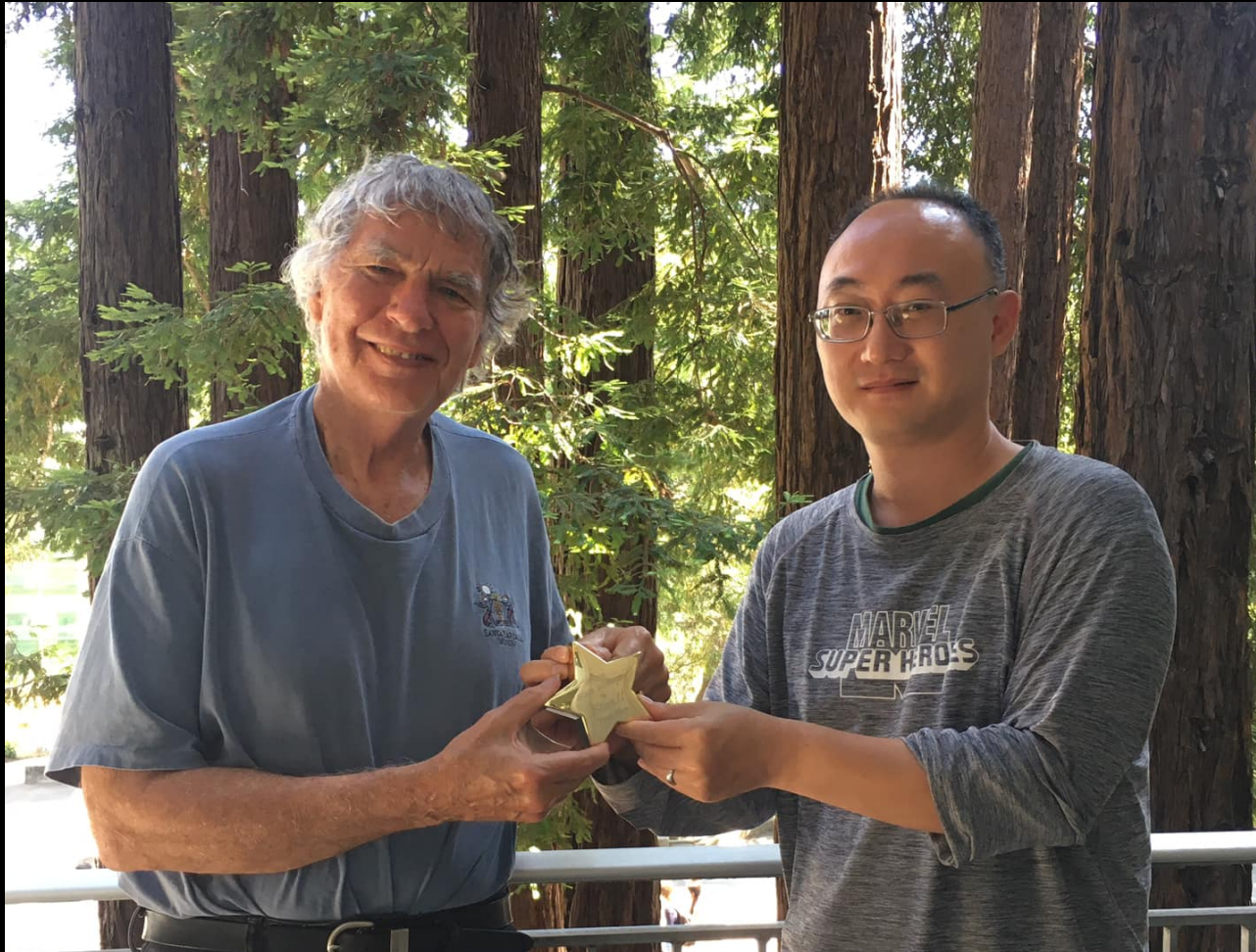
- Chen W-Y; Chen K-J; Maeda K; Ono M; Ou P-S; Roepke FK, "Supernovae Shock Breakout from Red Supergiants in Two Dimensions", ApJ, 2026, 999, 56
- Ou P-S; Chen K-J, "Critical Metallicity of Cool Supergiant Formation. II. Physical Origin", ApJ, 2026, 2026, 999, 109
- Chen K-J; Ho M-Y; Tung P-C, "Formation of Supersonic Turbulence in the Primordial Star-forming Cloud", ApJL: 988(2), id.L67, Aug, 2025
- Matsuoka T; Maeda K; Chen K-J, "Inferring a Dense Confined Circumstellar Medium around Supernova Progenitors via Long-term Hydrodynamical Evolution", ApJL: 988(2), L53 (8pp), Aug, 2025
- Chen KJ, "Origins of supermassive black holes in galactic centers", MPLA: 40 (23), id. 2530007, Jul, 2025
- Tung PC; Chen K-J, "Coevolution of Dwarf Galaxies and Their Circumgalactic Medium Across Cosmic Time", ApJ: 988(1), id.127, Jul, 2025
- Chen W-Y; Chen K-J; Ono M, "Multidimensional Radiation Hydrodynamics Simulations of SN 1987A Shock Breakout", ApJ: 976(1), id.147 (22 pp), Nov, 2024
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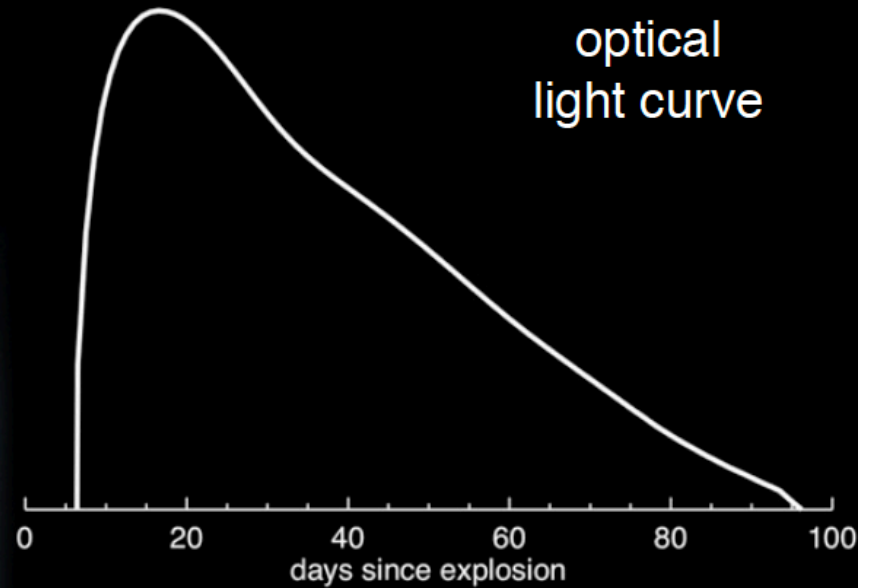
Key supporter for my SN study- Stan Woosley



Visiting Stan at UCSC in 2024 for his 80th birthday

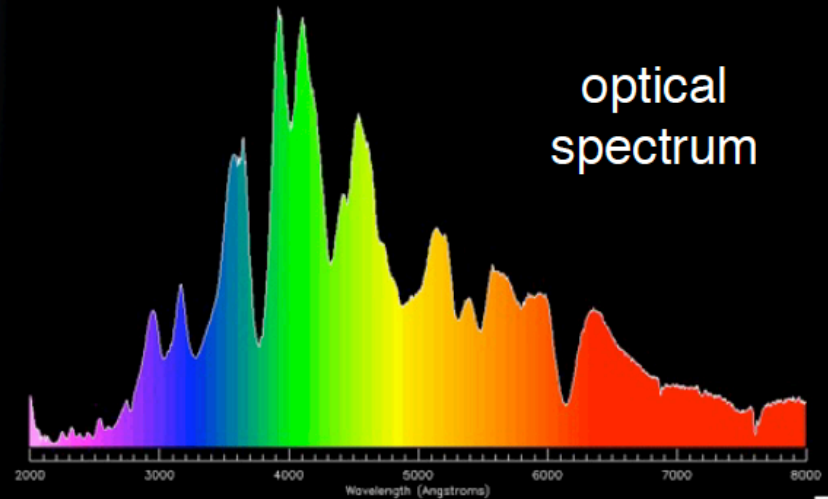
supernovae and the transient universe

optical
light curve



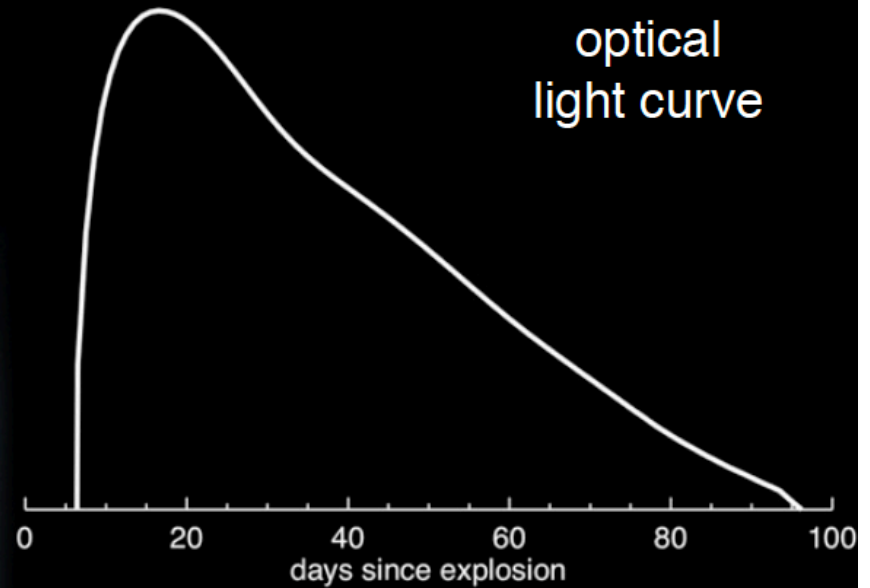
SN 1994D

optical
spectrum

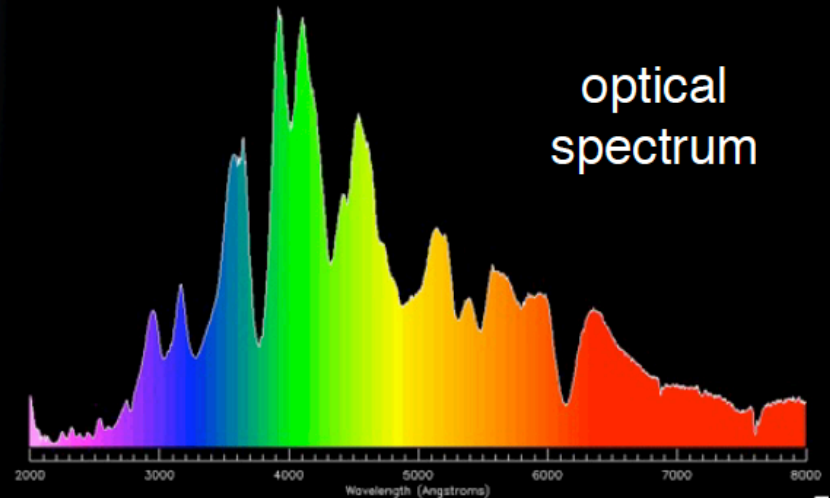


supernovae and the transient universe

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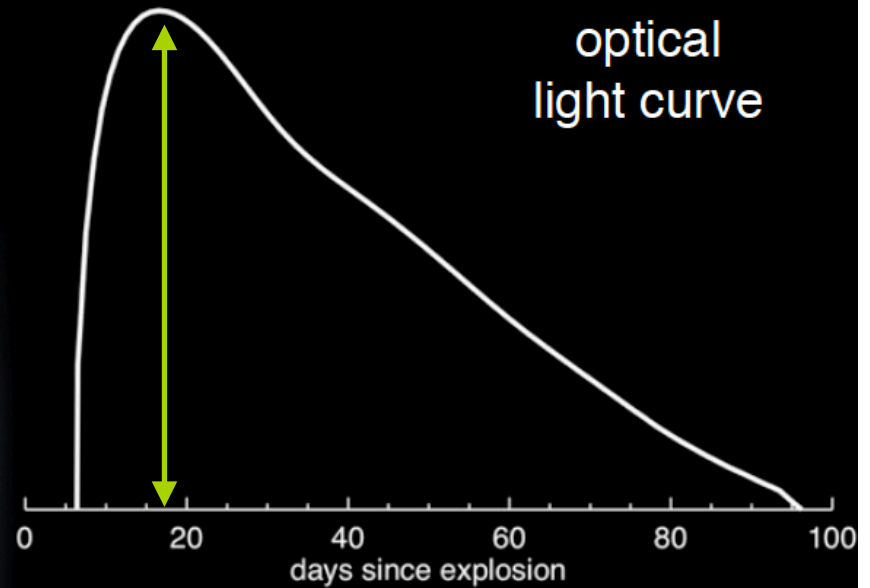


SN 1994D

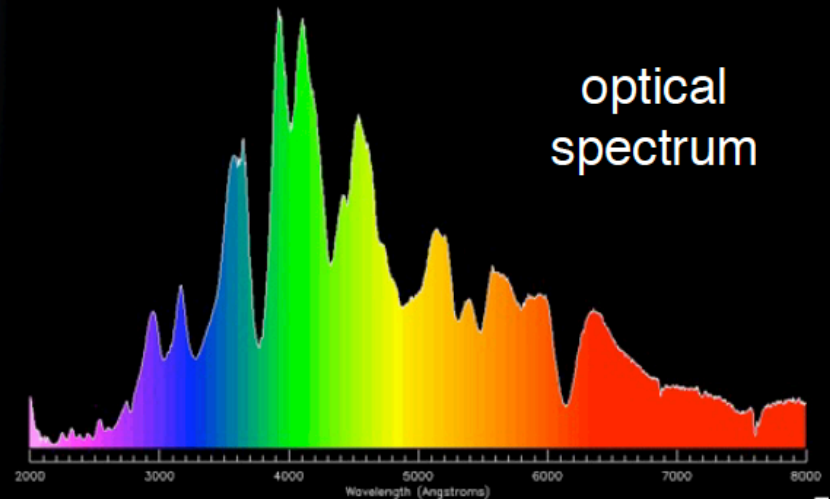


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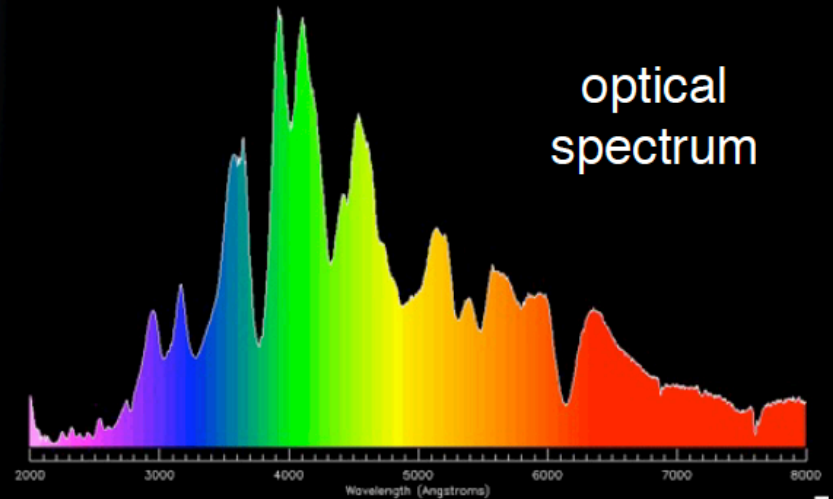
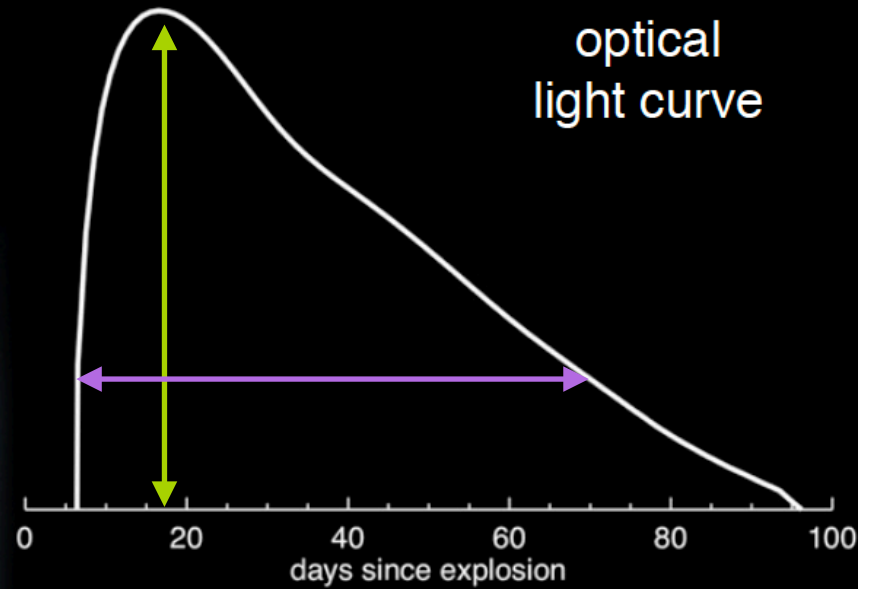
SN 1994D



supernovae and the transient universe



SN 1994D



Understating the physics behind observed SNe

peak luminosity (ergs/sec)

10^{45}

10^{44}

10^{43}

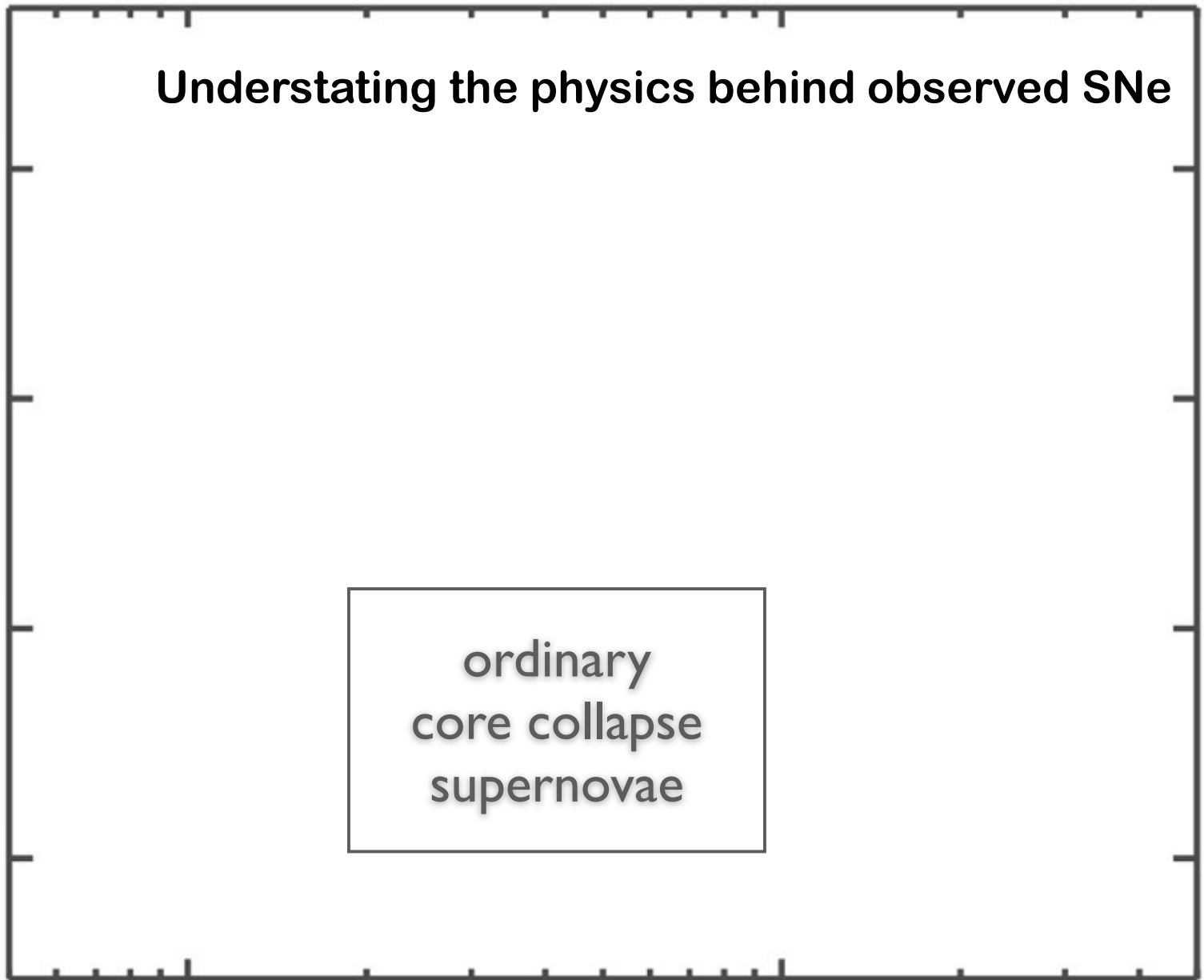
10^{42}

10

100

light curve duration (days)

ordinary
core collapse
supernovae



Understating the physics behind observed SNe

peak luminosity (ergs/sec)

10^{45}

10^{44}

10^{43}

10^{42}

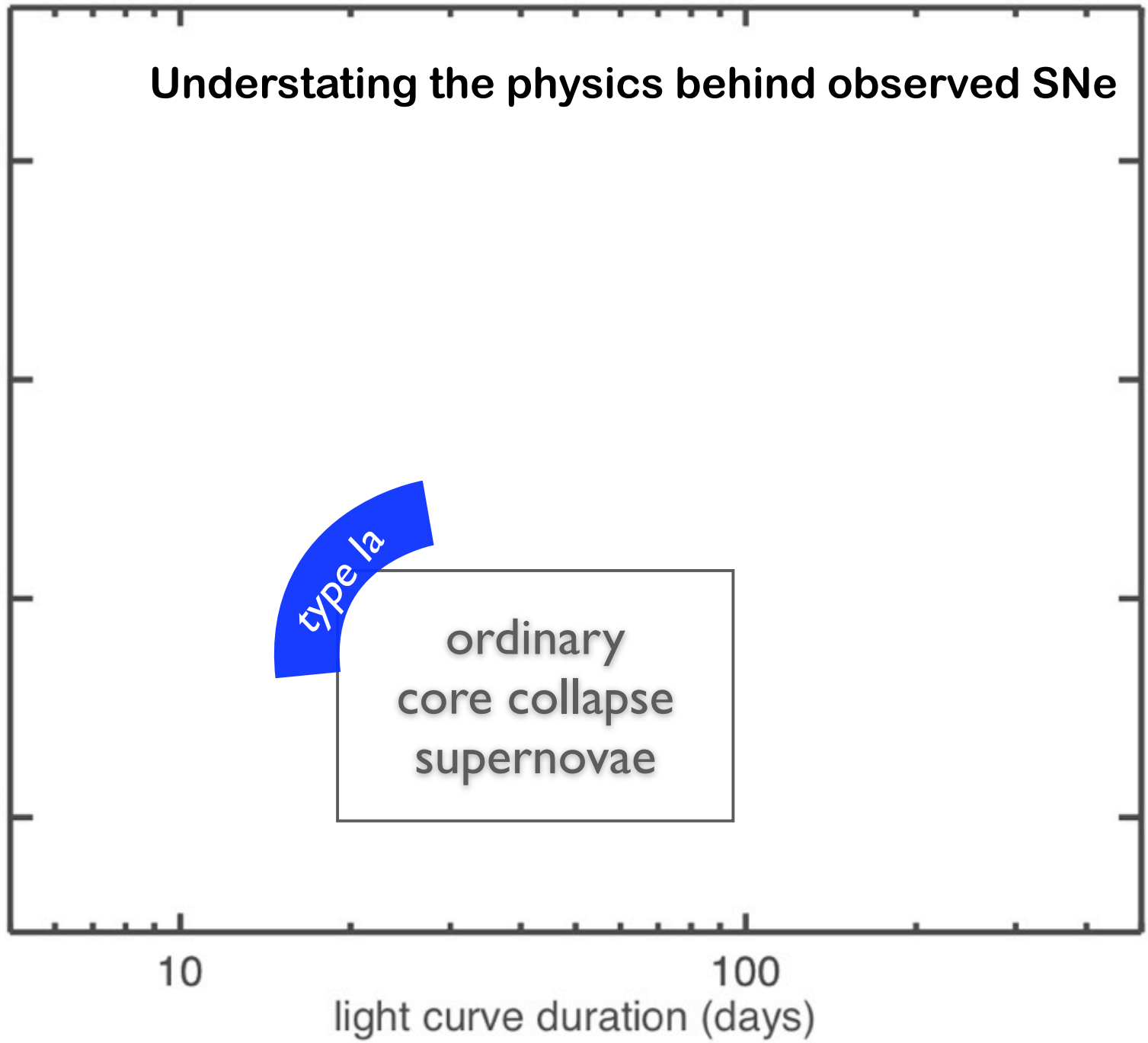
type Ia

ordinary
core collapse
supernovae

10

100

light curve duration (days)



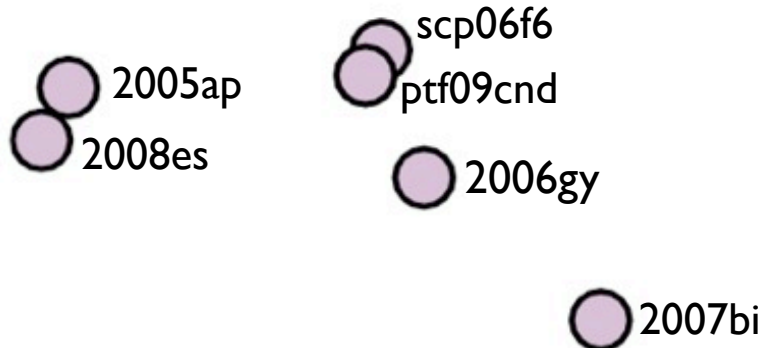
Understating the physics behind observed SNe

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 10^{44}
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 10^{42}

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light curve duration (days)

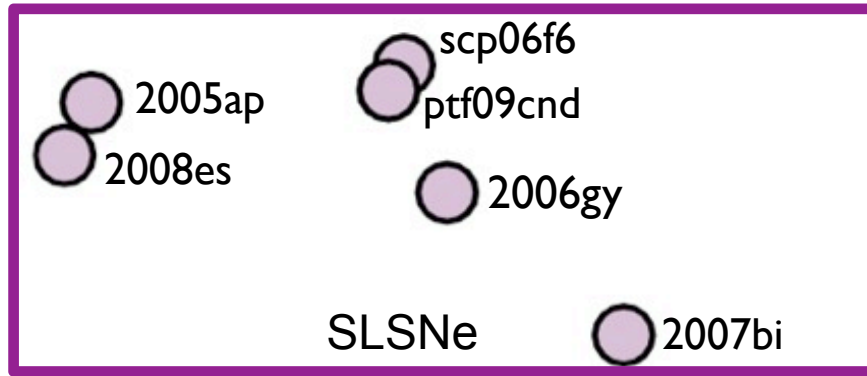
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Understating the physics behind observed SNe

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type Ia

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supernovae

SLSNe

2005ap
2008es

scp06f6
ptf09cnd

2006gy

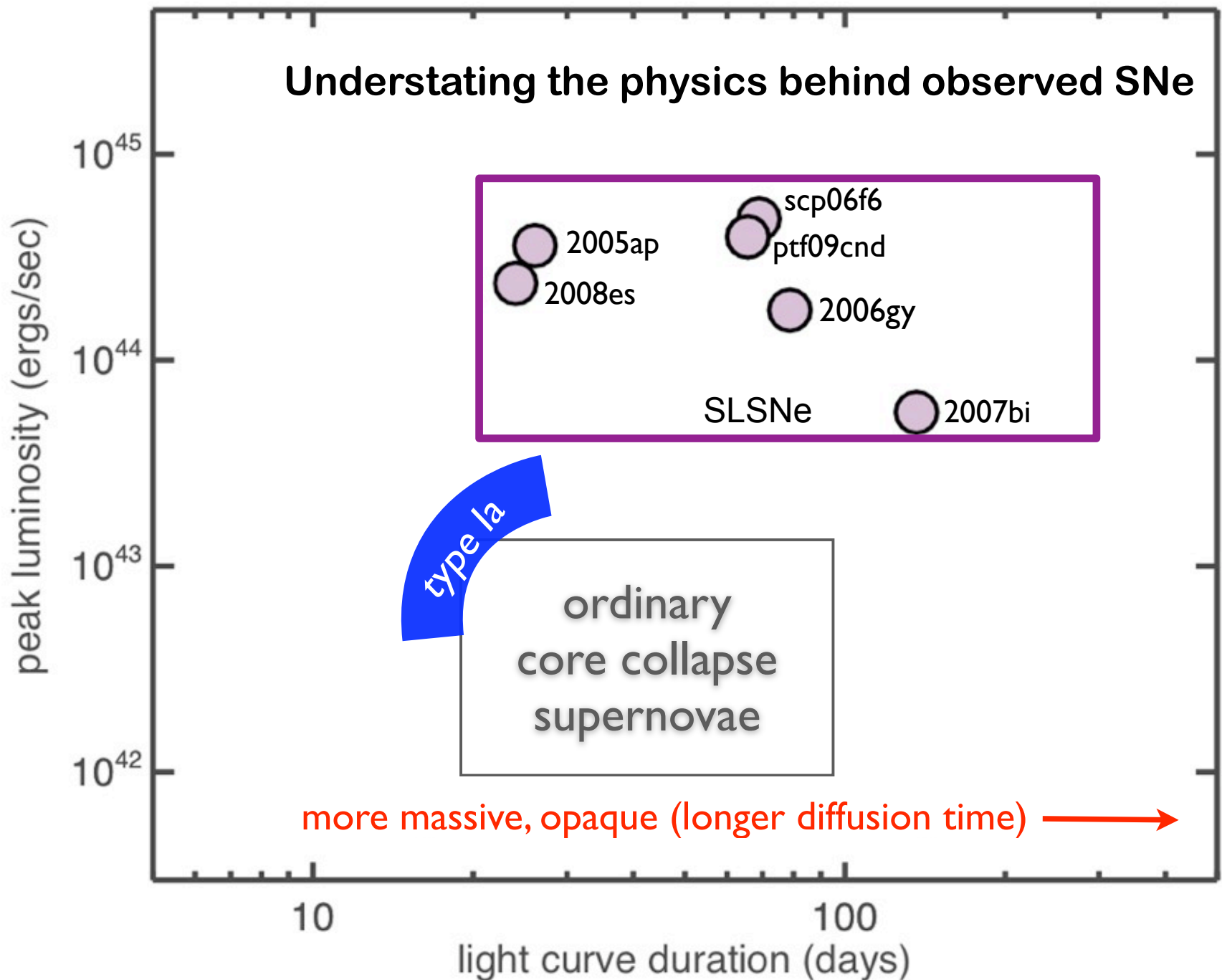
2007bi

more massive, opaque (longer diffusion time) →

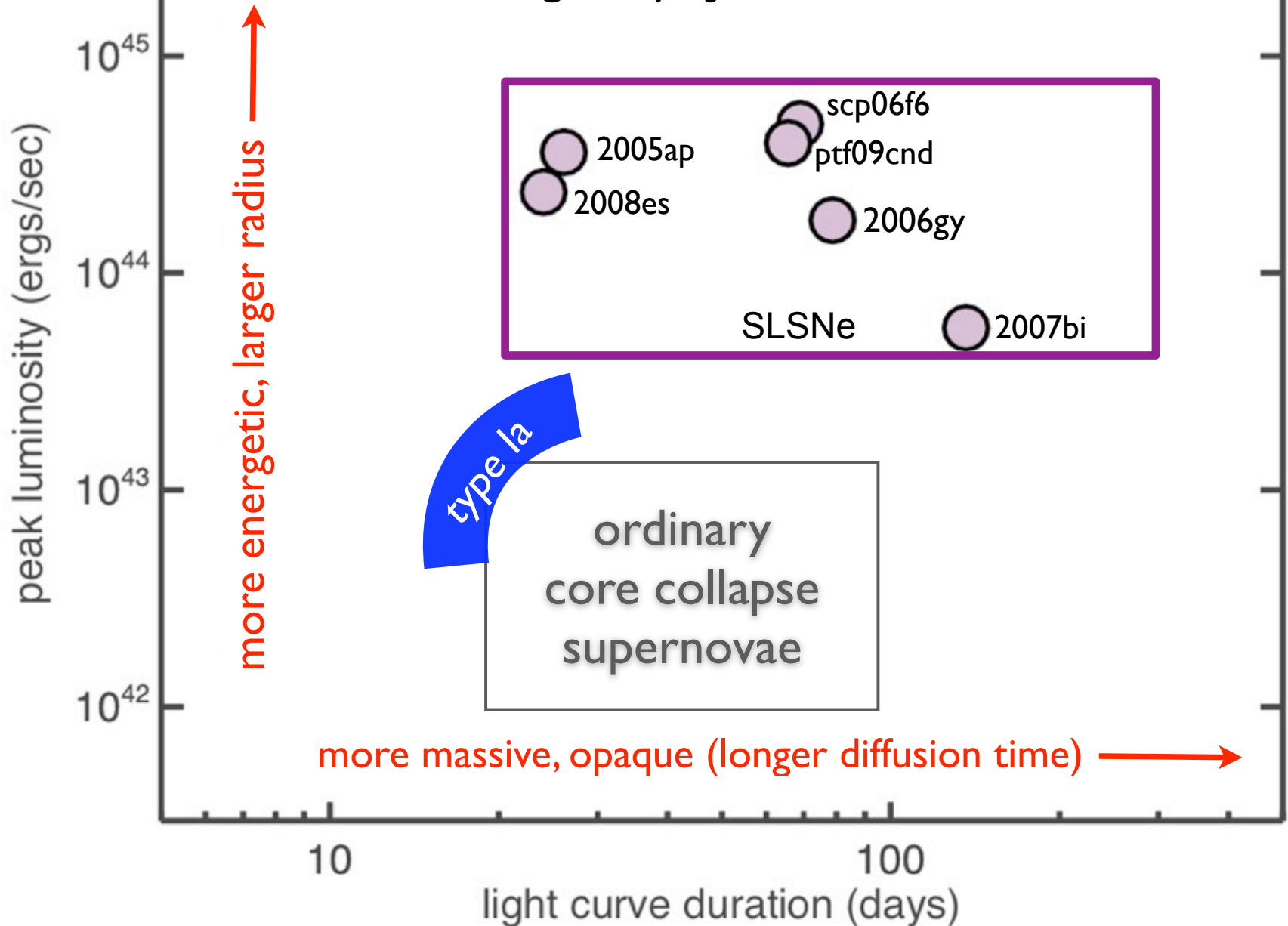
10

100

light curve duration (days)



Understating the physics behind observed SNe



Energy budget of SLSNe luminosity

Radiation energy budget $\sim 10^{51}$ erg

Energy budget of SLSNe luminosity

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Unlikely

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ms Magnetar...

Energy budget of SLSNe luminosity

Radiation energy budget $\sim 10^{51}$ erg

Unlikely

ms Magnetar...

Tons of Ni ($>10 M_{\odot}$) such PSNe

Energy budget of SLSNe luminosity

Radiation energy budget $\sim 10^{51}$ erg

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Kinetic energy to radiation

Energy budget of SLSNe luminosity

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Unlikely

ms Magnetar...

Tons of Ni ($>10 M_{\odot}$) such PSNe

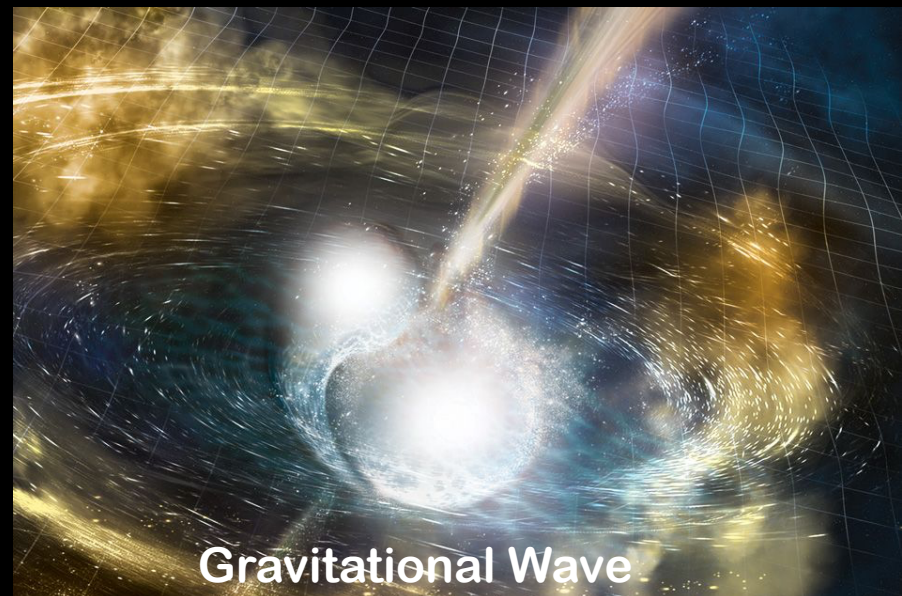
Kinetic energy to radiation

What is a Magnetar?

A magnetar is an exotic type of neutron star, its defining feature that it has an ultra-powerful magnetic field. The field is about 1,000 times stronger than a normal neutron star and **about a trillion times stronger than the Earth's**. Magnetars are, by far, the most magnetic stars in the universe.

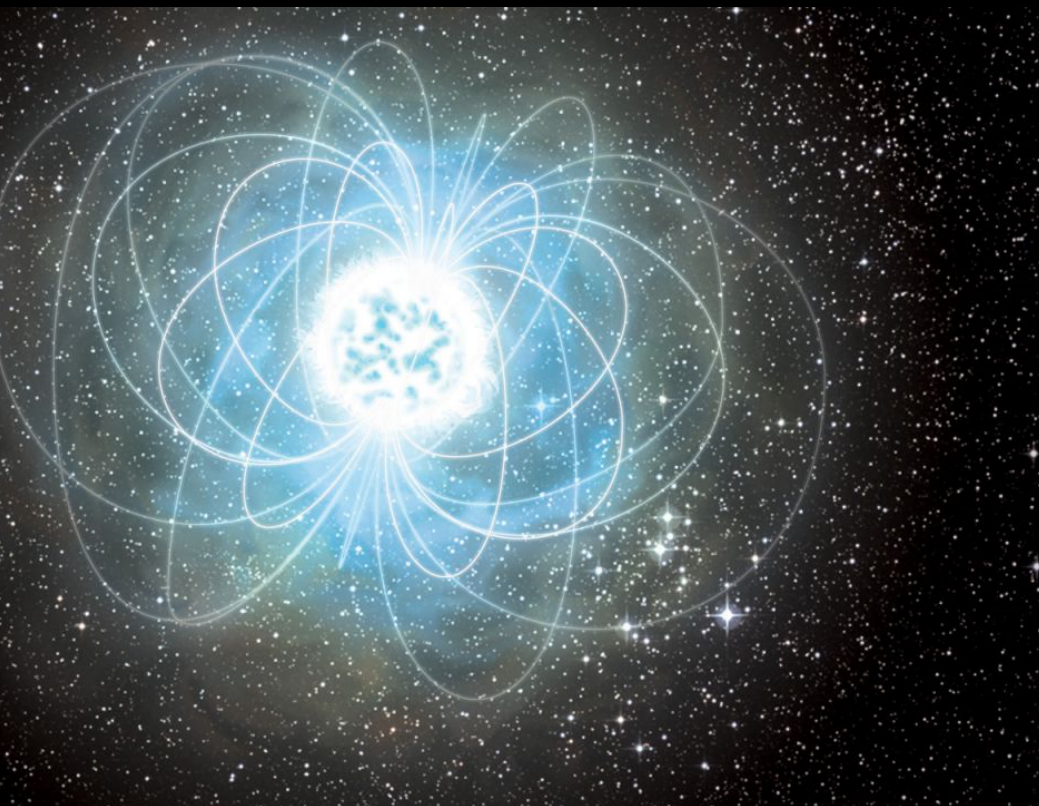


Mighty Magnetar!



How magnetic field and rotation help to power SLSNe?

Original Ideas from Maeda, Kasen, Bildsten, Woosley



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

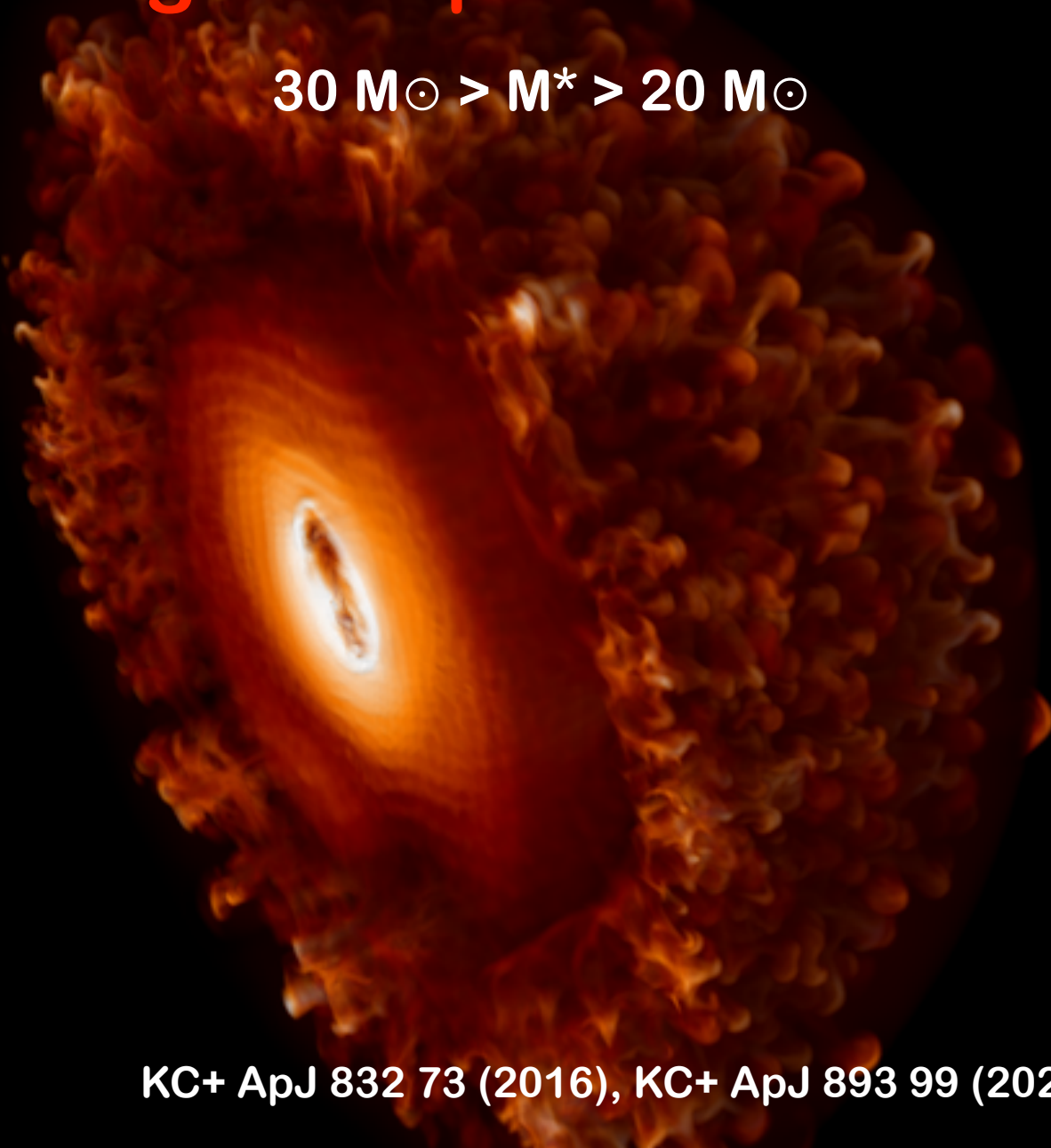
$$L_{\text{m}} = -\frac{32\pi^4}{3c^2} (B R_{\text{ns}}^3 \sin \alpha)^2 P^{-4} \\ \approx -1.0 \times 10^{49} B_{15}^2 P_{\text{ms}}^{-4} \text{ erg s}^{-1}$$

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

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

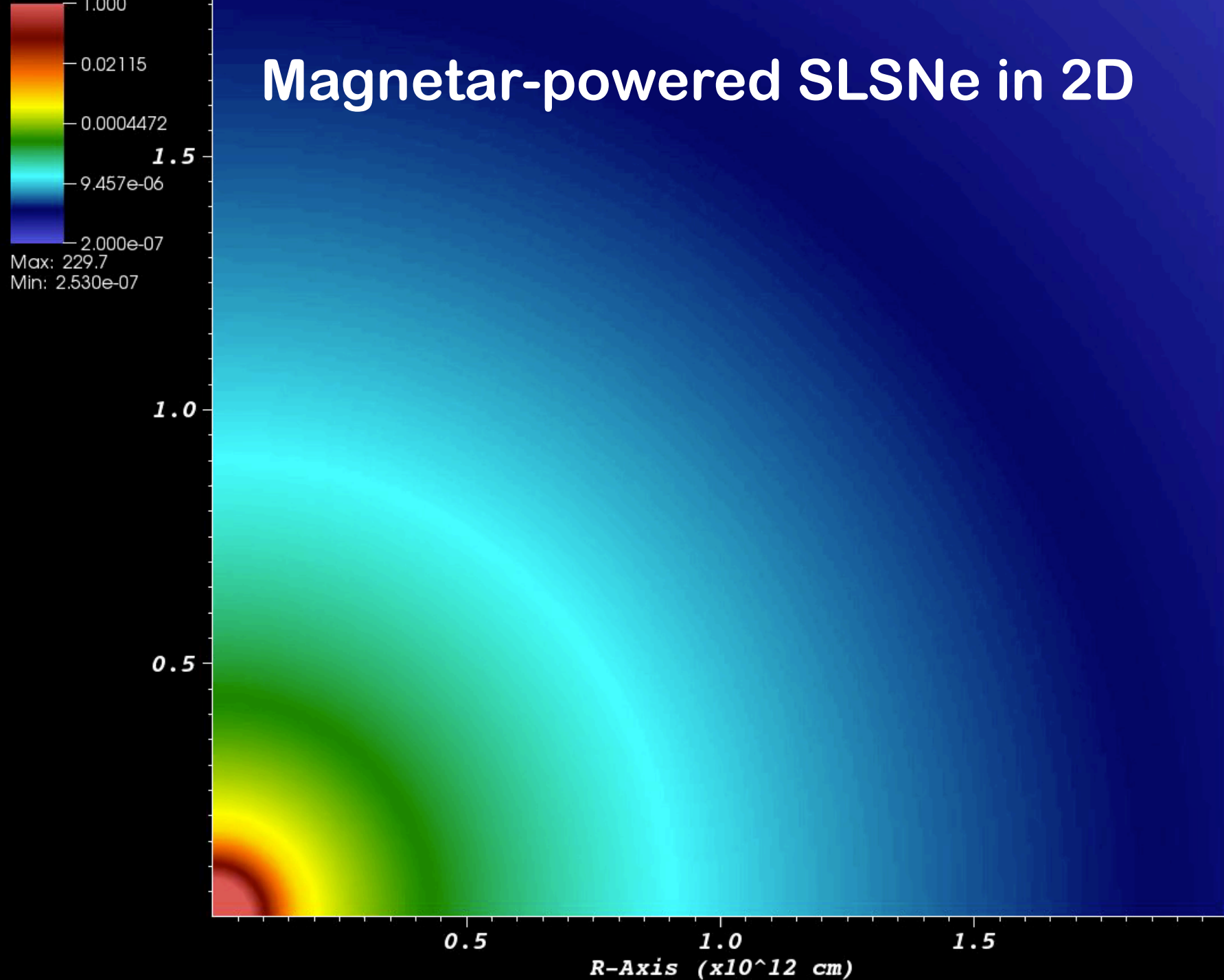
Magnetar-powered SLSNe

$$30 M_{\odot} > M^* > 20 M_{\odot}$$

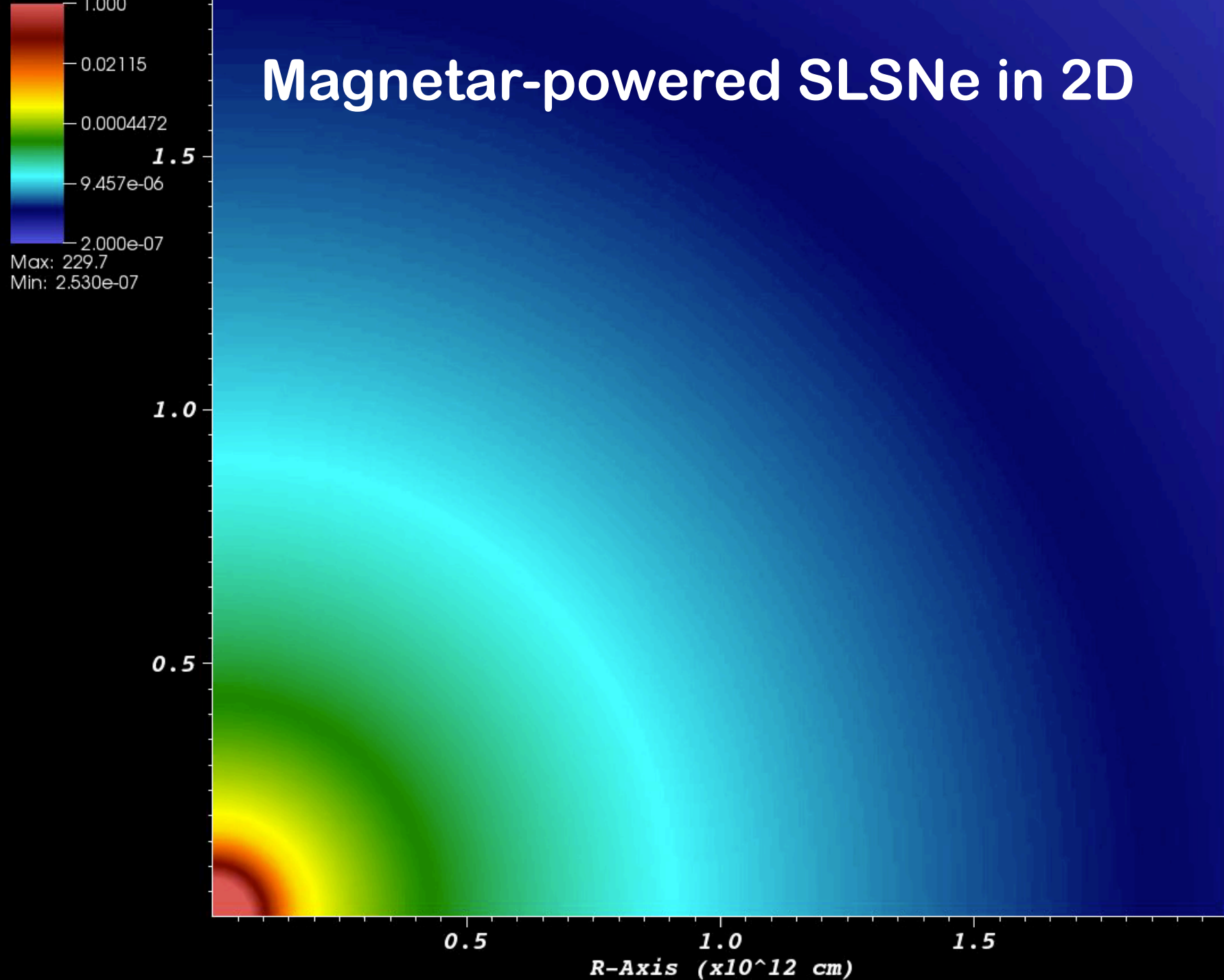


KC+ ApJ 832 73 (2016), KC+ ApJ 893 99 (2020)

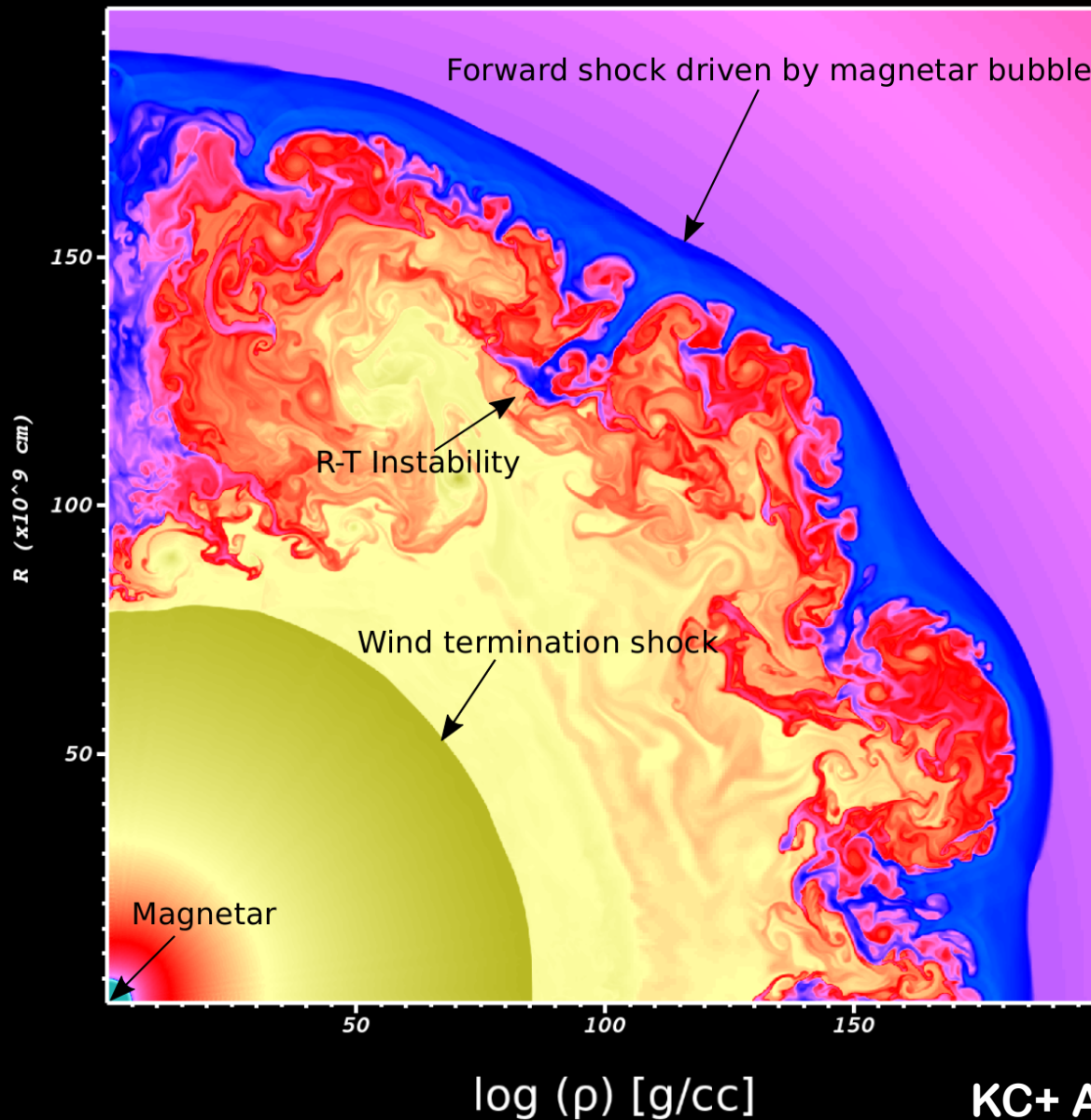
Magnetar-powered SLSNe in 2D



Magnetar-powered SLSNe in 2D

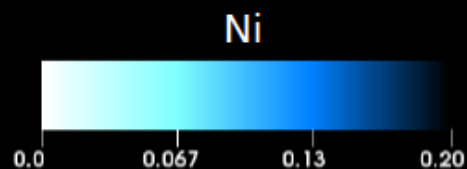
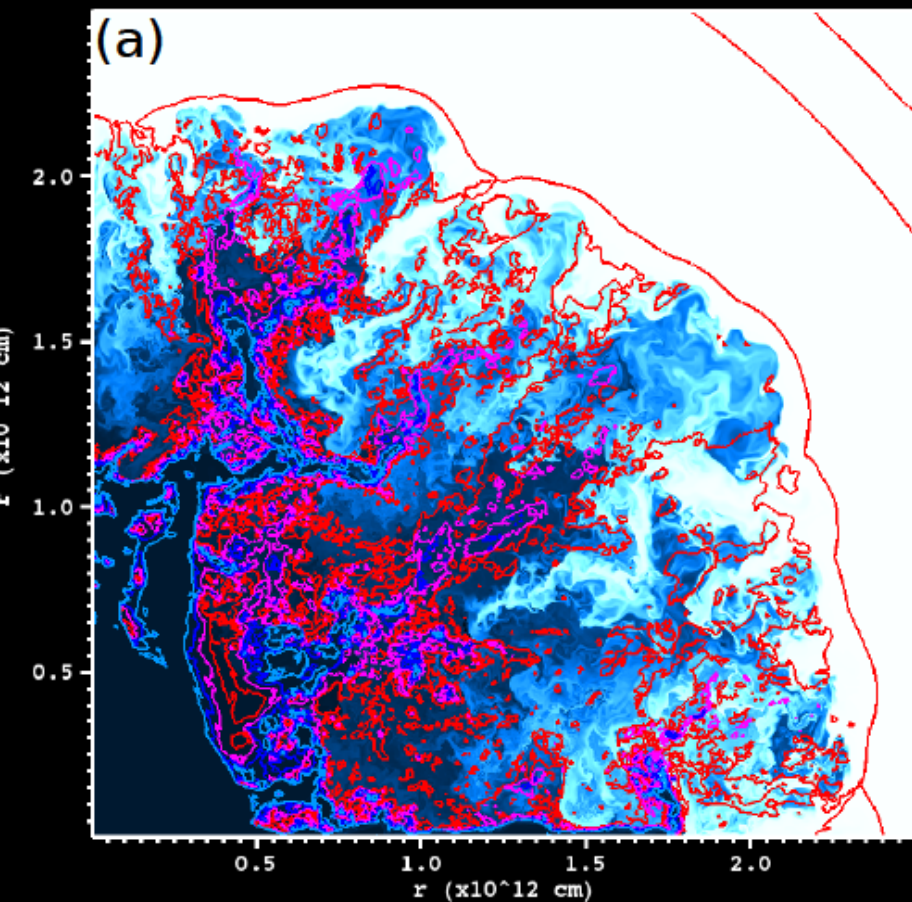


Mixing structure

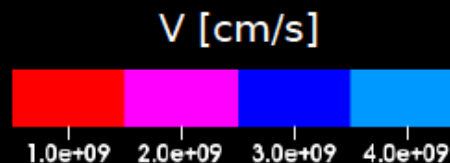
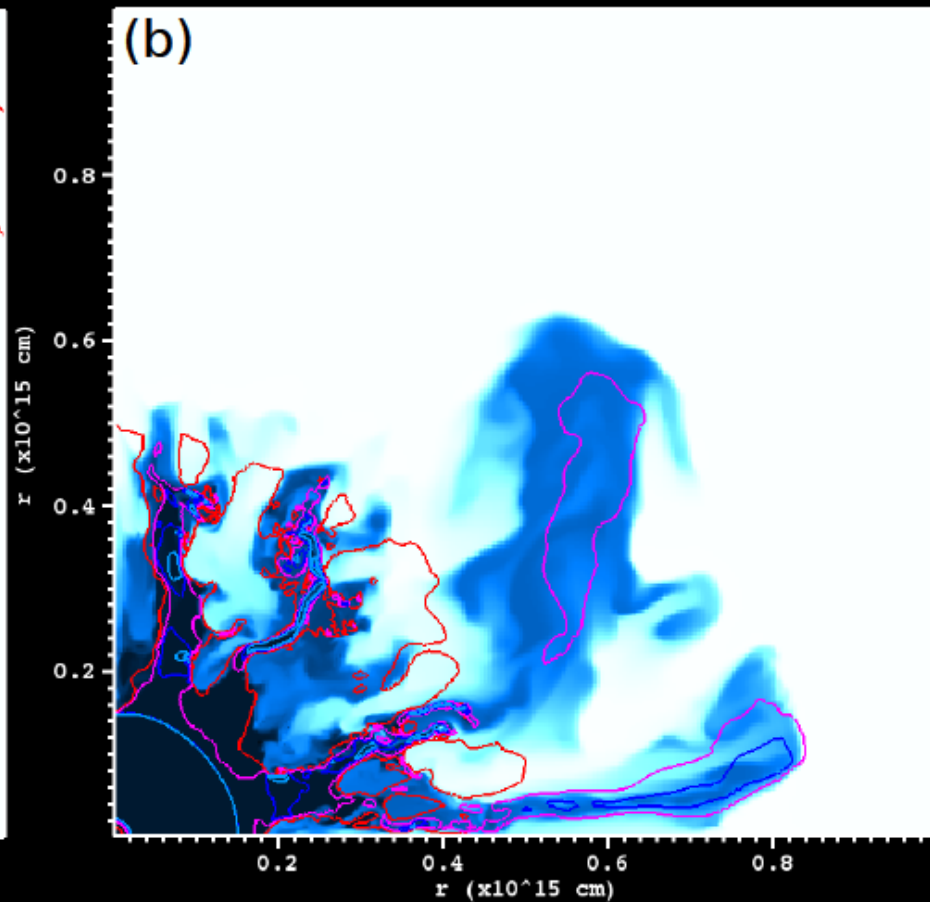


Radiation Breakout

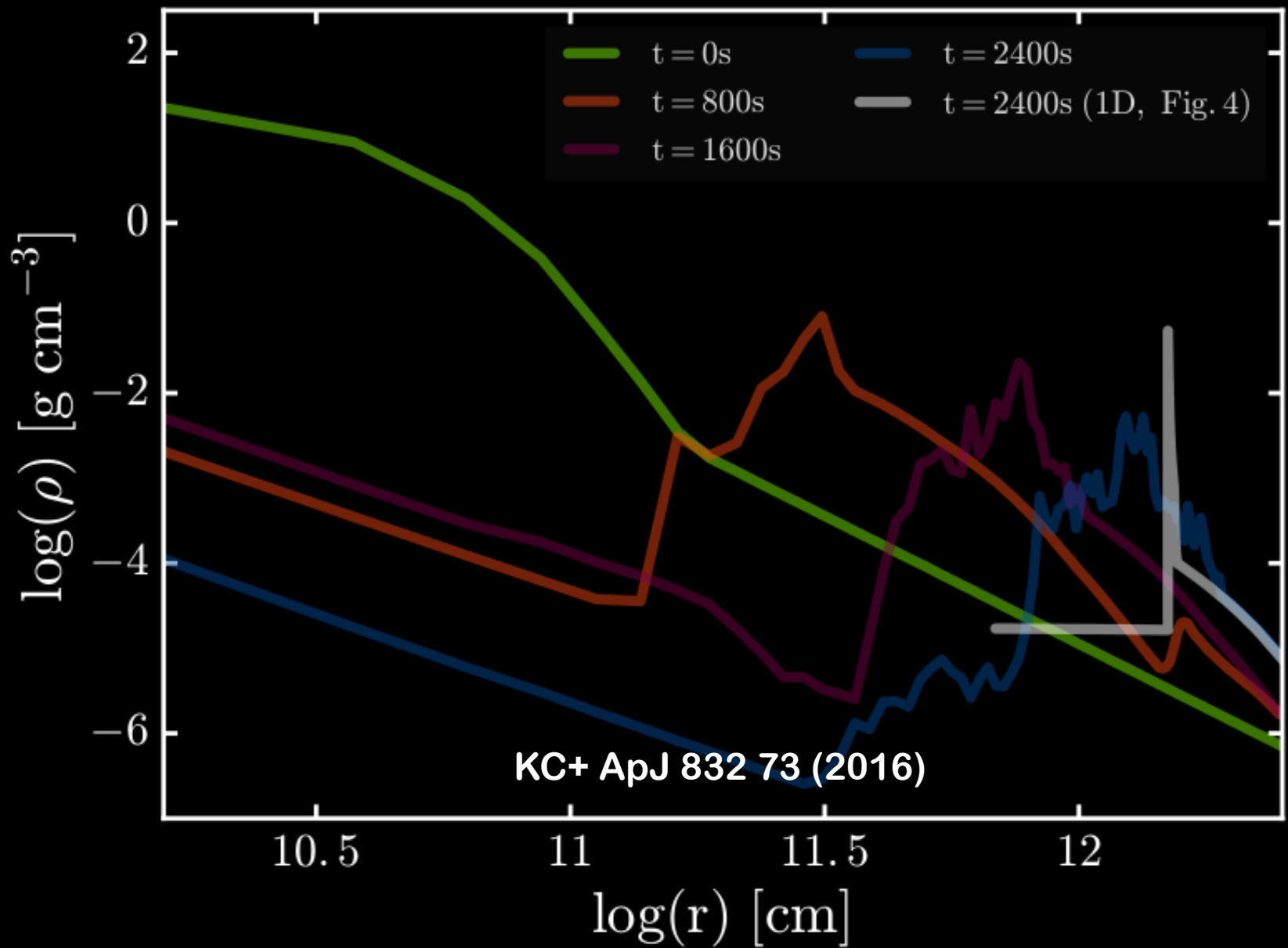
$P = 1 \text{ ms}$, $B = 4E14 \text{ G}$



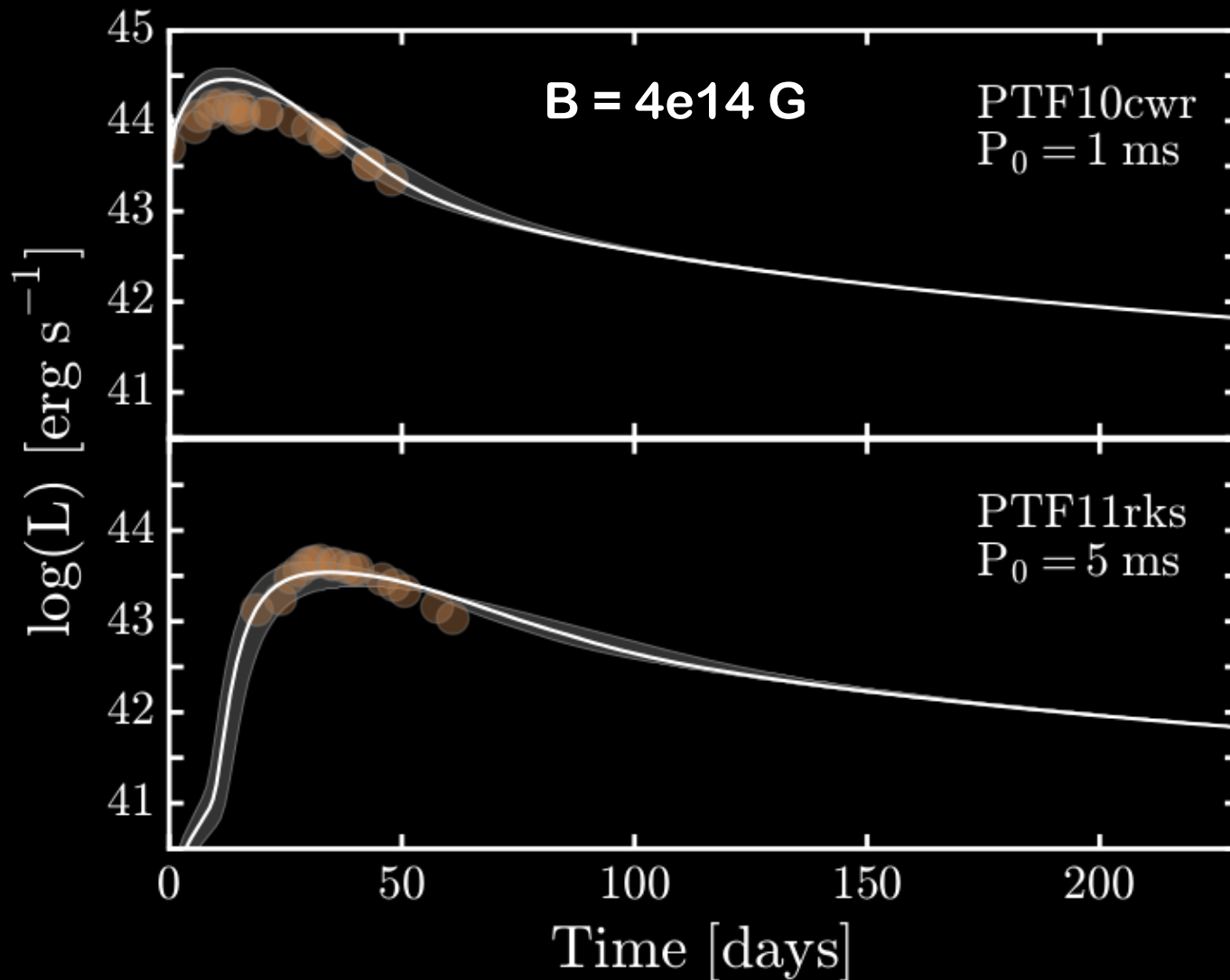
$P = 5 \text{ ms}$, $B = 4E14 \text{ G}$



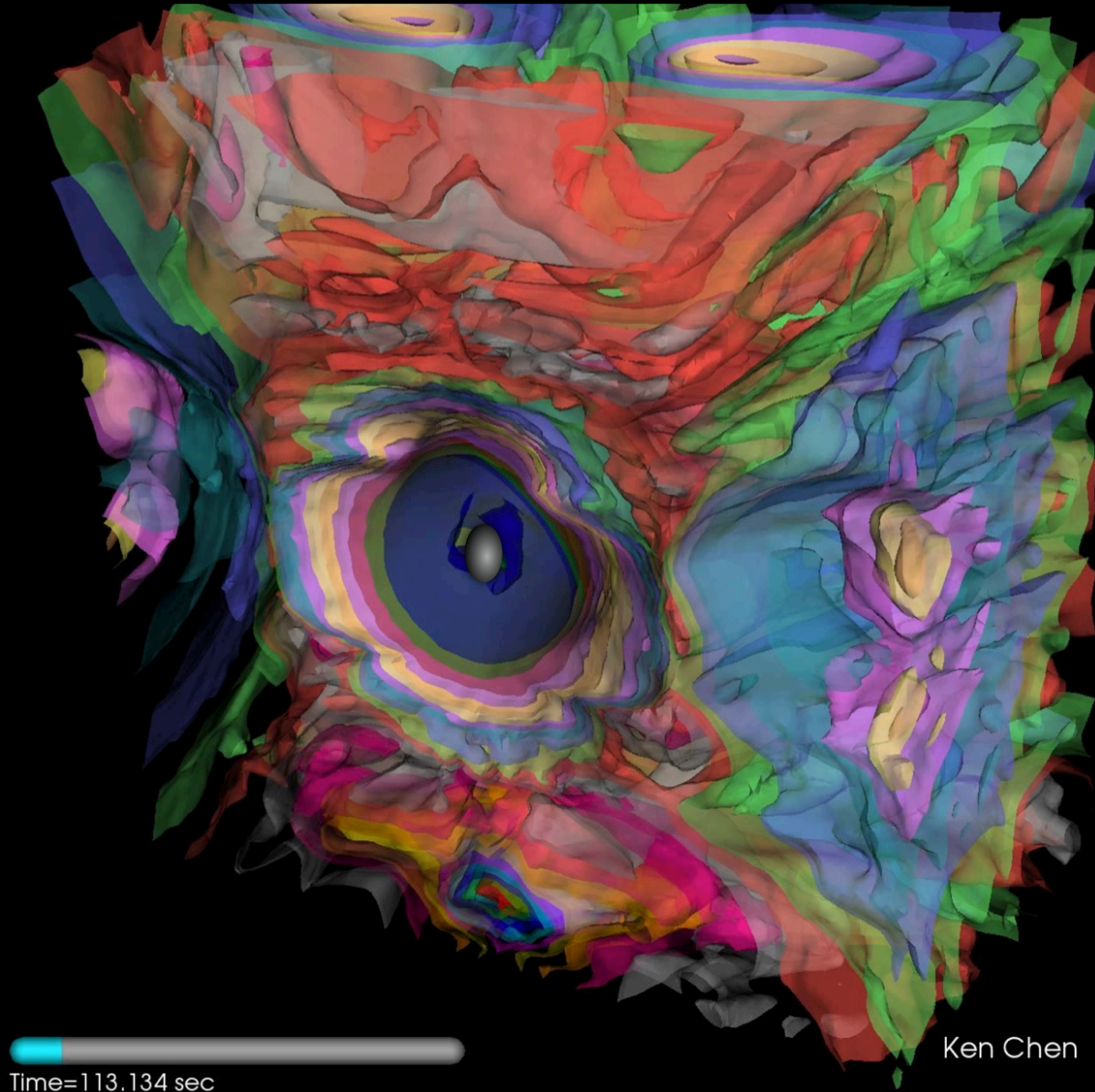
1D vs 2D



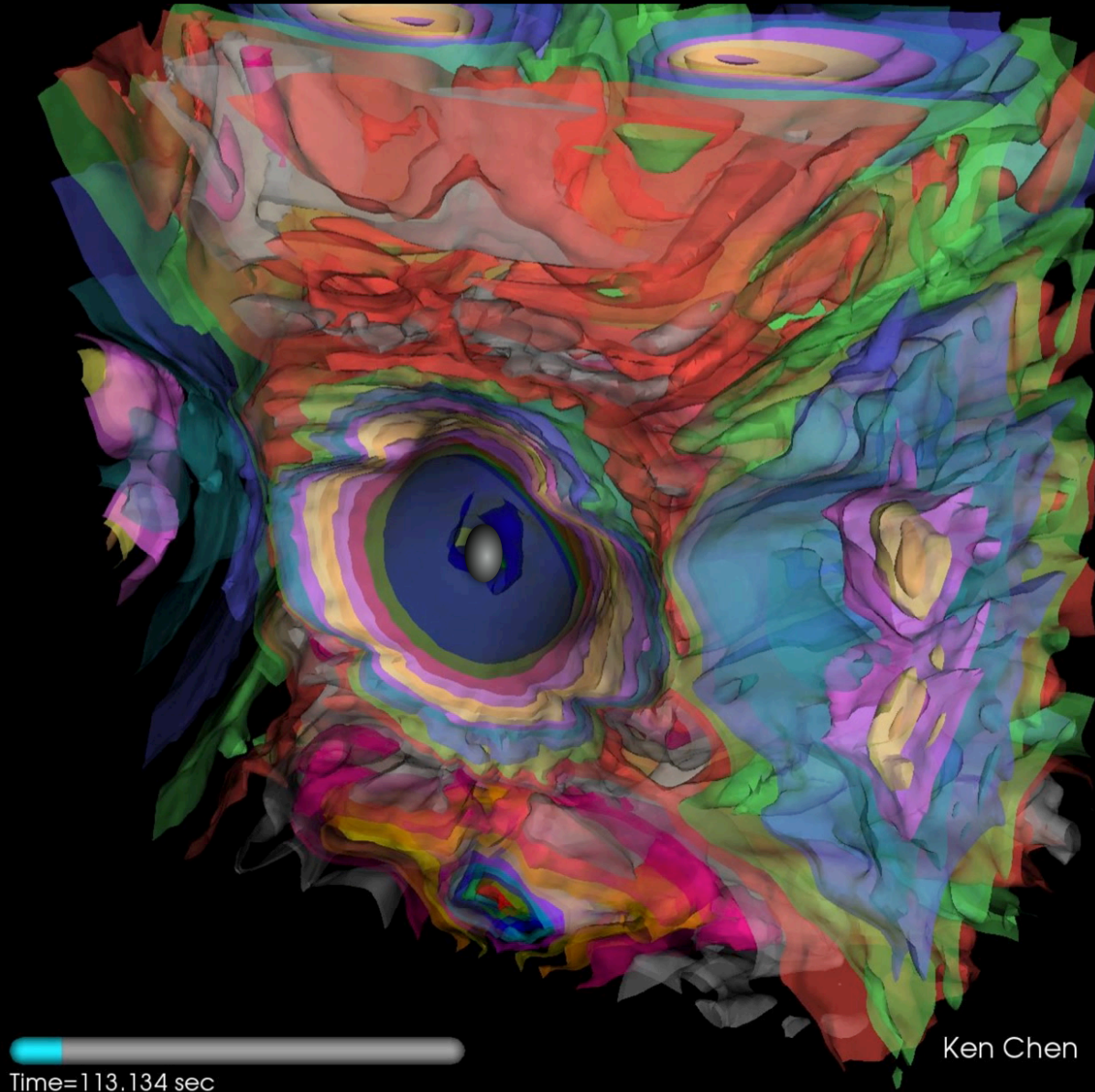
Superluminous SNe by Magnetar



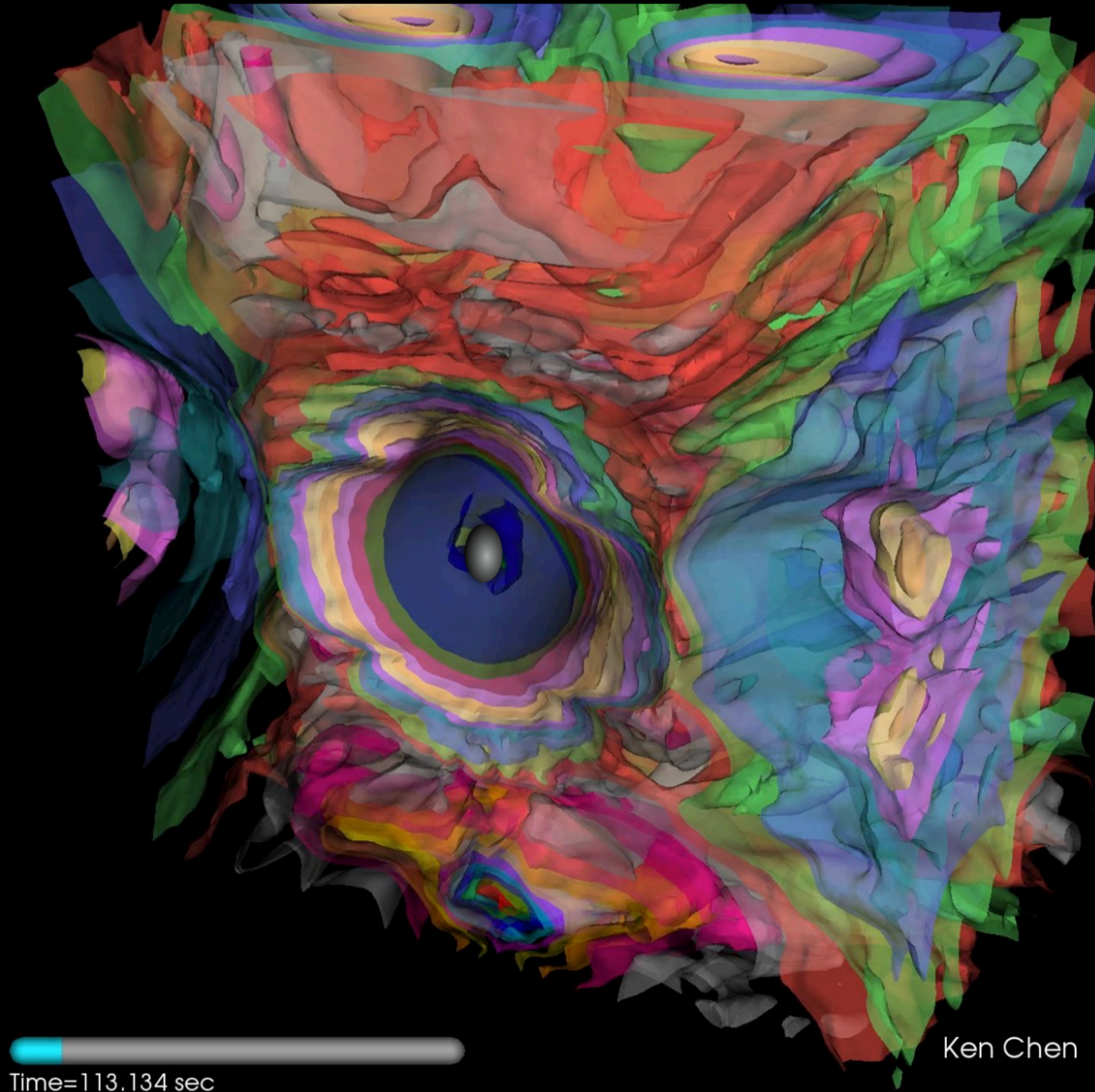
3D Turbulent Structure



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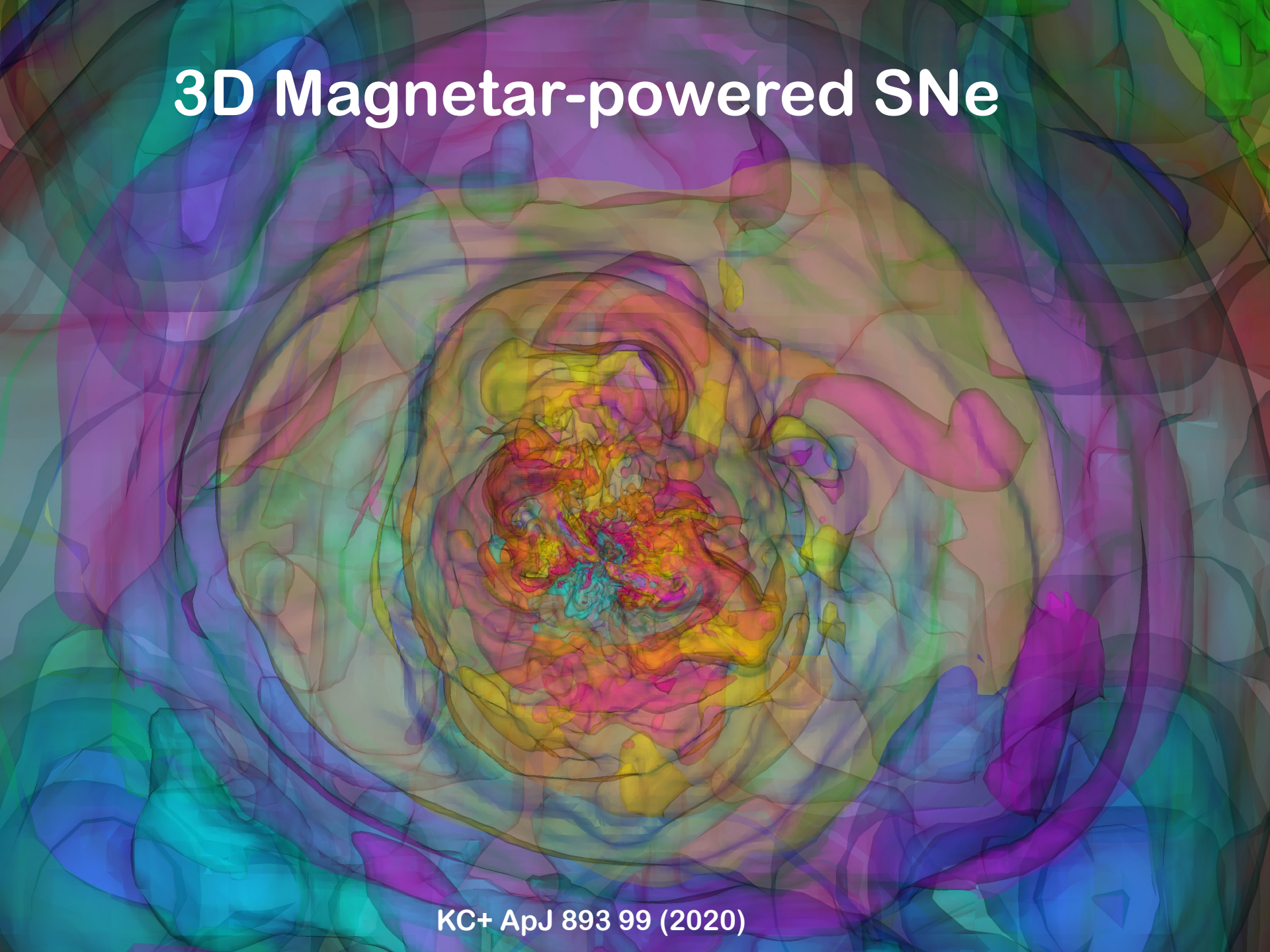


3D Turbulent Structure



3D Magnetar-powered SNe

KC+ ApJ 893 99 (2020)



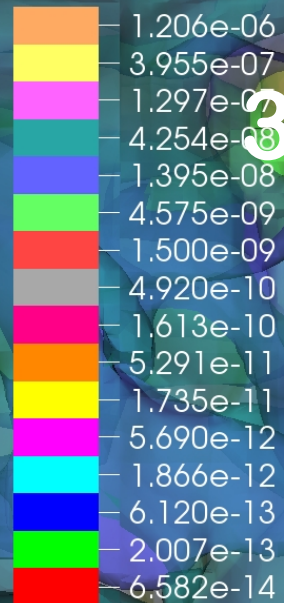
3D Magnetar-powered SNe



Max: 3.677e-06
Min: 2.158e-14

KC+ ApJ 893 99 (2020)

3D Magnetar-powered SNe

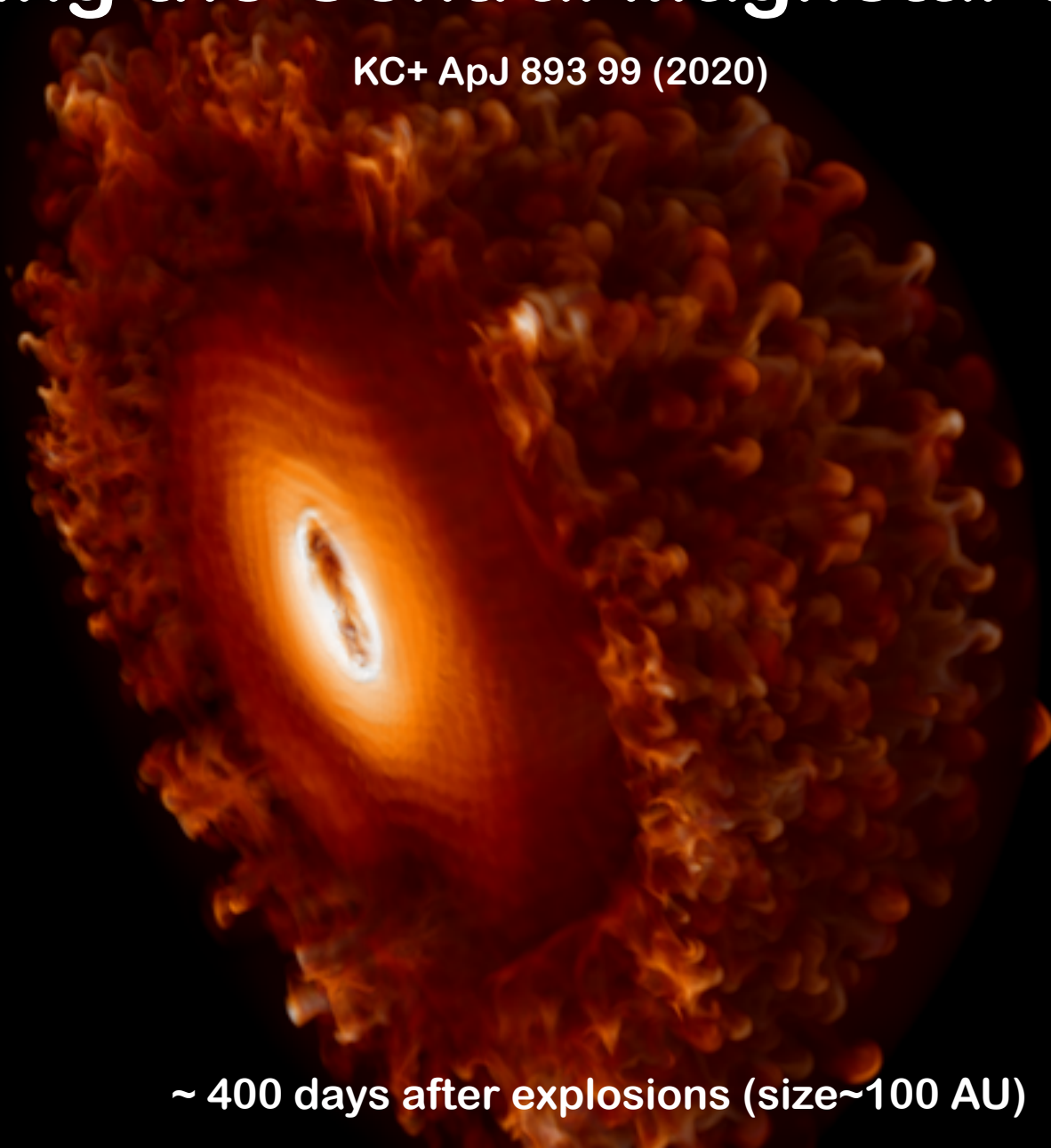


Max: 3.677e-06
Min: 2.158e-14

KC+ ApJ 893 99 (2020)

Bridging the Central Magnetar to its SNR

KC+ ApJ 893 99 (2020)

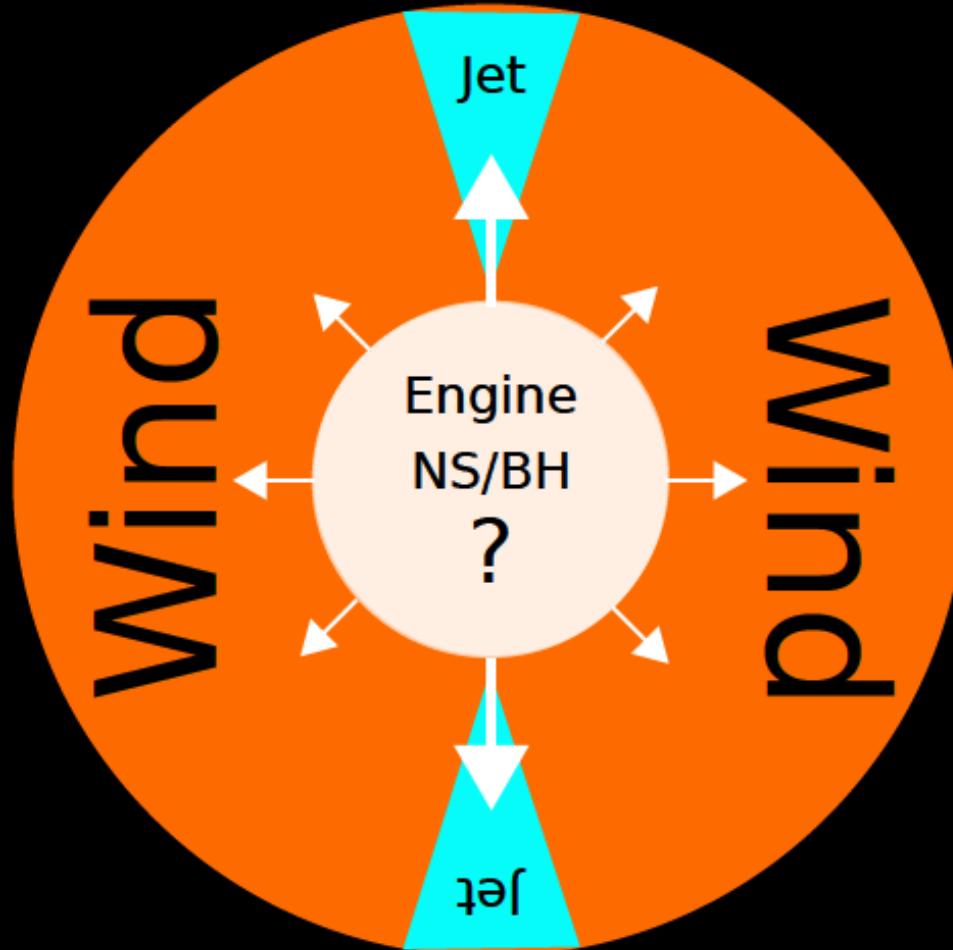


~ 400 days after explosions (size~100 AU)

Very Energetic SNe - Hypernovae

$$60 M_{\odot} > M^* > 30 M_{\odot}$$

$$B > 1e16 \text{ G}, P < 1 \text{ ms}$$

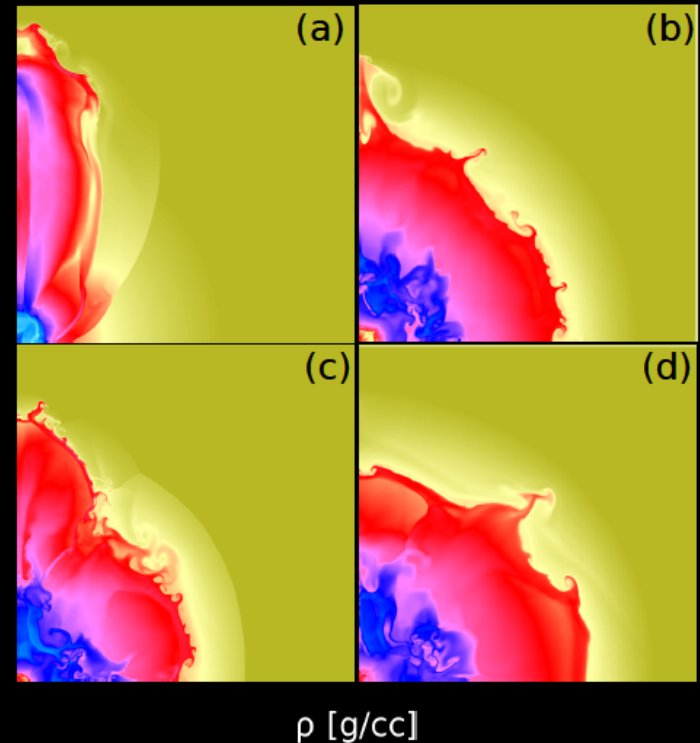
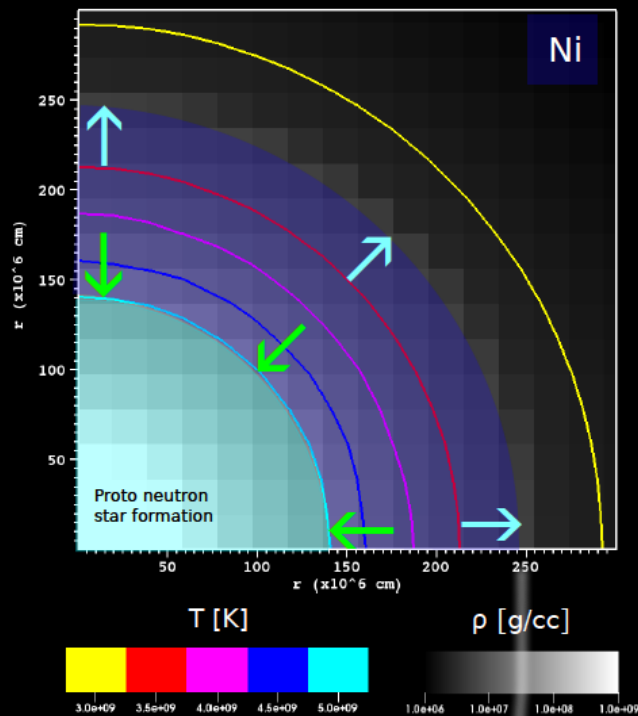


Hypernova explosion

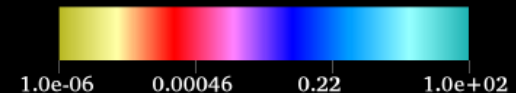
TABLE 1
MAGNETAR-POWERED EXPLOSIONS

Model	Type	Engine Type	^{56}Ni Mass $M_{\odot}$	Remnant	M_{ej} $M_{\odot}$	E_{ej} 10^{51} erg
A	J	J(2.5° , ϵ)	0.016	$4.54M_{\odot}$ BH	5.46	9.84
B	W	W(90° , ϵ)	0.038	$1.66M_{\odot}$ NS	8.34	11.34
C	J+W	J(2.5° , 0.1ϵ), W(0.9ϵ)	0.036	$1.66M_{\odot}$ NS	8.34	11.19
D	J+W	J(10° , 0.1ϵ), W(0.9ϵ)	0.037	$1.66M_{\odot}$ NS	8.34	10.35

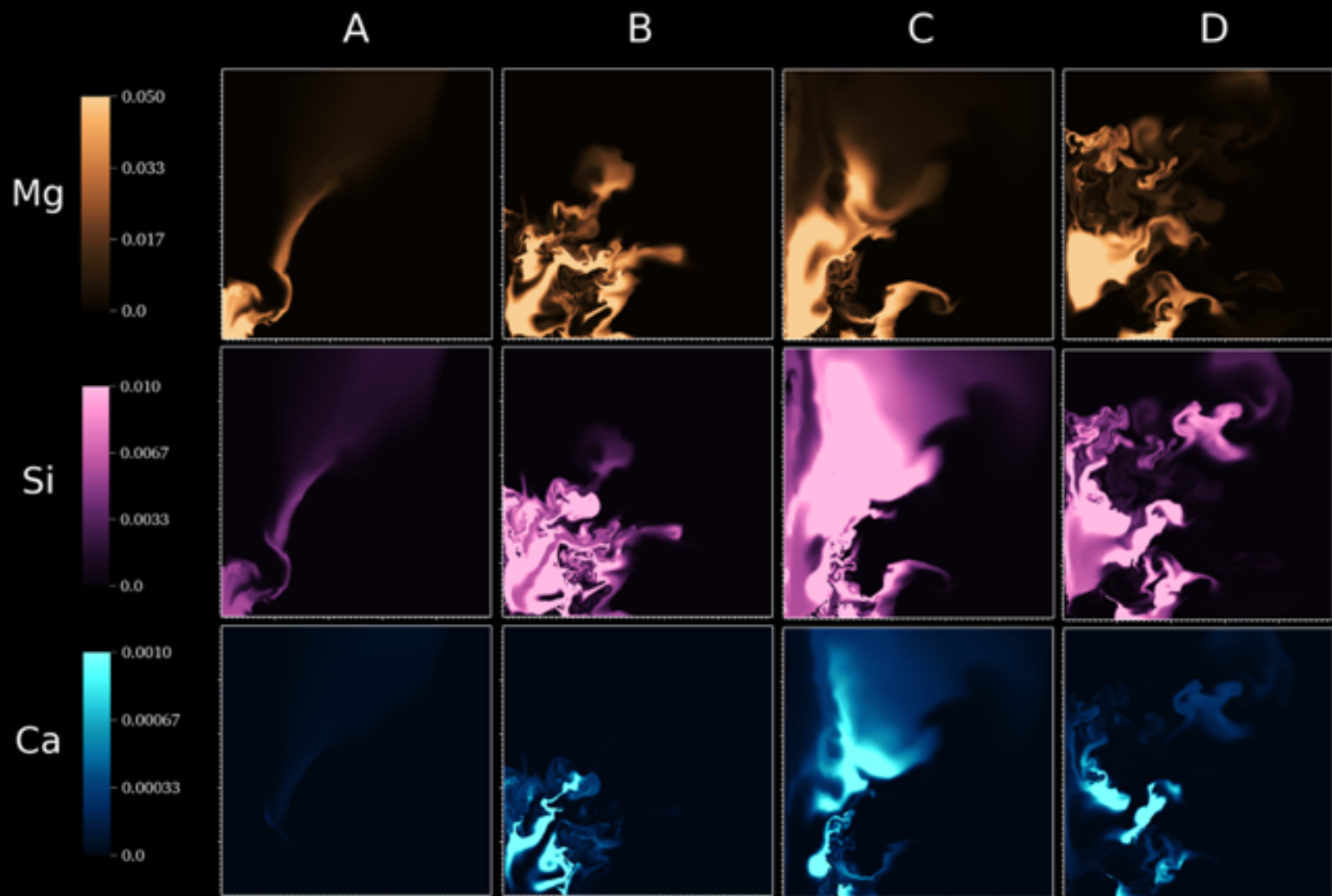
NOTE. — The rate of energy deposition is $\epsilon = 10^{51}$ erg s^{-1} and its duration is 20 sec



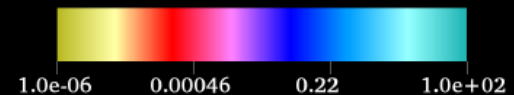
KC+ ApJ 839 85 (2017)



Hypernova explosion

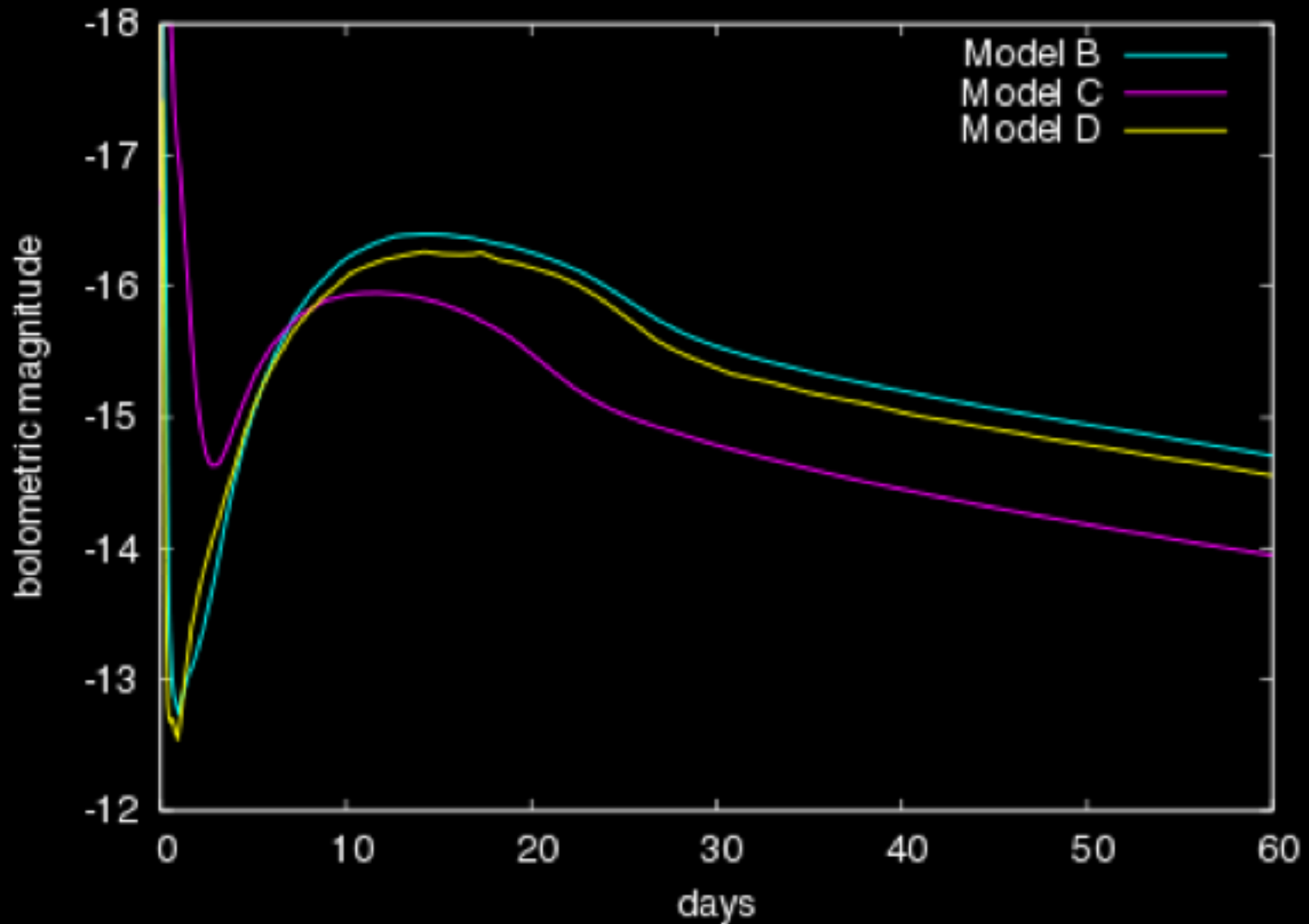


KC+ ApJ 839 85 (2017)

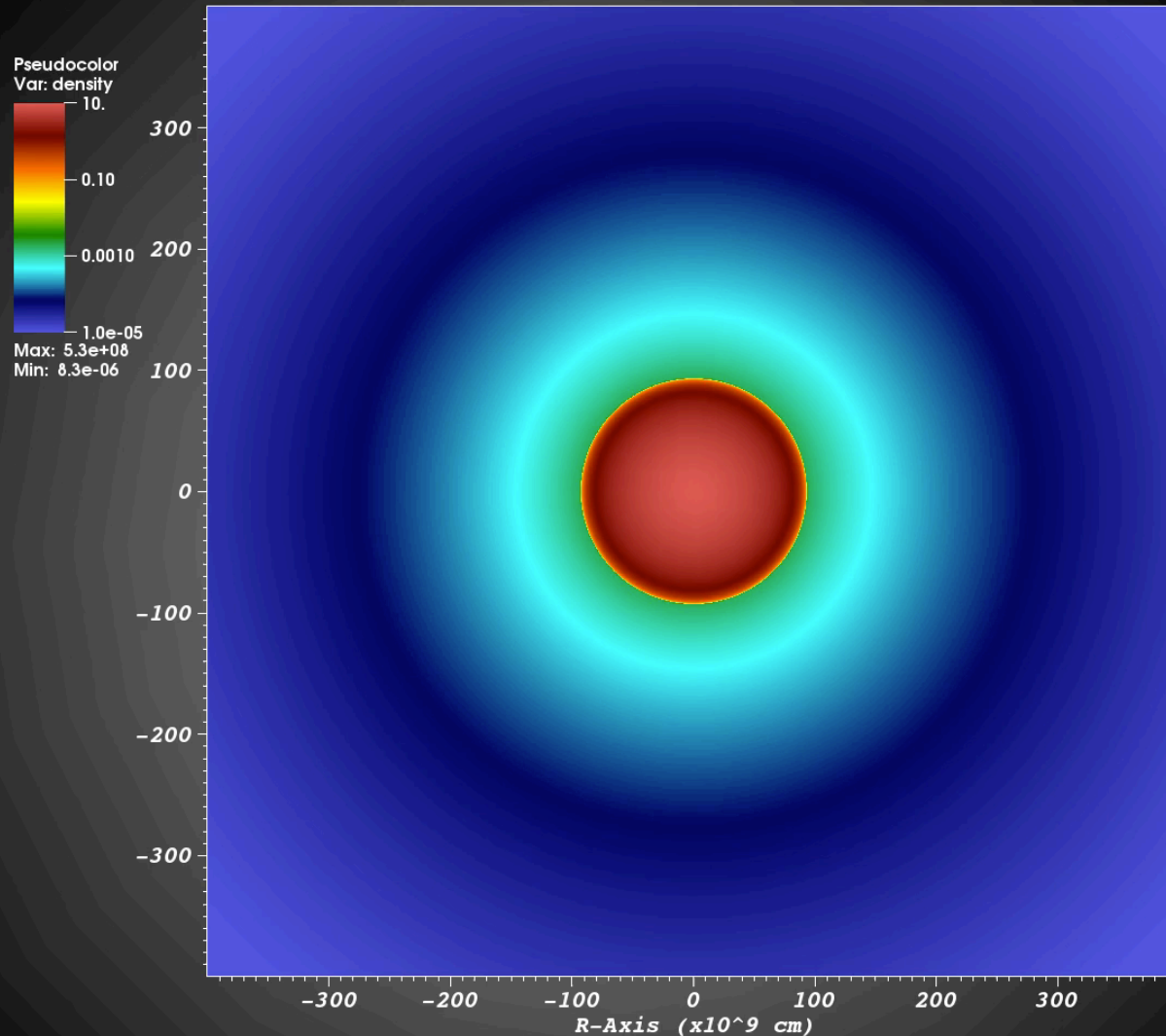


Light Curves

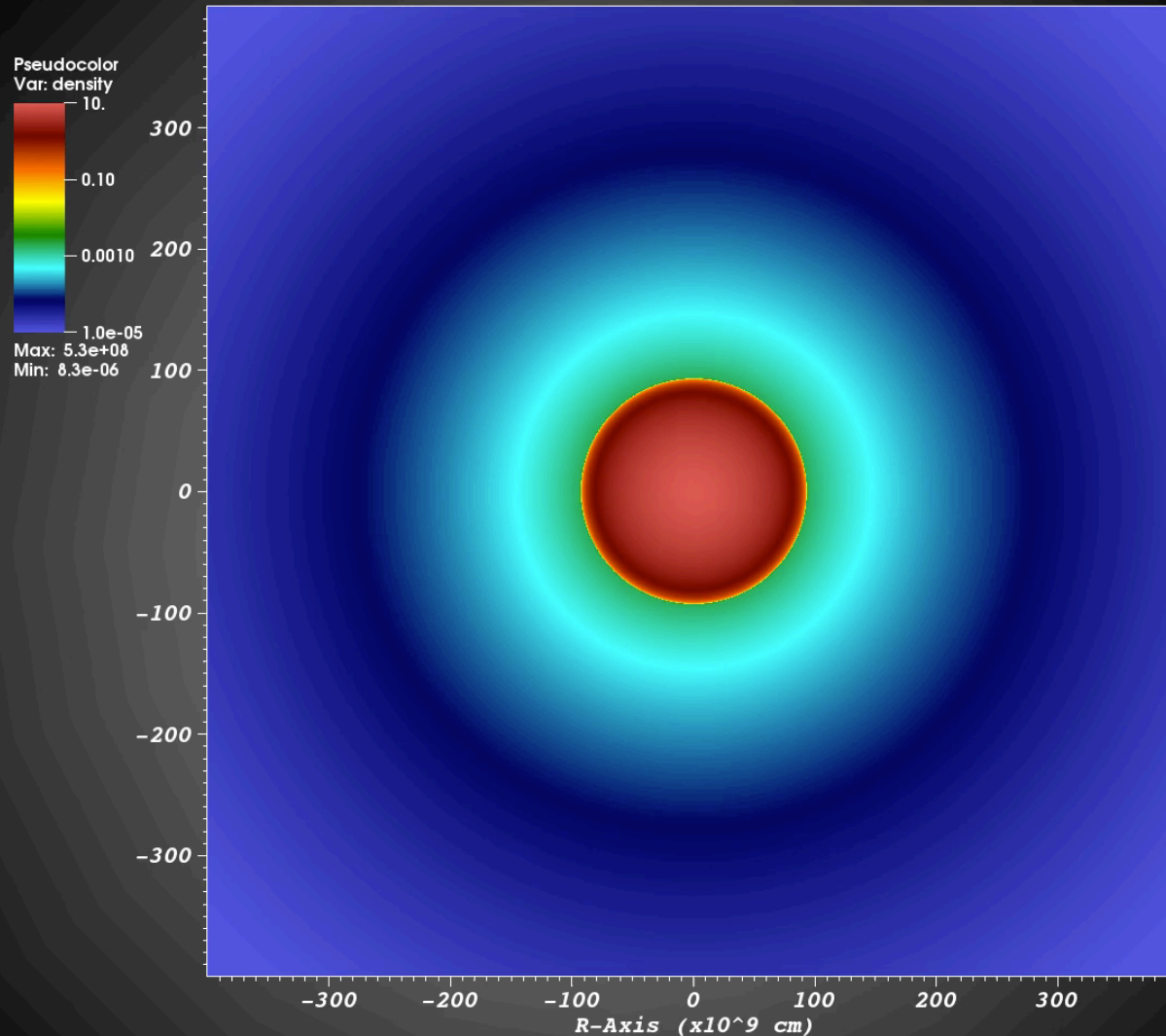
Good models to explain the SN Ic-BL events



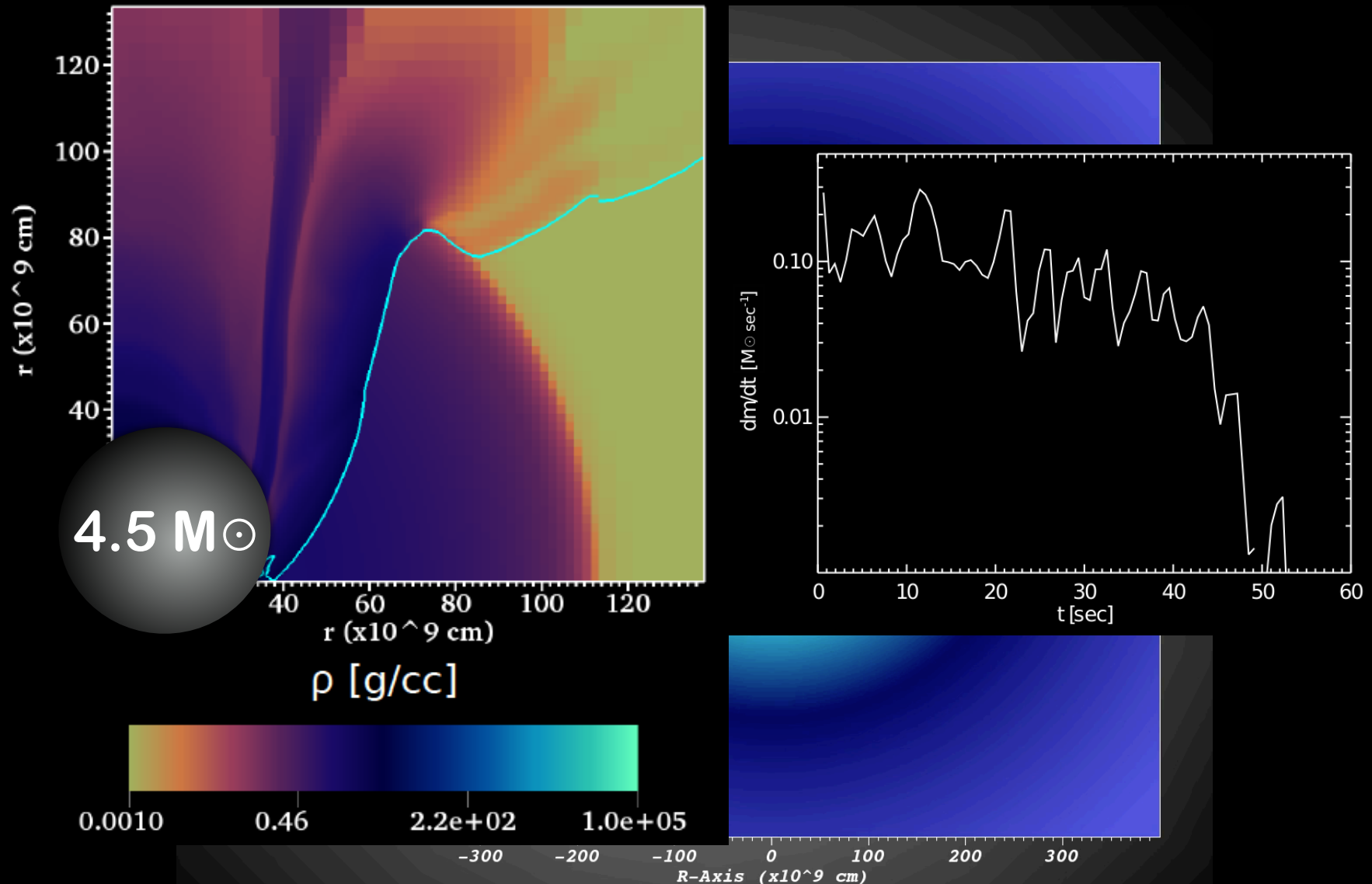
Black hole forming Channel Jet only model



Black hole forming Channel Jet only model



Black hole forming Channel Jet only model



Take Home Message



Take Home Message

- **Mighty magnetar! GRB, FRB, SLSNe, HNe....**



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- Simple dipole formula applicable for magnetar?



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- Simple dipole formula applicable for magnetar?
- Violent mixing in Magnetar-powered SNe
- 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 required to model the mixing and signatures properly.