Physics of Supernovae

Ke-Jung (Ken) Chen

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ASIAA(中研院天文所)

MMA Workshop, NCTS, 10/20/2020

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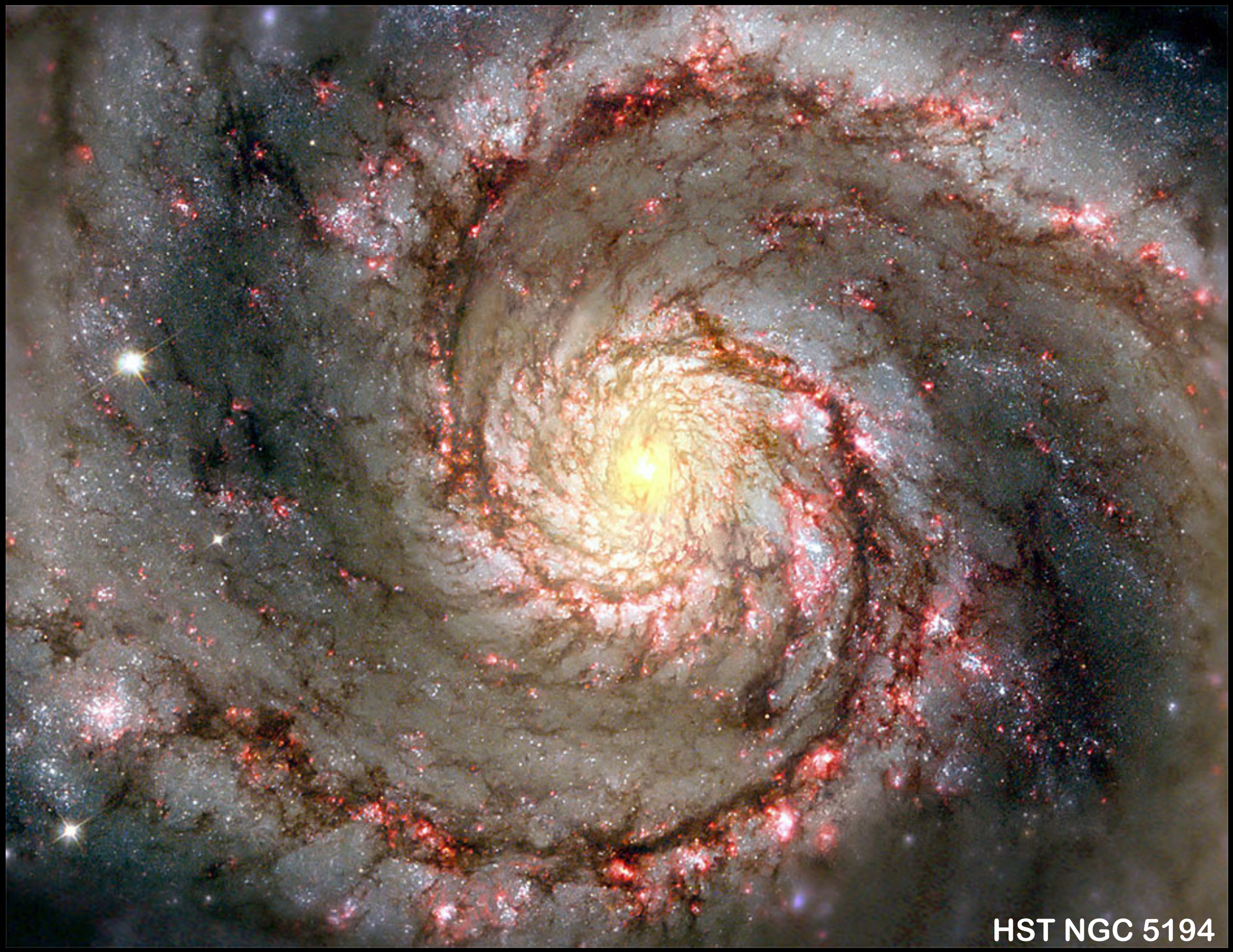
Awesome galaxies come first!



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HST M82

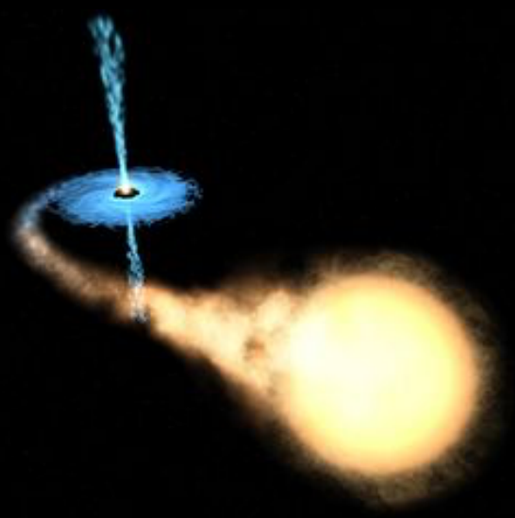
Astrophysics within a Galaxy?

Astrophysics within a Galaxy?
A gray box within many gray boxes

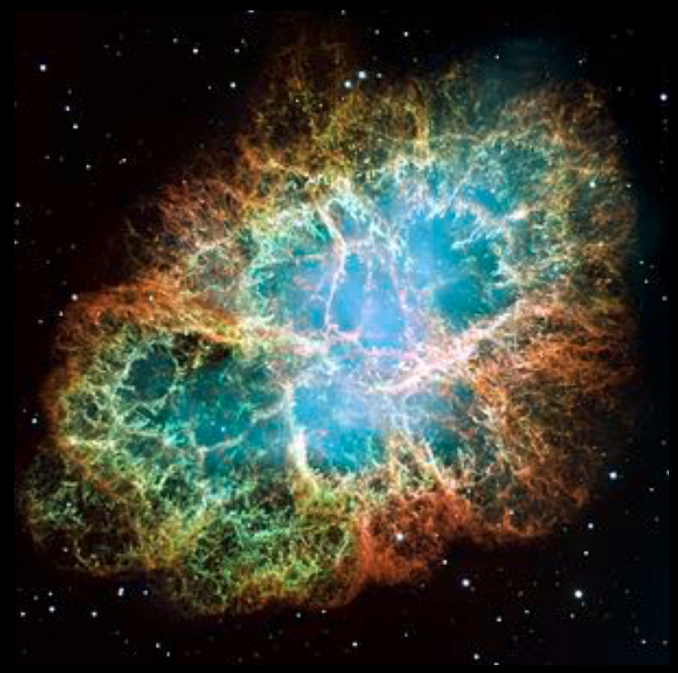
Star Formation

AGB stars

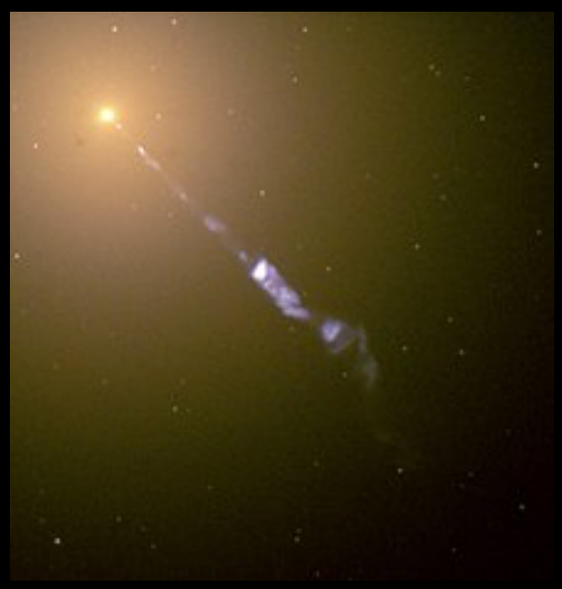
Massive Stars



X-ray Binaries



SN/SNR



AGN

Astrophysics within a Galaxy?
A gray box within many gray boxes

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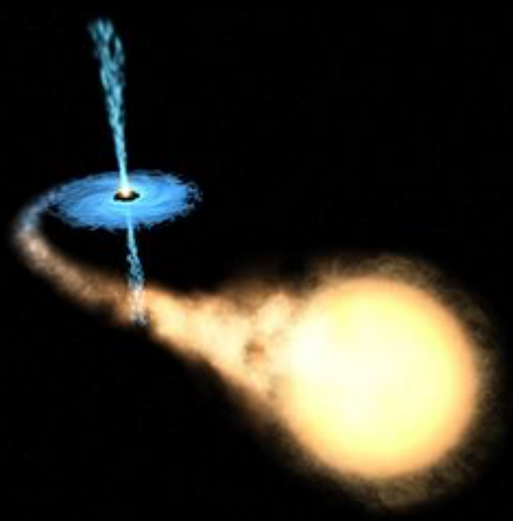
Massive Stars

Twist of Star Formation, ISM, Stellar Evolution + Tons of Micro Physics?



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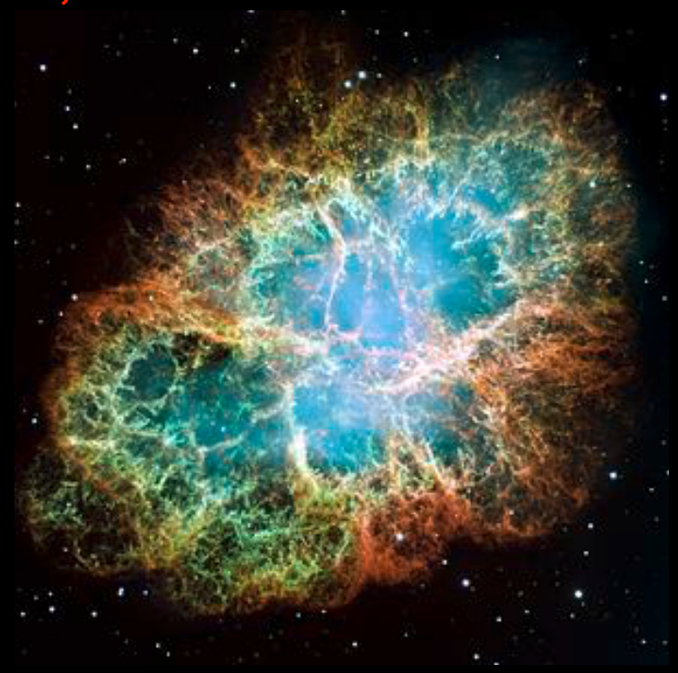

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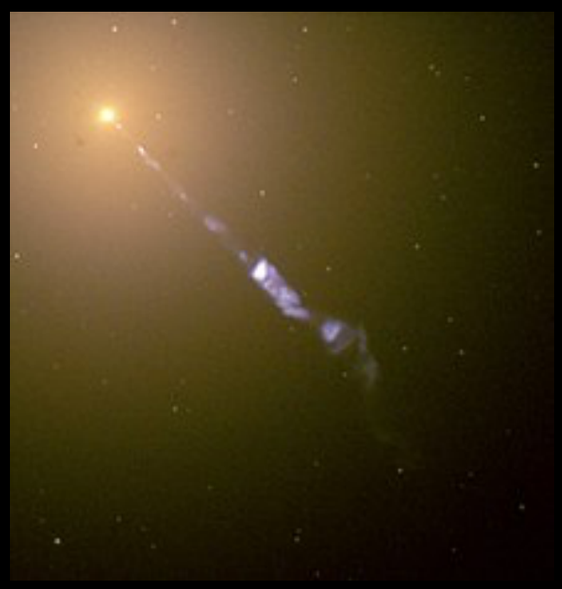

AGN


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Massive Stars and their SNe

- Exceptional brightness and explosion
- Heavy elements
- Fundamental physics
- Accessibility in Research (models and observations)

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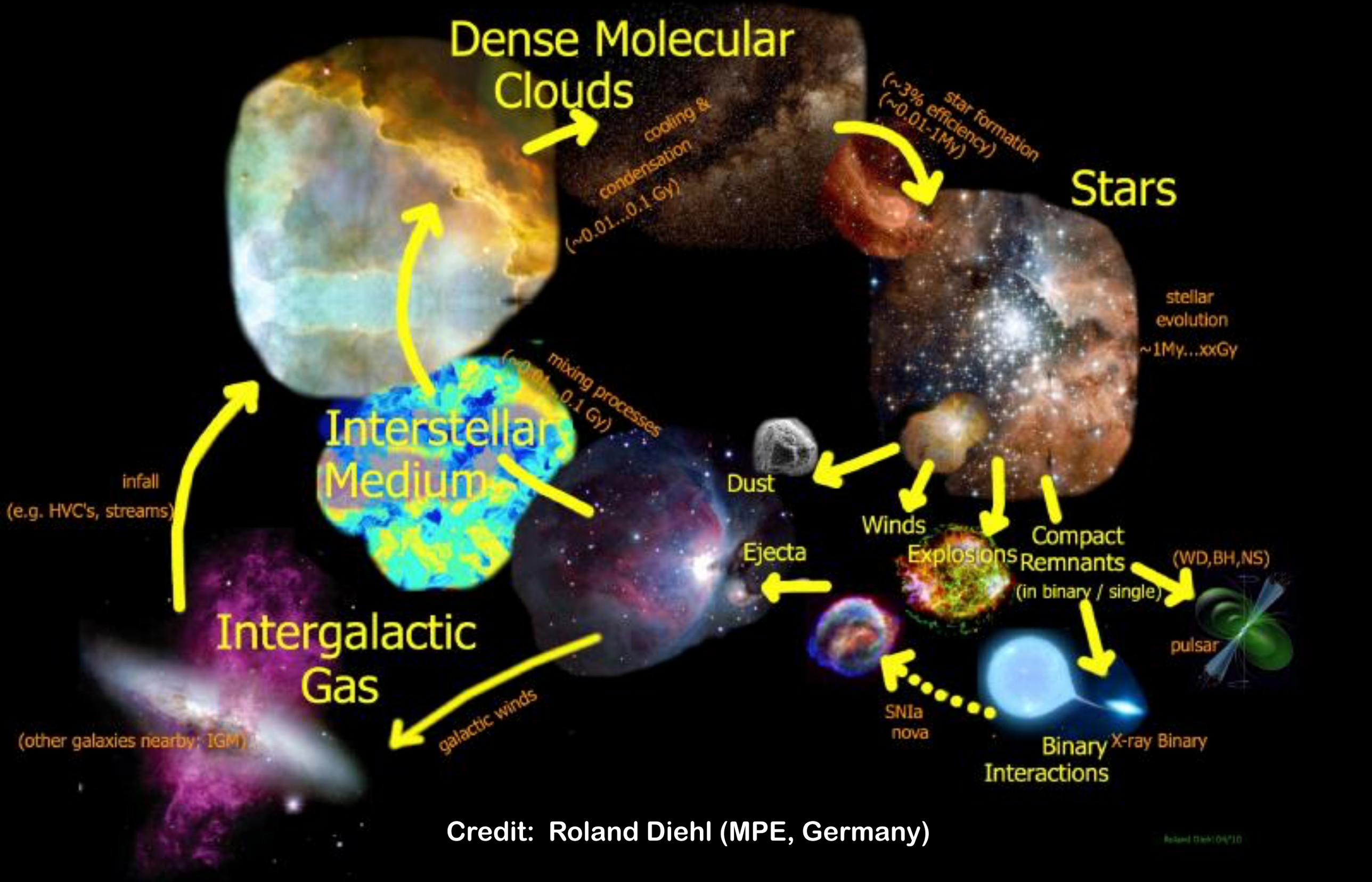
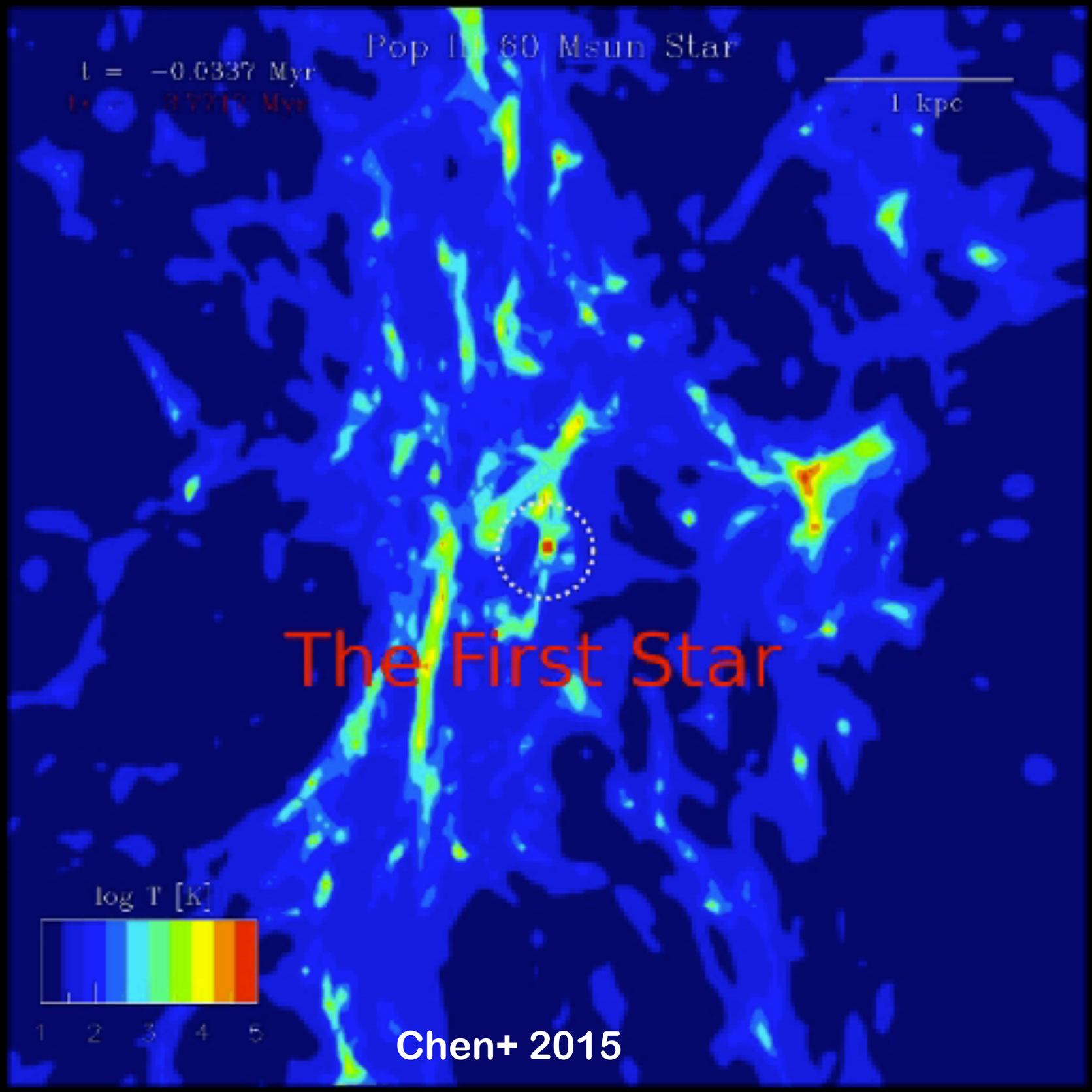
- Key driver of the baryonic cycle

Baryonic Cycles in the Universe



Credit: Roland Diehl (MPE, Germany)

Cosmological Simulations of Pop III Stellar Feedback



Chen+ 2015

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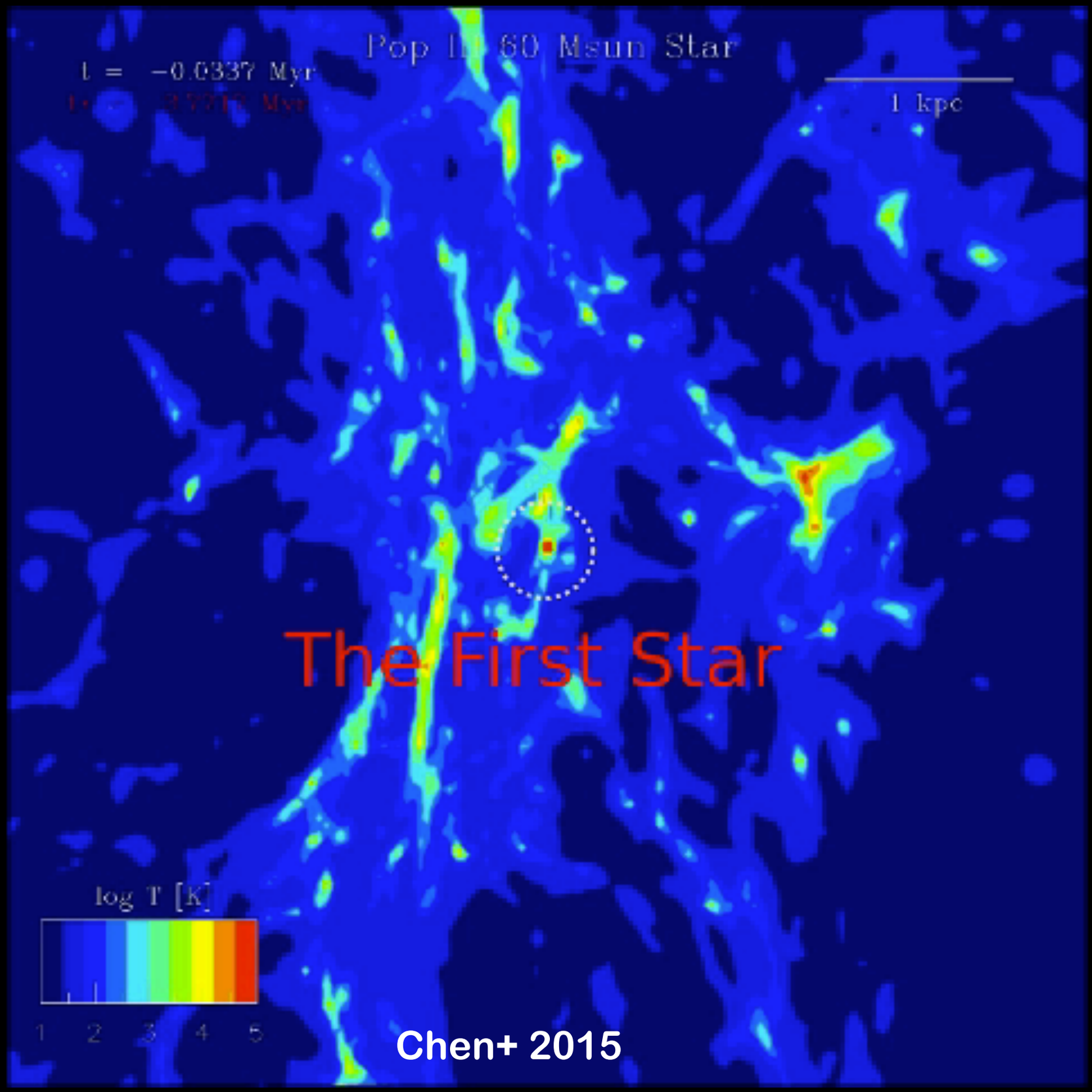

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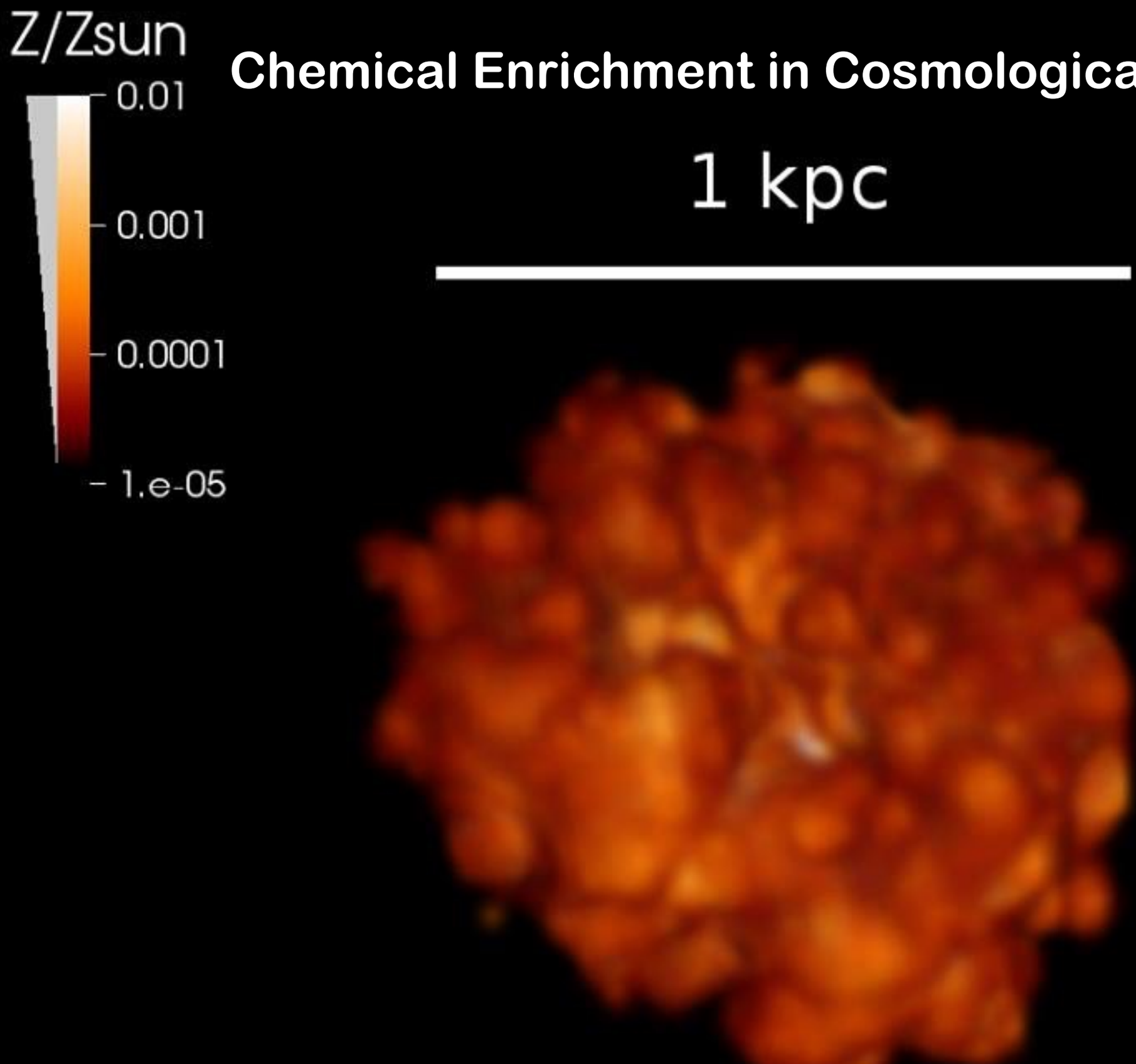
Chemical Enrichment in Cosmological Simulations



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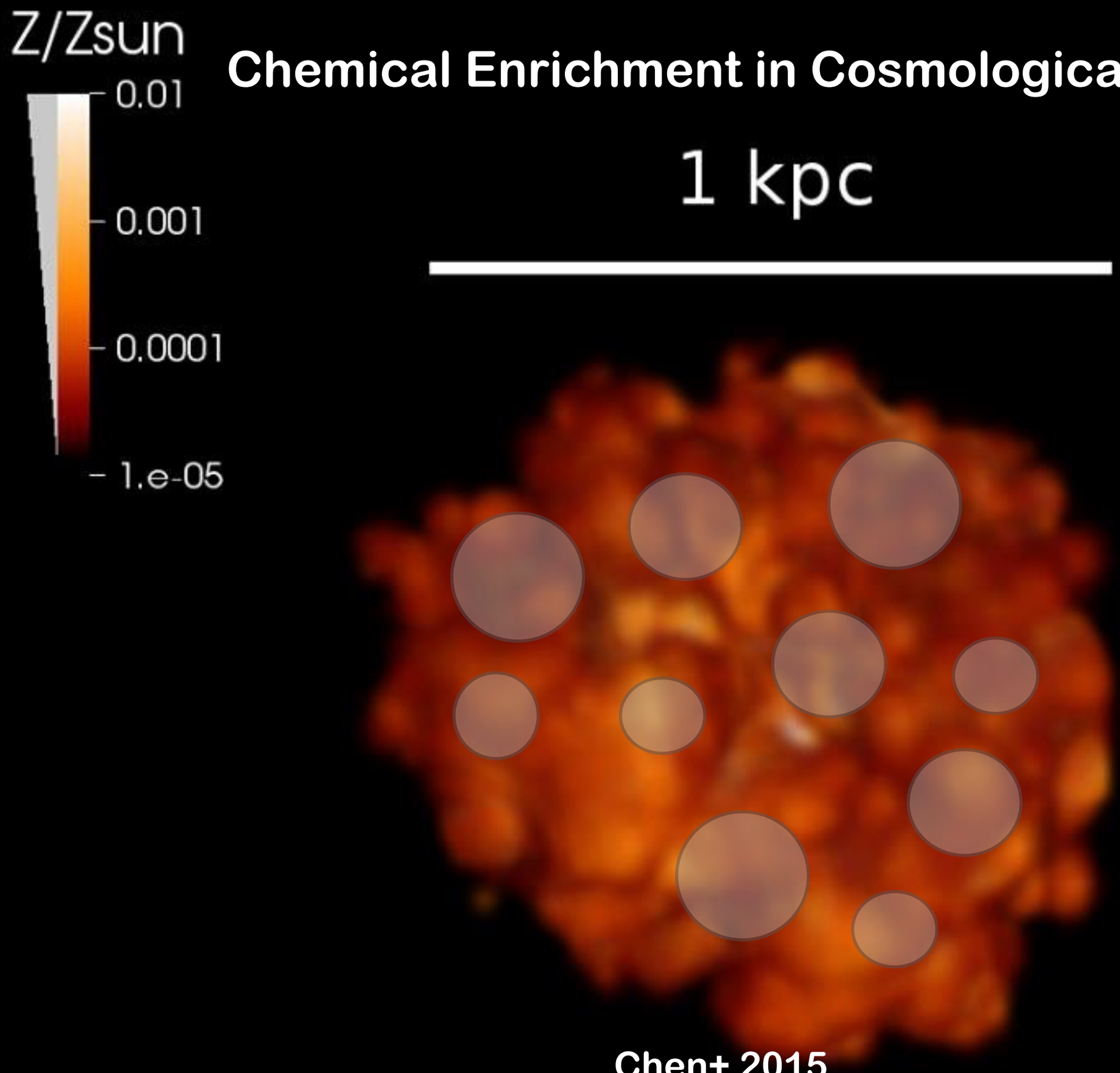

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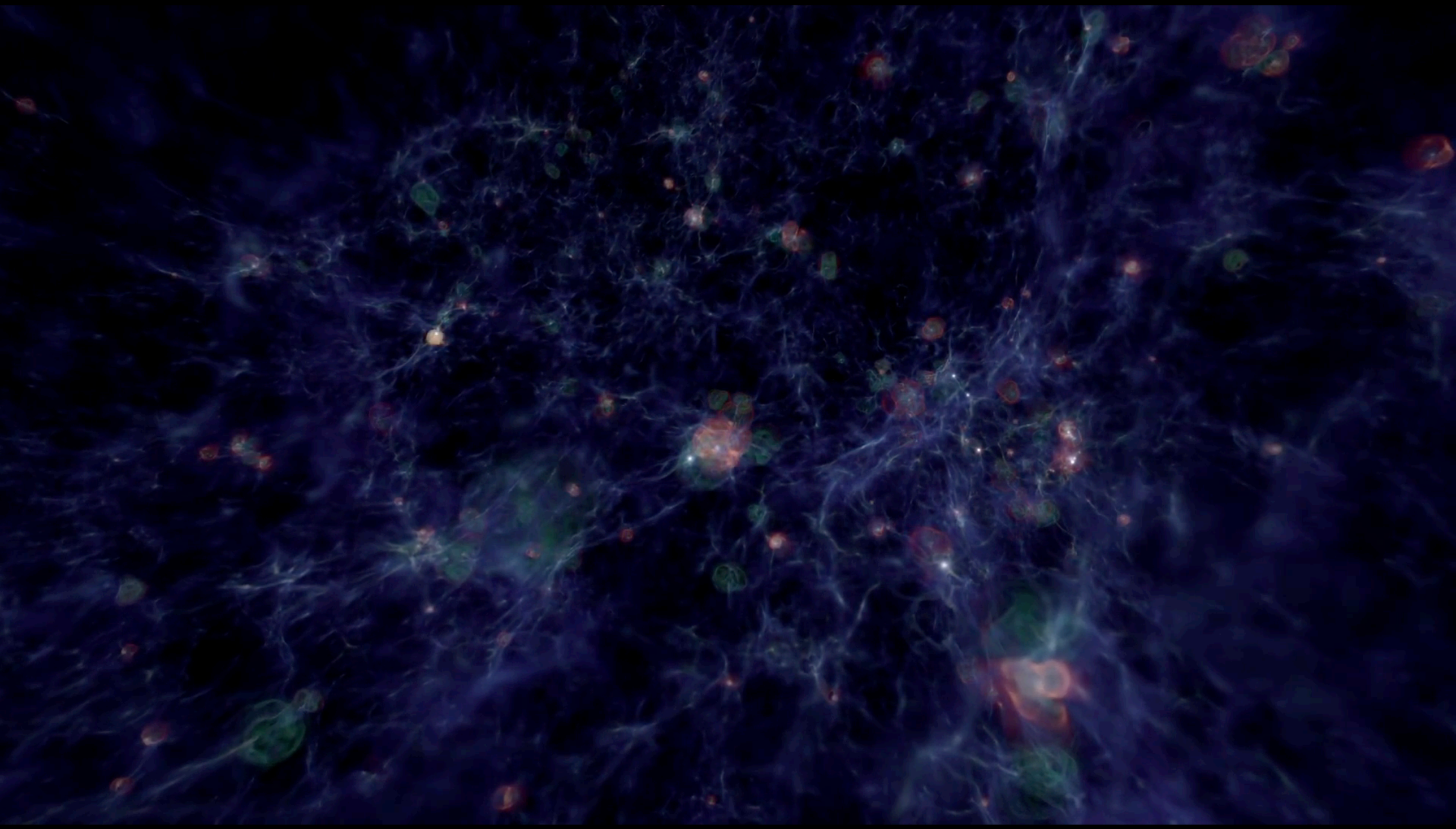
The First Stars and Supernovae



Courtesy of John Wise

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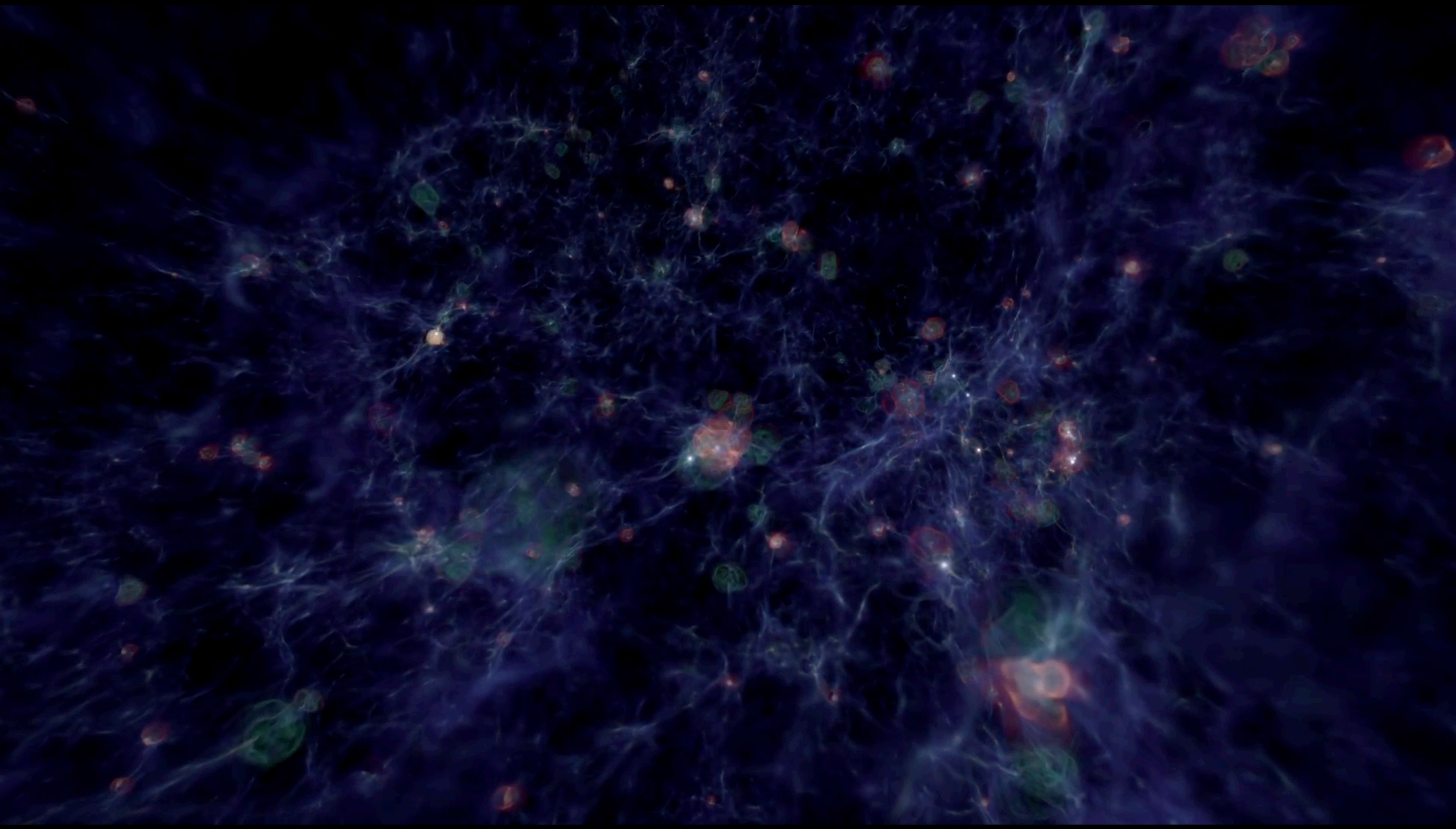

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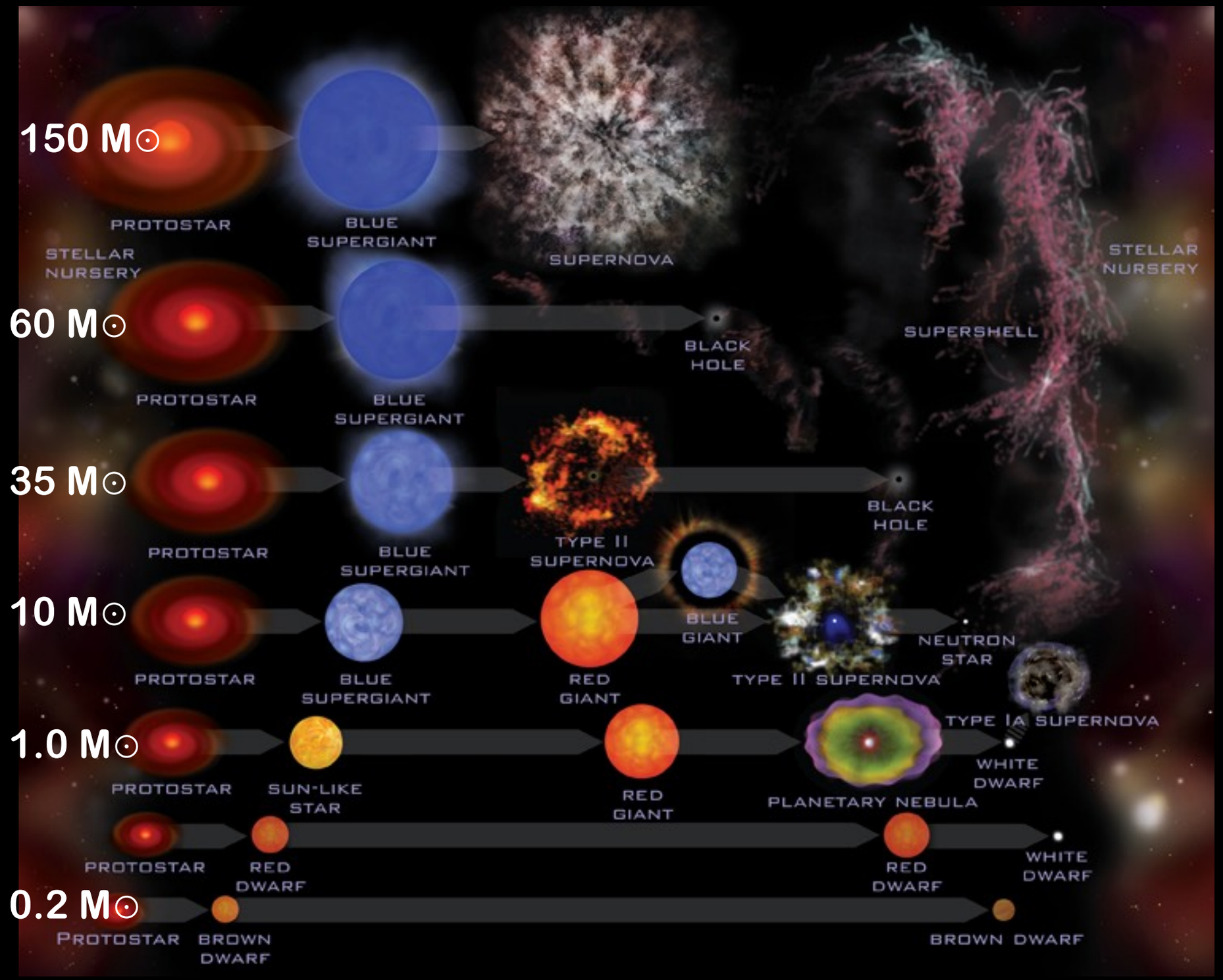
Deaths of Stars

MASS



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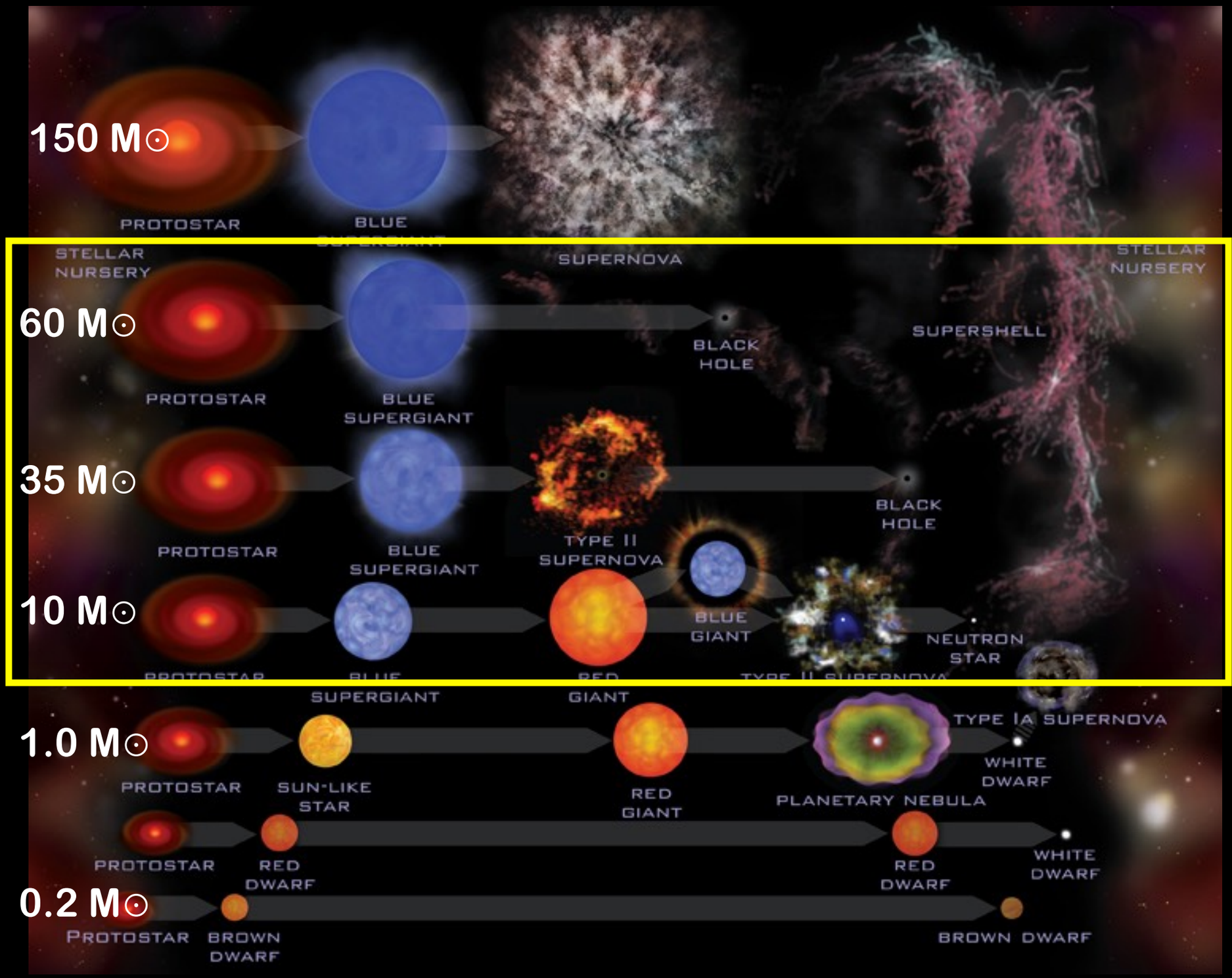

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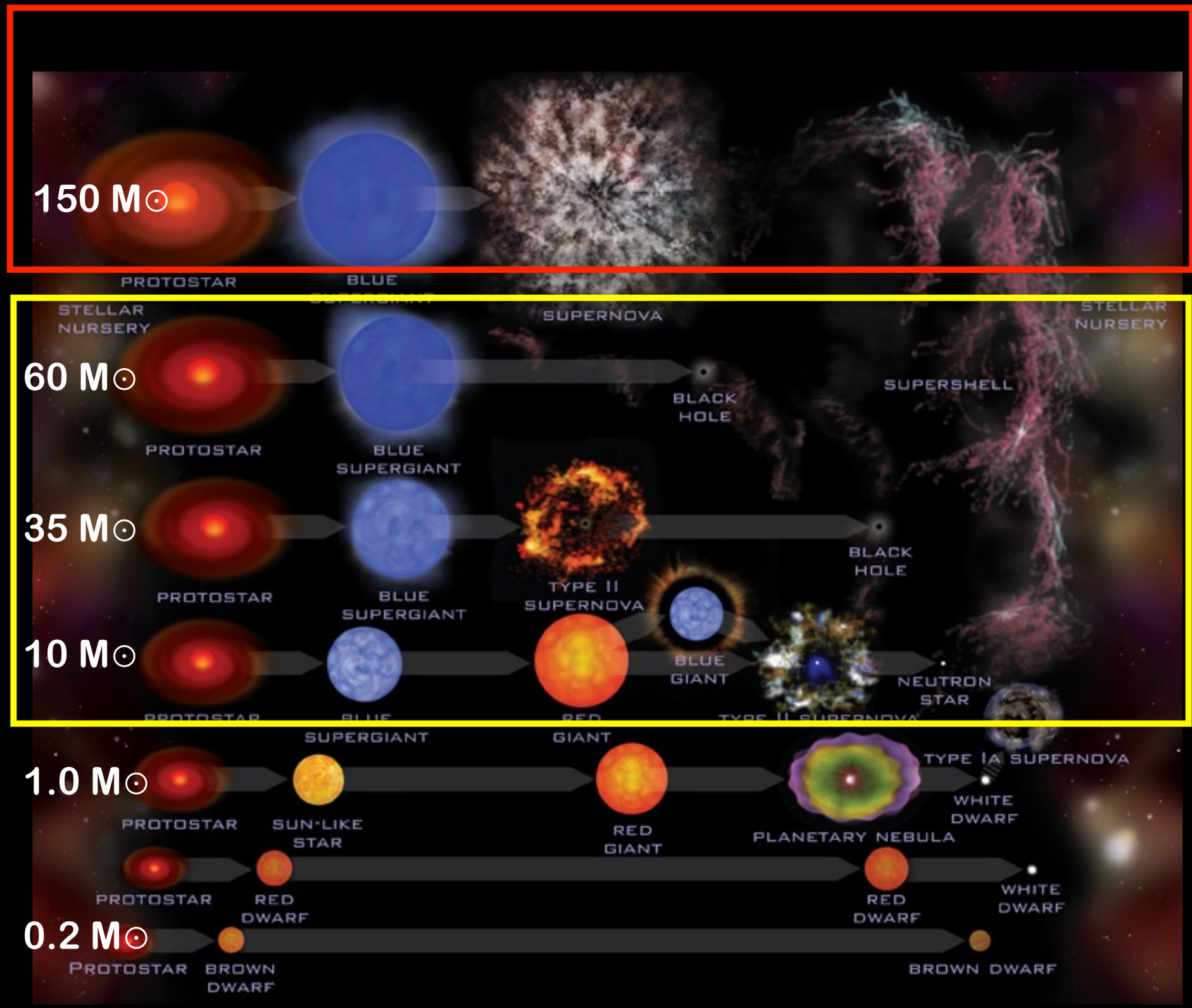

MASS

Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

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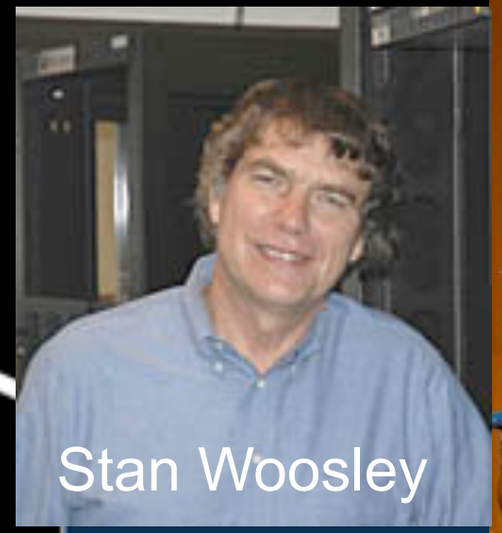
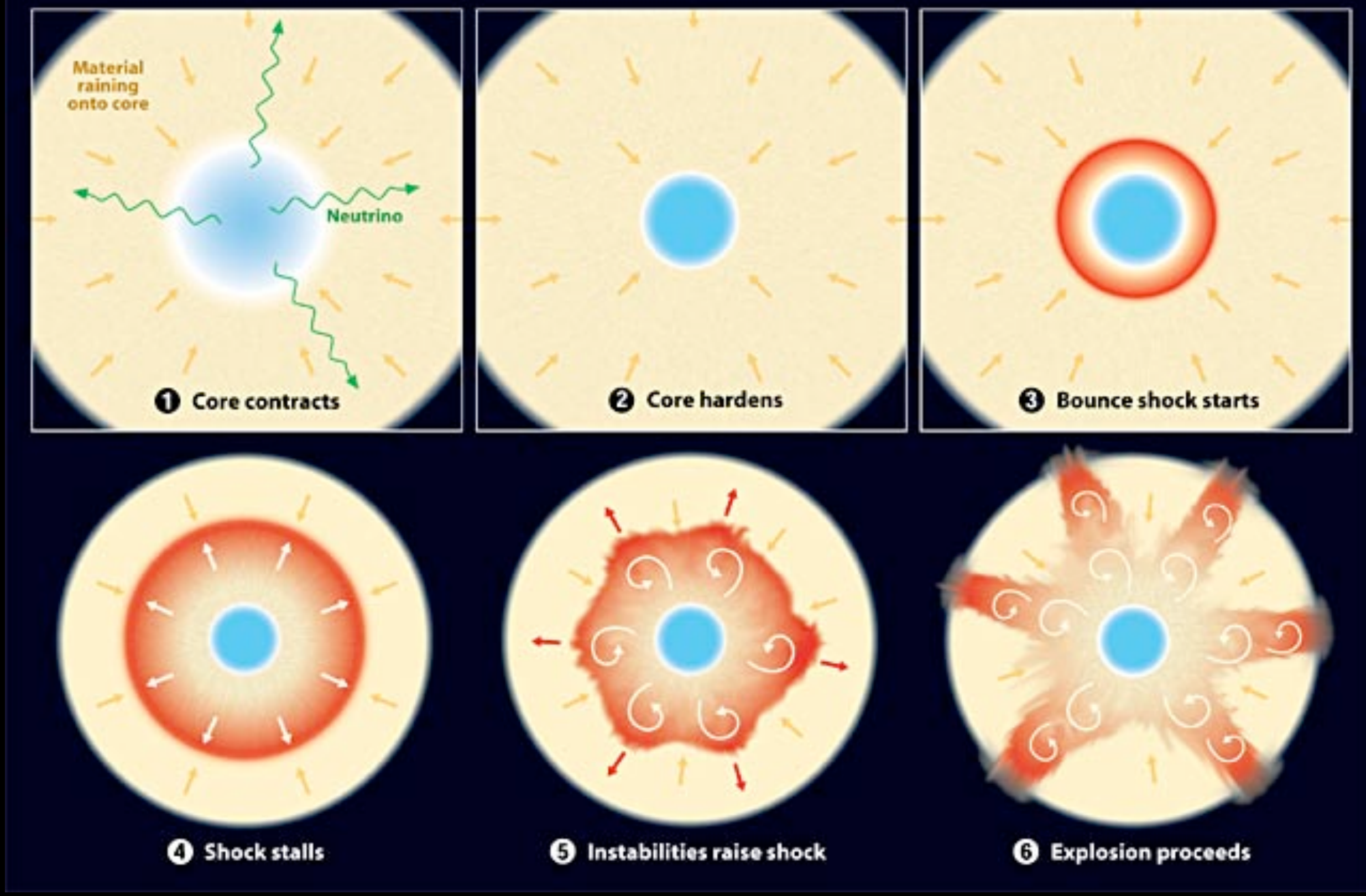
When Massive Stars Die, How Do They Explode?


Stan Woosley


Alex Heger

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 $M_\odot$

Neutrino as a Dynamite



Neutrino Burst Properties:

$$E_{tot} \sim \frac{3}{5}\frac{GM^2}{R}$$

$\sim 3\times10^{53}$ erg

$M = 1.5\ M_\odot$

$R = 10$ km

emitted roughly equally in ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$

Scattering: $\kappa_{\nu s} \approx 1.0\times10^{-20}\left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2\,\text{gm}^{-1}$

Absorption: $\kappa_{\nu a} \approx 4\kappa_{\nu s}$

Time scale

$$\tau_{Diff} \sim \left(\frac{R^2}{l\,c}\right) \qquad l = \frac{1}{\kappa_\nu \rho}$$

$\kappa_\nu \sim 10^{-16}\ \text{cm}^2\ \text{gm}^{-1}$ for $\varepsilon_\nu = 50$ MeV

$\rho \sim 3\times10^{14}\ \text{gm cm}^{-3} \quad \Rightarrow \quad l \sim 30$ cm $\qquad$ R ~ 20 km

$$\tau_{Diff} \sim \left(\frac{(2\times10^6)^2}{30\cdot3\times10^{10}}\right) \sim$$ 5 sec

Very approximate

Challenges

- Tough physics – nuclear EOS, neutrino opacities
- Tough problem computationally – must be 3D (convection is important). 6 flavors of neutrinos out of thermal equilibrium (thick to thin region crucial). Must be follwoed with multi-energy group and multi-angles
- Magnetic fields and rotation may be important
- If a black hole forms, problem must be done using relativistic (magnto-)hydrodynamics (general relativity, special relativity, magnetohydrodynamics)

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The central engine (neutron star/black hole) is the key!

Neutrino-Powered SNe

Fe-core Collapse SNe
Nordhaus+ 2010
Using CASTRO

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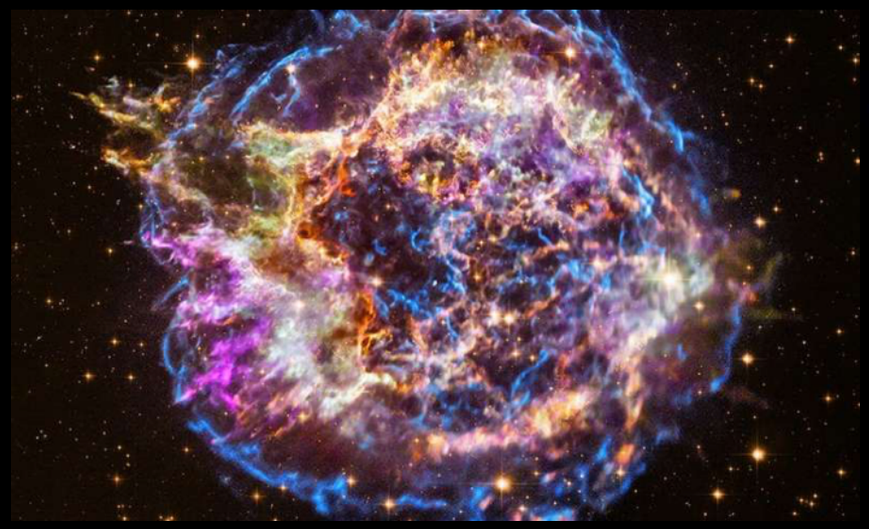

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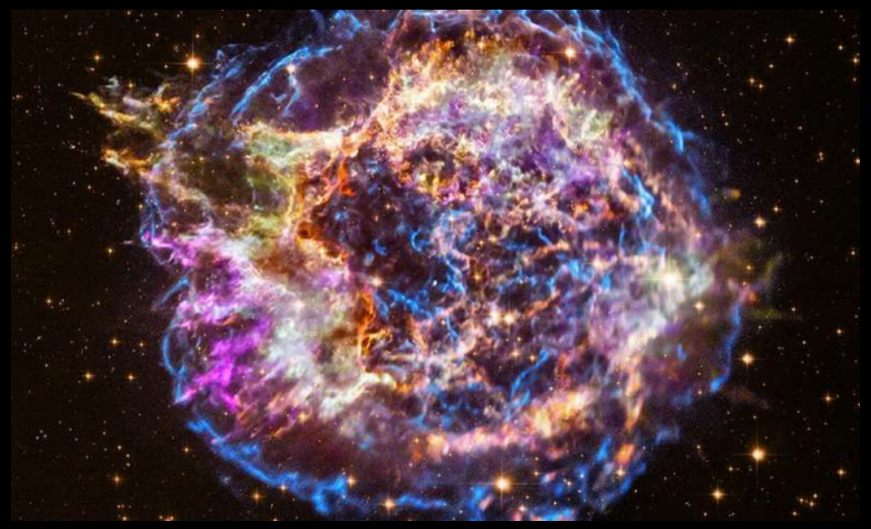
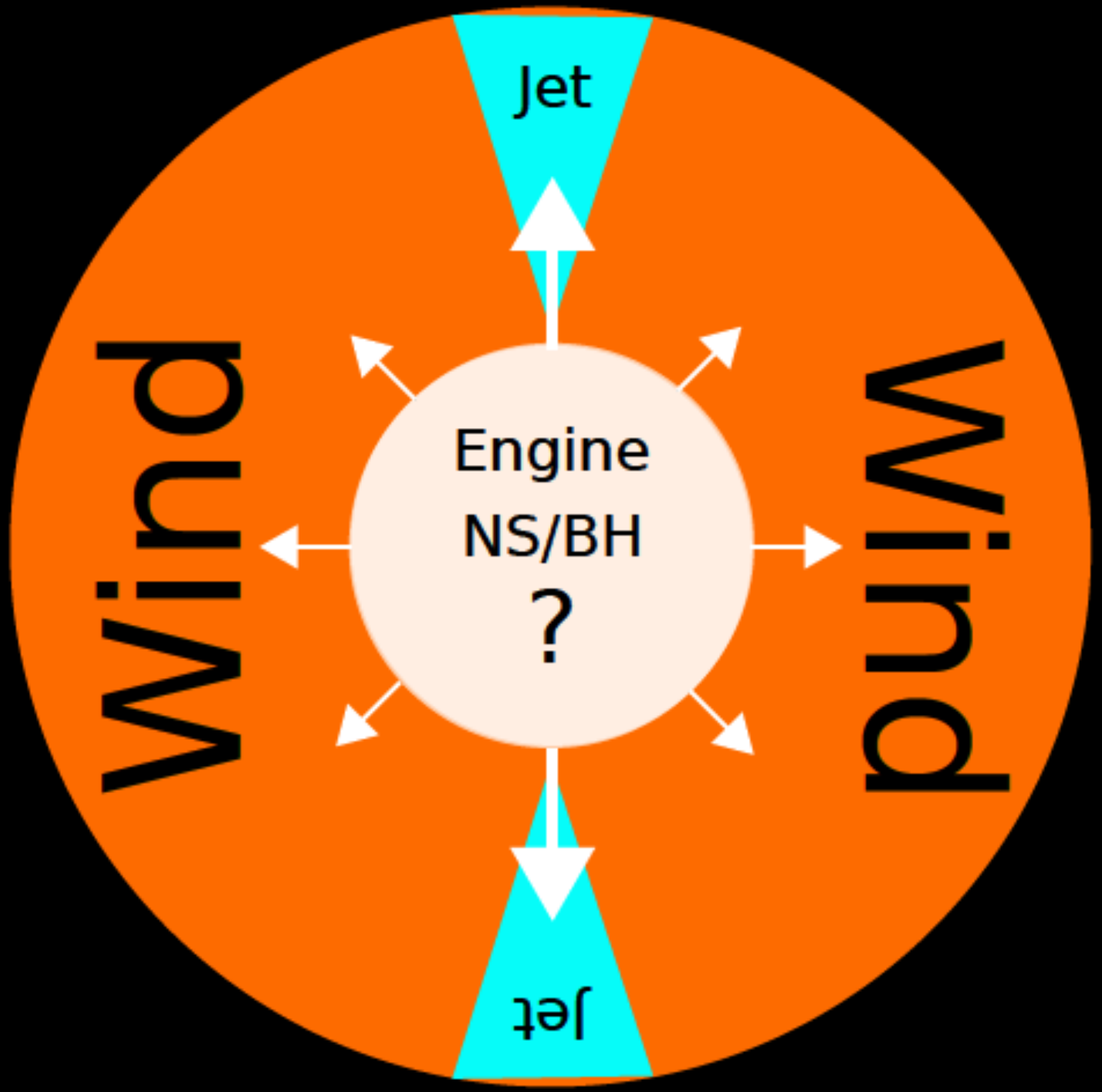


Hypernova and GRB !!!

60 M⊙ > M* > 30 M⊙



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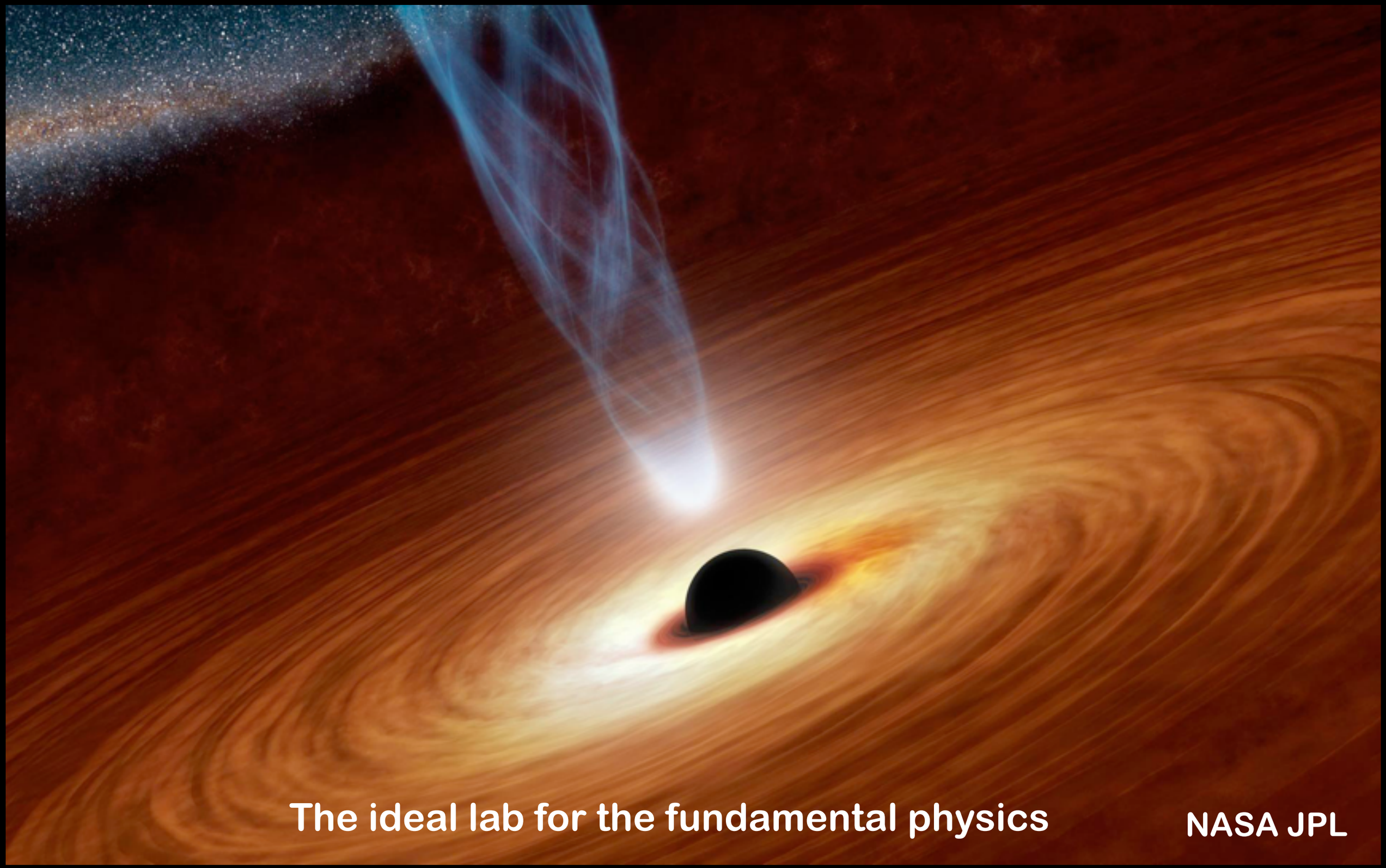
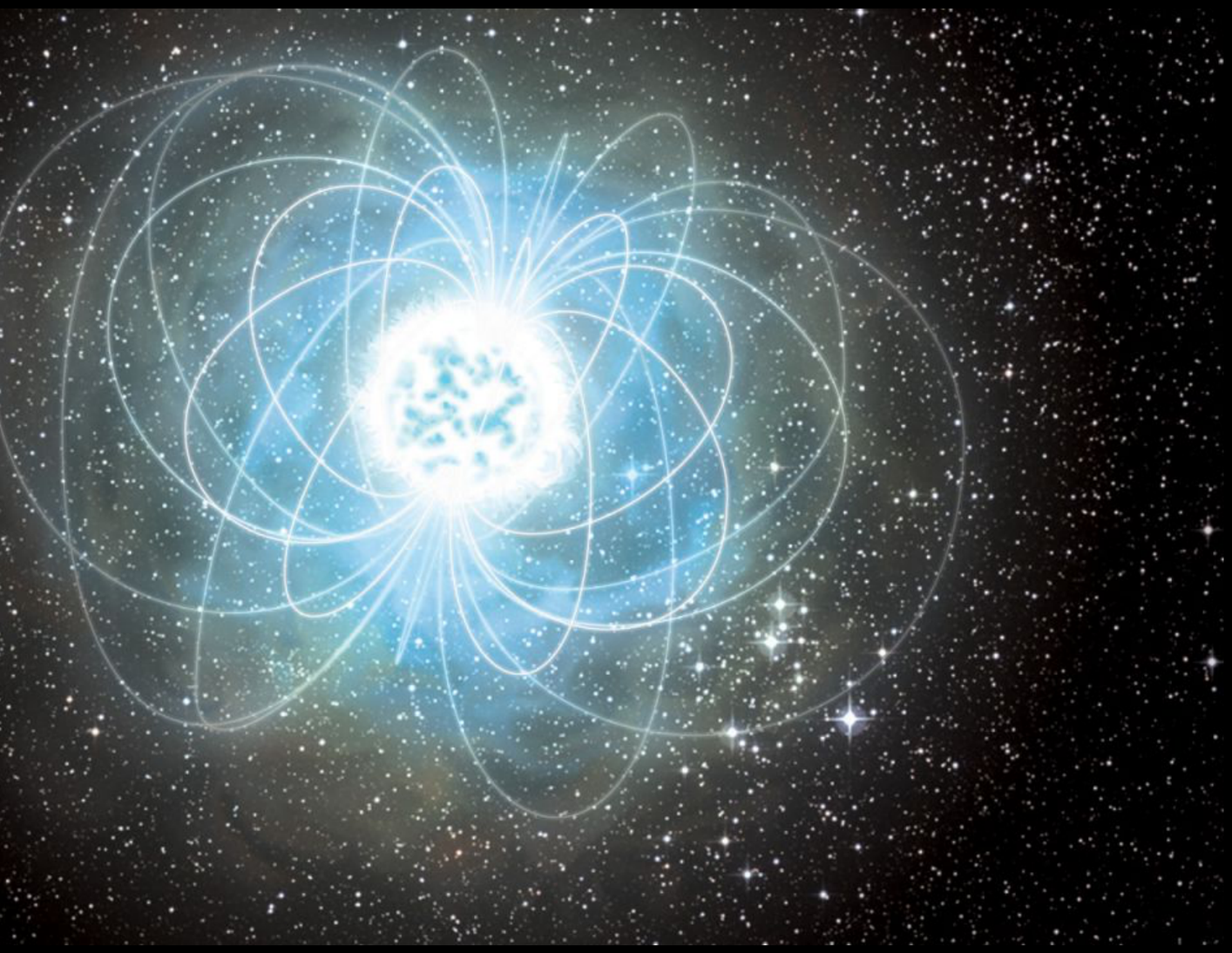


Magnetar Physics 101



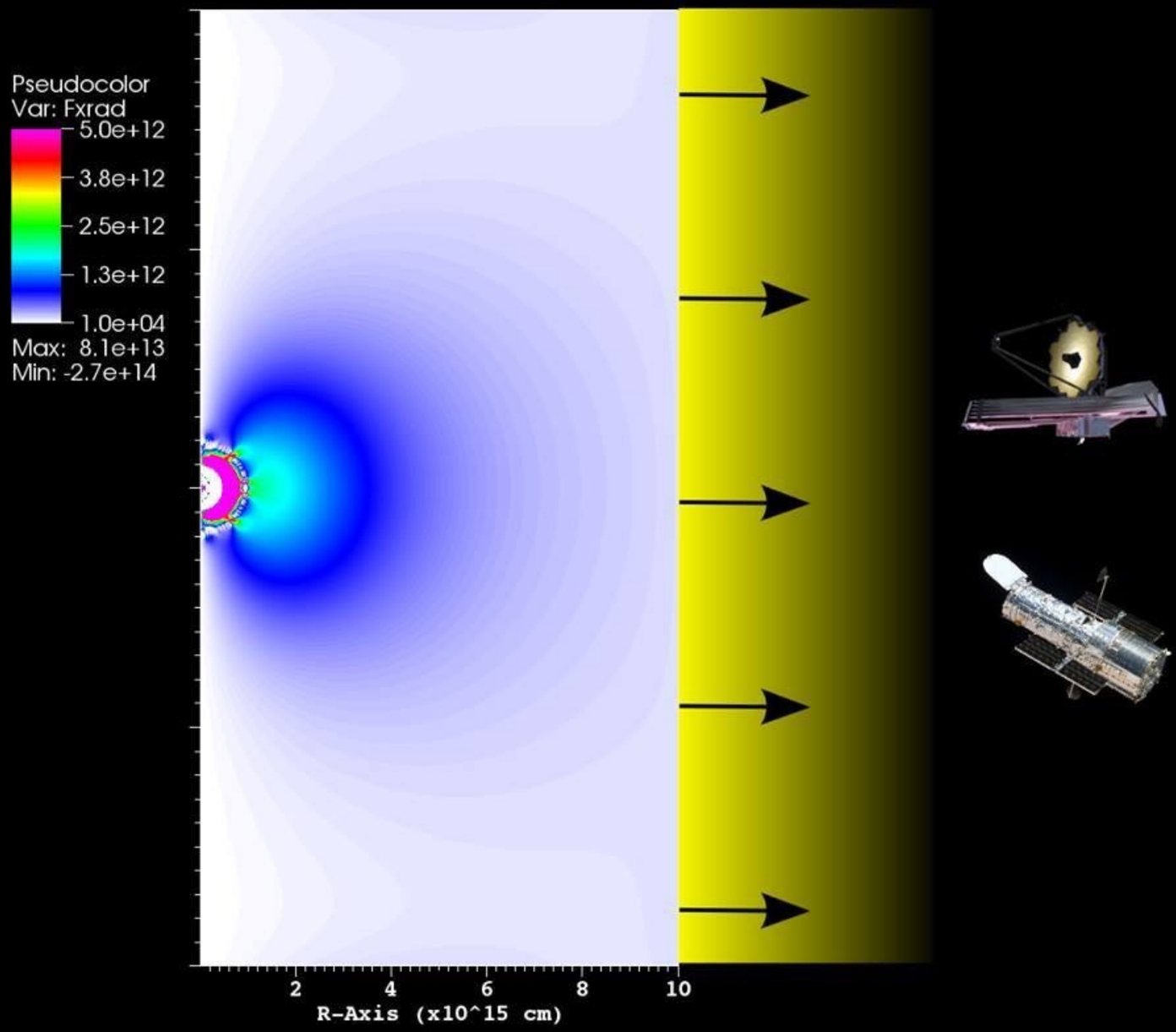
$$E = \frac{1}{2} I \omega^2 \approx 2 \times 10^{52} P_{ms}^{-2} \quad \text{erg}.$$

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

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

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

Model and Observation



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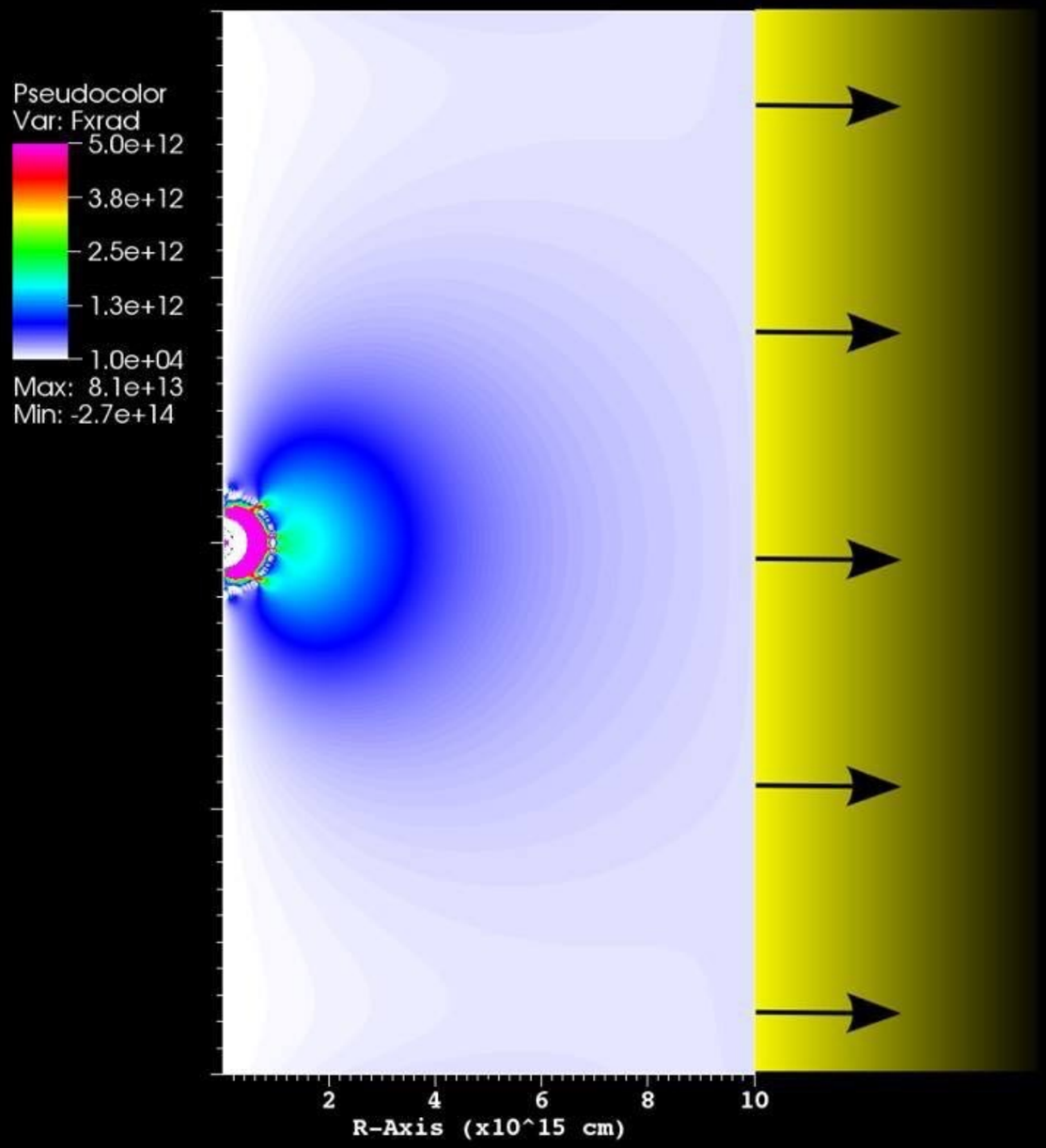
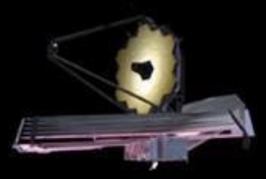
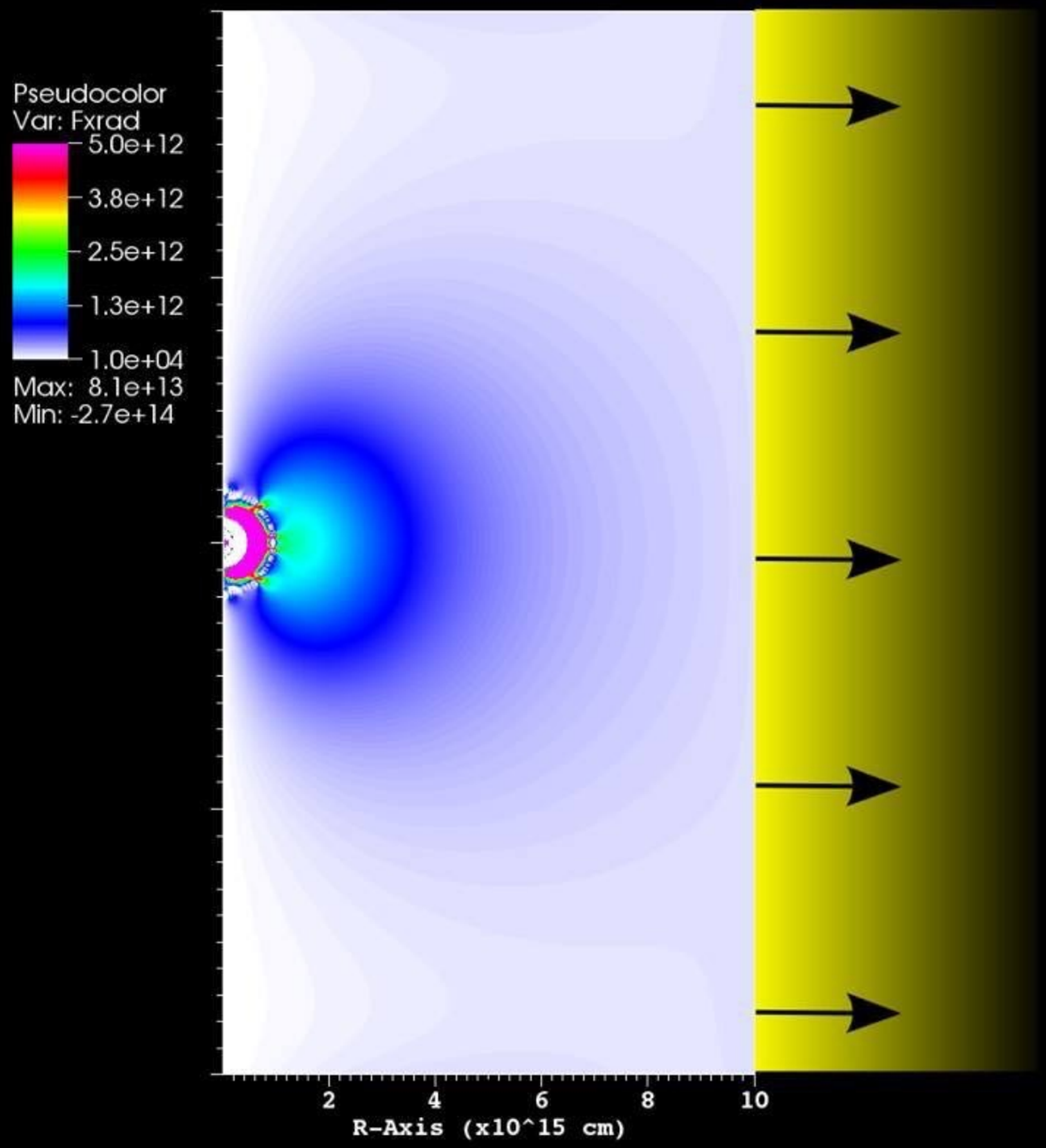


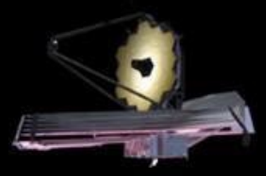


1D models

Stellar Evolution > Explosions > lights > yields

Model and Observation





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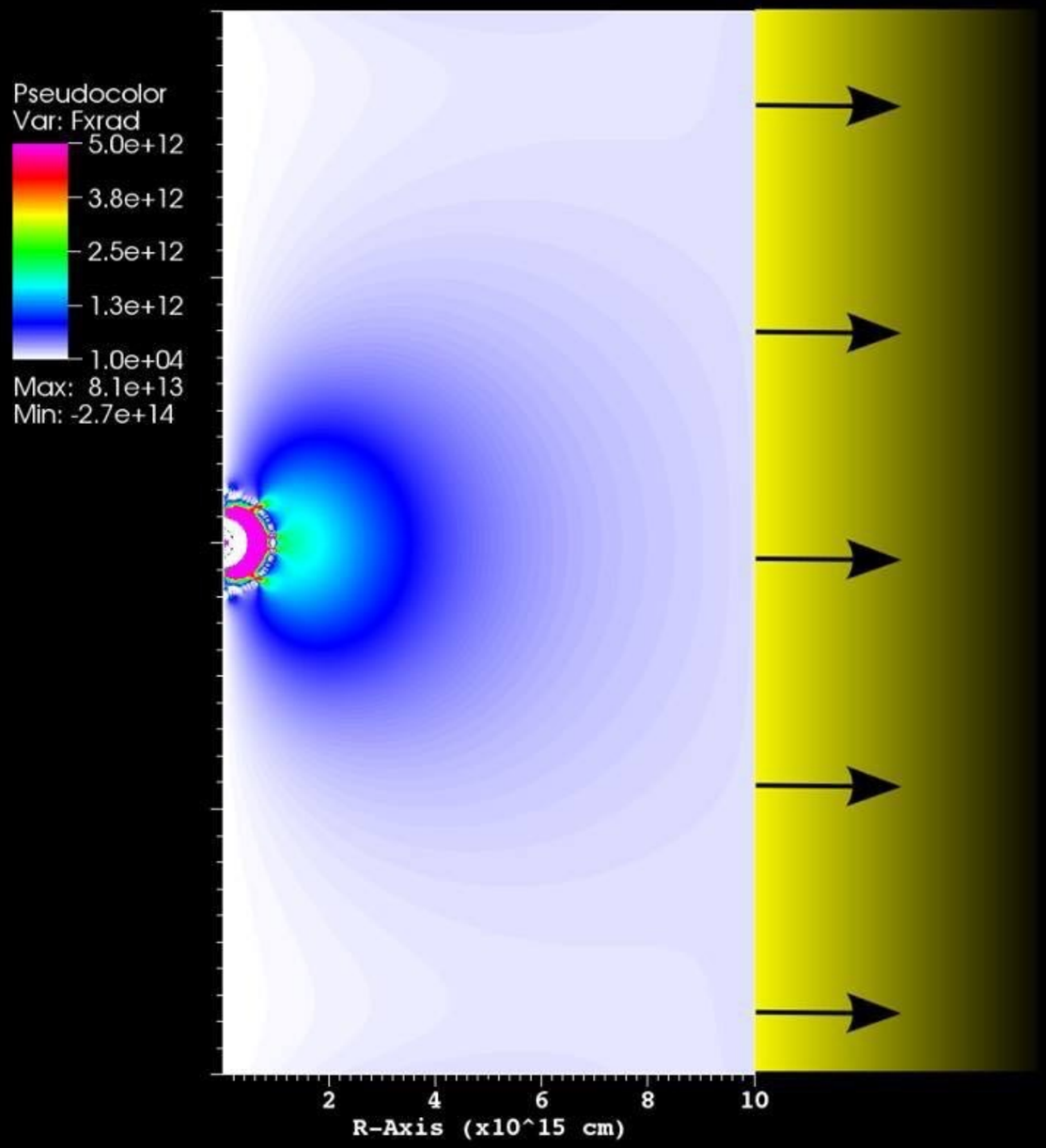

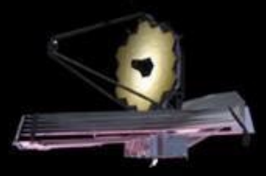

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Multi-D models

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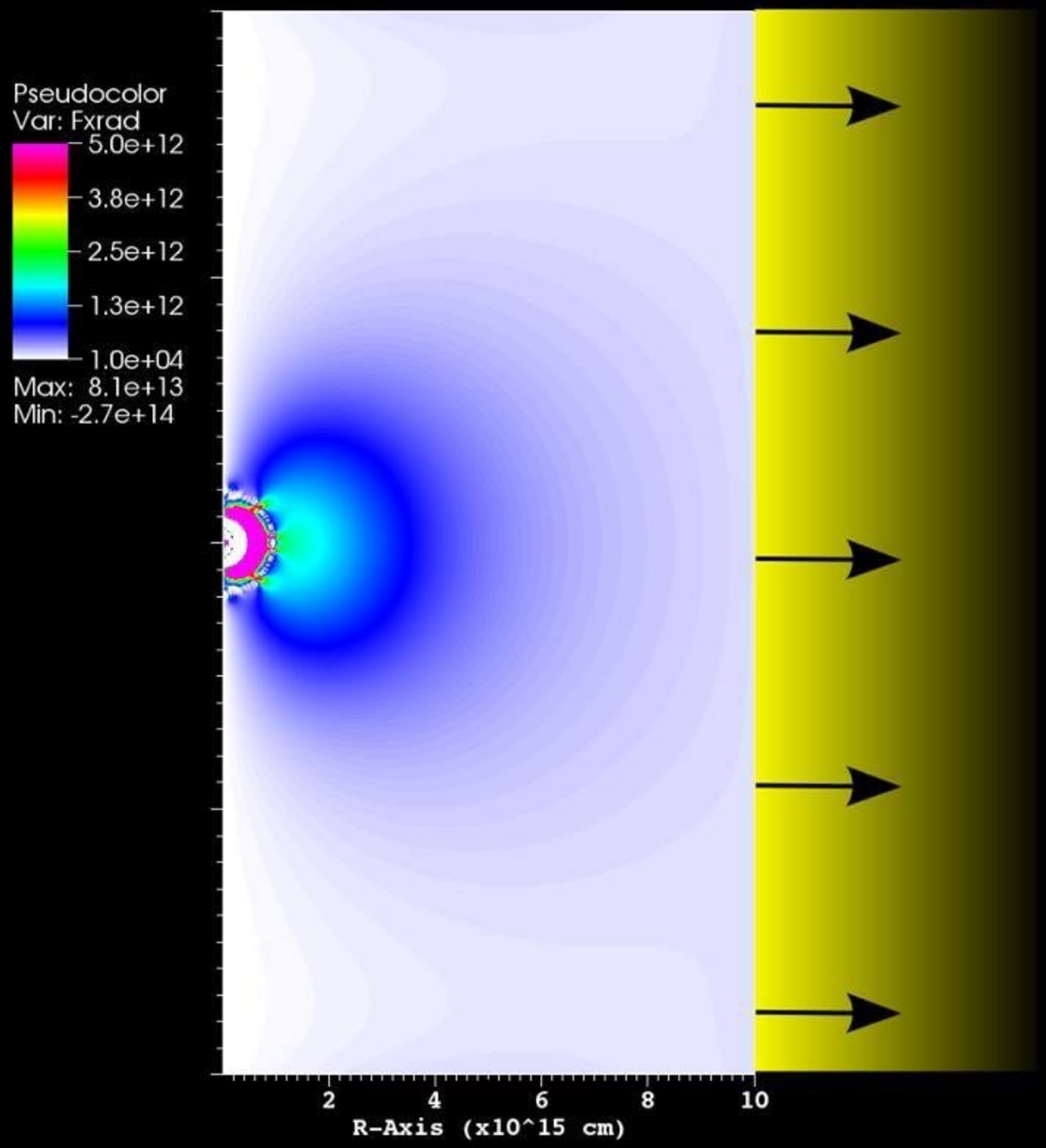
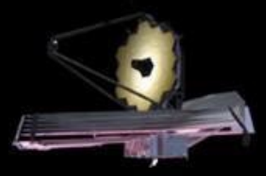
Model and Observation





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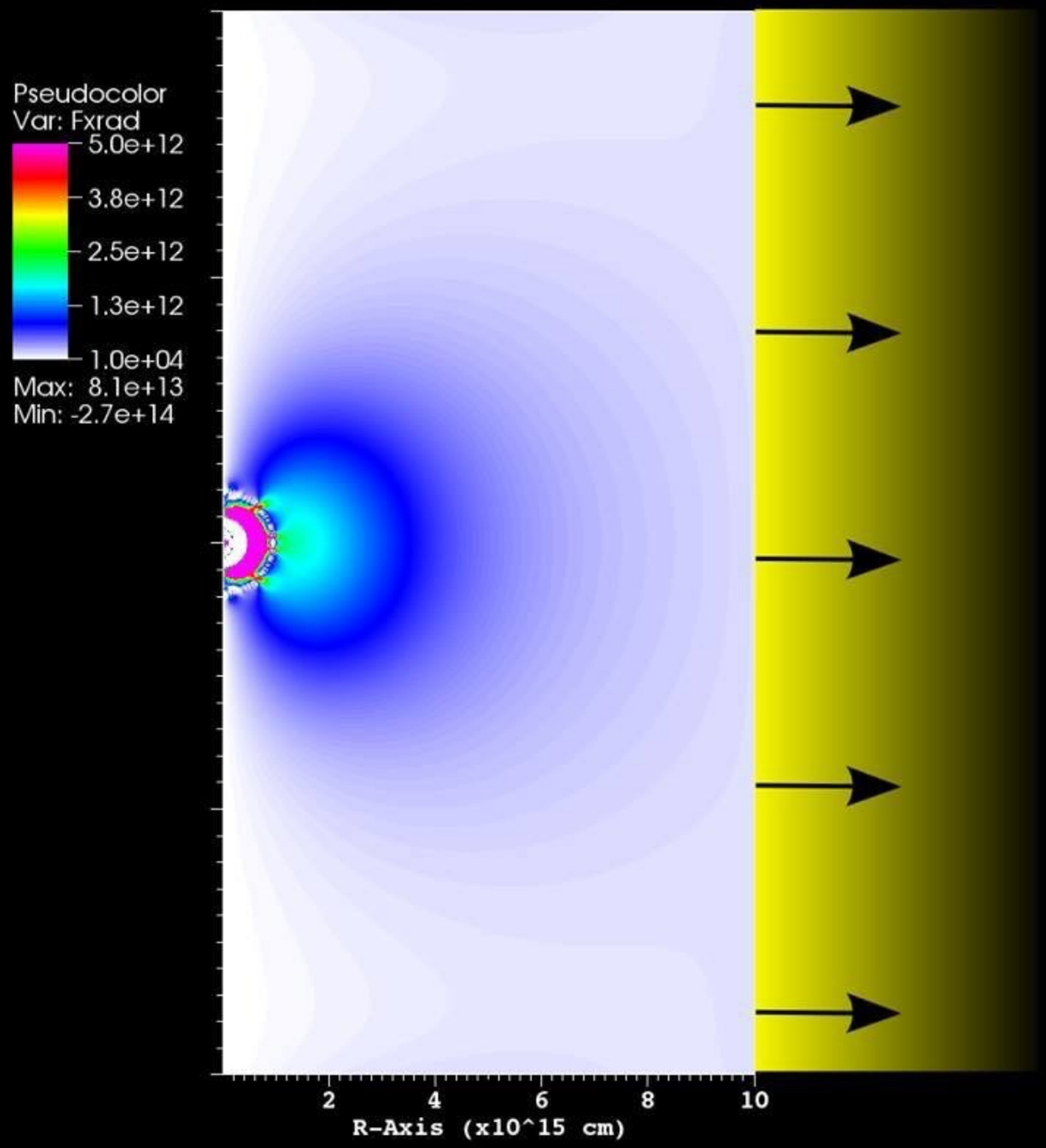

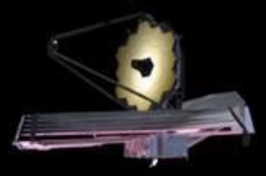

1D models

Stellar Evolution > Explosions > lights > yields

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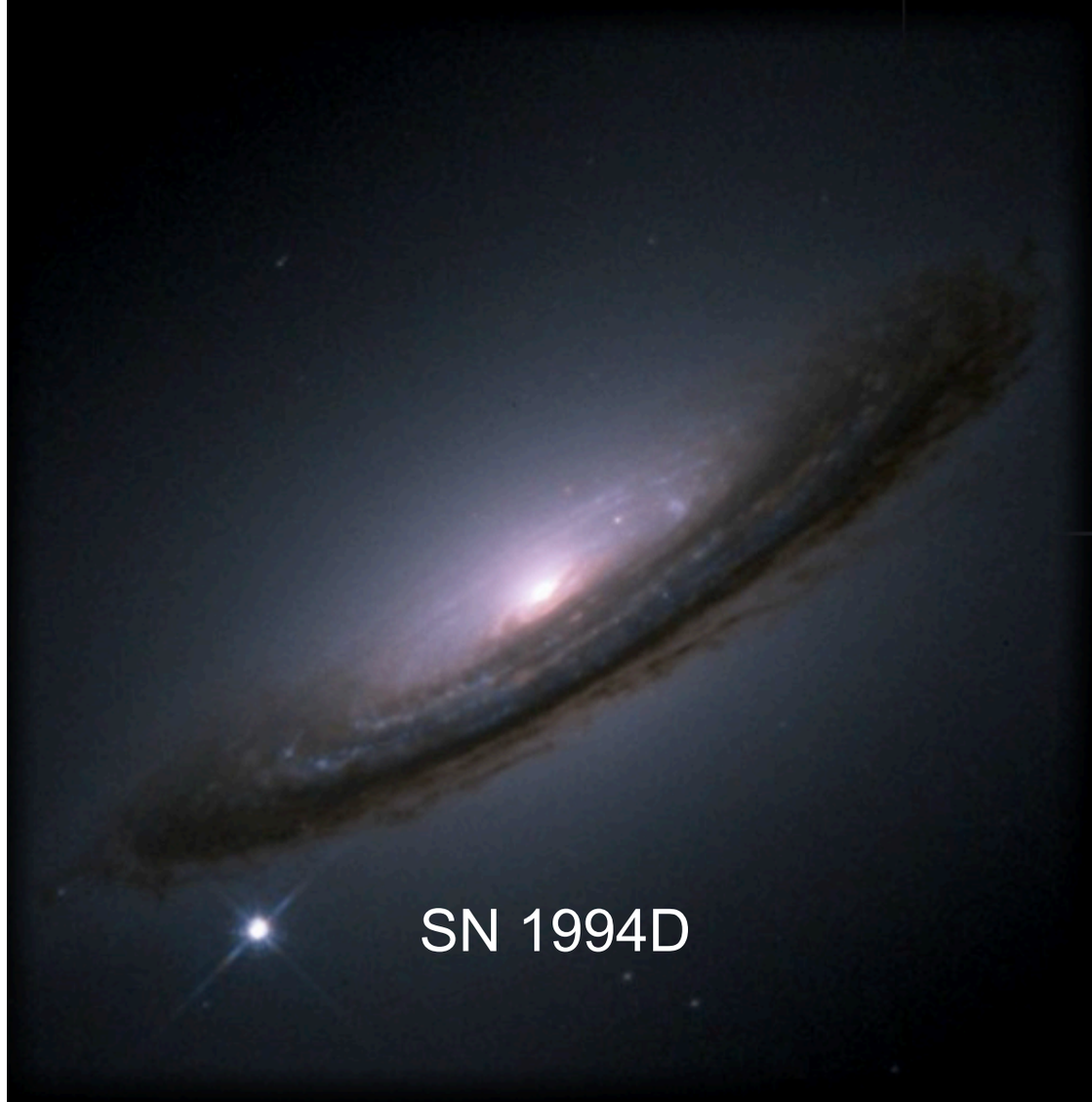
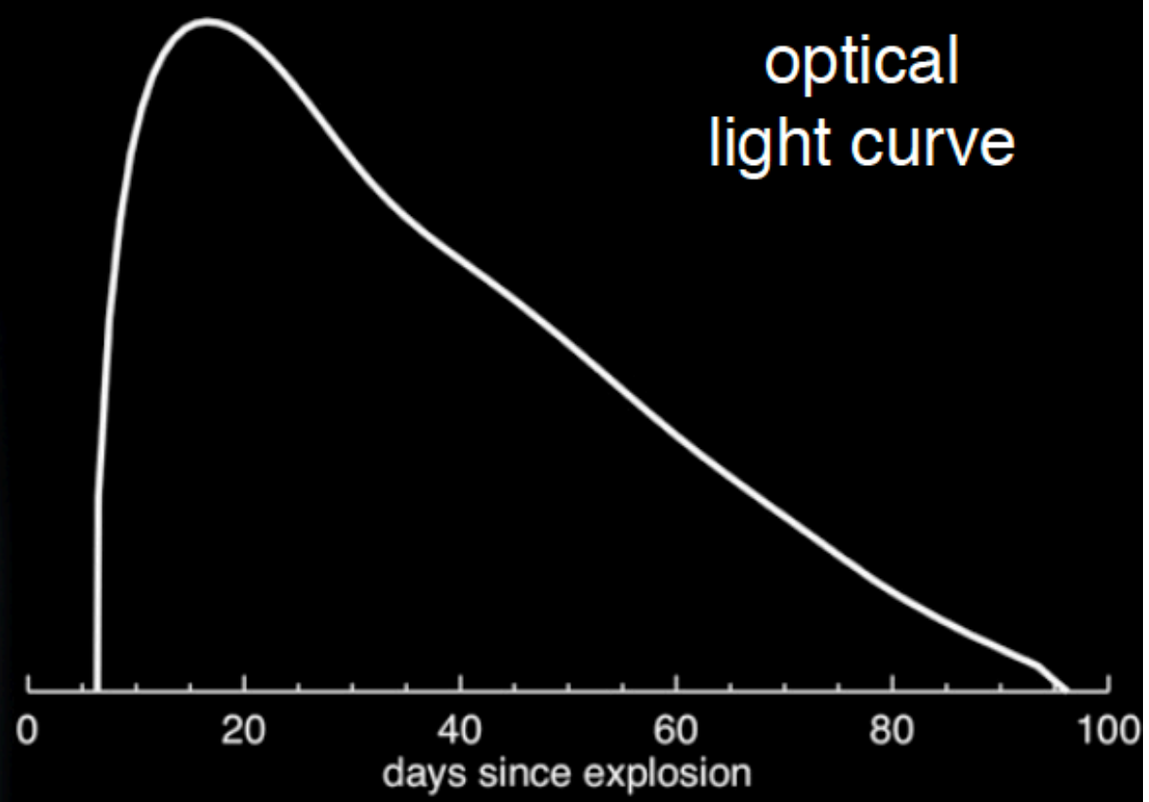
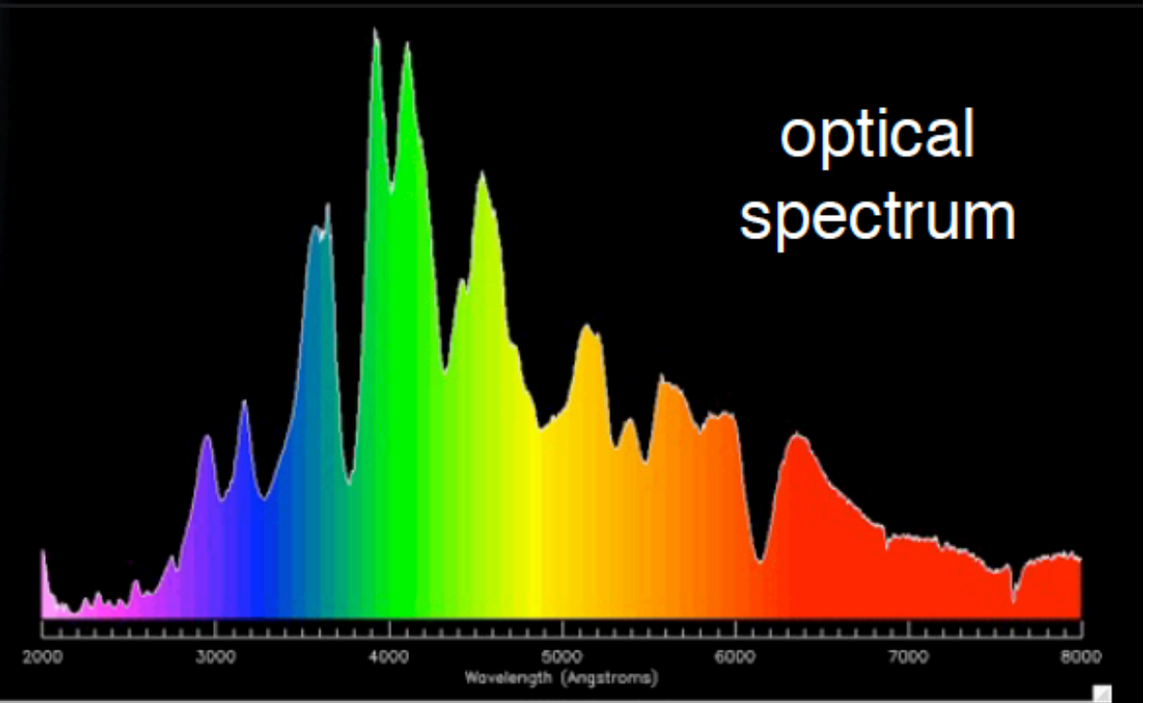
Observations !!!

SNe Observation

supernovae and the transient universe

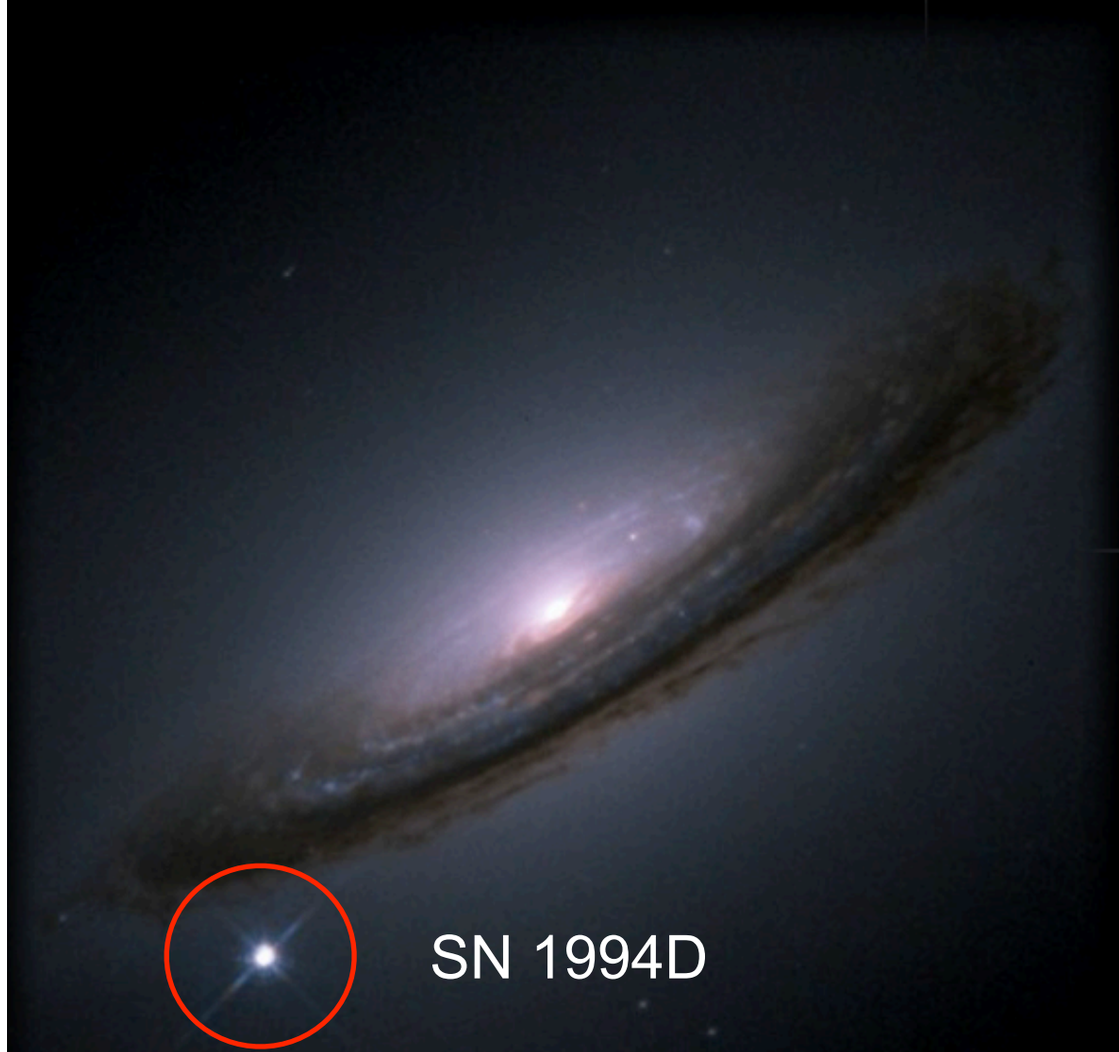


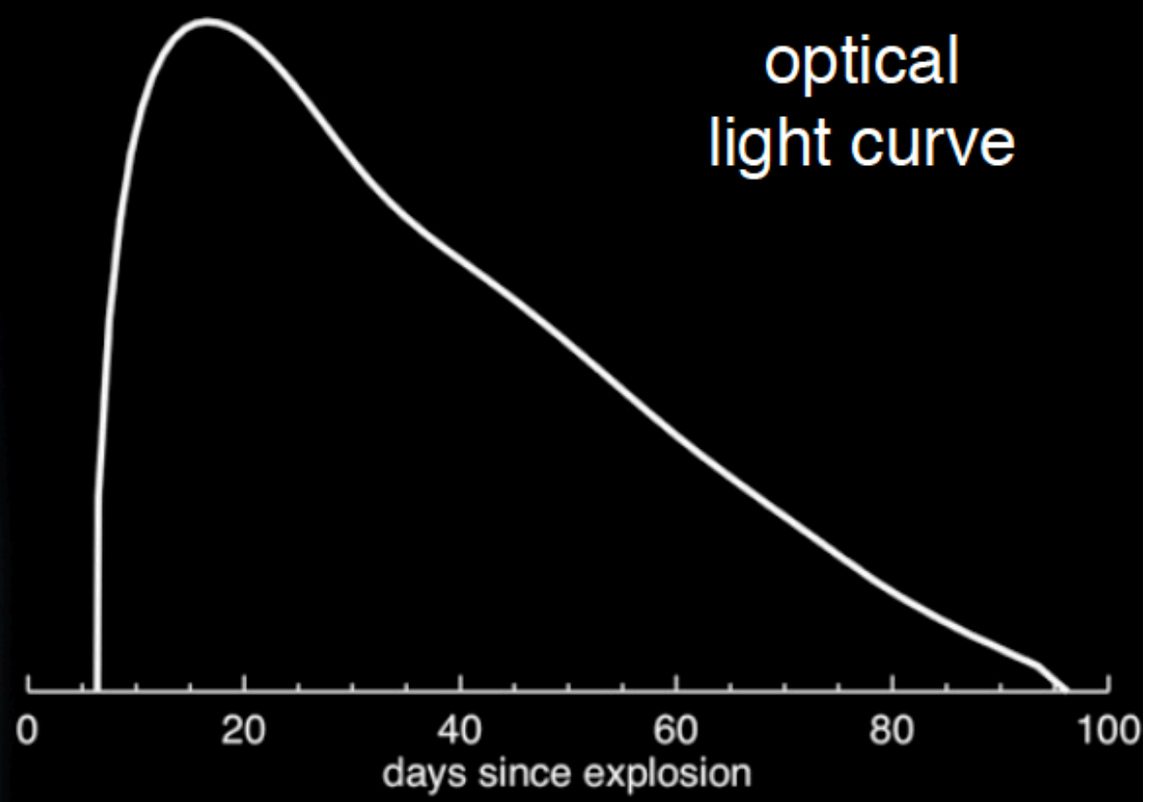


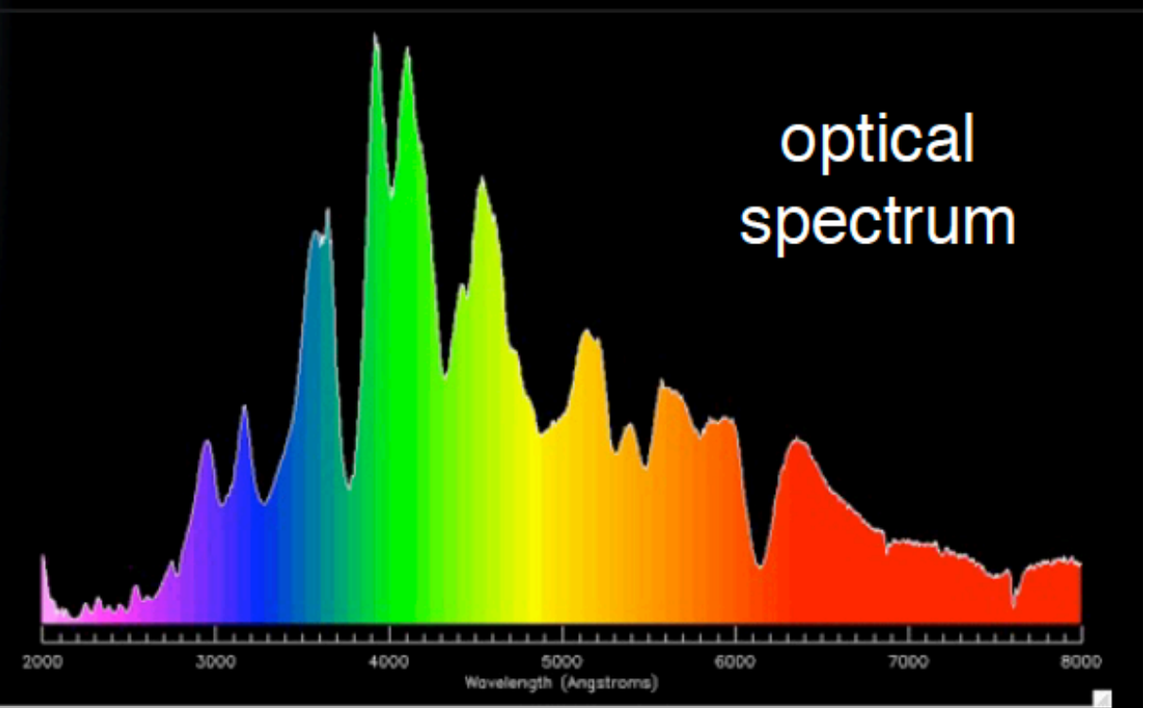


SNe Observation

supernovae and the transient universe







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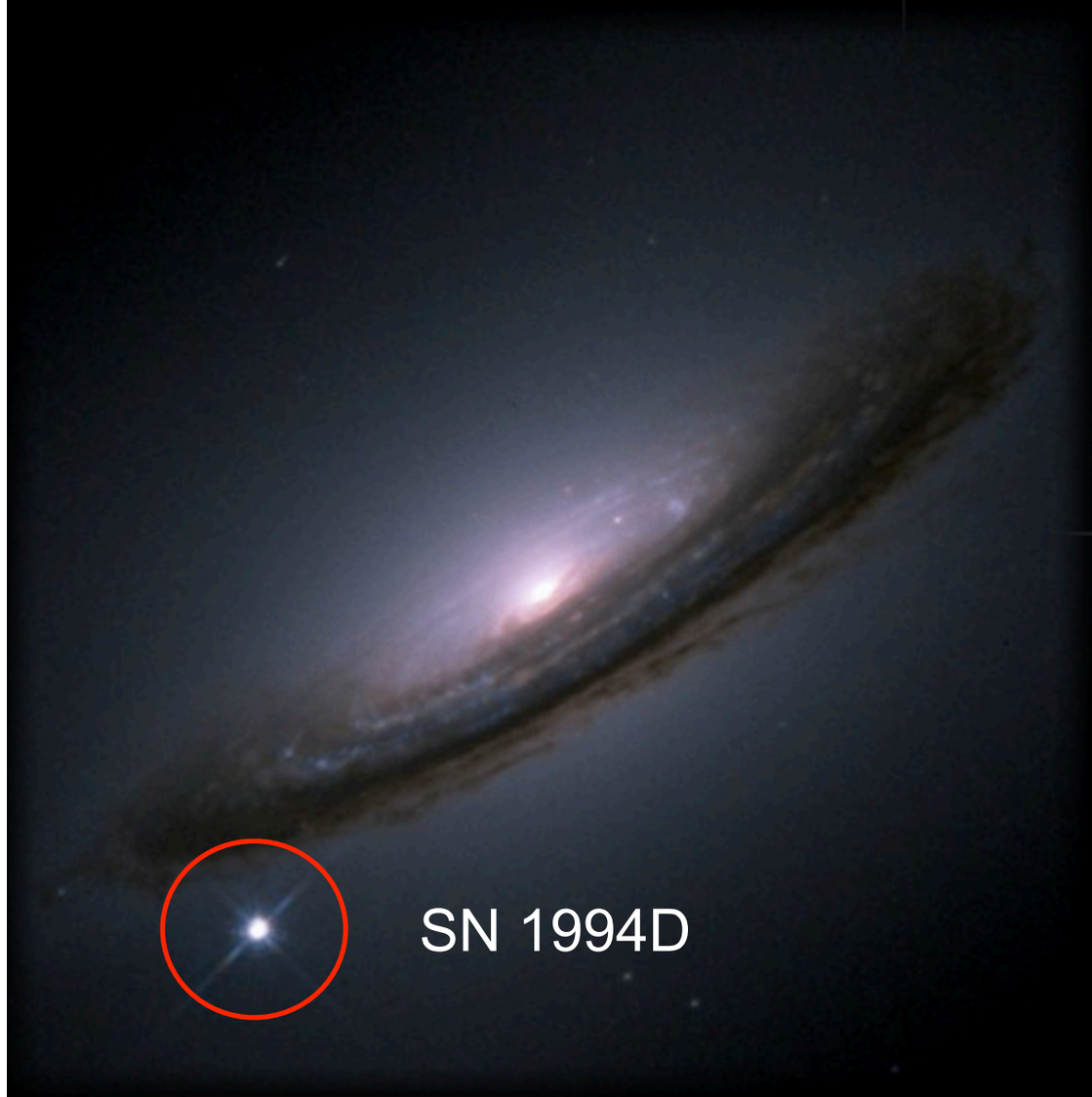
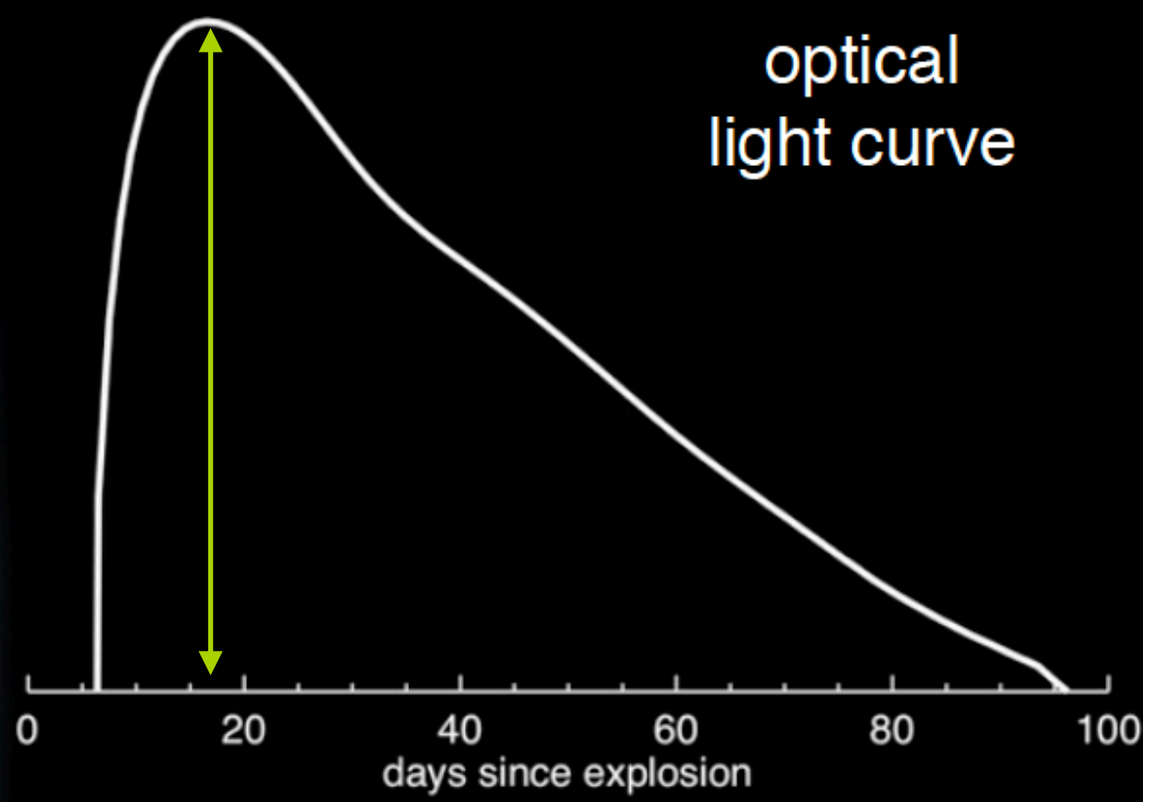
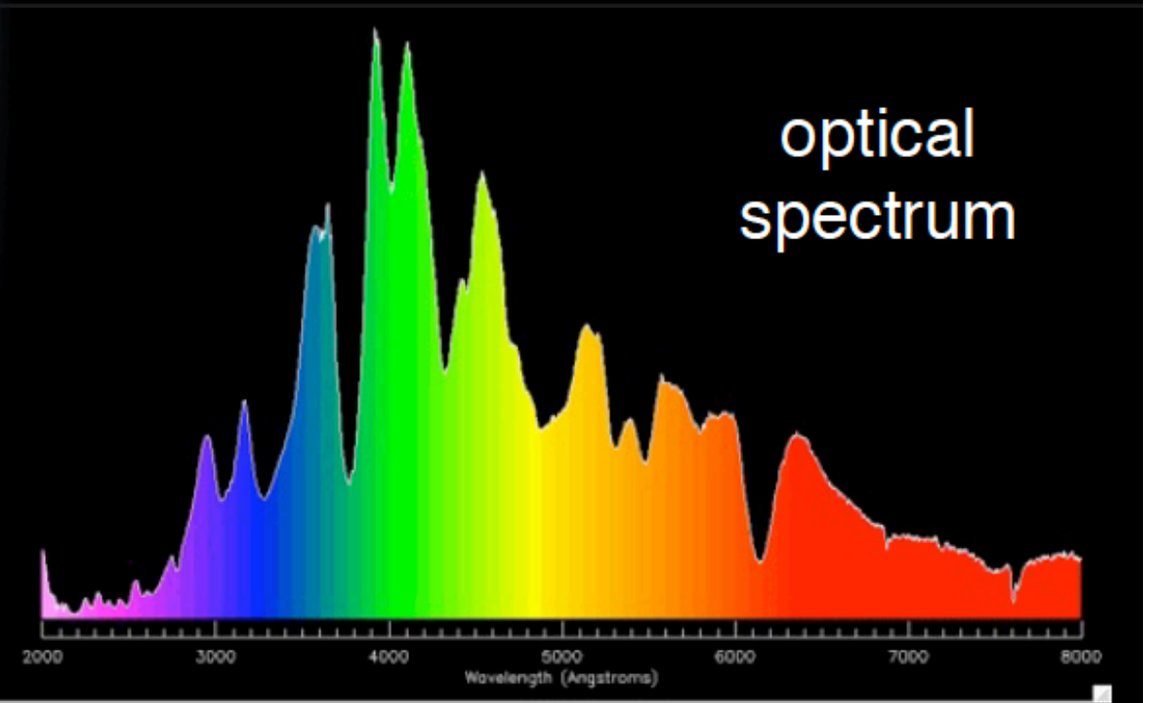
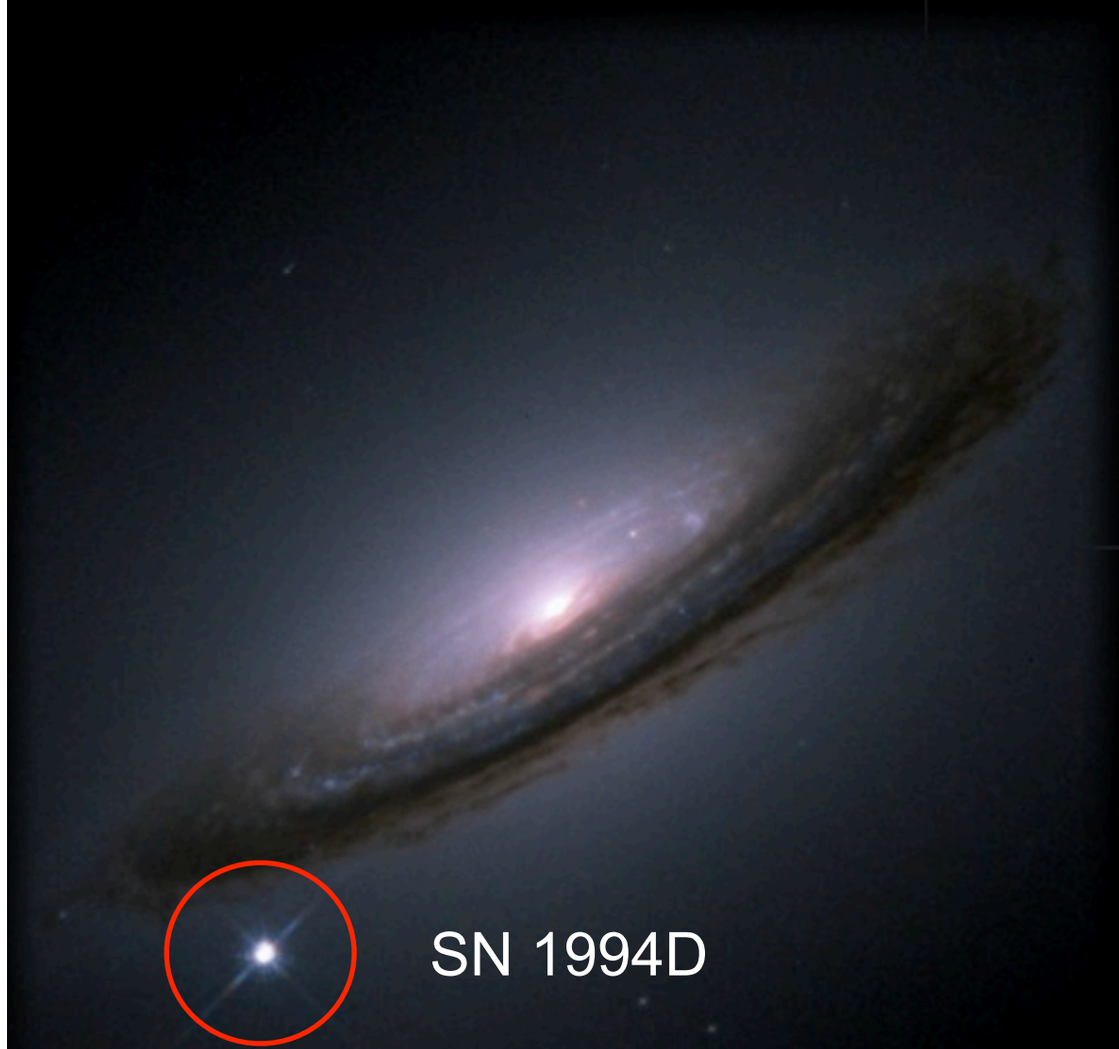


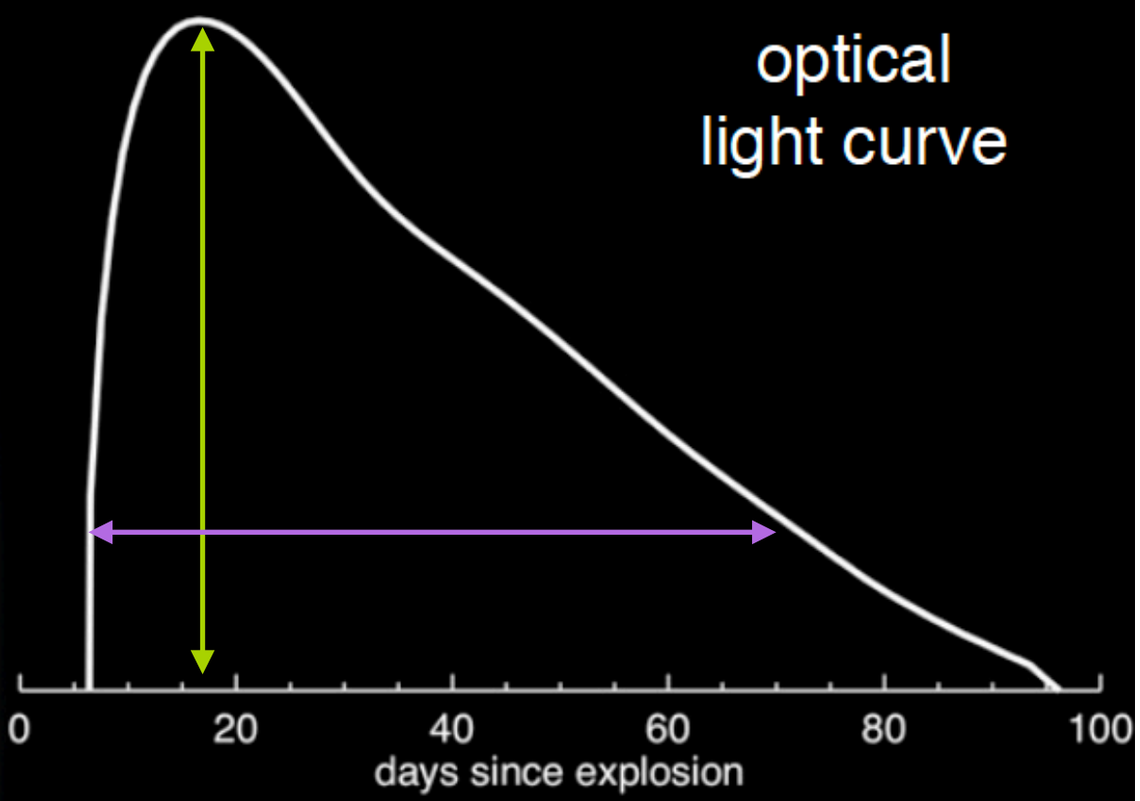


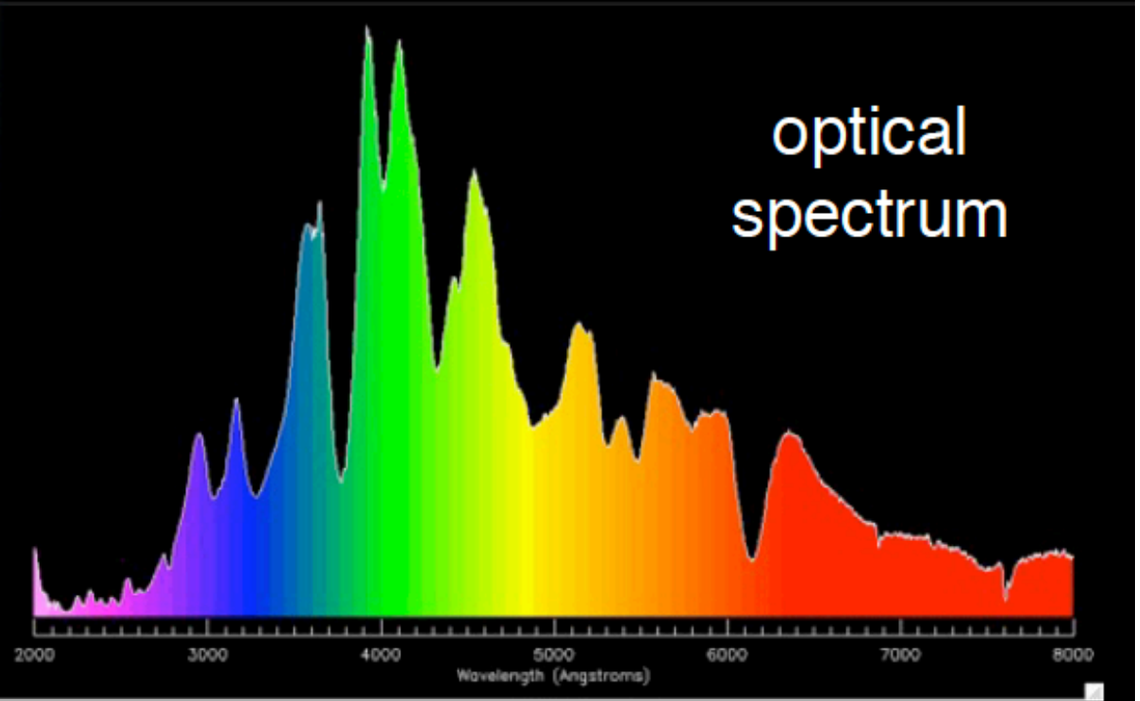


SNe Observation

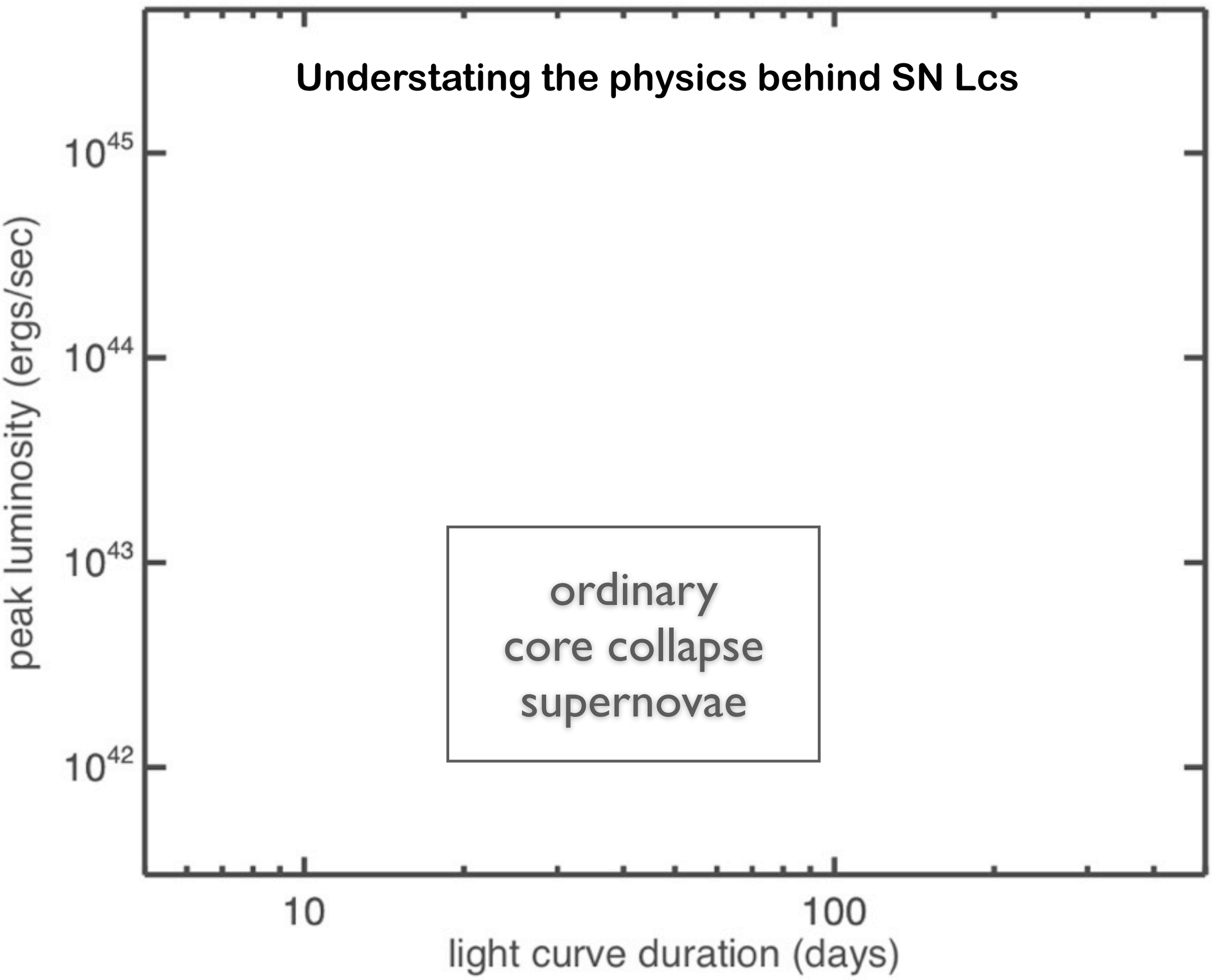
supernovae and the transient universe



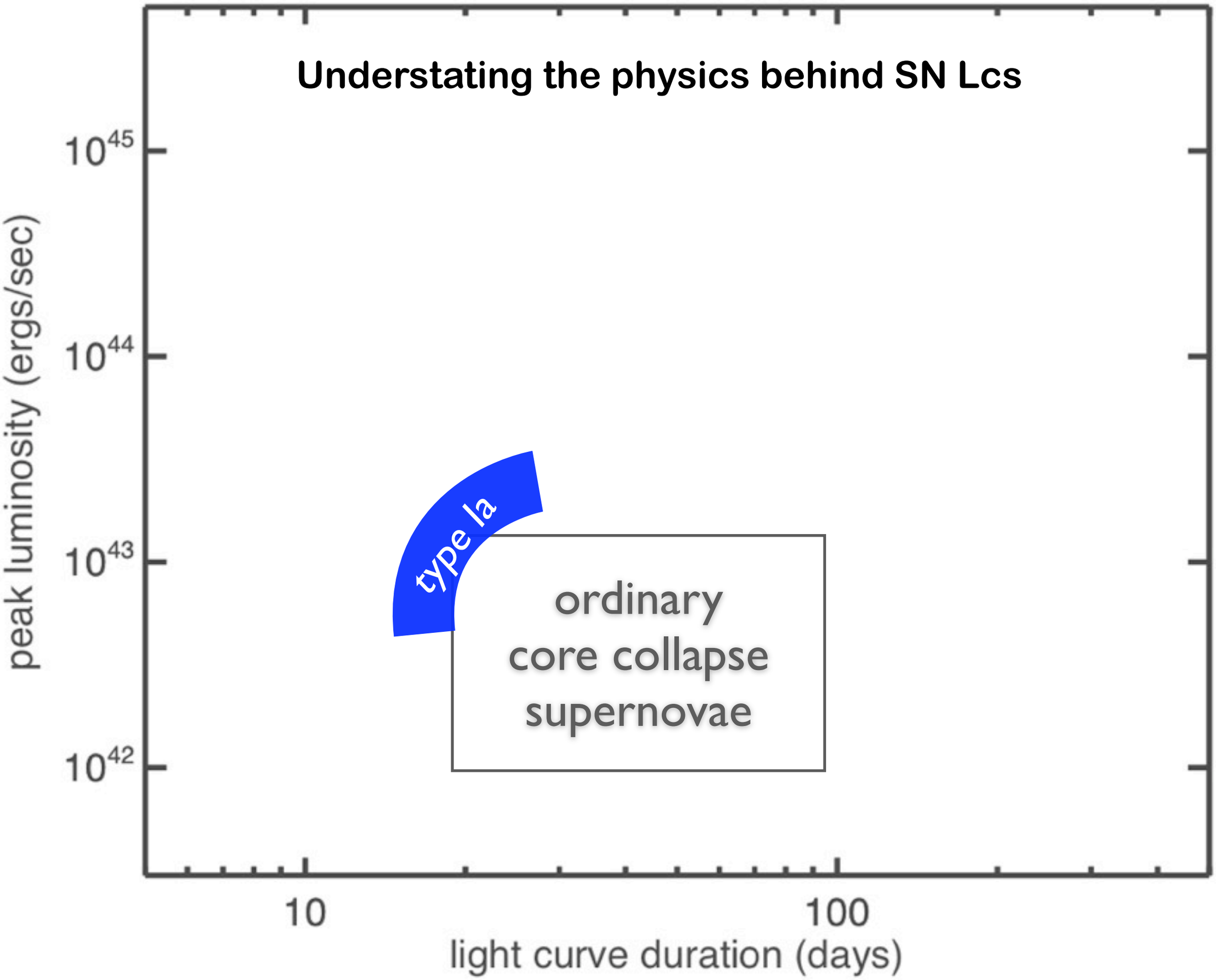




Understating the physics behind SN Lcs



Understating the physics behind SN Lcs



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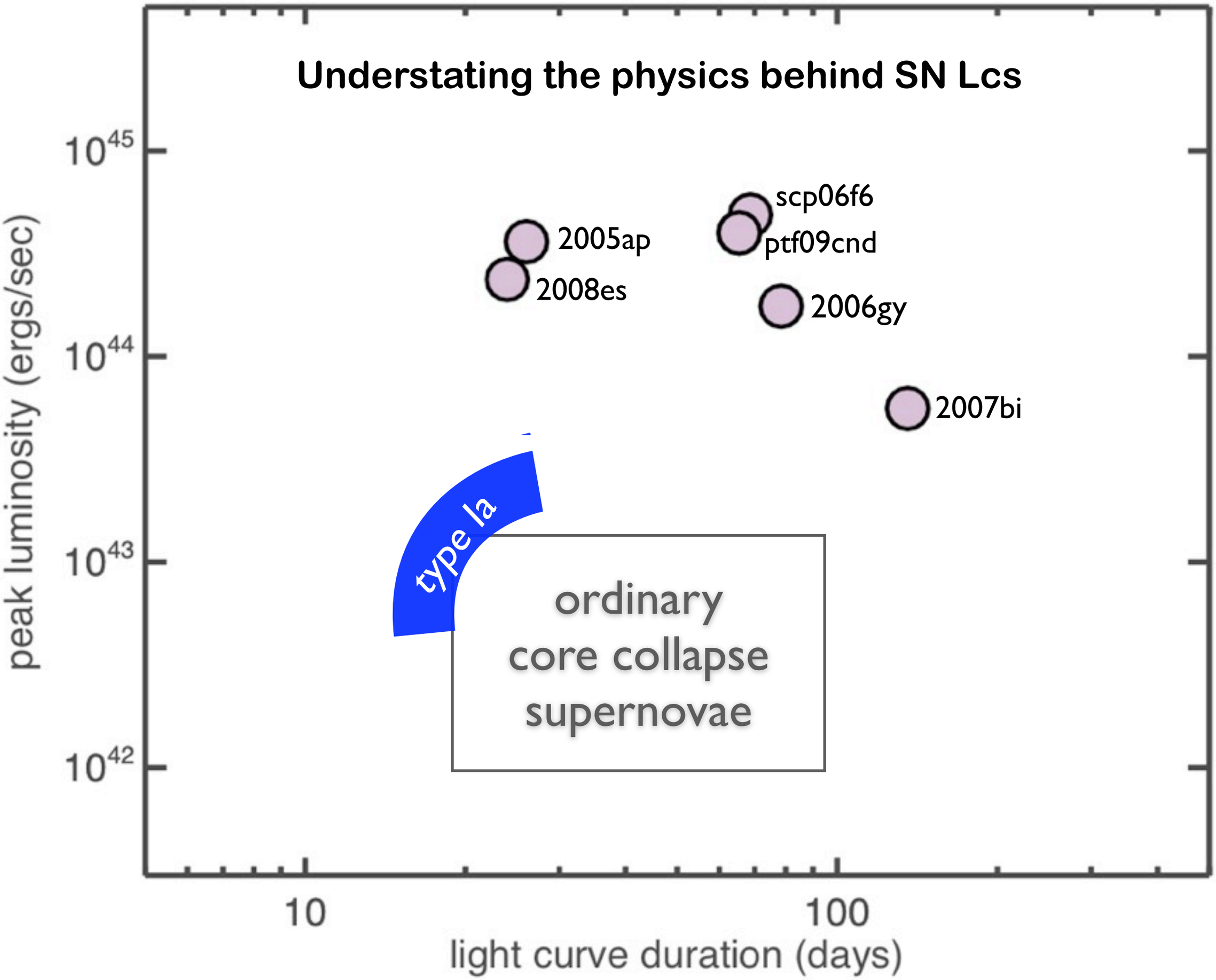
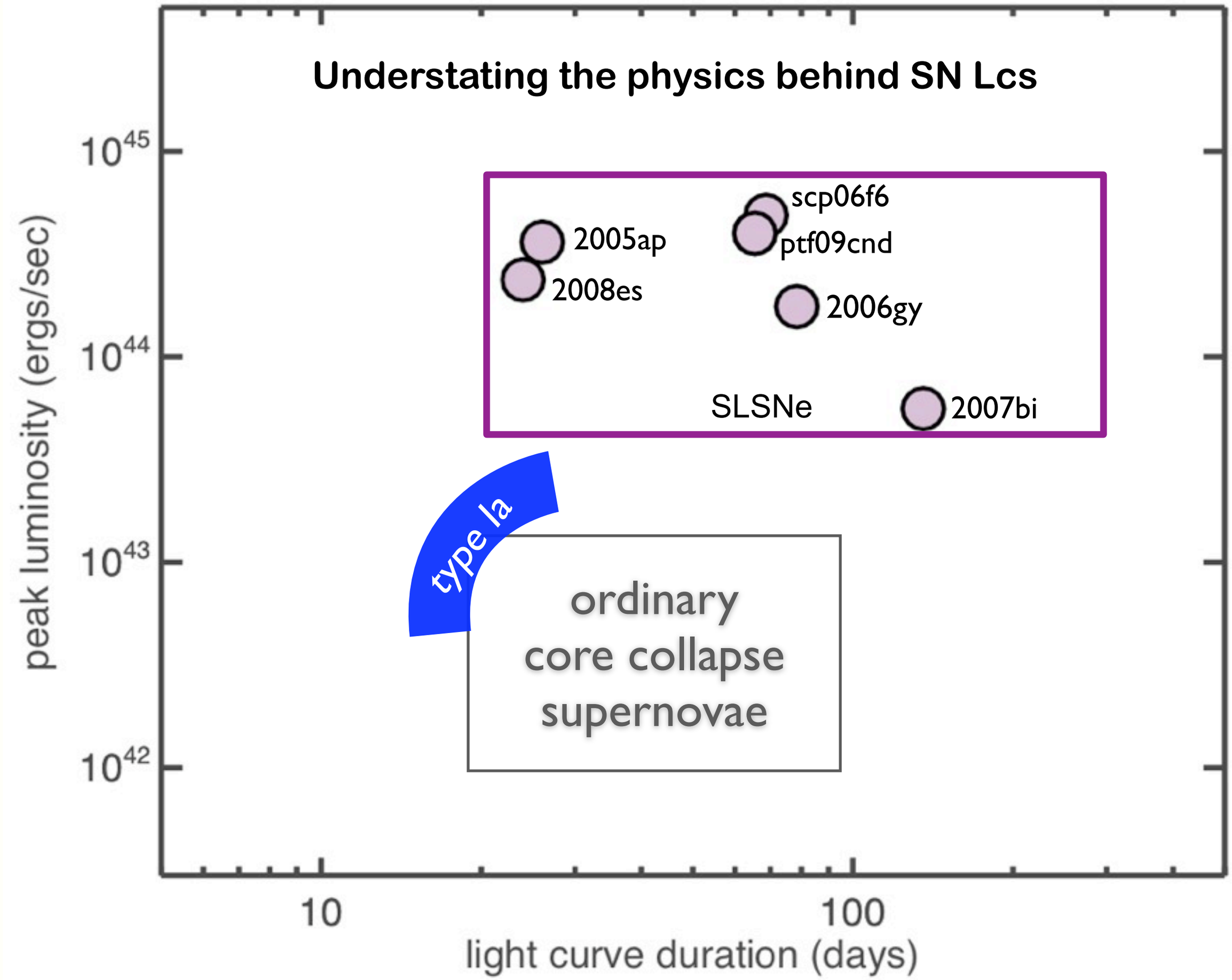


Understating the physics behind SN Lcs



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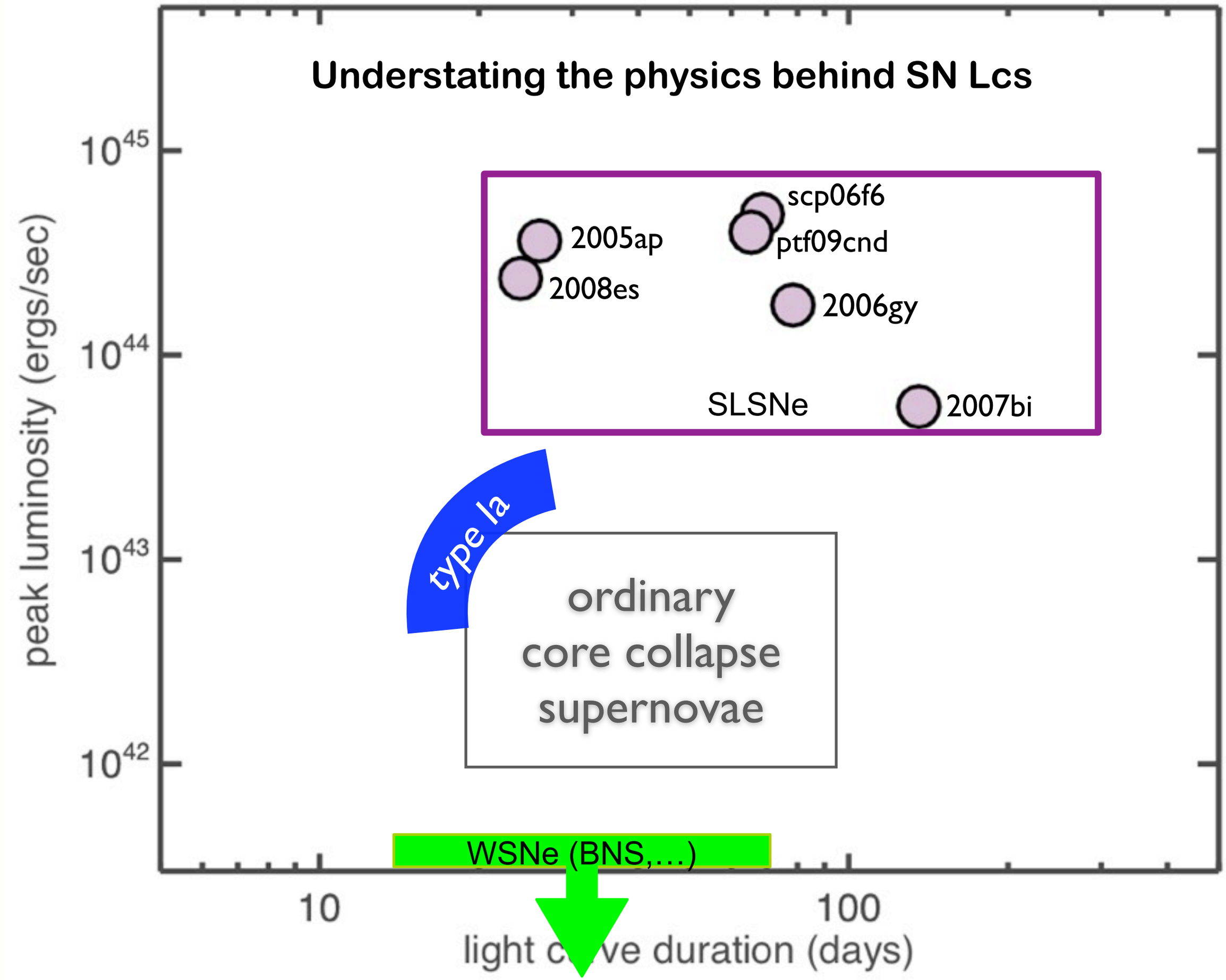

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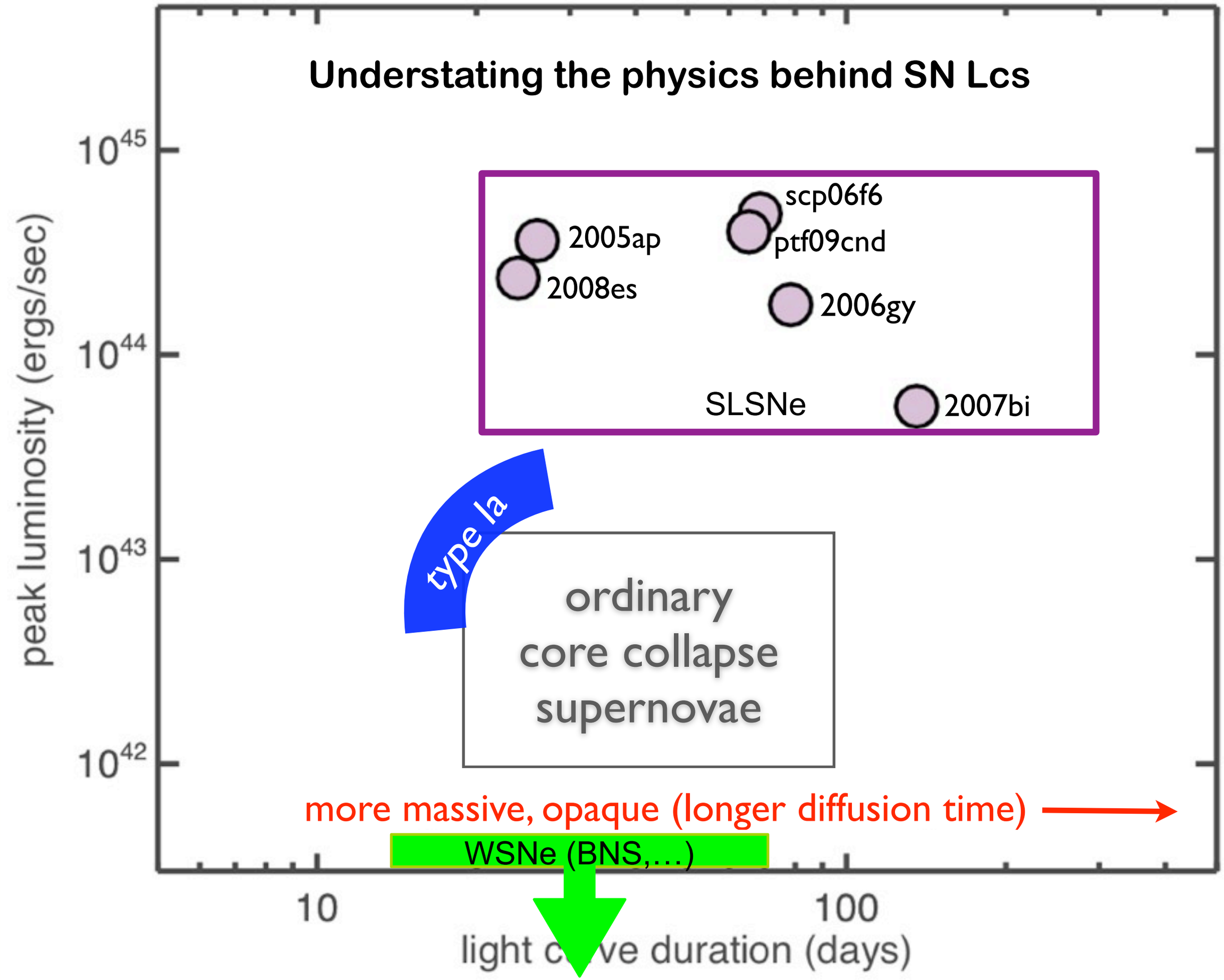
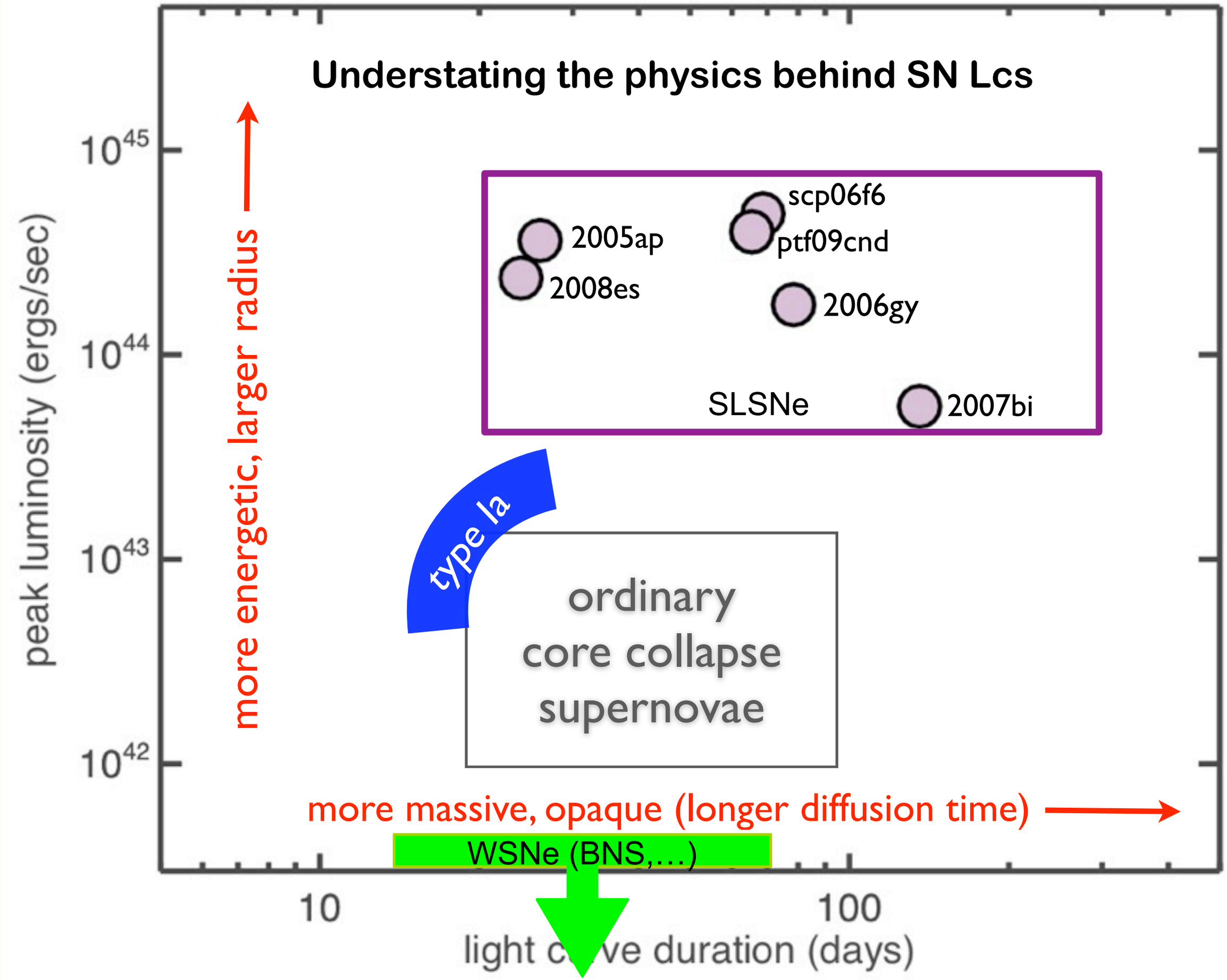


Understating the physics behind SN Lcs



Supernovae Light Curves

Diffusion Time = Expansion Time:

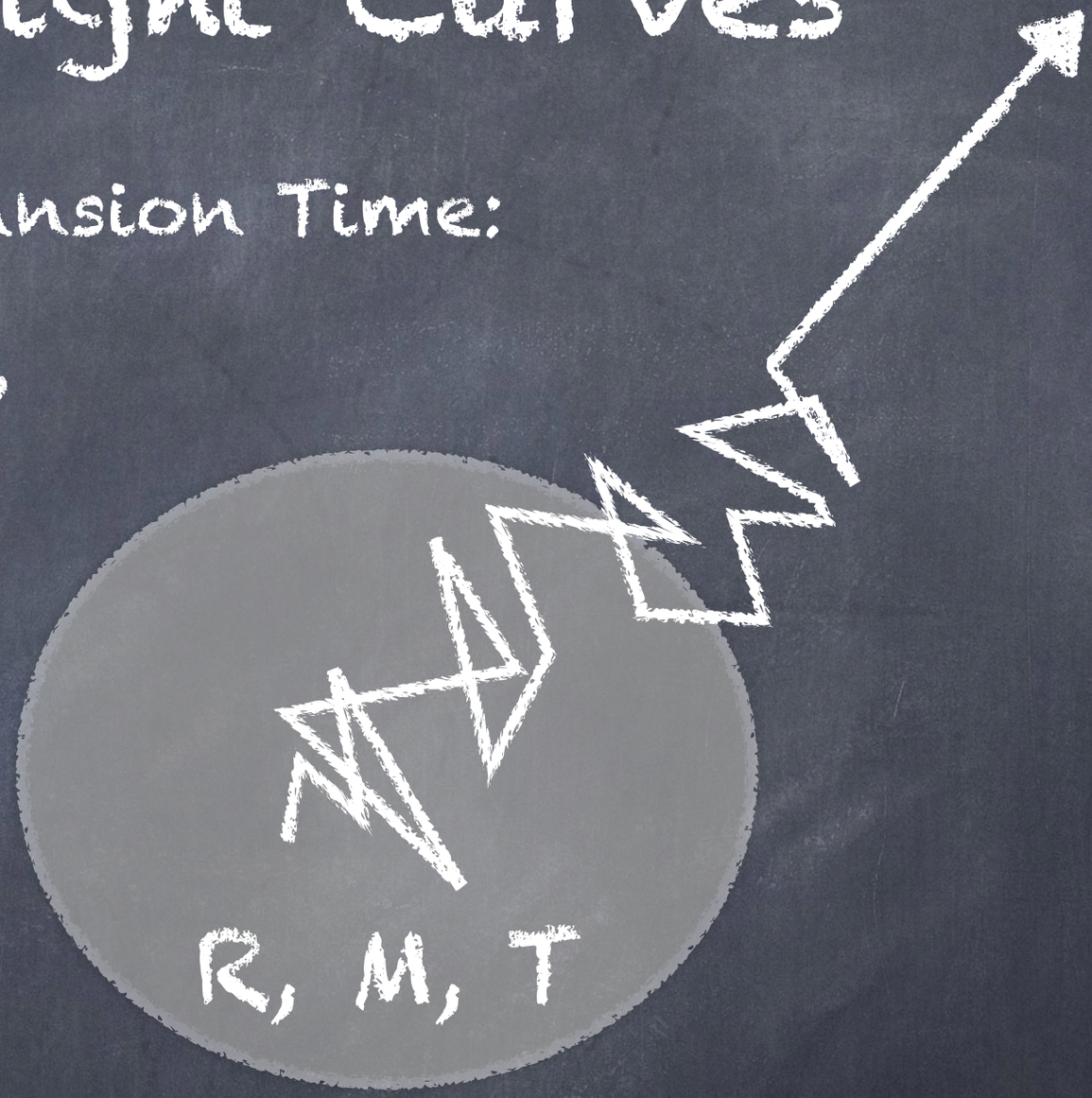
$$t_{diff} = t_{exp}$$

$$t_{exp} \approx \frac{R}{V}$$

$$t_{diff} \approx \tau\left(\frac{R}{c}\right) \approx \kappa\rho R\left(\frac{R}{c}\right) \approx \frac{\kappa M}{Rc}$$

$$t_{sn} \approx \sqrt{\frac{\kappa M}{Vc}} \qquad V \approx \sqrt{\frac{E}{M}}$$

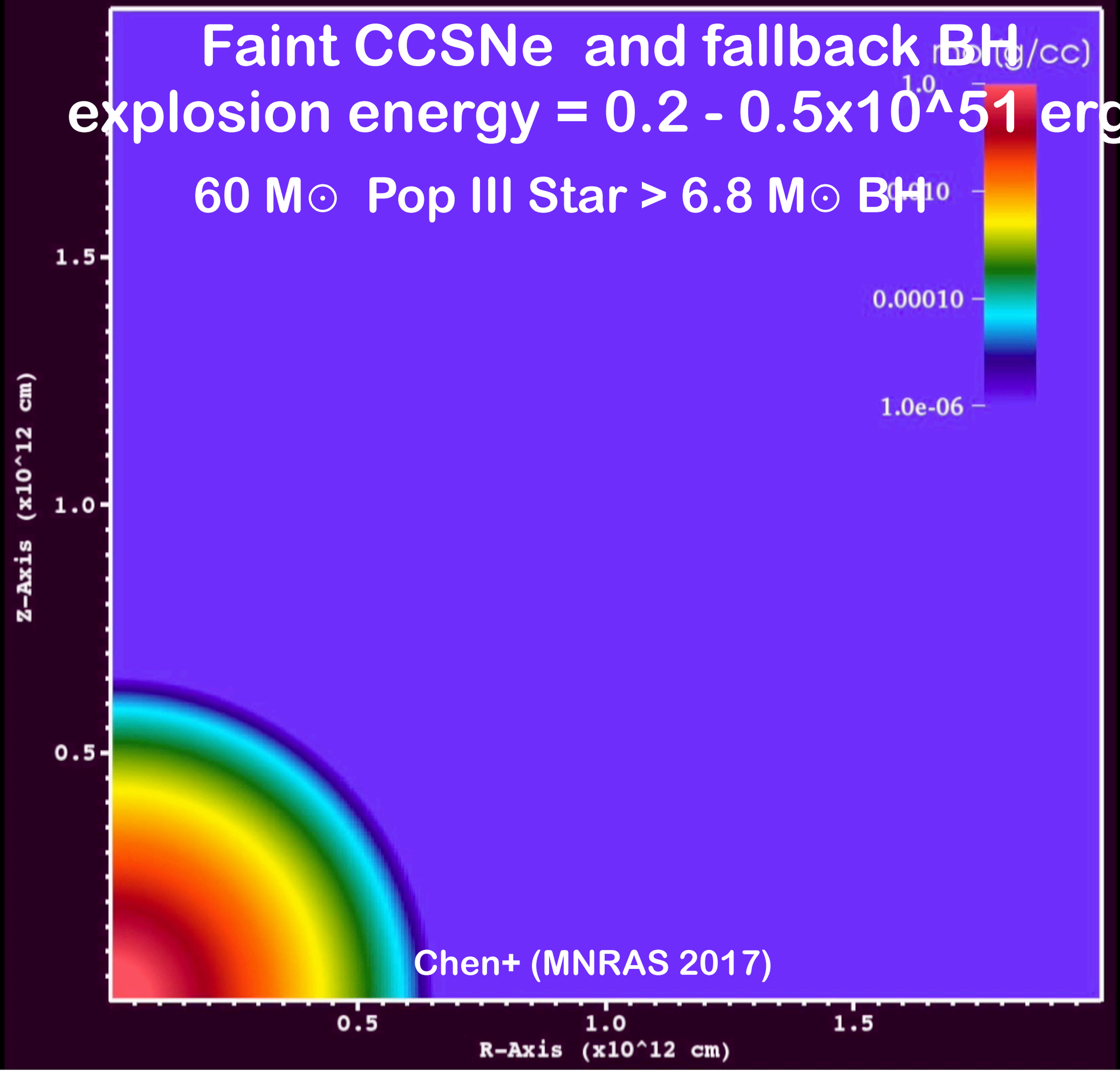
$$t_{sn} \approx 29 M_{sun}^{\frac{3}{4}} \kappa_{0.4}^{\frac{1}{2}} E_{51}^{-\frac{1}{2}} \text{days}$$



$$L_{sn} \approx \frac{E_r}{t_{diff}} \approx \frac{E_o\left(\frac{R_o}{Vt_{diff}}\right)}{t_{diff}} \approx \frac{E_o R_o}{\frac{\kappa M}{c}} \approx 10^{41} M_{sun}^{-1} \kappa_{0.4}^{-1} E_{51}^{1} \text{erg / s}$$

Faint CCSNe and fallback BH
explosion energy = 0.2 - 0.5x10^51 erg)

60 M⊙ Pop III Star > 6.8 M⊙ BH



Chen+ (MNRAS 2017)

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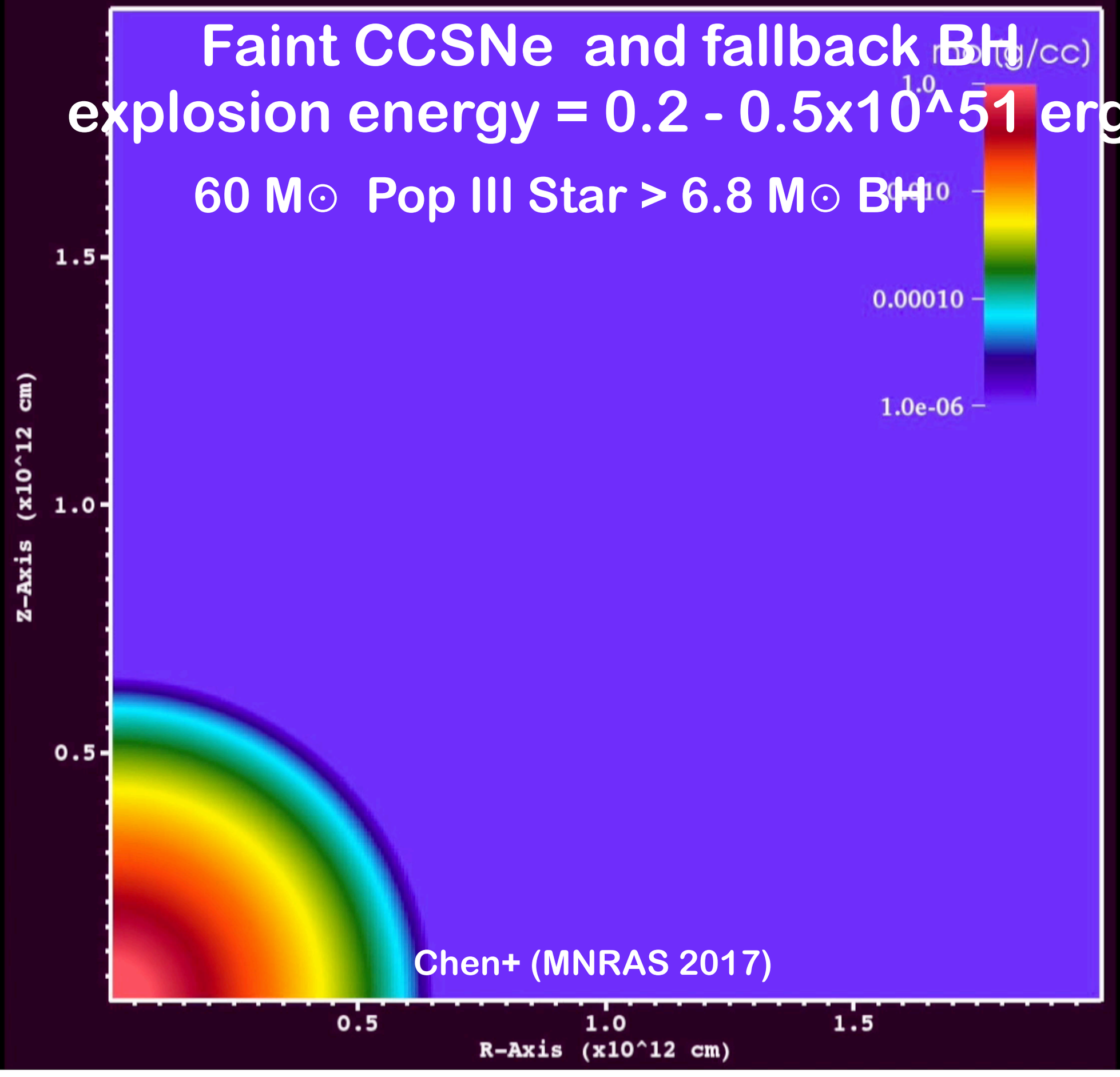
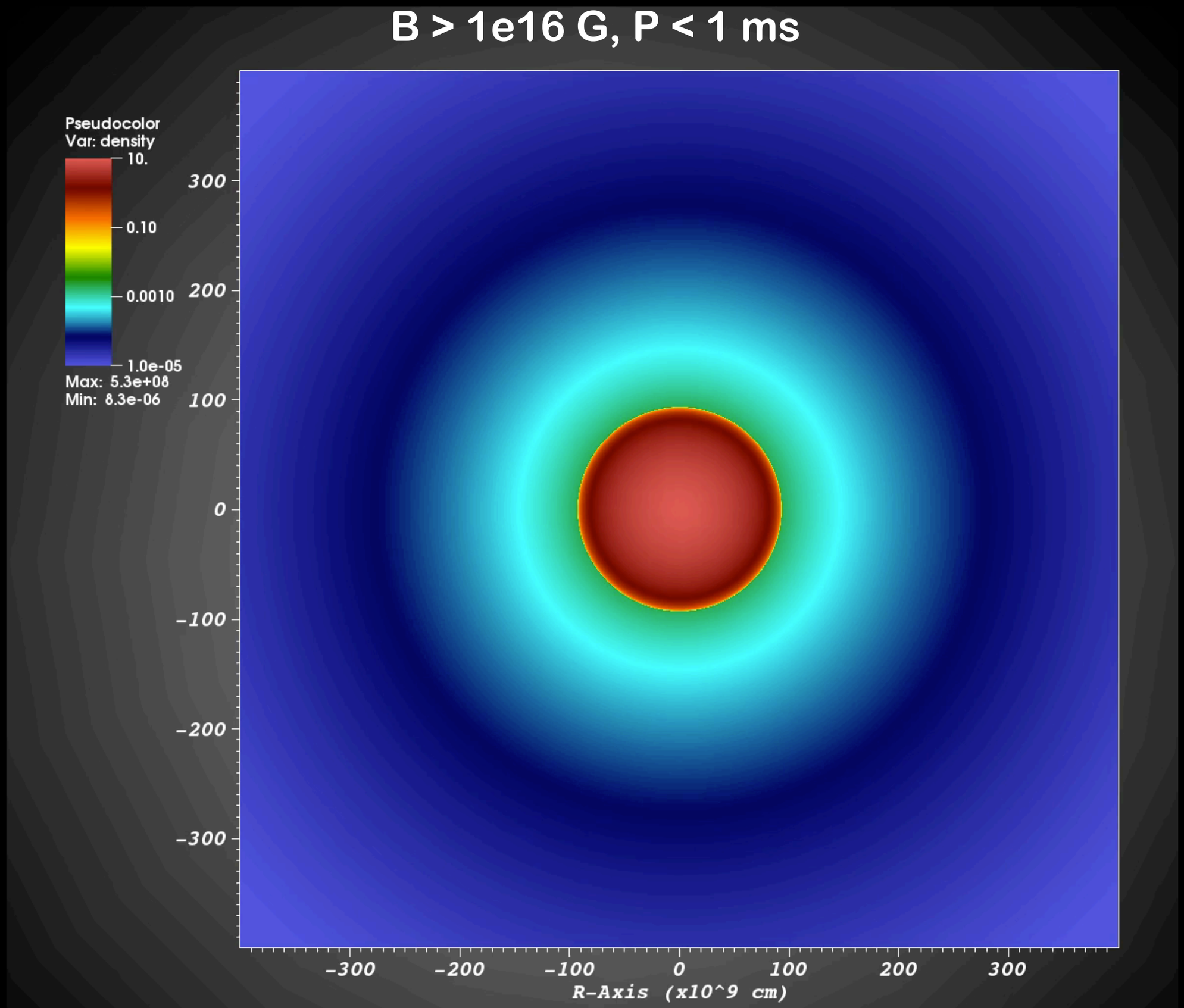
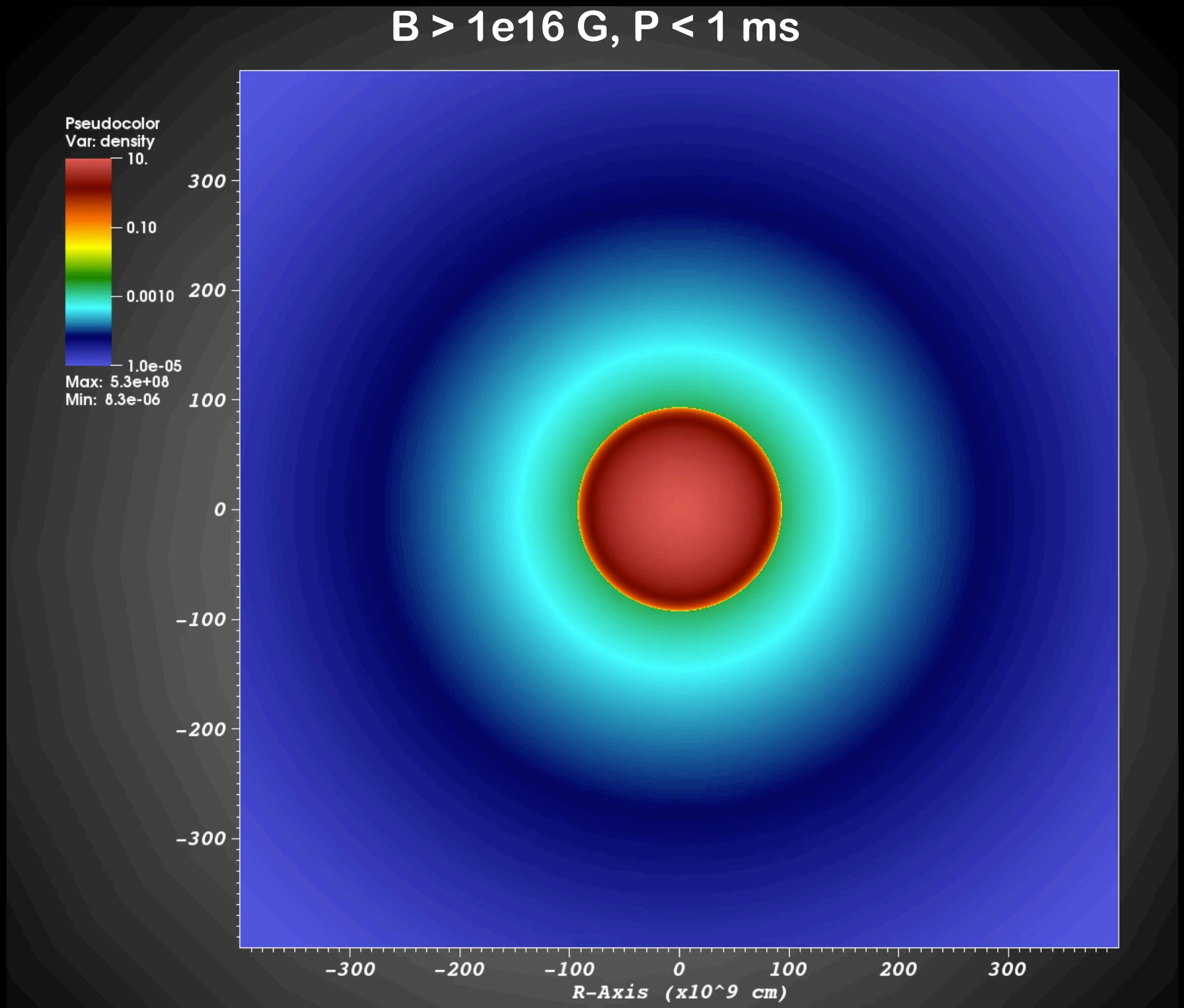


Chen+ (MNRAS 2017)

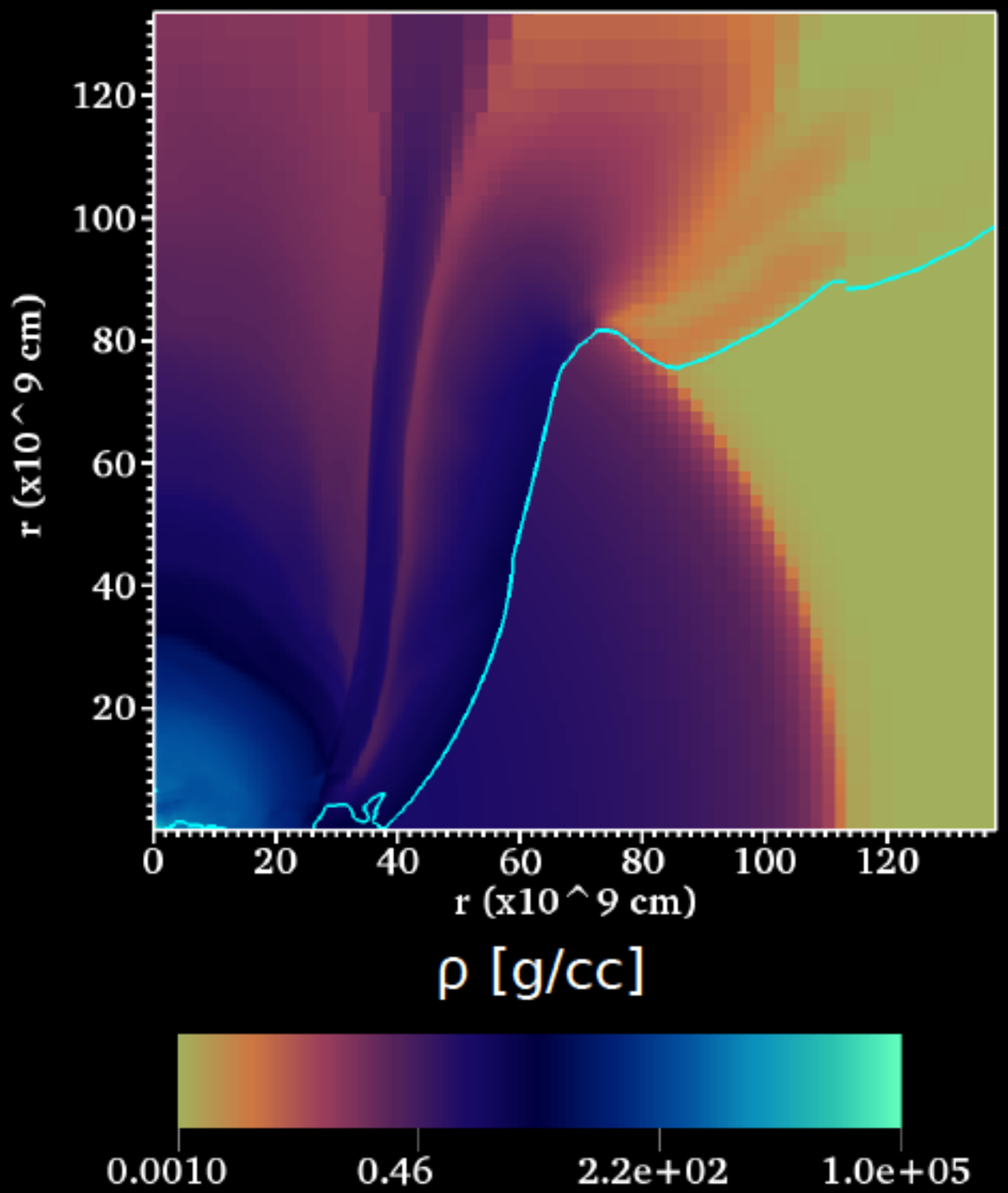
Magnetar-Powered Hypernovae and GRB

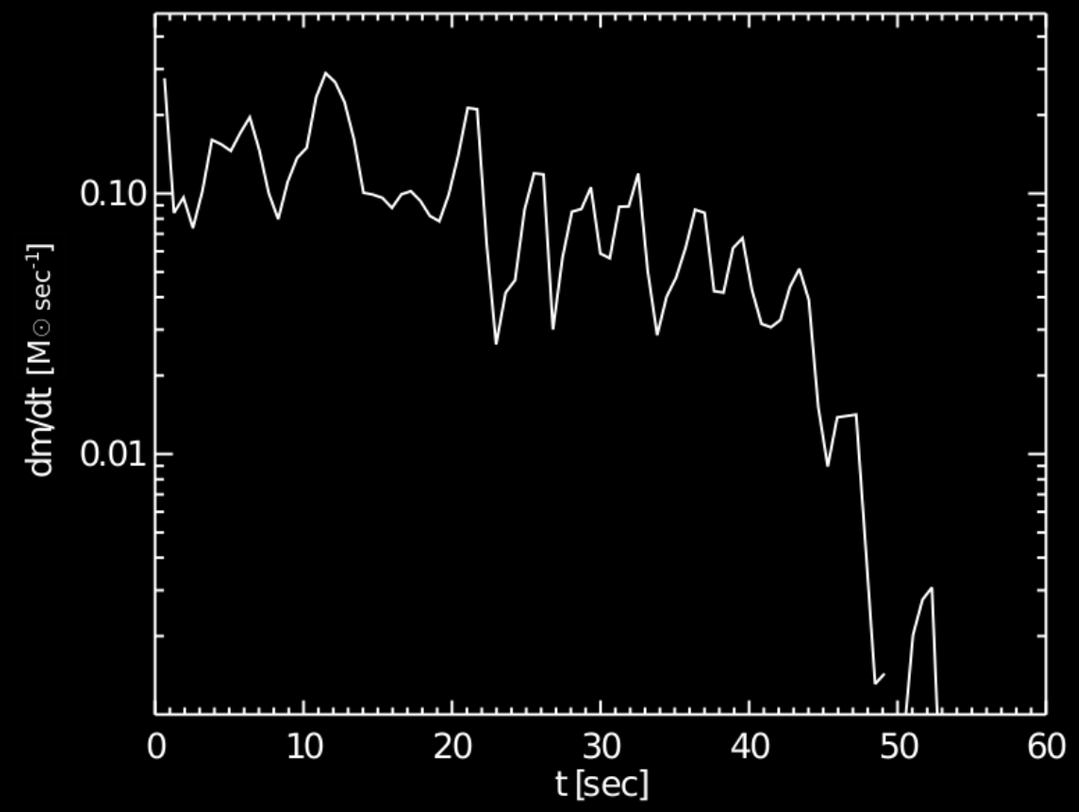


Magnetar-Powered Hypernovae and GRB



Fallback BH formation from Hypernovae

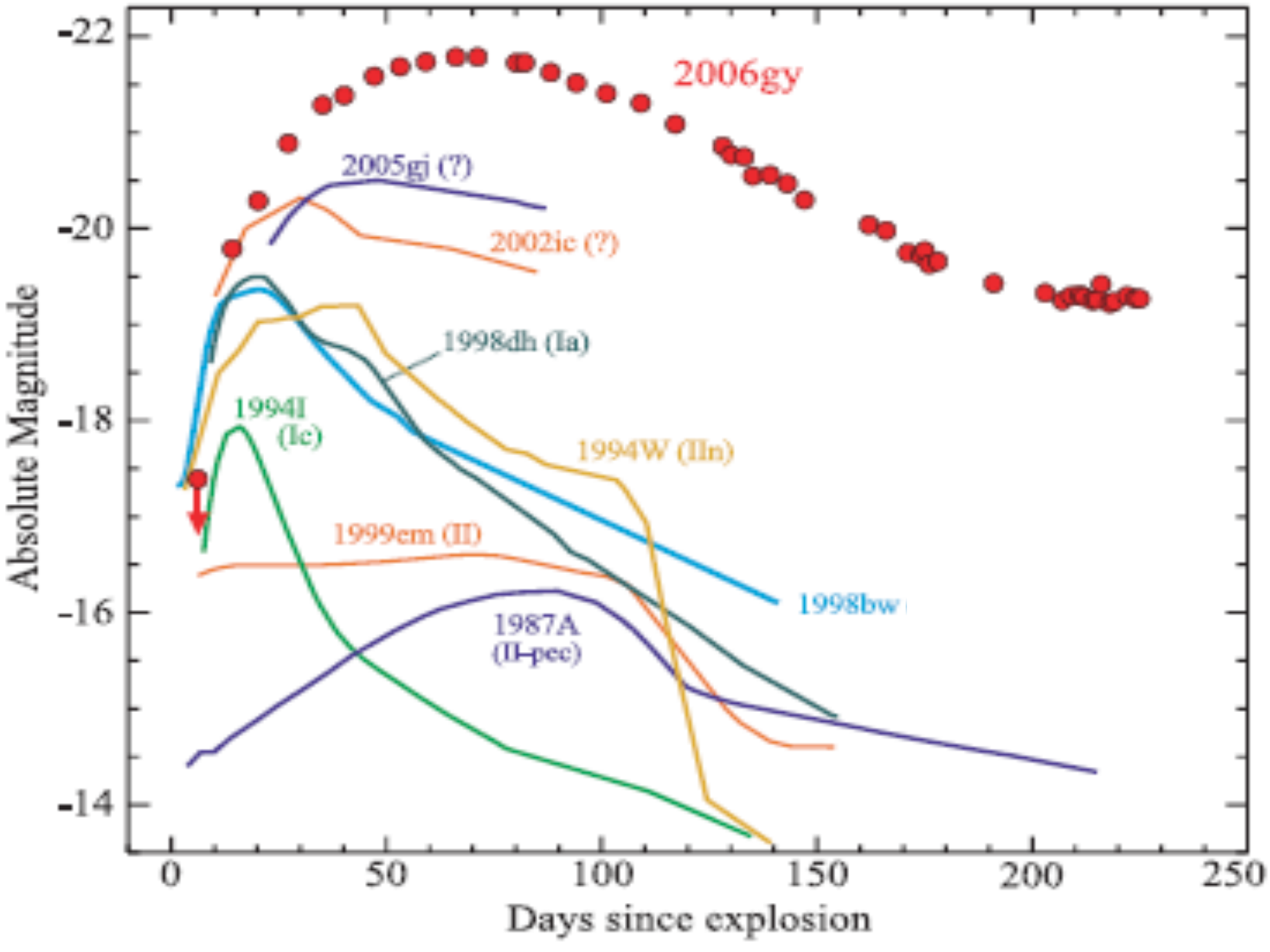




8 M⊙ CO Star > 4.54 M⊙ BH

Chen+ ApJ 2017

Super Luminous SNe (SLSNe)



Smith+ 2007

Energy budget of SLSNe luminosity

Radiation energy budget ~ 10^{51} erg

- Explosion itself ??

- Neutron Stars?

- Radioactive Isotopes?

- Shock/ejecta/CSM collisions?

Energy budget of SLSNe luminosity

Radiation energy budget ~ 10^{51} erg

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  Unlikely

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  Tons of Ni (>10 M⊙)

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Energy budget of SLSNe luminosity

Radiation energy budget ~ 10^{51} erg

- Explosion itself ??

  Unlikely

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  ms Magnetar

- Radioactive Isotopes?

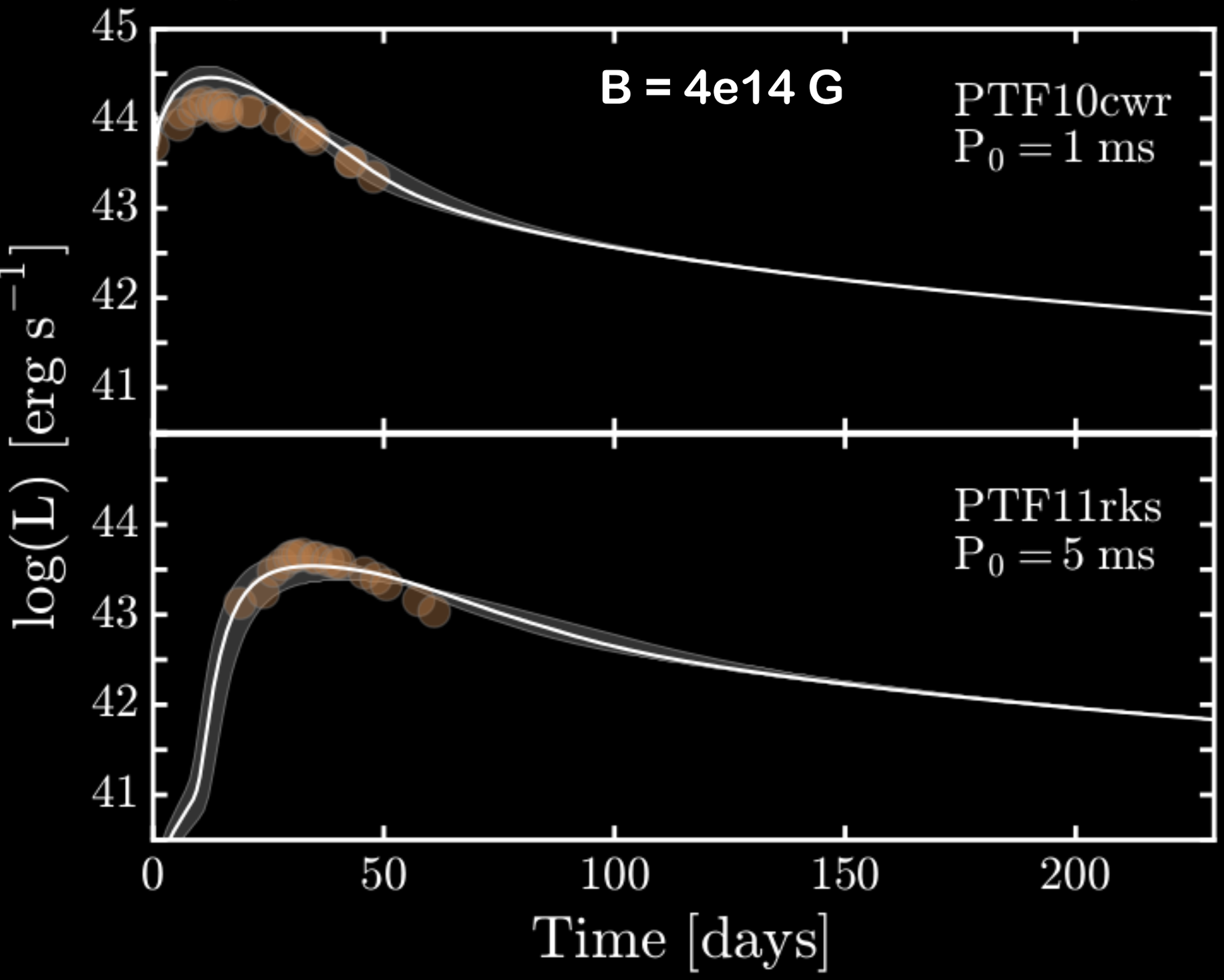
  Tons of Ni (>10 M⊙)

- Shock/ejecta/CSM collisions?

  Kinetic energy to radiation

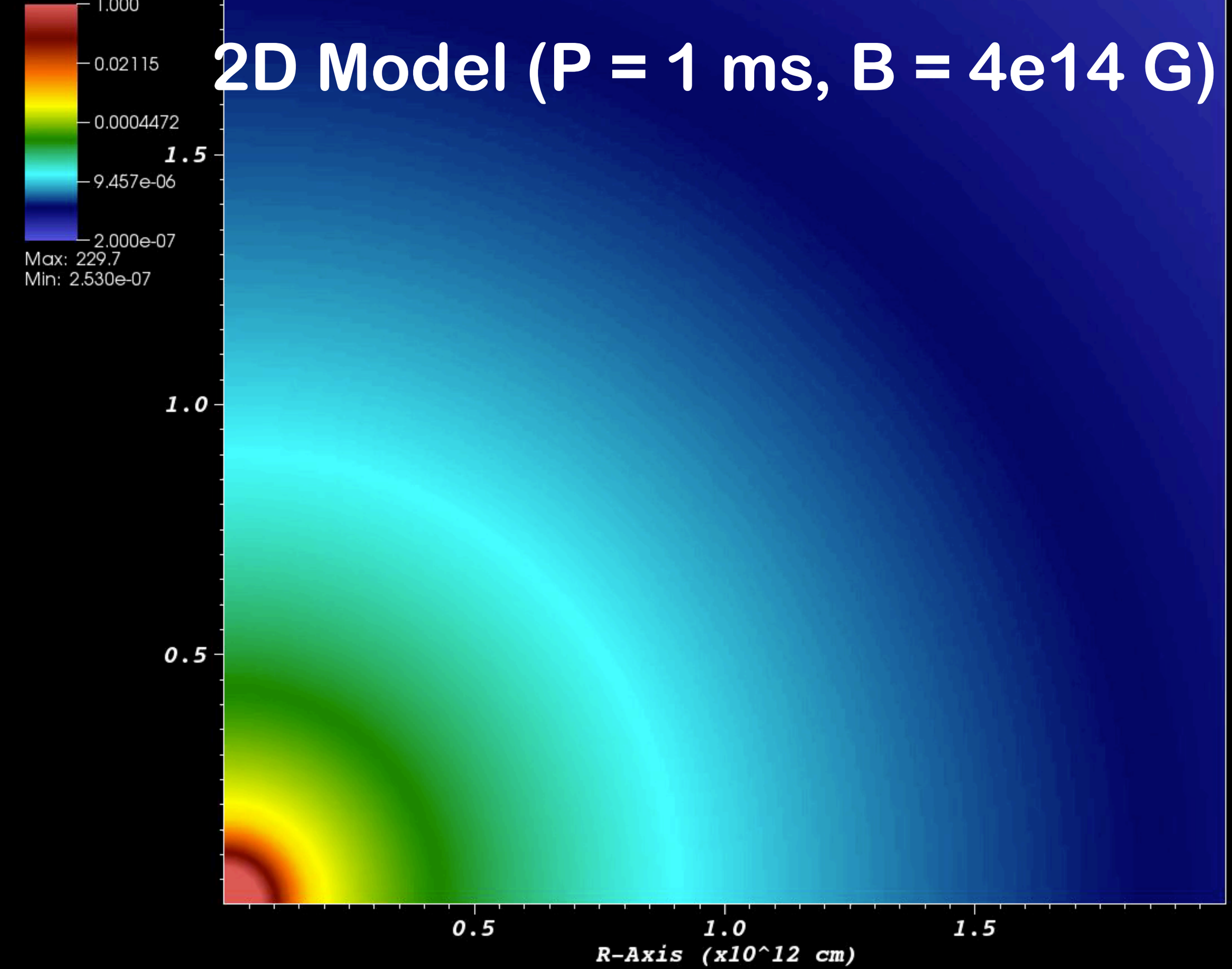
Superluminous SNe by magnetar

Original Ideas from Maeda, Kasen, Bildsten, Woosley



Chen+ (ApJ 2016)

2D Model (P = 1 ms, B = 4e14 G)



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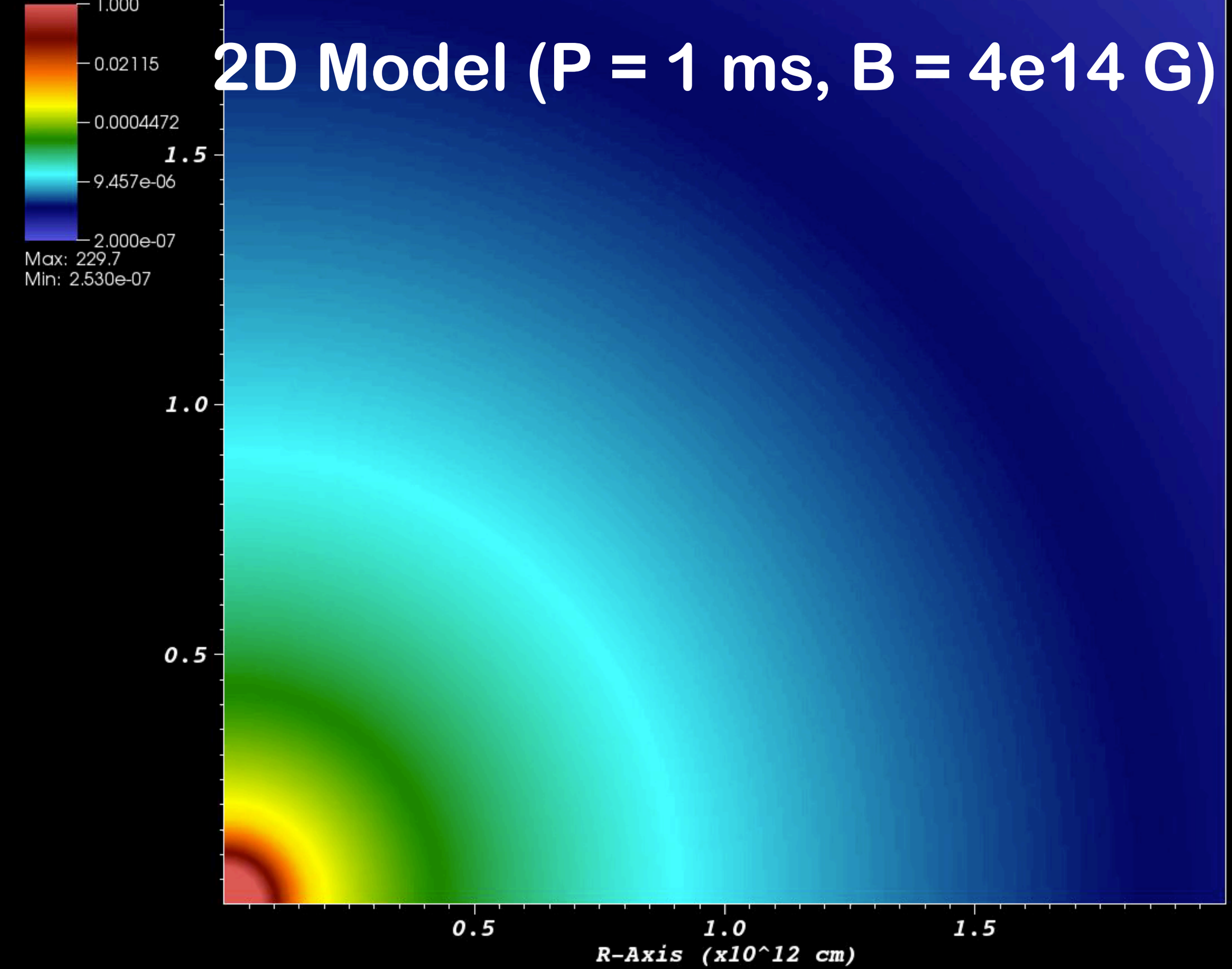
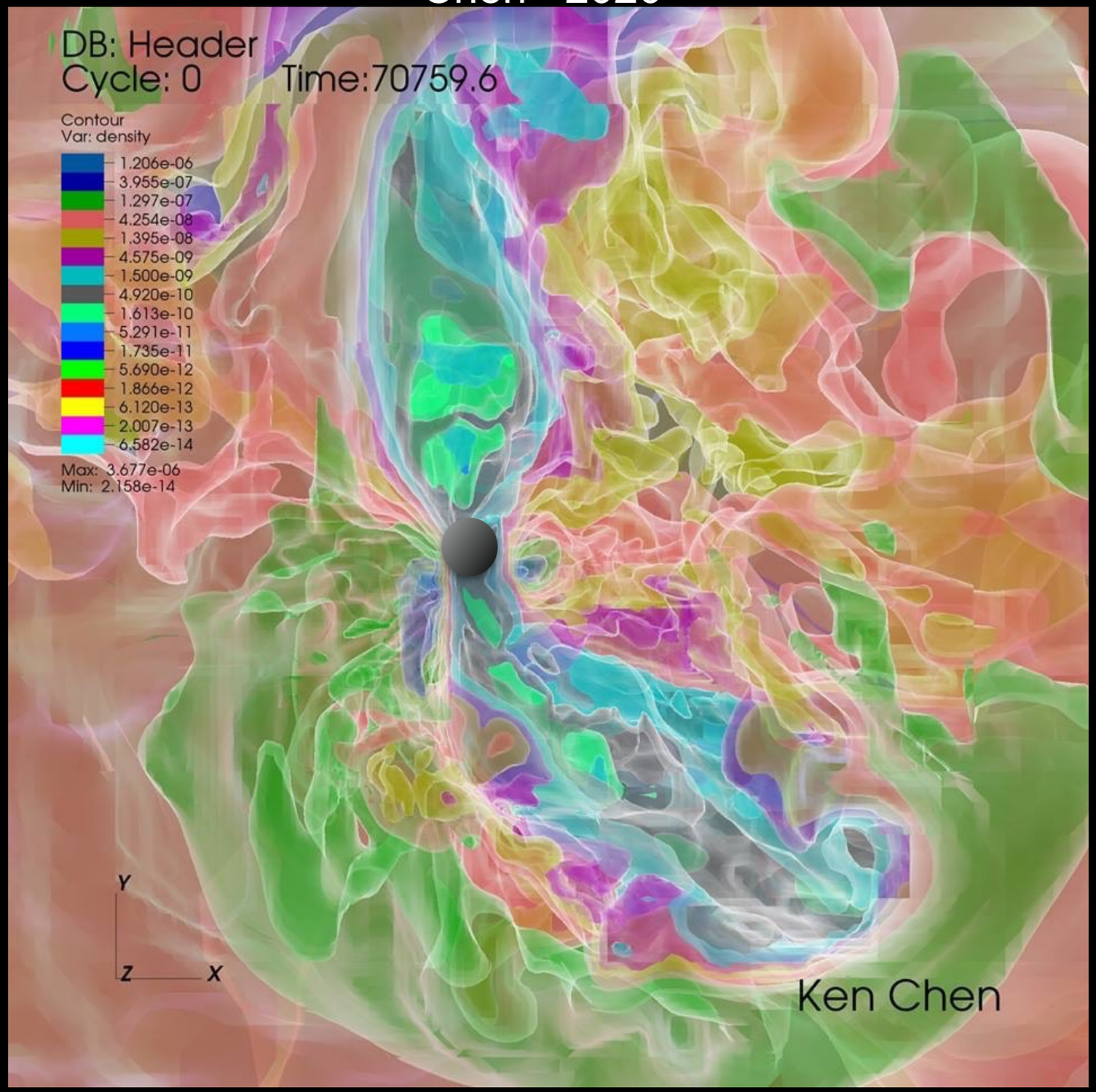


3D Magnetar-powered SLSNe

Bridging the central engine to its observational signatures

Chen+ 2020

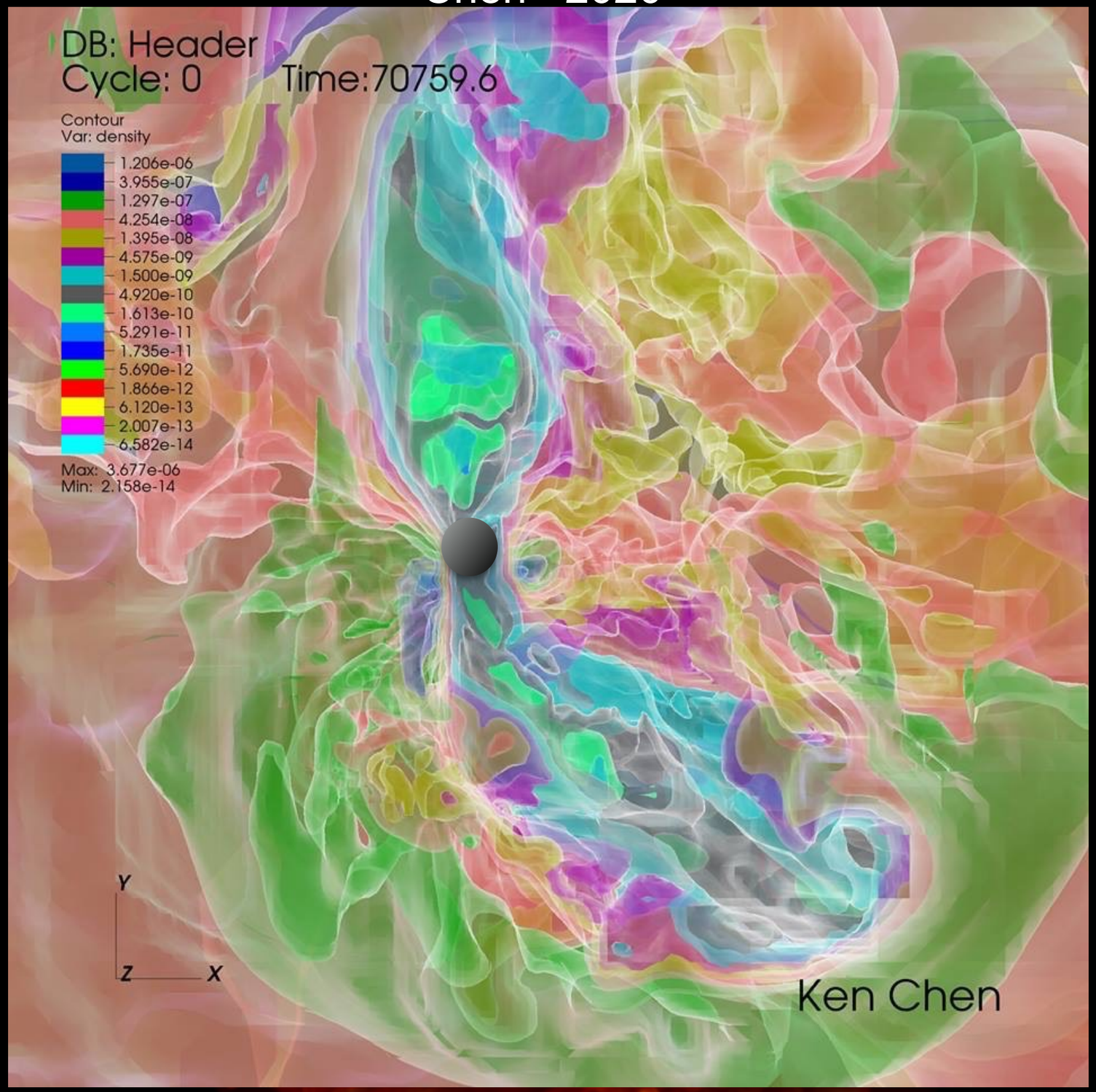


A full 3D magentar-powerd SNe

3D Magnetar-powered SLSNe

Bridging the central engine to its observational signatures

Chen+ 2020



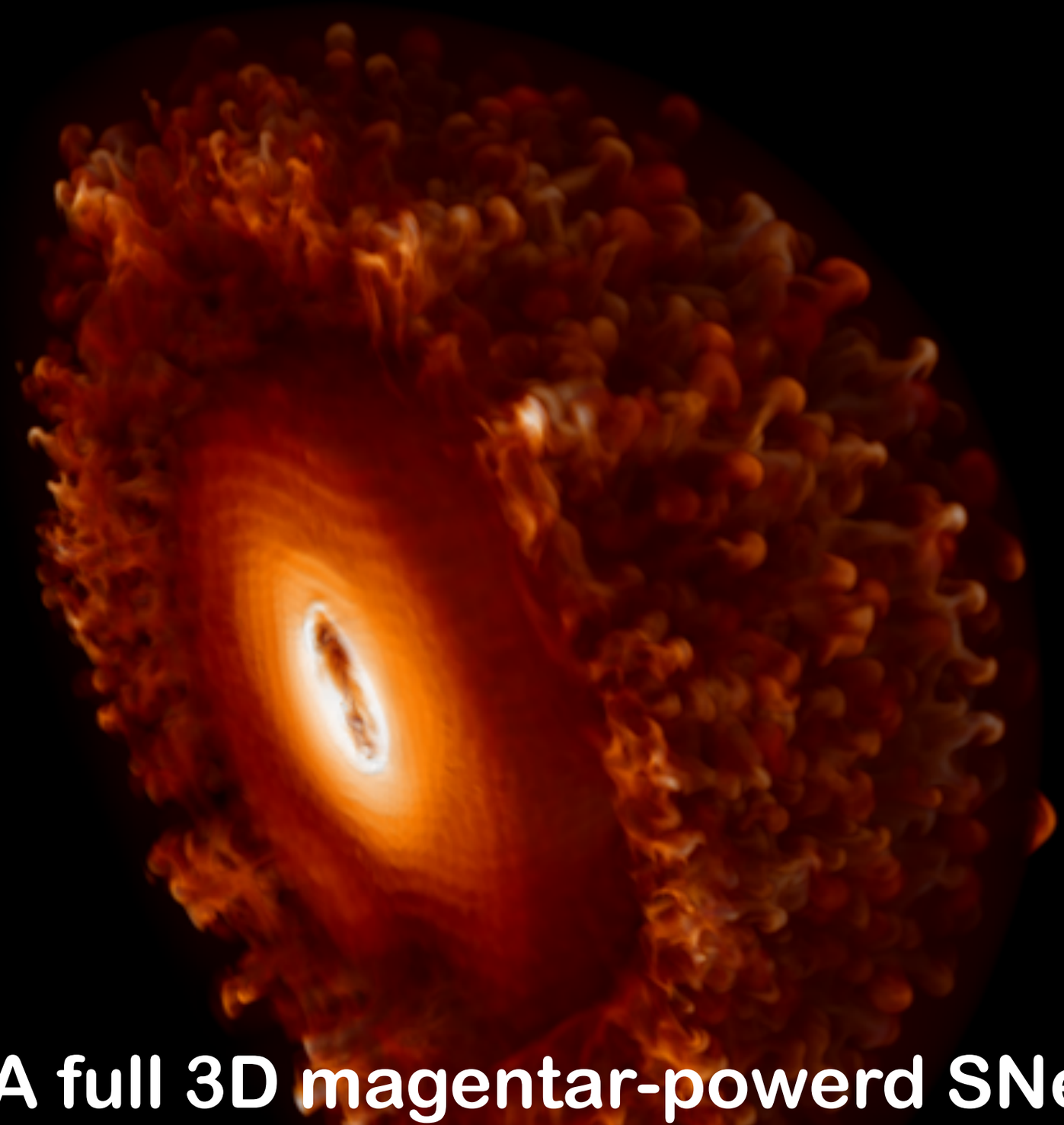
A full 3D magentar-powerd SNe

3D Magnetar-powered SLSNe

Bridging the central engine to its observational signatures

Chen+ 2020

400 days after explosions



A full 3D magentar-powerd SNe

Death of massive stars and their black holes

Woosley, Heger, & Weaver (2002)

MS Mass	He Core	Supernova Mechanism
	(solar mass ⊙)	
$10 \leq M \leq 80$	$2 \leq M \leq 32$	Fe core collapse to a neutron star or black hole

BH up to ~ 32

$80 \leq M \leq 150$	$35 \leq M \leq 60$	Pulsational pair instability followed by core (PPSN)

BH up to ~ 60, fallback can add up??

$150 \leq M \leq 250$	$60 \leq M \leq 133$	Pair instability supernova (PSN)

BH ~ 0 ?

$250 \leq M$	$133 \leq M$	All BH or any Bang??

1D stellar evolution issues: mass loss, rotation, convection ?

Multi-D Explosions issues: explosion engines, fallback ?

Take Home Message

Thoughts on Impacts of SNe feedback on galaxies

IMF? Stellar physics? Explosion physics?

- Massive stars and their supernovae are critical to galaxy evolution.
- The importance of fallback/mixing during the explosion cannot be ignored.
- GW opens a new window of SNe.
- Metal yields can be used to trace the stellar population in the galaxies.
- SNe Feedback in cosmological zoom-in simulations can be improved.