Nuclear burning in massive stars @YITP-OzGrav Workshop 26.07.2021

Where are PISNe?

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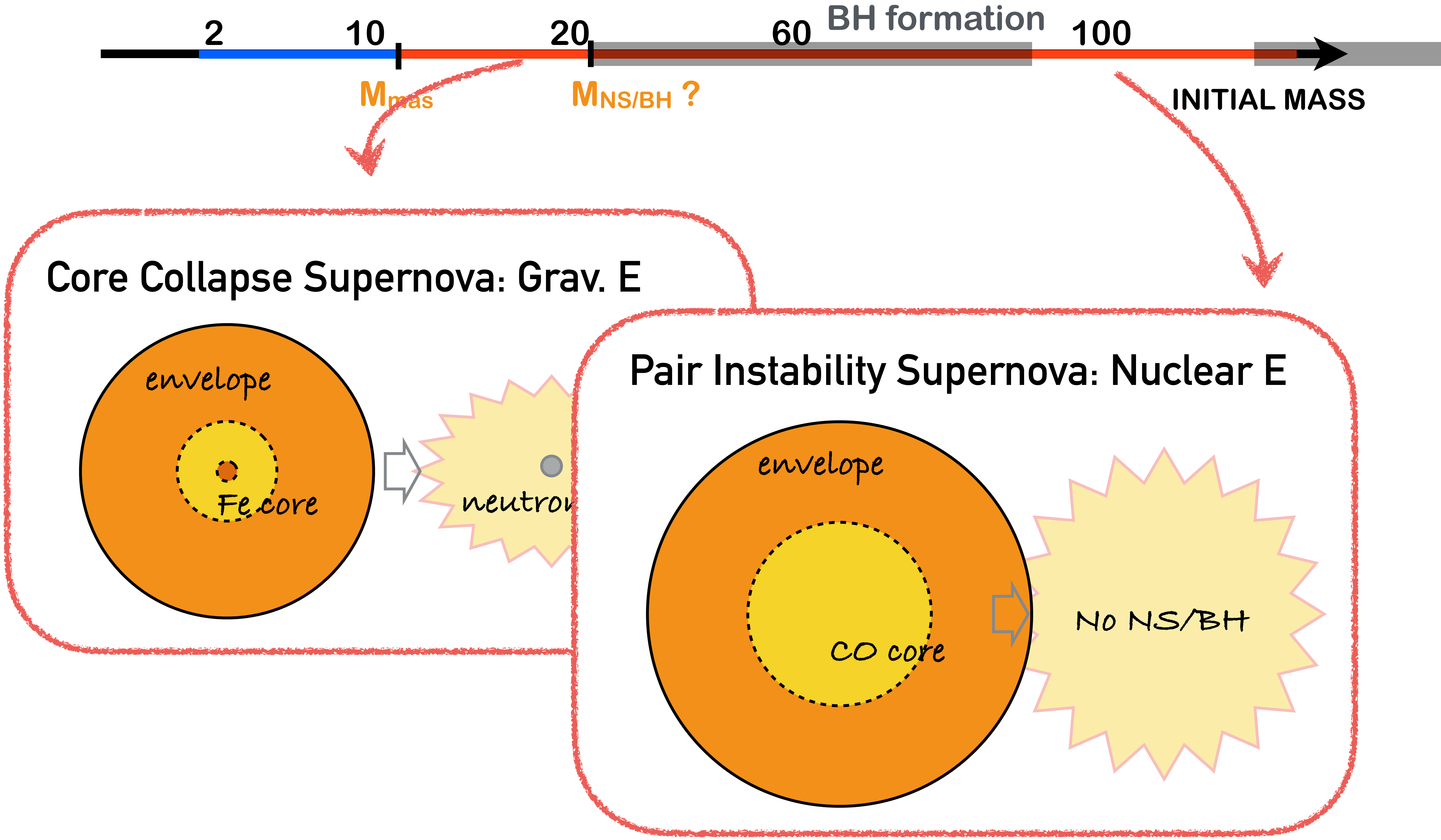
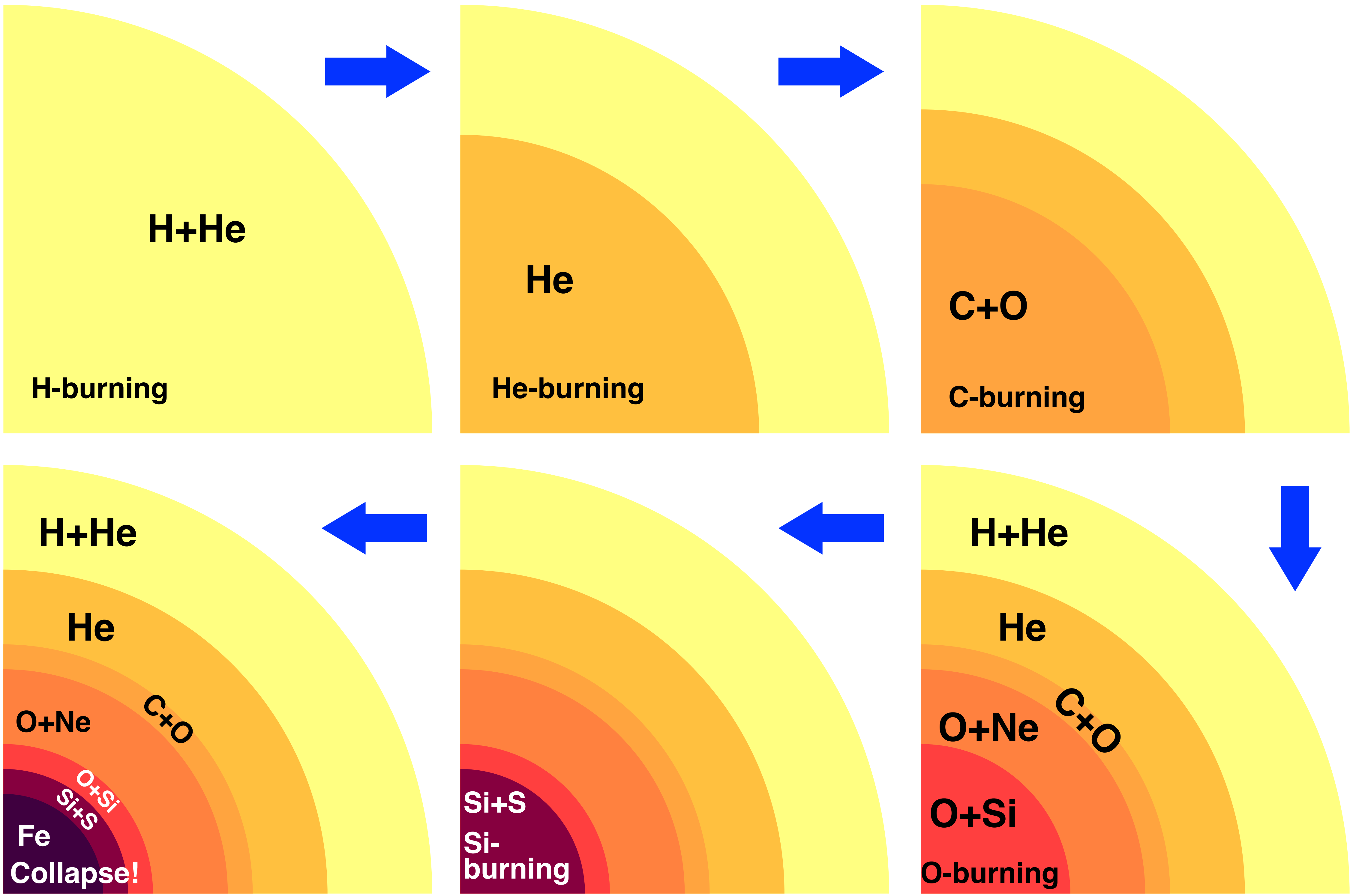
Types of supernovae



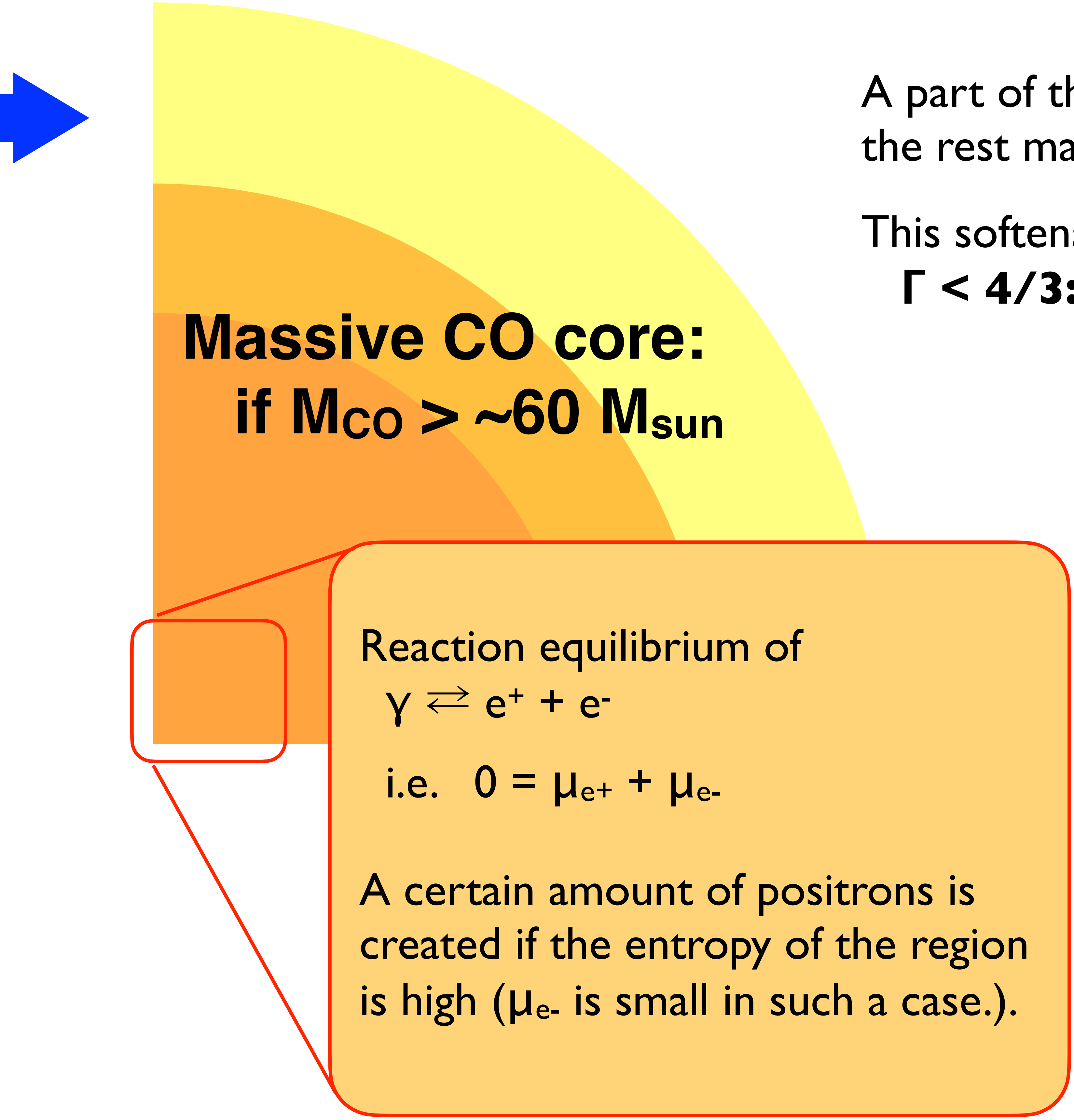
Theoretical understanding

Hydrostatic Evolution

Canonical massive star evolution (M_{ini} ~10-25 $M_\odot$):



Hydrodynamical Instability



Massive CO core:
if $M_{CO} > \sim 60\ M_{sun}$

Reaction equilibrium of
$\gamma \rightleftarrows e^{+} + e^{-}$

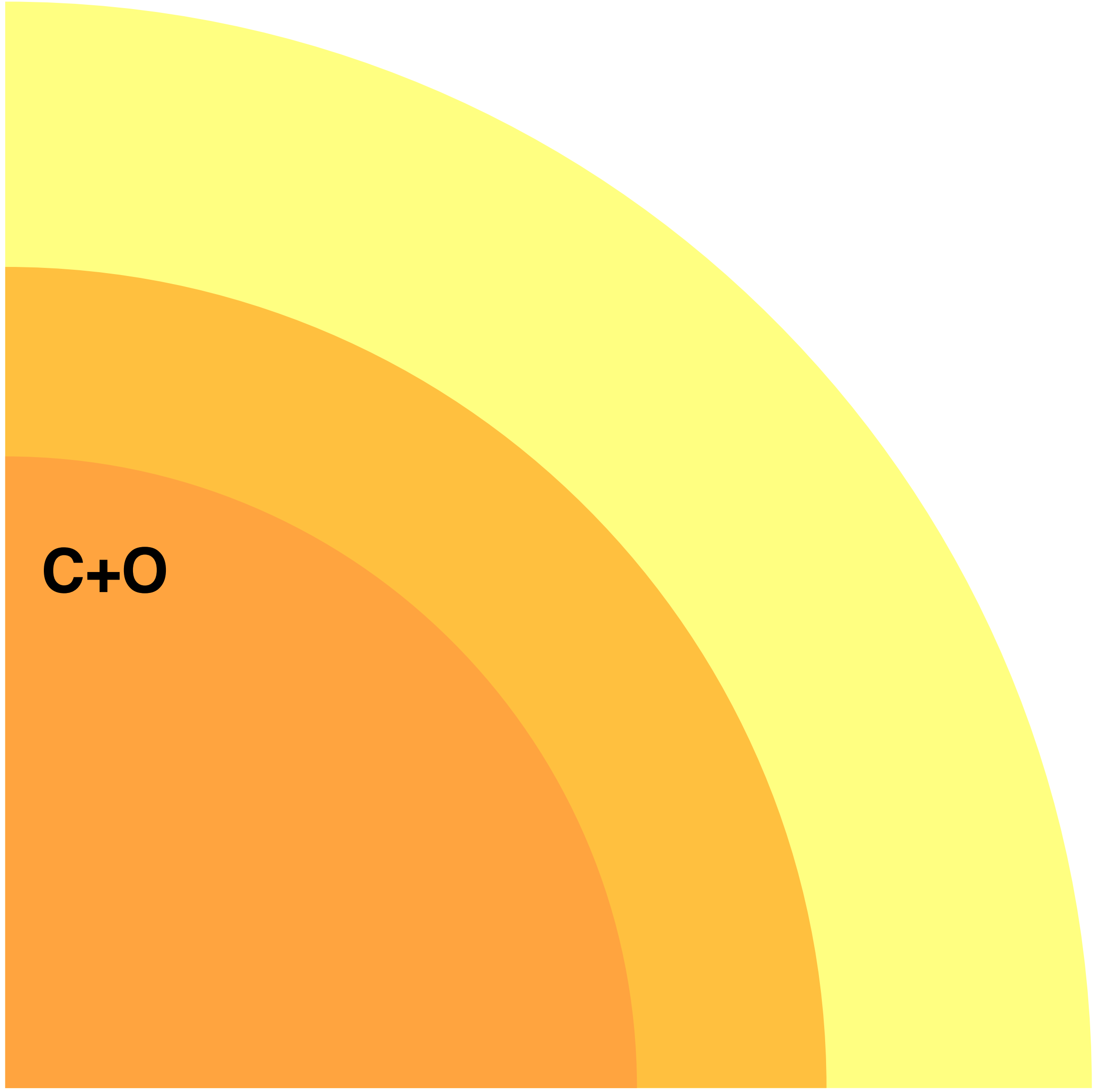
i.e. $0 = \mu_{e+} + \mu_{e-}$

A certain amount of positrons is created if the entropy of the region is high (μ_{e-} is small in such a case.).

A part of the thermal energy is converted into the rest mass due to the e^{+}-e^{-} pair creation.

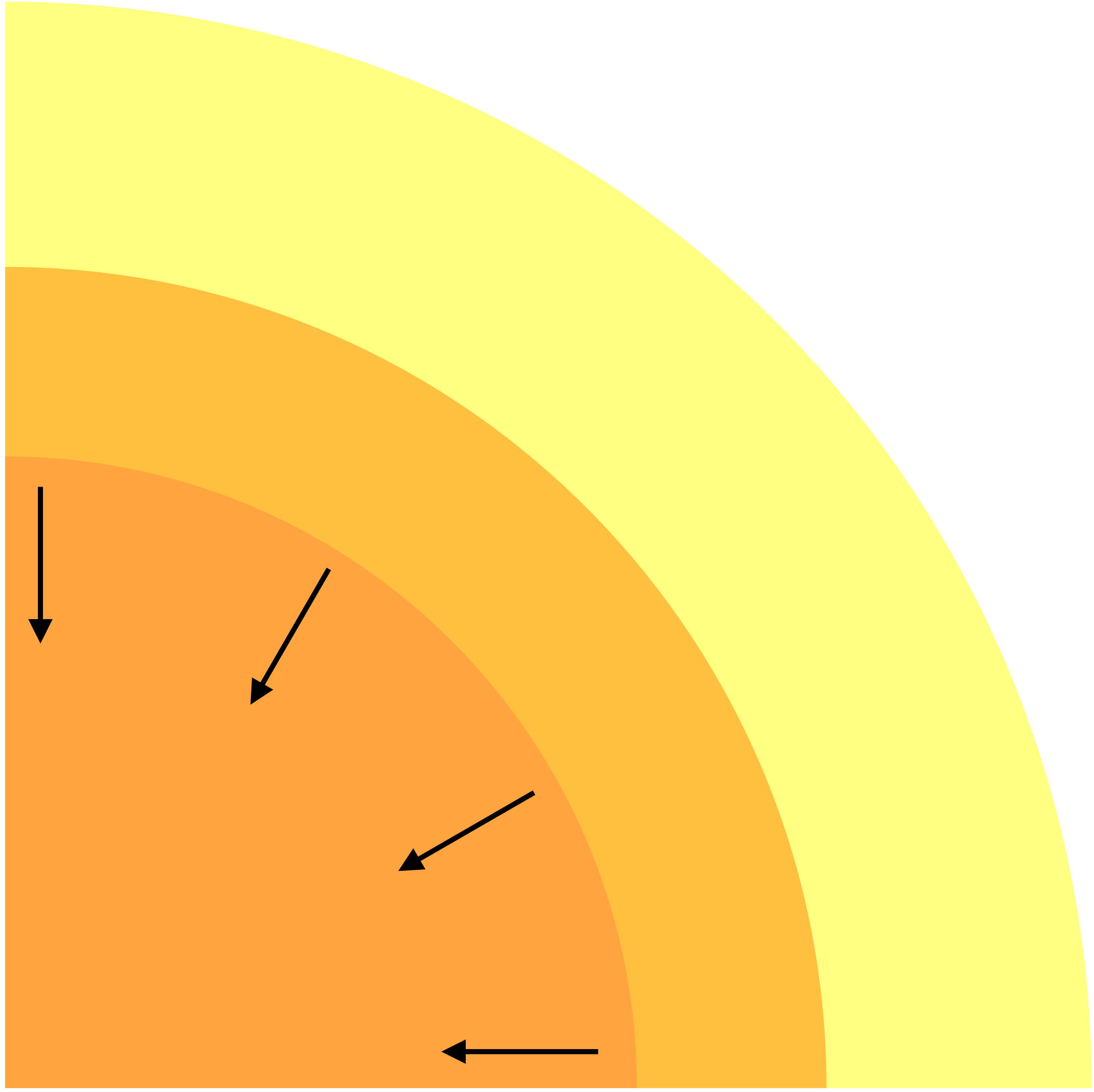
This softens the pressure, thus,
$\Gamma < 4/3$: Pair Instability.

Thermonuclear explosion



Originally, the core is made of C+O.

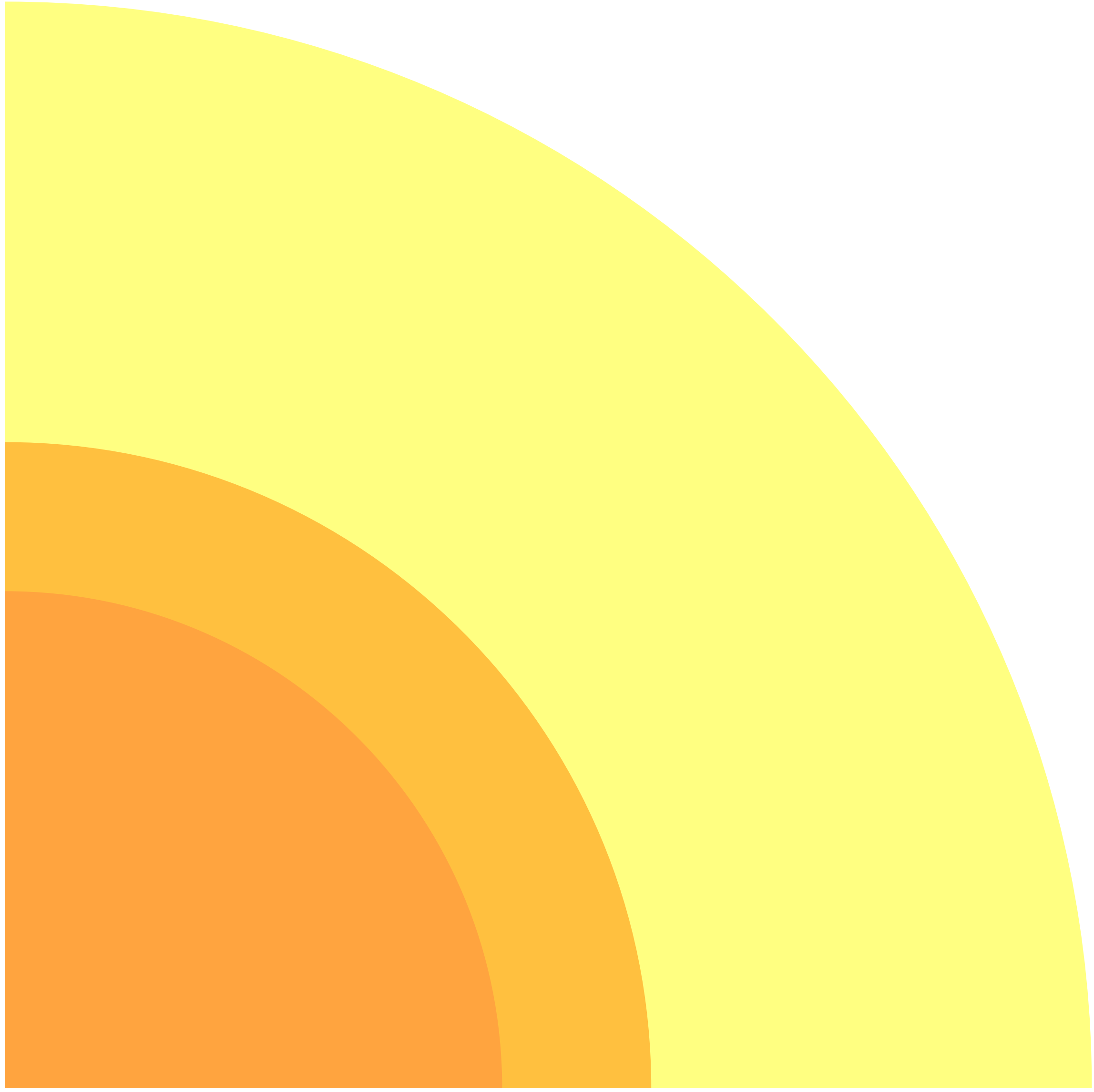
Thermonuclear explosion



Originally, the core is made of C+O.

The CO core contracts due to the pair instability.

Thermonuclear explosion

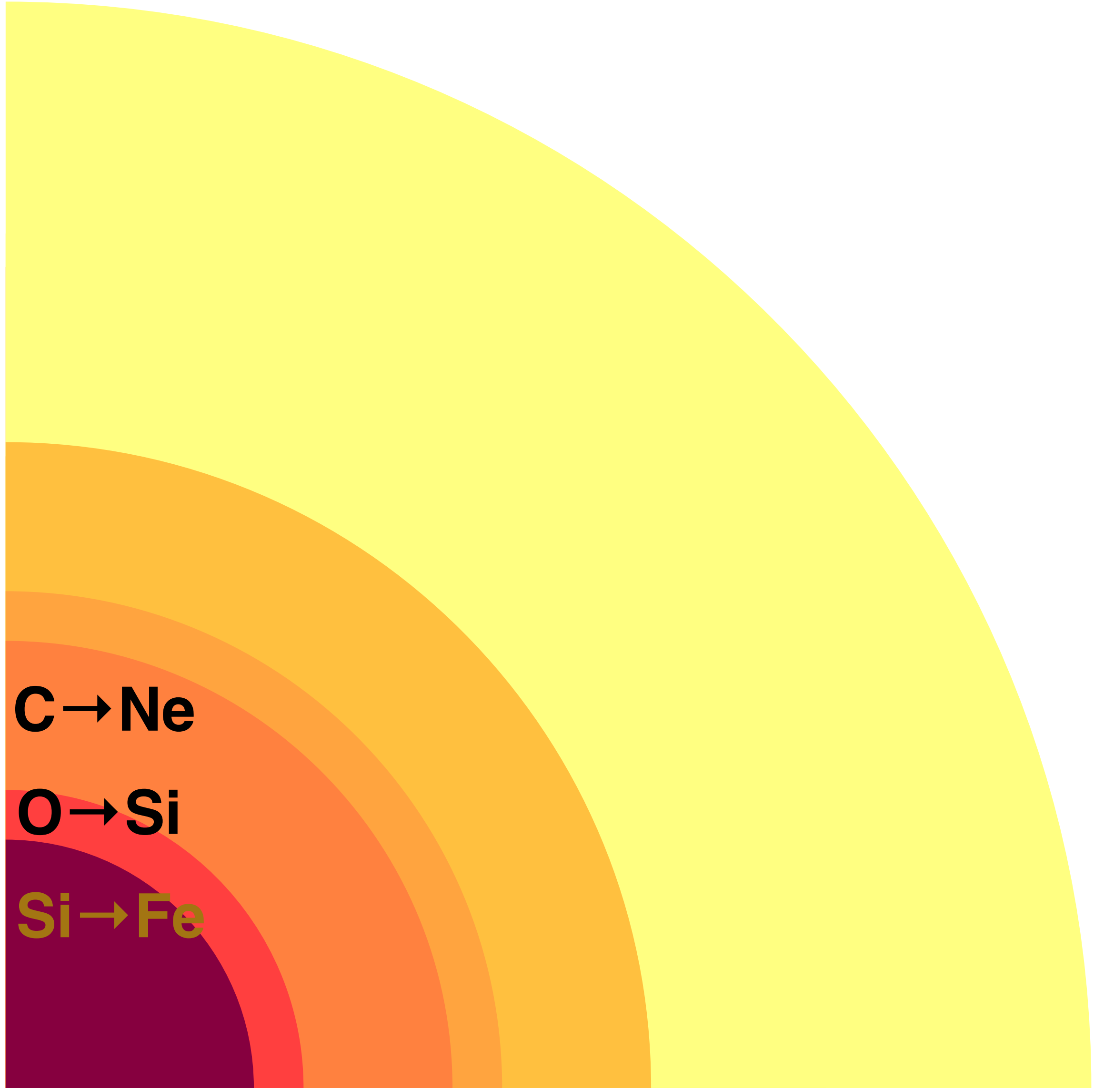


Originally, the core is made of C+O.

The CO core contracts due to the pair instability.

As the core shrinks, the temperature increases,

Thermonuclear explosion



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The CO core contracts due to the pair instability.

As the core shrinks, the temperature increases, and nuclear reactions changes the composition.

Thermonuclear explosion

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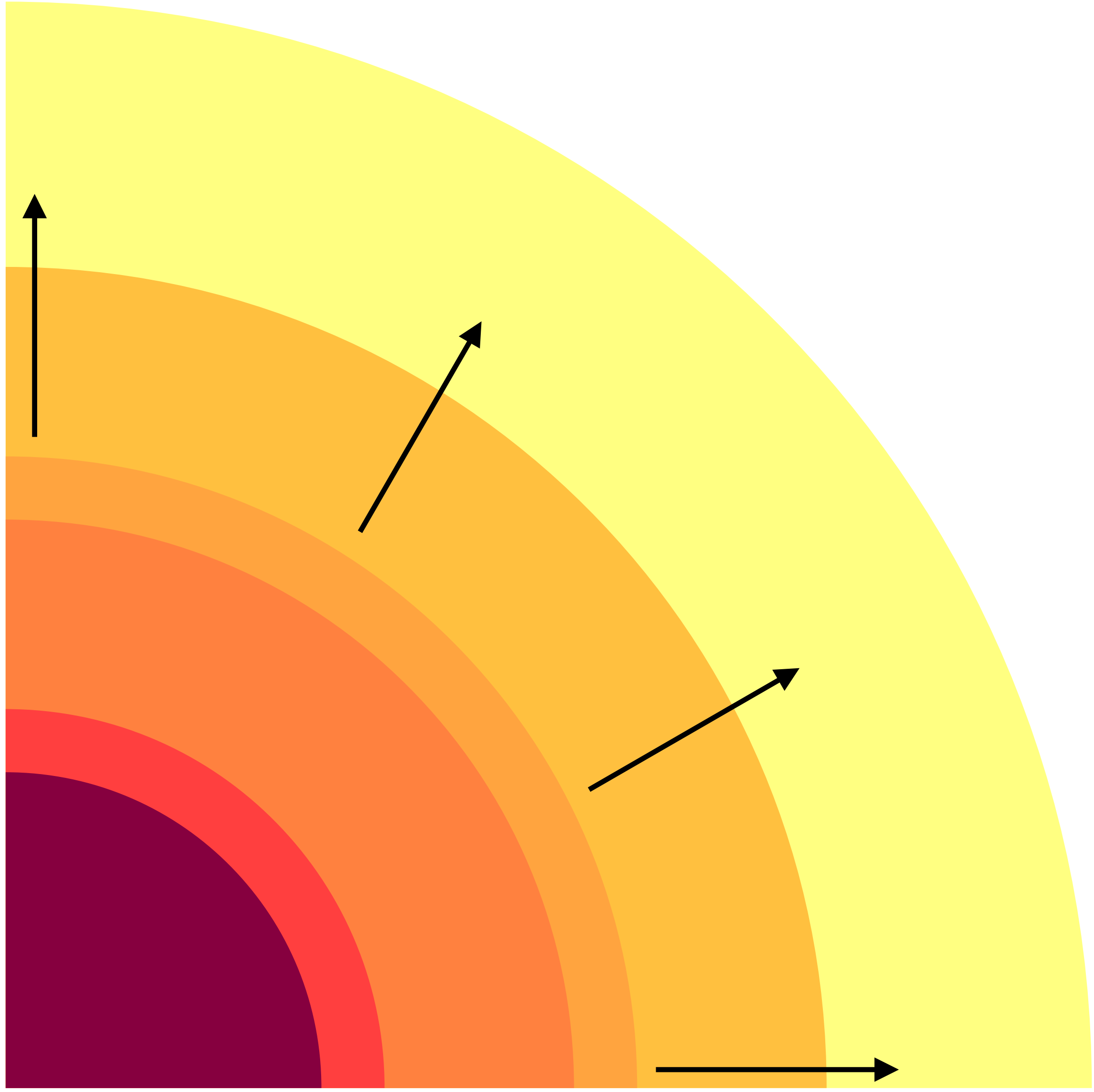
As the core shrinks, the temperature increases, and nuclear reactions changes the composition.

The nuclear reaction also deposits energy to heat the core.

Thermonuclear explosion



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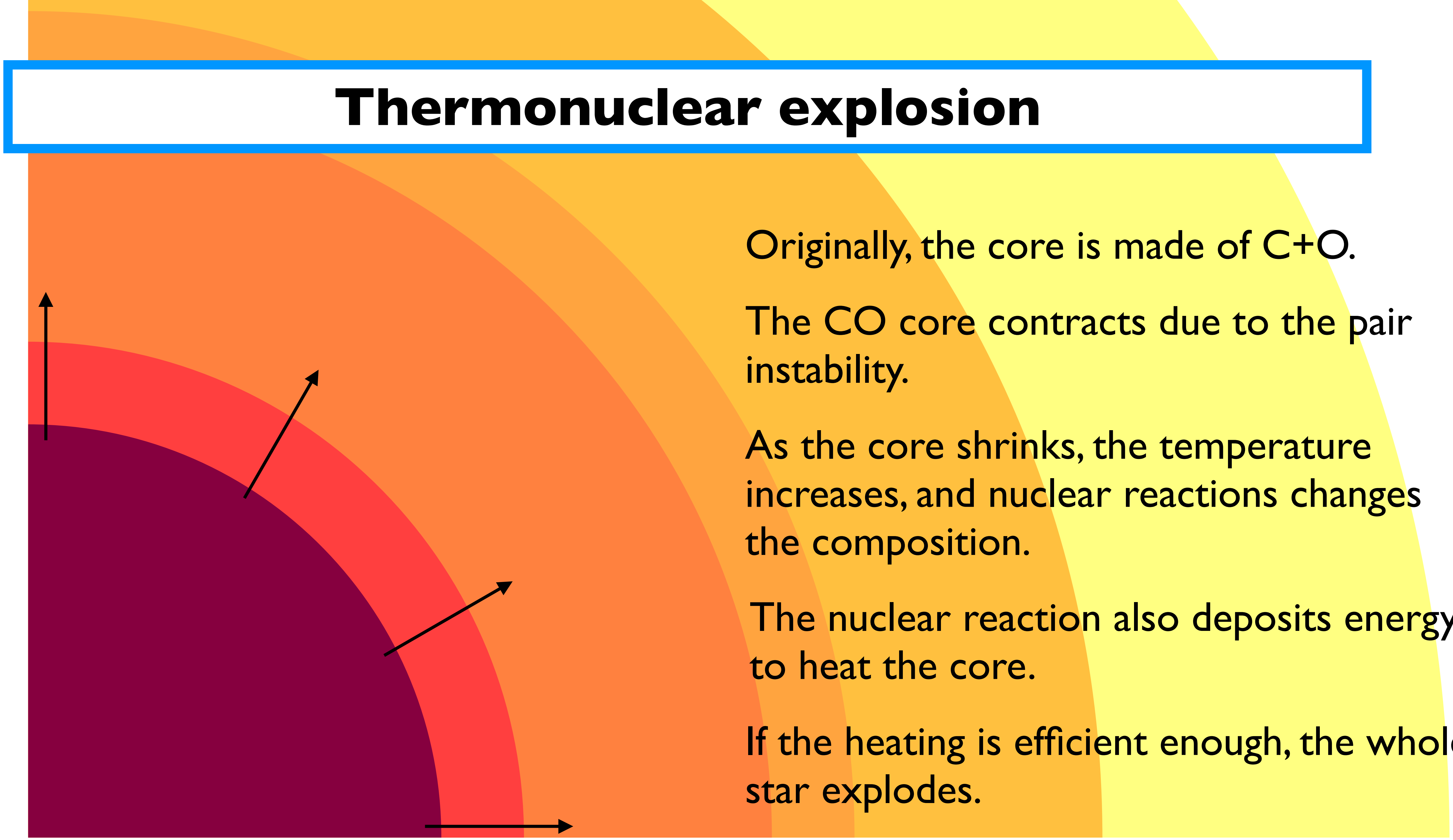
Thermonuclear explosion



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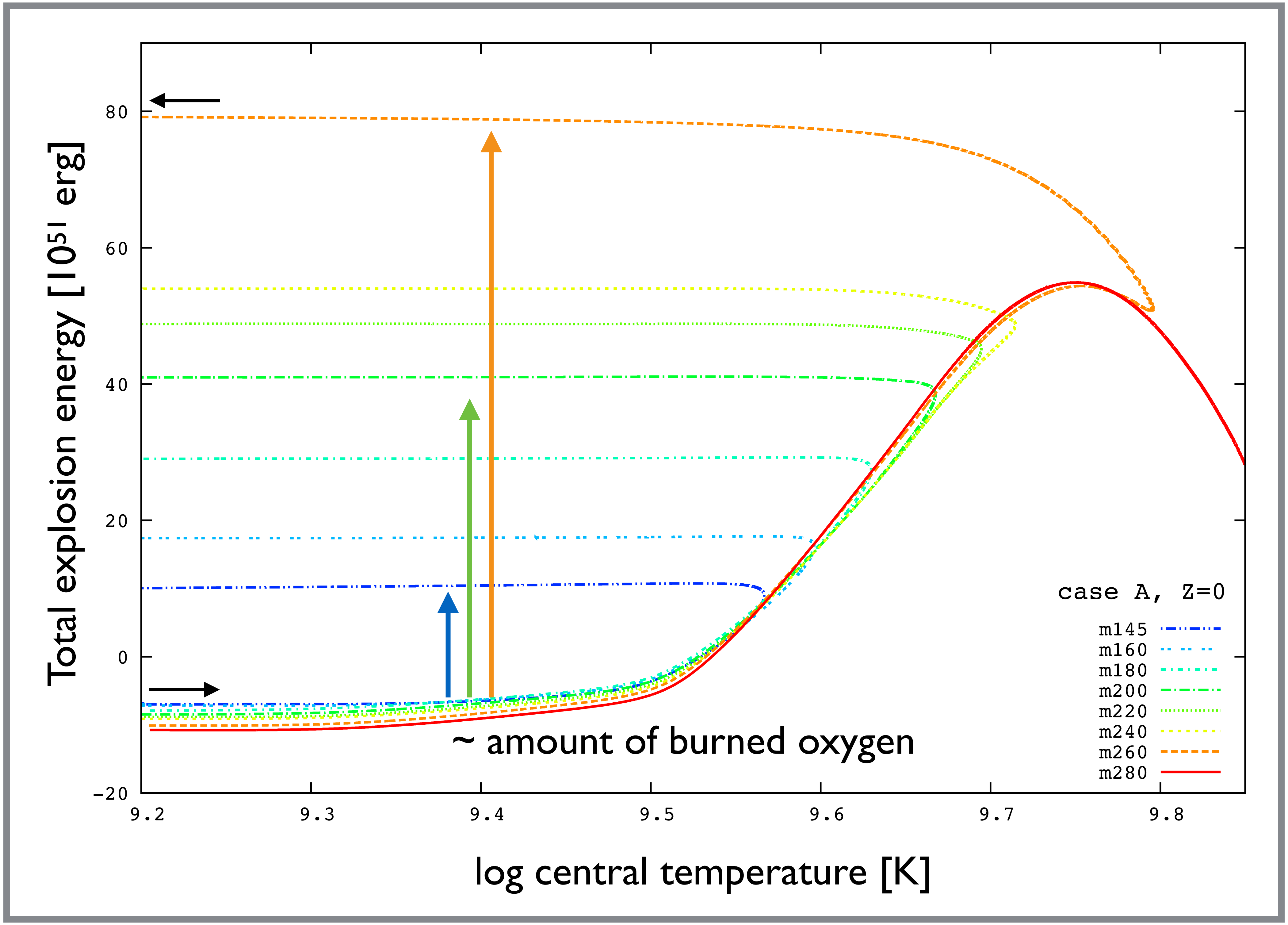
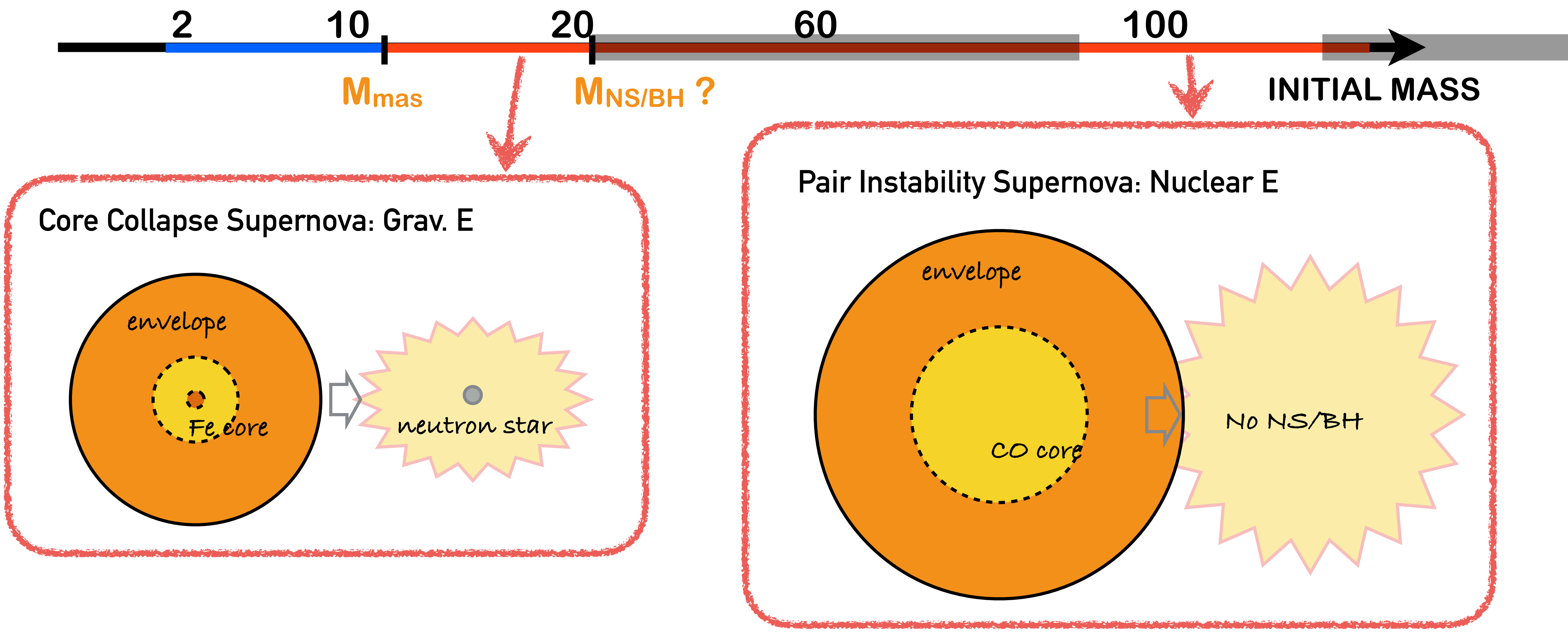
Pair instability supernova

KT+ 2016) simulation results: total energy vs central temperature





Core Collapse Supernova: Grav. E

Pair Instability Supernova: Nuclear E

If the star forms a ~60-120 M_{sun} CO core, it will explode as a PISN.

-No dimensionality
-definite instability
-simple energy source

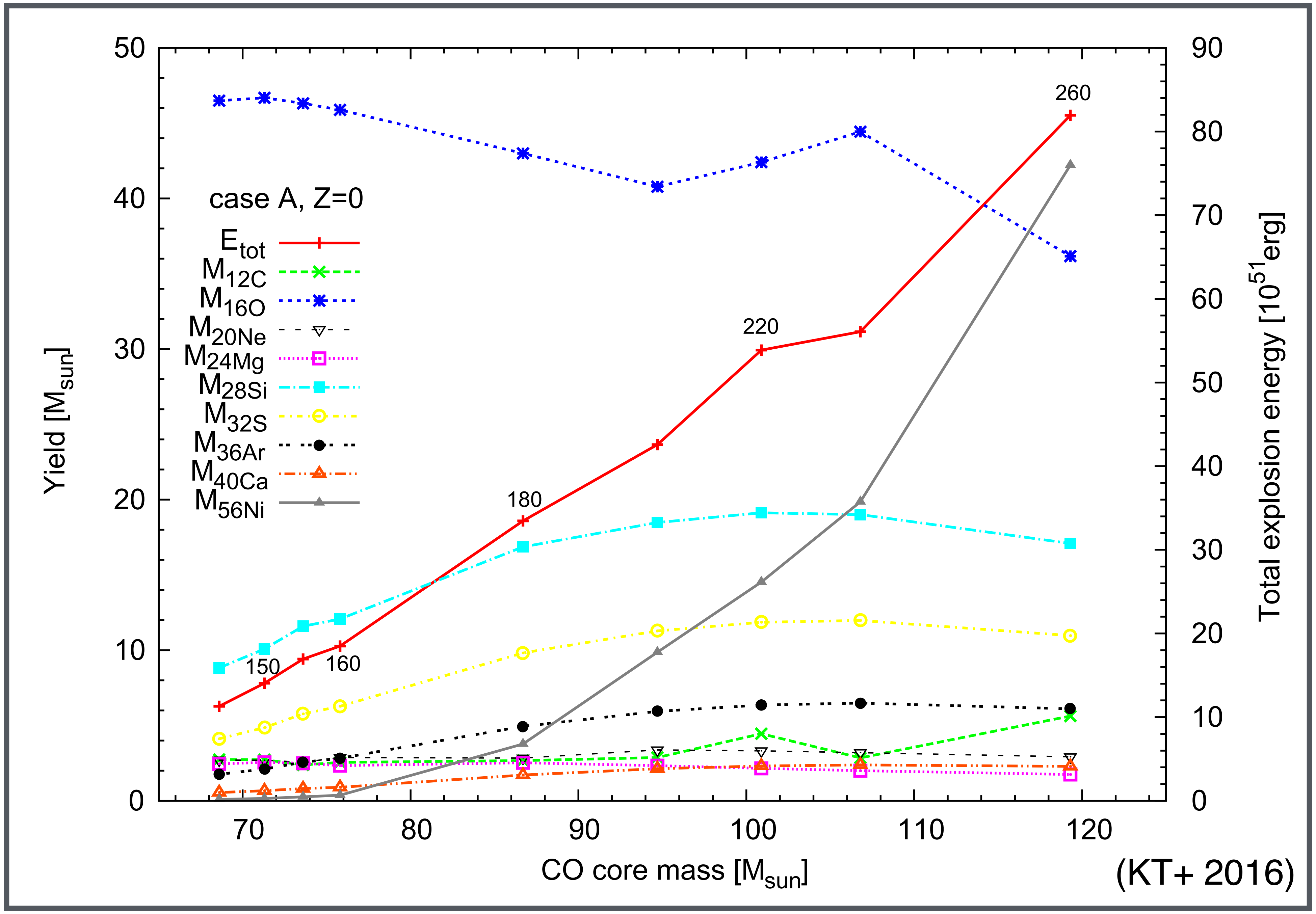
PISN is one of the most **robust** prediction in stellar physics.

Observational support?

1. direct observation
2. remnant search from extremely metal poor stars
3. BH mass distribution

1. Direct observation

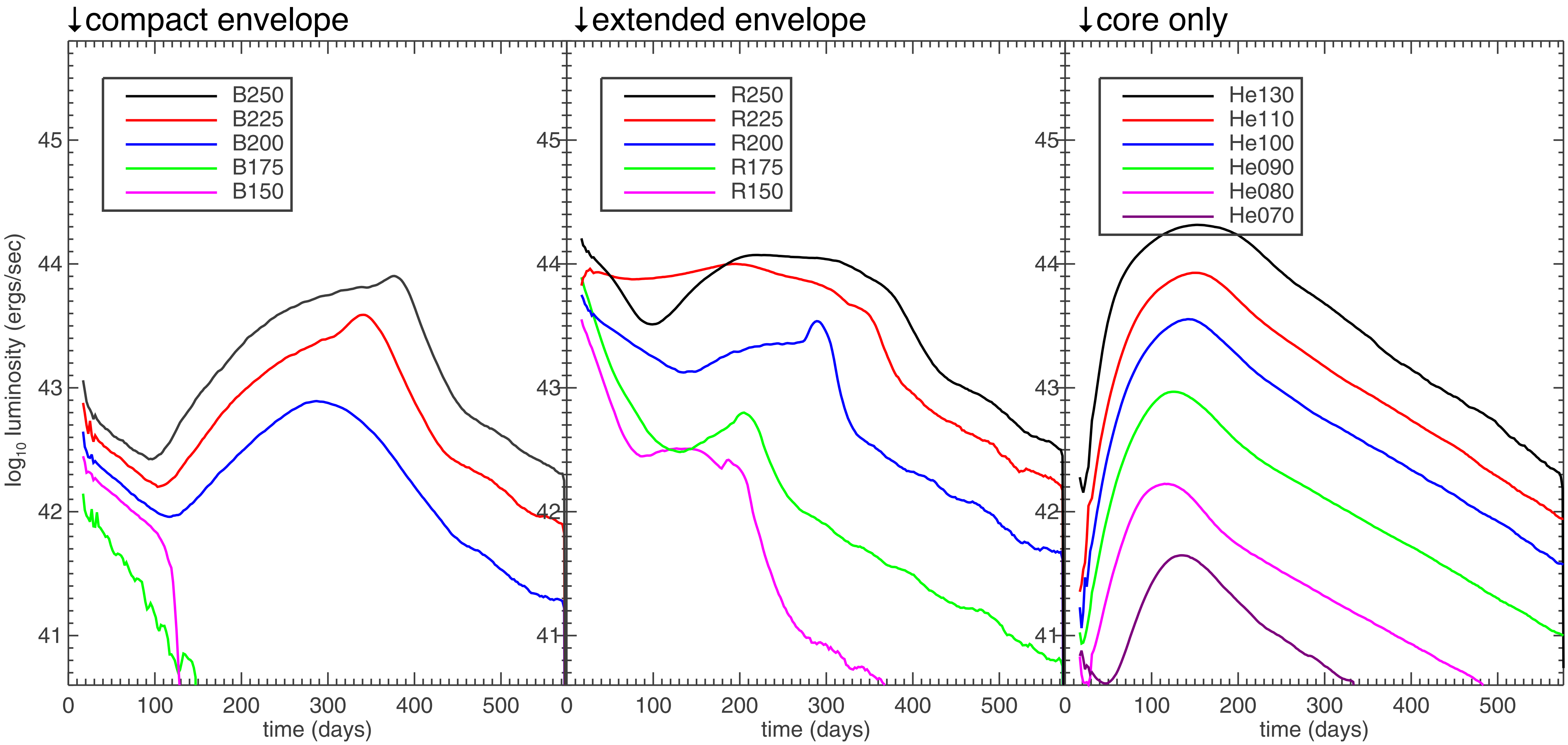
Theoretical expectation



(KT+ 2016)

-large ejecta mass (>10 M☉)
-large explosion energy (>10^{52} erg)
-massive PISN yields large amount of 56Ni

Theoretical expectation



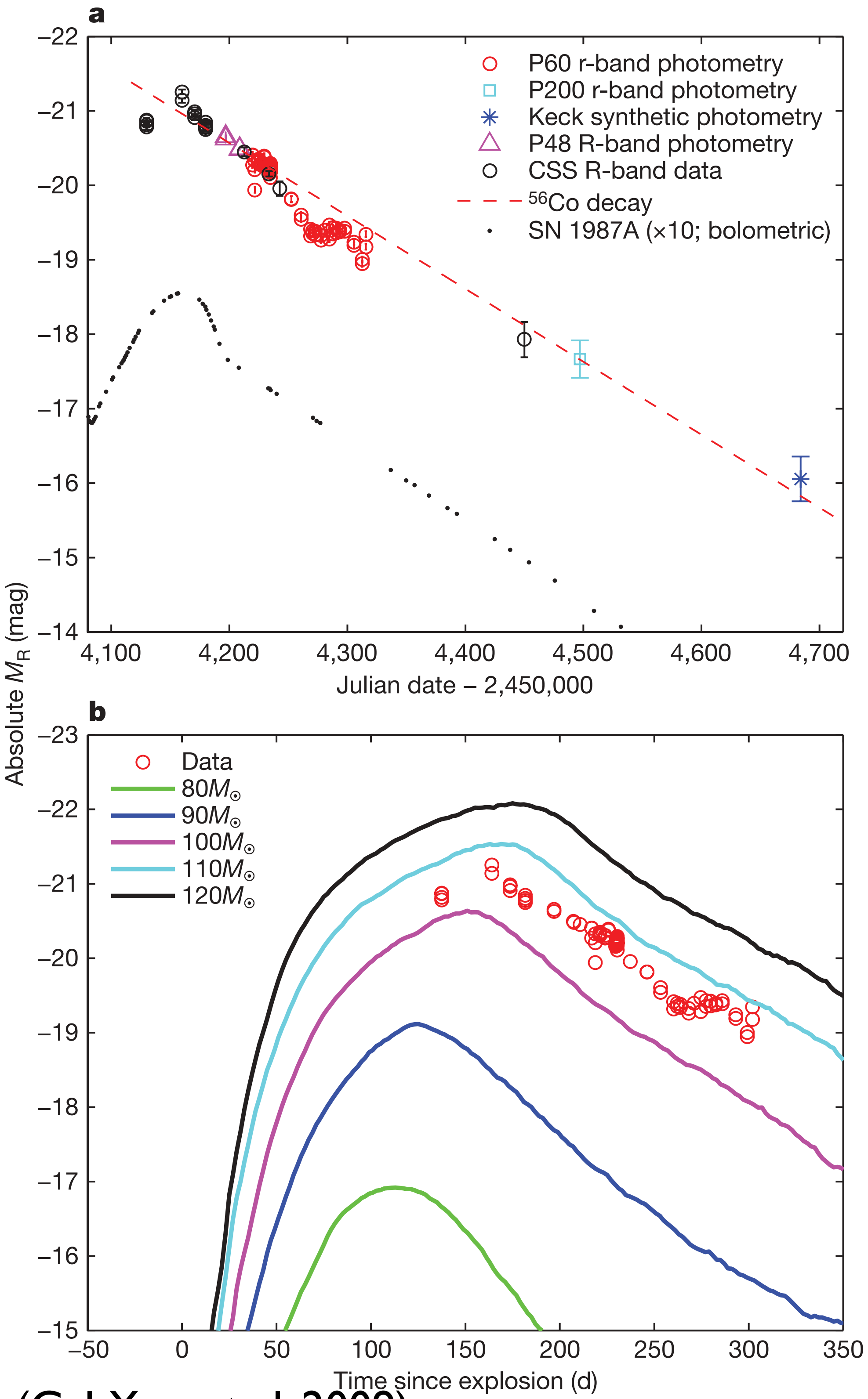
(Kasen+ 2011)

-long timescale (~years): $t_{\rm diff} = 2.27 \times 10^1 {\rm d} \times \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{\kappa}{0.4\ {\rm cm^2\ g^{-1}}}\right)^{1/2} \left(\frac{v}{10^9\ {\rm cm\ s^{-1}}}\right)^{-1/2}$

-very dim to extremely **bright** (<~10^{44} erg s^{-1})

-bright tail due to radioactive decay of 56Ni → 56Co → 56Fe

Is SN 2007bi a PISN?



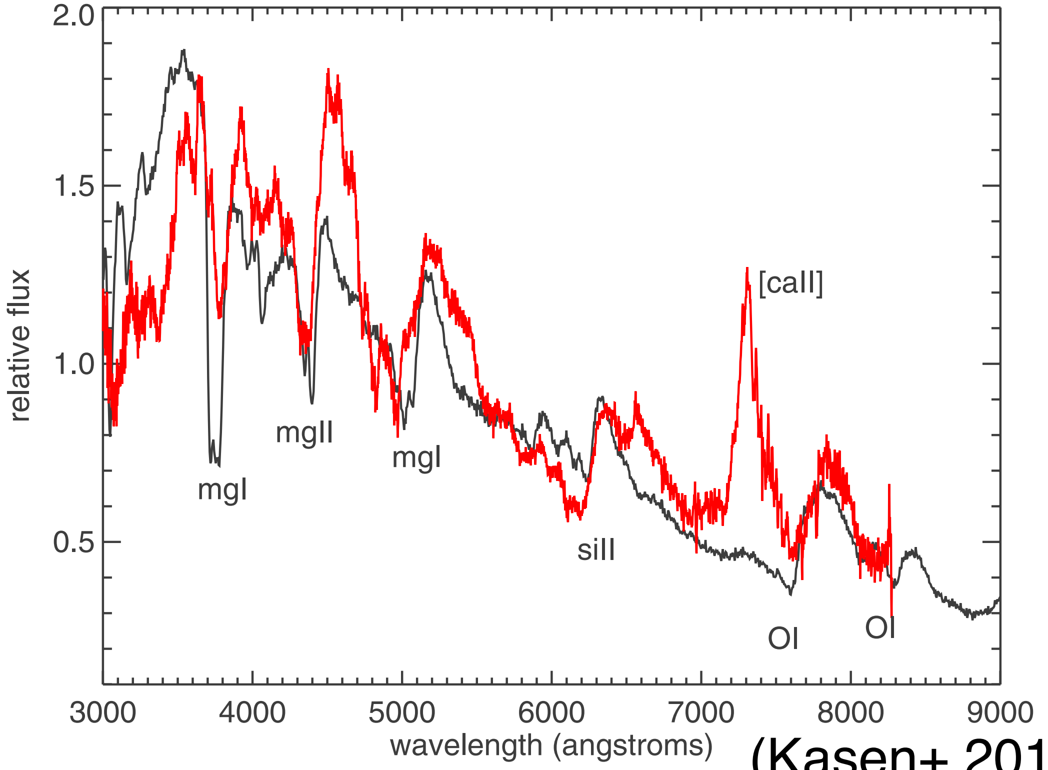
(Gal-Yam et al. 2009)

On 2007 April, a luminous, **slowly evolving type Ic** supernova with **^{56}Co decline tail** has been detected.

A PISN model of 100 $M_\odot$ He star provides good explanation for

the light curve (Gal-Yam+09)

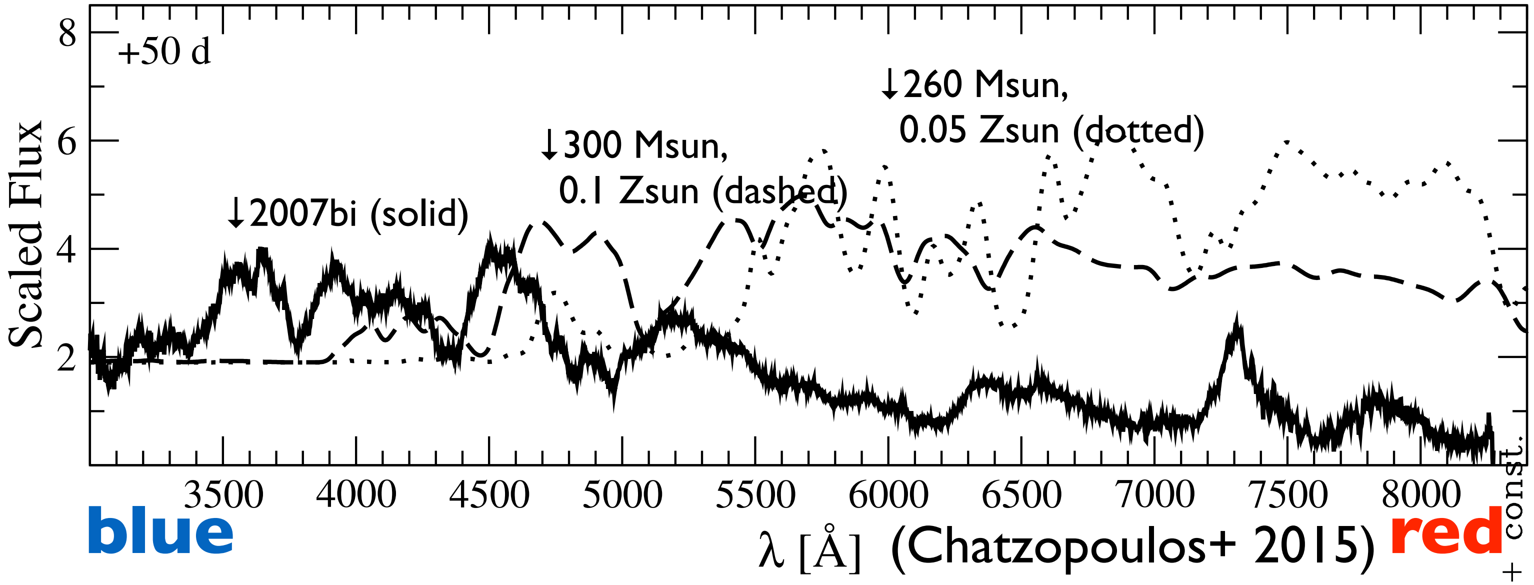
and the Mg lines (Kasen+11).



(Kasen+ 2011)

Is SN 2007bi a PISN?

However, more recent spectral analyses claim that PISN spectra should be much **redder** than SN 2007bi (Dessart+12,13, Chatzopoulos+15).



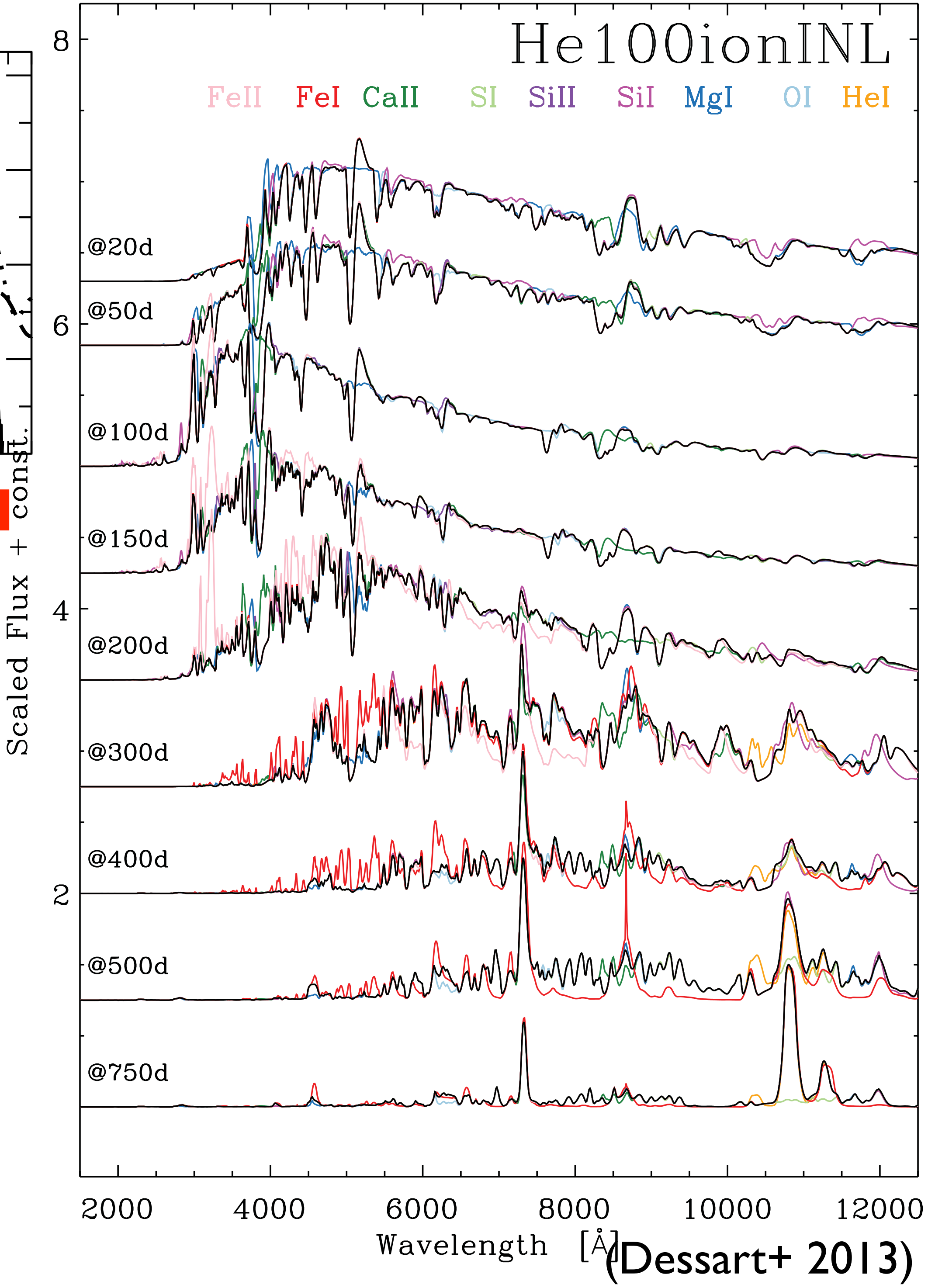
↓2007bi (solid)

↓300 Msun, 0.1 Zsun (dashed)

↓260 Msun, 0.05 Zsun (dotted)

blue (Chatzopoulos+ 2015) **red**

↓significant absorption by FeII, CaII, FeI reddens the spectrum



(Dessart+ 2013)

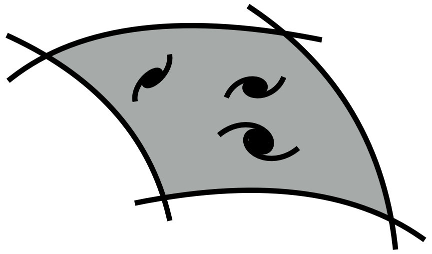
SN2007bi is the best observed supernova of the class SLSN-R so far.

There has been no convincing PISN detection.

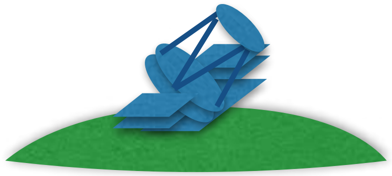
see also Kozyreva+14, Smidt+15, Jerkstrand+16, Mazzali+19, but also see Kozyreva&Blinnikov15

search for long-lasting SNe

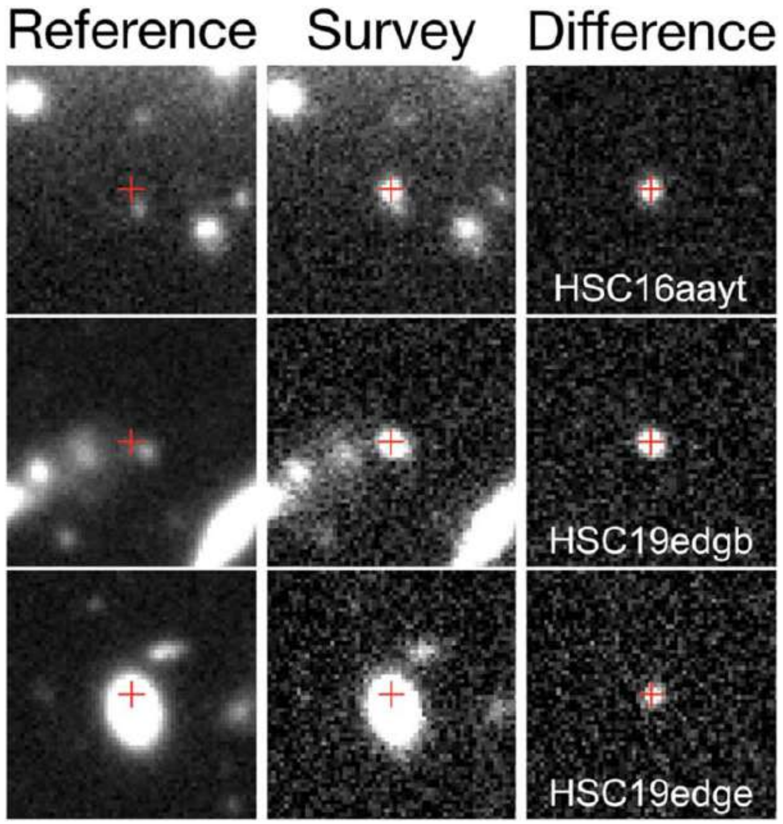
Moriya et al. (2021) have repeatedly observed **the same field** in the sky **for 3 years** to find **transients lasting for more than a year.**



~1 PISN is expected to be detected with 2 yr-long detection by assuming the rate of 100 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.



3 long-lasting SNe are discovered, however, **none of them are compatible with the PISN model.**



→type IIn at z=0.68

→type IIn at z=0.23 or UV-bright SLSN at z=2.7

→type IIn (?) at z=0.33

at $z < -3$,
- PISN rate $< 100\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- PISN/CCSN < ~0.01-0.1%

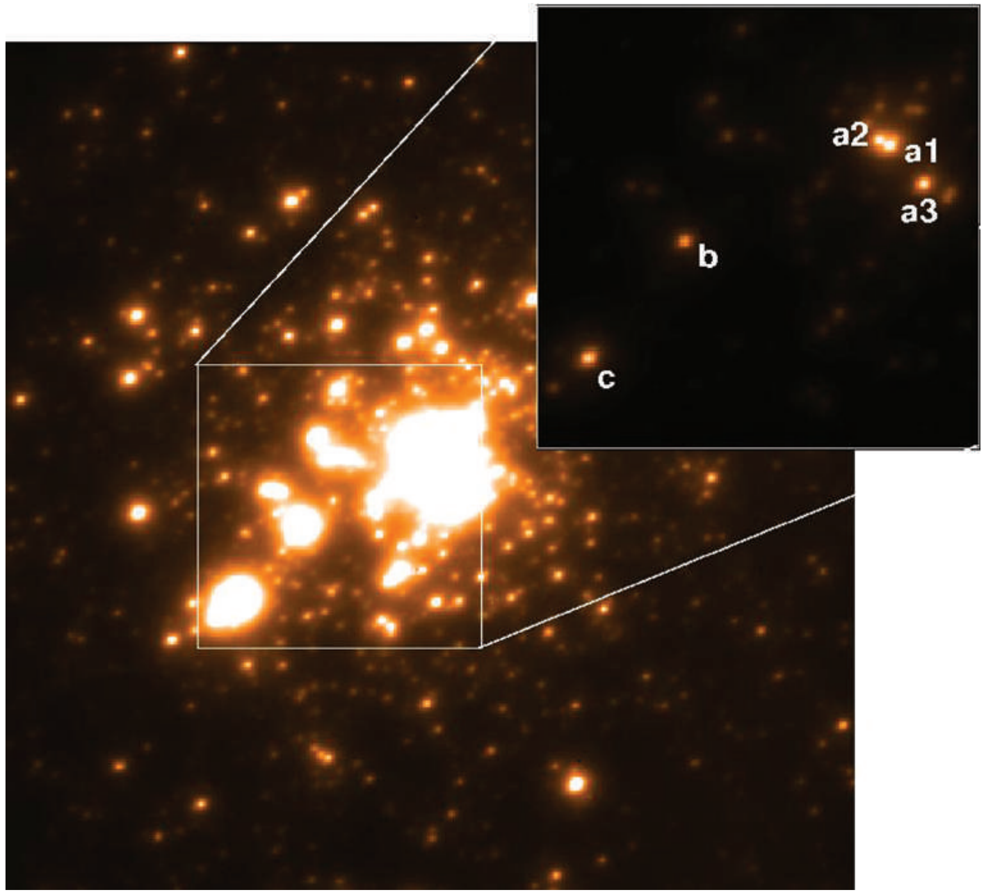
PISN progenitors in the local universe?

It is likely to be rare to contain the large enough mass for PISN in the local universe.

Very massive stars are rare to be formed.
Salpeter IMF →
(PISN mass range)/(CCSN mass range) ~ 0.01%.

$M_{ini} > 100\ M_\odot$ stars at the R136 (LMC)

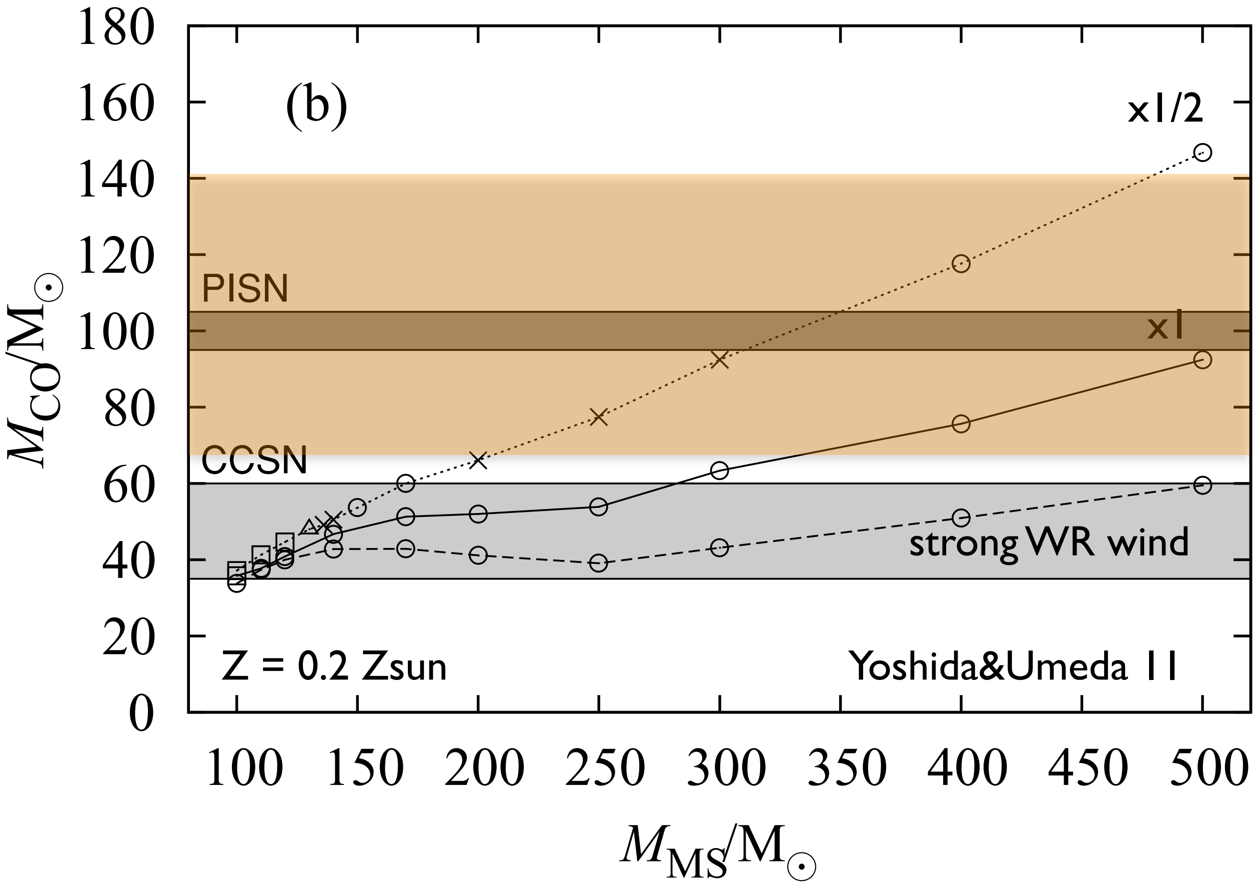
(e.g. Crowther et al. 2010, 2016)



Due to the strong wind, the initial mass for PISNe might require >500 $M_\odot$ for $Z=1/5\ Z_\odot$.

(see also Langer 2007)

Effective mass loss on the PISN progenitor

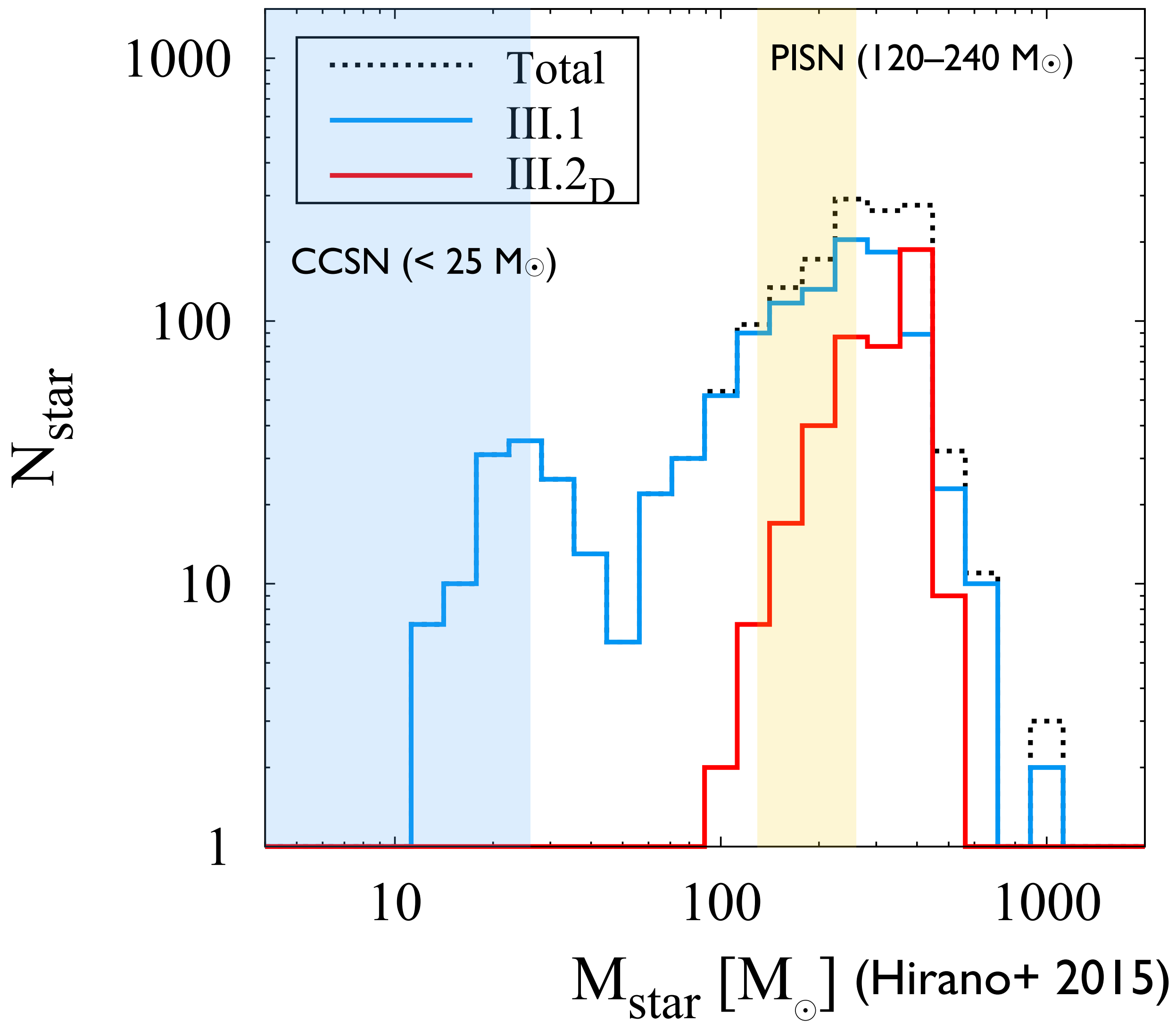


2. remnant search from EMP stars

PISN progenitors in the early universe?

In the metal-free early universe, PISNe would be much more frequently formed than in the local universe.

-**top-heavy** initial-mass-function (~100 M$_\odot$?)
-**negligible** wind mass loss rate



(Hirano+ 2015)

Hirano et al. (2015) estimates
25% of metal-free stars may become PISN,
while 3.1% of them form neutron stars.
→ **PISNe/CCSNe ~10**.

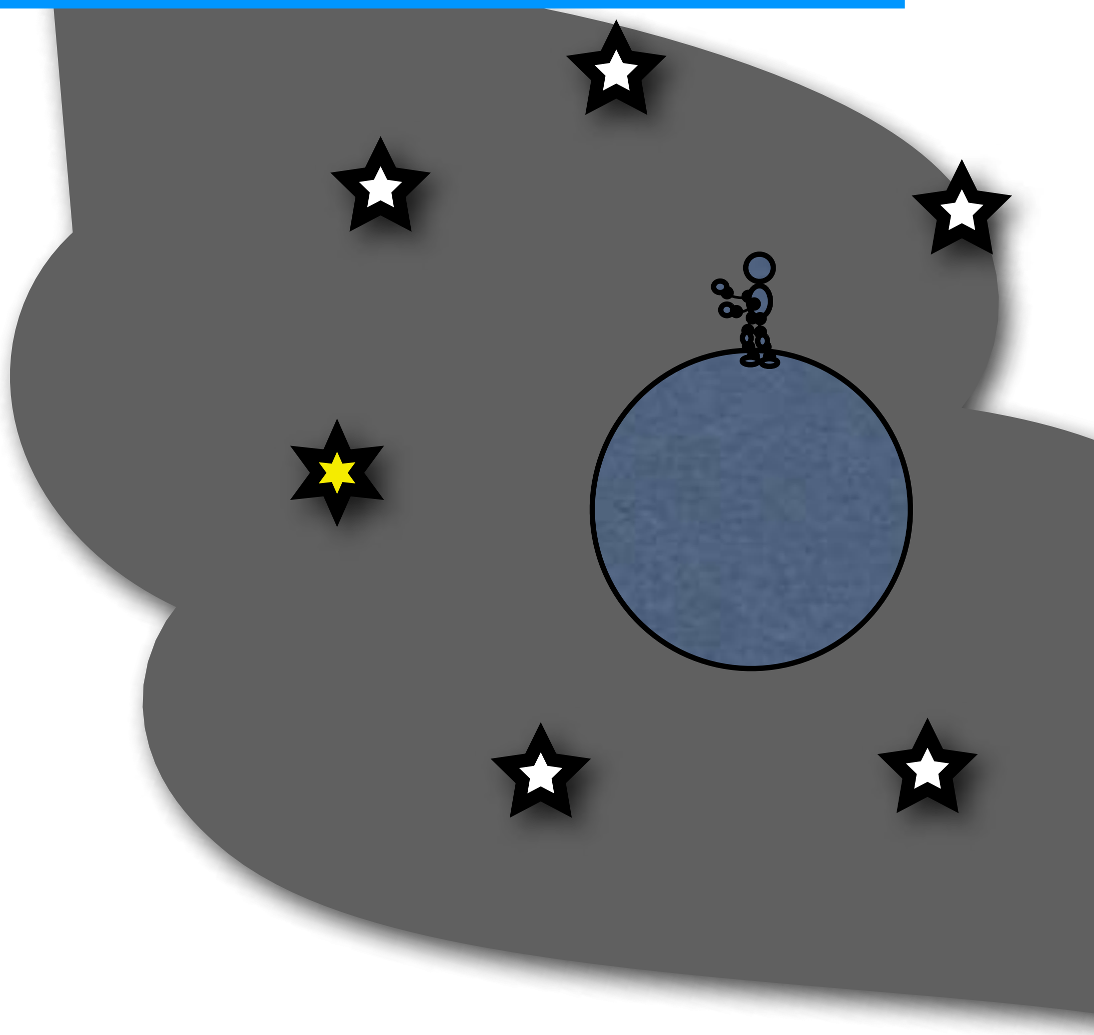
(Extremely) Metal poor stars

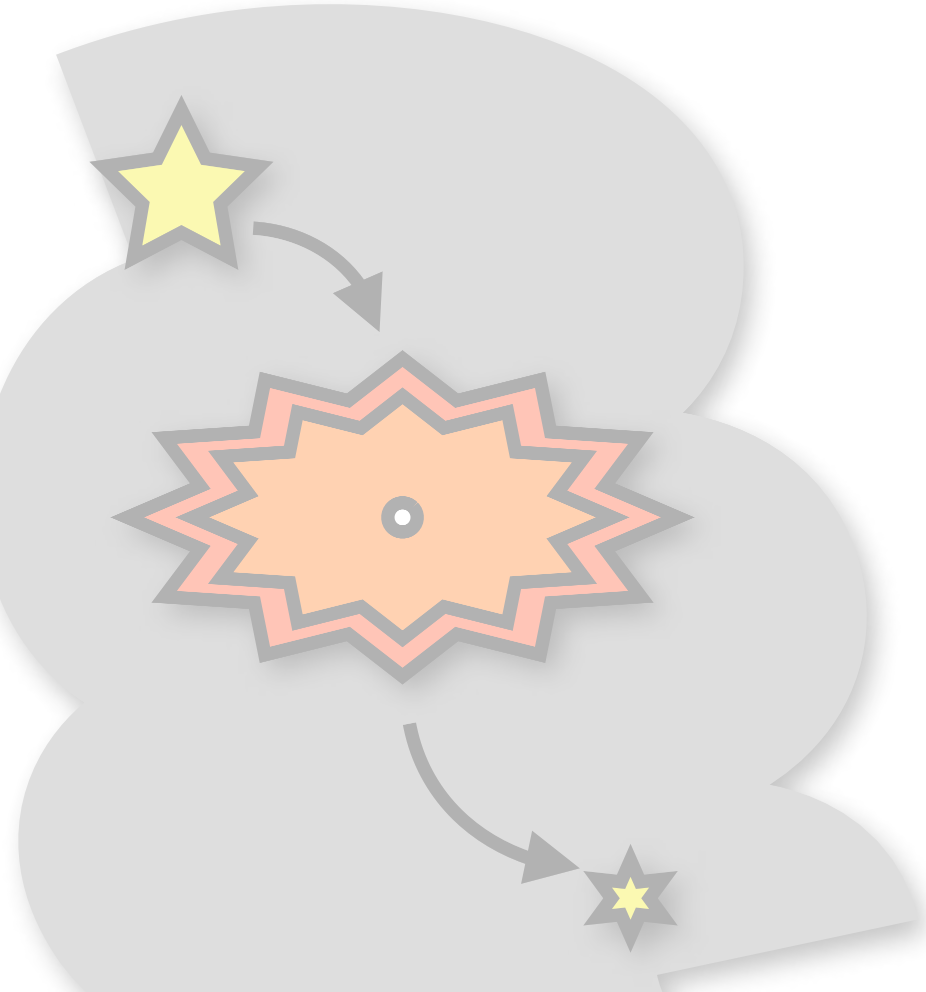
(Extremely) Metal poor stars

In our Galaxy, there is a group of stars that contain only a small fraction of metals.

Stars that contain less than a thousandth of metals of the sun are called **extremely-metal-poor (EMP)** stars.

How did EMP stars form?





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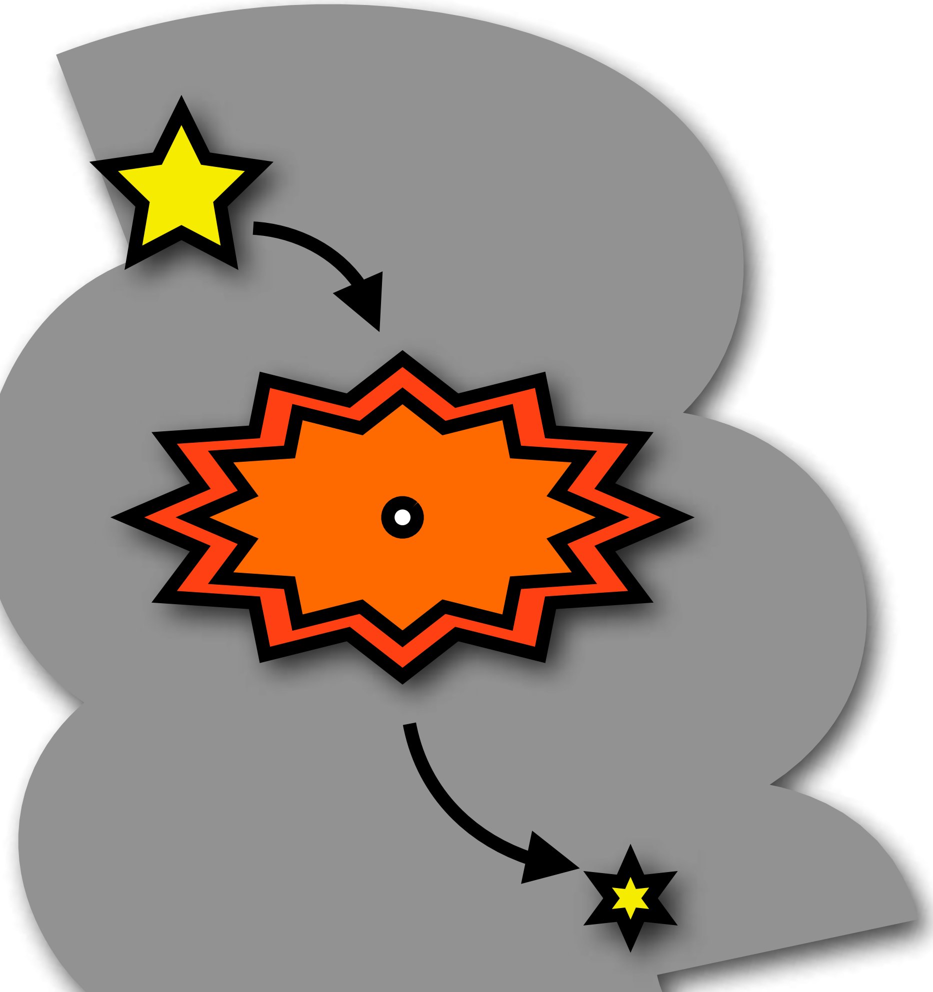


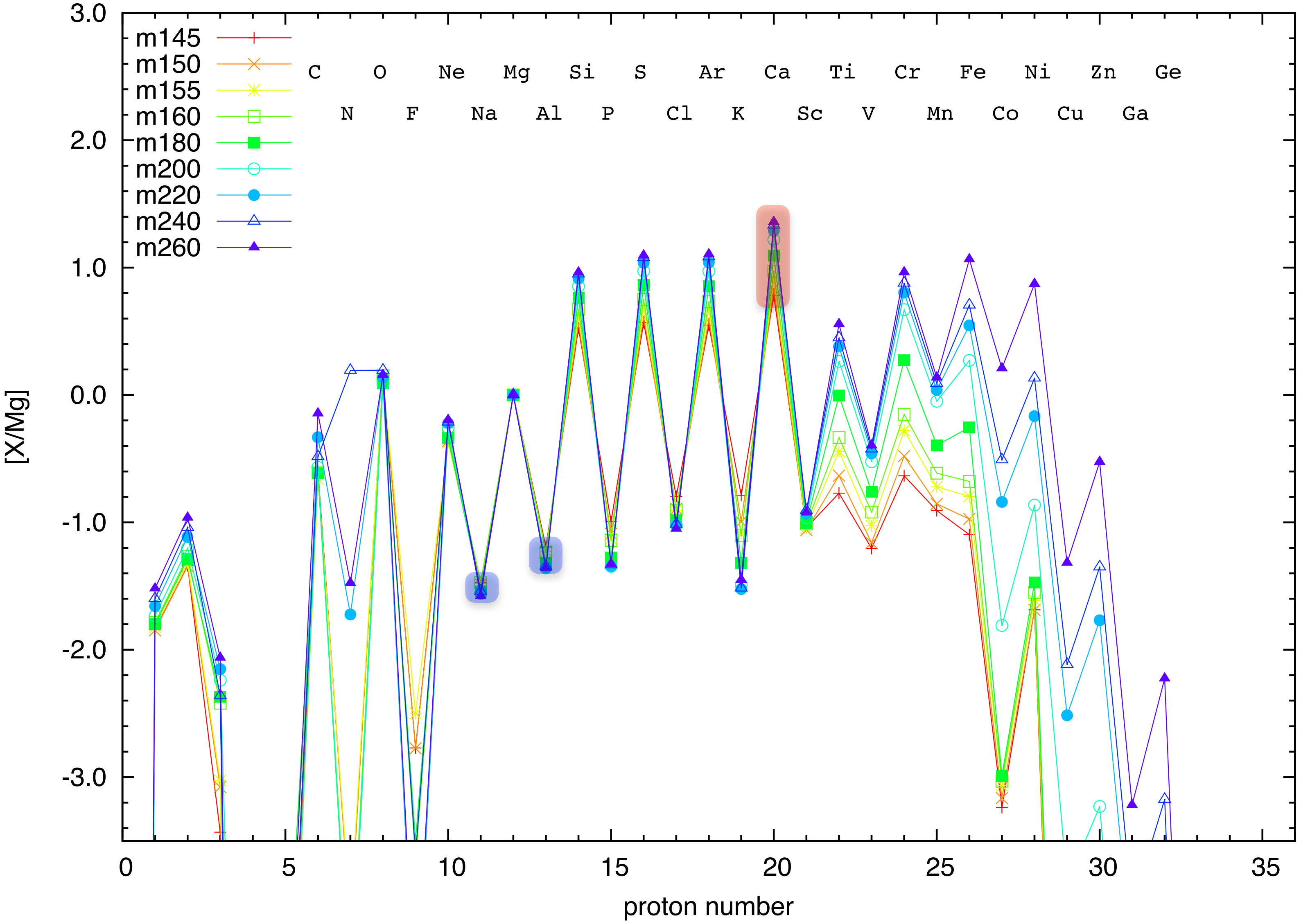
EMP stars could be children of metal-free stars,

because theory predicts that single shot supernova will achieve metal pollution of primordial gas clouds with 1/1000 $Z_\odot$ level.

If this is true, the chemical abundance of EMP stars should represent the characteristic abundance pattern of the mother supernova.

Characteristic abundance pattern of PISNe

Indeed, PISN ejecta will show very peculiar abundance pattern.



KT+ 2018a

1. Enhancement of O burning products: characterized by large [Ca/Mg].
2. Strong contrast between odd-Z and even-Z elements: small [Na/Mg] and [Al/Mg].

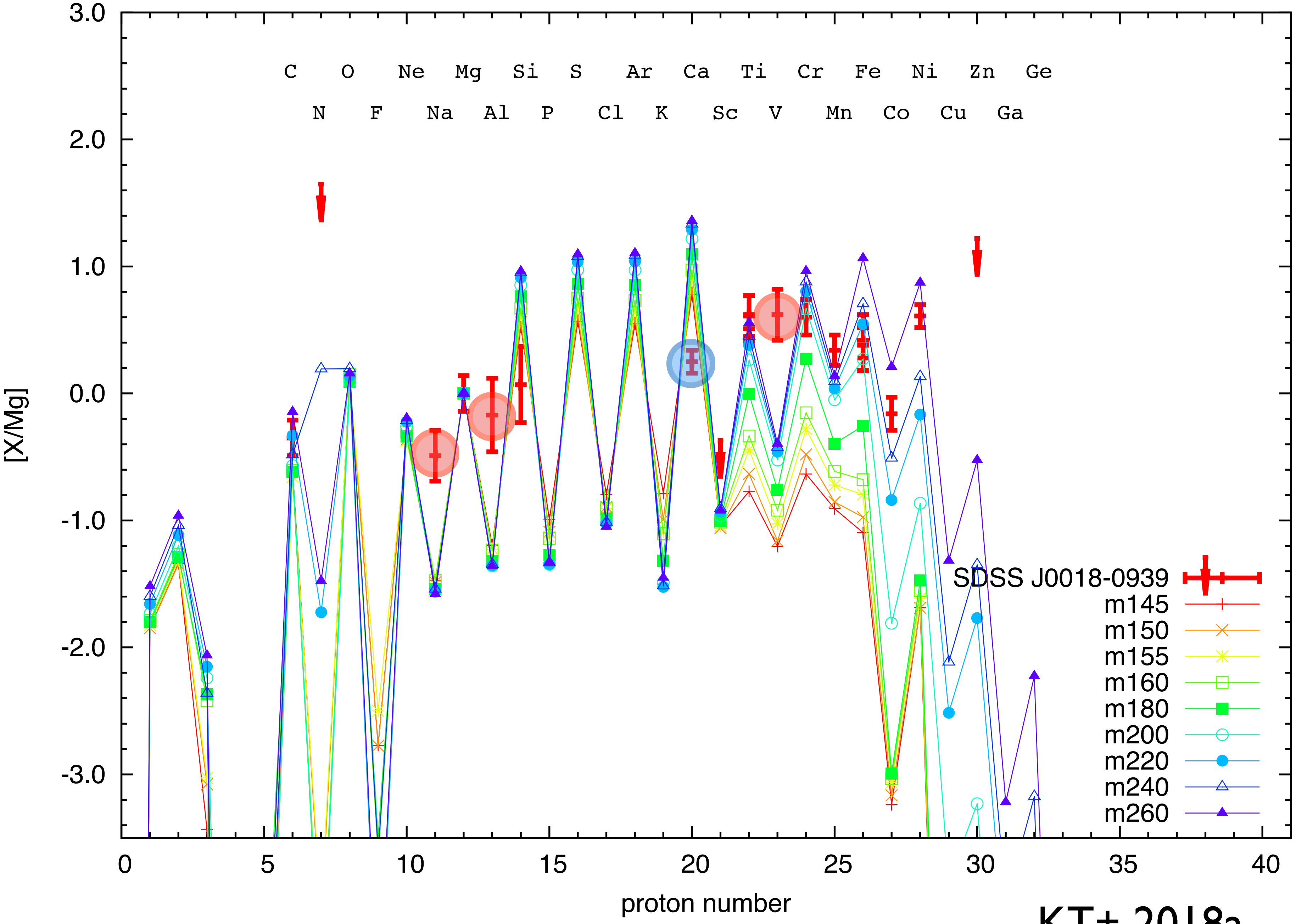
$[X/Y]=\log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$

Is SDSS J0018-0939 a PISN child?

SD J0018-0939 ([Fe/H]=-2.46, Aoki+14)

The exceptionally small [Co/Ni] ratio may be consistent with PISN abundance.

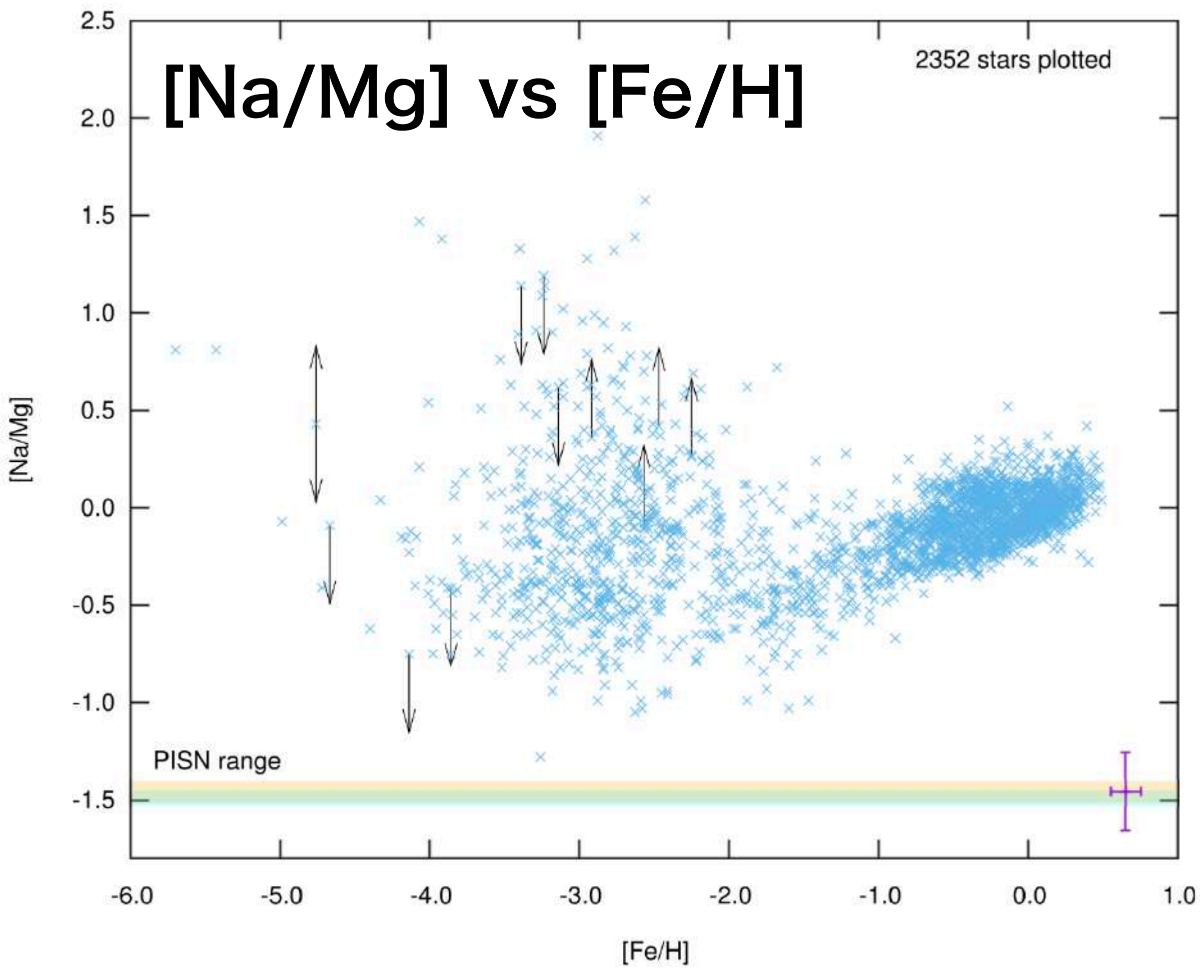
However, strong tension exits for **too large Na, Al, V** and **too small Ca**

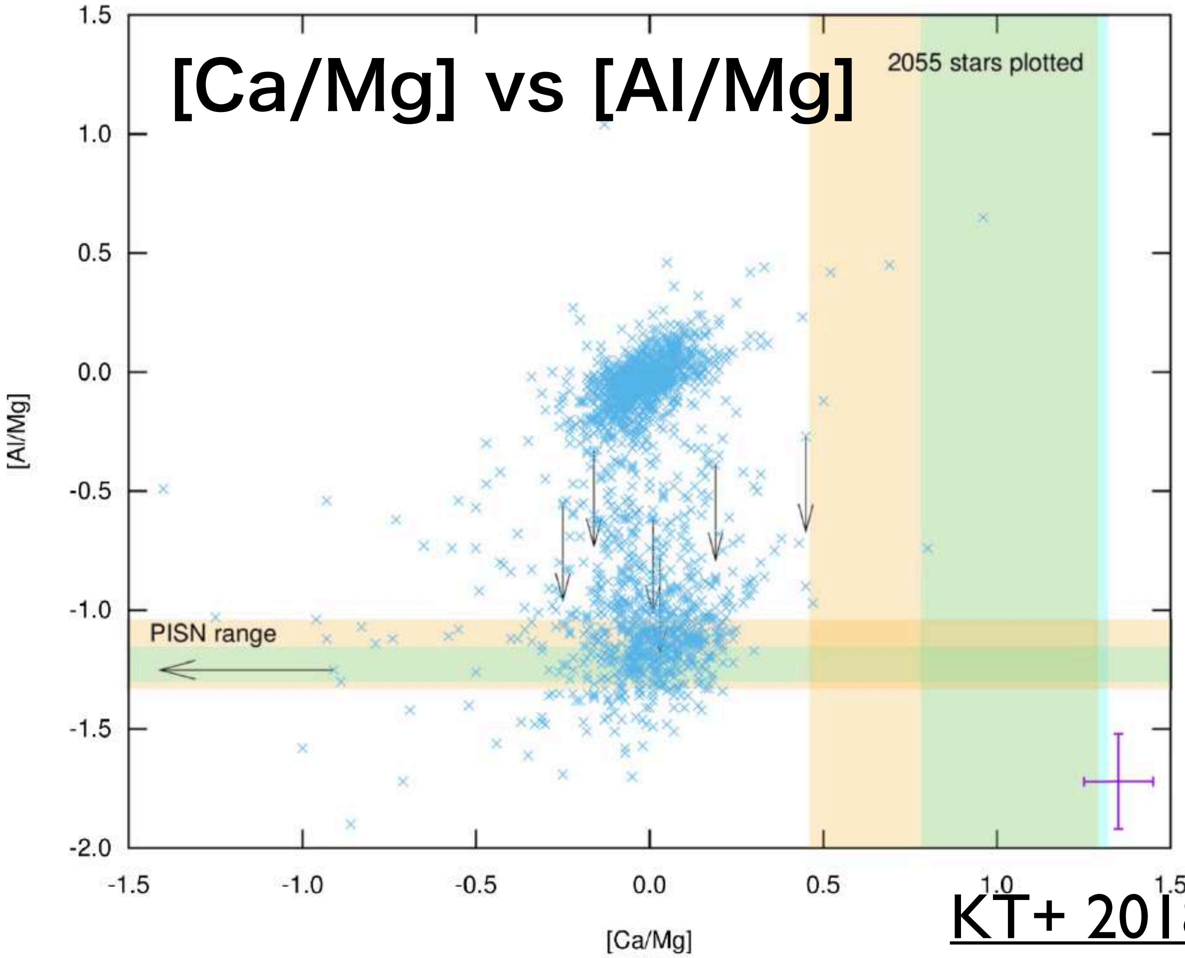


KT+ 2018a.

systematic search

KT+2018 have conducted the first systematic comparison with the theoretical yield and a large sample (>2,000) of MP stellar abundances.





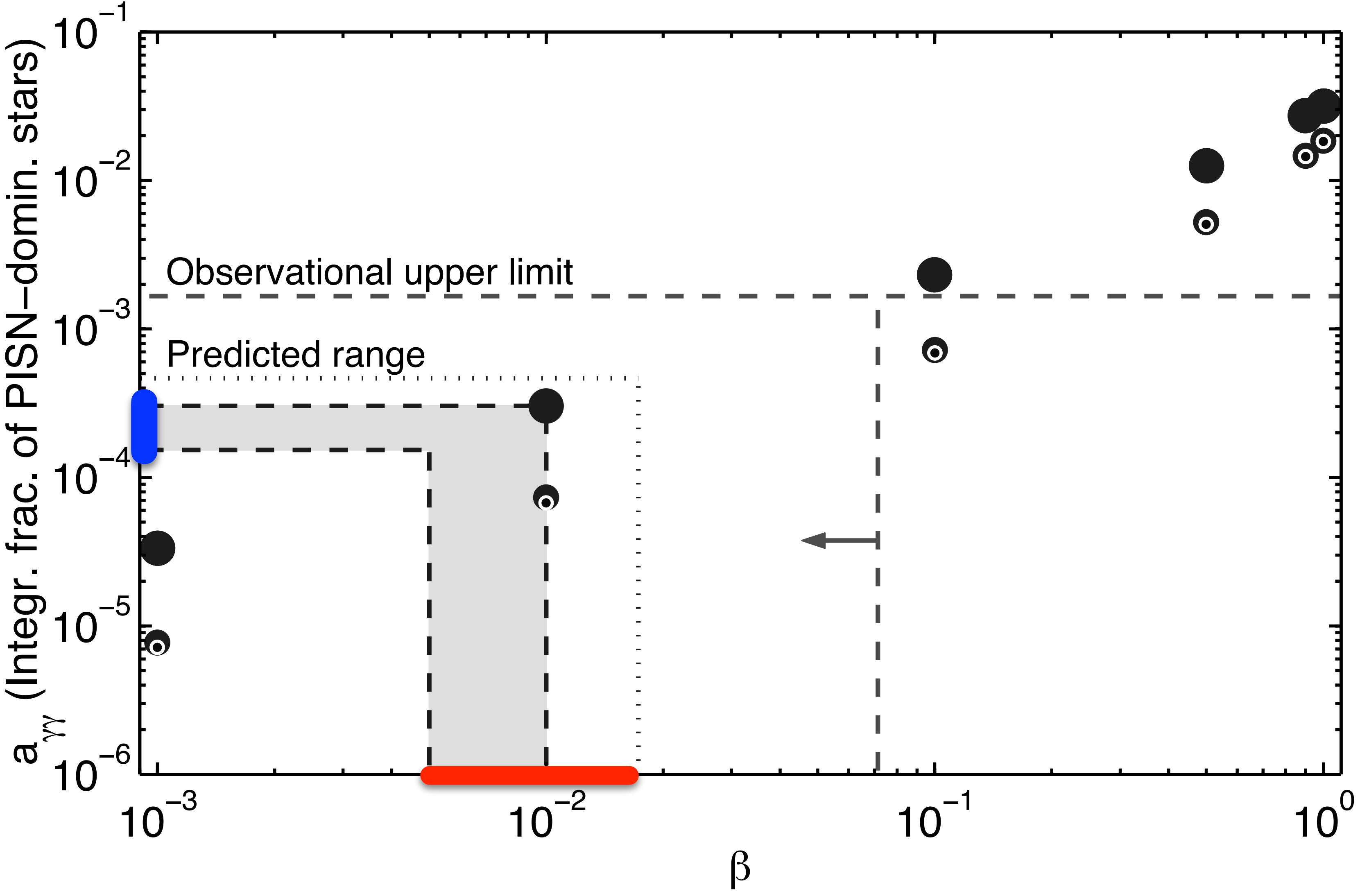
KT+ 2018a.

→Until now, no MP stars that show abundance pattern compatible with PISN models have been found.

PISN-dominated metal-poor stars

The sample number of 2,000 might not be enough.

Karlson+ 08



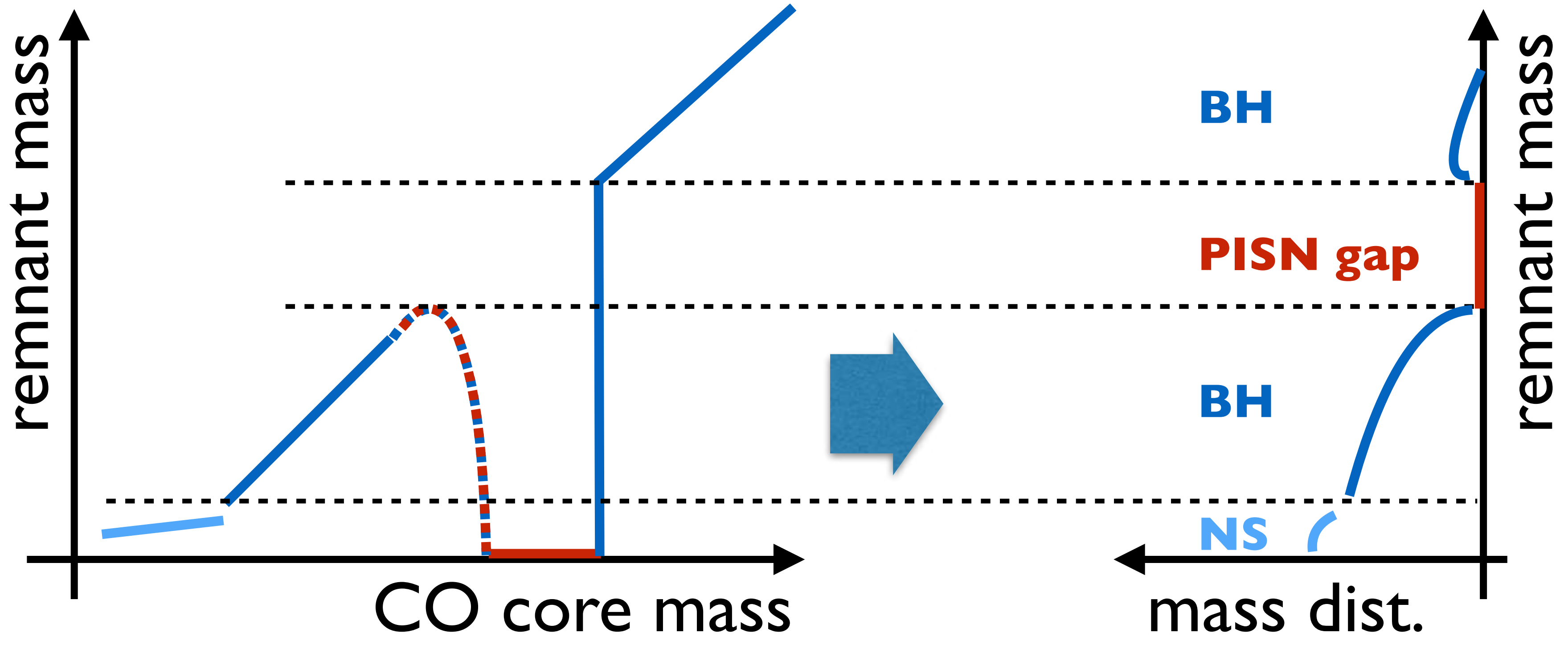
β: the number ratio between (Pop III PISNe)/(Pop III CCSNe). **0.005−0.02** by Greif&Bromm 06

$a_{\gamma\gamma}$: fraction of PISN-dominated MP ([Ca/H] < -2) stars

1/2,000−1/10,000 MP stars in [Ca/H] < -2 are estimated to be children of Pop III PISNe.

3. BH mass distribution

PISN mass gap



stars with **~2-10 M$_\odot$ CO cores** will form **neutron stars**.

>~10 M$_\odot$ will form **black holes**.

~60-120 M$_\odot$ becomes **PISN**, leaving no remnants.

>~120 M$_\odot$ collapse into **BH**s.

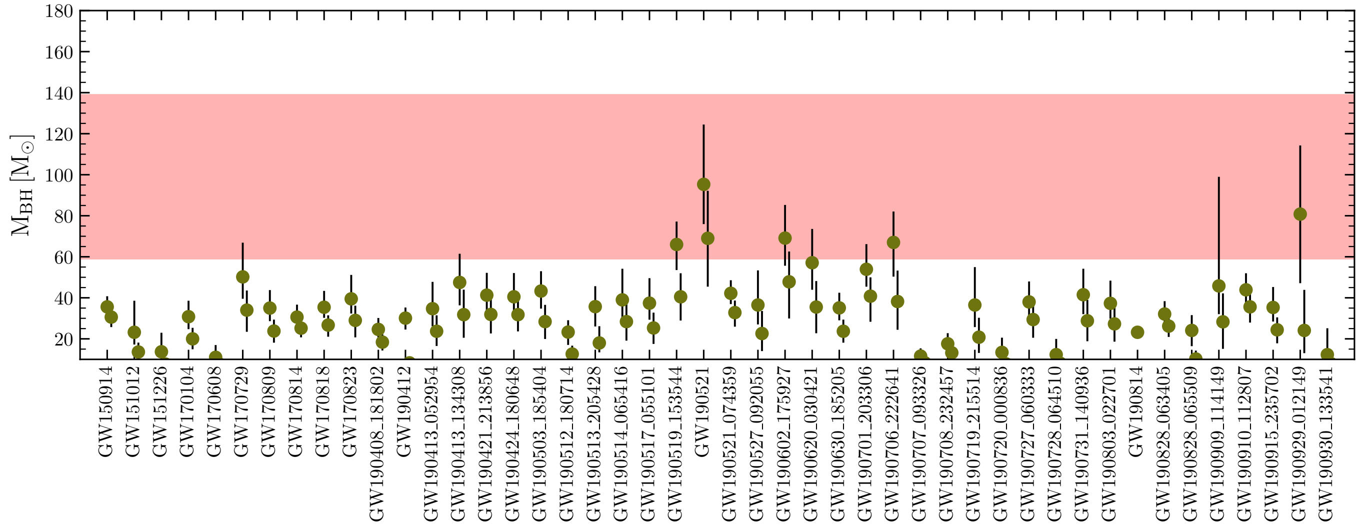
~40-60 M$_\odot$ collapse into **BH**s
significant mass ejection by **PI**.

→PISN results in **the PISN mass gap** in the BH mass distribution.

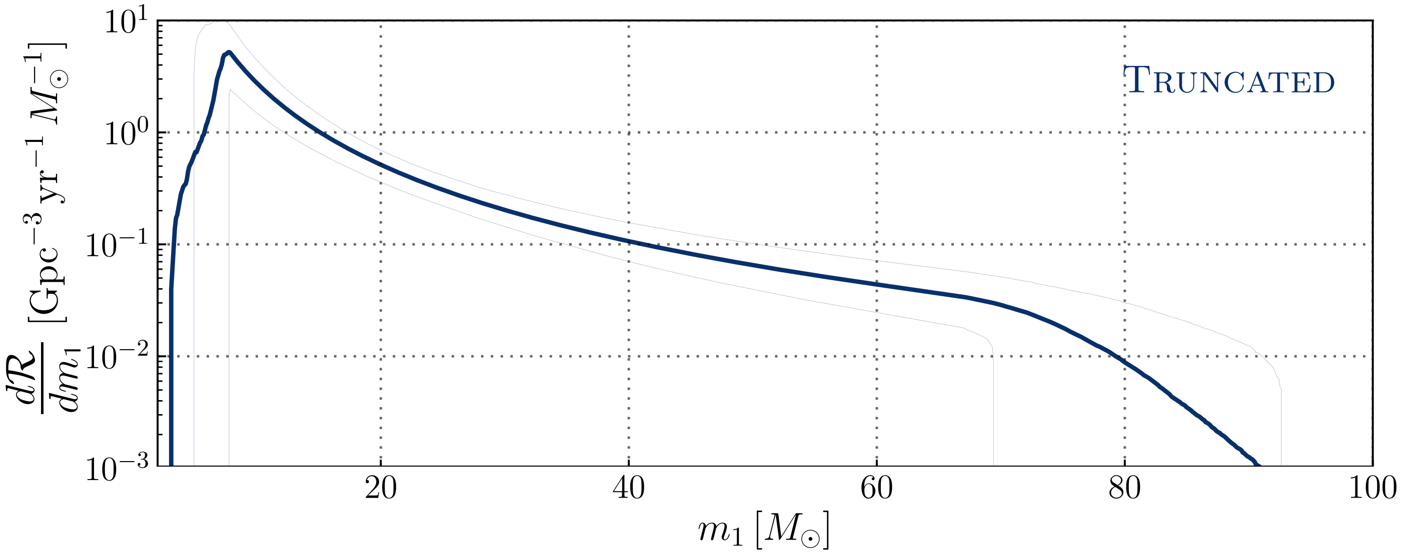
BH mass detection by Laser interferometers

Today, BH masses can be measured by laser interferometric GW detectors.

Mehta+21: BH masses from GWTC-1 & -2



GWTC-2, Population Properties:



✓ m1 < 45 M⊙ for 97.1% of BBH systems

- no detection of BHs > 100 M⊙

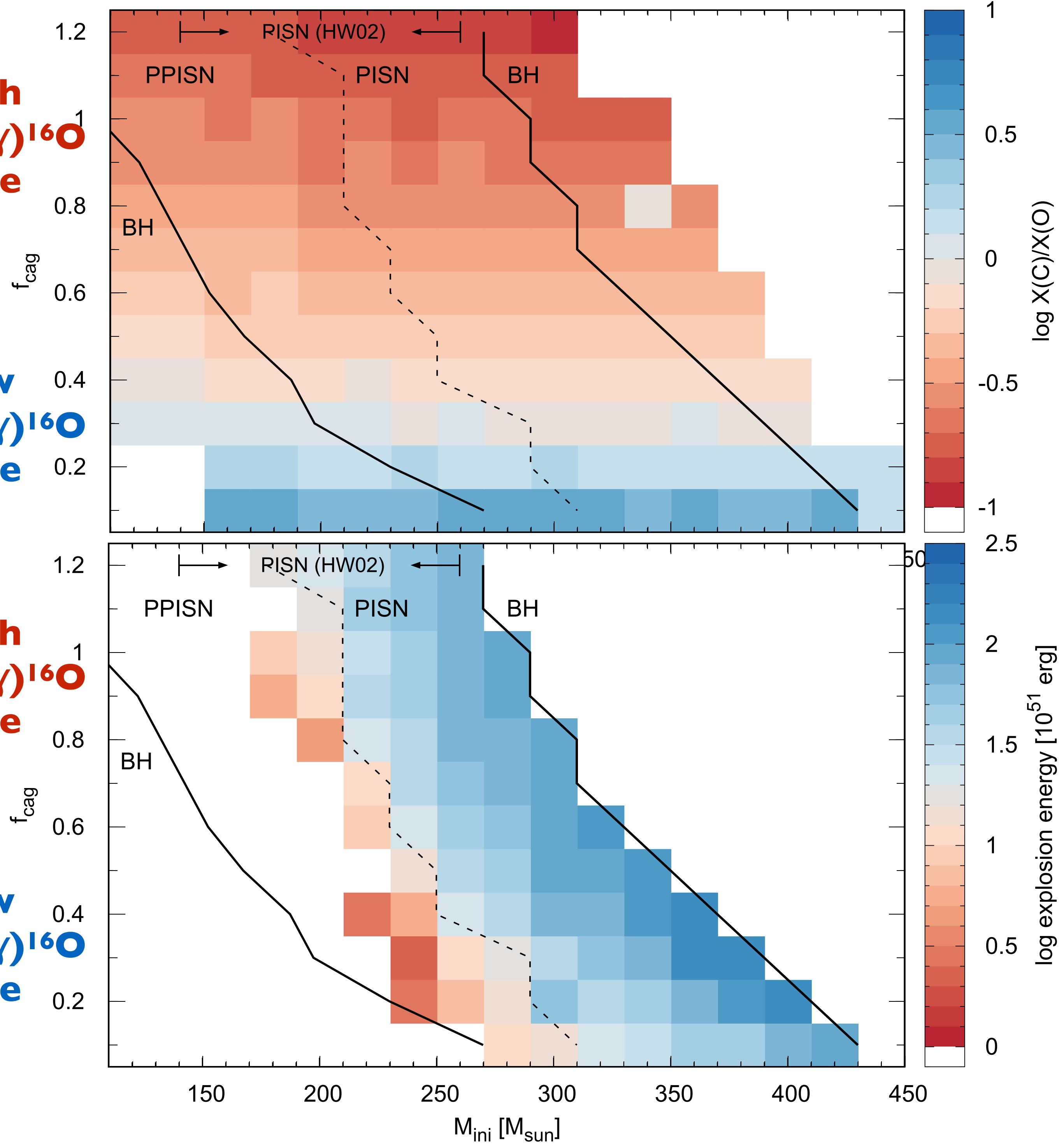
→GWTC-2 result is consistent with **the PISN mass gap**, but **not yet definitive**.

? several high-mass detections (GW190521, GW190602_175927, GW190519_153544)

Uncertainties

KT18 has firstly showed the significance of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate to the PISN mass range.

KT 2018



↑
high
$^{12}C(\alpha,\gamma)^{16}O$
rate

low
$^{12}C(\alpha,\gamma)^{16}O$
rate
↓

↑
high
$^{12}C(\alpha,\gamma)^{16}O$
rate

low
$^{12}C(\alpha,\gamma)^{16}O$
rate
↓

Low $^{12}C(\alpha,\gamma)^{16}O$ reaction rate results in **high C/O ratio**.

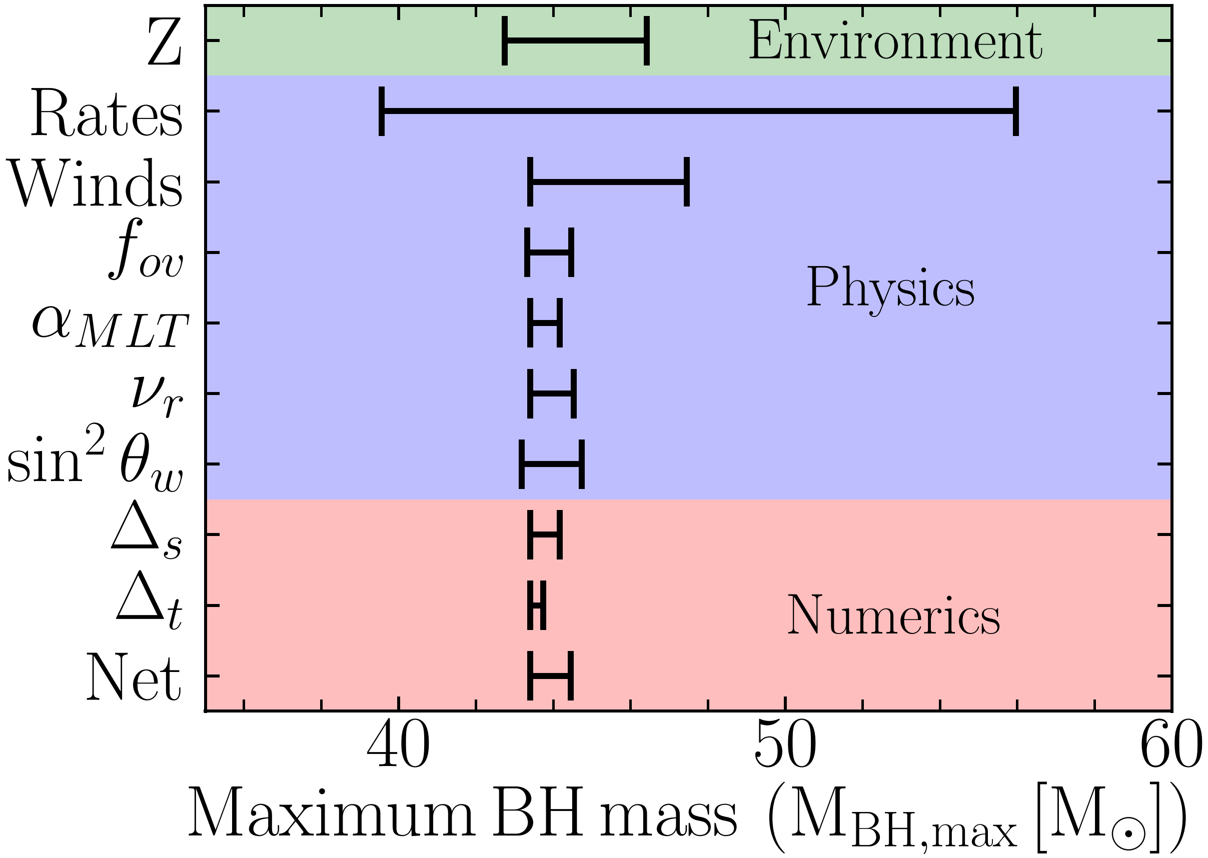
high C/O ratio results in **high PISN mass range**.

…more effective C burning stabilizes the core.

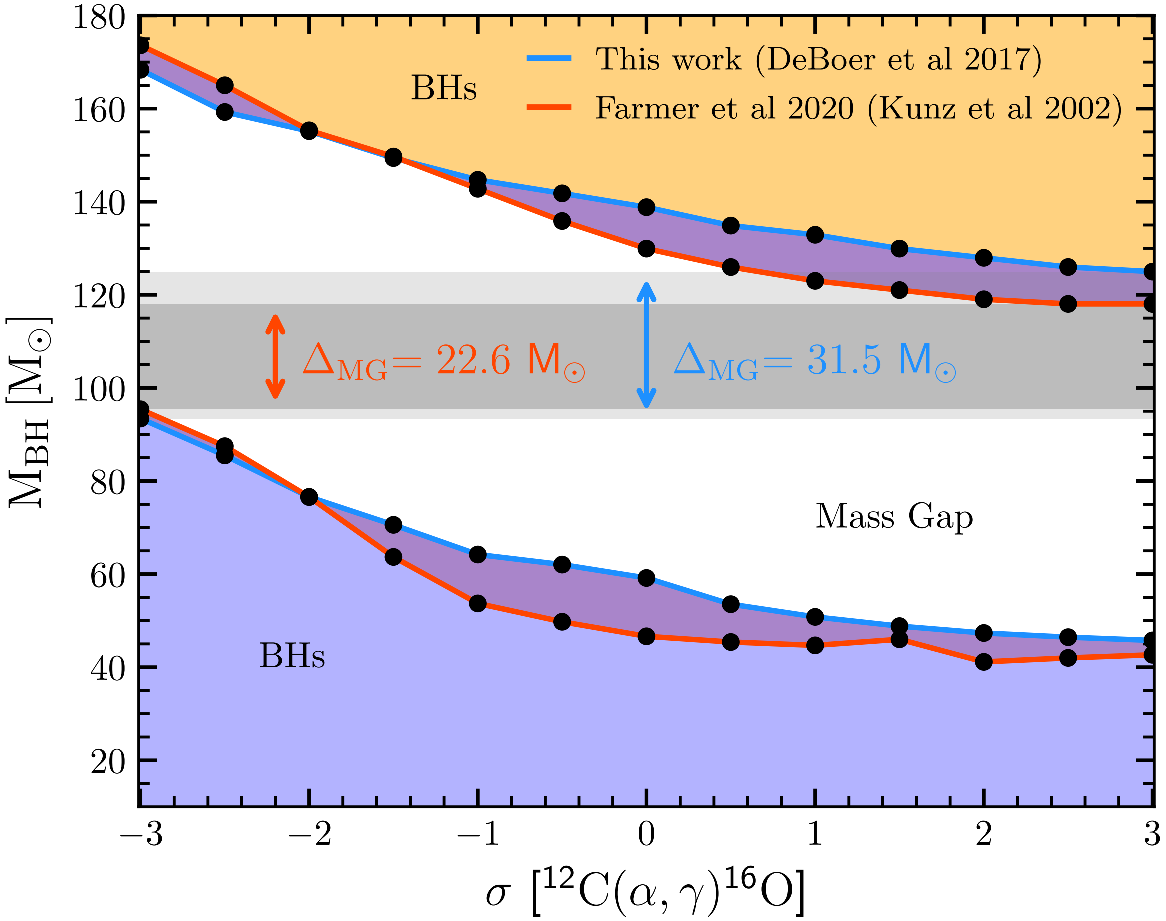
Uncertainties

The biggest uncertainty for the PISN mass gap seems to be the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.

Farmer+19



Mehta+21



(see also Woosley & Heger 2021)

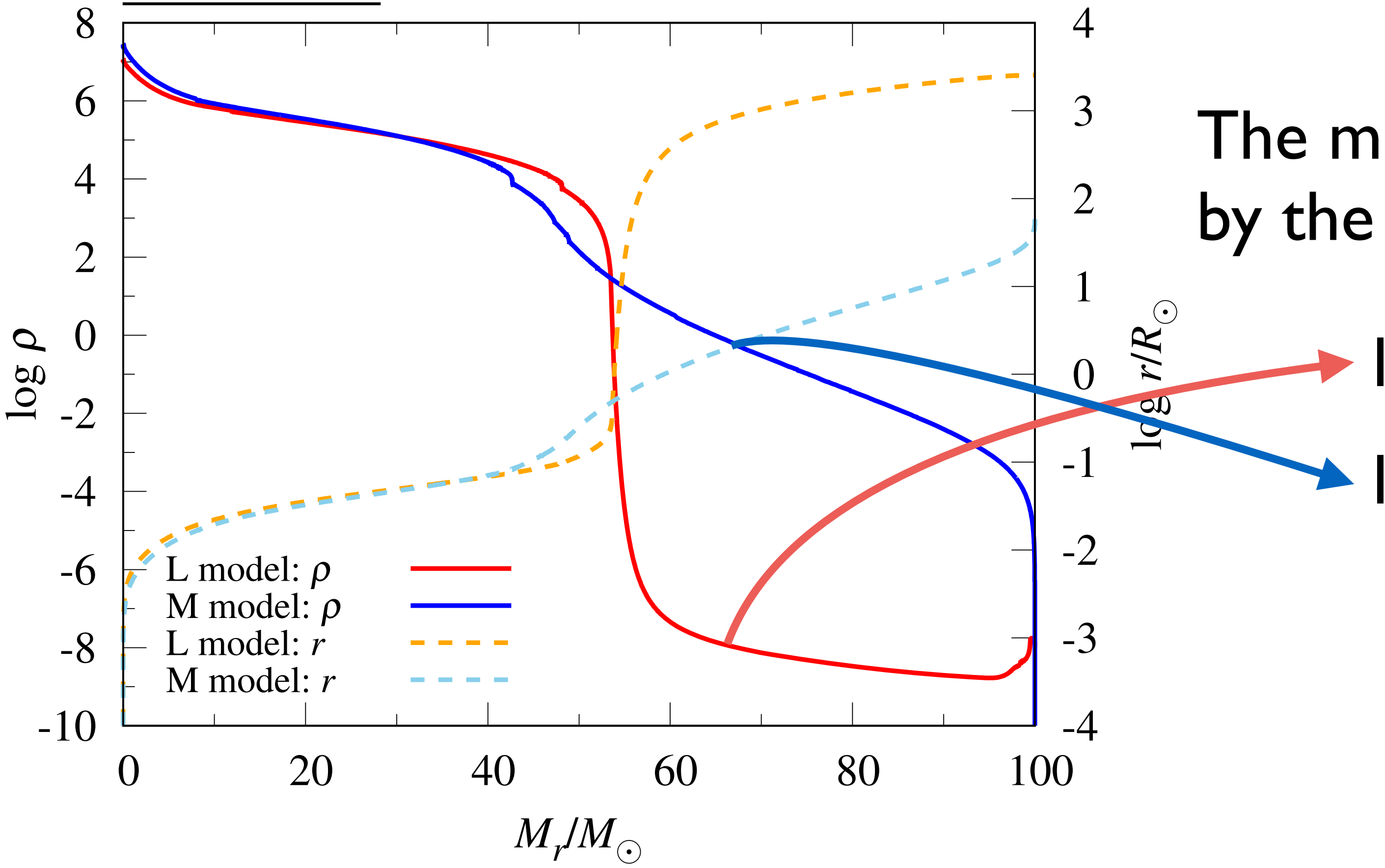
BHs of ~**40-80 $M_\odot$** can be formed within the uncertainty of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.
→shifting the PISN gap.

Uncertainties

Other possibilities

- rotation (Marchant & Moriya 2020)
- super-Eddington accretion (van Son et al. 2020)
- compact envelope PPISN (Umeda et al. 2020)

→filling the PISN gap.



Umeda+20

The momentum of the explosion is dumped by the dense envelope (Kasen+11, KT+18).

leave **52.2 M$_\odot$ BH** (as usual).

leave **91.7 M$_\odot$ BH** (in the PISN gap).

Conclusions

PISN is one of the most **robust** prediction in stellar physics.

The explosion mechanism is well understood.
-no dimensionality
-definite instability
-simple energy source

We are awaiting for the confident observational confirmation.

Direct observation: not yet. PISN in the local universe is rare?

Nucleosynthetic remnant: not yet. require more EMP stars?

PISN mass gap: most promising? But be cautious for uncertainties.

End