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Stellar feedback

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Les Houches Winter School on Star Formation, Feb 2024

What is stellar feedback?

- **Stellar feedback = injection of** ***matter***, ***momentum*** and ***energy*** by stars into the circumstellar medium

- **Stellar feedback processes:**
  - Photons & ionising radiation
  - Winds
  - Accretion, jets & outbursts (proto-/pre-MS stars)
  - Supernovae
  - Cosmic rays
  - Binary stars
  - X-ray binaries
  - Runaway stars
  - …

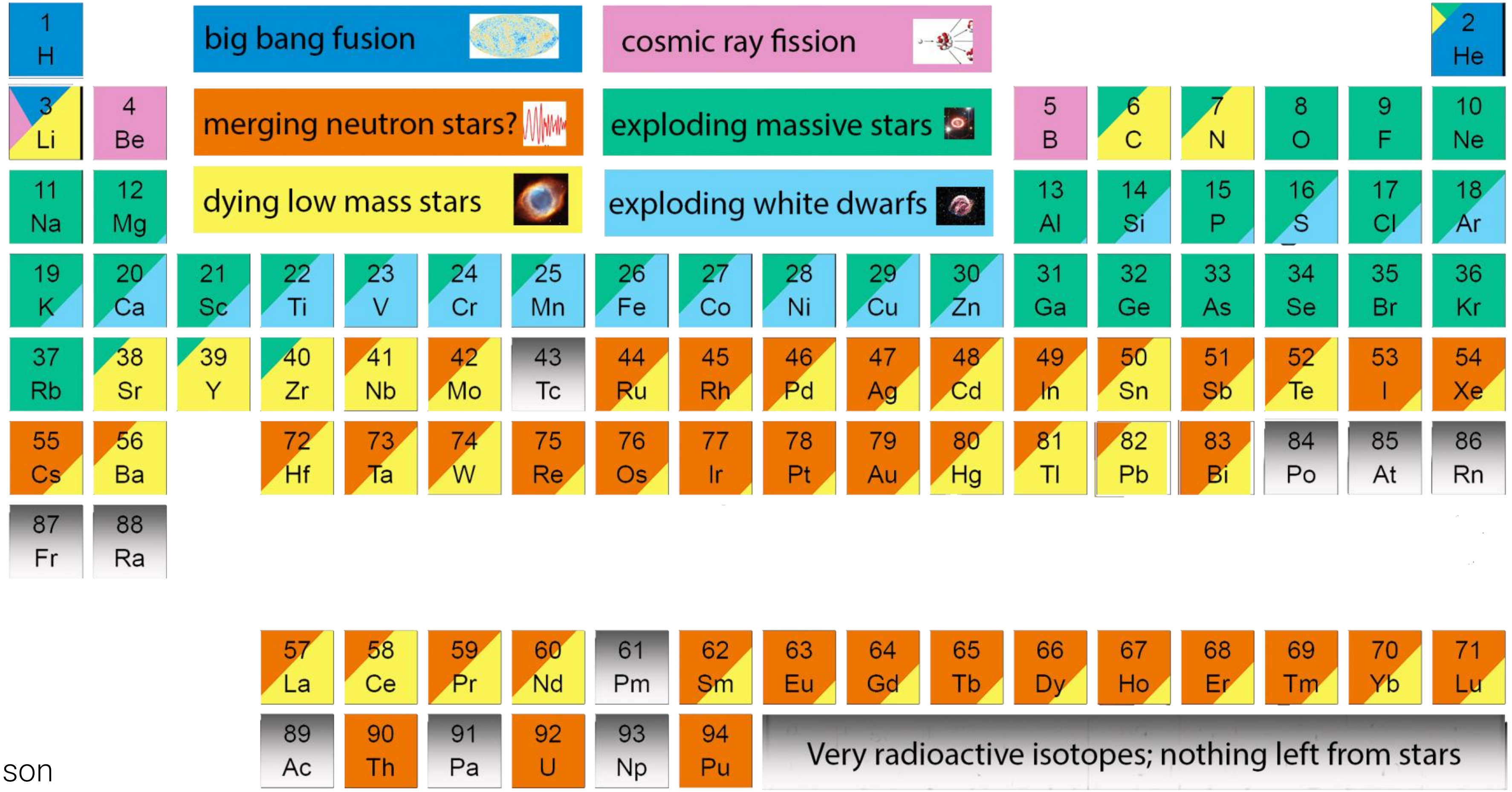
Suggested literature

- Hartquist, Dyson, Ruffle 2004, *Blowing Bubbles In The Cosmos: Astronomical Winds, Jets, and Explosions* (book)
- Krumholz et al. 2014, *Star Cluster Formation and Feedback* (review; Protostars and Planets VI)
- Dale 2015, *The modelling of feedback in star formation simulations* (review)
- Zhang 2018, *A Review of the Theory of Galactic Winds Driven by Stellar Feedback* (review)
- Hodges-Kluck et al. 2019, *Astro2020 Science White Paper: Hot Drivers of Stellar Feedback from 10 to 10,000 pc*
- Geen et al. 2023, *Bringing Stellar Evolution and Feedback Together: Summary from a Lorentz Center Workshop*

Why does stellar feedback matter?

Stellar feedback…

- …enriches Universe with chemical elements



Credit: Jennifer Johnson

Why does stellar feedback matter?

Stellar feedback…

- …enriches Universe with chemical elements
- …helped to reionise Universe after dark ages

Why does stellar feedback matter?

Stellar feedback…

- …enriches Universe with chemical elements
- …helped to reionise Universe after dark ages
- …dictates appearance & evolution of galaxies
- …regulates star formation (inhibits & triggers SF)
  → (in-)efficiency of star formation
- …drives galactic winds and affects intergalactic medium (chemical enrichment, temperature, …)
- …sets life-cycle of giant molecular clouds
- …is necessary for forming realistic galaxies in simulations (e.g. properties at z=0)
  → also limits formation of dwarf galaxies
- …

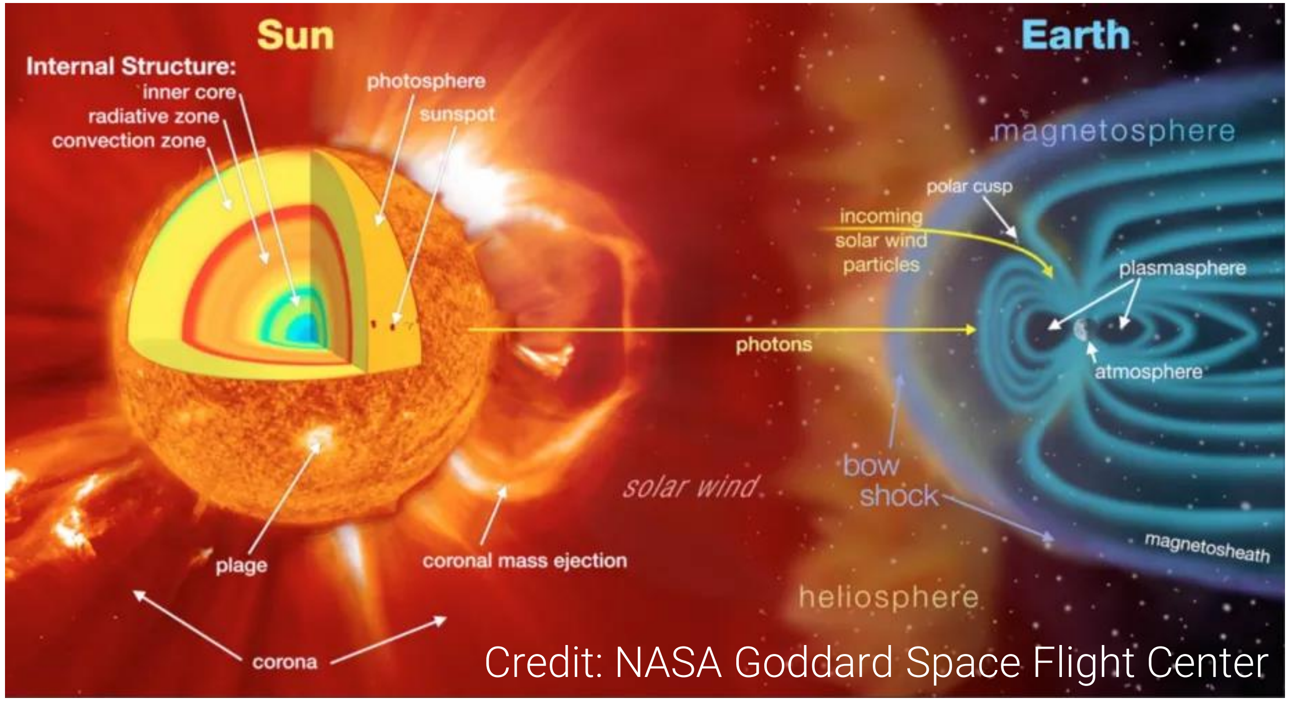
Credits: NASA/ESA

Credits: NASA/ESA/CSA/ Judy Schmidt

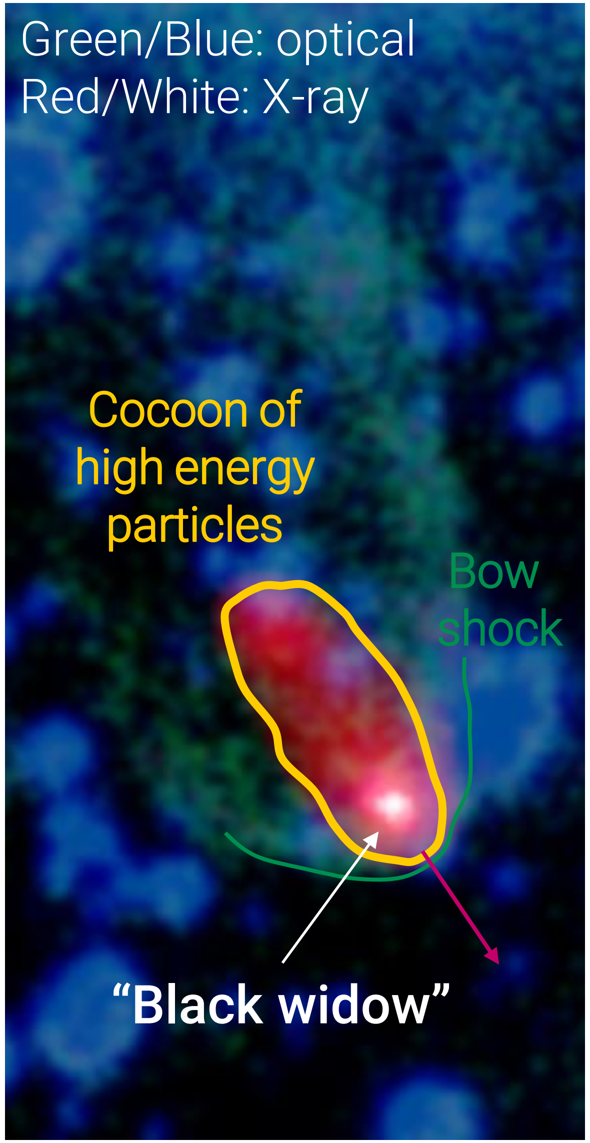
Credits: NASA/ESA/CSA/STScI

Disclaimer

- **Stellar feedback relevant on many scales**
  → depends on application
  → not all scales covered in lecture (e.g. planetary scale)
- **Stellar feedback intrinsically linked to environment** – feedback from stars in vacuum does not do much…
  → effective stellar feedback



Credit: NASA Goddard Space Flight Center



Credit: NASA/Chandra; AAOJ

Radiation feedback

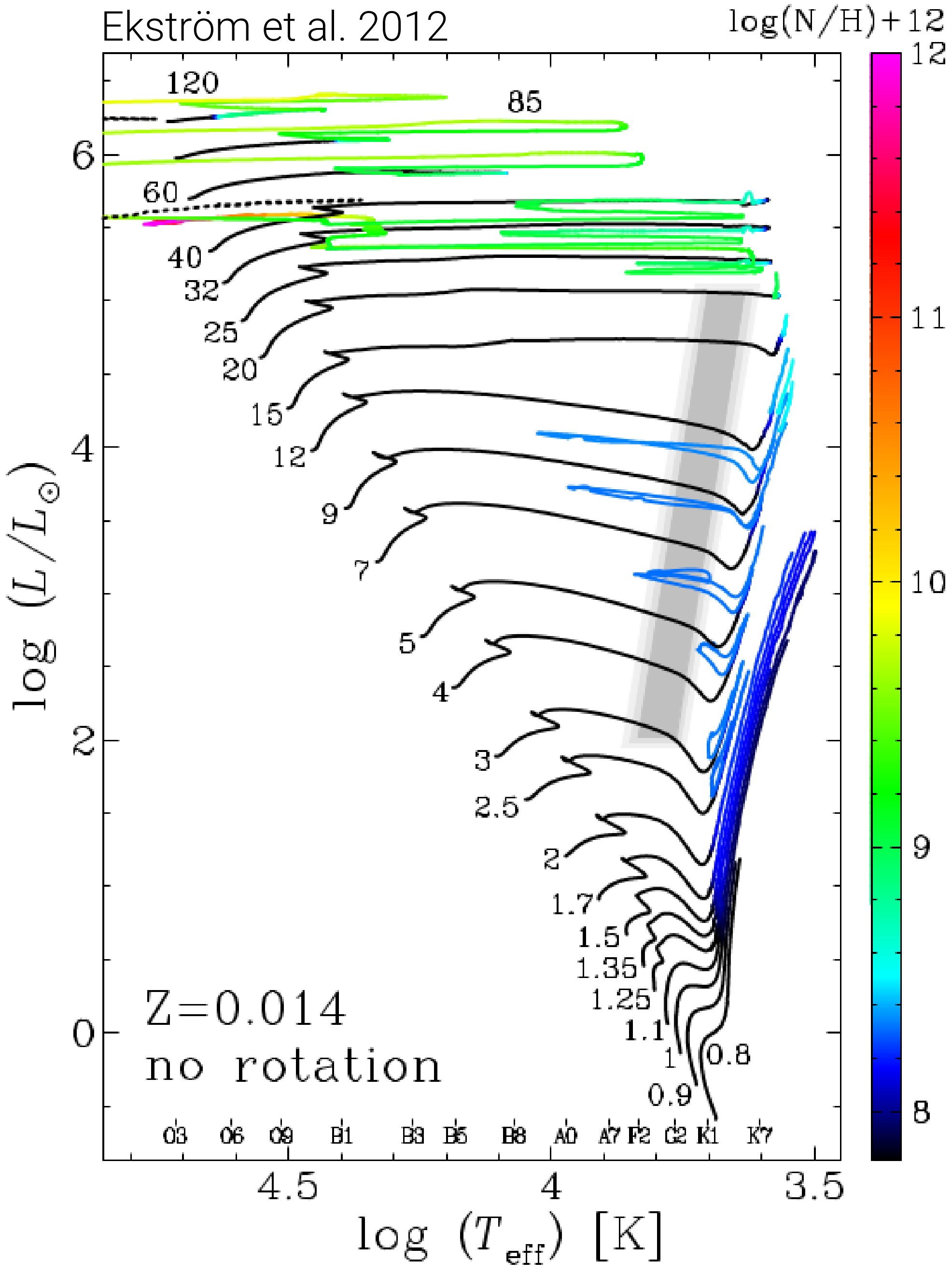
Credit: Stephan Hamel

Radiation feedback

- **Main effects**: **ionisation**, **heating** and **radiation pressure**
- Depends on **stellar source** and **environment**, i.e. its optical depth/ability to absorb photons

  Example: Radiation pressure/radiative momentum flux: → $\mathbf{P_{rad}(r) = f_{trap}\, L / 4\pi r^2 c}$
  (f_{trap}: encapsulates uncertain photon absorption, e.g. $f_{trap} = 1$ all photons absorbed once; complex radiative transfer problem)

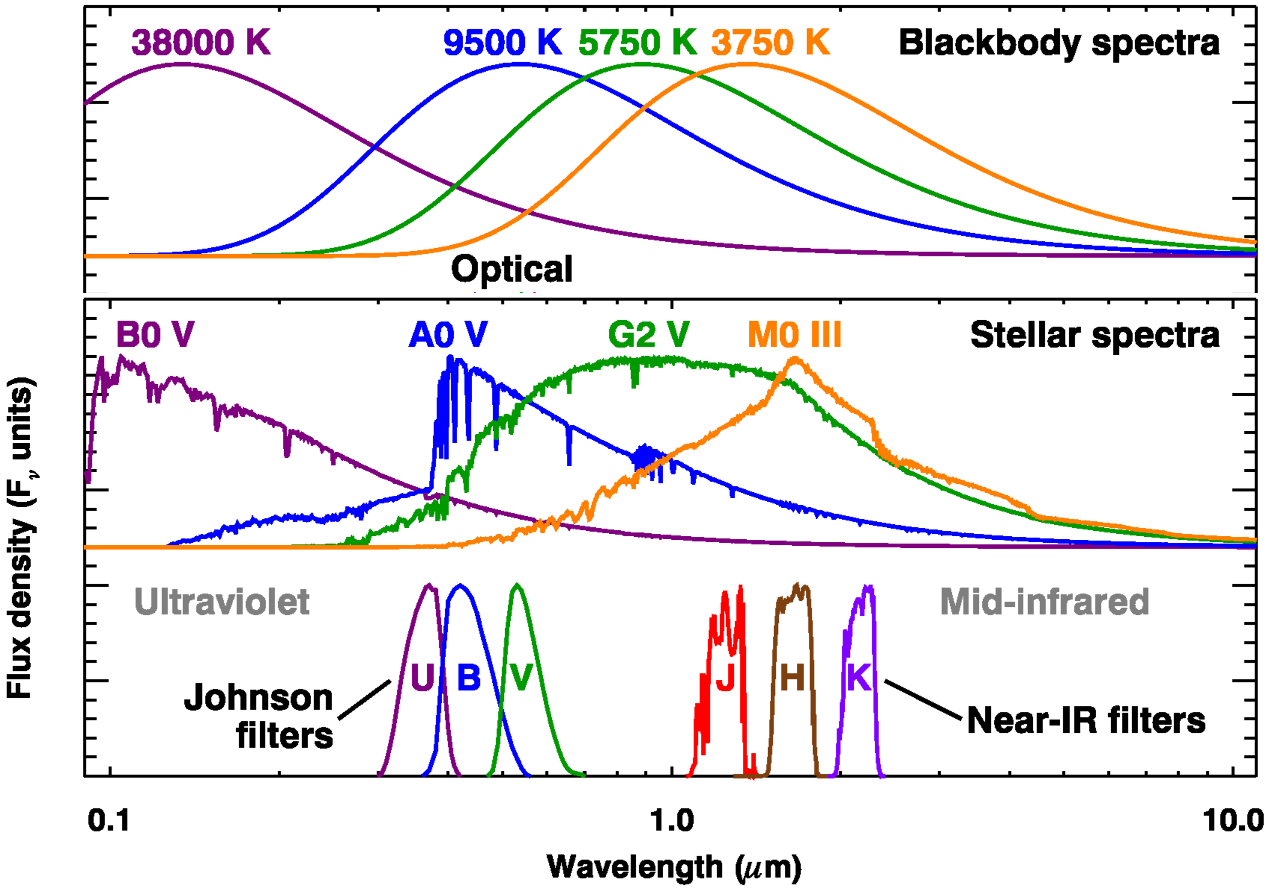
- Stellar sources: **steep mass-luminosity relation**
  - One very massive star can be worth millions of Suns in terms of radiative luminosity
  - Effective temperature/spectral energy distribution sets individual photon energies (e.g. UV vs IR)



Ekström et al. 2012

Spectral energy distribution of stars (→ T_{eff})

Credits: Gregory Sloan



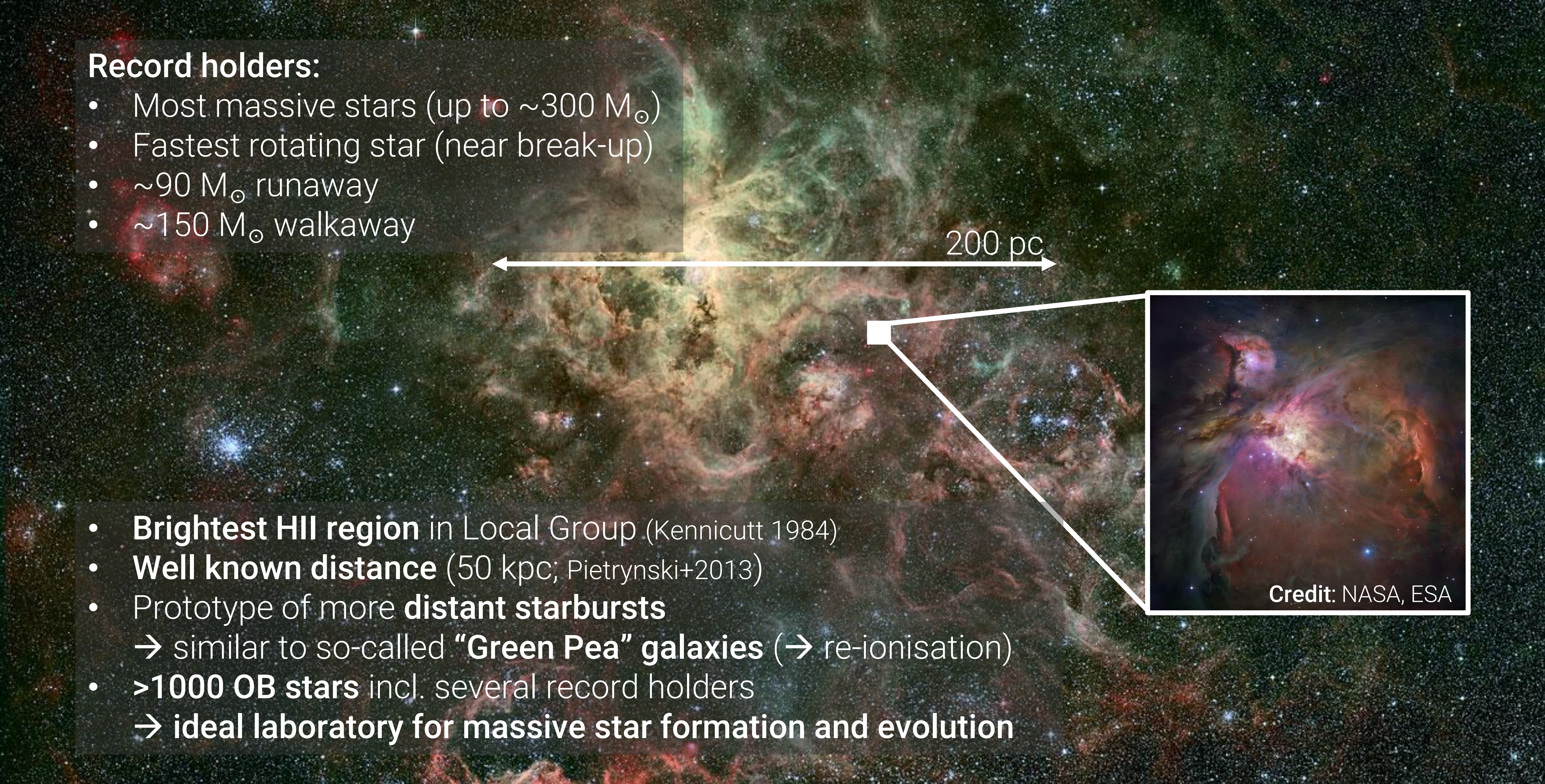
- Traditionally, treat stars as black bodies
  → T_{eff} sets spectral energy distribution
- **But**: photons interact with gas in atmosphere, modifying the SED (e.g. Balmer break, absorption/emission lines)
  → exact stellar ionising & heating radiation
- **Reminder**: T_{eff} of models such that *stellar flux $L/4\pi R^2$ = black body flux of σT_{eff}^4*
  - Eddington grey atmosphere (T-τ relation)
    → $T_{eff}^4 = 4/3\, T^4\, (\tau + 2/3)$ → get T
  - Atmosphere ***defined*** at $\tau = 2/3$ → $T_{eff} = T$
    → half of photons escape freely ($e^{-2/3} \sim 0.5$)

The 30 Doradus starburst

Record holders:

- Most massive stars (up to ~300 $M_\odot$)
- Fastest rotating star (near break-up)
- ~90 $M_\odot$ runaway
- ~150 $M_\odot$ walkaway

- **Brightest HII region** in Local Group (Kennicutt 1984)
- **Well known distance** (50 kpc; Pietrynski+2013)
- Prototype of more **distant starbursts**
  → similar to so-called **“Green Pea” galaxies** (→ re-ionisation)
- **>1000 OB stars** incl. several record holders
  → **ideal laboratory for massive star formation and evolution**

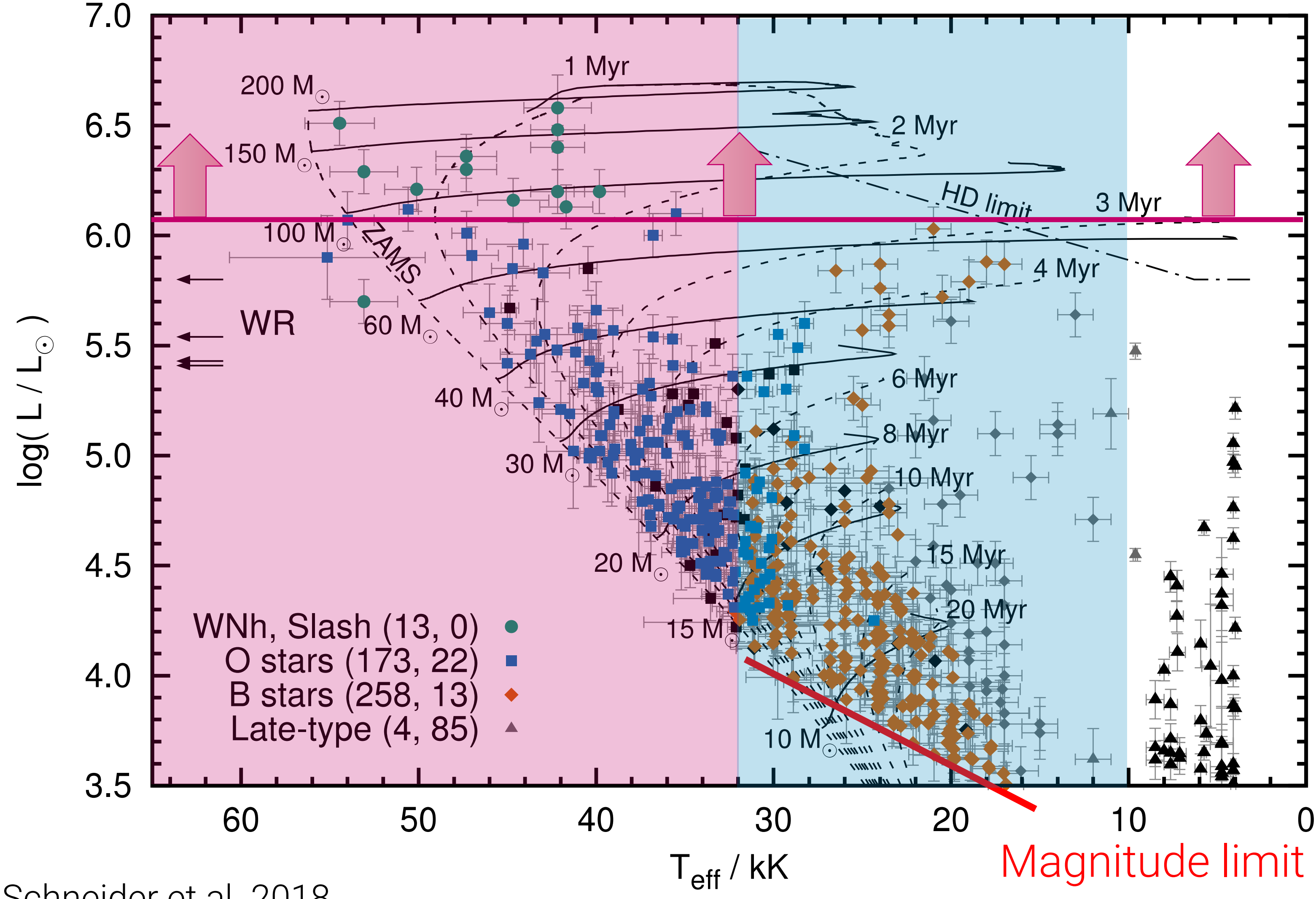


Credit: NASA, ESA

Credit: ESO/R. Fosbury (ST-ECF)

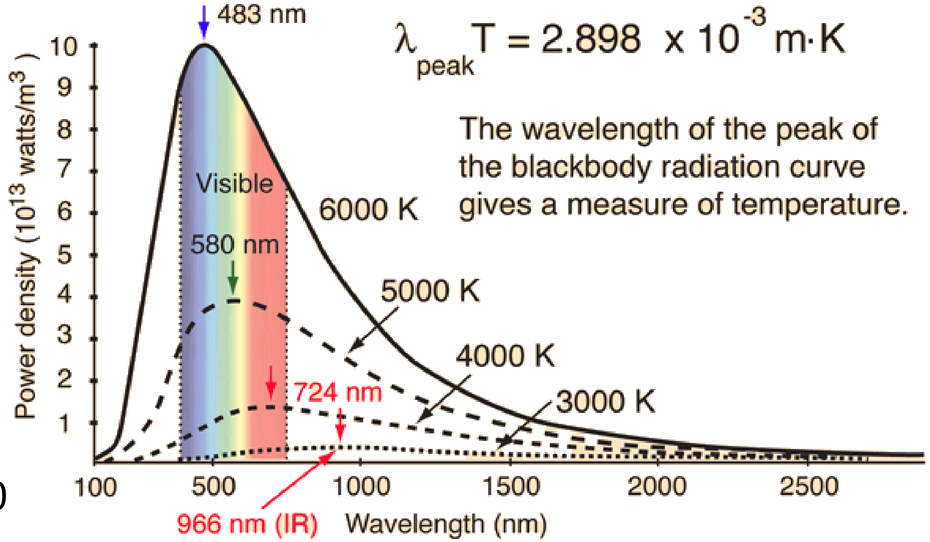
Massive stars in 30 Doradus

~25% of ionising radiation from stars with $M_{ini} > 100\ M_\odot$
(Doran+2013)

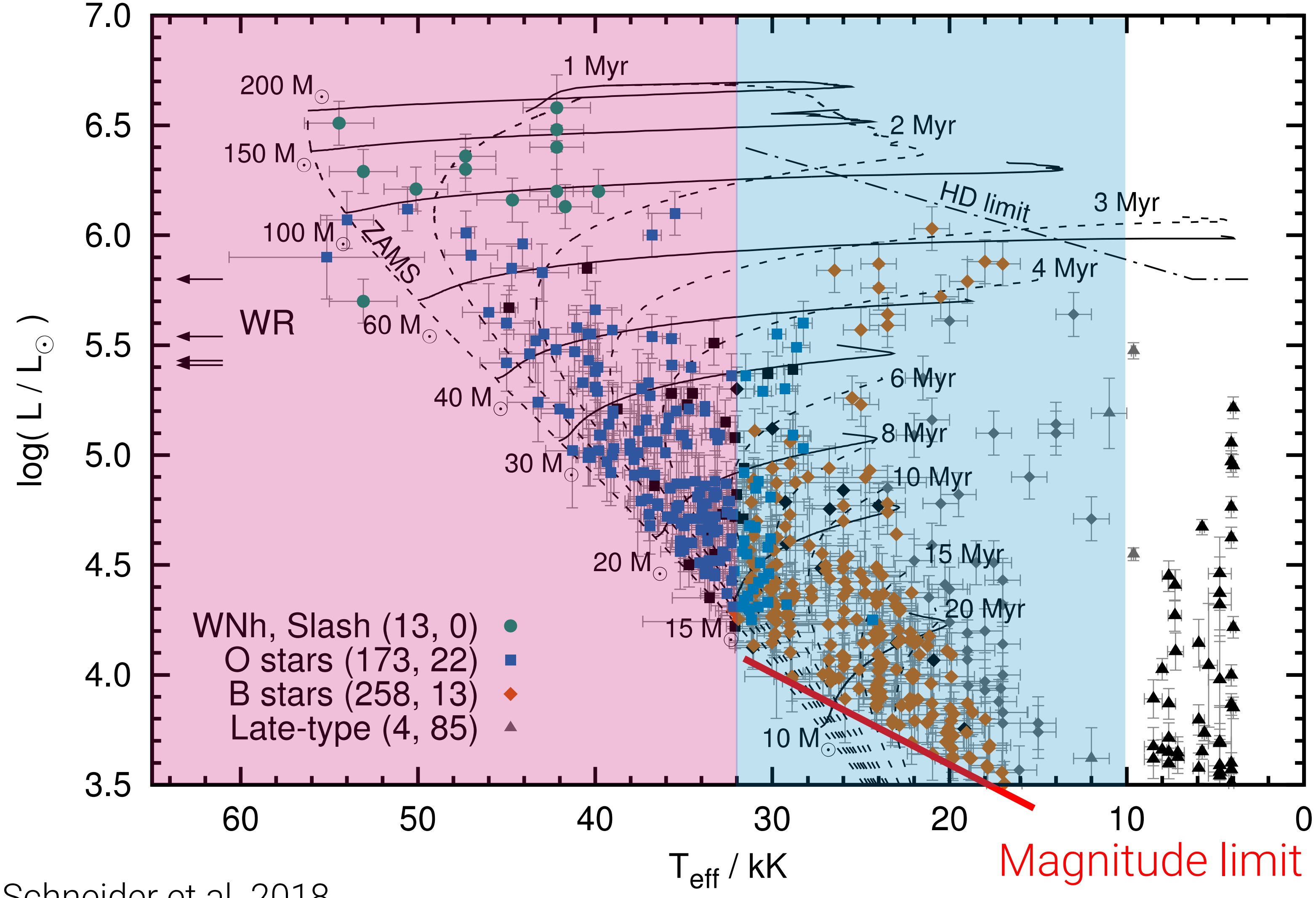


Schneider et al. 2018

- One very massive star can be worth millions of Suns in terms of luminosity
- **→ T_{BB} ~ 32,000 K * E_{ion}/13.6 eV**
- **Tail of BB**: still H-ionising photons for **32 kK < Teff < 10 kK**
  → HII regions from OB stars



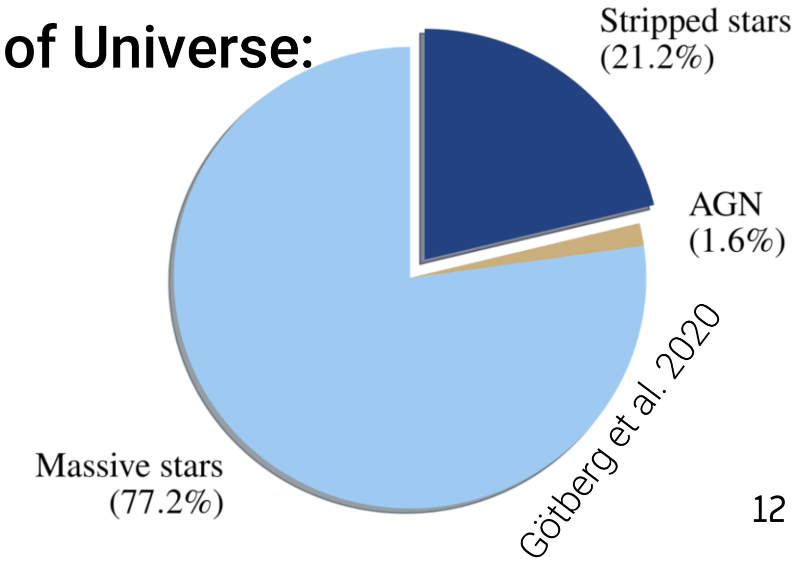
Massive stars in 30 Doradus



Schneider et al. 2018

- One very massive star can be worth millions of Suns in terms of luminosity
- → T_{BB} ~ 32,000 K * E_{ion}/13.6 eV
- **Tail of BB**: still many H-ionising photons for **32 kK < Teff < 10 kK**
  → **HII regions from OB stars**

H-reionisation of Universe:



Stellar winds

Credit: Hubble, NASA/ESA, Judy Schmid

Stellar winds

- **Stellar wind**: mechanism that accelerates stellar surface layers to beyond *escape velocity* and thereby drives a (spherically-symmetric) *outflow*
- **Example: photon-driven winds:**

$$a_{\rm rad} = \frac{1}{c}\int_0^\infty \kappa_\nu(r)\,F_\nu(r)\,{\rm d}\nu \equiv \kappa_F(r)\frac{L}{4\pi c r^2}$$

with the flux-weighted mean opacity κ_F(r)

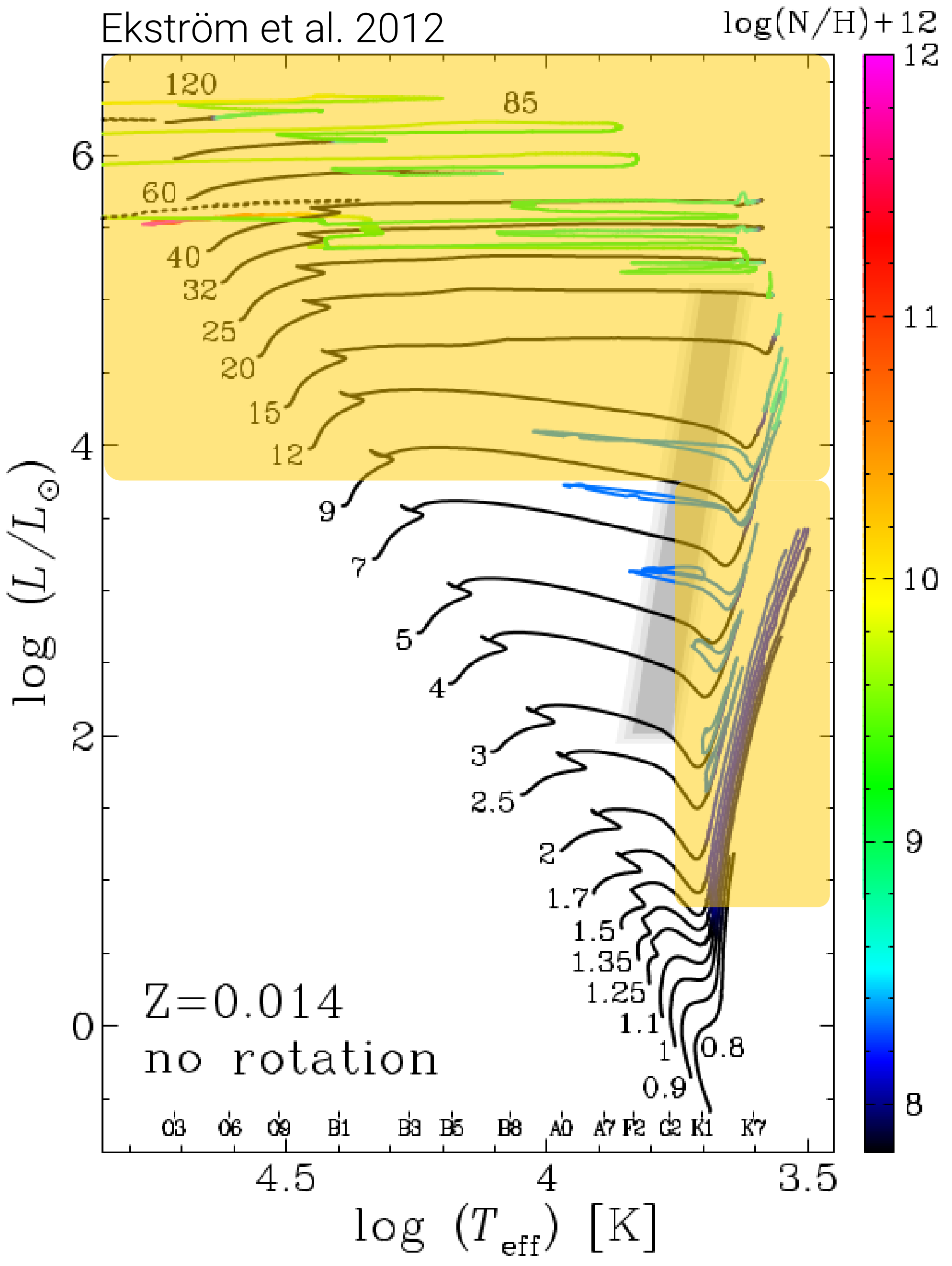
- W.r.t. grav. acceleration, obtain **Eddington factor**

$$\Gamma_{\rm rad}(r) = \frac{a_{\rm rad}(r)}{g(r)} = \kappa_F(r)\frac{L}{4\pi c G M} \propto \kappa_F \frac{L}{M}$$

- $\Gamma_{\rm rad}$ = 1 & electron scattering, $\kappa_{\rm es}$ = 0.2 (1+X) cm^2 g^{-1},

$$L_{\rm edd} = \frac{4\pi c G M}{\kappa_{\rm es}} \approx 3\times10^4\left(\frac{M}{{\rm M}_\odot}\right){\rm L}_\odot$$

Eddington luminosity



Ekström et al. 2012

Stellar winds

Line driving

- **Massive-star winds are line-driven**
  → ζ Pup (O supergiant, T_{eff} ~ 42 kK)
- **Wind launching** (i.e. wind mass loss rate)
  → iron (Fe) most relevant
- **Terminal wind velocity**
  → other atoms dominant (e.g. O, N, C)

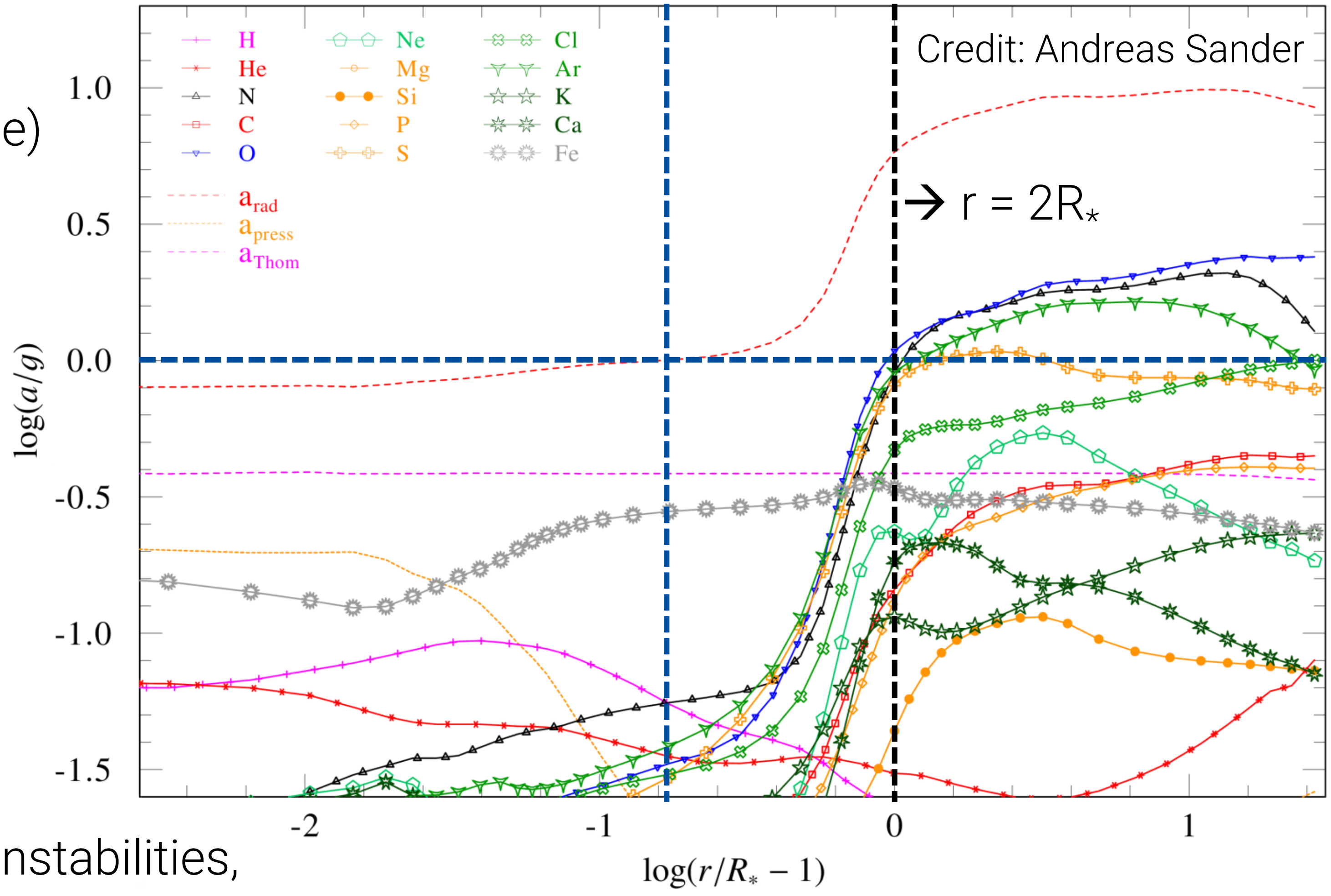
- **→ strong iron/metallicity dependence**

$$\dot{M} \propto Z^{0.5\ldots0.8}$$

- **Winds in low-Z environments/ early Universe much weaker**
  → less wind feedback
- Other driving mechanisms: pulsations, instabilities, photon driving on molecules & dust, …

Critical point:
→ wind launching

← Stellar surface



Credit: Andreas Sander

→ r = 2R*

Stellar winds

Hot star wind:
→ Vink+ 2000
→ Björklund+ 2021

Wolf-Rayet star wind:
→ Nugis & Lamers
→ Sander & Vink 2020

Feedback by stellar winds

- Integrated wind momentum

$$p_{\rm wind} = \int_0^\tau \dot{M}(t) v_\infty(t)\,{\rm d}t$$

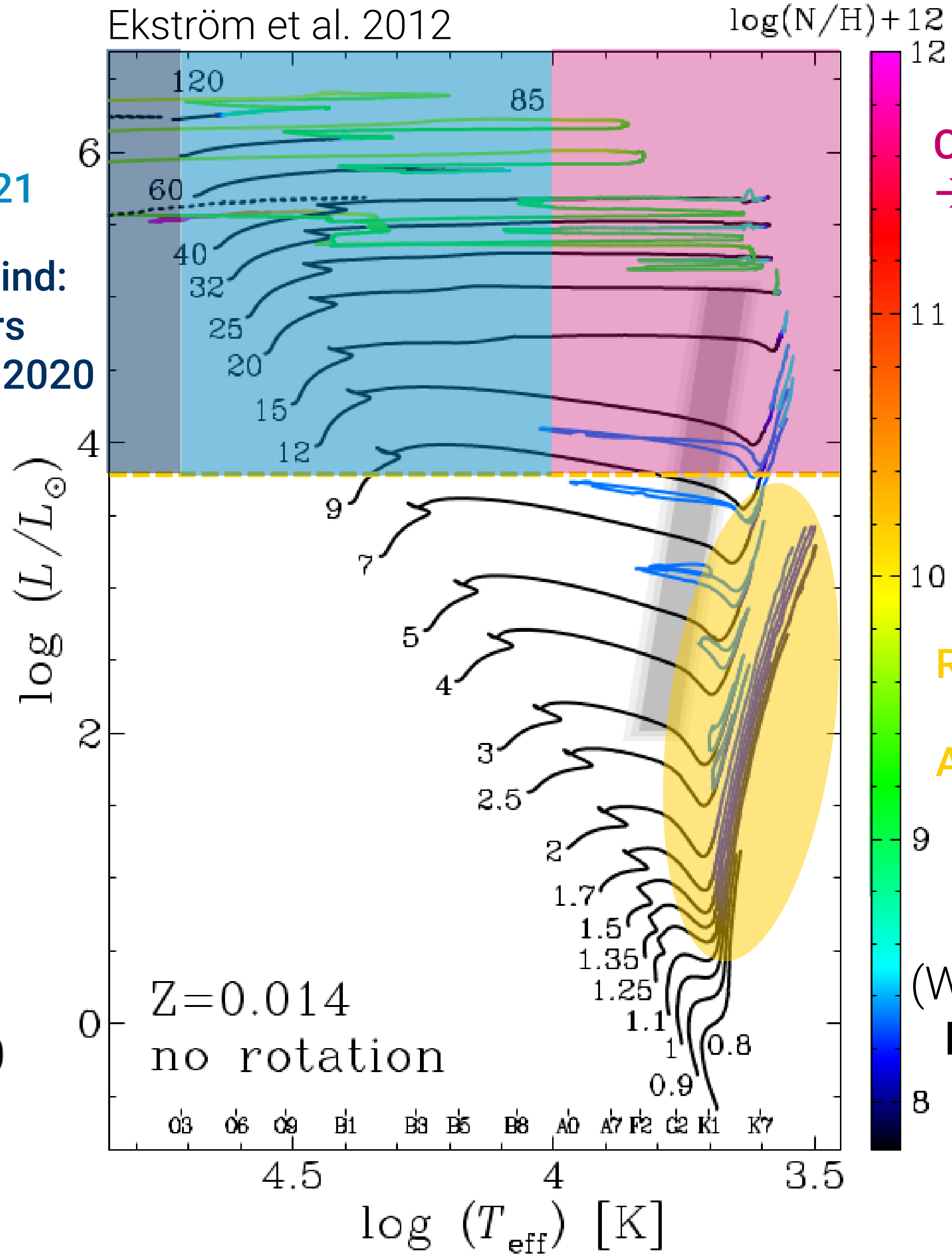
- Integrated wind energy

$$E_{\rm wind} = \int_0^\tau \frac{1}{2}\dot{M}(t) v_\infty^2(t)\,{\rm d}t$$

- Needs: wind velocity & mass loss rates

$$v_\infty = \underbrace{\sqrt{\frac{2GM}{R}}}_{=v_{\rm esc}} \begin{cases} 0.7 & T_{\rm eff} < 12.5\,{\rm kK} \\ 1.3 & 12.5 \le T_{\rm eff}/{\rm kK} < 21.0 \\ 2.6 & T_{\rm eff} \ge 21\,{\rm kK} \end{cases}$$

(Lamers et al. 1995)



Cool star wind:
→ Nieuwenhuijzen & de Jager 1990

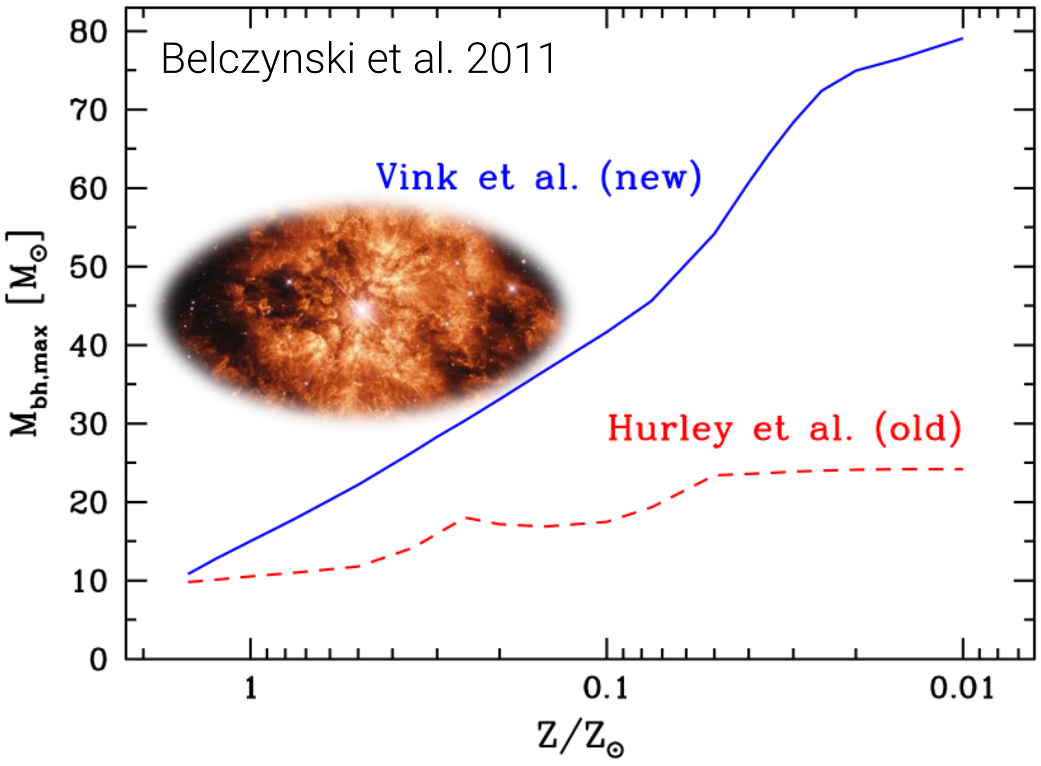
RGB:
→ Reimers 1975
AGB:
→ Bloecker 1995

(Wind scheme from **Henneco+ 2023**)

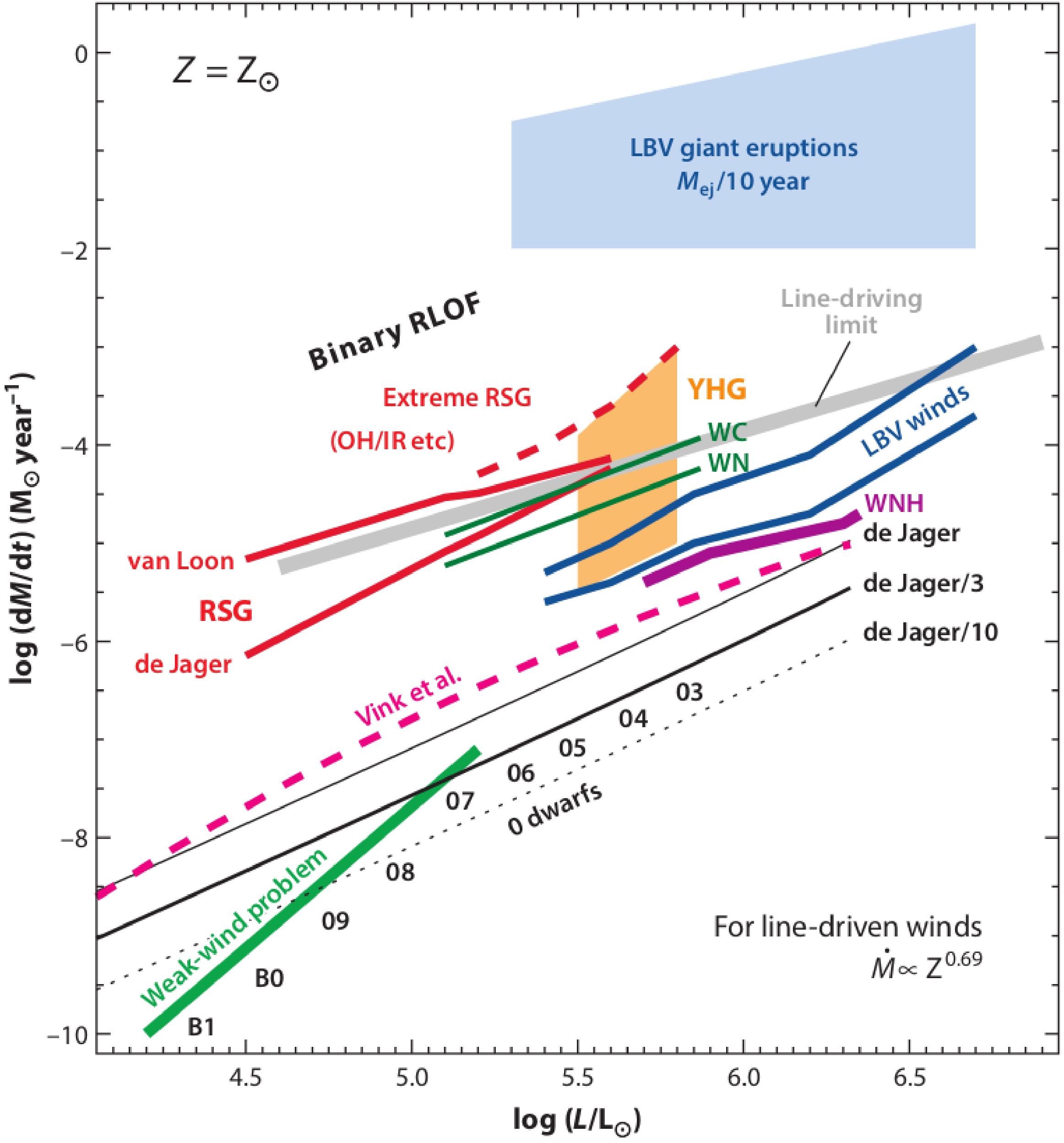
Stellar winds

Uncertainties

- **Wind mass loss rates are uncertain**
  → easily by factors of ~2–3; up to factor 10
- **Weak wind problem**
- **Enhanced mass loss close to Eddington limit**



Smith 2014



Typical winds of massive stars

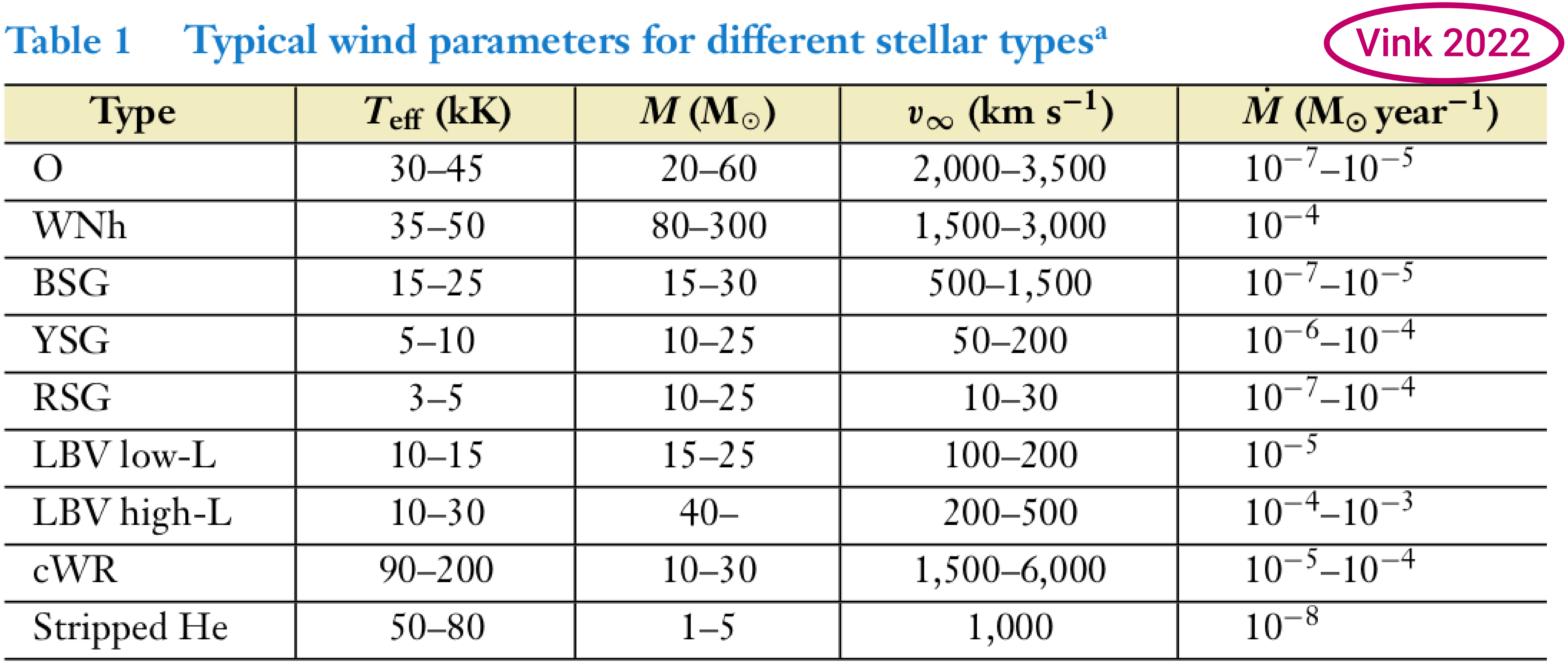


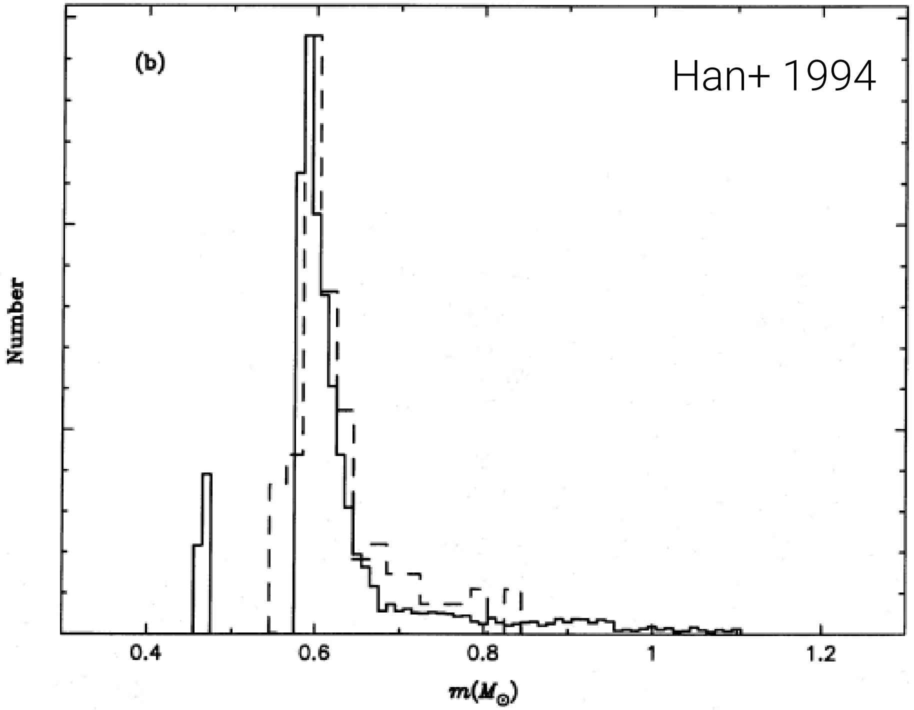
Table 1 Typical wind parameters for different stellar types[a]

Type	T_{eff} (kK)	M ($M_{\odot}$)	v_{∞} (km s^{-1})	$\dot{M}$ ($M_{\odot}$ year^{-1})
O	30–45	20–60	2,000–3,500	10^{-7}–10^{-5}
WNh	35–50	80–300	1,500–3,000	10^{-4}
BSG	15–25	15–30	500–1,500	10^{-7}–10^{-5}
YSG	5–10	10–25	50–200	10^{-6}–10^{-4}
RSG	3–5	10–25	10–30	10^{-7}–10^{-4}
LBV low-L	10–15	15–25	100–200	10^{-5}
LBV high-L	10–30	40–	200–500	10^{-4}–10^{-3}
cWR	90–200	10–30	1,500–6,000	10^{-5}–10^{-4}
Stripped He	50–80	1–5	1,000	10^{-8}

Vink 2022

Envelope instabilities, eruptions & outflows

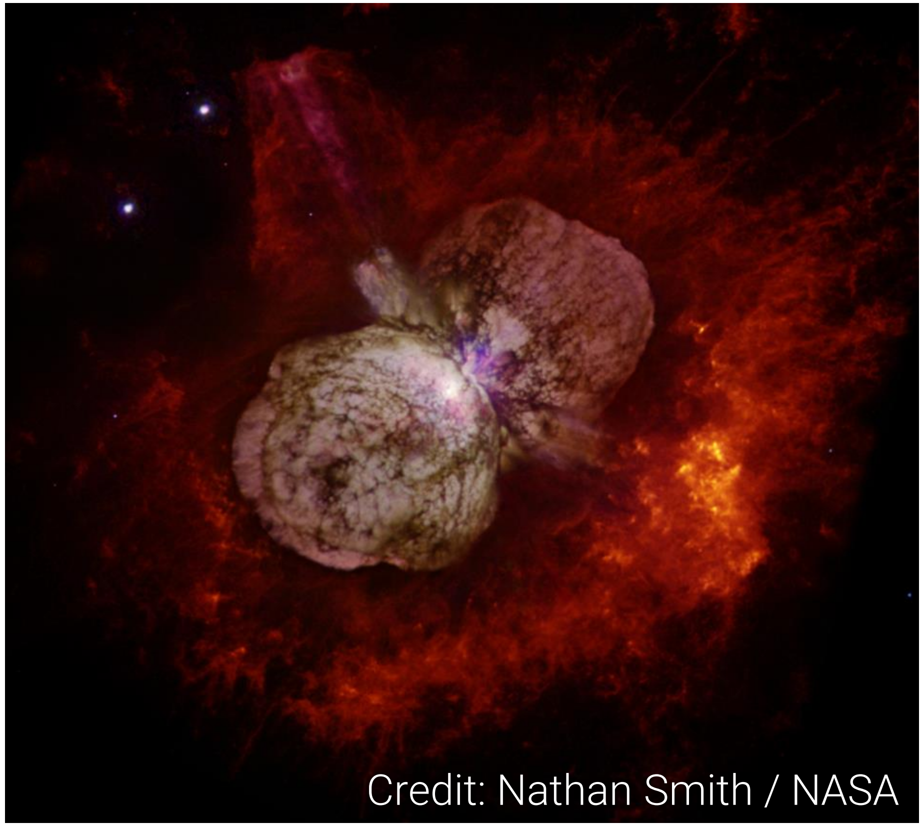
- **Why do most WDs have ~0.6 $M_\odot$?**



→Envelope instability once $E_{bind} > 0$

→Significant mass loss/feedback

- **Luminous blue variables** (e.g. S Dor stars)


Credit: Nathan Smith / NASA

- Envelope instability? Giant eruptions with up to near SN energies (~10^{50} erg)

Accretion, jets & outbursts

Credit: ESA/Webb, NASA, CSA, Tom Ray (Dublin)

Accretion

- **Trivial statement**: to form stars, need accretion
- **Maybe less obvious**: accretion releases energy, hence produces feedback:
  →mass ΔM accreting on star of mass M and radius R releases grav. potential energy $GM\Delta M/R$
  →For mass accretion rate $\dot{M}$, produce luminosity

$$L_{\mathrm{acc}} \approx \frac{GM\dot{M}}{R}$$

- Not all of released grav. potential energy radiated away (e.g. kinetic/rotational energy, magnetic fields, driving of outflows, …)

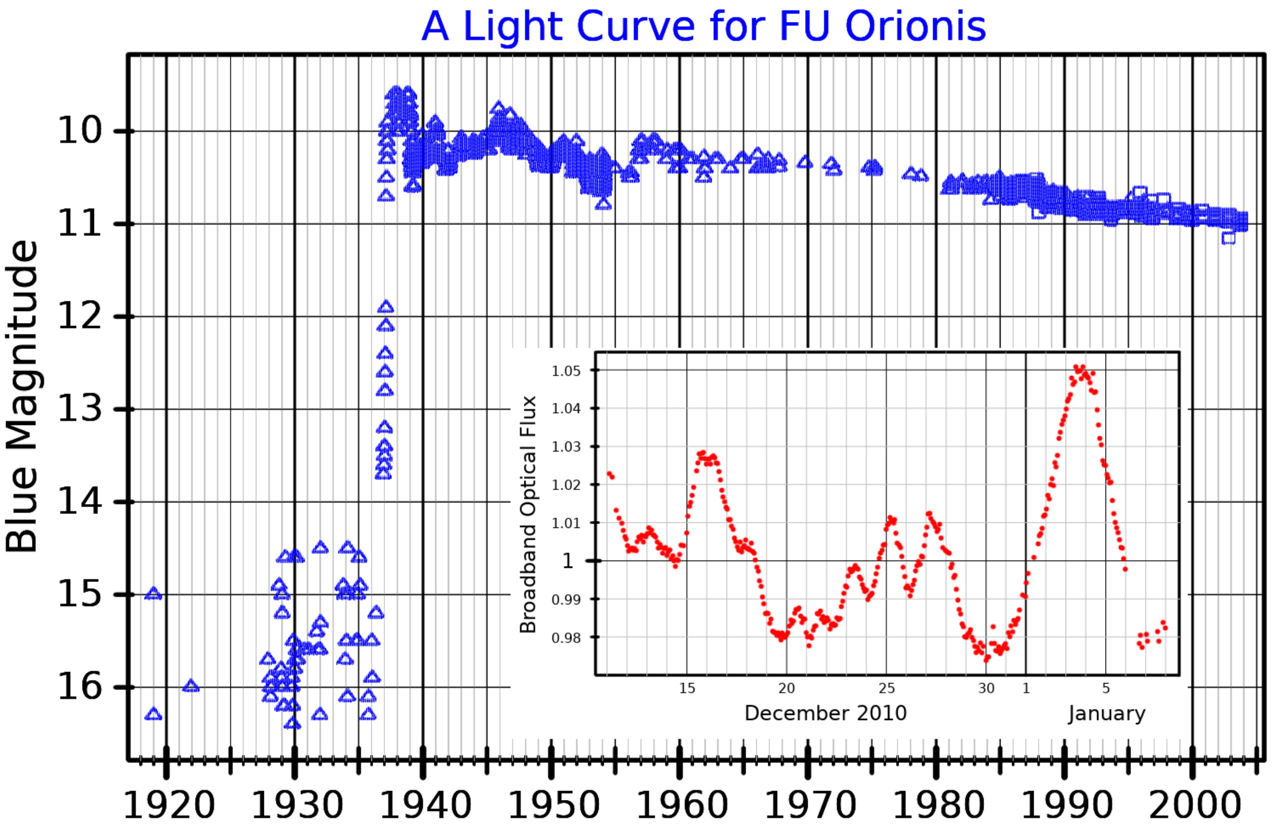
Comparison

- 1 $M_\odot$ star accreting at $10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$:
  → $L_{\mathrm{acc}} \sim 15\ L_\odot$
  → $L_{\mathrm{acc}} > L_*$
- >9 $M_\odot$ stars accreting at $<10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$:
  → $L_{\mathrm{acc}} < L_*$
- *Rule of thumb*: once there are OB stars, they dominate the radiative feedback

Episodic accretion and outbursts

- Accretion not steady but episodic & variable
- Occasionally, have **enhanced accretion rates**
  → **Outburst-like increase of L_{acc}**
  → Example: **FU Orionis-like outbursts**

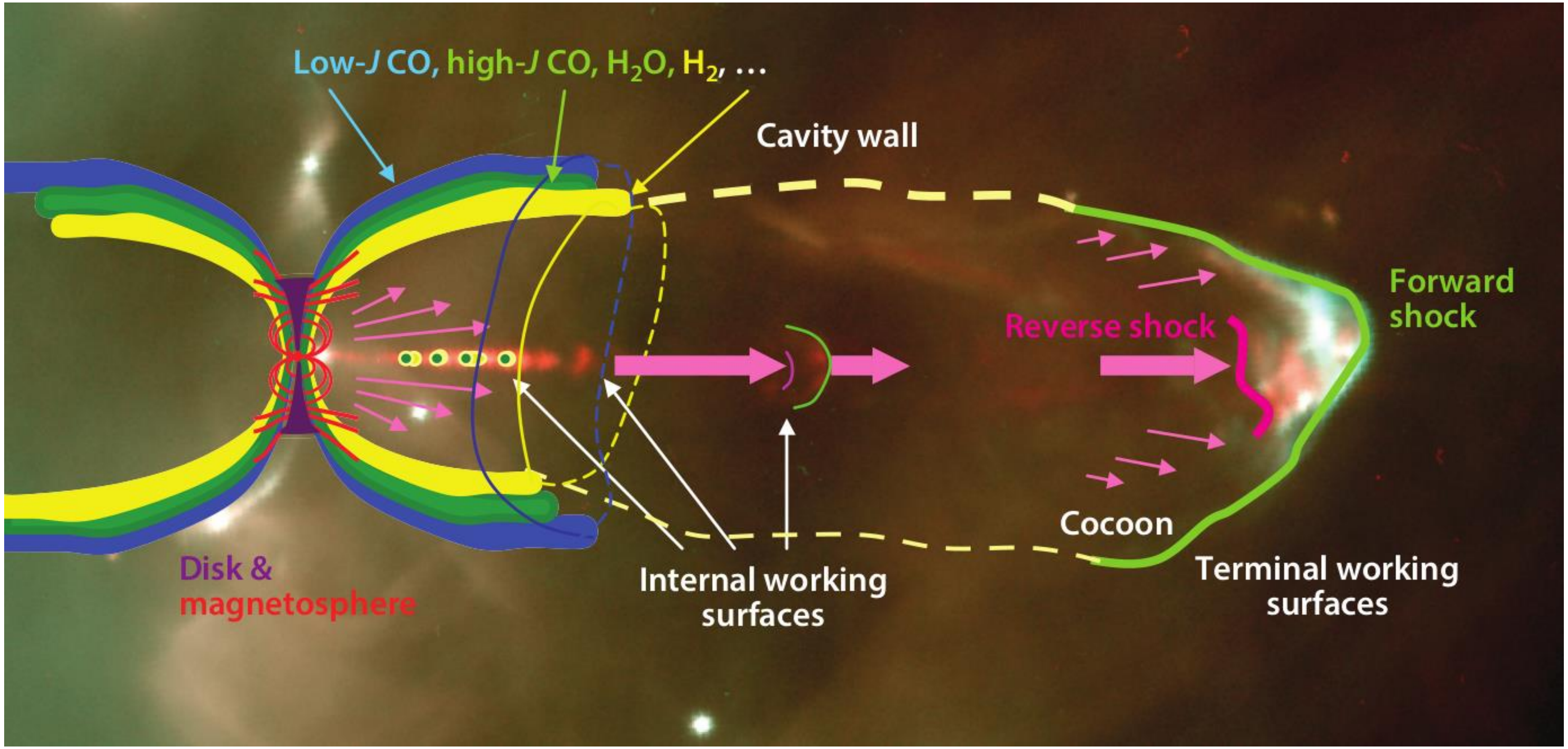
- What causes enhanced accretion? Unknown, there are several ideas (e.g. Audard+2014, Vorobyov+2021, Borchert+2022a,b):
  - MRI triggered by ionisation increase
  - Clump accretion by disk fragmentation
  - Close encounters with other stars
  - Planet-disk interaction
  - …



Long-term data from Clarke+2005 and short timescale variations from Siwak+2013 (inset).
Figure Credit: Wikipedia

Jets and bipolar outflows

- Review on protostellar outflows: **Bally 2016**
  → bipolar outflows/jets are magnetically-driven



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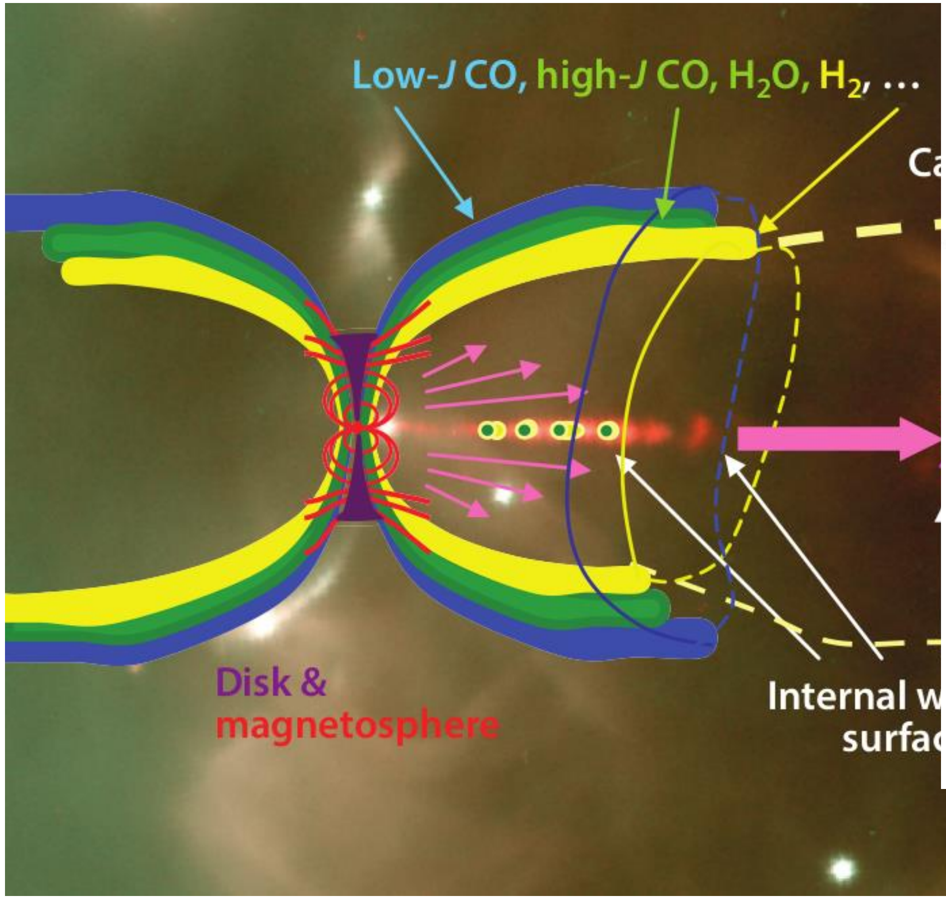
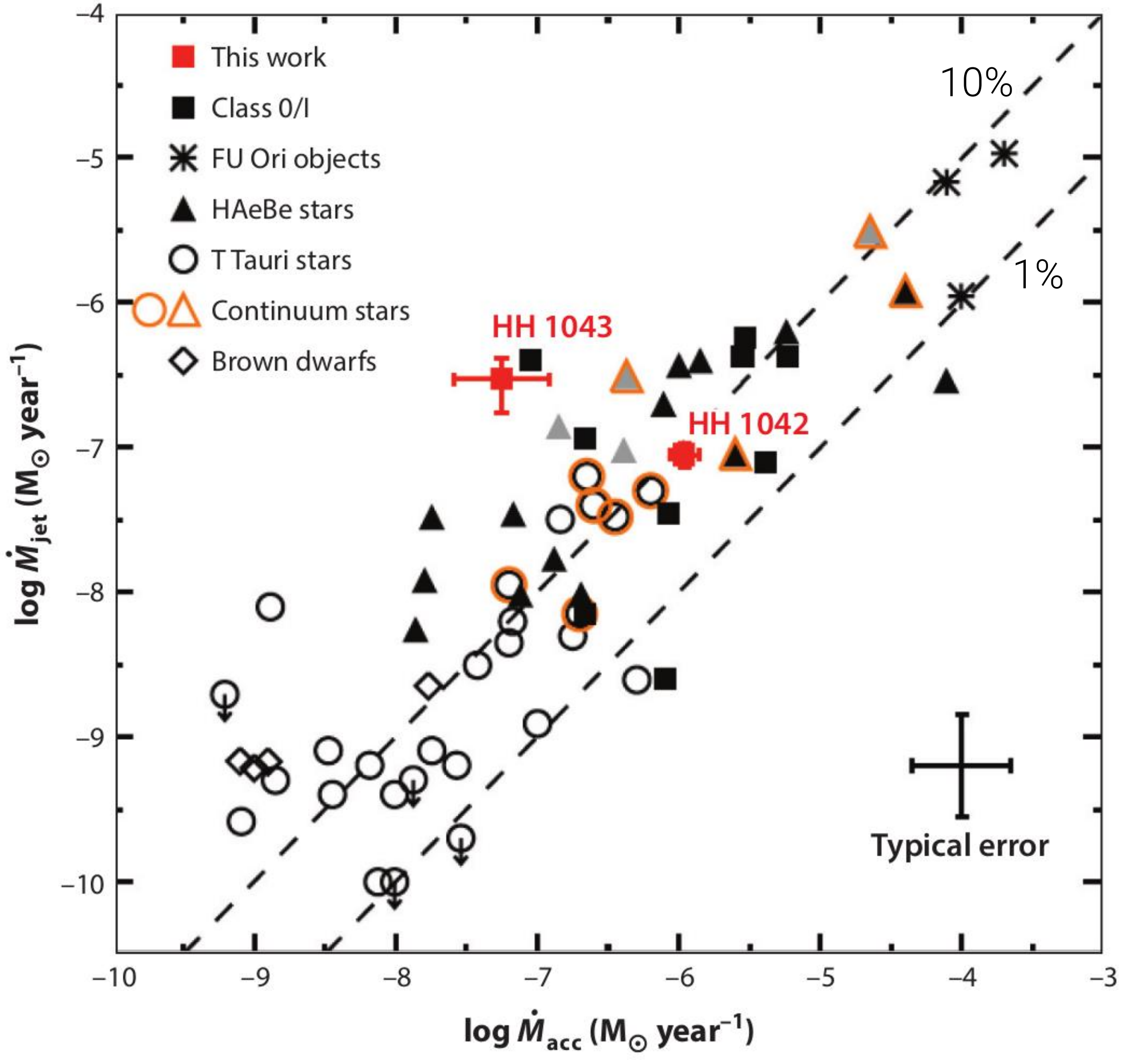




Jets and bipolar outflows

- Outflows: magneto-centrifugal (Blandford & Payne 1982) & magnetic pressure driven (Lynden-Bell 2003)

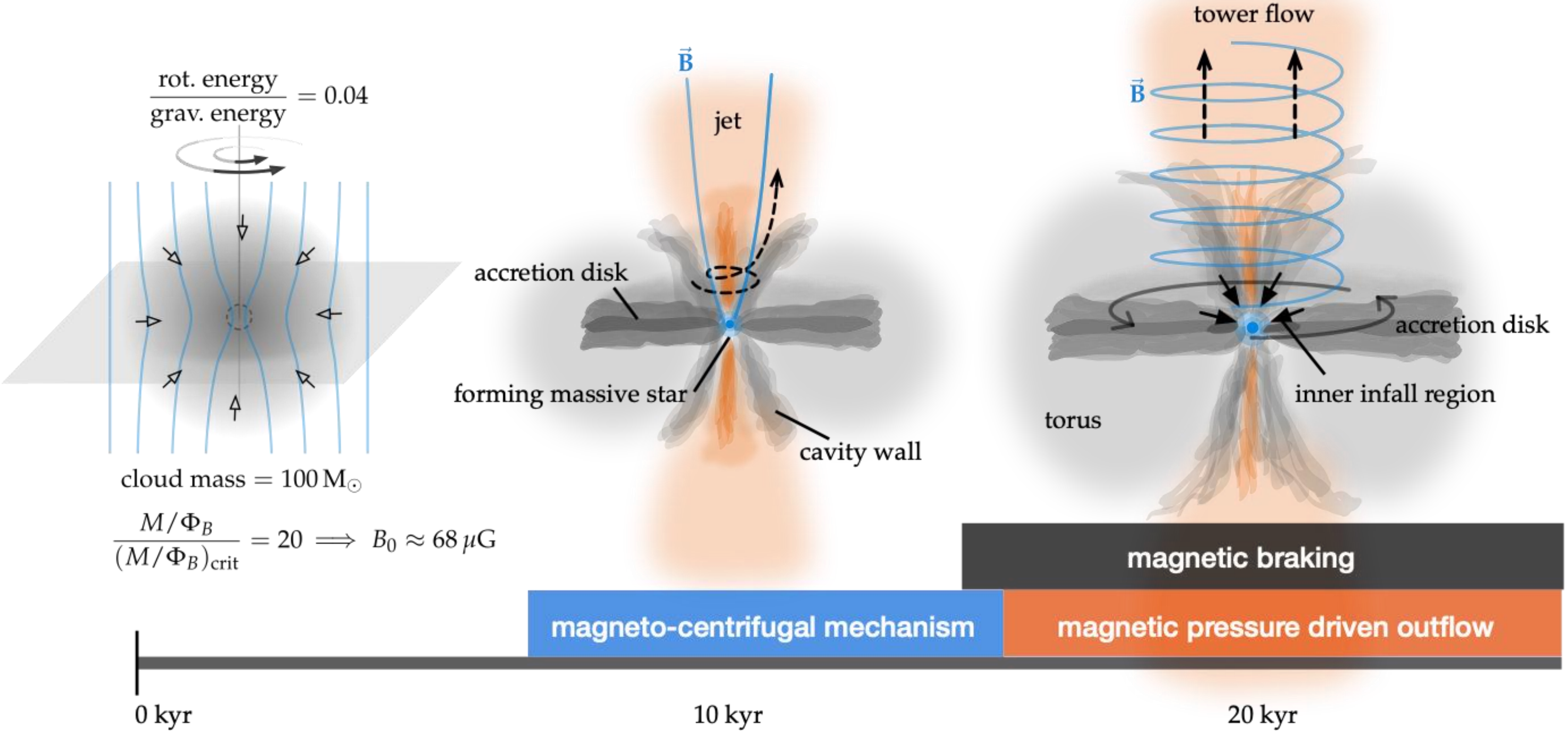
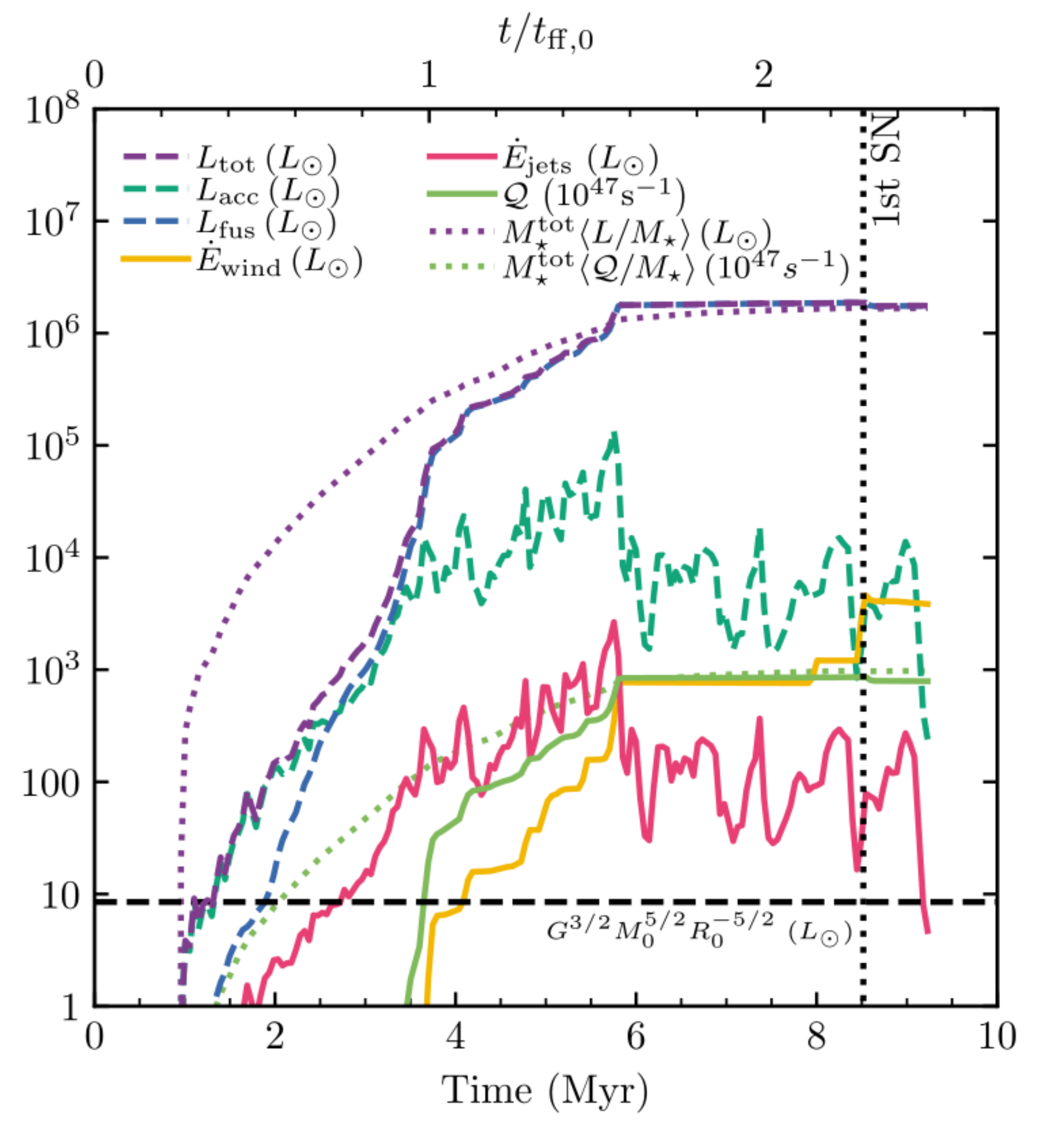


Figure credit: Gandre Oliva (https://www.gandreoliva.org/posters/jets2021)

Jets and bipolar outflows



Grudic+2022; initial cloud mass 2x10^4 $M_\odot$, radius 10 pc

- Exact launching mechanism of jets unclear (so-called X-winds also possible, see Shu+1994) → see reviews by Pudritz & Ray 2019 and Krumholz & Federrath 2019
- Effective modelling (as in Cunningham+2011): fraction f_m of accreted mass is ejected in bipolar outflow of velocity

$$v_{\mathrm{jet}} = f_{\mathrm{K}}\sqrt{\frac{GM}{R}}$$

into cone of angular size θ_0

$$\xi(\theta,\theta_0) = \left(\ln\left(\frac{2}{\theta_0}\right)\sin^2\theta + \theta_0^2\right)^{-1}$$

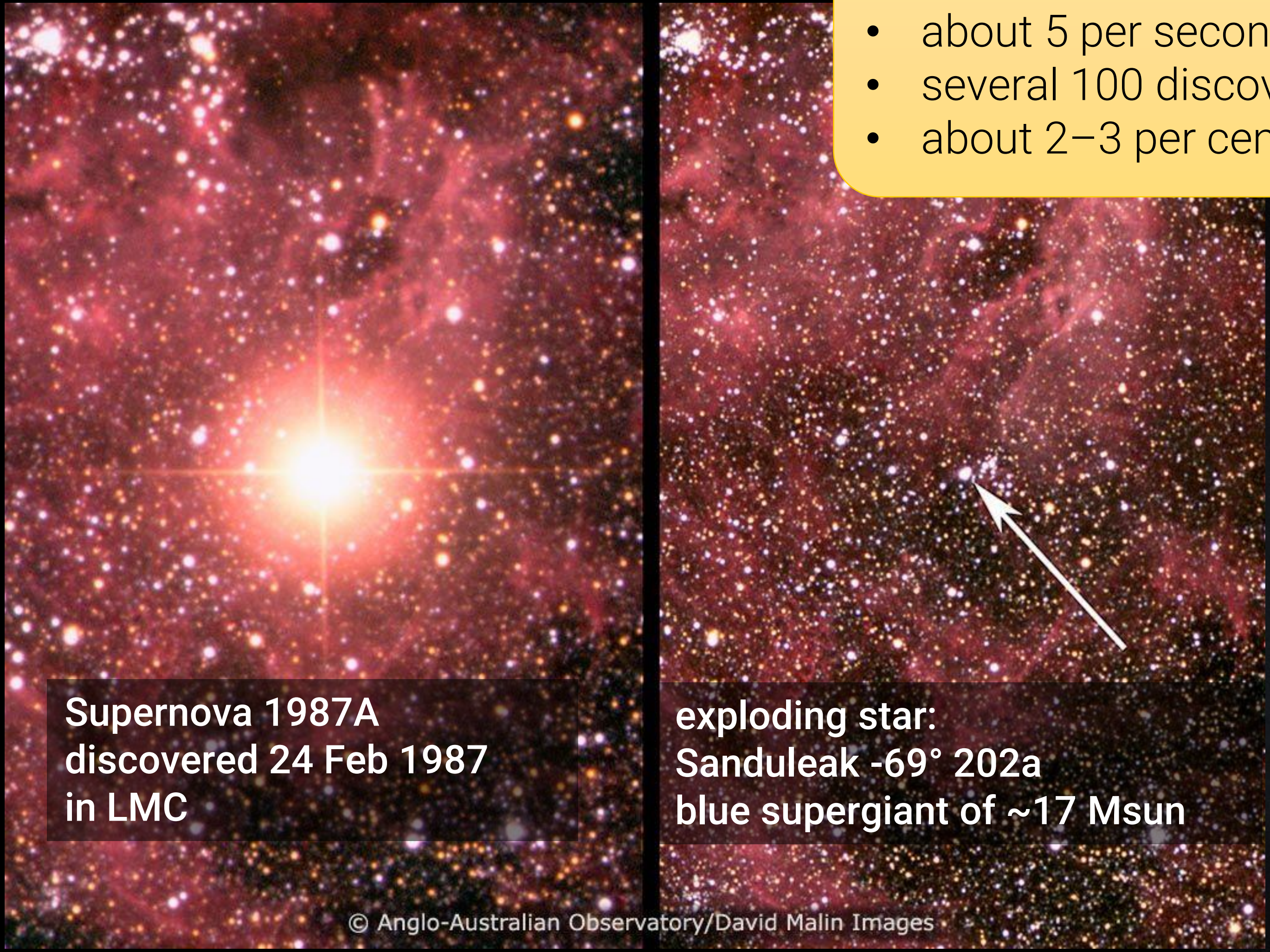
- Initially, jets dominate feedback momentum, but not energy (Grudic+2022)

Supernovae

Credit: X-ray: NASA/CXC/J.Hester (ASU); Optical: NASA/ESA/J.Hester & A.Loll;
Infrared: NASA/JPL-Caltech/R.Gehrz

Supernovae

Rates:
- about 5 per second in the Universe
- several 100 discovered per year
- about 2–3 per century in Milky Way

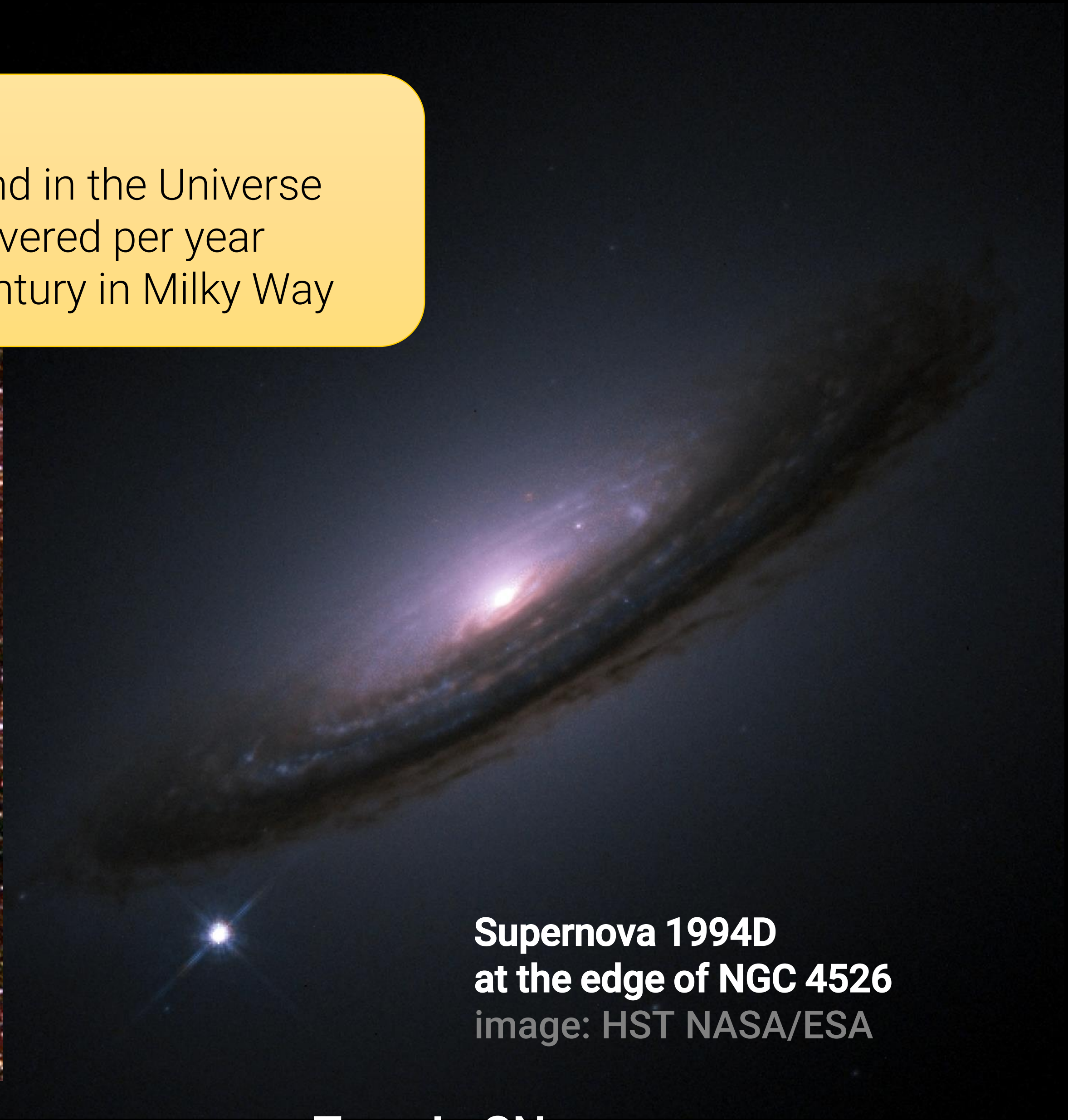


Supernova 1987A
discovered 24 Feb 1987
in LMC

exploding star:
Sanduleak -69° 202a
blue supergiant of ~17 Msun

© Anglo-Australian Observatory/David Malin Images

Type II SN

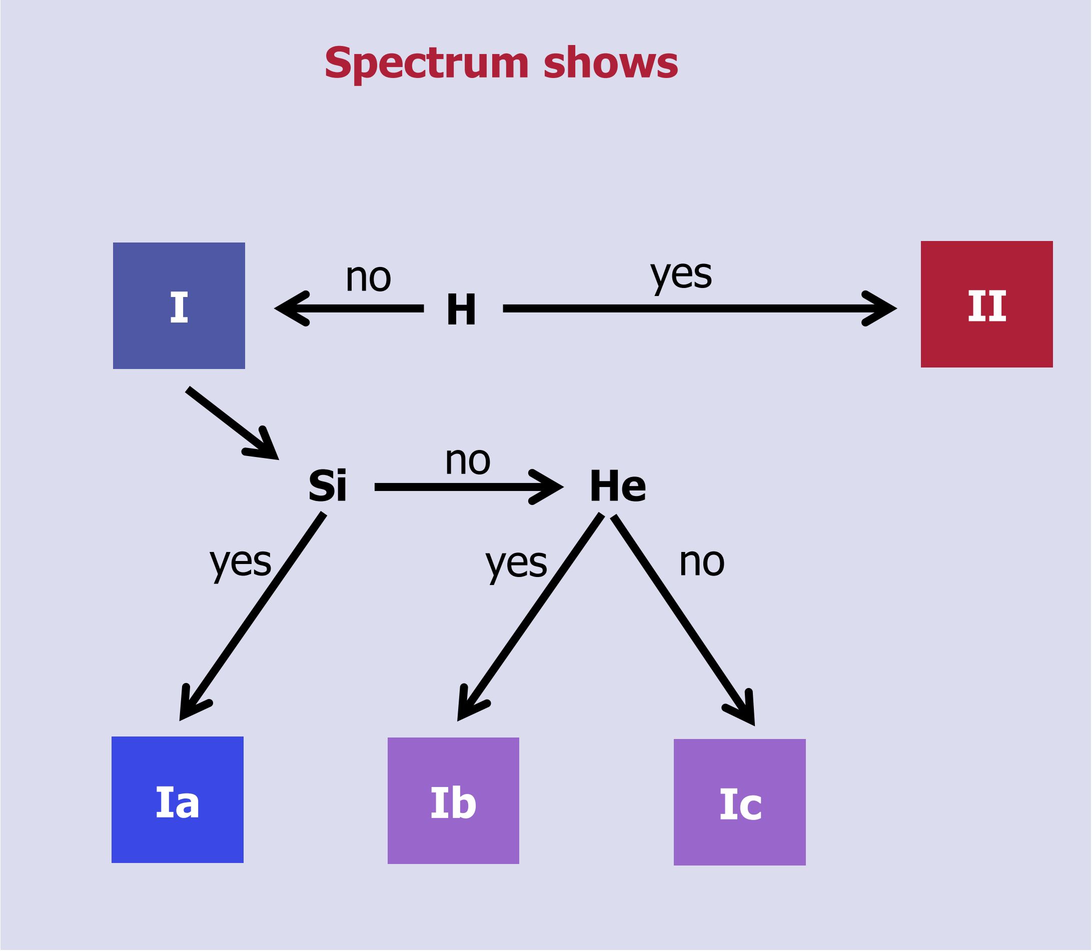


Supernova 1994D
at the edge of NGC 4526
image: HST NASA/ESA

Type Ia SN

Supernova classification

- **Classification according to spectral features**



Spectrum shows

I ← no **H** yes → **II**

I → **Si**

Si no → **He**

Si yes → **Ia**

He yes → **Ib**

He no → **Ic**

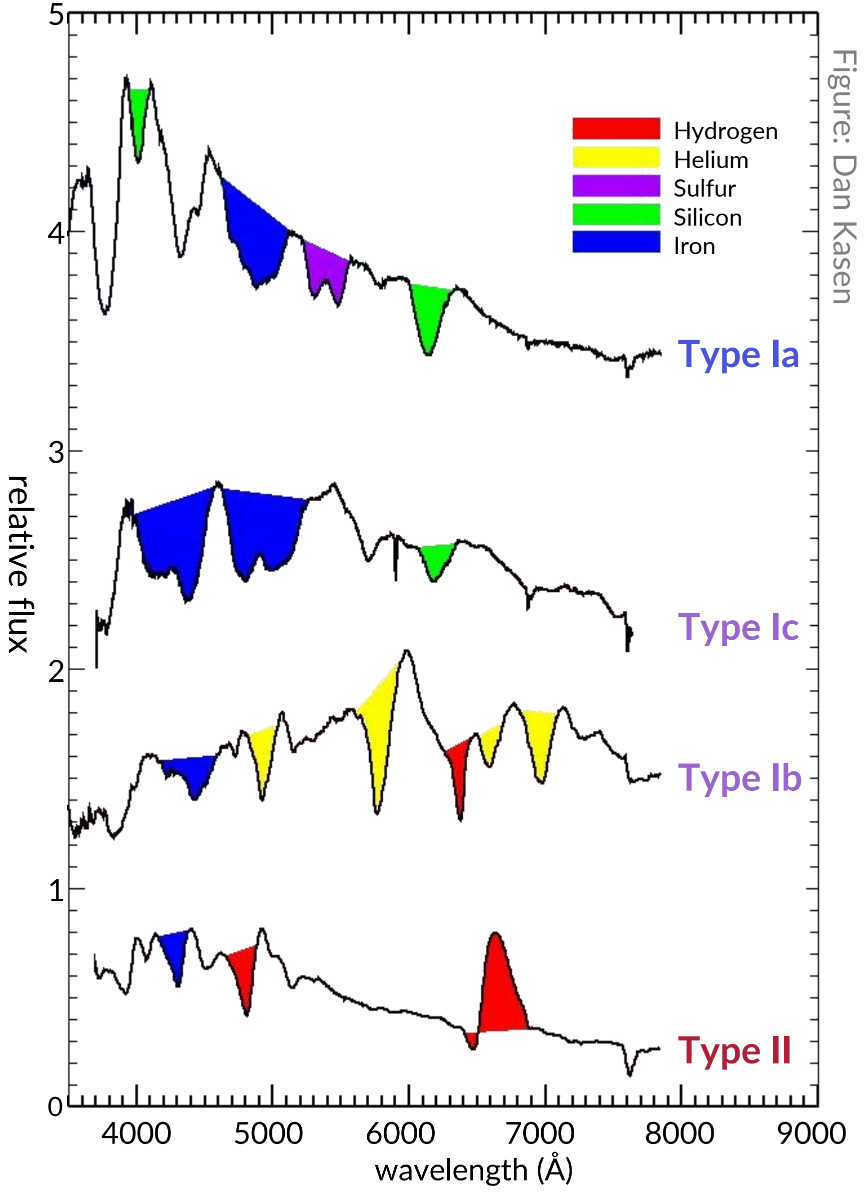
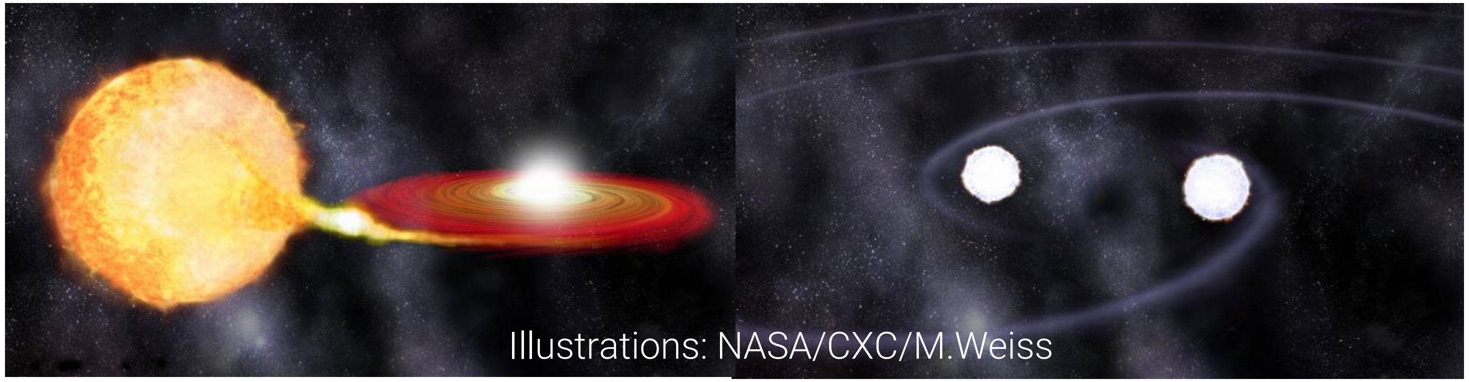


Figure: Dan Kasen

Supernova classification

- **Classification according to explosion physics**

- **SN Ia: exploding white dwarfs**
  (single or double degenerate channel)
  → long delay time (easily 10^9 yr after star birth)
  → mostly irrelevant for mechanical feedback
  → not for chemical enrichment (e.g. iron!)
- **Here: focus on SNe from massive stars (short delay)**


Illustrations: NASA/CXC/M.Weiss

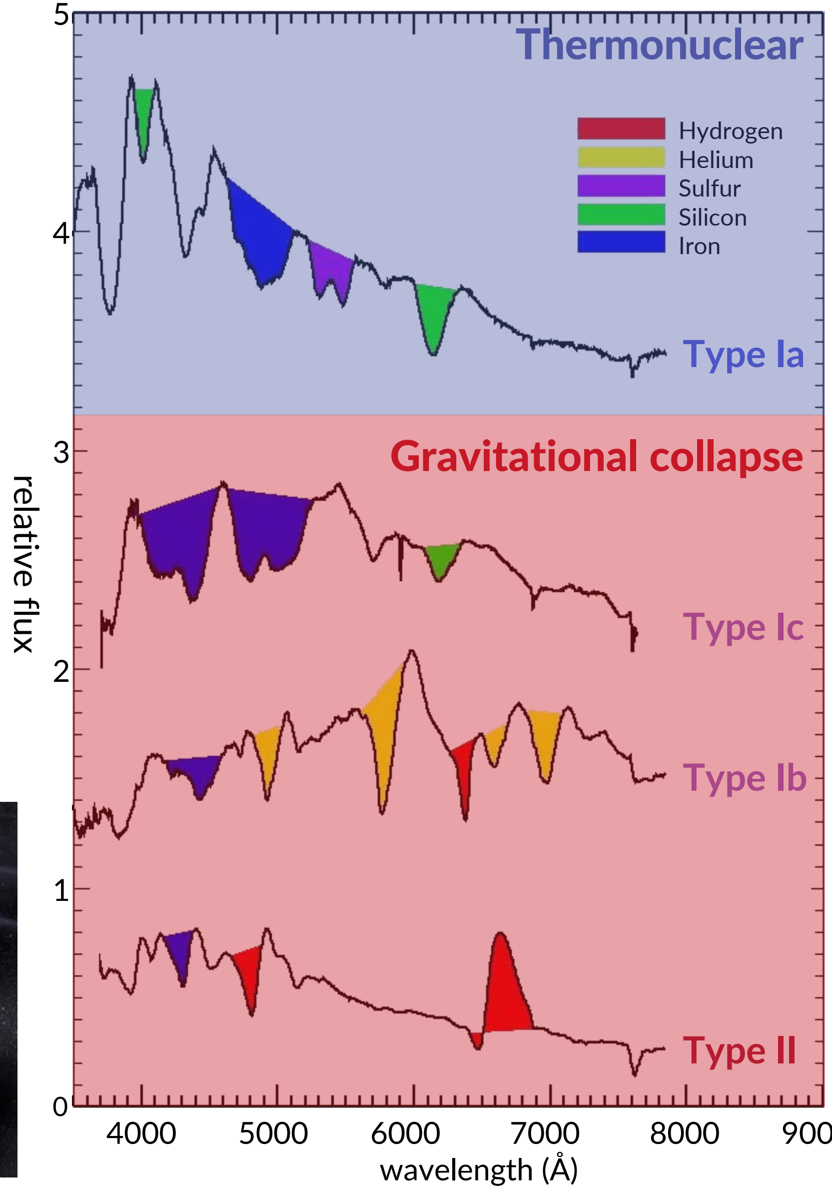
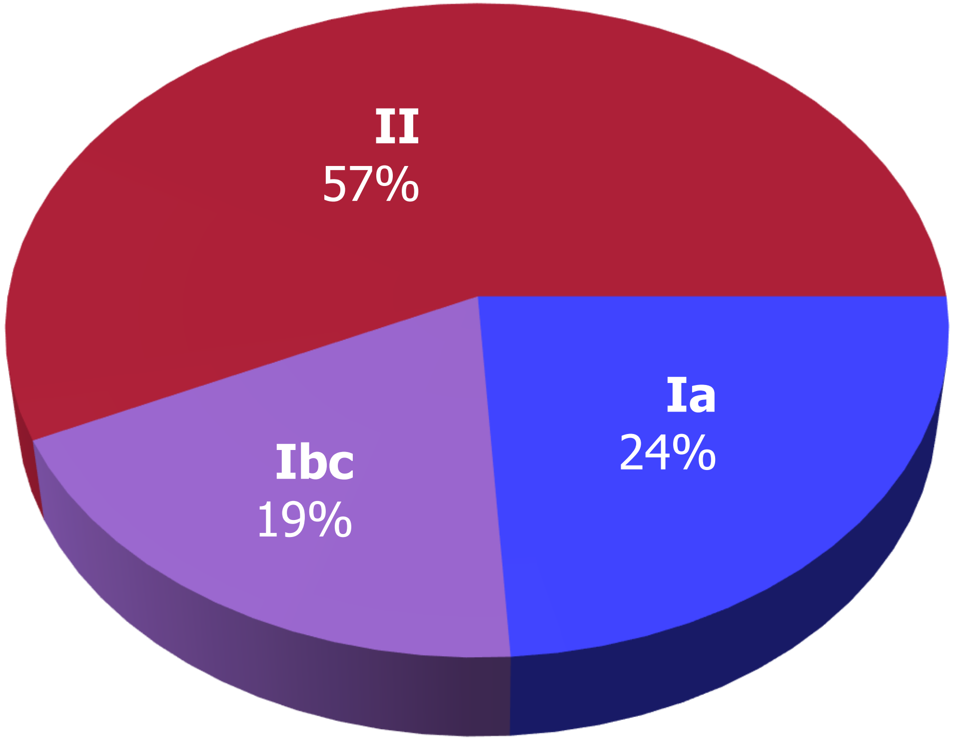


Figure: Dan Kasen

Supernova rates

- Volume-limited (Li et al. 2011)

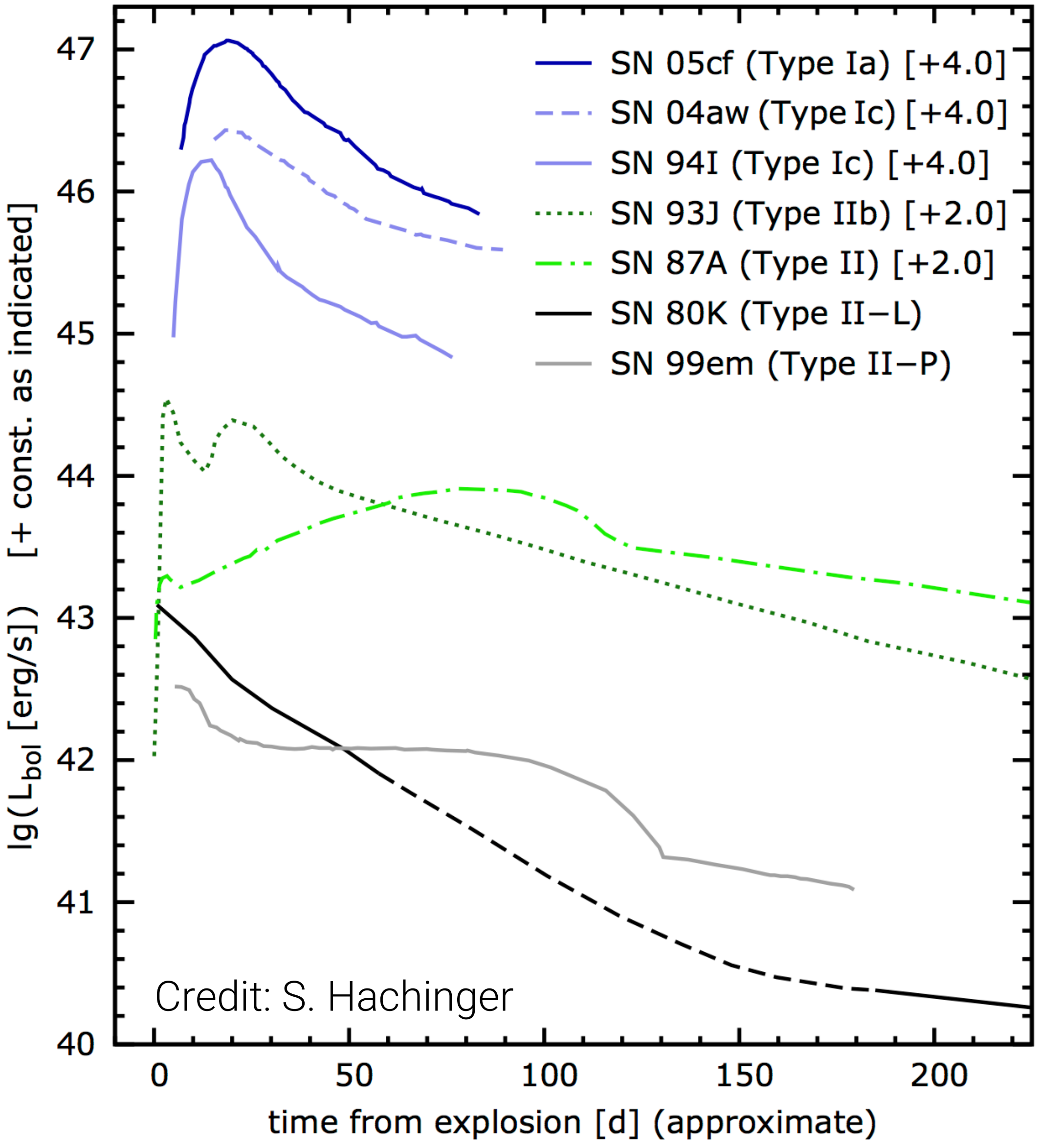


Supernova energetics

- **Threefold feedback:**
  1. **Supernova lightcurve** → radiation
  2. **Supernova explosion energy** → mechanical
  3. **Cosmic rays** → energetic particles (later)

SN lightcurve (usually neglected)

- **SN II: ~10^{49} erg; SN Ia: ~10^{49}–10^{50} erg**
- Peak luminosity: 10^{41}–10^{43} erg/s
  → up to 100 times that of 10^5 $M_\odot$ SF region
  (e.g. 30 Doradus → 10^{41}–10^{42} erg/s)
- Photon luminosity of one massive star over entire life: 10^{52}–10^{53} erg
- **Energy sources**: thermal emission from hot plasma (+ H & He recombination), interaction with mass shell, nuclear (Ni decay)



Credit: S. Hachinger

Supernova energetics

- **Threefold feedback:**
  1. **Supernova lightcurve** → radiation
  2. **Supernova explosion energy** → mechanical
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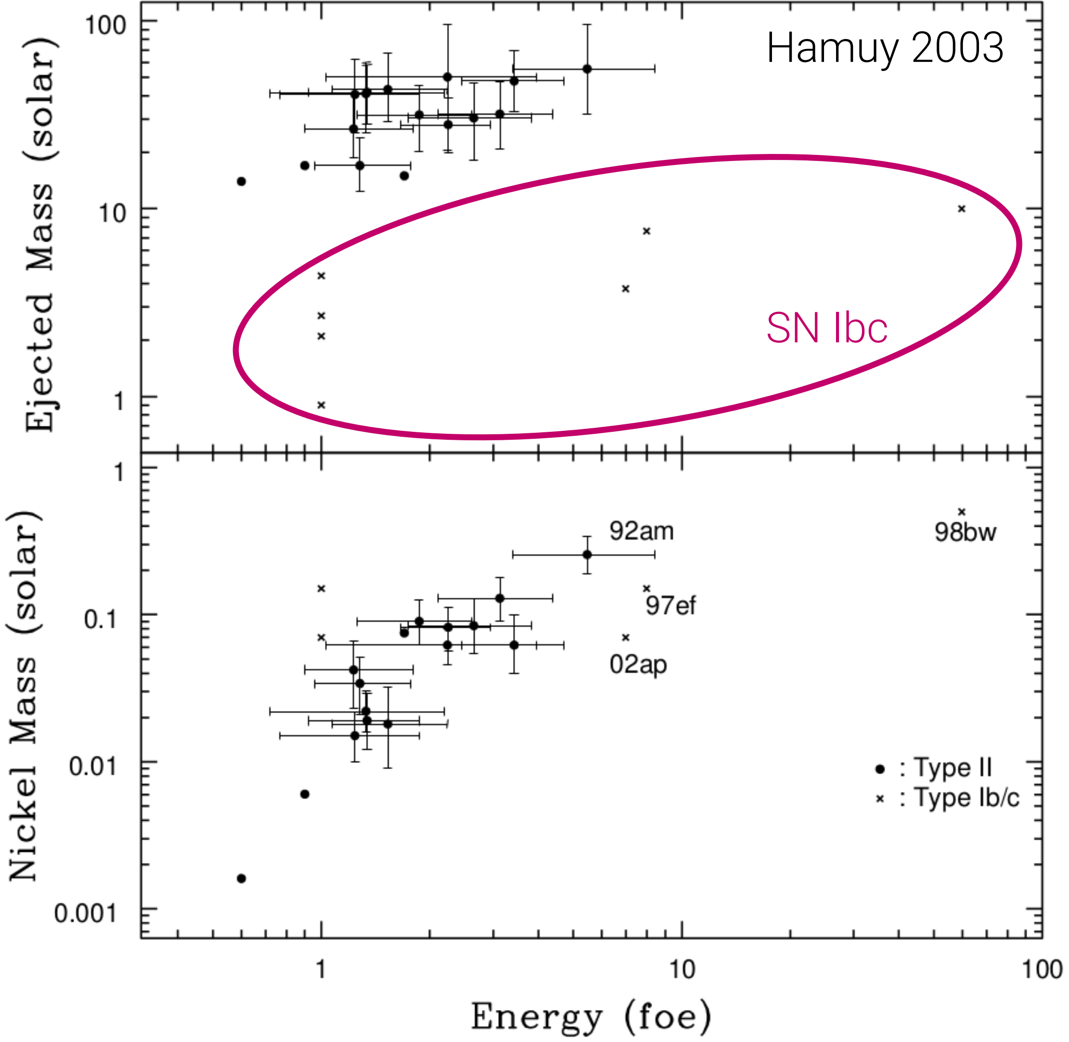
Supernova explosion energy

- **SN II & Ia: ~0.5 – 5 x 10^{51} erg** (10^{51} erg = 1 foe = 1 B [Bethe])
- Ejecta velocities: 10^3–10^4 km/s
- Nickel masses: 0.001–0.3 $M_\odot$
- Ejecta masses: ~0.1–60 $M_\odot$

No SN Ia, only SN Ibc & II



Supernova energy source

Core collapse SNe

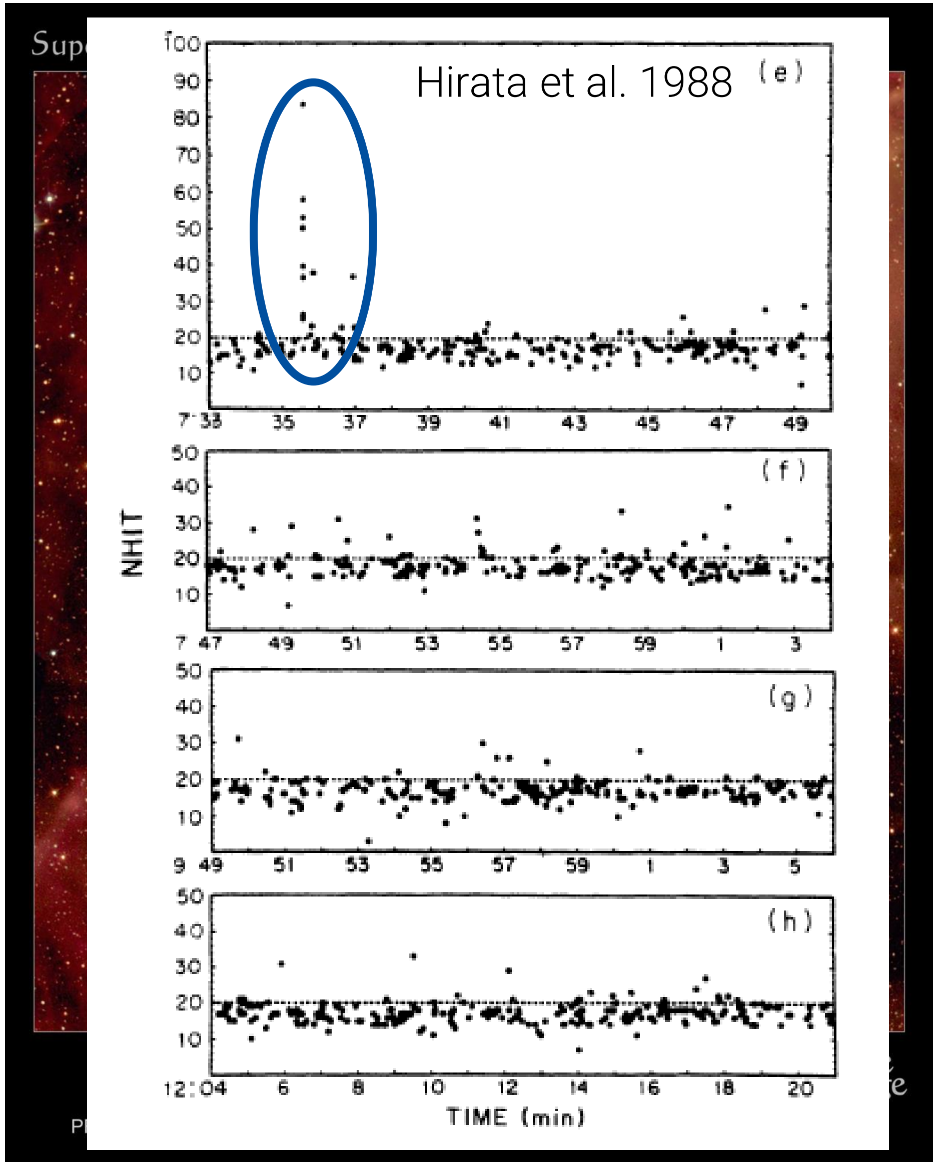
- **Observed kinetic energy: ~10^{51} erg**

- **Energy source**: collapse to neutron star?
  → "gravity bomb"
- Release of gravitational binding energy: Earth-size iron core (R_{Fe}~3000 km) collapses to proto-NS (R_{NS}~12 km)

$$\Delta E_{\text{bind}} = \frac{GM^2}{R_{\text{NS}}} - \frac{GM^2}{R_{\text{Fe}}} \approx \frac{GM^2}{R_{\text{NS}}} \approx 10^{53}\,\text{erg}$$

- **→ Sufficient to power supernova!**

- What happens to majority of energy? → neutrinos!


Hirata et al. 1988

Supernova energy source

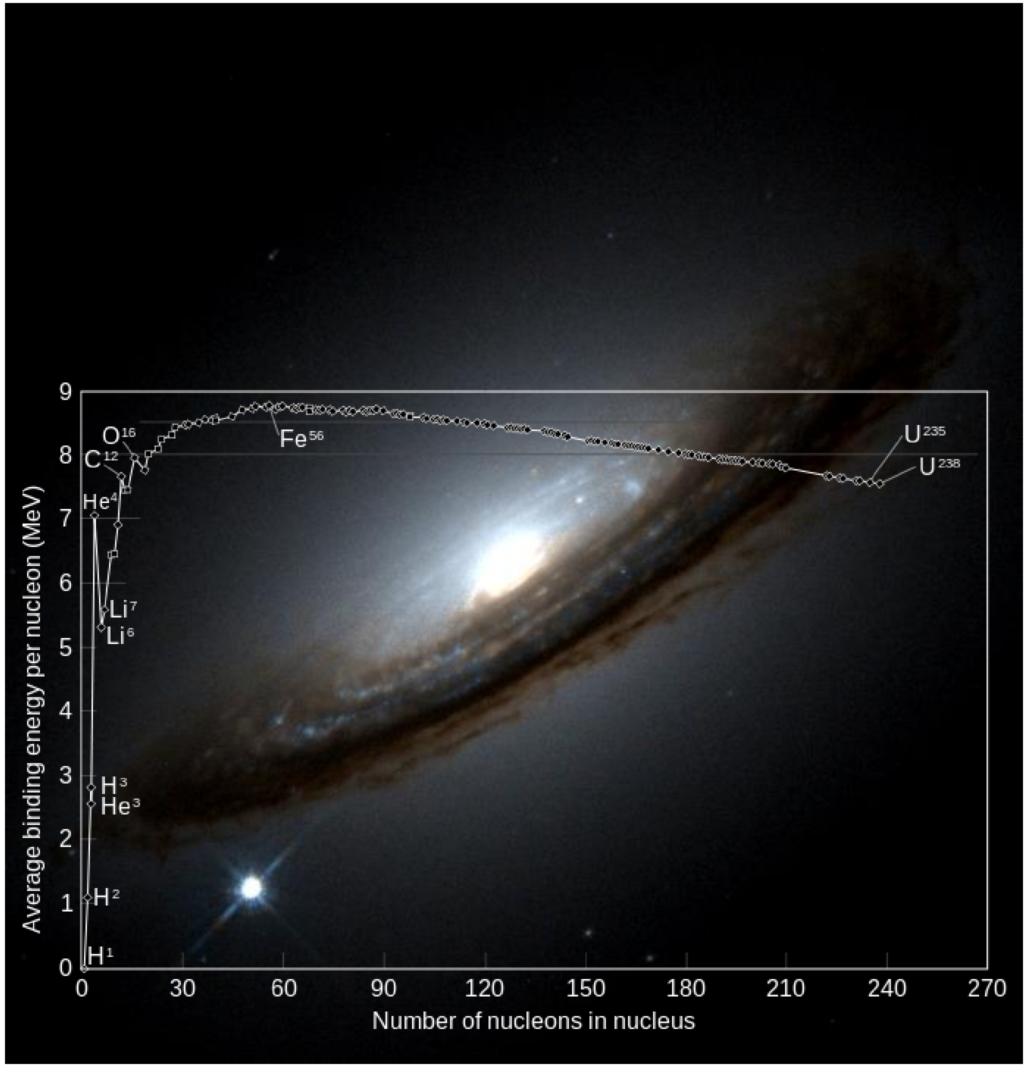
Thermonuclear SNe

- **Observed kinetic energy: ~10^{51} erg**

- **Energy source**: nuclear energy?
- no H, He in SNe Ia spectra
  → exploding star: C+O white dwarf

- Energy release due to burning of C+O material to 56Ni: 7.86 x 10^{17} erg/g
- Chandrasekhar-mass (1.4 $M_\odot$) WD: → 2 x 10^{51} erg

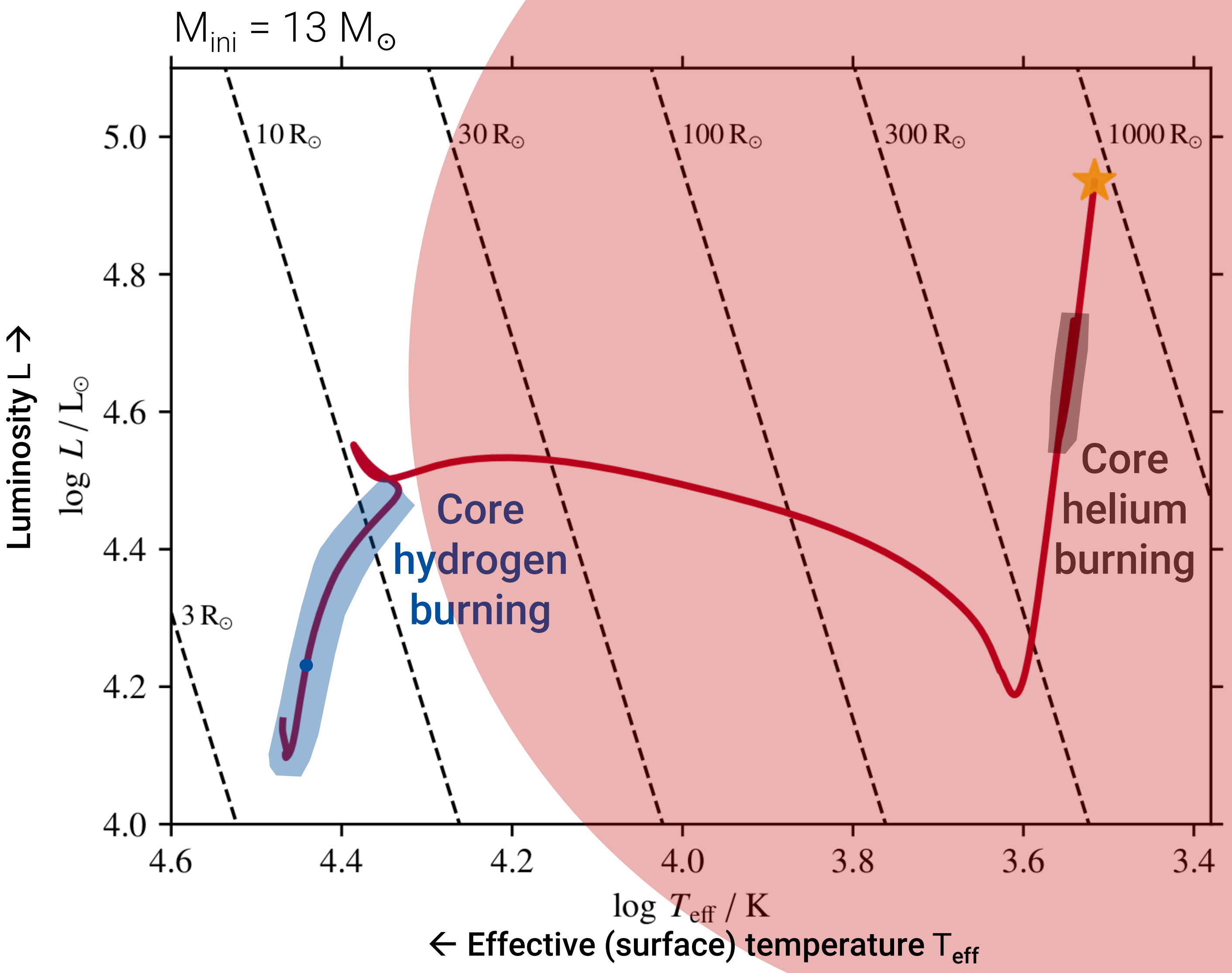
- → **Sufficient to power supernova!**



Stars 101:

Surface evolution

$1M_\odot$ = 1 solar mass
$1R_\odot$ = 1 solar radius
$1L_\odot$ = 1 solar luminosity



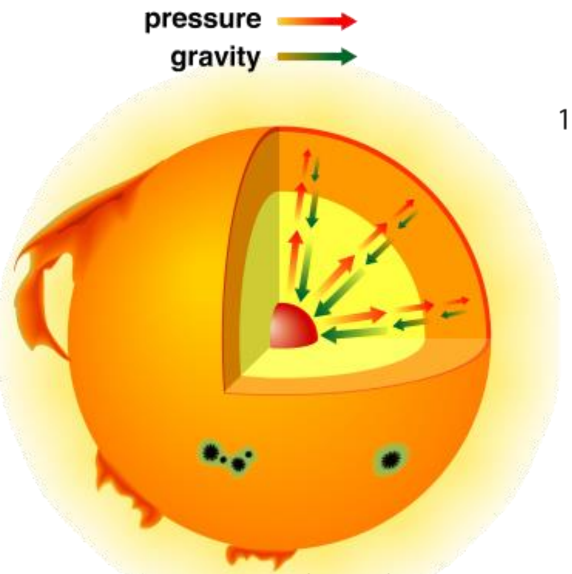
- Evolution of a 13 $M_\odot$ star in **Hertzsprung–Russell diagram**
- Lines of constant radii from Stefan-Boltzmann law of black body

$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$

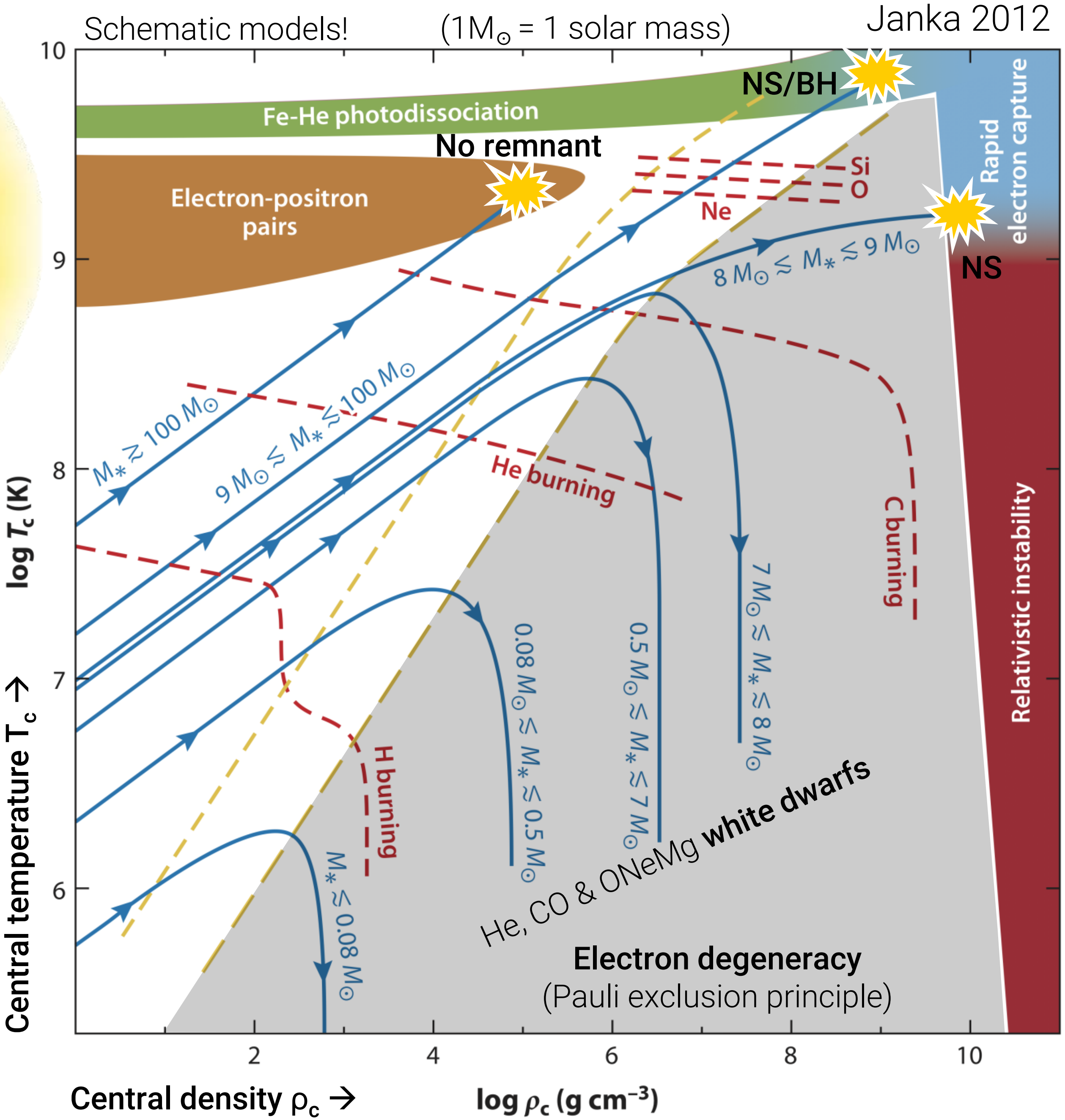
- While **core contracts**, the **entire star expands**
- Star becomes red supergiant and then explodes in supernova, leaving behind a neutron star
- More massive stars evolve faster

Stars 101:
Core evolution

- **Life of a star: eternal fight against gravity → Contraction**
- **Contraction halted temporarily** by episodes of **nuclear burning**, e.g.
  - Hydrogen burning: H → He
  - Helium burning: He → C, O
- **End of life**: reaching **death zones** (>8 $M_\odot$; supernova, formation of neutron star or black hole) or **gravity permanently balanced by degenerate electrons** in white dwarfs (<8 $M_\odot$)



$$T_c \sim M^{2/3} \rho_c^{1/3}$$



Schematic models!

(1$M_\odot$ = 1 solar mass)

Janka 2012

Image credit: http://cse.ssl.berkeley.edu/bmendez

Stars 101

Chandrasekhar mass M_{Ch}

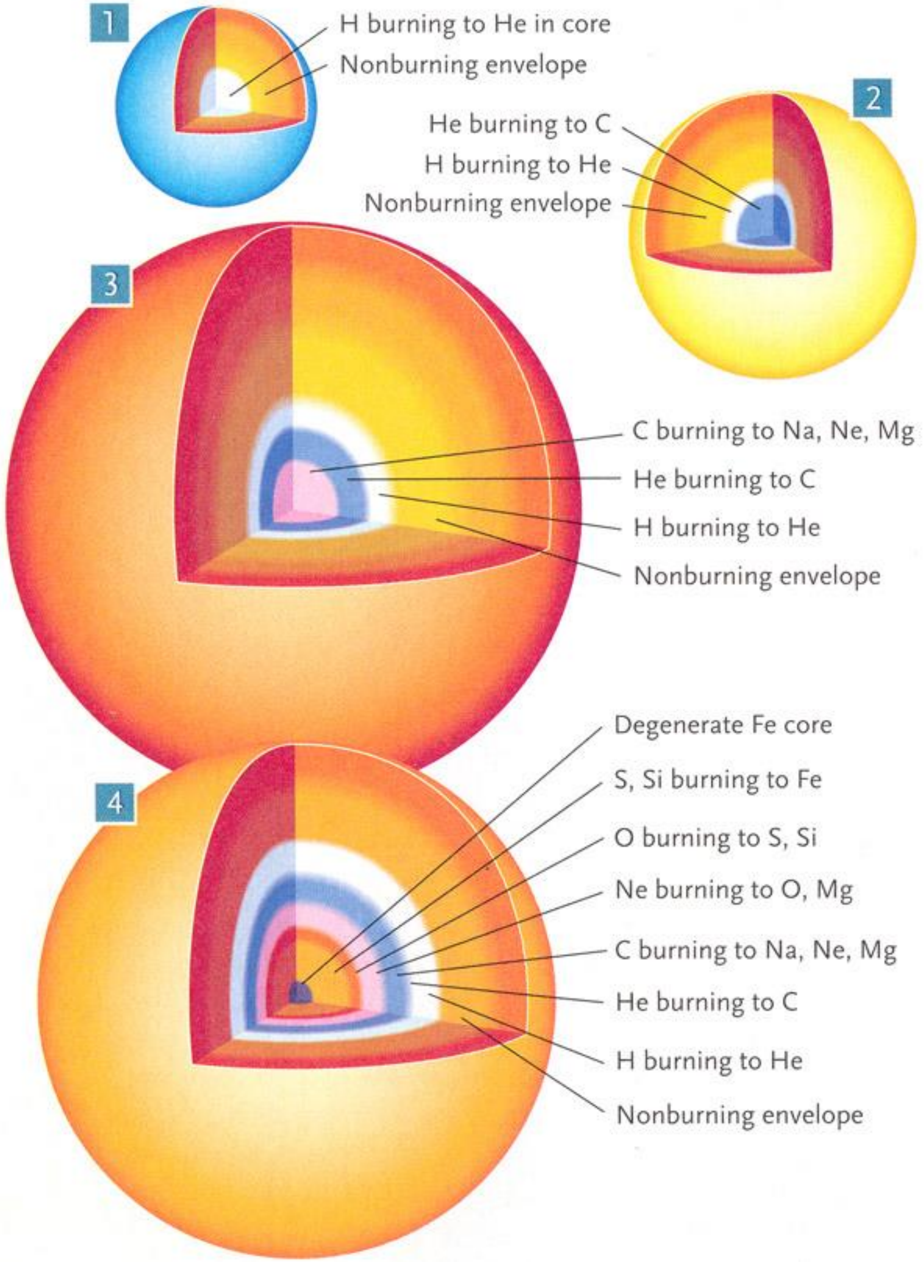
- Nuclear burning until iron core formation
  → nuclear fusion of iron-group elements impossible
  → only electron degeneracy left to balance gravity

- Once core mass exceeds effective **Chandrasekhar mass**, core starts to collapse (+ additional instabilities)

$$M_{\mathrm{Ch}} \sim 1.43(2Y_{\mathrm{e}})^2\, M_{\odot} \qquad Y_{\mathrm{e}} \equiv \frac{Z}{A}$$

- Two ways to reach M_{Ch}:
  1) add mass (shell burning, [accretion in SN Ia])
  2) reduce Y_e (electron capture reactions)

Image credit: Casey Reed

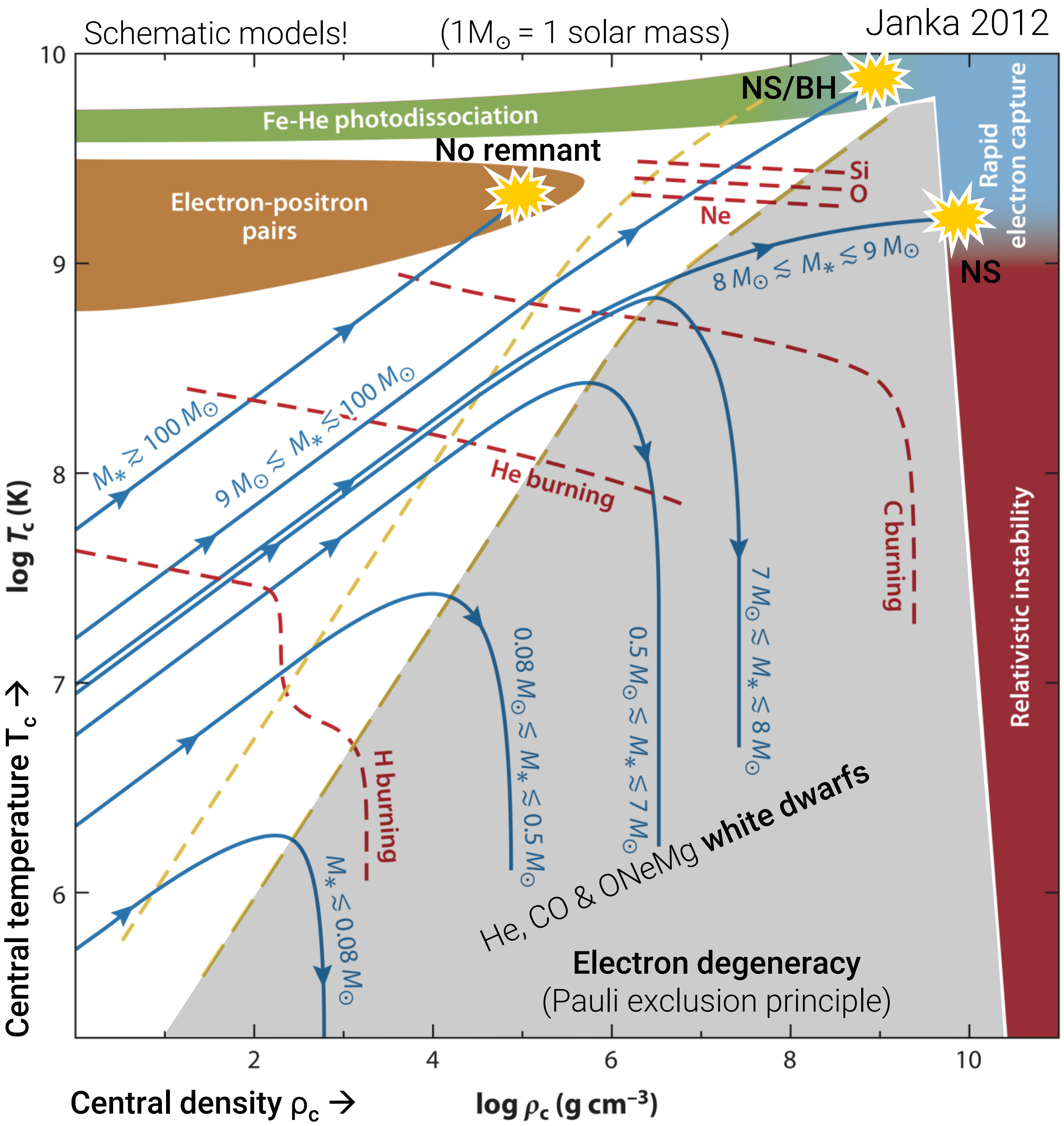


Three death zones

- **Electron capture supernovae**

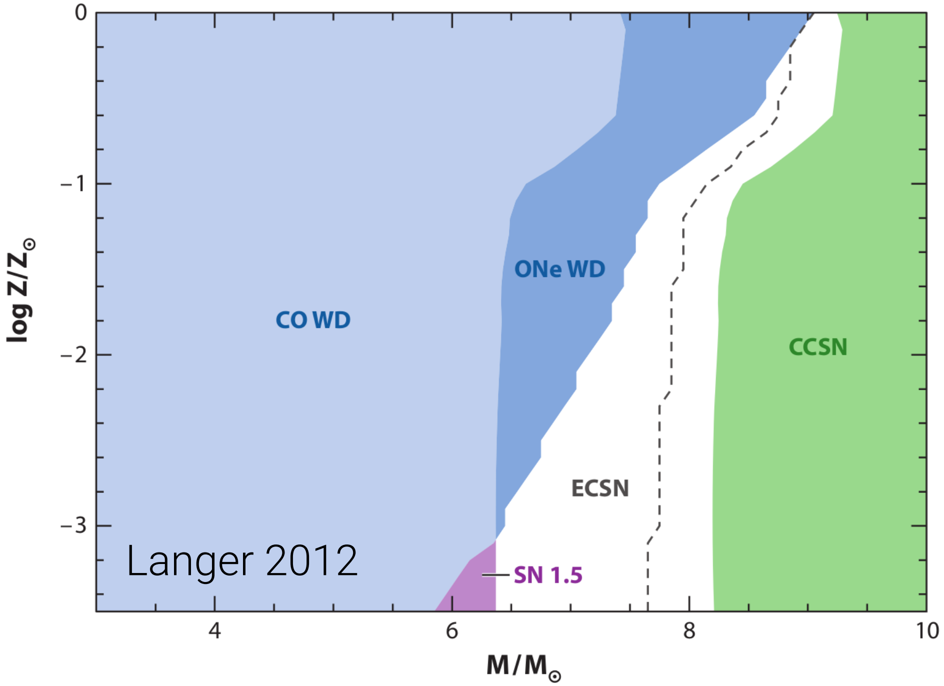
- **Core collapse supernovae**

- **Pair instability supernovae**
  + pulsational pair instability SNe

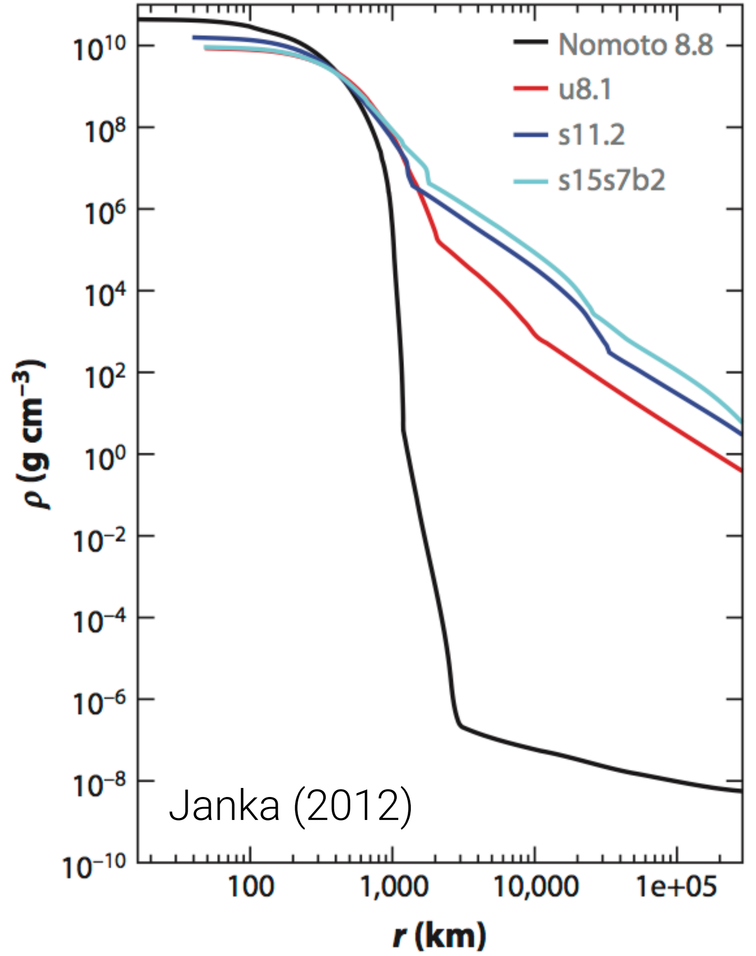


Electron capture supernovae

- applies to solar metallicity stars in range ~8/9...10 $M_\odot$
  → about 20 to 30% of all CCSNe may be ECSNe
- Core reaches electron-degeneracy before Ne burning
- Electron captures on 20Ne and 24Mg lower Ye
  → M_{Ch} is reduced & core collapses
- Mass window can shift with other parameters (e.g. Z, binarity)



Langer 2012



Janka (2012)

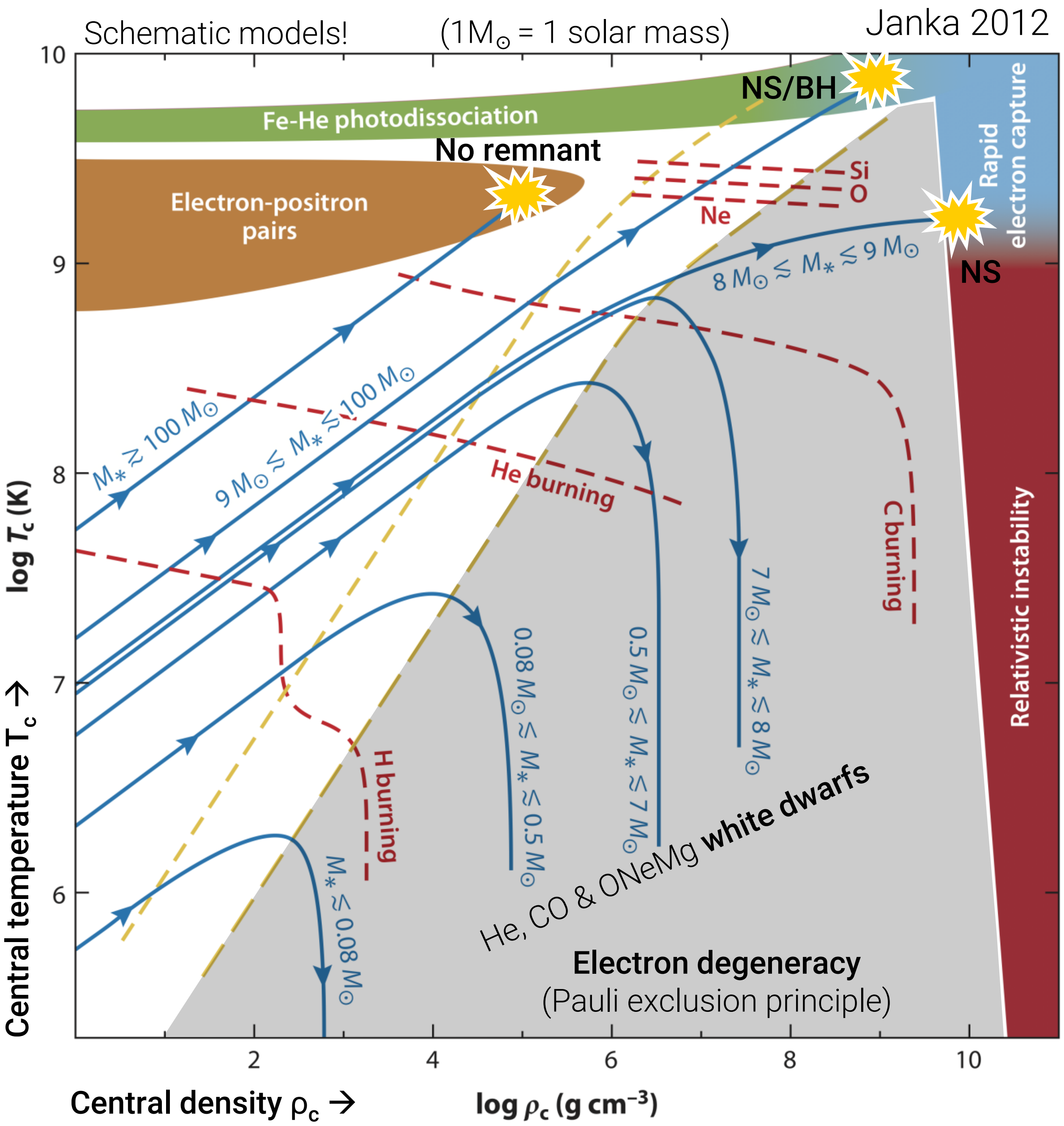
- Steep density decline at edge of O-Ne core:
  → special explosion characteristics compared to SNe from higher-mass stars (little mass ejection, very little Ni → faint, **smaller explosion energies ~10^{50} erg**)

Three death zones

- Electron capture supernovae

- **Core collapse supernovae**

- Pair instability supernovae
  + pulsational pair instability SNe

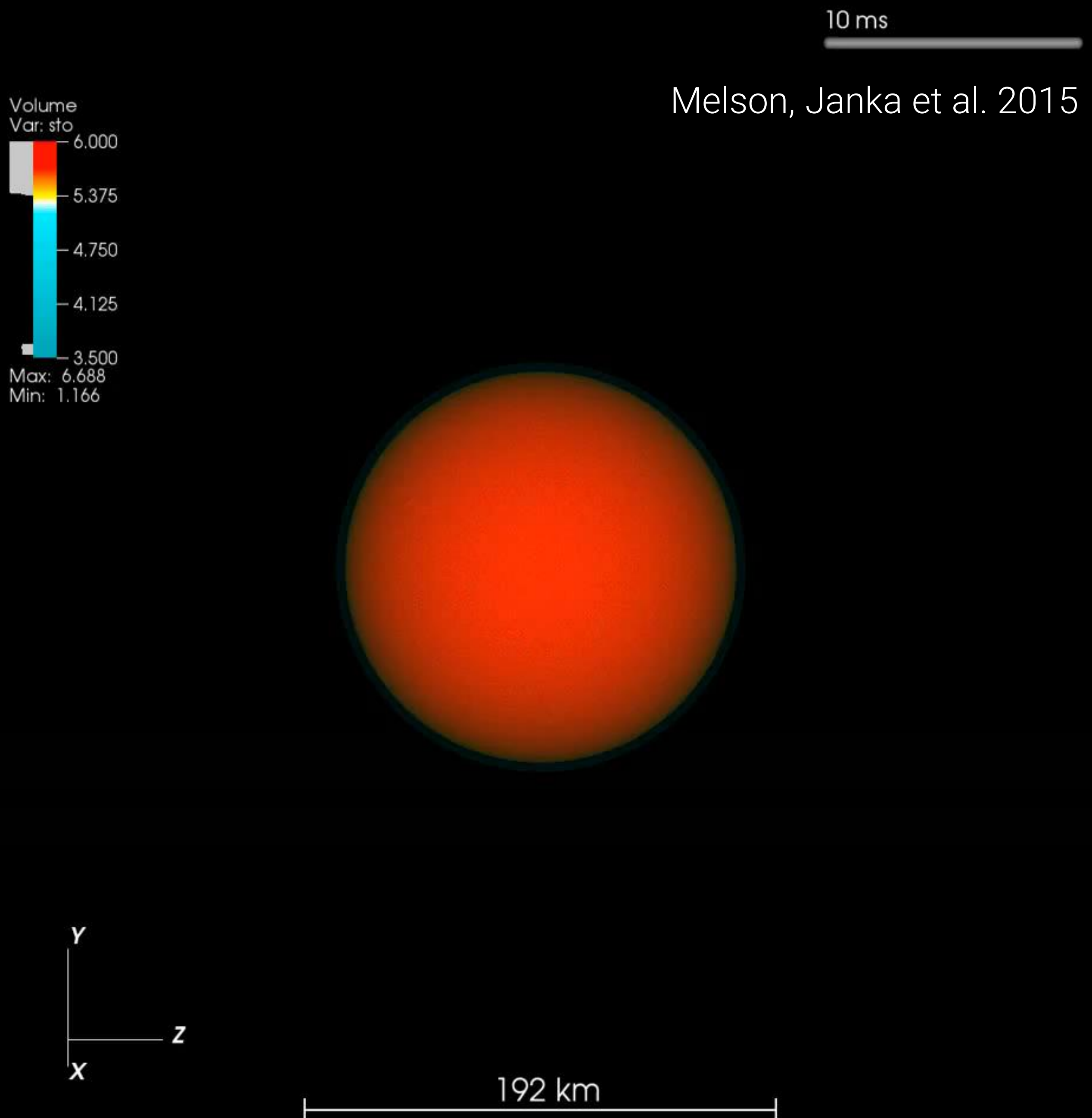

Schematic models! (1M$_\odot$ = 1 solar mass)

Janka 2012

Core collapse supernovae

The “gravity bomb”

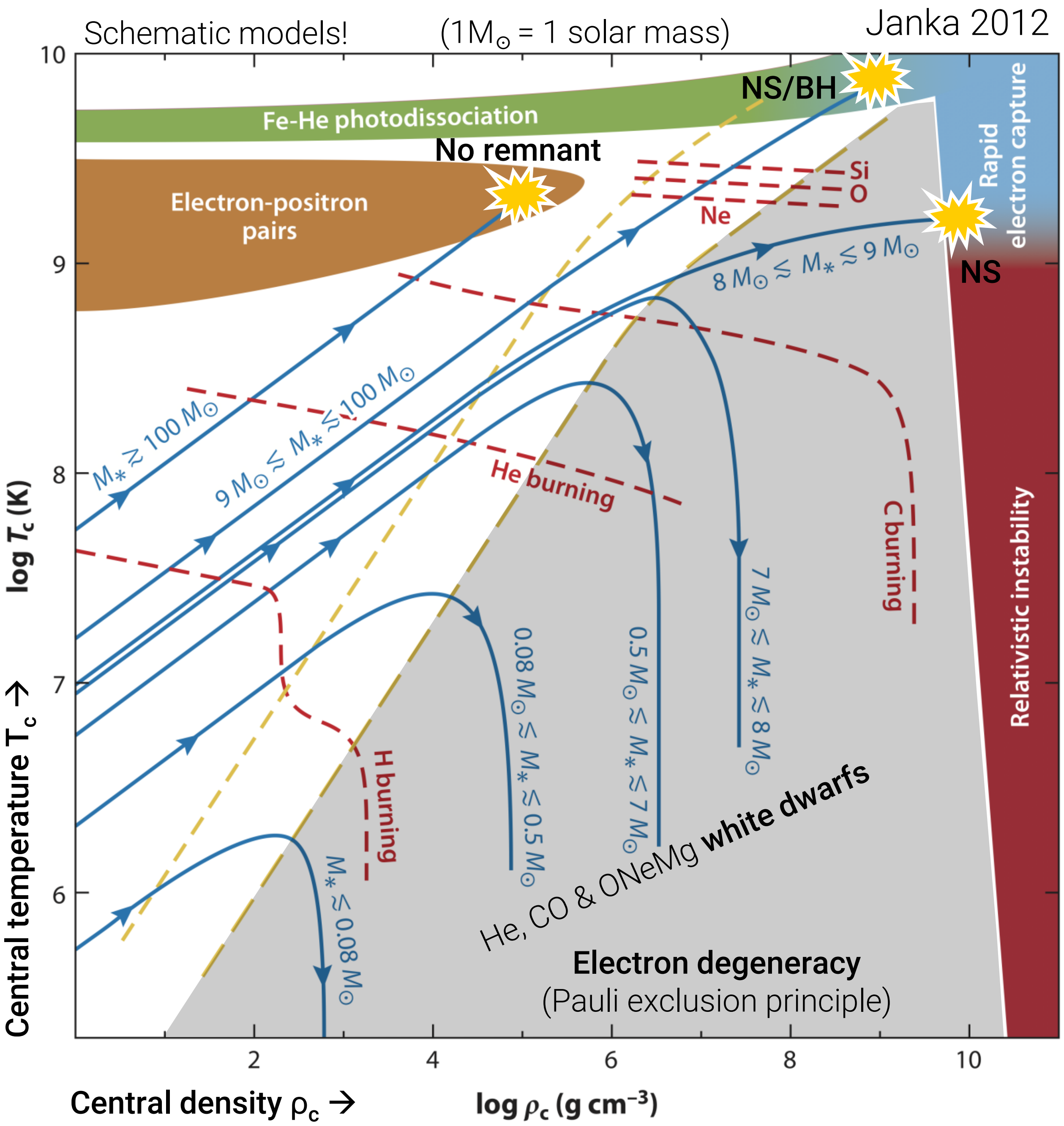
- **Core collapse** triggered if **iron core mass > effective Chandrasekhar mass**
- Energy source: **gravitational energy**
  → ~99% released in neutrinos (SN1987A)
  → how to use neutrinos to explode star?
- **Core bounce** and **shock formation** at nuclear densities (ρ ~ 10^{14} g cm^{-3})
- **Shock stalls** (→ dissociation of nuclei)
- **Proto-NS forms** and the **released neutrinos heat gain region behind shock → convection**
- **Threshold process**: if enough energy deposited, shock is revived, and **star explodes**
- **Simulations**: consistent explosions among different groups, yet too little energy
  (e.g. O’Connor+2018, Burrows & Vartanyan 2021)



Melson, Janka et al. 2015

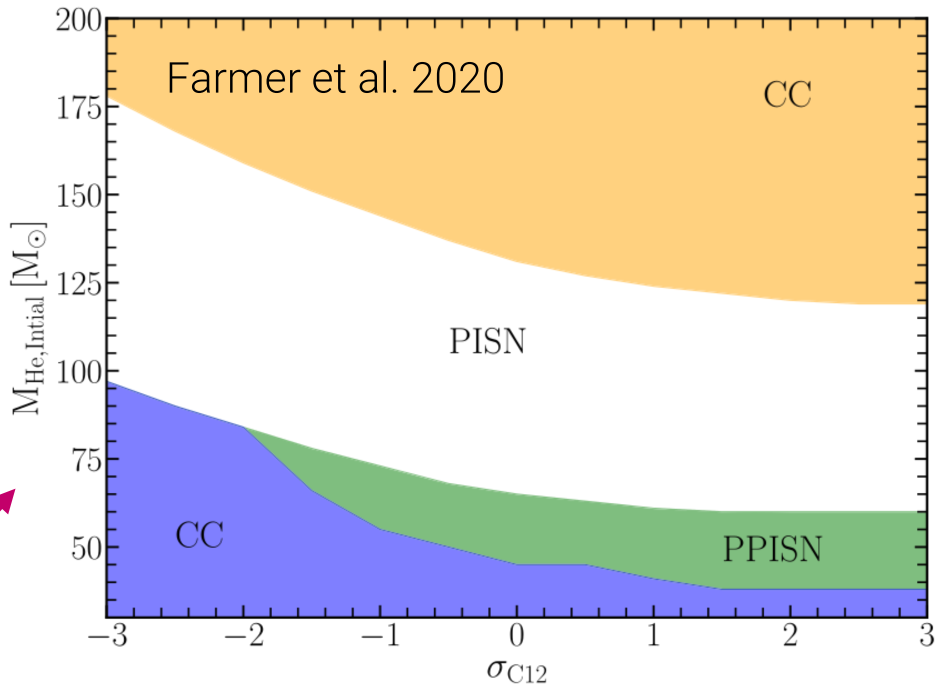
Three death zones

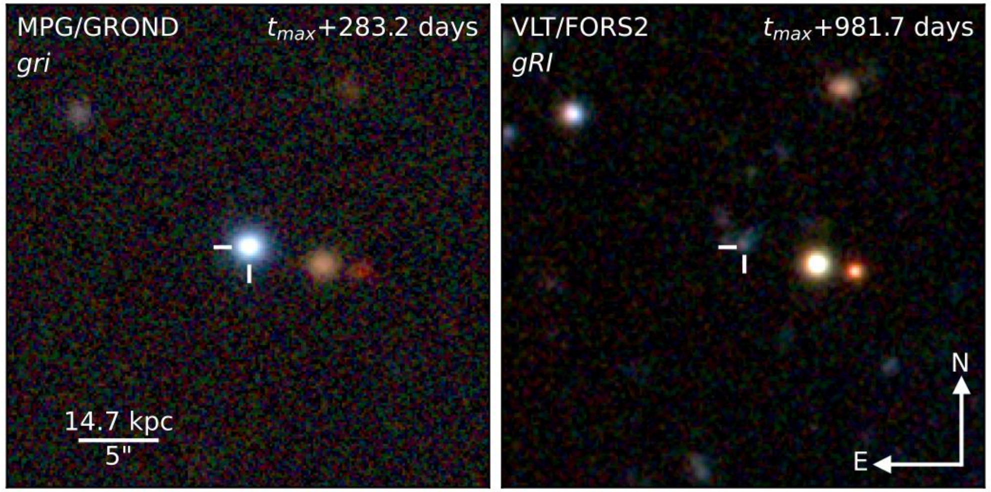
- Electron capture supernovae
- Core collapse supernovae
- Pair instability supernovae
  + pulsational pair instability SNe



Pair instability supernovae

- Stars with initial mass above ~100 $M_\odot$ → very hot
- **Pair instability after C burning** at T~1GK: formation of e^+e^--pairs from high-energy photons converts thermal energy into rest-mass energy
  → reduces adiabatic index of E.o.S. below 4/3
- **Thermonuclear explosion** of left nuclear fuel
  → enough to completely disrupt the star? → mass-dep.
- Mass range uncertain, e.g., nuclear reaction rates
- Occur only at $Z<Z_\odot/10$ (Langer 2007)
- **Explosion energy: ~10^{53} erg**, can produce more than 50 $M_\odot$ of 56Ni, but most events will produce "usual" CCSN Ni masses
- Best candidate so far: SN 2018ibb (Schulze+2023)



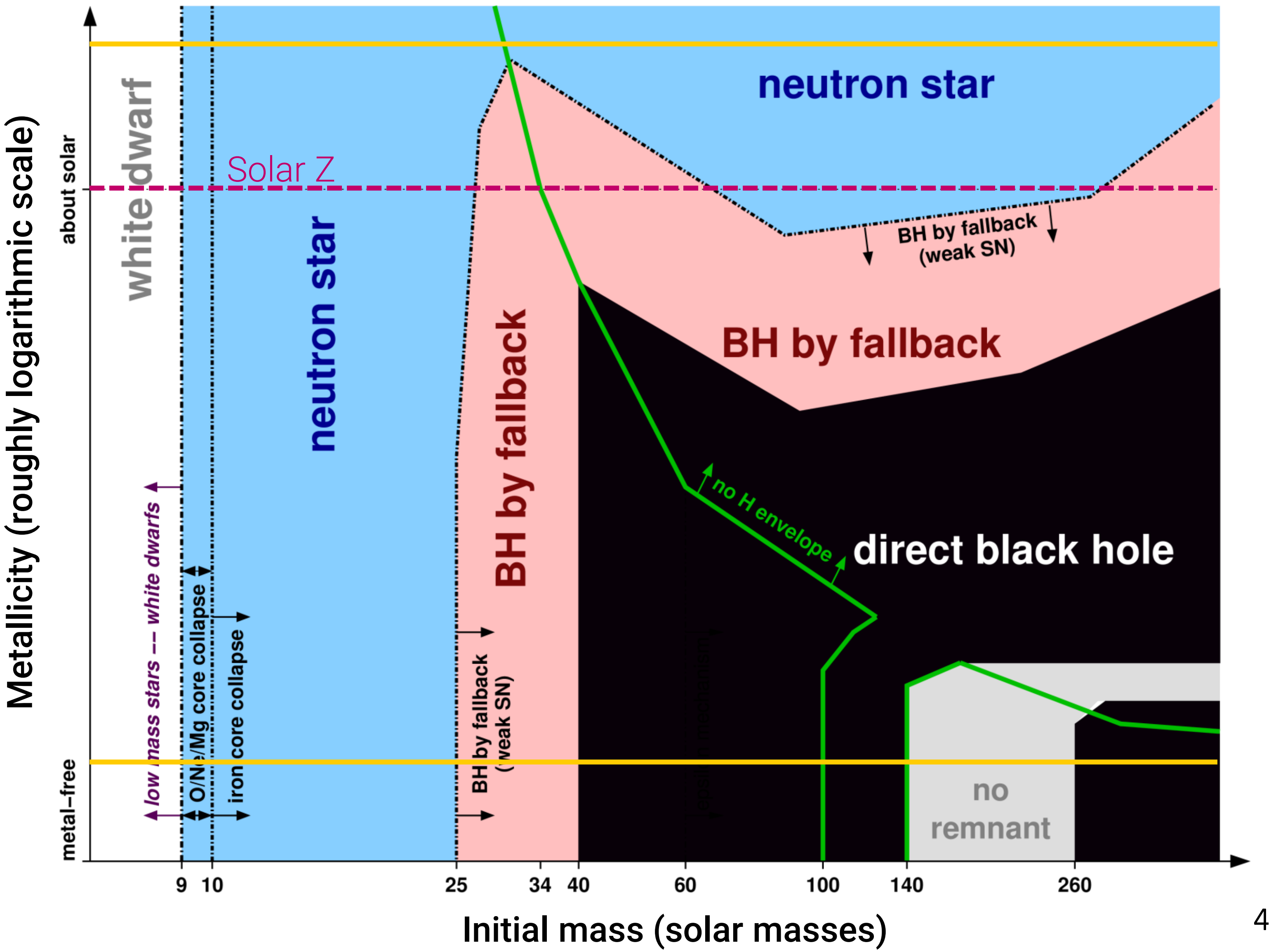


SN 2023ibb; Schulze et al. 2023

Stars 101: How massive single stars end their life

- **What we teach in lectures:**
  - **8/9–10 $M_\odot$**: electron capture supernova (core collapse)
  - **10–25 $M_\odot$**: iron core collapse supernova → **neutron star**
  - **25–40 $M_\odot$**: weak core collapse supernova → **black hole** by fallback
  - **>40 $M_\odot$**: no supernova → collapse to **black hole**

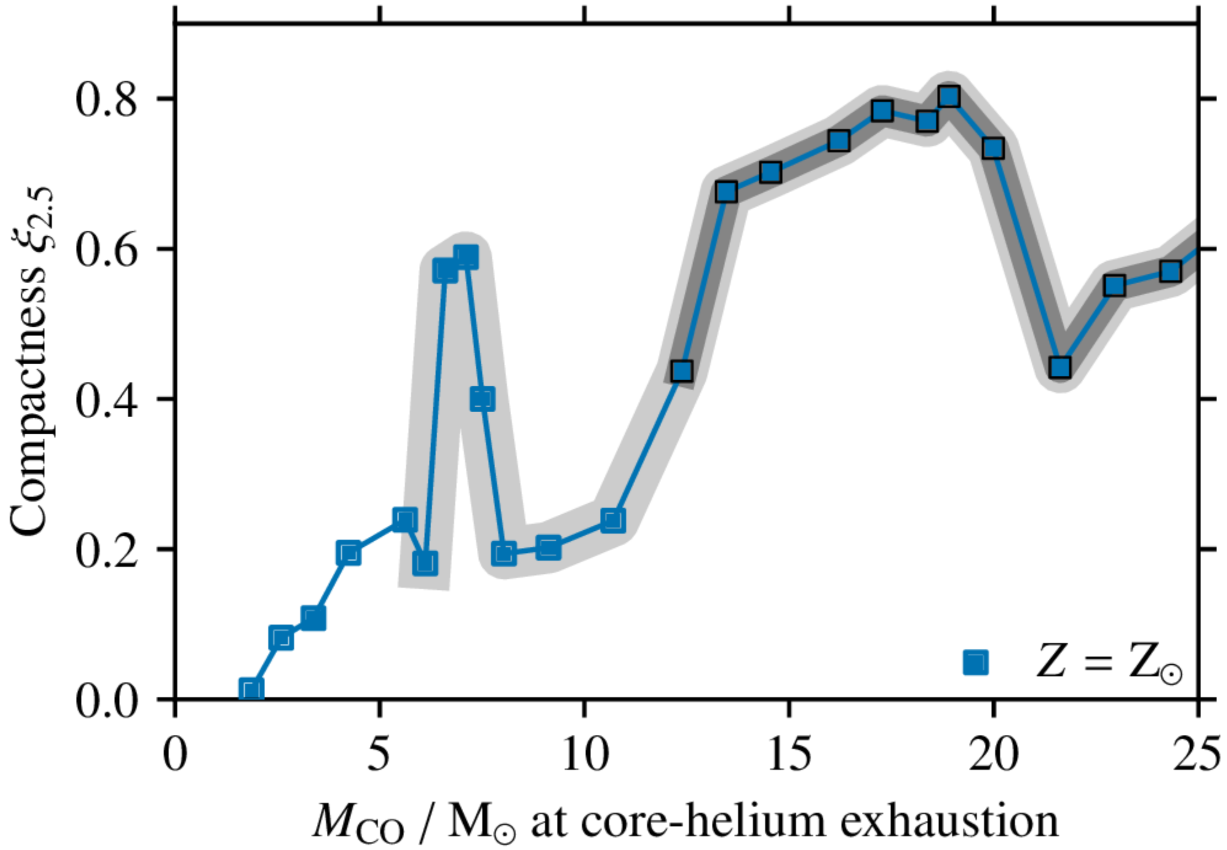
- **Special cases:** → stellar winds
  - **High-Z**: no black holes at all
  - **Low-Z:** pair-instability supernovae, no remnant → **PISN BH gap: ~45–120 $M_\odot$**



Heger et al. 2003; Heger, Müller & Mandel 2023

Final fate of (single) stars (CCSNe)

A closer look at the pre-SN stellar structure



- **Pre-SN stellar structure summarised by compactness parameter ξ_M**

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\ \mathrm{km}}$$

- **Non-monotonic landscape** with core mass of stars (here CO core mass M_{CO})
- Stars with large ξ_M difficult to explode

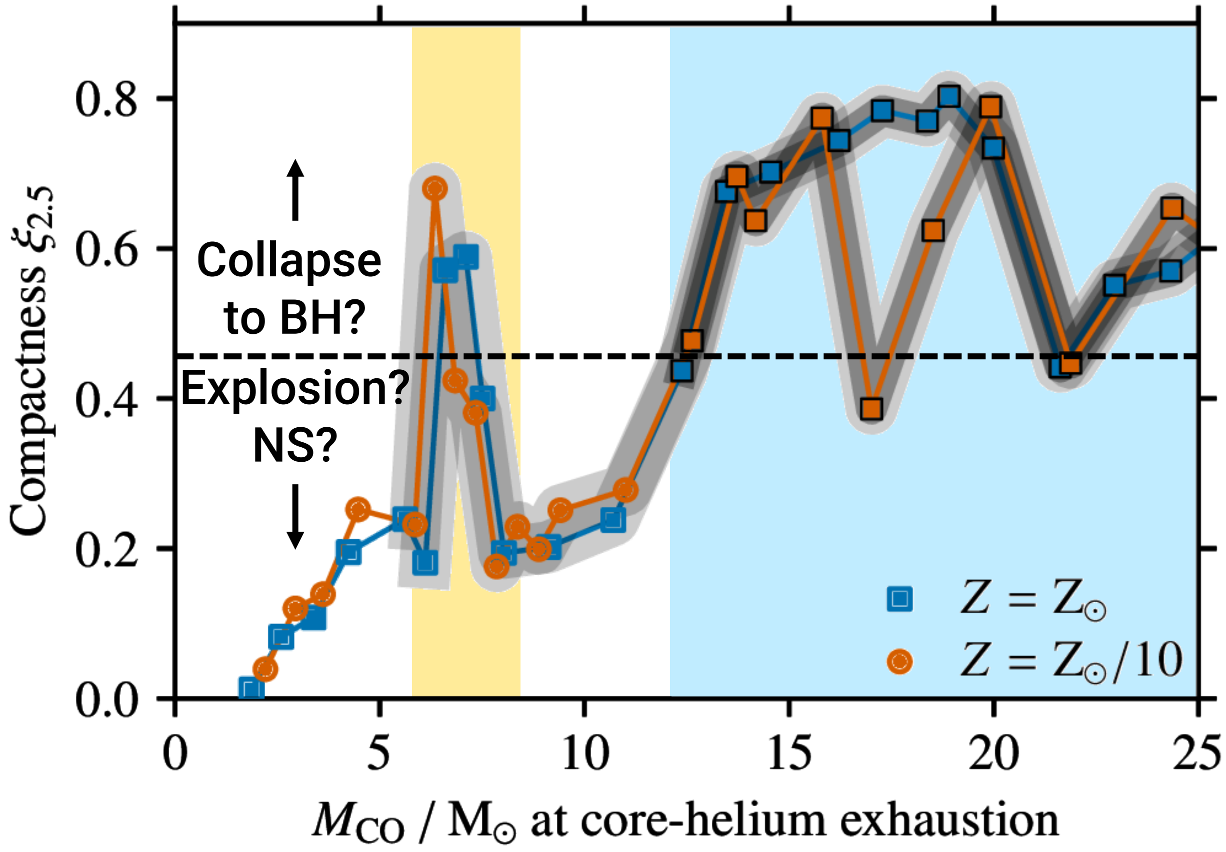
Schneider et al. 2021

See also Sukhbold & Woosley 2014, Sukhbold+2016, Chieffi & Limongi 2020, Takahashi+2023, …

Final fate of (single) stars (CCSNe)

A closer look at the pre-SN stellar structure

$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\ \mathrm{km}}$$



- **Compactness as explosion criterion:**
  - $\xi_{2.5} > 0.45$ → Collapse to BH?
  - $\xi_{2.5} < 0.45$ → Explosion and NS formation?

- **High compactness** at
  → M_{CO} **~7.5** $\mathrm{M}_\odot$ ("compactness peak") and
  → M_{CO} **> 13** $\mathrm{M}_\odot$
- Driven by **neutrino-dominated carbon and neon burning**

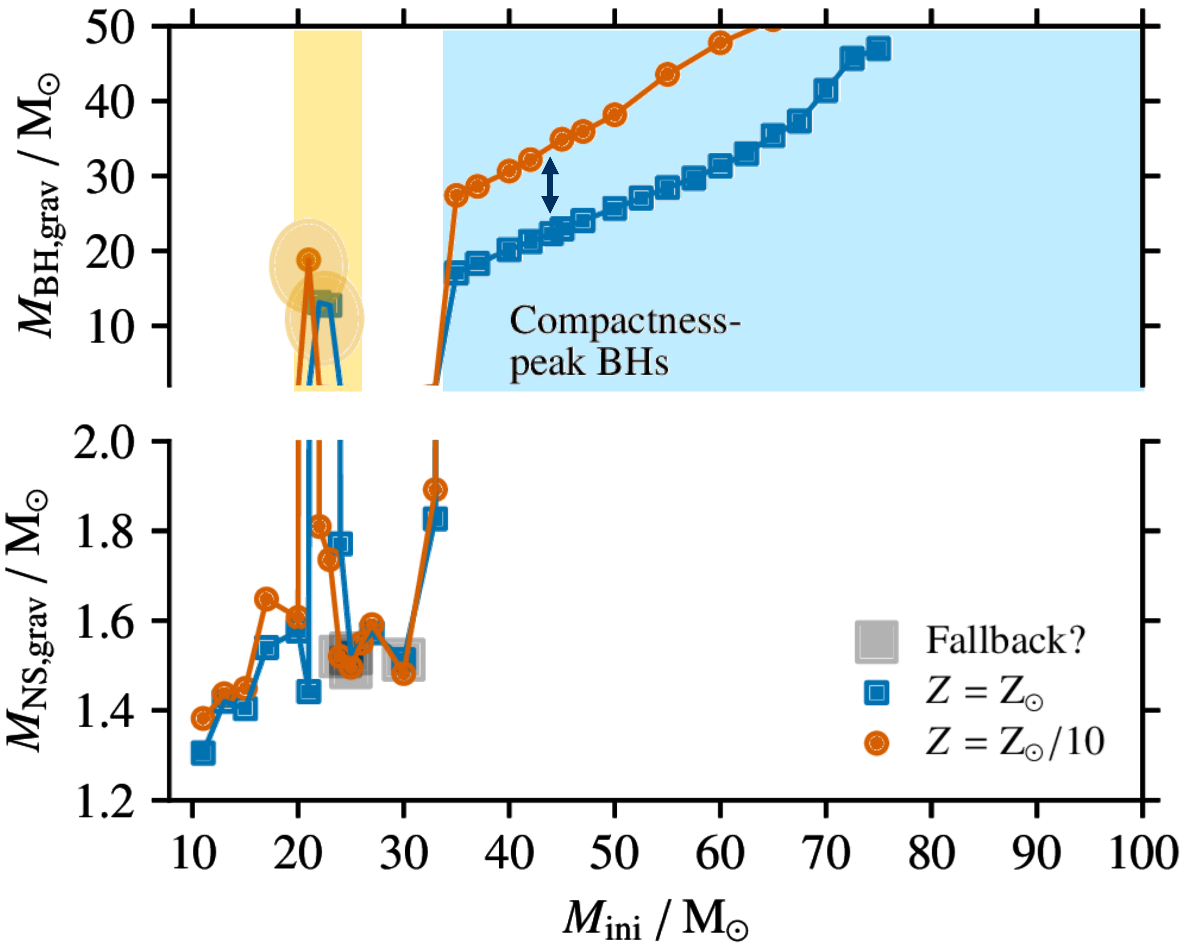
- **Compactness pattern not strongly metallicity dependent**
  (unless winds erode helium and CO cores)

Schneider et al. 2021, 2023

See also Sukhbold & Woosley 2014, Sukhbold+2016, Chieffi & Limongi 2020, Takahashi+2023, …

Final fate of (single) stars (CCSNe)

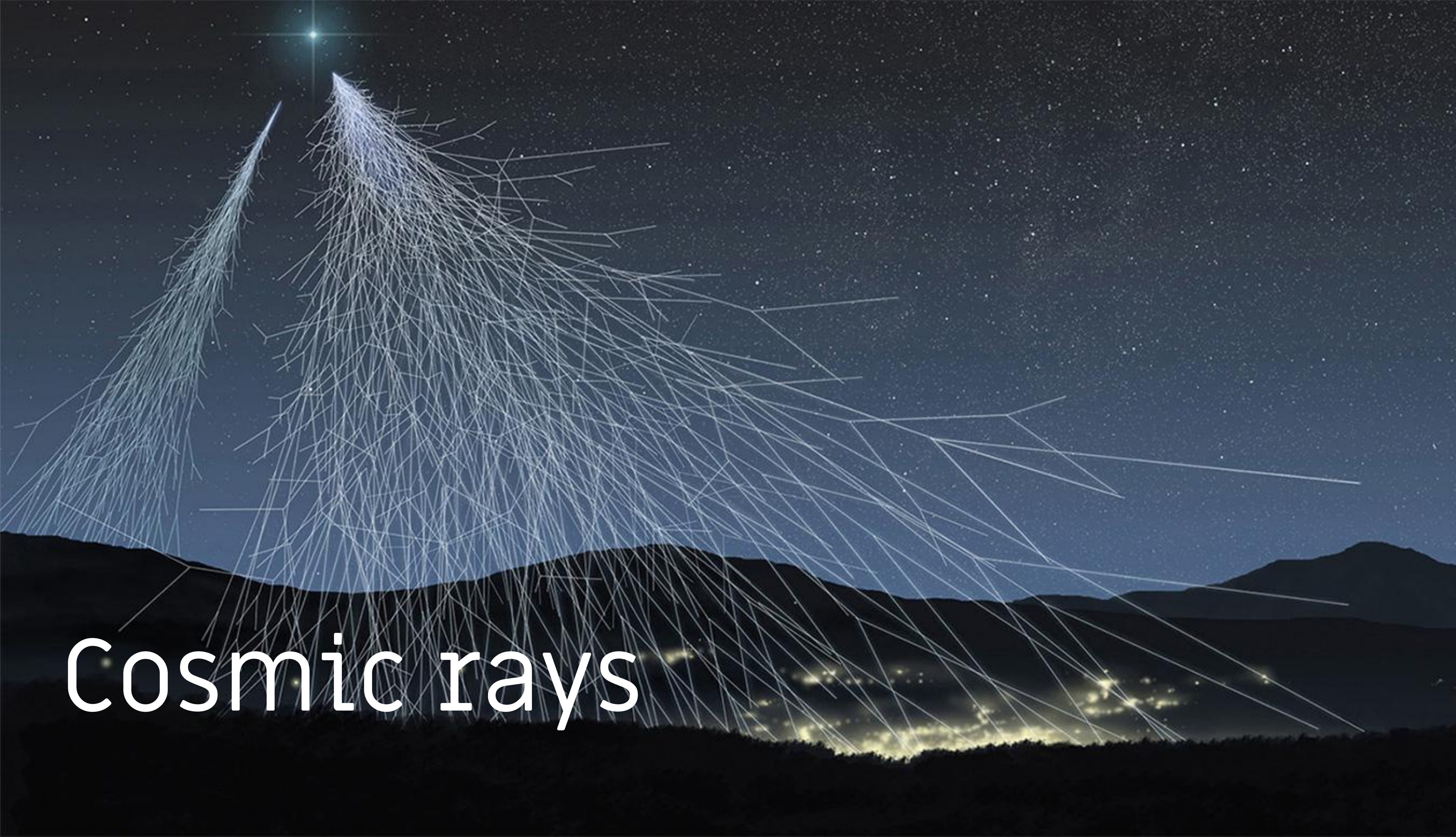
Compact remnant masses



Schneider et al. 2021, 2023

- Models exploded with **semi-analytic, ν-driven SN model of Müller et al. 2016**
- Explodability largely follows compactness (cf. O'Connor & Ott 2011, Ugliano+2012, Sukhbold & Woosley 2014, Ertl+2016, Müller+2016, …)
- **BH formation** at
  → **$M_{\mathrm{ini}} \sim 20$–$25\ M_\odot$** ("compactness peak")
  → **$M_{\mathrm{ini}} \sim 25$–$35\ M_\odot$**: some fallback BHs
  → **$M_{\mathrm{ini}} > 35\ M_\odot$**
- At lower **$Z = Z_\odot/10$**, essentially **same landscape**, but **BHs more massive**
  → weaker winds, hence less mass loss
- *Warning*: highest BH masses unrealistic because of missing enhanced mass loss from LBVs etc.

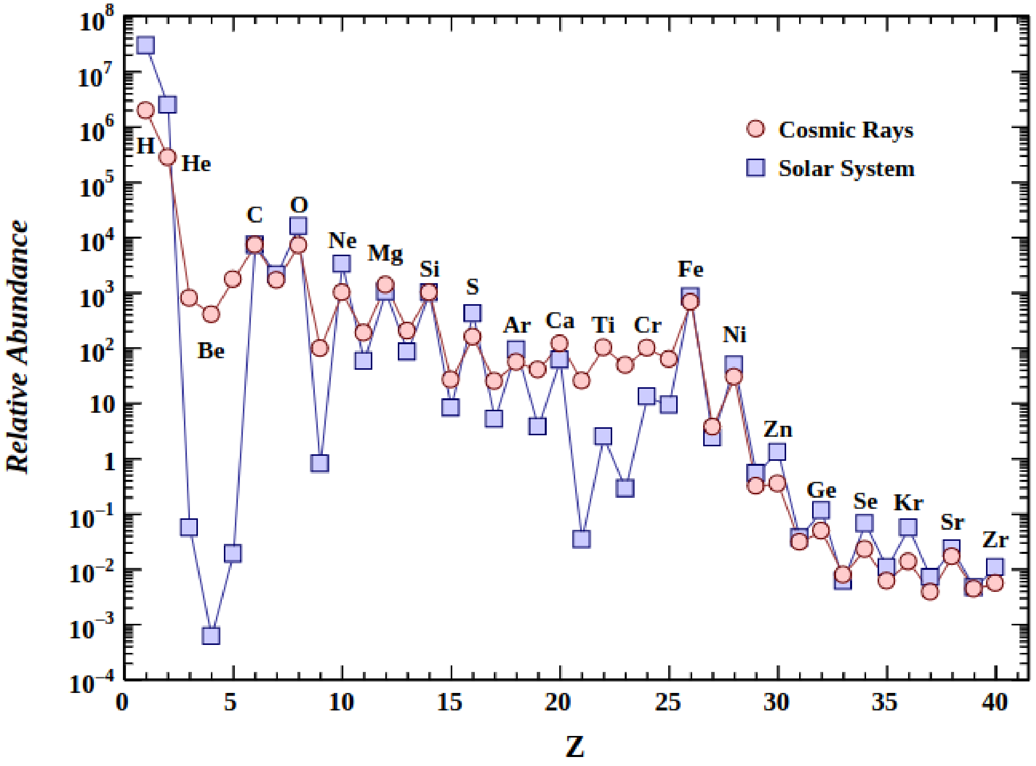
Cosmic rays



Credit: ASPERA/Novapix/L. Bret

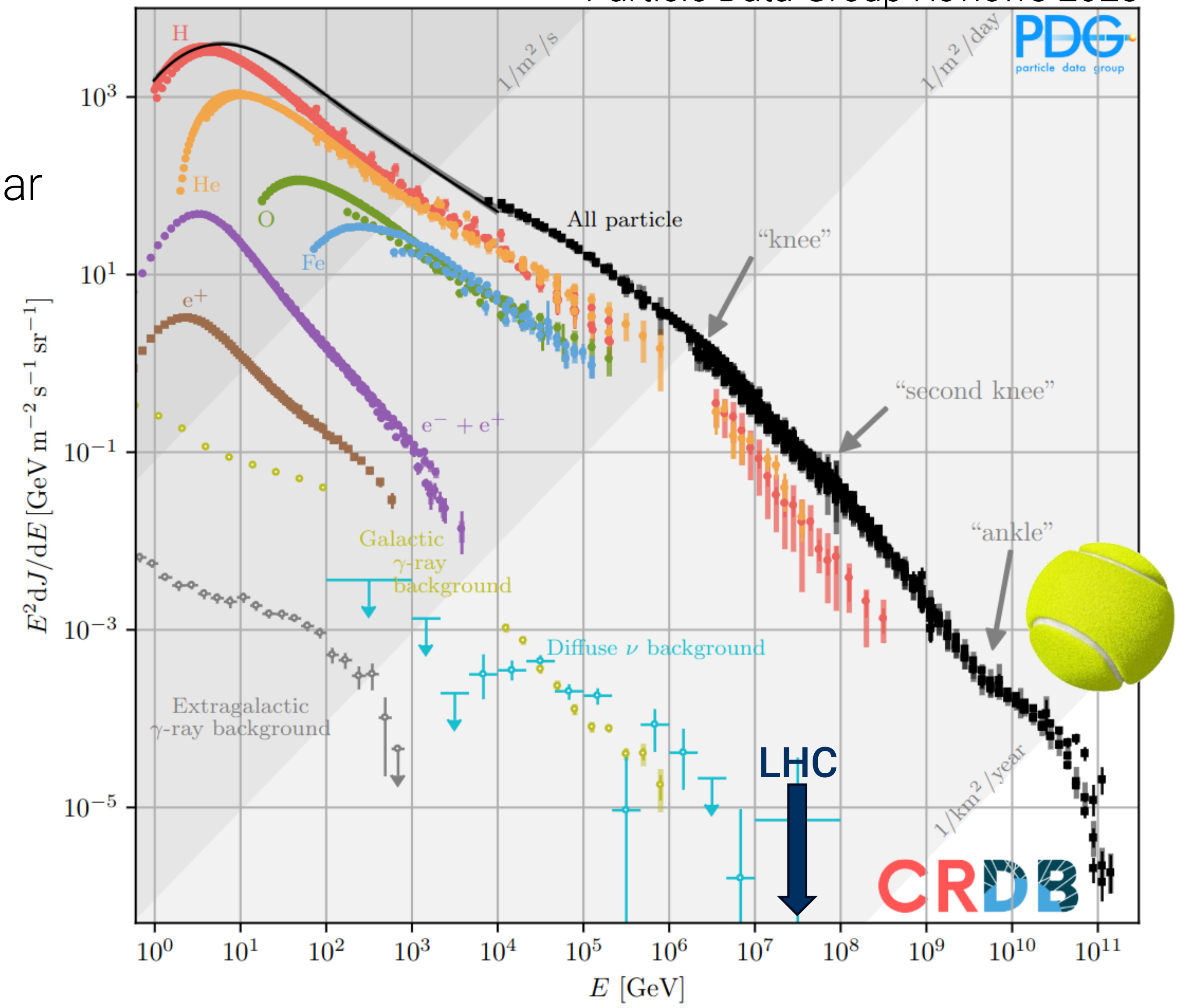
What are cosmic rays (CRs)?

- **Relativistic particles** originating outside the solar system (Galactic & extra-galactic)
  → ~99% atomic nuclei (90% p or H), ~1% e$^-$



Particle Data Group Reviews 2022

Particle Data Group Reviews 2023



Where do cosmic rays come from?

- Mostly: **particles accelerated in SN shock fronts**
  → up to knee (protons) and beyond (heavier atoms)
  → **diffusive shock acceleration** (Fermi acceleration)
  → highest energies: extra-galactic (AGNs?)
- Particles repeatedly cross shock front and each time gain energy (Krymskii 1977, Axford+1978, Bell 1978, Blandford & Ostriker 1978)

$$\frac{\Delta\epsilon}{\epsilon} = \frac{v_{\rm shock}}{c}$$

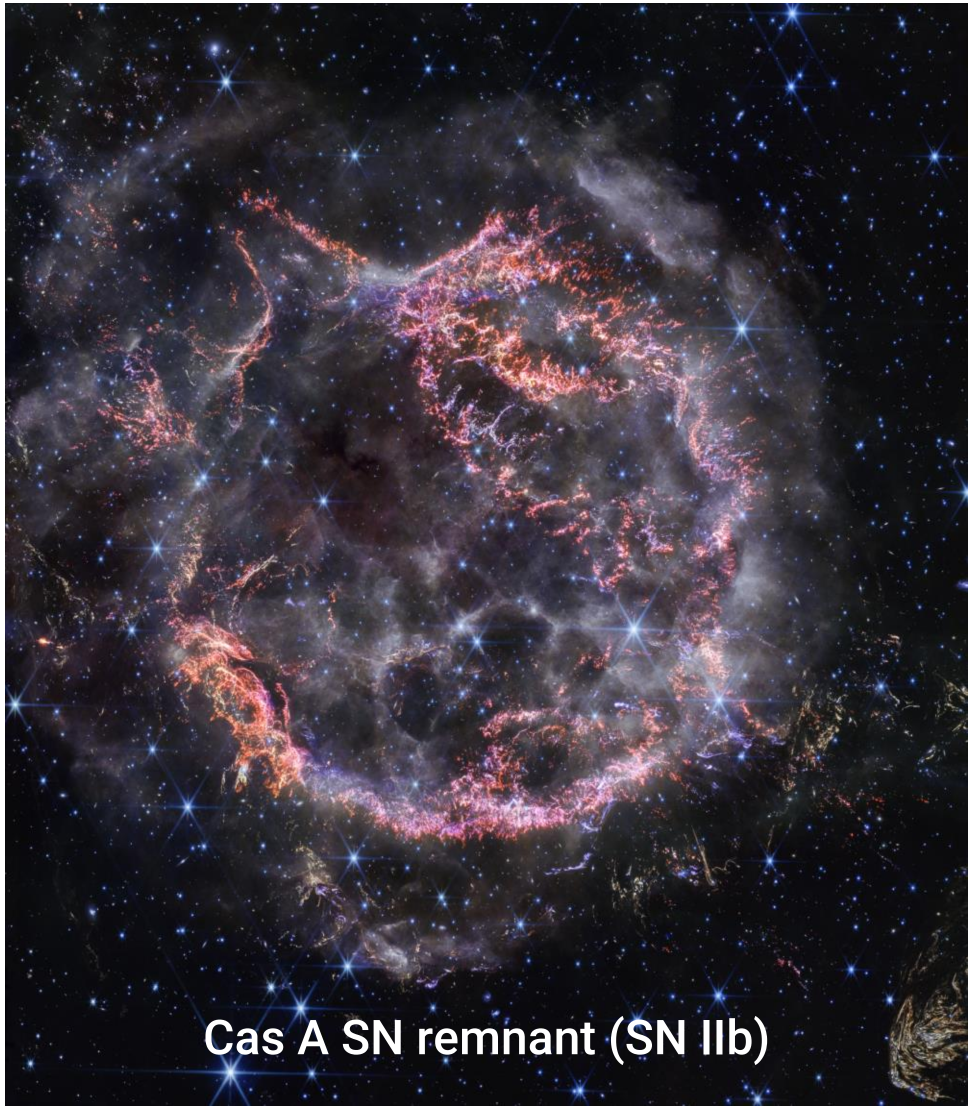
- Results in power-law energy distribution
- Fits energetics in MW: CRs diffusive escape losses

$$L_{\rm CR} = \frac{V_{\rm MW}\varepsilon_{\rm CR}}{\tau_{\rm esc}} \sim 3\times10^{40}\,{\rm erg\,s^{-1}}$$

- Can transfer ~10% of SN shock energy to CRs

$$L_{\rm CR} \sim 0.1 L_{\rm SN} \sim \frac{0.1 E_{\rm SN}}{\tau_{\rm SN}} \sim \frac{0.1\times10^{51}\,{\rm erg}}{100\,{\rm yr}} \sim 3\times10^{40}\,{\rm erg\,s^{-1}}$$

Credit: NASA, ESA, CSA, STScI, Danny Milisavljevic, Ilse De Looze, Tea Temim

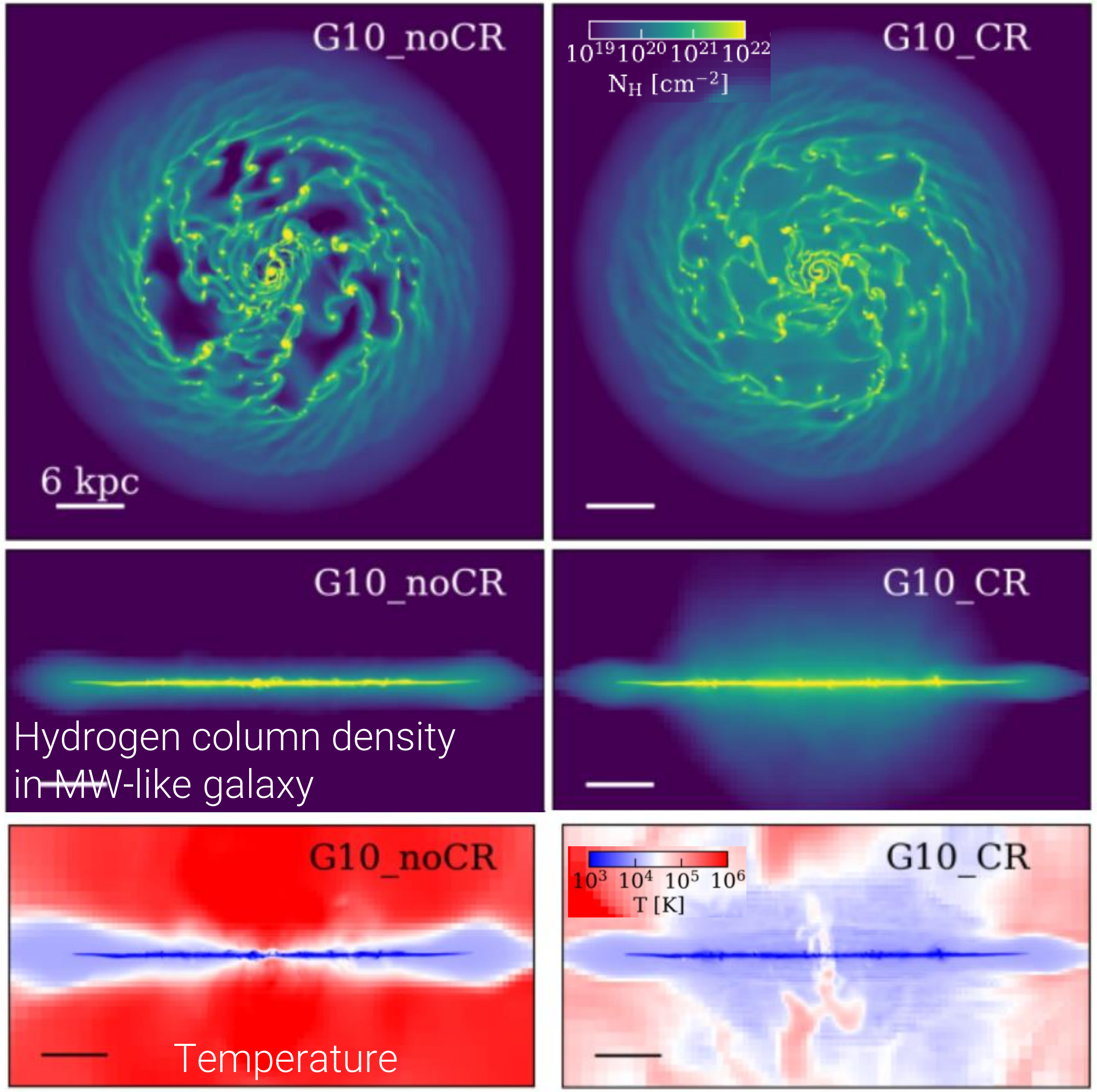


Cas A SN remnant (SN IIb)

What is the feedback of cosmic rays?

- Review: **Ruszkowski & Pfrommer 2023**

- CRs meander along B-fields of galaxies or escape galaxy depending on energy
- CRs ionization (most have few GeV & can penetrate optically thick regions)
- CR-driven galactic winds → CR pressure gradient
- CR feedback reduces SF rate
  → helps solve missing satellites problem?
- CRs lead to cooler ISM and galactic outflows
- Nucleosynthesis: production of Li, Be and B



Farcy et al. 2022

Hydrogen column density in MW-like galaxy

Temperature

Binary stars

Credit: ESO/M. Kornmesser/S.E. de Mink

Binary stars

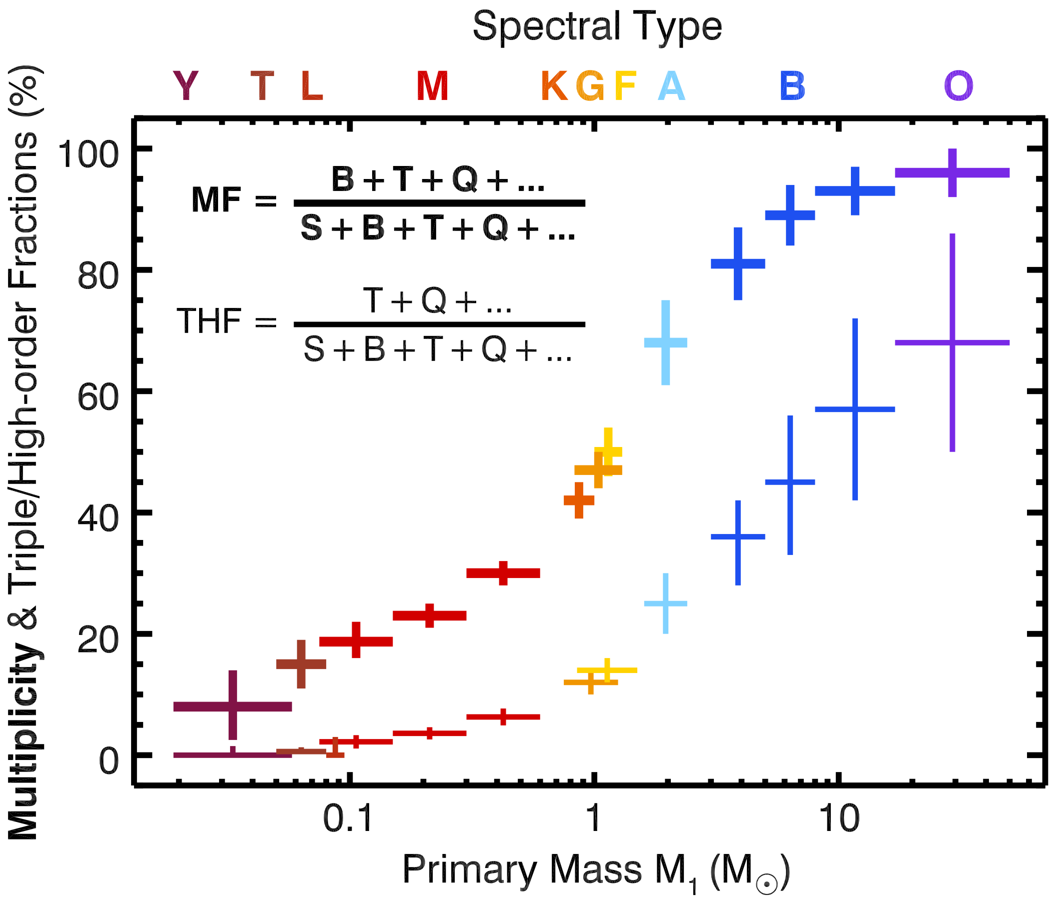
- **Most massive stars are in binaries** (Sana+2012, *Science*)
  → huge consequences for evolution and final fate

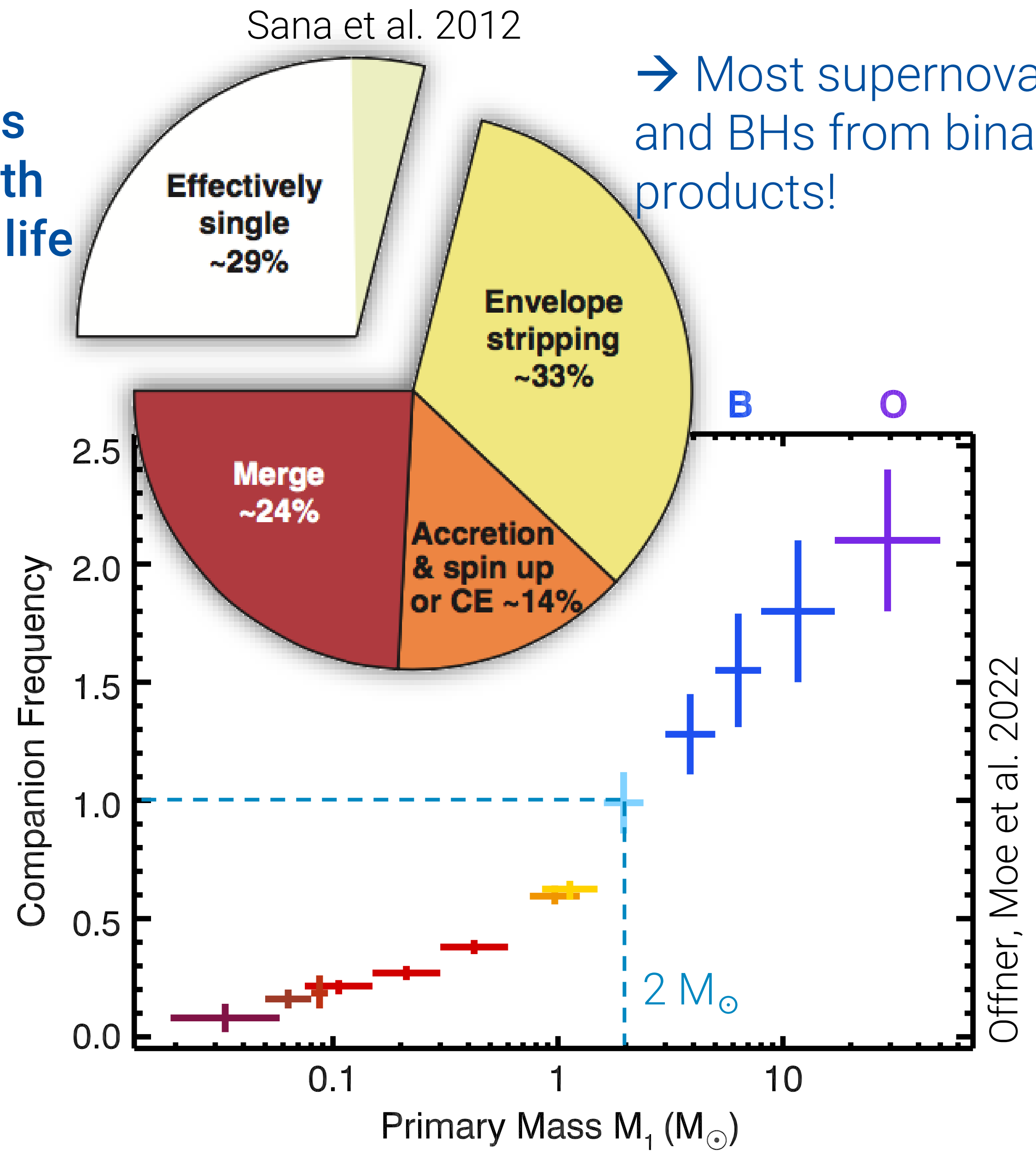
Credit: ESO/L. Calçada/M. Kornmesser/S.E. de Mink

Binary stars

Most massive stars exchange mass with companion during life

→ Most supernovae and BHs from binary products!



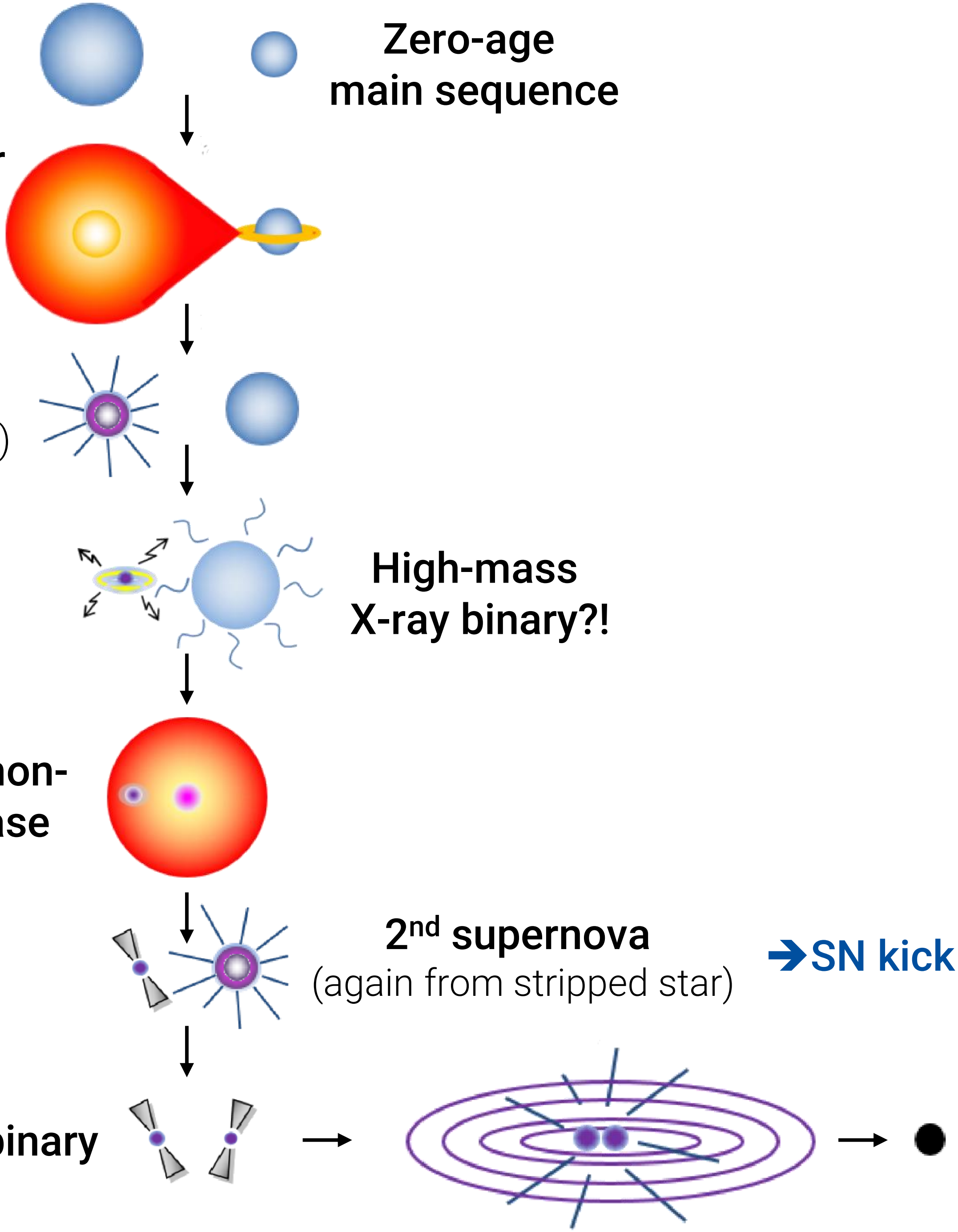


Sana et al. 2012

Offner, Moe et al. 2022

e.g. Kobulnicky & Fryer 2007, Mason+2009, Sana+2012, 2013, Chini+2012, Kobulnicky+2014, Moe & Di Stefano 2017, …

Binary stars



Zero-age main sequence

1st mass transfer phase

1st supernova
(from stripped star)

→SN kick!

High-mass X-ray binary?!

2nd MT: common-envelope phase

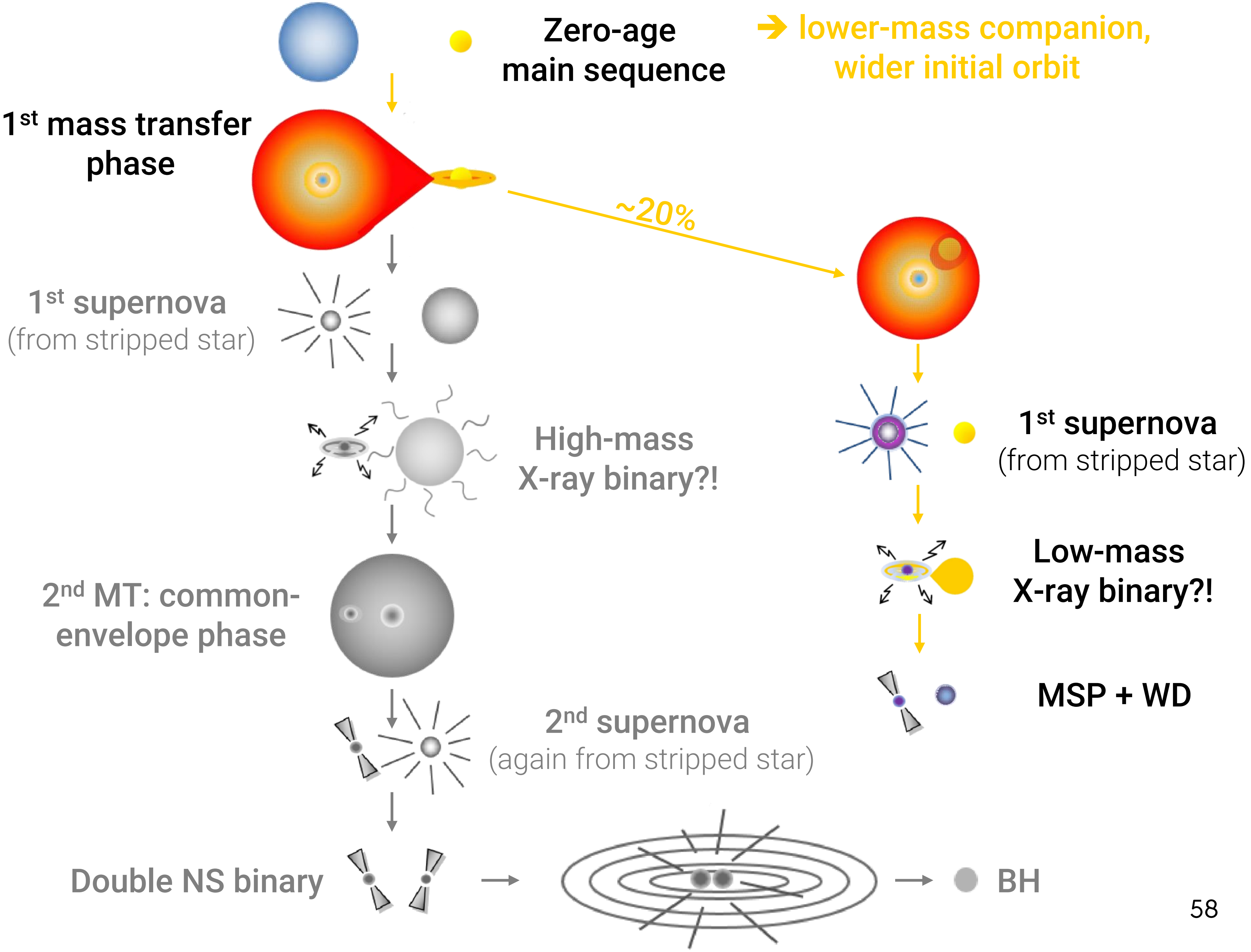
2nd supernova
(again from stripped star)

→SN kick!

Double NS binary → → **BH**

Image credits: Thomas Tauris

Binary stars



Zero-age main sequence

➔ lower-mass companion, wider initial orbit

1st mass transfer phase

~20%

1st supernova
(from stripped star)

High-mass X-ray binary?!

1st supernova
(from stripped star)

Low-mass X-ray binary?!

2nd MT: common-envelope phase

MSP + WD

2nd supernova
(again from stripped star)

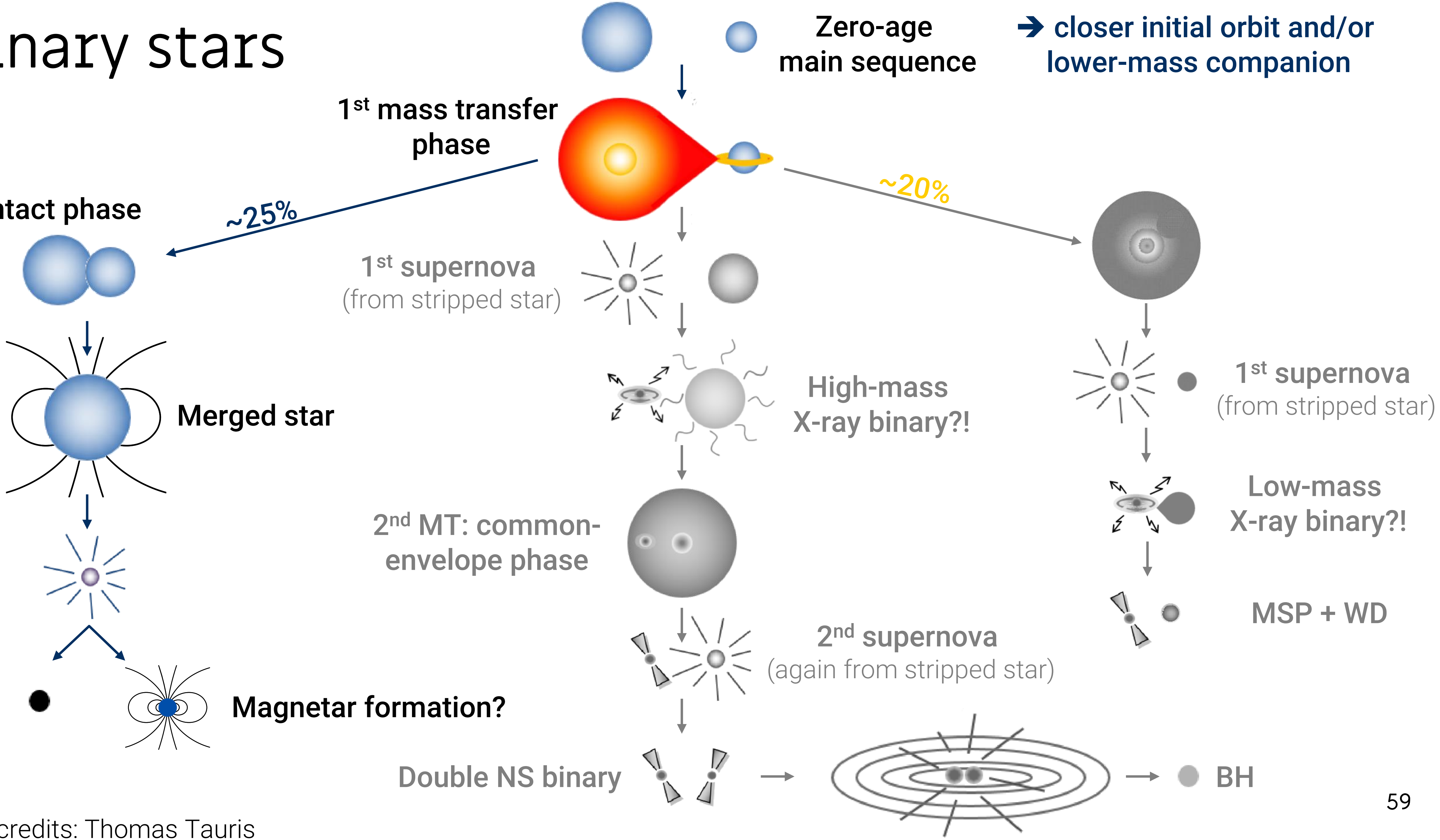
Double NS binary

→

→ BH

Image credits: Thomas Tauris

Binary stars



Zero-age main sequence

➔ closer initial orbit and/or lower-mass companion

1st mass transfer phase

~25%

~20%

Contact phase

Merged star

BH

Magnetar formation?

1st supernova (from stripped star)

High-mass X-ray binary?!

2nd MT: common-envelope phase

2nd supernova (again from stripped star)

Double NS binary

BH

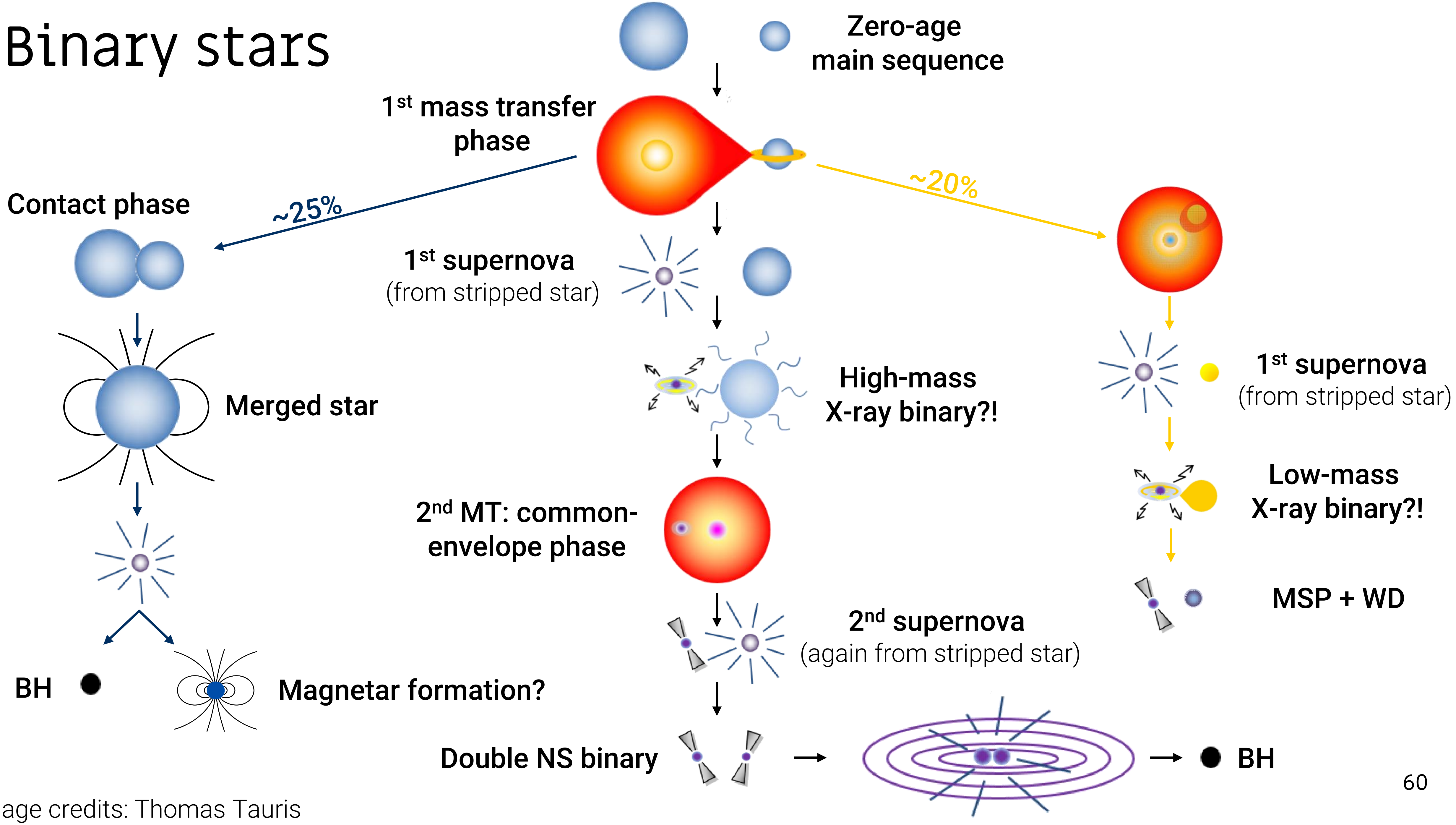
1st supernova (from stripped star)

Low-mass X-ray binary?!

MSP + WD

Image credits: Thomas Tauris

Binary stars



Zero-age main sequence

1st mass transfer phase

~25%

~20%

Contact phase

1st supernova
(from stripped star)

Merged star

High-mass X-ray binary?!

1st supernova
(from stripped star)

Low-mass X-ray binary?!

2nd MT: common-envelope phase

MSP + WD

2nd supernova
(again from stripped star)

BH

Magnetar formation?

Double NS binary

BH

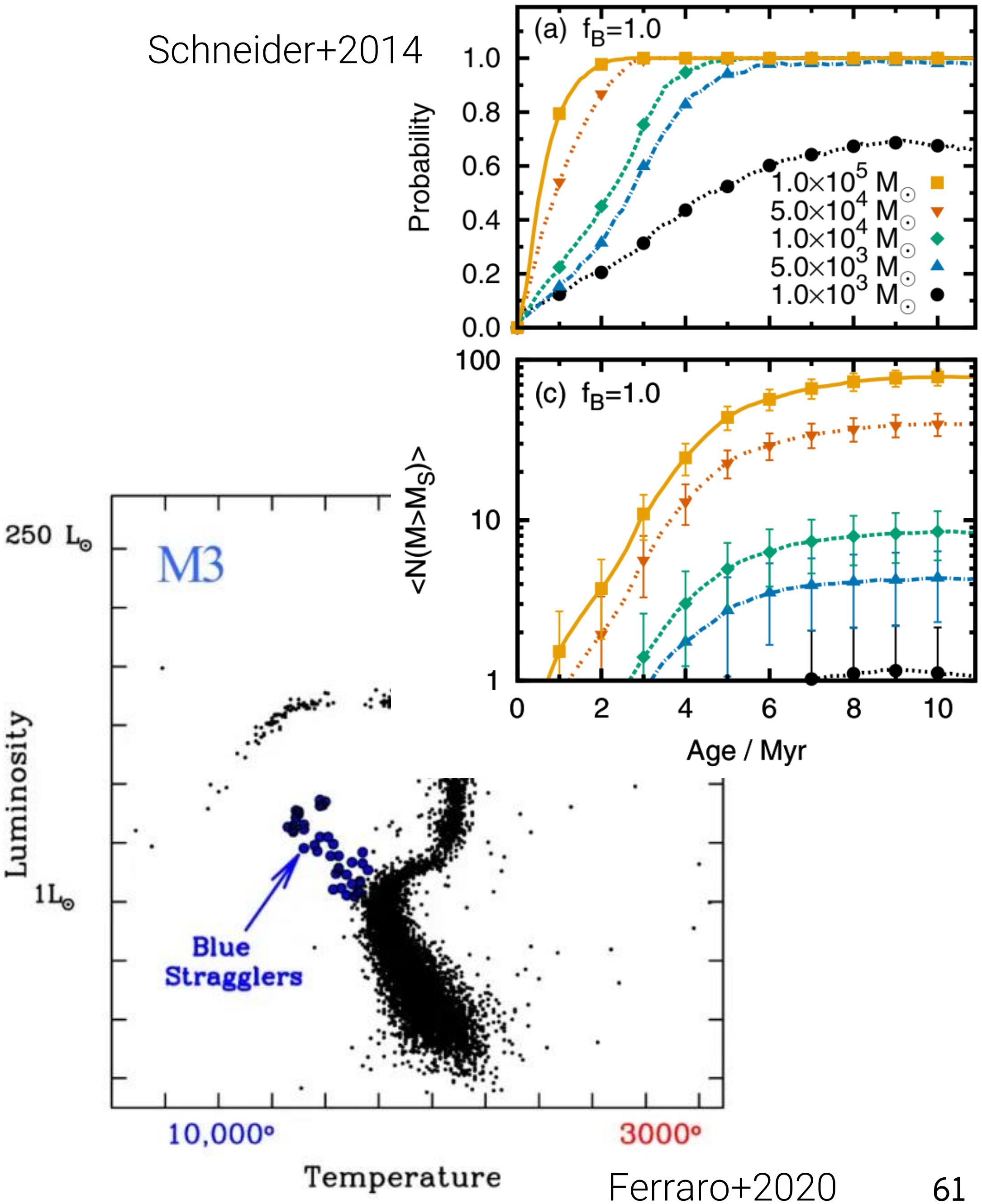
Image credits: Thomas Tauris

The most massive stars

Blue stragglers and rejuvenation

- **30 Doradus**: observationally, the **most massive ~30** out of ~1200 hot stars (→ WR, Of, WNh) contribute **40−50% to ionising and wind luminosity** (Doran+2013)
- Good chance that **several are blue stragglers**

- **Blue stragglers:** hot (i.e. blue) and luminous extension of main-sequence in star clusters
- **Origin:** accretors of binary mass transfer and/or stellar mergers (→ binary evolution & cluster dynamics)
- Blue stragglers are **rejuvenated** and **appear younger**
- Show up within Myr
- ➔ delayed feedback from massive stars



Schneider+2014

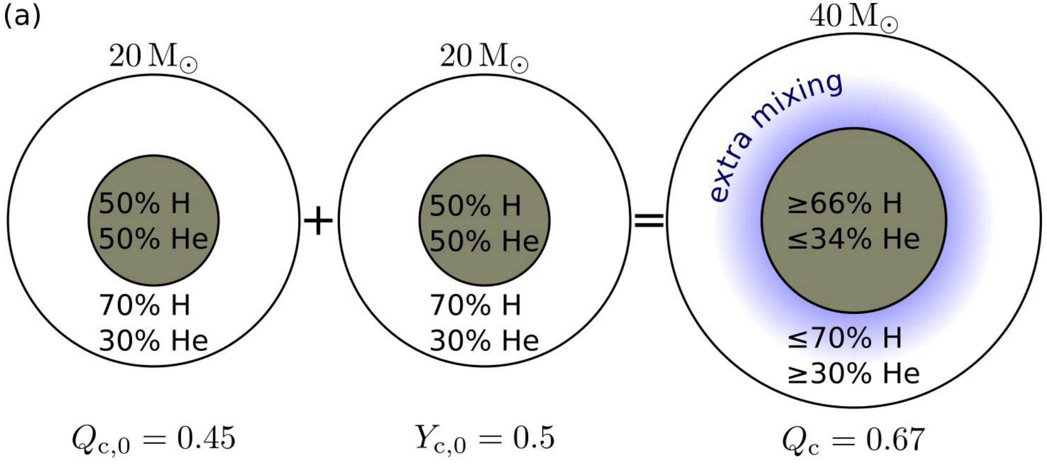
Ferraro+2020

Blue straggler stars: rejuvenation

Rejuvenation

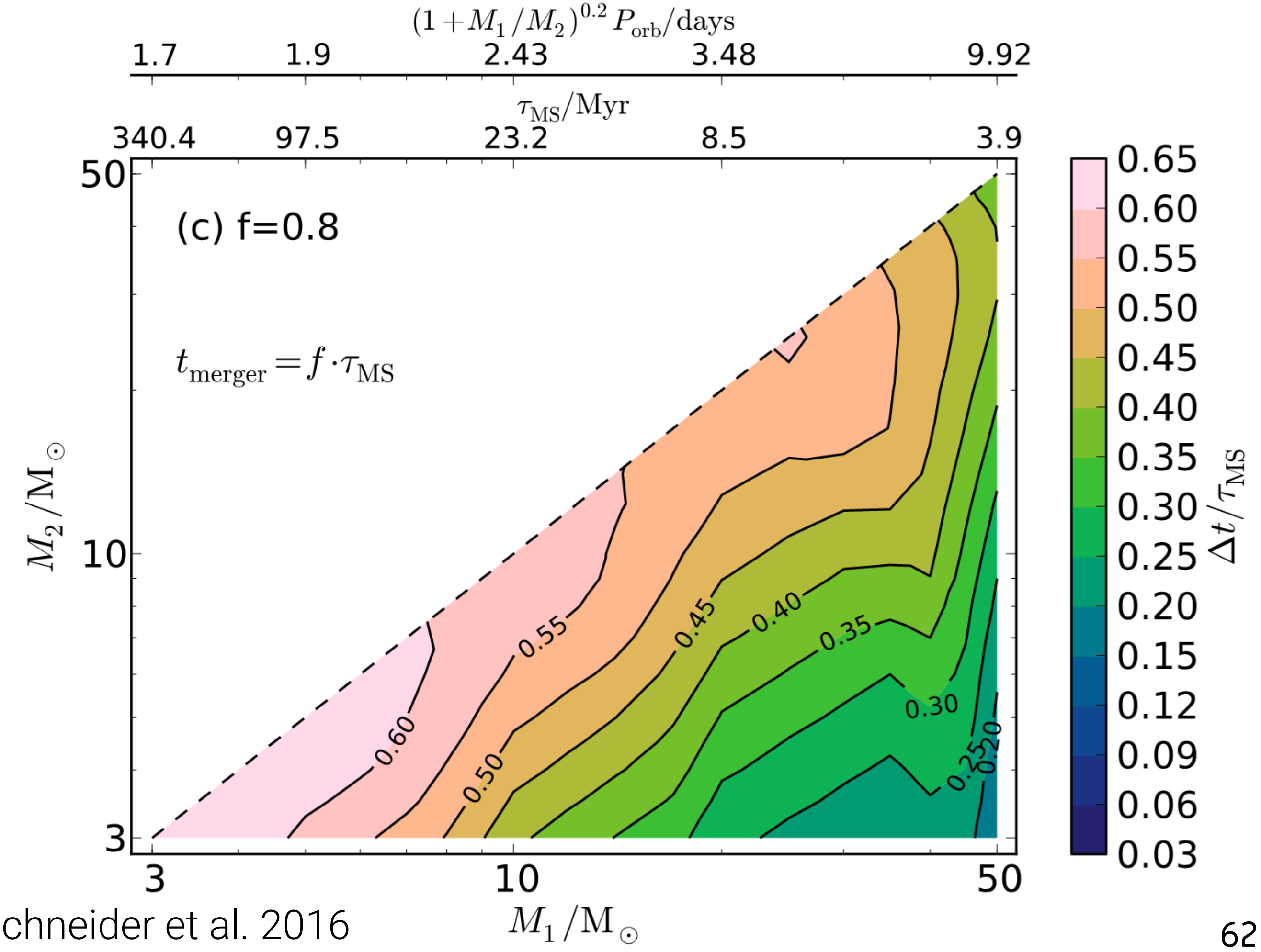
- **Apparent:** shorter lifetimes associated with more massive star
- **True:** mixing of fresh fuel into core (mixing during coalescence & transient conv. core during thermal relaxation)

Warning: cluster age determination



$$\Rightarrow Y_c = \frac{Q_{c,0}}{\alpha Q_c} Y_{c,0} \leq Y_{c,0} \quad \Rightarrow \Delta Y_c = Y_{c,0} - Y_c \propto Y_{c,0}$$

Simple rejuvenation recipes calibrated on mixing in SPH head-on collisions: **Glebbeek & Pols 2008**, Glebbeek et al. 2013, Schneider et al. 2016



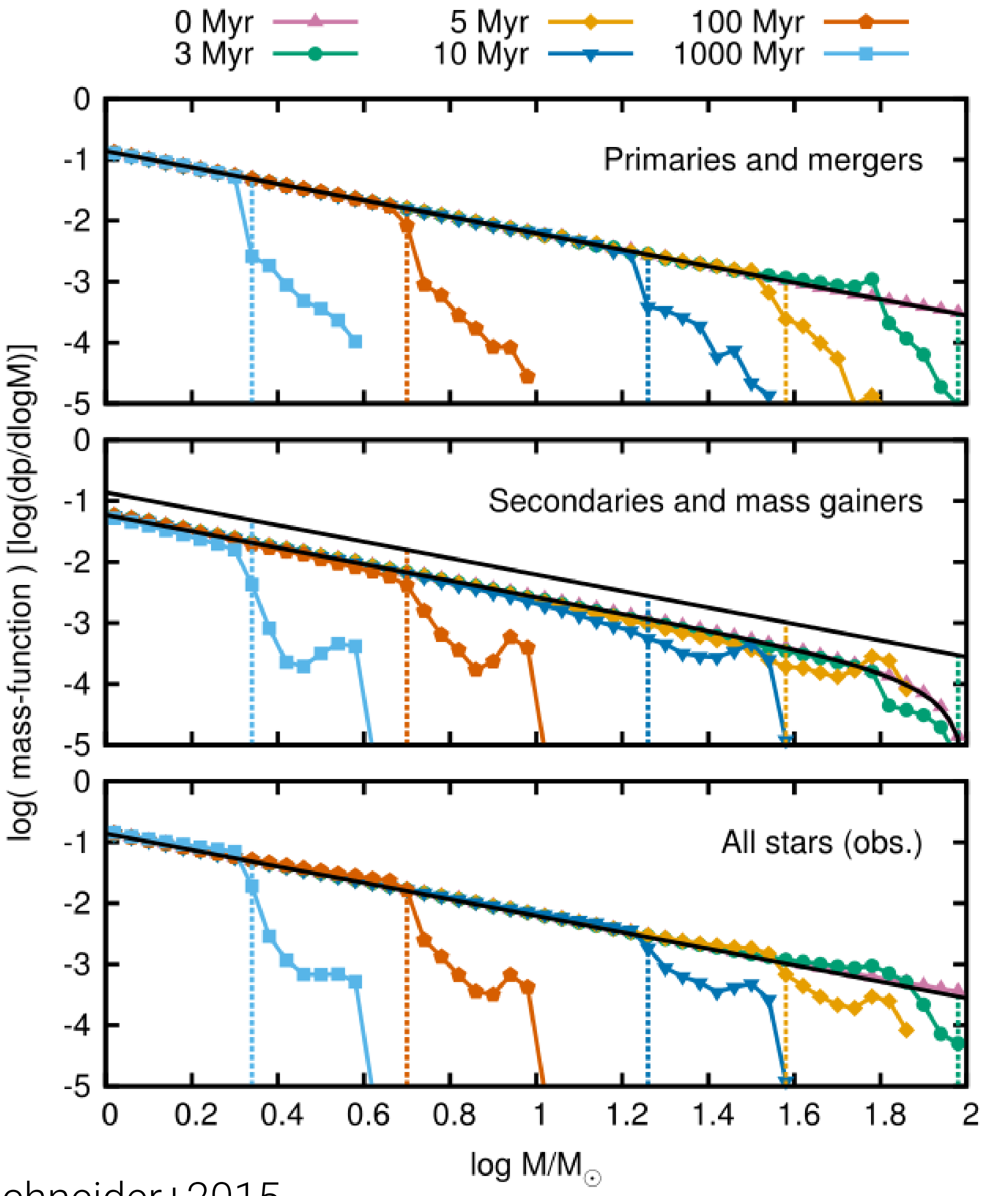
Schneider et al. 2016

The most massive stars

Effective mass function

- Blue stragglers up to ~twice more massive
- For feedback matters, treat as extension of the mass function of a stellar population

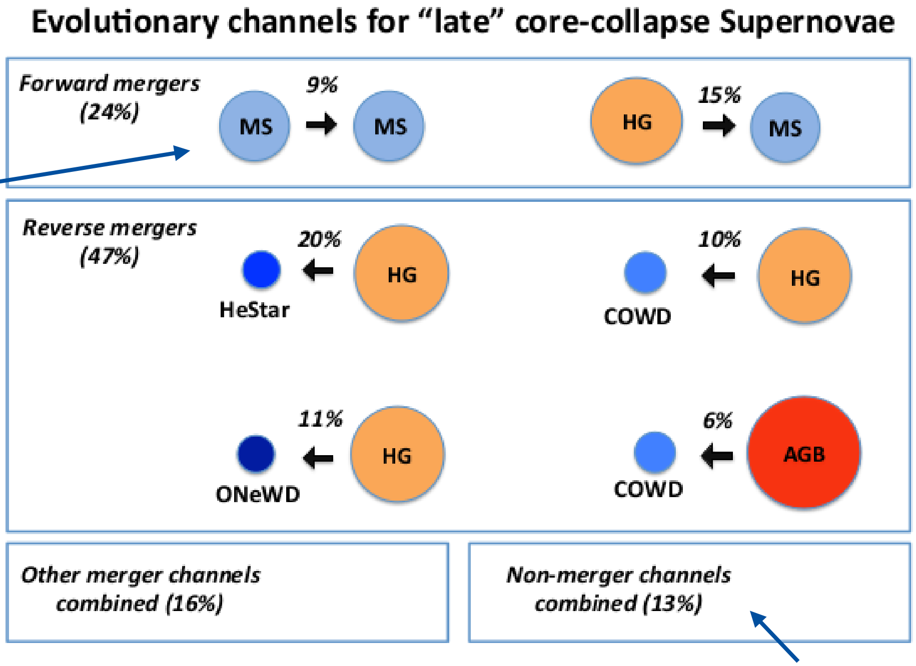
- **Example**: massive blue stragglers increase ionizing radiation and lead to delayed feedback because of rejuvenation
  → increase escape fraction of ionizing radiation
  (e.g. Secunda+2020)



Schneider+2015

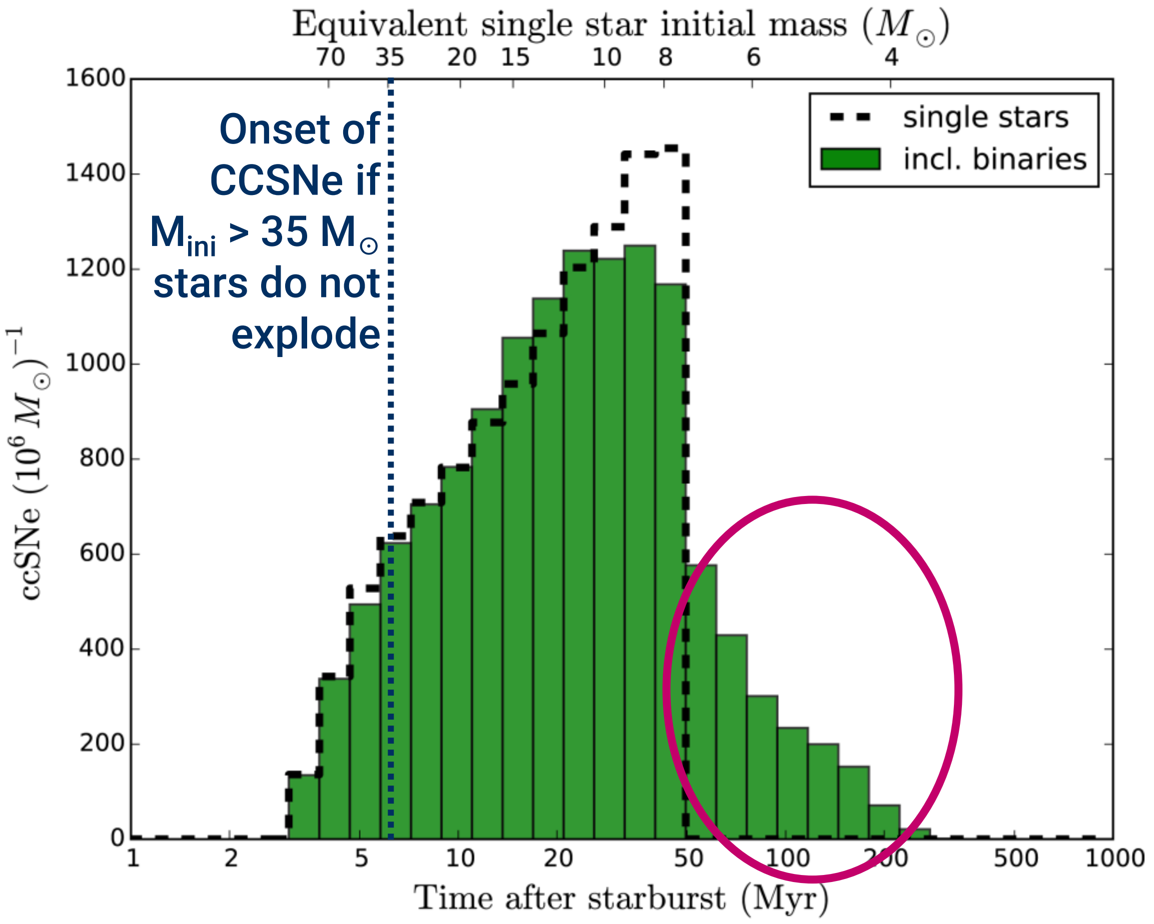
Delayed SN feedback from massive binary stars

- Binary mass accretion & mergers lead to late SNe compared to single stars
  - SNe from single stars over after ~50 Myr
  - With binaries, **~15% of SNe at ages >50 Myr**



BSS

BSS (accreting secondaries)

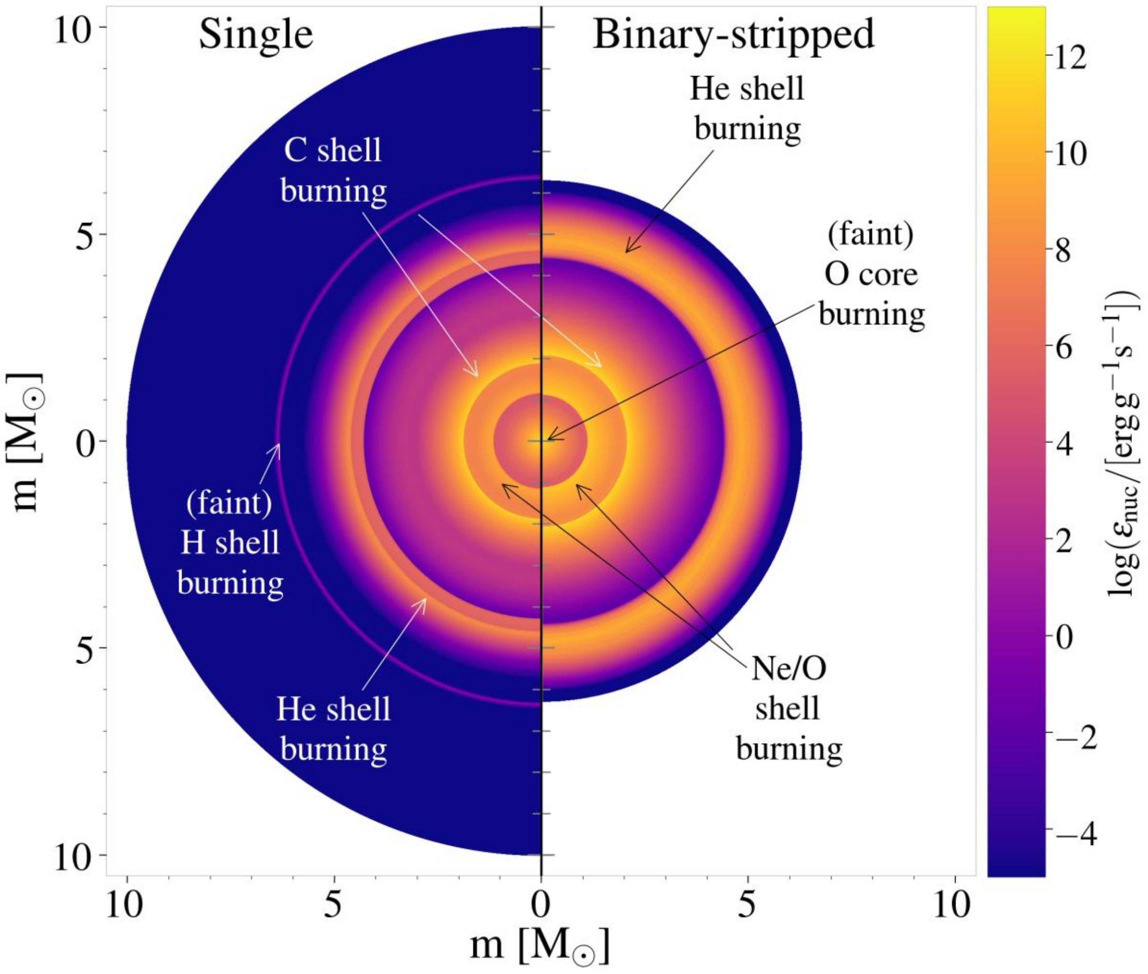


Onset of CCSNe if M_{ini} > 35 $M_\odot$ stars do not explode

Zapartas+2017

Stripped binary stars

Explodability and SN energetics



Laplace et al. 2021; **TULIPS visualisation** (Laplace 2022)

Nuclear burning structure in **single** vs. **binary-stripped star** at end of core oxygen burning
→ same 6.3 M$_\odot$ core mass (Case B)

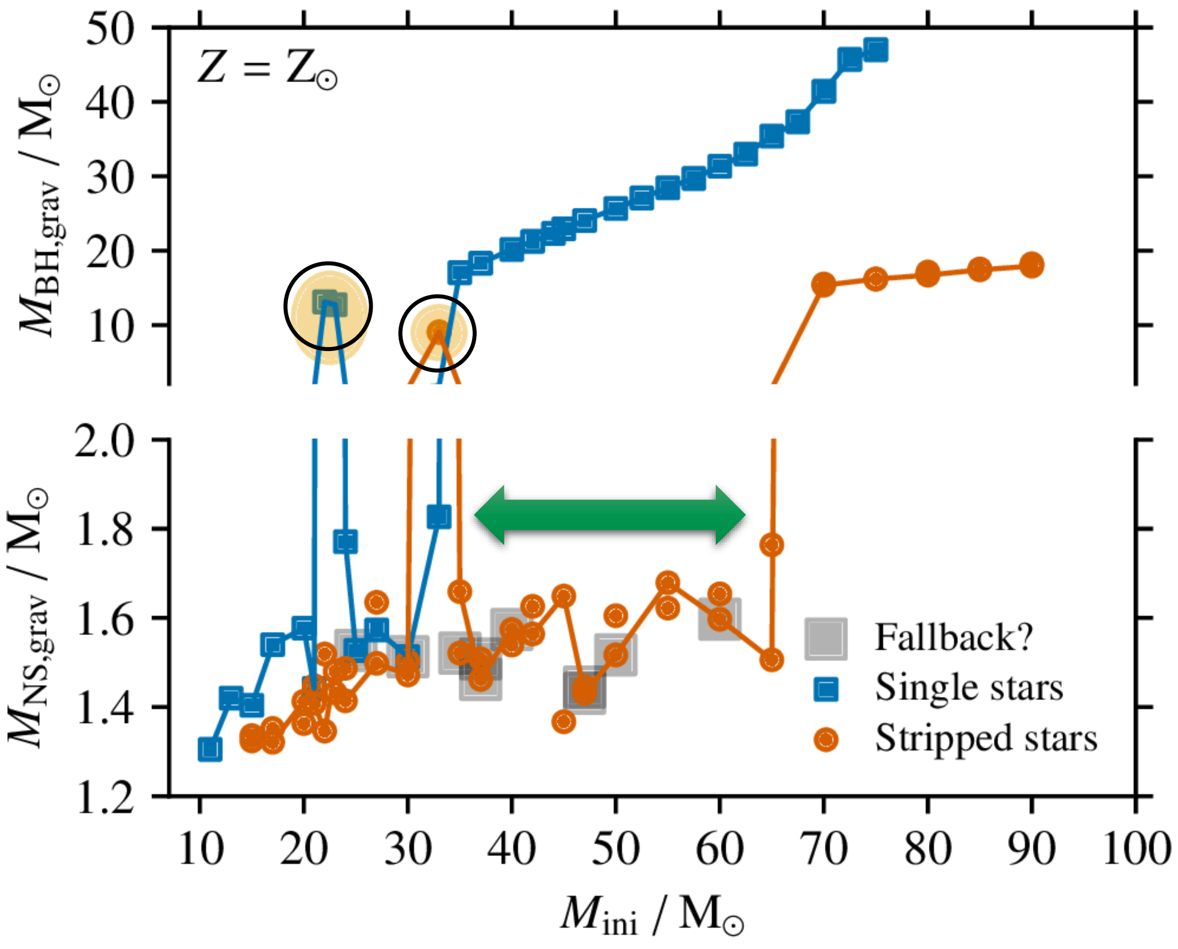
Clearly **different burning properties** mainly caused by absence of hydrogen shell burning

Stripped stars have *different* pre-SN structure

(cf. Timmes+1996, Wellstein & Langer 1999, Brown+2001, Podsiadlowski+2004, Woosley 2019, Schneider+2021, …)

Stripped binary stars

Explodability and SN energetics



Schneider et al. 2021

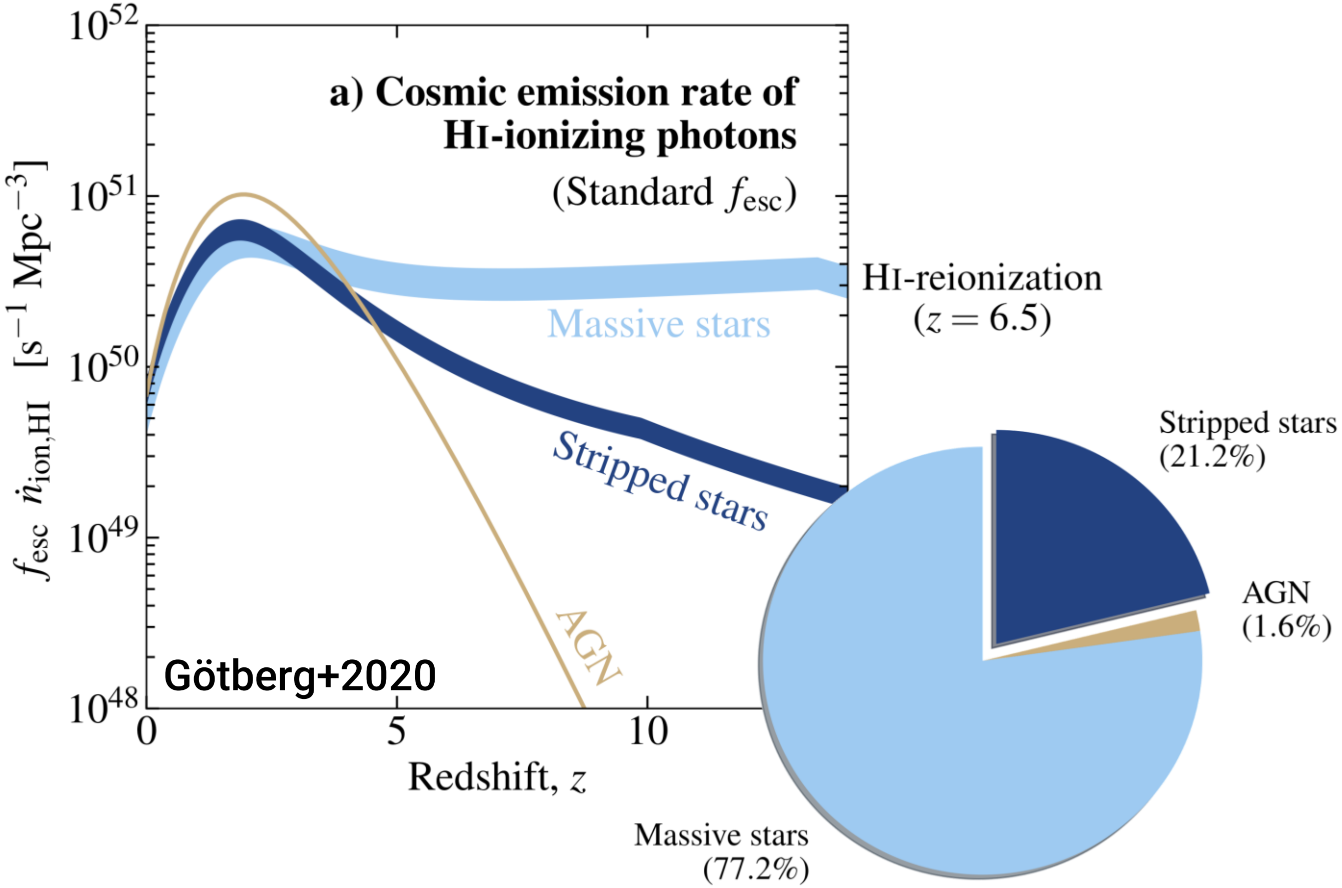
- **Island of BH formation** (compactness-peak BHs)
- **Neutron star formation/SN explosions:**
  → Single stars: $M_{ini} < 35\ M_\odot$
  → Binary-stripped stars: $M_{ini} < 70\ M_\odot$
- Stripped stars have **higher explosion energies** ($\Delta E_{expl} \sim 0.2$ B)

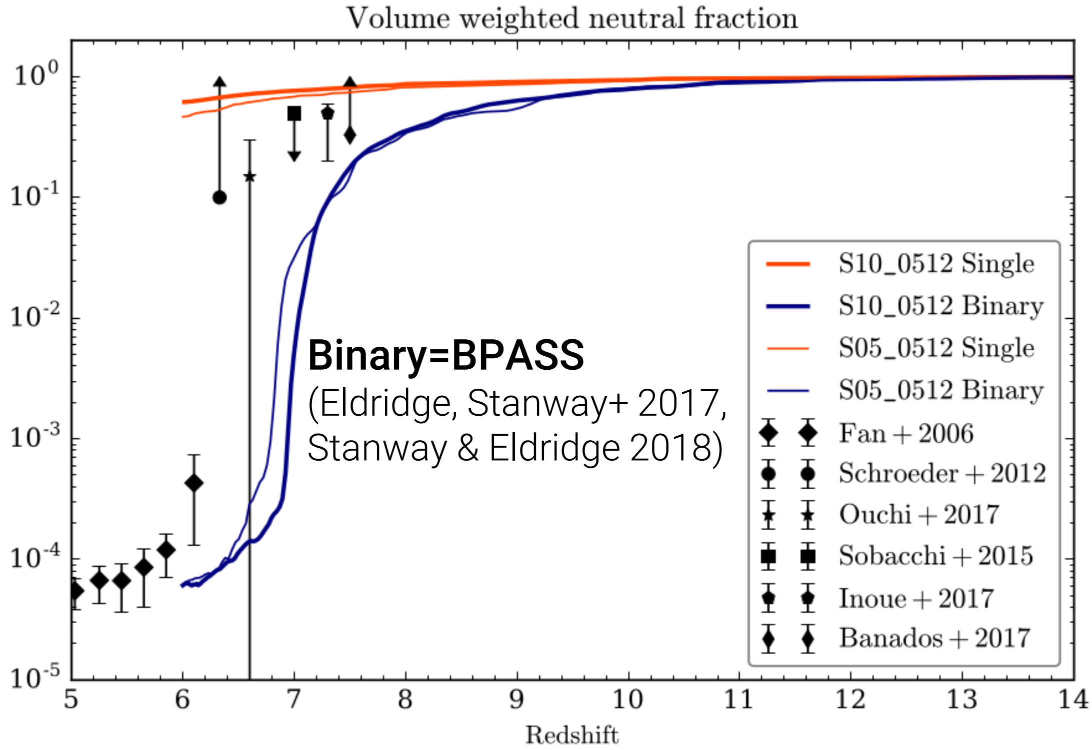
- **Implications for feedback**
  - First SNe from stripped stars (~4 Myr) & on average more energetic
  - SNe from genuine single stars after ~6 Myr
  - Metallicity dependence: higher/lower Z → earlier/later SNe
  - Number of SNe: 35 vs 40 $M_\odot$ → 3% diff.; island of BH formation → 5% diff.

Stripped binary stars

Cosmic reionisation

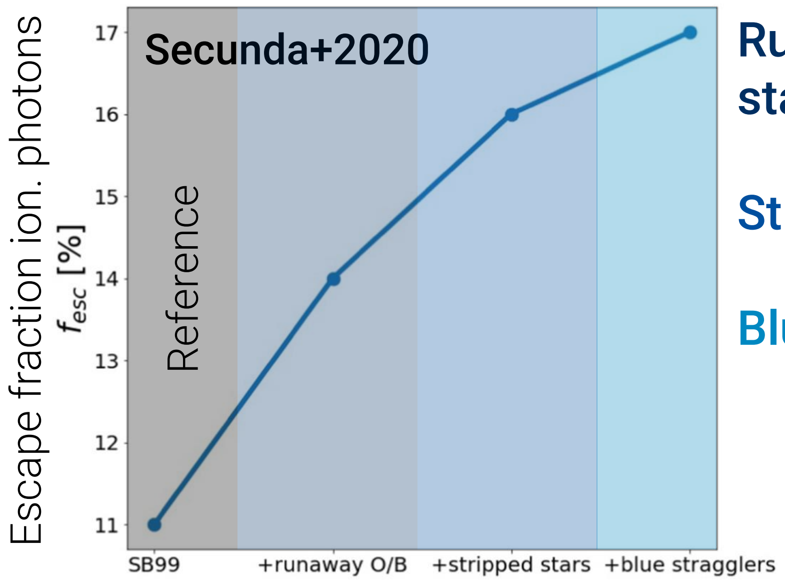
- **Massive stars:** hot, luminosities of up to ~10^6 solar
- **Stripped stars**: high T_{eff} → ionising radiation





Binary=BPASS
(Eldridge, Stanway+ 2017,
Stanway & Eldridge 2018)

Rosdahl+2018, SPHINX



Runaway OB stars

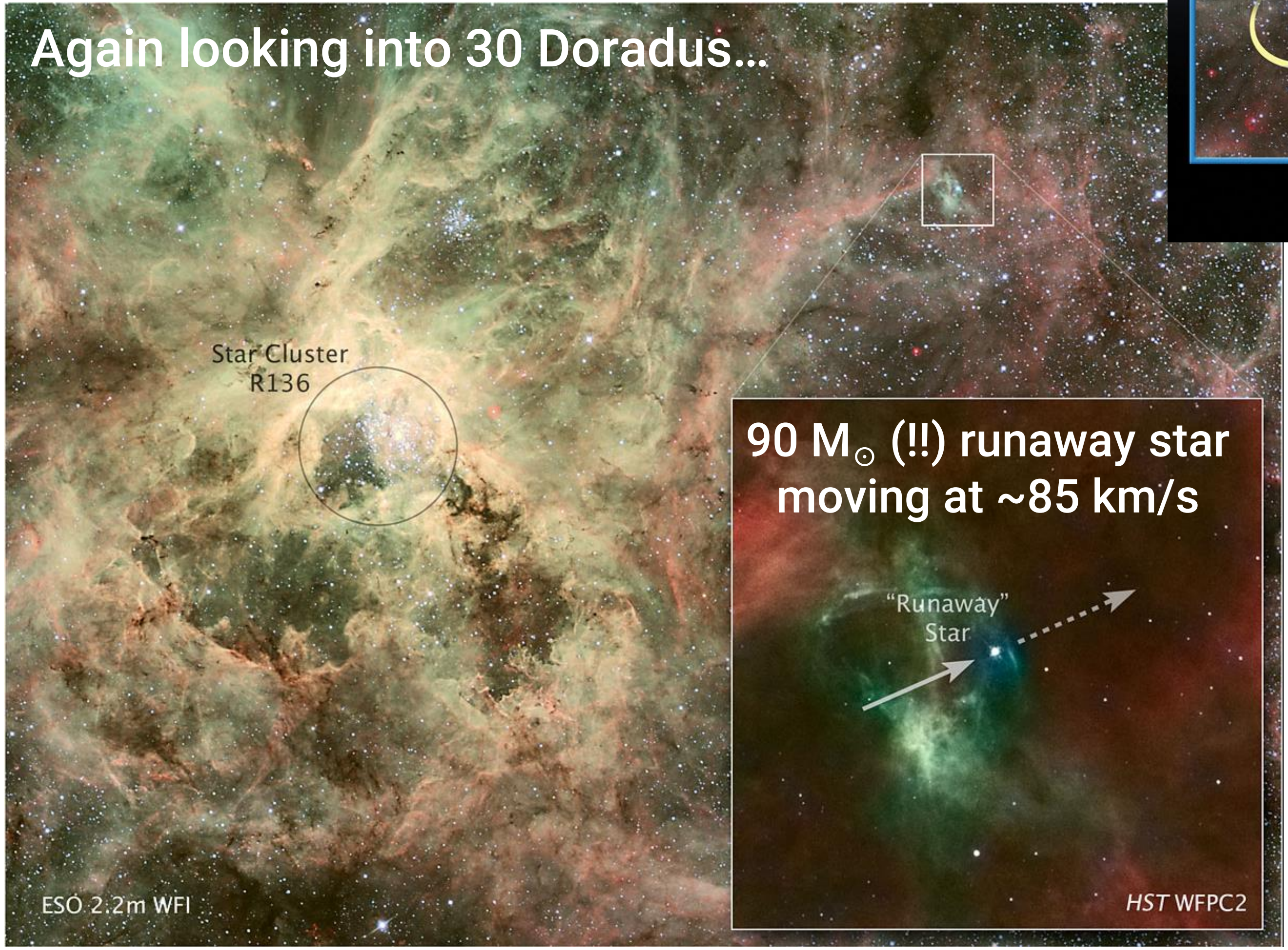
Stripped stars

Blue stragglers

E.g. Stanway+2016, Ma+2016, Rosdahl+2018, Götberg+2018, 2019, 2020, Secunda+2020

Runaway stars

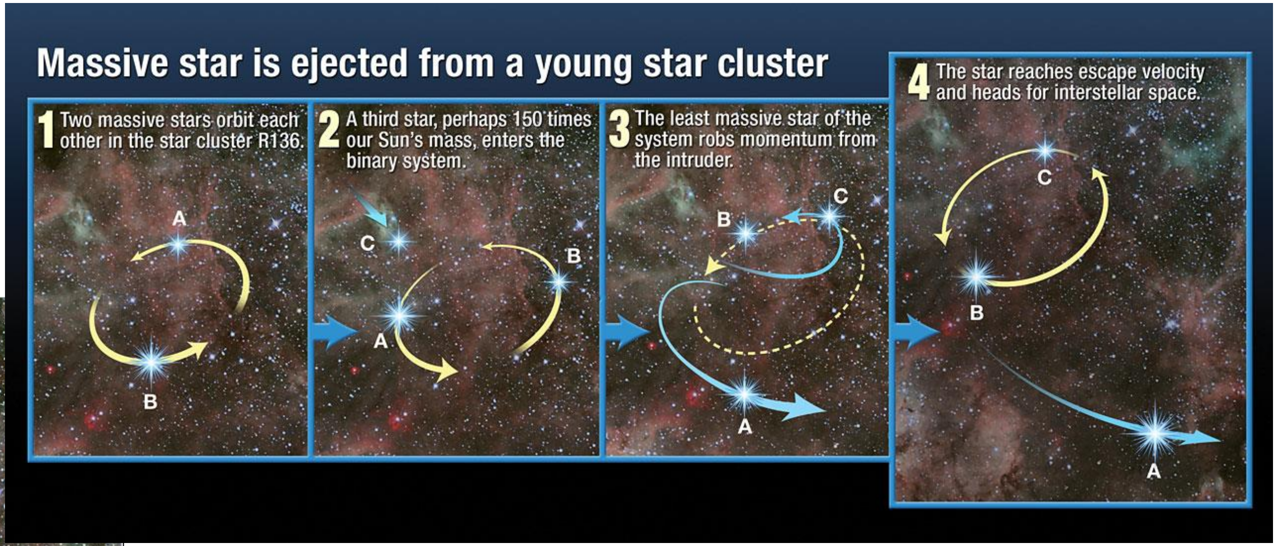
Evans+2010



Again looking into 30 Doradus…

90 $M_\odot$ (!!) runaway star moving at ~85 km/s

Credit: NASA/ESA/STScI/ESO



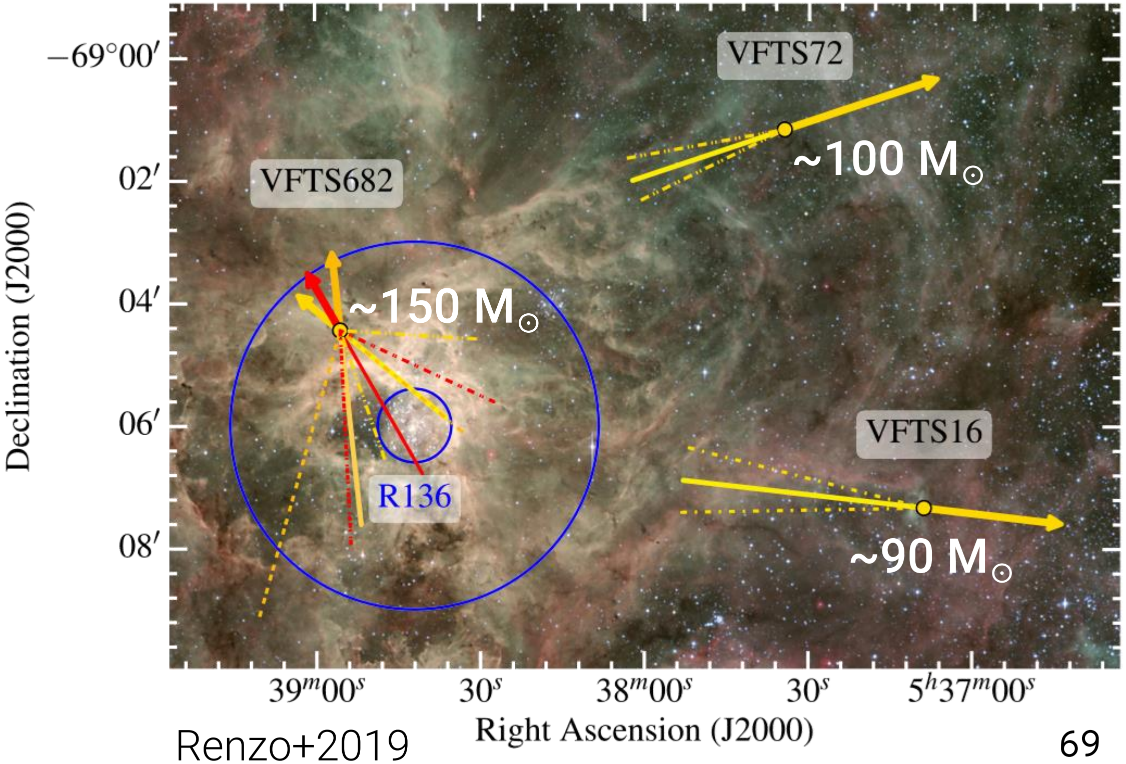
Massive star is ejected from a young star cluster

1 Two massive stars orbit each other in the star cluster R136.

2 A third star, perhaps 150 times our Sun's mass, enters the binary system.

3 The least massive star of the system robs momentum from the intruder.

4 The star reaches escape velocity and heads for interstellar space.



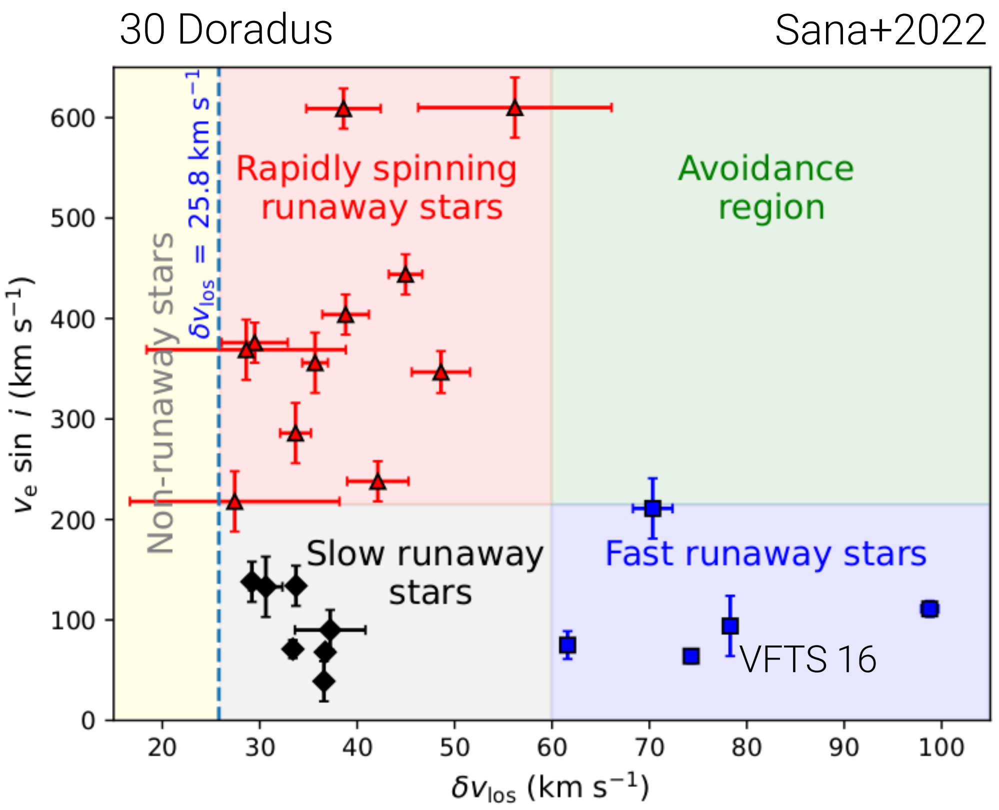
Renzo+2019

Runaway stars

- **Up to 30% of OB stars move at v > 30 km/s**
  → runaways
- **Formation channels:**
  - Dynamical ejection from dense stellar region
  - SN explosion in binary star system
    - Disruption if SN ejecta mass > half of binary mass

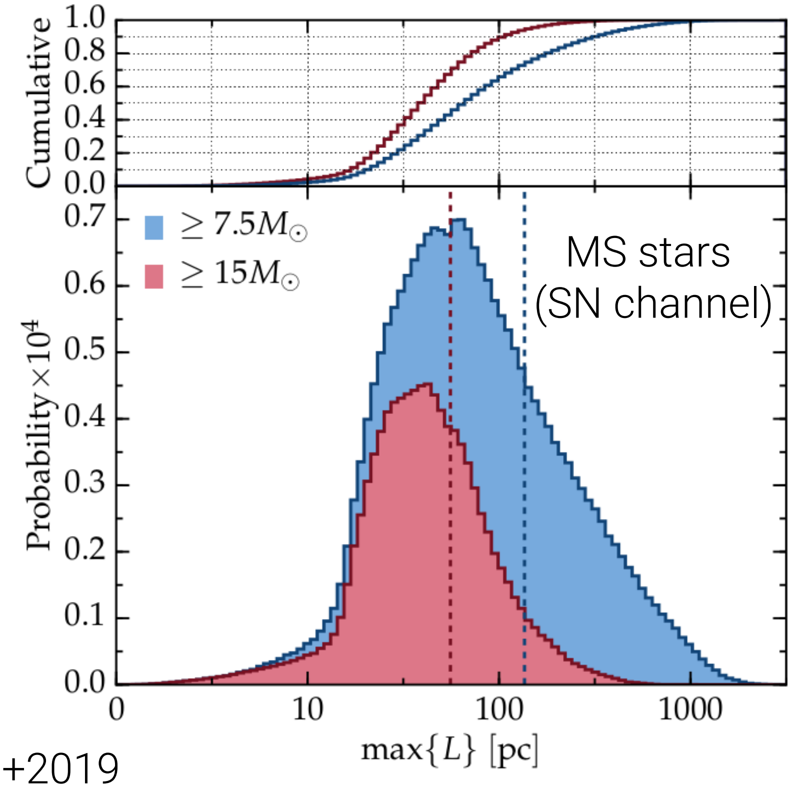
$$\Delta M > \frac{M_1 + M_2}{2}$$

      → star ejected with orbital velocity
    - Kick of NS/BH from SN explosion disrupts binary
      → star ejected with orbital velocity
      → **dominant contribution**
    - Ejected MS stars: slow velocities → walkaways
      (<30-40 km/s, Renzo+2019)

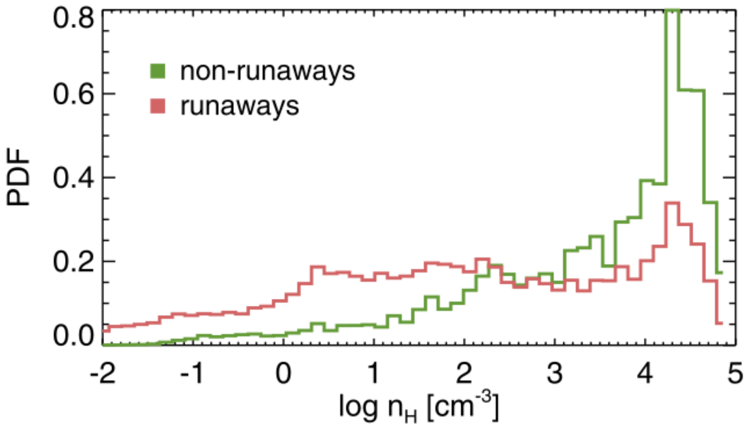


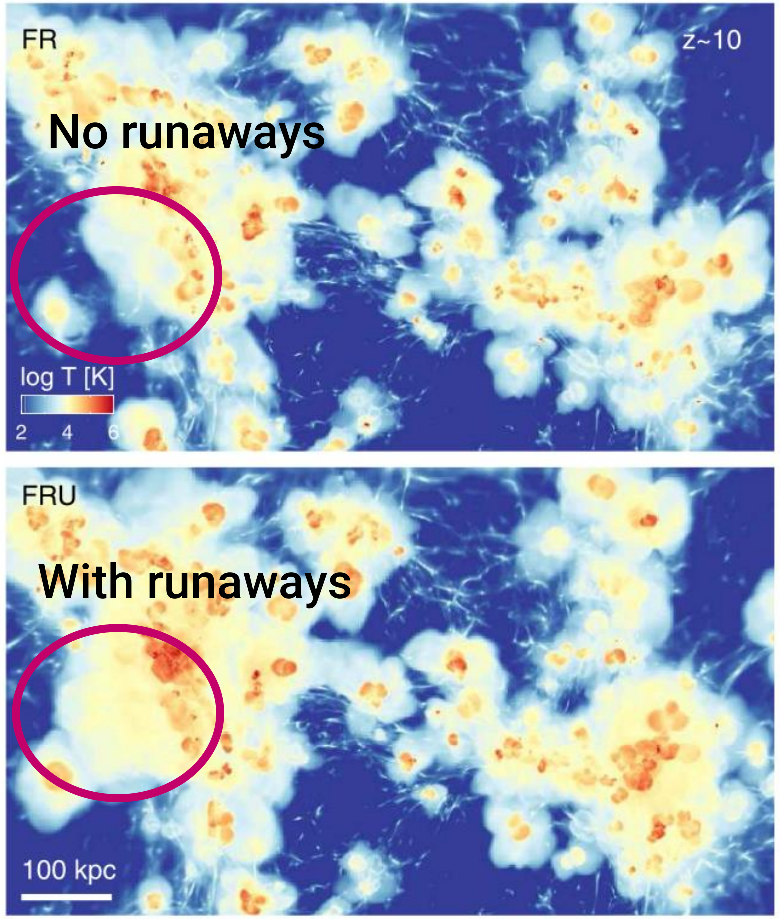
Runaway stars

- Runaways can travel large distances and deposit their feedback (radiation, SNe, winds, …) far from SF sites → e.g. increases escape fraction of ionizing radiation by factors 1.1–8 (Conroy & Kratter 2012, Kimm & Cen 2014, Ma+2016, Secunda+2020)



Renzo+2019





Kimm & Cen 2014

X-ray binaries

Accreting NSs and BHs

Three categories defined by mass of donor star

- **Low-mass X-ray binary (LMXB)**
  → $M_{donor} < 1.5\ M_\odot$

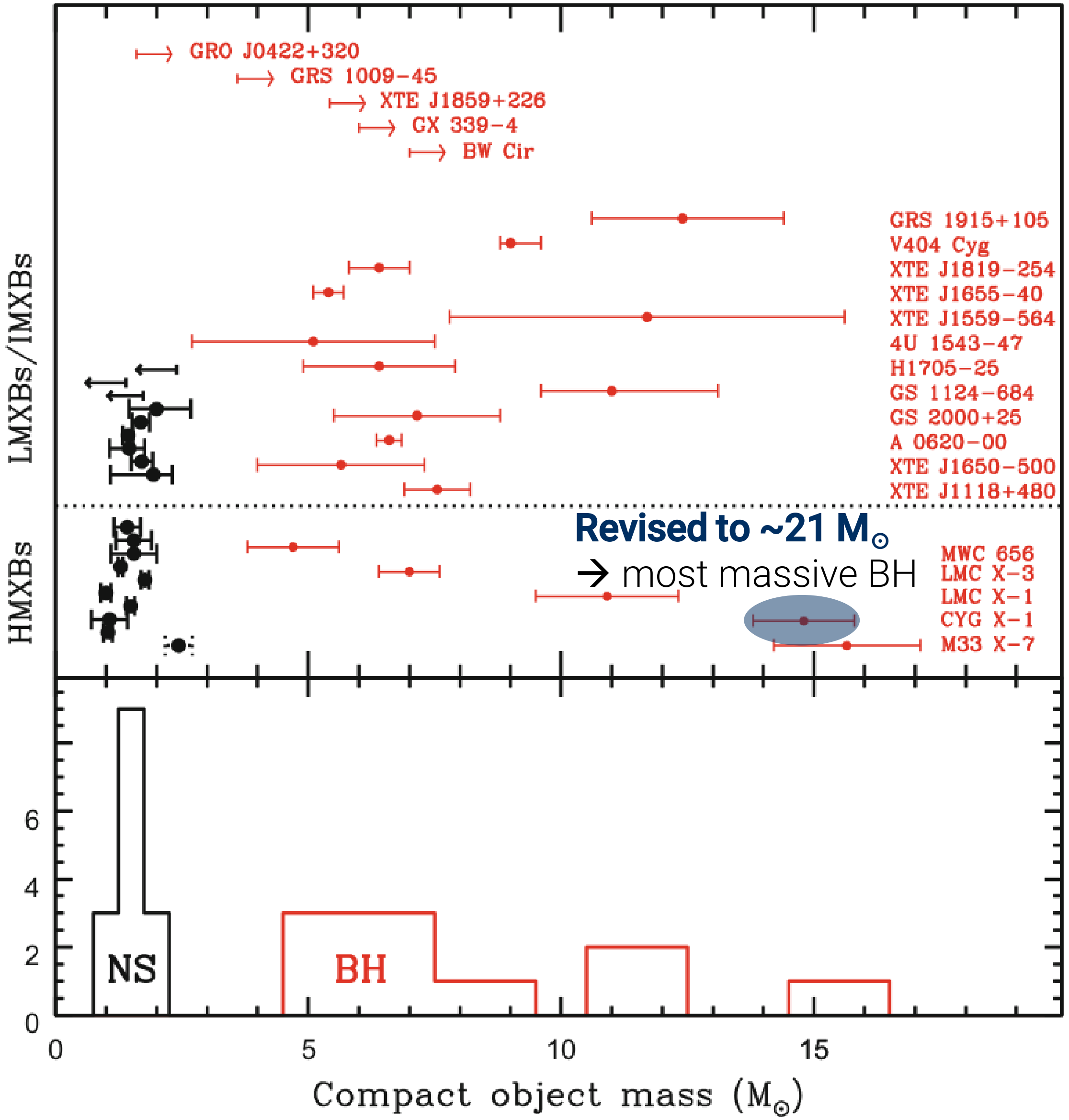
  → **RLOF**, globular clusters, young & old stellar pops.

- **Intermediate-mass X-ray binary (IMXB)**
  → $1.5\ M_\odot < M_{donor} < 5\ M_\odot$

- **High-mass X-ray binary (HMXB)**
  → $M_{donor} > 10\ M_\odot$

  → **wind-fed**, young stellar pops.

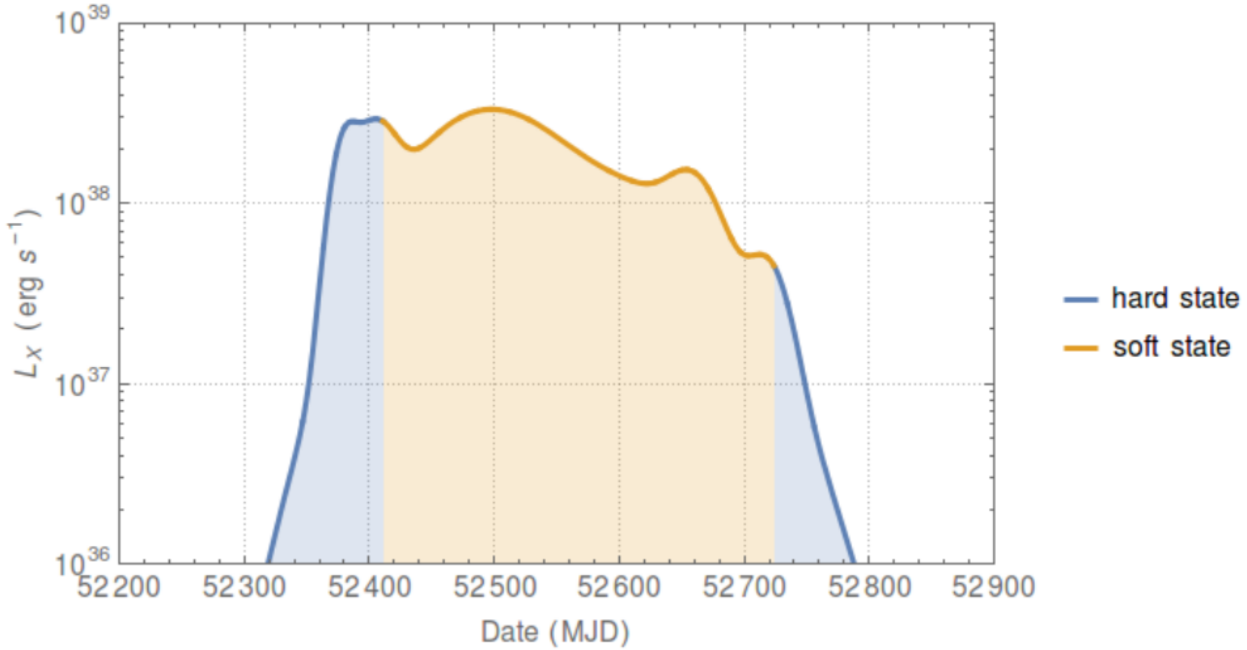
Casares 2017



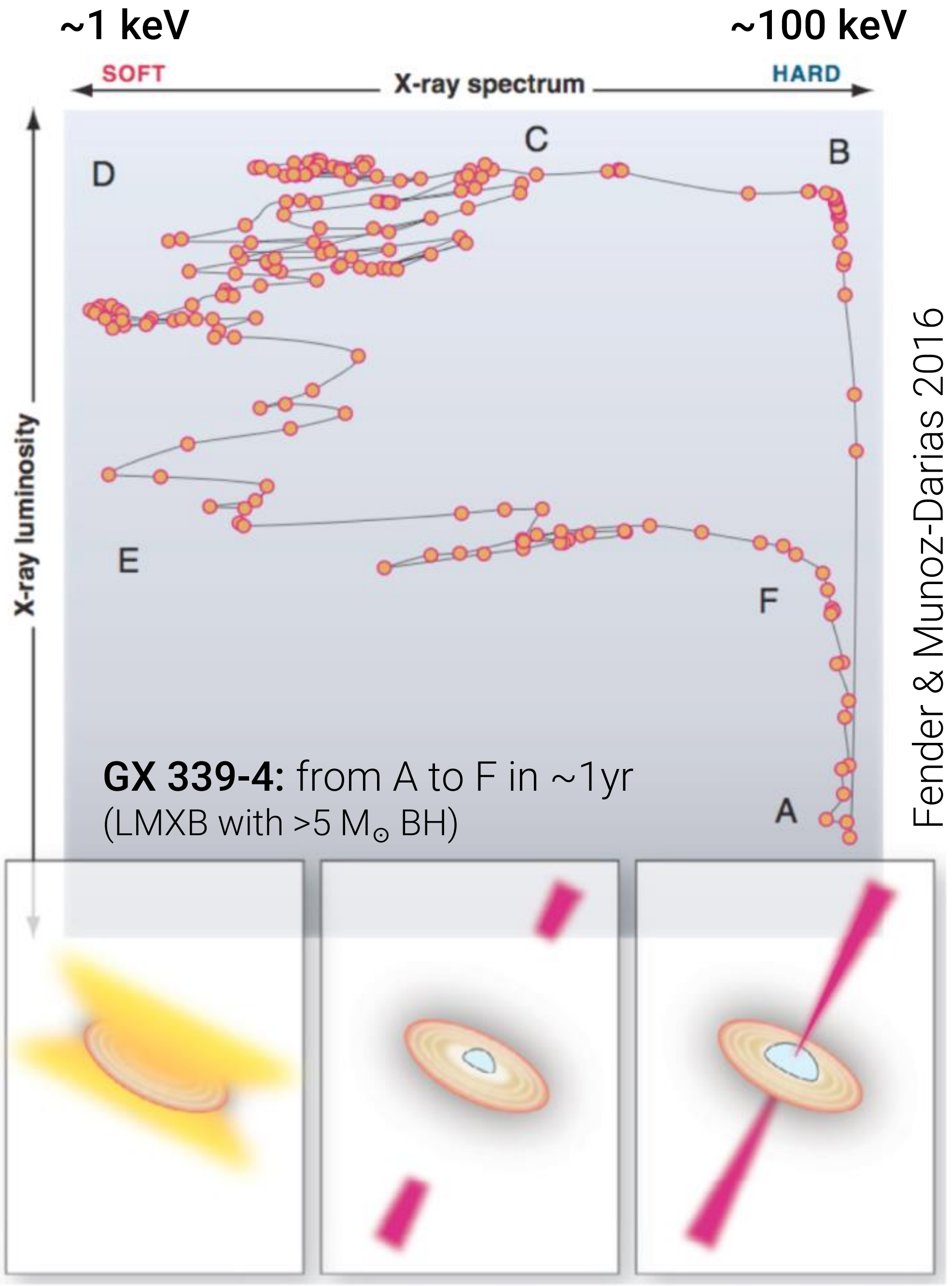
Revised to ~21 $M_\odot$
→ most massive BH

X-ray binaries

- **Persistent** and **transient sources**
- Transients → related to disk instability → AGNs
  - Hard state: steady jet
  - Soft state: disk wind, no jet
- Available accretion power: $P_{\mathrm{acc}} = \frac{GM\dot{m}}{r} = \eta \dot{m} c^2$



Fender & Munoz-Darias 2016



GX 339-4: from A to F in ~1yr
(LMXB with >5 $M_\odot$ BH)

Fender & Munoz-Darias 2016

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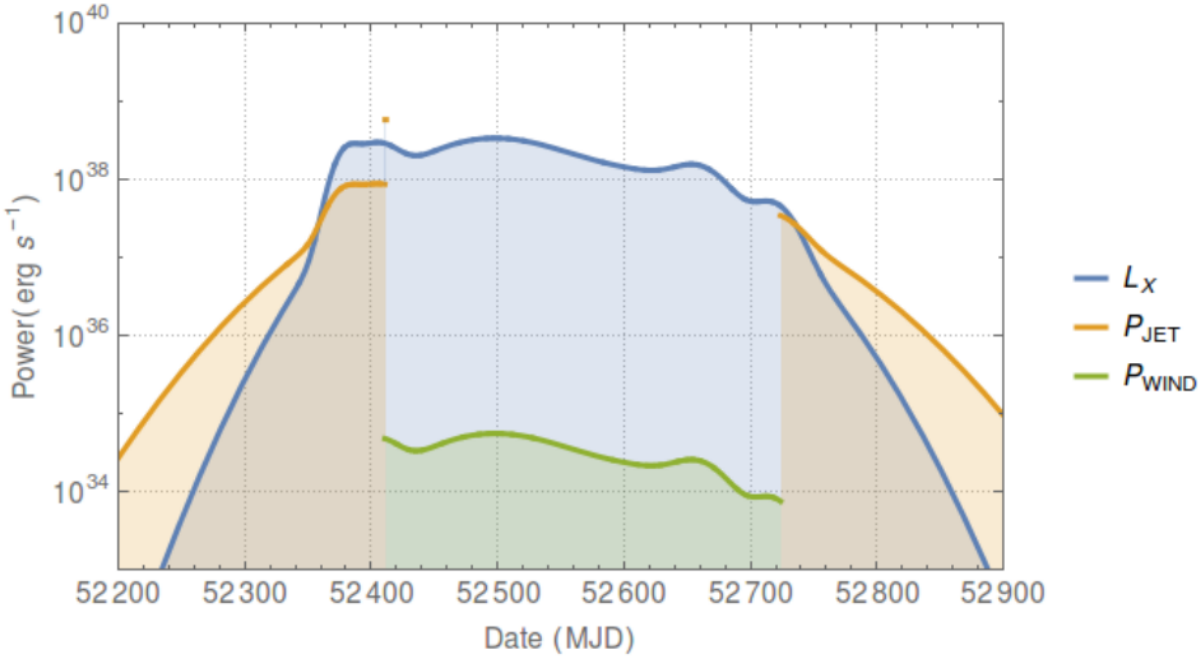
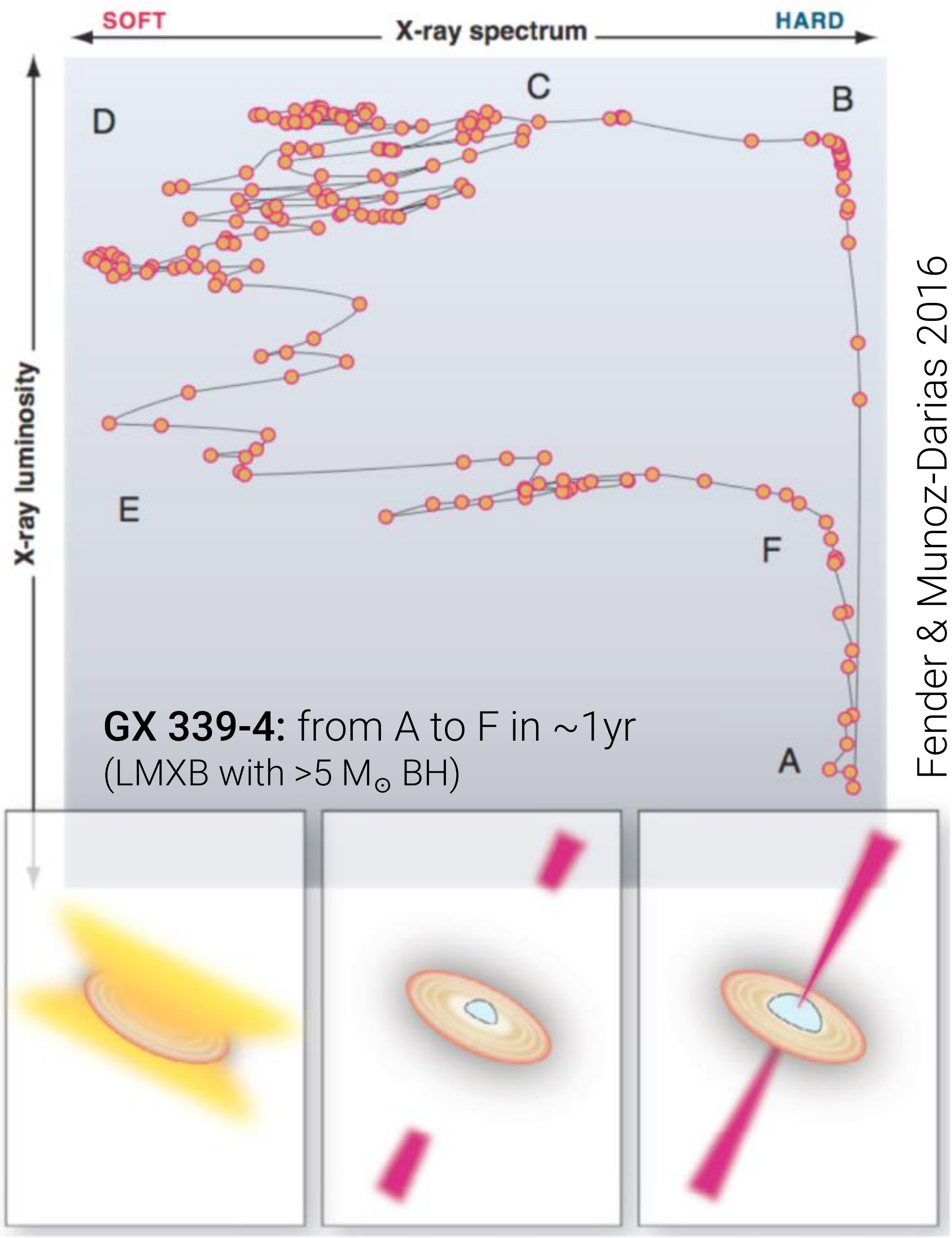


Fender & Munoz-Darias 2016

~1 keV

~100 keV



GX 339-4: from A to F in ~1yr

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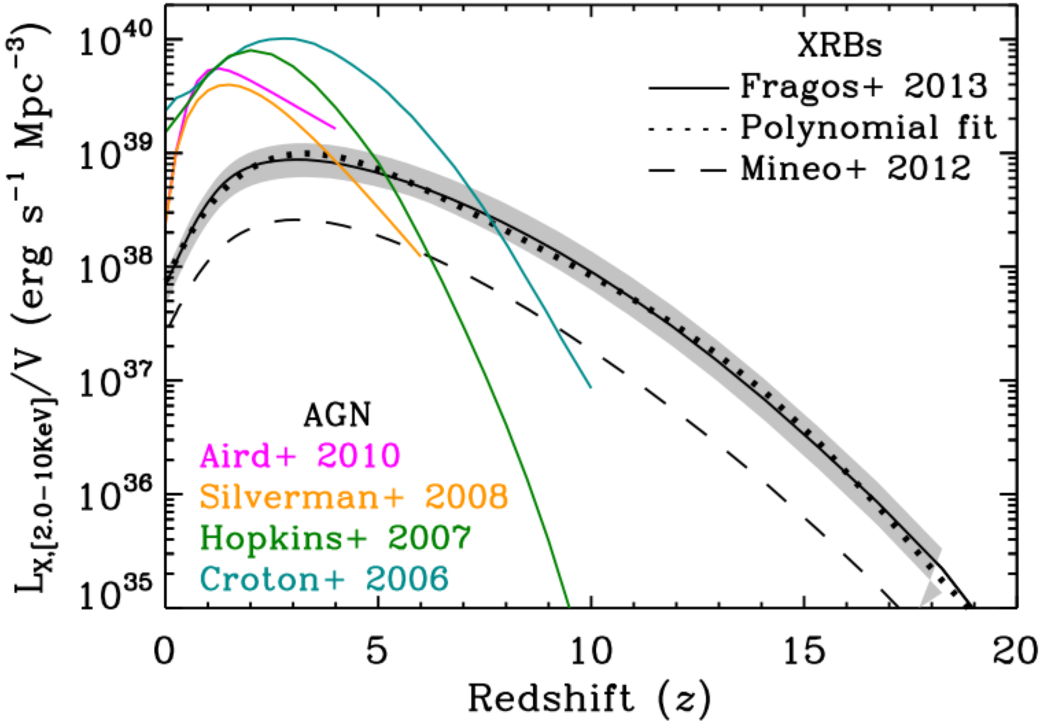
Fender & Munoz-Darias 2016

X-ray binaries

- X-ray sources in universe: AGNs and X-ray binaries
  (+ colliding wind binaries, massive stars, …)
- High redshift: X-ray luminosity from X-ray binaries larger than that of AGNs?!
  → reionization!

- Models for X-ray binary feedback: Fragos+2013
- Further reading: Justham & Schawinski 2012

Fragos+2013

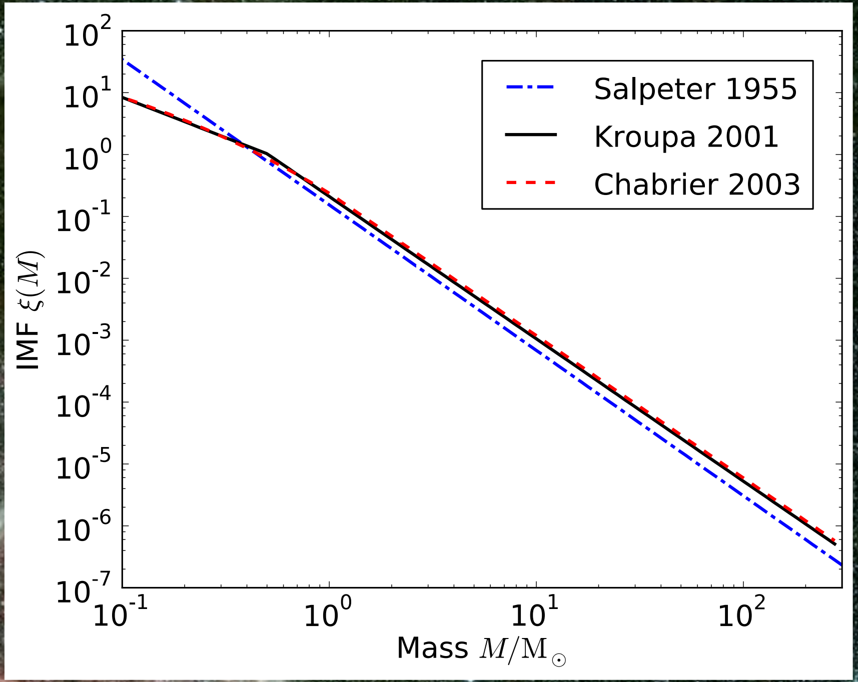


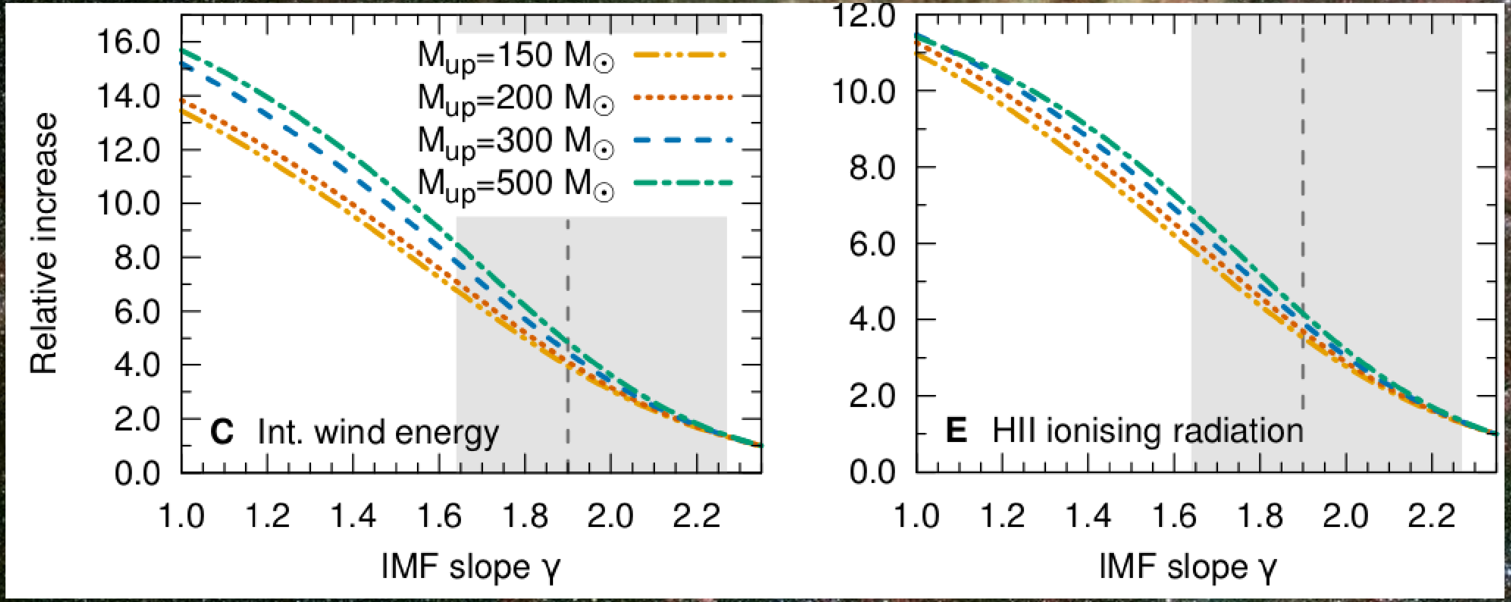
IMF and integrated stellar feedback

Stellar initial mass function (IMF)

- **0.5% of stars >10 $M_\odot$ contain 20% of mass** (1 CCSN/10^2 $M_\odot$ and 1 PISN/10^4 $M_\odot$)
- $\gamma < 2.00$: most mass in high mass stars & need M_{max}

30 Doradus: top-heavy IMF (γ ~1.90; **Schneider+2018**)
→ **enhanced feedback!**





$$\xi(M) = \frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-\gamma}$$

$$(\Gamma = \gamma - 1)$$

Salpeter:
γ=2.35
(Γ=1.35)

Credit: ESO/R. Fosbury (ST-ECF)

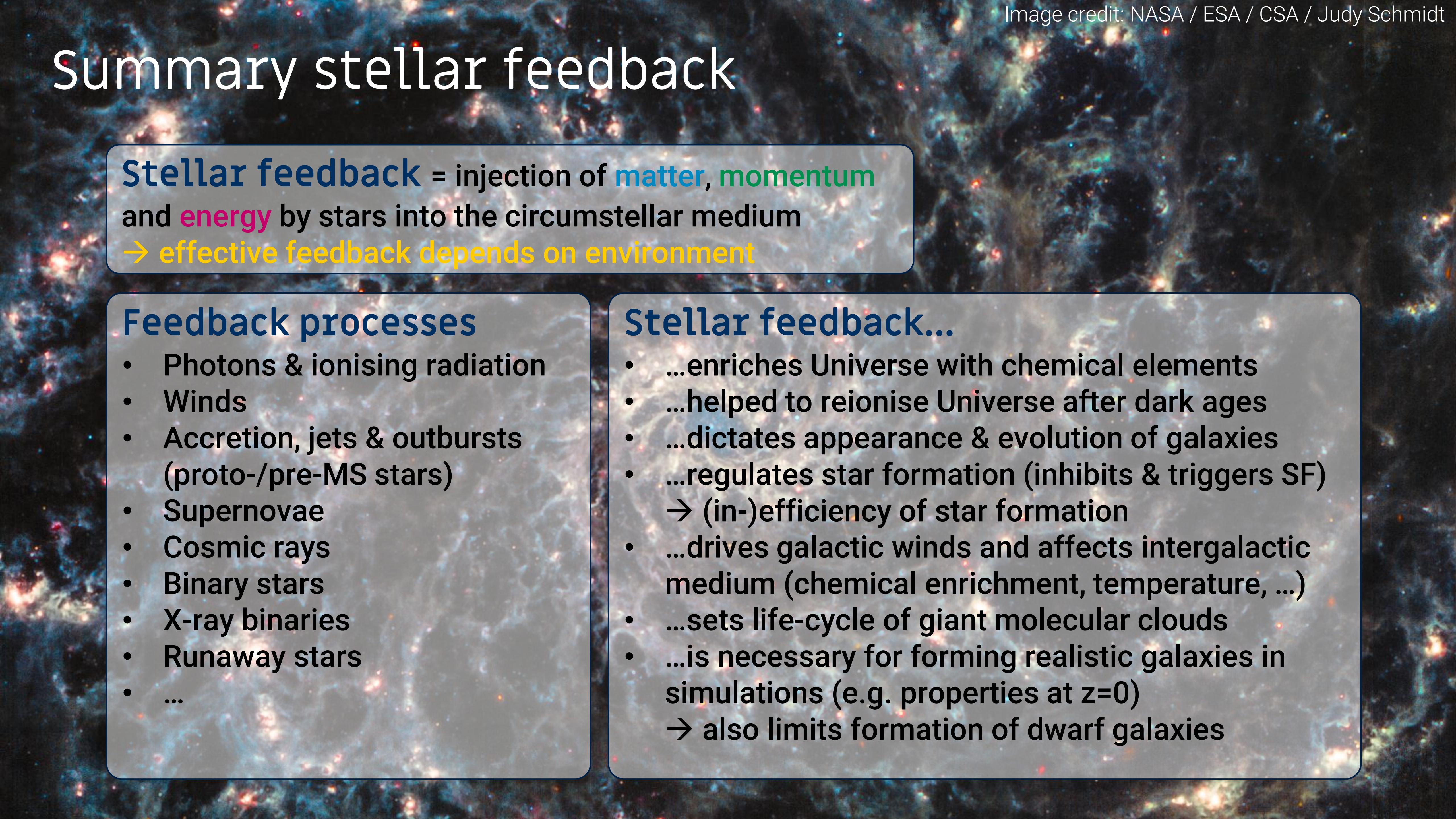


Image credit: NASA / ESA / CSA / Judy Schmidt

Summary stellar feedback

Stellar feedback = injection of matter, momentum and energy by stars into the circumstellar medium
→ effective feedback depends on environment

Feedback processes

- Photons & ionising radiation
- Winds
- Accretion, jets & outbursts (proto-/pre-MS stars)
- Supernovae
- Cosmic rays
- Binary stars
- X-ray binaries
- Runaway stars
- …

Stellar feedback…

- …enriches Universe with chemical elements
- …helped to reionise Universe after dark ages
- …dictates appearance & evolution of galaxies
- …regulates star formation (inhibits & triggers SF)
  → (in-)efficiency of star formation
- …drives galactic winds and affects intergalactic medium (chemical enrichment, temperature, …)
- …sets life-cycle of giant molecular clouds
- …is necessary for forming realistic galaxies in simulations (e.g. properties at z=0)
  → also limits formation of dwarf galaxies