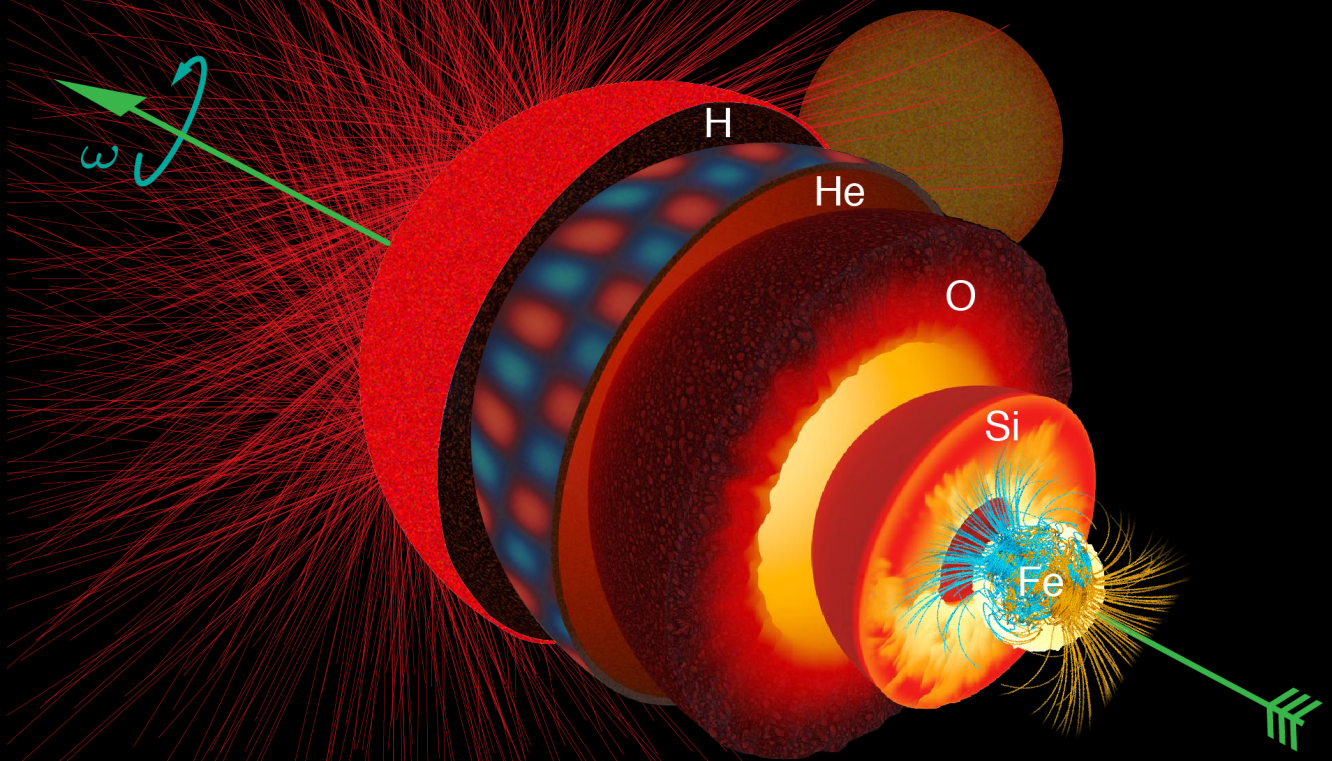
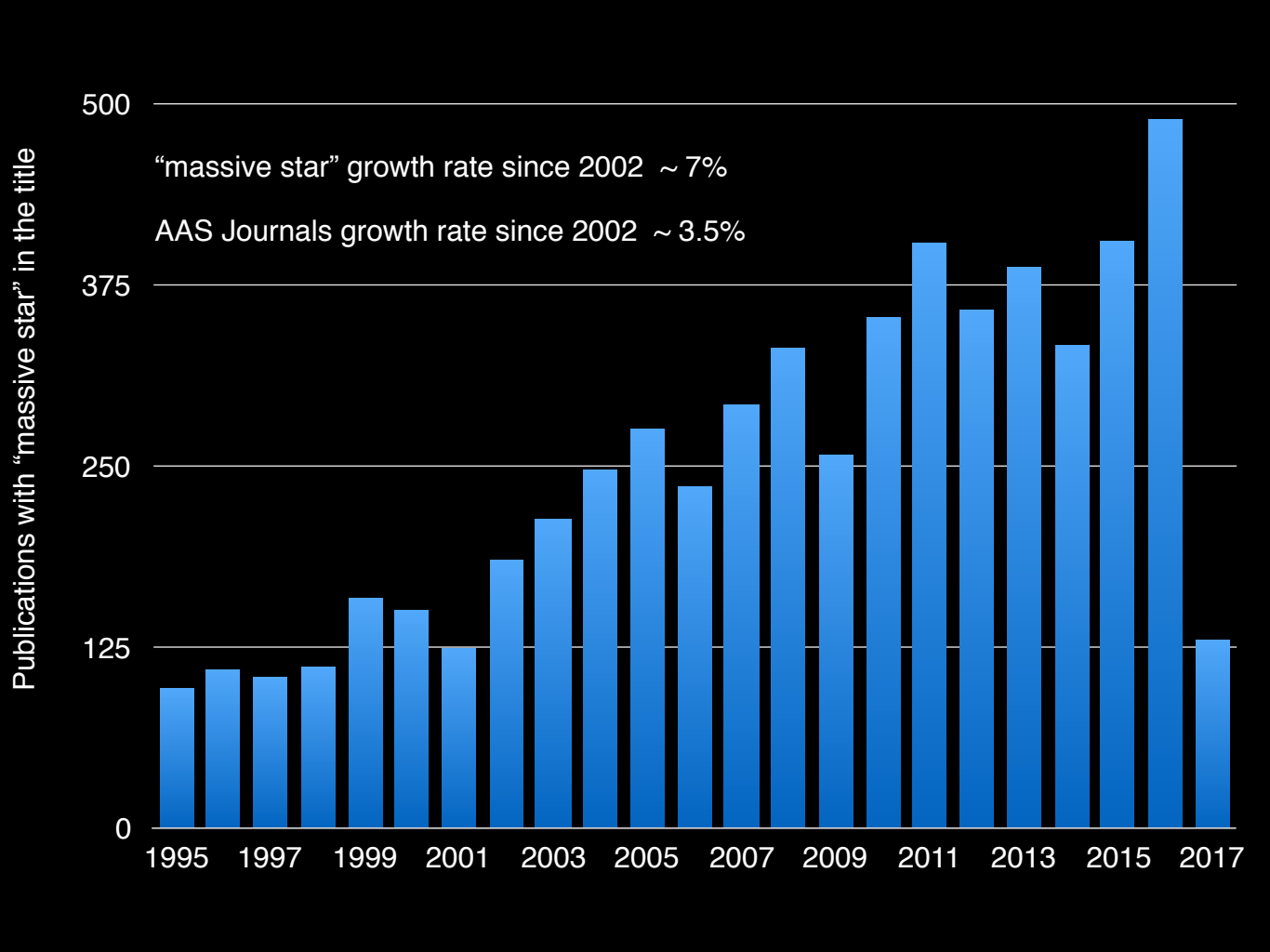
A Bonanza of Frontiers




Publications with “massive star” in the title
500
375
250
125
0
“massive star” growth rate since 2002 ~ 7%
AAS Journals growth rate since 2002 ~ 3.5%
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017

ensembles of 1d stellar models

Fields et al 2017

Yoon et al 2017

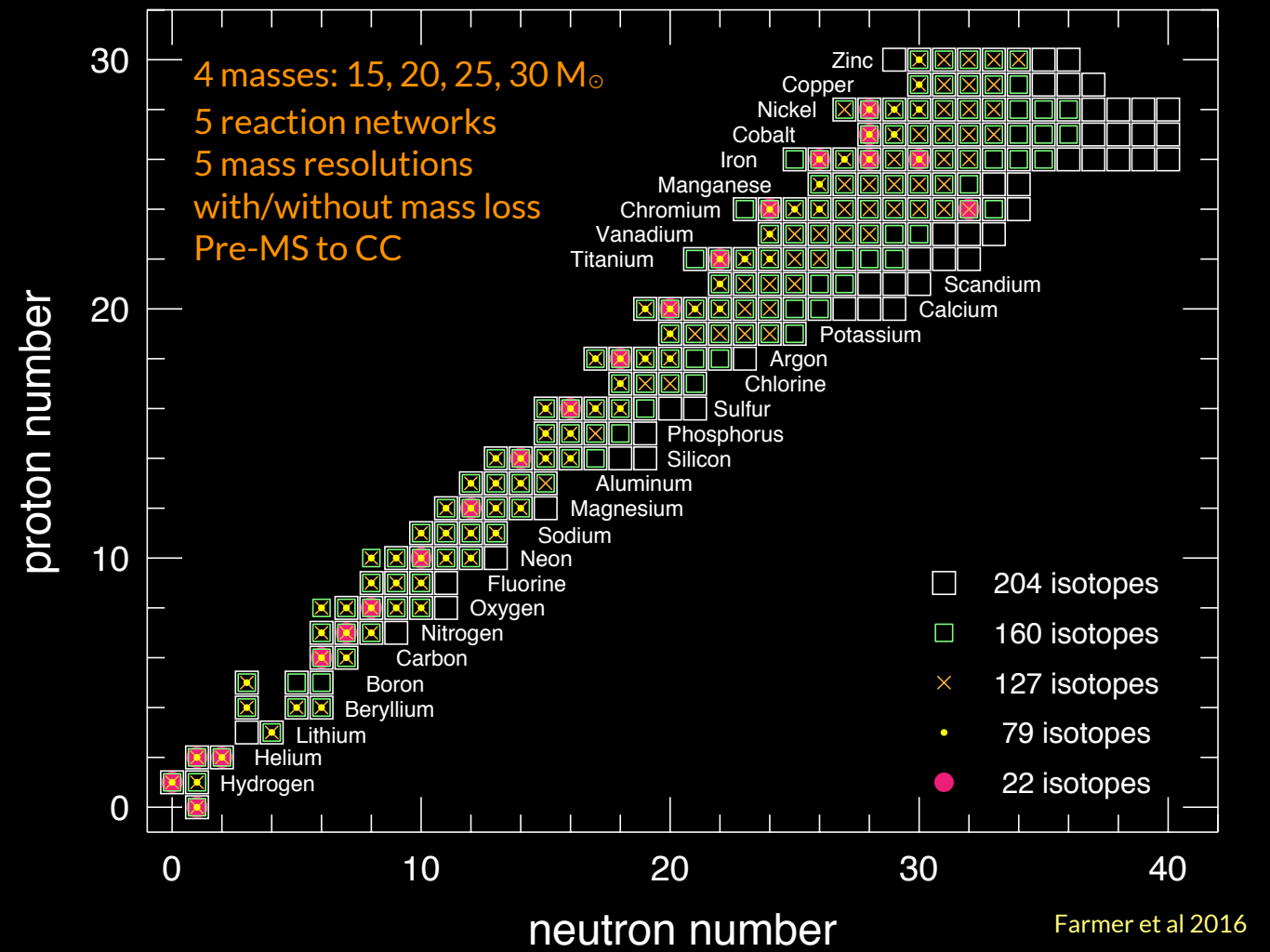
Petermann et al 2017

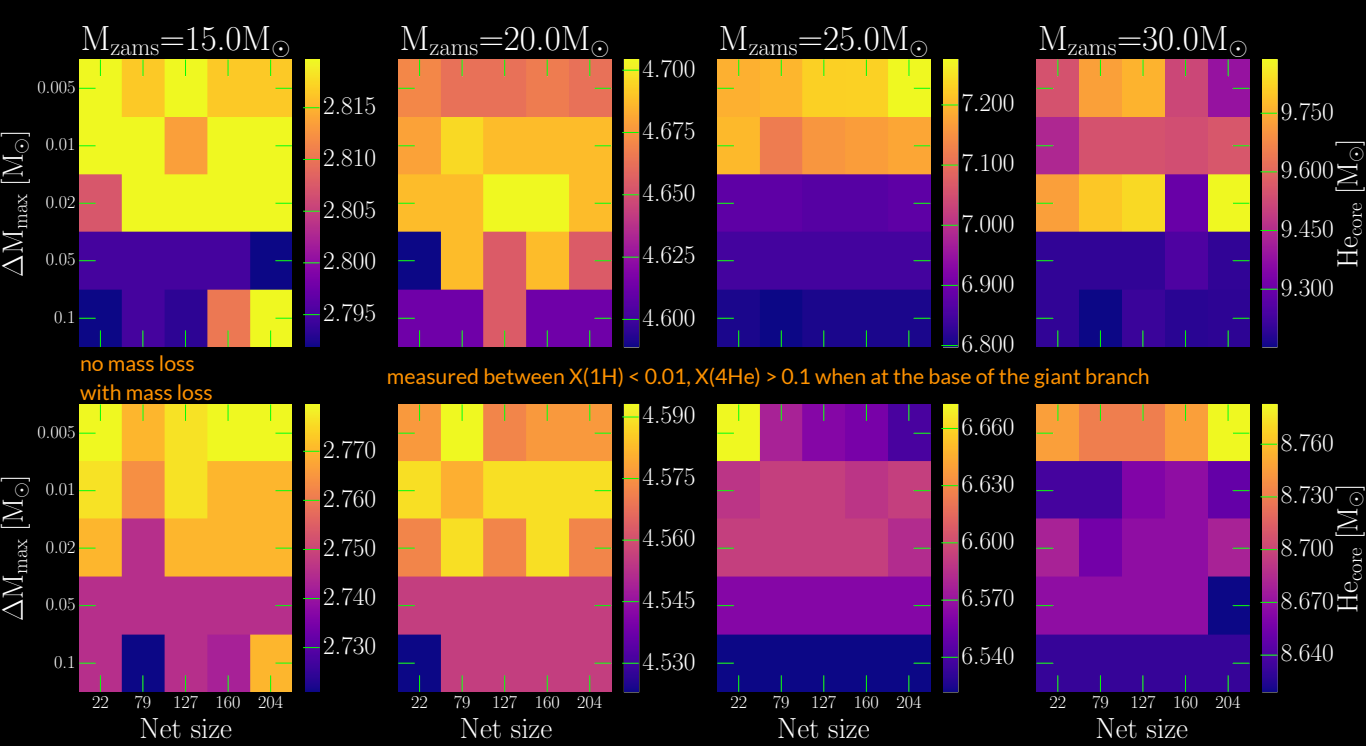
Ertl et al 2016

Farmer et al 2016

Sukhbold et al 2016

Property	$15\,M_\odot$		$20\,M_\odot$	
	$\dot{M}=0$	$\dot{M}\neq 0$	$\dot{M}=0$	$\dot{M}$
$He_{core}\ [M_\odot]^{a,b}$	$2.82^{2.82}_{2.79}$	$2.77^{2.78}_{2.72}$	$4.67^{4.70}_{4.59}$	4.
$C_{core}\ [M_\odot]$	$2.51^{2.58}_{2.49}$	$2.44^{2.53}_{2.43}$	$4.19^{4.75}_{4.04}$	4.
$O_{core}\ [M_\odot]$	$1.41^{1.43}_{1.35}$	$1.40^{1.42}_{1.32}$	$1.54^{2.47}_{1.43}$	1.
$Si_{core}\ [M_\odot]$	$1.15^{1.38}_{1.02}$	$1.15^{1.39}_{1.08}$	$1.38^{1.65}_{1.30}$	1.


4 masses: 15, 20, 25, 30 M⊙
5 reaction networks
5 mass resolutions
with/without mass loss
Pre-MS to CC
Zinc
Copper
Nickel
Cobalt
Iron
Manganese
Chromium
Vanadium
Titanium
Scandium
Calcium
Potassium
Argon
Chlorine
Sulfur
Phosphorus
Silicon
Aluminum
Magnesium
Sodium
Neon
Fluorine
Oxygen
Nitrogen
Carbon
Boron
Beryllium
Lithium
Helium
Hydrogen
204 isotopes
160 isotopes
127 isotopes
79 isotopes
22 isotopes
proton number
neutron number
0
10
20
30
40
Farmer et al 2016

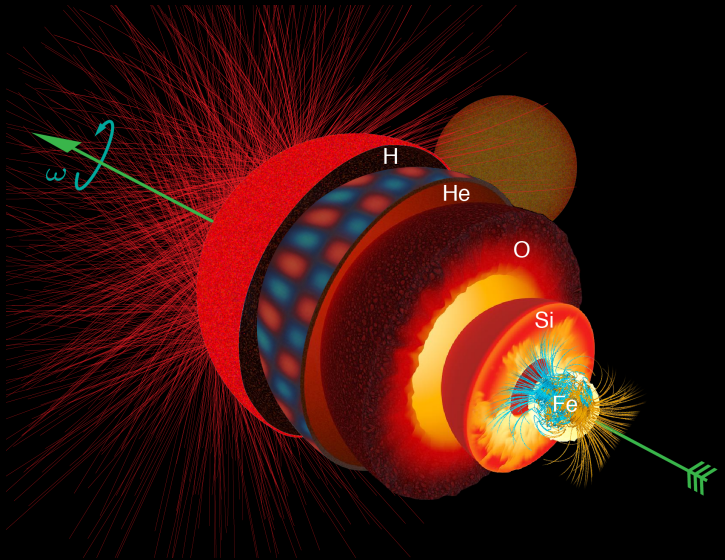


The step function with mass resolution is due to layered convection/semiconvection penetrating (or not) the H-burning core or H-burning shell. If it penetrates, fresh H fuel increases the He-core mass.

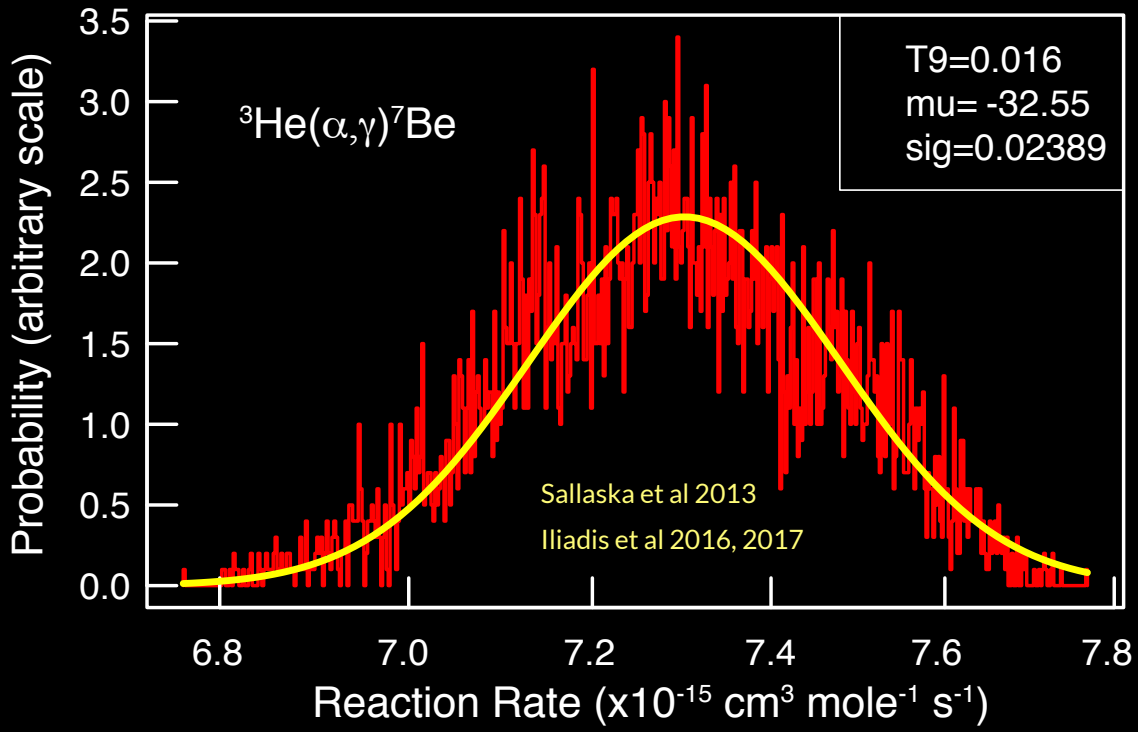
Farmer et al 2016

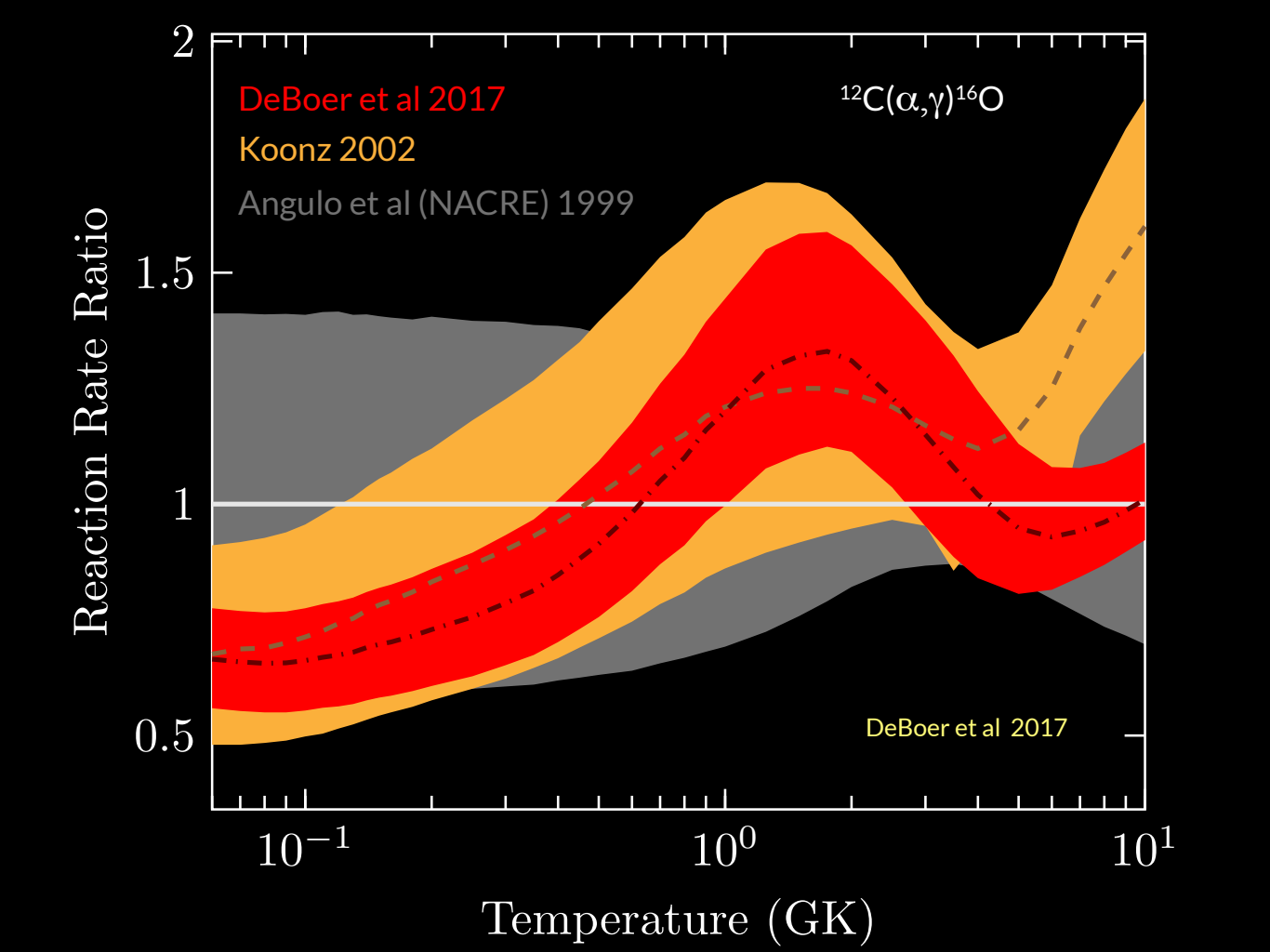
How do the properties of massive stars, evolved from the main-sequence, vary with respect to the composite experimental uncertainties in the reaction rates?

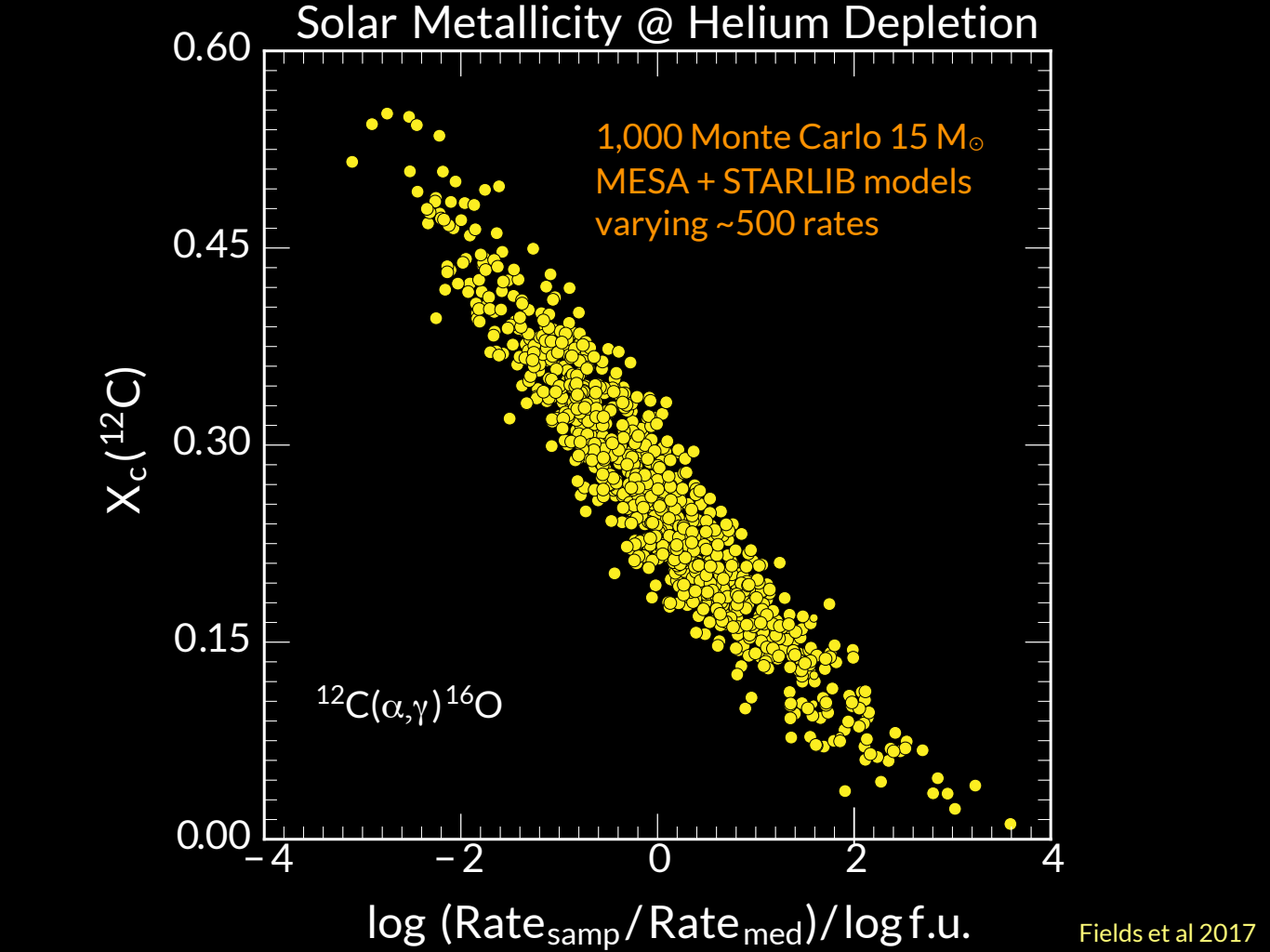
$$\sum \delta(\text{reaction rates}) = ?$$

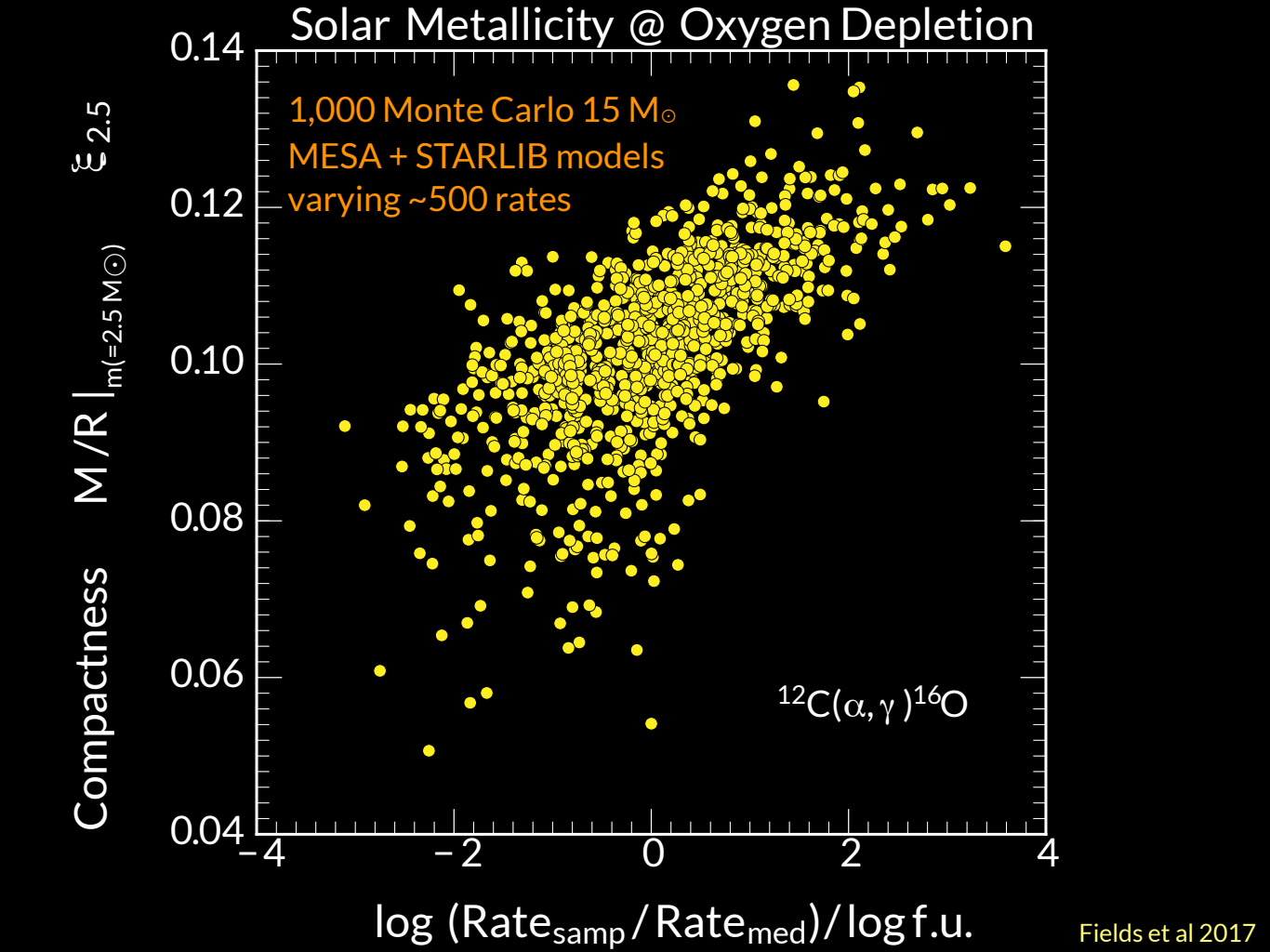


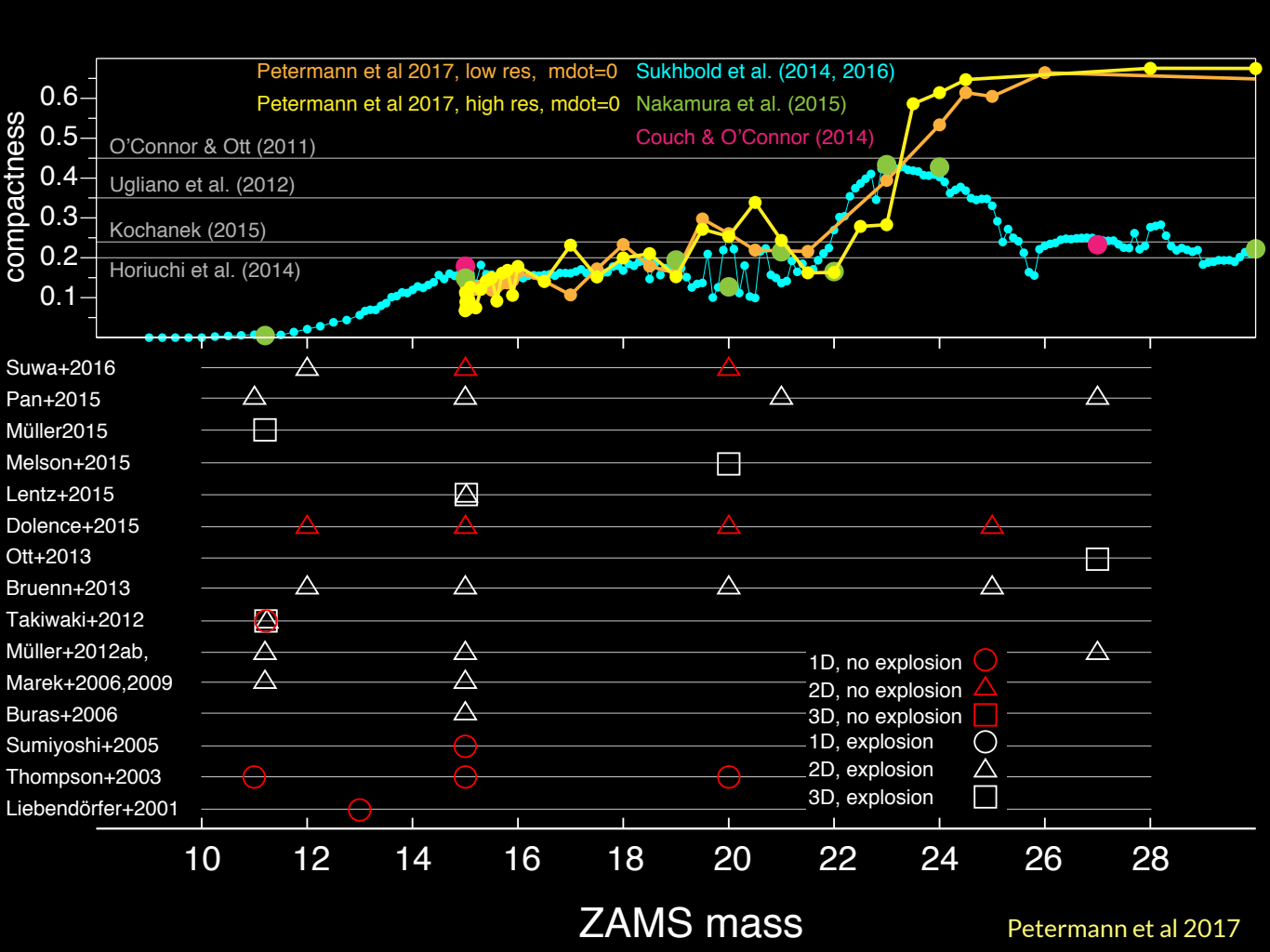
STARLIB is the first (and only) tool offering a Monte Carlo / Bayesian reaction rate probability density due to experimental uncertainties.




DeBoer et al 2017
Koonz 2002
Angulo et al (NACRE) 1999
$^{12}C(\alpha,\gamma)^{16}O$
DeBoer et al 2017
Reaction Rate Ratio
2
1.5
1
0.5
10^{-1}
10^{0}
10^{1}
Temperature (GK)


Solar Metallicity @ Helium Depletion
1,000 Monte Carlo 15 M⊙
MESA + STARLIB models
varying ~500 rates
$^{12}C(\alpha,\gamma)^{16}O$
$X_c(^{12}C)$
0.60
0.45
0.30
0.15
0.00
−4
−2
0
2
4
log (Rate$_{samp}$ / Rate$_{med}$) / log f.u.
Fields et al 2017


Solar Metallicity @ Oxygen Depletion
1,000 Monte Carlo 15 M⊙
MESA + STARLIB models
varying ~500 rates
$^{12}C(\alpha,\gamma)^{16}O$
Compactness M/R|m(=2.5 M⊙) ξ2.5
0.14
0.12
0.10
0.08
0.06
0.04
−4
−2
0
2
4
log (Rate_samp / Rate_med) / log f.u.
Fields et al 2017


compactness
0.6
0.5
0.4
0.3
0.2
0.1
Petermann et al 2017, low res, mdot=0
Petermann et al 2017, high res, mdot=0
O'Connor & Ott (2011)
Ugliano et al. (2012)
Kochanek (2015)
Horiuchi et al. (2014)
Sukhbold et al. (2014, 2016)
Nakamura et al. (2015)
Couch & O'Connor (2014)
Suwa+2016
Pan+2015
Müller2015
Melson+2015
Lentz+2015
Dolence+2015
Ott+2013
Bruenn+2013
Takiwaki+2012
Müller+2012ab,
Marek+2006,2009
Buras+2006
Sumiyoshi+2005
Thompson+2003
Liebendörfer+2001
1D, no explosion
2D, no explosion
3D, no explosion
1D, explosion
2D, explosion
3D, explosion
10
12
14
16
18
20
22
24
26
28
ZAMS mass
Petermann et al 2017

some developing trends

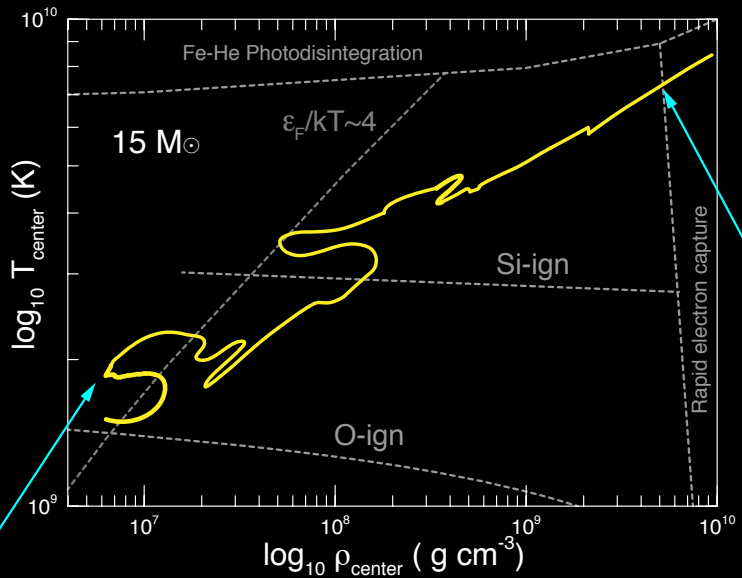
Pre-SN ν detection

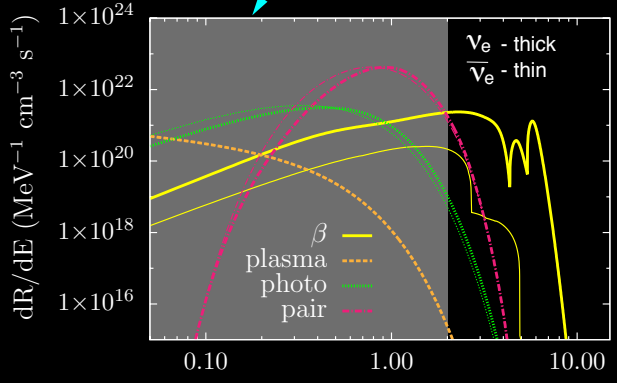
Patton et al 2016

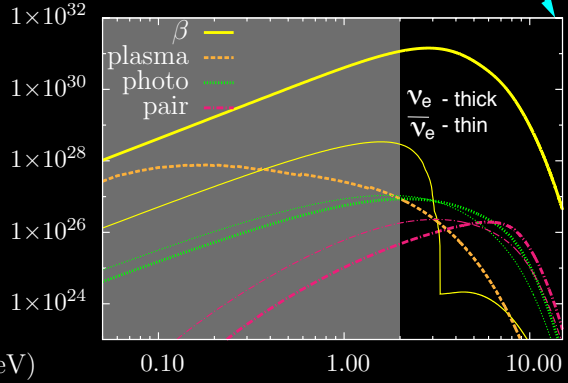
Yoshida et al 2016

Patton et al 2017

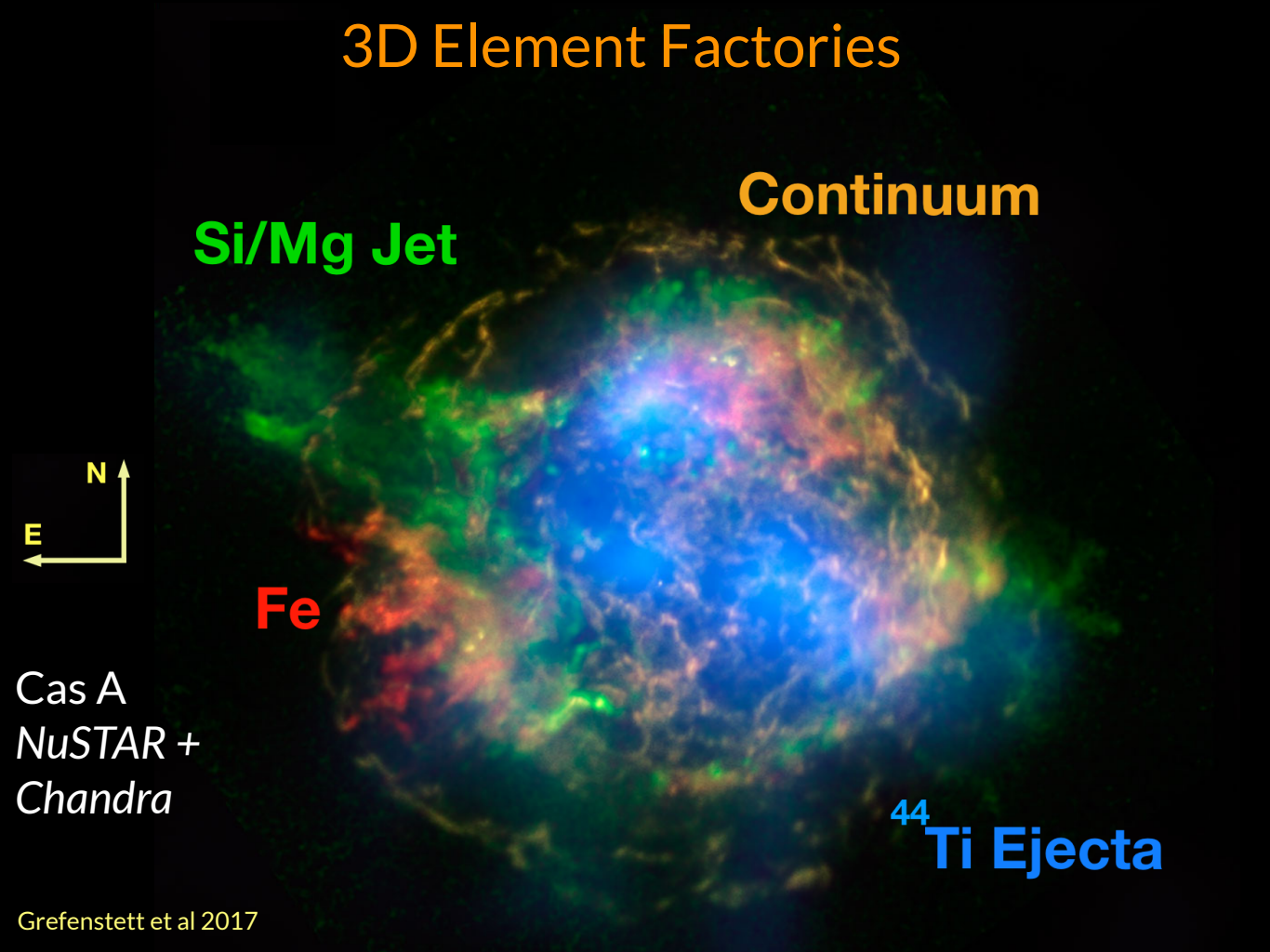
Misch & Fuller 2017



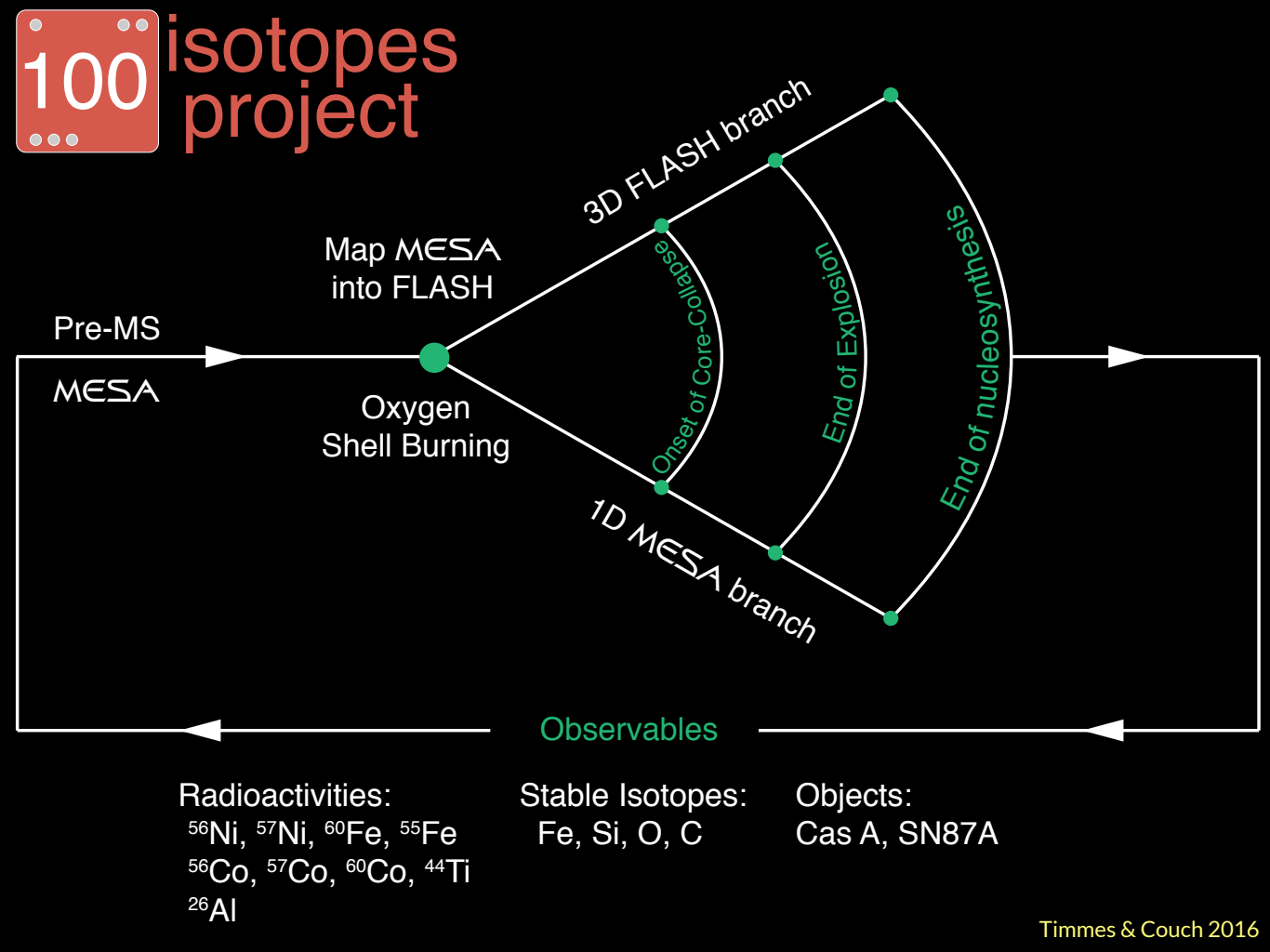




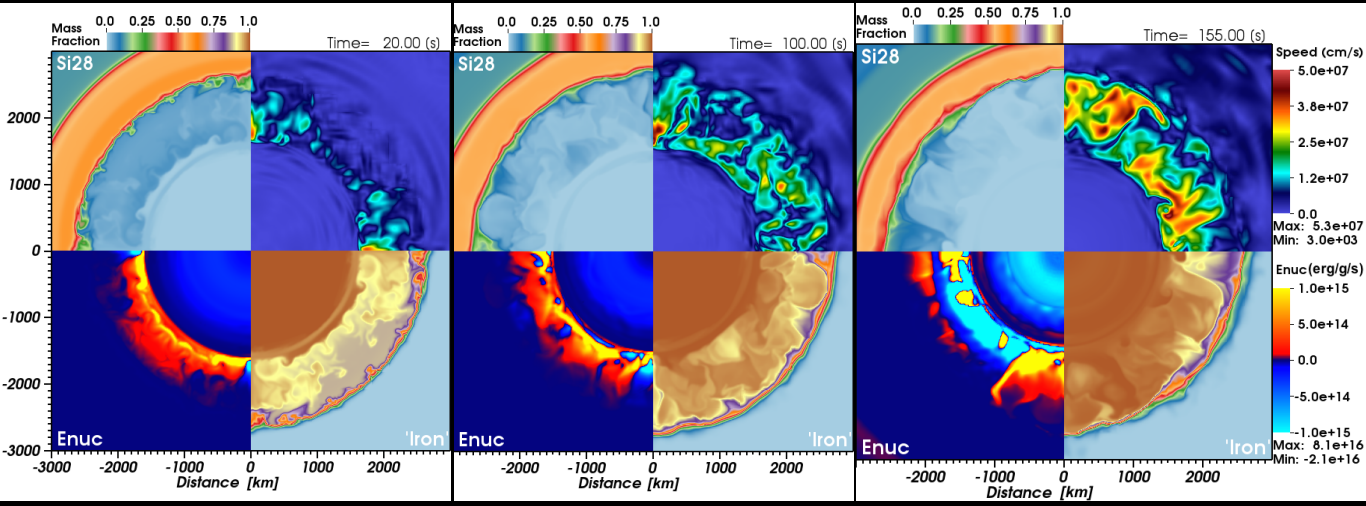
3D Element Factories



Grefenstett et al 2017

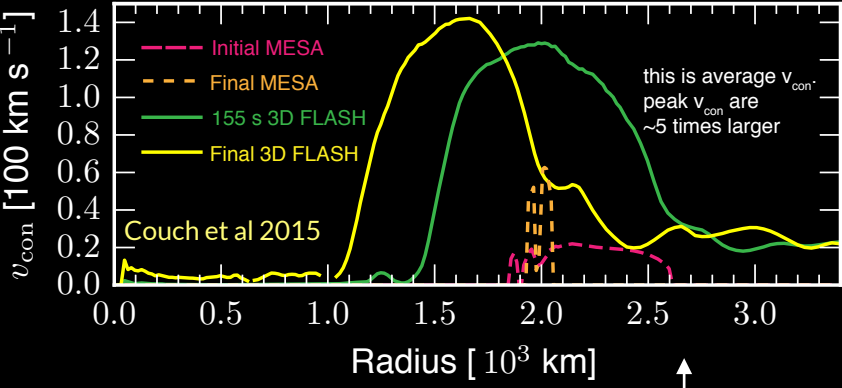

100 isotopes project
3D FLASH branch
Map MESA into FLASH
Pre-MS
MESA
Oxygen Shell Burning
Onset of Core-Collapse
End of Explosion
End of nucleosynthesis
1D MESA branch
Observables
Radioactivities:
56Ni, 57Ni, 60Fe, 55Fe
56Co, 57Co, 60Co, 44Ti
26Al
Stable Isotopes:
Fe, Si, O, C
Objects:
Cas A, SN87A
Timmes & Couch 2016

A 21 isotope 15 $M_\odot$ MESA model at shell Si-burning was mapped into a 21 isotope 3D FLASH initial model.

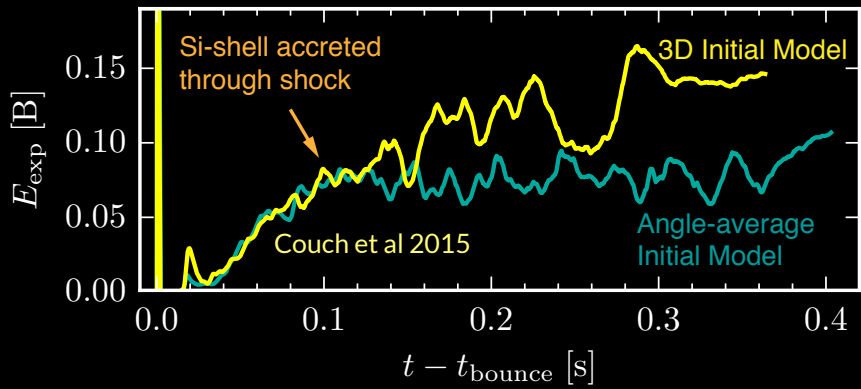


Couch et al 2015

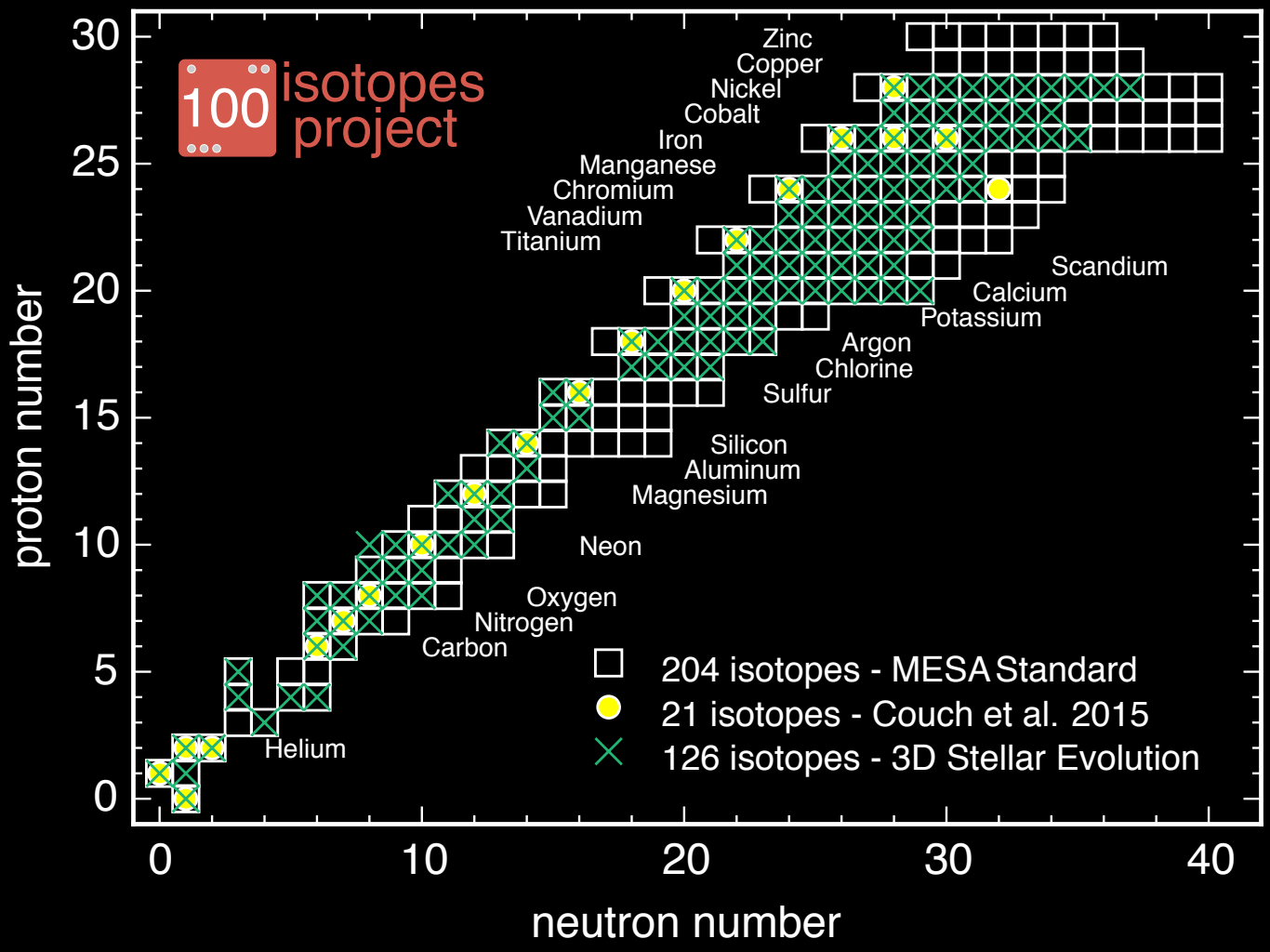
First 3D simulation of the final minutes of iron core growth, up to and including core-collapse.



The stronger turbulence from a non-spherical progenitor enhances the (diagnostic) explosion energy.



Nishimura (西村信哉) et al 2017
Jones et al 2017
Müller et al 2016


100 isotopes project
Zinc
Copper
Nickel
Cobalt
Iron
Manganese
Chromium
Vanadium
Titanium
Scandium
Calcium
Potassium
Argon
Chlorine
Sulfur
Silicon
Aluminum
Magnesium
Neon
Oxygen
Nitrogen
Carbon
Helium
204 isotopes - MESA Standard
21 isotopes - Couch et al. 2015
126 isotopes - 3D Stellar Evolution
proton number
neutron number
0
5
10
15
20
25
30
0
10
20
30
40

comments and discussion