The hidden harmony is better than the obvious one.

Heraclitus

KITP - Accretion and
Explosion: the Astrophysics
of Degenerate Stars

20Feb2007

On Variations in the Peak Luminosity of Type Ia Supernovae

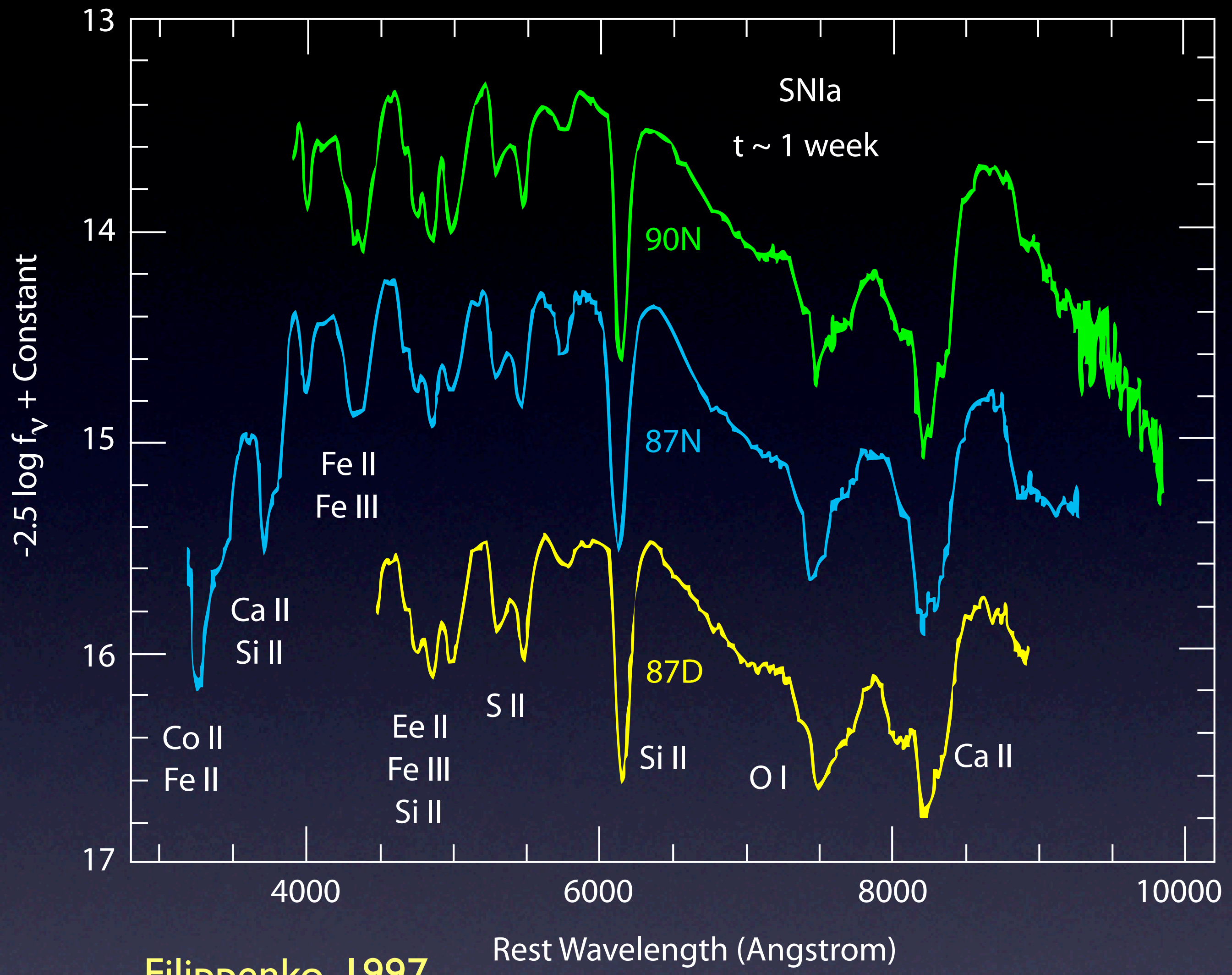
Frank Timmes
Thermonuclear Applications Group X-2
Los Alamos National Laboratory

LA-UR-04-5097

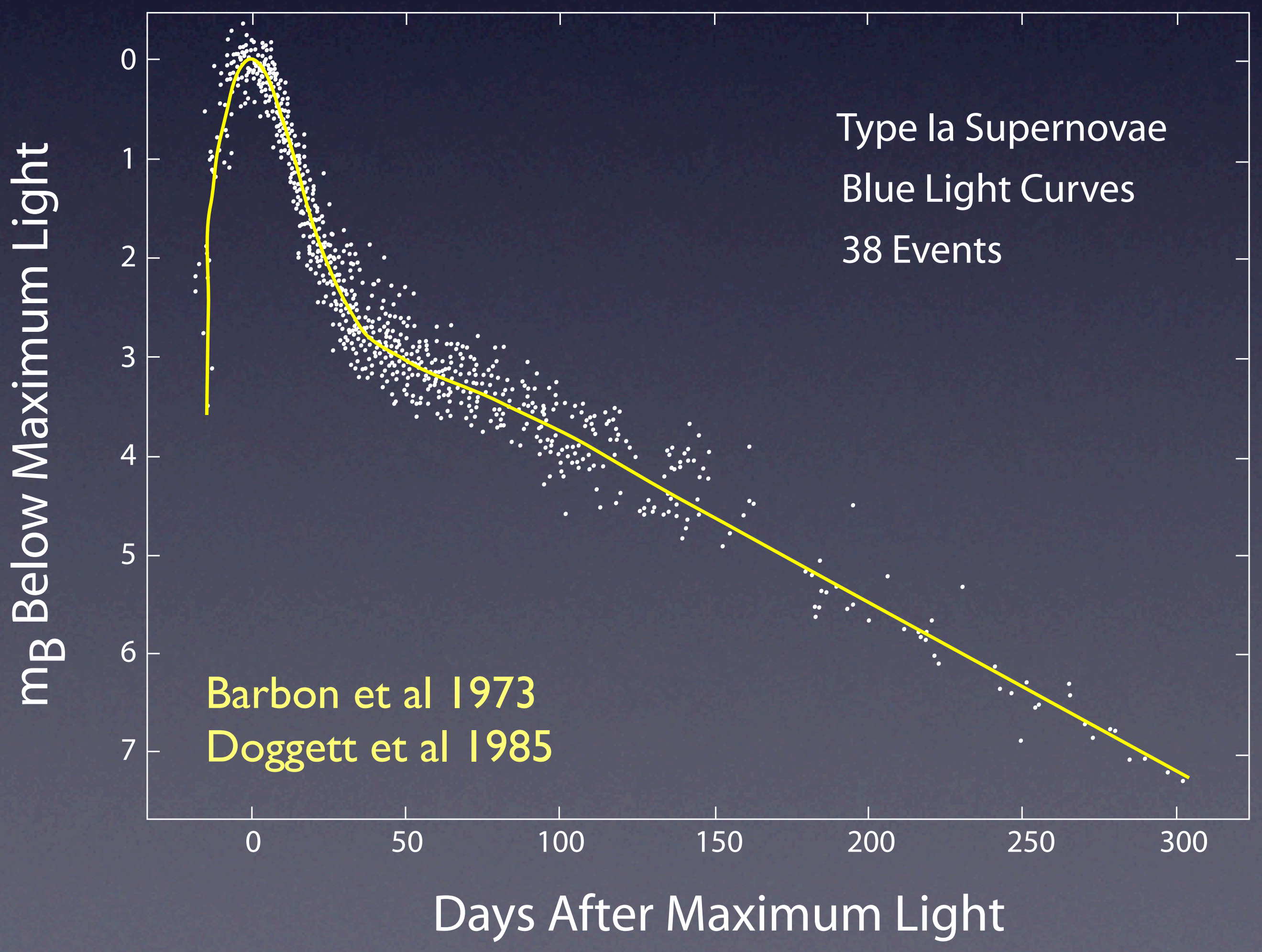
An outline of this talk on thermonuclear supernovae

- A few observations
- Why the intrinsic scatter?
- Tracking the proton/neutron ratio
- Some new results

The spectra and light curves near peak light are similar.



Filippenko, 1997

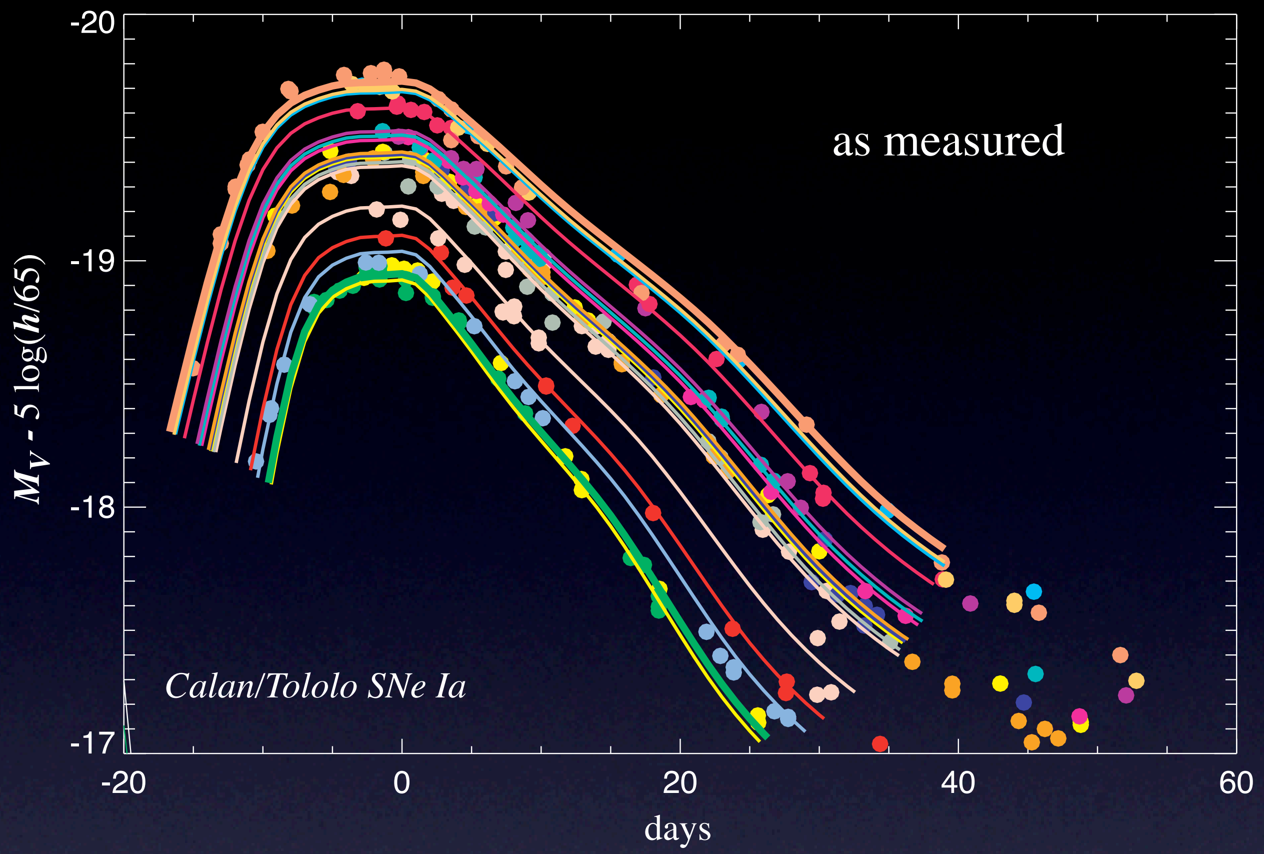


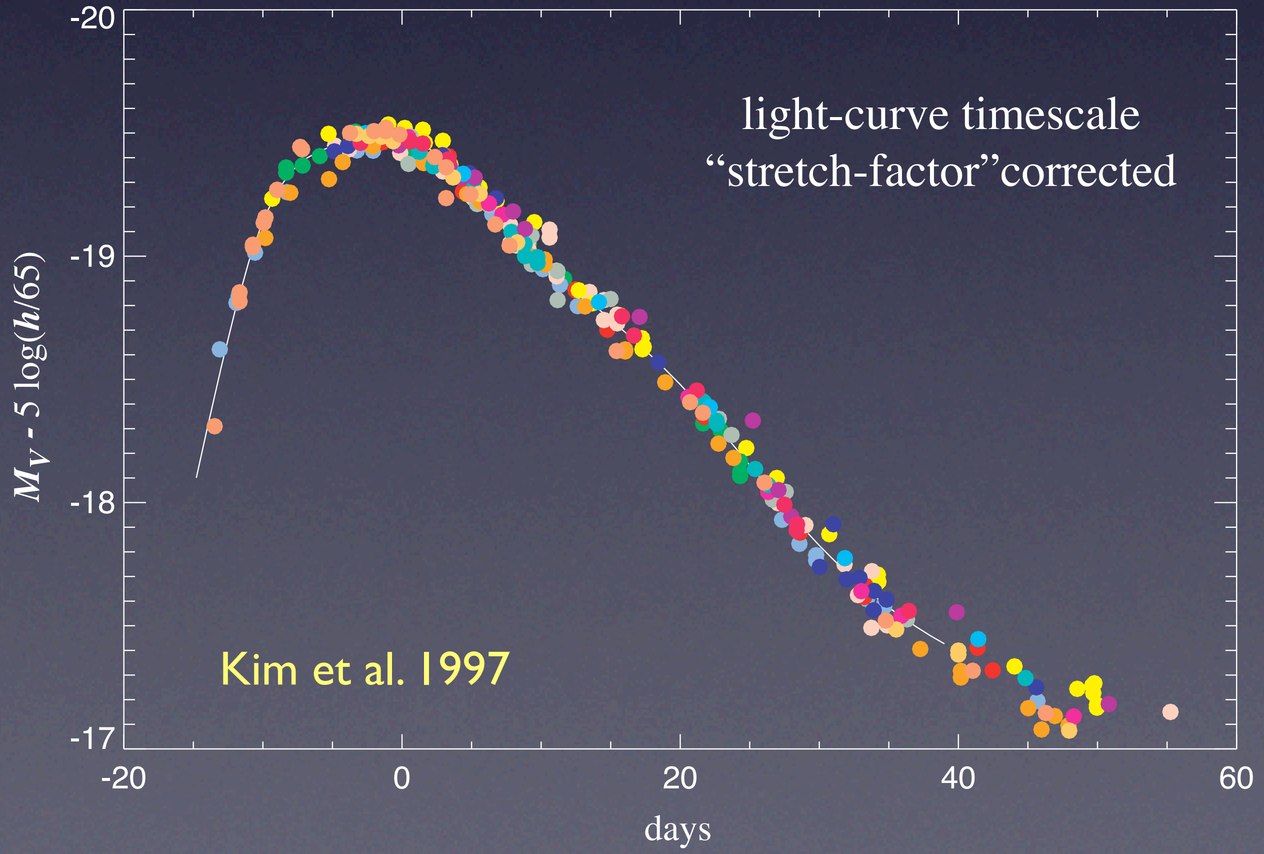
Barbon et al 1973
Doggett et al 1985

Brighter light curves are broader.

- The Phillips relation compensates for the variation in peak luminosity to give a standard candle.

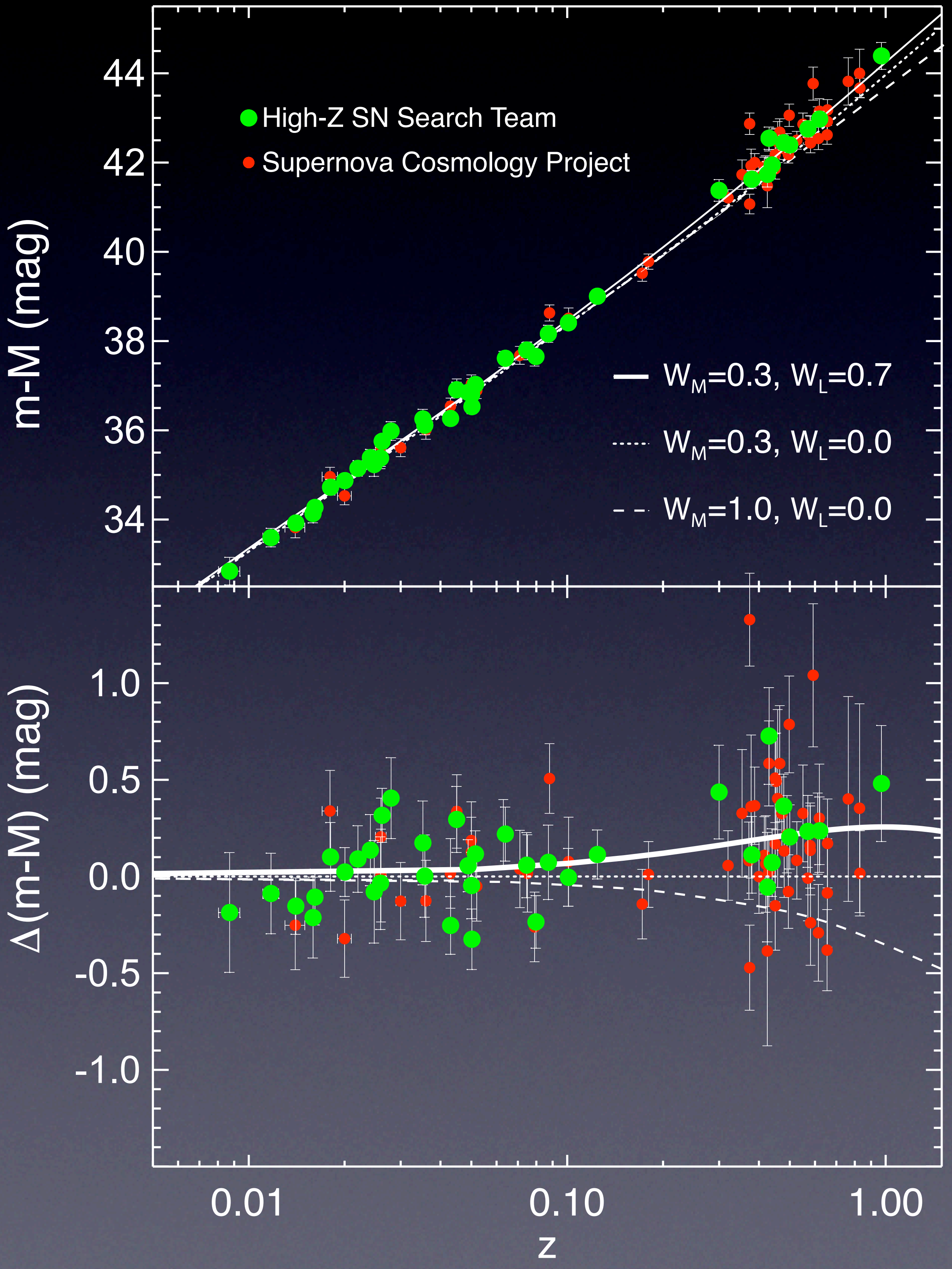
- This makes the peak luminosity a function of a single parameter: e.g., the width of the light curve or the mass of ^{56}Ni ejected.





Kim et al. 1997

Dimmer than the template is interpreted as evidence an accelerating universe.



Accelerating

Low Density

High Density

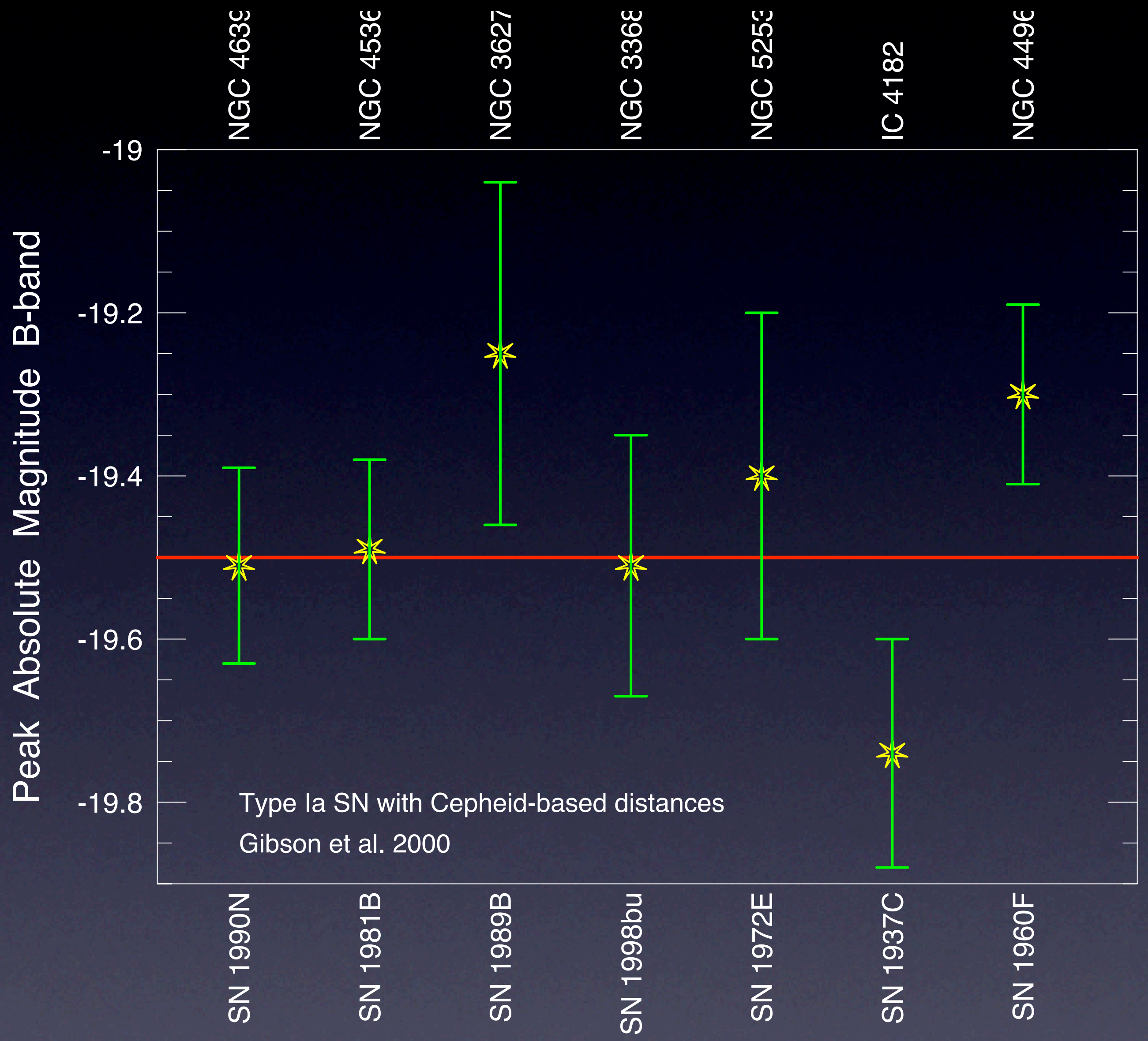
Accelerating

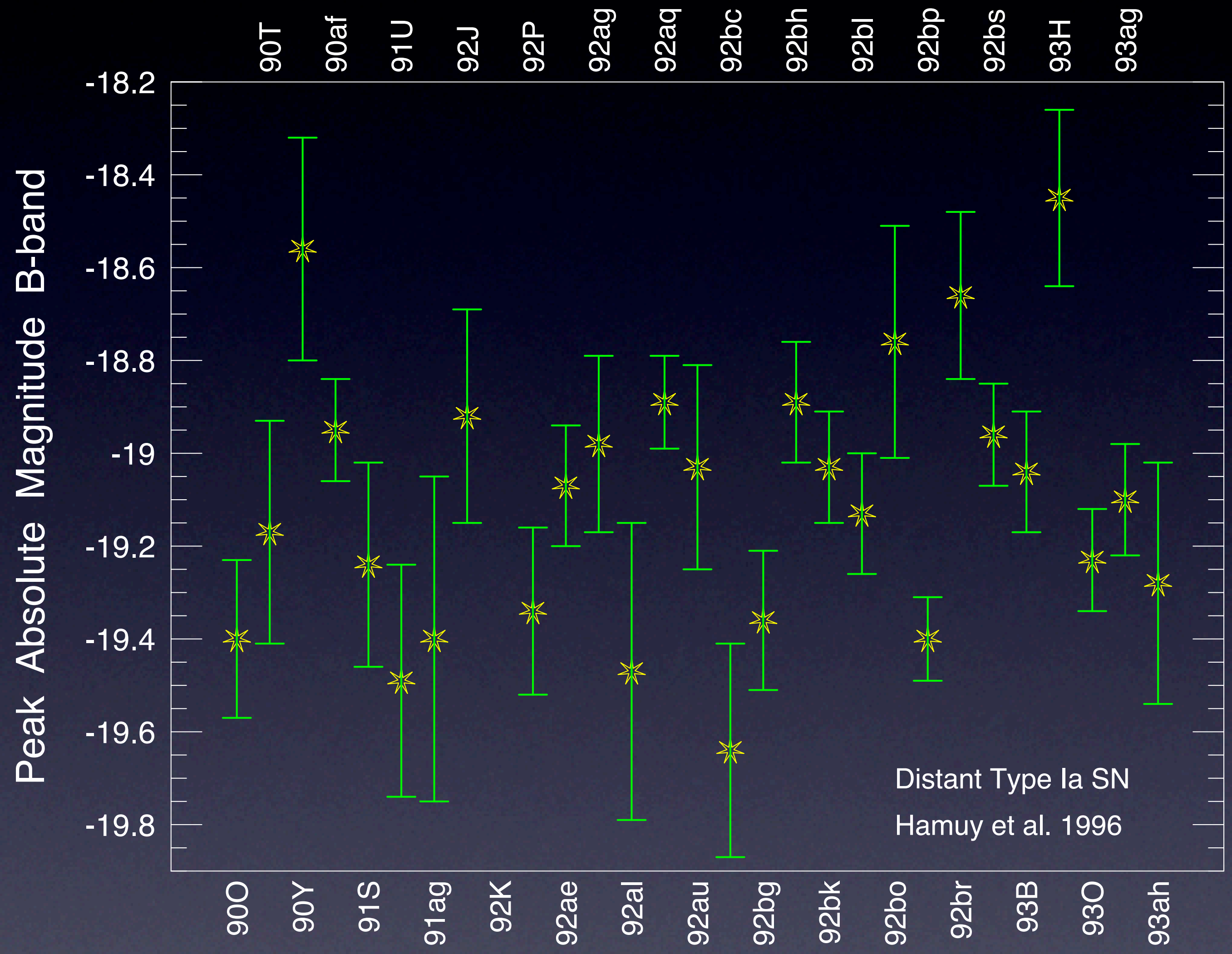
Low Density

High Density

Riess et al. 1998

For nearby supernovae, the intrinsic variation in peak magnitude is ~0.5 in the B and V bands.


Type Ia SN with Cepheid-based distances
Gibson et al. 2000


Distant Type Ia SN
Hamuy et al. 1996

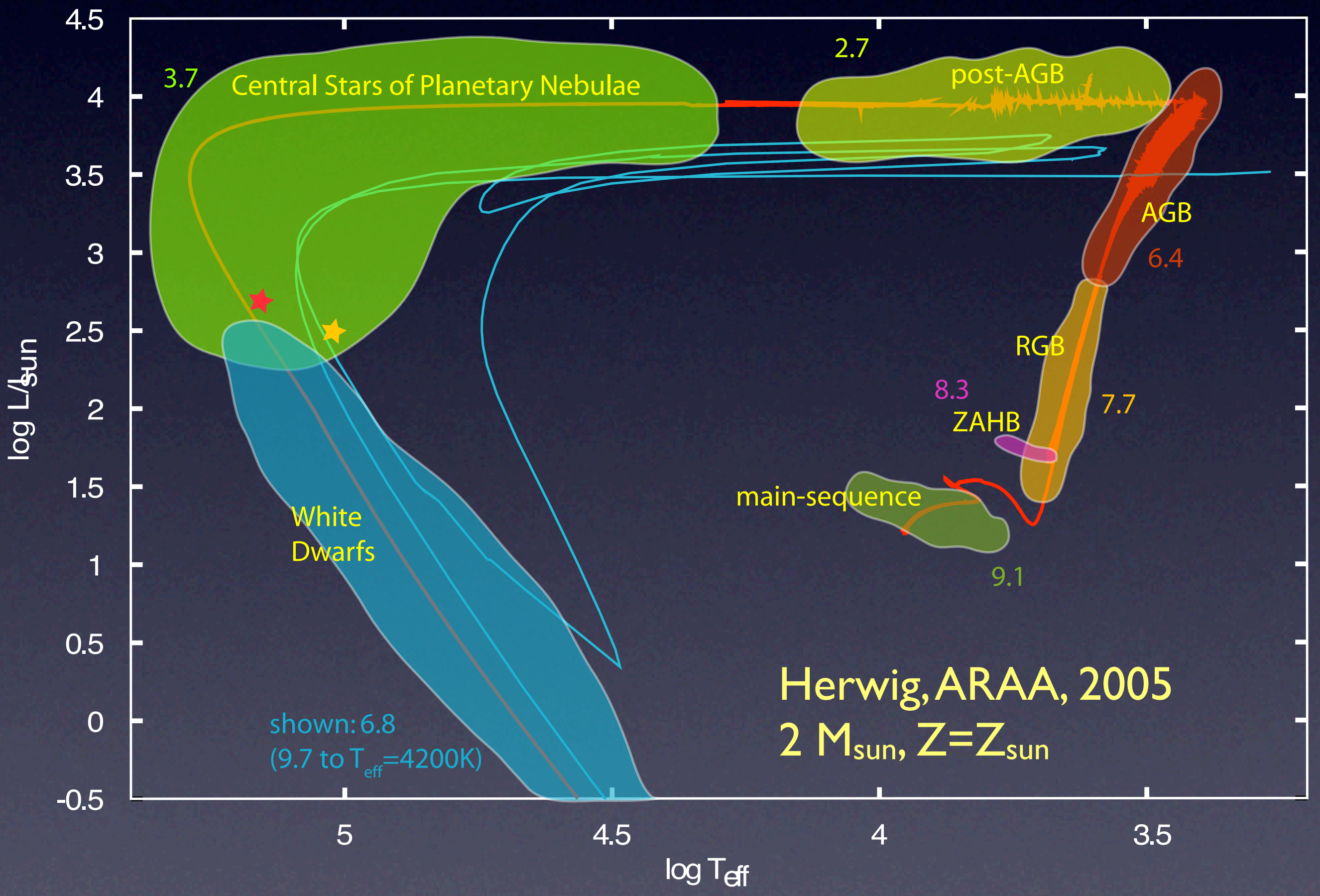
For more distant events, there are several sub-luminous events which broaden the variation to about 1 magnitude in B.

Let's re-explore the idea that variations in the peak luminosity originate in part from a scatter in the metallicity of the main-sequence stars that become white dwarfs.

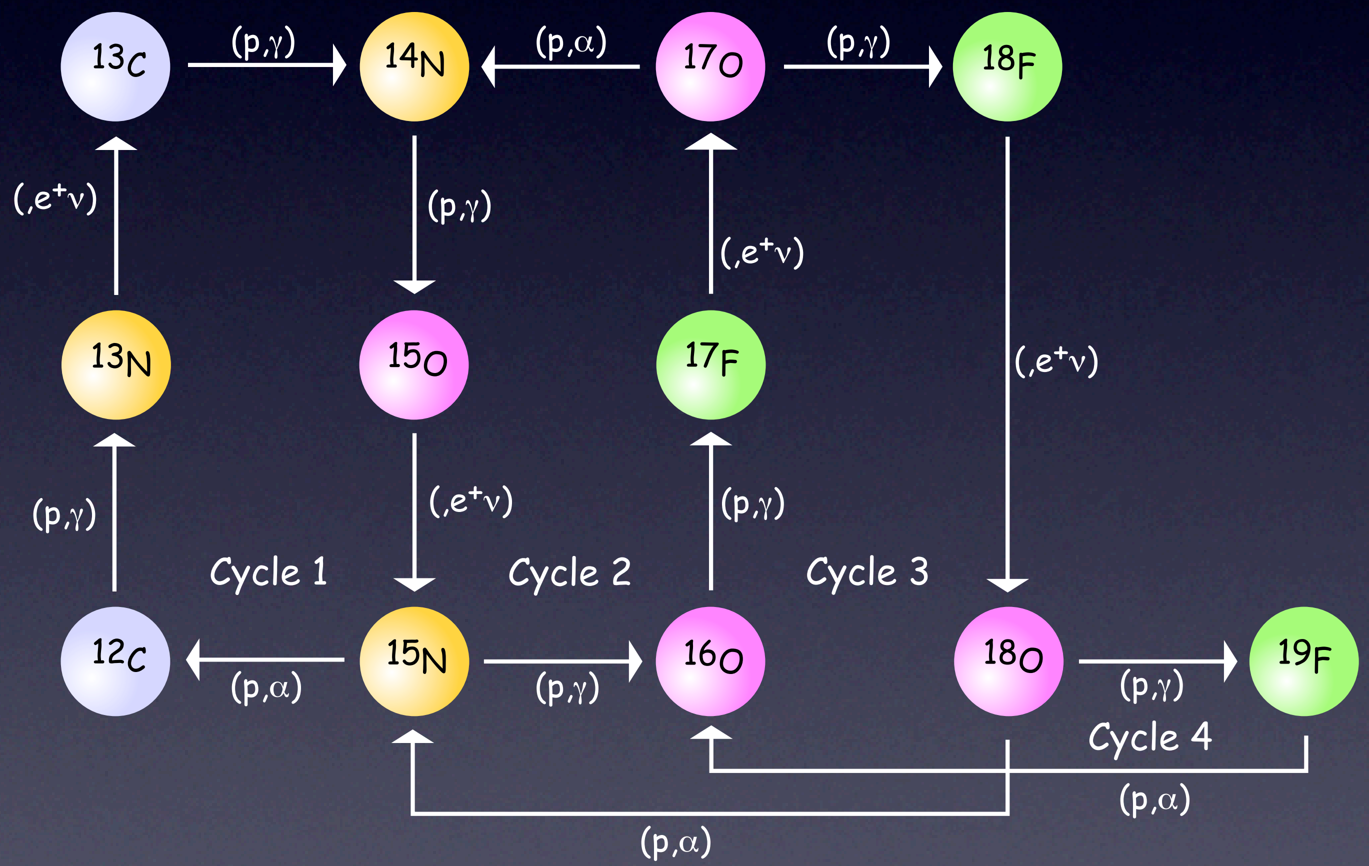
School of Athens
1510
Raffaello Sanzio

Most of a main-sequence star's initial metallicity comes from the CNO and ^{56}Fe nuclei inherited from its ambient interstellar medium.

The slowest step in the hydrogen burning CNO cycle is ^{14}N(p,γ). All the CNO piles up at ^{14}N when hydrogen burning is done.



Herwig, ARAA, 2005
2 M_{sun}, $Z=Z_{sun}$



During helium burning all of the ^{14}N is converted into ^{22}Ne by ^{14}N(α,γ)^{18}F (β^+,ν_e)^{18}O (α,γ)^{22}Ne.

Mass and charge conservation set the white dwarf's ^{22}Ne mass fraction and neutron enrichment

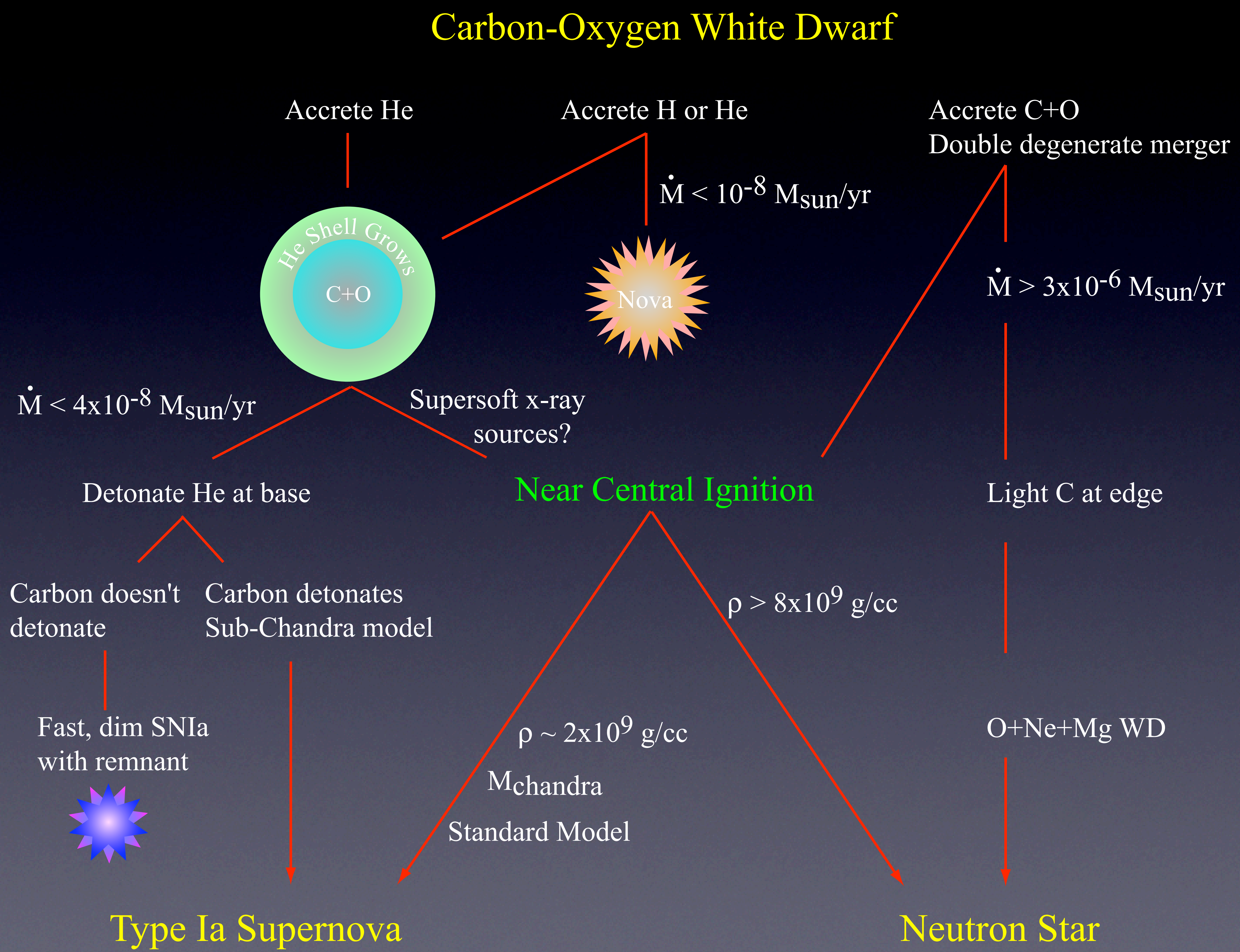
$$\sum_{i=1}^{n} \mathrm{X}_i = 1 \qquad\qquad \mathrm{Y}_e = \sum_{i=1}^{n} \frac{\mathrm{Z}_i}{\mathrm{A}_i} \mathrm{X}_i$$

$$\mathrm{X}(^{22}\mathrm{Ne}) = 22 \left[\frac{\mathrm{X}(^{12}\mathrm{C})}{12} + \frac{\mathrm{X}(^{14}\mathrm{N})}{14} + \frac{\mathrm{X}(^{16}\mathrm{O})}{16} \right]$$

$$\mathrm{Y}_e = \frac{10}{22}\,\mathrm{X}(^{22}\mathrm{Ne}) + \frac{26}{56}\,\mathrm{X}(^{56}\mathrm{Fe}) + \frac{1}{2}\left[1 - \mathrm{X}(^{22}\mathrm{Ne}) - \mathrm{X}(^{56}\mathrm{Fe})\right]$$

Assuming the ^{22}Ne and ^{56}Fe are uniformly distributed.

We’ll assume the standard model of a Type Ia supernova.



Carbon-Oxygen White Dwarf

Accrete He

Accrete H or He

Accrete C+O
Double degenerate merger

$\dot{M} < 10^{-8}$ M_{sun}/yr

$\dot{M} > 3x10^{-6}$ M_{sun}/yr

$\dot{M} < 4x10^{-8}$ M_{sun}/yr

Supersoft x-ray
sources?

Detonate He at base

Near Central Ignition

Light C at edge

Carbon doesn't
detonate

Carbon detonates
Sub-Chandra model

$\rho > 8x10^{9}$ g/cc

Fast, dim SNIa
with remnant

$\rho \sim 2x10^{9}$ g/cc

O+Ne+Mg WD

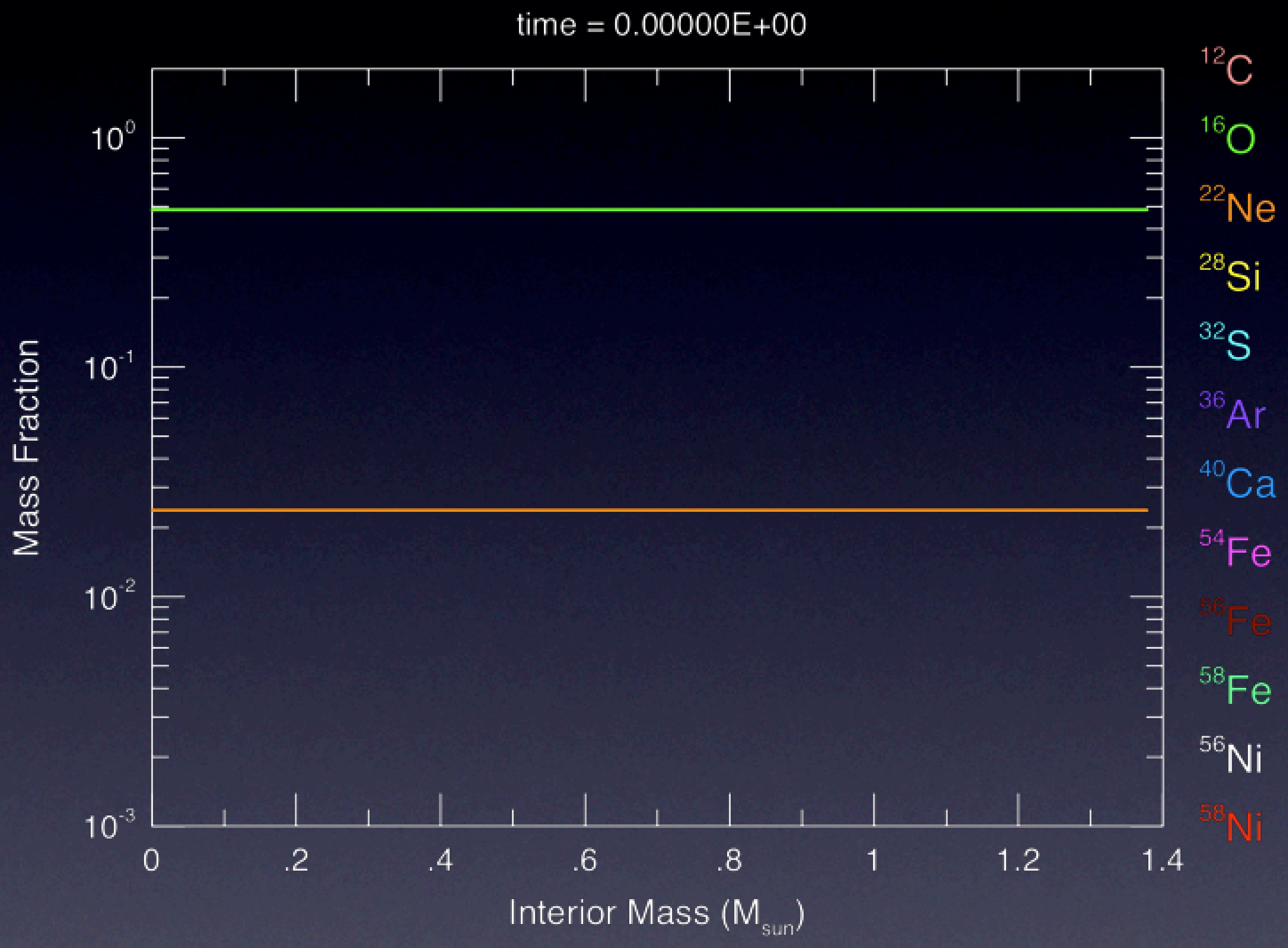
$M_{chandra}$

Standard Model

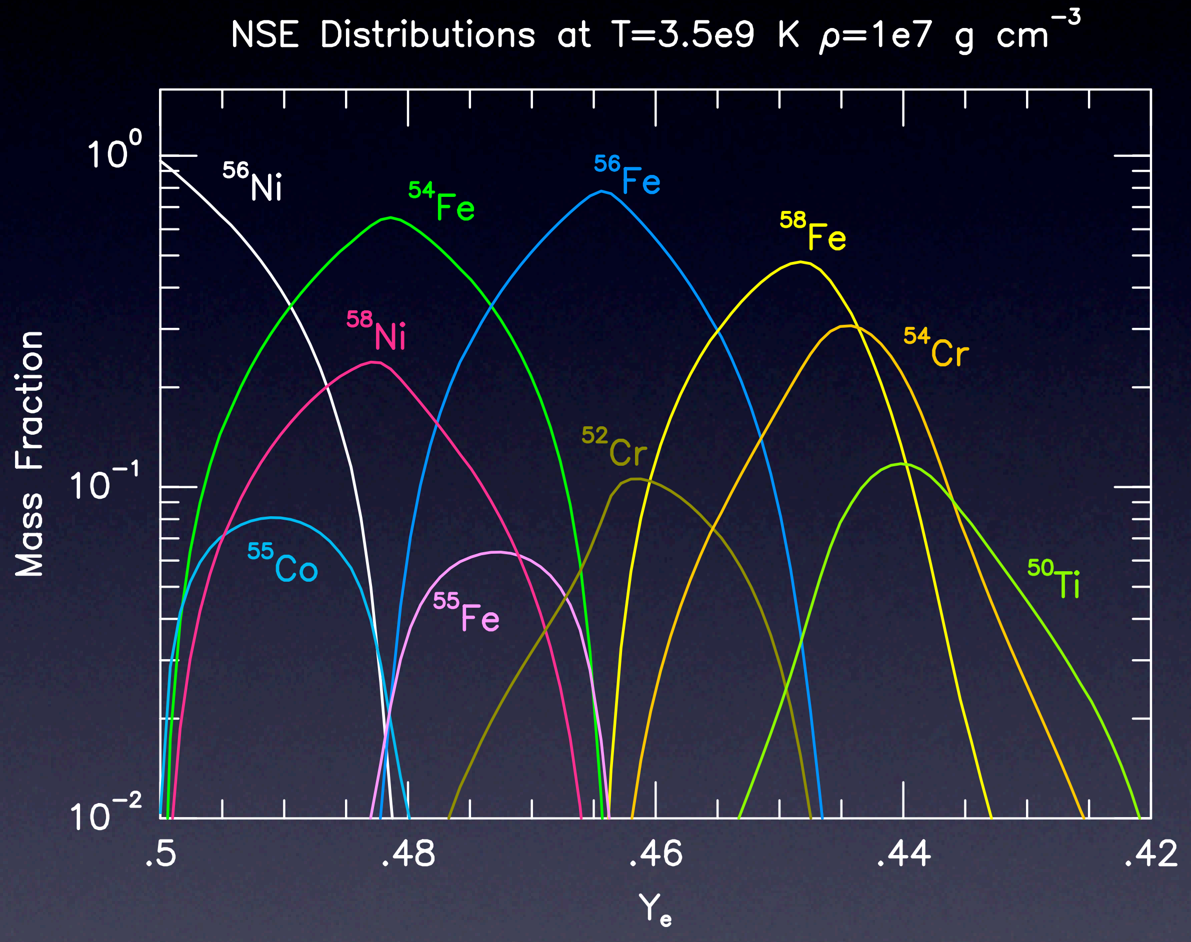
Type Ia Supernova

Neutron Star

Nearly all such 1D models produce most of their ^{56}Ni in a nuclear statistical equilibrium environment between ~ 0.2 and 0.8 M_{sun}.

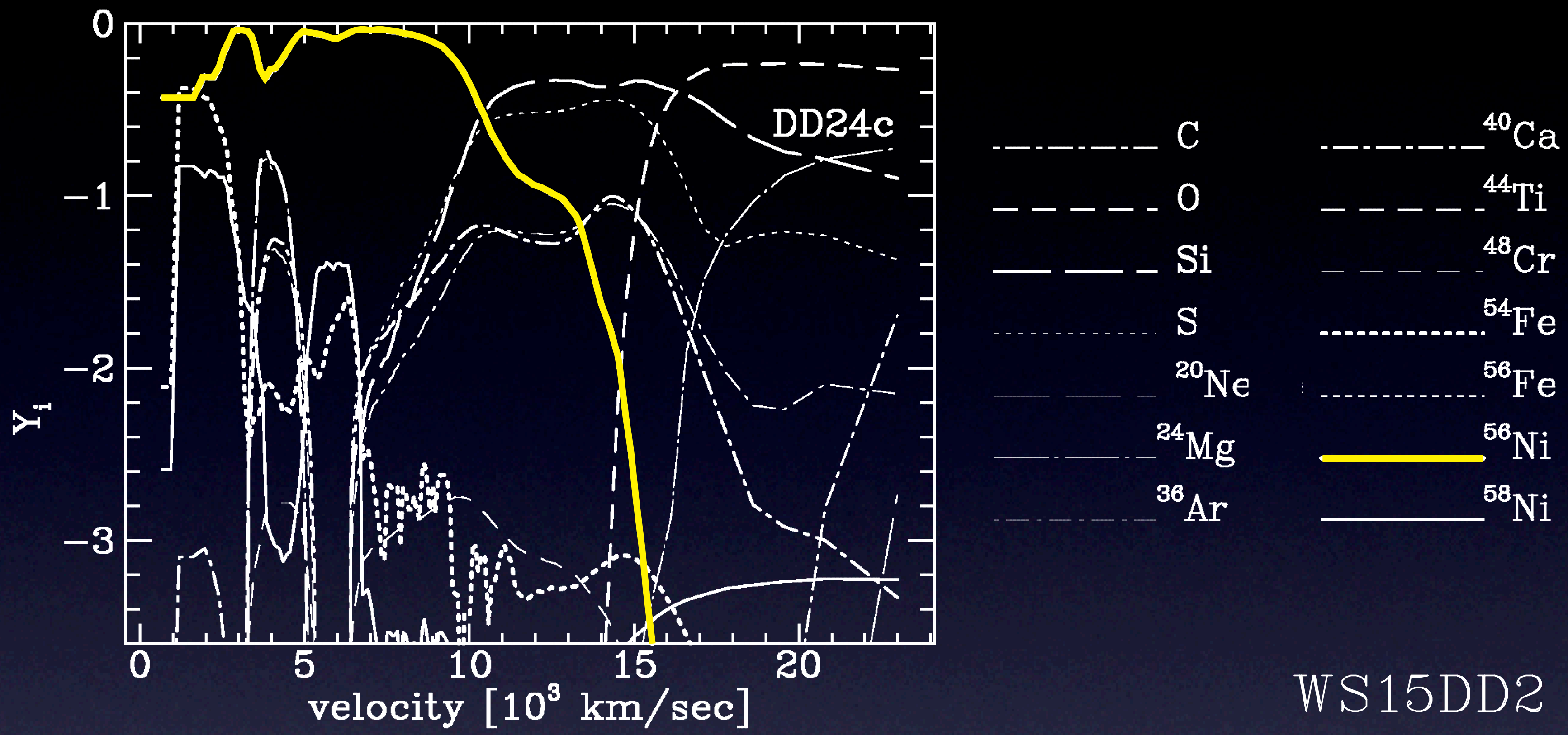


W7, Nomoto et al. 1984

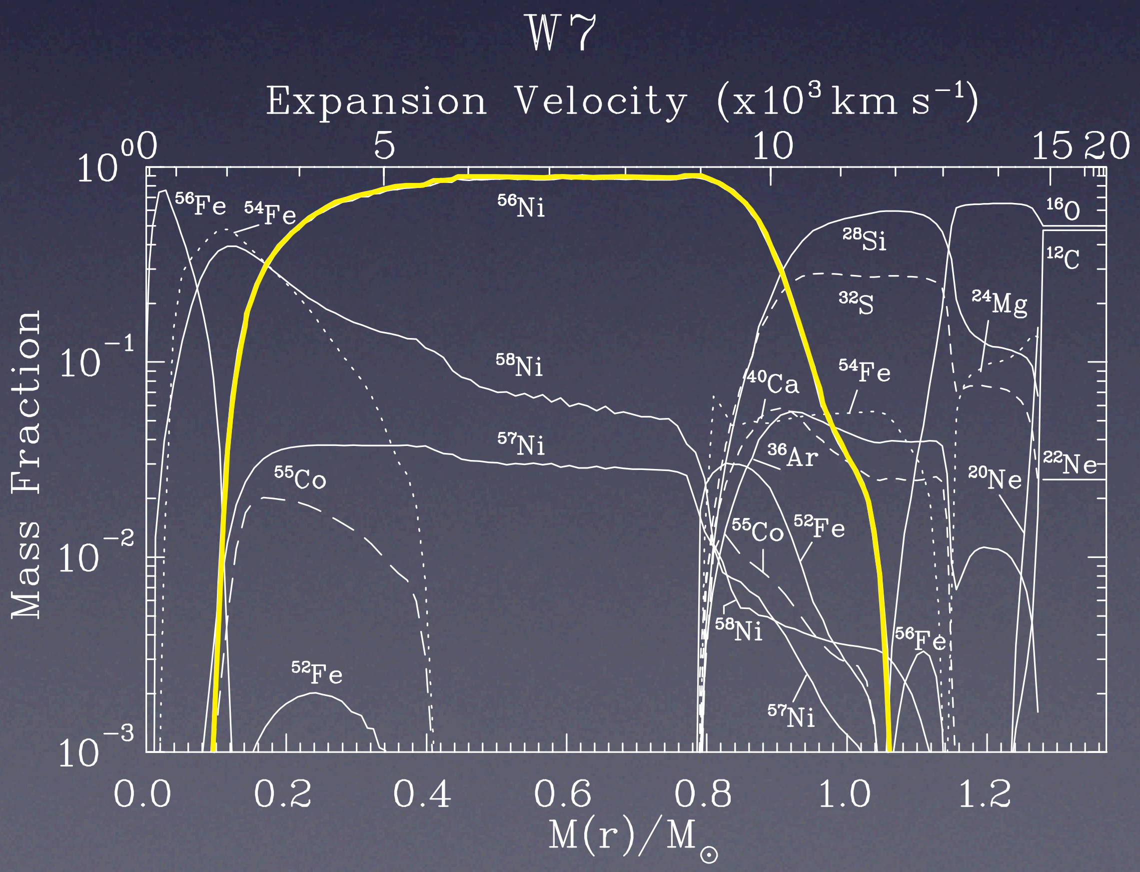


In this region, weak reactions occur on time-scales longer than the time-scale for disruption of the white dwarf.

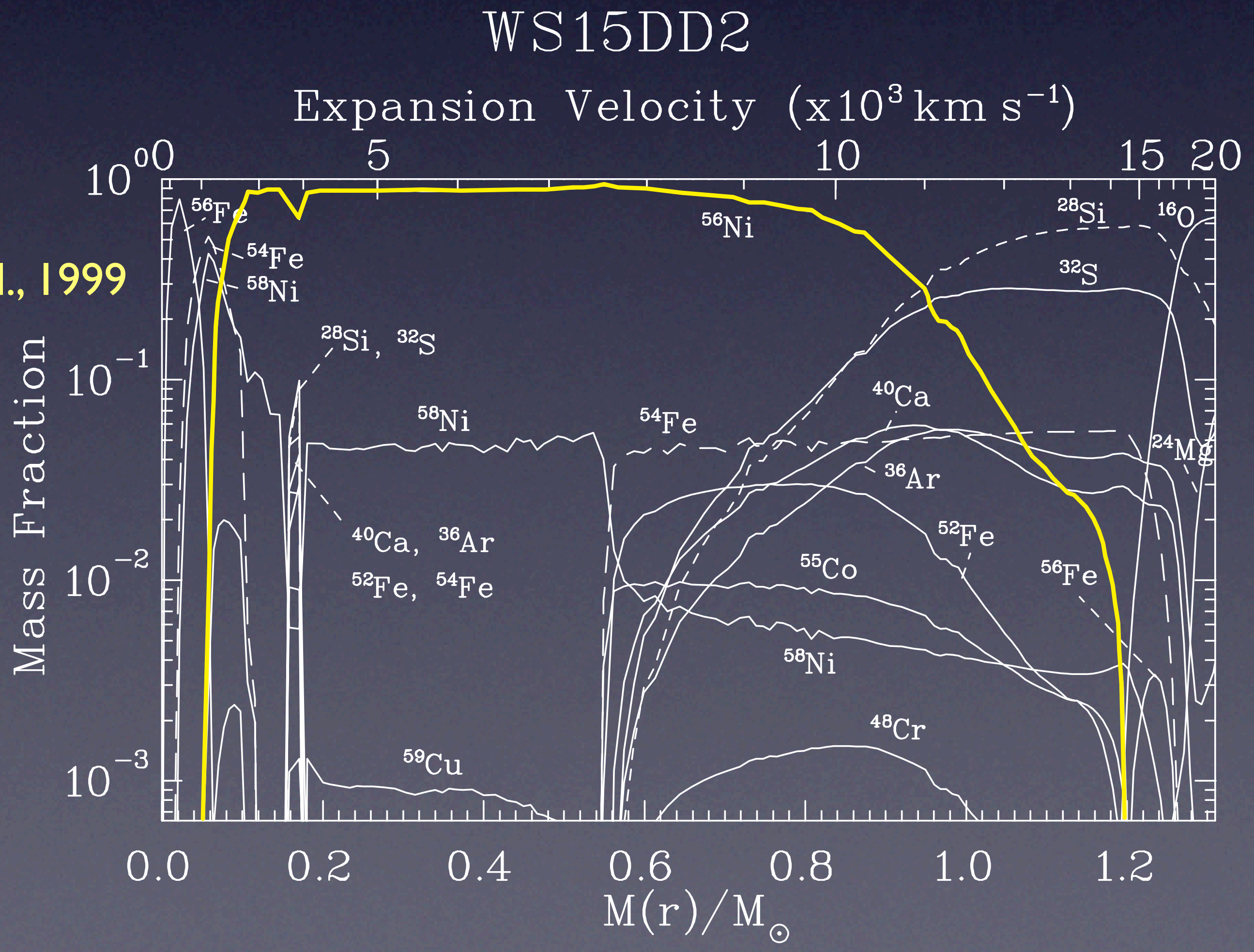
While many 1D models have sophisticated flame treatments, we want to elucidate physics that are robust to any complicated hydrodynamics.



Höflich et al., 1998



Iwamoto et al., 1999



Consider the case when ^{56}Ni and ^{58}Ni are the only two species in nuclear statistical equilibrium. Mass and charge conservation

$$\sum_{i=1}^{n} \mathrm{X}_i = 1 \qquad \mathrm{Y}_e = \sum_{i=1}^{n} \frac{\mathrm{Z}_i}{\mathrm{A}_i} \mathrm{X}_i$$

imply a linear relationship between the mass fraction of ^{56}Ni and Y_e:

$$X(^{56}\mathrm{Ni}) = 1 - X(^{58}\mathrm{Ni}) = 58\mathrm{Y}_e - 28$$

We can set this final Y_e equal to the initial Y_e of the white dwarf since weak interactions don’t dominant where most of the ^{56}Ni is made.

$$\mathrm{X}(^{56}\mathrm{Ni}) = 1 - 0.057 \frac{Z}{Z_\odot}$$

The average peak B and V magnitudes of nearby Type Ia events imply ~0.6 M_{sun} of ^{56}Ni is produced. Using this fiducial mass gives

$$\mathrm{M}(^{56}\mathrm{Ni}) = \int \mathrm{X}(^{56}\mathrm{Ni})dm \approx 0.6 \left[1 - 0.057\frac{Z}{Z_\odot}\right] M_\odot$$

If a third isotope is present, say ^{54}Fe, then Saha-like equations must be solved for the NSE distribution. The net result is a slightly shallower slope

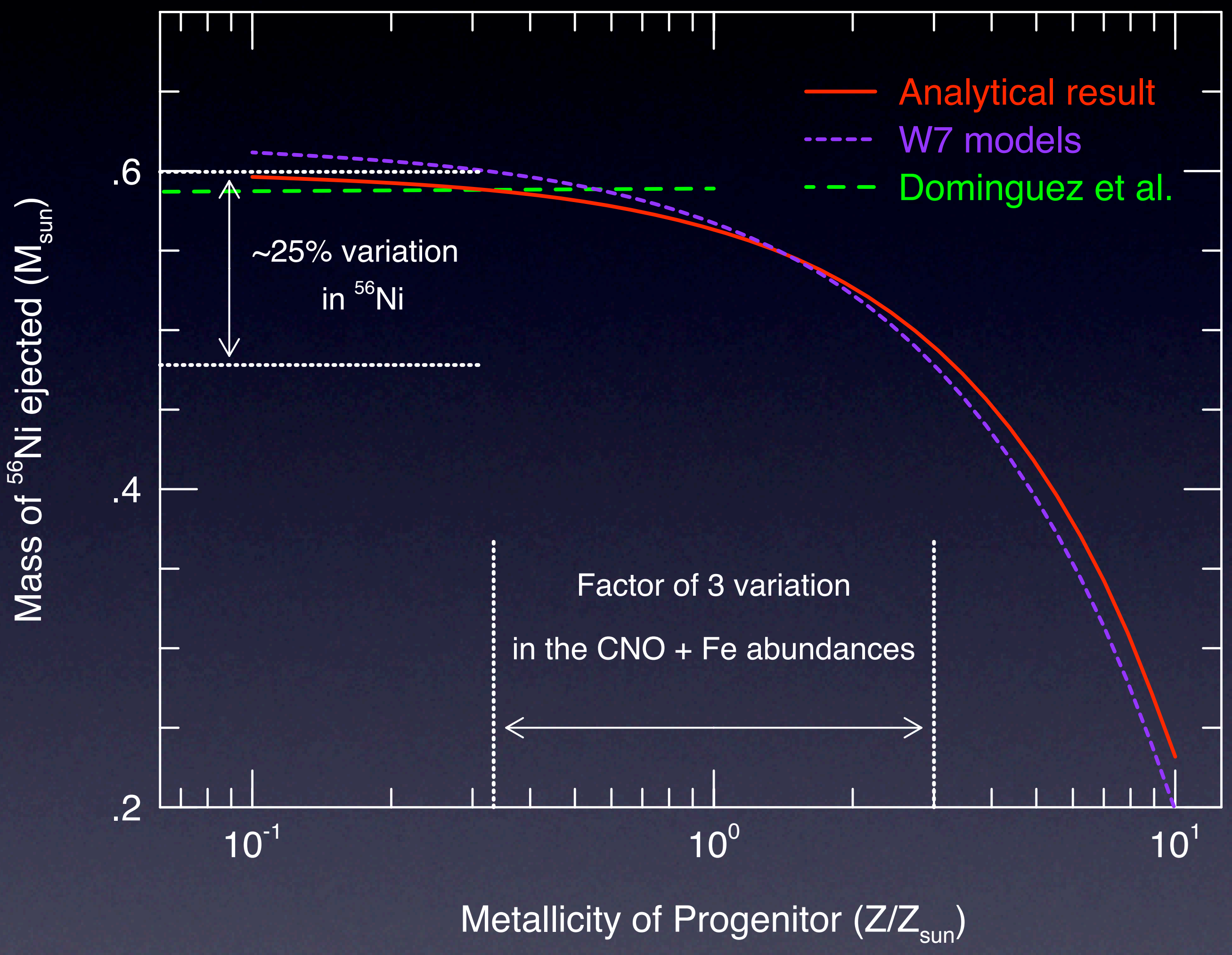
$$\mathrm{M}(^{56}\mathrm{Ni}) \approx 0.6 \left[1 - 0.054\frac{Z}{Z_\odot}\right] M_\odot$$

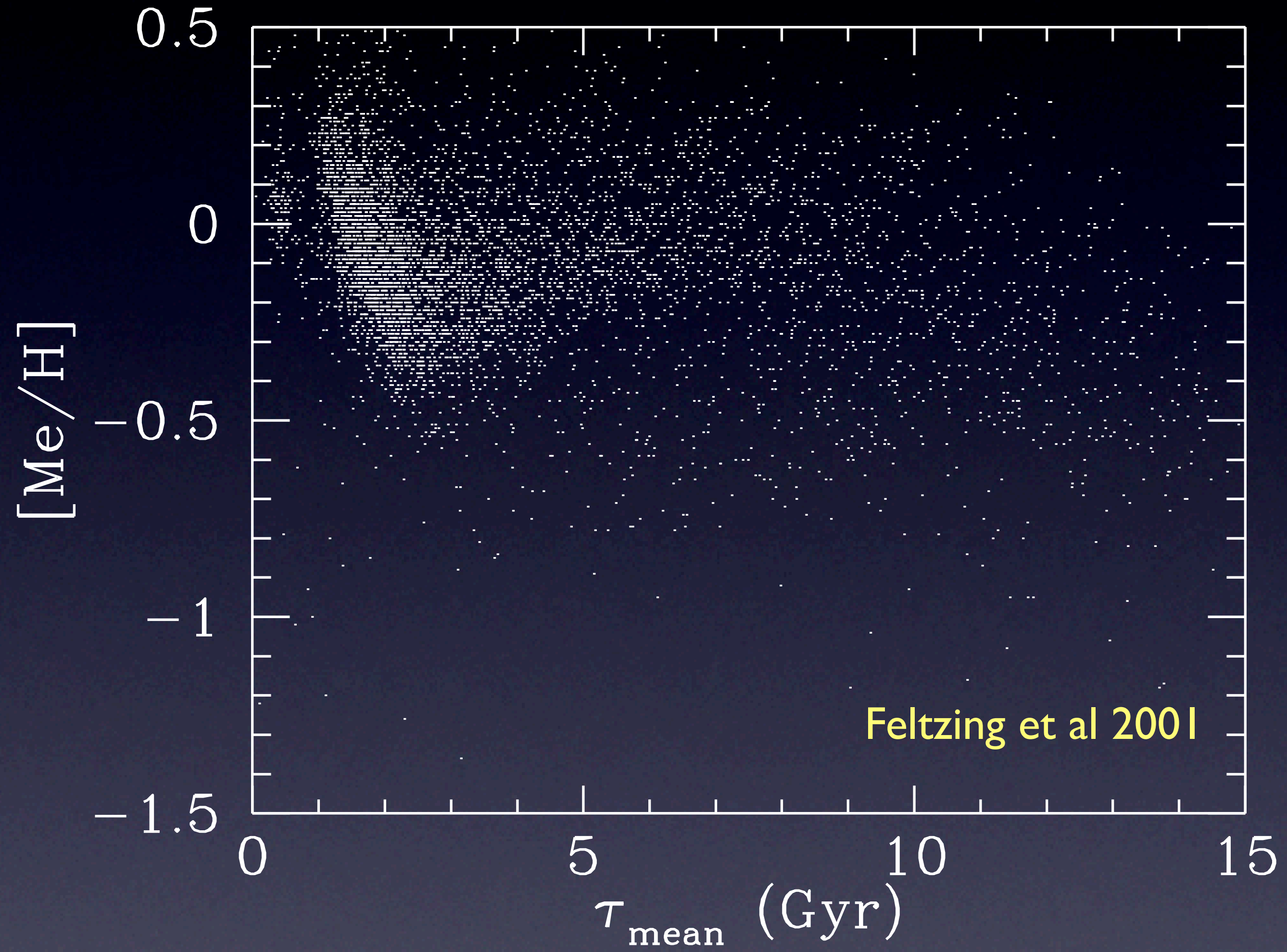
This result is robust.

As long as the region that reaches NSE does so on a timescale over which Y_e is nearly constant, then the mass of ^{56}Ni produced is largely independent of the details of flame front propagation.

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.” - Tommy Gold

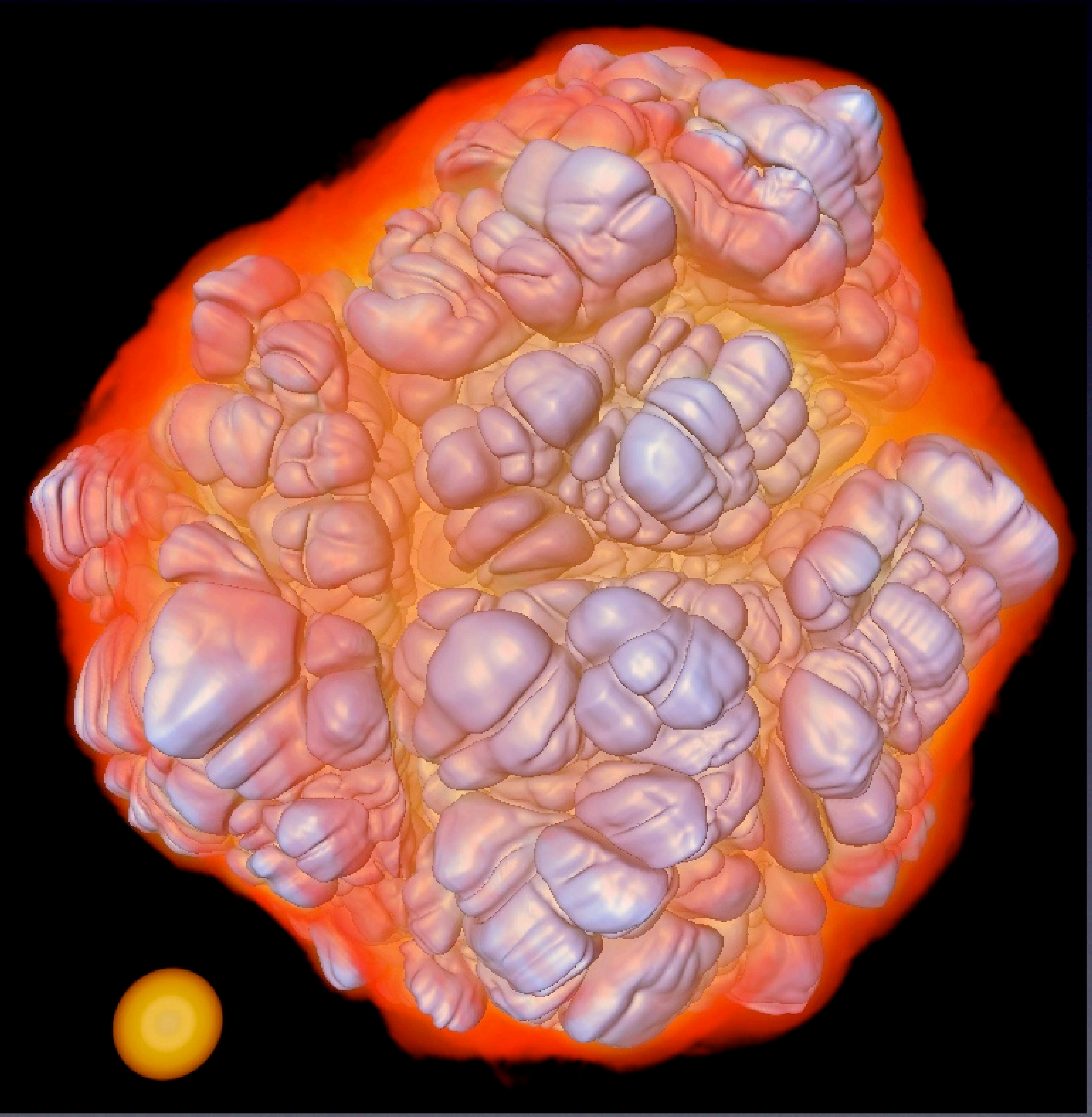
Post-processing thermodynamic trajectories of 1D simulations reproduces the analytical result to within 5%.



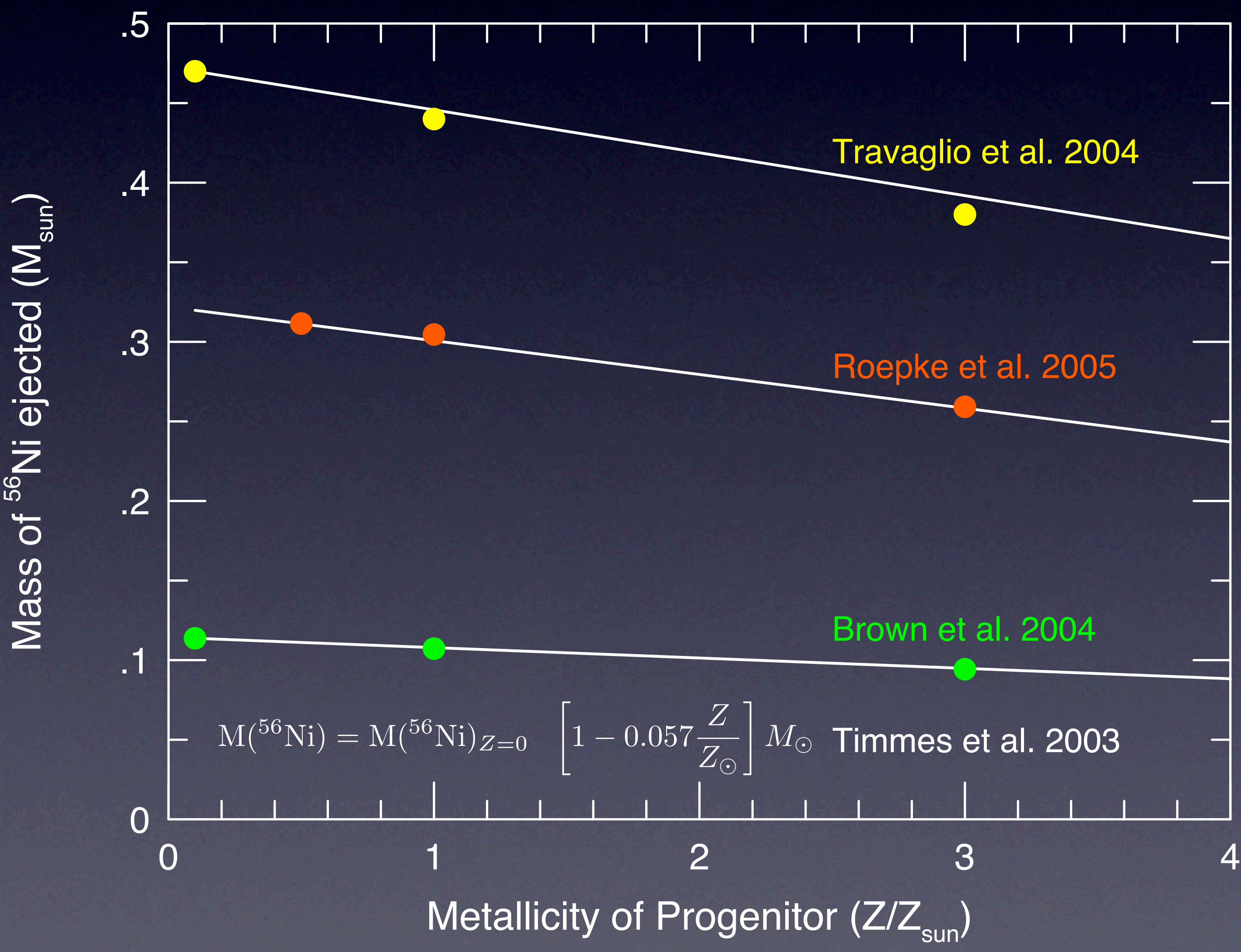


A factor of 3 scatter in the initial metallicity leads to a variation of about 25% (0.13 Msun, $\Delta M_V \sim 0.3$ mag) in the mass of ^{56}Ni ejected, accounting for most, but not all, of the observed variation.

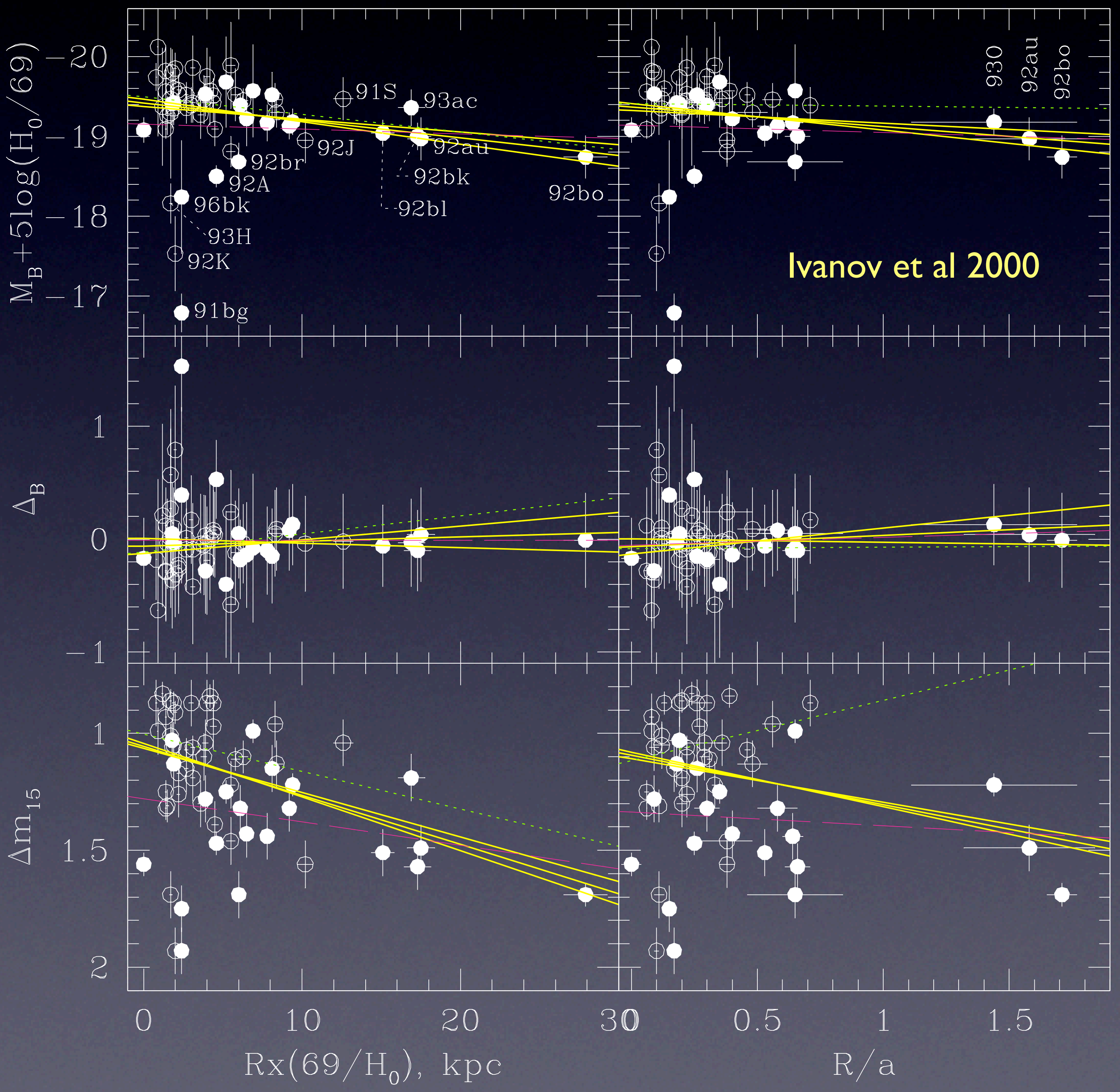
From 3D simulations the Max Planck group find ^{56}Ni variations of 2% from the C/O ratio, 7% from the central density, 20% from metallicity.

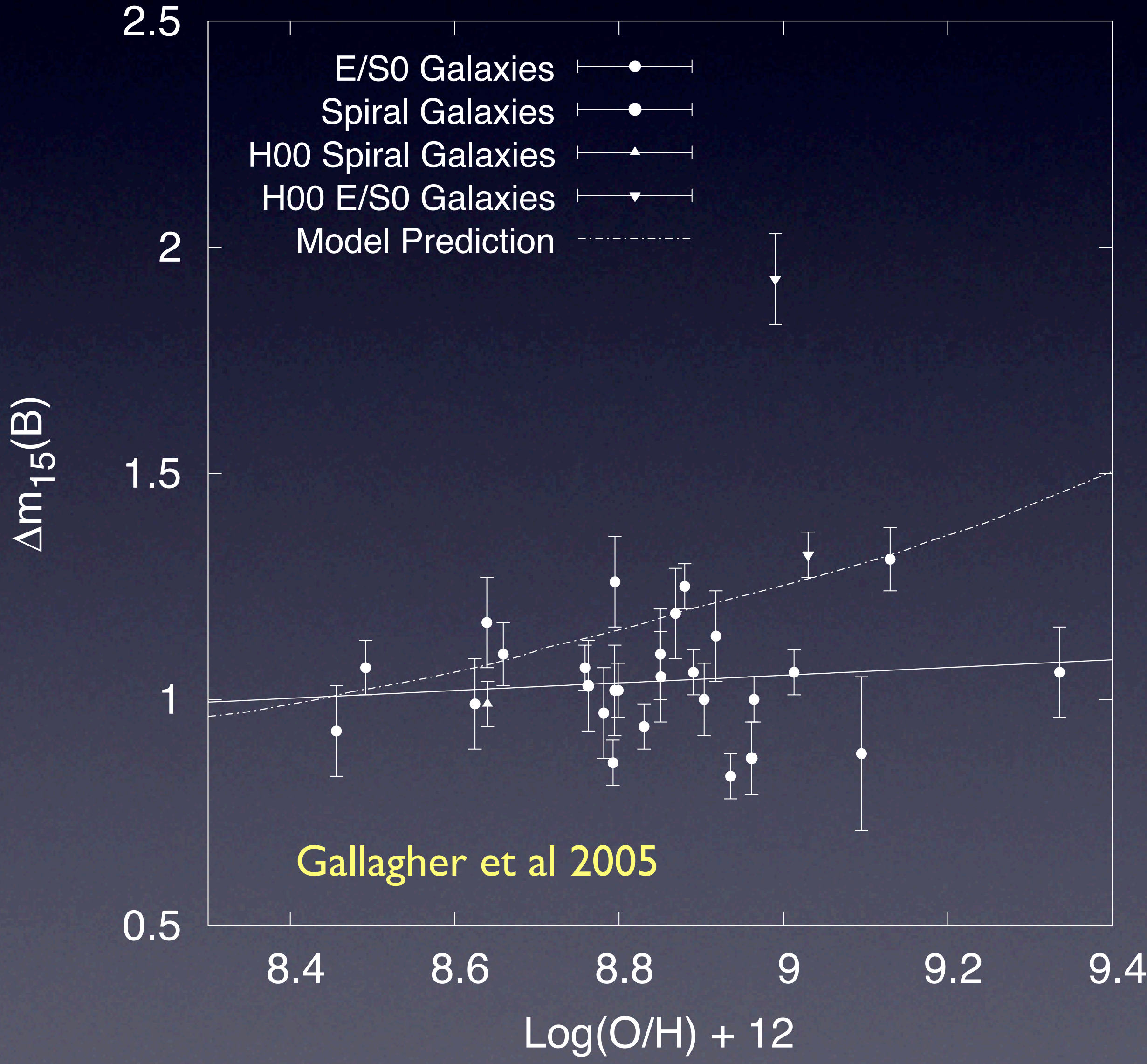


Röpke et al. 2005



From ~60 host galaxies, Ivanov et al (2000) and Gallagher et al (2005) suggest age rather than metallicity better expresses the observed trends.

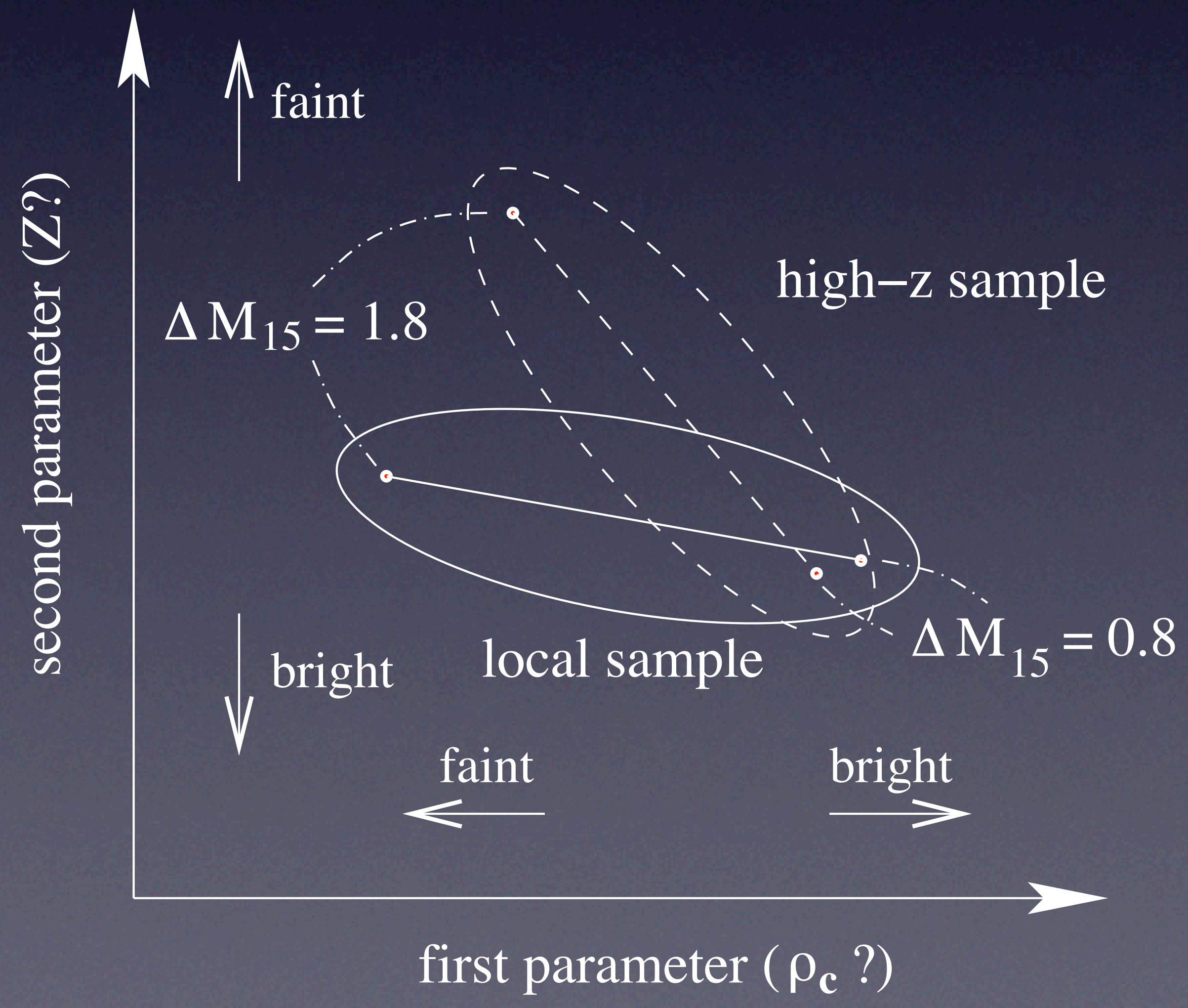


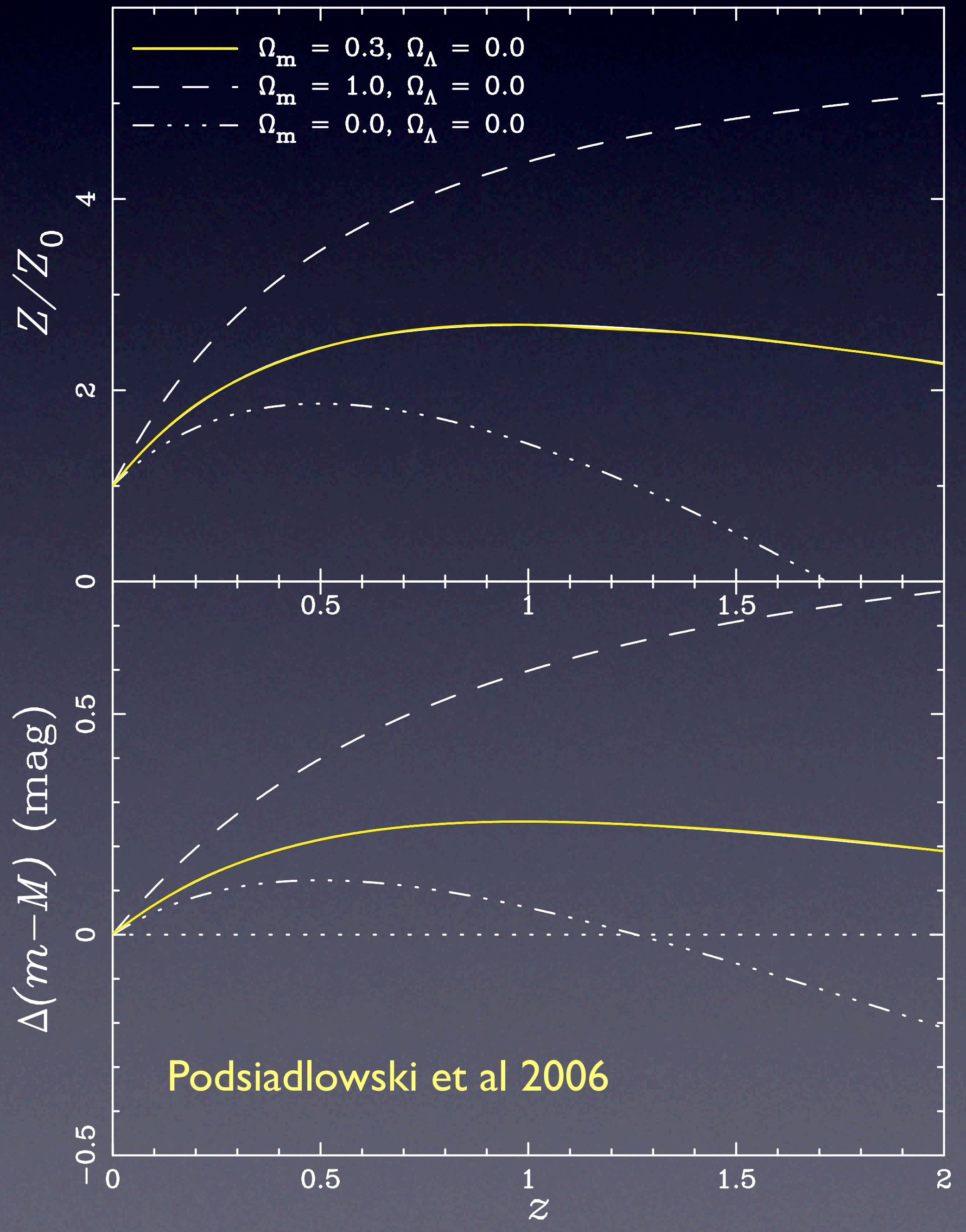


Podsiadlowski et al 2006 showed that electron captures on ^{22}Ne during the simmering phase could magnify the effect of metallicity

$$X(^{56}\mathrm{Ni}) = 1 - \begin{pmatrix}0.165\\0.111\\0.058\end{pmatrix}\frac{Z}{Z_\odot}$$

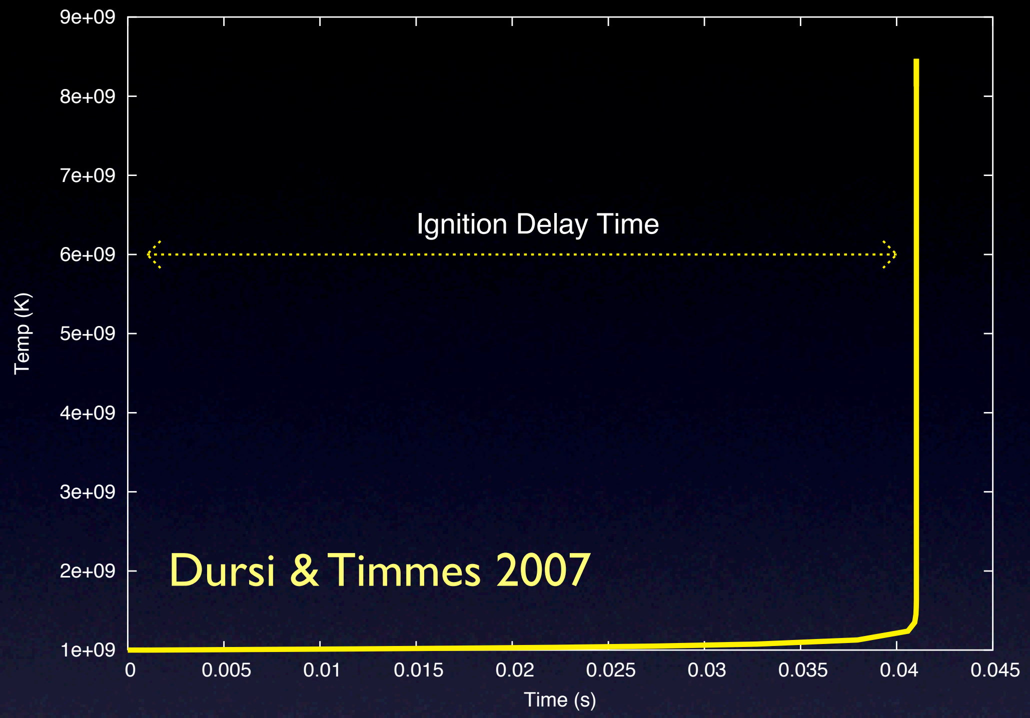
and examined the effects of metallicity on the determination of cosmological parameters.

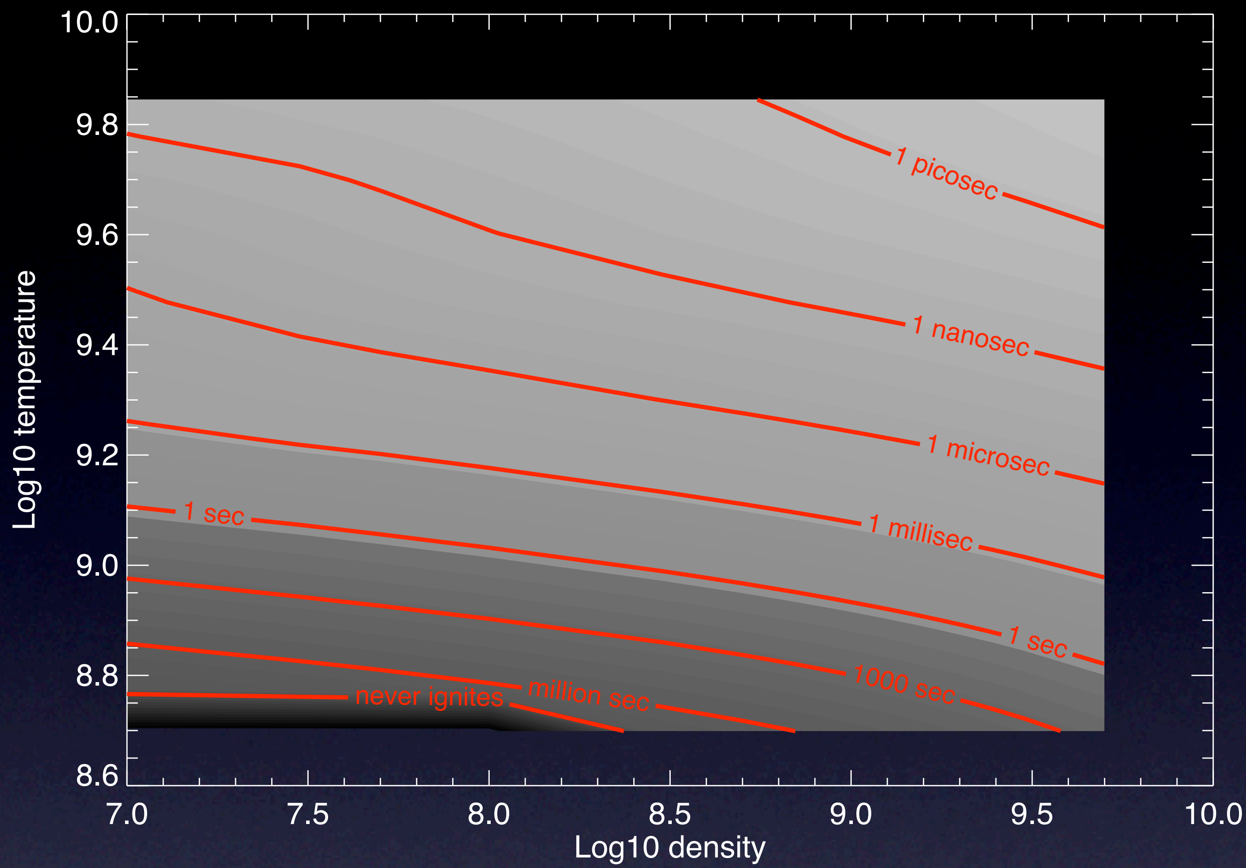




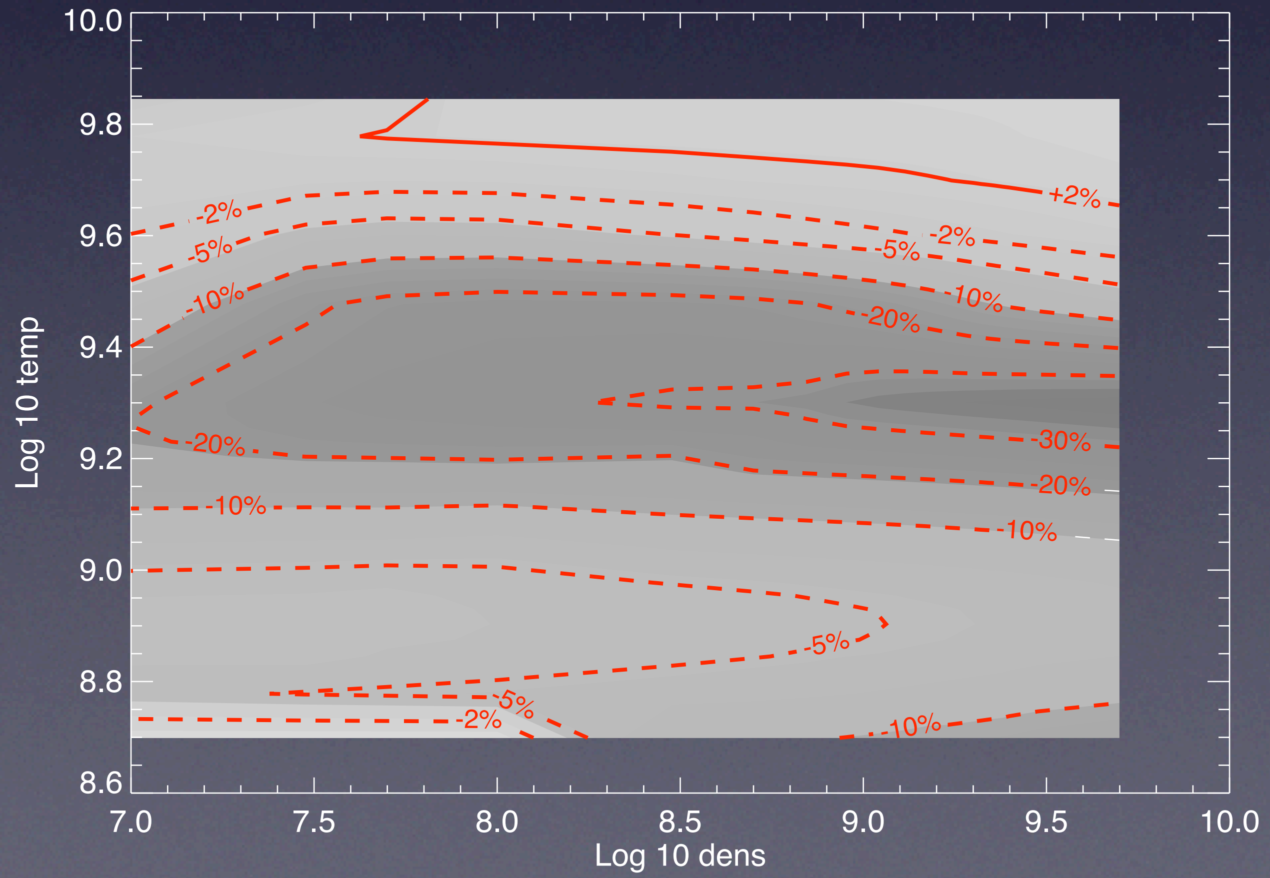
Podsiadlowski et al 2006

Metallicity reduces the ignition time; even modest amounts of ^{22}Ne can reduce the ignition time of CO mixtures 20-30% +



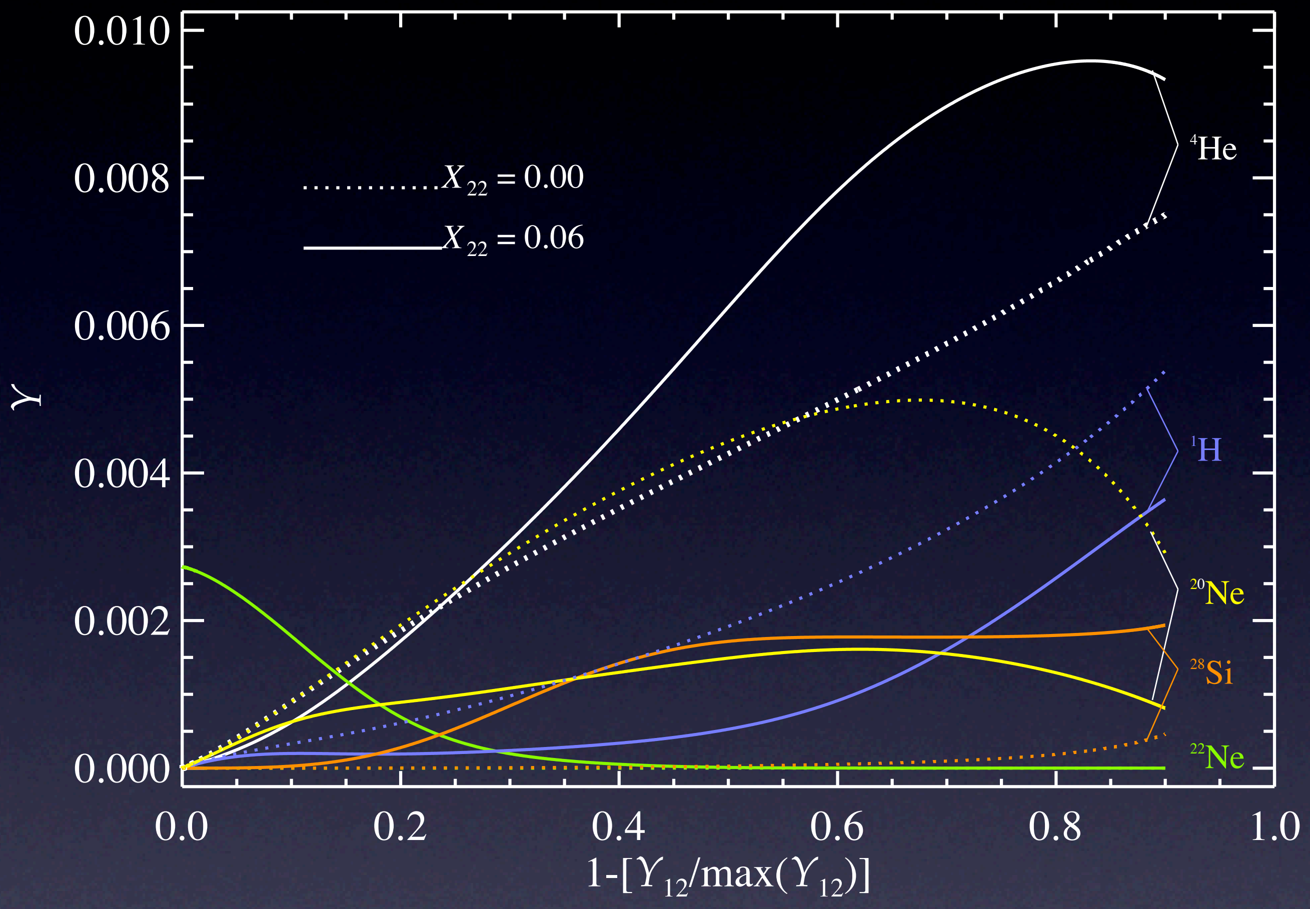


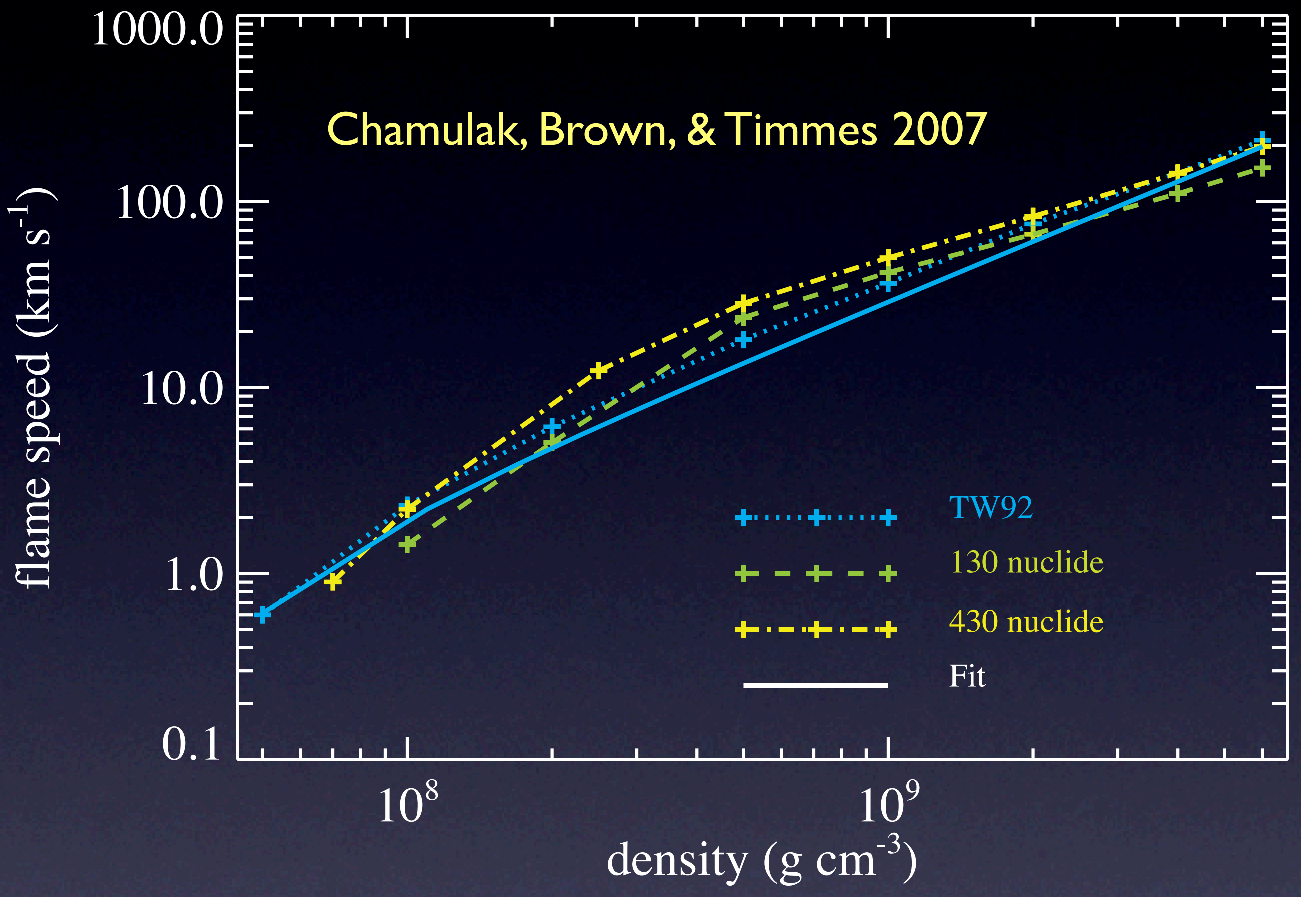
Ignition occurs at rare peaks in the tails of PDFs; ^{22}Ne can greatly increase probability of points igniting.



Different state at ignition time for metal-rich WD? If so, may introduce a metallicity-central density entanglement.

Metallicity increases the laminar flame speed; being roughly linear with ^{22}Ne and ~ 30% for X(^{22}Ne)=0.06.



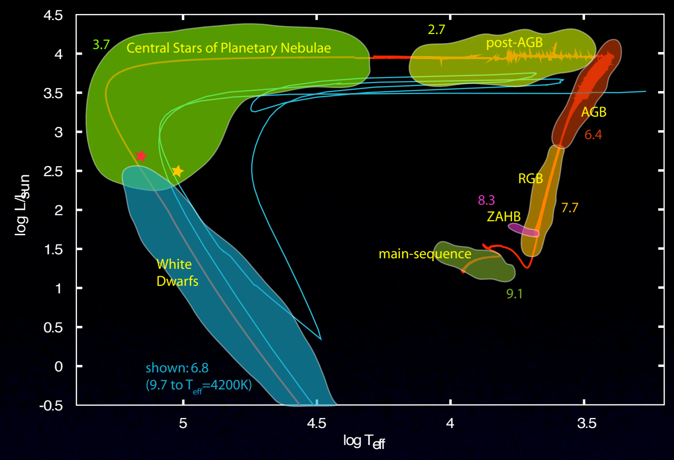


$$D_{\rm lam} = [23.26\rho_9 + 37.34\rho_9^{1.1} - 1.288] \times \left[1 + 0.3\left(\frac{X_{22}}{0.06}\right)\right] \times \left|0.3883\left(\frac{X_{12}}{0.5}\right) + 0.09773\left(\frac{X_{12}}{0.5}\right)^3\right| \ {\rm kms}^{-1}$$

These results pertain to the initial burning front near the center, and at late times where the flame may make a transition to distributed burning.

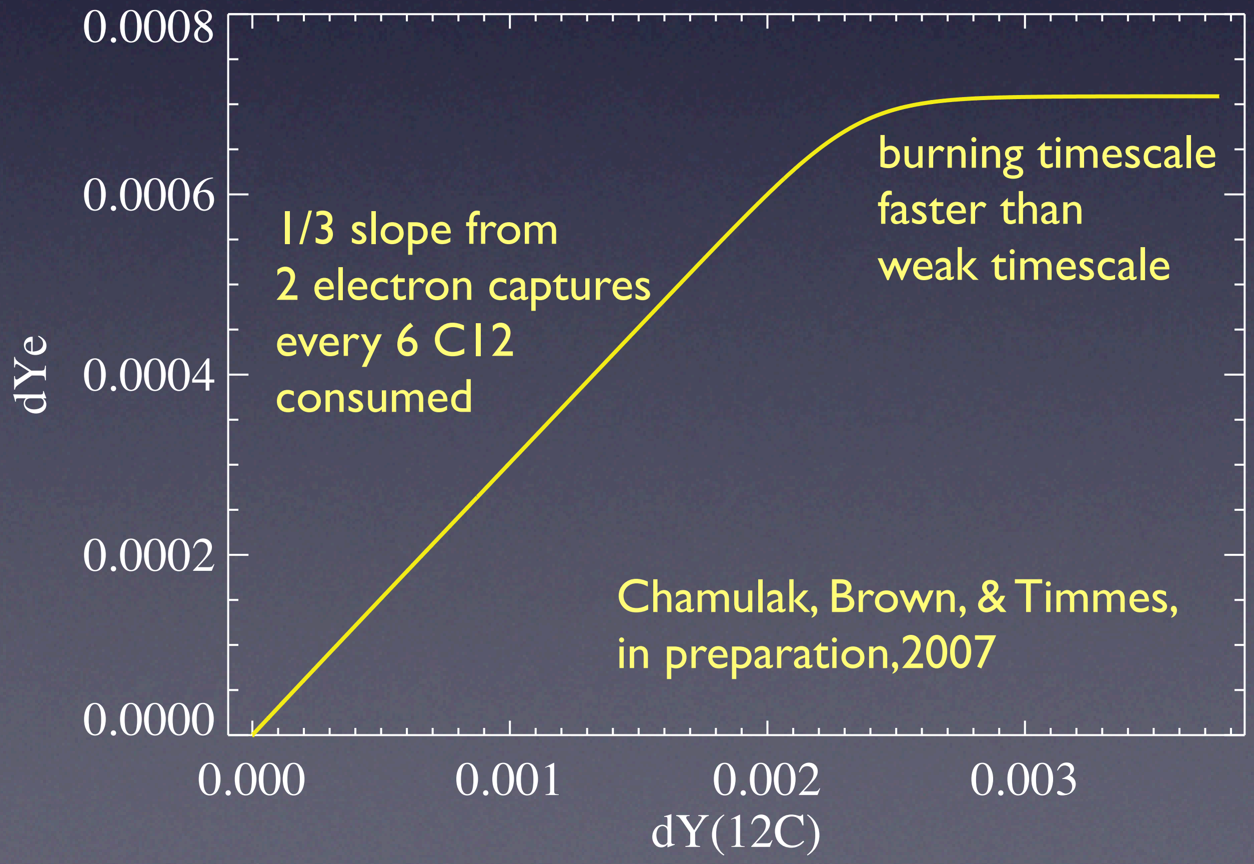
Can ^{22}Ne be produced in-situ?

Yes, during the helium shell flashes in an AGB star.
Falk Herwig and I are calculating some numbers.



Yes, during laissez-faire carbon burning during the simmering phase!

Self-heating calculations suggest
$^{12}C(^{12}C,p)^{23}Na(e^-,\nu)^{23}Ne$ and
$^{12}C(p,\gamma)^{13}N(e^-,\nu)^{13}C$
operate with enough vigor to
make a Y_e floor.

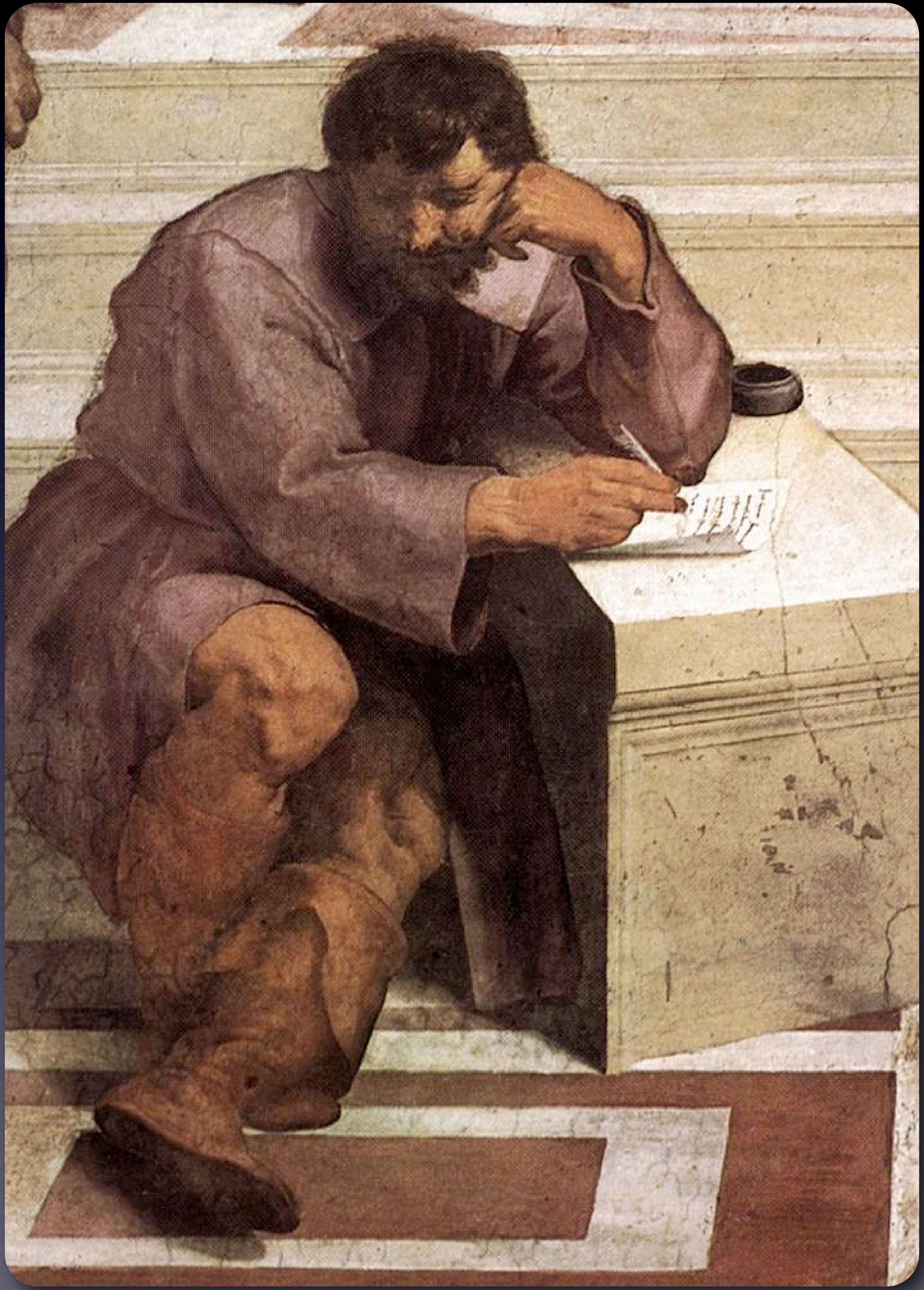


1/3 slope from
2 electron captures
every 6 C12
consumed

burning timescale
faster than
weak timescale

Chamulak, Brown, & Timmes,
in preparation,2007

Destiny
Dark Energy Space Telescope



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