Type Ia Supernovae

Energetics, Explosions, and Nucleosynthesis

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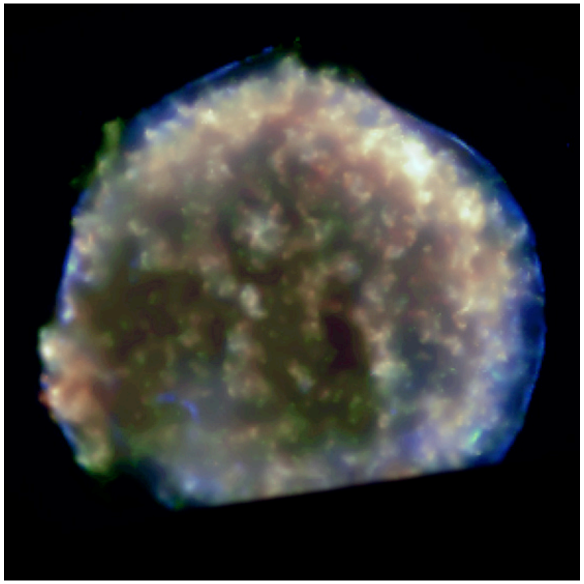
SN 1994D

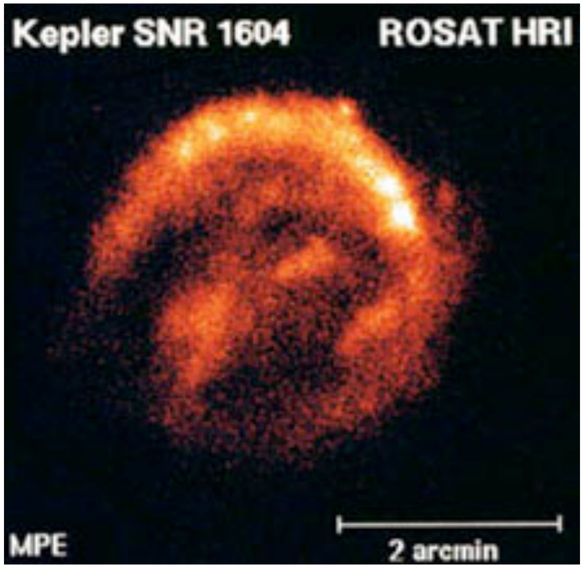
“Recent” Galactic SNe Ia?

One evening when I was contemplating as usual the celestial vault, whose aspect was so familiar to me, I saw, with inexpressible astonishment, near the zenith, in Cassiopeia, a radiant star of extraordinary magnitude.
Struck with surprise, I could Hardly believe my eyes.

Tycho Brahe,

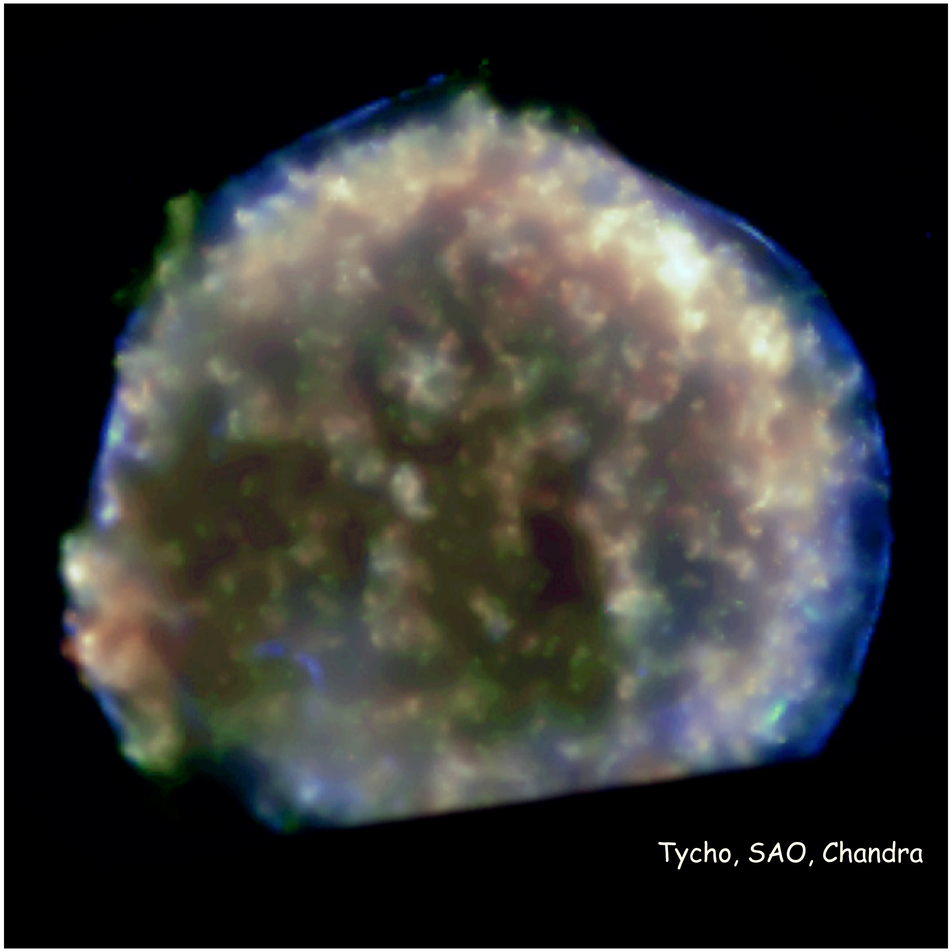
November 1572





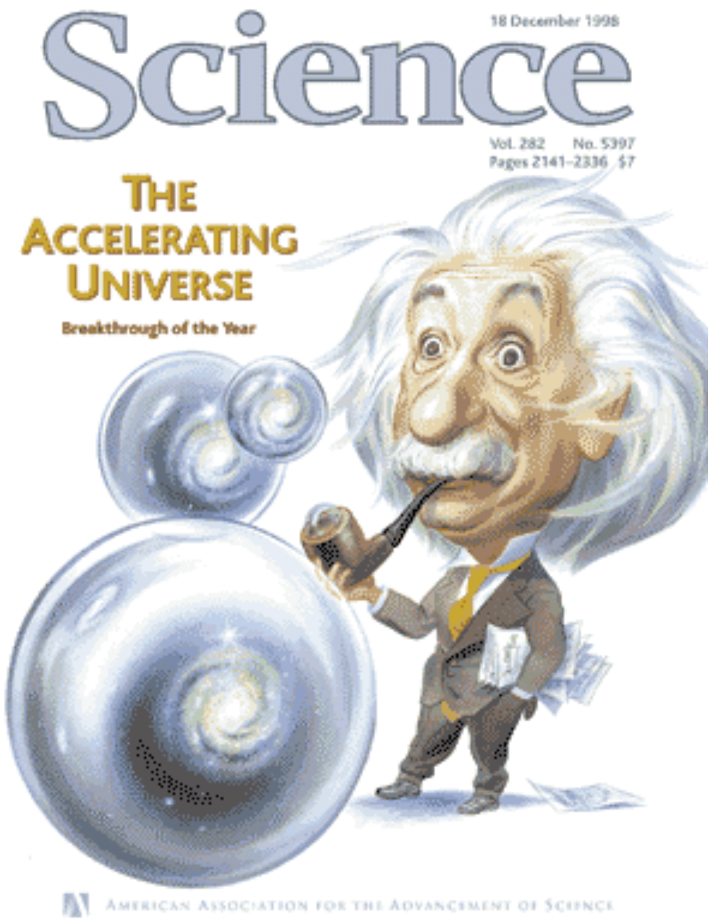
Type Ia Supernovae in our Galaxy

SN	Distance (kpc)	m_v
185	1.2 ± 0.2	-8 ± 2
1006	1.4 ± .3	-9 ± 1
1572	2.5 ± 0.5	-4.0 ± 0.3
1604	4.2 ± 0.8	-4.3 ± 0.3



- The expected rate in the Milky Way is about 1 every 100 years, but dozens are found in other galaxies every year. The expected ratio (by number) for our Galaxy over its lifetime is SNe II/SNe Ia ≈ 3-6.

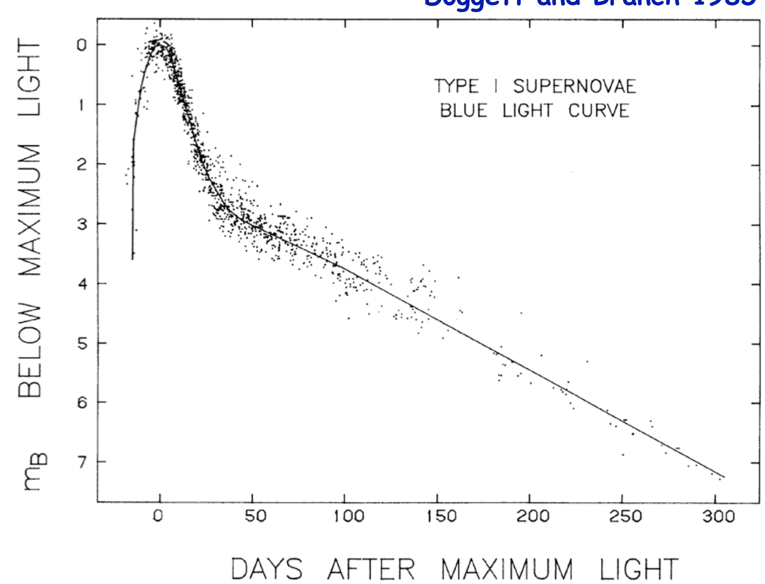
Supernovae Ia and Cosmology



In 1998, SNe Ia played a major role in the "science breakthrough of the year:"

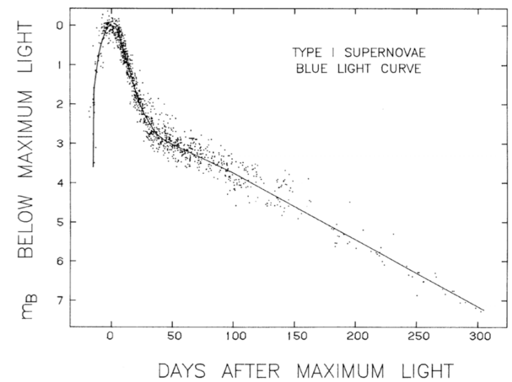
Using SNe Ia as distance indicators (standard candles), two groups of astronomers found strong indications for an accelerating cosmic expansion.

Doggett and Branch 1985



Significance of Type Ia Supernovae

Doggett and Branch (1985)



SNe Ia and Cosmology

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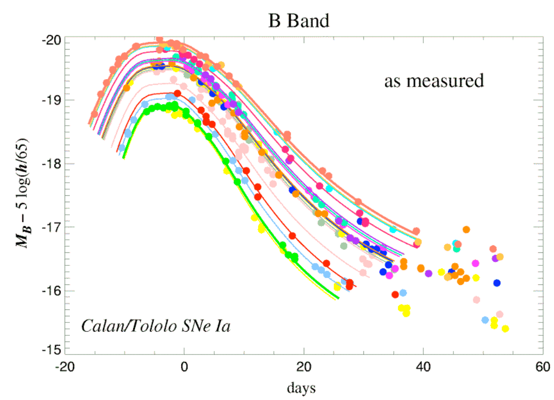
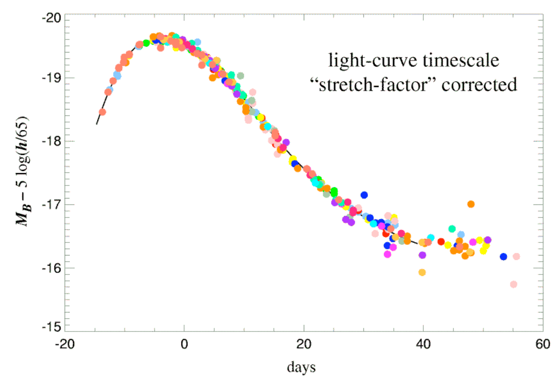


- **The Phillips relation compensates for the observed variation in peak luminosity to provide an effective "standard candle."**

- **Brighter SNe Ia decline more slowly.**
Peak luminosity ∝ ^{56}Ni mass ejected.

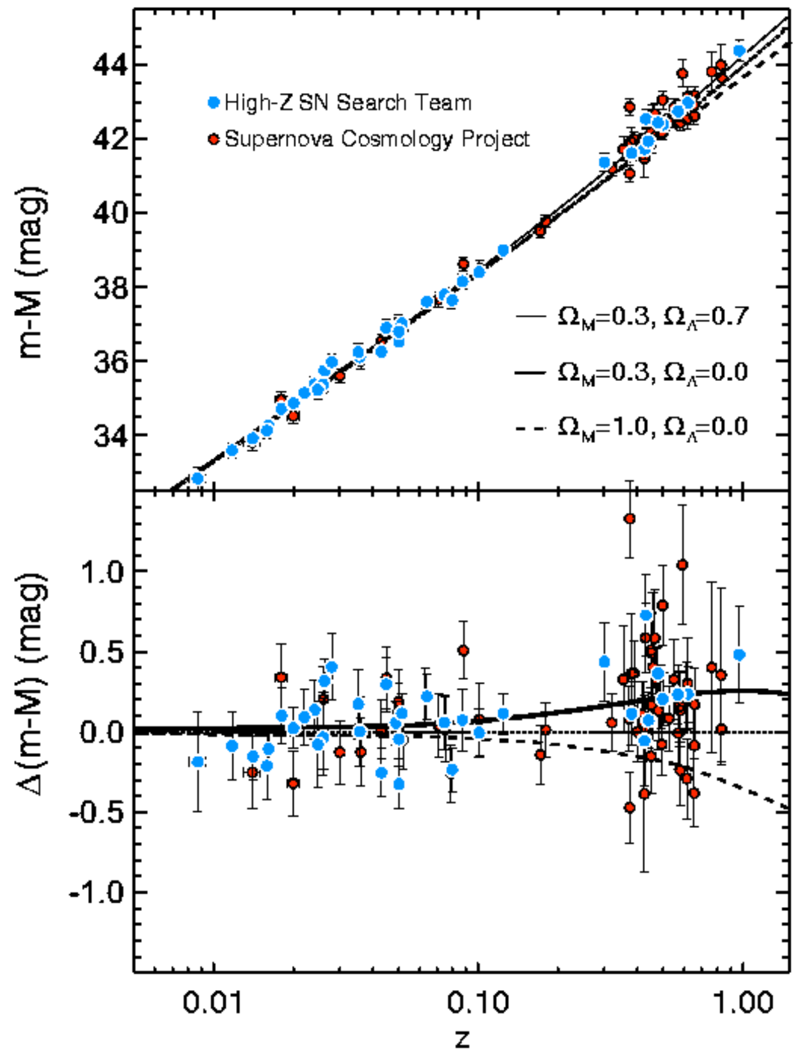


- **Synthesis of iron peak nuclei (^{56}Ni).**

Hubble Diagram: High-z and SCP Type Ia SNe

- Hubble diagram showing Type Ia SNe from both High-*z* and SCP teams, compared to expectation for various cosmologies

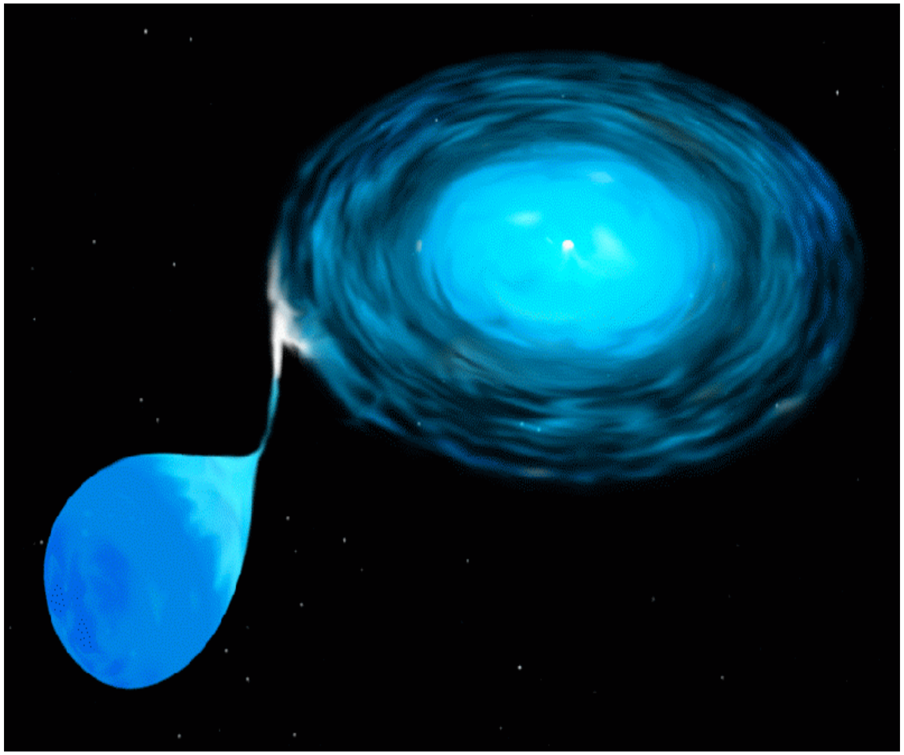
- Differential magnitude as a function of *z* relative relative to expectation for a flat universe



Type Ia Supernova: Observations

- General properties of SNe Ia:
  - Very homogeneous and bright
  - Spectra: no H, lots of Si, Mg, Ca ..
  - Light curve powered by radioactive decay of ^{56}Ni.
- Many independent observables:
  - Spectrum as function of time, light curve, location (host population), velocity of ejecta.

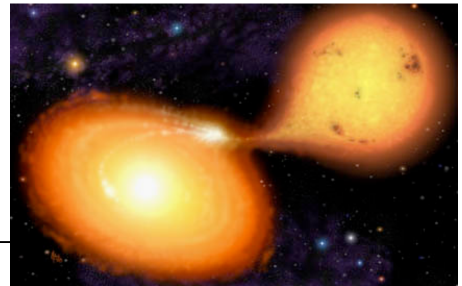
Type Ia Supernovae: Theory



- "Standard model" (Hoyle & Fowler 1960):
  - SNe Ia are thermonuclear explosions of C+O white dwarf stars.
- Evolution to criticality:
  - Accretion from a binary companion (Whelan and Iben 1973) leads to growth of the WD to the critical (Chandrasekhar) mass (1.4 solar masses).
- After ~1000 years of thermonuclear "cooking", a violent explosion is triggered at or near the center.
- Complete incineration occurs within two seconds, leaving no compact remnant.
- **Light curve powered by radioactive decay of ^{56}Ni. Peak luminosity $\propto$ M(^{56}Ni).**

- **SNe Ia play a significant role as distance indicators (and as probes of dark energy) due to the calibration (the Philips Relation) of peak brightness with the width of their light curves.**

Evolution Towards SN Ia

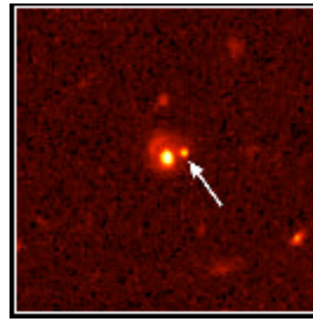


Mark A. Garlick

Accretion

- stellar evolution code with accretion/binary evolution code

$>10^8$ yr

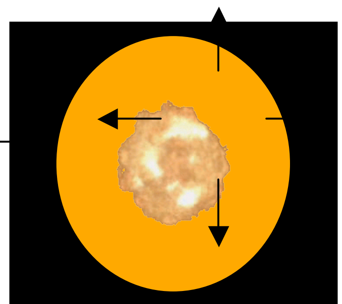


P. Garnavich/CfA

Light curve

- free expansion of envelope
- multi-group (non-LTE) radiation transport

~ seconds

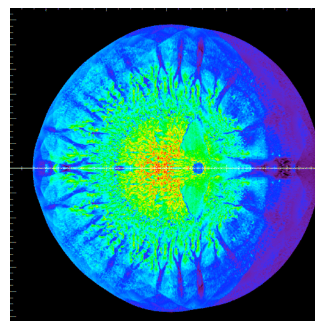


Smoldering

- subsonic convection in core of white dwarf
- low Mach number flow solver
- conductive heat transport

~ 1000 yr

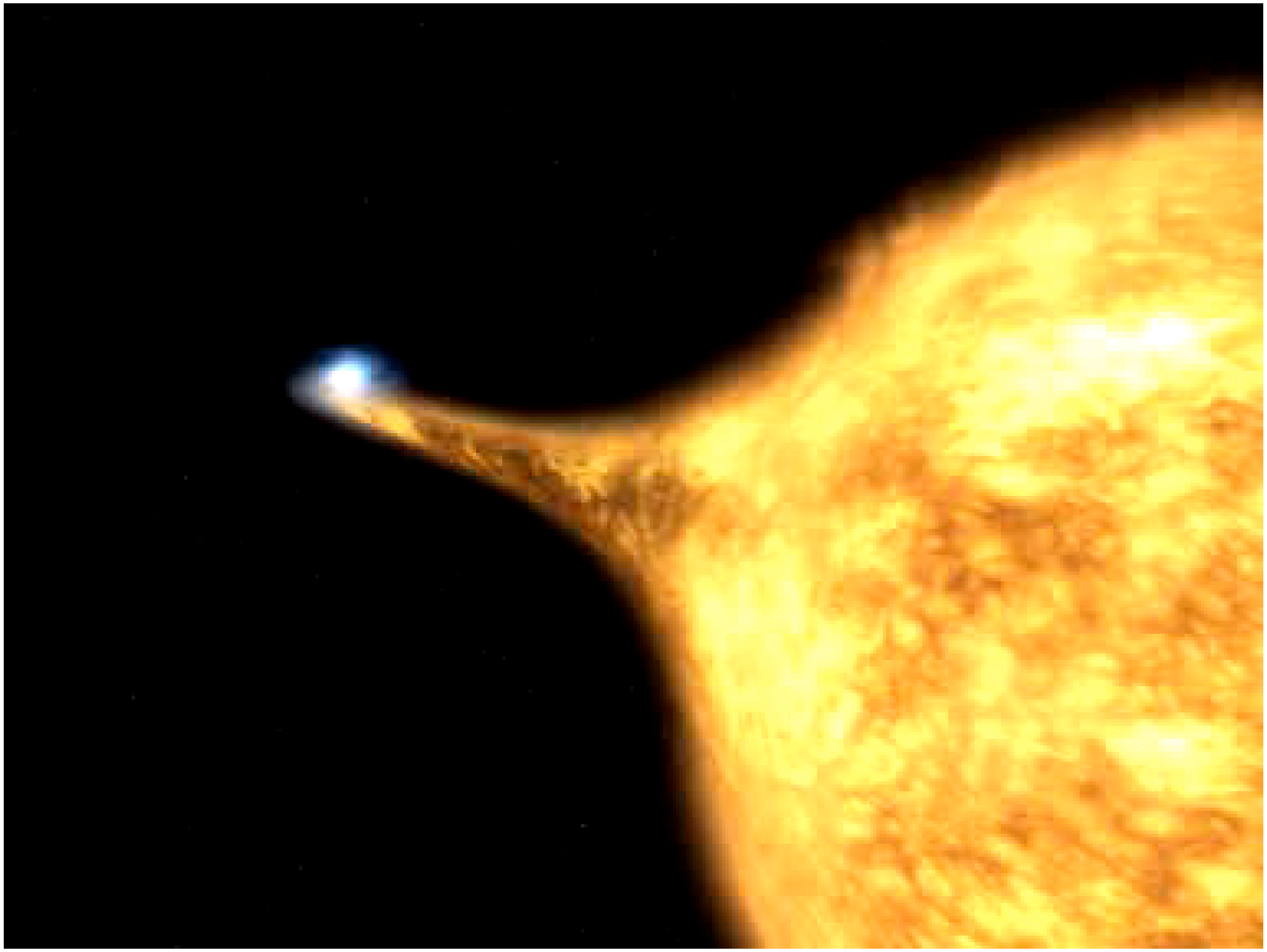
ignition



Flame

- initial deflagration
- DDT or expansion/recollapse
- FLASH (compressible module) with subgrid model or front-tracking
- conductive heat transport

The Standard Model for SNe Ia



- **Progenitor: White dwarf in a binary system**
- **Growth to the Chandrasekhar limit by mass transfer**

SNe Ia Supernova Energetics

- **The assumed initial model for a Type Ia supernova consists of a carbon-oxygen white dwarf of mass approaching the Chandrasekhar limit:**
  - **$M_{Chandrasekhar} = 1.4/(\mu_e/2)^2\ M_{\odot}$**
- **Note the critical nuclear energetics of some possible products of explosive nucleosynthesis (keep in mind that a mixture of equal parts by mass ^{12}C and ^{16}O has a mean binding energy (Mev/amu), B/A=7.829):**
  - **^{4}He: B/A=7.074; ^{12}C: B/A=7.68; ^{16}O: 7.977; (^{12}C+^{16}O): B/A=7.829; ^{24}Mg: B/A= 8.261; ^{28}Si: B/A=8.448; ^{56}Ni: B/A=8.643; ^{56}Fe: B/A=8.791**
  - **^{12}C to ^{24}Mg yields 0.581 Mev/amu**
  - **^{12}C+^{16}O to ^{28}Si yields 0.619 Mev/amu**
  - **^{12}C+^{16}O to (25% ^{4}He + 75% ^{56}Ni, ~ 8.25) yields ~ 0.422 Mev/amu**
  - **^{12}C+^{16}O to ^{56}Ni yields 0.814 Mev/amu**
- **Note that for a 1.4 solar mass white dwarf, the 0.814 Mev/amu released in the production of pure ^{56}Ni implies a total energy input of 2.2×10^{51} ergs.**

A Flame Model for Simulations of Deflagrations

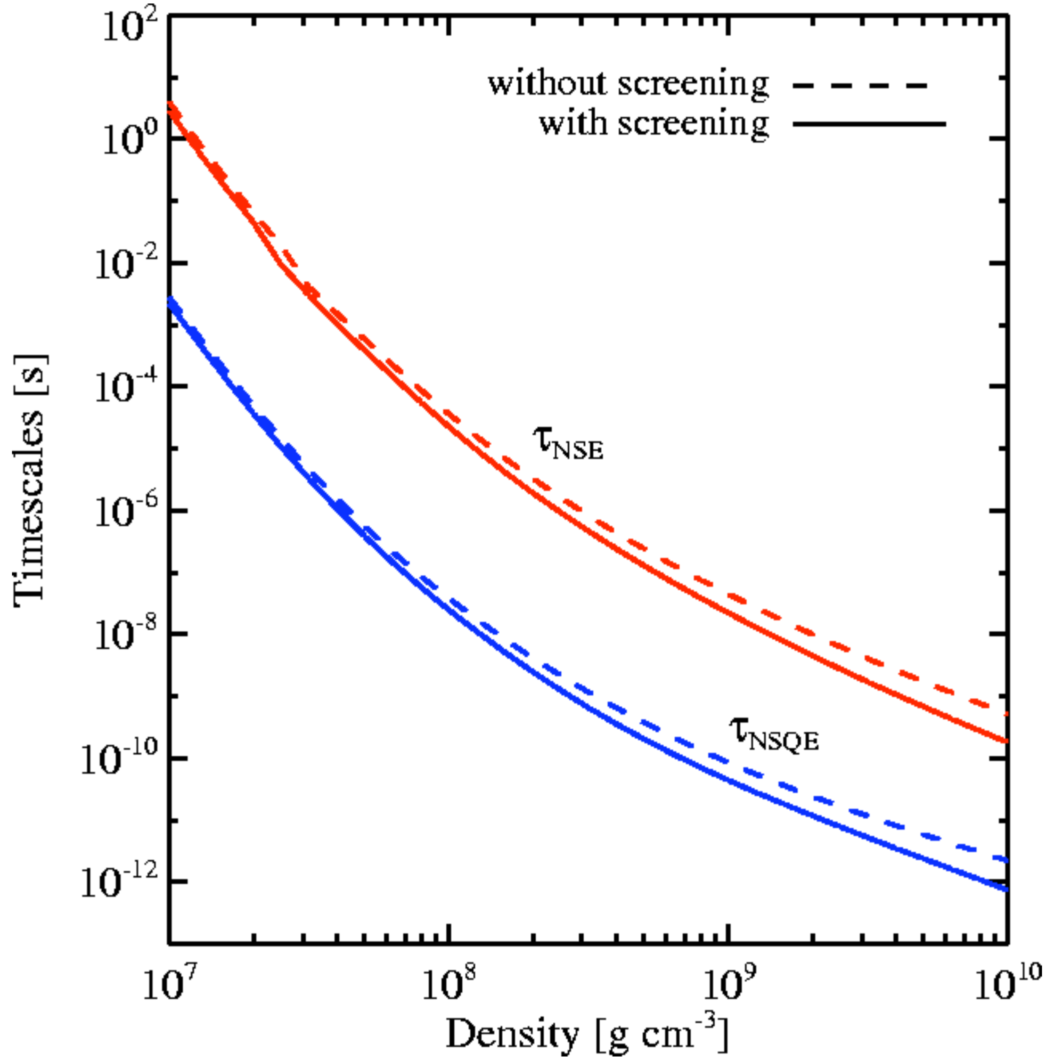
- The ("thick") flame model utilized at Chicago (Calder et al. 2006) builds on the advection-diffusion-reaction model of Khokhlov. The three stage structure of the flame reflects the distinct phases: (1) ^{12}C burning to ^{16}O and ^{24}Mg; (2) ^{16}O burning to ^{28}Si and "intermediate mass elements" in "quasi-equilibrium;" and (3) ^{28}Si burning to NSE (nuclear statistical equilibrium).

- The flame model - its energetics and timescales for energy release and neutronization - was calibrated with 'self-heating' reaction network calculations.

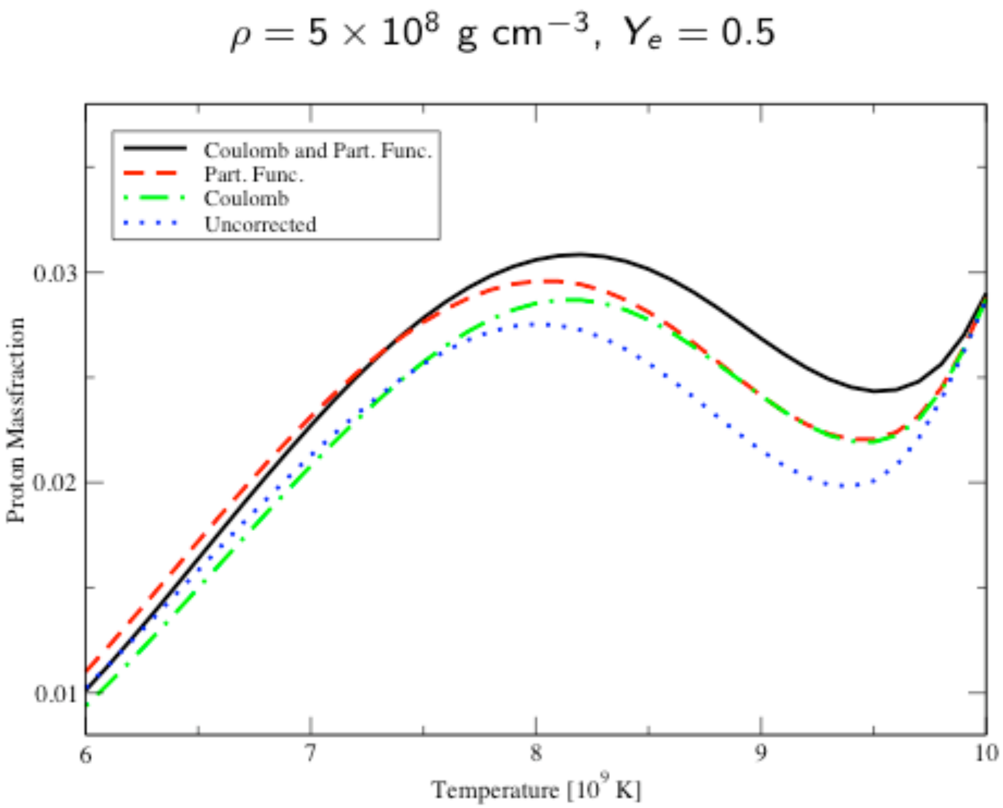
- Burning to NSE in the self-heating calculations typically leaves a significant fraction of the available nuclear energy untapped. (Note that the burning of equal masses of ^{12}C and ^{16}O to equal masses of ^{4}He and ^{56}Ni (in nuclear statistical equilibrium) yields effectively zero nuclear energy release.) A characteristic abundance pattern is 25% ^{4}He and 75% ^{56}Ni.

- Energy is subsequently released in the post-flame evolution to a ^{56}Ni dominated NSE with expansion and neutronization. Its effects are most pronounced in studies of off-center ignition.

Self-Heating Network Study



Effects of Coulomb Corrections

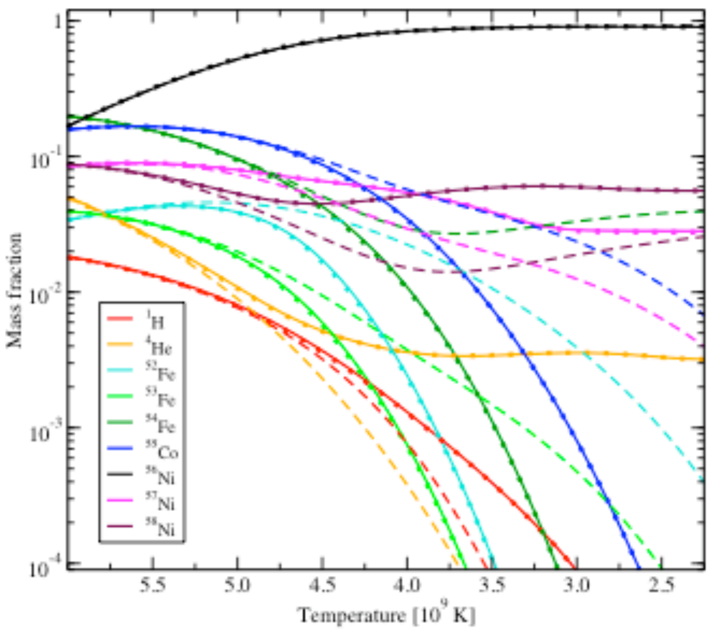


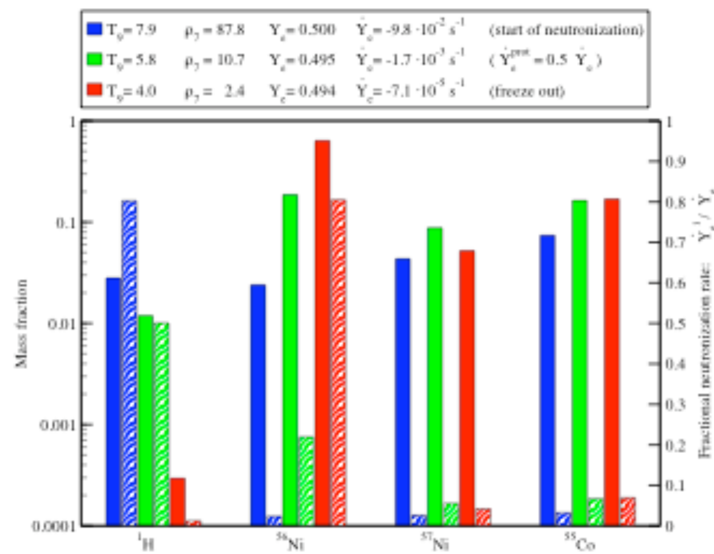
- **Coulomb corrections and temperature dependent nuclear partition functions significantly affect NSE mass fractions.**
- Increases $\dot{Y}_e$, $\bar{Q}$ and $\bar{A}$.
- **We were the first to include effects in NSE evolution in SNe Ia simulations.**

Courtesy: Ivo Seitenzahl

Coulomb Corrections and Neutronization

- Protons dominate rate at high temperature where neutronization is vigorous and they are well described by NSE.
- ^{56}Ni dominates rate at low temperature, where it is well described by NSE.
- **$\dot{Y}_e$ well approximated for high and low T by NSE. Y_e reached in simulation agrees well with post-processing of network. Justifies method.**

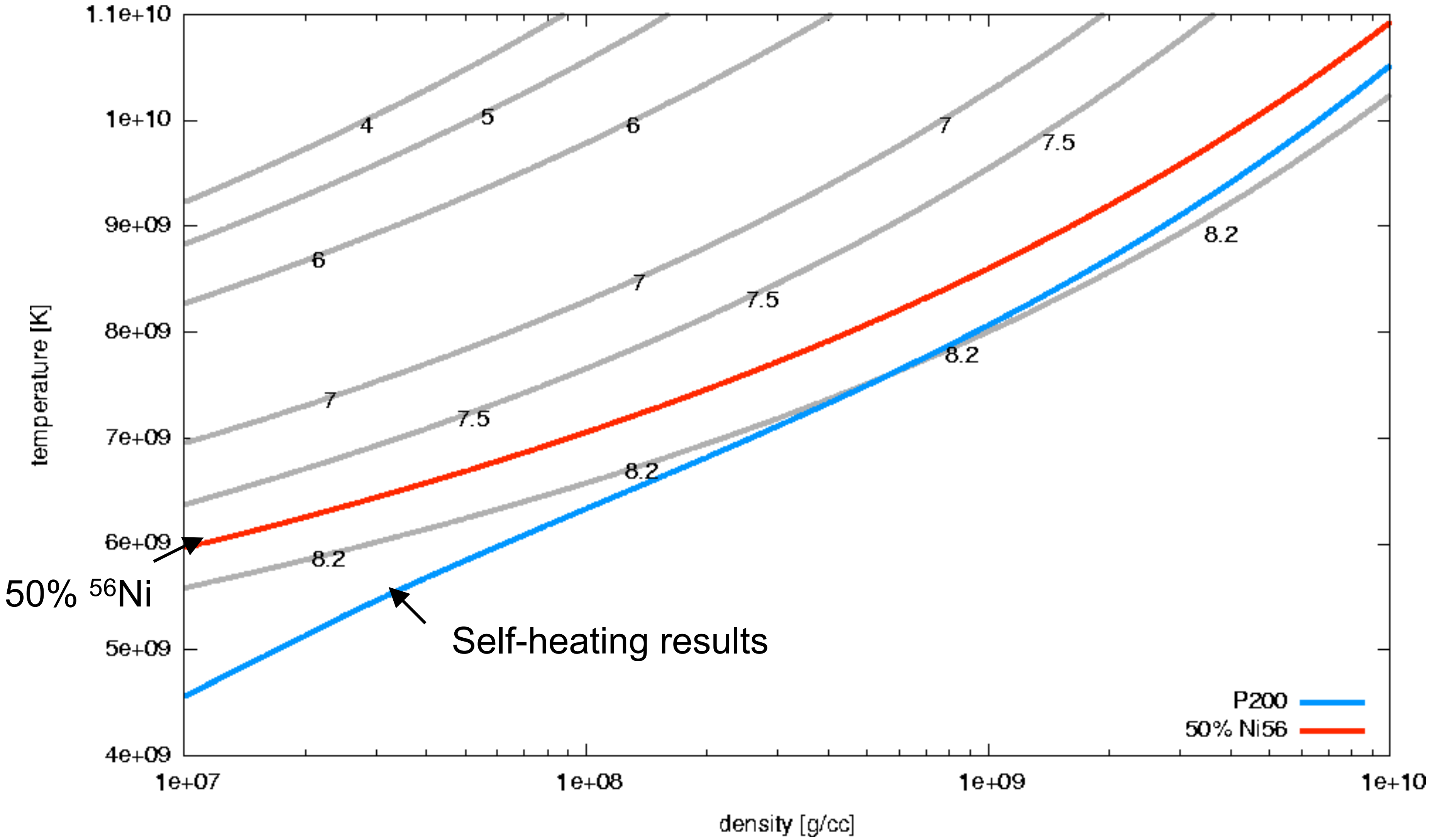




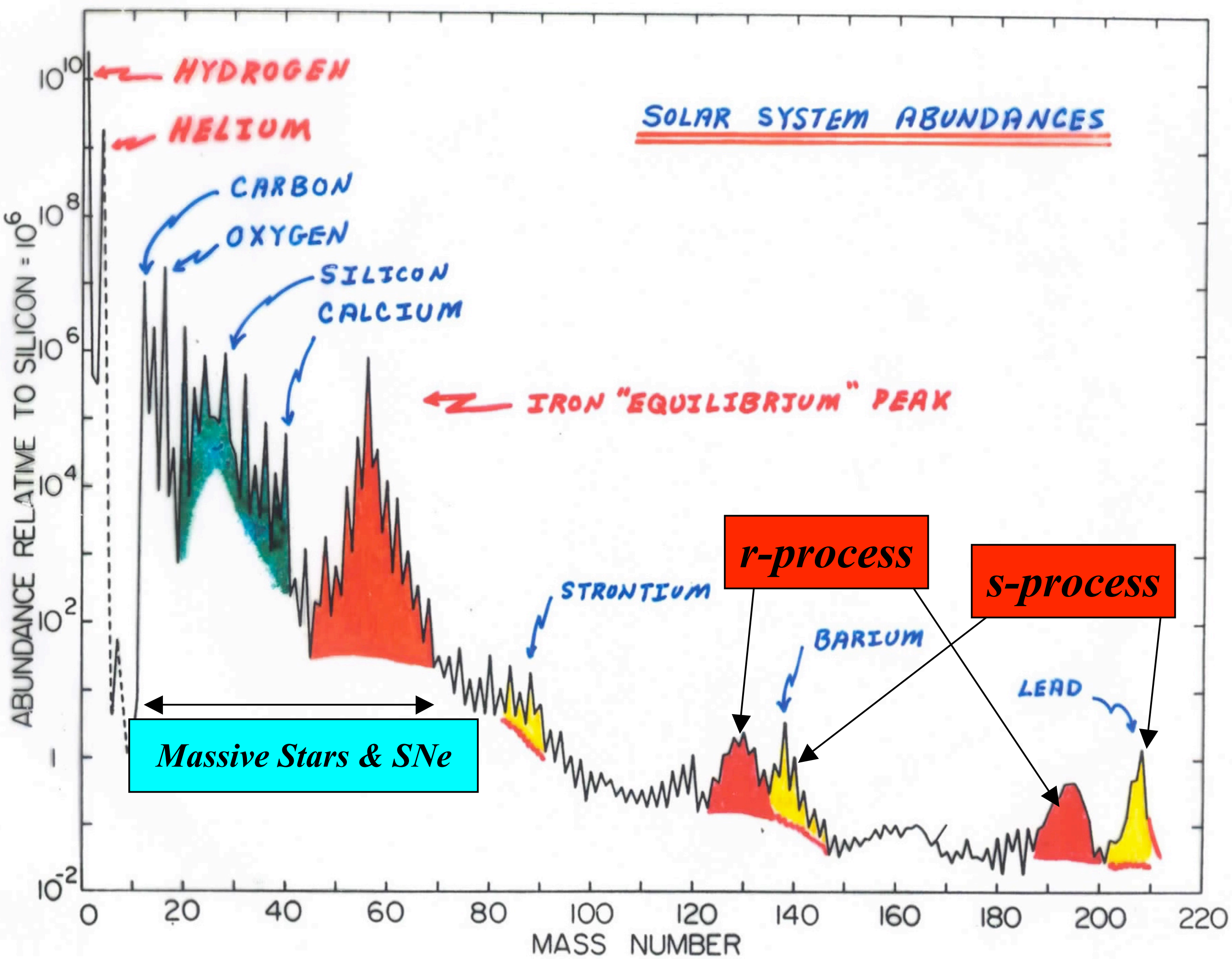
NSE mass fractions are solid bars.
Relative contribution to $\dot{Y}_e$ are dashed bars.

Courtesy: Ivo Seitenzahl

Average Binding Energy per Nucleon



"Cosmic" Abundances of the Elements



Signatures of nuclear systematics:

α-particle nuclei are dominant ^{12}C --- ^{40}Ca

dominance of unstable α-nuclei decay products: ^{44}Ti$\Rightarrow$^{44}Ca, ^{48}Cr$\Rightarrow$^{48}Ti, ^{52}Fe$\Rightarrow$^{52}Cr, ^{56}Ni$\Rightarrow$^{56}Fe, ^{60}Zn$\Rightarrow$^{60}Ni, ^{64}Ge$\Rightarrow$^{64}Zn, ^{68}Se$\Rightarrow$^{68}Zn, ^{72}Kr$\Rightarrow$^{72}Ge

nuclear statistical equilibrium centered on mass A=56 (^{56}Ni in situ)

neutron shell structure reflected in the heavy element region at magic numbers N=50, 82, and 126 (s- and r-processes)

Why ^{56}Ni ?

^{56}Ni Production in Explosive Nucleosynthesis

- **Pre-explosion compositions involve largely nuclei of Z ≡ N, viz. ^{12}C, ^{16}O, ^{28}Si (for SNe II).**

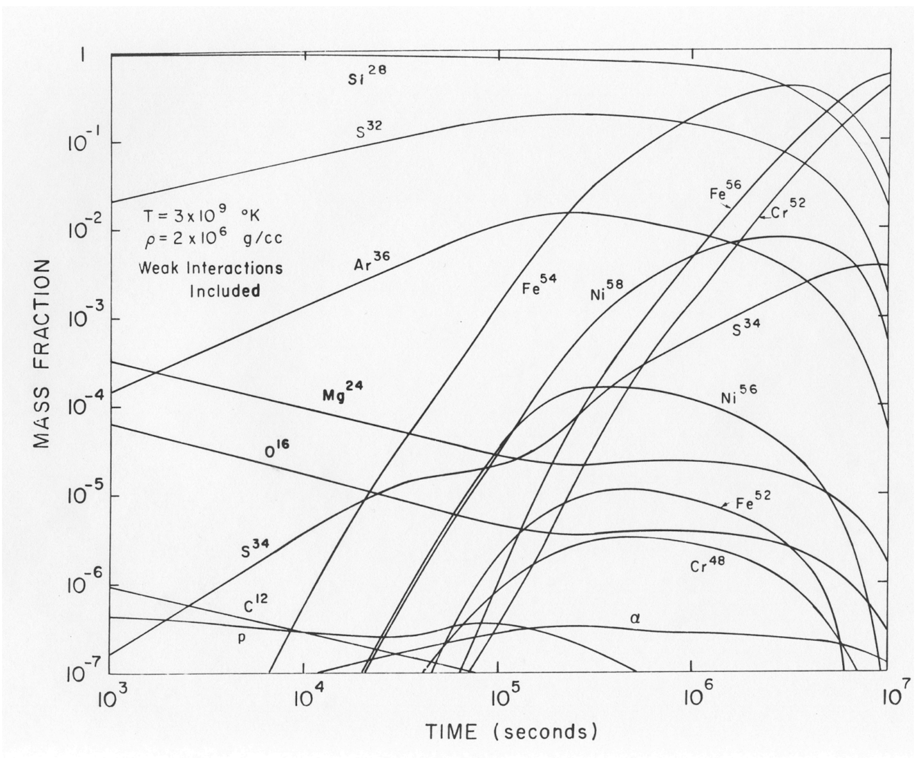
- **Explosive burning at temperatures T > 4×10^{9} ^{o}K typically occurs on timescales ≤ seconds.**

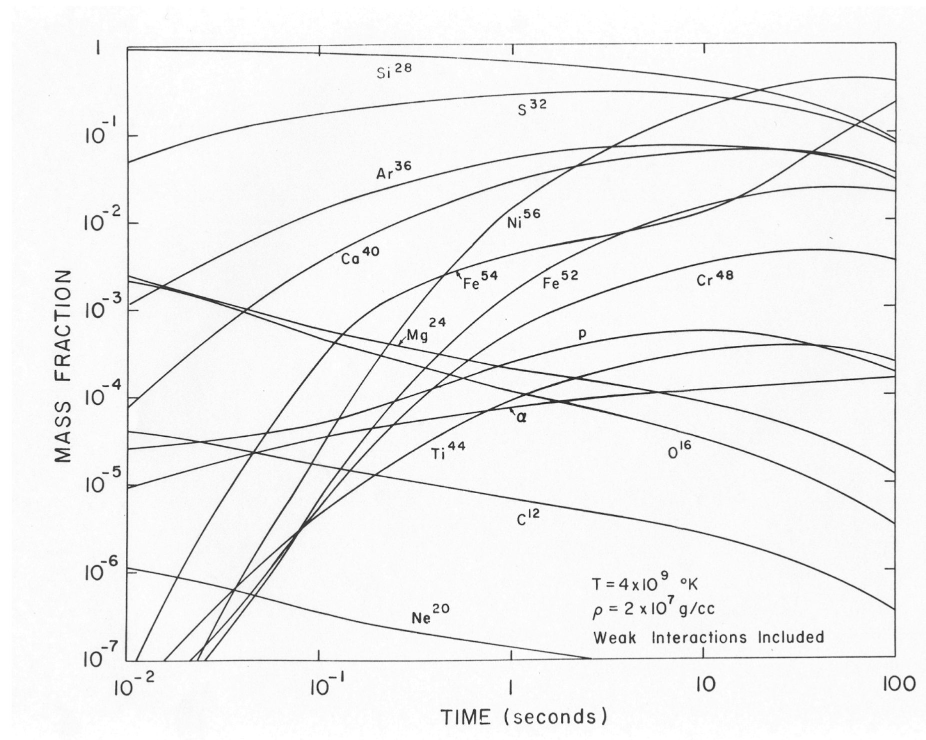
- **Supernova nucleosynthesis sees reactions occurring on a dynamical timescale.**

- **Weak interactions proceed too slowly to convert any significant fraction of protons to neutrons.**

- **It follows that the main (*in situ*) iron-peak products of explosive nucleosynthesis in supernovae are proton-rich nuclei of Z≈N, viz. ^{44}Ti, ^{48}Cr, ^{52}Fe, ^{56}Ni, ^{60}Zn, and ^{64}Ge (Cameron 1963; Truran, Arnett, and Cameron 1967).**

Silicon Burning with Weak Interactions = f(T)





Truran 1965

Solar System Iron Production

- The abundances of most of the iron-peak nuclei in Solar System matter were formed under proton rich ($Y_e \approx 0.5$) conditions in explosive nucleosynthesis.

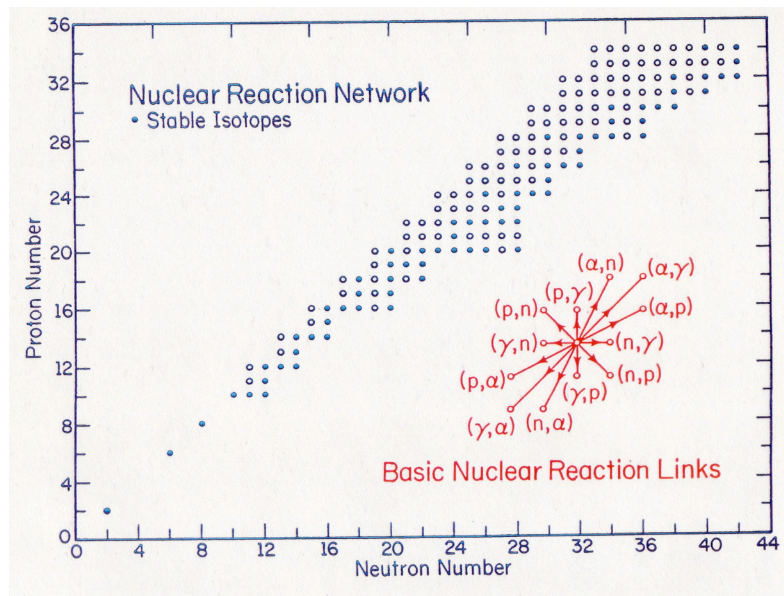
- This is reflected in isotopic production of even-Z elements.
  - ^{48}Ti and ^{49}Ti formed in situ as ^{48}Cr and ^{49}Cr
  - ^{50}Cr as ^{50}Cr: ^{52}Cr and ^{53}Cr formed as ^{52}Fe and ^{53}Fe
  - ^{54}Fe as ^{54}Fe; ^{56}Fe and ^{57}Fe formed as ^{56}Ni and ^{57}Ni
  - ^{58}Ni as ^{58}Ni; ^{60}Ni,^{61}Ni,^{62}Ni formed as ^{60}Zn,^{61}Zn, and ^{62}Zn
  - ^{64}Zn contributions from ^{64}Ge ?
  - ^{72}Ge contributions from ^{72}Kr ?
  - Odd-Z: ^{51}V (^{51}Mn), ^{55}Mn (^{55}Co), ^{59}Co (^{59}Cu), ^{63}Cu (^{63}Ga)

⇒ The isotopic compositions of Cr, Fe, and Ni are derived from isotopes of different elements formed in explosive nucleosynthesis.

Explosive Nucleosynthesis of Iron Group Nuclei

❑ Nuclear Physics Needs: masses & reaction rates for buildup along the α-chain (e.g. the study of $^{44}Ti(\alpha,p)^{47}V$ at ATLAS). Rates for flow through ^{64}Ge and ^{68}Se (waiting point nuclei in the rp-process) may prove critical.

Kr	72, 76, 78
Br	71
Se	68, 69, 70, 72, 74, 76
As	67, 75
Ge	64, 65, 66, 70, 72, 73, 74
Ga	63, 69, 71
Zn	60, 61, 62, 64, 66, 67, 68, 70
Cu	59, 63, 65
Ni	56, 57, 58, 60, 61, 62, 64
Co	55, 59
Fe	52, 53, 54, 56, 57, 58
Mn	51, 55
Cr	48, 49, 50, 52, 53, 54
V	47, 50, 51
Ti	44, 45, 46, 47, 48, 49, 50
Sc	43, 45
Ca	40, 42, 43, 44, 45, 46, 48

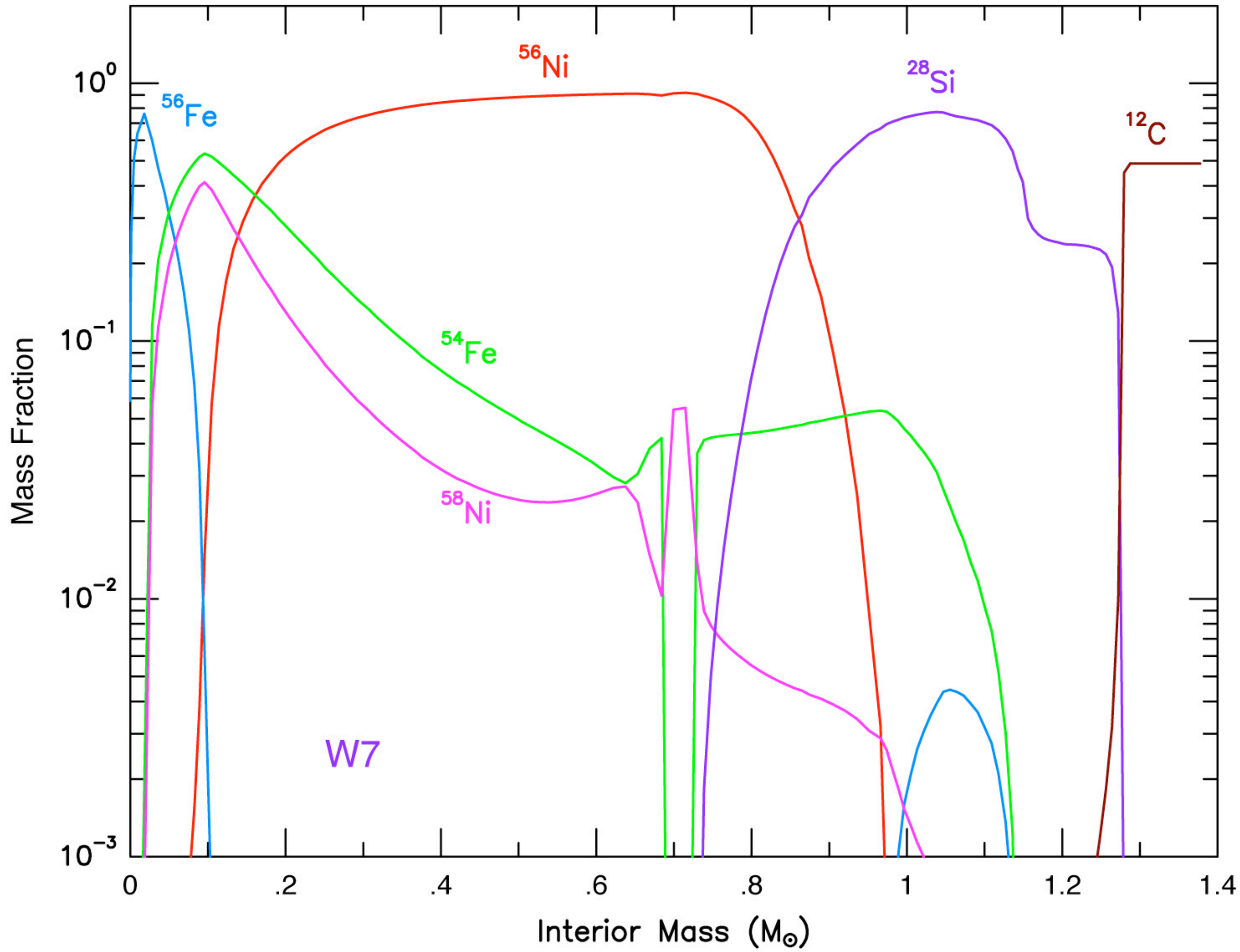


(Truran 1965)

^{56}Ni and SNe Ia Peak Luminosities

- **It is generally understood that the peak luminosities of SNe Ia are proportional to the mass ejected in the form of ^{56}Ni (The "Arnett Law"). This view is directly supported by energetic considerations:**
    - **The conversion of ^{12}C and ^{16}O to ^{56}Ni in 1.4 $M_{\odot}$ releases 0.814 MeV/nucleon or ~ 1.8 x 10^{51} ergs.**
    - **The gravitational binding energy of a 1.4 $M_{\odot}$ white dwarf is approximately 5x10^{50} ergs.**
    - **The kinetic energy associated with 1.4 $M_{\odot}$ of ejecta moving at a velocity approaching 10^{9} cm s^{-1} is ~1.4x10^{51} ergs.**
- **The bulk of the energy released in burning to ^{56}Ni is thus expended in overcoming gravitational binding and imparting high velocities to the ejecta. It is the subsequent decay of ^{56}Ni (τ=8.8 days) through ^{56}Co (τ=111.3 days) to ^{56}Fe that powers the light curve.**

Nickel Production in SNe Ia



Timmes, Brown, & Truran 2003

Modeling SNe Ia: Where do we Stand?

- **We understand(?) SNe Ia to involve thermonuclear incineration of a Chandrasekhar mass CO white dwarf.**

- **Carbon Detonation Model: We fully recognize that a pure detonation (e.g. Arnett 1969) which yields iron-peak nuclei only (Arnett, Truran, and Woosley 1971) cannot be appropriate, as it fails to explain the concentrations of abundances of intermediate mass nuclei in SNe Ia ejecta (Branch et al. 1981)/**

- **Carbon Deflagration Model: Early sub-sonic flame evolution yields pre-expansion and insures that the outer regions are not burned to ^{56}Ni (Thielemann, Nomoto, and Yokoi 1986). The flame must start out as a deflagration but ultimately approach sound speed (e.g. Nomoto's W7), in order to be consistent with the observed velocities of intermediate mass nuclei, e.g. silicon and magnesium.**

- **The emphasis in most recent large scale multi-dimensional simulations has been on 2D and 3D simulations of the deflagration phase (e.g. ongoing studies at Munich, Chicago, Santa Cruz, Jerusalem, …) --- and on questions as to how this might possibly lead to detonation.**

Supernova Ia Nucleosynthesis: Detonation

- ❑ **Early studies of Type Ia models and associated nucleosynthesis focused on the "carbon detonation model" of Arnett (1969).**

- ❑ **We now recognize that this results in the burning of the entire core to ^{56}Ni, in disagreement with recent spectroscopic studies of SNe Ia ejecta which reveal the presence of intermediate mass elements.**

⇒ A Pure Detonation Fails

552 Thermonuclear Reactions and Nucleosynthesis

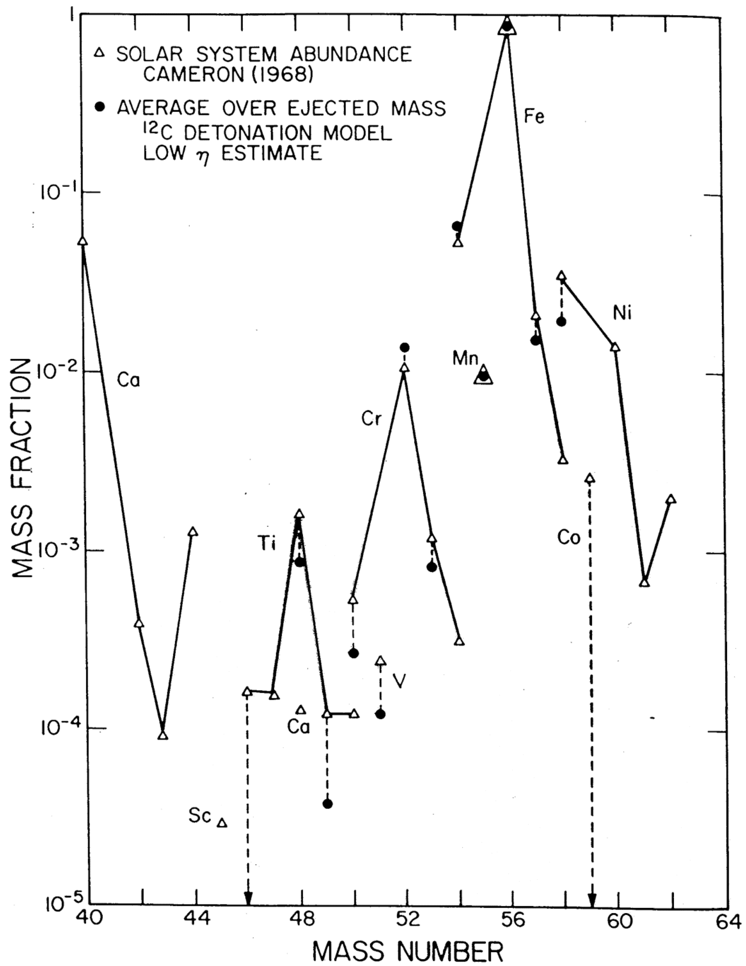
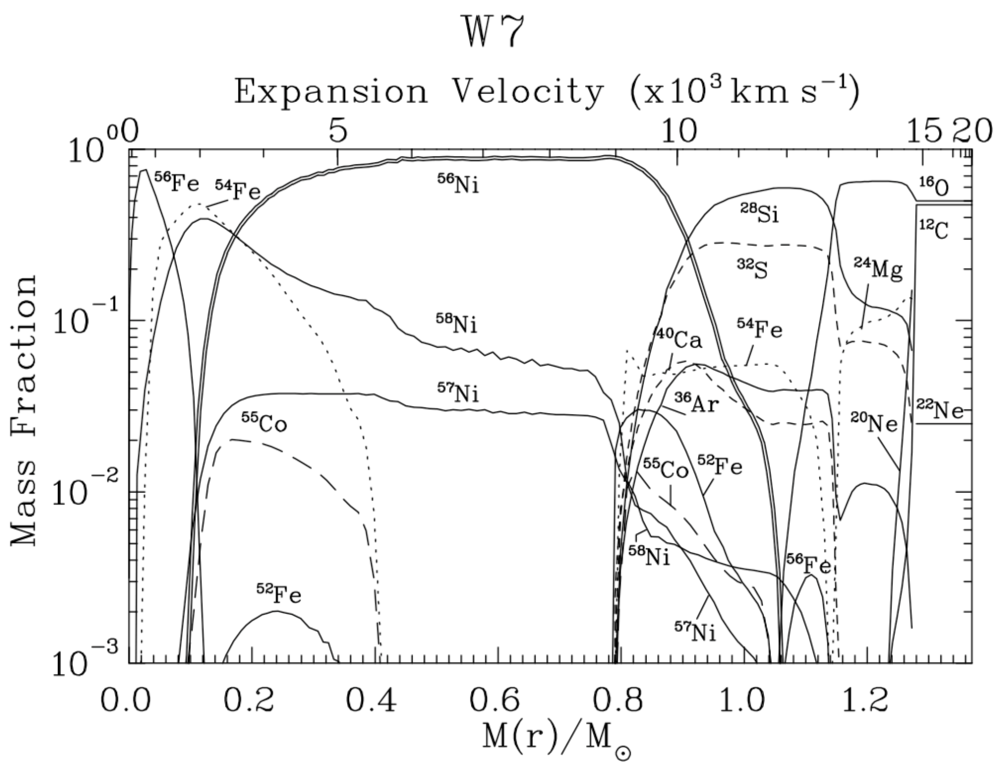


Figure 13. The nuclear abundances by mass produced in the mass zones ejected in the ^{12}C detonation model are compared to the solar system abundances. The two distributions are normalized at ^{56}Fe. The "low η" estimate of the neutron excess was employed.

(Truran, Arnett, and Woosley 1971)

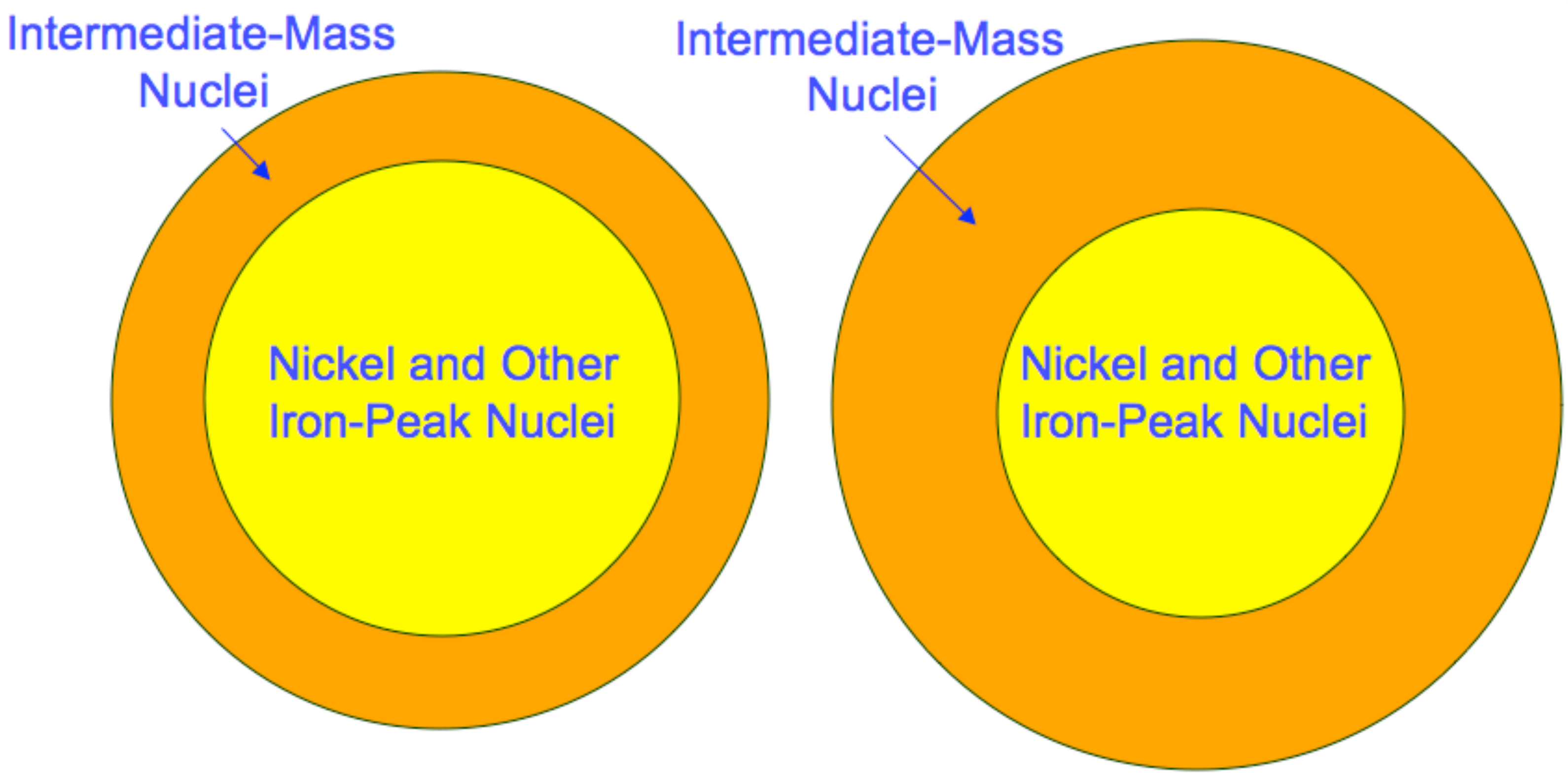
Deflagration Model

- Nearly all one-dimensional Chandrasekhar mass models of Type Ia supernovae produce most of their ^{56}Ni in a nuclear statistical equilibrium environment between mass shells 0.2 $M_{\odot}$ and 0.8 $M_{\odot}$ (Nomoto 1984).
- In this region weak reactions occur on timescales exceeding the timescale for disruption of the white dwarf by a burning front.



(Iwamoto et al. 1999)

Pre-Expansion and SNe Ia Peak Luminosities



Products of nuclear burning essentially depend only on density at which burning occurs -- iron-peak nuclei at high densities, intermediate mass nuclei at lower densities

Simulations of Deflagration Phase of SNe Ia

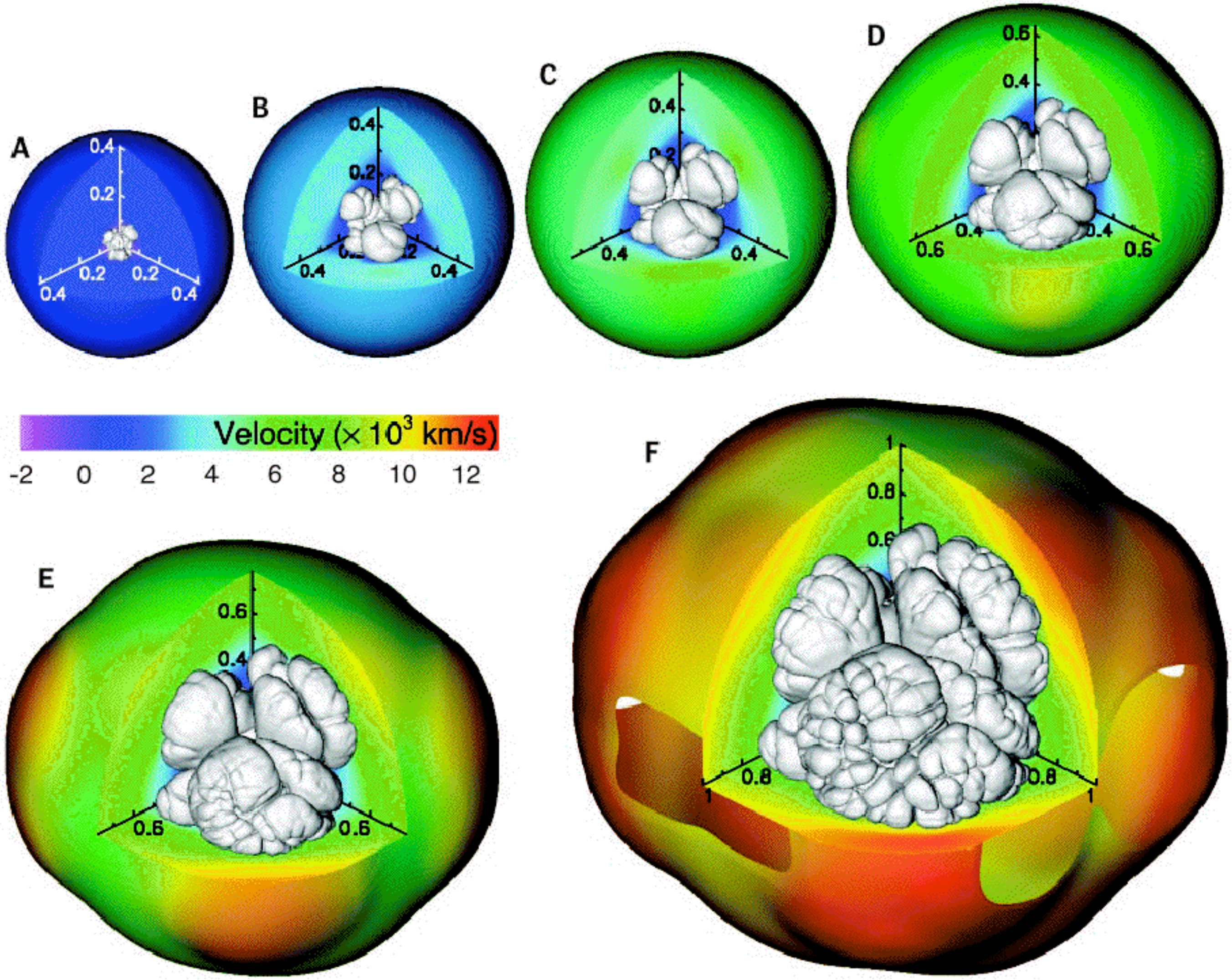
- **Recent multidimensional hydrodynamic simulations of Type Ia SNe have concentrated on (early) flame propagation as a deflagration front (Calder et al. 2003; Roepke & Hillebrandt 2004; Hillebrandt & Roepke 2005; Gamezo & Khokhlov 2005; Livne, Asida, & Hoeflich 2005; Roepke, Woosley, & Hillebrandt 2006; Calder et al. 2006).**

- **There remains some debate as to whether a pure deflagration can explain the observed behaviors of representative SNe Ia, or whether alternatively a delayed detonation (e.g. DDT) must occur.**

- **The detailed energetics of the deflagration and the post-flame nuclear evolution of the white dwarf matter (particularly for the GCD picture) remain critical issues which must be calculated accurately to provide realistic determinations of:**

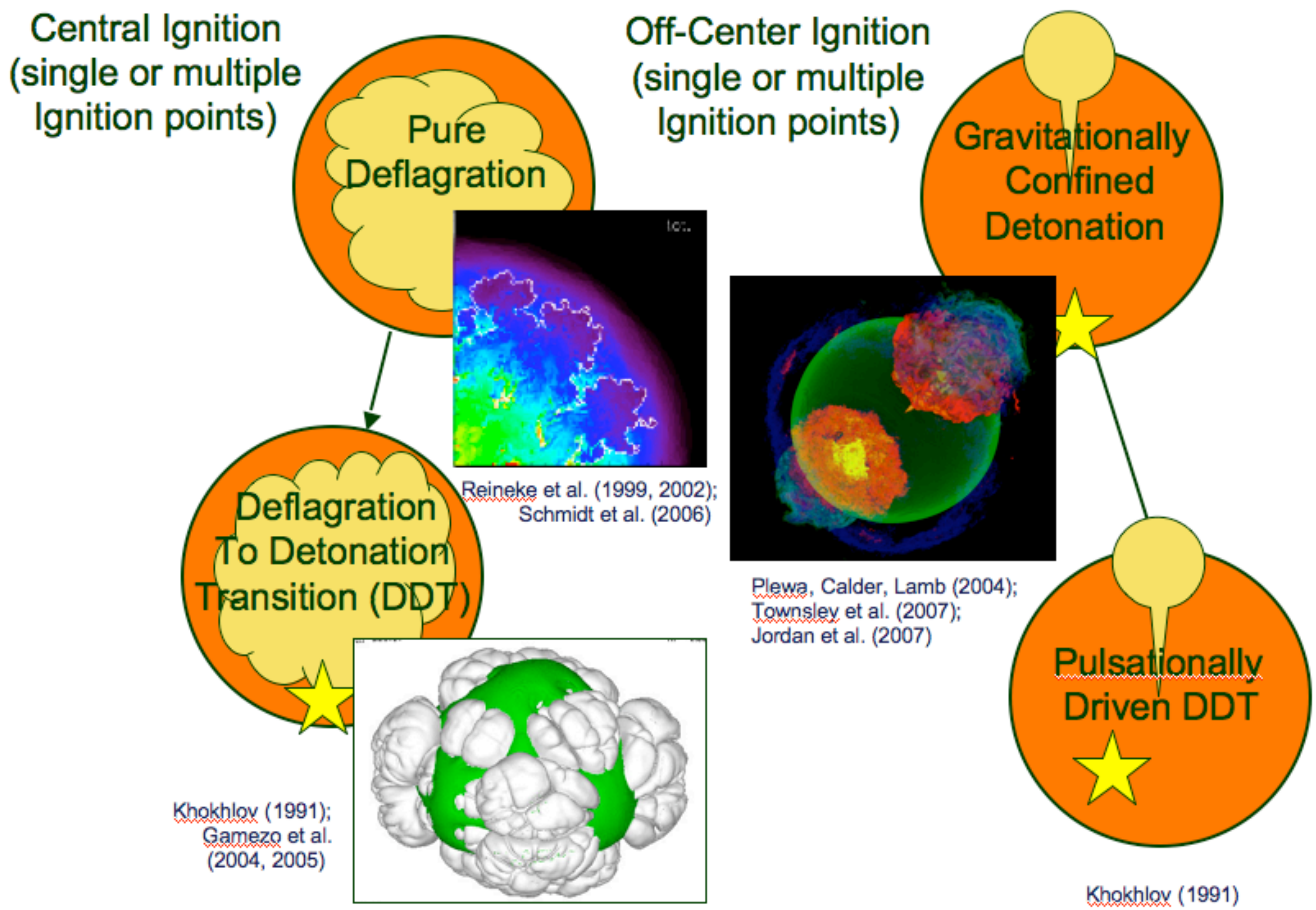
  - **the total energy release,**
  - **the distribution of nucleosynthesis products in the ejecta,**
  - **the degree of neutronization of the ejected matter, and thus**
  - **the mass of ^{56}Ni ejected (which determines the peak luminosity.)**

Deflagration Model: Central Ignition



Gamezo et al. (2002)

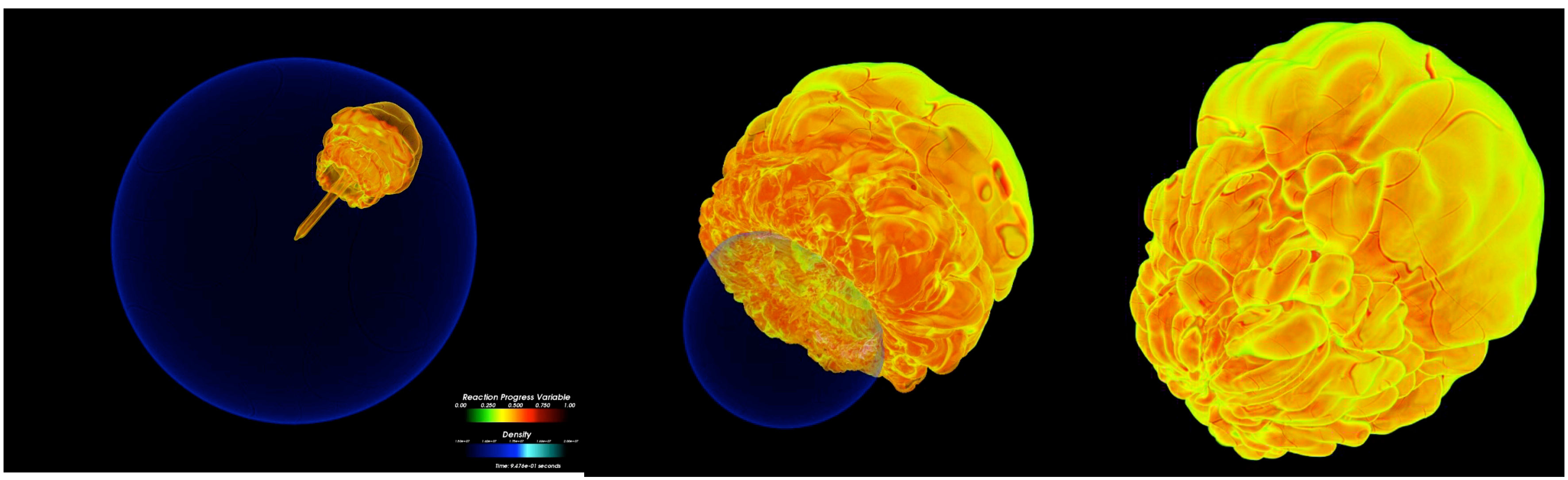
Considered Explosion Models for SNe Ia



<u>Courtesy: Don Lamb</u>

Gravitationally Confined Detonation (GCD) Model

- **Large-scale, 3D, multi-physics simulations show that an off-center ignition creates a hot bubble of material that rises rapidly to surface of the white dwarf (Calder .. Truran .. et al. 2003; Jordan, .. Truran .. et al. 2007).**
- **As the bubble breaks the surface, confined by gravity, hot material will flow across the surface of the star at high velocity pushing matter from the surface layers of the star ahead of it.**
- **The flow converges at the opposite point on the surface of the star; the resulting compression raises the temperature and density of the material, initiating detonation.**
- **This represents a model of Type Ia SNe for which detonation may possibly occur "naturally" (i.e., without being put in by hand).**
- **Pre-expansion of star occurs while hot bubble material is flowing across surface of star, so that when detonation occurs, density of star has decreased enough that both nickel and intermediate mass elements are produced.**



Role of Flame and Ash Energetics

- **Buoyancy of bubble is the key – this depends on composition and energy produced in flame and in "ash."**
  - Binding energy of NSE state at end of flame determines the composition and energy release (temperature).
  - Binding energy of NSE state continues to change as density decreases and composition changes in rising bubble.
  - Weak interactions (neutronization) also produce composition changes and gain/loss of energy.
- **Accurate treatments of composition and energy changes are essential.**

GCD Evolution to Detonation: Temperature

FLASH CENTER

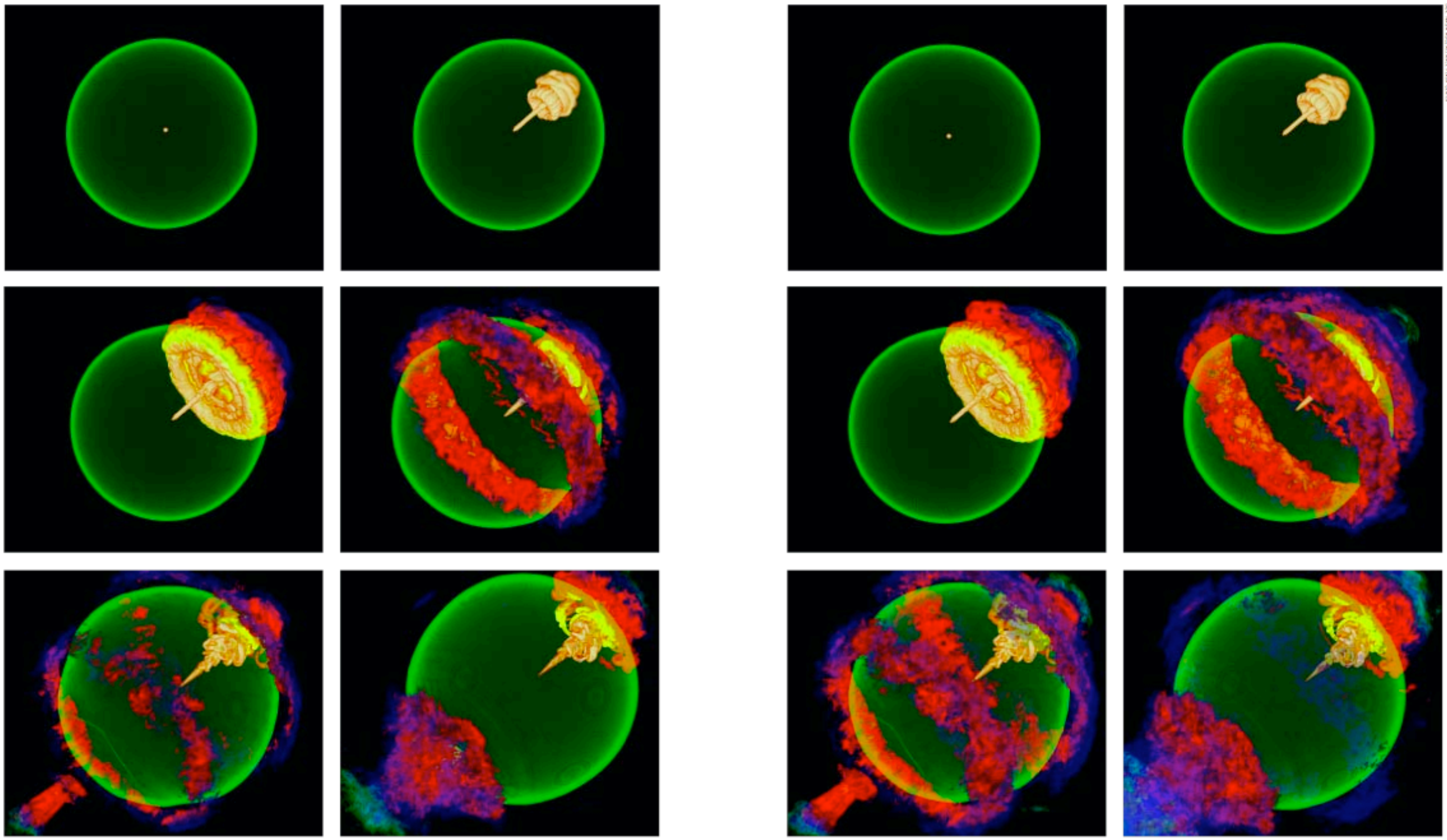
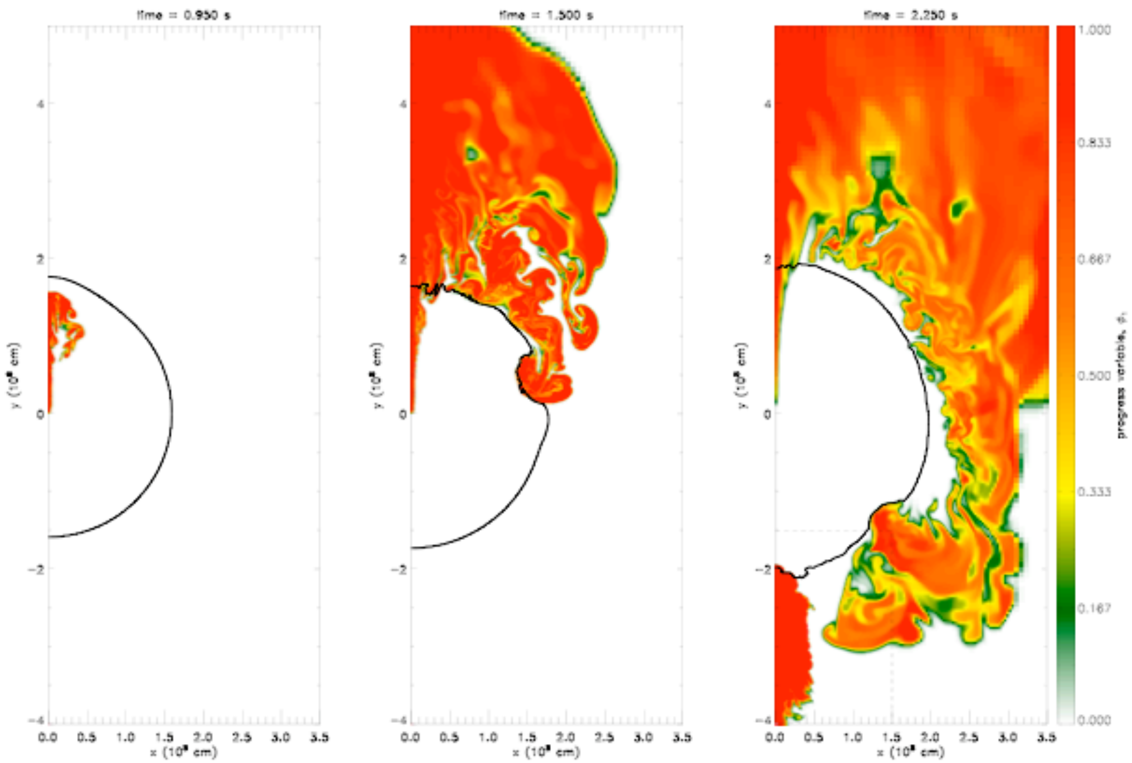


Figure 4. *In these 3D simulations of the successive phases of the GCD explosion mechanism for Type Ia supernovae, the surface of the white dwarf is shown in green and the temperature of the matter in the burned ash and flowing over the surface of the star is shown in various colors, with blue being the coolest and yellow being the hottest. Images on the left-hand page are from the same simulation as those on the right-hand page, but with temperatures colored differently in the visualization. Note the outward- and inward-directed jets that form when the material flowing over the stellar surface collides at the "south pole" of the star.*

Jordan et al. (2007)

Initiation of Detonation

Carbon-burning ashes

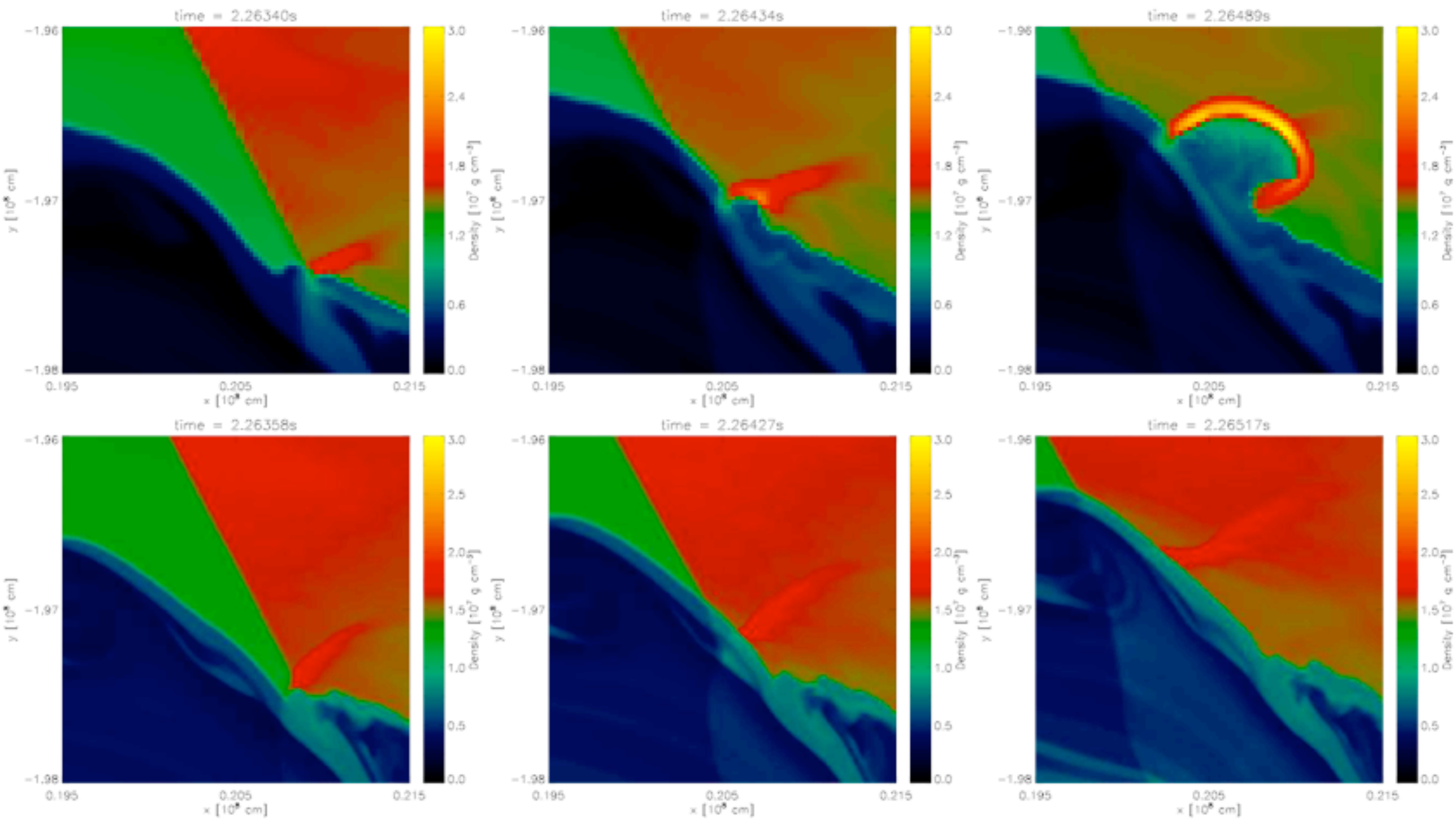


1. Buoyant deflagration bubble rises
2. Ashes break out before now expanded star is completely burned
3. Ashes remain bound and compress antipode, jet and detonation form

Meakin, Seitenzahl et al.(2008), arXiv:0806.4972

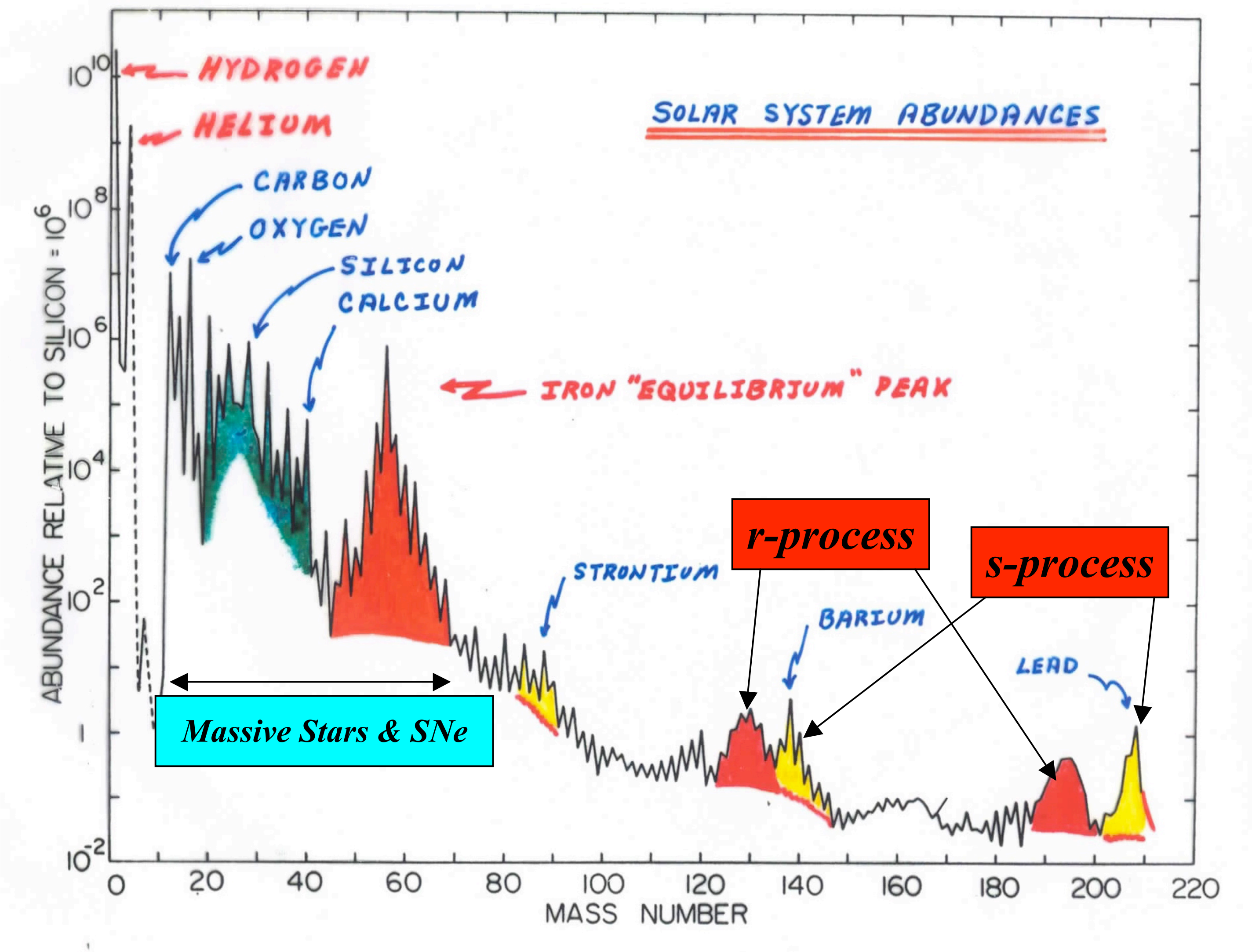
Meakin et al. (2008)

Initiation of Detonation



(Seitenzahl et al. 2008)

"Cosmic" Abundances of the Elements



Signatures of nuclear systematics:

α-particle nuclei are dominant ^{12}C --- ^{40}Ca

dominance of unstable α -nuclei decay products: ^{44}Ti⇒^{44}Ca, ^{48}Cr⇒^{48}Ti, ^{52}Fe⇒^{52}Cr, ^{56}Ni⇒^{56}Fe, ^{60}Zn⇒^{60}Ni, ^{64}Ge⇒^{64}Zn, ^{68}Se⇒^{68}Zn, ^{72}Kr⇒^{72}Ge

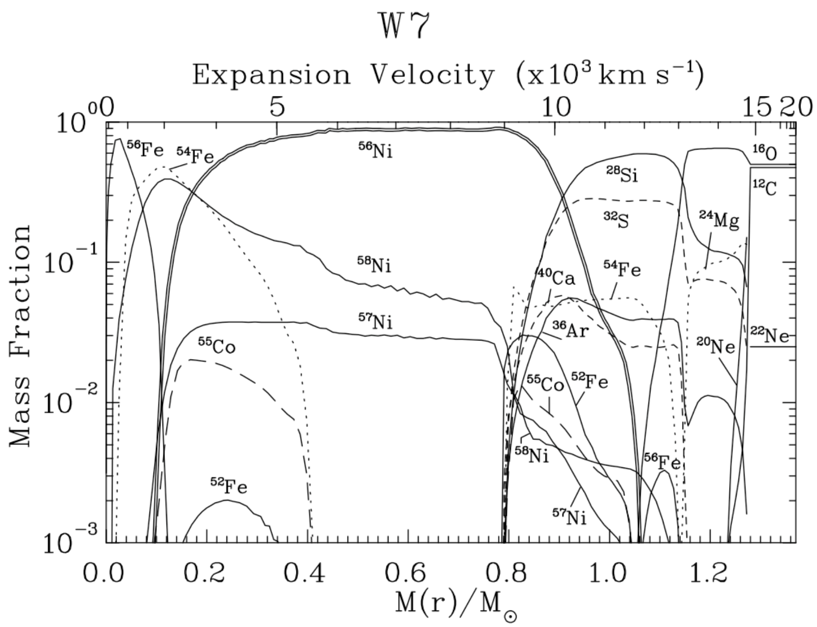
nuclear statistical equilibrium centered on mass A=56 (^{56}Ni in situ)

neutron shell structure reflected in the heavy element region at magic numbers N=50, 82, and 126 (s- and r-processes)

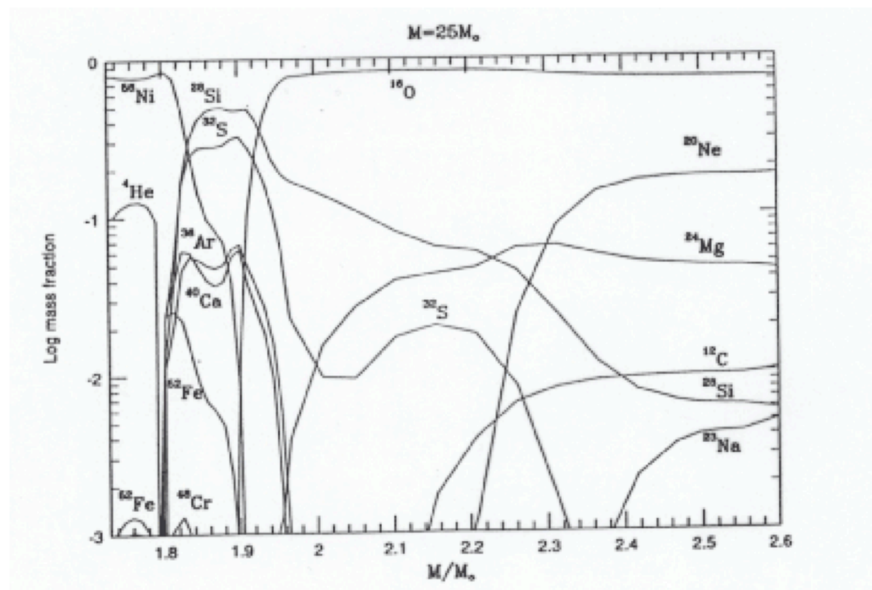
Supernova Nucleosynthesis Contributions

- **Type Ia Supernovae**
  - **Nucleosynthesis: 1/2 to 2/3 iron-peak nuclei. Luminosity $L_{max} \propto M(^{56}Ni)$. ($\tau_{nucleosynthesis} > 10^9$ yrs)**

- **Type II Supernovae**
  - **Nucleosynthesis: oxygen to iron ([O/Fe]~0.4) and n-capture products through uranium. ($\tau_{nucleosynthesis} < 10^8$ yrs)**



(Iwamoto et al. 1999)

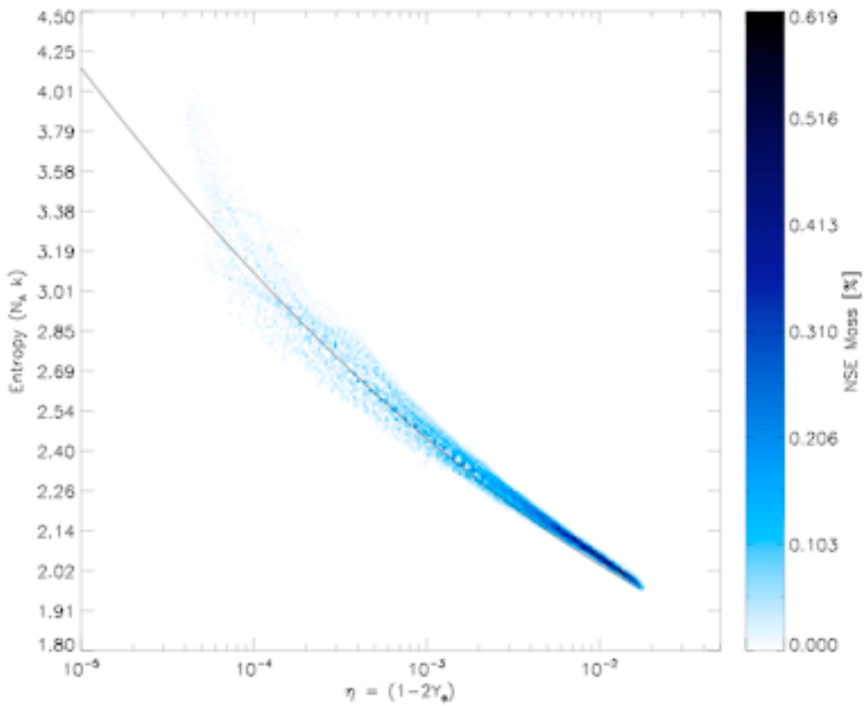


(Thielemann et al. 1992)

Tracer Particles and Nucleosynthesis

- Simulations include (typically $10^5 - 10^6$) massless tracer particles that flow passively across the grid.
- Tracer particles record thermodynamic trajectories, temperature and density as a function of time along the path.
- Trajectories can be post processed afterwards by integrating a nuclear reaction network along the trajectory.
- By averaging over an appropriately distributed family of tracers one obtains the final abundance distribution of the SN. **Computationally expensive given large number of tracers!**
- **Calculating Fe-peak yields based on a suite of analytic trajectories characterized by final entropy and neutron excess and is computationally much less demanding (runs on my desktop).**

Entropy-Neutron Excess Correlation



Meakin, Seitenzahl et al.(2008), arXiv:0806.4972

- **Material processed by the detonation shows tight correlation between final entropy and neutron excess.**
- Correlation arises due to strong dependence of both entropy generation and rate of electron capture on density.
- **Generate table of freezeout yields by integrating suite of analytic trajectories along line.**
- Only viable since NSE based neutronization scheme gives accurate final Y_e.

Observational Constraints on SNe Nucleosynthesis

- SNe Ia and SNe II both form ^{56}Fe as ^{56}Ni:
  - ^{56}Co and ^{57}Co gamma rays from SNe 1987A
  - Light curves for both SNe Ia and SNe 1987A

- [O/Fe] and [α-nuclei/Fe] histories for Galaxy, Damped Lyman-α systems, etc. imply the delayed entry of SNe Ia nucleosynthesis products, while observations suggest that the Type Ia rate is roughly proportional to the star formation rate.

- SNe Ia synthesize and eject $\approx$ 0.6-0.8 $M_{\odot}$ of iron while SNe II eject $\approx$ 0.1 $M_{\odot}$ (SNe 1987A).

- Elevated [α-nuclei/Fe] levels together with Fe yields from Ia's and II's imply that the total number of SNe II which have occurred in our Galaxy is $\approx$ 3 times the number of SNe Ia.

Observational Constraints on SNe Nucleosynthesis

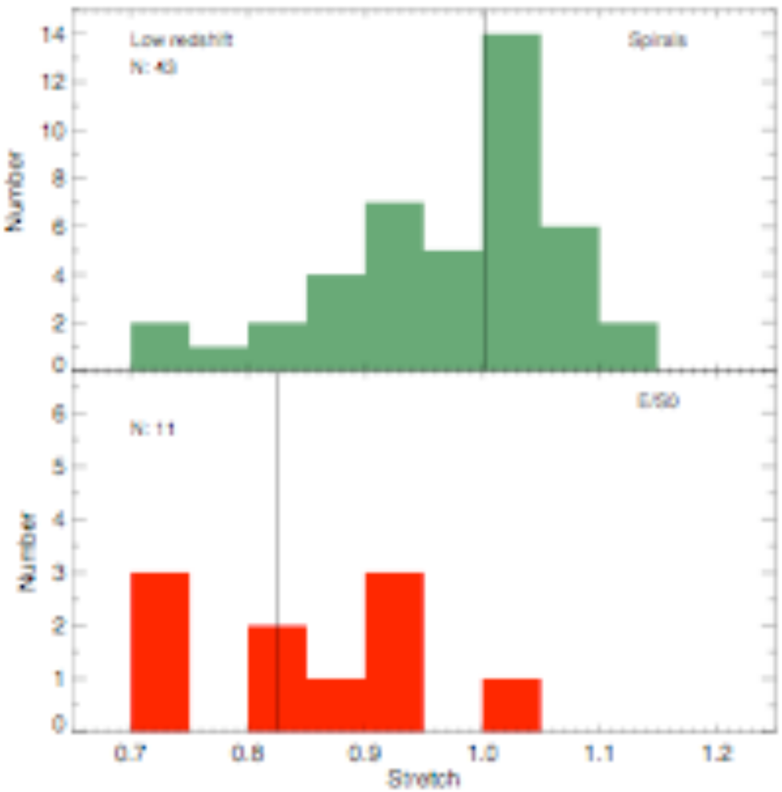
- Dwarf spheroidal galaxies (e.g. Sculptor) are found to be characterized by [α-nuclei/Fe] histories that differ from that of halo field stars and globular clusters.

- Rate SNe Ia traces star formation history

- Isotopic information regarding iron and iron-peak nuclei other than in solar system matter is sketchy at best:
    - Galactic cosmic ray isotopic patterns for Fe, Ni, and Zn from ACE
    - Anomalous isotopic patterns in meteorites

- Abundance constraints on Type Ia supernova brightness?

Supernova Ia: Progenitors and Sites



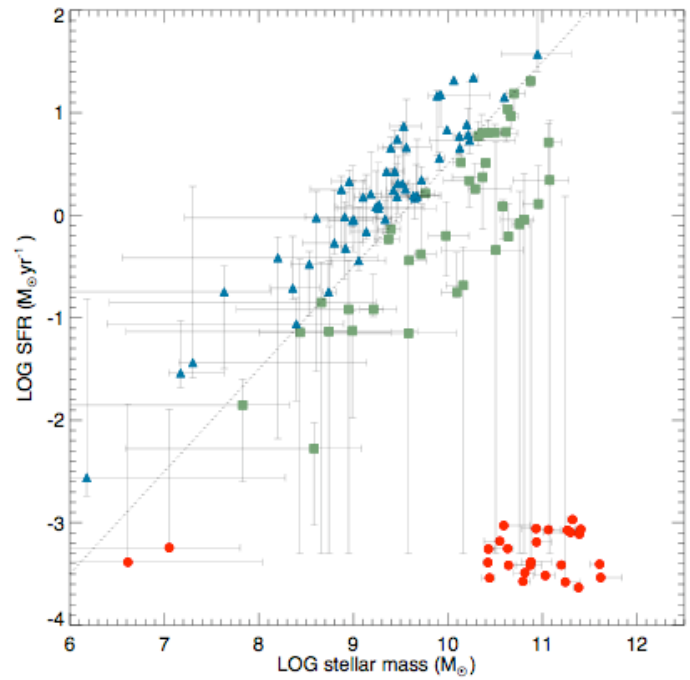


FIG. 5.— The distribution of the SN Ia host galaxies in the SFR-mass plane. Each galaxy is coded according to its assigned type. Passive galaxies are shown as circles (red), normal star-forming galaxies as squares (green), and vigorous star-formers as triangles (blue). The black diagonal dotted line shows the division in specific star-formation rate used to sub-divide those hosts that are star-forming. The passive galaxies (which have a zero SFR in our models) are assigned a random SFR centered on $0.005 M_\odot yr^{-1}$ for illustration purposes.

(Sullivan et al. 2006)

Possible Stellar Population Dependences

- High metallicity populations may be expected to exhibit lower peak Supernova Ia luminosities.

- Metal rich galaxies (e.g. E galaxies) may thus be expected to have fewer bright SNe Ia and to exhibit less scatter in peak luminosity..

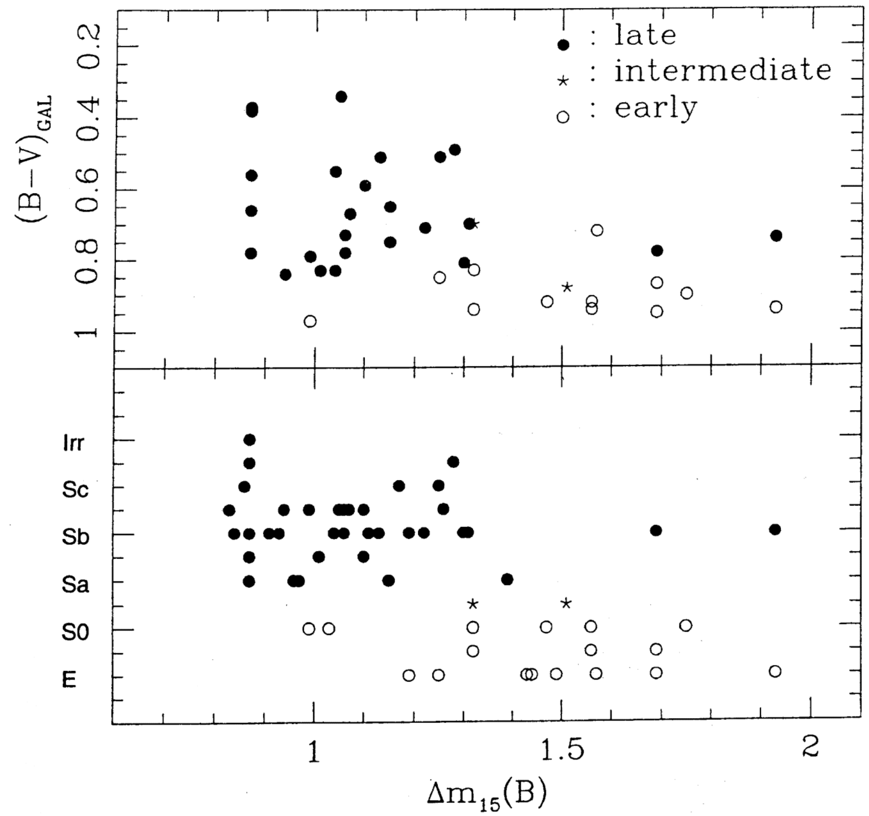


FIG. 1.—$B-V$ color (*top*) and morphological type (*bottom*) of the SN host galaxy vs. decline rate of the SN.

(Hamuy et al. 2002)

Neutronization, ^{56}Ni, and SNe Ia Peak Luminosities

- Neutronization of matter ejected in SNe Ia favors the production of neutron-rich isotopes (e.g.^{54}Fe, ^{58}Ni) at the expense of ^{56}Ni.
- This can arise during the explosion via electron capture, or it can be a direct consequence of initial composition:
  - Hydrogen burning (CNO): initial CNO nuclei $\Rightarrow$ ^{14}N.
  - Helium burns ^{14}N to ^{22}Ne: $^{14}N(\alpha,\gamma)^{18}F(e^+,\nu)^{18}O(\alpha,\gamma)^{22}Ne$
- The white dwarf progenitors of Type Ia supernovae have a composition of ^{12}C, ^{16}O, and approximately 2.5 percent ^{22}Ne.
- High metallicity populations may be expected to exhibit lower peak Supernova Ia luminosities.
- In the dense inner regions of the CO progenitor cores of Type Ia supernovae, electron captures can effect significant neutron enrichment and low ^{56}Ni production

Possible Stellar Population Dependences

- High metallicity populations may be expected to exhibit lower peak Supernova Ia luminosities.

- The range of metallicities characteristic of the stellar components of spiral galaxies can yield significant scatter in peak luminosities of their SNe Ia.

- Early type galaxies - particularly those of higher mass - are characterized by abundances ≈ 2-3 $Z_{\odot}$ and may therefore both show less scatter in peak luminosity and have fewer of the brightest SNe Ia.

Conclusions: Metallicity Dependence

- **The brightness of a Type Ia supernova at maximum is a function of the mass of ^{56}Ni produced.**
- **^{56}Ni is formed in nuclear statistical equilibrium in matter characterized by a Y_e approaching 0.5 (e.g. $Z \approx N$)**
- **The critical region of formation in Type Ia events is that from $\approx$ 0.2-0.8 solar masses.**
- **The mass of ^{56}Ni formed in NSE in this critical region is sensitive to the initial composition of the star (^{22}Ne).**
- **Metal rich galaxies (e.g. E galaxies) may be expected to have fewer bright SNe Ia.**
- **Nucleosynthesis considerations suggest that the SNe Ia events in spiral galaxies like our Milky Way galaxy should be systematically brighter. (Two kinds of SNe Ia ??)**

GCD Model and SNe Ia Luminosity Spread

A critical question to be addressed is whether the GCD model can reproduce the observed spread in peak luminosities of SNe Ia. Recalling that peak SNe Ia brightness is proportional to the mass of ^{56}Ni synthesized in the event, we note:

- Initial conditions for which nuclear ignition occurs at a single point offset from the center of the star produces a high concentration of ^{56}Ni, allowing the GCD mechanism to explain bright SNe Ia.

- Within the framework of the GCD model, anything that increases the mass burned in the rising bubble necessarily increases the amount of pre-expansion prior to detonation ⇒ *reduction in the ^{56}Ni mass produced* ⇒ *a correspondingly lower peak luminosity*.

- A possible model for such increased burning prior to detonation might involve a choice of initial conditions for which **nuclear ignition occurs at multiple points** (not a single point) offset from the center, burning more mass and driving greater preexpansion, thus **yielding** (following detonation) **less ^{56}Ni mass and thus a less luminous SNe Ia event**.

SN 1994D

Outstanding Issues in SNe Ia Research

- There is increasing agreement that it is difficult for a pure deflagration to provide sufficient energy both to unbind the white dwarf and to explain the observed kinetic energy of the ejecta. Deflagrations of complete white dwarfs in 3-D for a range of conditions are needed to address this question.

- The suggestion of a gravitationally confined detonation trigger needs to be further explored to determine the range of initial conditions that might reasonably be expected to give rise to such behavior.

- Implementation of Lagrangian tracer particles has now enabled SNe Ia researchers to determine the final composition of matter emerging from the deflagration phase for both central and off-center ignition.

- The fact that the peak luminosities of SNe Ia are proportional to the mass of ^{56}Ni ejected emphasizes the importance of reliable nucleosynthesis studies.

- The nature of the SNe Ia progenitor system remains unknown and is a major challenge to our understanding of these events.