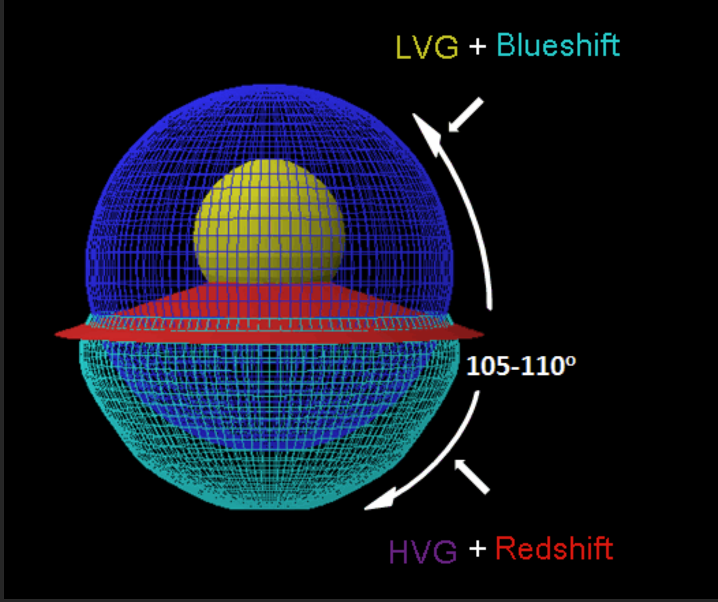

Asymmetry in TyPe Ia Supernovae: An Origin of Their Observational Diversities?

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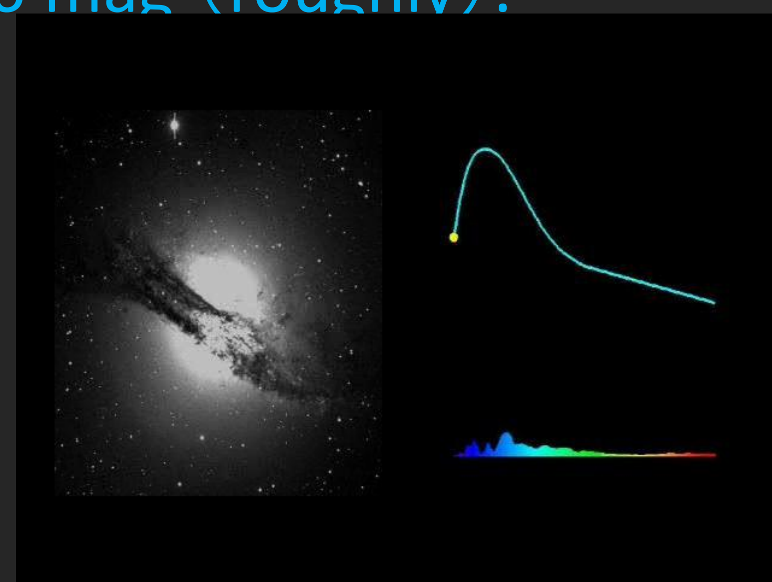
Observational Characteristics of Supernovae

- > 500 discoveries a year (557 for 2006, 584 for 2007).
  - **Only a part** (nearby) observed in detail.

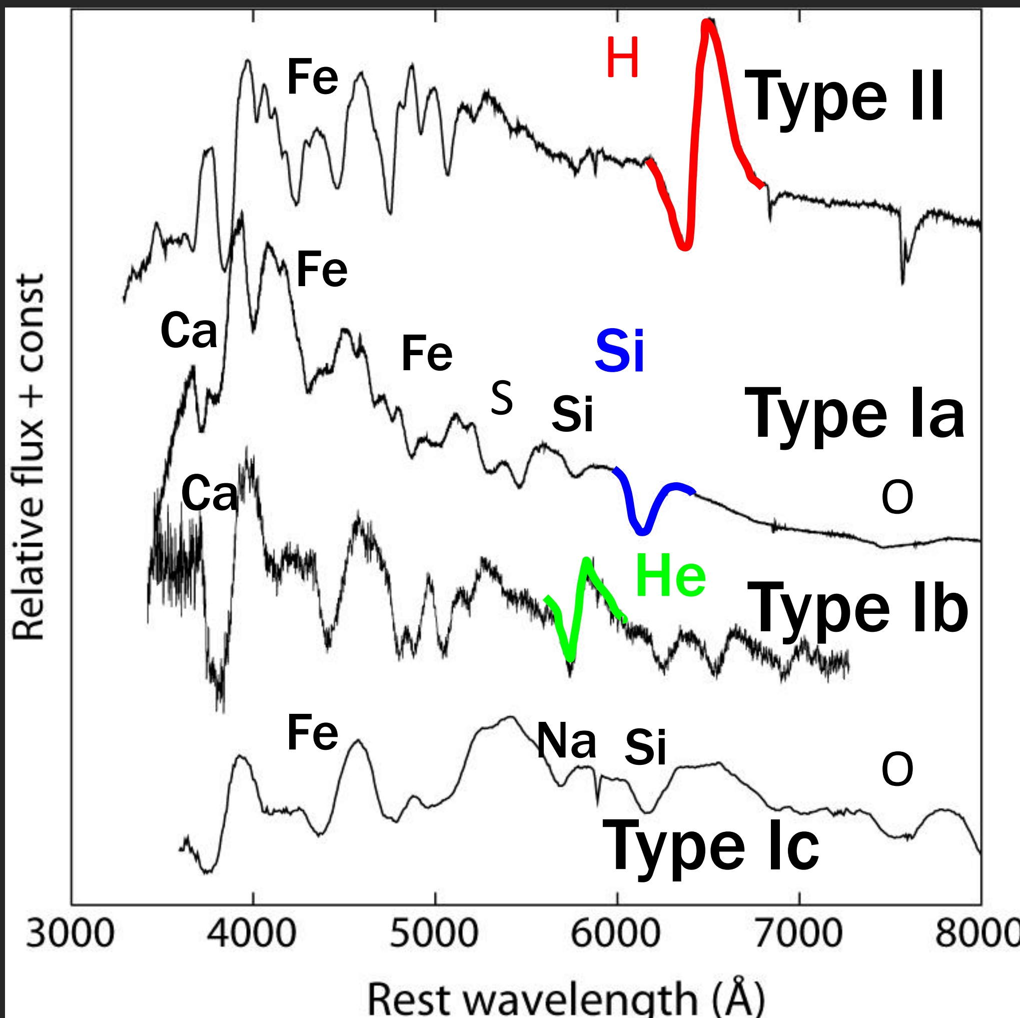
- Distance > ~ 10 Mpc (extragalactic).
  - **Point sources.**
  - Typical maximum mag. V > ~ 16 mag（roughly）.
- Most of obs. = Optical.
  - Imaging + spectra (time-dep.)

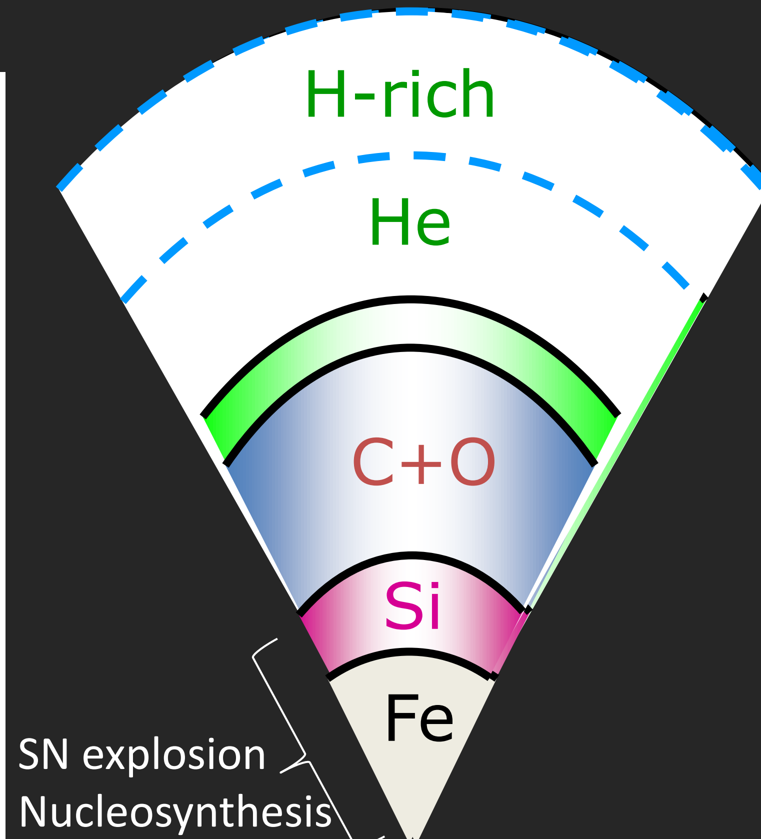
⬇ Interpretation

Supernova Physics（e.g., exp. mech.）



Spectroscopic Typing⇒Progenitor





Ib/c: massive He/CO star。

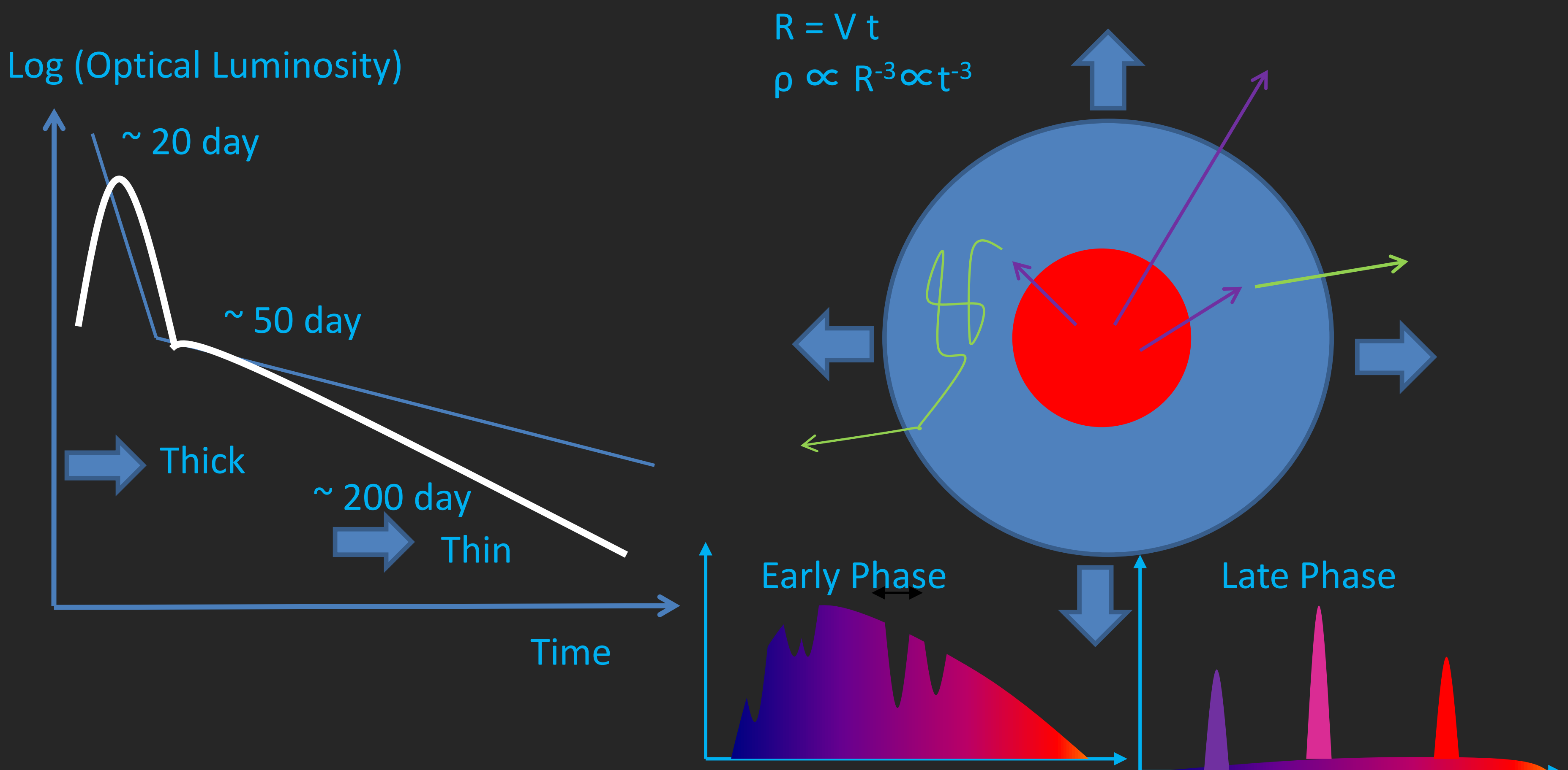
Ia：white dwarf（thermonuclear）。

Emission process is the same.

Emission Process in SNe Ia (and Ib/c)

- Power source: $^{56}Ni \Rightarrow {}^{56}Co \Rightarrow {}^{56}Fe$.

  8.8 day 113 day $\Rightarrow$ ~ 1 MeV γ (+ e+)



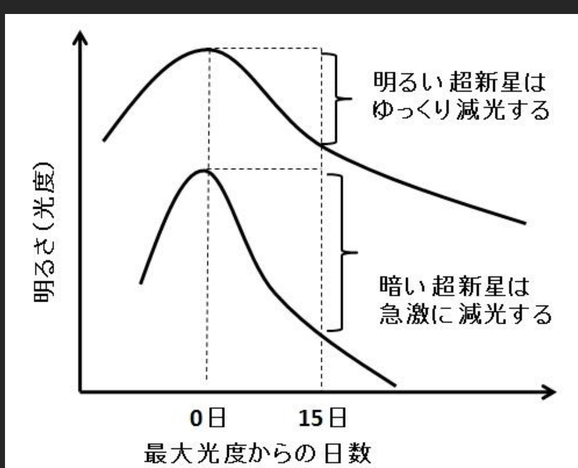
Type Ia Supernovae and cosmology

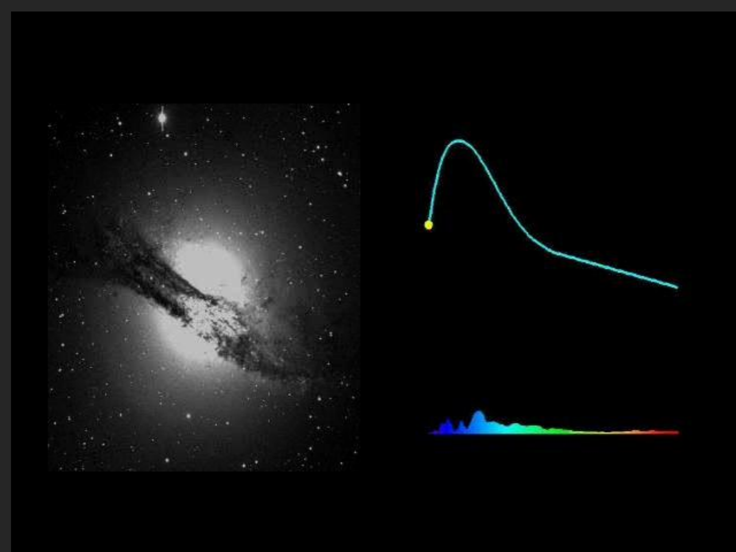
e.g., Nomoto+ 1984 ("w7 model")

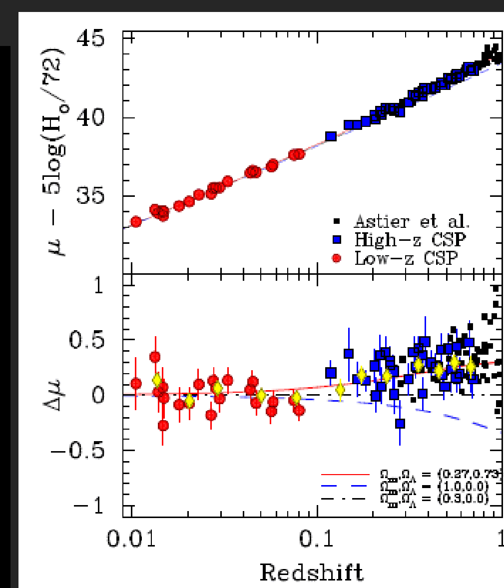
- Thermonuclear runaway of a white-dwarf (WD).
  - An explosion of a Chandrasekhar-mass WD.
  - No central remnant left.

e.g., Phillips 1993 ("Phillips relation")

- "Homogeneous" light curves→standard candles.
  - Light curve time scale ∝ Luminosity ← ^{56}Ni mass.
  - $\Omega_\Lambda \sim 0.73$!

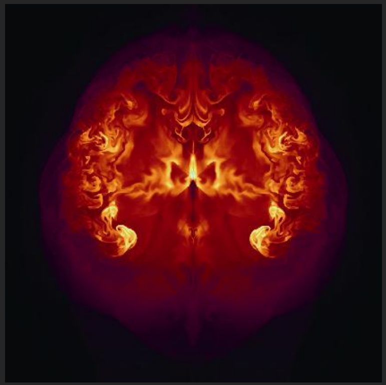






Asymmetry

Theory, Observation, then Unification?

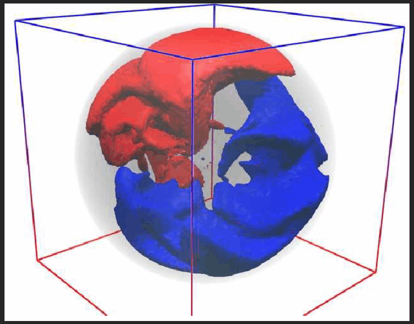


- **Off-set** SN Ia model.
  - KM+, 2010, ApJ, 712, 624.

- observational **evidence.**
  - KM+, 2010, ApJ, 708, 1703.

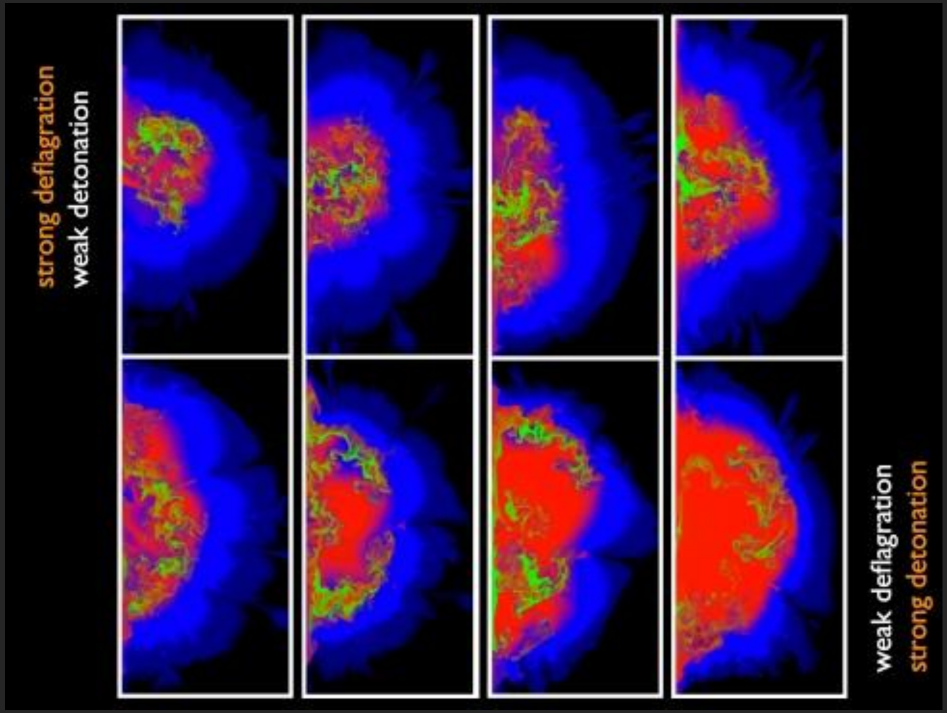
- Observational **diversities**.
  - KM+, 2010, Nature, 466, 82.
  - KM+, 2011, MNRAS, in press

Asymmetric explosions?



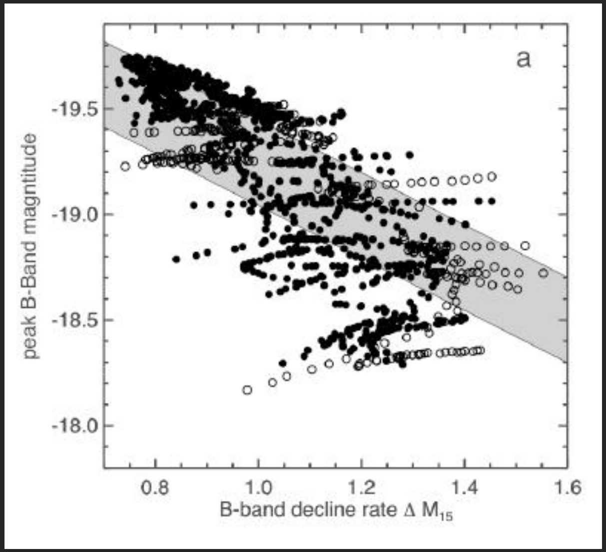
Dipole Convection in progenitor WD (Kuhlen+ 06)

- Details of the exp. not yet clarified.
- "spherical" explosion is standard, but it does **not have to be** in theories.



Kasen, Roepke, Woosley, 2009

Peak B



Δm_{15} (Light curve time scale)

But **NO** observational evidence

- Theorists have started thinking about the "asymmetric" explosion in these days.
  - Roepke+07, Jordan+08, Kasen+09.

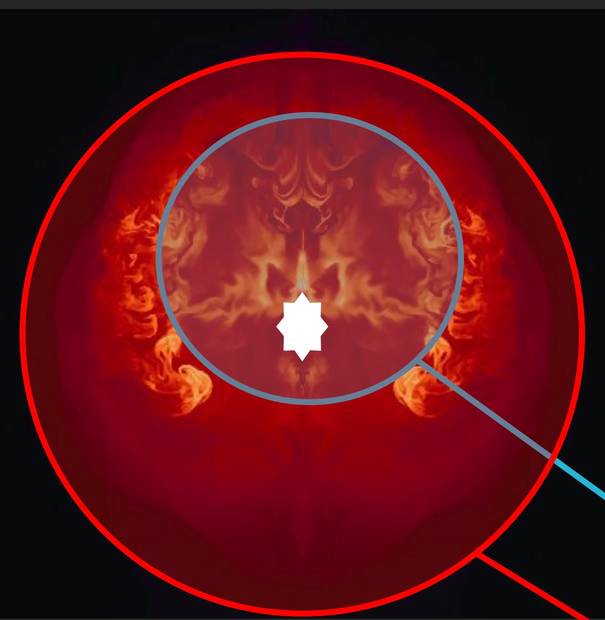
- **Big** problem here.
  - (Some) models may explain some observations, which **can however be explained by SPHERICAL** models as well.

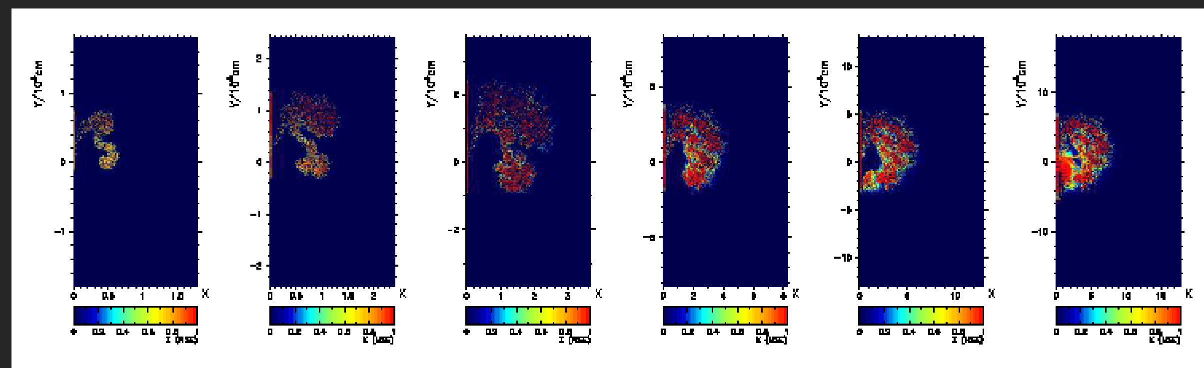
- We need **direct** evidence, which **contradicts any** spherical models.

Where to look into? High-density Ash!

- Example: Ignition at an **offset** (near the center).

Deflagration → Detonation → Fe-peak elements





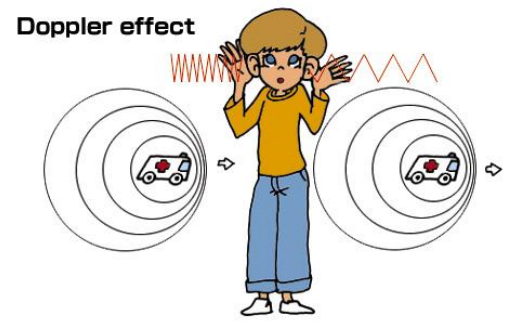
time →

Def. Ash = STABLE Fe+Ni, High Density

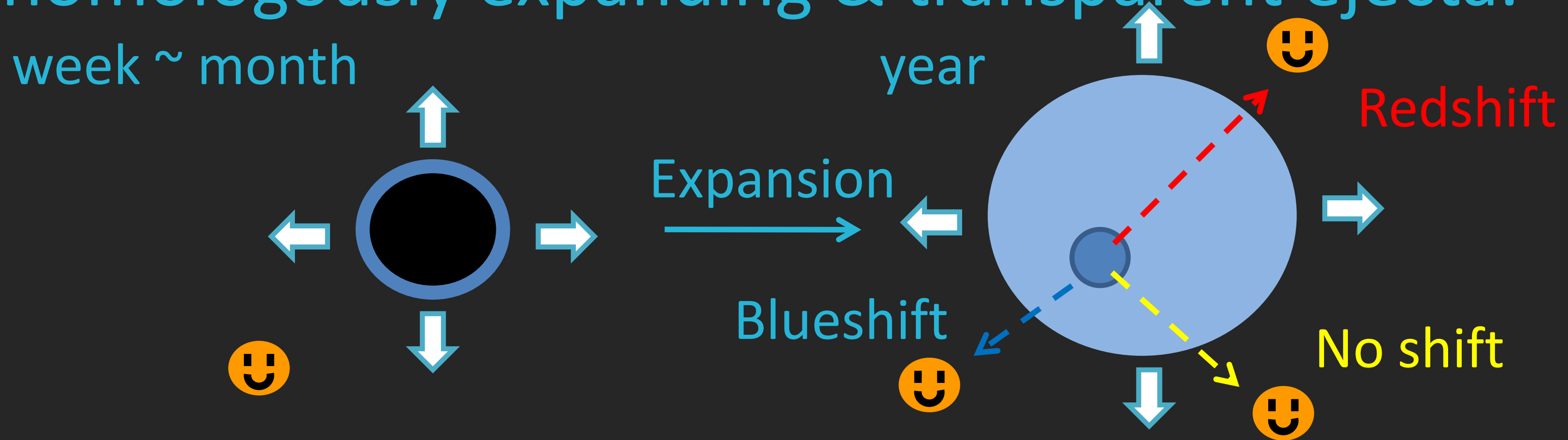
Det. Ash = ^{56}Ni (SN power!), Low Density

KM, Roepke, Fink, Hillebrandt, Travaglio, Thielemann, 2010, ApJ, 712, 624

How? Late-time spectra



- Just simple… **Doppler shift** diagnostic of homologously expanding & transparent ejecta.



- Simple, but not easy… faint (radioactive decay⇒~ 21 – 23 mag)
- Successful for SNe Ib/c to show their asymmetric nature.
    - KM, Kawabata, Mazzali+, 2008, Science, 319, 1220.
    - Modjaz+08, Taubenberger+09.

KM, Taubenberger, Sollerman+, 2010, ApJ, 708, 1703

Doppler shift diagnostics for SNe Ia

Ionization / particle

$$\frac{4\pi J_\gamma \sigma_\gamma}{\chi_{eff}} = \alpha n_e \frac{n_{i+1}}{n_i} \Rightarrow \frac{n_{i+1}}{n_i} \propto n_e^{-1} J_\gamma$$

^{56}Ni/Co/Fe: radioactive input

Thermal Balance

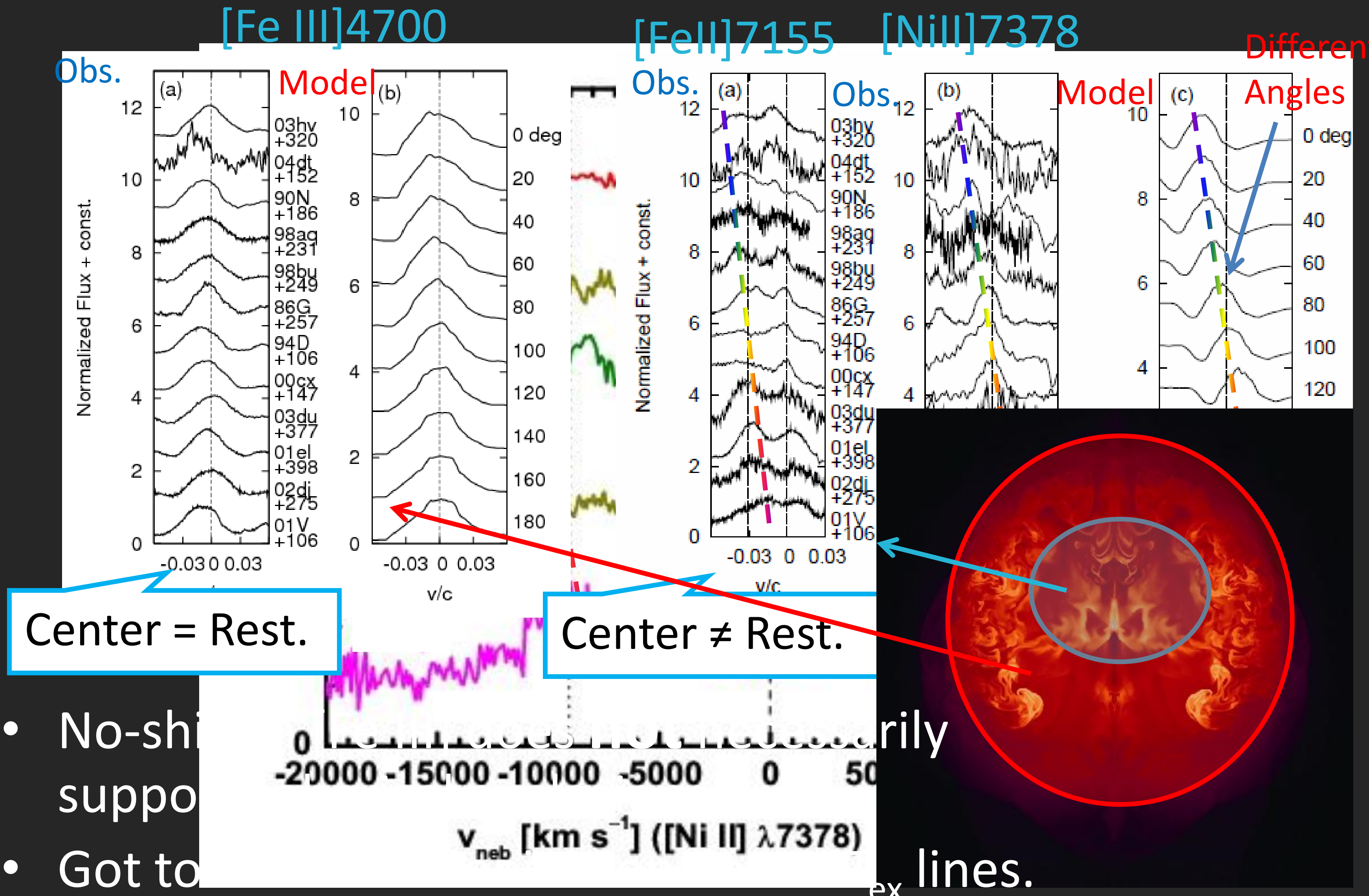
$$L_{line} \propto n_e n_0 \exp\left(-\frac{T_{ex}}{T_e}\right)$$

Excitation T of a line

- STABLE Fe+Ni, high density... **“Def. Ash”**
  - Low ionization(+1), low temperature (~ 5000K).
    - Representative = **[Fe II]7155, [Ni II]7378**.
- ^{56}Ni, low density... **“Det. Ash”**
  - High ionization(+2), high temperature (~ 10000K).
    - Representative = **[Fe III]4701**.

KM, Taubenberger, Sollerman+, 2010, ApJ, 708, 1703

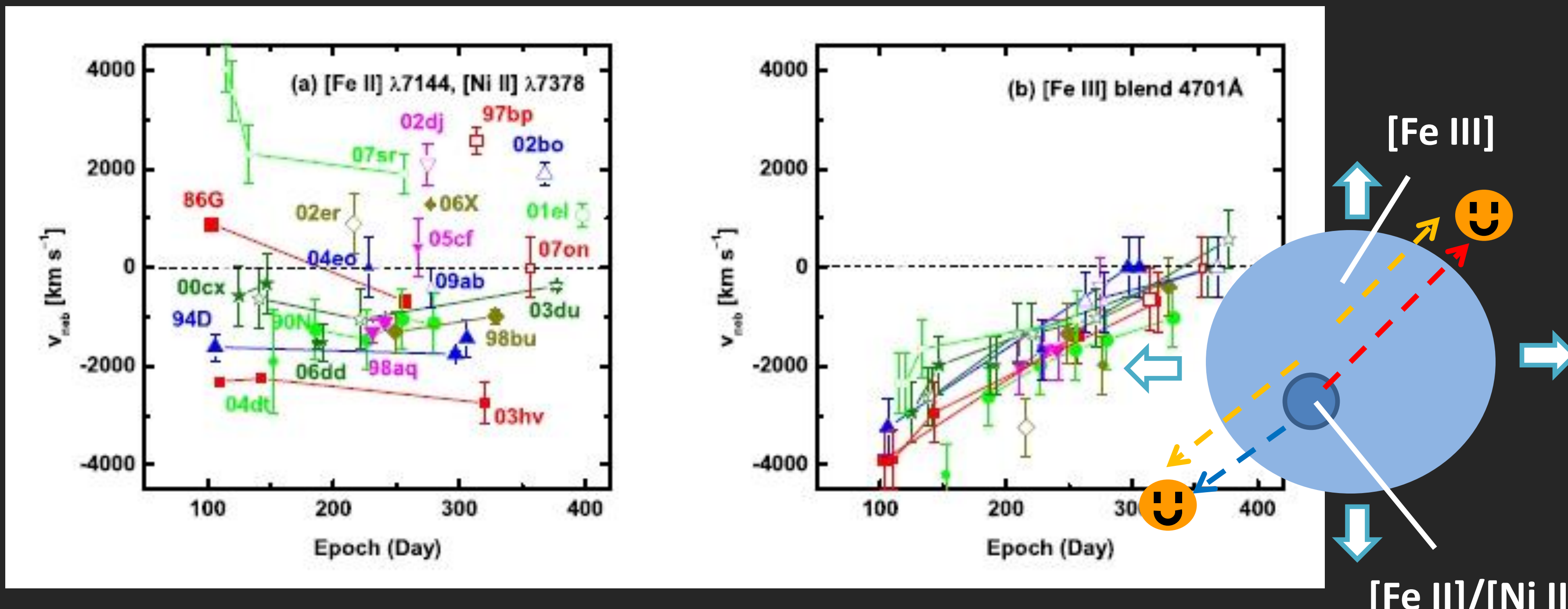
It is there! The first evidence of asymmetry



- No-shi … rily suppo …
- Got to … ex lines.

Evidences… not model dependent.

- Purely observational statements.



No correlation w/ epoch.
The shift does not evolve for each SN.
Large variation of the Doppler shift.
→ Offset + viewing angle.

Correlation w/ epoch.
The shift evolves with time.
Little variation for given epoch.
→ Radiation transfer. Spherical.

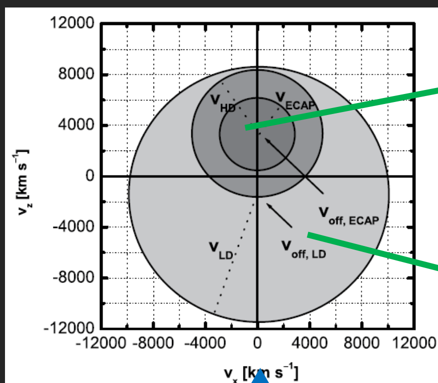
Obs. from Motohara+06, Gerardy+07, Leloudas+ 09

A **strong** case: 2003hv

Looks like **spherical**, if you look at only this line! (as people did.)

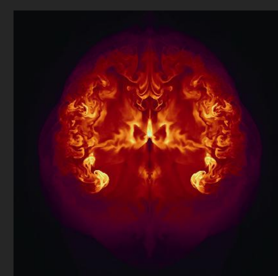
Off-set

Obs

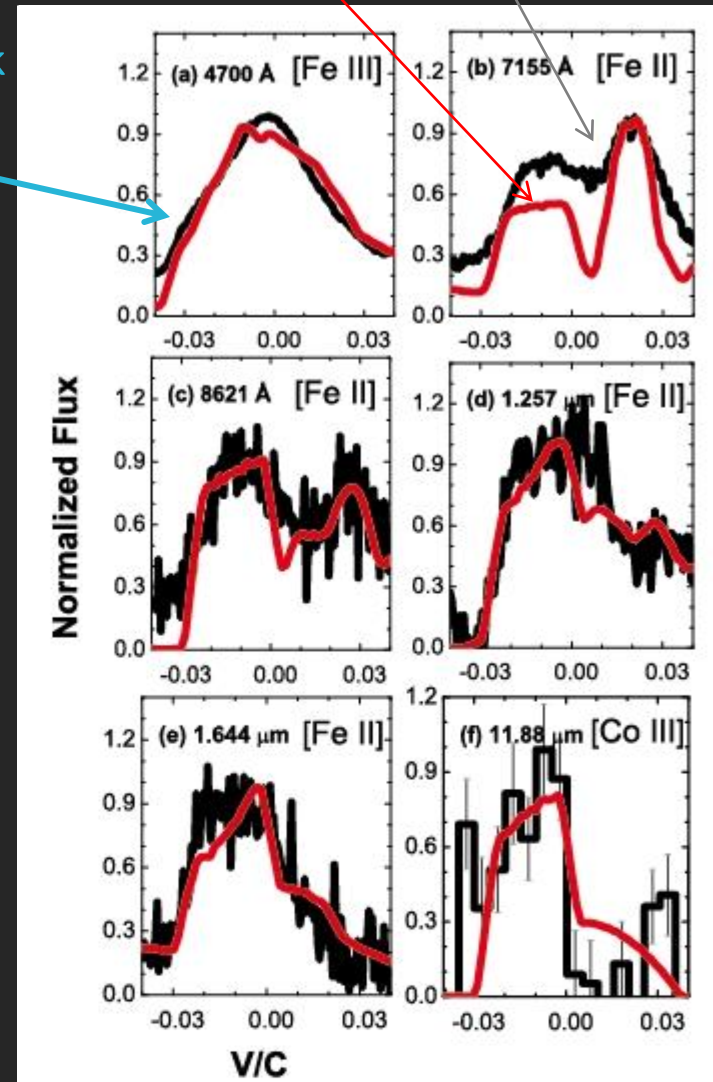


Steble Fe+Ni, high ρ

^{56}Ni, low ρ



Toy model



- Two categories in lines.
  - No shift.
  - blue-shift.
    - The shift behavior **as expected.**

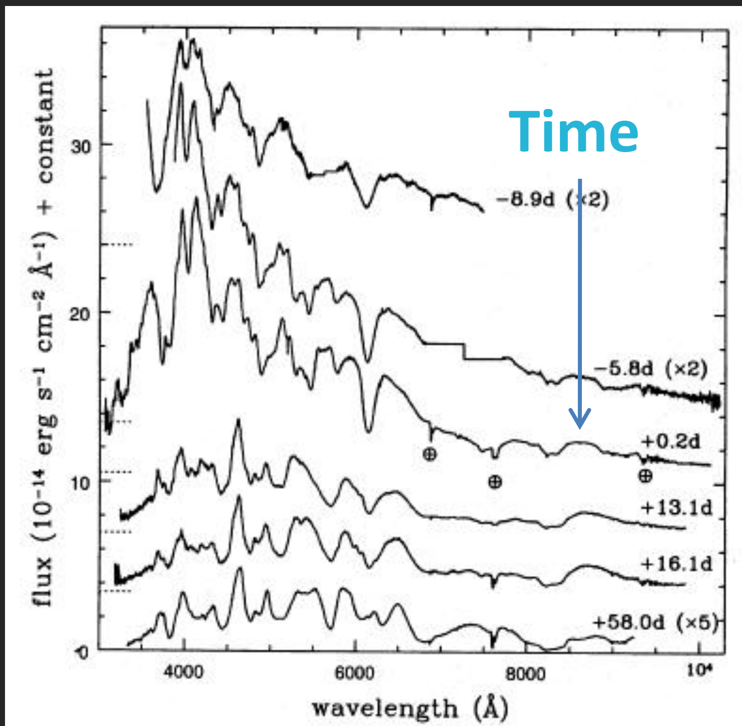
Computation by 3D nebular code by KM+ 2006

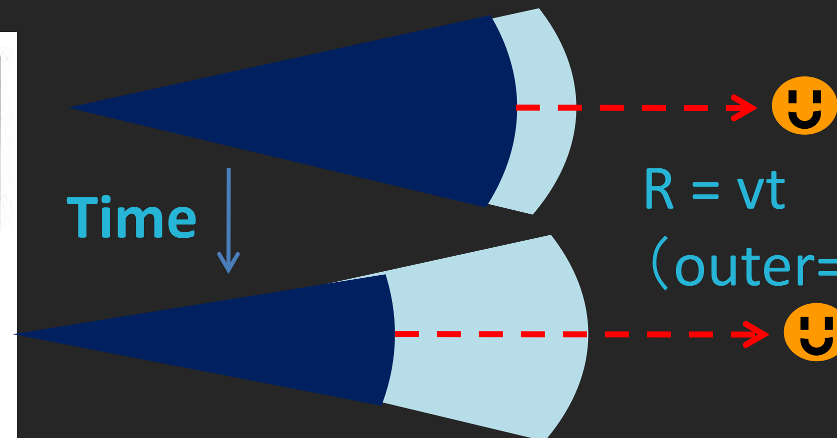
Tackling Observational Diversities

- Expectation.
  - SNe Ia look different for different viewing direction.

- Any implications in Observations?
  - Spectral Evolution Diversity.
  - Peak Color Diversity.

Spectral evolution **diversity**

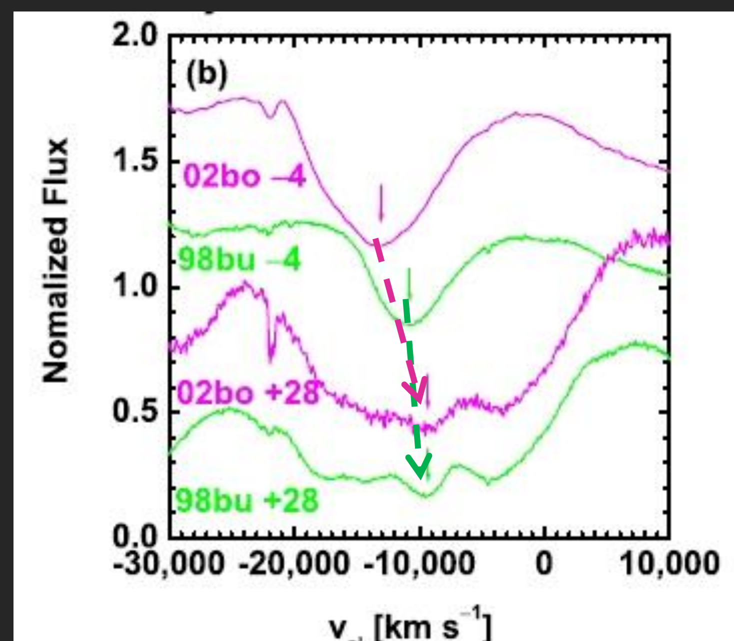




R = vt
(outer=faster)

Velocity of absorbing materials decreases with time.

The way **different for different SNe**.



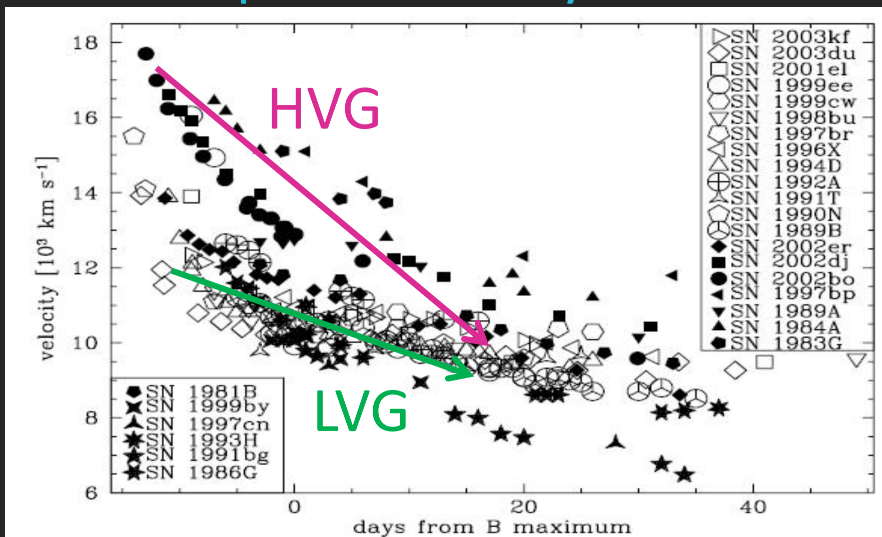
SN 2002bo
Rapid
evolution

SN 1998bu
Slow
evolution

HVG/LVG = High/Low Velocity Gradient

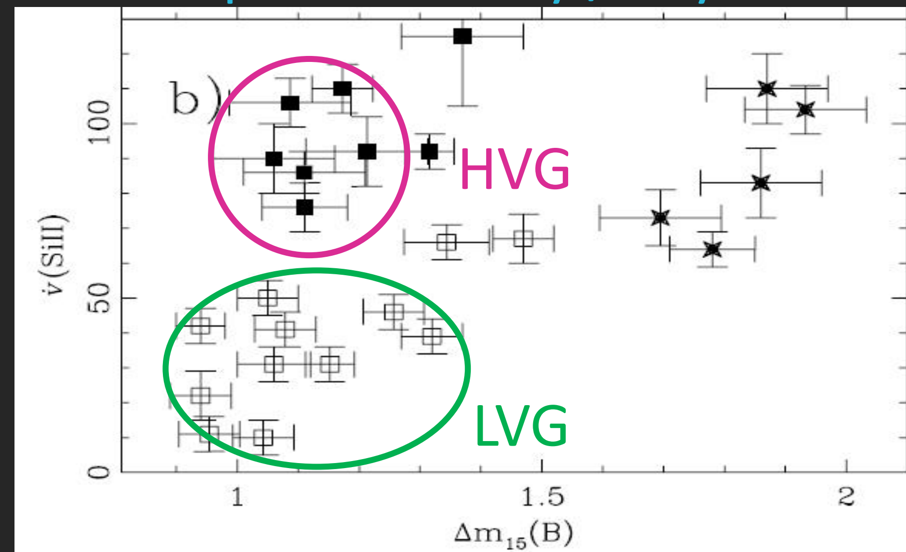
Spectral evolution **diversity**

Si II absorption velocity



Days

Si II absorption velocity / day



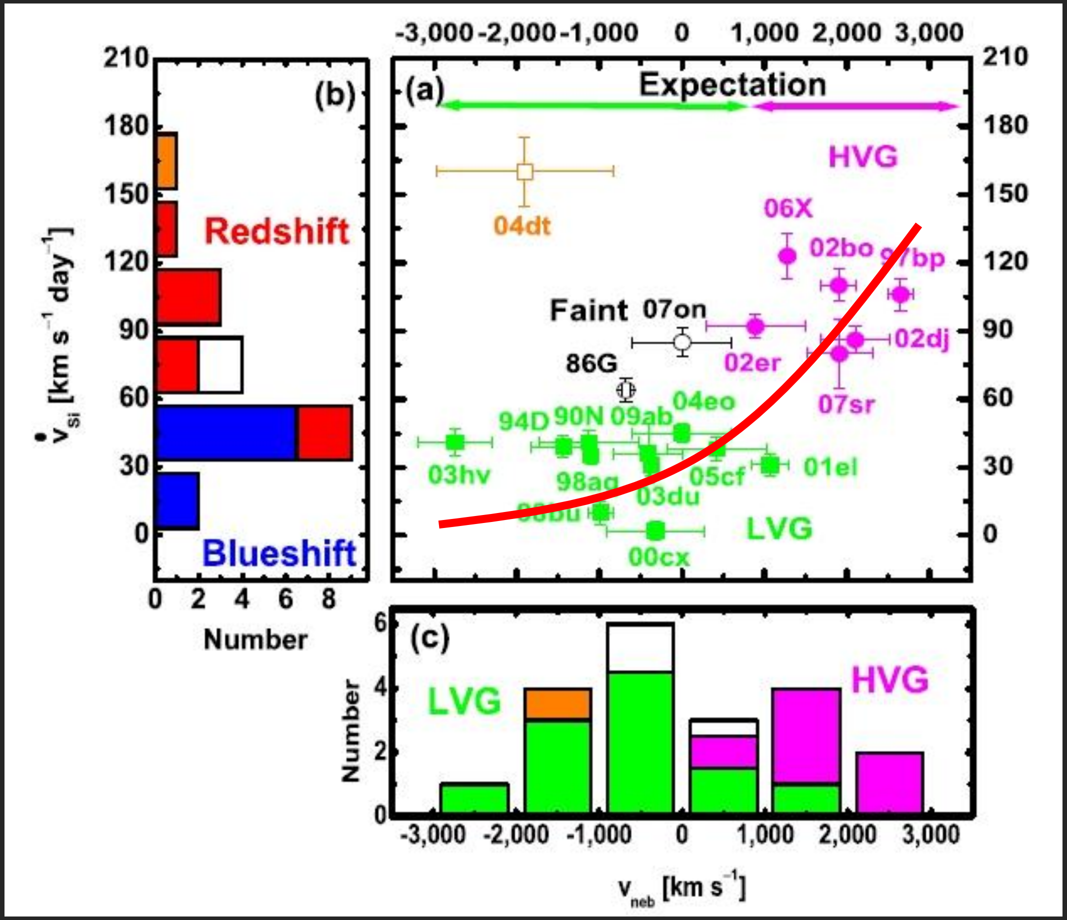
Light curve time scale = Luminosity indicator

- Spectral evolution does **not correlate** with the "luminosity".
  - The no-correlation noticed by Benetti+05, raising a challenge to the concept of "SNe Ia = uniform class = good standard candles"

KM, Benetti, Stritzinger+, 2010, Nature, 466, 82

Just a viewing angle!

Speed of the spectral evolution (Velocity Gradient)



- Prob. for chance coincidence = **0.06%**

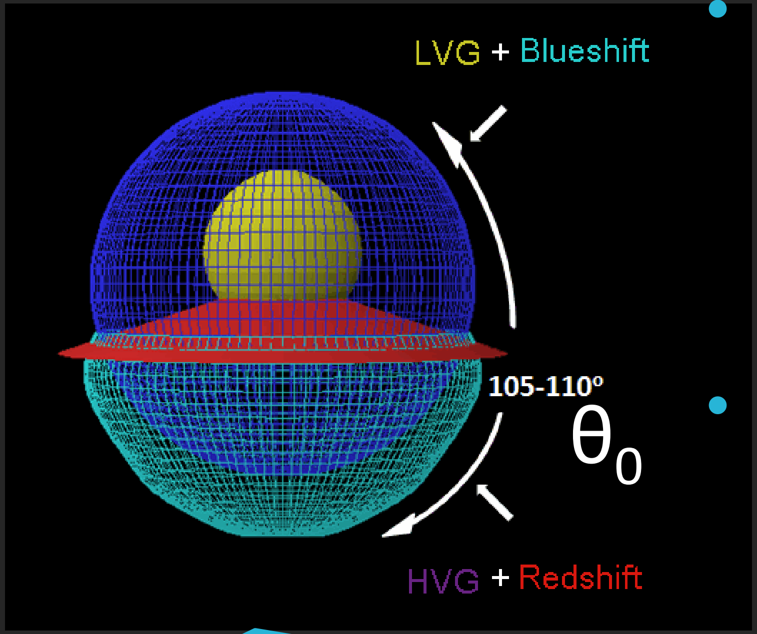
HVG all viewed at the direction **OPPOSITE** to the deflagration ash.

Wavelength Shift of [Fe II]7155+[Ni II] 7378 = **viewing angle**

“typical” SN Ia configuration

Shift = -3,500 km s^{-1} × cosθ
LVG: -3,000 < θ < 1,000 km s^{-1}
HVG: 1,000 < θ < 3,000 km s^{-1}
θ_0= acos(-1000/3500)

Distribution of wavelength shift



Number ratios HVG/LVG

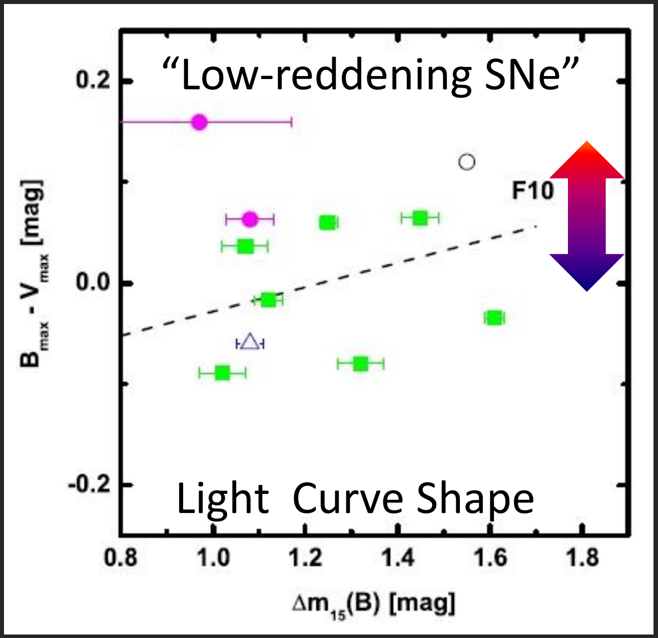
- One assumption:
  - Off-set = 3,500 km s^{-1} for the deflagration ash is **generic**.
- Two **independent** information points to the **same** config.
  - **105-110º** for the transition angle.

HVG:LVG = 1:2 (numbers)
1-cosθ_0/1+cosθ_0= LVG/HVG = 2

KM, Leloudas, Stritzinger+, 2011, MNRAS, in press

Diversity in Color?

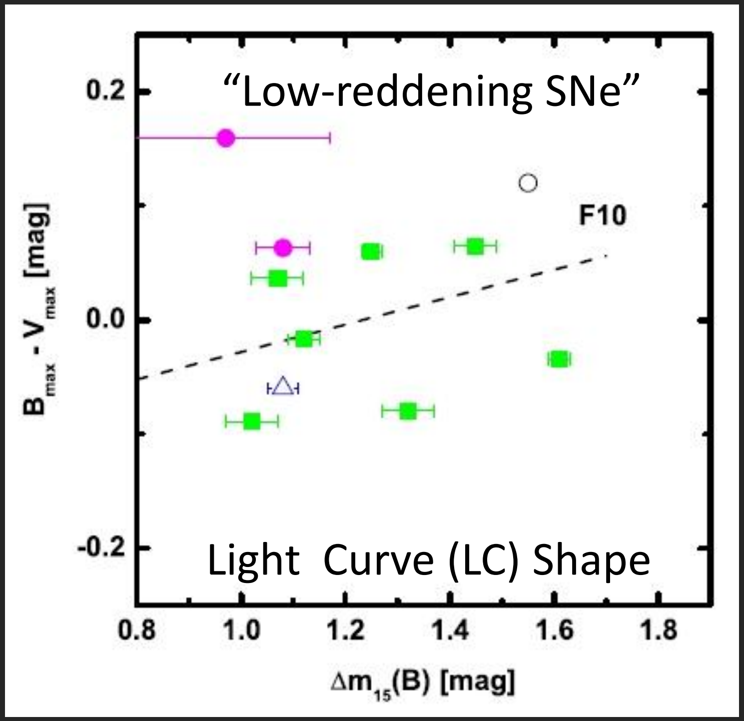
- Why does it matter? – Essential in SN cosmology.
- **Observed color + magnitude → distance.**
  - extinction = observed color – **intrinsic color**.
  - distance = obs. mag. – absolute mag. – extinction
- Intrinsic color depends on
  - Light curve shape.
  - +alpha → **color diversity**.



KM, Leloudas, Stritzinger+, 2011, MNRAS, in press

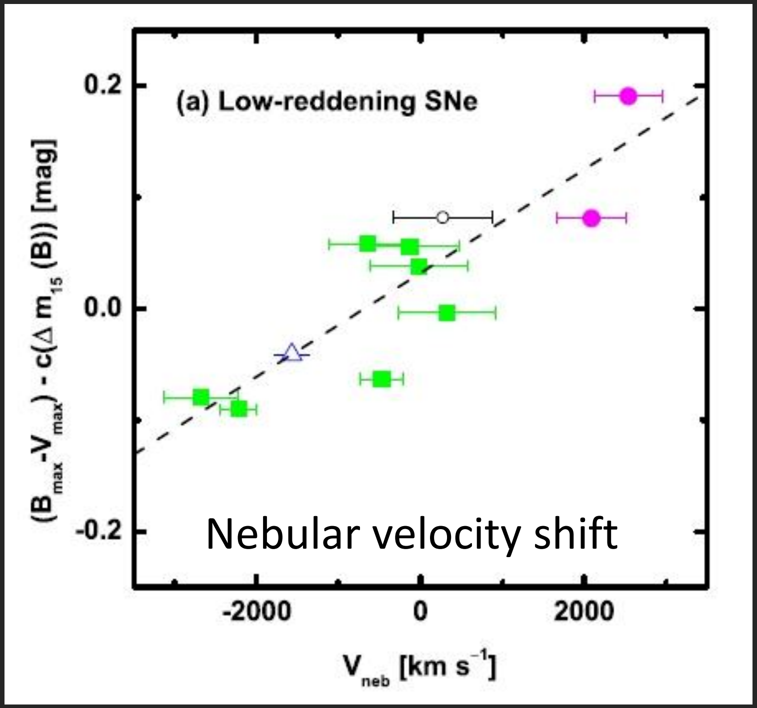
Intrinsic color variation from asymmetry

- “low-reddening SNe” → **observed color ~ intrinsic.**
  - Either in E/S0 or in the outskirts.
- “Viewing direction” → intrinsic color variation (?).
  - C.f., HVGs are red (Pignata+ 08, Wang+09).



residual

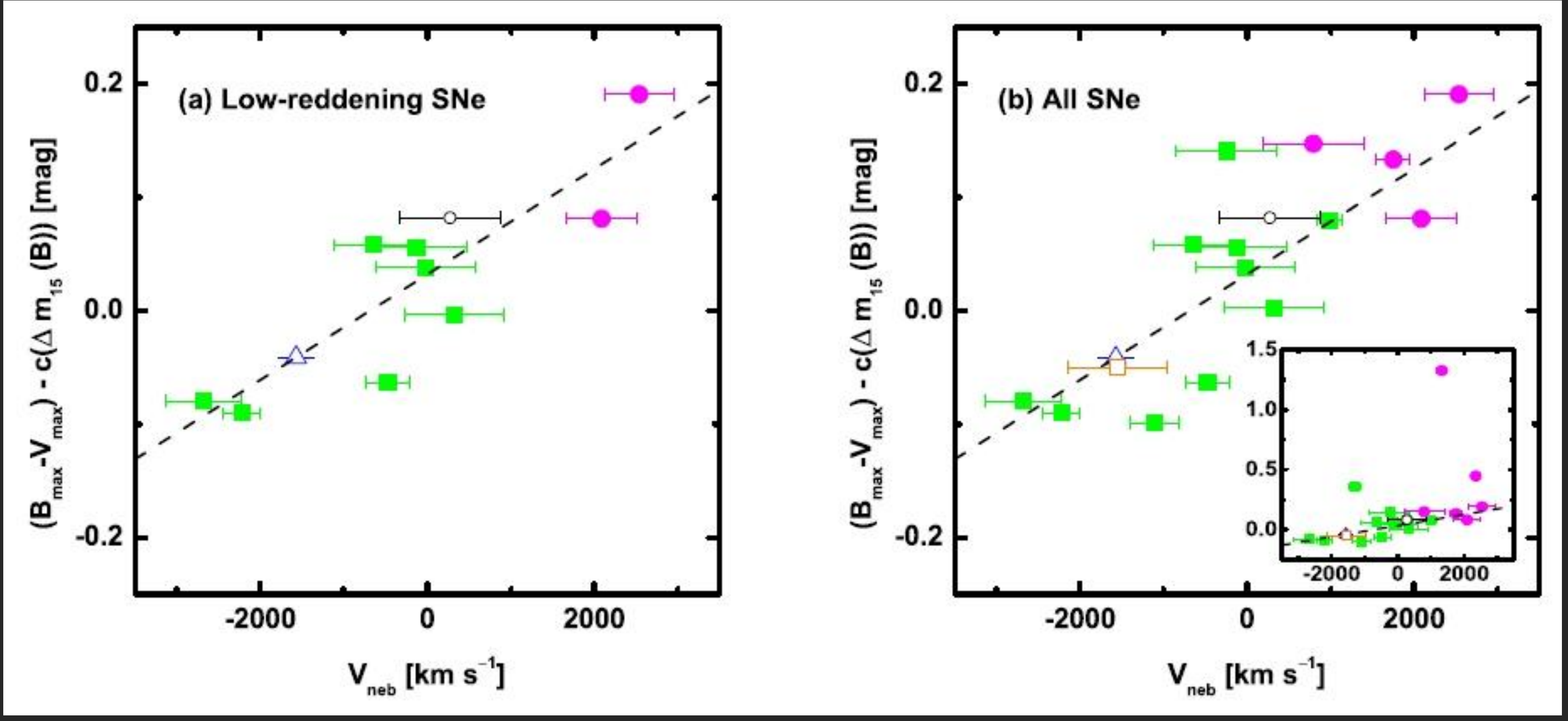
Observed color w/ LC correction



Host extinction: Real or Artifact?

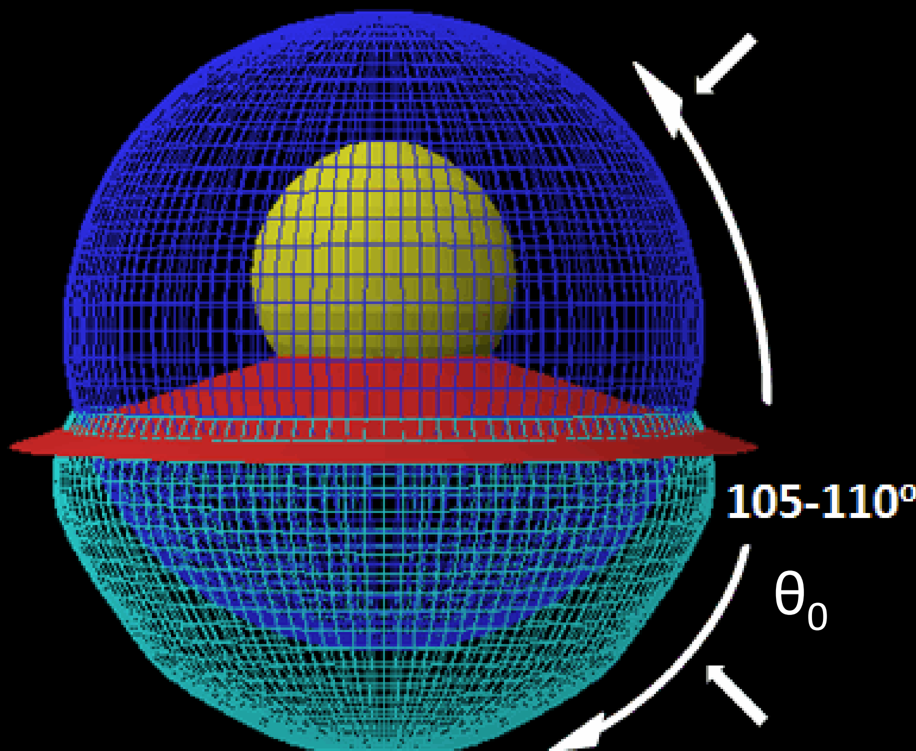
- A part (not all) of the previously derived "host extinction" may be due to "intrinsic color".
  - **Host extinction should be revised.**

"Low-reddening" SNe (host morphology) — No selection for reddening



Asymmetry → Observational Diversities

LVG + Blueshift + Bluer color



First-order

Not seriously affecting distance measurement (random/statistic effect)

Second-order

Better distance calibration? (color/extinction estimate)

HVG + Redshift + Redder color

Conclusions

Asymmetry

- Is a **generic** feature.
  - Late-time spectra have provided the **first evidence**.
    - Strong support for the "one-sided" nature.
  - **Solves a part of "diversities"** in SNe Ia.
    - A simple answer to the diversities in **spectral evolution/color**.
    - Would **not** introduces **z-dependent systematic errors** in cosmology (it is a random effect).
    - However, might affect the extinction. May introduce some **(z-independent) systematics**?
    - Unification of further diversities?