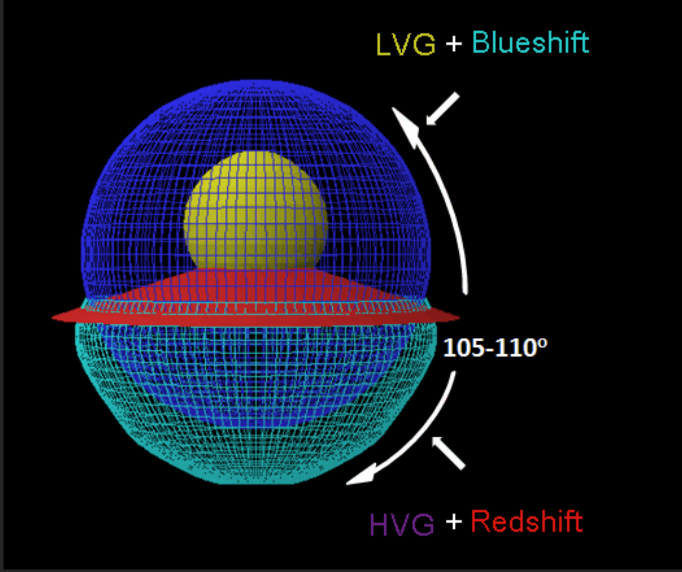
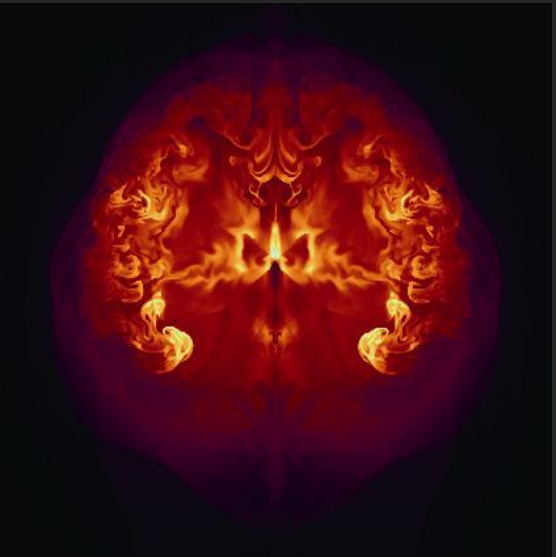


Supernova Explosion Mechanism probed by late-time NIR spectroscopy with AO



Keiichi Maeda (IPMU)
Kentaro Motohara (Inst. Astron.)
Masaomi Tanaka (IPMU)
Ken'ichi Nomoto (IPMU)

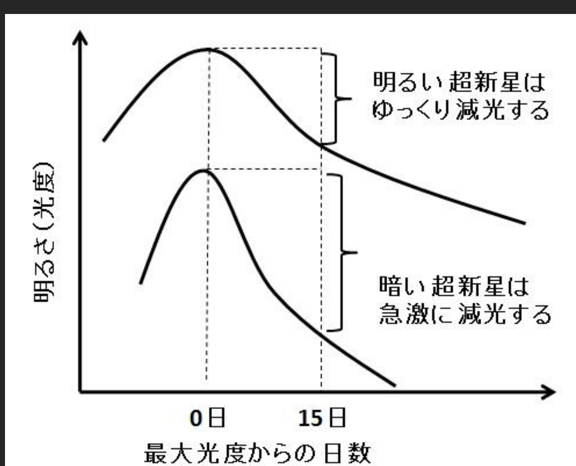
A proposal

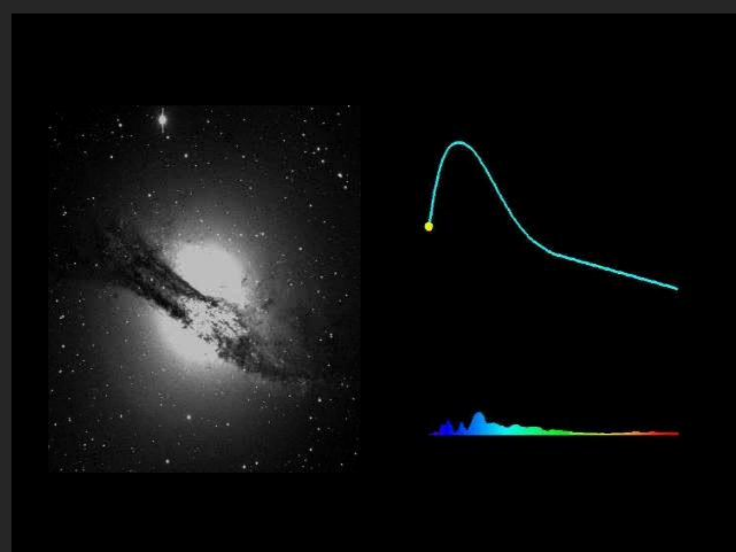
- ~ 3 - 5 SN Ia **NIR late-time spectra** per year.
  - Preferentially **with optical spectra**.

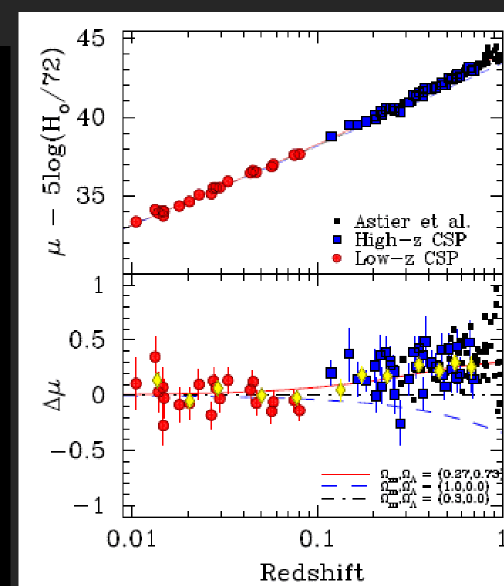
- This will hopefully provide insights into,
  - Explosion mechanism.
    - Fuel to **astrophysics.**
  - Standard-candle-natures of SNe Ia.
    - Fuel to **cosmology.**

Type Ia Supernovae

- Thermonuclear runaway of a white-dwarf (WD).
  - An explosion of a Chandrasekhar-mass WD.
  - No central remnant left.
- “Homogeneous” light curves→standard candles.
  - Light curve time scale∝Luminosity.
  - $\Omega_\Lambda \sim 0.73$!





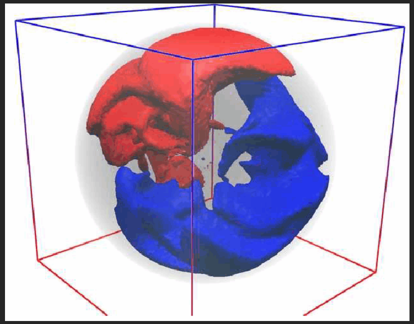


Explosion Geometry is A Key

- The ignition process **yet to be clarified.**
  - The geometry→**How the ignition takes place.**

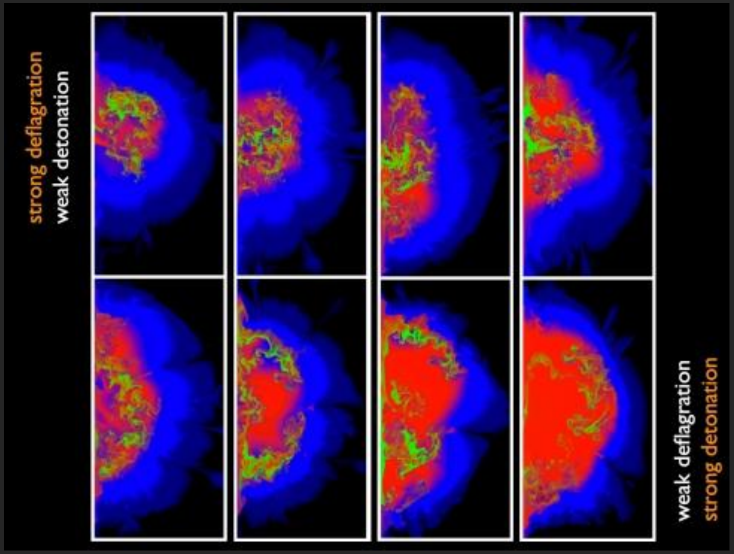
Bulk (off-set) asymmetry in the ignition?

+ hydro mixing?

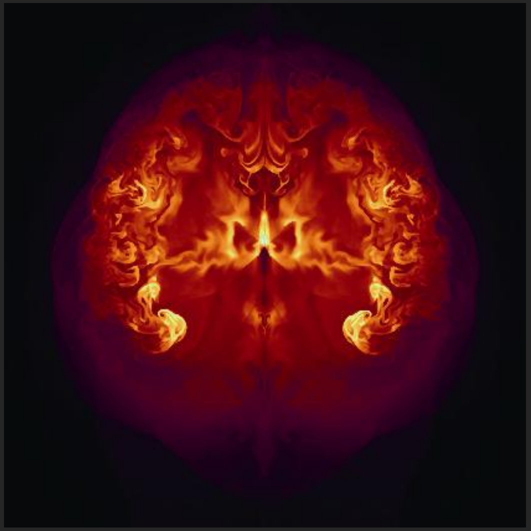


Convection within WD
Kuhlen+ 2006

Kasen+ 2009

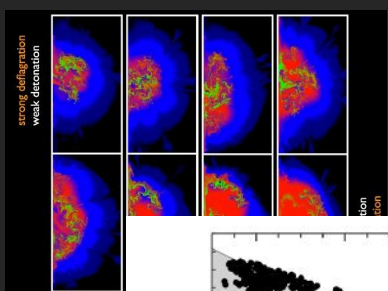


KM, Roepke, Fink+, 2010, ApJ, 712, 624



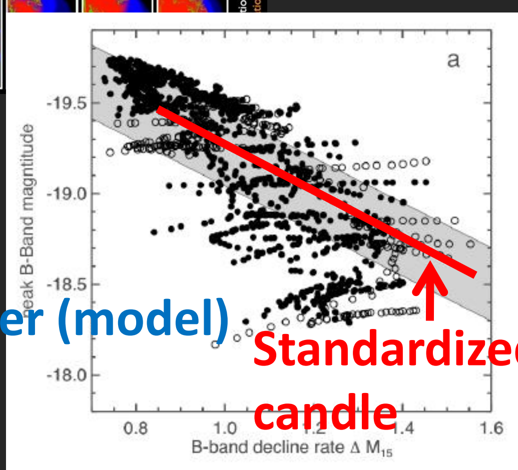
Explosion Geometry is A Key

- **Issues remain** for their natures as standard candles. Especially, **diversities do exist.**
  - The geometry→**Origin of diversity? →calibration?**



Kasen+ 2009

M_B

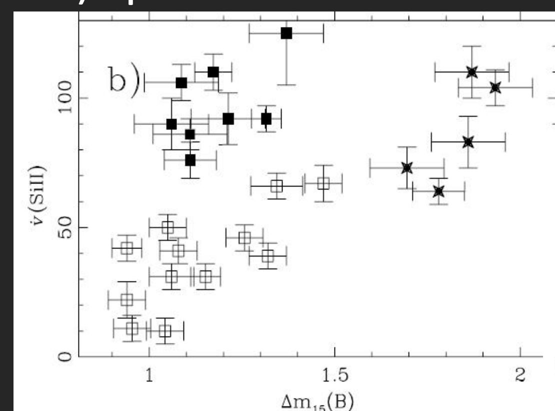


Scatter (model)

Standardized candle

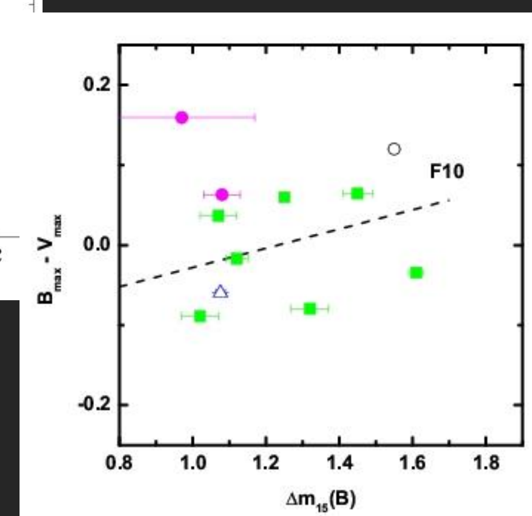
Δm_{15} (decline rate)

(early-phase) spectral feature Benetti+ 2005



Δm_{15} (decline rate)

Peak color B-V

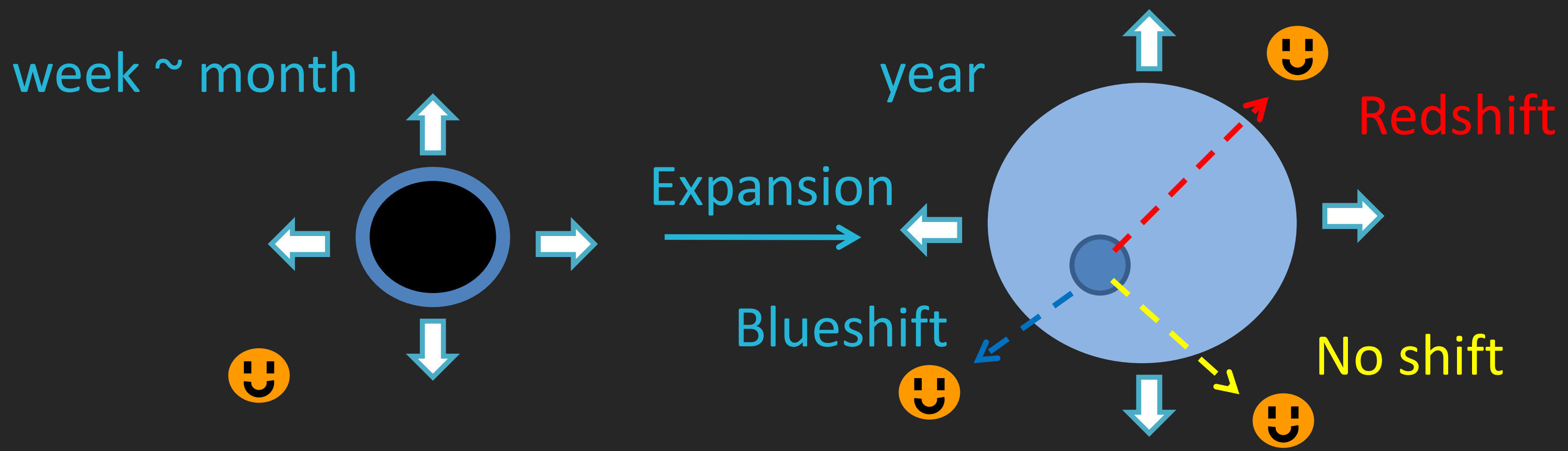


Cf. Folatelli+ 2010

Δm_{15} (decline rate)

How? Late-time spectra

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



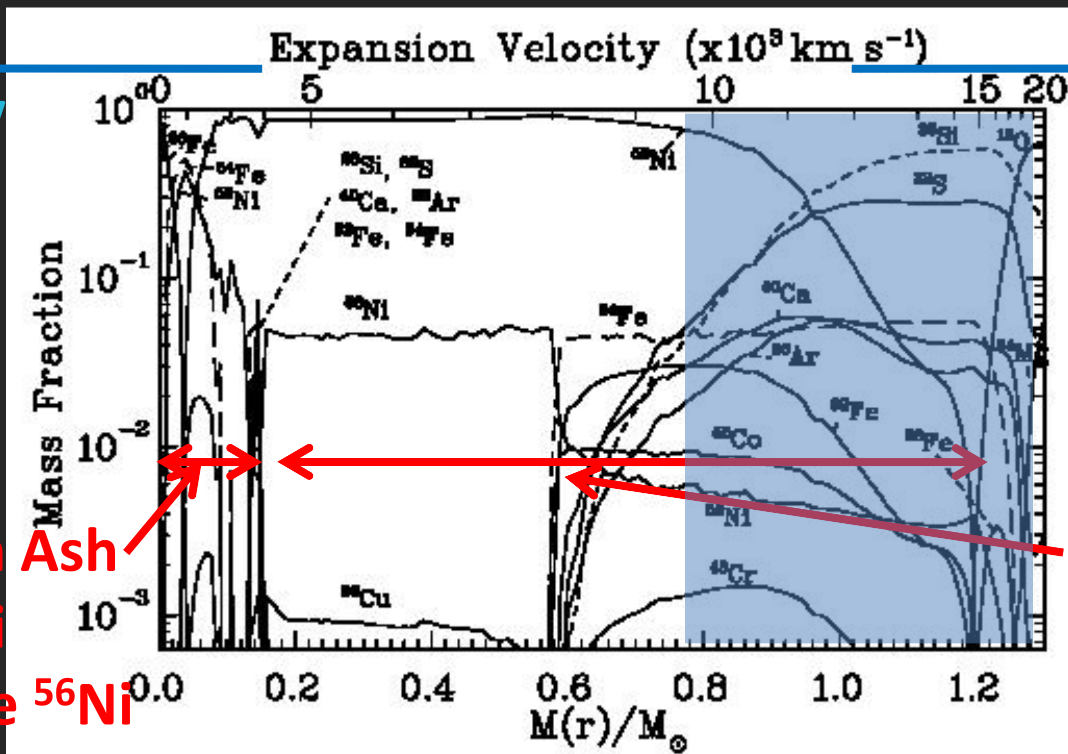
- Successful for core-collapse SNe to show the asymmetric and (likely) bipolar nature.
  - KM, Kawabata, Mazzali+, 2008, Science, 319, 1220.
  - Modjaz+08, Taubenberger+09.

Which lines tell what?

- Standard explosion scenario:
  - "Deflagration-to-Detonation Transition"
    - (but pure-deflagration models can give something similar.)

Center
High density

Outer
Low density

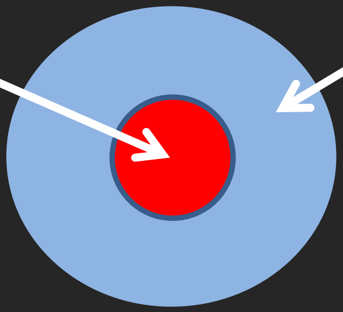


Deflagration Ash
Stable Fe, Ni
+ radioactive ^{56}Ni

Detonation Ash
^{56}Ni (+ Si, S, …)

Iwamoto+ 1999

Which lines tell what?



Def. Ash
Stable Ni, Fe
High density
→ low Ionization
low temperature

Det. Ash
^{56}Ni (→γ-ray)
low density
→ high Ionization
high temperature

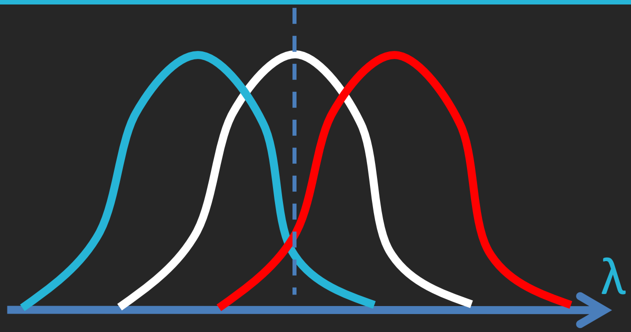
Wavelength (μm)	Ion	Term	E_u (cm^{-1})[b]	Shift[c]	Region[d]
0.4658	Fe III	$^5D_4$–$^3_2F_4$	21462.2	No	LD
0.4701	Fe III	$^5D_3$–$^3_2F_3$	21699.9	No	LD
0.4734	Fe III	$^5D_2$–$^3_2F_2$	21857.2	No	LD
0.5262	Fe II	$a^4F_{7/2}$–$a^4H_{11/2}$	21430.4	No	LD
0.7155	Fe II	$a^4F_{9/2}$–$a^2G_{9/2}$	15844.7	Yes	HD
0.7378	Ni II	$^2D_{5/2}$–$^2F_{7/2}$	13550.4	Yes	ECAP
0.8617	Fe II	$a^4F_{9/2}$–$a^4P_{5/2}$	13474.4	Yes	HD
1.257	Fe II	$a^6D_{9/2}$–$a^4D_{7/2}$	7955.3	Yes	HD
1.644	Fe II	$a^4F_{9/2}$–$a^4D_{7/2}$	7955.3	Yes	HD

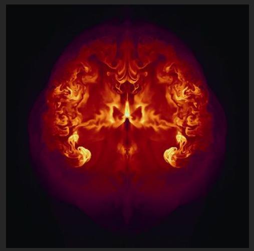
"Det." (LD rows)

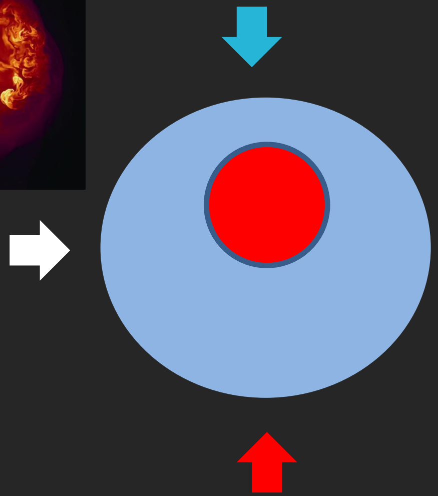
"Def." (HD rows)

KM, Taubenberger, Sollerman+ 2010

Which lines tell what?







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"Det."

"Def."

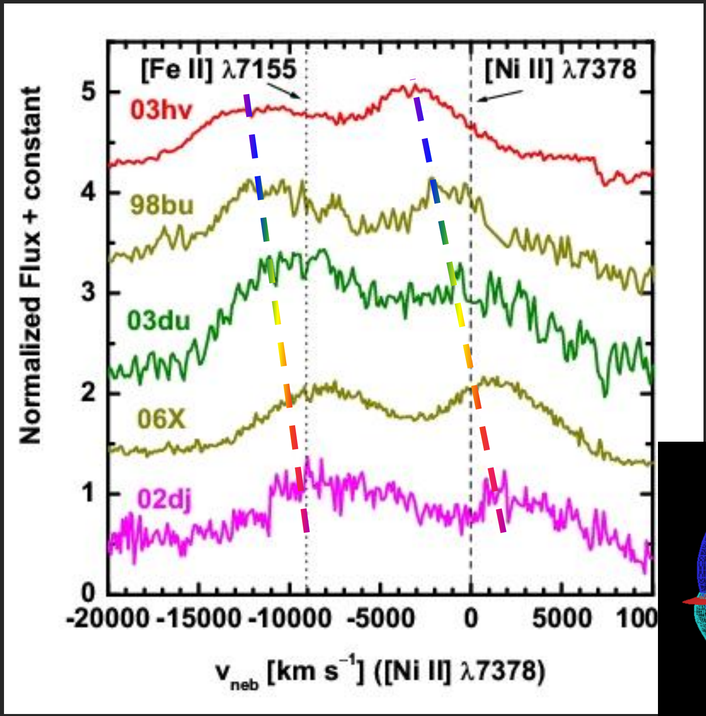
Probing "Asymmetric Ignition"

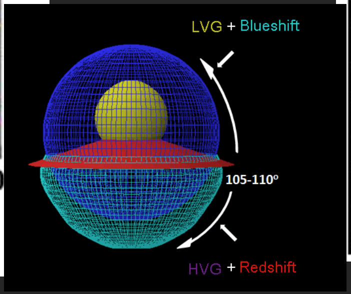
Optical Diagnostics – Bulk asymmetry

- ~ 20 SNe with published late-time spectra.

"Off-set " in the def. ash.

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



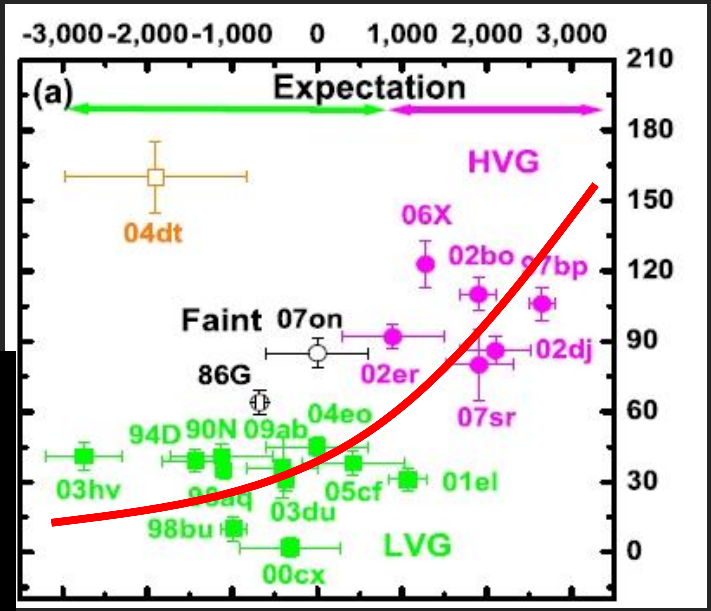


λ (in Velocity)

"Viewing angle" as the origin of (early-phase) spectral diversity.

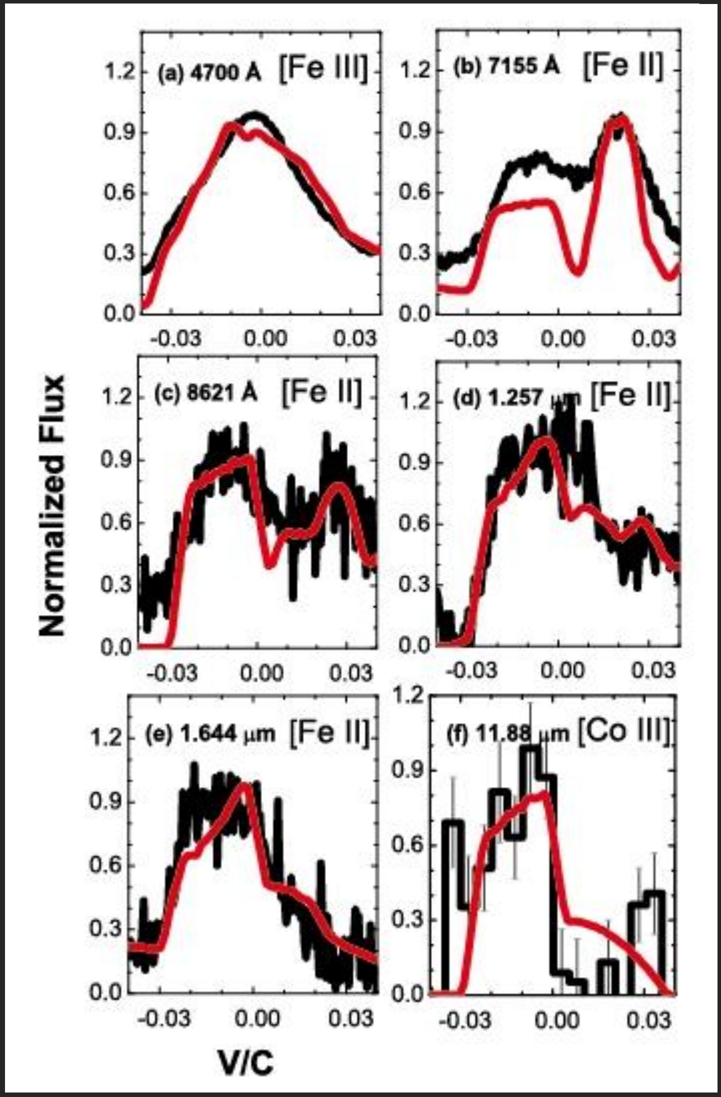
KM, Benetti, Stritzinger+ 2010, Nature, 466, 82

Speed of spectral evolution in early phases



Velocity shift → Viewing angle

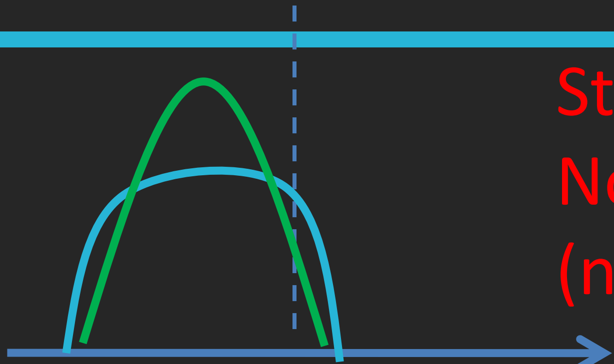
SN 2003hv – from optical through NIR



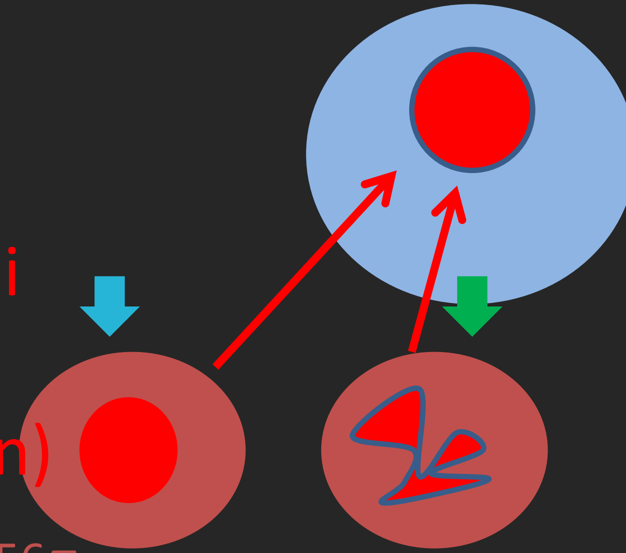
- The **only** example for which the "asymmetry" has been tested w/ NIR and Mid-IR emission lines.
  - Emission lines from the "deflagration ash" all show "blueshift".
  - Emission lines from the ""detonation ash" show "no-shift".

KM, Taubenberger, Sollerman+ 2010
Data from Gerardy+ 05, Motohara+ 06, Leloudas+ 09

Which lines tell what?



Stable Fe, Ni
No heating
(no emission)



$^{56}Ni \rightarrow ^{56}Fe$

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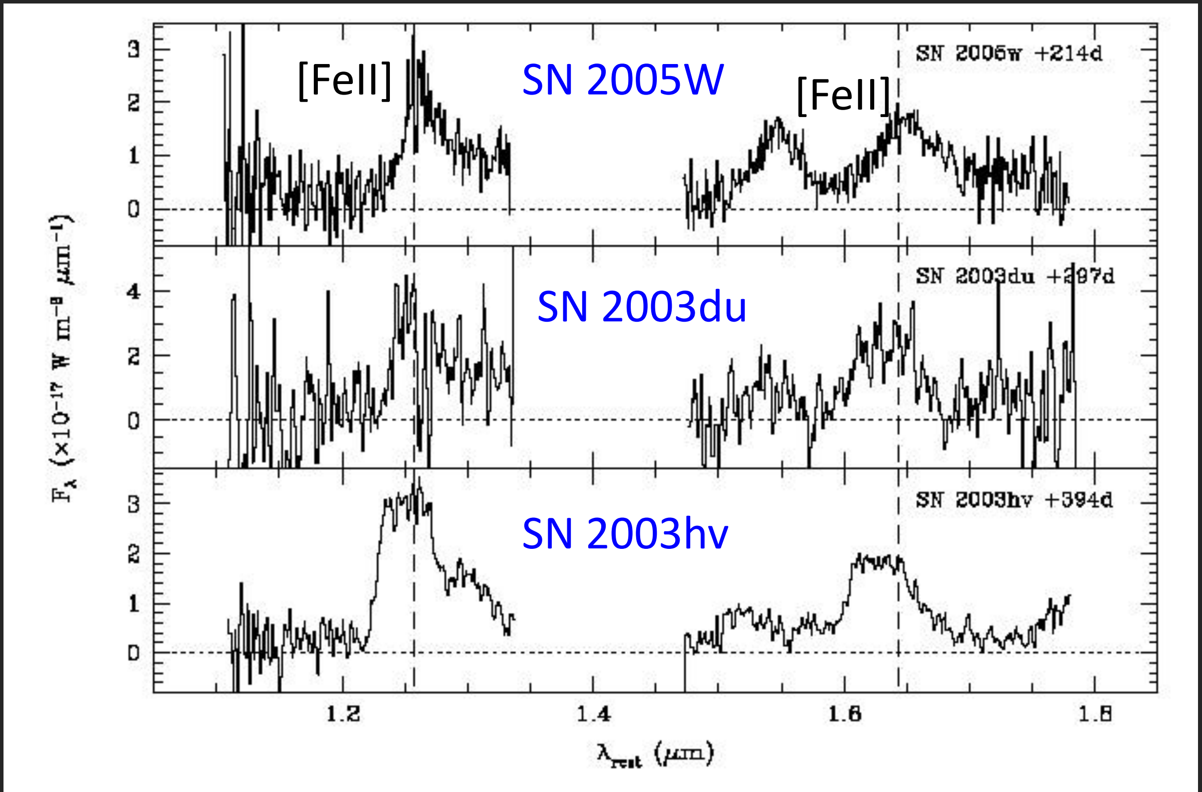
Clean to do this test

NIR Diagnostics – Details on mixing

- ~ 5 SNe with published late-time spectra.
  - 3 by Subaru/CISCO/OHS.



Peaked

Intermediate

Boxy

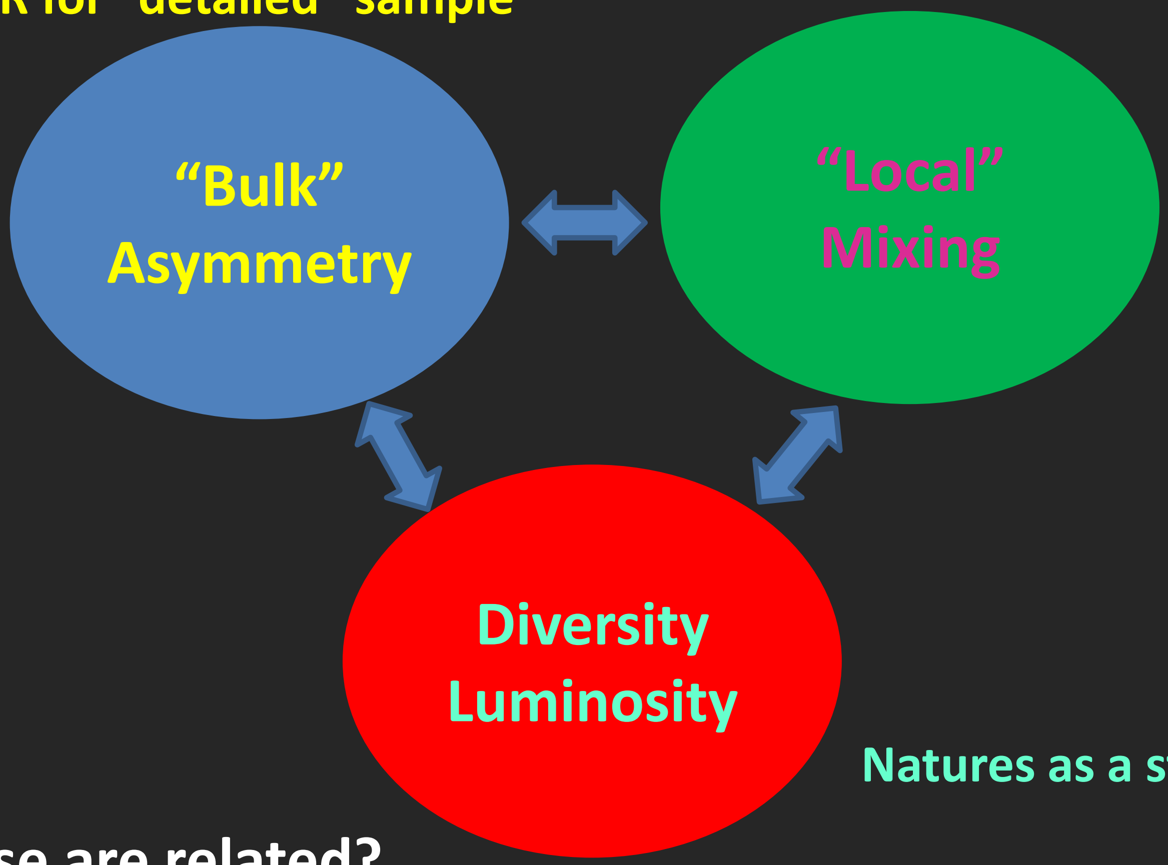
Different degree of the mixing? ←Initial ignition.

Motohara, KM, Gerardy+ 2006, ApJ, 652, L101; Hoflich+ 04

Synergy

Optical for "statistic" sample
Optical + NIR for "detailed" sample

NIR



Natures as a standard candle.

How these are related?

- Is the luminosity dependent on the "bulk" asymmetry and/or the "local" mixing?
- Which diversities explained by which.

How many SNe do we expect?

- IRCS, S/N ~ 5 for 4-5 hrs (spectroscopy)
  - @ 0.2” w/ AO, H ~ 20 - 21.
- SNe become faint at later epochs: @ 150 days.
  - SNe w/ peak mag < 16 would be H ~ 21.
    - ~ 10 – 15 SNe @ 1 semester.
- Out of ~ 10 – 15 SNe:
  - ~ 1/2 would satisfy the LGS condition.
  - ~ 1/3 would satisfy the (RA, dec) condition.
- Expectation = 1 – 3 SNe per semester **w/ AO**.

A Possible Strategy

- A problem in scheduling for normal mode.
  - Our targets (~ 150 days after the discovery) will be discovered **after** the usual deadline!
- ToO?
  - Not a usual ToO... Most of our targets will be decided **before** the semester is started!
- Also we want the synergy with the **optical** spectroscopy **(in normal mode).**
- **Suggestion welcome.**

Conclusions

- **Explosion geometry** of SNe Ia is becoming important field just recently.
  - Direct test for the explosion physics.
  - Application to cosmology. Origin of Diversities?

- **W/ AO**, NIR can probe up to 5 SNe in a year.
  - Mixing process of the very beginning of the explosion.
  - w/ optical, bulk asymmetry can also be derived.

  - Potentially improve our understanding of SNe Ia as standard candles.
    - A way to **better luminosity (distance) calibration?**