Chemical evolution of the Milky Way and its implications for the nature of SN Ia

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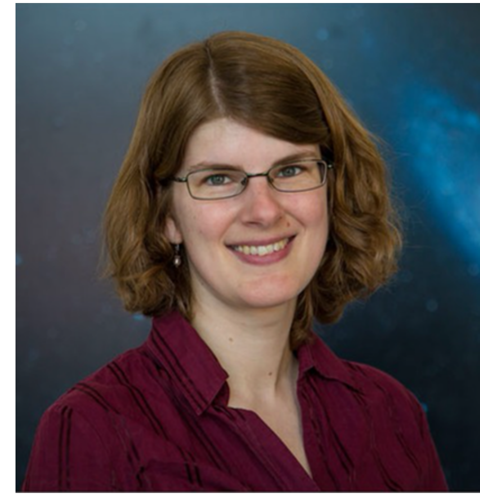

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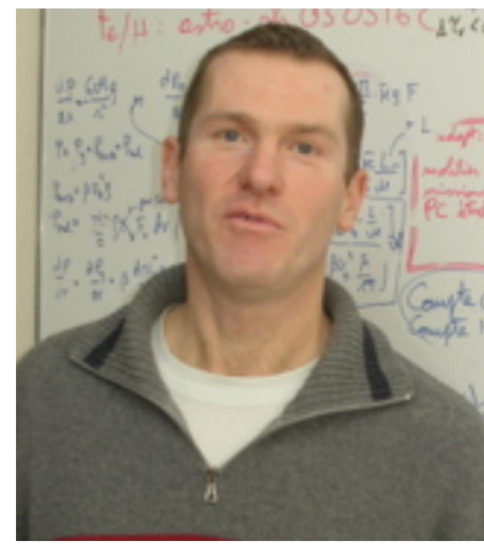
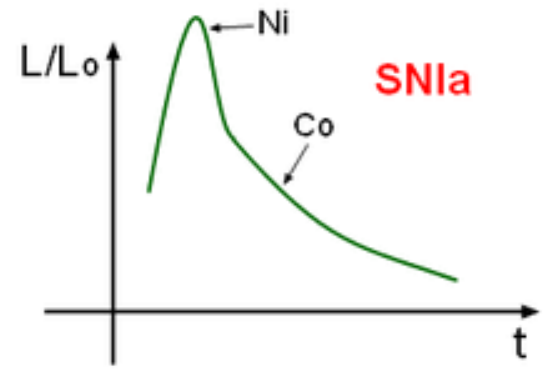
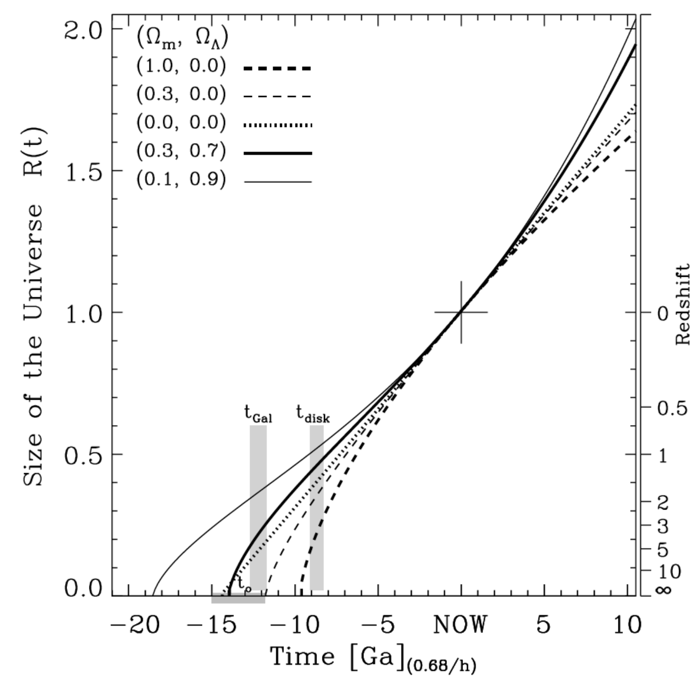


Bertrand Plez
University Montpellier

Outline

- Introduction: why SN Ia explosions?
- Physical properties of SN Ia
- Constraining SN Ia population using stars
    - Chemical abundances: 3D NLTE
    - Milky Way, dwarf Spheroidal galaxies
- Implications

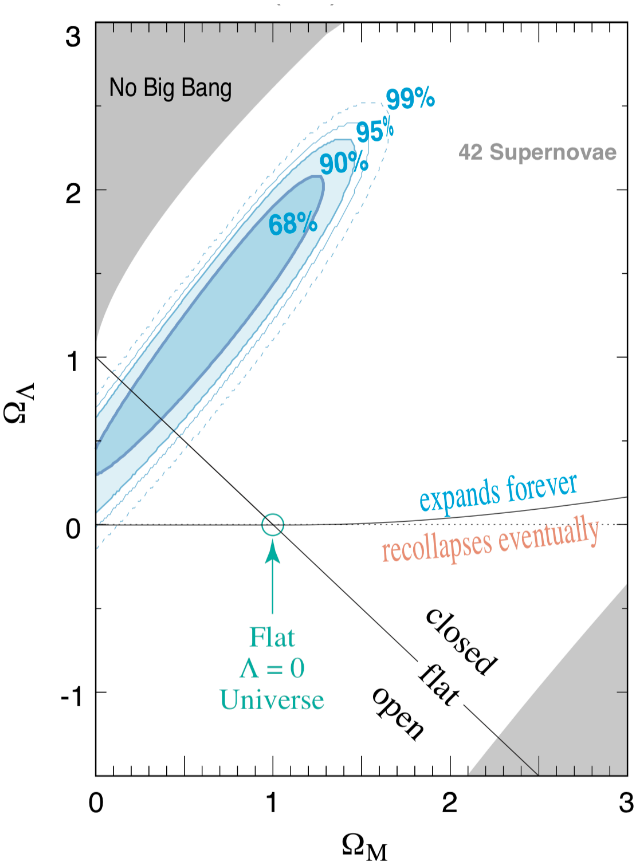




Lineweaver 1999

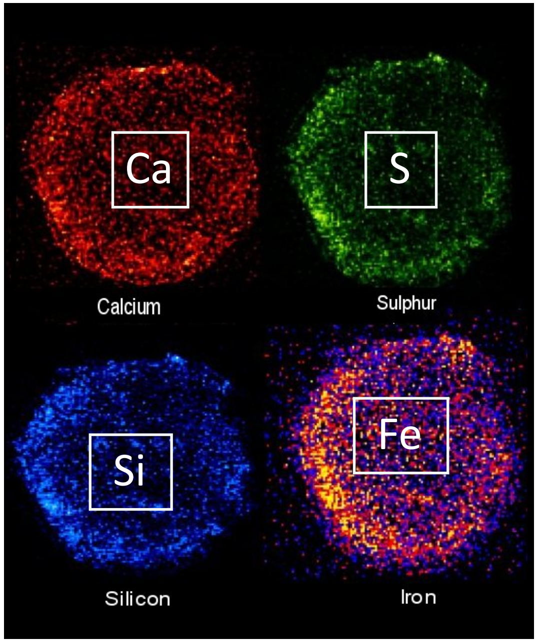
Supernovae Ia

Cosmology



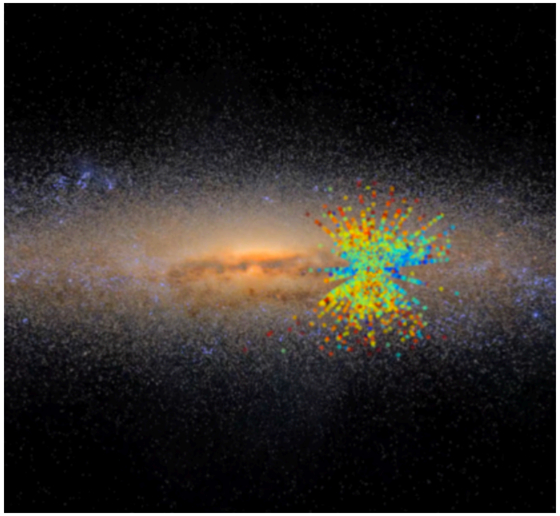
Supernova Cosmology Project
Perlmutter *et al.* (1998)

Factories of heavy elements



XMM-NEWTON map of
SN 1572 Ia remnant
David H. Lumb

Galaxy evolution

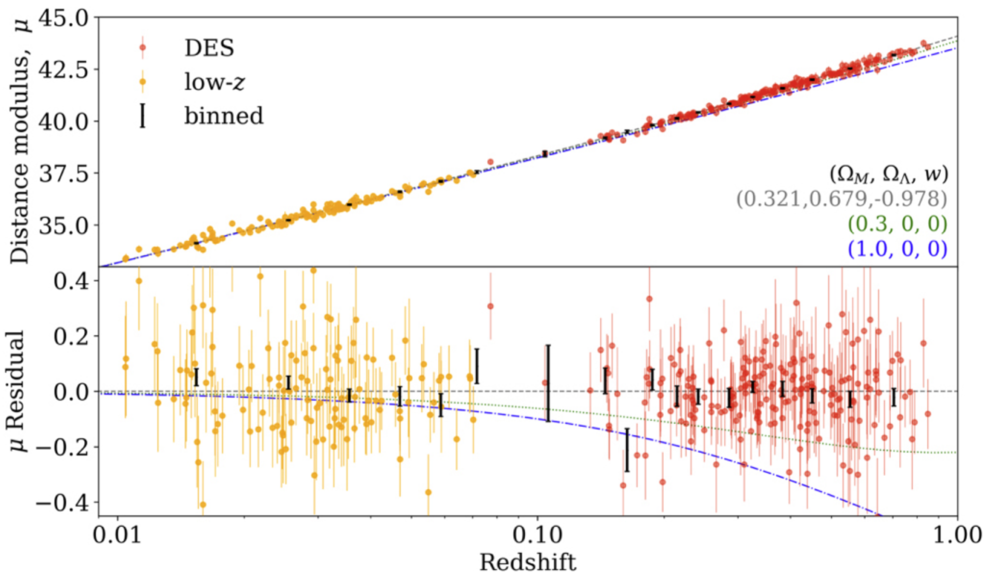


SN Ia and cosmology

- Standardizable candles: relations between L_{max} and LC width, and colour
- Once calibrated, used to constrain cosmology $\boxed{H_0, \Omega_m, \Omega_\Lambda, w}$

$$d_L = (1+z)c\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0[\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}$$



DES collaboration: Abbott+ 2019

Conley+ 2011, Sullivan+ 2011

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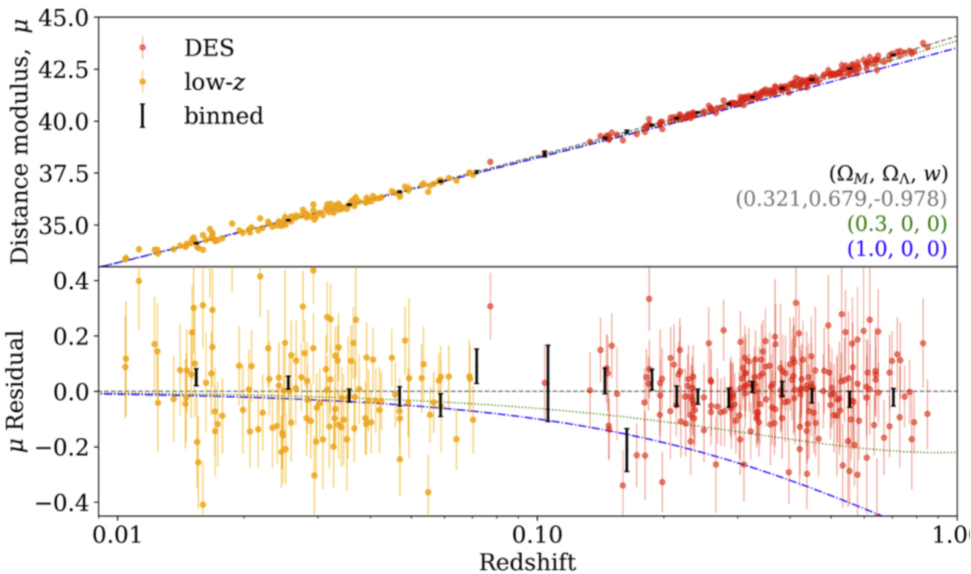

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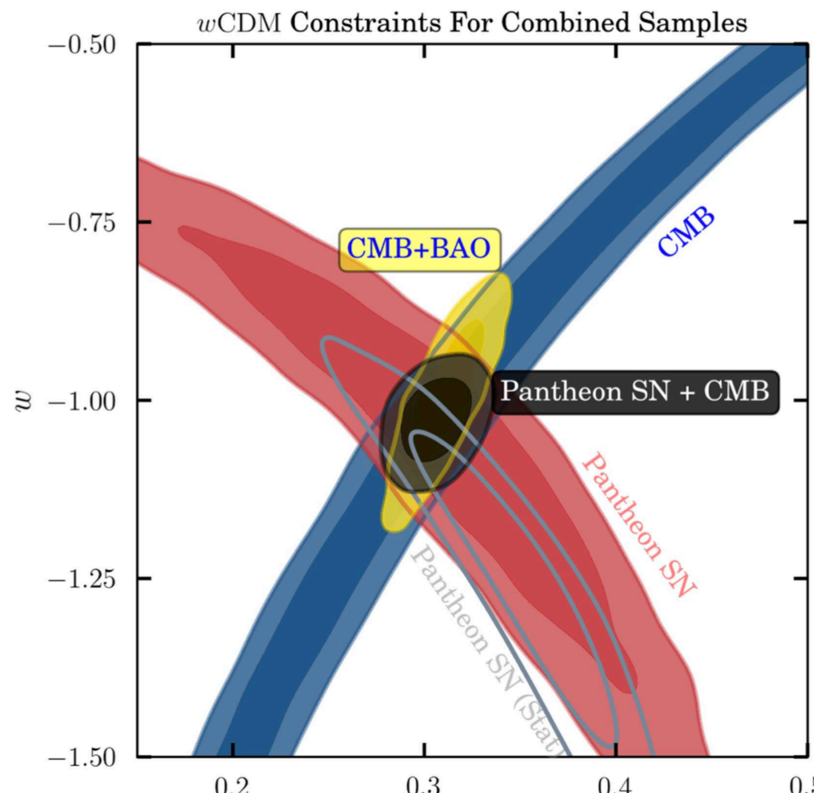
SNIa improve ***w*** *constraints by 50%*



Scolnic+ 2018

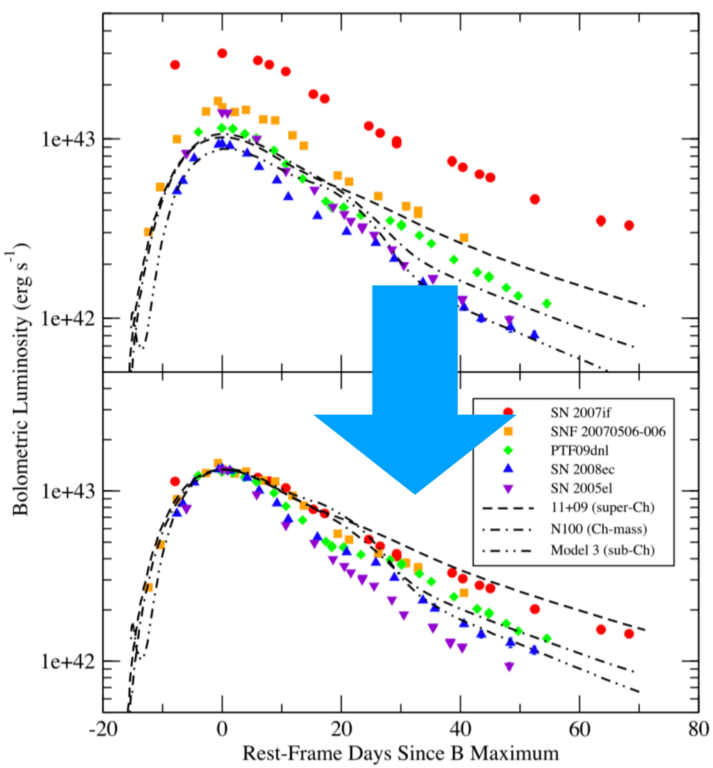
SN Ia fitting

- Standardizable candles: relations between L_{max} and LC width, and colour

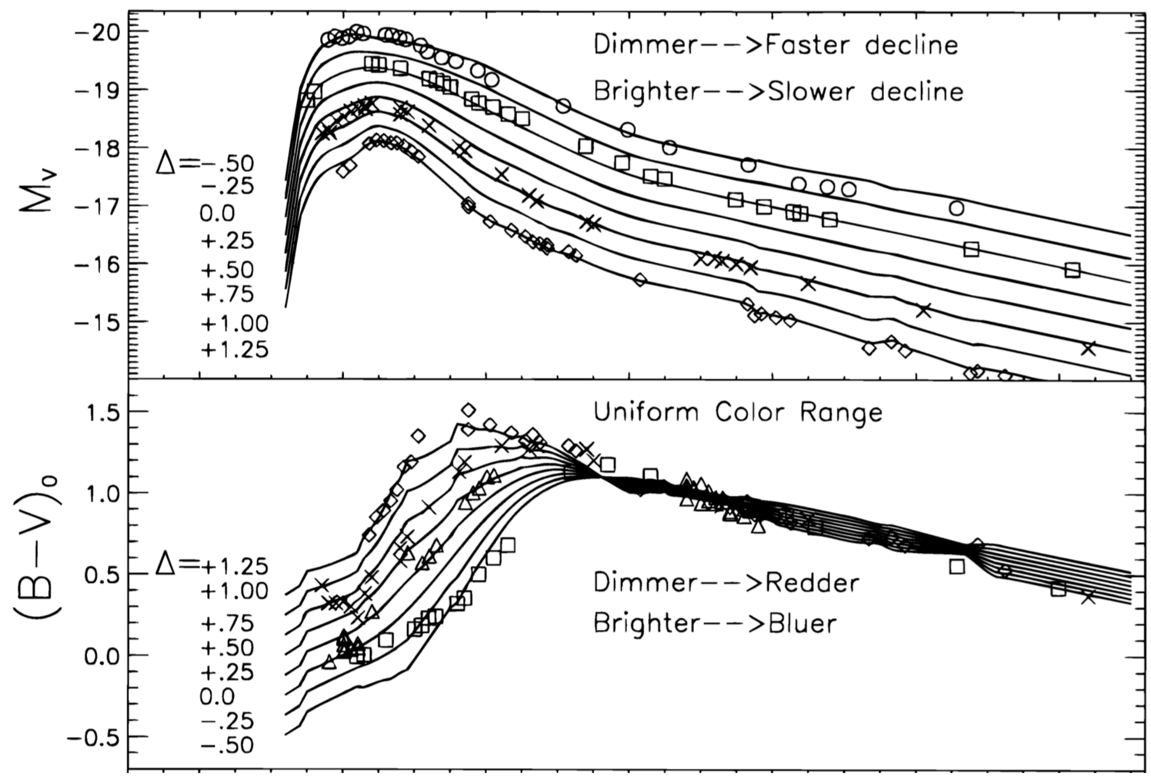
$$m_B^{\mathrm{corr}} = m_B + \alpha\,(s-1) - \beta\mathcal{C},$$

stretch correction colour correction

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



Scalzo+ 2014

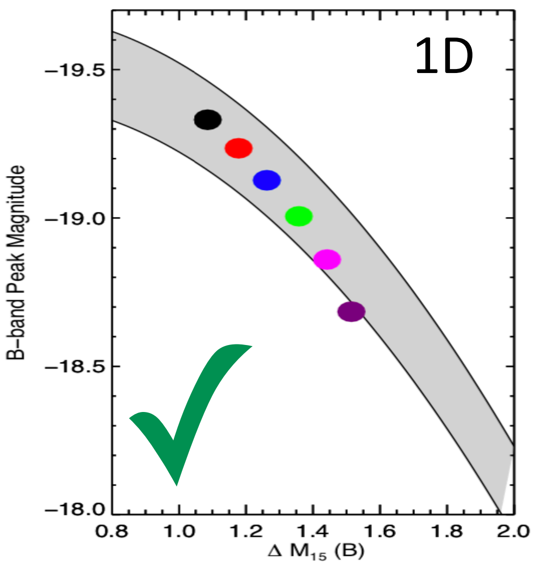


Philipps 1993, 1999, Riess+ 1996, 1998, Trimm 1998

Normal SN Ia used to work well in 1D

- ✓ Standardizable candles: relations between L_{max} and LC width, and colour

- ✓ empirical relations consistent with “normal’ Chandrasekhar-mass models (in 1D)



cf. Kasen & Woosley 2007

<u>Normal SN Ia cannot</u> be explaned by favoured 3D models

✓ Standardizable candles: relations between L_{max} and LC width, and colour

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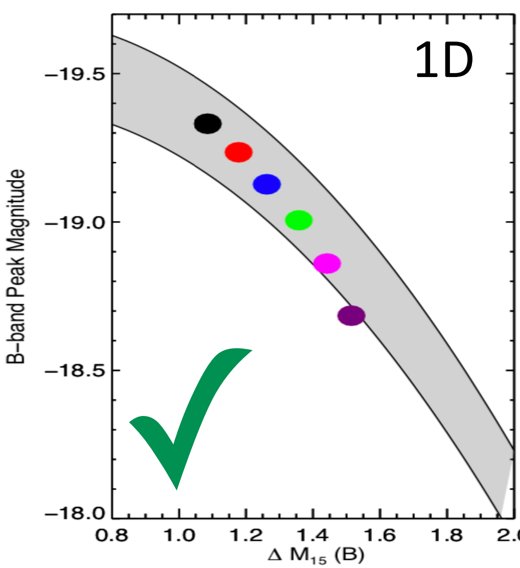

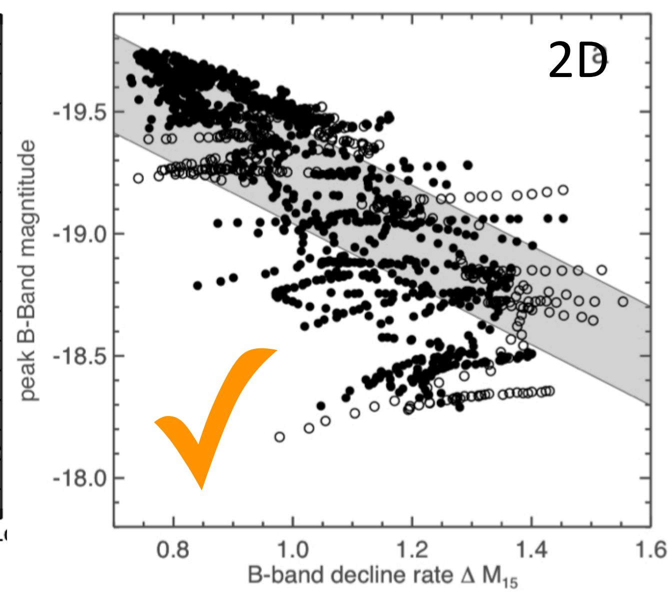

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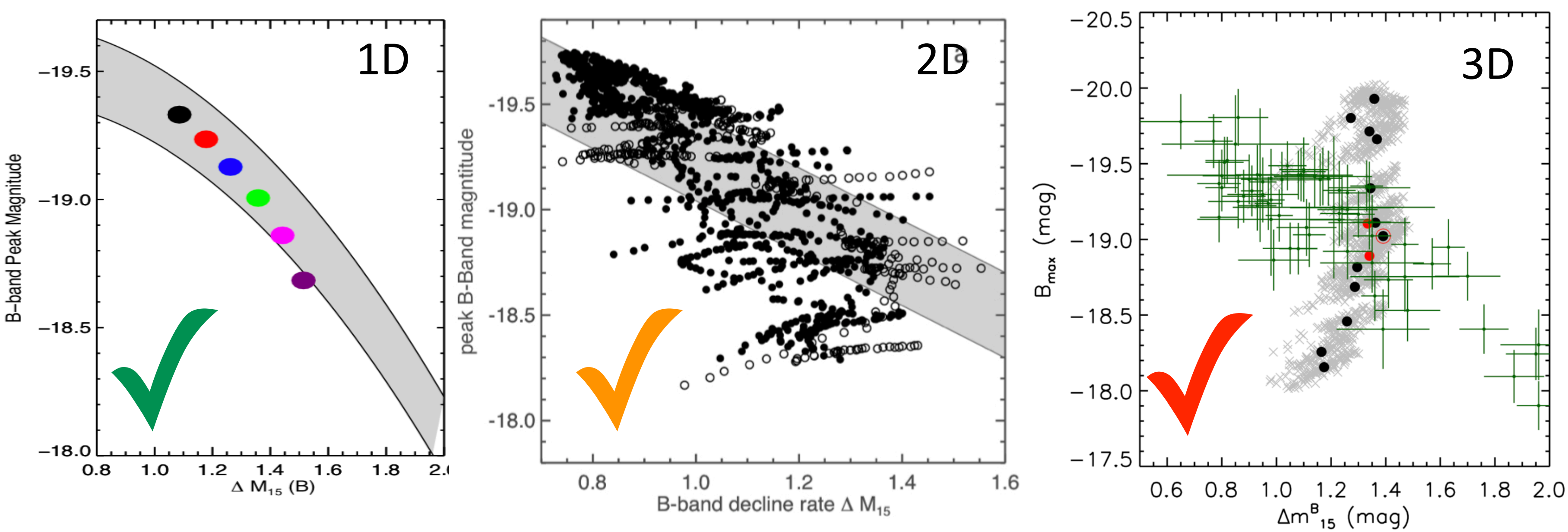

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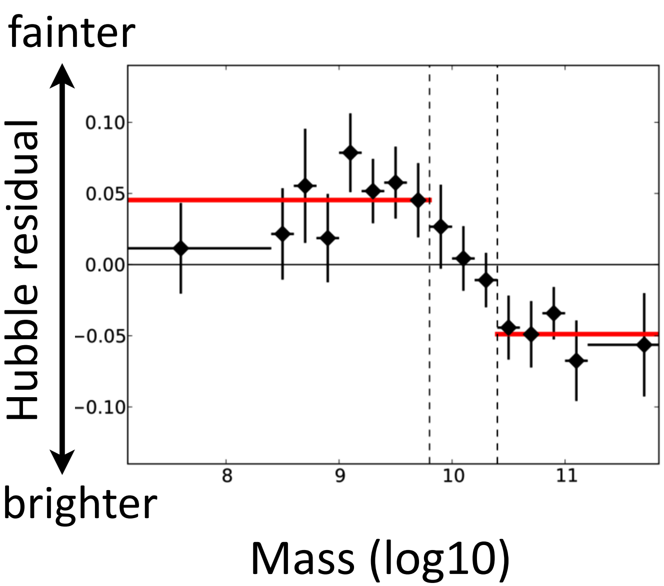
Systematics in Hubble residuals: environment?

- ✓ Standardizable candles: relations between L_{max} and LC width, and colour

- empirical relations consistent with "normal' Chandrasekhar-mass models (in 1D) ⟶ but not in 2D or 3D

- Hubble residuals correlate <u>with galaxy parameters</u>



Gallagher+ 2008, Sullivan+ 2011; Childress+2013, DES collaborarion: Smith+ 2020, Kang+2020 …

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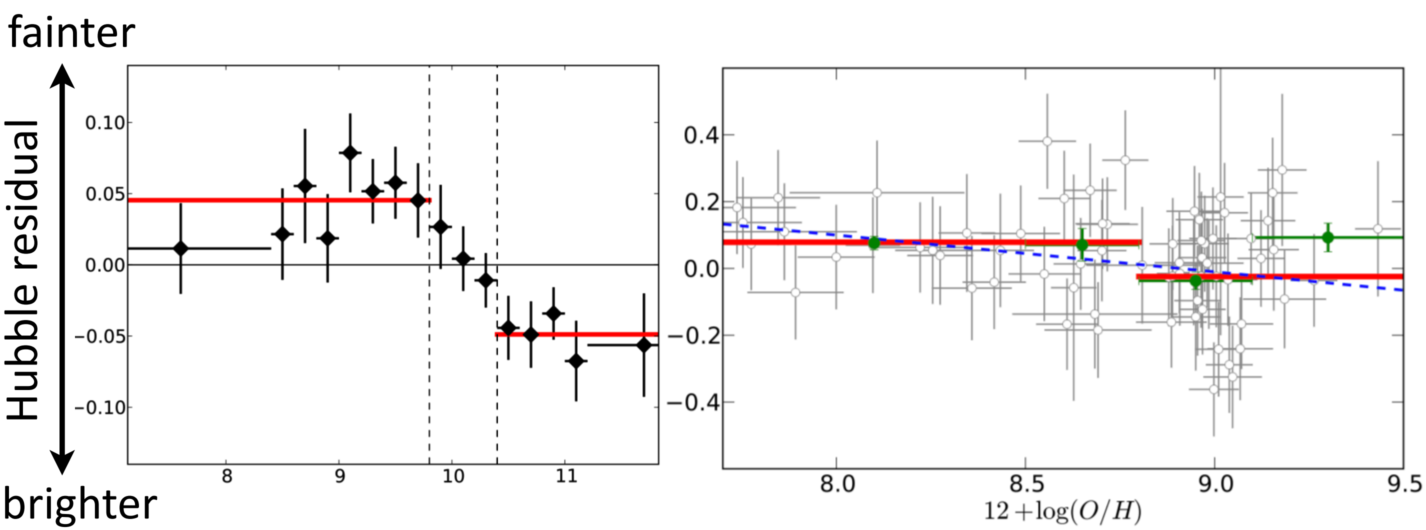

Mass (log10)

Metallicity

Gallagher+ 2008, Sullivan+ 2011; Childress+2013, DES collaborarion: Smith+ 2020, Kang+2020 …

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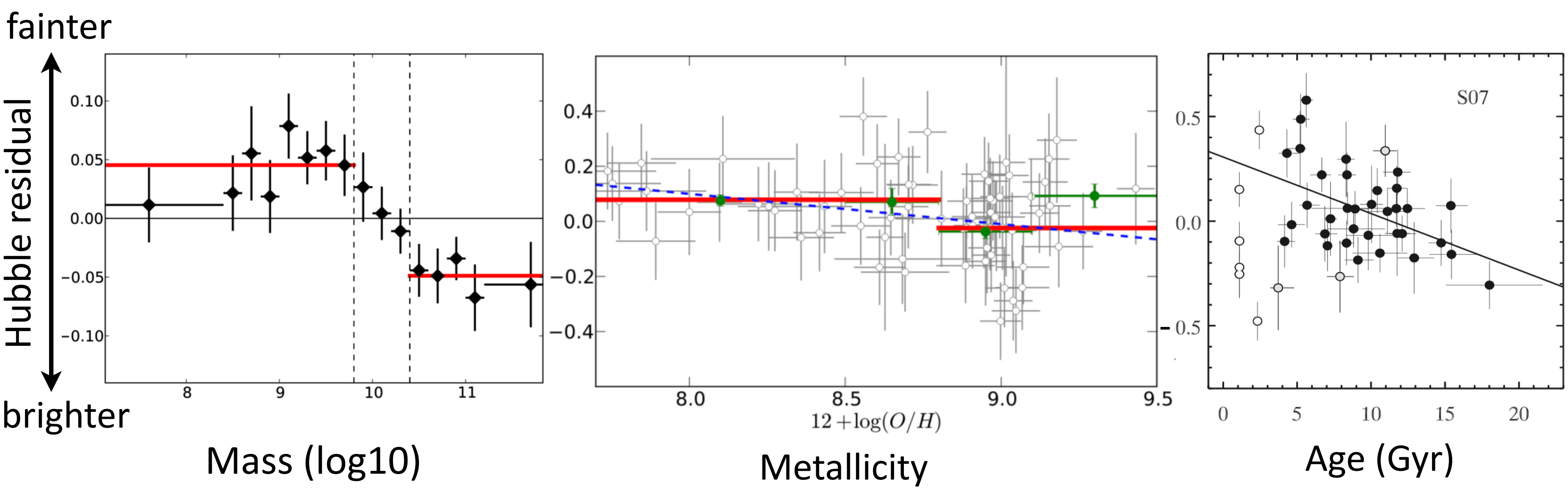


Gallagher+ 2008, Sullivan+ 2011; Childress+2013, DES collaborarion: Smith+ 2020, Kang+2020 …

Redshift evolution in SN Ia properties?

✓ Standardizable candles?

$$m_B^{\mathrm{corr}} = m_B + \alpha\,(s-1) - \beta\mathcal{C} + M_0 + \gamma G_{\mathrm{host}} + \mu_{\mathrm{bias}}$$

Galaxy mass "mass-step"

w-uncertainty Contributions for *w*CDM Model[a]

Description[b]	σ_w
Total Stat ($\sigma_{w,\mathrm{stat}}$)	0.042
Total Syst[c]	0.042
Total Stat+Syst	0.059
[Photometry and Calibration]	**[0.021]**
Low-z	0.014
DES	0.010
SALT2 Model	0.009
HST Calspec	0.007
[μ-Bias Correction: Survey]	**[0.023]**
†Low-z 3σ Cut	0.016
Low-z Volume Limited	0.010
Spectroscopic Efficiency	0.007
†Flux Err Modeling	0.001
[μ-Bias Correction: Astrophysical]	**[0.026]**
Intrinsic Scatter Model (G10 versus C11)	0.014
†Two σ_{int}	0.014
$\mathcal{C}$, x_1 Parent Population	0.014
†w, Ω_{m} in sim.	0.006
MW Extinction	0.005
[Redshift]	**[0.012]**
Peculiar Velocity	0.007
†z + 0.00004	0.006

- SN Ia in galaxies $< 10^{10.8}\ M_\odot$

$$1 + w = 0.22^{+0.152}_{-0.108}$$

- SN Ia in galaxies $> 10^{10.8}\ M_\odot$

$$1 + w = -0.03^{+0.217}_{-0.143}$$

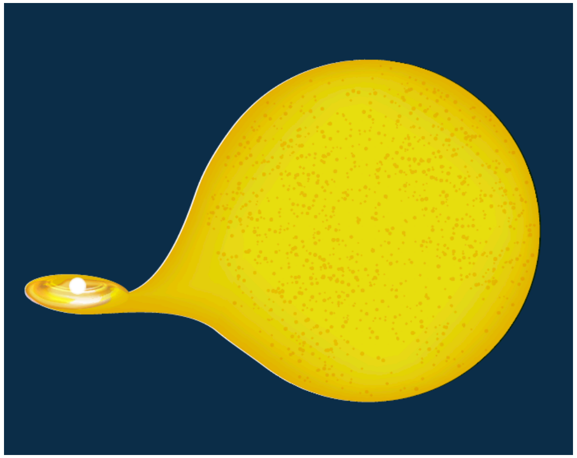
Kelly et al. 2010, Abbott et al. 2019

Take-home messages

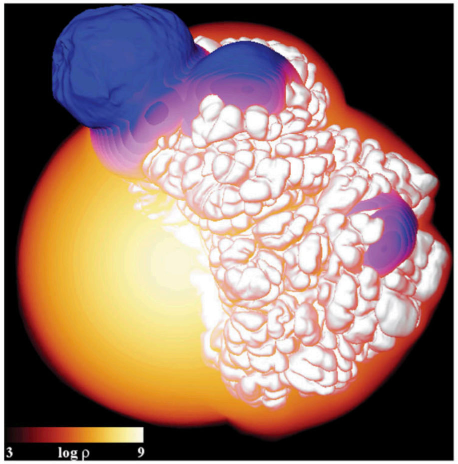
1. SN Ia do not have the same brightness, but even after empirical corrections for the width and colour, their brightness depends on galaxy properties. Different progenitor channels?

SN Ia fitting

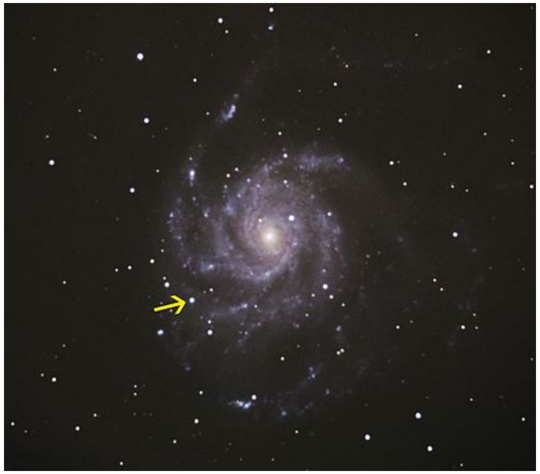
The use of SN Ia as standardizable candles critically depends on:



physical properties of progenitors



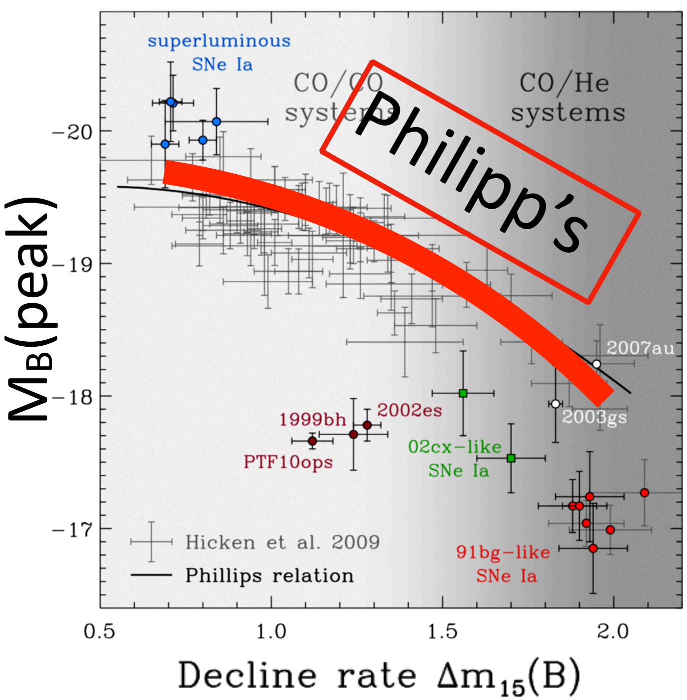
explosion mechanism and its dynamics



dependence of SN Ia population on the environment: age, mass, metallicity of the galaxy

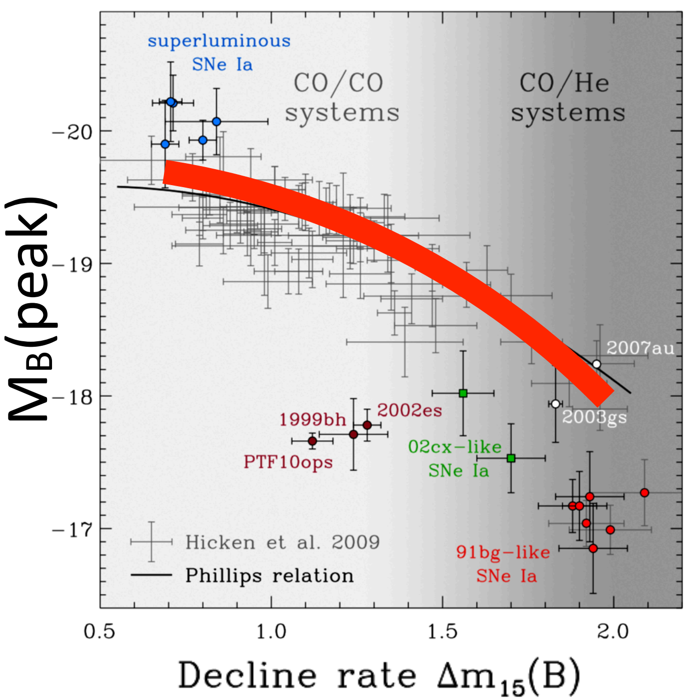
Nomoto 1980, Taam 1980, Woosley+1980..2011, Hillebrandt & Niemeyer 2000, Livne 1990, Fink+2007, Sim+2010, Nonaka+ 2011, Seitenzahl+2013, Piro+ 2015, Jacobs+ 2015, Fink+ 2018, Gronow+ 2020, …

A few years ago, we knew only normal ("Philipps"-like) SNIa



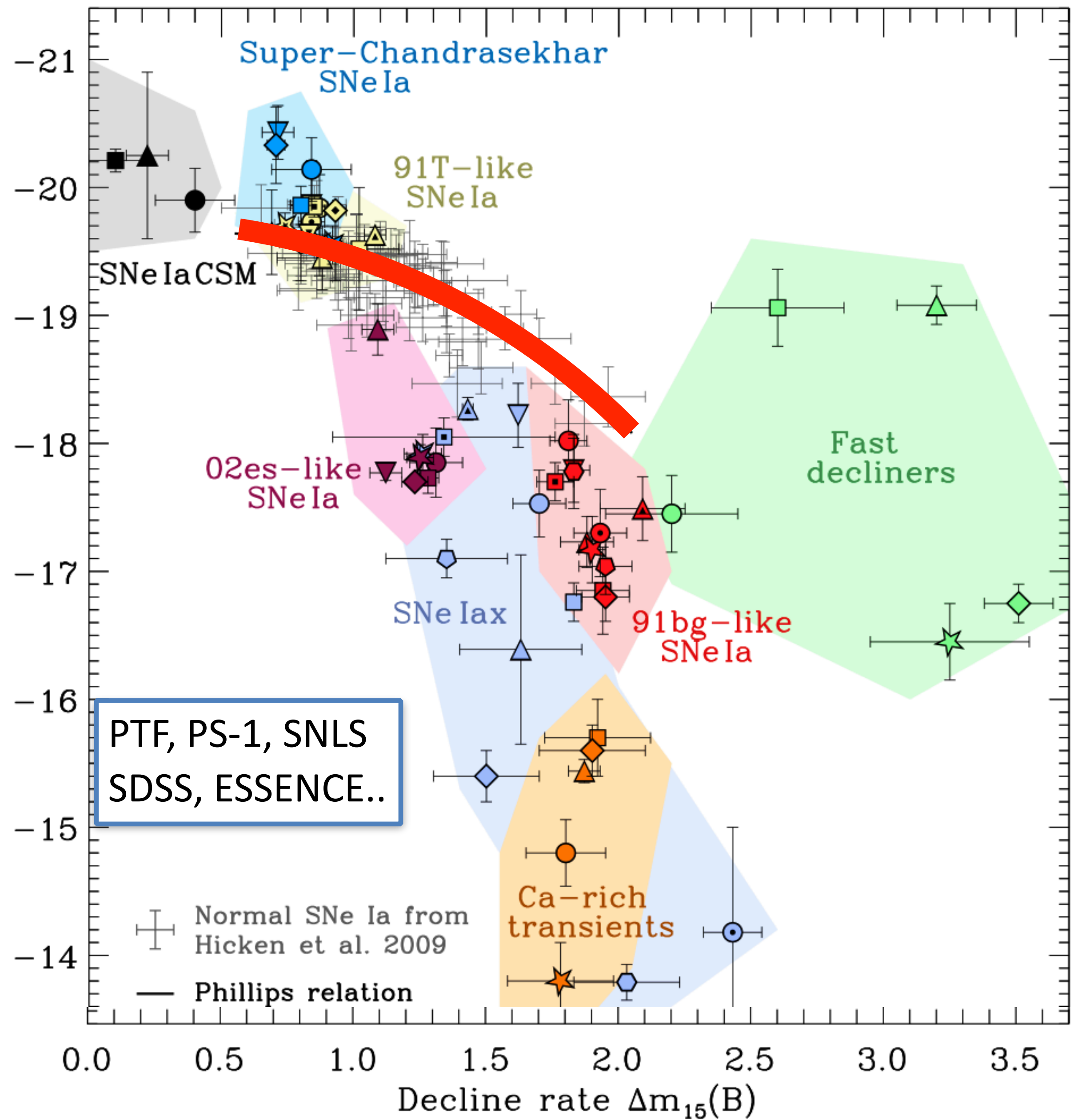
Pakmor+ 2013

Now: wide variety of SN Ia types known



Pakmor+ 2013

Philipps+ 1999



Tautenberger 2017, priv. comm

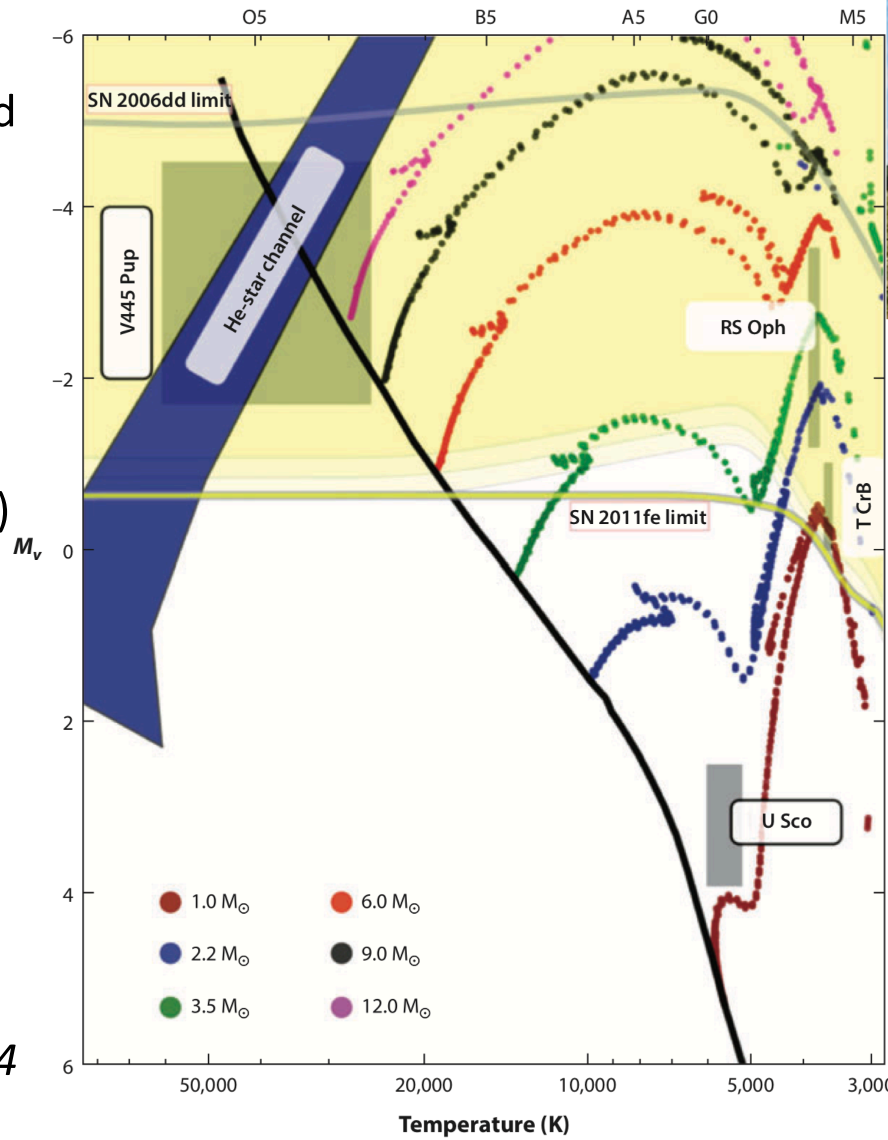
Frohmaier et al. 2018

No progenitor of SN Ia has been detected to date

extremely faint: only 2 candidates are known

SN 2006dd

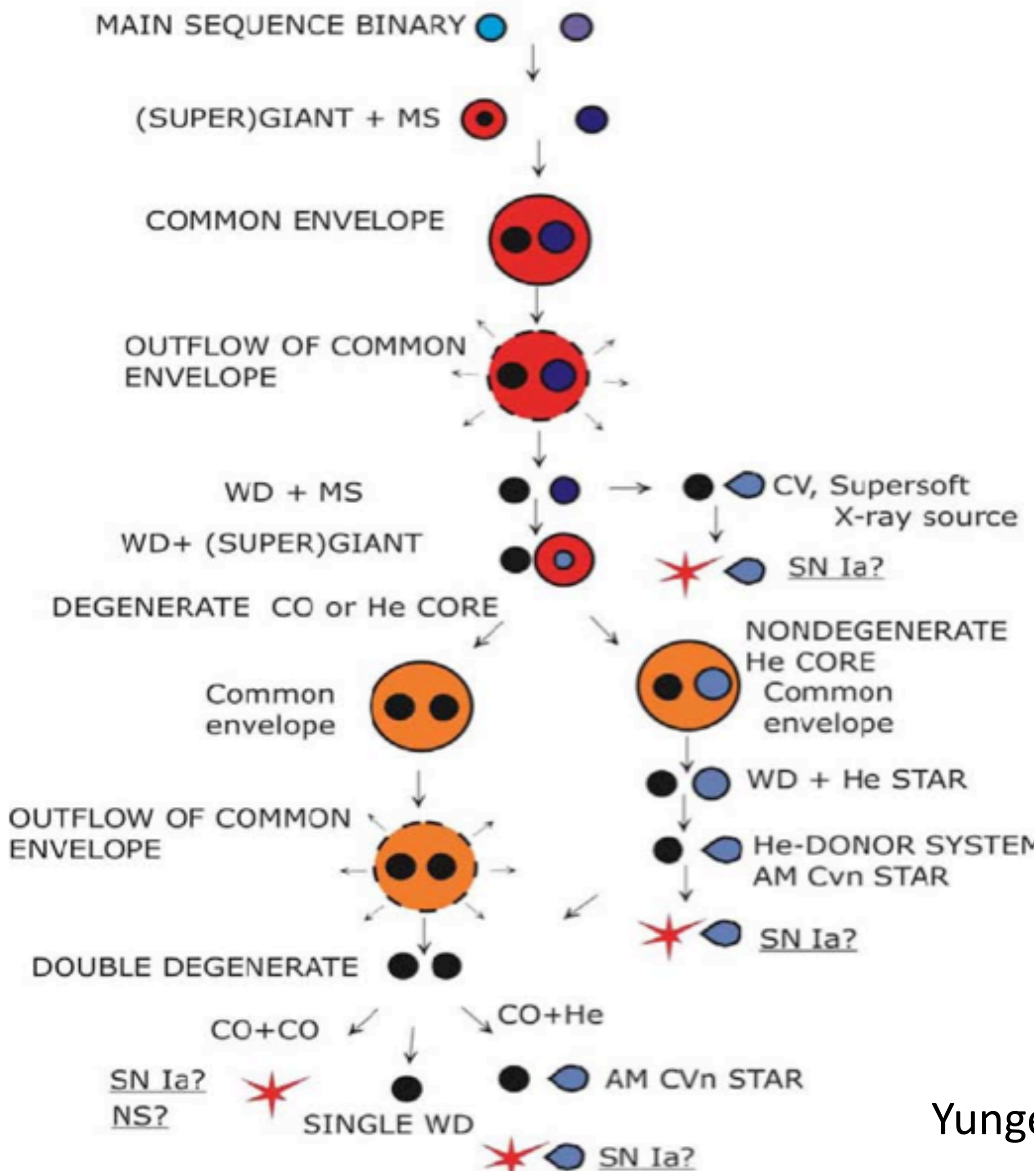
SN 2011fe
M 101 (~ 6 Mpc)



Maoz+ 2014

There are many ways to make a low-mass star explode

SN Ia: a thermonuclear explosion of a C-O white dwarf



Model	Mass	Components
A	sub-M_{ch} or M_{Ch}	double degenerate
B	sub-M_{Ch}	single degenerate
C	M_{Ch}	single degenerate

Yungelson & Livio 2000

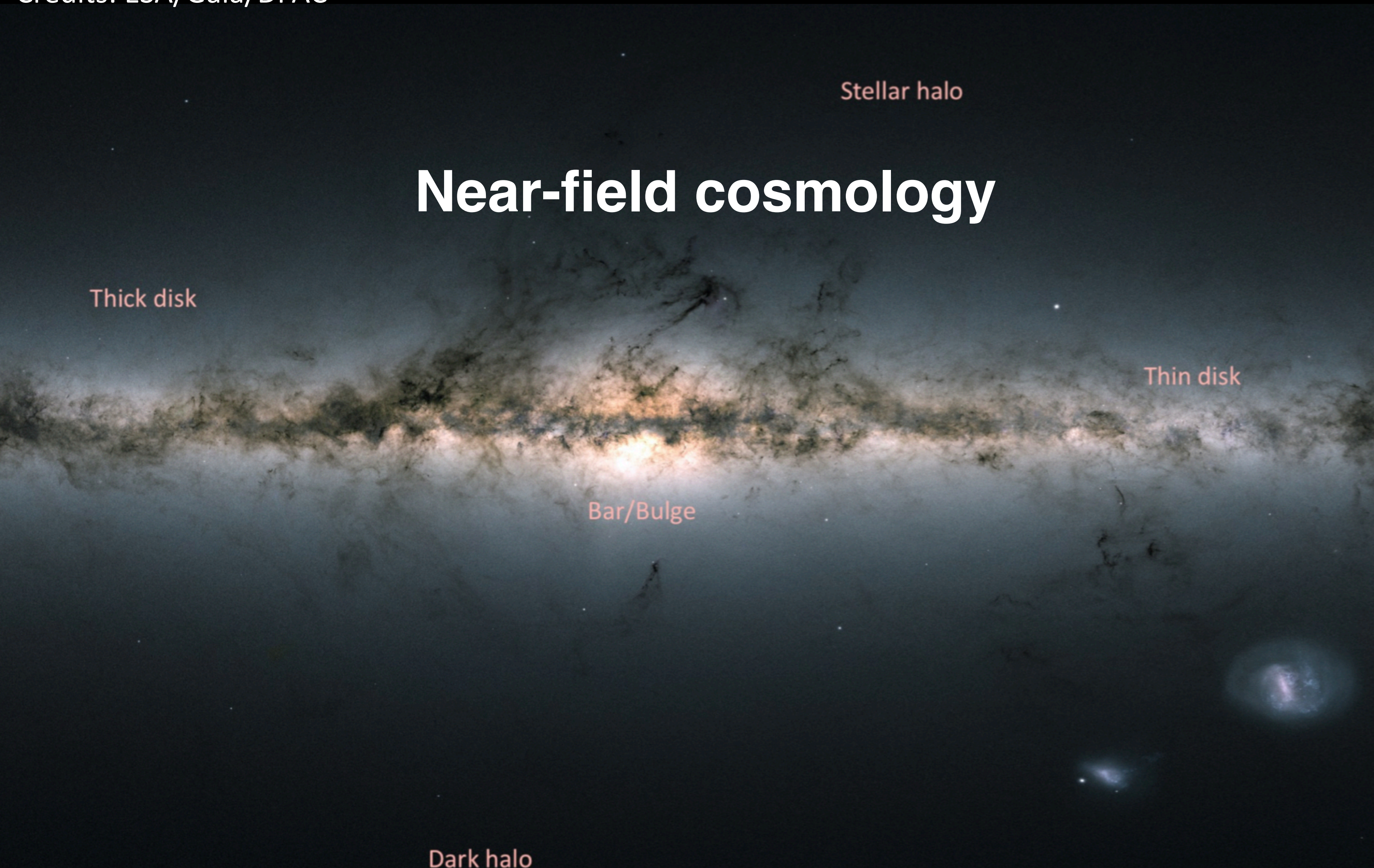
Take-home messages

1. SN Ia do not have the same brightness, but even after empirical corrections for the width and colour, their brightness depends on galaxy properties. Different progenitor channels?

2. Recent search programs uncovered large populations of 'exotic' SN Ia; ≈ consistent with the diversity of progenitor channels

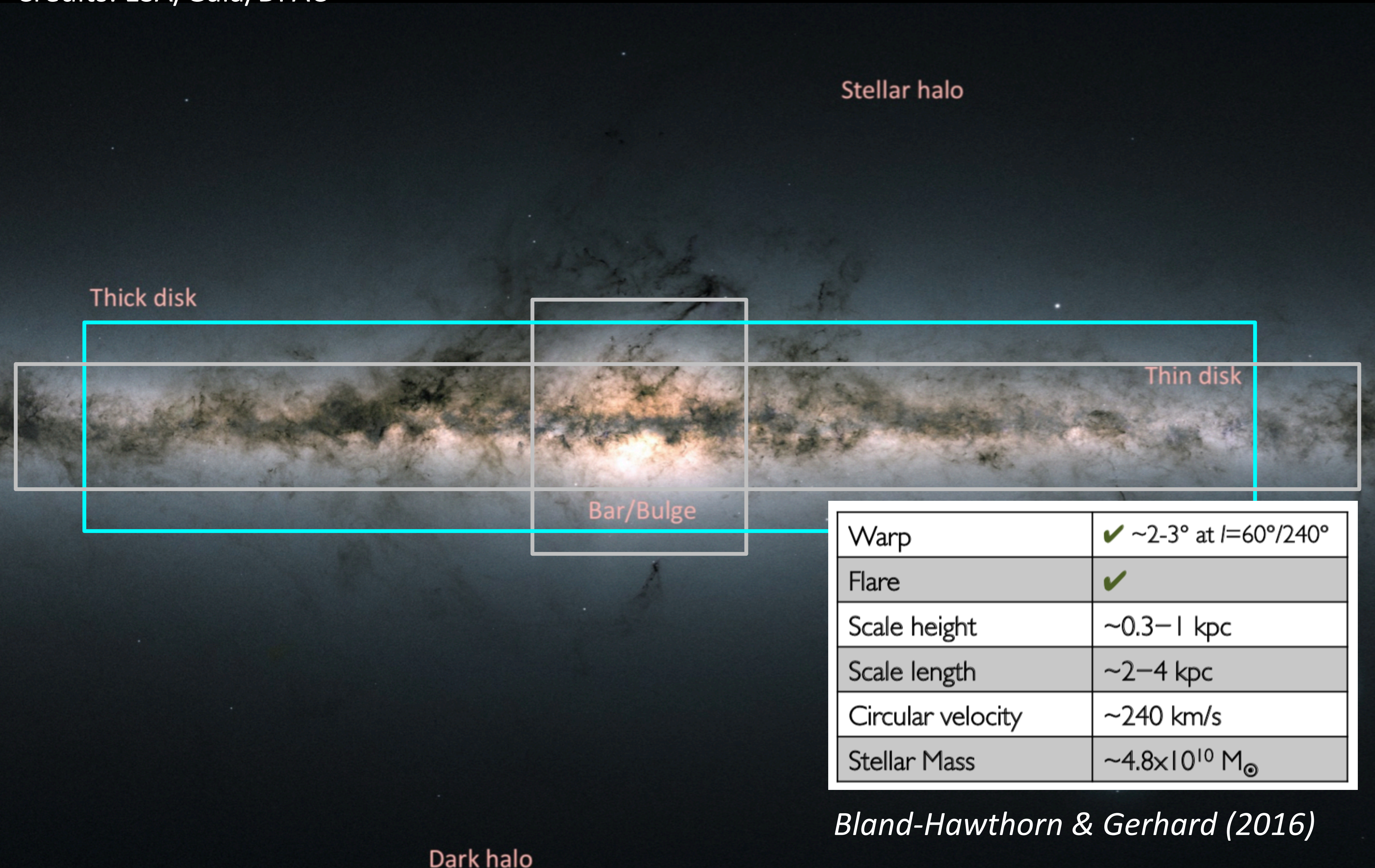
Credits: ESA/Gaia/DPAC

Near-field cosmology



Constrain SN Ia physics using the MW

Credits: ESA/Gaia/DPAC

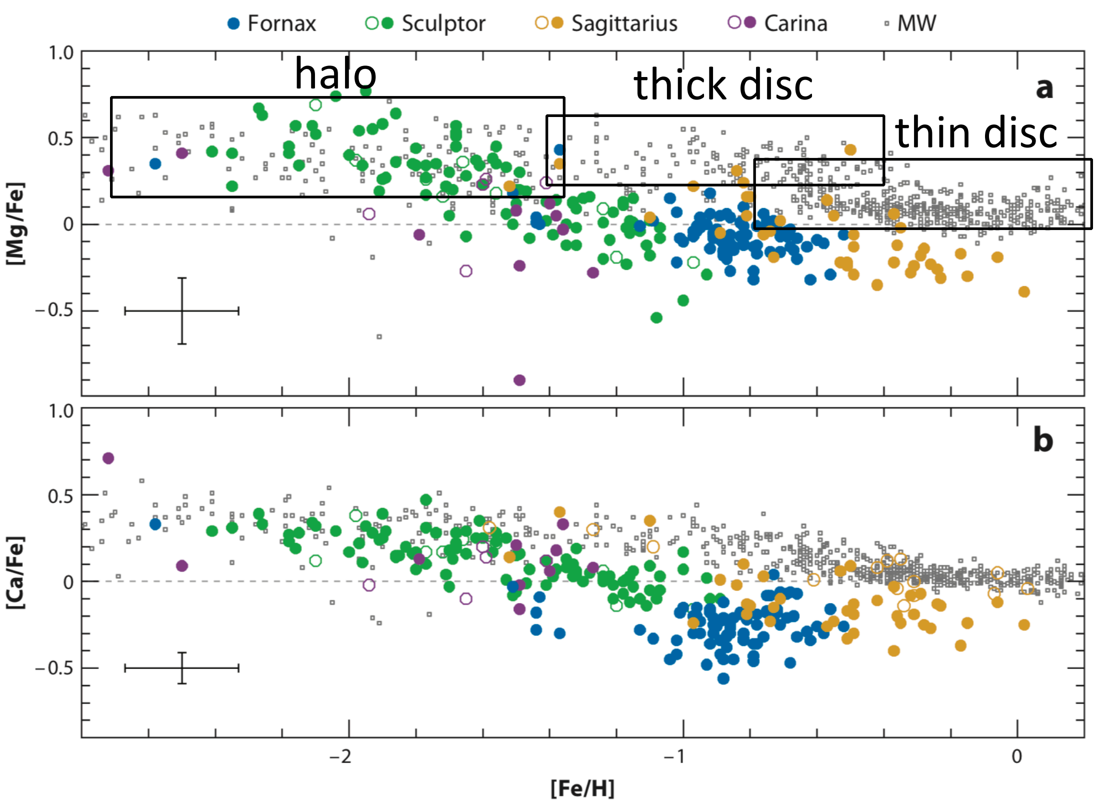


Warp	✔ ~2-3° at l=60°/240°
Flare	✔
Scale height	~0.3−1 kpc
Scale length	~2−4 kpc
Circular velocity	~240 km/s
Stellar Mass	~4.8x10^{10} $M_{\odot}$

Bland-Hawthorn & Gerhard (2016)

alpha-elements are sensitive to SNIa timescales

At early times: ISM enriched faster in elements produced in short-lived, massive stars (➛ SNe II)
Later also by longer- lived, low-mass stars (➛ SNe Ia, AGB)
Ratio of Mg, O (α) vs. Fe: “Clock” to gauge SF and enrichment time scales



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Matteucci & Brocato 1991 Tolstoy+2009, Kubryk+2015, …

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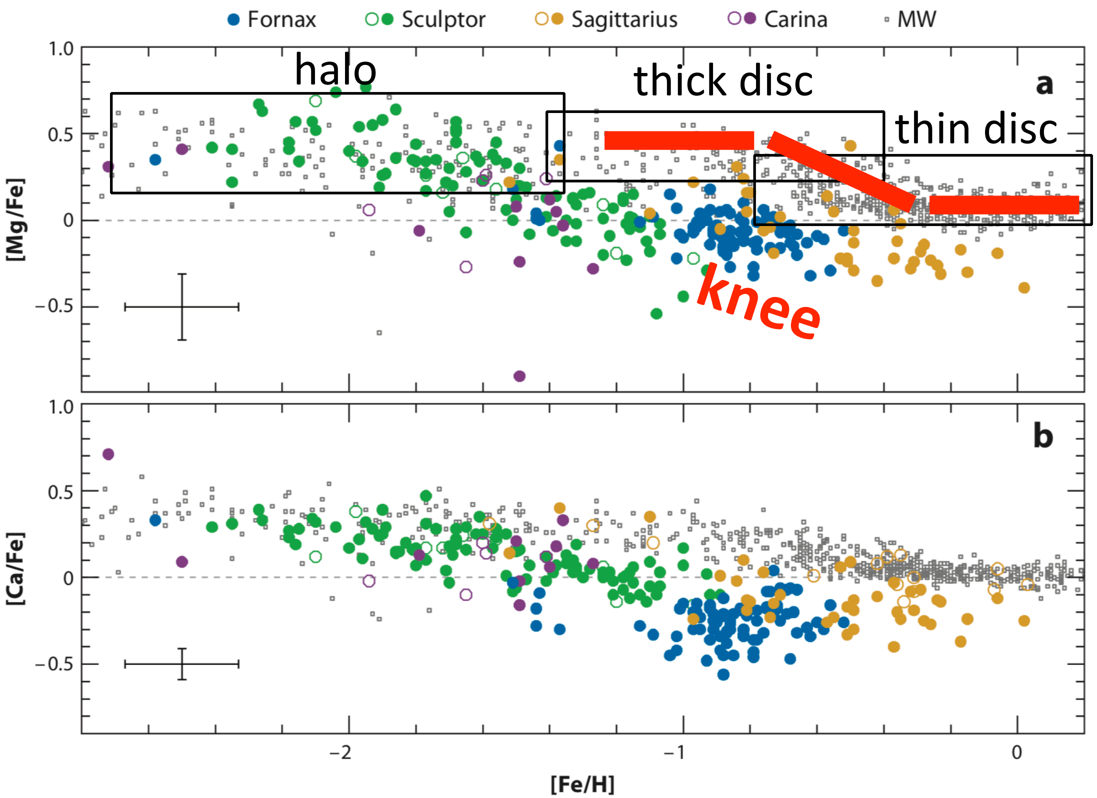

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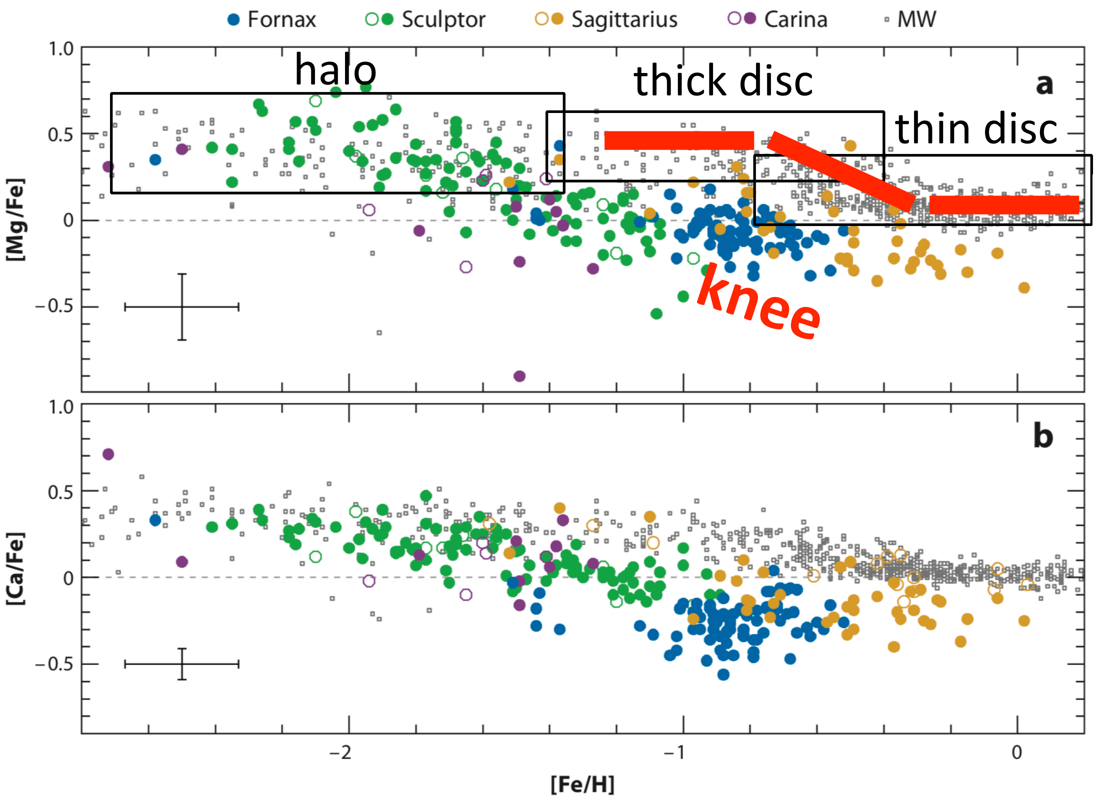

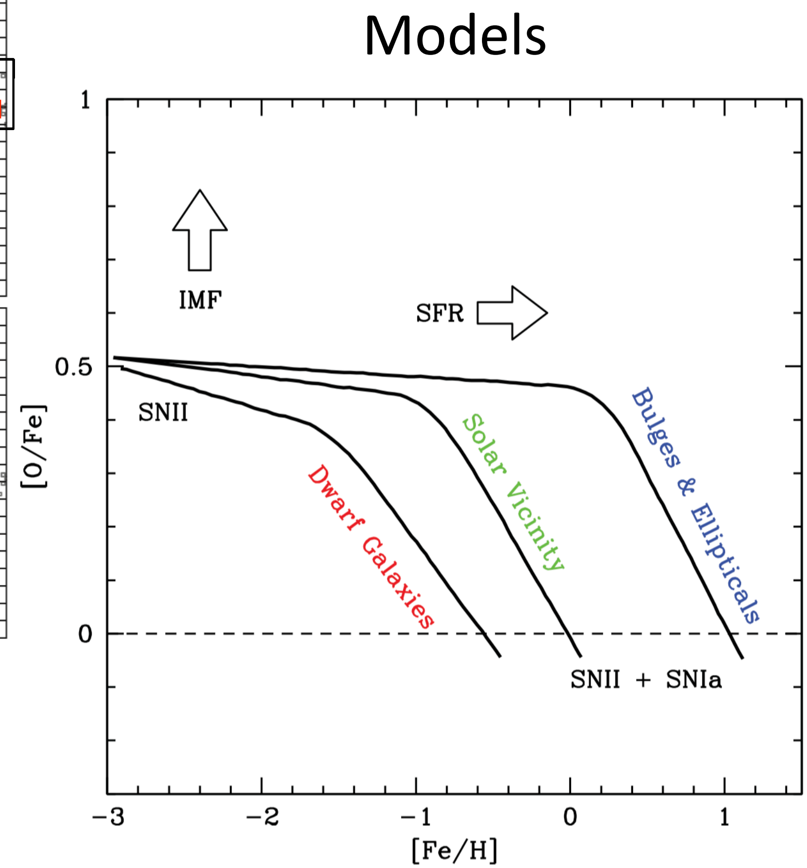

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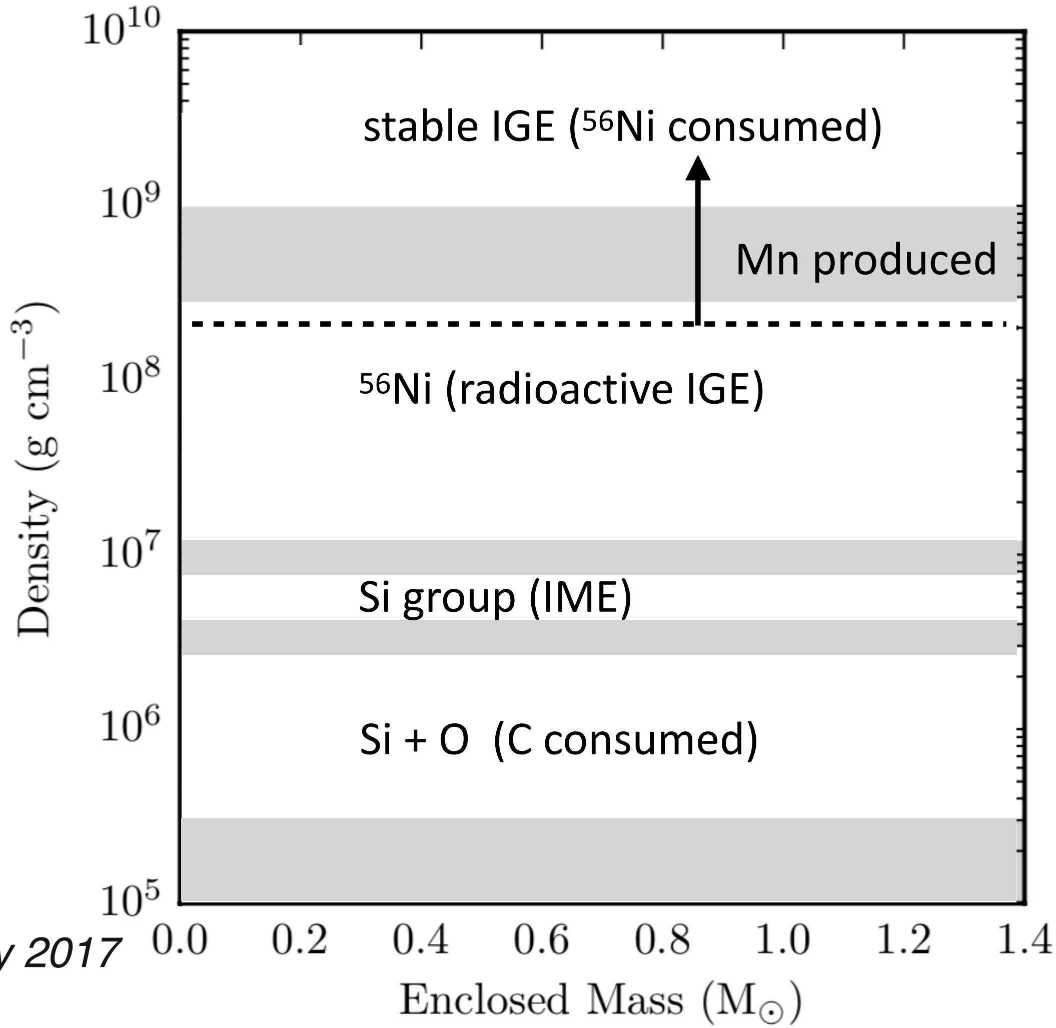
Fe-group elements are sensitive to SN Ia explosion physics

$^{55}Co^* \rightarrow {}^{55}Fe^* \rightarrow {}^{55}Mn$



Seitenzahl & Townsey 2017

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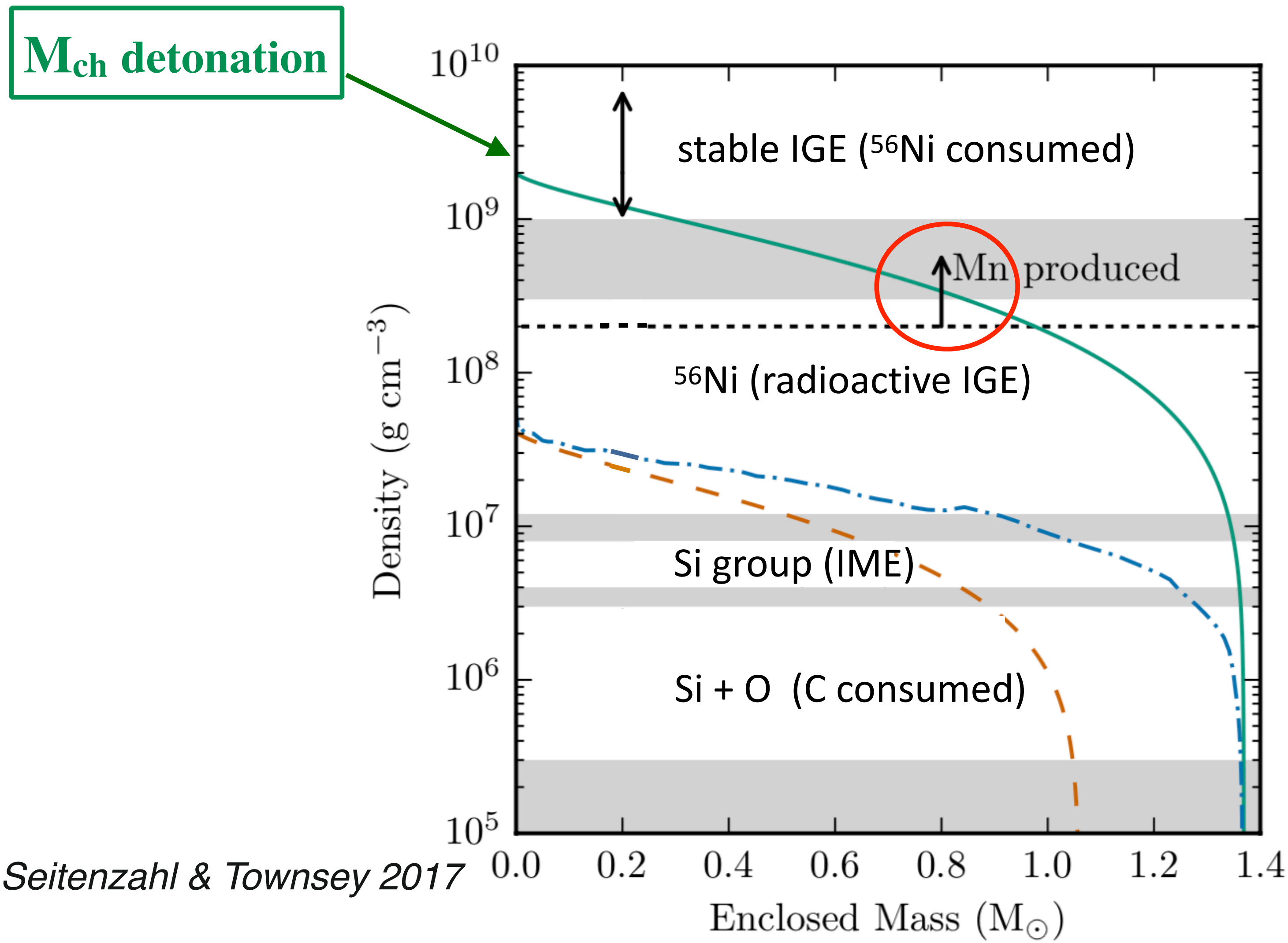

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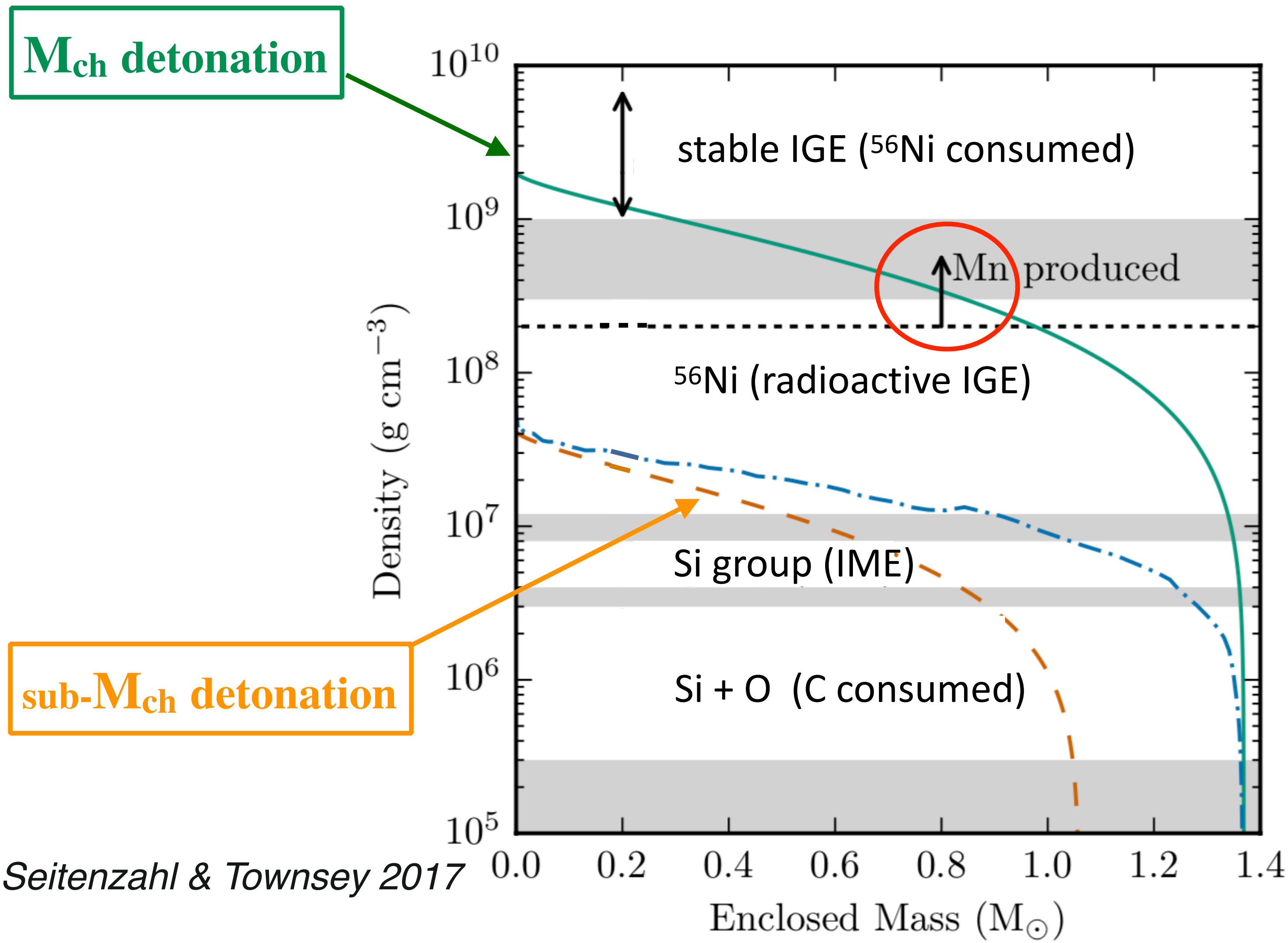

Seitenzahl & Townsey 2017

Mn and Fe are chemical clocks for SN Ia

Mn is the only product obtained in large quantities only from high-density burning

Model name	SN type	Masses	[Mn/Fe]
N100	Ia	near-M_{Ch}	0.33
N5def	Ia	near-M_{Ch}	0.36
N150def	Ia	near-M_{Ch}	0.42
W7	Ia	near-M_{Ch}	0.15
1.1_0.9	Ia	sub-M_{Ch}	–0.15[a]
1.06 $M_{\odot}$	Ia	sub-M_{Ch}	–0.13[a]
WW95B[b]	II	$11 < M/M_{\odot} < 40$	–0.15[c]
LC03D[d]	II	$13 < M/M_{\odot} < 35$	–0.27[c]
N06	II+HN	$13 < M/M_{\odot} < 40$	–0.31[c]

Seitenzahl et al. 2013

* for a solar metallicity SN

$$[Mn/Fe] \coloneqq \log(N(Mn) / N(Fe))_{\star} - \log(N(Mn) / N(Fe))_{\odot}$$

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10 Myr

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Constraints on SN Ia using stellar abundances

Core-collapse SNe

SN Ia

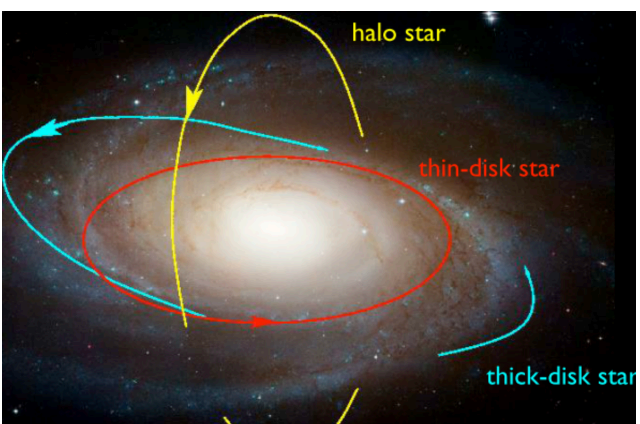
0 | 2 | 9 | age (Gyr)

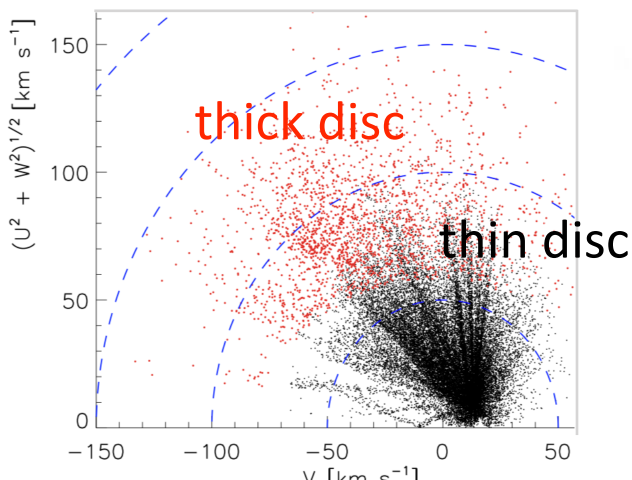
0 | 0.01 | Z_{sun} | metallicity

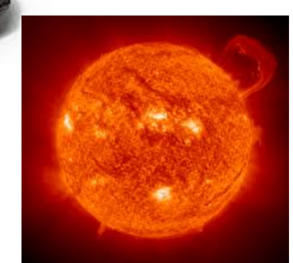
abundances in Galactic halo stars

abundances at the thick-to-thin disc transition

absolute Solar value + meteorites







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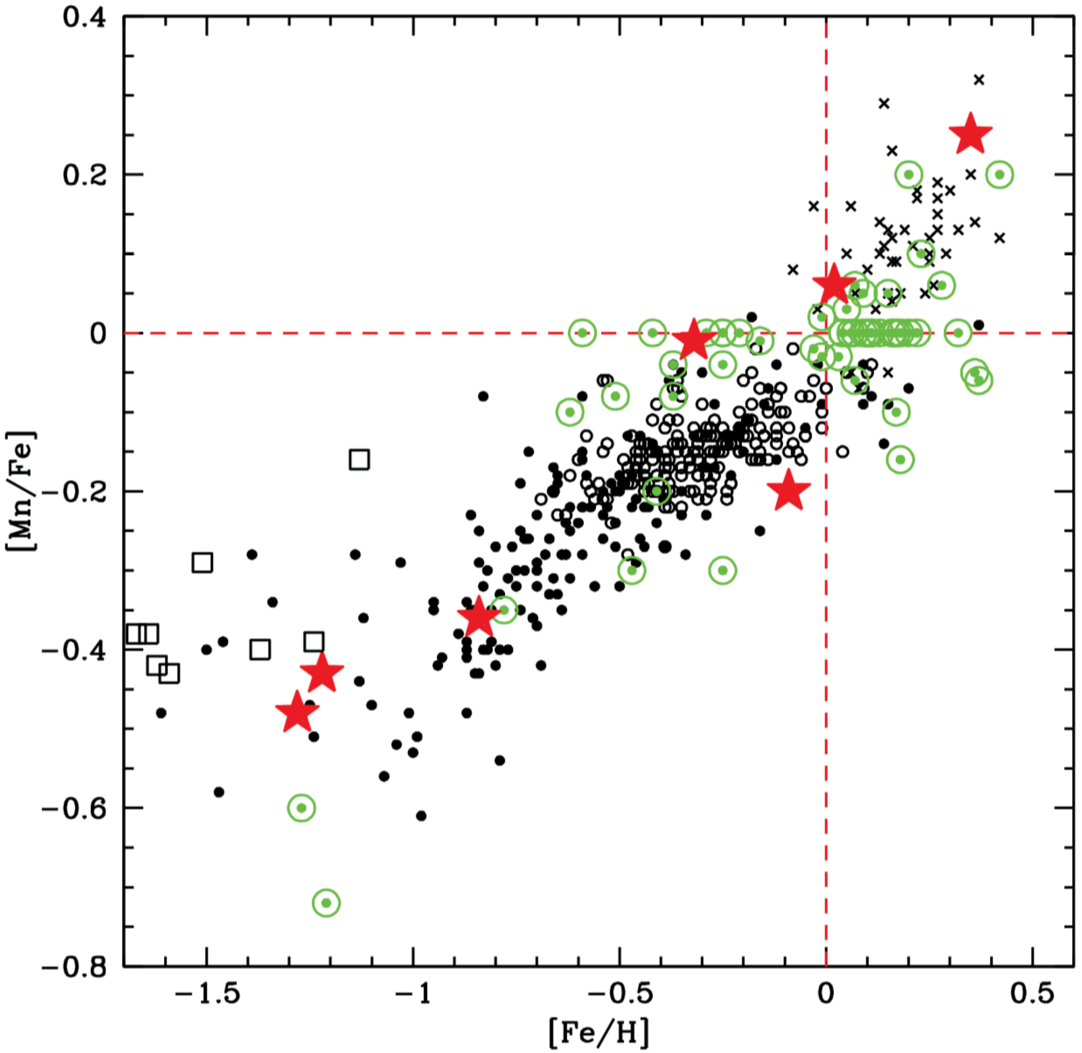
2. Recent search programs uncovered large populations of 'exotic' SN Ia; ≈ consistent with the diversity of progenitor channels

3. SN Ia rates and progenitors can be probed using Galactic abundances: "alpha-knee" gives the timescale of enrichment and Manganese over Iron abundance ratio probes explosion physics

Early [Mn/Fe] measurements in Galactic stars
no evidence for sub-Ch explosions



McWiliam (2016)

McWilliam et al. (2003), Barbuy et al. (2013), Reddy et al. (2003, 2006) , Sobeck et al. (2006), etc

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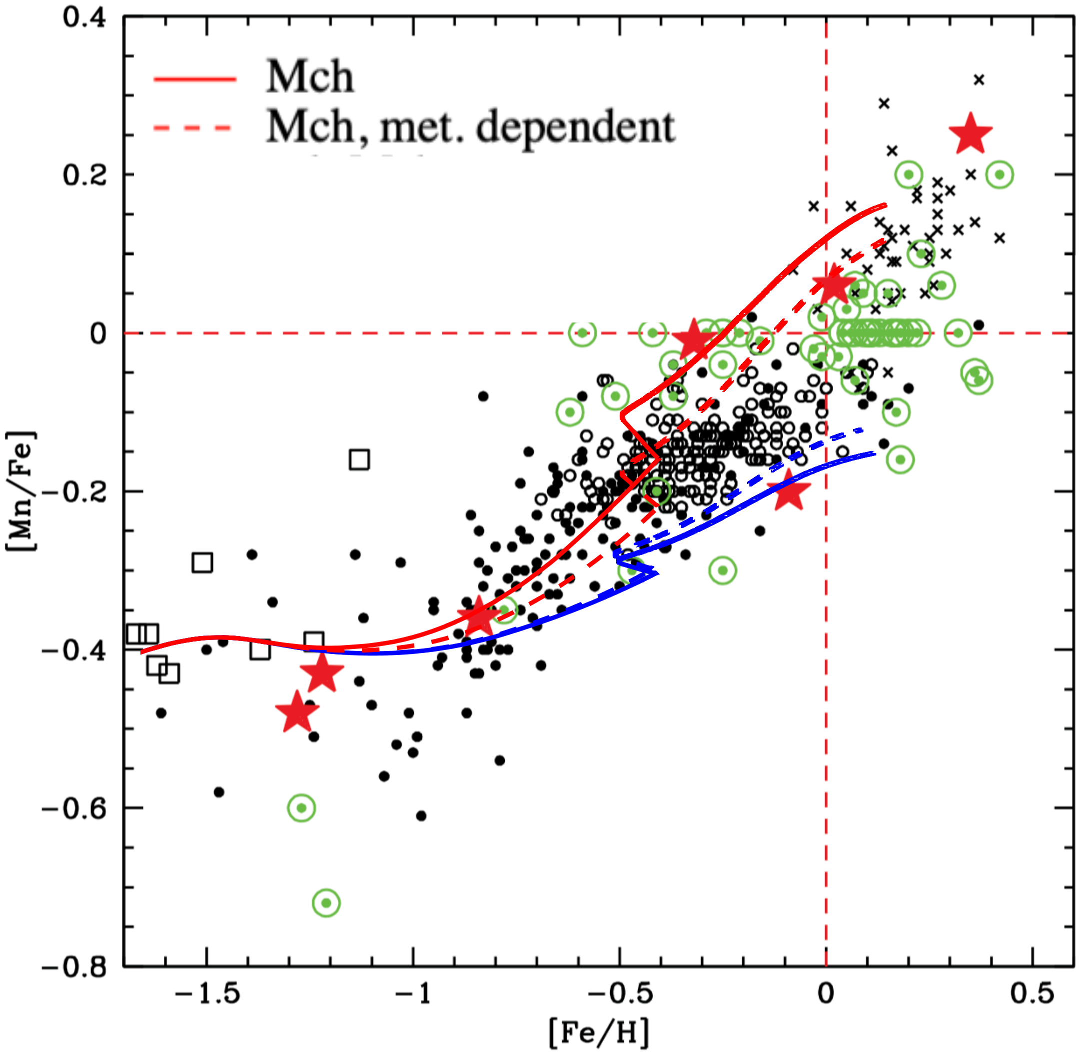


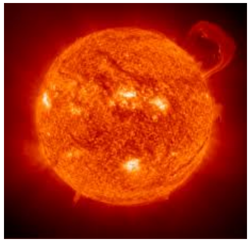
McWiliam (2016)

McWilliam et al. (2003), Barbuy et al. (2013), Reddy et al. (2003, 2006) , Sobeck et al. (2006), etc

But problems with spectroscopic measurements

- **solar abundances do not match the meteoritic values**

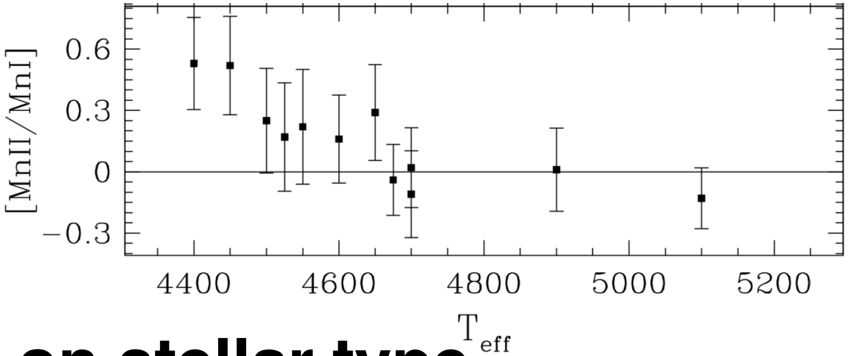
$\neq$



- **excitation and ionization imbalance**

Mn < Mn+

Mn (0 eV) << Mn (2+ eV)



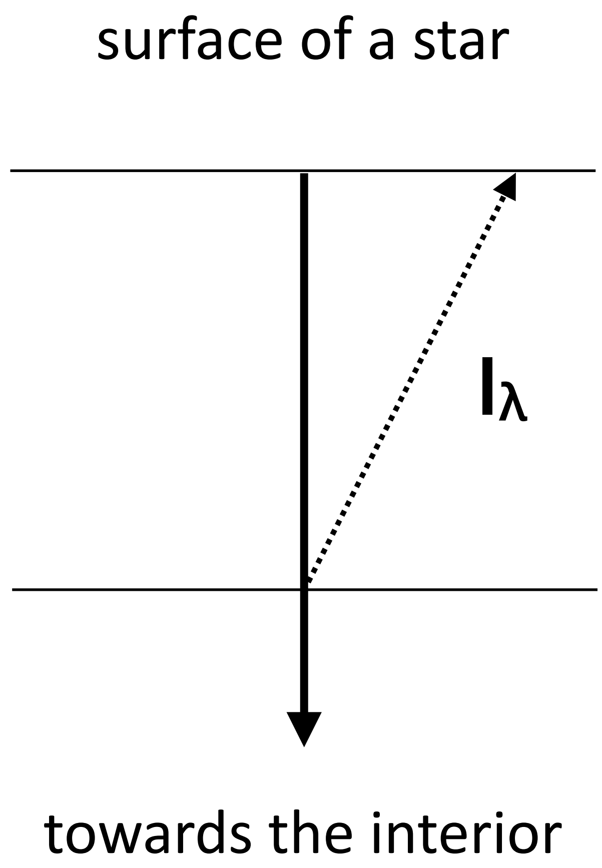
- **dependence of abundance on stellar type**

metal-poor dwarfs v giants

Johnson 2002, Bonifacio et al. 2009

Classical stellar atmospheres assume 1D LTE

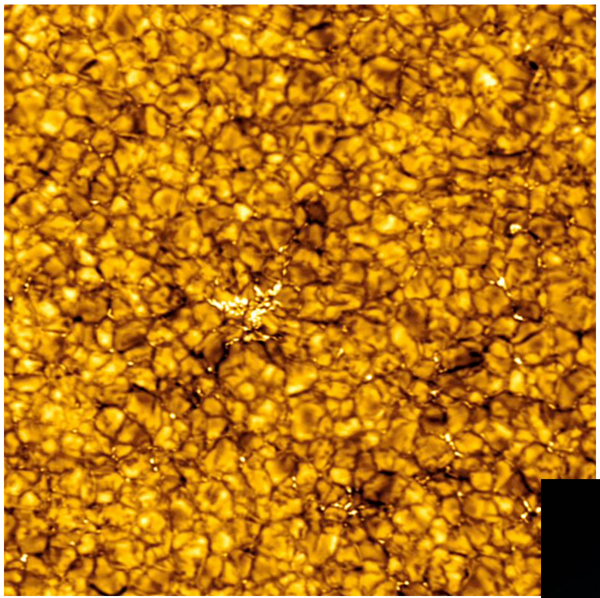
- 1D, hydrostatic equilibrium
- no radiation - particle interactions (**LTE = Local TE**)
- highly simplified convection & turbulence: “mixing length”, **ad-hoc velocities (V_{mic}, V_{mac})**



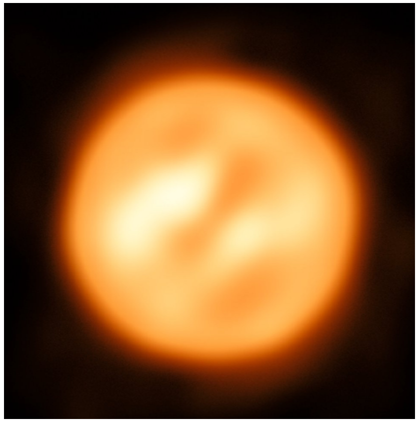
these assumptions violate any astrophysical object

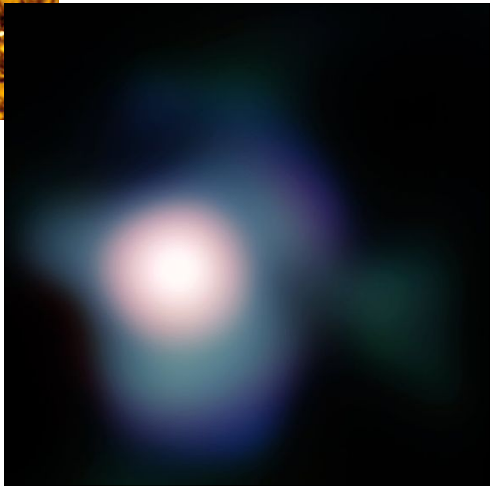
Observed stars are highly dynamic

observations: solar granulation, gas motions, hot spots, giant convective cells, variability, cold molecular shells …

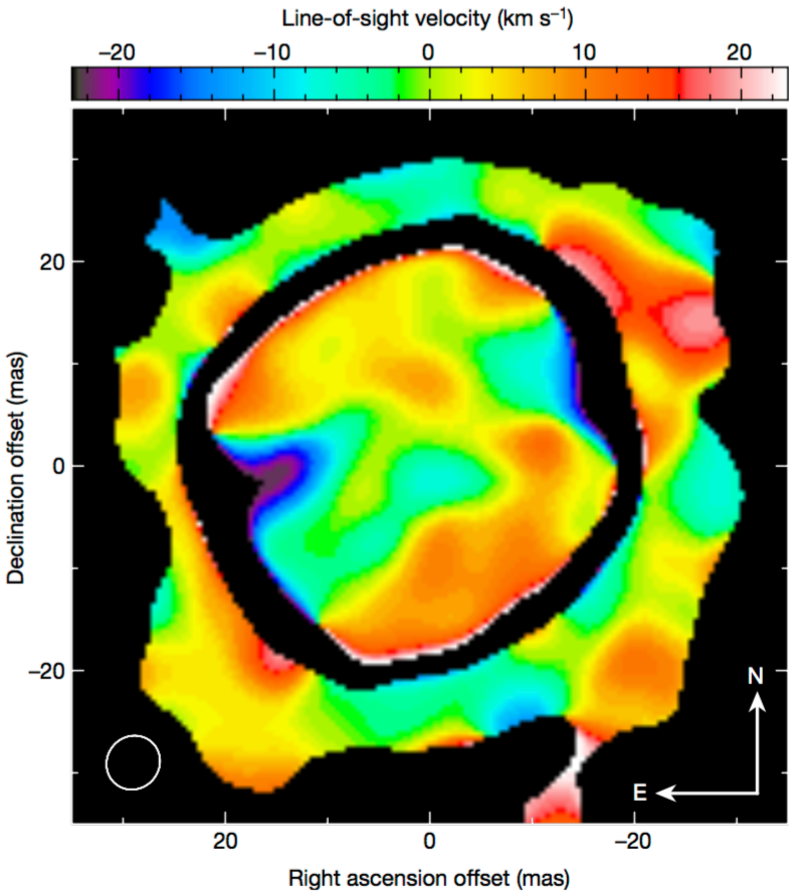


(c) Luc Rouppe van der Voort, Oslo





ESO/VLT

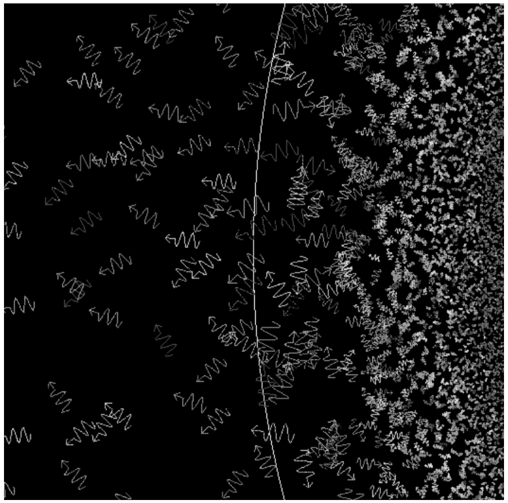


Ohnaka et al. 2017

3D convection and Non-Local Thermodynamic Equilibrium

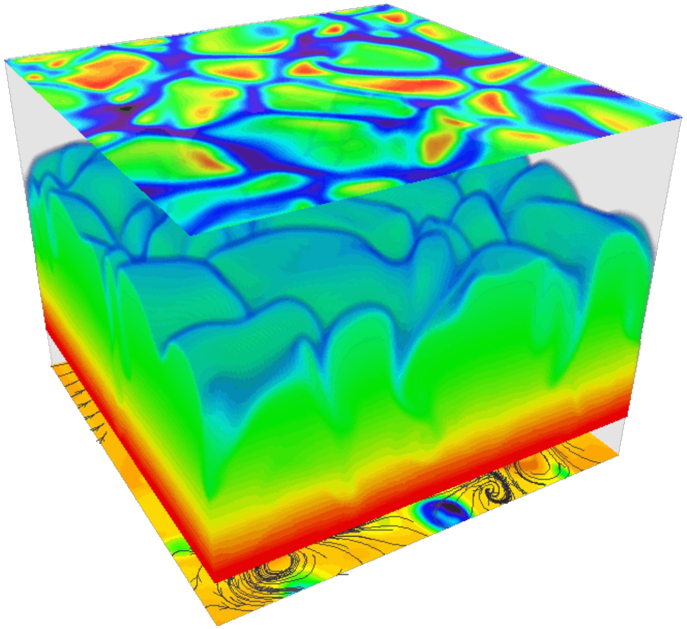
Non-LTE

$$\mathrm{n_i} \sum_{\mathrm{j}\neq\mathrm{i}}^{l} P_{\mathrm{ij}} - \sum_{\mathrm{j}\neq\mathrm{i}}^{l} n_{\mathrm{j}} P_{\mathrm{ji}} = 0$$



- strong non-local radiation field
  strong over-ionisation
- low densities => collisional
  thermalisation inefficient

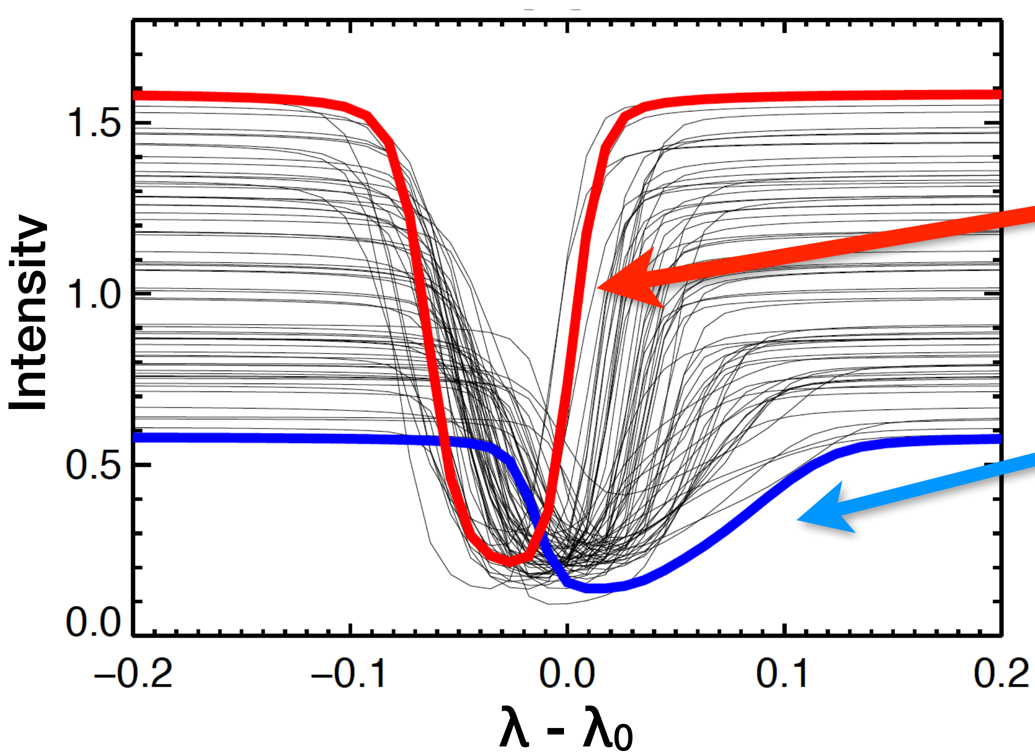
3D RHD simulations of convection

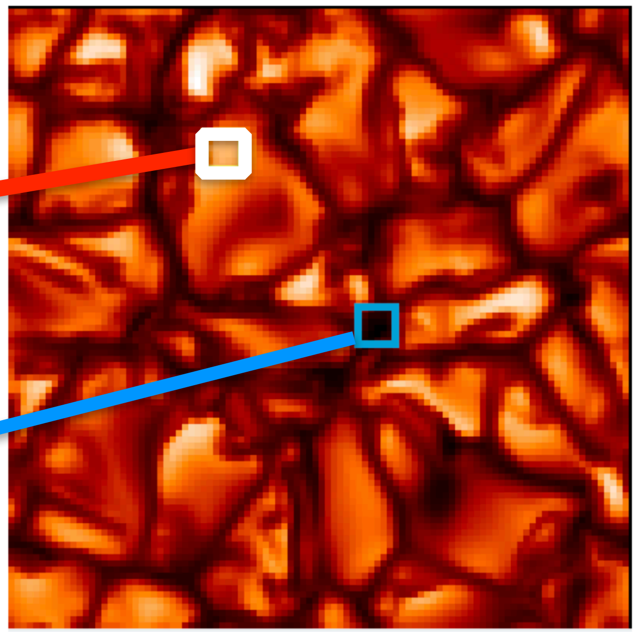


Stagger *(e.g. Magic et al. 2013)*
Bifrost *(e.g. Gudiksen et al. 2011)*
CO5BOLD *(e.g. Freytag et al. 2012)*
MURaM *(e.g. Voegler et al. 2005)*

First simulations of Mn and Fe in 3D Non-LTE

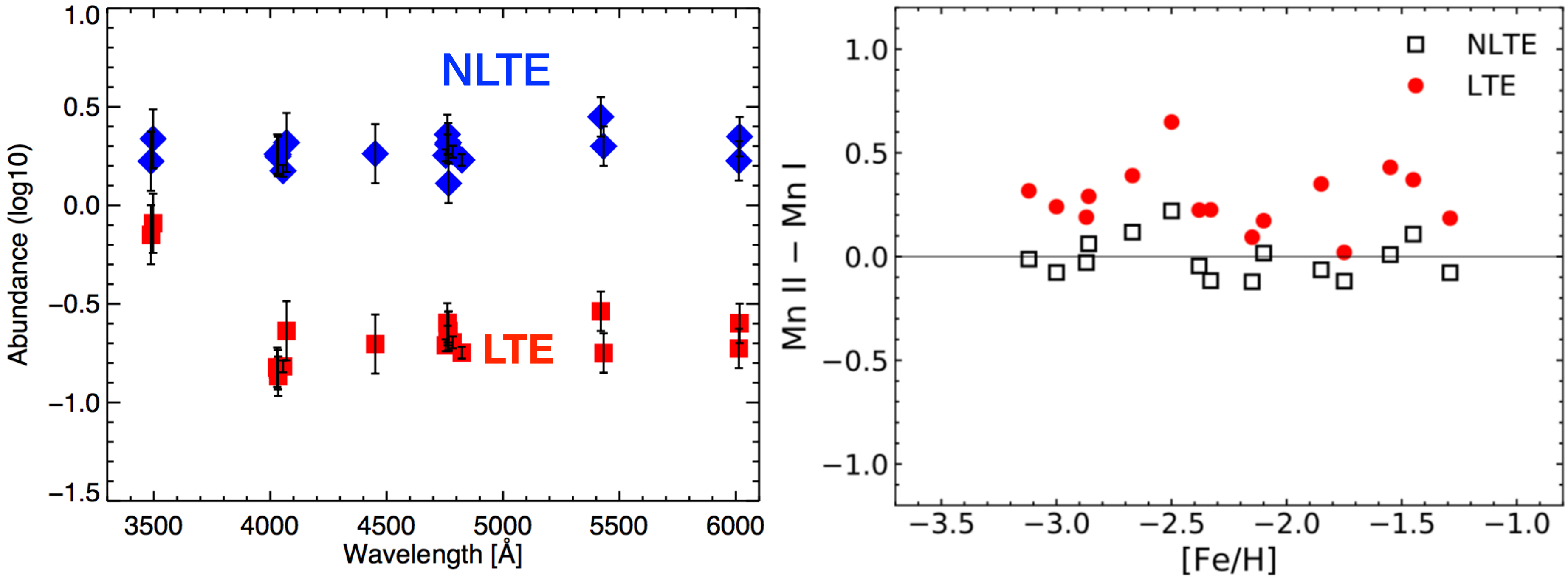
- state-of-the art atomic data (radiative cross-sections, collisional rates)
- parameter-free models
- no ad-hoc corrections to opacity, “turbulence”, etc





Bergemann et al. (2019)
Gallagher, Bergemann et al. (2020)

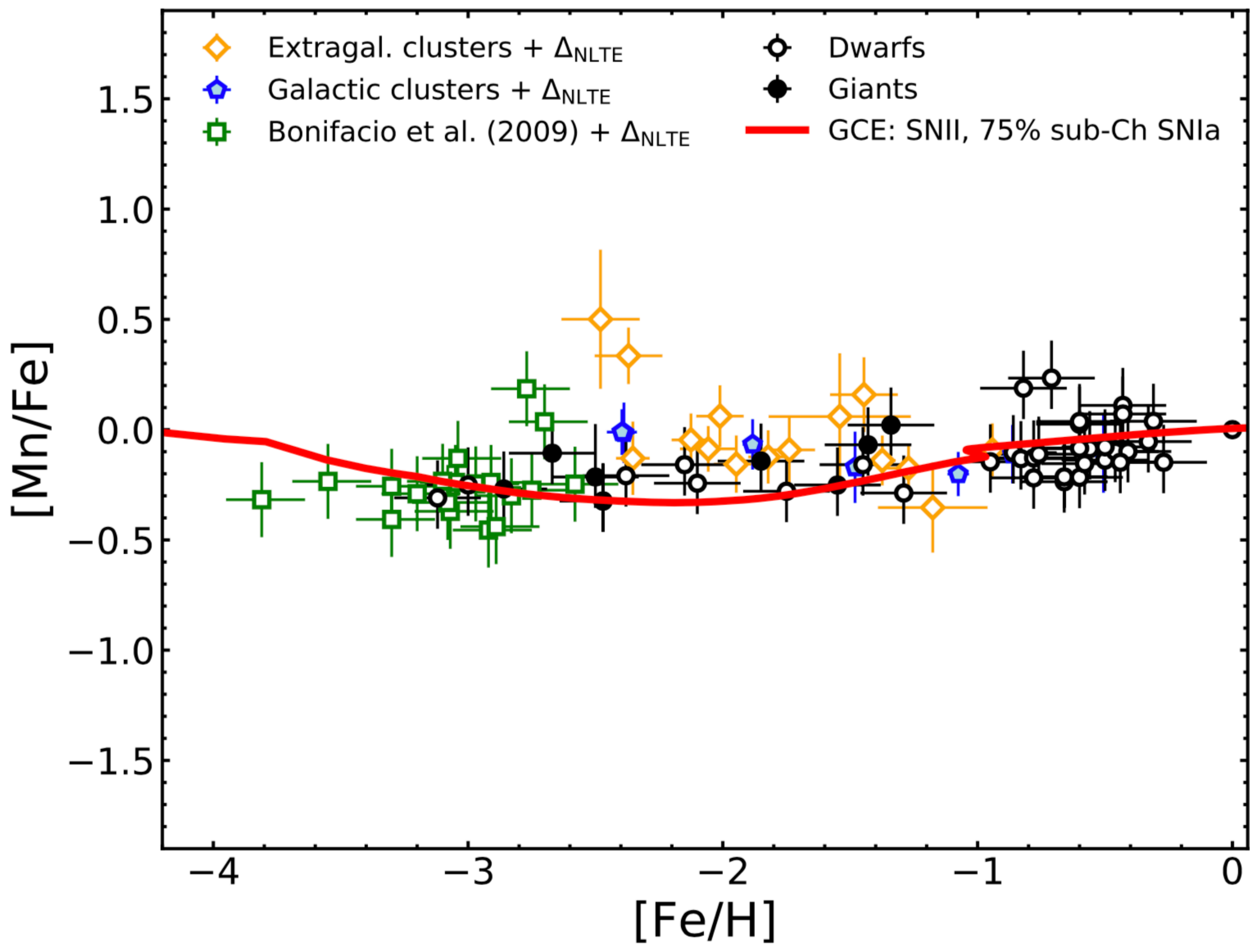
First simulations of Mn and Fe in 3D Non-LTE



- Sun - meteorites mismatch solved
- Excitation and Ionization balance cured
- Differences between LTE and NLTE abundances are large at low metallicity: hard UV radiation field, no line blanketing

Bergemann+ (2012, 2019), Lind, Bergemann+ (2012)

Galactic data favour sub-Ch explosions

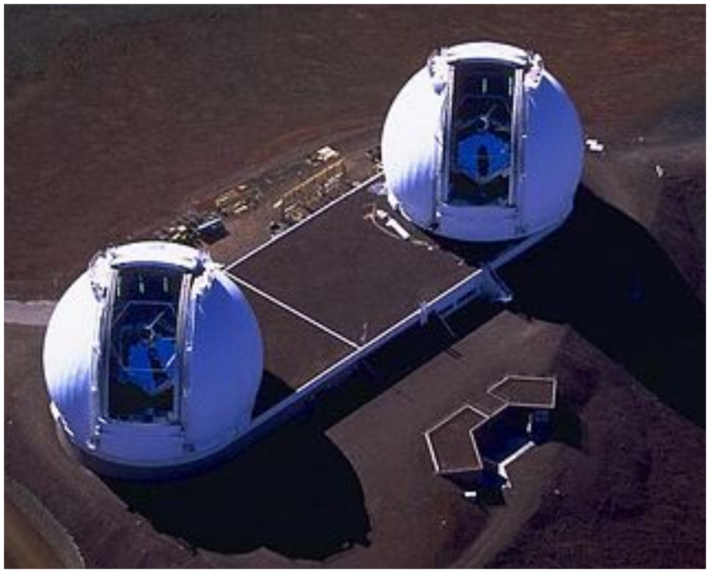


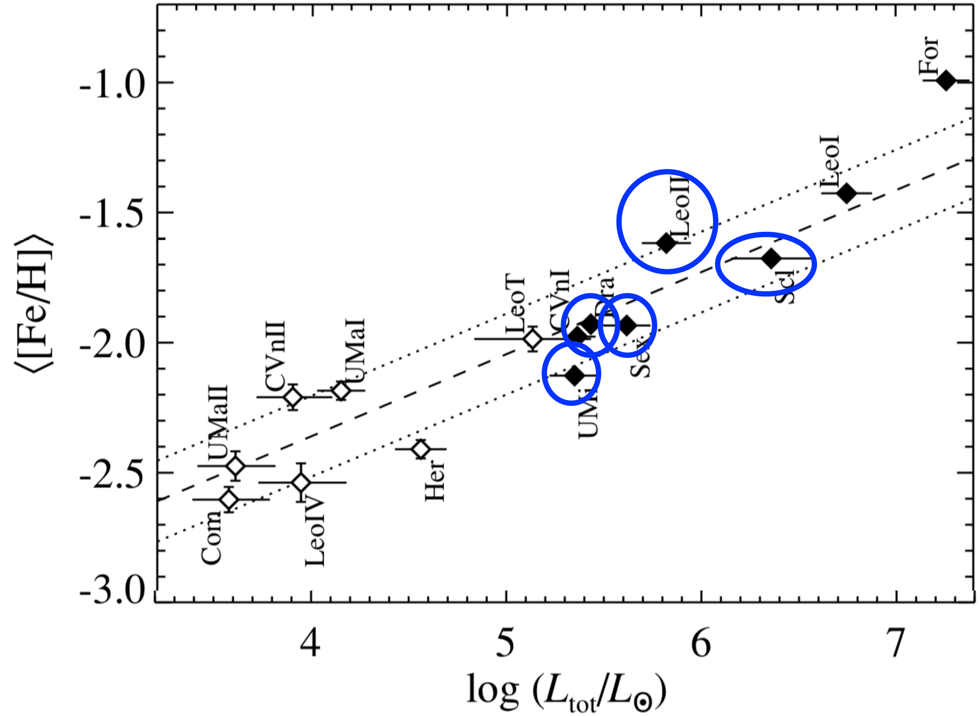
sub-Ch explosions 75%
(where previous LTE-based studies found 0)

Eitner, Bergemann et al. (2020)
Eitner, Bergemann, Larsen (2019)

Extragalactic measurements

large program to obtain DEIMOS spectra of dSph galaxies in the Local group

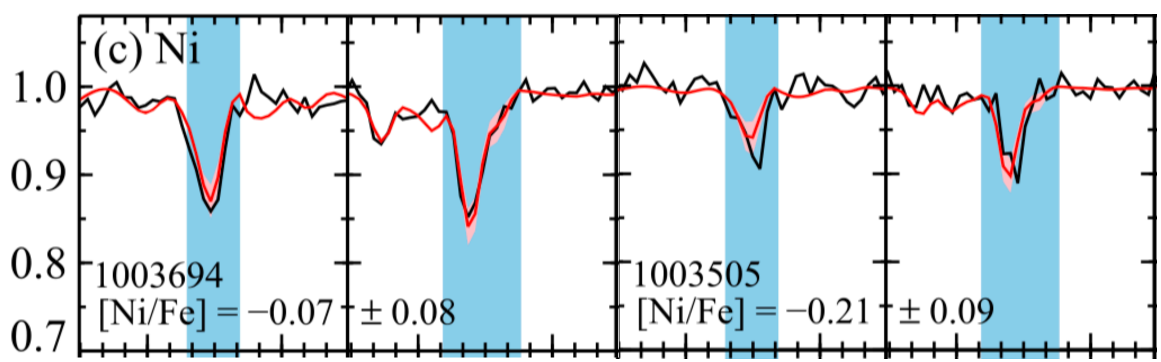




Kirby+ 2008, 2011a,b

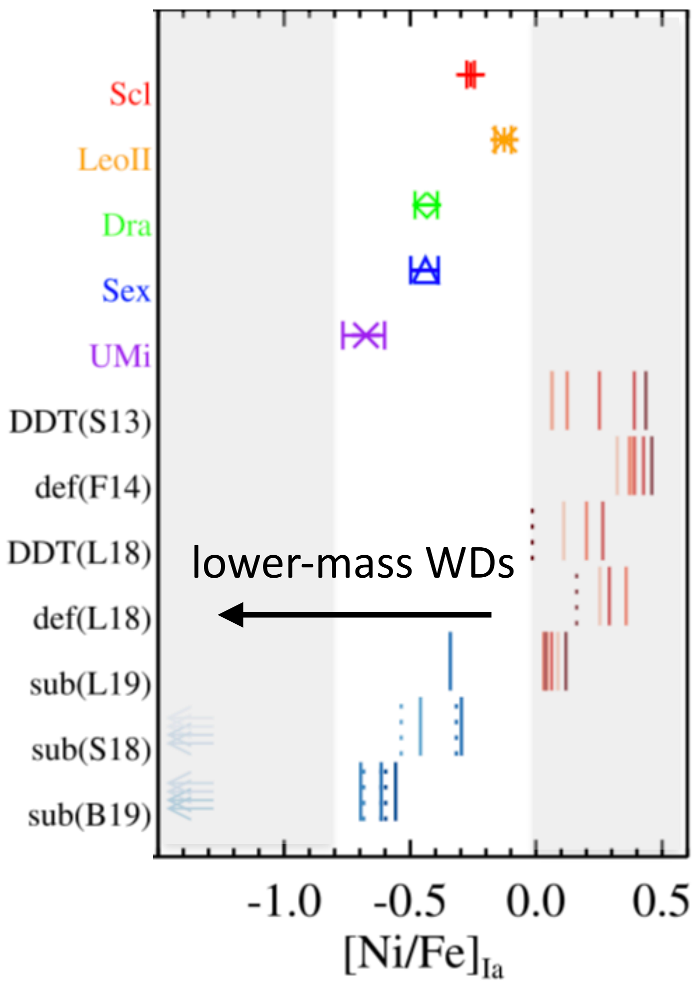
Kirby+, Bergemann et al. (2018)

Kirby+, Bergemann et al. (2019)



Extra-galactic data favour sub-Ch explosions

^{58}Ni



Kirby+, Bergemann et al. (2018)
Kirby+, Bergemann et al. (2019)

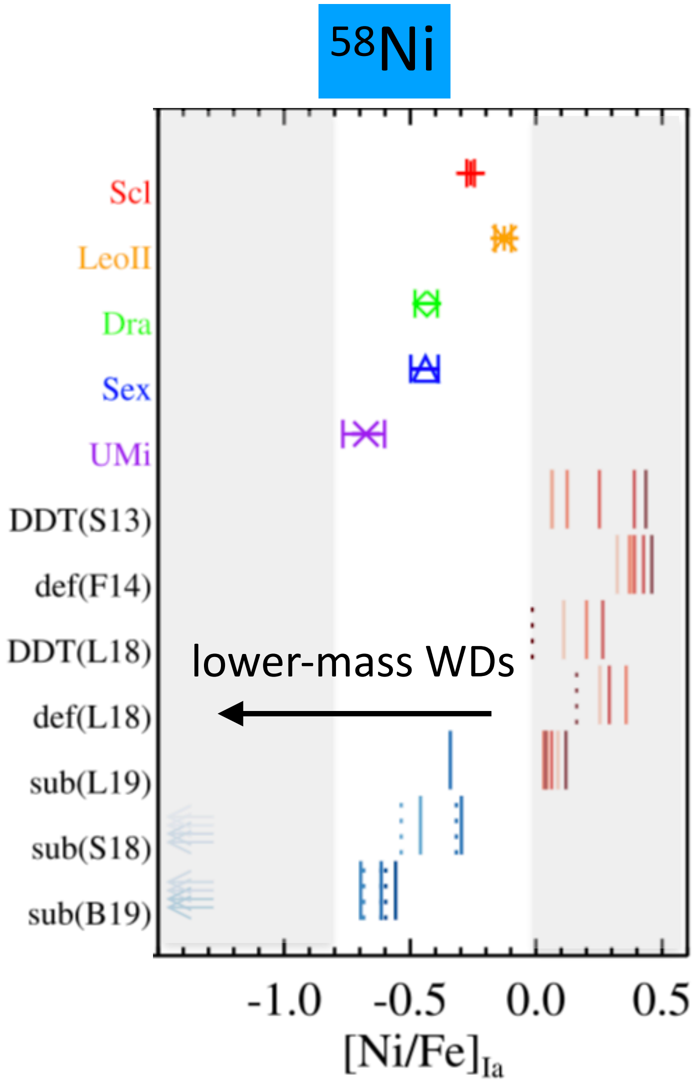
- ^{58}Ni co-produced with Mn, but is less dependent on physics of explosion

data: Sculptor, Leo, Draco, Sextans Ursa Minor

Chandrasekhar-mass models

sub-Chandrasekhar mass models

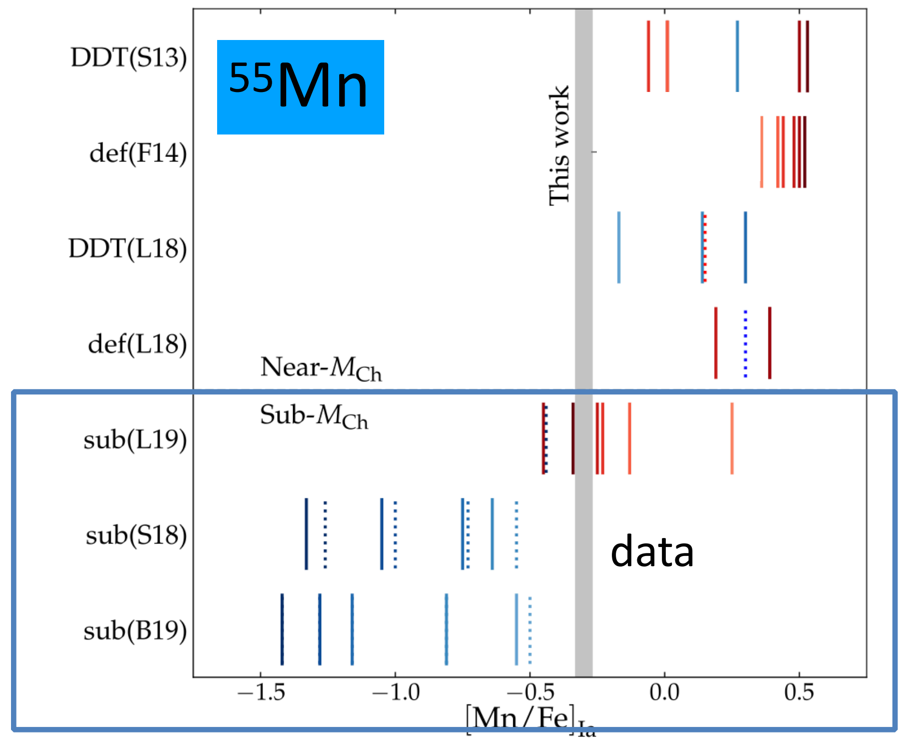
Extra-galactic data favour sub-Ch explosions



Kirby+, Bergemann et al. (2018)

Kirby+, Bergemann et al. (2019)

- ^{58}Ni co-produced with Mn, but is less dependent on physics of explosion
- More metal-poor systems prefer lower-mass binaries?



de los Reyes et al. (2020)

Take-home messages

1. SN Ia do not have the same brightness, but even after empirical corrections for the width and colour, their brightness depends on galaxy properties. Different progenitor channels?

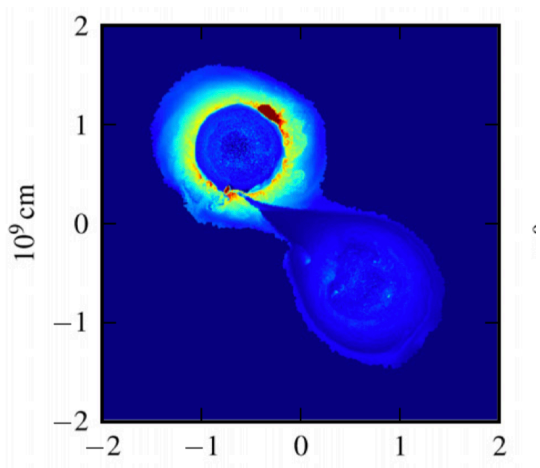
2. Recent search programs uncovered large populations of 'exotic' SN Ia; ≈ consistent with the diversity of progenitor channels

3. SN Ia rates and progenitors can be probed using Galactic abundances: "alpha-knee" gives the timescale of enrichment and Manganese over Iron abundance ratio probes explosion physics

4. data in the MW and dSph systems favour **sub-Ch models**
   thermal bomb explosion for core-collapse models (not canonical 'piston')

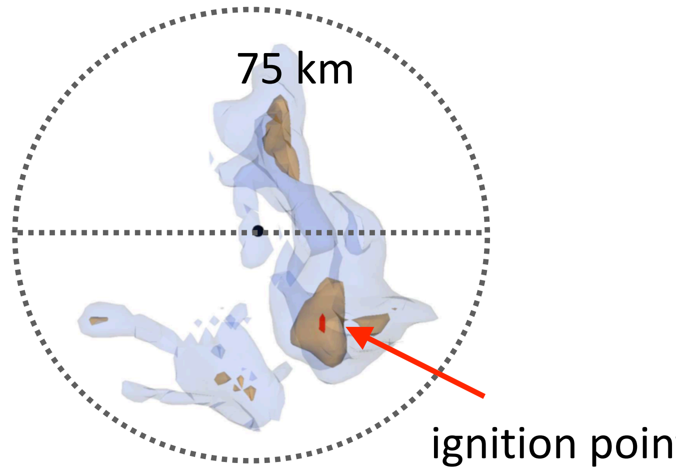
Other evidence for sub-Ch models

sub-MCh SN Ia



- ✓ numerous to explain SN Ia rates: WD collisions, violent mergers of WDs, He-accretion in an SD system
- ✓ range of masses diverse enough to explain SN Ia luminosities
- ✓ favoured by X-ray observations of intra-cluster medium

MCh SN Ia

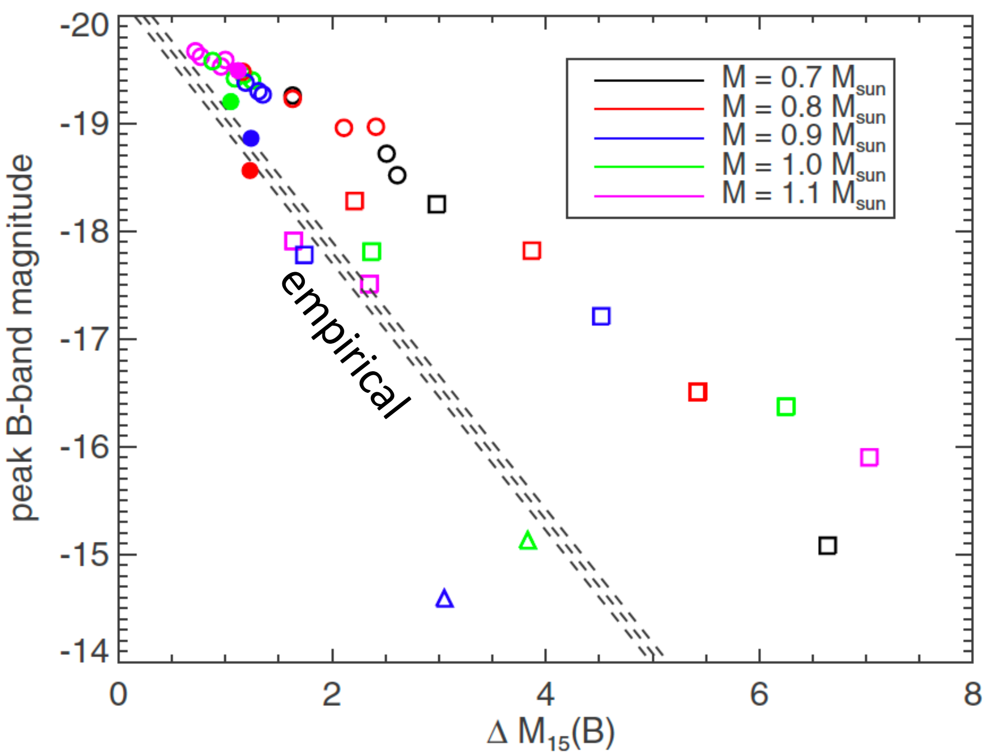


- ✓ well-understood, strong geometry effect; agree with Philipp's relations (in 1D)
- – need for fine-tuning of accretion rates (to avoid Nova or inflation)
- – # of accreting WDs disfavoured by X-ray observations of E/S0 galaxies

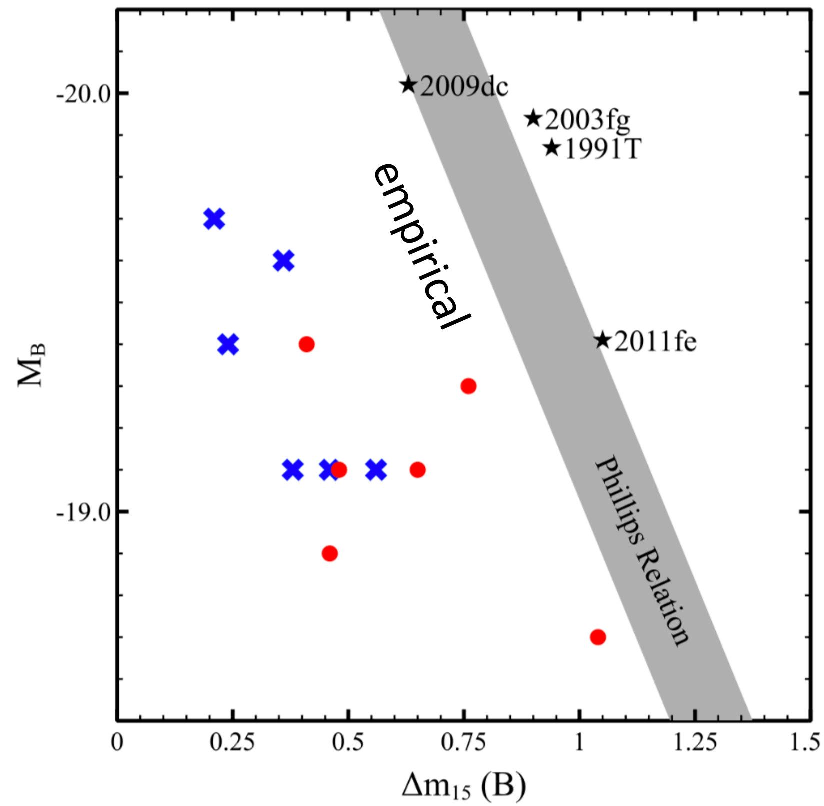
cf. Shen et al. 2017, Ruiter 2020, Mernier+ 2016, Pakmor+ 2013 , Hitomi Coll. 2017, Moll & Woosley

Does it matter for SNIa light-curve analysis?

- **single-degenerate** sub-Ch models give a wide range of transients; from "novae"-like to super-luminous SN Ia
- **double-degenerate** sub-Ch models - variety of outcomes, are brighter then "normal" and decline slower



Woosley & Kasen 2011



Raskin et al. 2014

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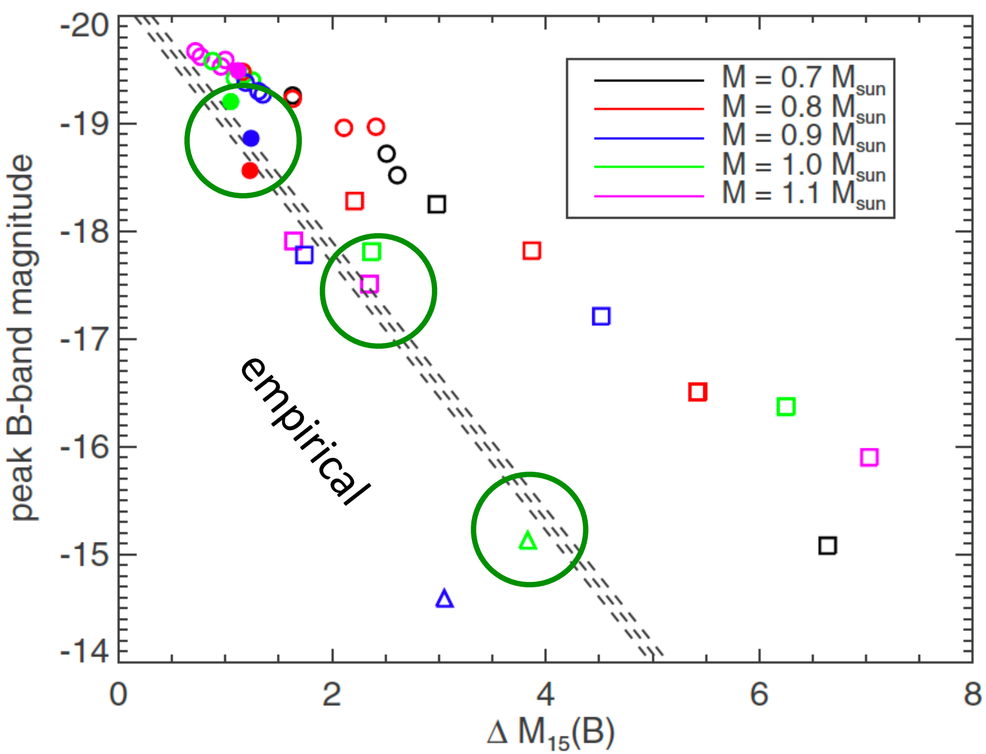

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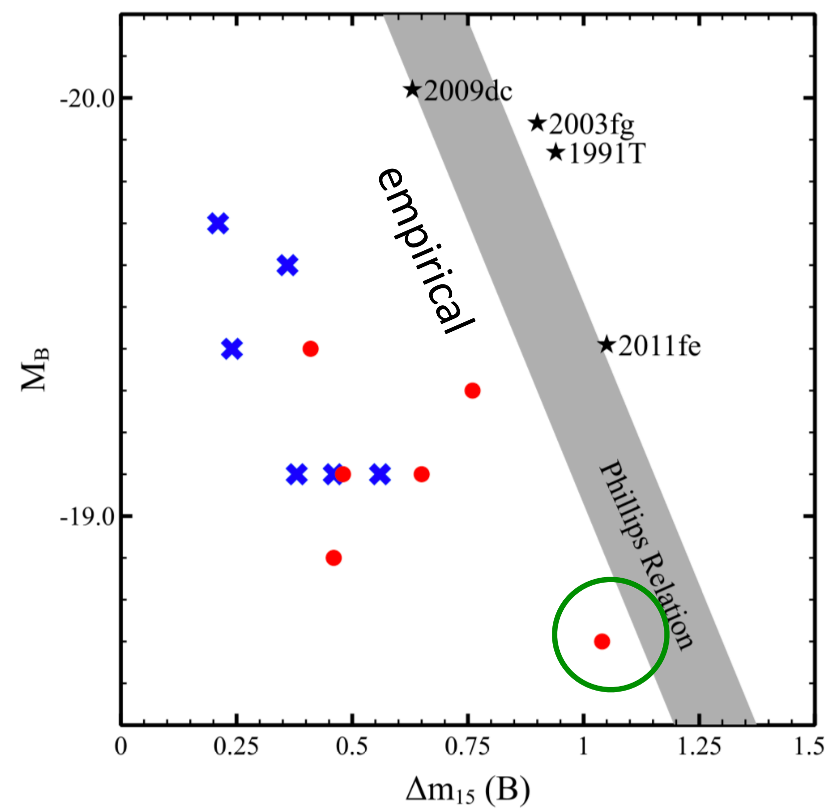


Raskin et al. 2014

Linking to galaxy properties

» if SN Ia models **+** chemical yields are **wrong**

1. correlations of Hubble residuals with age, mass, or metallicity are caused by something else

2. measurements in stars and/or Galactic models are wrong (unlikely given their success to reproduce MDF, AMR, morphology and radial gradients, abundance ratios…)

3. hard to reconcile with overall success of SN Ia models to reproduce post-explosion spectra (radiative transfer) and ^{56}Ni masses (nucleosynthesis + structure)

Linking to galaxy properties

» if SN Ia models **+** chemical yields are roughly **correct**

1. data in the MW and dSph systems favour **sub-Ch** model at the level of > 75%

2. **sub-Ch** models produce a continuum of W-C-L relationships, which depend on Z, age, mass… of a galaxy consistent with the “mass-step” in Hubble residuals?

3. local (calibrating) SN Ia samples are a biased sub-sample of the total (very inhomogeneous) population of SNIa?

Why do SN Ia surveys find > 70% of SN Ia that look like Philipp’s SN Ia?

Major revolution in understanding SN Ia

will come soon with all-sky large-spectroscopic surveys

Strong observational constraints on the population(s) and physics of **SN Ia** across the Milky Way and in Local group galaxies

<u>4MOST</u> (2022 - 2027)

S4 PI: Bensby & Bergemann

<u>MSE</u> (2026 …)

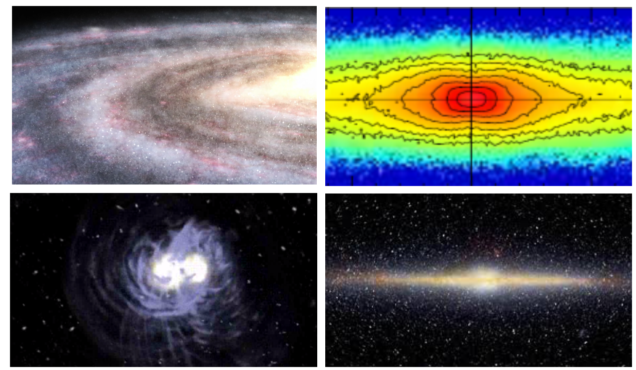
SWG lead:

Bergemann & Huber

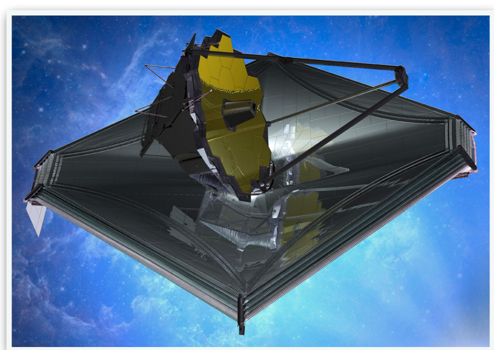
<u>JWST, ELT</u> (2026…)

extragalactic stellar spectroscopy

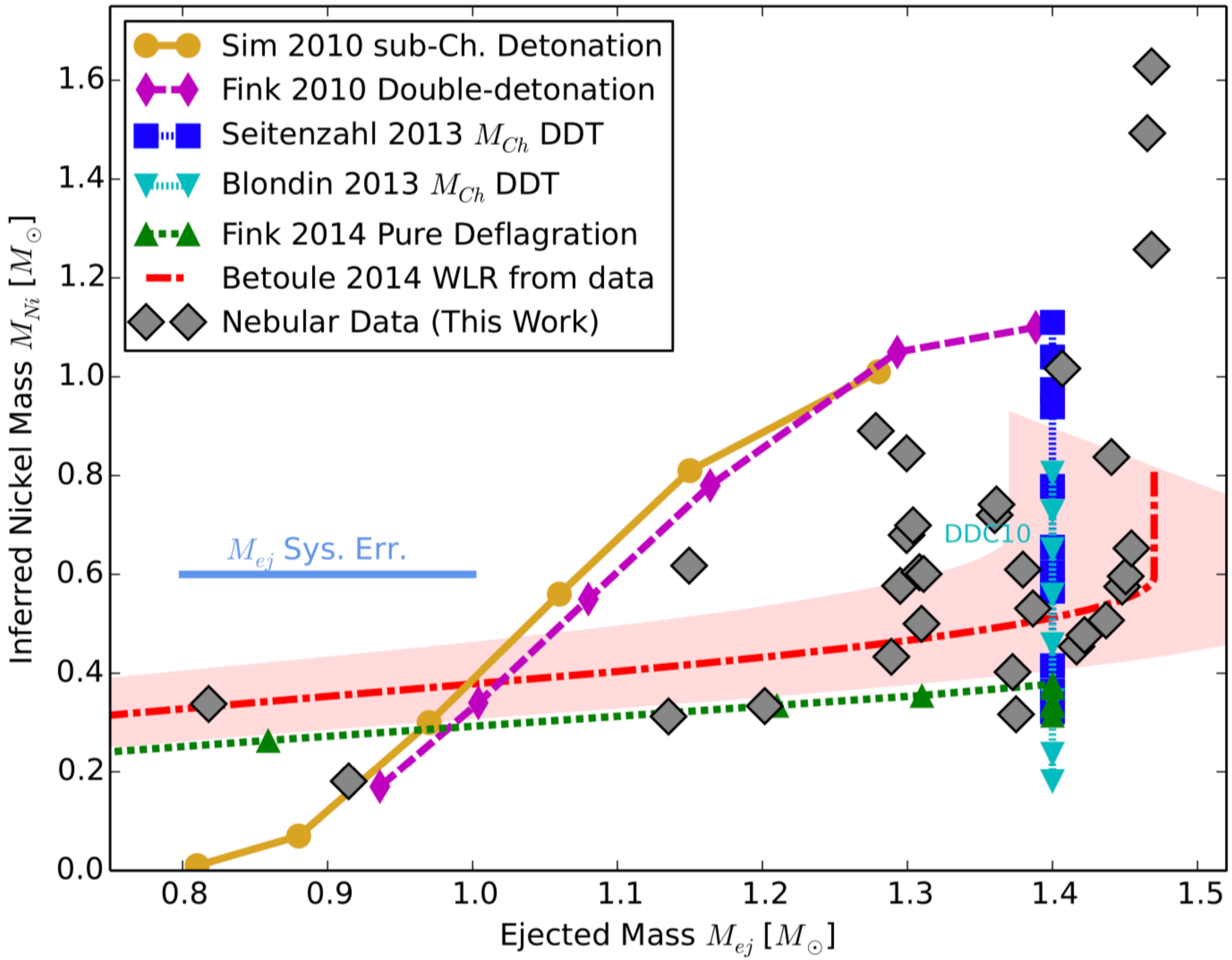
4MOST, WEAVE



JWST



ELT



Childress et al. 2015