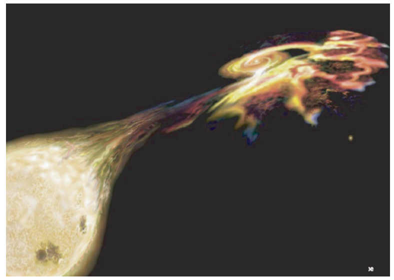
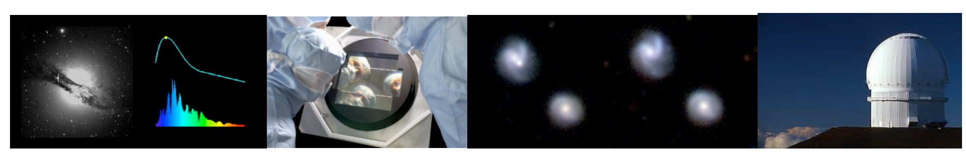
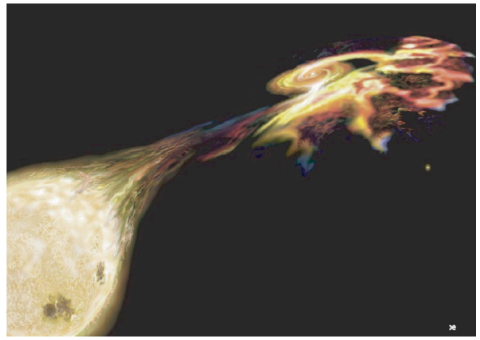


Nature of Type Ia Supernovae

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf





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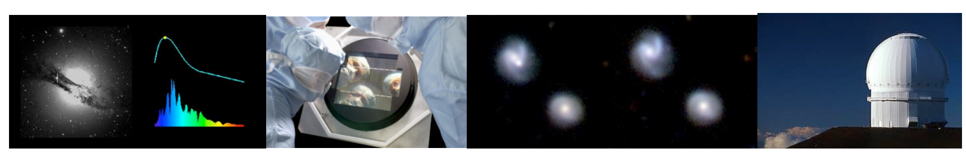
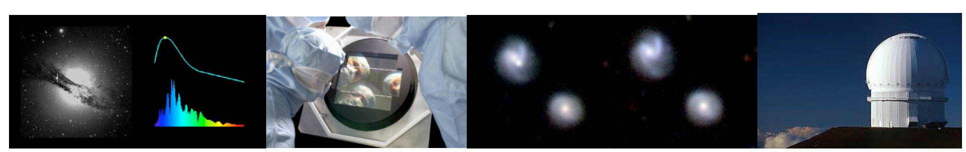


SN Ia progenitors

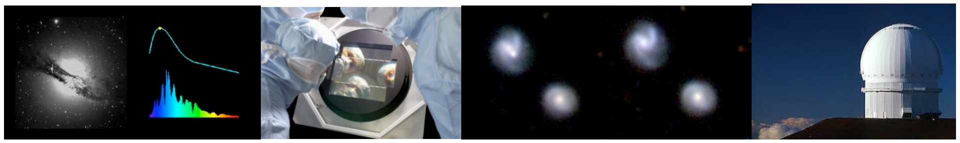
- Why important?
  - Among the most powerful explosions in the Universe (next to GRBs)
  - SNe Ia and cosmology
  - Role in chemical evolution and gas dynamics
- Scenario: exploding CO white dwarf near 1.4 $M_{sun.}$
  - Energy released (~0.5M_{sun} CO --> ^{56}Ni)
  - No H in spectrum
  - Light curve shape (radioactive decay)
  - Presence in old stellar pops (what else could they be?)



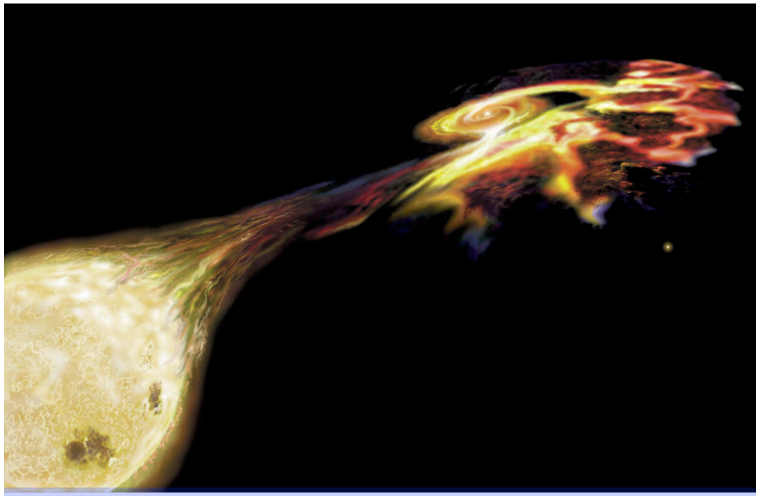
Two Basic Questions

- What is the "delay time distribution" of SNe Ia?
  - What is the main sequence mass of SNe Ia progenitors?
- By what evolutionary path(s) do white dwarfs become SNe Ia?

Basic questions, but no clear answers …

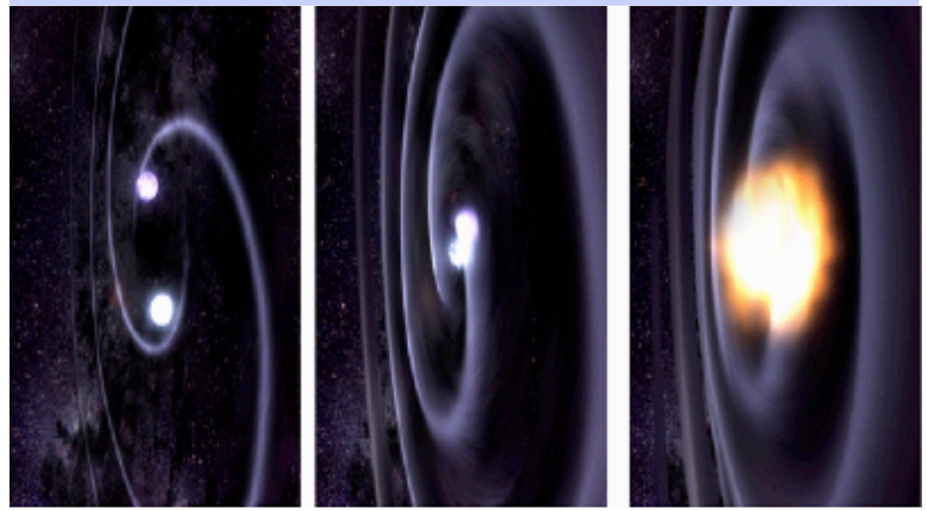


SN Ia Progenitors - 2 Broad Classes

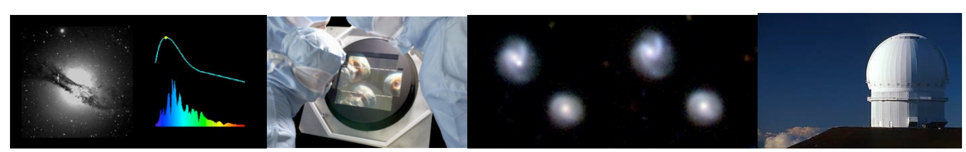


Single Degenerate - white dwarf + evolving secondary (M ~ 1.4 M_{sun} at explosion)

Double Degenerate - 2 white dwarfs (M_{tot} >= 1.4 M_{sun} at explosion)



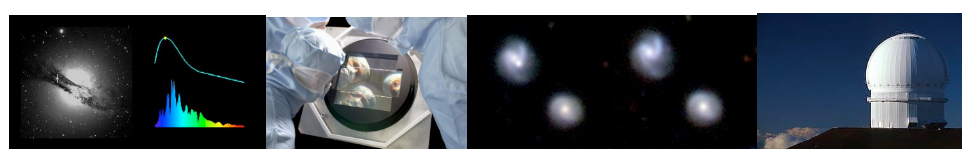
Key point: white dwarf maximum mass M = 1.4 M_{sun} (Chandrasekhar mass)



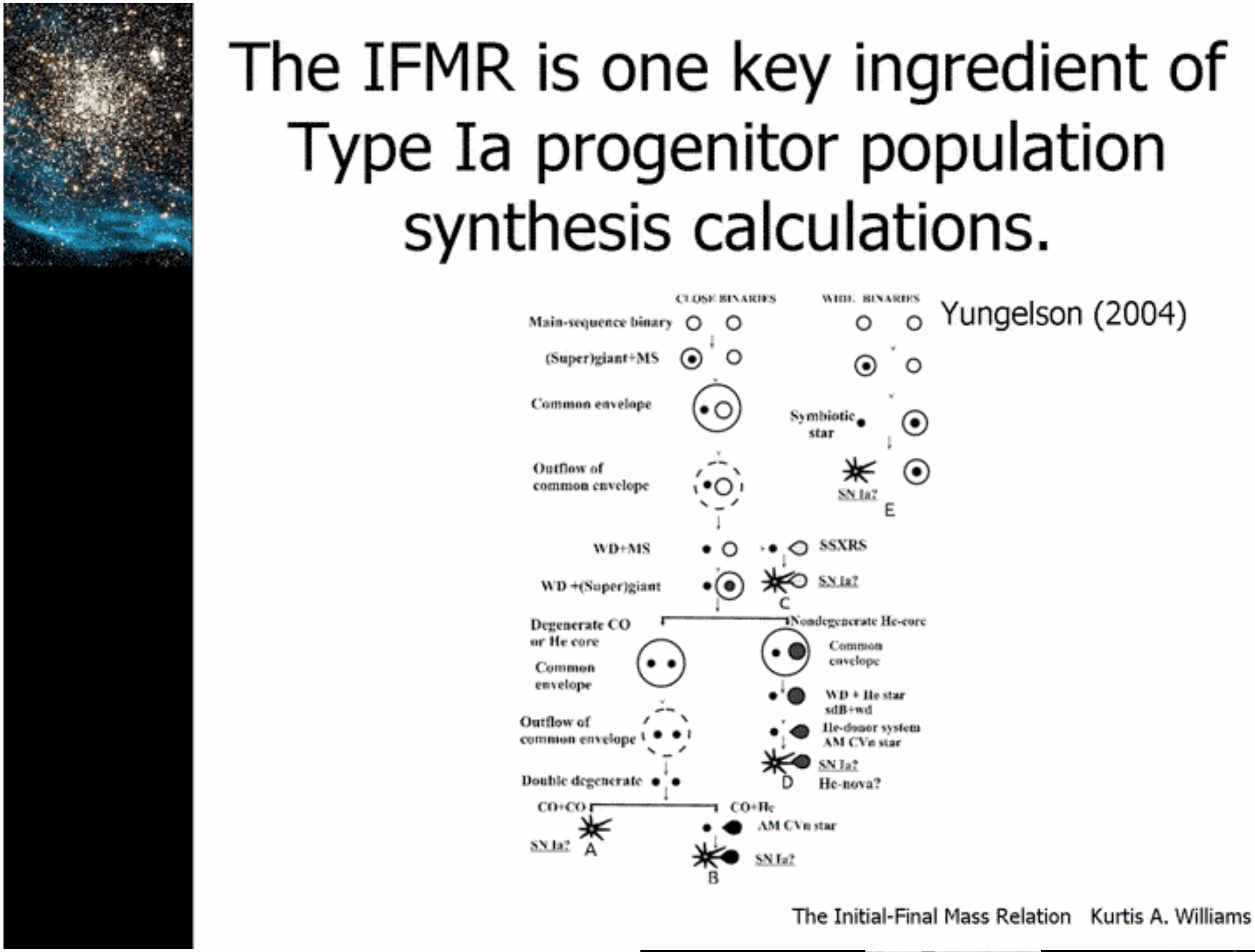
Ia progenitors

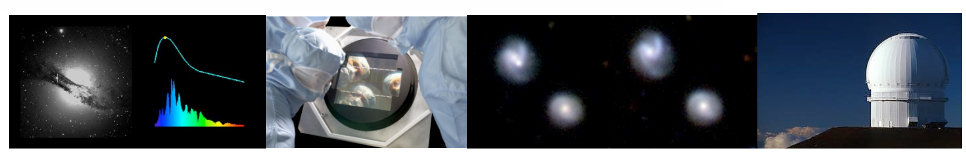
- Single Degenerate
  - White dwarf + evolving secondary
  - Evolving star overflows Roche lobe
  - Accretion of H-rich material onto CO WD
  - Mass loss rate 10^-7 Msun/yr – stable
    otherwise CE or nova
  - SNIa when M > M(Chandra)=1.4Msun
  - Deflagration (subsonic), at least initially

- Double Degenerate
  - Inspiral of 2 WD's by grav radn
  - Are there enough objects? Looks like yes – Napiwotzki KITP (but no slides yet!)
  - See later …



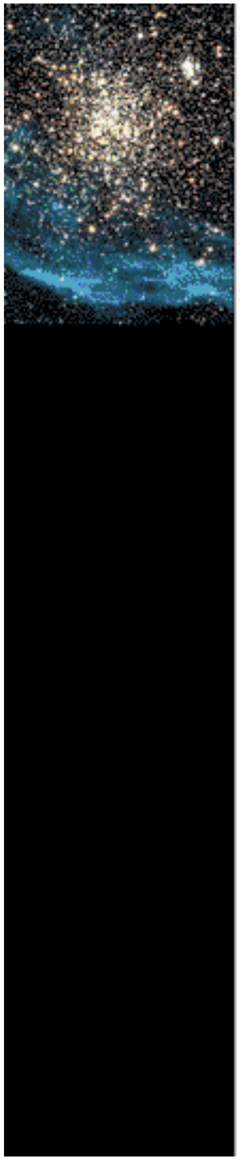
Yungelson's famous diagram



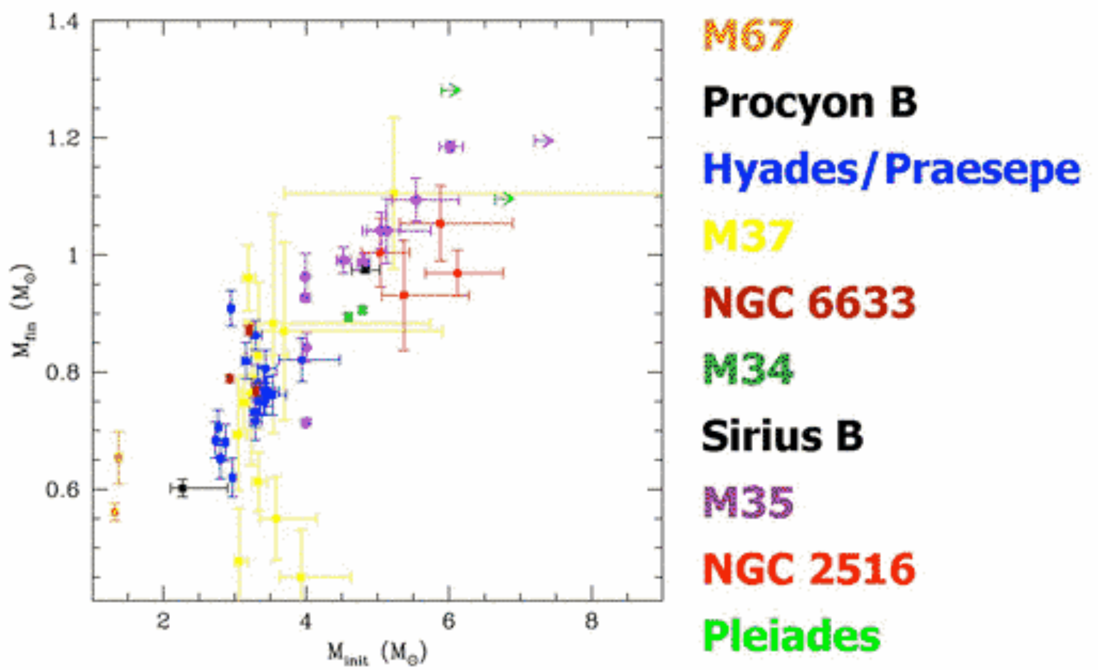


www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf

White dwarf vs main sequence mass



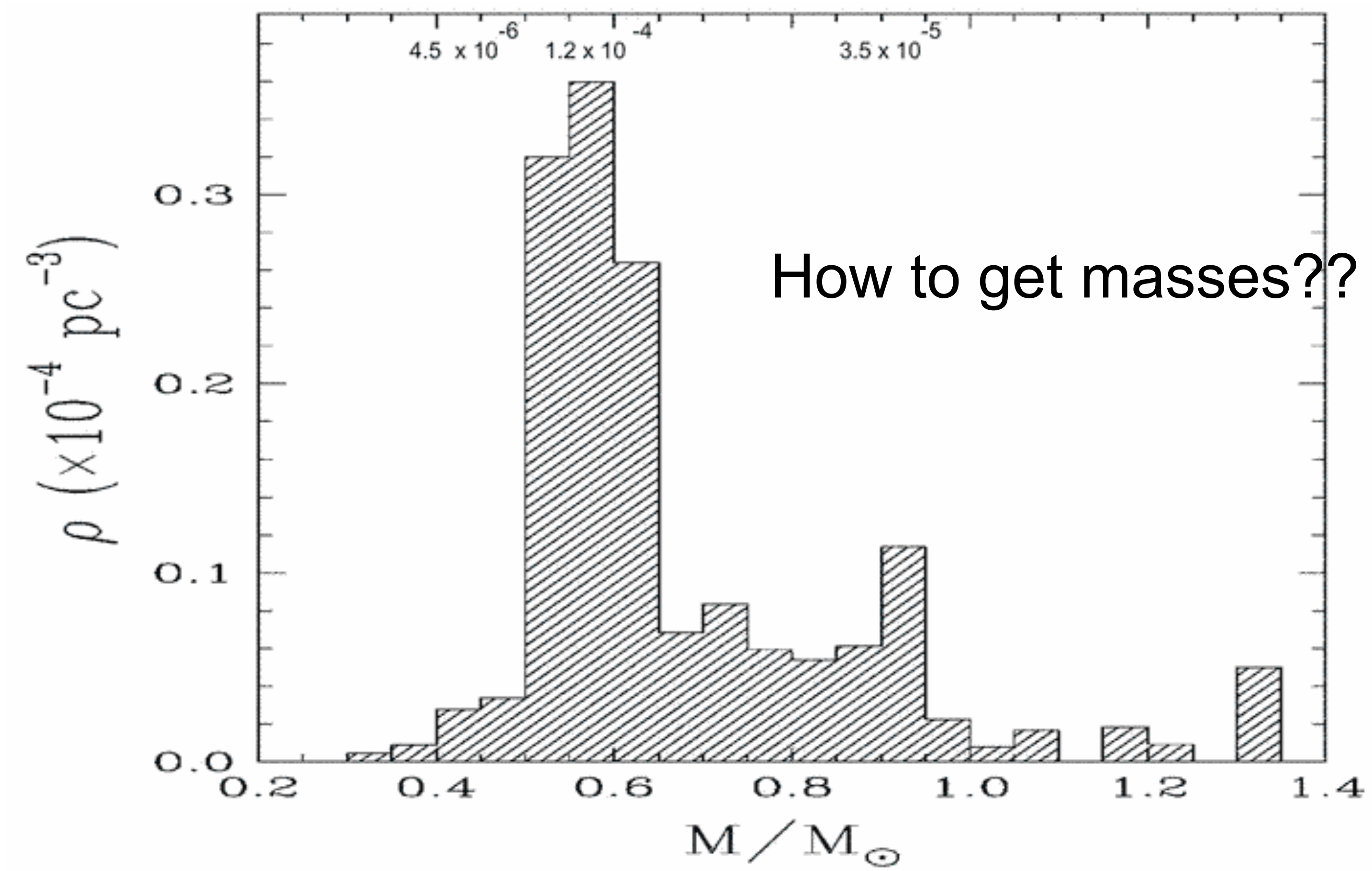
The current empirical IFMR has data from 11 star clusters and binary star systems.



The Initial-Final Mass Relation Kurtis A. Williams

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf

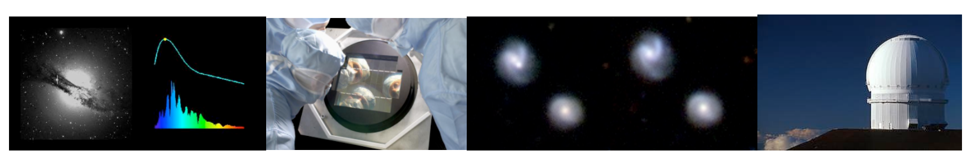
There are WD's near the Chandra limit!



How to get masses??

Mass Distribution Corrected to Fixed Volume of Space

March 19, 2007 KITP



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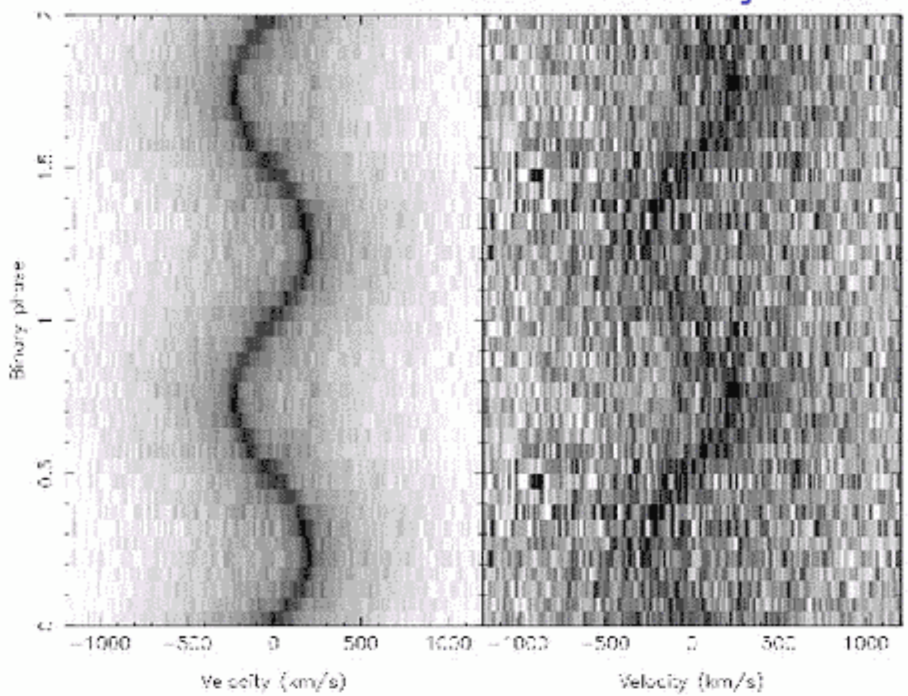
Double WD's -> DD Ia's?

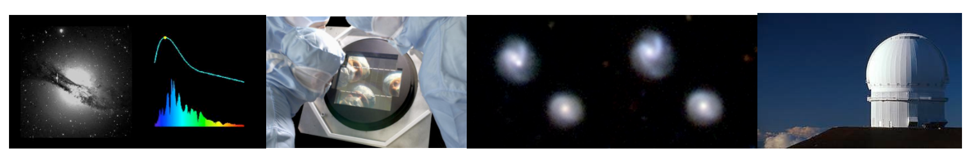
Double-lined systems



Moran, Marsh & Bragaglia (1997)

Maxted, Marsh & Moran (2002)

In some cases both white dwarfs can be seen allowing us to measure mass ratios. This is WD 0957-66, $P = 88\,\mathrm{min}$, $q = M_{\mathrm{bright}}/M_{\mathrm{faint}} = 1.15 \pm 0.10$.



SPY=Supernova Ia Progenitor Survey

R. Napiwotzki et al.

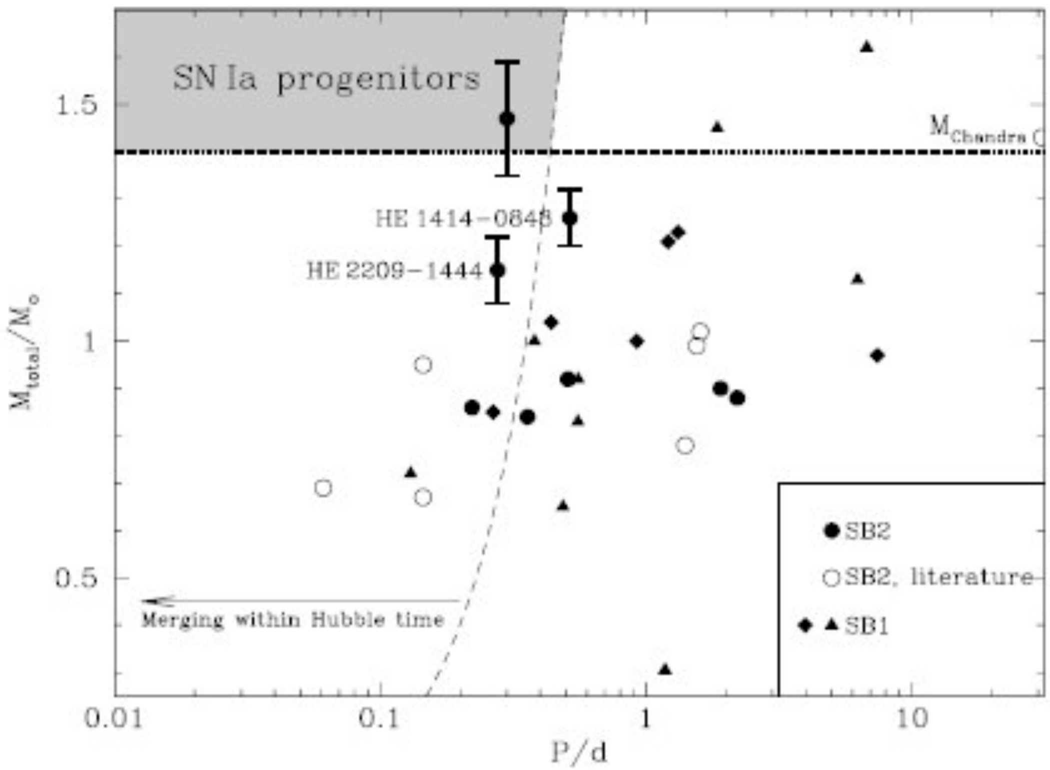
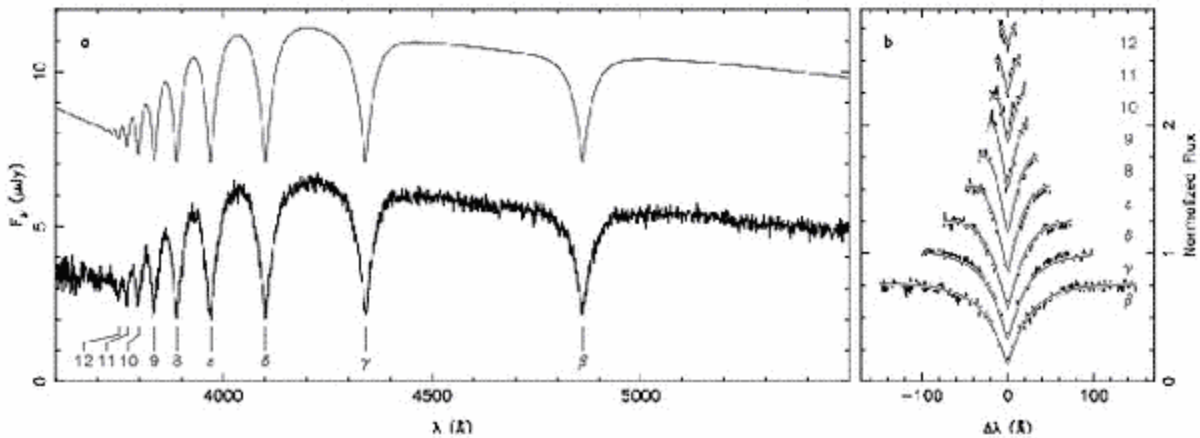


Figure 2. Periods (P) and system masses ($M_{\rm total}$) determined from follow-up observations of DDs from SPY. Results for double-lined systems are compared to previously known systems. The other DD systems are single-lined (triangles: WD primaries; diamonds: sdB primaries). The masses of the unseen companions are estimated from the mass function for the expected average inclination angle ($i = 52°$).

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf

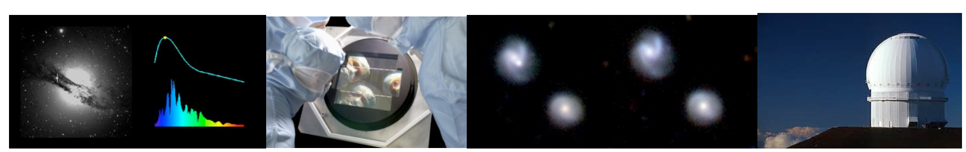
WD’s are mostly He or CO, not H!

He WD companion to PSR J1911-5958A



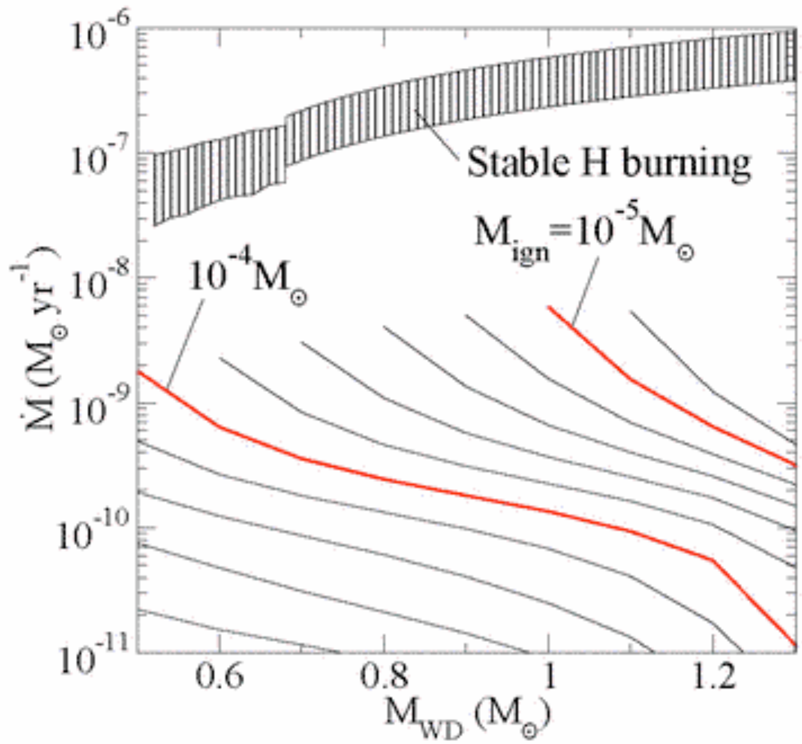
Bassa et al (2006), $P = 20\,\mathrm{h}$, $M_{\mathrm{WD}} = 0.18\,\mathrm{M}_\odot$.

NB. Hydrogen flotsam: He and CO white dwarfs usually appear to be pure hydrogen. Only distinguishable by mass.



Stable burning for SD model

Available Parameter Space



Contours spaced by $\Delta \log(M_{ign}/M_{\odot}) = 0.2$

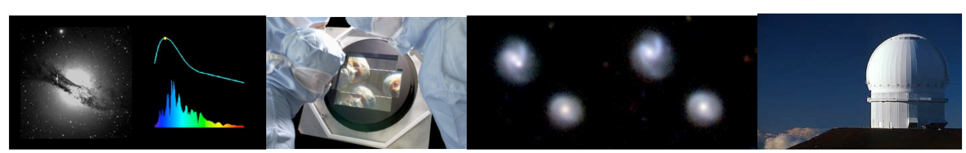
Townsley & Bildsten 2005, ApJ, 628, 395

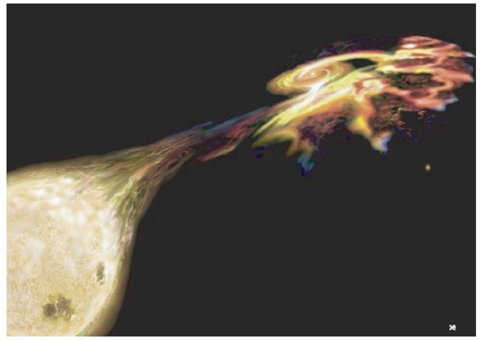
Strong contrast in M_{ign} at around few$\times 10^{-10} M_{\odot}$ yr^{-1} created by change in ignition mode due to different T_c as determined by $\langle \dot{M} \rangle$ (more on this later).

CVs generally are thought to have accretion rates that are low or high, but not much in between.

A system at a given mass can have a factor of 10 range in M_{ign} depending on what evolutionary stage it is in.

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf





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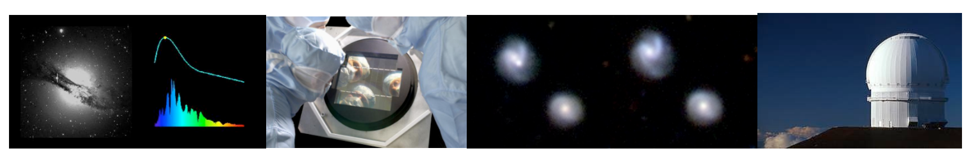
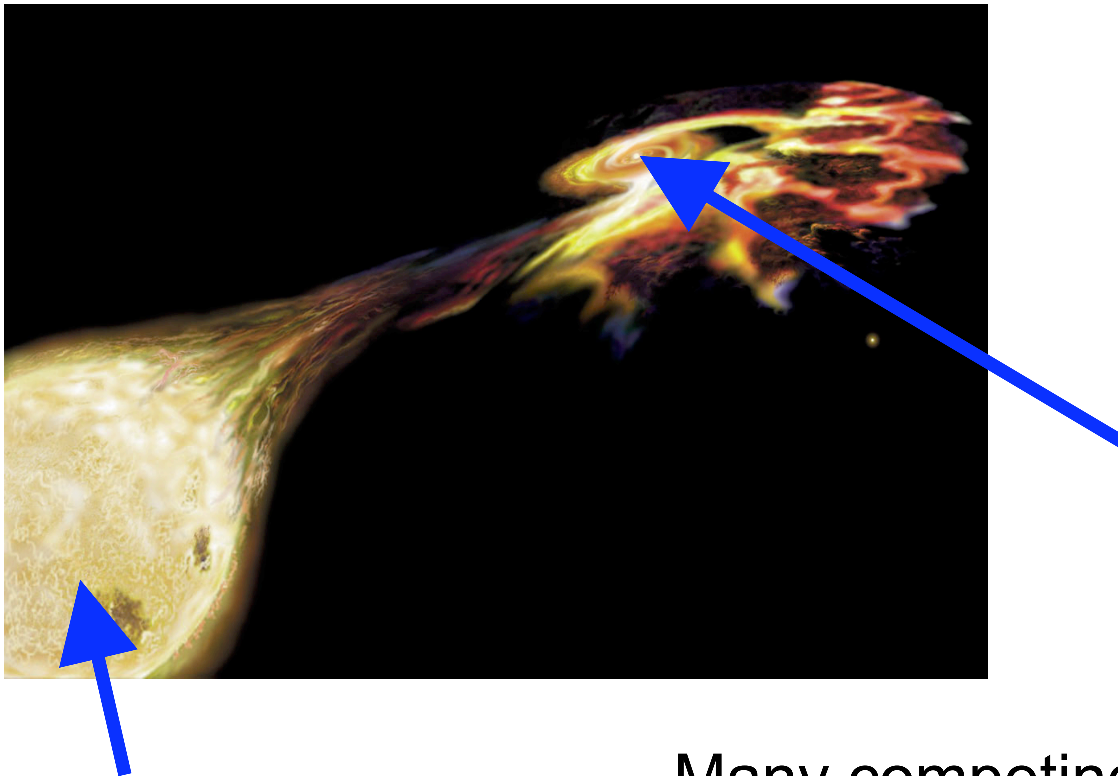




SN Ia Progenitor

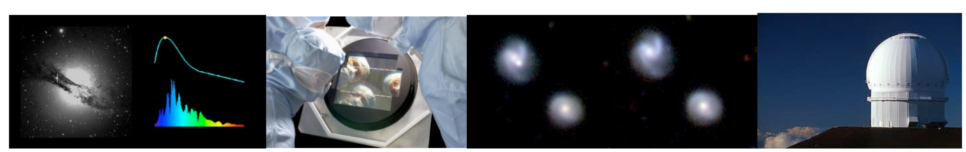
White dwarf

Companion:
subgiant?
White dwarf?

Many competing models for:

- Nature of the “second star”
- Single versus double degenerate
- Young versus old progenitor
- Explosion mechanism?
- Mass transfer mechanism?

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf



SNLS-03D3bb (Howell et al. Nature 2006)

- z=0.24, star-forming host
- Most luminous SNIa ever discovered (M_V=-20.0, 10 billion Lsun)
- Lies off the stretch-L relation - too bright for its stretch s=1.13 by 4.4 sigma

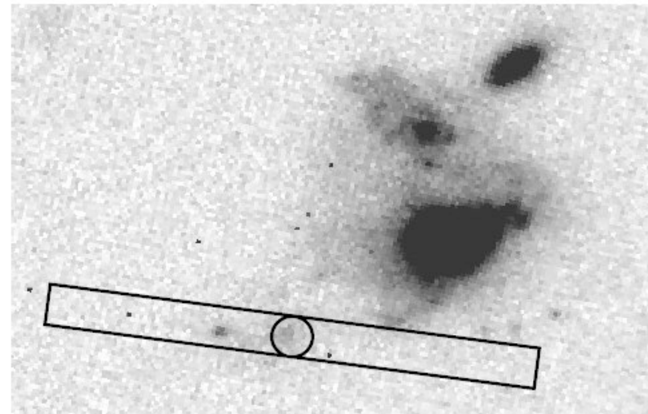
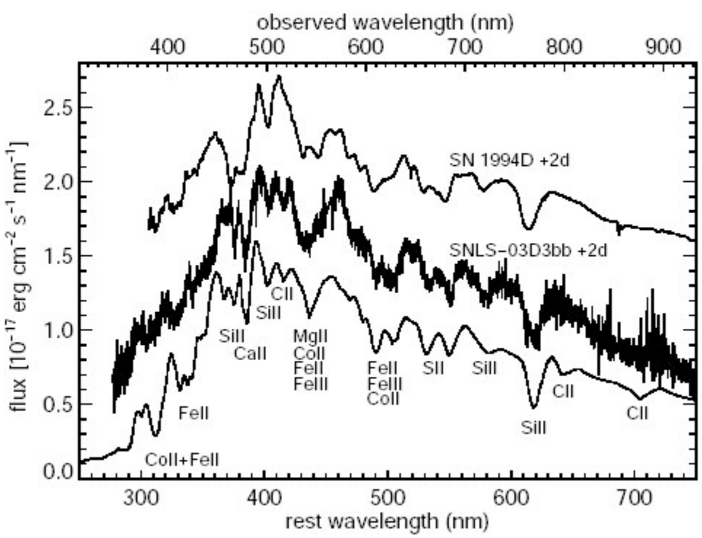
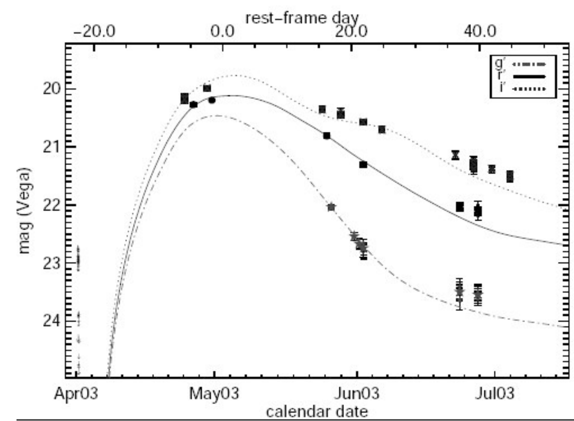
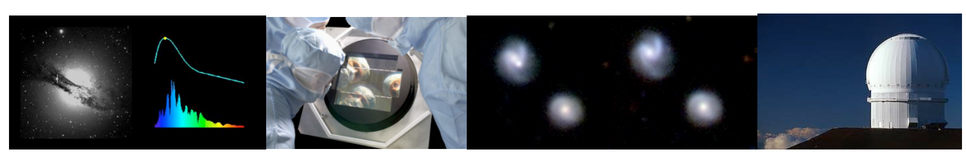


Fig. 1.— A Hubble Space Telescope ACS image of the host galaxy of SNLS-03D3bb taken through the F814W filter. Though the supernova is not present in this image, the circle marks its position. The spectroscopic slit was placed at 261° to get the redshifts of both the small host and the larger neighboring galaxy. Both are at $z = 0.2440$.



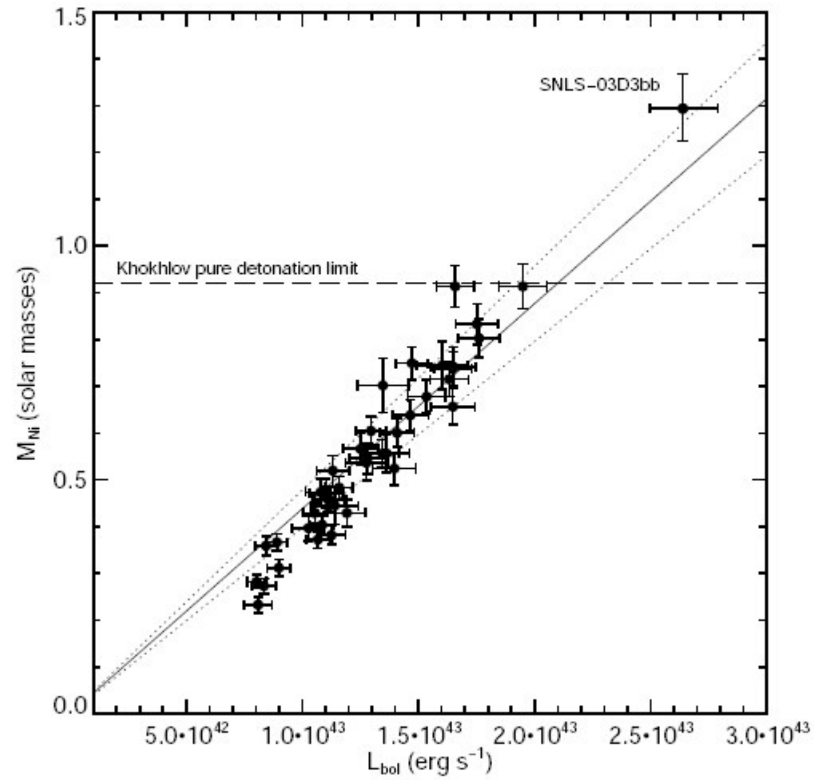




www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf

03D3bb

- Requires 1.3 Msun of ^{56}Ni to power light curve, 2Msun total mass
  - “normal” SNIa – 0.6 Msun of ^{56}Ni
  - 03D3bb is 2.2x brighter, therefore has 2.2x Ni mass
  - Detailed calculation using Arnett models agrees well
- Mass = > Chandra mass of 1.4 Msun!



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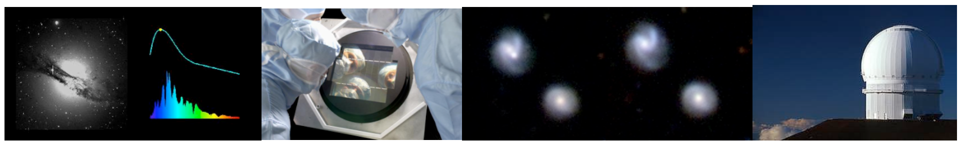
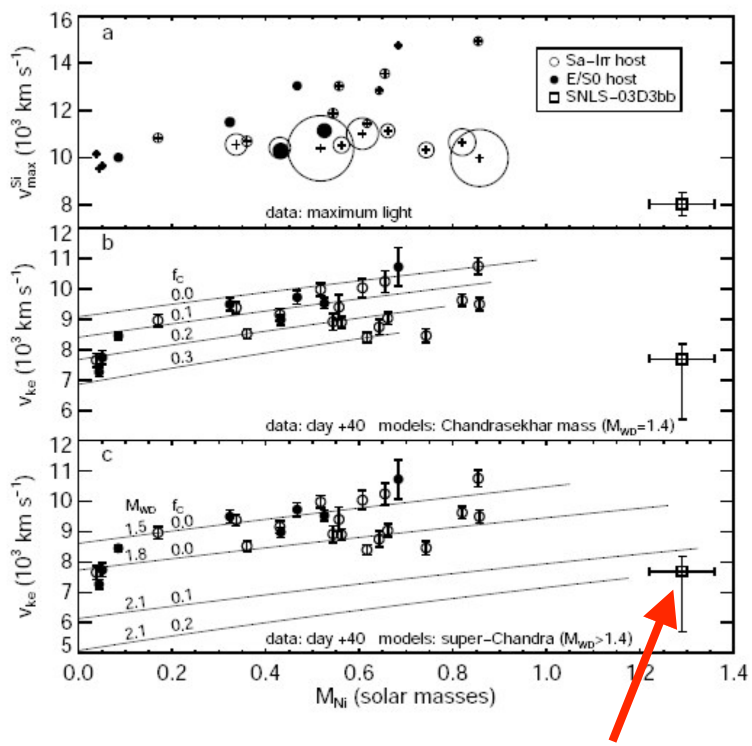


03D3bb

- Low velocity of ejecta (8000 km/s)
  - Also implies super-Chandra mass
- Conclusion: either (i) a rapidly rotating WD, or (ii) WD-WD merger
- Implications for cosmology (this object was not used in Astier et al 2006)



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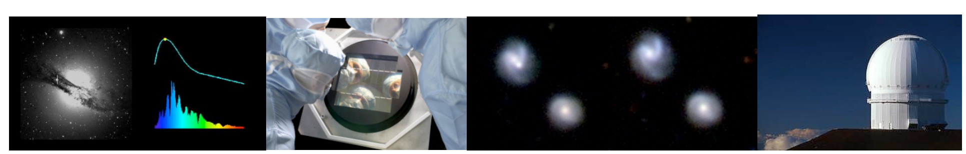

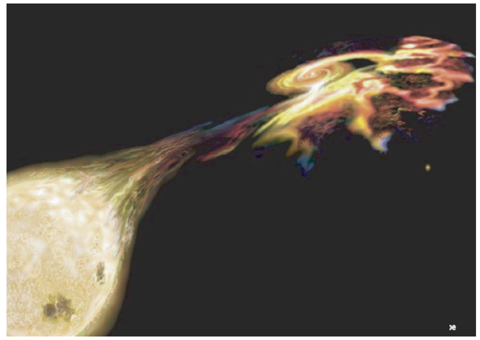

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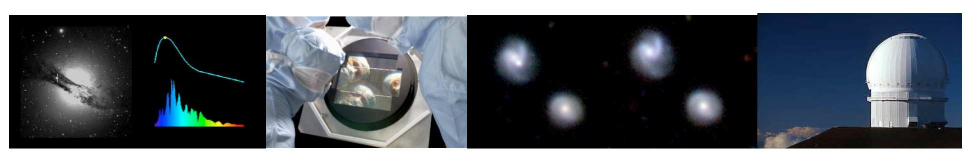

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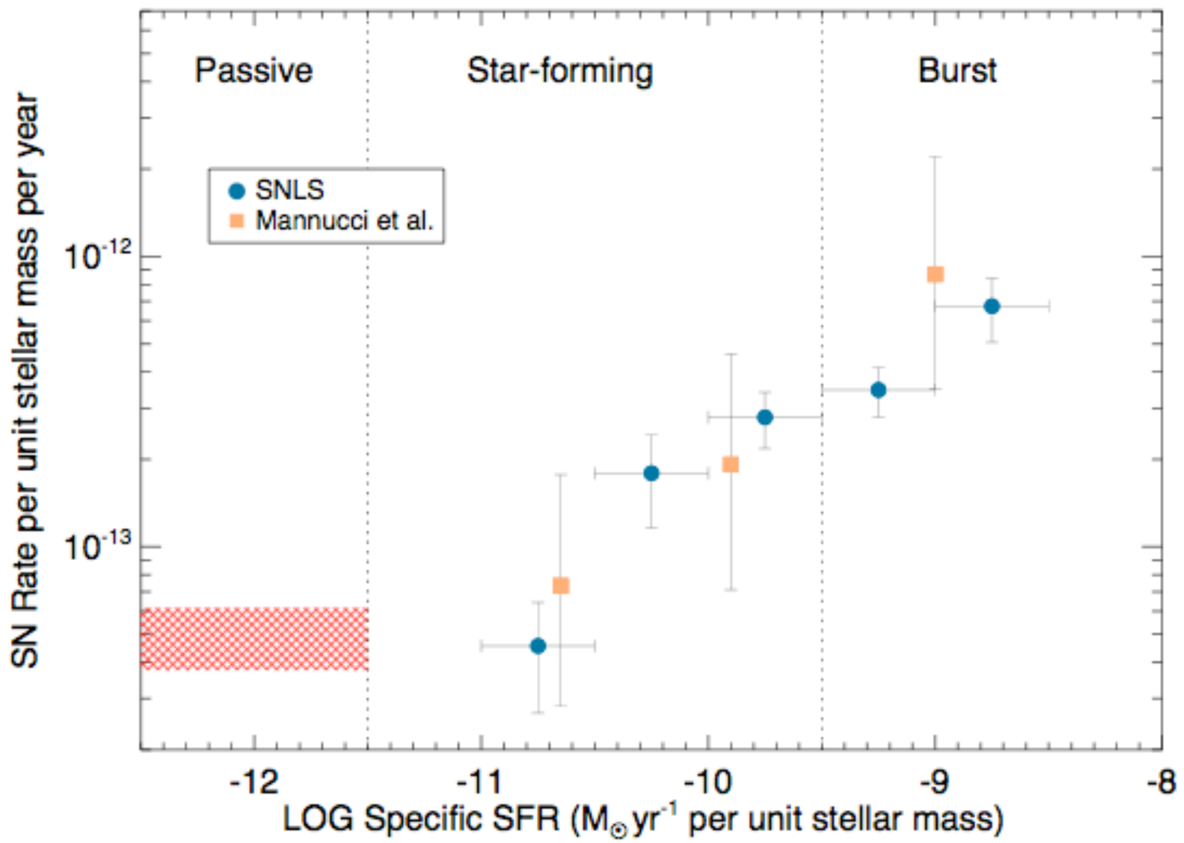
SN Ia rate depends on SFR

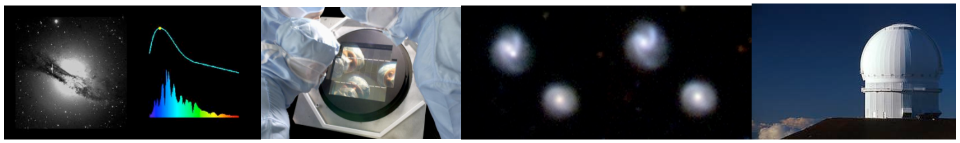
SNR/M



Mannucci et al 2006
Sullivan et al 2006

SFR/M

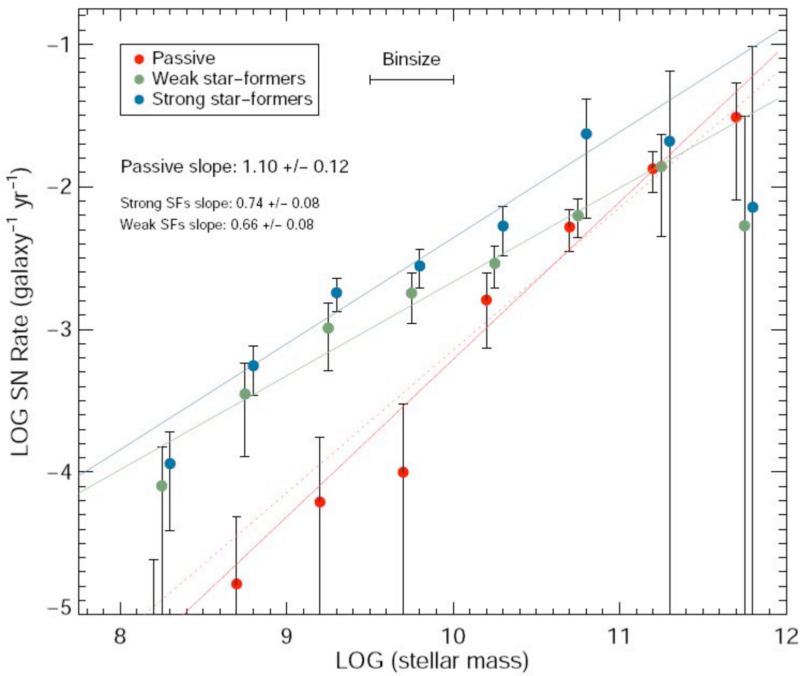
www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf



Scannapieco and Bildsten 2005

$$\mathrm{SN\ rate} = A \cdot M + B \cdot SFR$$

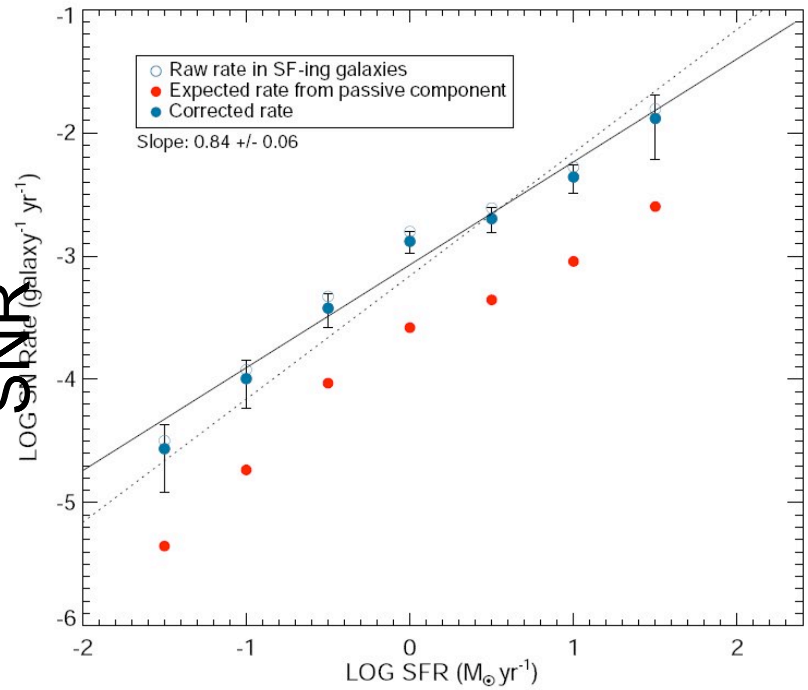
SNR



M

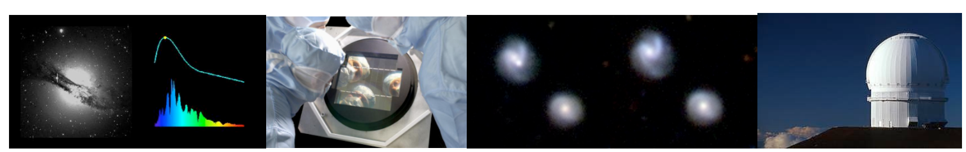
Sullivan et al 2006

SNR



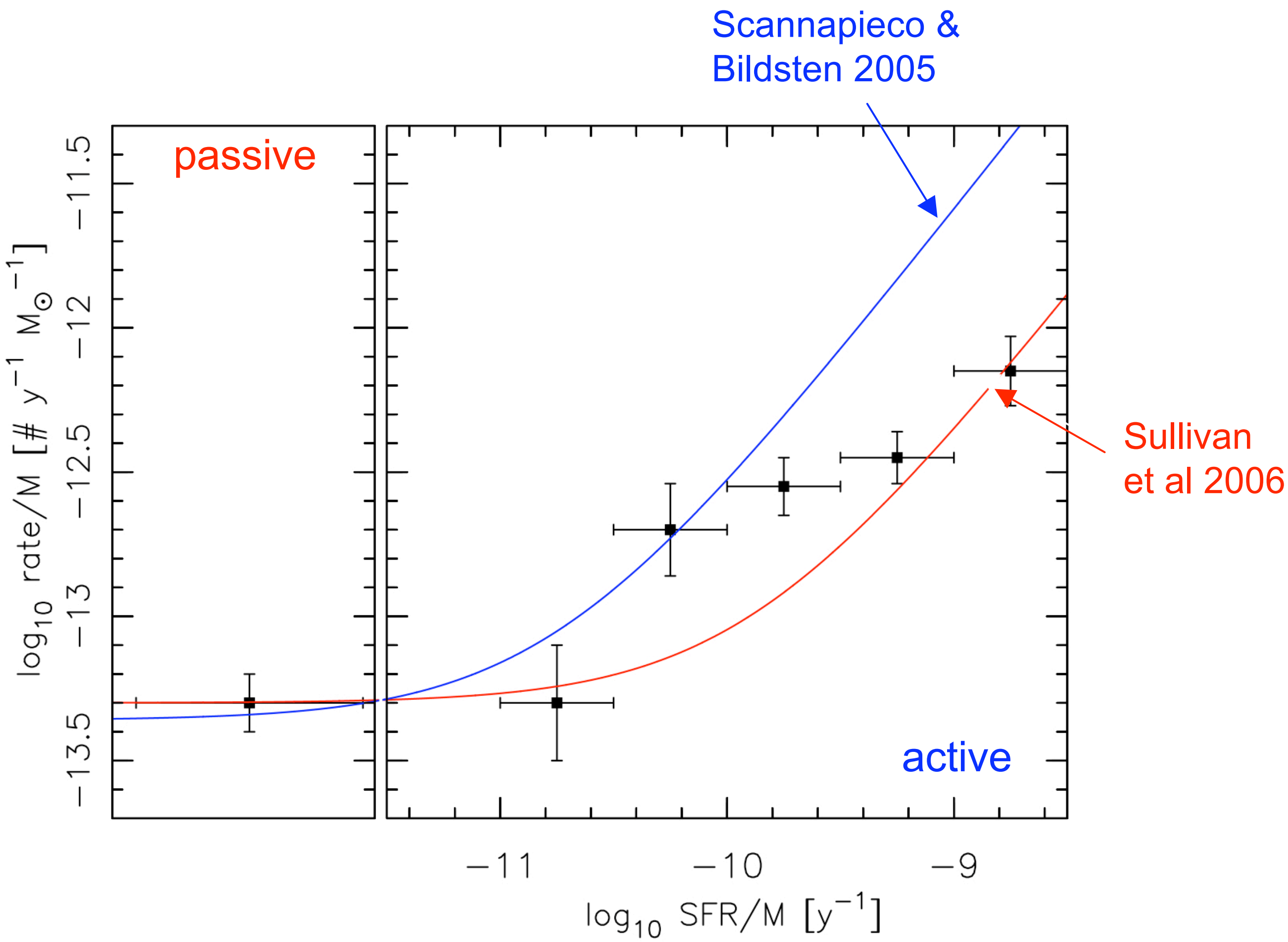
SFR

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf



$$\text{SN rate} = A \cdot M + B \cdot SFR$$

$$\rightarrow SNR / M = A + B(SFR / M)$$



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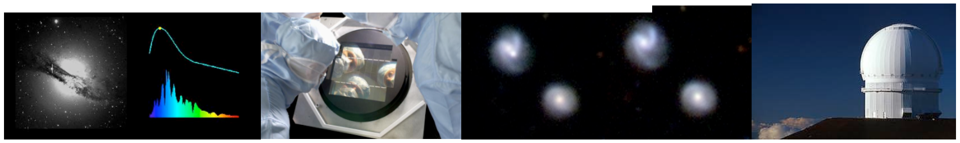

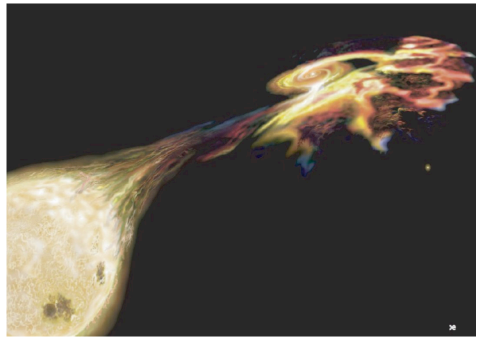

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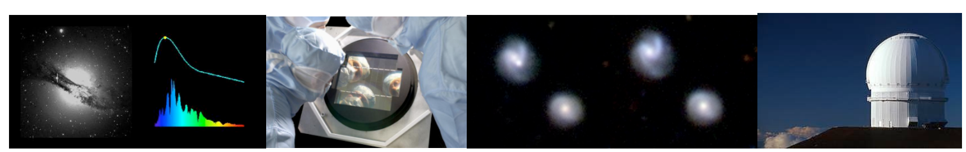
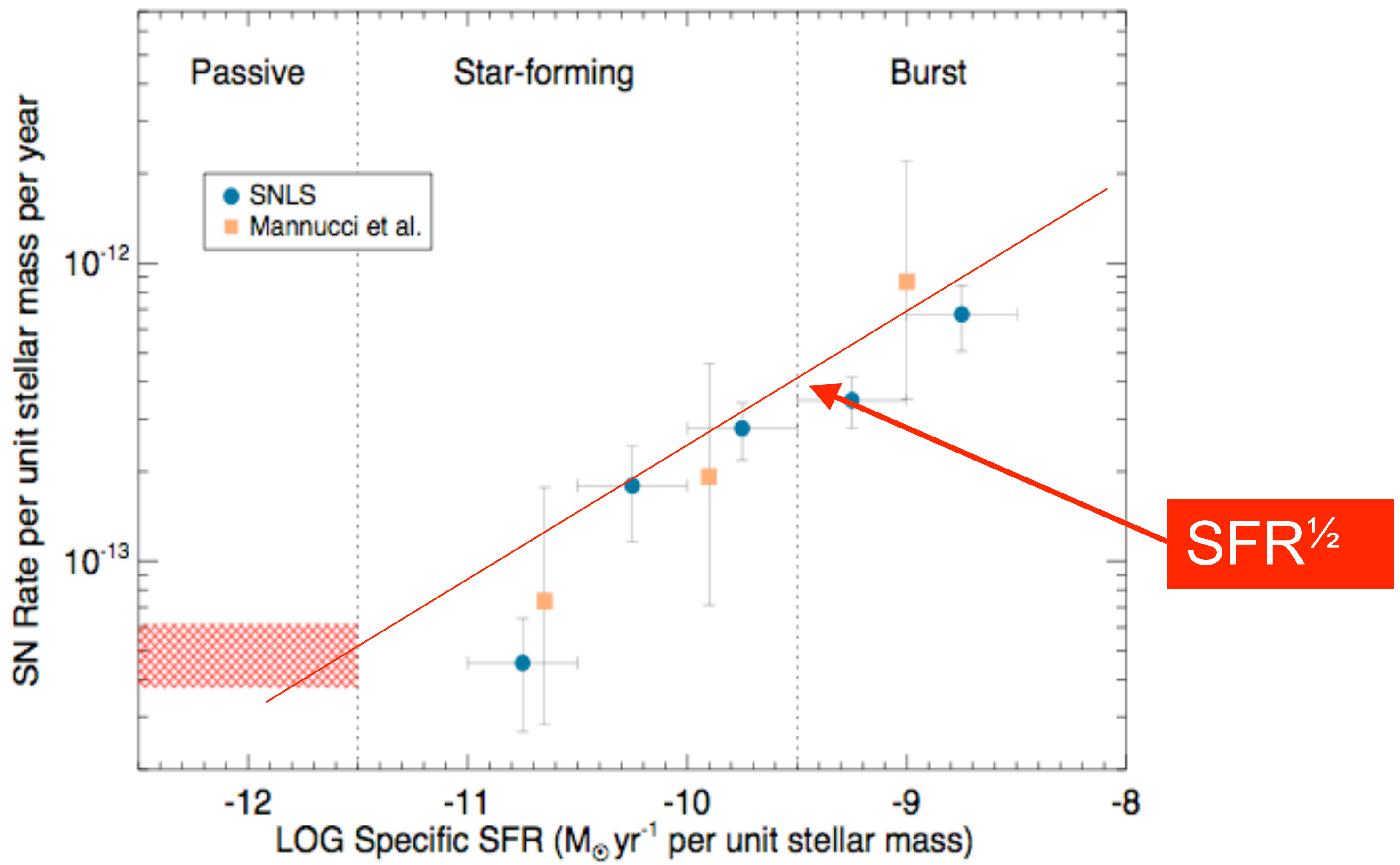


SN Ia rate depends on SFR

$$cf. \quad SNR/M = A + B(SFR/M)$$



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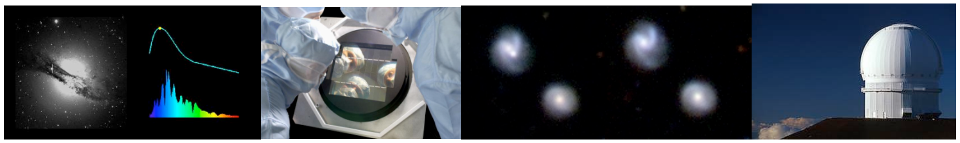
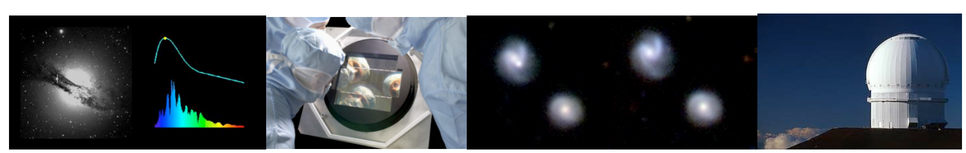


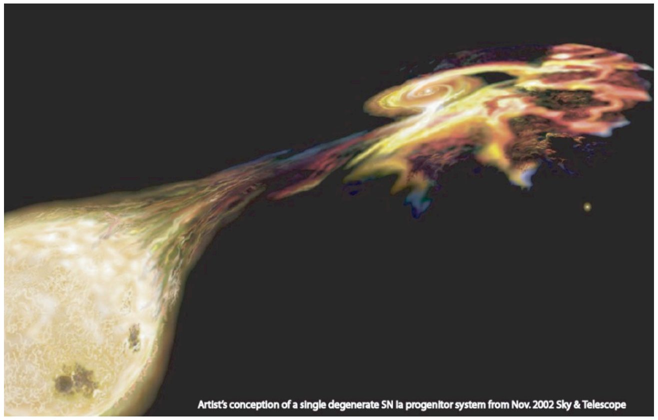
A+B: Dirty Questions …

$$SNR = A \cdot M + B \cdot SFR$$
$$SNR/M = A + B\,(SFR/M)$$

- Does this imply two paths to SNe Ia? …
- … or is there a simple unifying picture that can be used to understand the A+B prescription for the SN Ia rate?
  - Continuum of delay times – more natural?
- *Why do the A and B values have the values that are observed?*
- *Why ~√SFR dependence rather than ~SFR?*
- *Why is fit so poor in the SNR/M -- SFR/M plane, given great fit in the SNR - SFR plane??*



Simple Model for WD formation



mass fcn $\frac{dN}{dM} \propto M^a$

evol timescale $\tau \propto M^b$

$$a \cong -2.35, \quad b \cong -2.5$$

$$M \propto \tau^{1/b}, \frac{dM}{d\tau} \propto \tau^{1/b-1}$$

$$\frac{dN}{d\tau} = \frac{dN}{dM} \cdot \frac{dM}{d\tau}$$

$$\propto \tau^{(a-b+1)/b}$$

$$\propto \tau^{-0.5\pm}$$

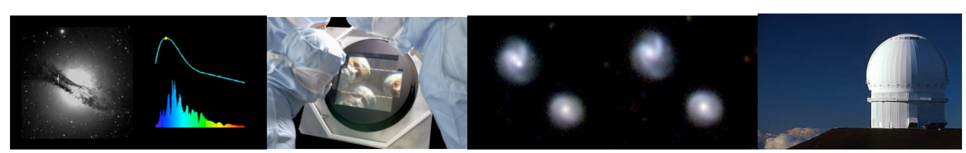
Assume

- Salpeter IMF
- $t_{evol} \sim M^{-2.5}$

Result:

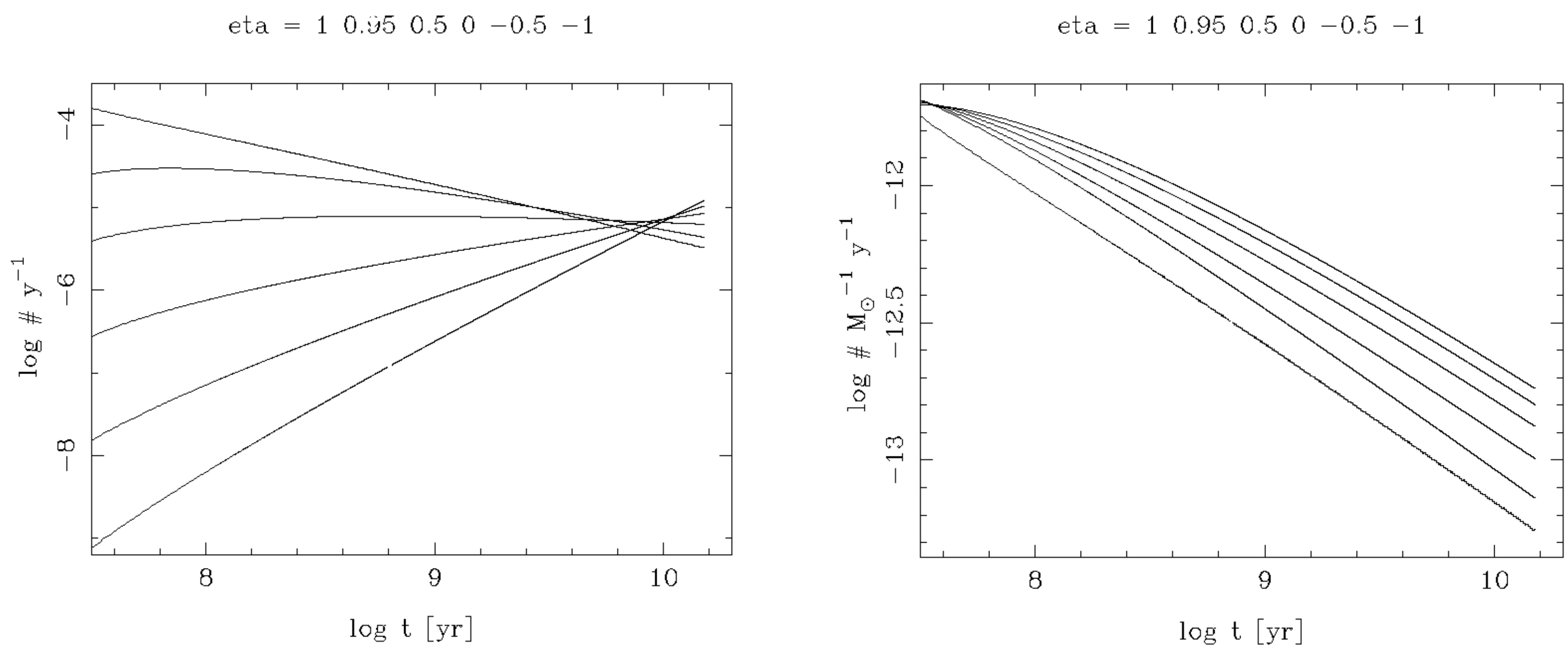
- WD formation rate ~ $t^{-0.5}$

www.astro.uvic.ca/~pritchet/SN/A580-2008-IV.pdf



WD Formation Rate vs Time

- Simple SFR(t) ~ $t^{-\eta}$ to allow for range of ages
- Correct ages



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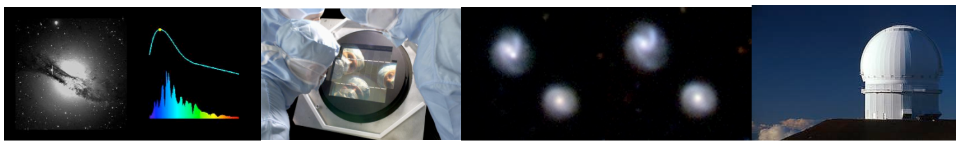
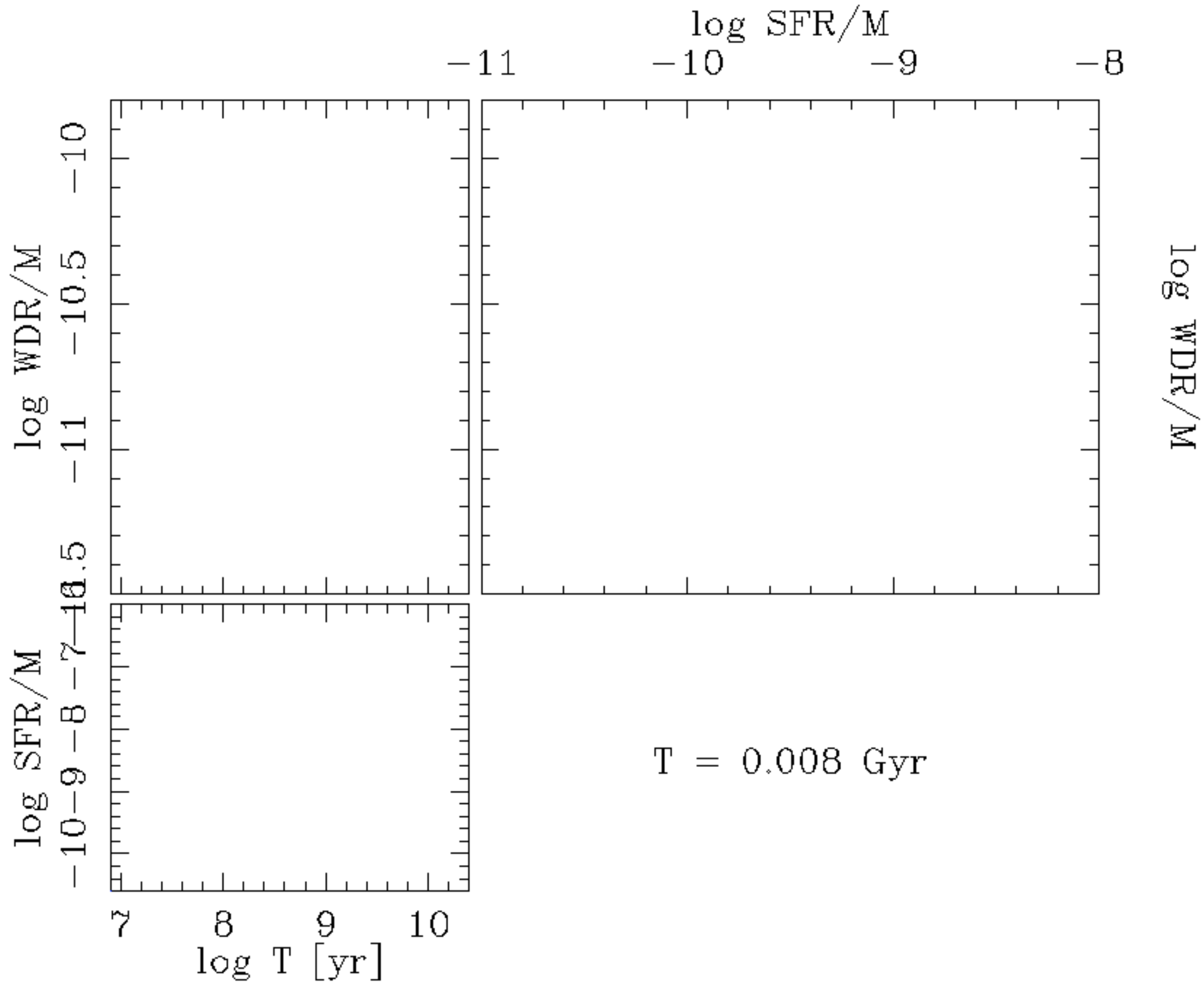
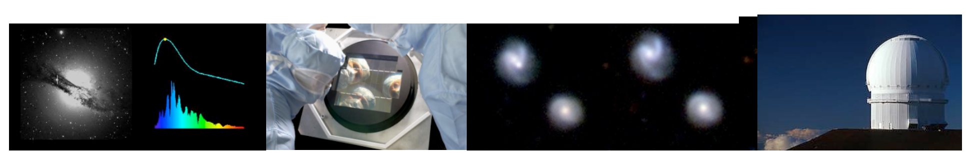


4 different η values





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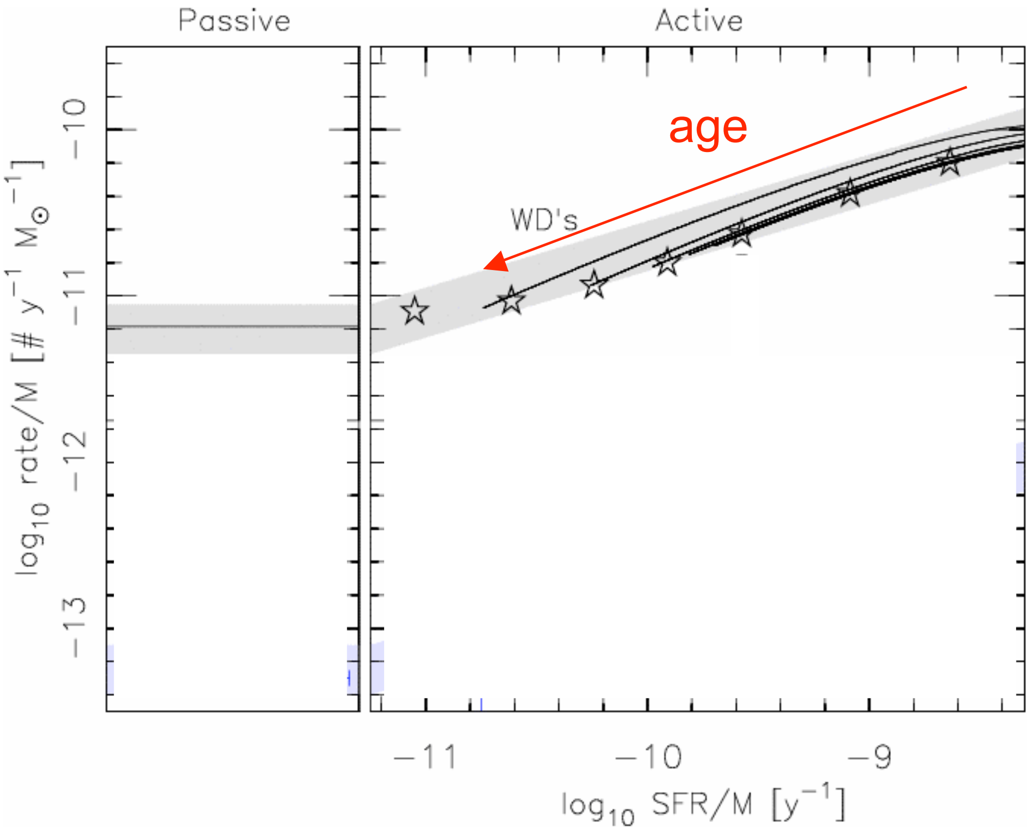
Models vs Observations



- includes passive galaxies
- SFR~t$^{-\eta}$, expon, Pegase infall, composite pops, random bursts …
- *Locus of WD formation rates independent of SFR(t)*

SN Ia rate is 0.8±0.2% of the WD formation rate

= conv eff if q=1

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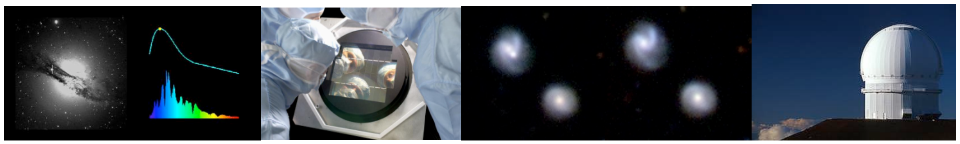
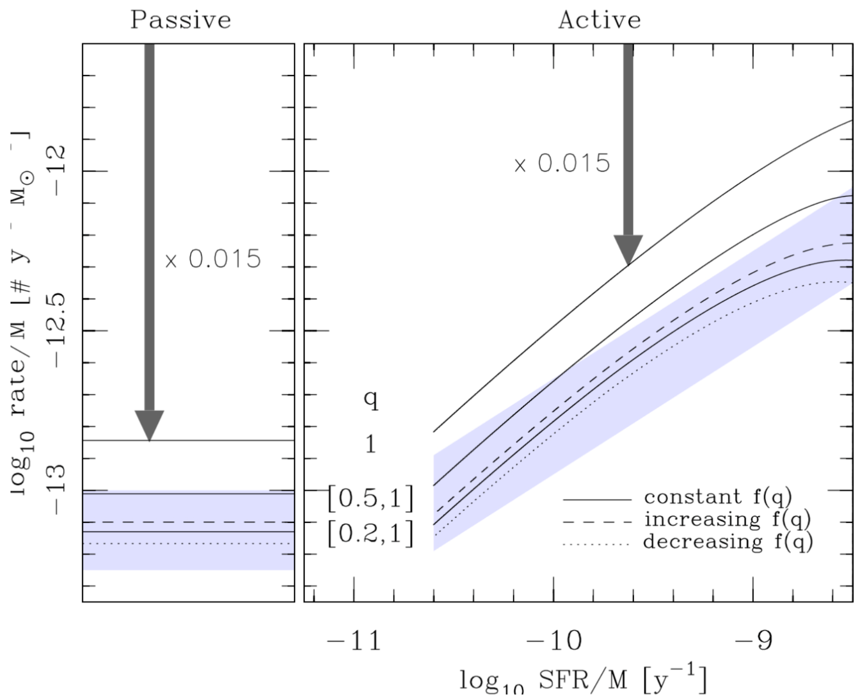


WD-SN Ia conversion efficiency



SD model:

- Delay time depends on evolutionary time of secondary
- Delay time = $t_{WD} + \Delta t(q)$, where $q=m_2/m_1$
- For close binaries, distribution of q is flat or slowly increasing - secondaries not drawn from IMF

Observations "can be described by" an SD model with ~1-2% of WD's becoming SNe Ia.

- constant conversion efficiency (X)
- OK for any mass range for which SD channel dominates

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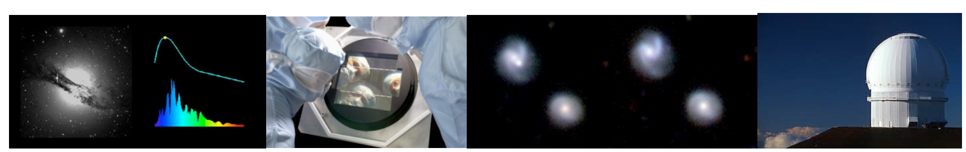
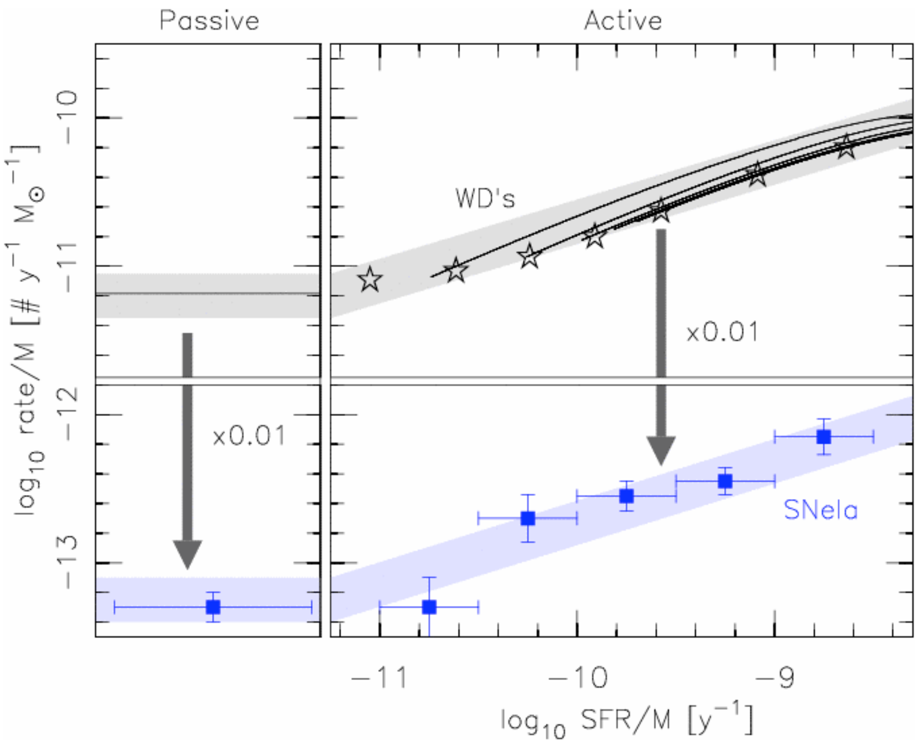


Meaning



- Only physics is evolutionary timescales + SD assumption
- Single component model – not A+B
  - Same model for active and passive
  - Single free parameter normalization - $f_{SN\ Ia}$
- Continuous distribution of delay times

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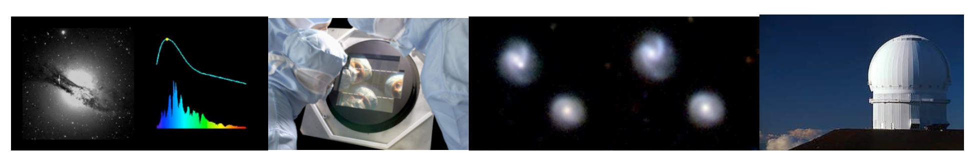
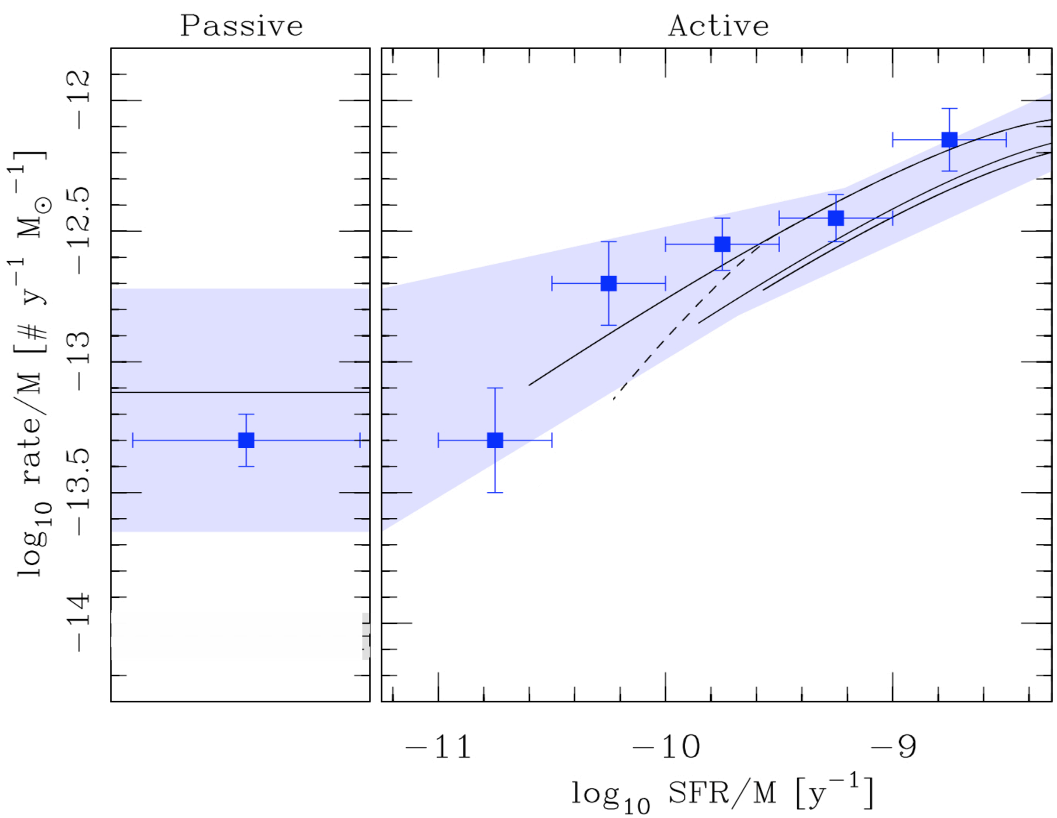


DTD ~ $t^{-0.5\pm0.2}$



- Independent of SD model or assumptions re efficiency
- $t^{-0.5}$ what you expect for SD + constant conversion efficiency

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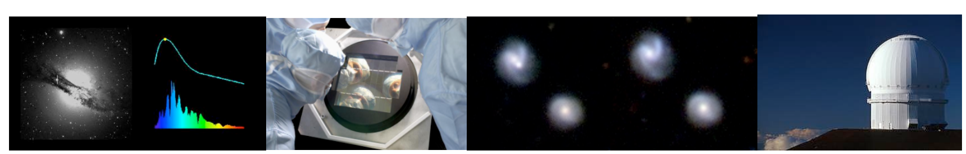
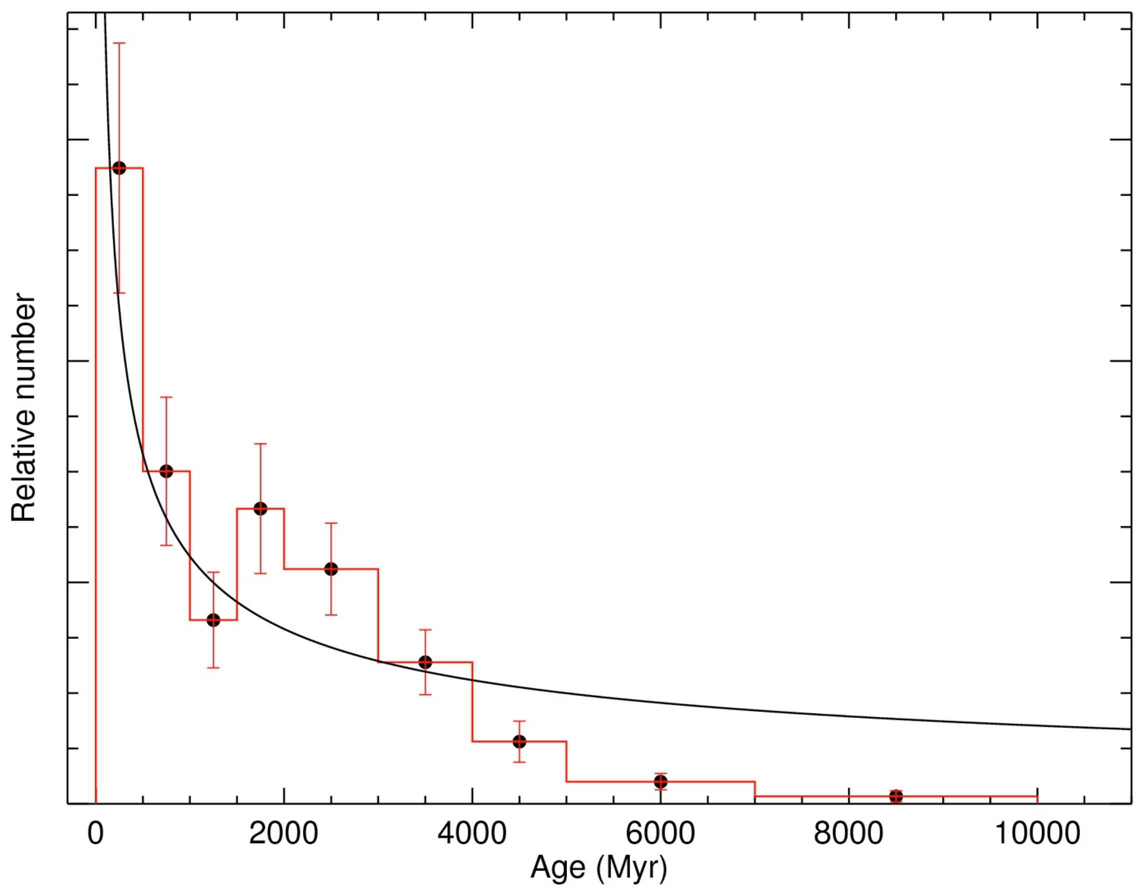


Sullivan empirical DTD

- $t^{-0.5}$
- Ignores last 2 points
- *cf.* Nomoto, Totani (this mtg)



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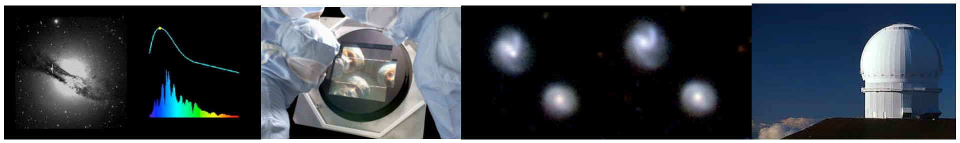
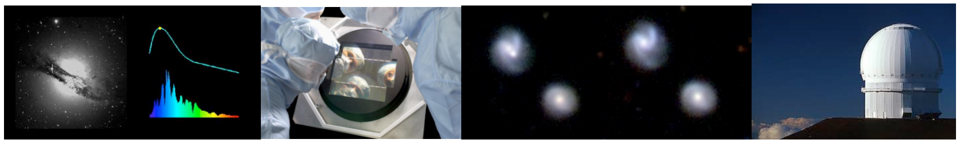


Efficiency vs mass (SD)

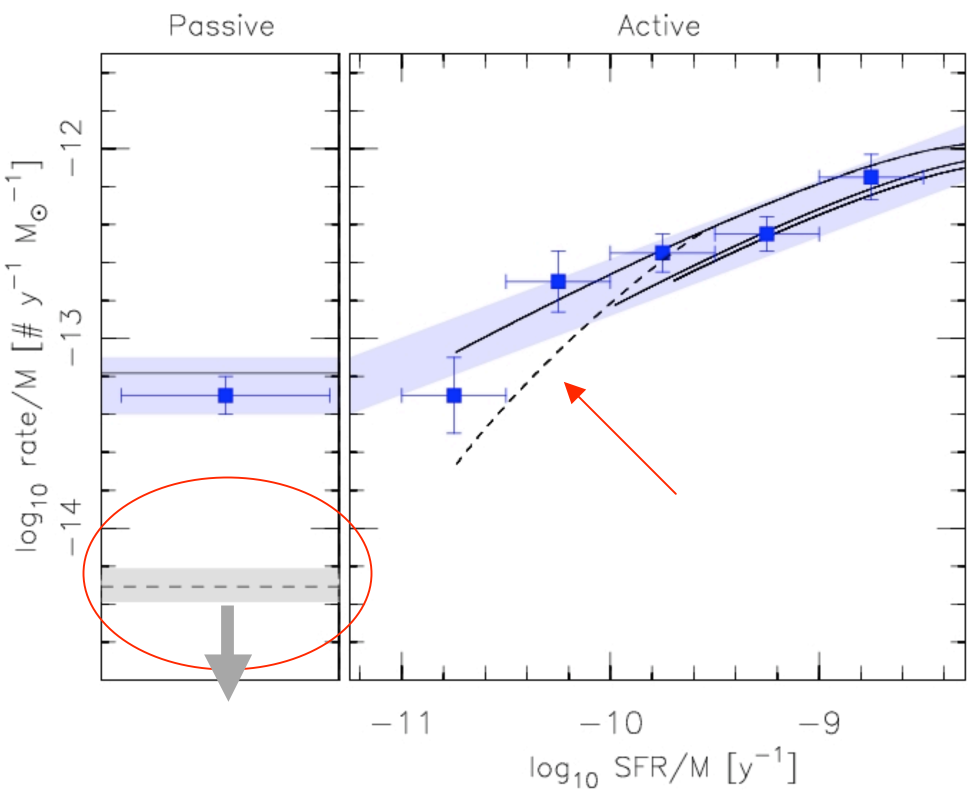
- 1 M_{sun} main sequence stars find it very difficult to get to the Chandra mass and make a Type Ia SN (e.g. Greggio 2005, Yungelson & Livio 2000, …)
  - Close binaries with primary < $2M_{sun}$ make a He WD, not a C+O WD
  - Mass arguments: 1 M_{sun} on the m.s. makes a 0.5 M_{sun} WD, hard to imagine 2 x 1 M_{sun} making a 1.4 M_{sun} WD
  - Most of companions to 1 M_{sun} stars haven't evolved yet
  - binary frequency lower for low mass objects (?)

Therefore fraction of WD's that make SNe Ia should be much lower at low masses (>10x).



Effects of efficiency

- Normalized at high mass (short timescale) end
- Assume efficiency drops by 10x from M=3 to 1 Msun (conservative)



- ***Single Degenerate model cannot explain all SNe Ia. Some other mechanism must be involved for at least some SNe Ia.***
- ***But for any mass range where SD dominates, conversion efficiency is ~1%***

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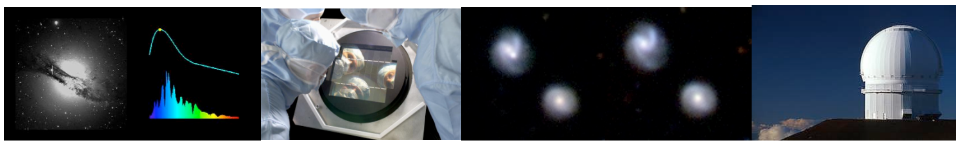
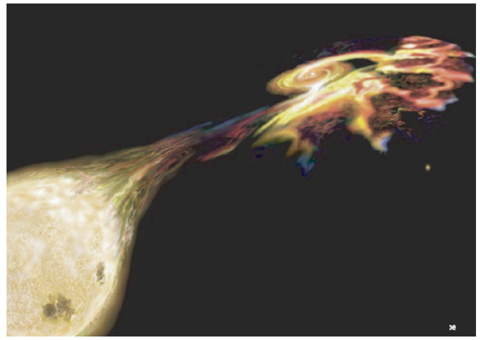
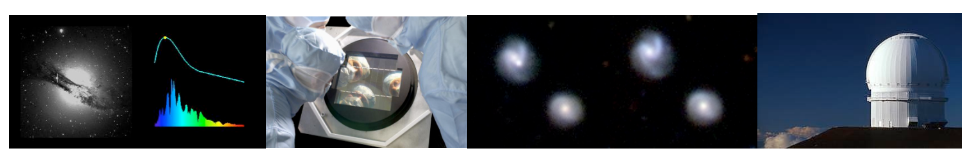
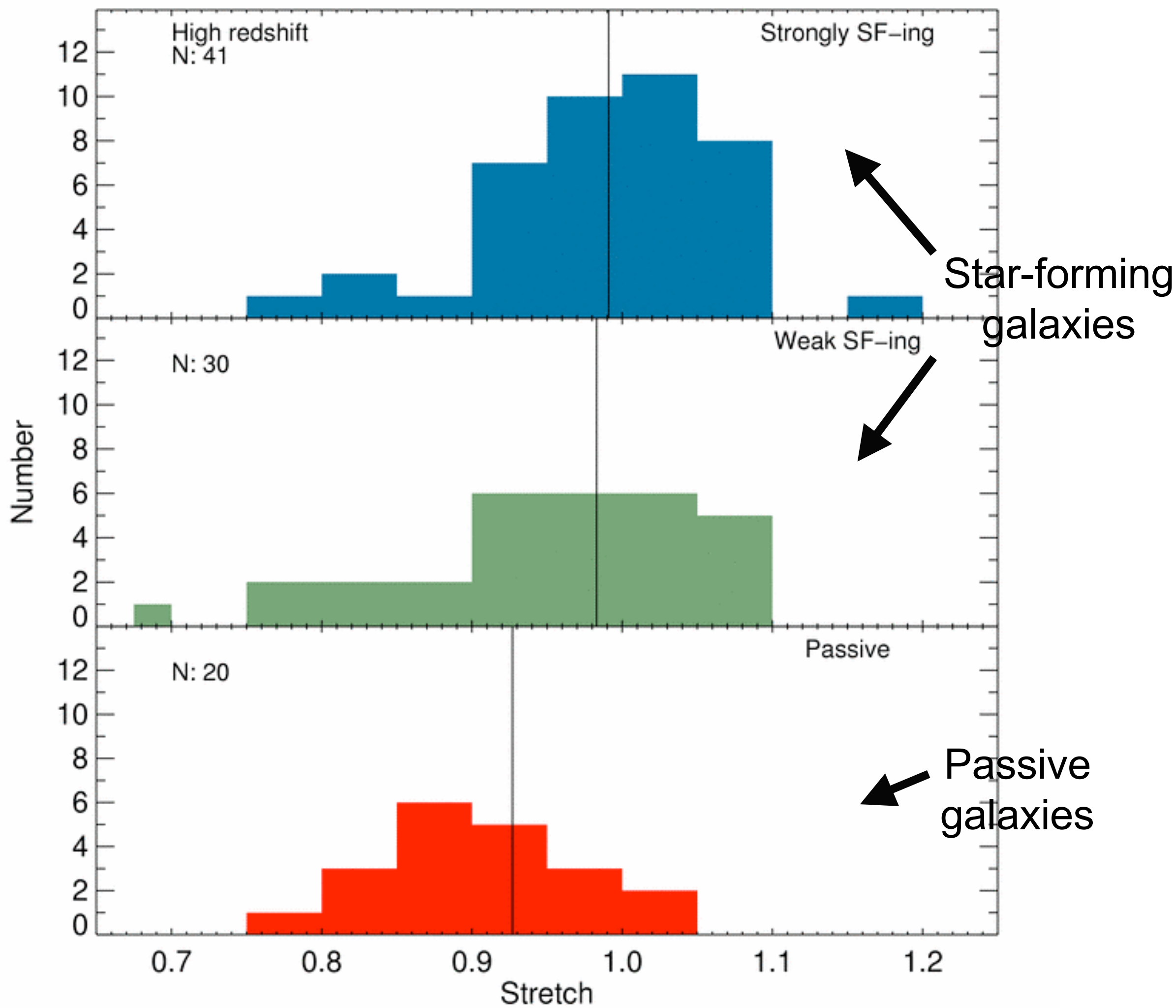




- *Introduction - SD vs DD etc*
- *03D3bb - SuperChandra!*
- *SNIa rates vs. Host Galaxy Properties*
- *A Simple Model and its Implications*
- *Implications for Cosmology?*
- *Conclusions*



“Stretch” and Environment



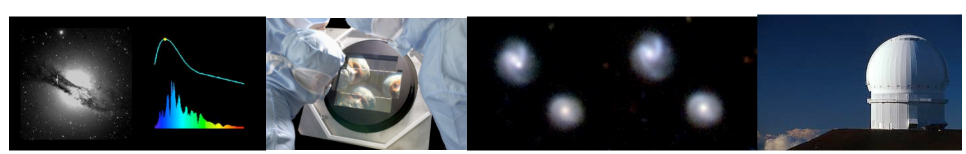
Similar trend observed at low-redshift

Simplest inference:

Older progenitors produce smaller stretch, fainter SNe

Younger progenitors produce larger stretch, brighter SNe

←Fainter/faster SNe Stretch Brighter/slower SNe →



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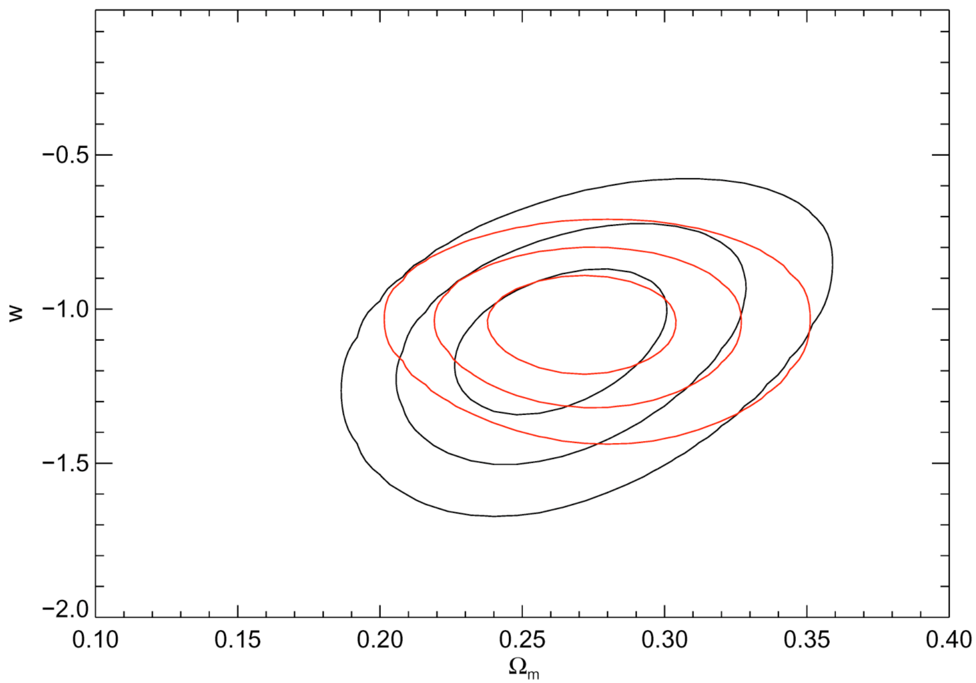
Cosmology vs Host SFR

- Black: SFR < 10^{-12} Msun/yr, red > 10^{-12} Msun/yr



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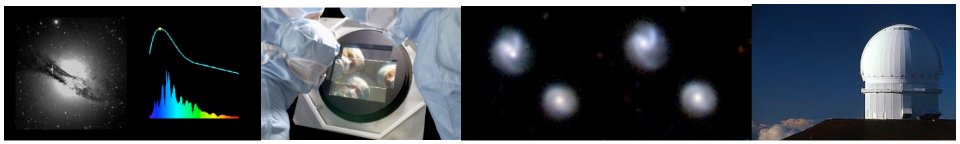

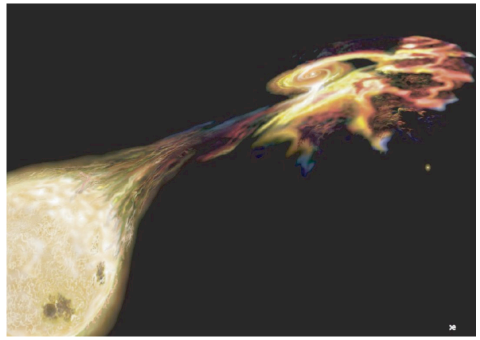

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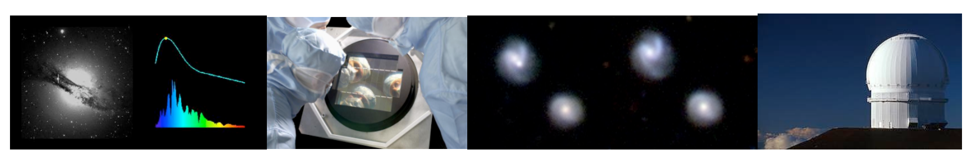

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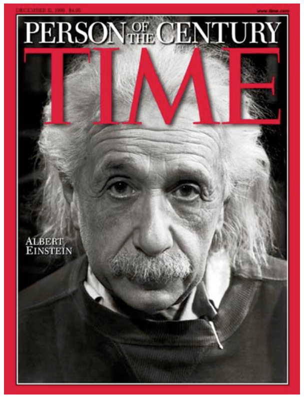
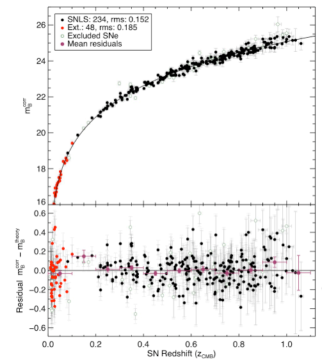
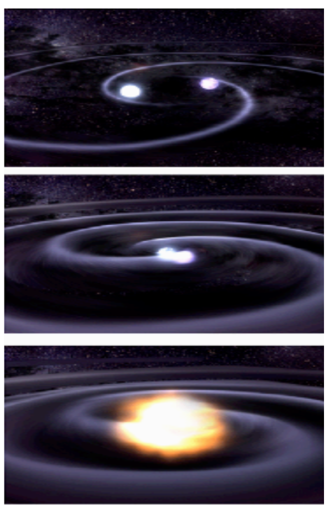
Conclusions

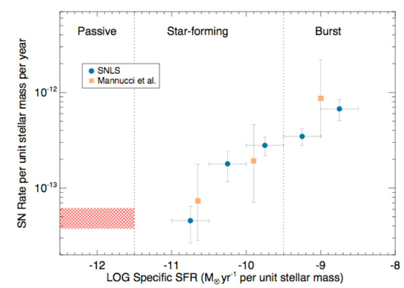


- w = -1 (preliminary) from 3rd year data (N=250).
  - Dark energy resembles pure Einsteinian cosmological constant (vacuum energy).
  - Most accurate estimate of w yet





- SNIa rate depends on SFR
  - progenitors found in young and old stellar populations
  - Natural explanation from evolutionary timescales
  - 1% of white dwarfs become SNeIa
  - SNeIa not only from single degenerate progenitors



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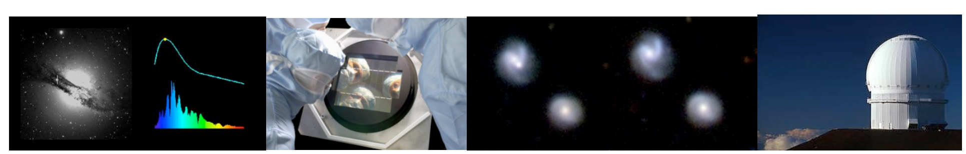

Nine Challenges for the Future

dw/dz

- Systematics - calibration to <1%
- Astro systematics - z dependence of properties

- Astrophysical understanding of SNeIa
- Origin of intrinsic scatter - reduce?

- Importance of BAO, WMAP for Ω_m
- Assumption of flatness

- Low z sample - largest gain
- Higher z sample
- Larger samples with DES, LSST, JDEM …

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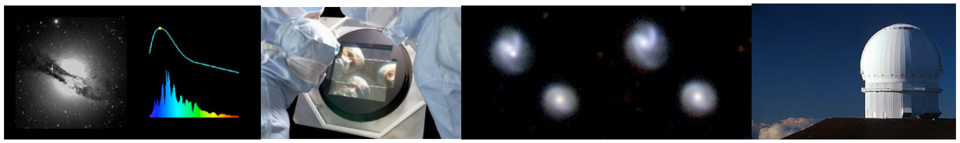
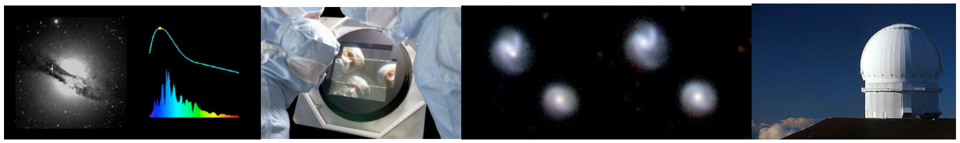
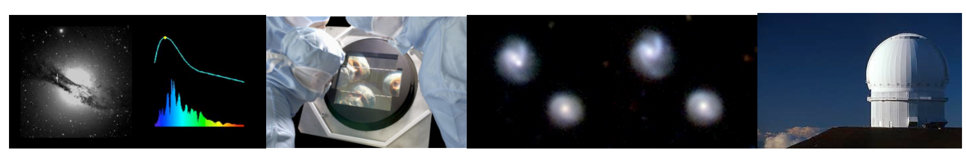


Projects

- Reduce intrinsic scatter?
- Photometric classification? (esp. Ibc vs. II)
- Nature of late time light curves in Ia's, and relation to early-time light curves
- Rates of SNeII vs z and corresponding SFR(z)
- High z (z>1), AO photometric followup
- Sub-mm properties of SNIa hosts and SNII hosts
- Search for SNeII in ULIRGs
- A+B or equivalent **within** hosts (i.e. vs R!)
- UV properties of SNeIa





Cosmic SFR(z)

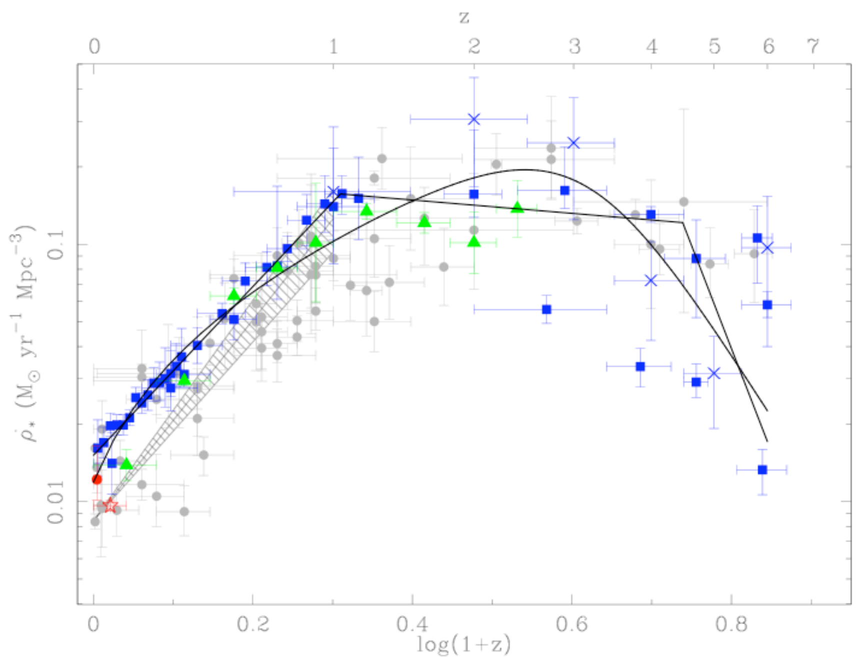
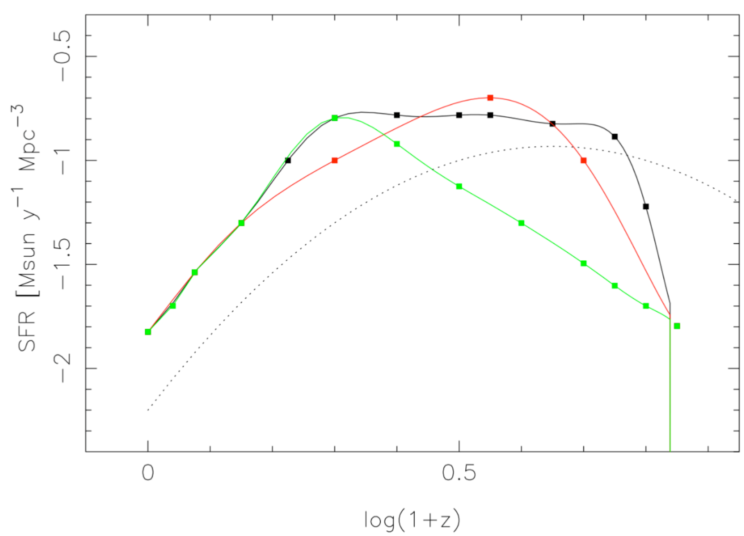


Figure 1. Evolution of SFR density with redshift (scaled assuming the SalA IMF). Circles are from the compilation of Hopkins (2004). The hatched region is the 24 μm SFH from Le Floc'h et al. (2005). Triangles are 24 μm data from Pérez-González et al. (2005). The open star at $z = 0.05$ is based on 1.4 GHz data from Mauch (2005). The filled circle at $z = 0.01$ is the Hα estimate from Hanish et al. (2006). Squares are UV data from Baldry et al. (2005); Wolf et al. (2003); Arnouts et al. (2005); Bouwens et al. (2003a,b, 2005a); Bunker et al. (2004); Ouchi et al. (2004). Crosses are the UDF estimates from Thompson et al. (2006).

Hopkins and Beacom 2006



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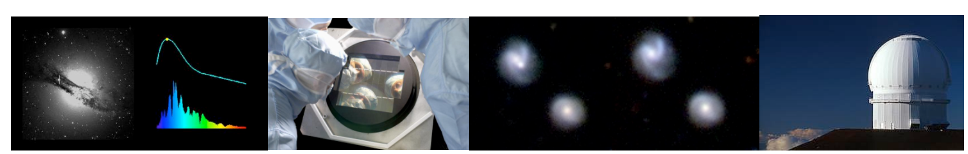
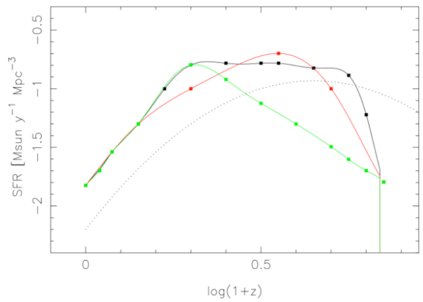
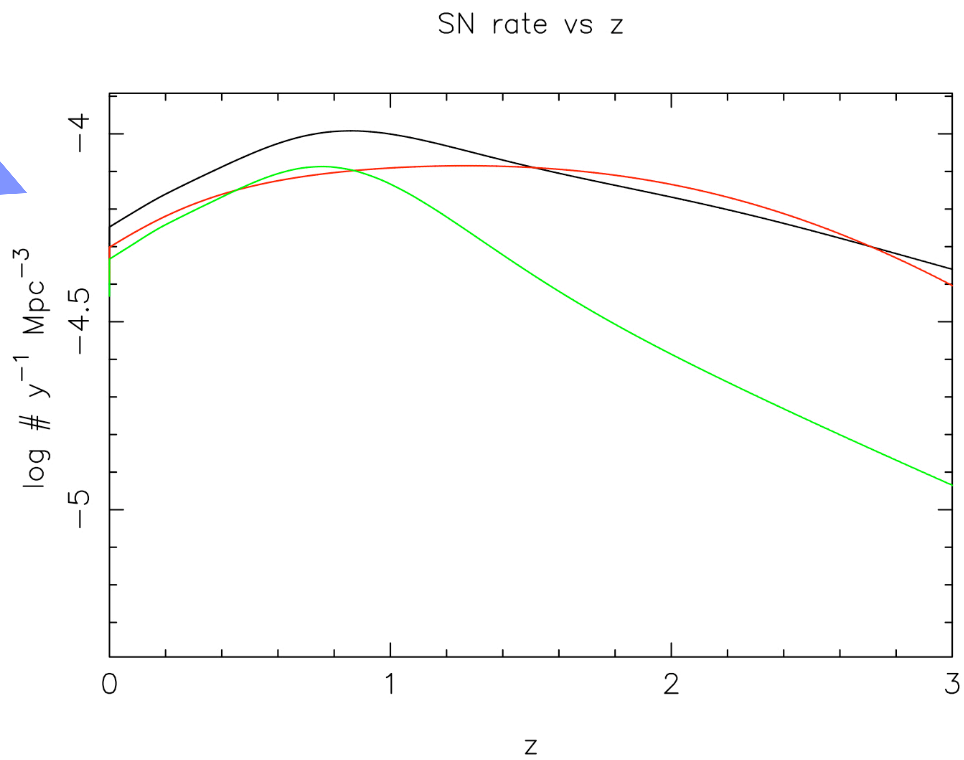


SNR predictions from SFR(z)





- SFR(z) gives SFR(t) per Mpc^3
- Normalization somewhat arbitrary
- SN rate very sensitive to exact SFR(z)

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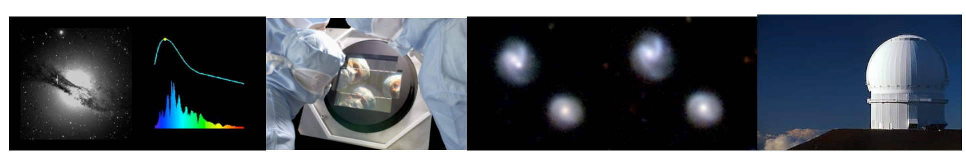
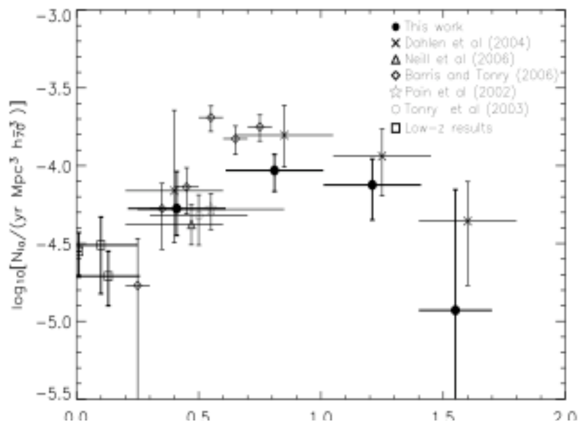
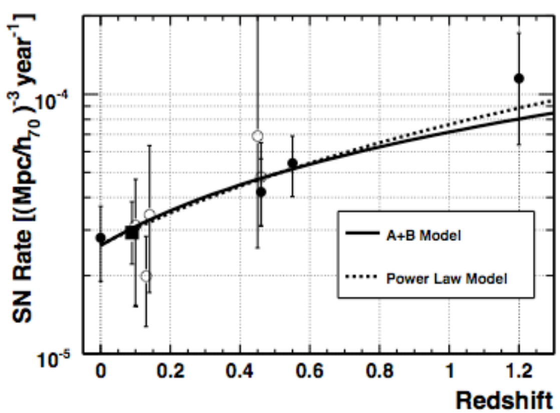


SNR predictions from SFR(z)

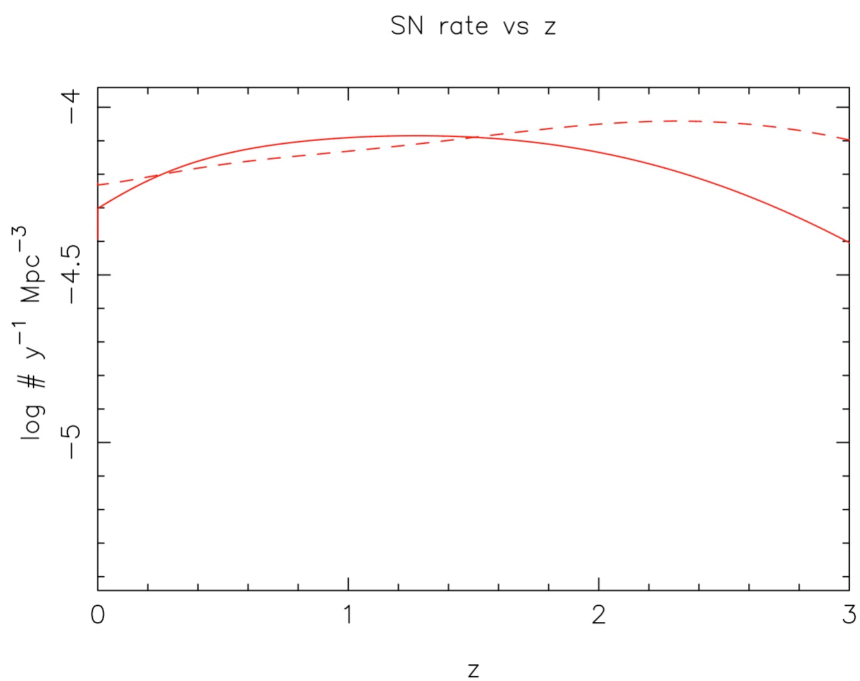
- Solid=model, dashed=A+B (Sullivan 2006)

Kuznetsova et al 2008





Dilday et al 2008



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