Finding Failed Supernovae

Scott Adams

March 21, 2017

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Evidence for fSNe

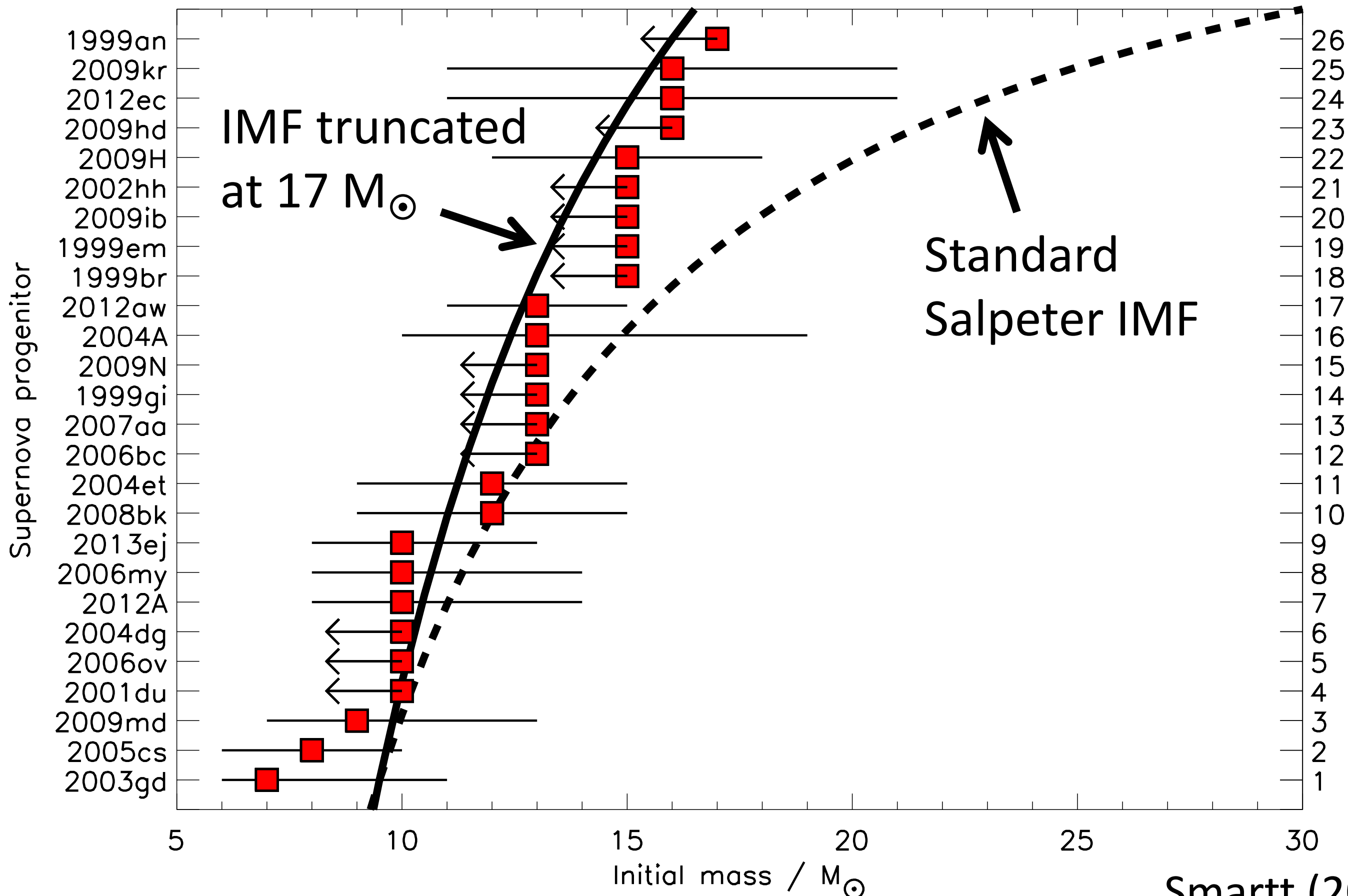
The Mapping Between SN Progenitors and Outcomes

- ~10 with reasonable multi-band photometry, almost all for Type IIP

- There is a deficit of higher mass progenitors (Kochanek et al. 2008)

- Best quantified by Smartt et al. (2009) – Type IIP red supergiant progenitors seen from ~8 to ~$17M_{\odot}$, but expected to die as a red supergiants up to ~$25M_{\odot}$
  - See Smartt 2015 for recent review

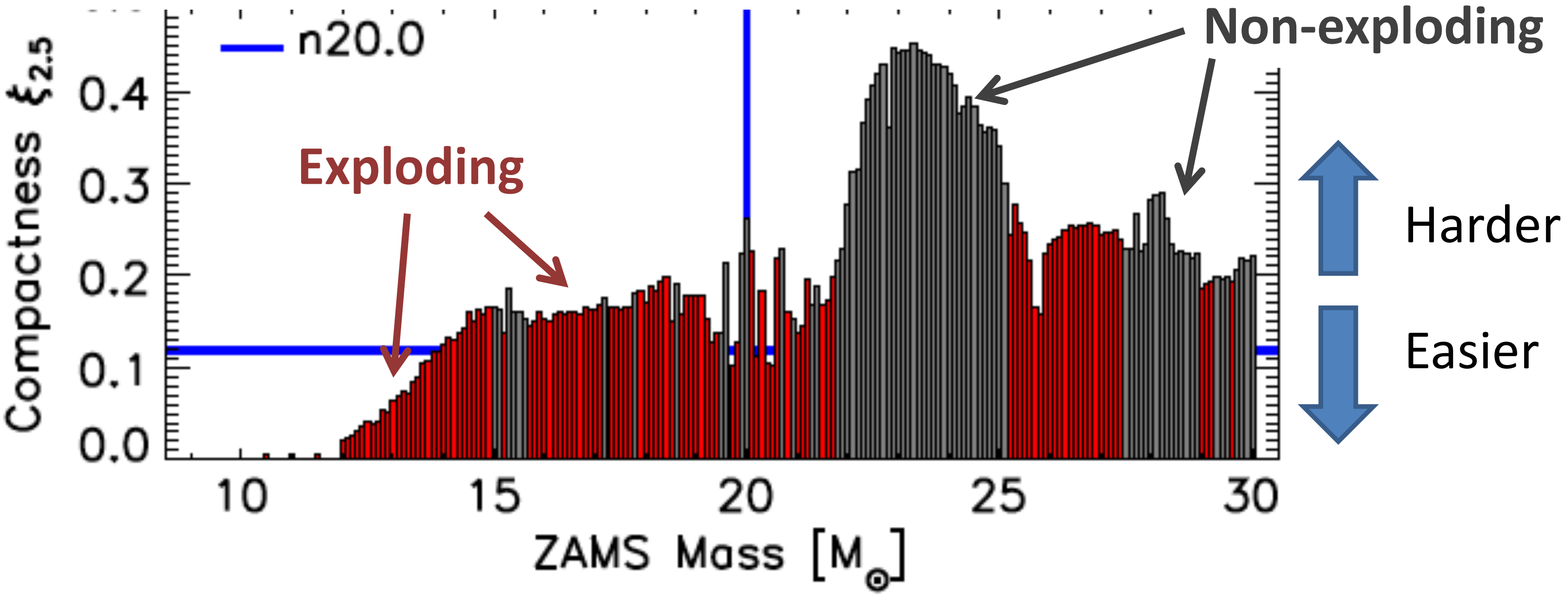
- Missing red supergiant progenitors would correspond to 10-30% of core collapses



Smartt (2015)

Explodability

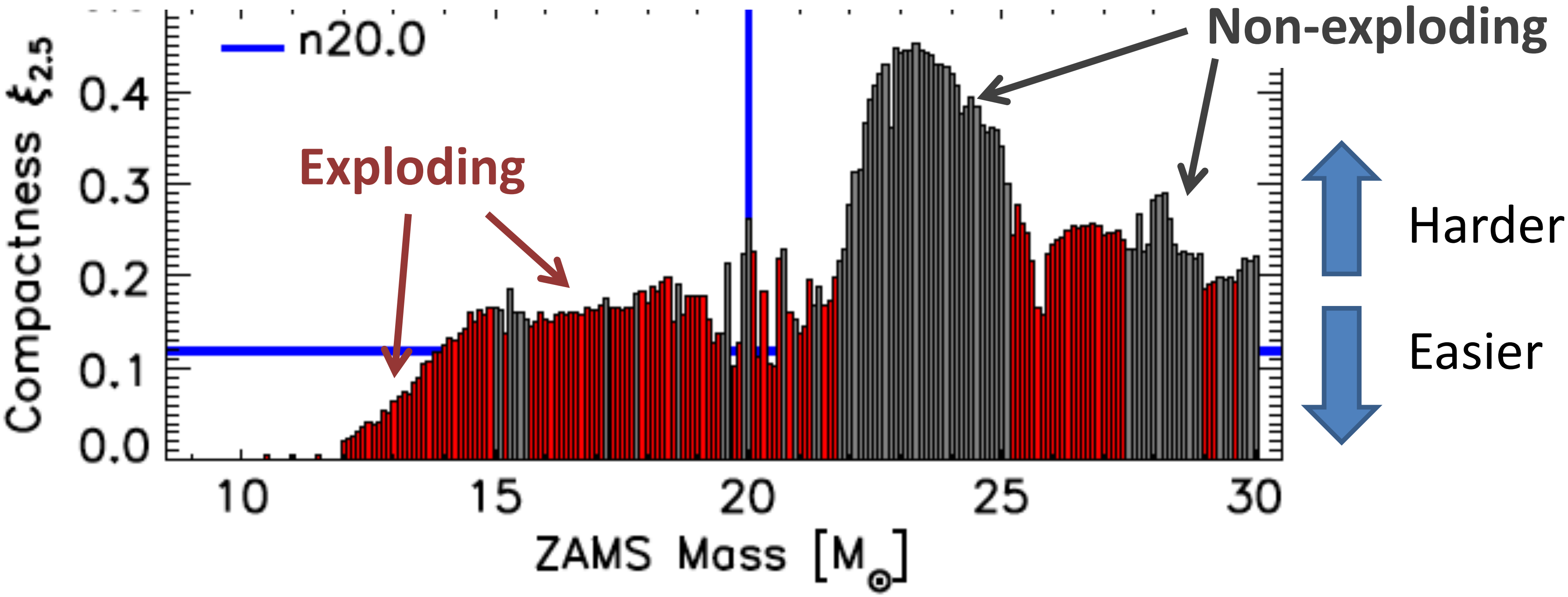
- Roughly characterized by "compactness" $\xi \sim M/R$ of the pre-collapse star outside the iron core
  - O'Conner & Ott (2011), Ugliano et al. (2012), Sukhbold & Woosley (2014), Pejcha & Thompson (2015), Ertl et al. 2016



Ertl et al. 2016

Explodability

- Rou**Distribution of progenitors essentially cuts off where the compactness jumps upwards**/R of the
  - O'C y (2014), Pejc



Ertl et al. 2016

Other Evidence

Same high mass progenitor deficit when estimating masses from nearby stellar population (Jennings et al. 2014)

Compact object mass function (Kochanek 2014, 2015)

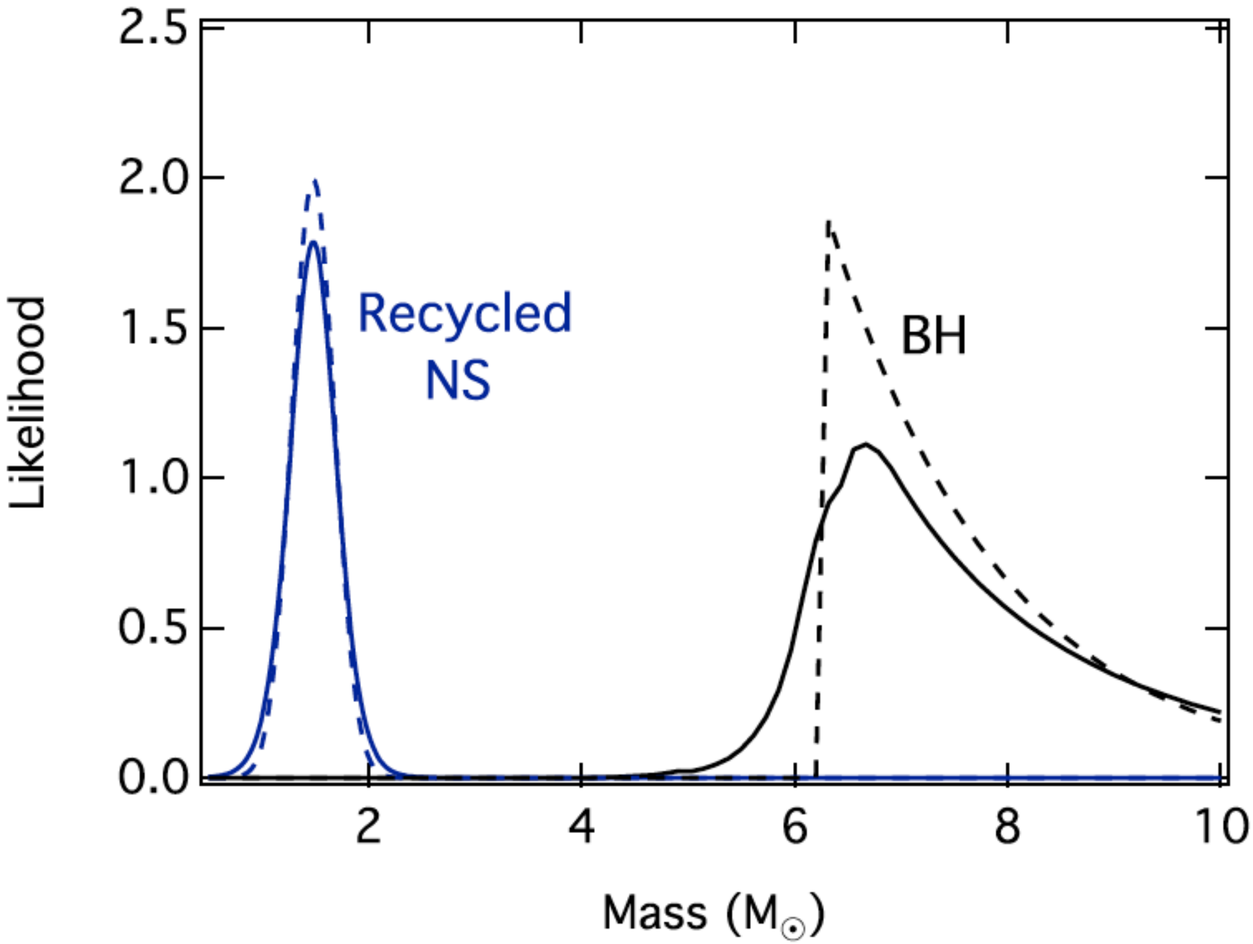
SN rate may not match massive star formation rate (Horiuchi et al. 2011, 2014)

Massive merging black holes detected by LIGO (Abbott et al. 2016)

Compact Object Masses

Difficult to produce mass gap with BHs formed by fallback

fSNe naturally explain the gap (Kochanek 2014,15)



Ozel 2012

Other Evidence

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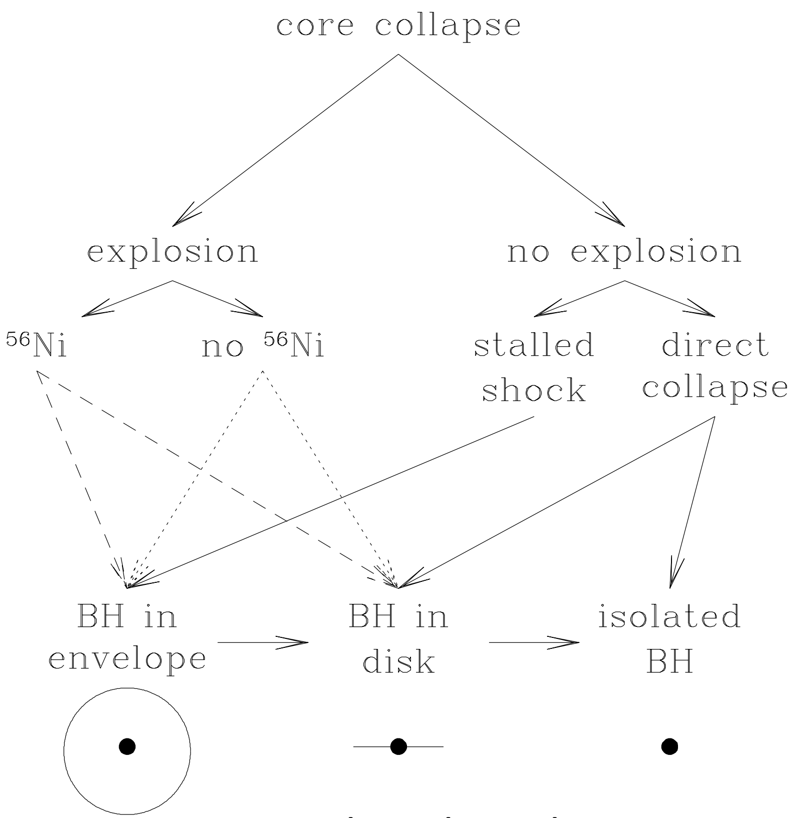
Associated Transients?



Kochanek et al. 2008

- Red supergiants → ejected envelope powers a ~ $10^6 L_\odot$, cool (~3000-4000K), long (~ year) transient powered largely by H recombination (Lovegrove & Woosley 2013), along with a ~10 day, more luminous, shock breakout peak (Piro 2013), and very late time dust formation (Kochanek 2014).
- Can have direct collapse with no transient (Woosley & Heger 2012)
- Accretion may power a short, luminous transient (Kashiyama & Quataert 2015)

Focus on disappearance rather than relying on transient signal

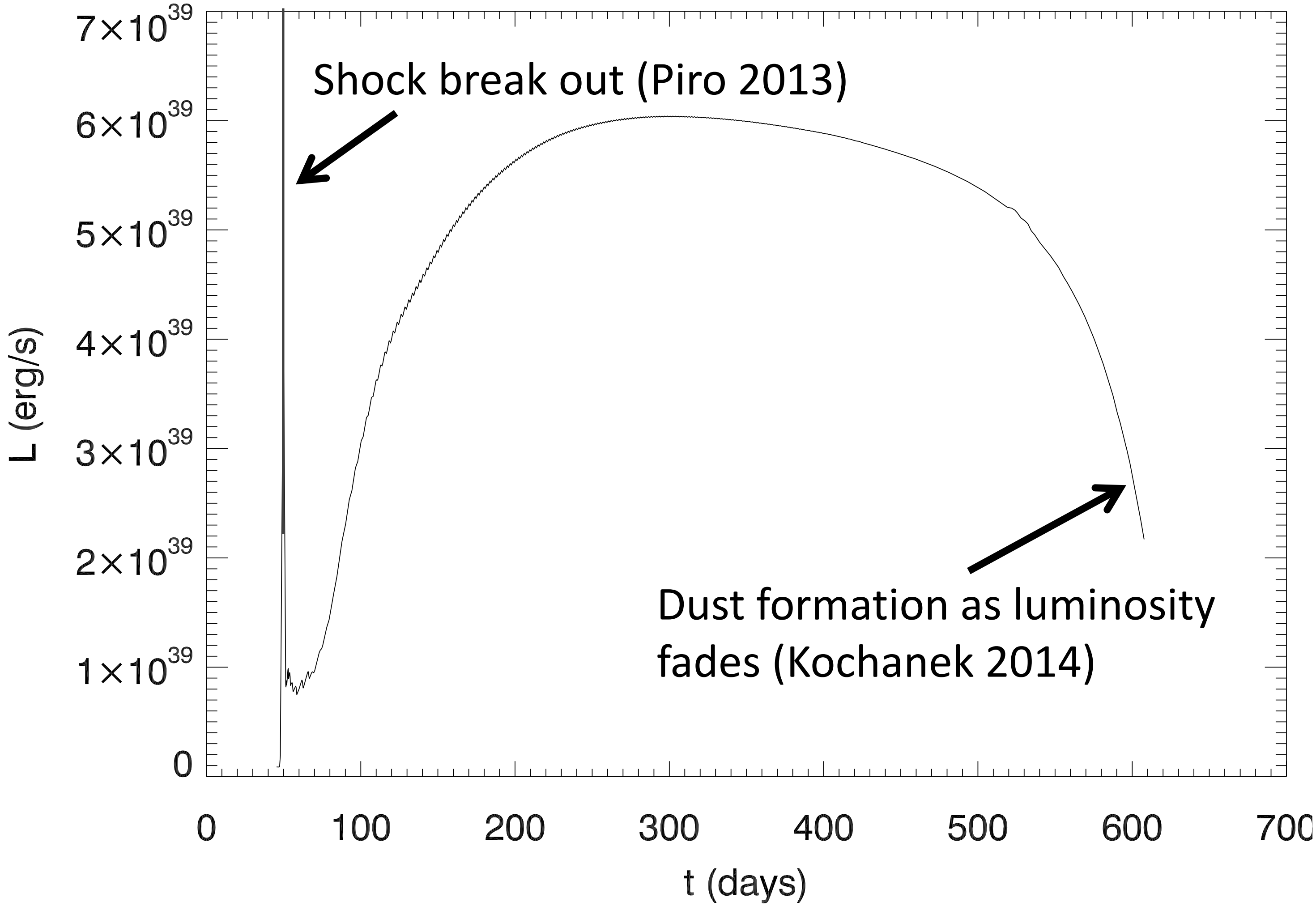
The Nadezhin (1980) Mechanism

- The envelopes of red supergiants are so weakly bound that the drop in gravitational potential during a failed SN through neutrino mass-energy loss unbinds the hydrogen envelope
- Numerically verified by Lovegrove & Woosley (2013)

→ Failed SN of red supergiants (and WR stars) produce black holes with the mass of the helium core not the total mass of the star

→ Failed ccSN provide the first natural explanation of the compact remnant mass function – successful SN (almost always) make NS with negligible fall back, failed SN make BH with the mass of the helium core (Kochanek 2014)

Nadezhin Mechanism



Lovegrove & Woosley (2013)

How Do You Find Failed SN?

Cleanest would be gravitational waves or neutrinos – but only possible in Galaxy, so rate is ~1/500 years

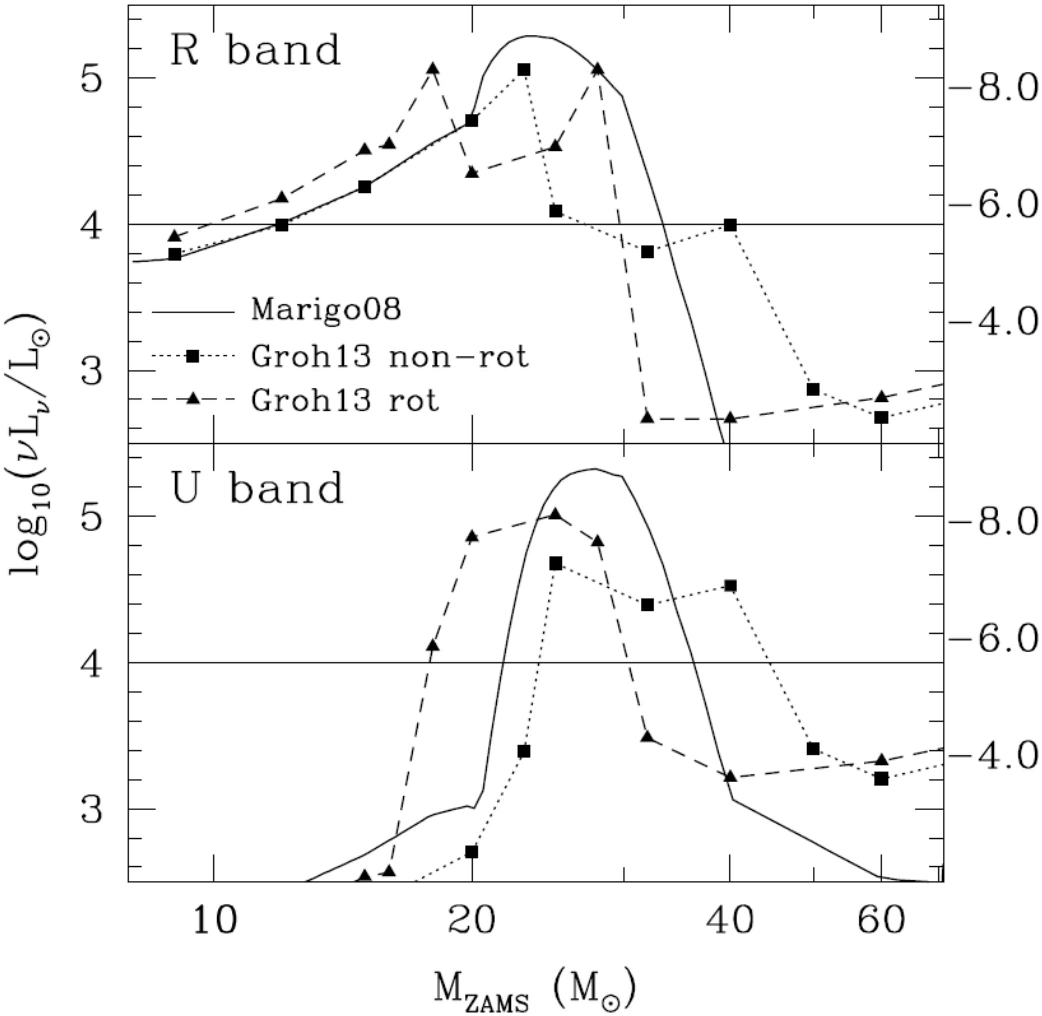
Instead search nearby galaxies for stars which "disappear", possibly with an intervening transient (Kochanek et al. 2008)

Feasible on an 8m to ~ 10 Mpc – galaxies with an SN rate of ~1/year → failed SN every 3-10 years

LBT Survey for Failed Supernovae

Kochanek et al. 2008; Gerke et al. 2015;
Adams et al. 2016a,b

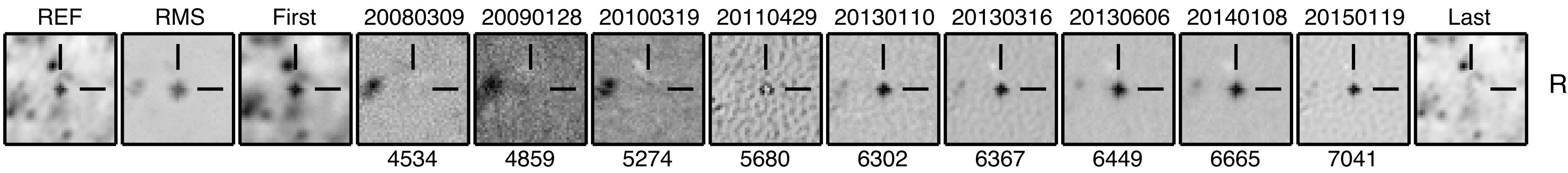
LBT Survey



Gerke et al. 2015

- 27 nearby galaxies
- Historical ccSN rate of ~ 1/year → failed SN every 3-10 years
- UBVR imaging to a typical depth of about 1 count per $L_\odot$
- Analyze using difference imaging
- Examine everything that:
  - varied by more than $10^4 L_\odot$ in any band
  - > $10^5 L_\odot$ for 3 months to 3 yrs

A Real Dying Star – SN 2011dh



Gerke et al. 2015

Supernova here May 31, 2011 (excised)!

- A roughly $10^5 L_\odot$, 13-7$M_\odot$, yellow supergiant (probably due to mass transfer – Maund et al. 2011, van Dyk et al. 2011, 2014)

Slowly Fading Candidate: N6503-SF1

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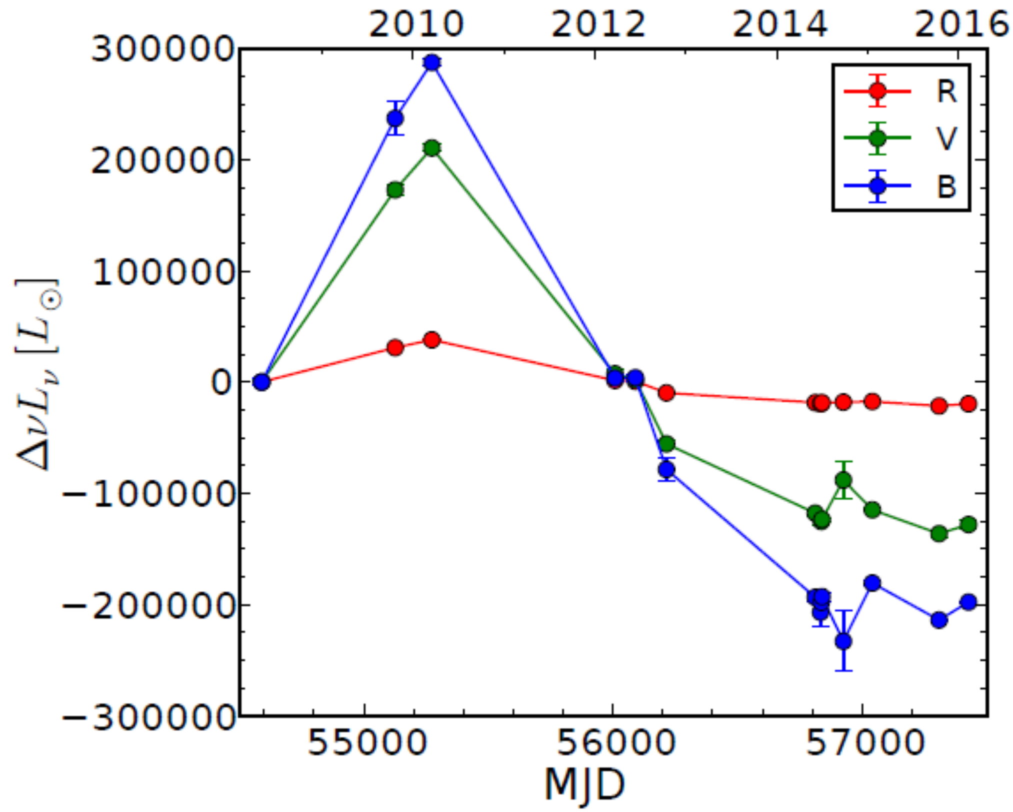
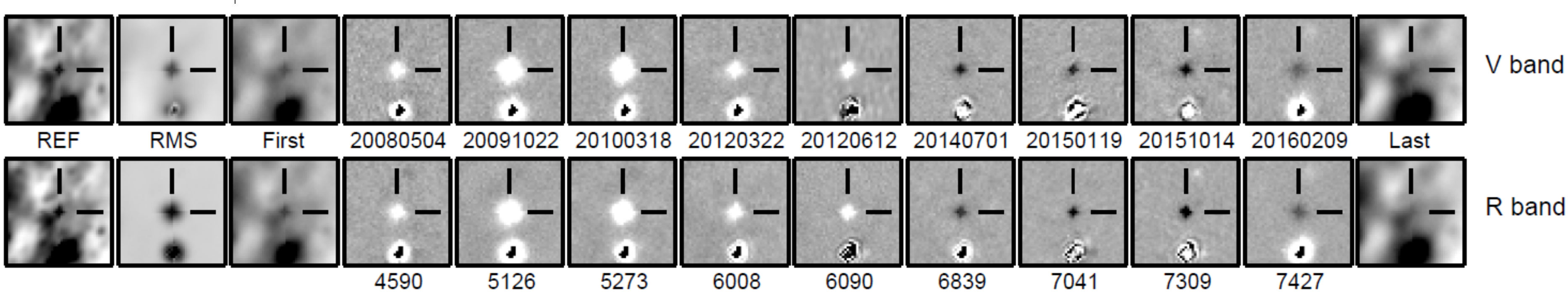


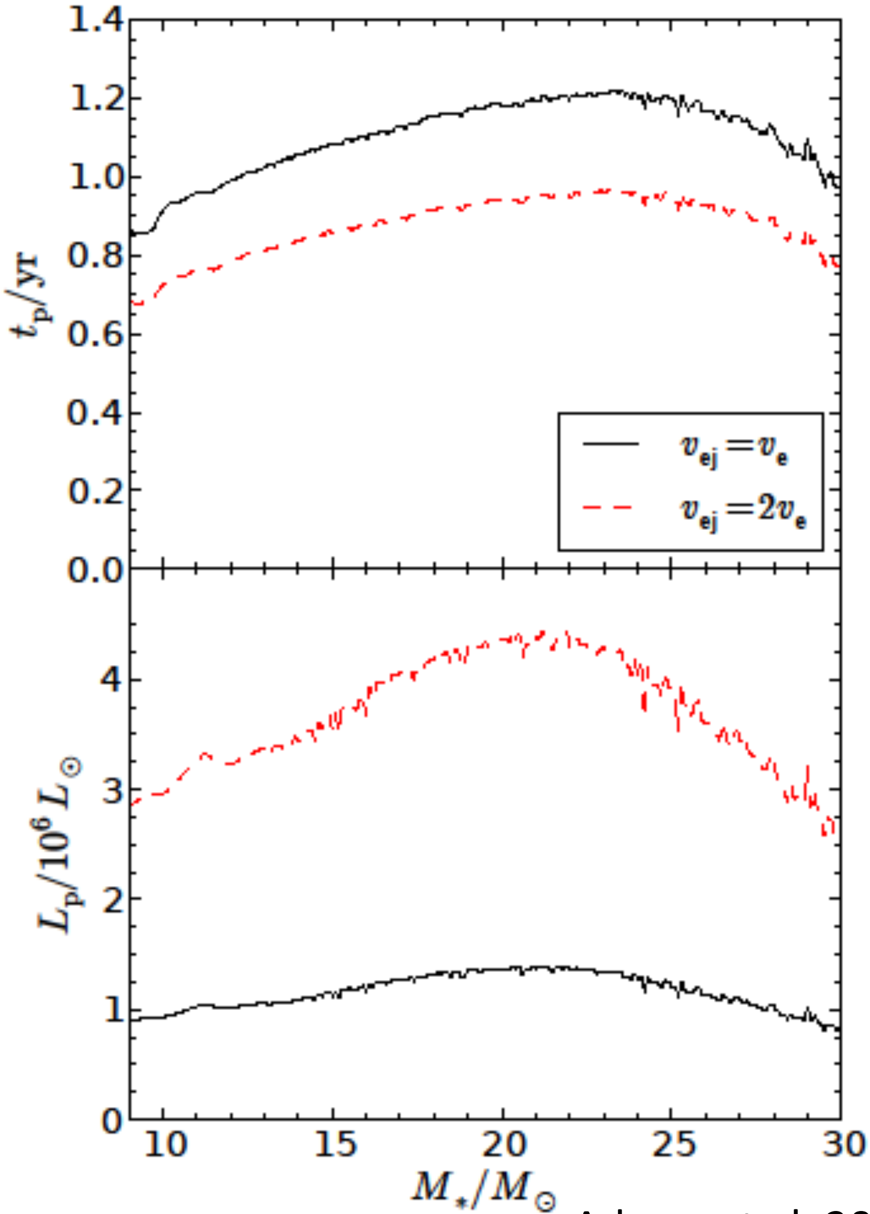


Adams et al. 2016a

Recombination-powered Transients

- Popov 1993 scalings solved in terms of escape velocity
- Max ~1 yr transient
- ~ $10^6 L_\odot$

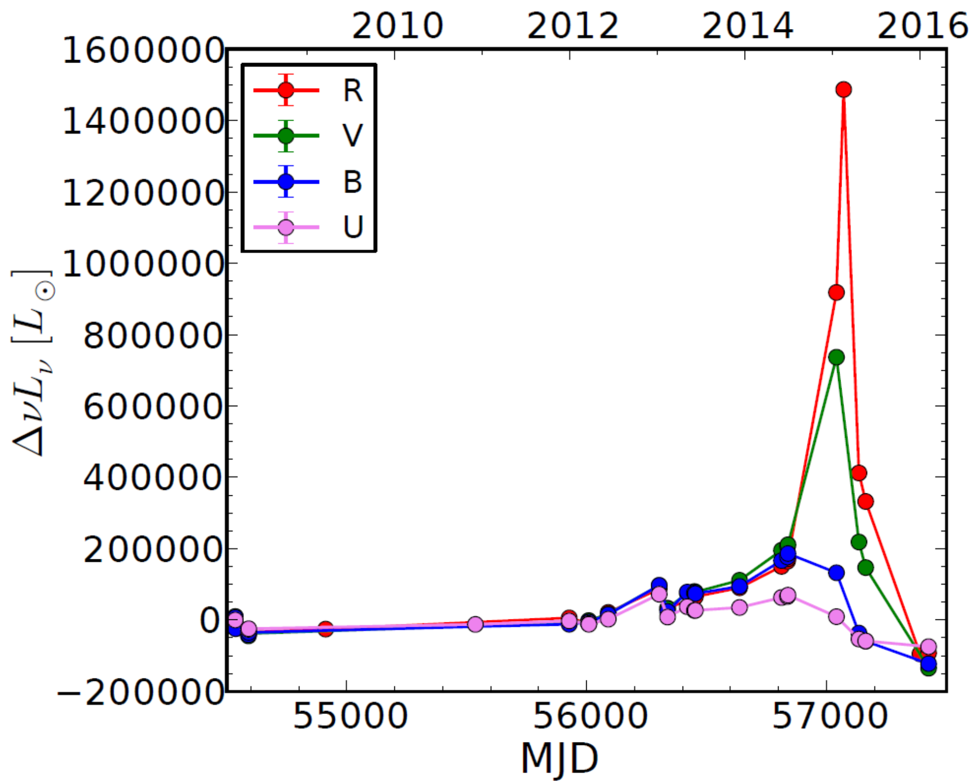
- Most candidates decline too slowly

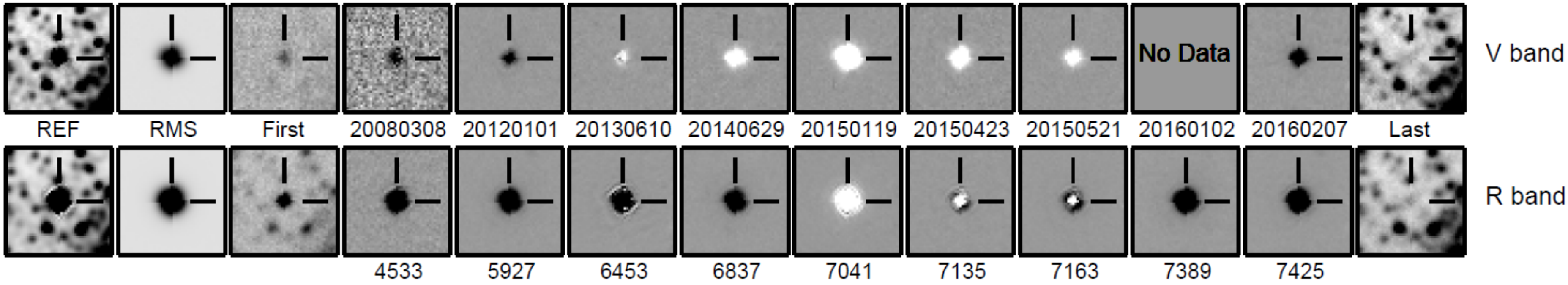


Adams et al. 2016a

M101 Stellar Merger

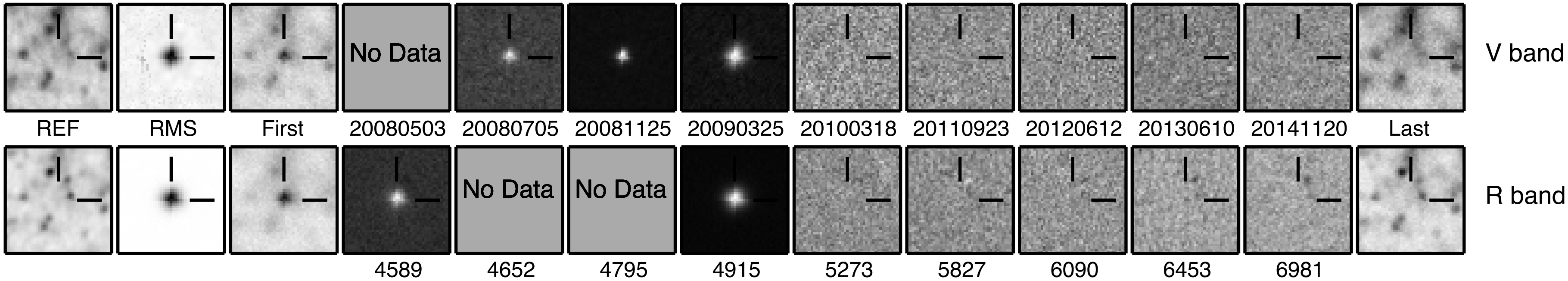
- Could we confuse mergers for failed SN?
  - Expect a few (Kochanek, Adams, Belczynski 2014)
  - Need IR follow-up



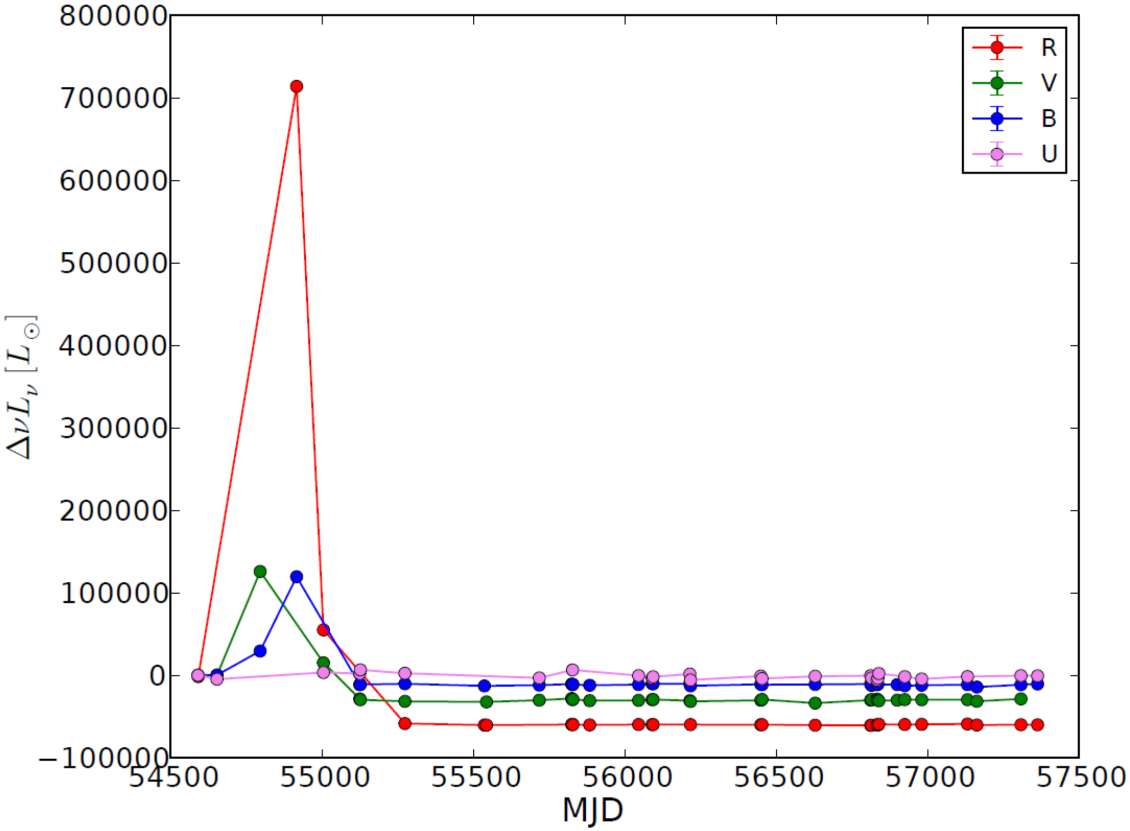


Adams et al. 2016a

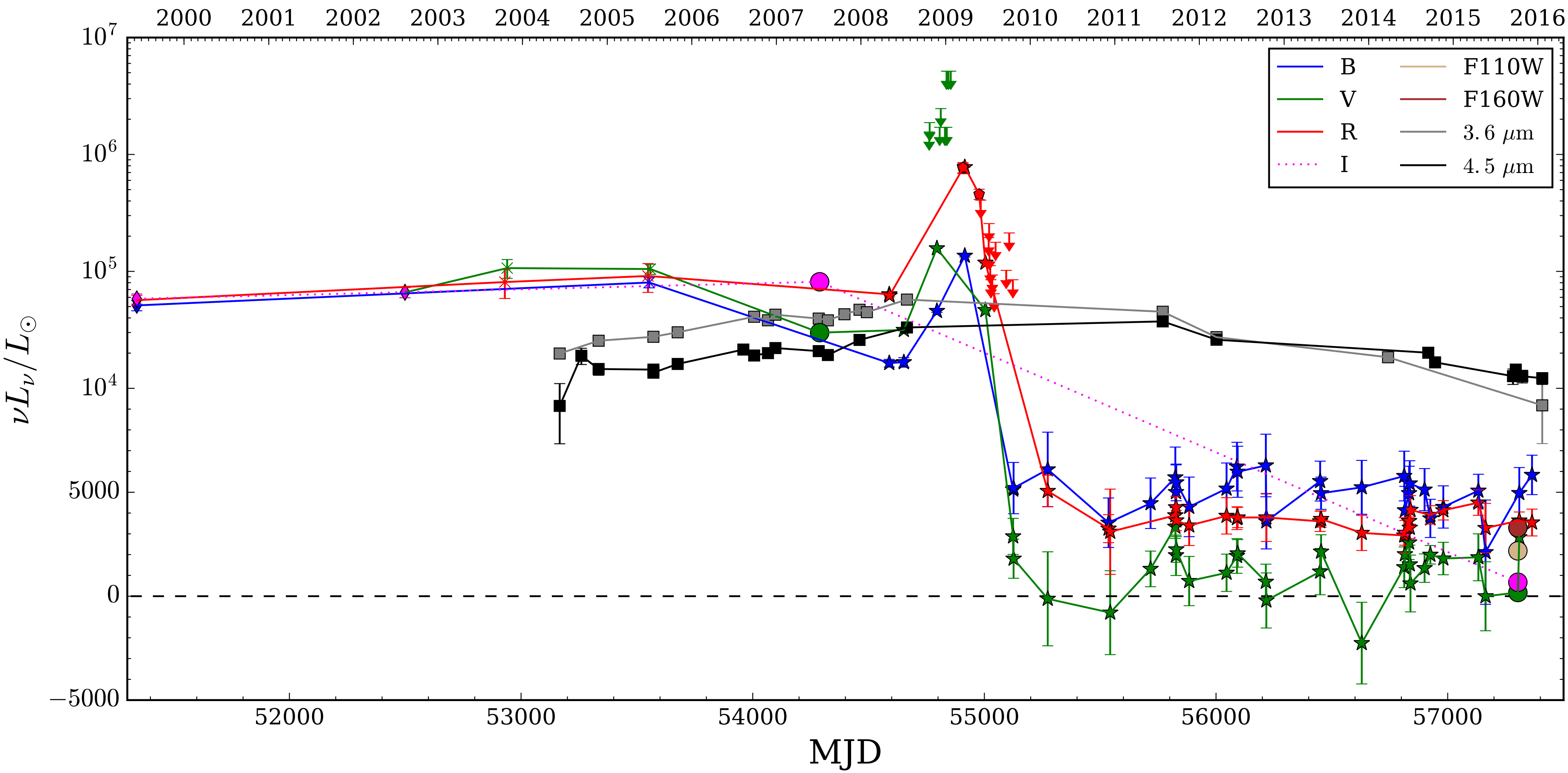
fSN Candidate: N6946-BH1



- Identified in Gerke et al. 2015
- Roughly constant prior to 2008 (seen in archival CFHT data back to early 2000s)
- Poorly sampled transient in late 2008/early 2009 (~$10^6 L_\odot$) – consistent with Lovegrove & Woosley (2013)
- Has not been seen since (2010 onward)

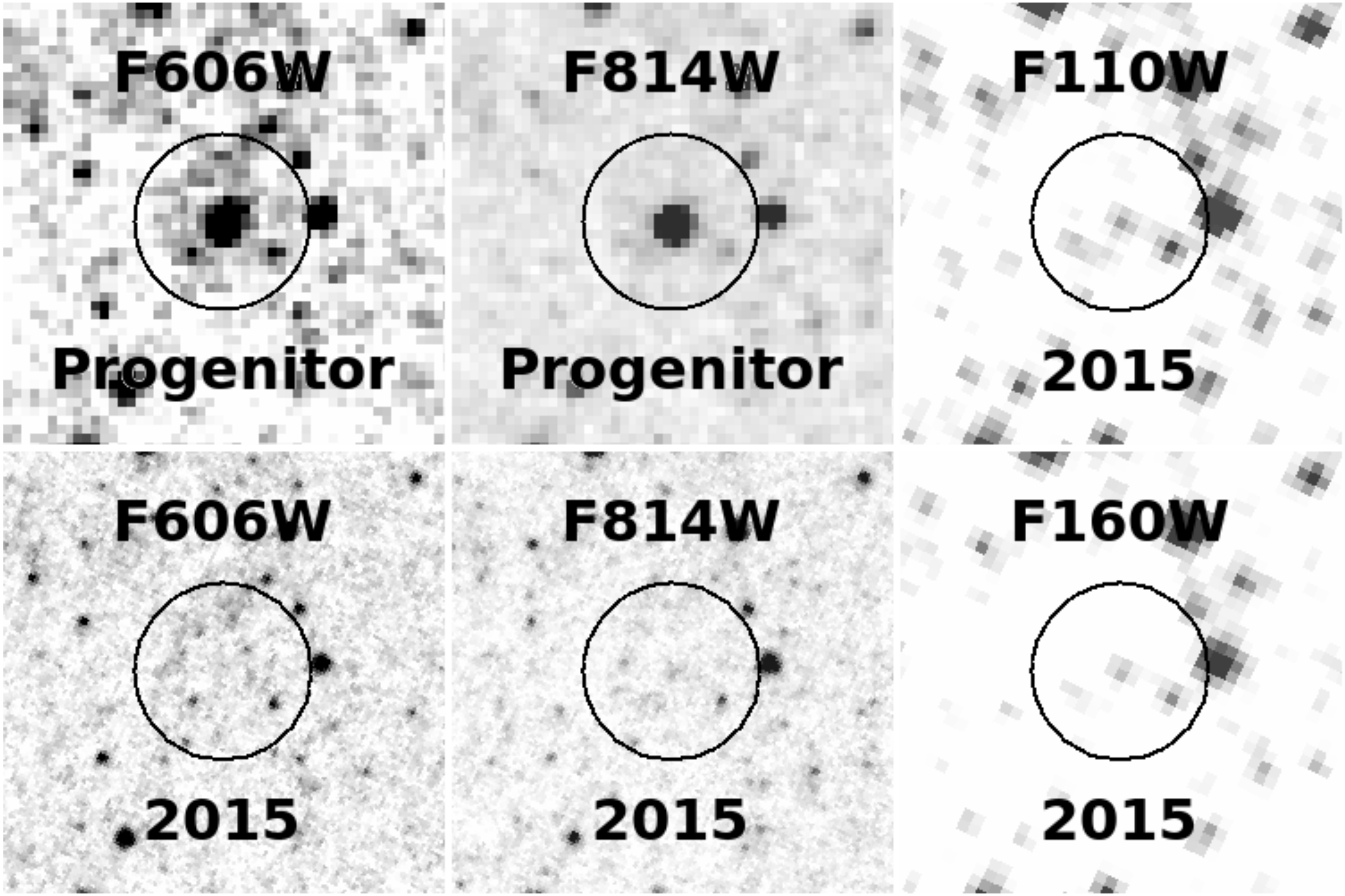


N6946-BH1: Light Curve



Adams et al. 2016b

HST Follow-up



Adams et al. 2016b

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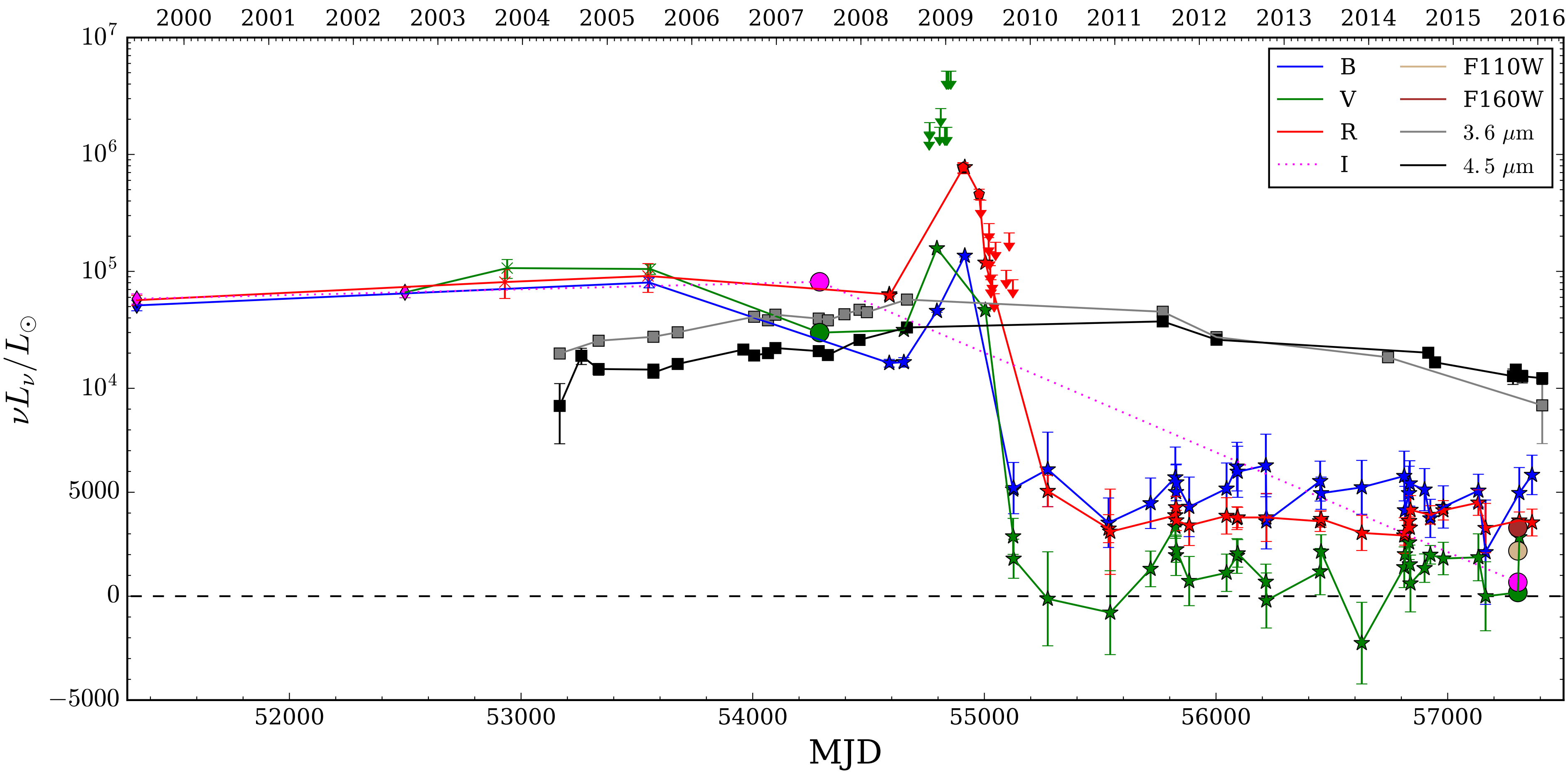
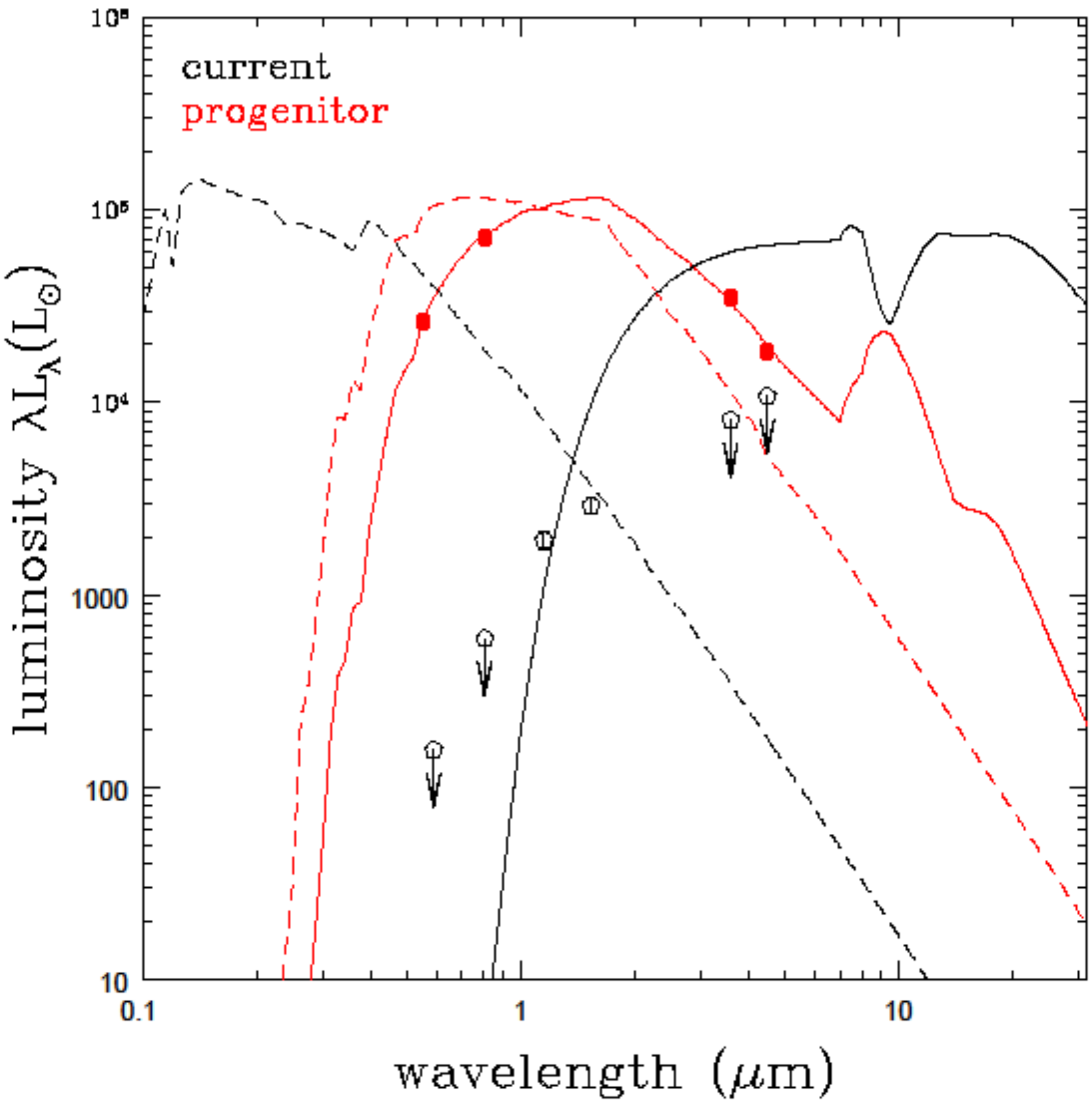


Adams et al. 2016b

N6946-BH1: Dusty Wind



Adams et al. 2016b

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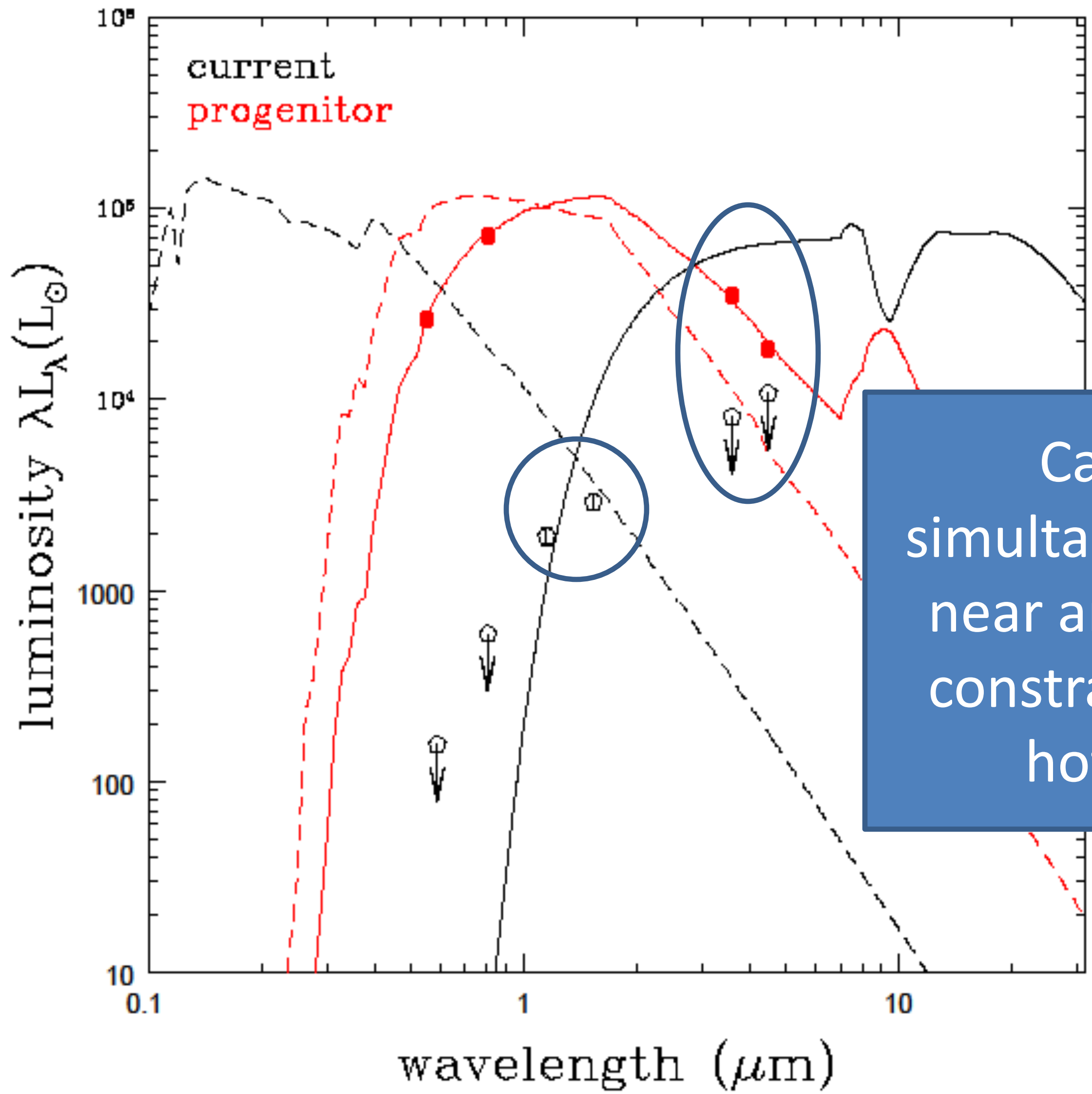
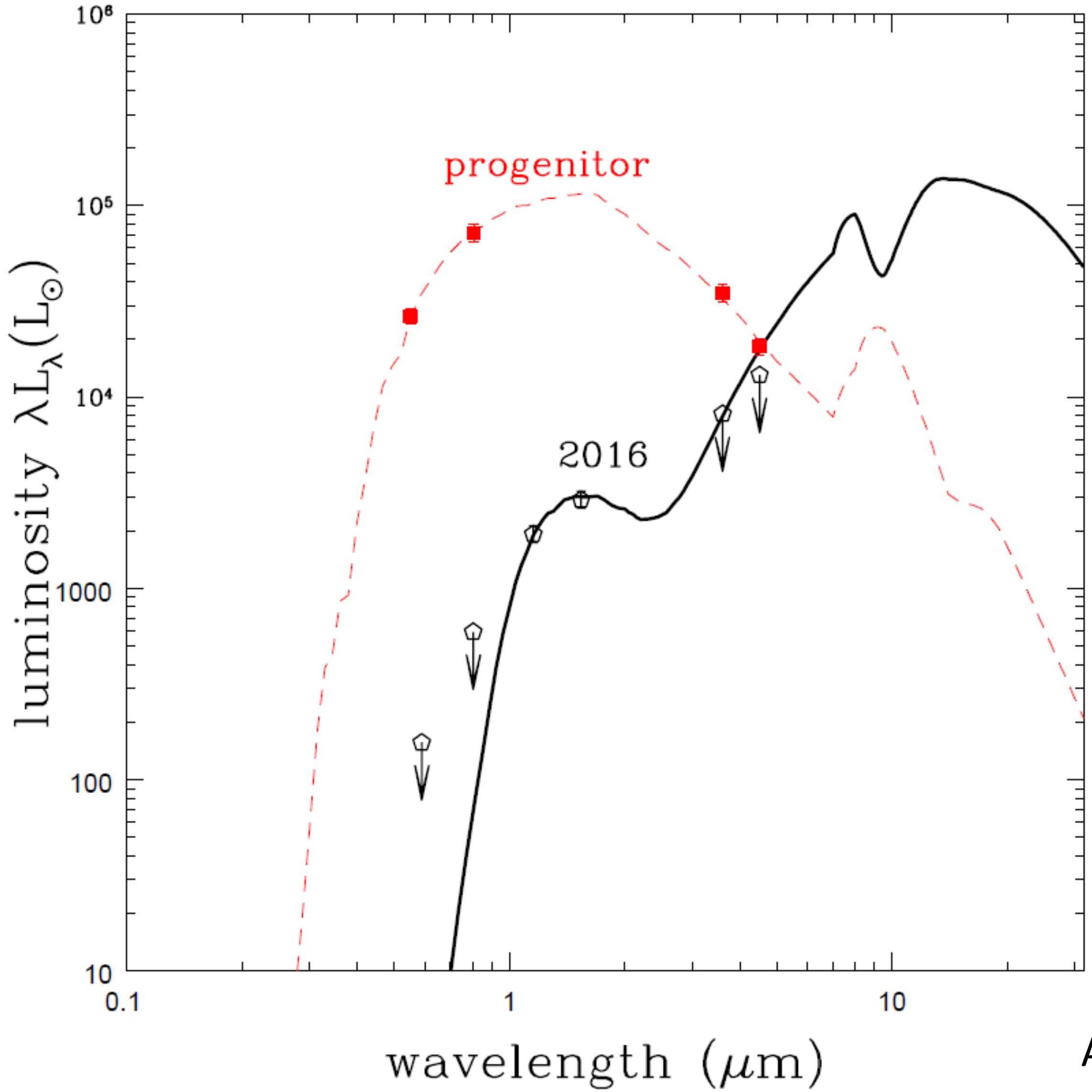


Cannot simultaneously fit near and mid-IR constraints with hot dust

Adams et al. 2016b

N6946-BH1: Dusty Shell



Adams et al. 2016b

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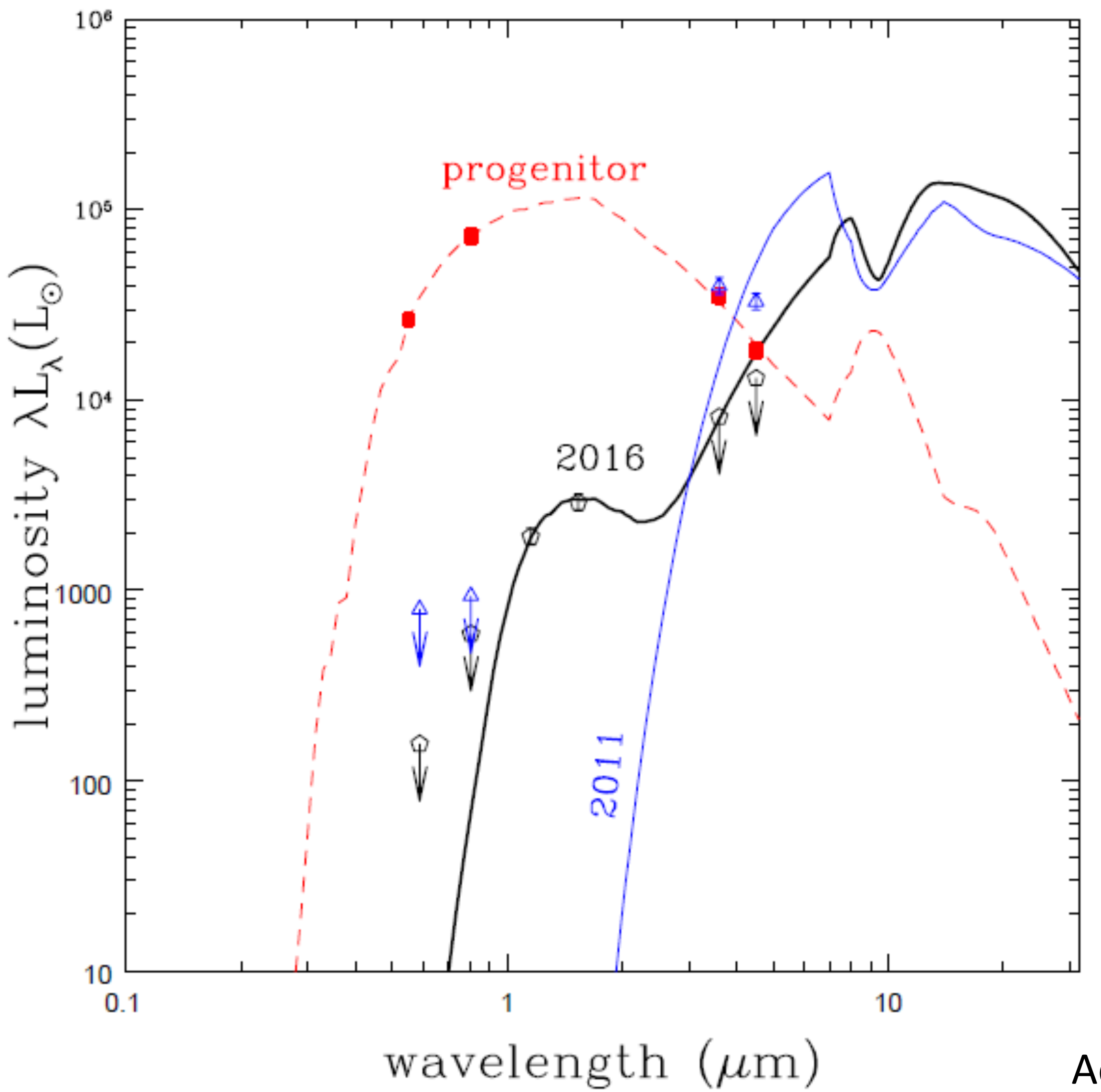

Adams et al. 2016b

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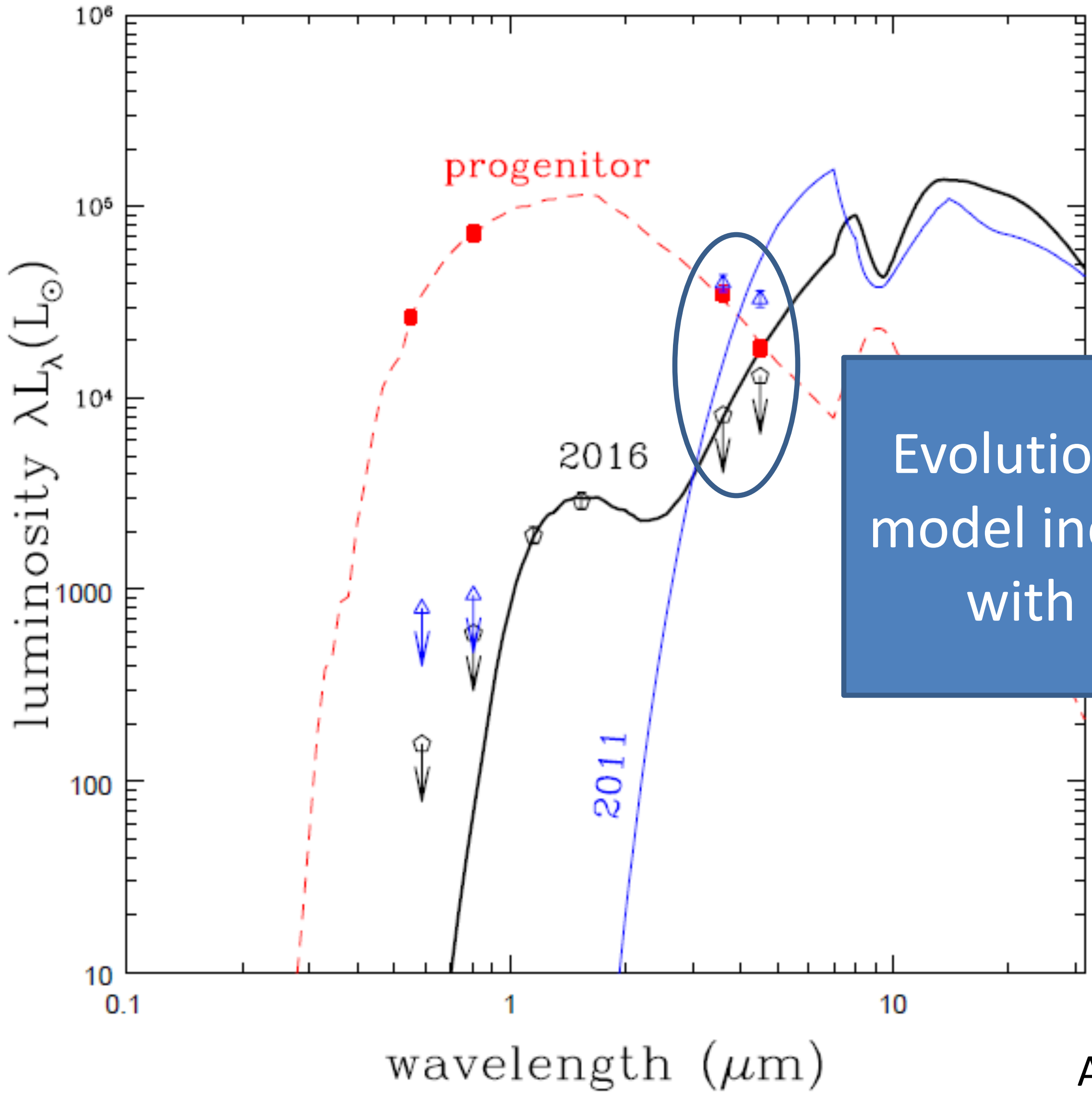
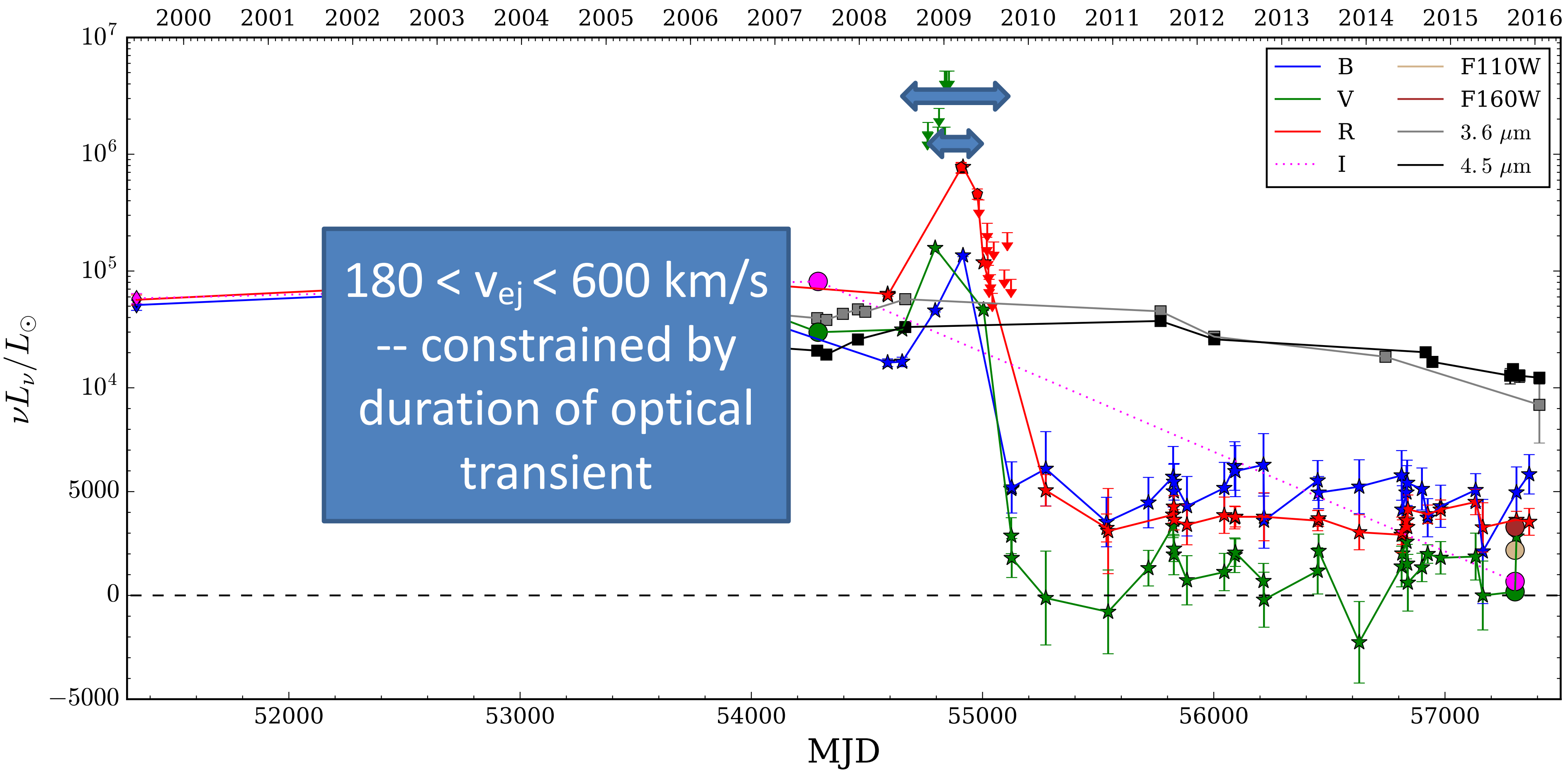


Evolution of shell model inconsistent with IR flux

Adams et al. 2016b

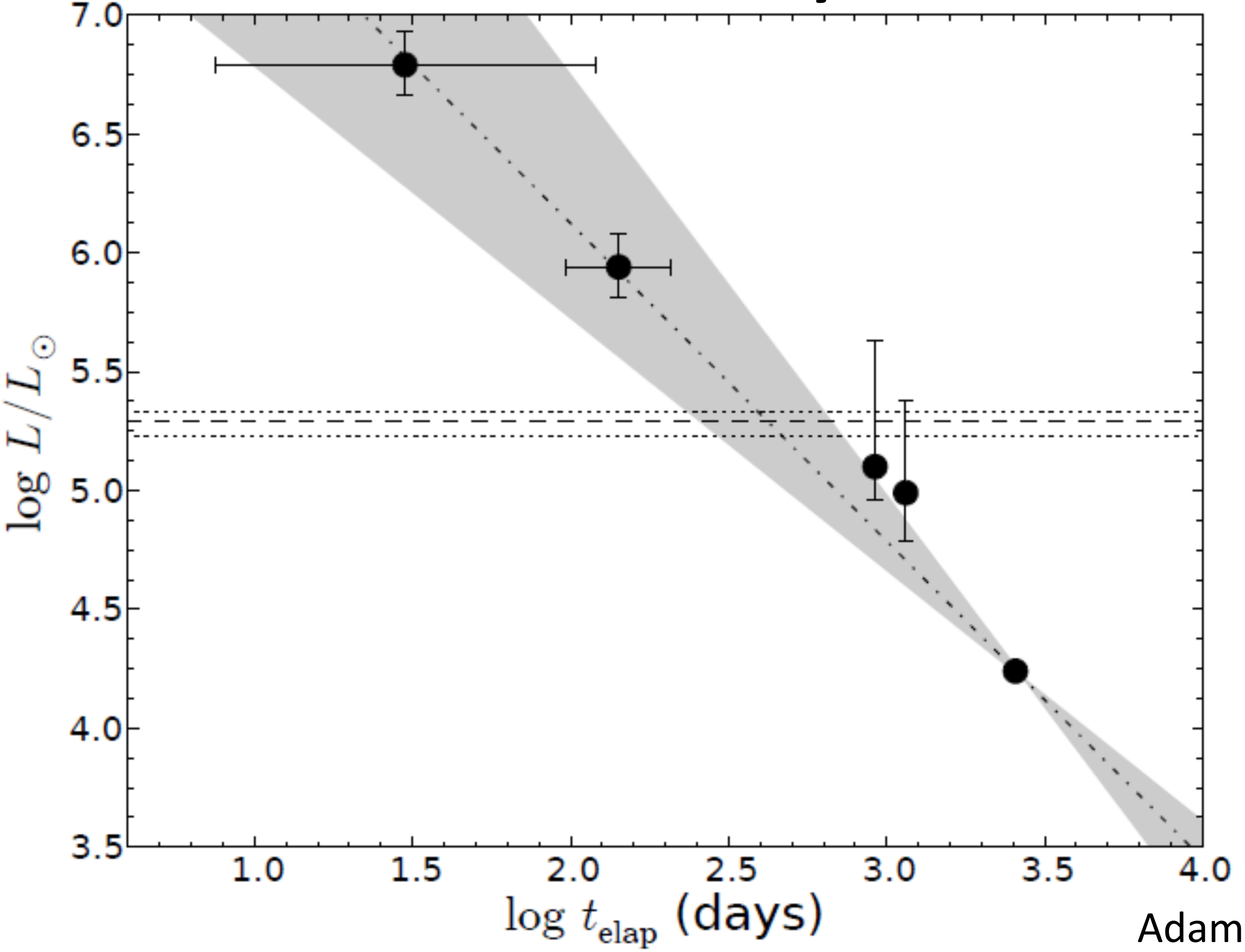
N6946-BH1: Light Curve



180 < v_{ej} < 600 km/s -- constrained by duration of optical transient

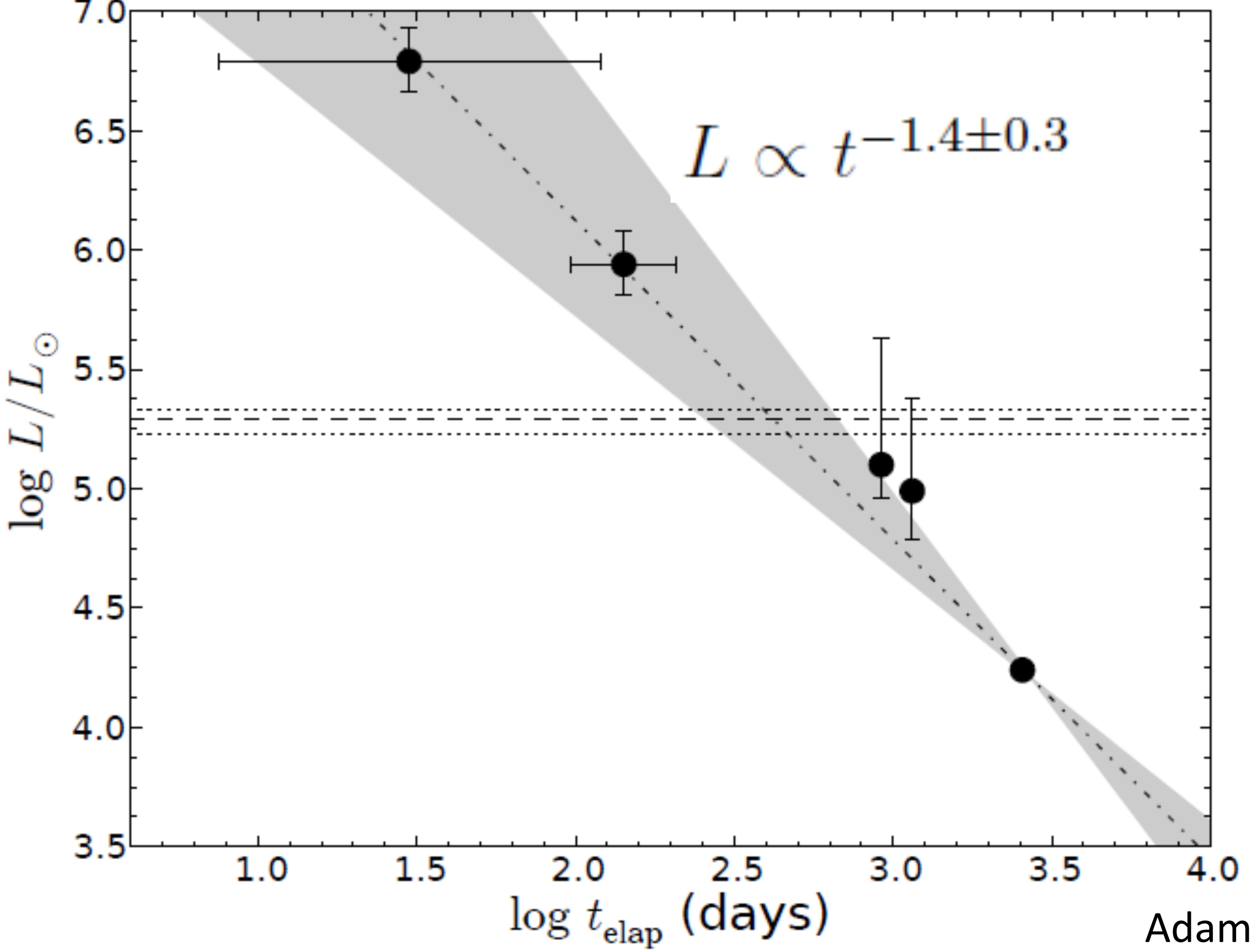
Adams et al. 2016b

Bolometric Luminosity Evolution



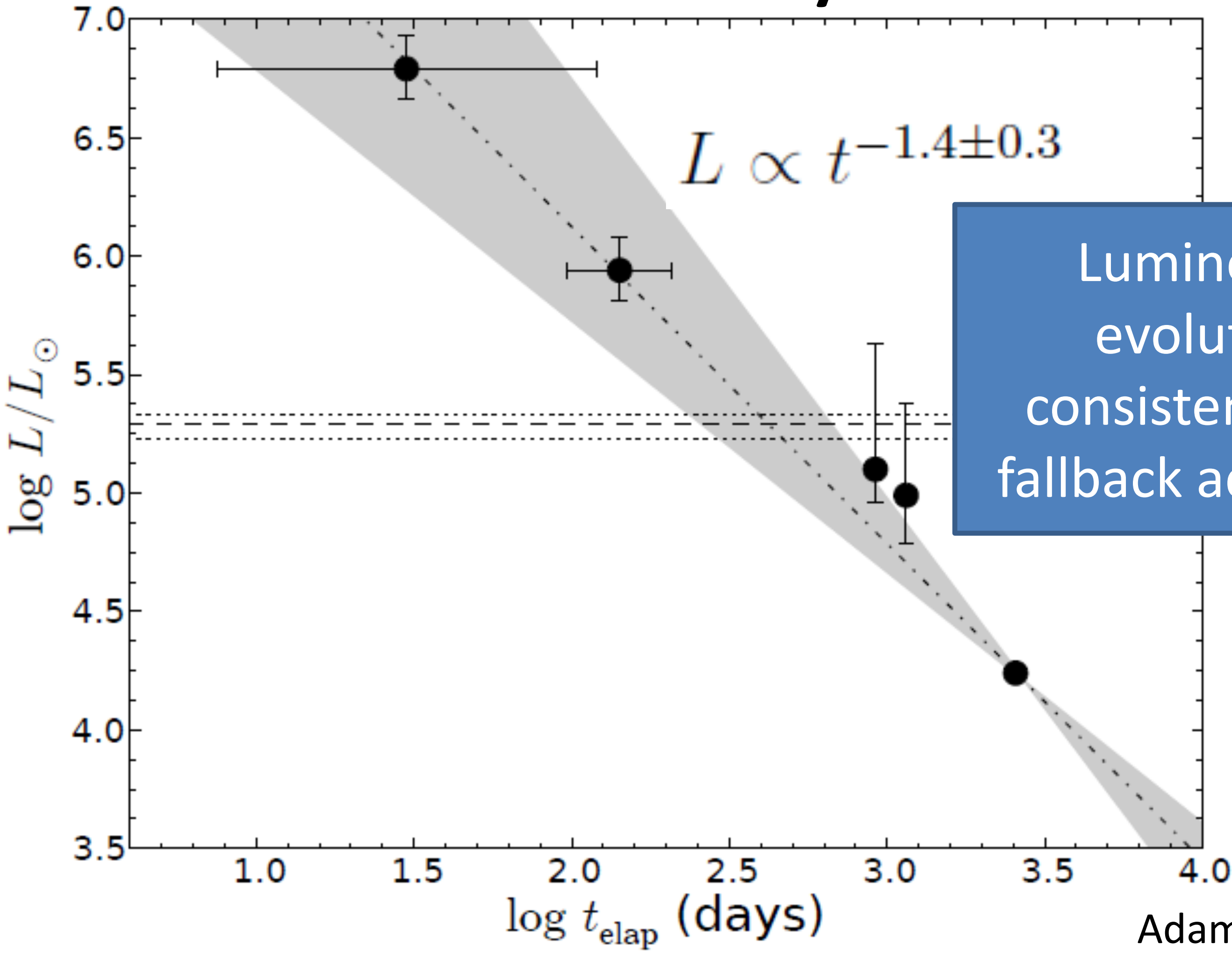
Adams et al. 2016b

Bolometric Luminosity Evolution



Adams et al. 2016b

Bolometric Luminosity Evolution



Luminosity evolution consistent with fallback accretion

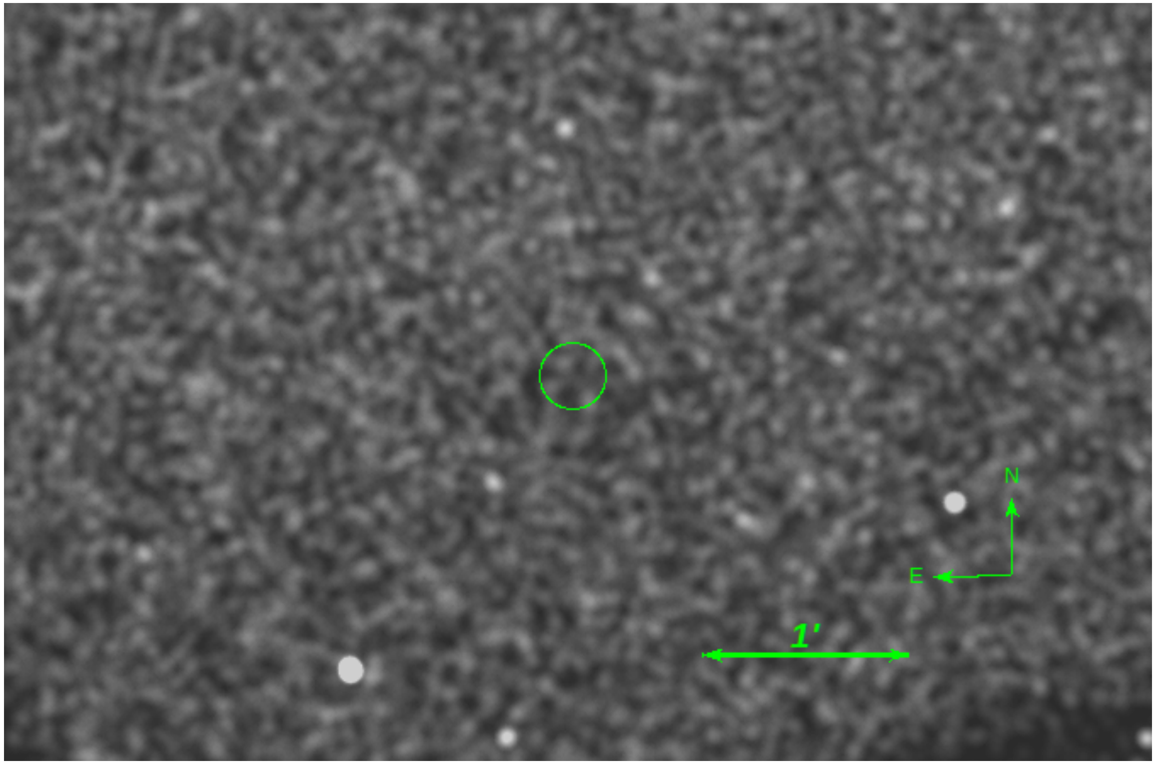
Adams et al. 2016b

X-rays?

X-rays?

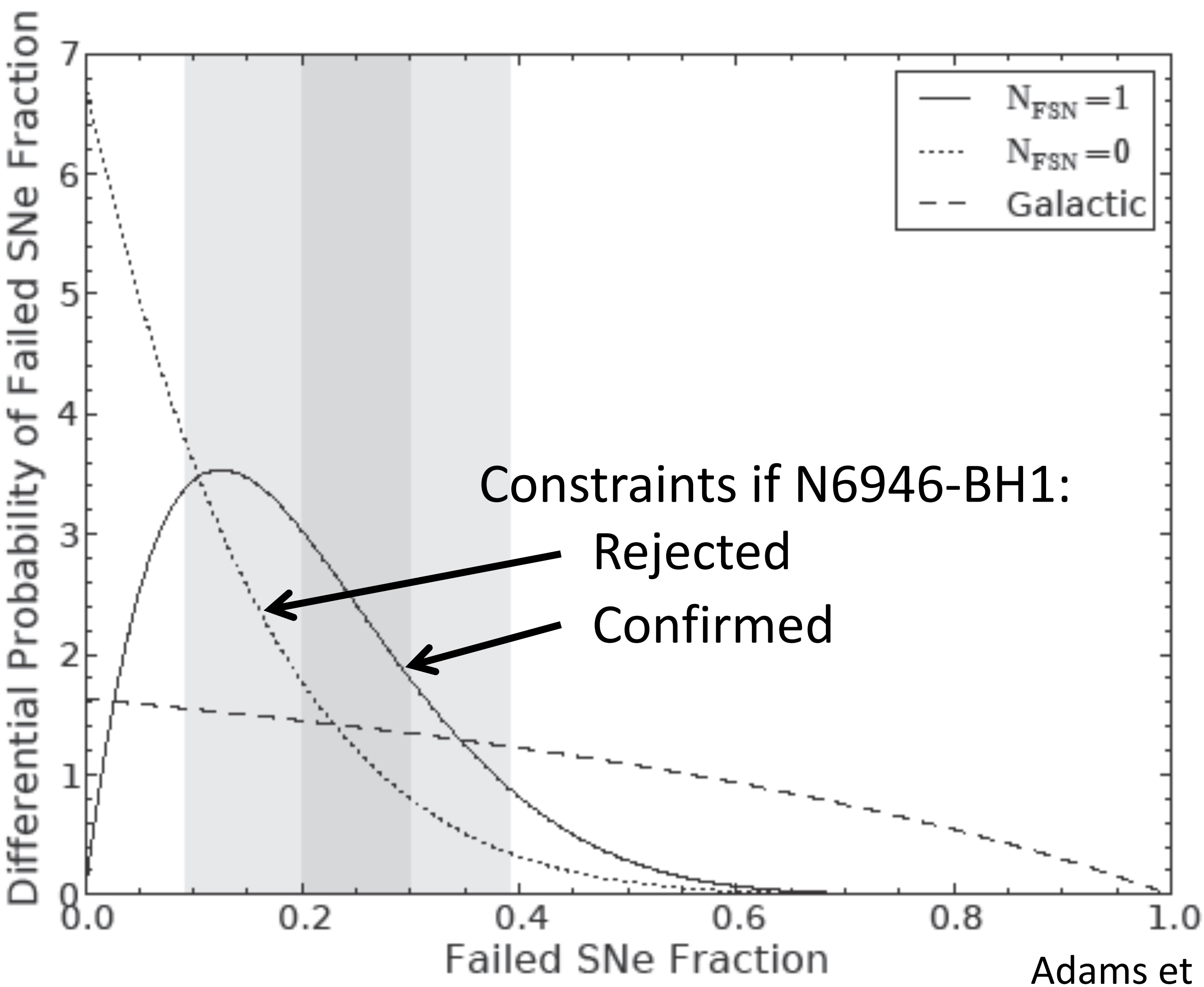
Non-detection; envelope ejected at < 10^3 km/s

Need JWST to rule out cold dust



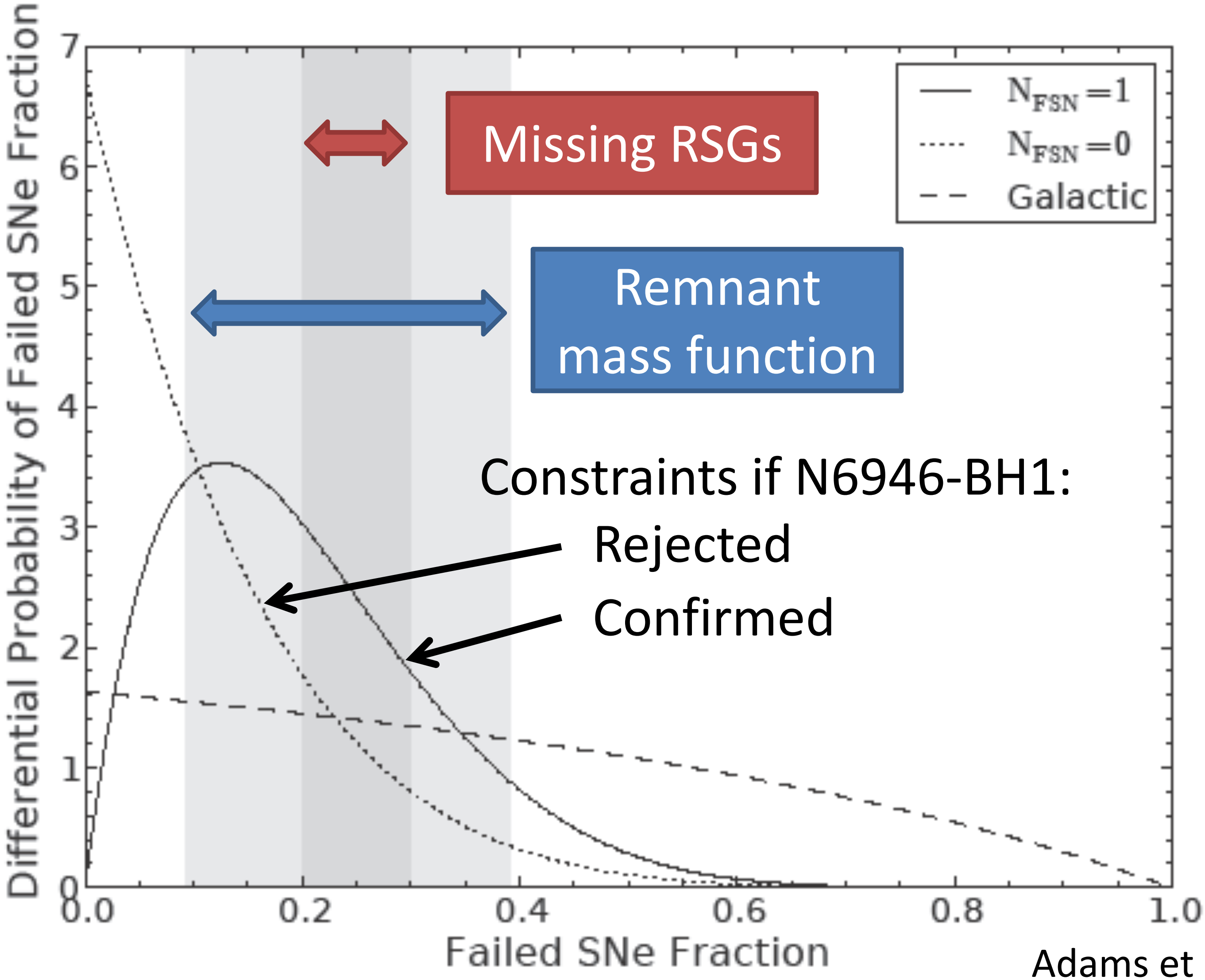
Dai et al. in prep.

Failed SN Fraction



Adams et al. 2016b

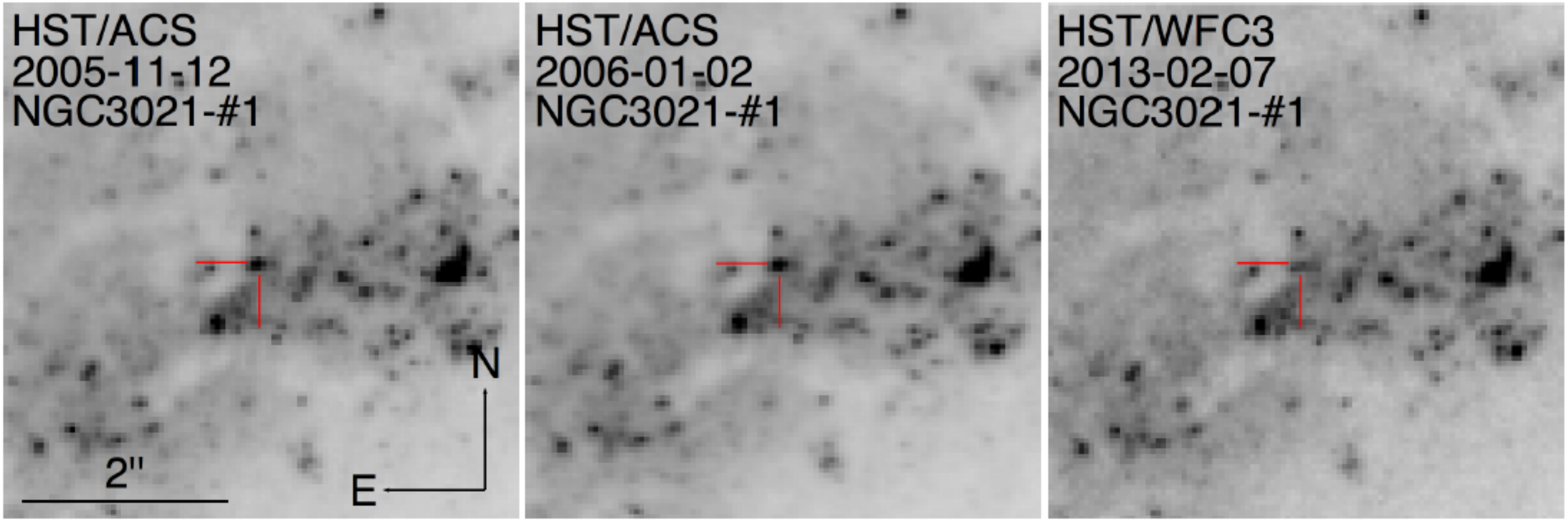
Failed SN Fraction



Adams et al. 2016b

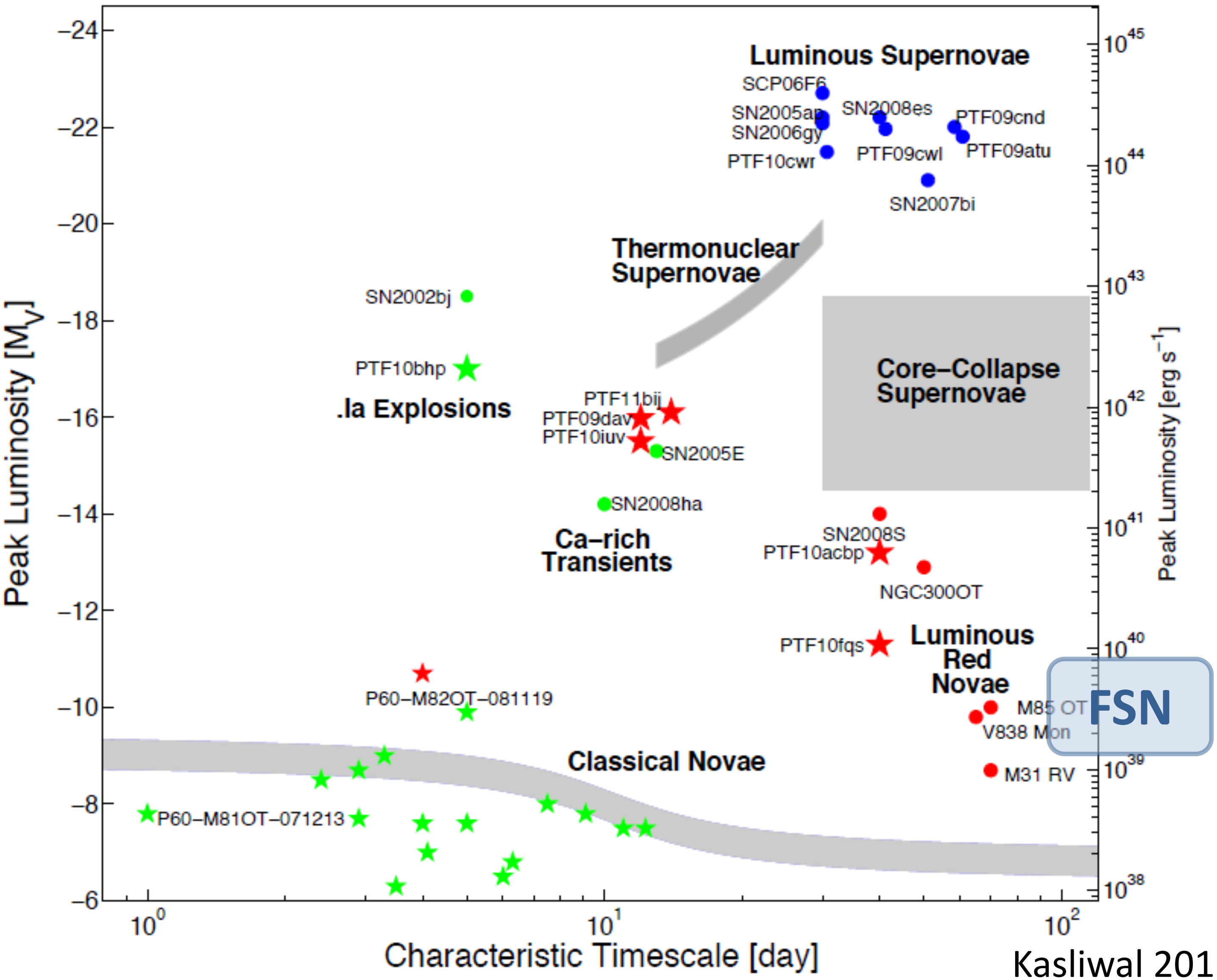
Archival HST Search

Reynolds et al. 2015 also found possible fSN candidates in search of HST archives



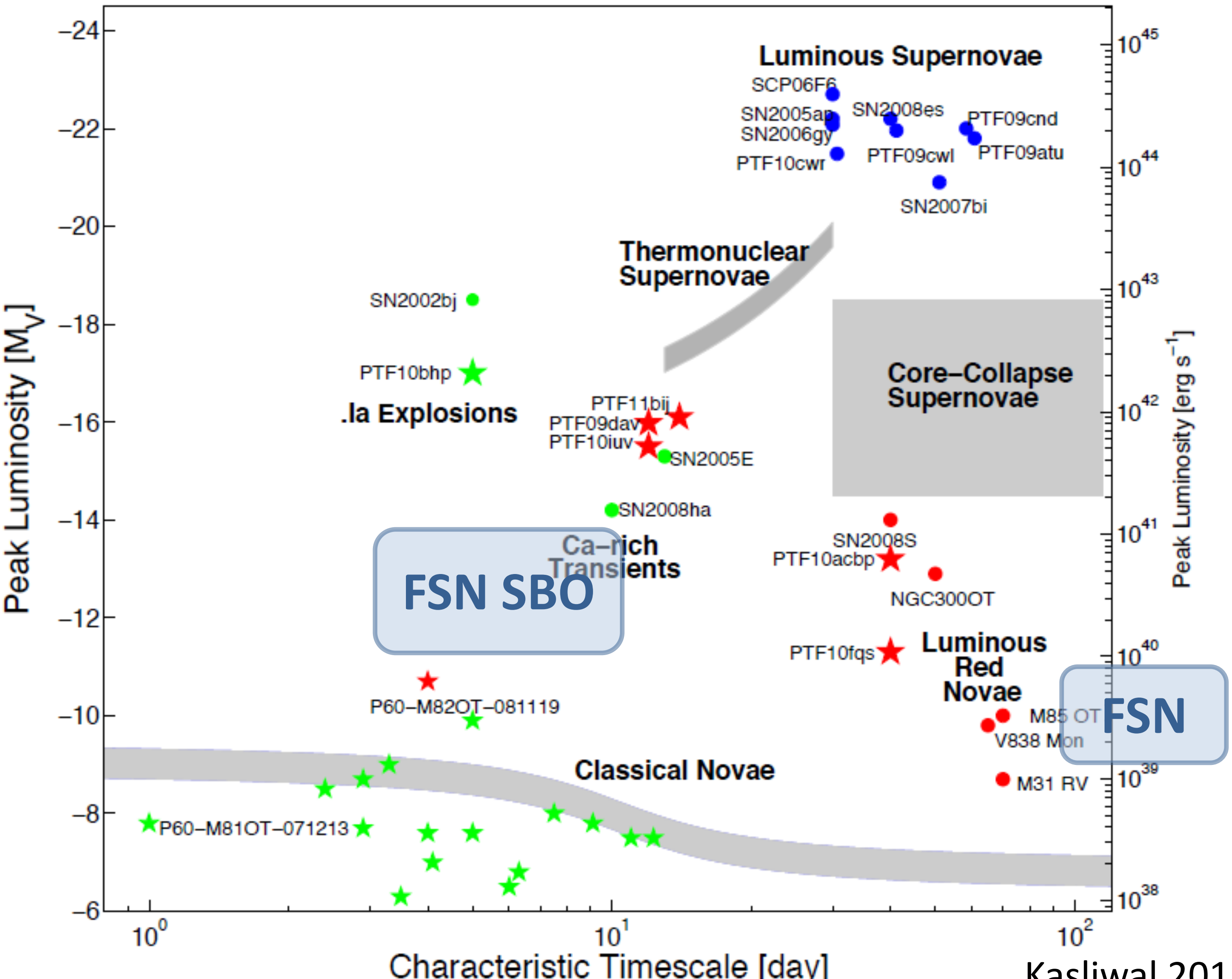
Reynolds, Fraser & Gilmore 2015

Failed SN with ZTF



Kasliwal 2012

Failed SN with ZTF



Kasliwal 2012

Summary

– First failed SN candidates have been identified
  - N6946BH1 very promising – possibly first discovery of a BH birth
  - JWST observations needed to rule out cold dust
– Implies: ~14% of core collapses fail (5-47%)
  - Resolves RSG problem
  - explains BH mass function
– Theory: fallback accretion in failed SNe?

Discussion and Questions