Finding Failed Supernovae

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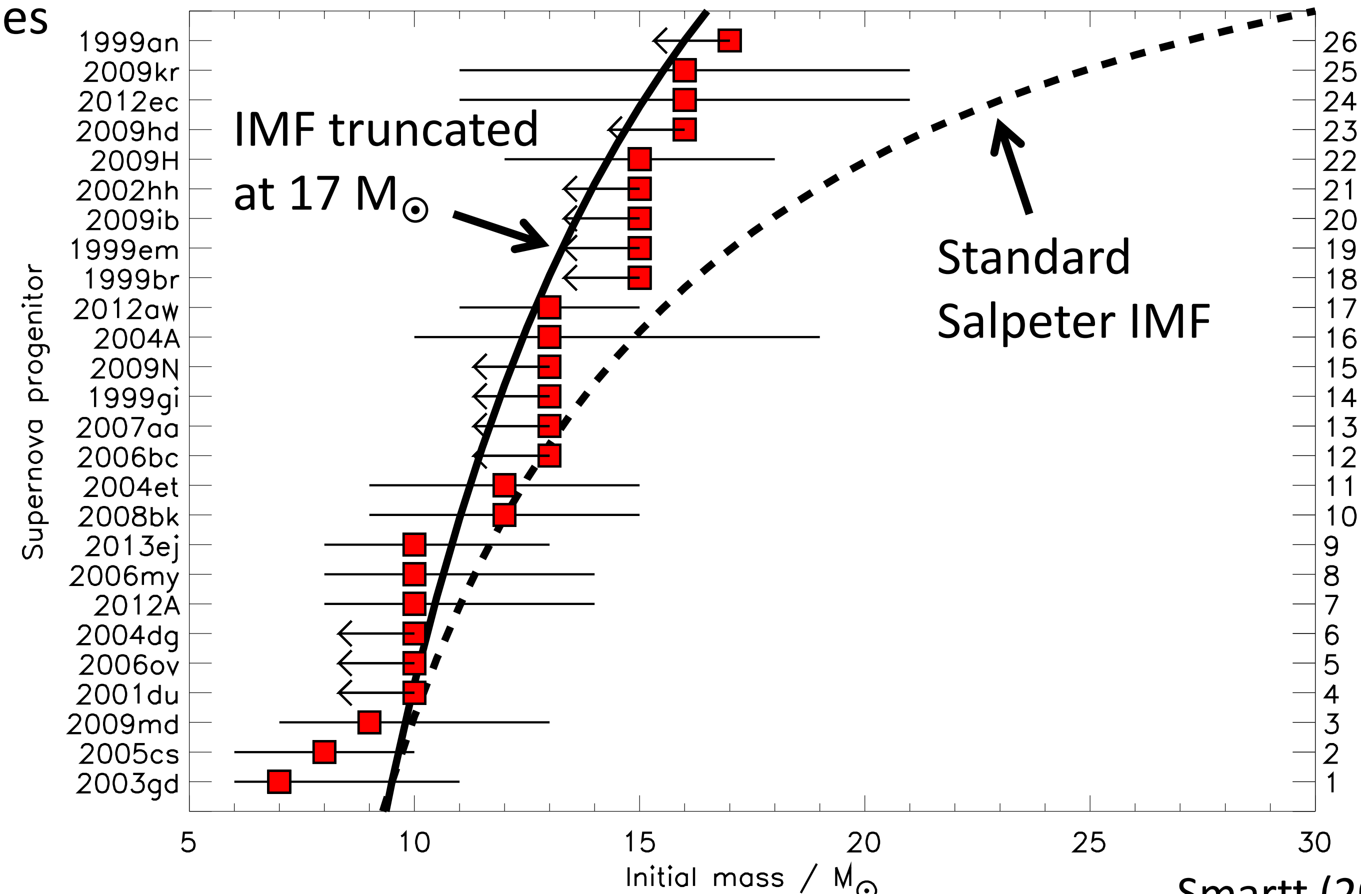
Evidence for FSNe

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 ~17$M_\odot$, but expected to die as a red supergiants up to ~25$M_\odot$
  - See Smartt 2015 for recent review

- Distribution of progenitors essentially cuts off exactly where the compactness jumps upwards
- Missing red supergiant progenitors would correspond to 10-30% of core collapses



Smartt (2015)

Other Evidence

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

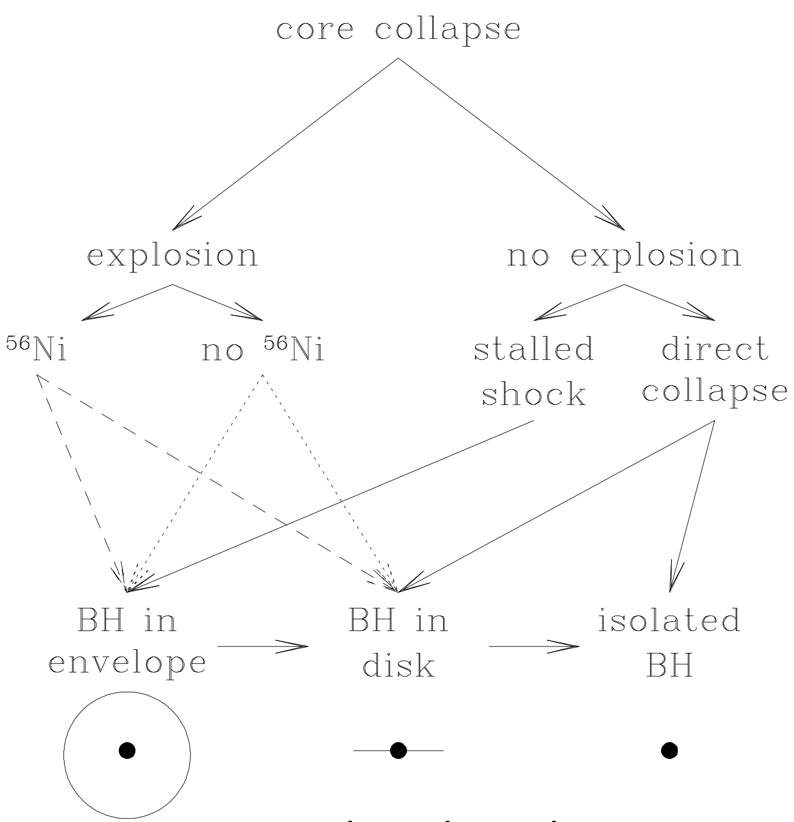
Compact object mass function (Kochanek 2014, 2015)

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)

GROWTH
Global Relay of Observatories Watching Transients Happen

Associated Transients?



Kochanek et al. 2008

Little studied:

- 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

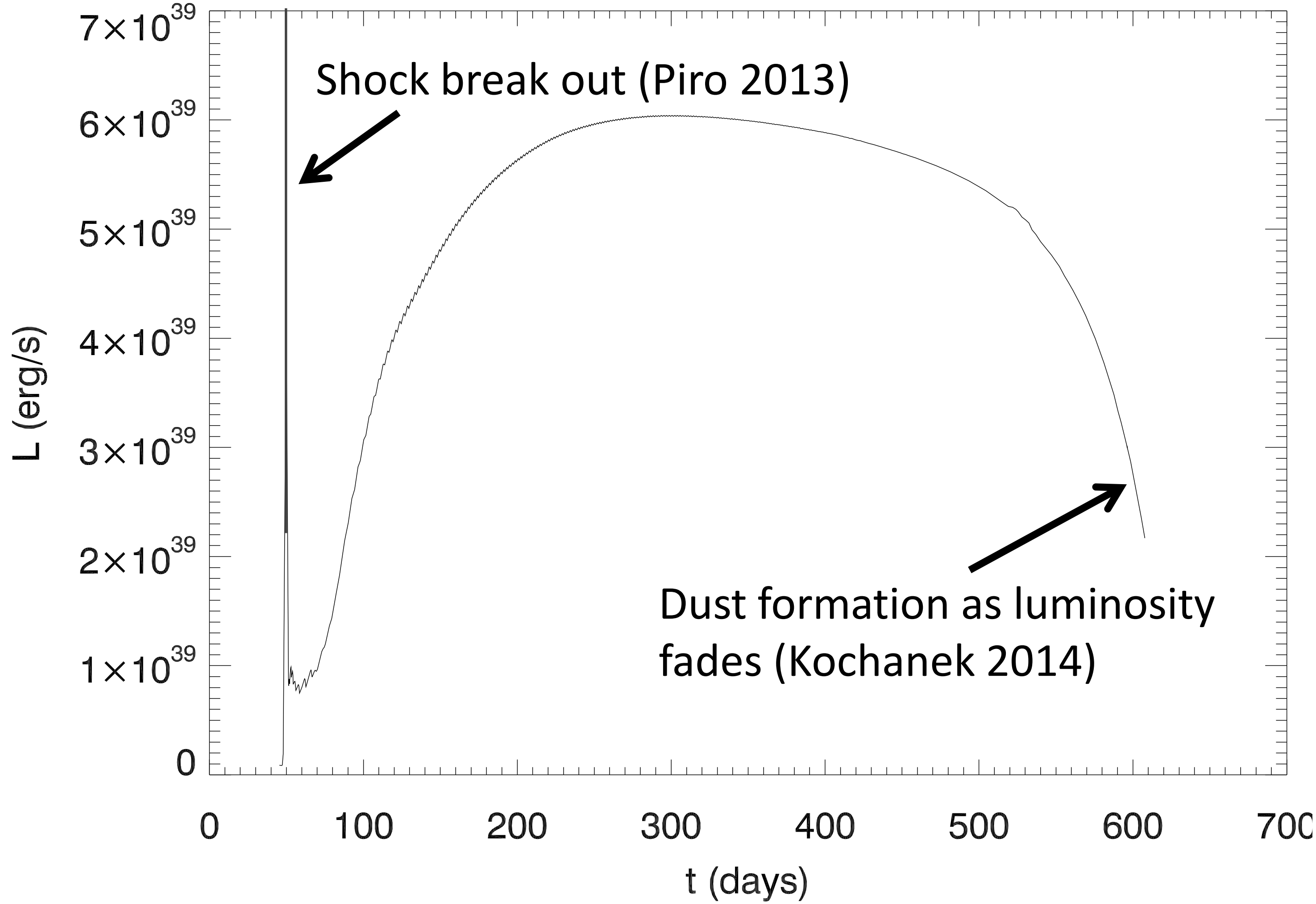
The Nadezhin (1980) Mechanism

- 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

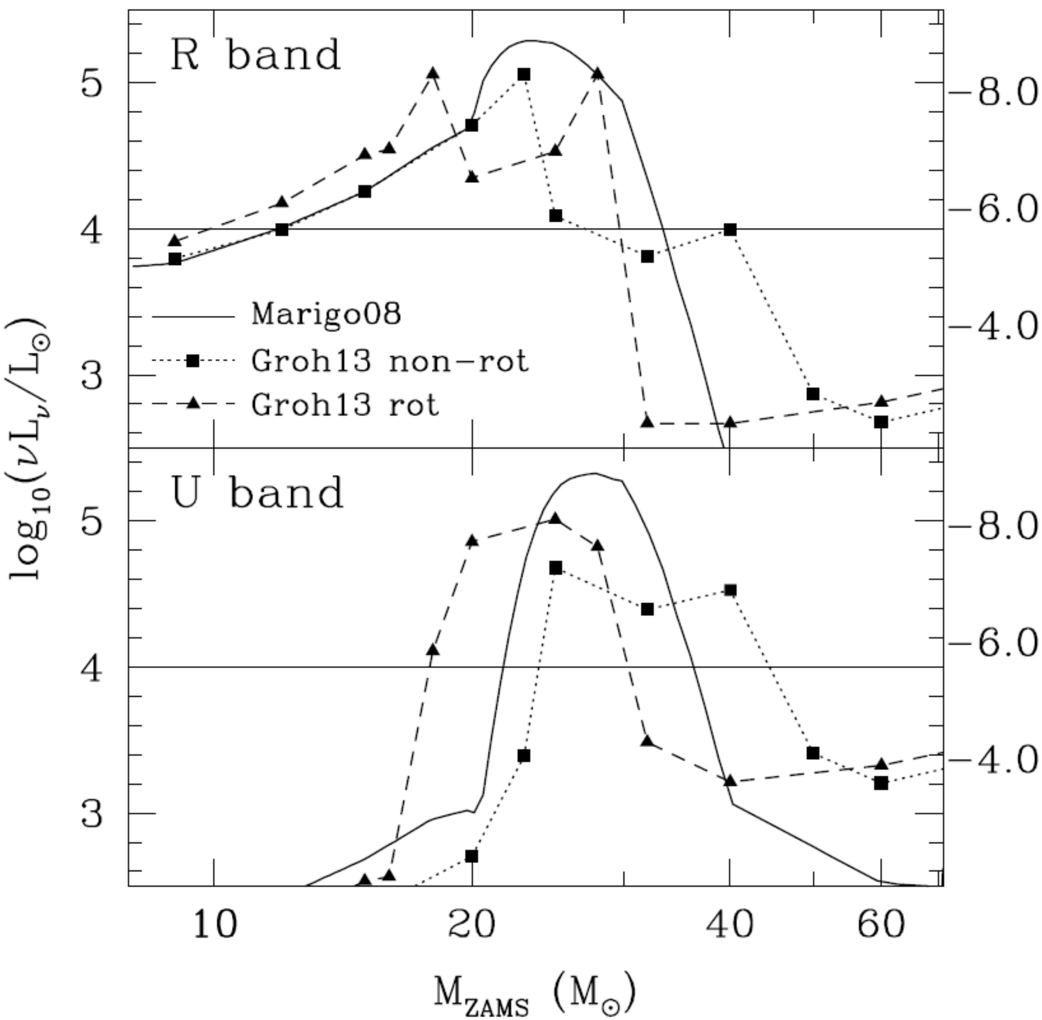
Instead search nearby galaxies for stars which “disappear”, possibly with an intervening transient (Kochanek et al. 2008)

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. in prep.

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

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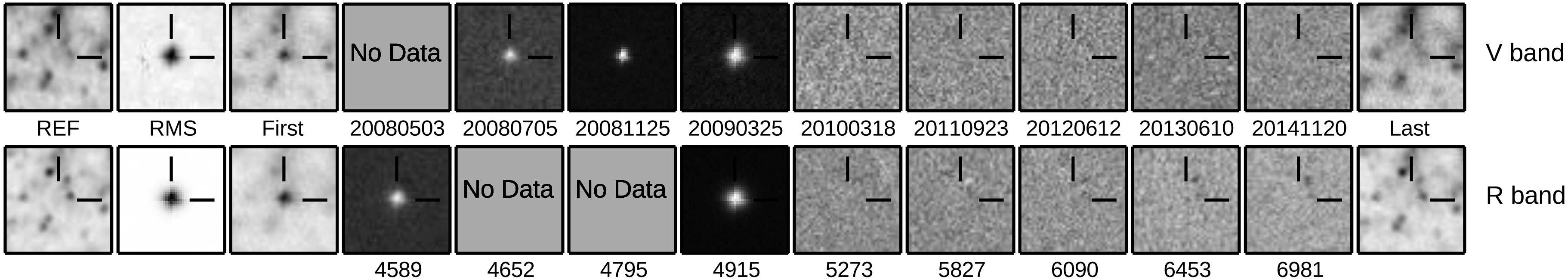
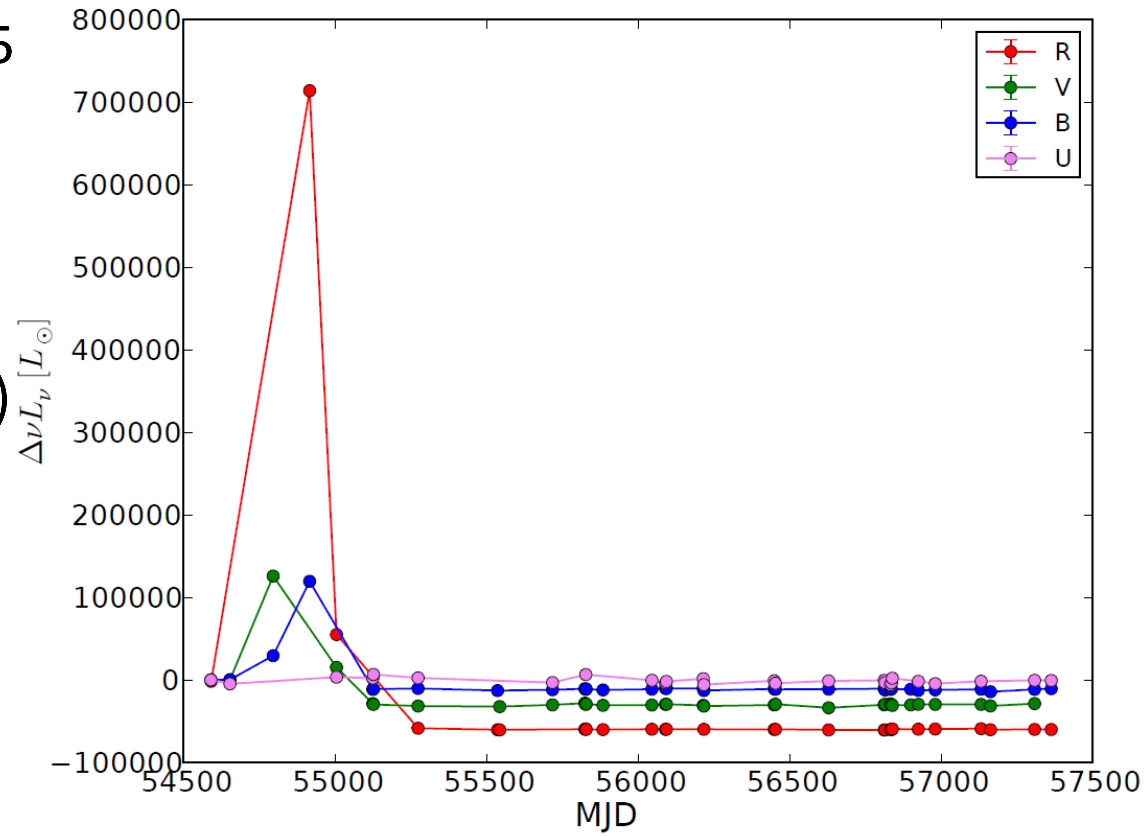
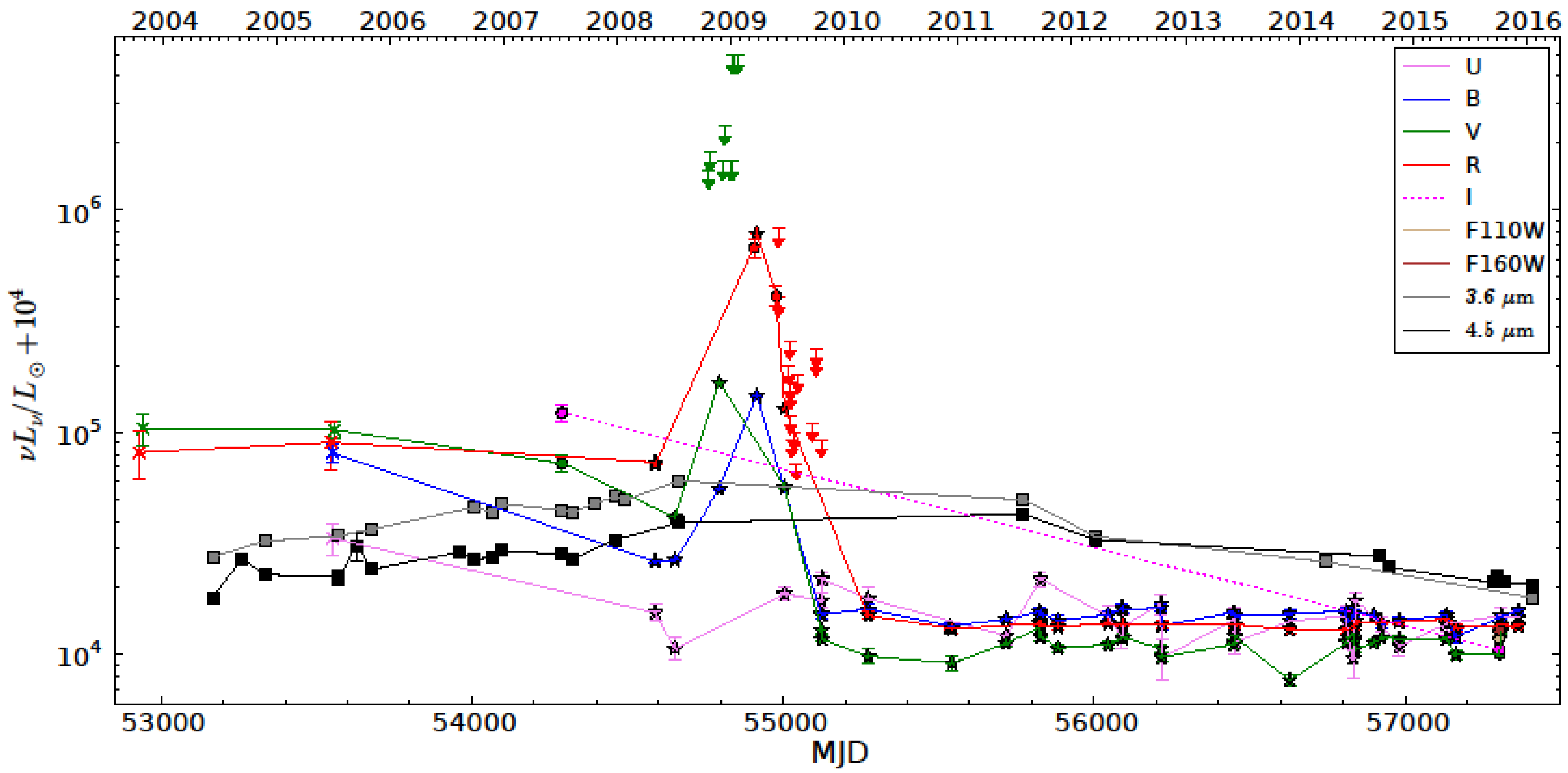
FSN Candidate: N6946-BH1



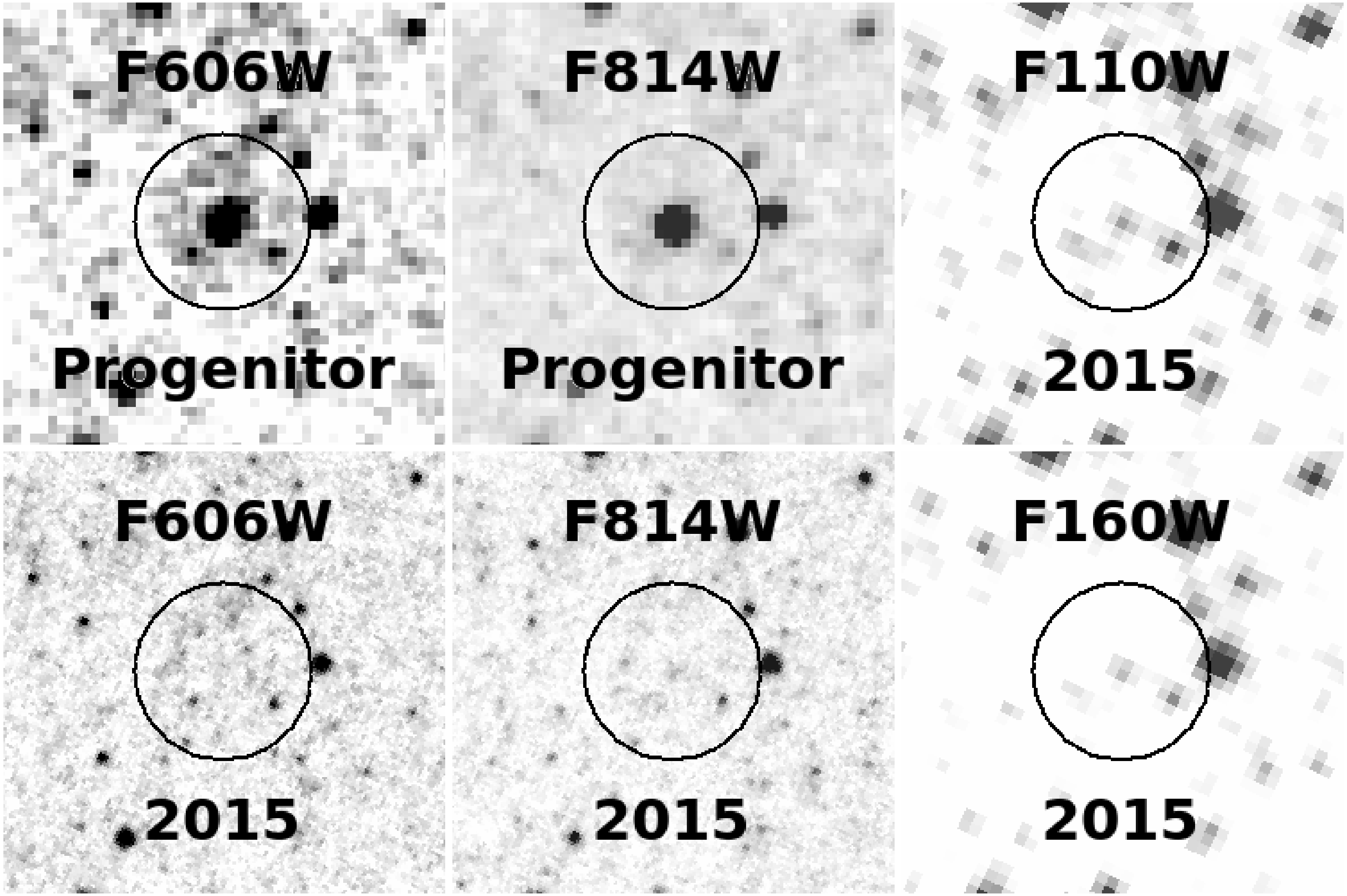
- Identified in Gerke et al. 2015
- Roughly constant prior to 2008 (seen in archival CFHT data back to early 2000s)
- Poorly sampled transient in late 2008/early 2009 (~$10^6 L_\odot$) – consistent with Lovegrove & Woosley (2013)
- Has not been seen since (2010 onward)



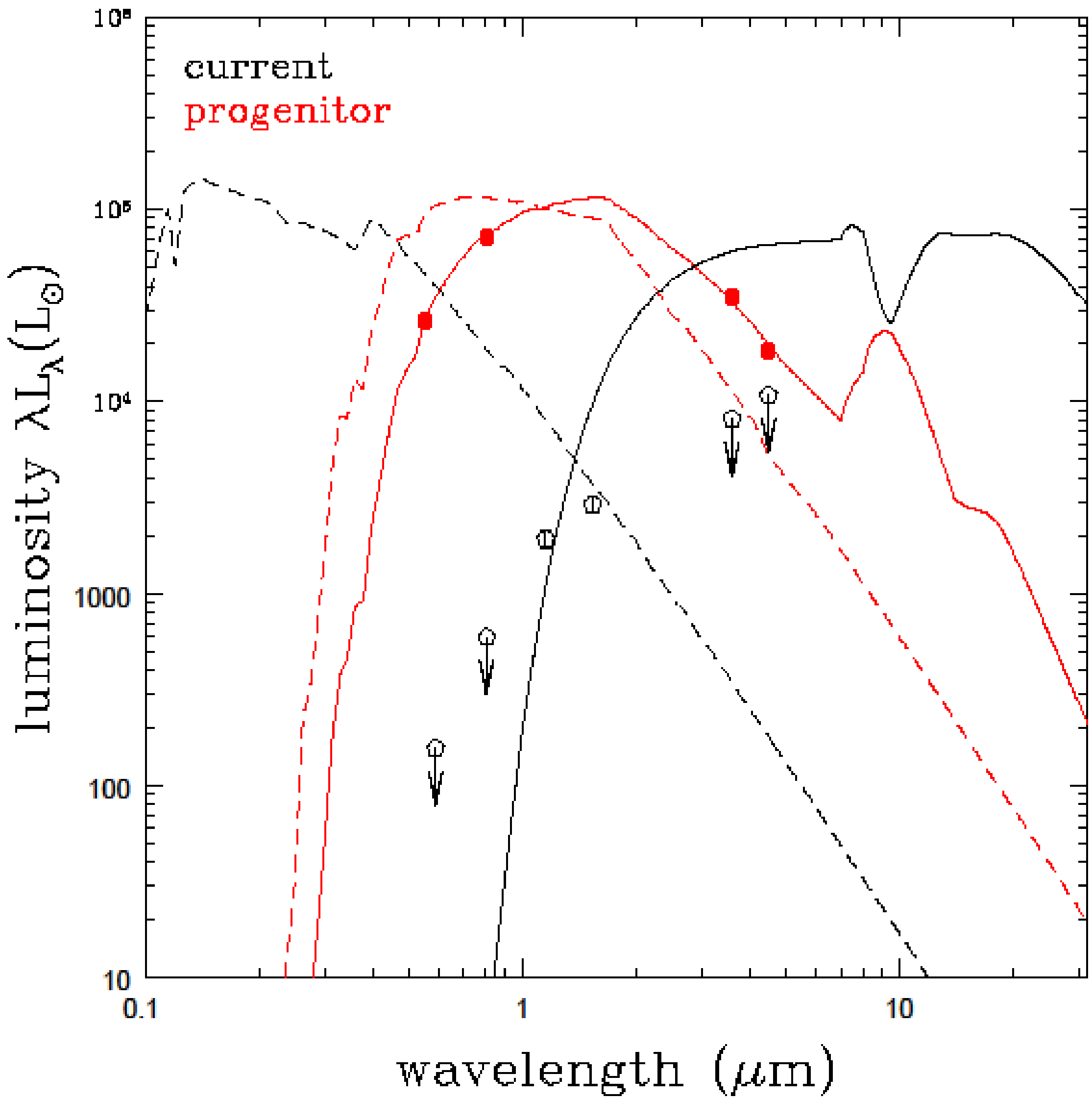
N6946BH1: light curve



HST Follow-up



N6946-BH1: Dusty Wind



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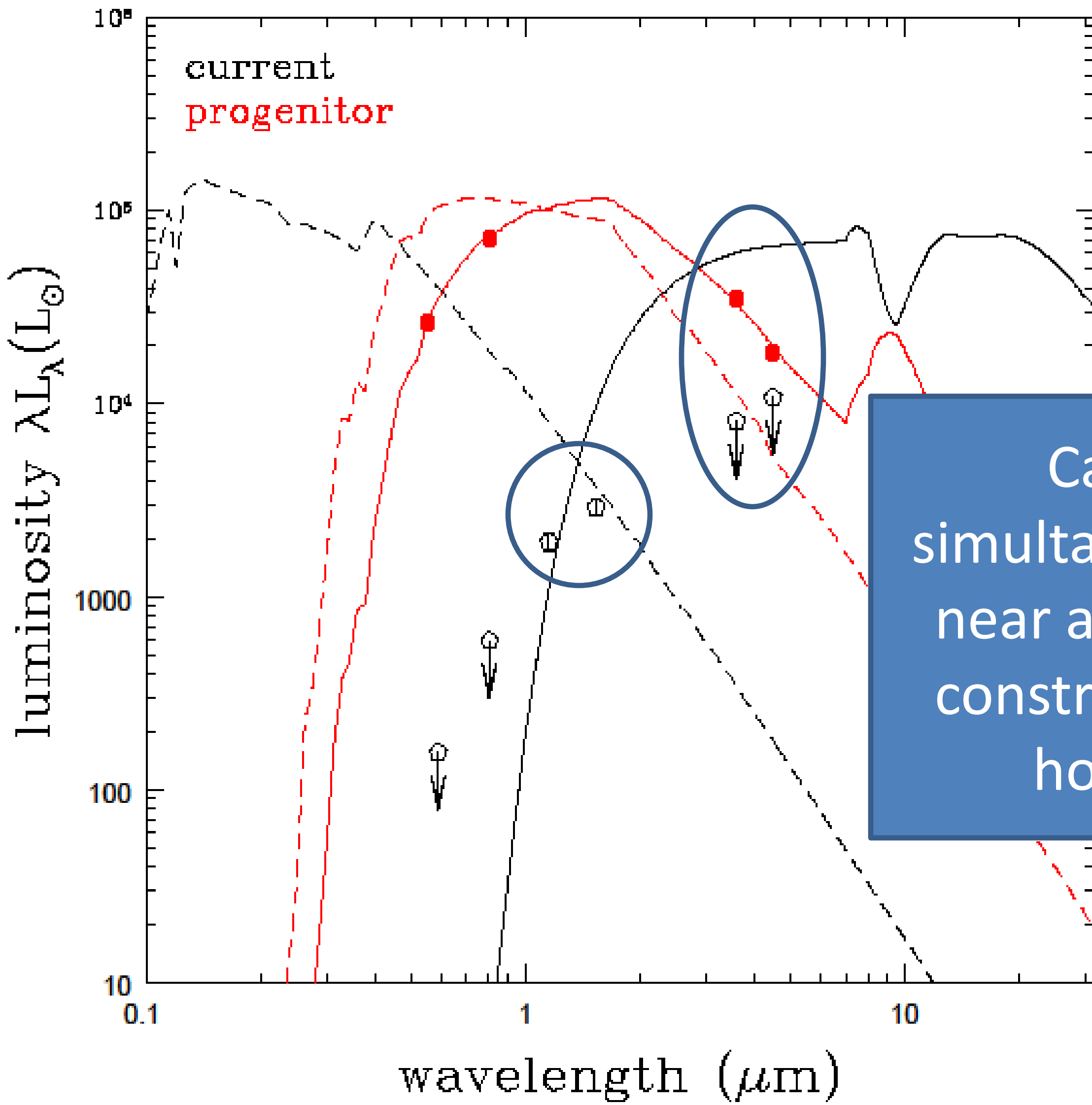
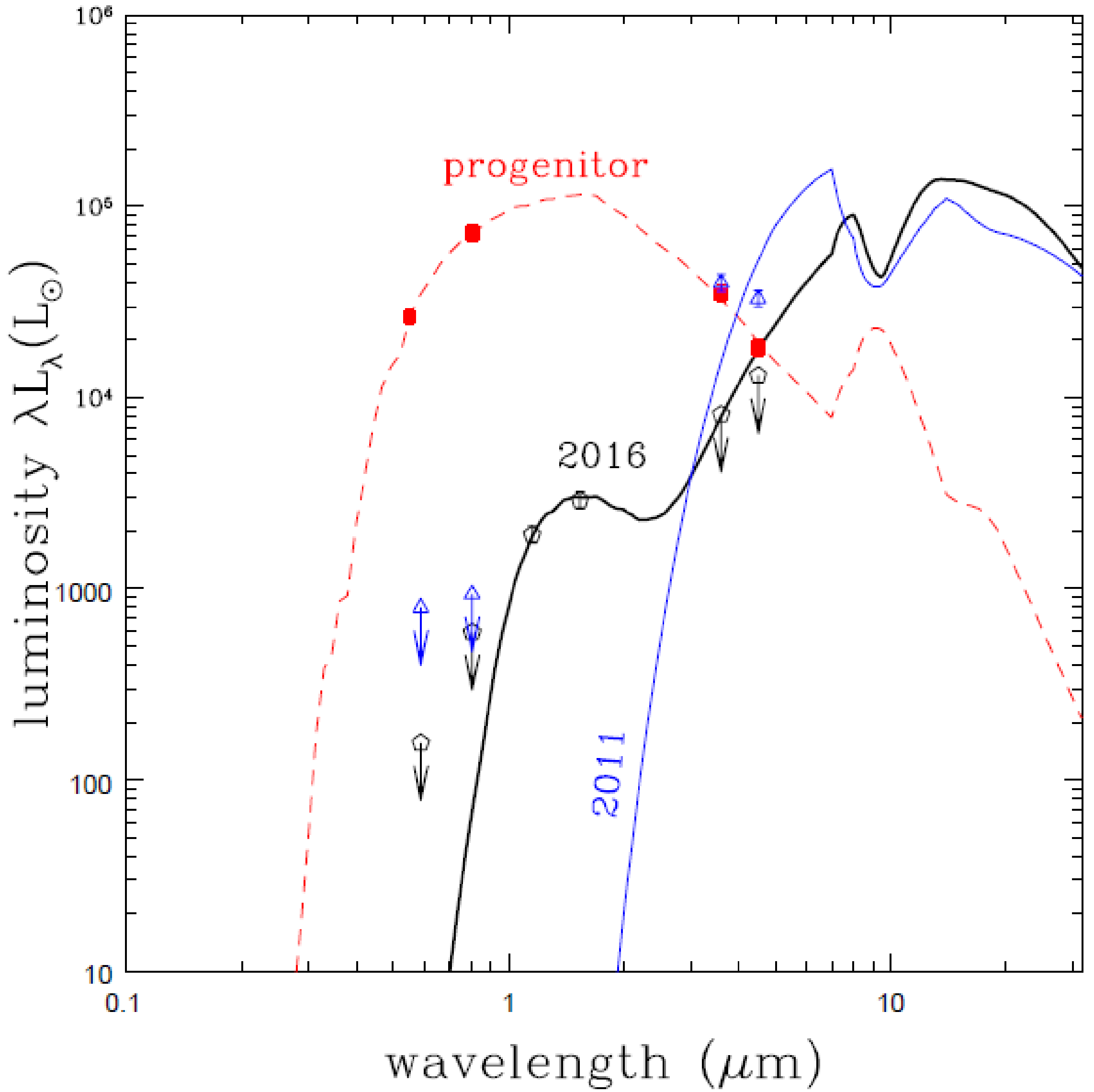


Cannot simultaneously fit near and mid-IR constraints with hot dust

N6946-BH1: Dusty Shell



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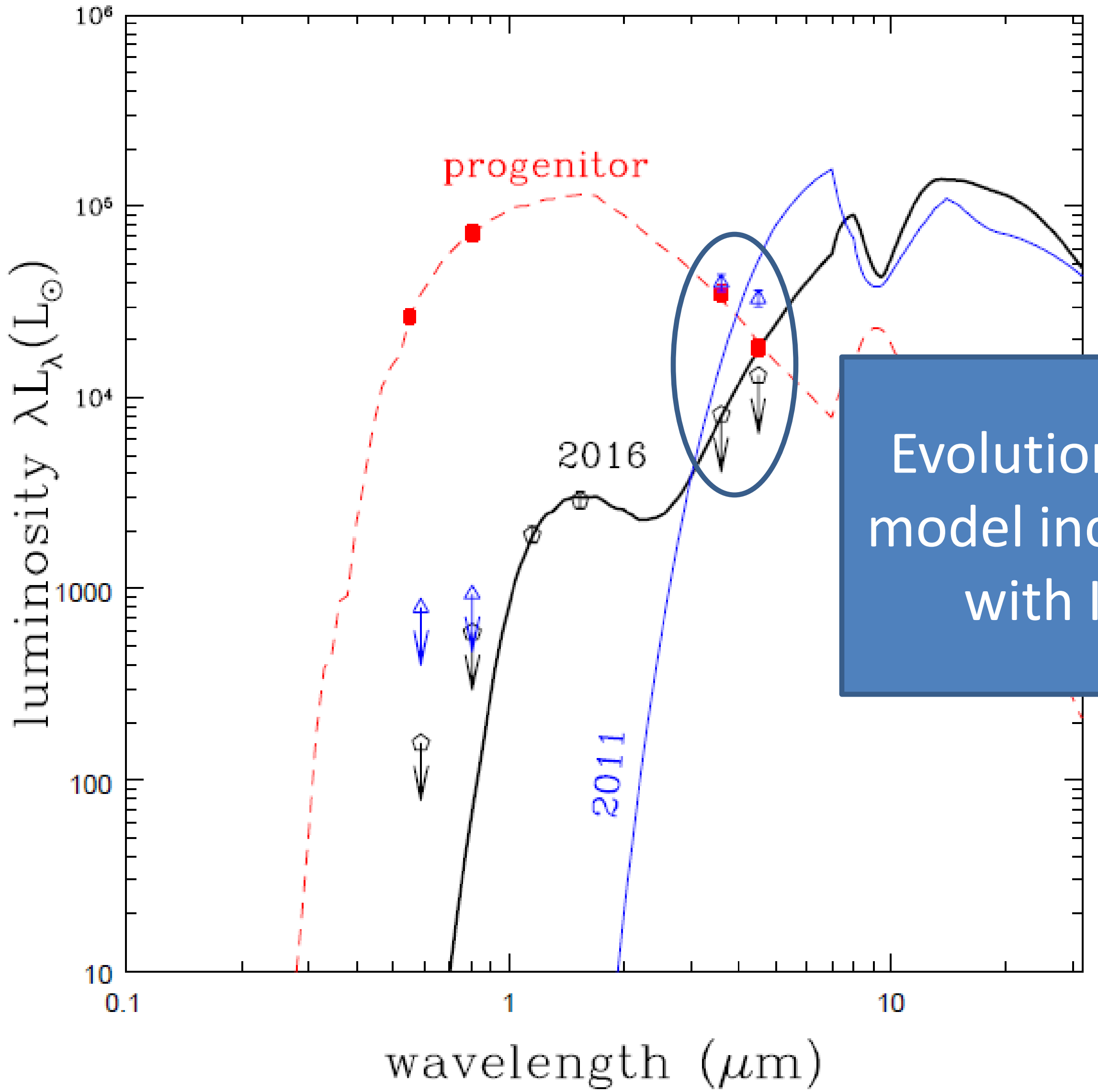
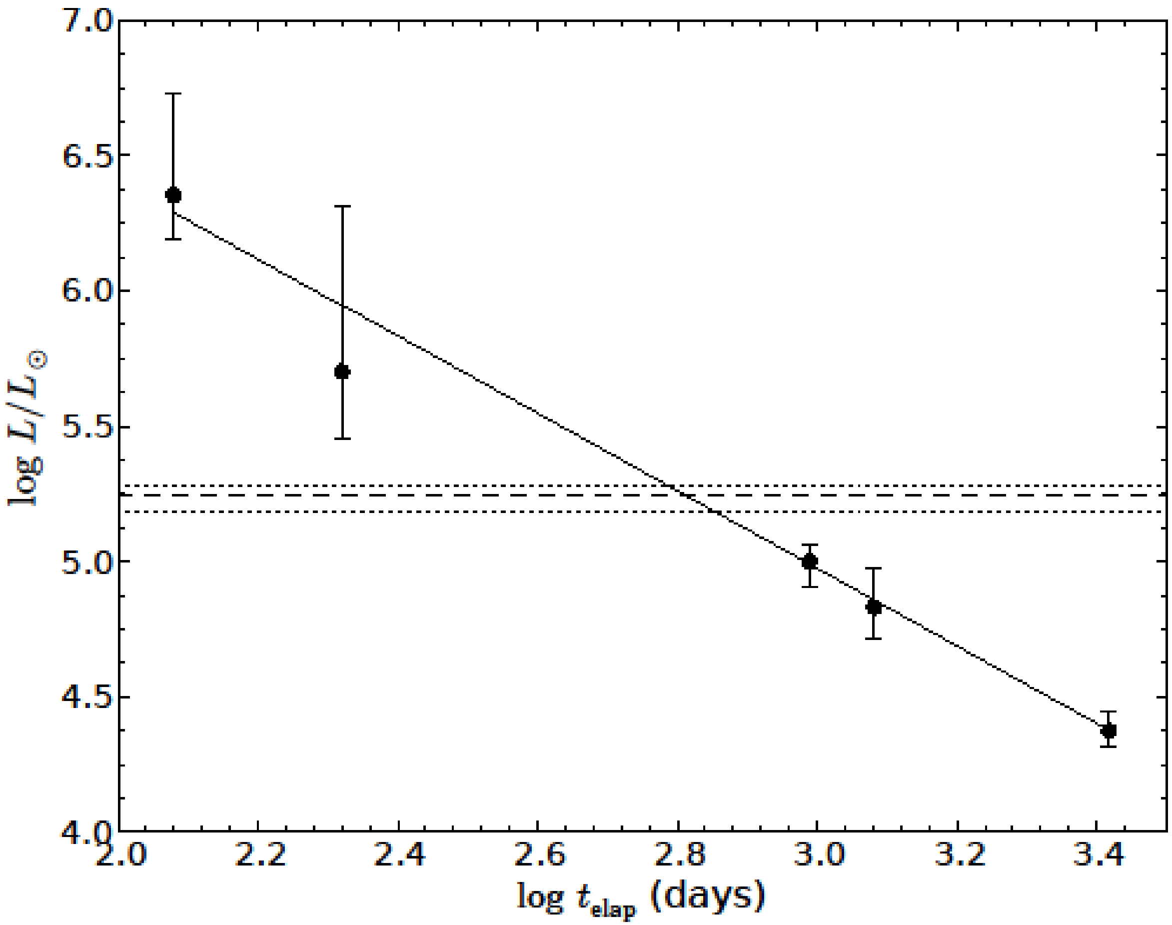


Evolution of shell model inconsistent with IR flux

Bolometric Luminosity Evolution



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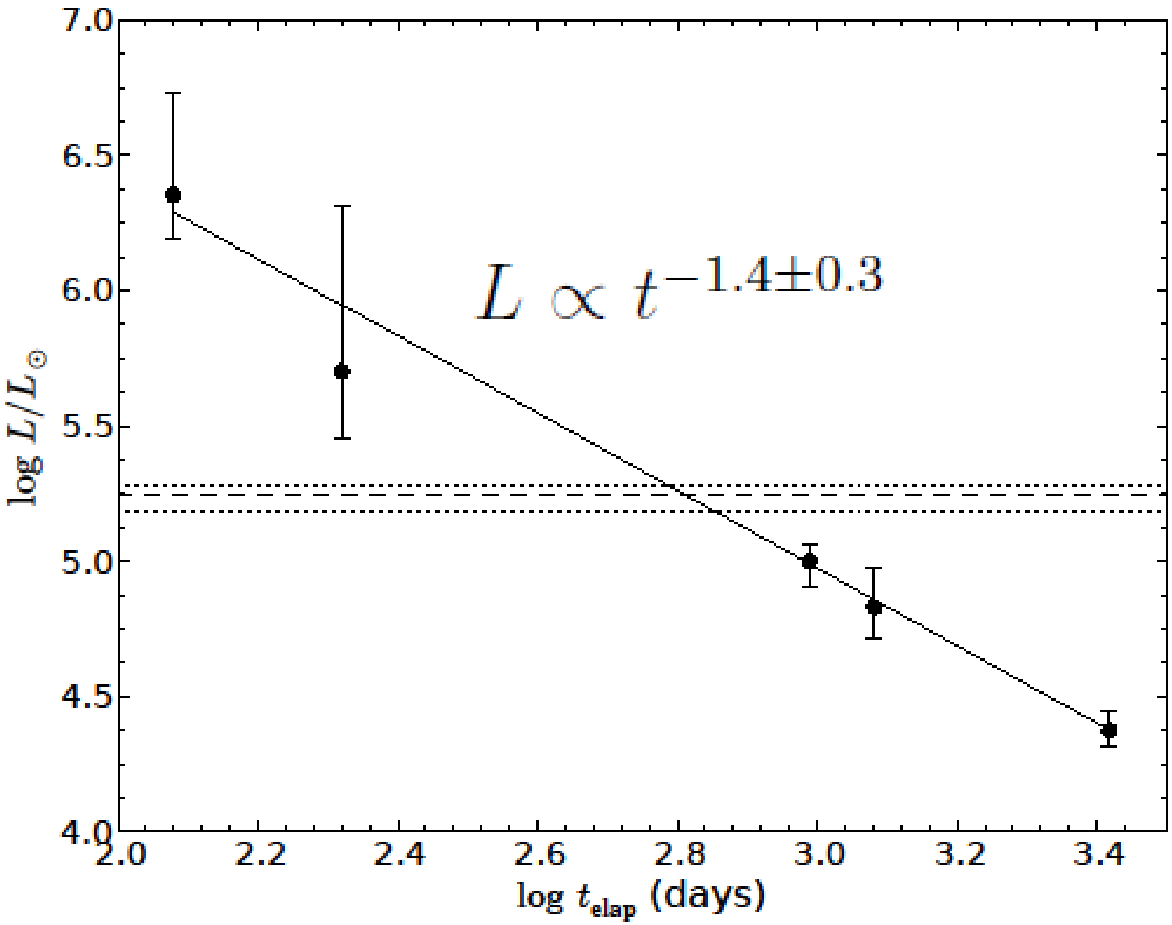

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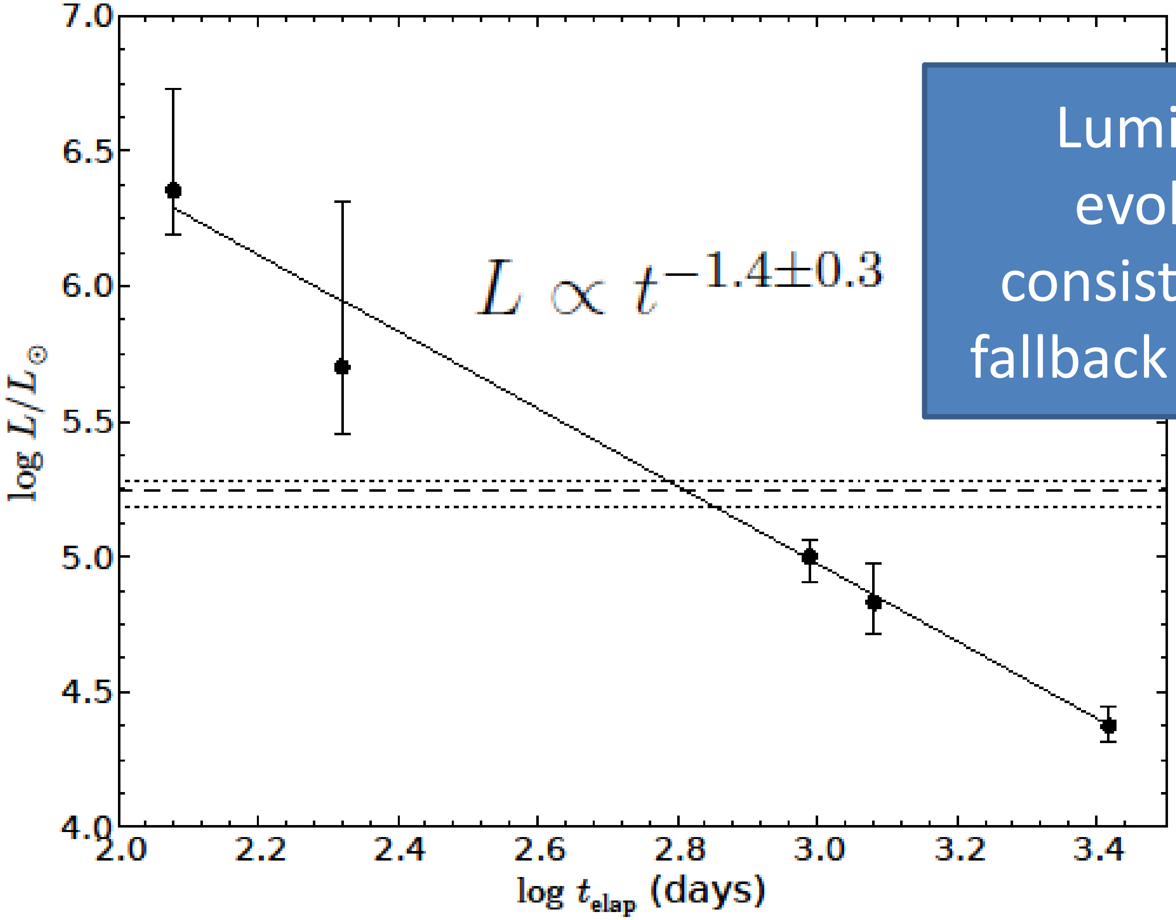
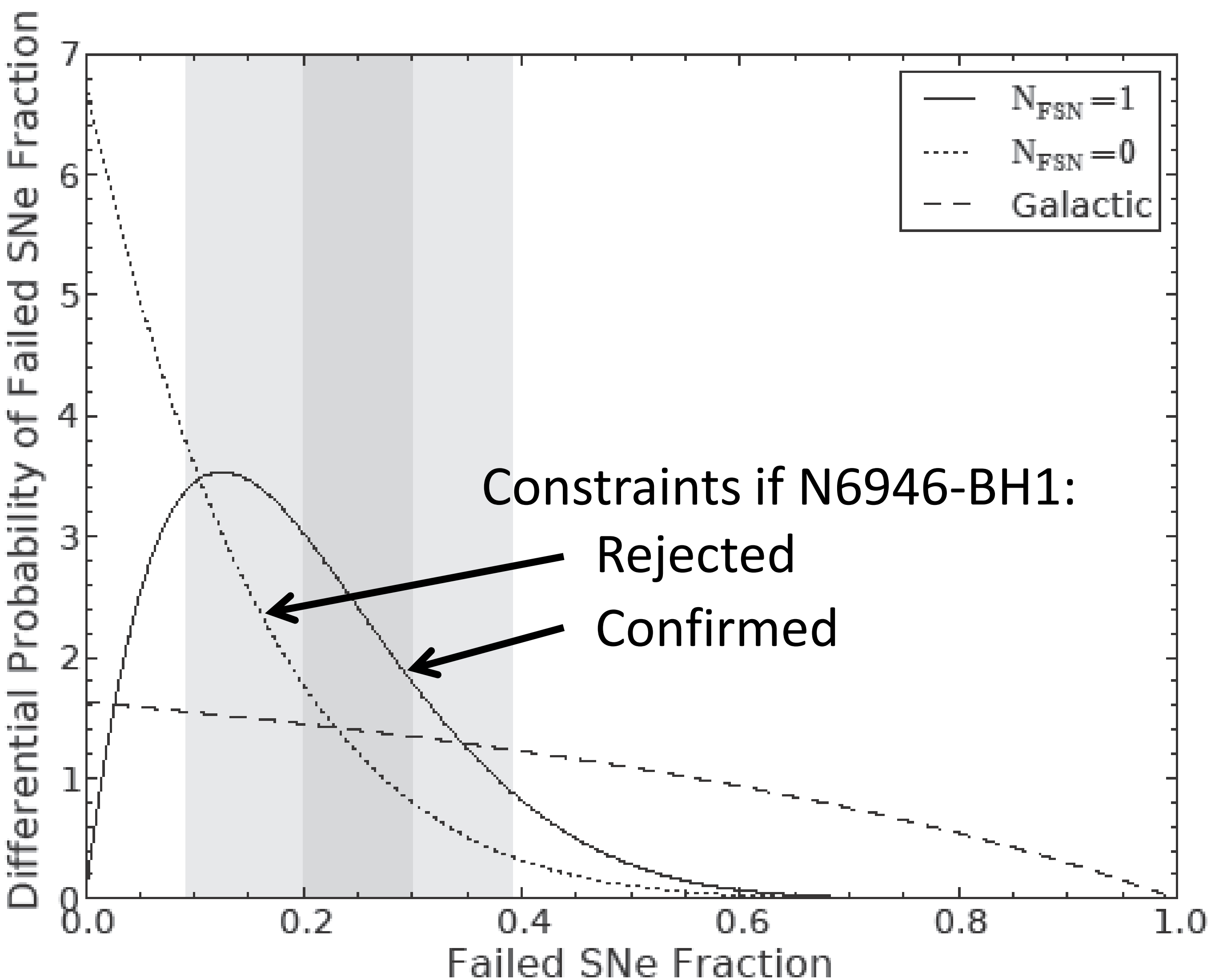


Luminosity evolution consistent with fallback accretion

Failed SN Fraction



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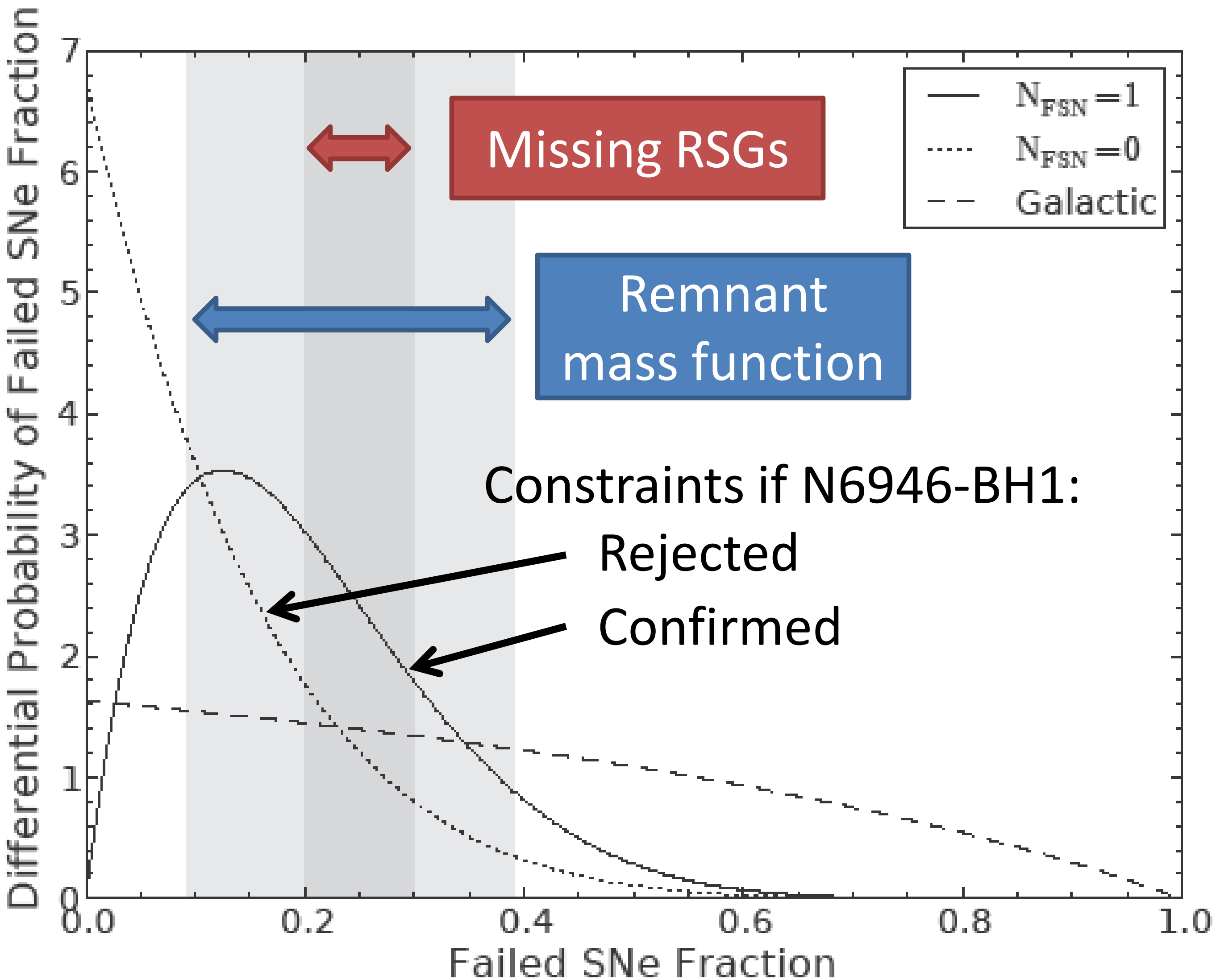
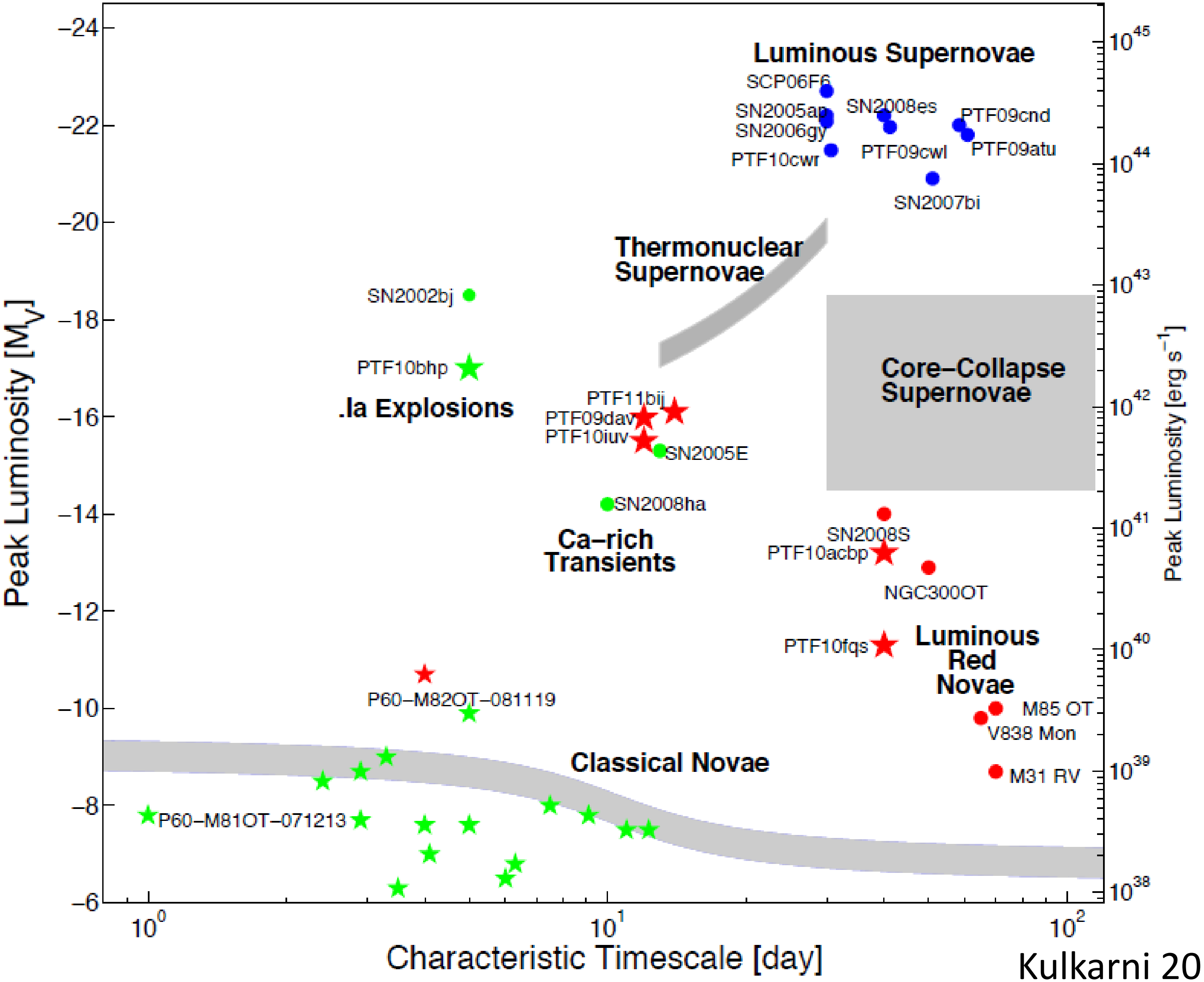
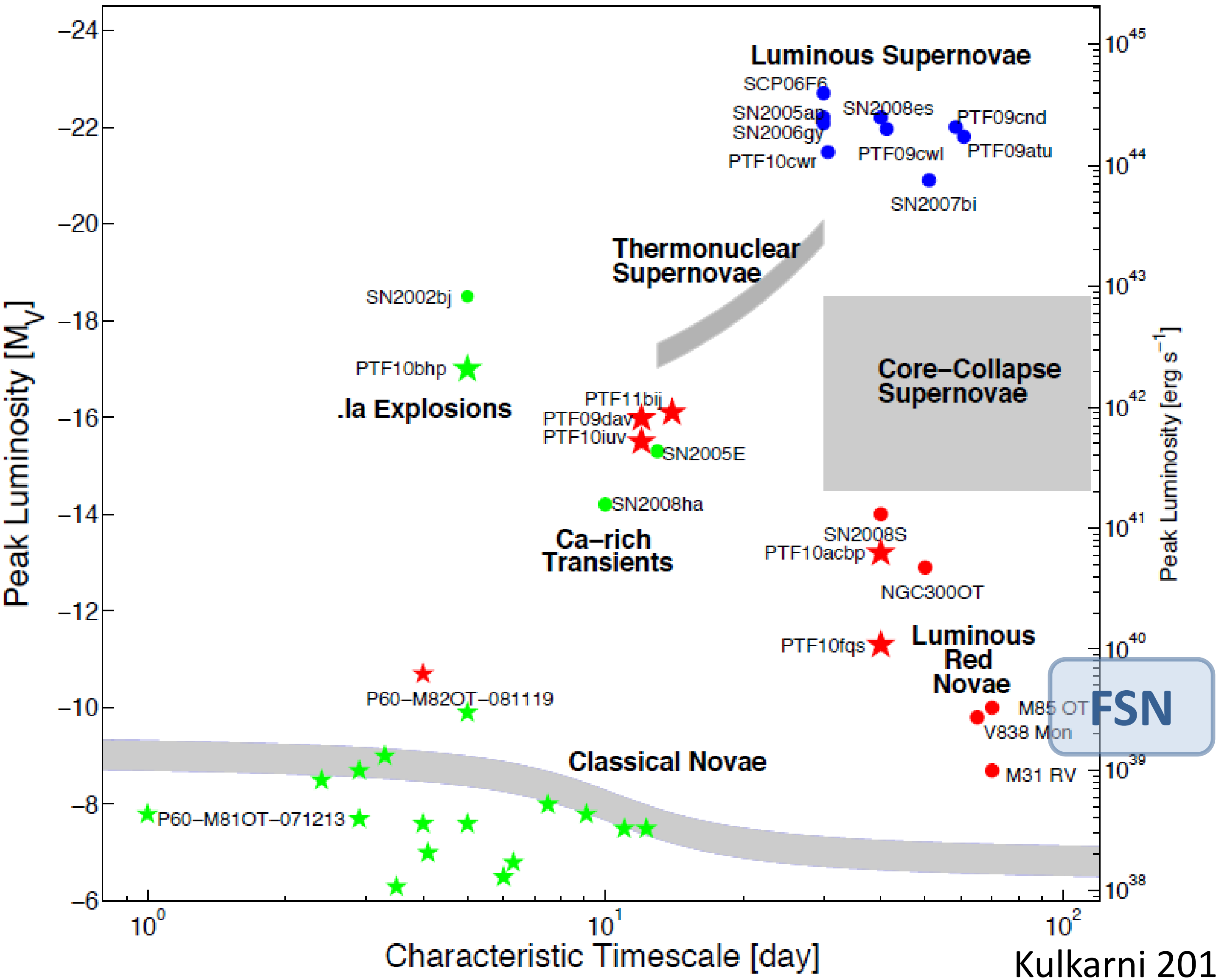


ZTF and GROWTH



Kulkarni 2012

ZTF and GROWTH



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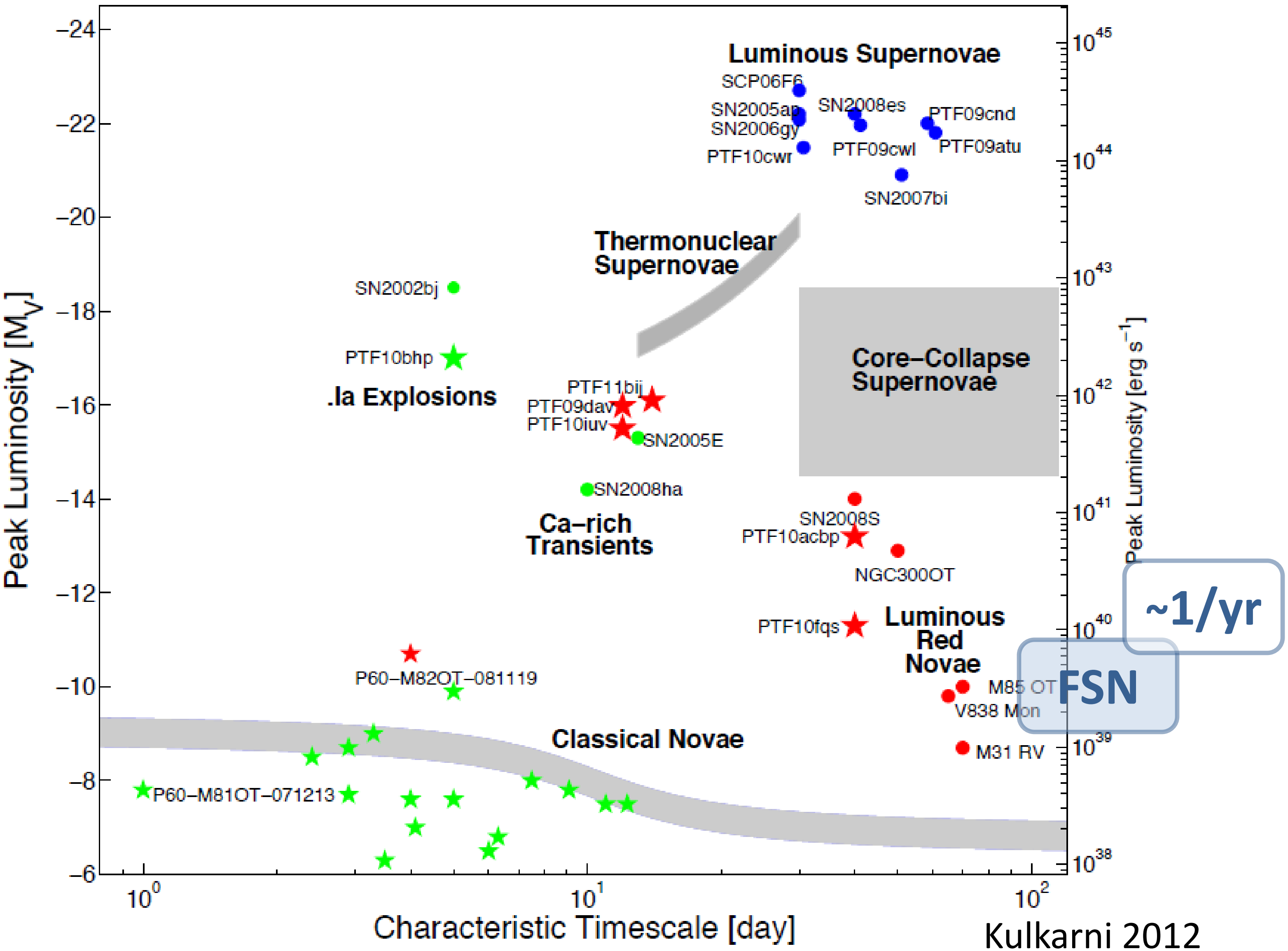

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ZTF and GROWTH

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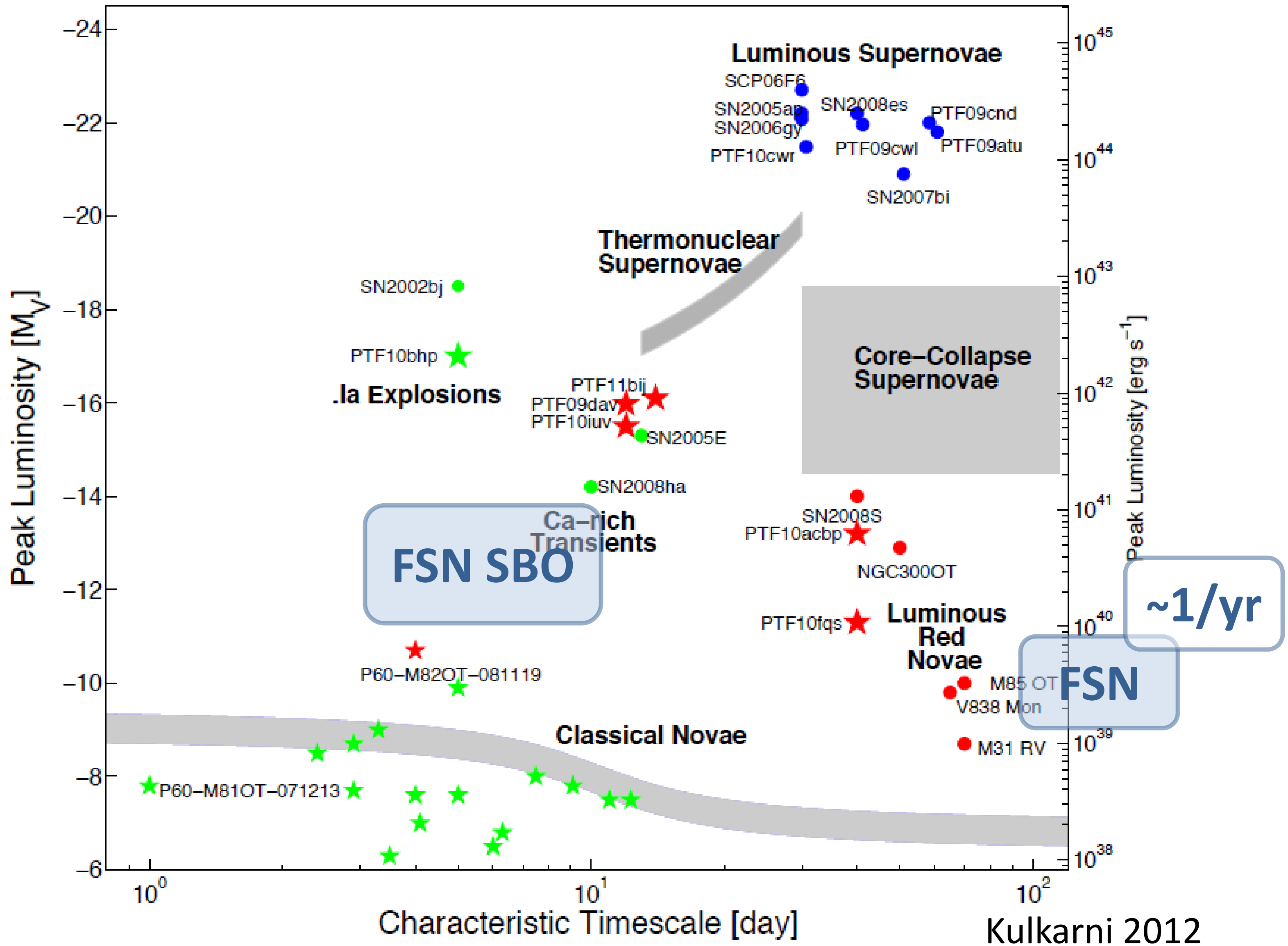

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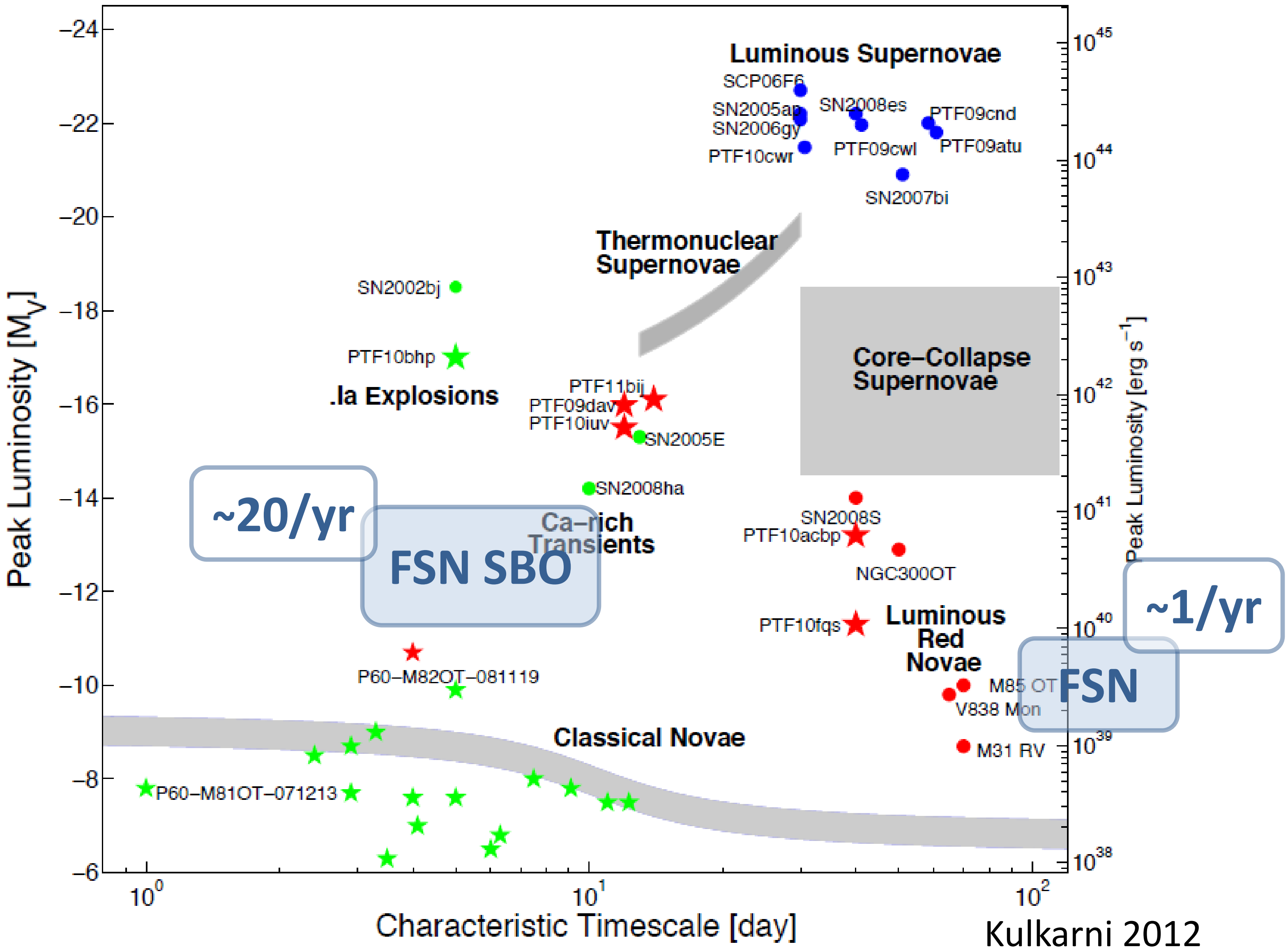

Kulkarni 2012

Summary

- N6946-BH1
  - Possibly first failed SN & first newly-formed BH discovered
- If confirmed: ~14% of core collapses fail (5-47%)
  - Resolves RSG problem; explains BH mass function
  - ZTF should detect dozens fSN SBO per year
    - Timescales & peak wavelength ideal for GROWTH follow-up
    - SBO constrains progenitor radius
    - SBO + recombination plateau together constrain explosion energy and ejecta mass
- If rejected: <35% (90% confidence) of core collapses fail

N6946BH1: light curve