The Importance of Early EM Observations of Neutron-Star Mergers and How to Get Them

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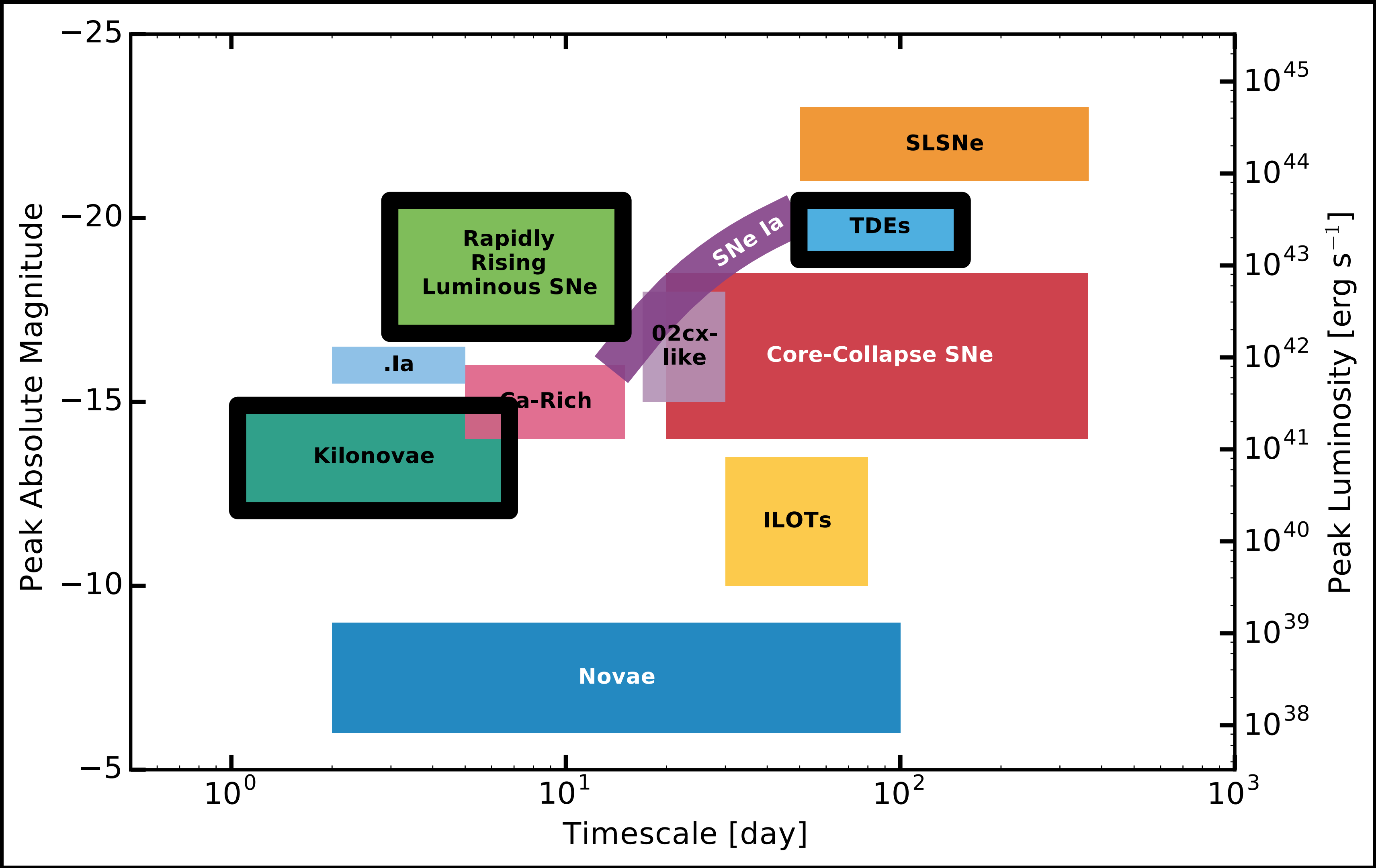
Surveys of the Transient Sky are Flourishing

All-Sky Automated Search for Supernovae (ASAS-SN)
Catalina Sky Survey (CSS)
Catalina Real-Time Transient Survey (CRTS)
Dark Energy Survey (DES)
Evryscope
Gaia
Zwicky Transient Facility (ZTF)
Kepler-2 (K2)
Kilodegree Extremely Little Telescopes (KELT)
La Silla Quest
Optical Gravitation Lensing Experiment (OGLE)
Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)
SkyMapper Southern Sky Survey

(partial list, more being planned and built)

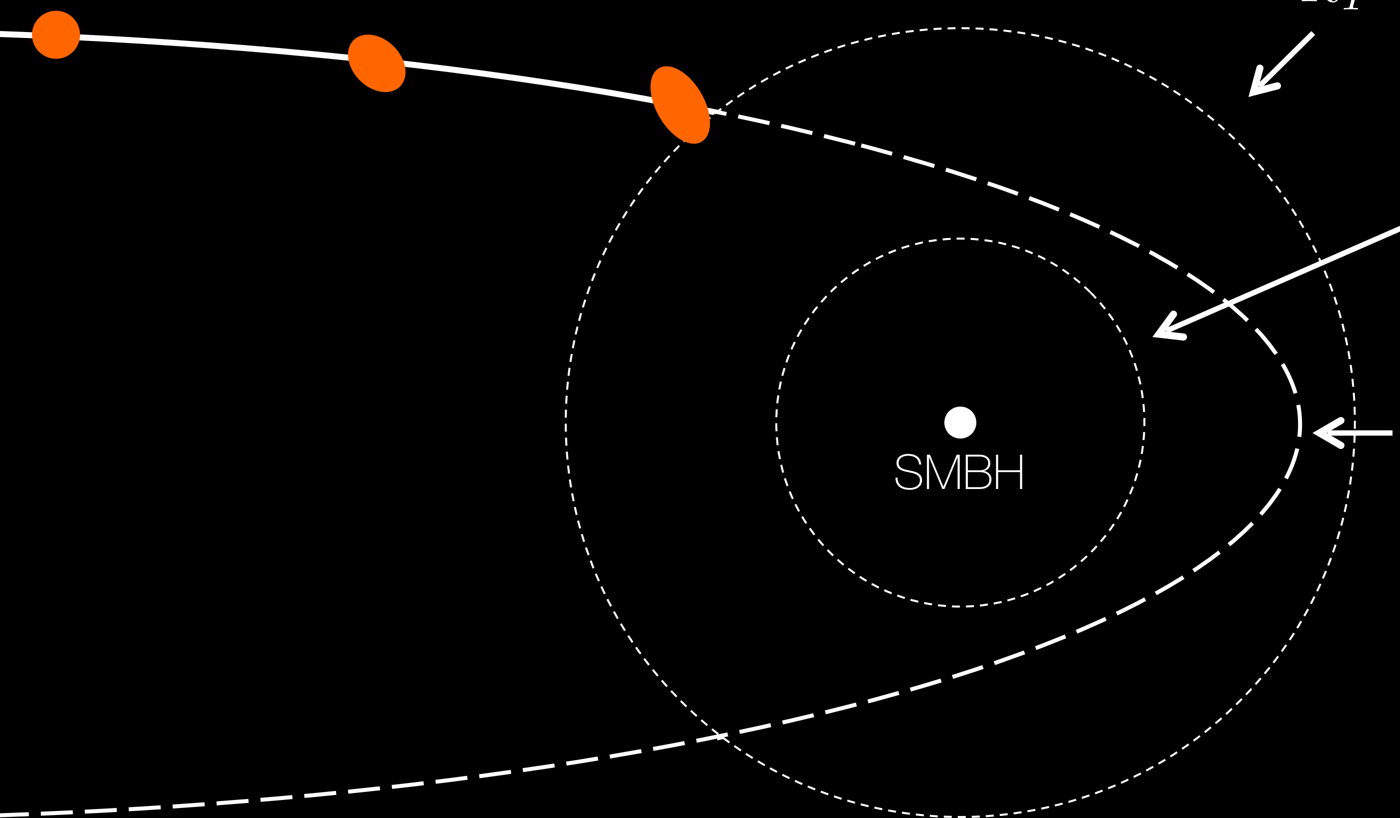
The Phase Space of Transients is Being Filled



Part I:
Tidal Disruption Events

Important Scales

$$R_T = \left(\frac{M_{BH}}{M_*}\right)^{1/3} R_*$$



$$R_S = \frac{2GM_{BH}}{c^2}$$

$$R_p$$

$$\beta = R_T/R_p$$

$$R_T \gtrsim R_S \text{ for } M_{BH} \lesssim 10^8 M_\odot \cdot \left(\frac{R_*}{R_\odot}\right)^{3/2} \left(\frac{M_*}{M_\odot}\right)^{-1/2}$$

A Tidal Disruption Event (TDE) is Complicated

NASA, S Gezari/JHU and J Guillochon/UCSC

Motivation: Study SMBHs

TDEs can be used to study quiescent massive black holes (and the M-Sigma relation) **beyond the nearby Universe** and test **GR**

Not A New Idea, But Events Are Rare

Hills (1975) – A star could be disrupted by a massive BH.

Rees (1988), Phinney (1989), Evans & Kochanek (1989) – Half of the material is bound, half unbound, expect emission when the bound material falls back to the BH as $t^{-5/3}$.

From the accretion onto the SMBH, expect emission in soft x-rays and hard UV.

Donley et al. (2002), Wang & Merritt (2004), Kesden (2012), Stone & Metzger (2014) – Rate is 10^{-4}-10^{-5} events per galaxy per year.

Early Observations Were Archival, Sparse Data

ROSAT (X-Rays) – 5 archival candidates (Donley et al. 2002).

XMM-Newton (X-Rays) – 5 additional archival candidates (Esquej et al. 2007).

SDSS (optical) – 2 archival candidates (van Velzen et al 2011).

GALEX (UV) + CFHT (optical) – one candidate (~year cadence light curve; Gezari et al. 2006).

Two Major Discoveries in 2011 and 2012

High Energy TDEs

Swift J1644 (Bloom et al. 2011, Burrows et al. 2011, Levan et al. 2011, Zauderer et al. 2011)

Gamma and X-rays, radio
No optical

Non-thermal spectrum
Plateau in X-ray light curve then $\sim t^{-5/3}$ decline

Additional events:
Swift J2058 (Cenko+ 12), Swift J1112 (Brown+ 15)

Optical-UV TDEs

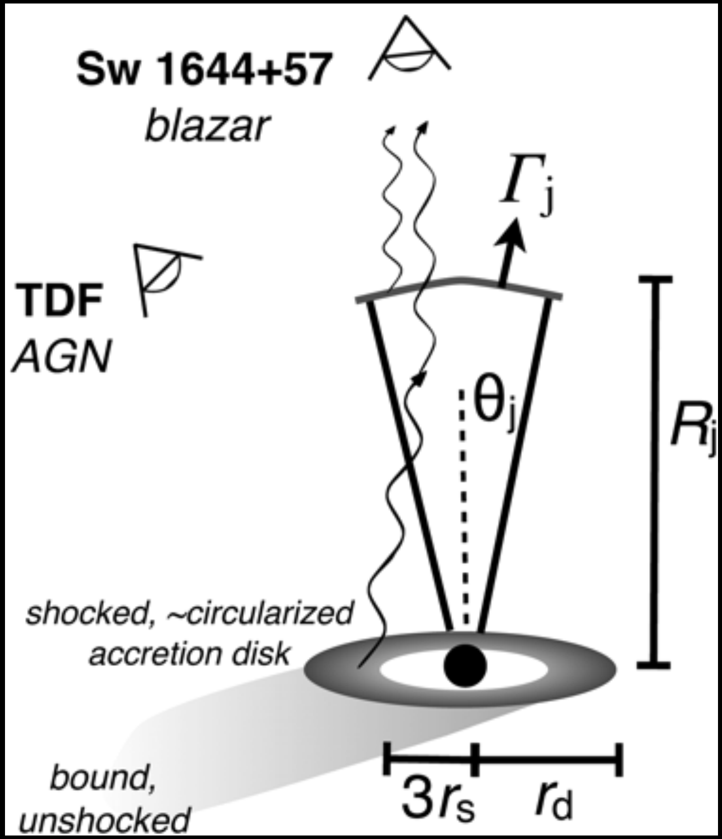
PS1-10jh (Gezari et al. 2012)

UV / Optical
No X-rays

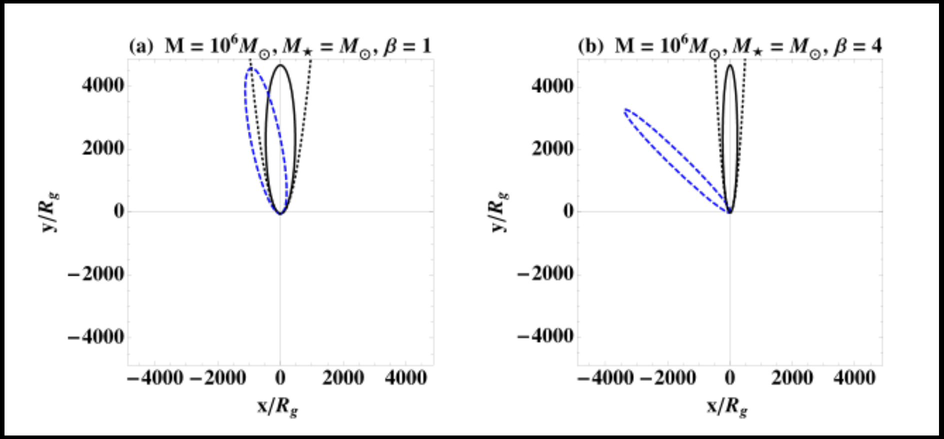
Hot blackbody (30,000K)
Smooth rise and fall light curve $\sim t^{-5/3}$ decline

Additional events:
IA+ 14, Holoien+ 14, 16a,b, Wyrzykowski+ 16, Hung+ 17 Blagorodnova+ 17,19, …

Why Two So Different Types of TDEs?

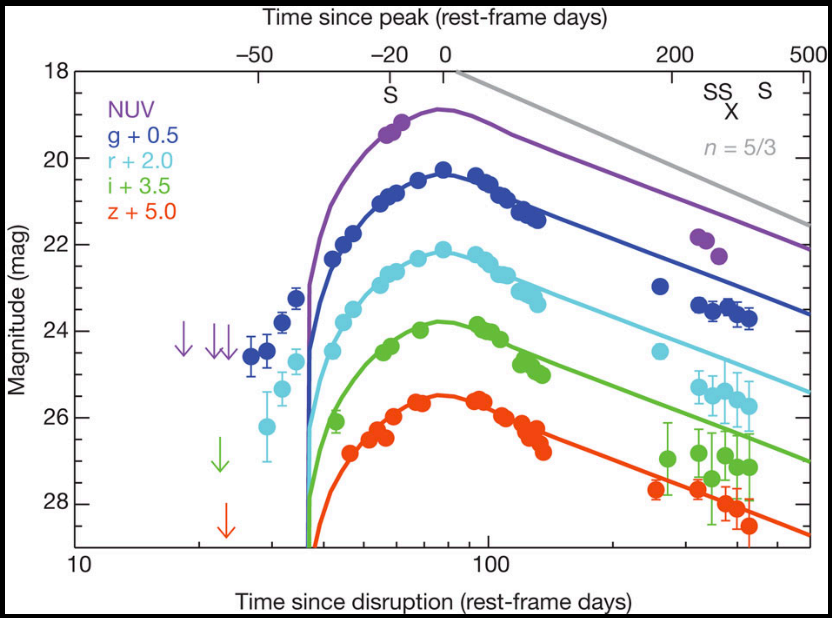


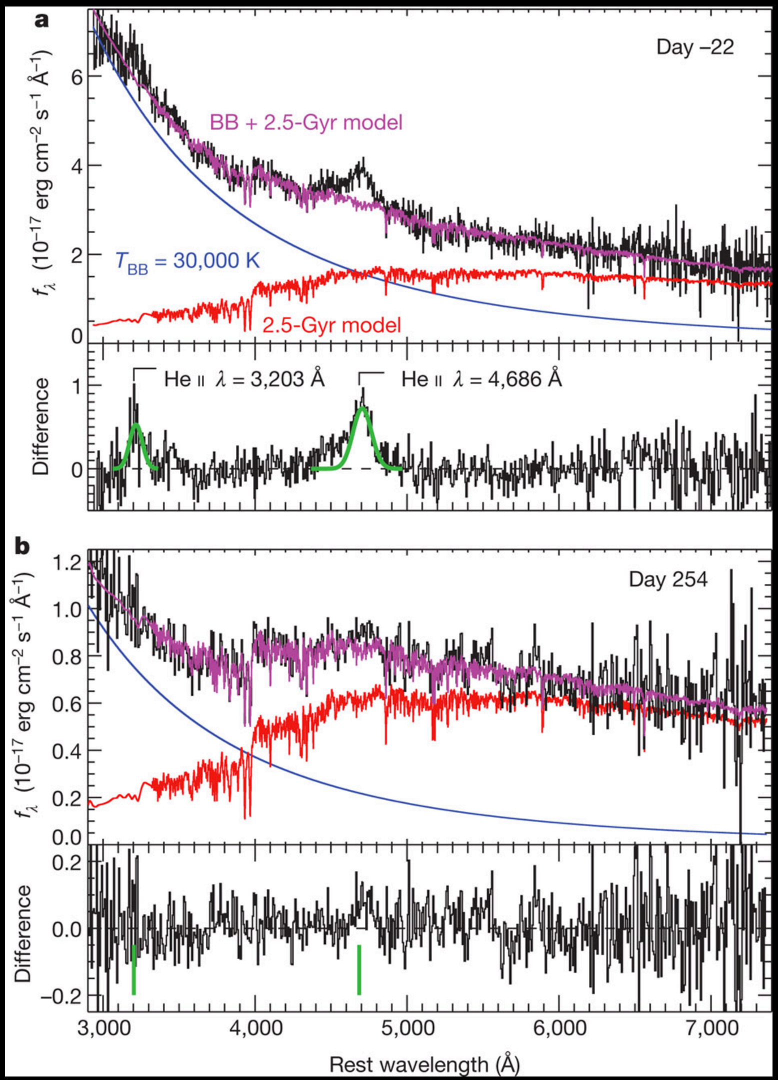
Bloom et al. (2011): Viewing angle effect



Dai et al. (2015): β effect

PS1-10jh: The First Optical + NUV TDE





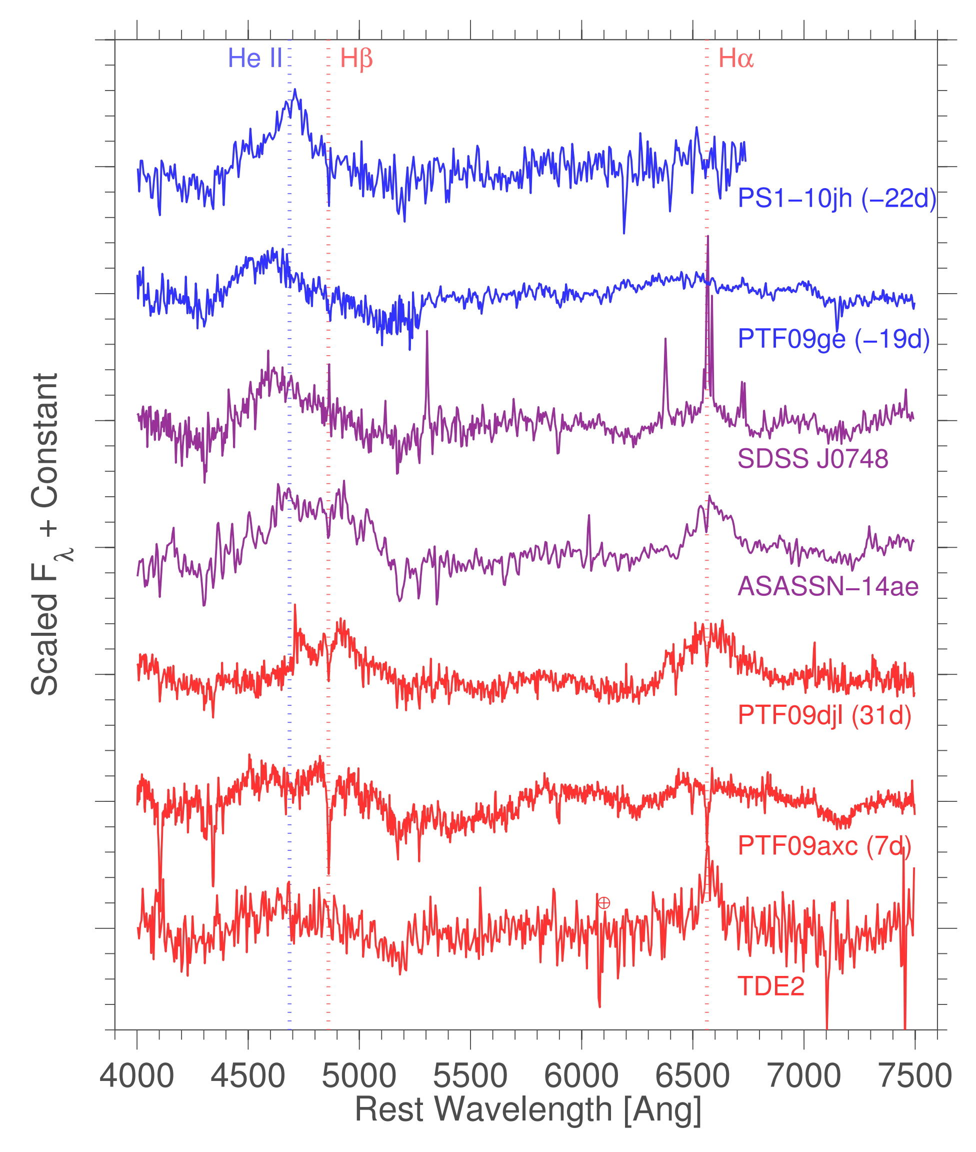
- Coincident with the center of a non-starforming galaxy.
- Peak magnitude -20
- Constant blue colors
- Only broad He II in spectrum

Gezari et al. (2012)

PS1-10jh Does Not Look as Expected for a TDE

Expected	Observed	
Center of galaxy	Center of galaxy	✓
$L \propto t^{-5/3}$	$L \propto t^{-5/3}$	✓
$T \sim 10^5 - 10^6$ K	$T = 3 \cdot 10^4$ K	✗
$R \sim R_T \sim 10^{13}$ cm	$R \sim 10^{15}$ cm	✗
$E \sim 0.1 M_\odot c^2 \sim 10^{53}$ erg	$E \sim 10^{51}$ erg	✗
Evolving Temperature	Constant Temperature	✗
Hydrogen from the star	No hydrogen, only helium	✗

Forming a Class, All in Galaxy Centers



Gezari+ 12

Arcavi+ 14

Wang+ 11

Arcavi+ 14
Holoien+ 14

Arcavi+ 14

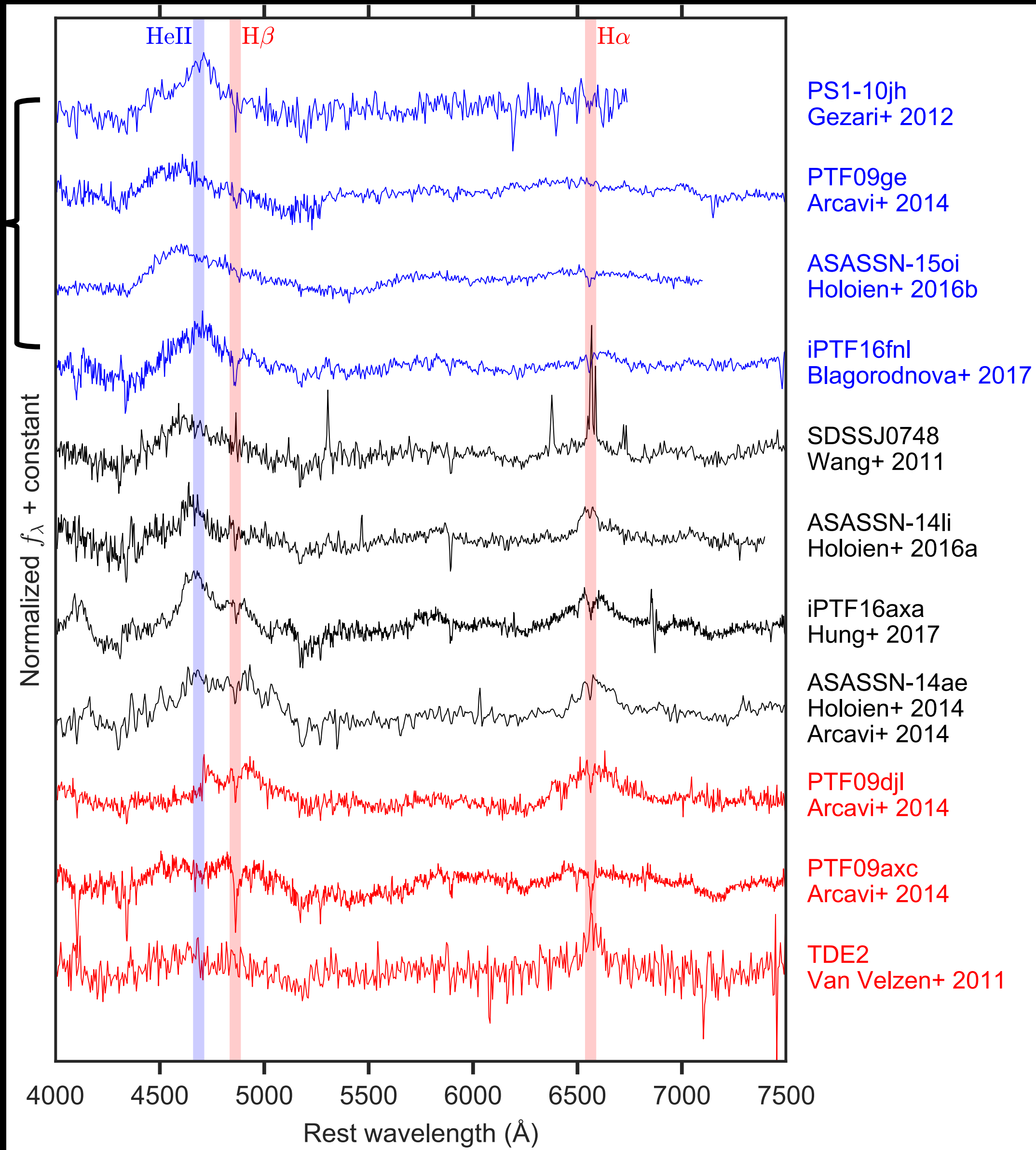
Arcavi+ 14

van Velzen+ 11

Arcavi et al. 2014

A Set of Events Now, All in Galaxy Centers

1/3 of disrupted stars are helium stars? Not likely.



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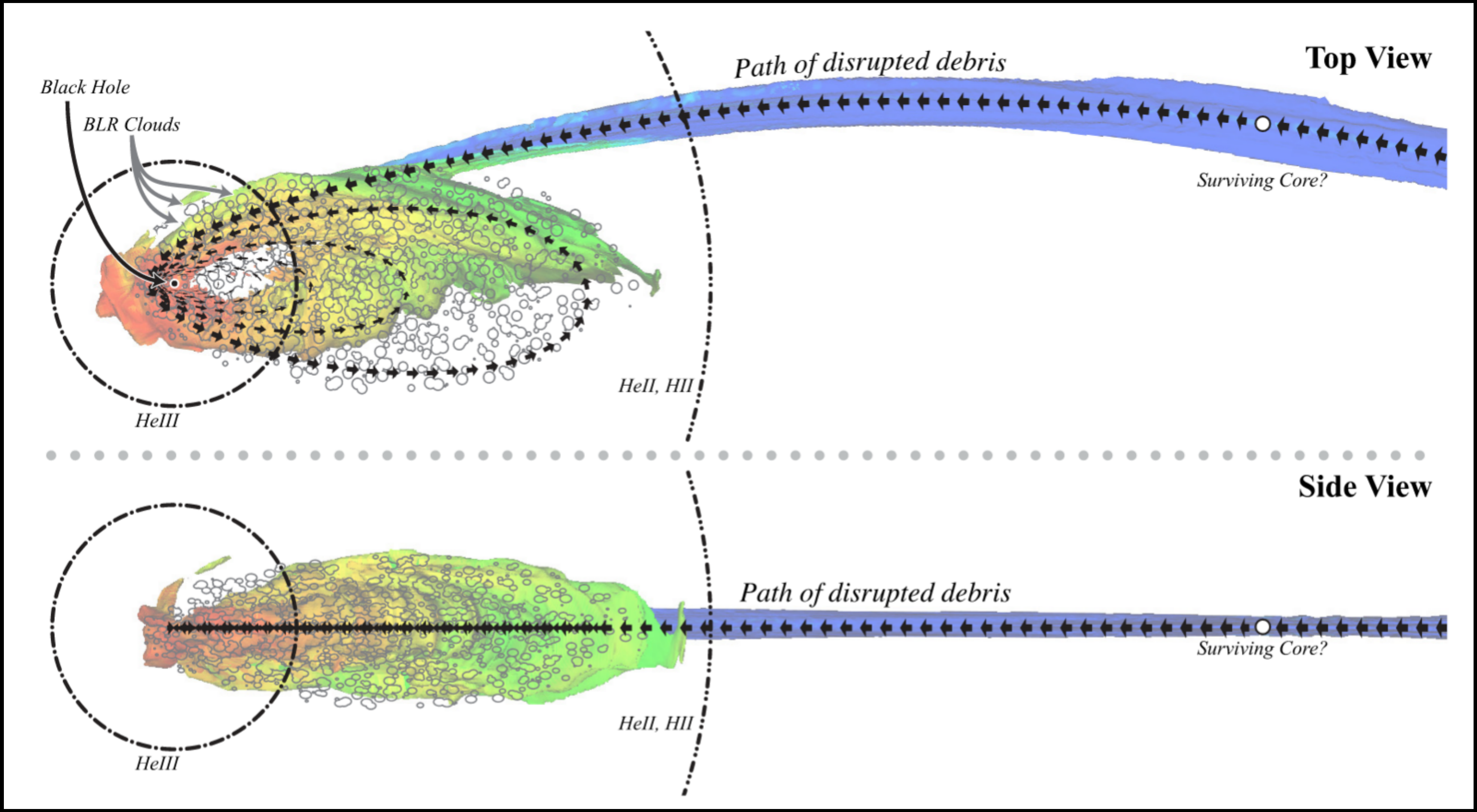
Are We Looking Through Reprocessing Material?



Guillochon et al. 2014

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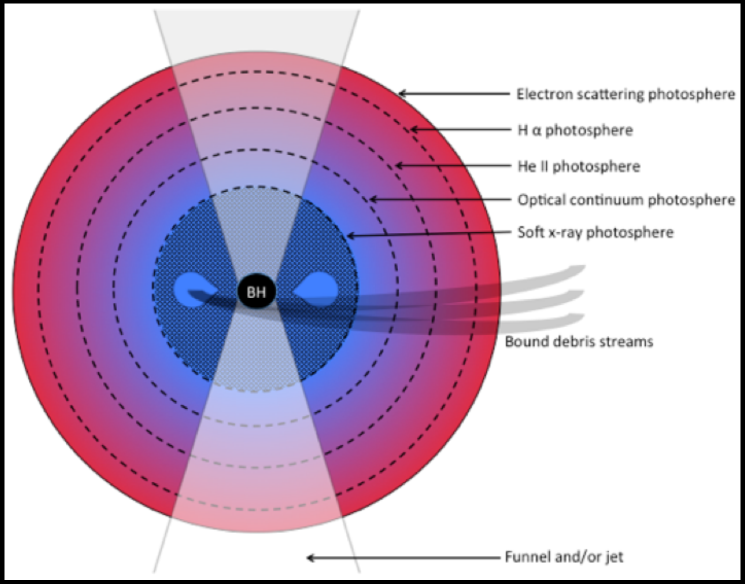
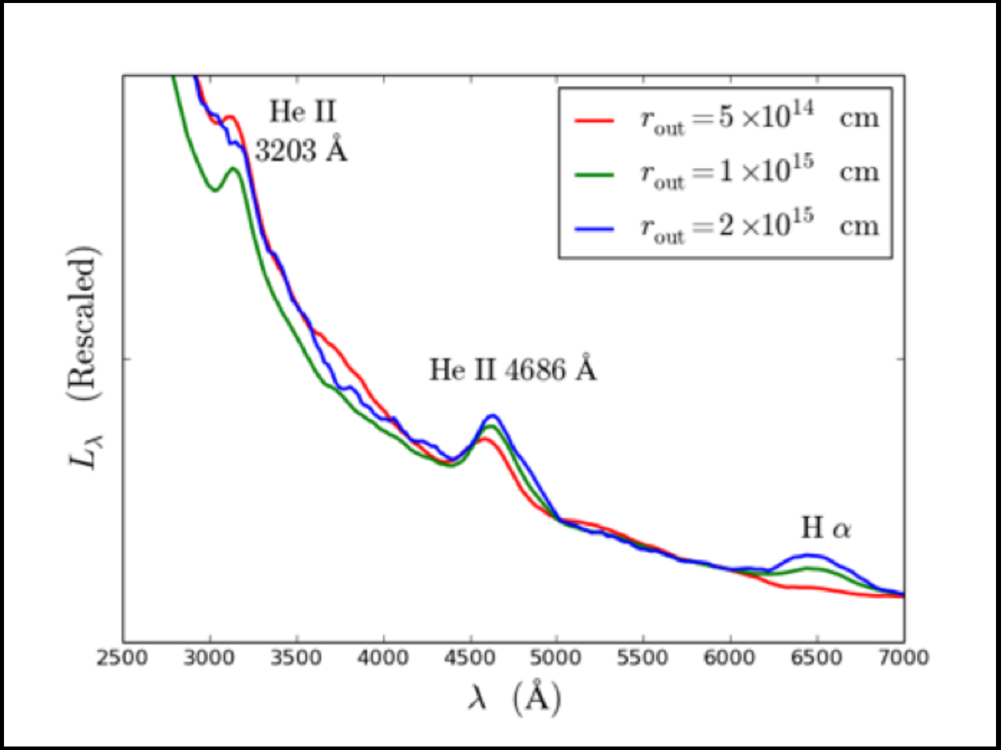


The presence of reprocessing material explains:

1. The low temperatures
2. The large radii
3. The lack of hydrogen in the spectra



Roth et al. 2016

Self Collision Shocks Important for Loosing Energy

WD–BH encounter

****

masses (sol.)	0.2 (WD) & 1000 (BH)
in. separation	50 (in 1.E9 cm)
hydrodynamics	SPH (4 030 000 particles)
EOS, gravity	Helmholtz, N
nucl. burning	red. QSE–network (Hix 98)
simul. time	5.4 min
color coded	column density
penet. factor	12

coding, simulation, visualisation: S. Rosswog

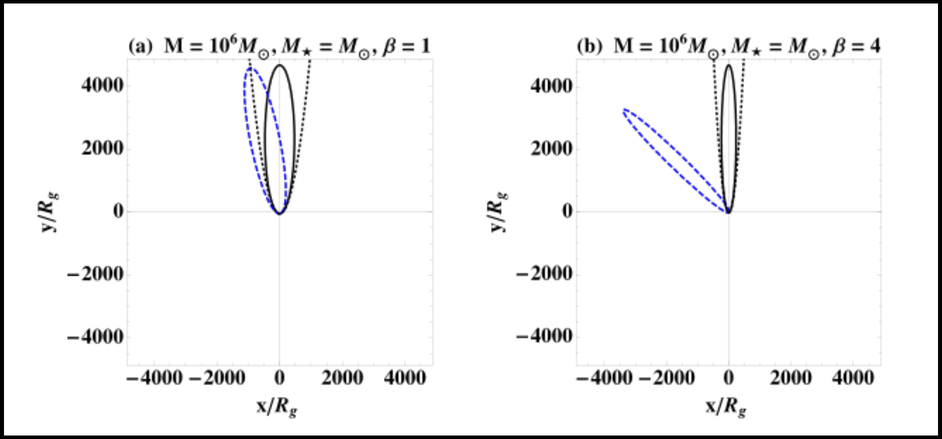
Rosswog et al. 2008

Video available at:
http://compact-merger.astro.su.se/Movies/IMBH1000_WD02_4e6parts_P12_N.mov

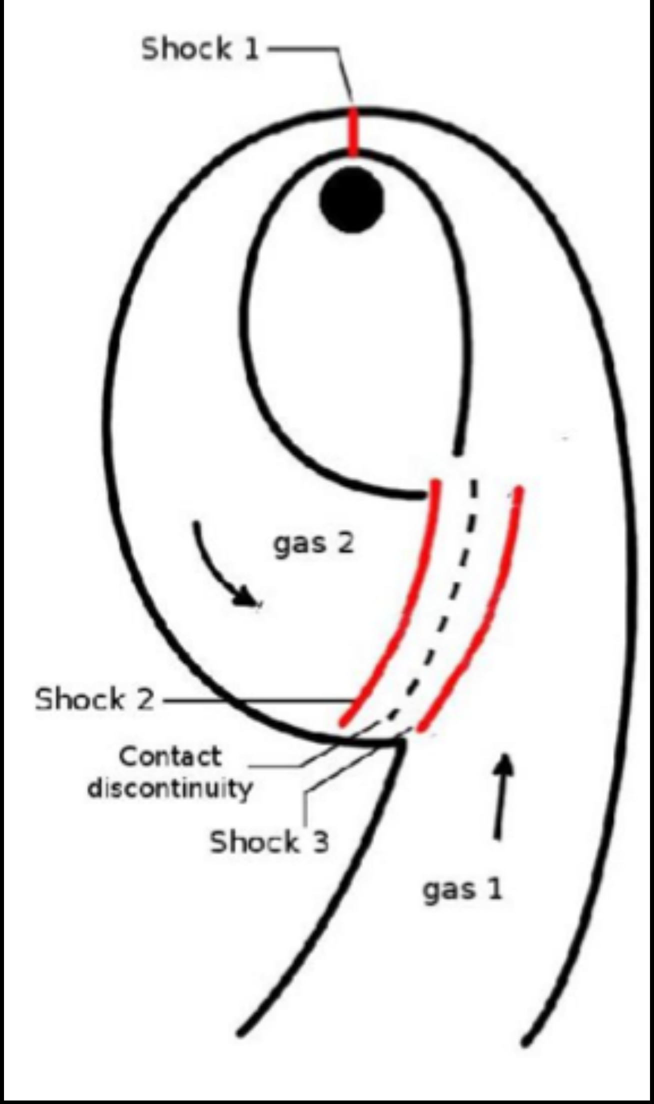
Are We Seeing the Energy from Outer Shocks?

Self crossing shocks explain:

1. The low temperatures
2. The large radii
3. The mechanism by which the material circularizes in order to accrete to the black hole
4. The two different TDE types?

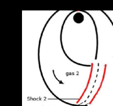
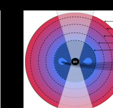
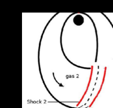
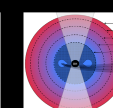
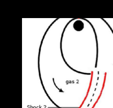
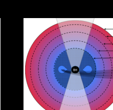


Dai et al. (2015): β effect



Piran et al. 2015

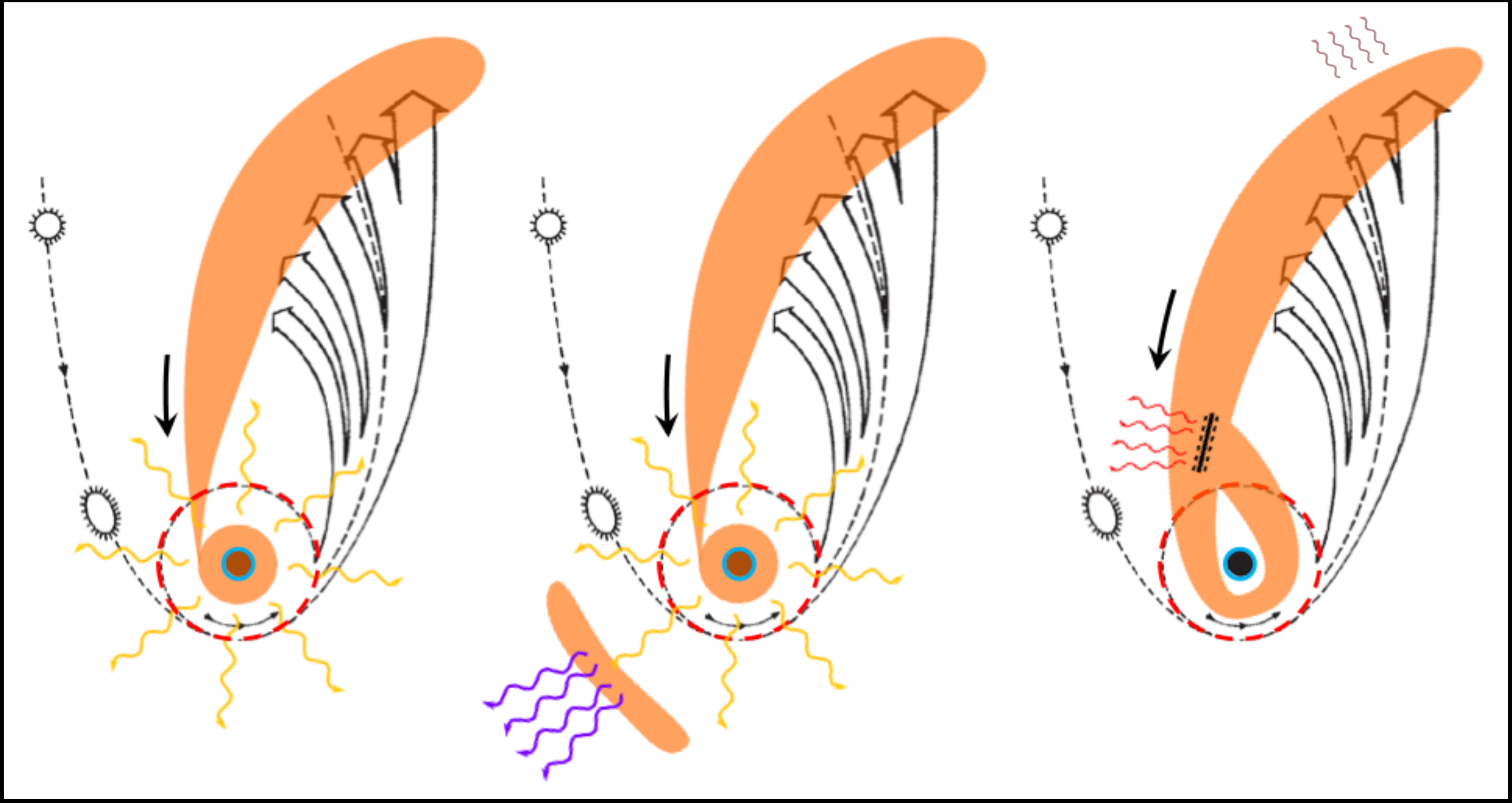
Two Models for the Emission of Optical TDEs

Expected	Observed		
Center of galaxy	Center of galaxy	✓	
$L \propto t^{-5/3}$	$L \propto t^{-5/3}$	✓	
$T \sim 10^5 - 10^6$ K	$T = 3 \cdot 10^4$ K		 
$R \sim R_T \sim 10^{13}$ cm	$R \sim 10^{15}$ cm		 
$E \sim 0.1 M_\odot c^2 \sim 10^{53}$ erg	$E \sim 10^{51}$ erg	✗	
Evolving Temperature	Constant Temperature	?	
H from the star	No H, only He		 

Different Emission Mechanisms for TDEs

Unbound Material
ISM interaction

Adapted from Rees (1988) by C. Bonnerot

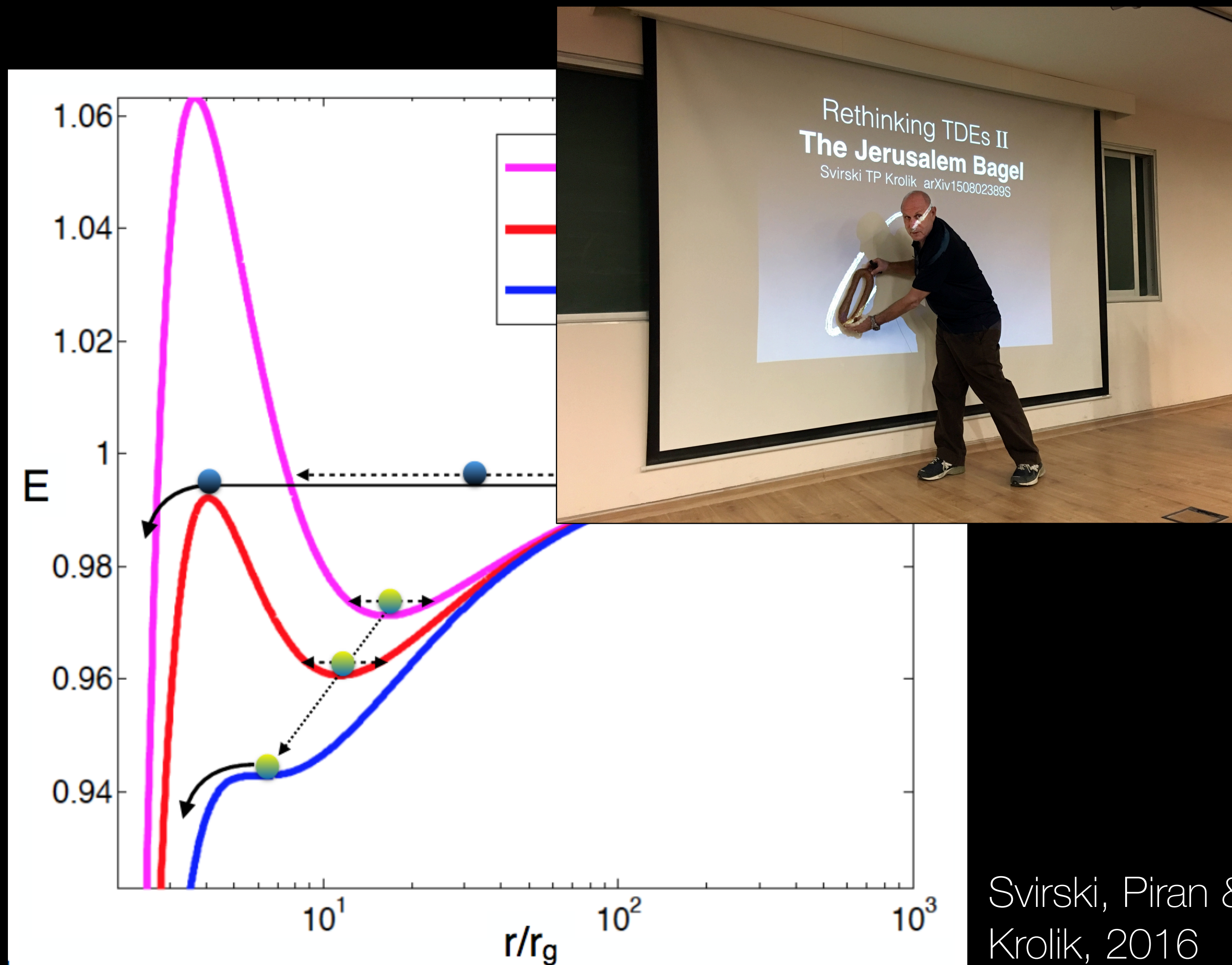


Accretion

Reprocessed Accretion

Outer Shocks

The Jerusalem Bagel Model: Elliptical Accretion



Svirski, Piran & Krolik, 2016

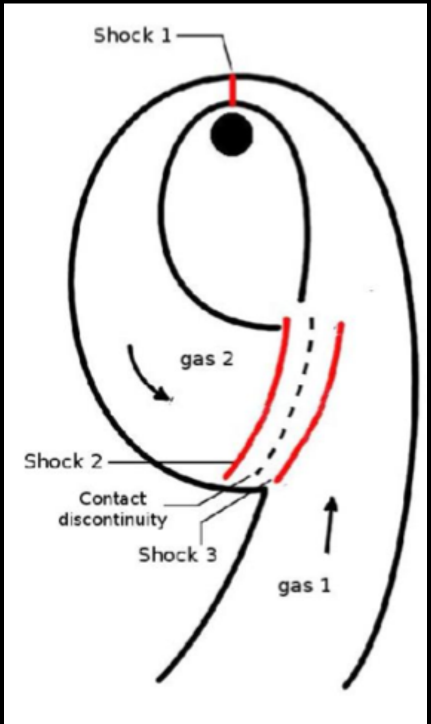
Motivation: Study SMBHs and Accretion Physics

TDEs can be used to study quiescent massive black holes (and the M-Sigma relation) **beyond the nearby Universe** and test **GR**

But first, we need to understand the events: what they look like and why, how are the TDE observables related to the black hole properties

GR Effects Play Crucial Role in TDE Emission

Stream collisions due to GR precession



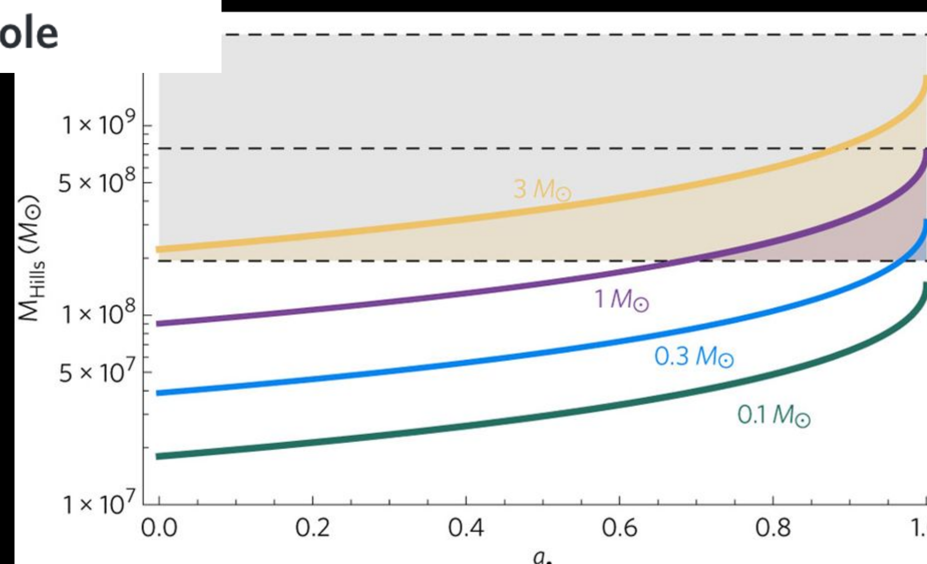
GR Effects Play Crucial Role in TDE Emission

Stream collisions due to GR precession

BH Spin can push maximal mass up

nature astronomy
LETTERS
PUBLISHED: 12 DECEMBER 2016 | VOLUME: 1 | ARTICLE NUMBER: 0002

The superluminous transient ASASSN-15lh as a tidal disruption event from a Kerr black hole



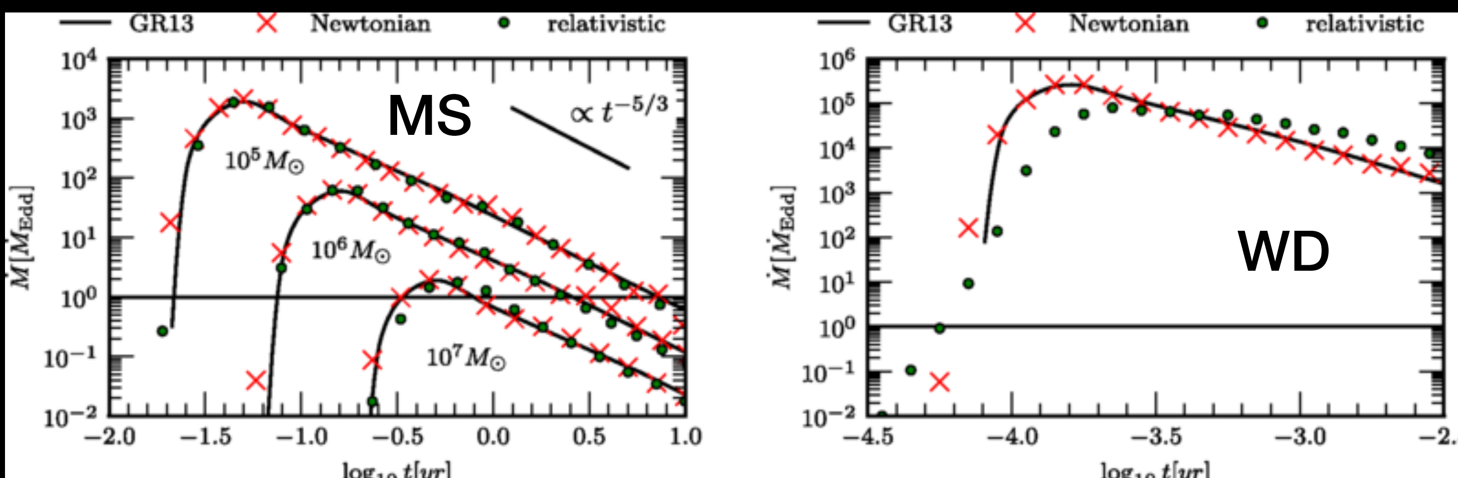
Leloudas et al. 2016

GR Effects Play Crucial Role in TDE Emission

Stream collisions due to GR precession

BH Spin can push maximal mass up

GR affects the TDE light curve



Cheng et al. 2015

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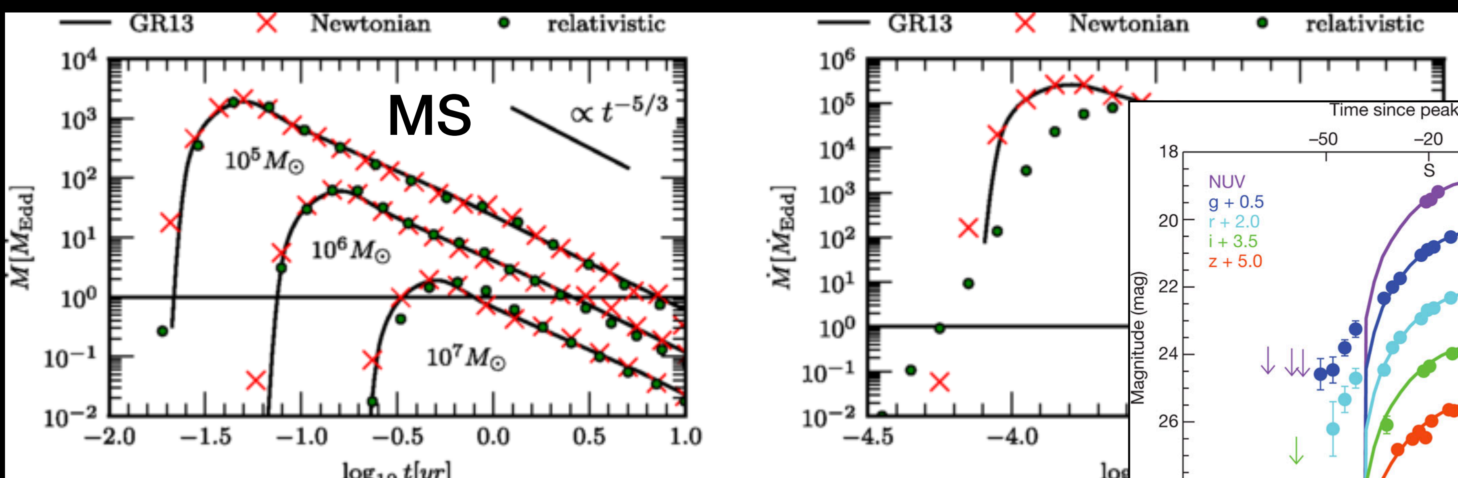
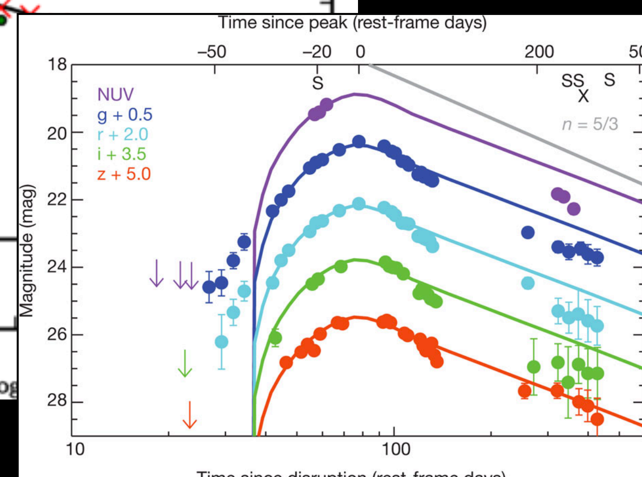


Cheng et al. 2015



Gezari et al. 2012

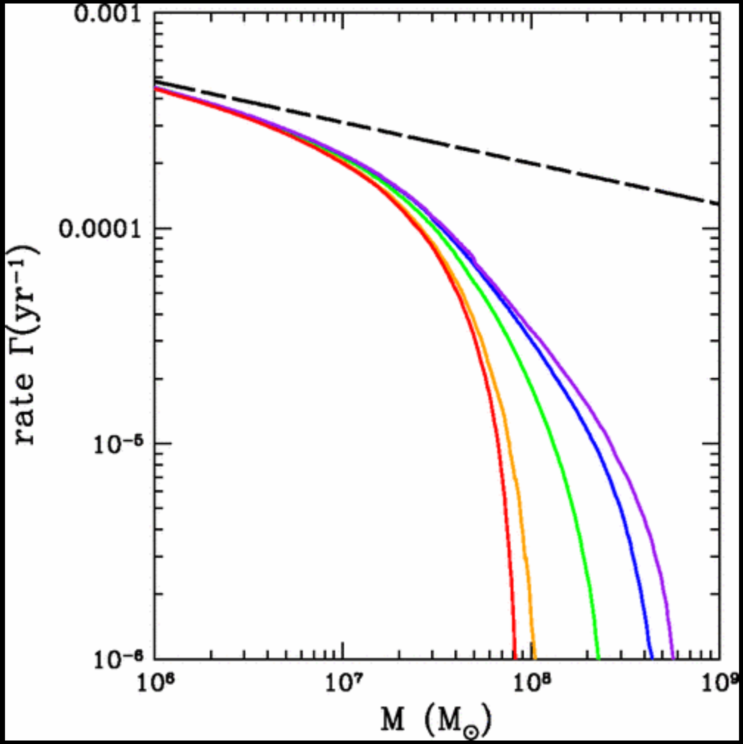
GR Effects Play Crucial Role in Forming TDEs

Stream collisions due to GR precession

BH Spin can push maximal mass up

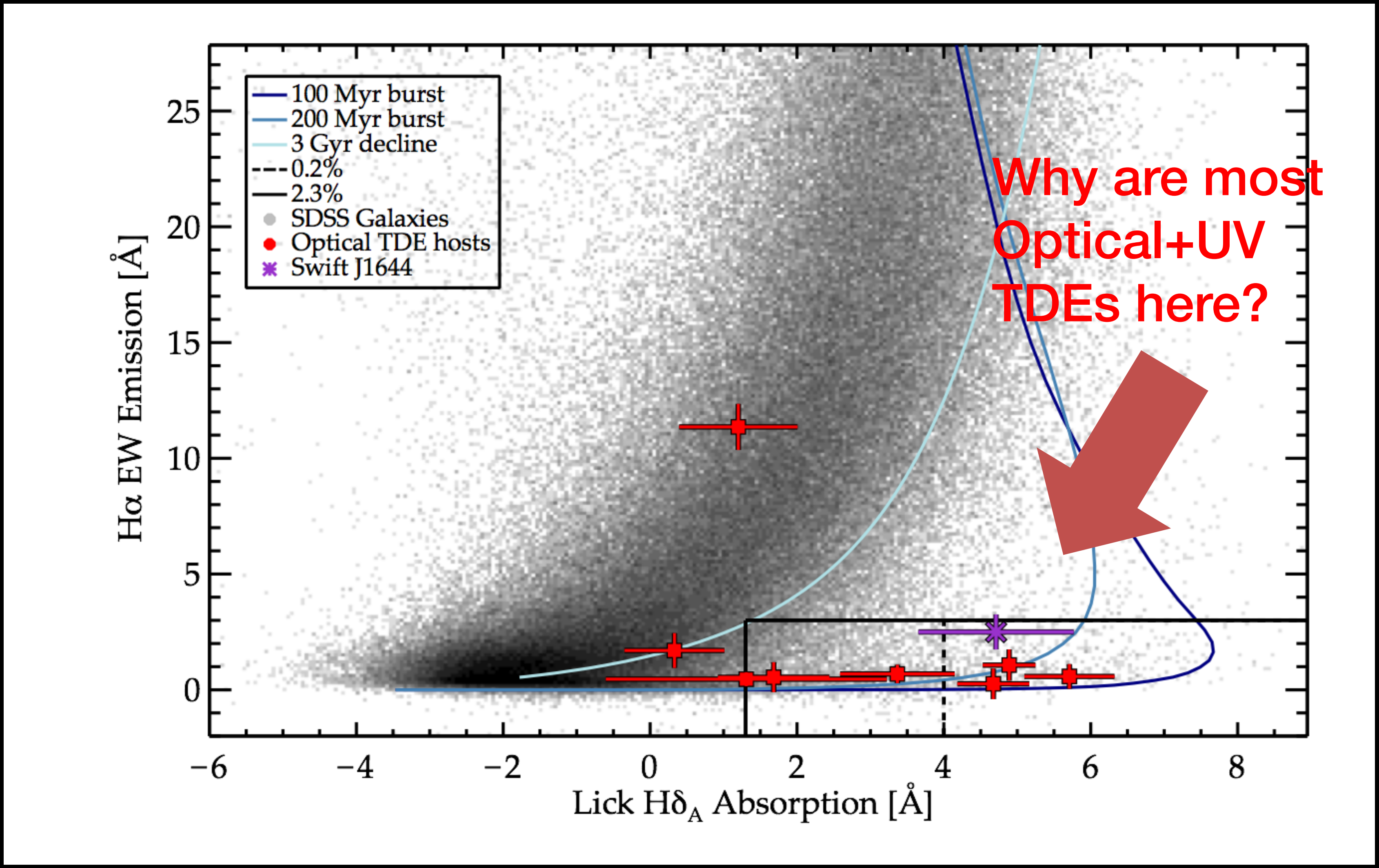
GR affects the TDE light curve

GR affects the TDE rate



Kesden 2012b

Optical+UV TDEs Prefer Post-Starburst Galaxies



French, Arcavi & Zabludoff, 2016

Part I Summary

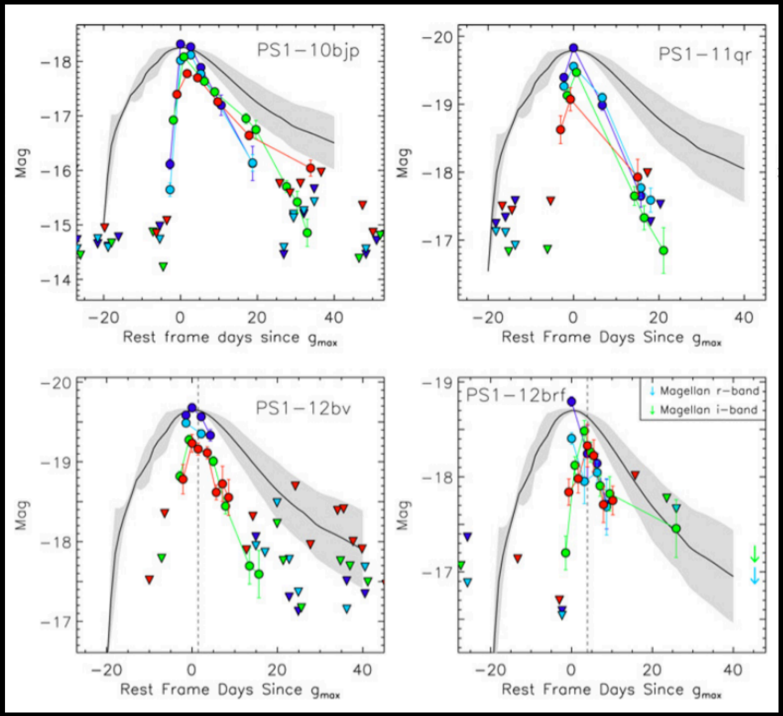
Last few years: A class of blue broad He-II "Optical-UV TDEs" with common (weird) host galaxy preference

Emission sources under debate, lots of room for a **variety of transient phenomenon**.

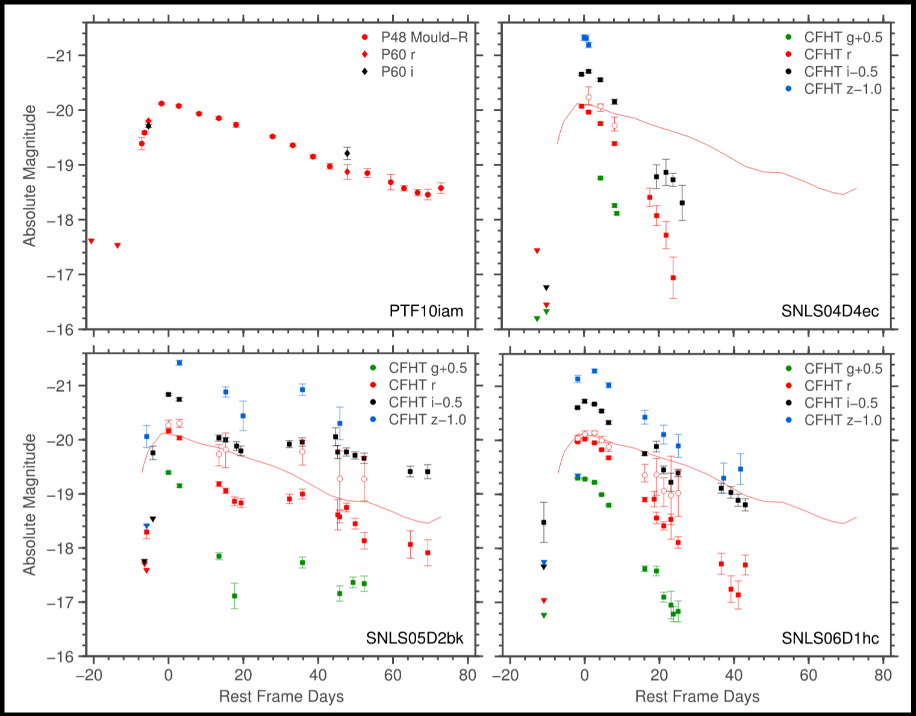
Now: Large diversity of optical events being revealed, **opportunities to test several GR effects observationally**

Part II:
Extreme Supernovae

Luminous Rapidly Evolving Events

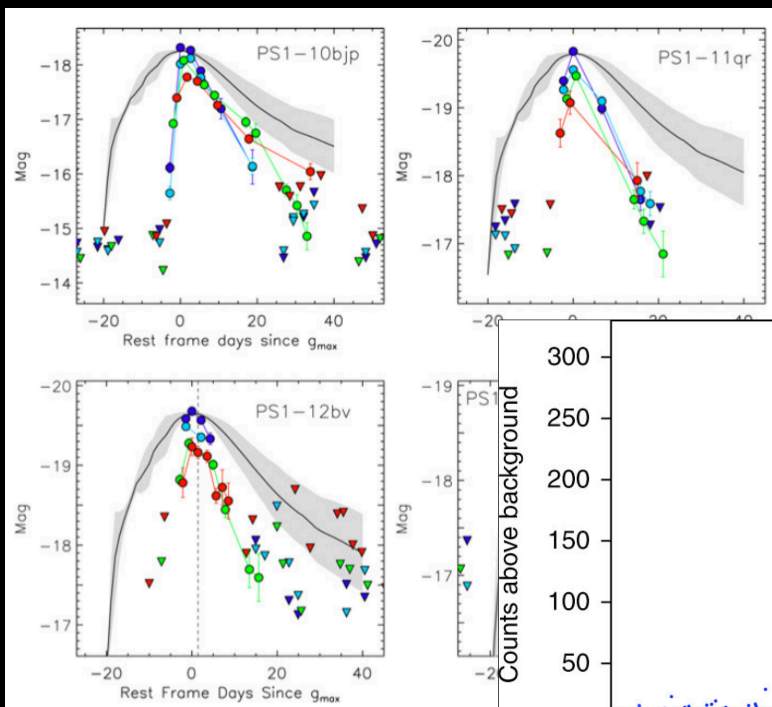


Drout et al. (2014)

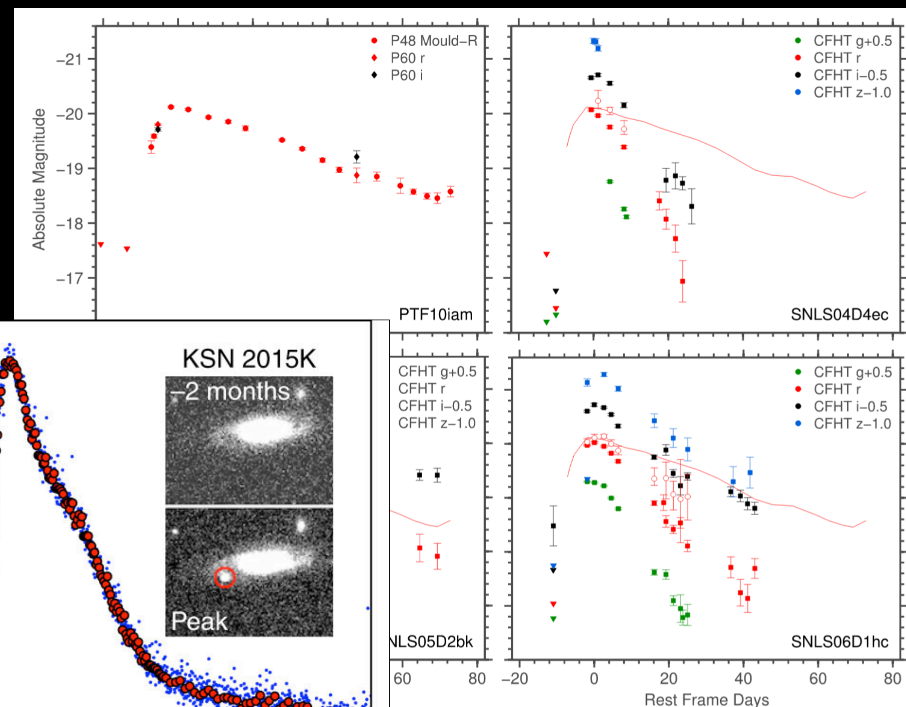


Arcavi et al. (2016)

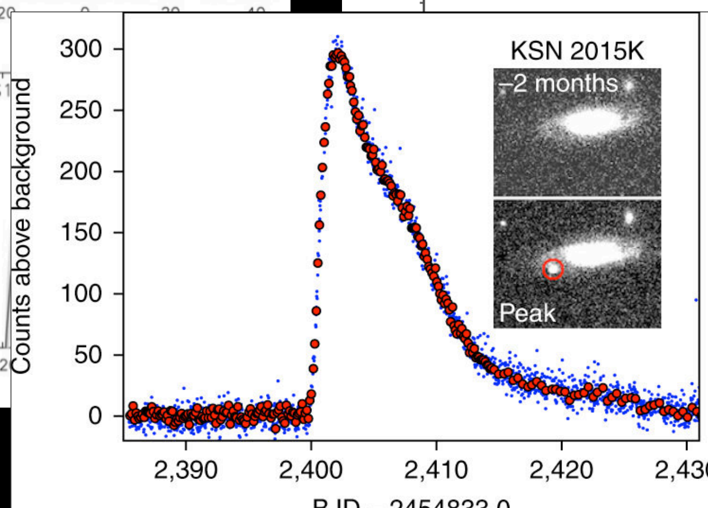
Luminous Rapidly Evolving Events



Drout et al. (2014)

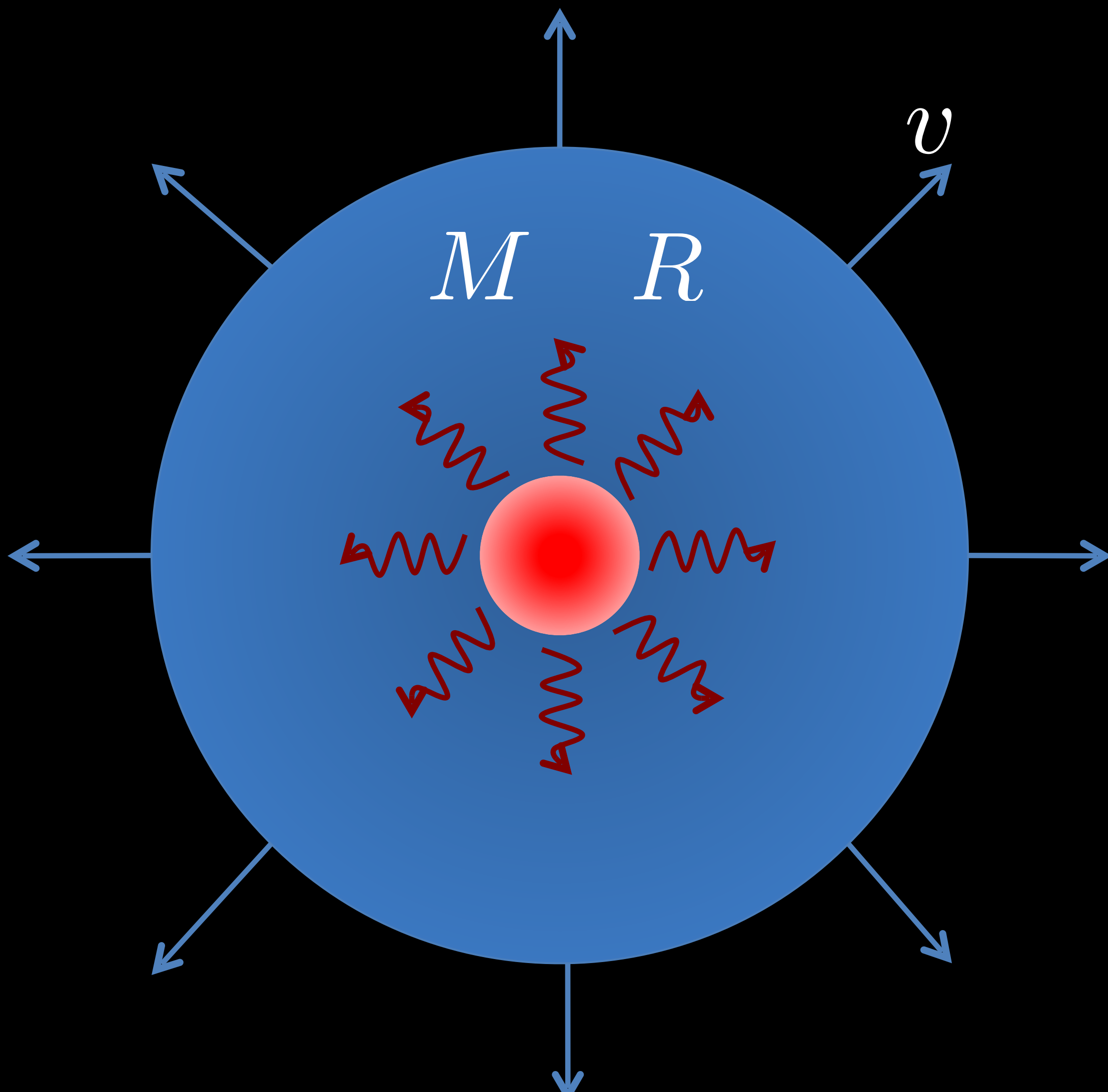


6)



Rest et al. (2018)

Rise Time ~> Mass Ejected in Explosion



$$\tau_{\rm diff} \sim \frac{N\lambda}{c} \sim \frac{R^2}{\lambda c} \sim \frac{\kappa M}{Rc}$$

$$R = vt$$

$$\tau_{\rm diff} \sim \frac{\kappa M}{vtc}$$

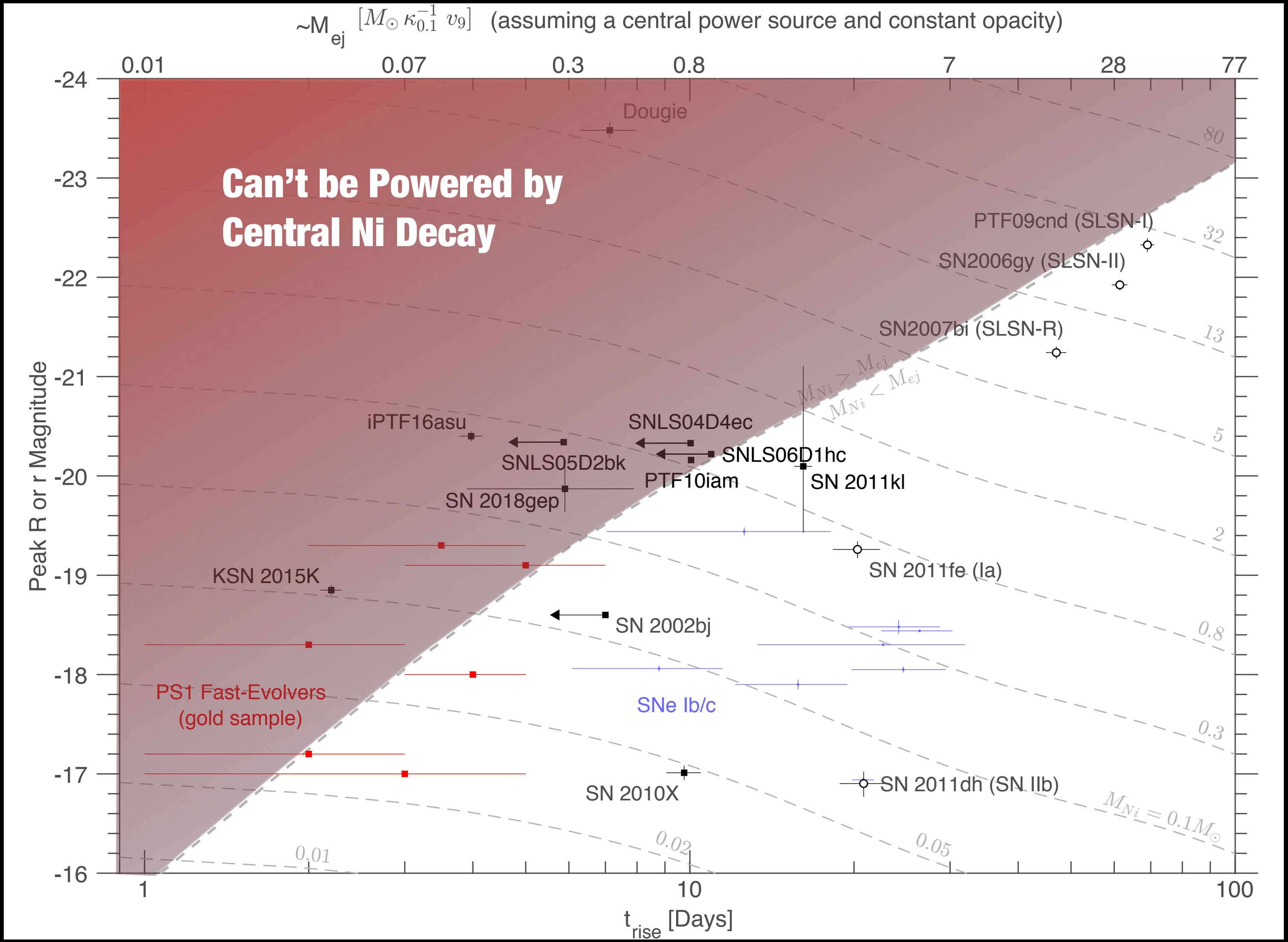
$$t = \tau_{\rm diff}$$

$$t \sim \sqrt{\frac{\kappa M}{vc}}$$

time to peak luminosity

Fast & Luminous Can't be Ni-Powered

$$t_{peak} \approx \sqrt{\frac{\kappa M}{vc}}$$



Adapted from Arcavi et al. (2016)

Fast & Luminous Can't be Ni-Powered

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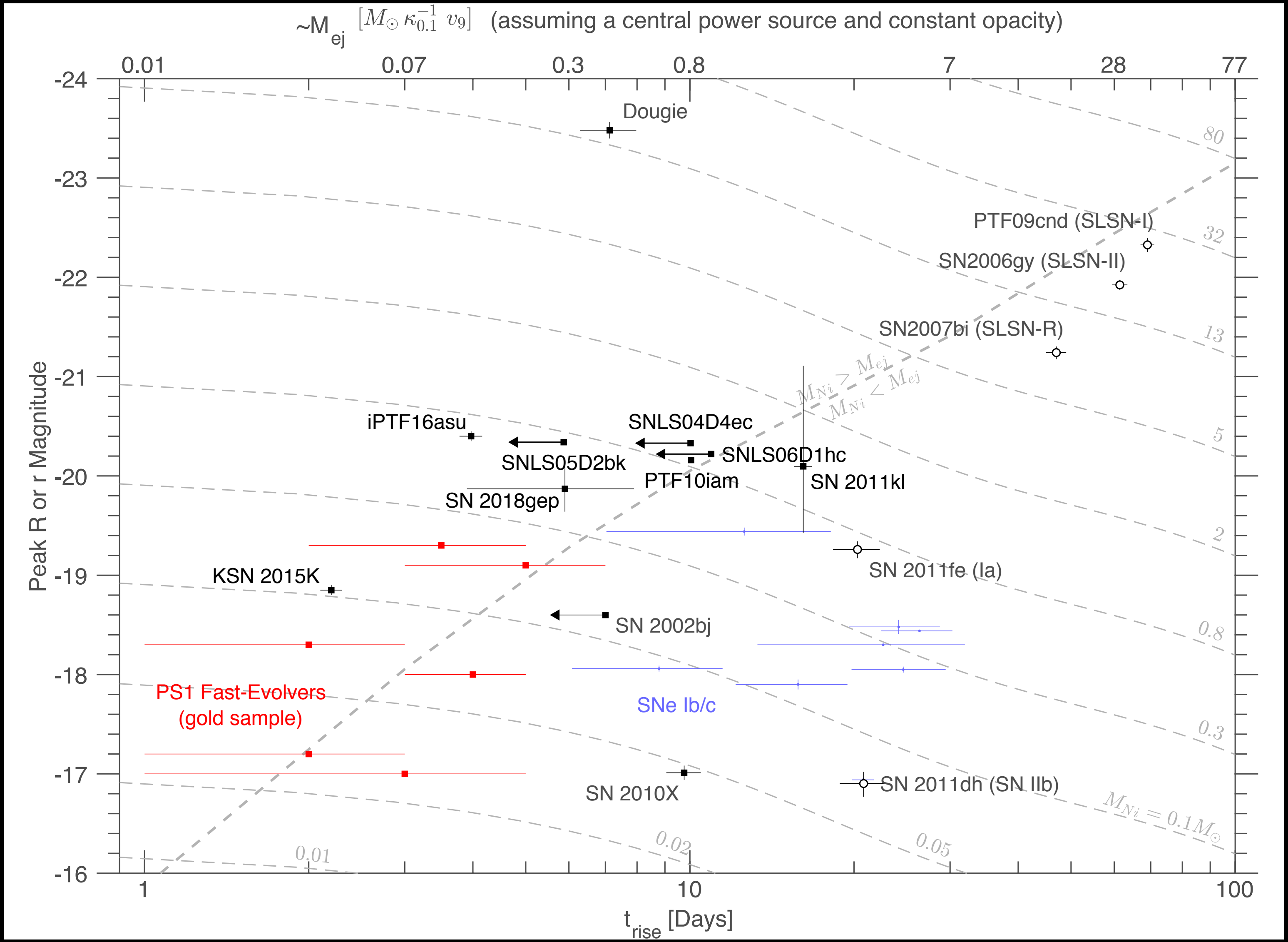
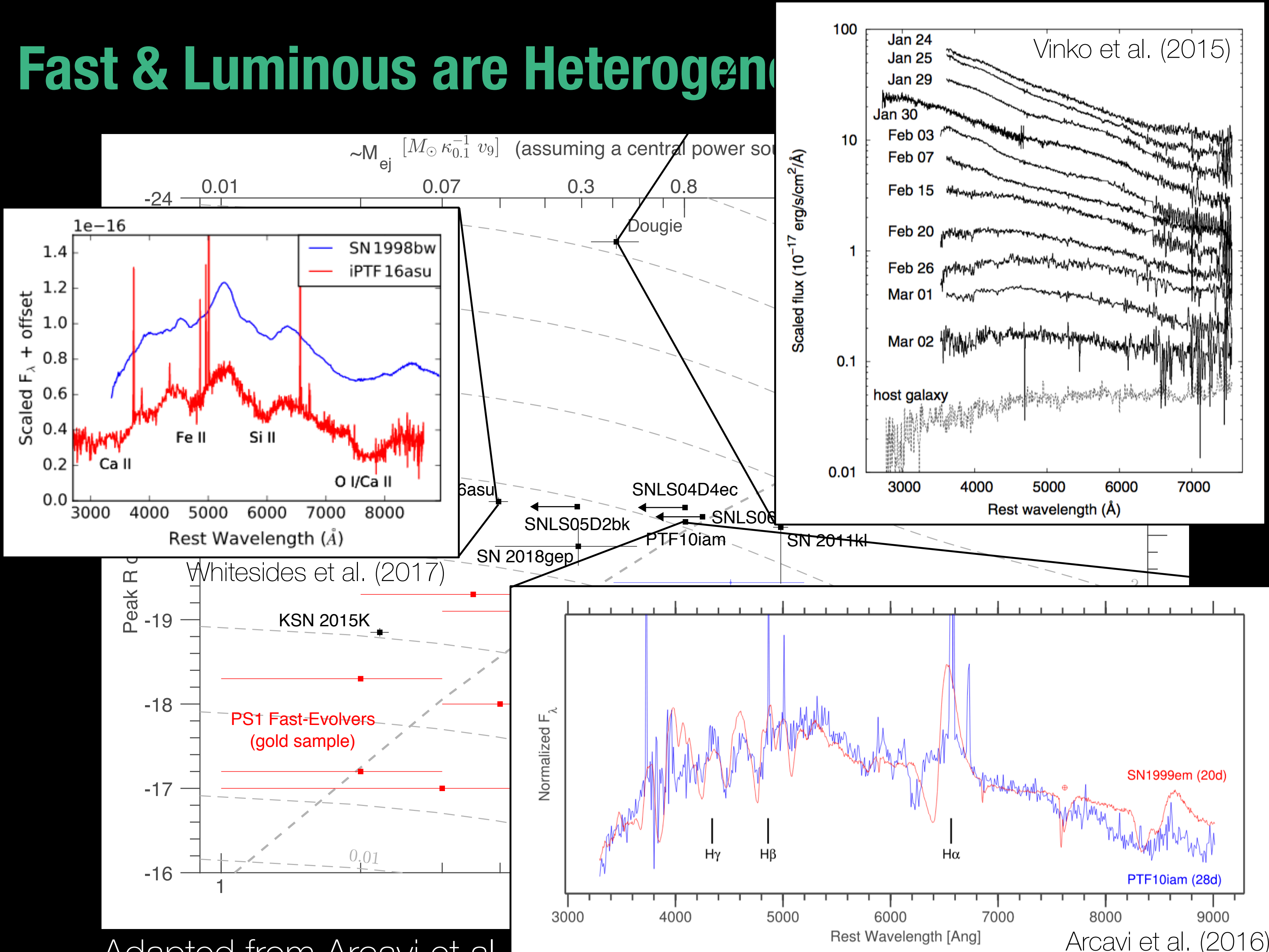


Adapted from Arcavi et al. (2016)

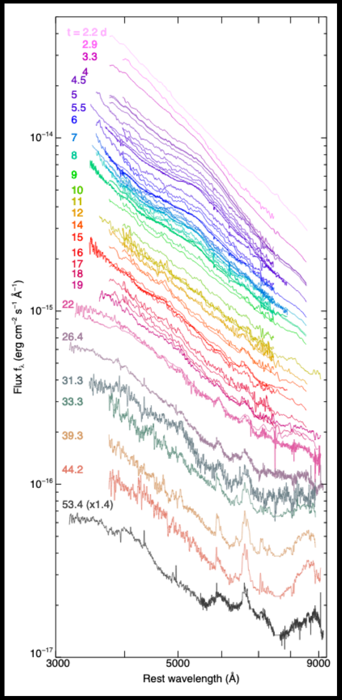
Fast & Luminous are Heterogene

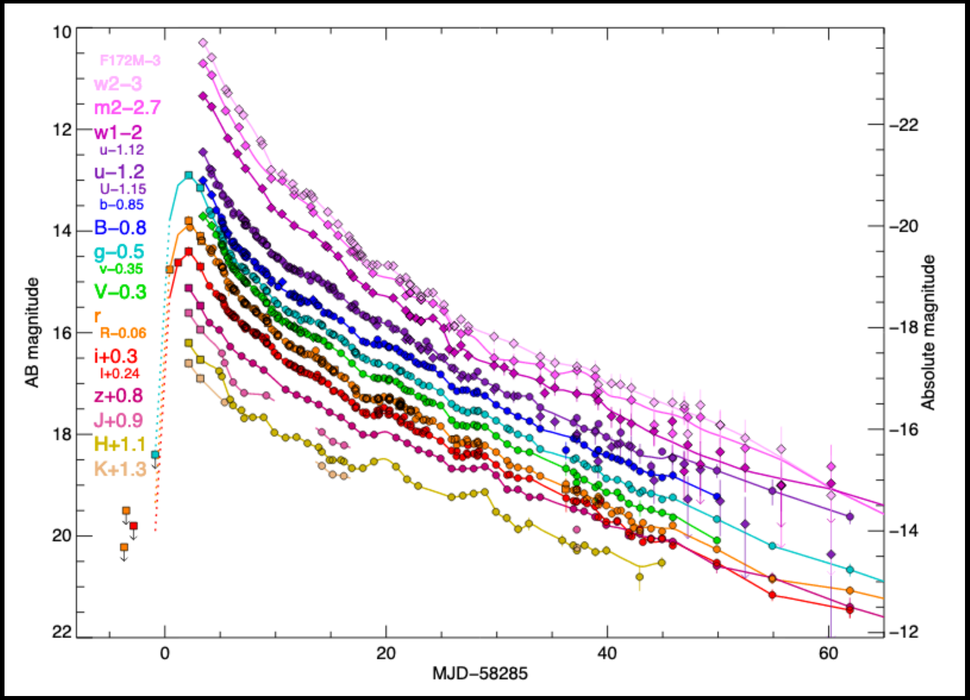


Adapted from Arcavi et al.

Holy (AT 2018)cow! Very Fast, Luminous, Blue

- Luminous, very rapid decline (~1-2 mags per week)
- Mostly featureless blue continuum, some broad features reported





Perley et al. 2019

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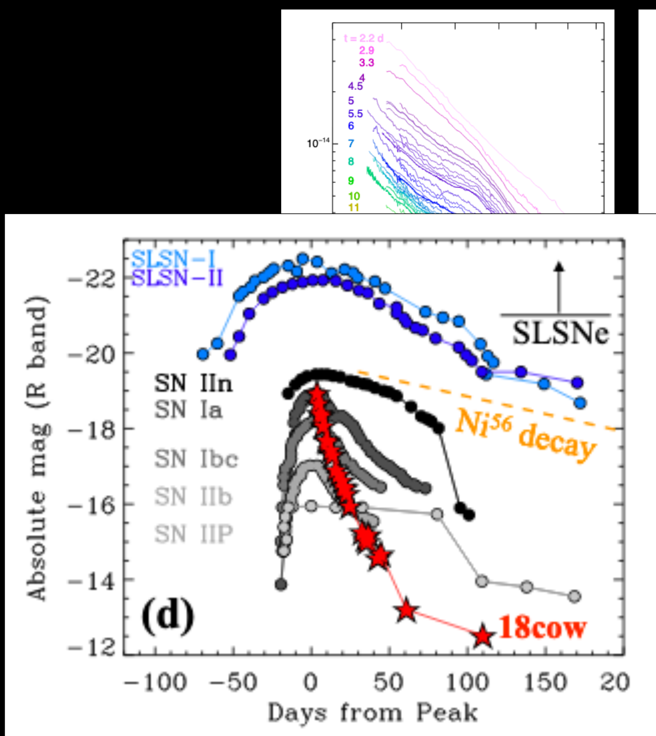

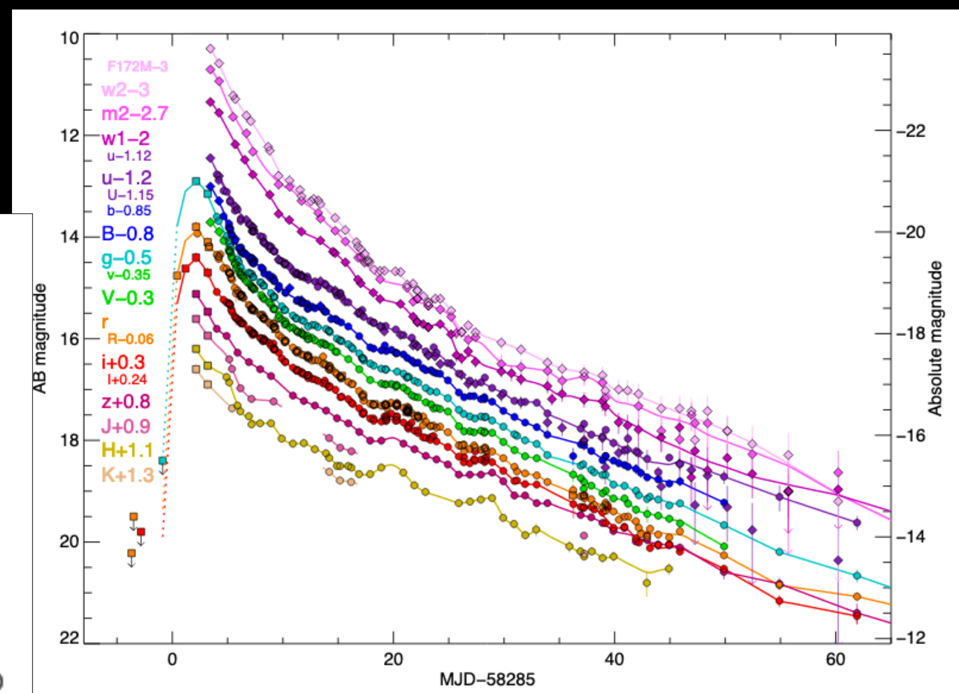

Margutti et al. 2019

Perley et al. 2019

Luminous Rapidly Evolving Events

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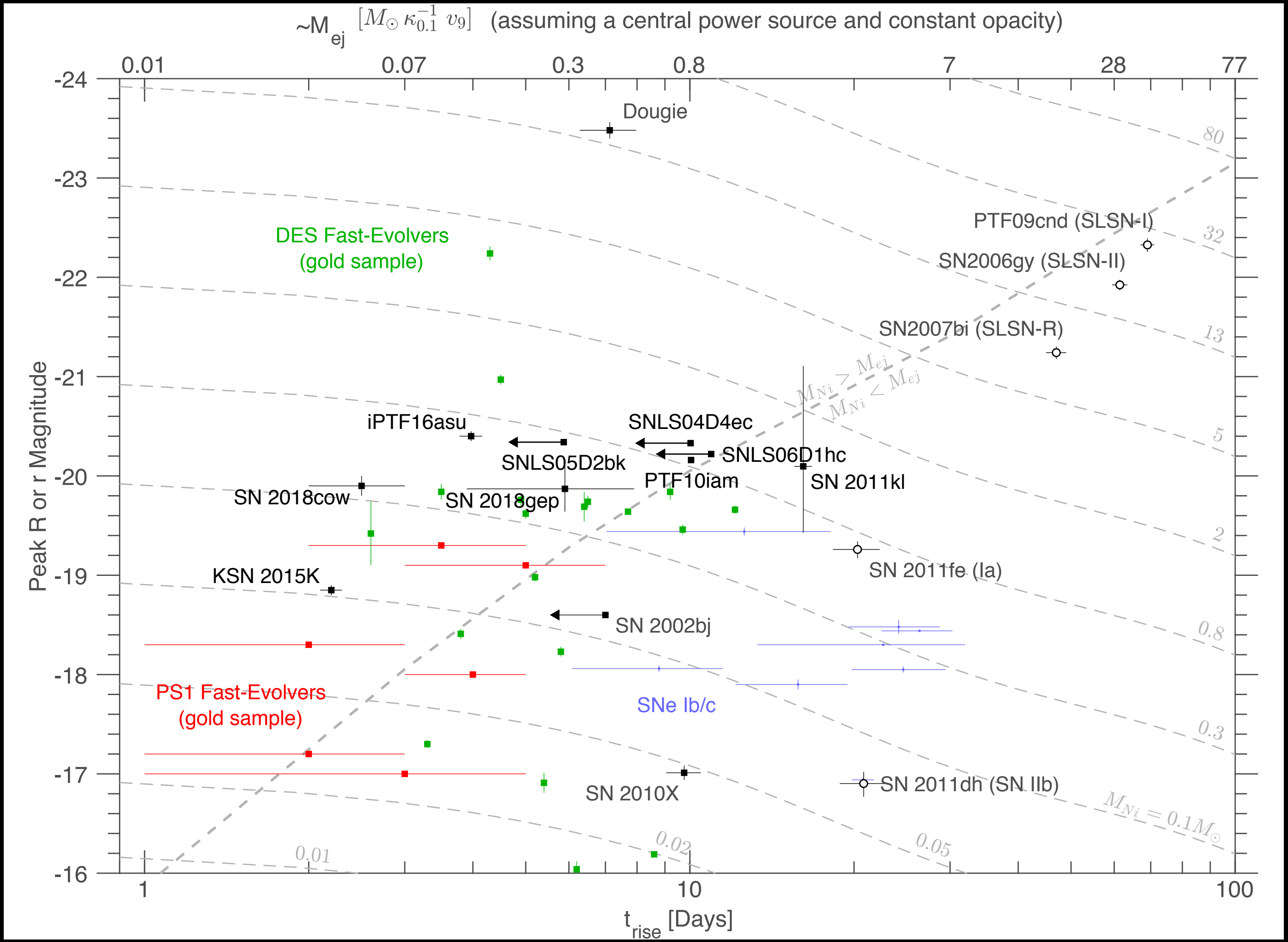


Adapted from Arcavi et al. (2016)

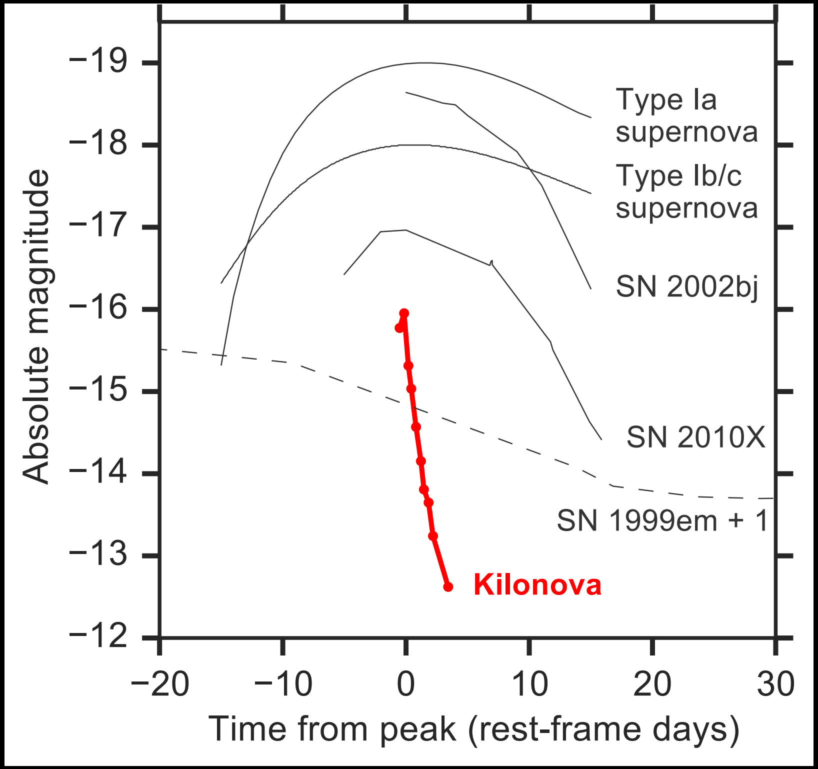
Part II Summary

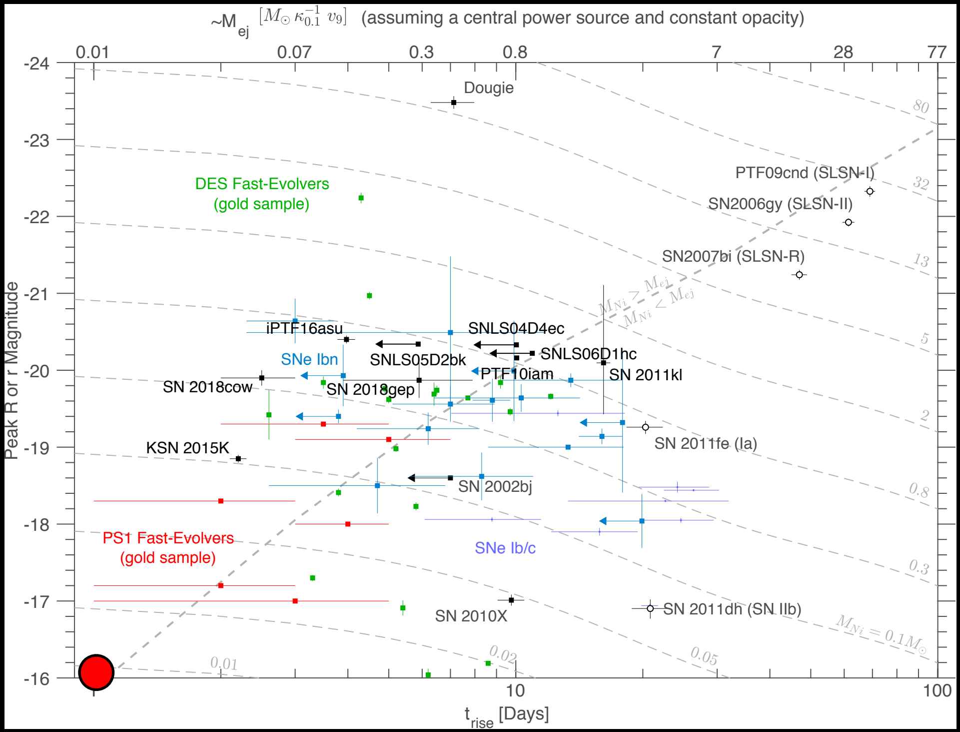
Last few years: A class of rapidly rising luminous transients, which **can not be powered by standard Ni decay**.

Emission source still unclear, likely **several classes of events**.

High cadence surveys coupled to **rapid response followup facilities** could solve the mystery.

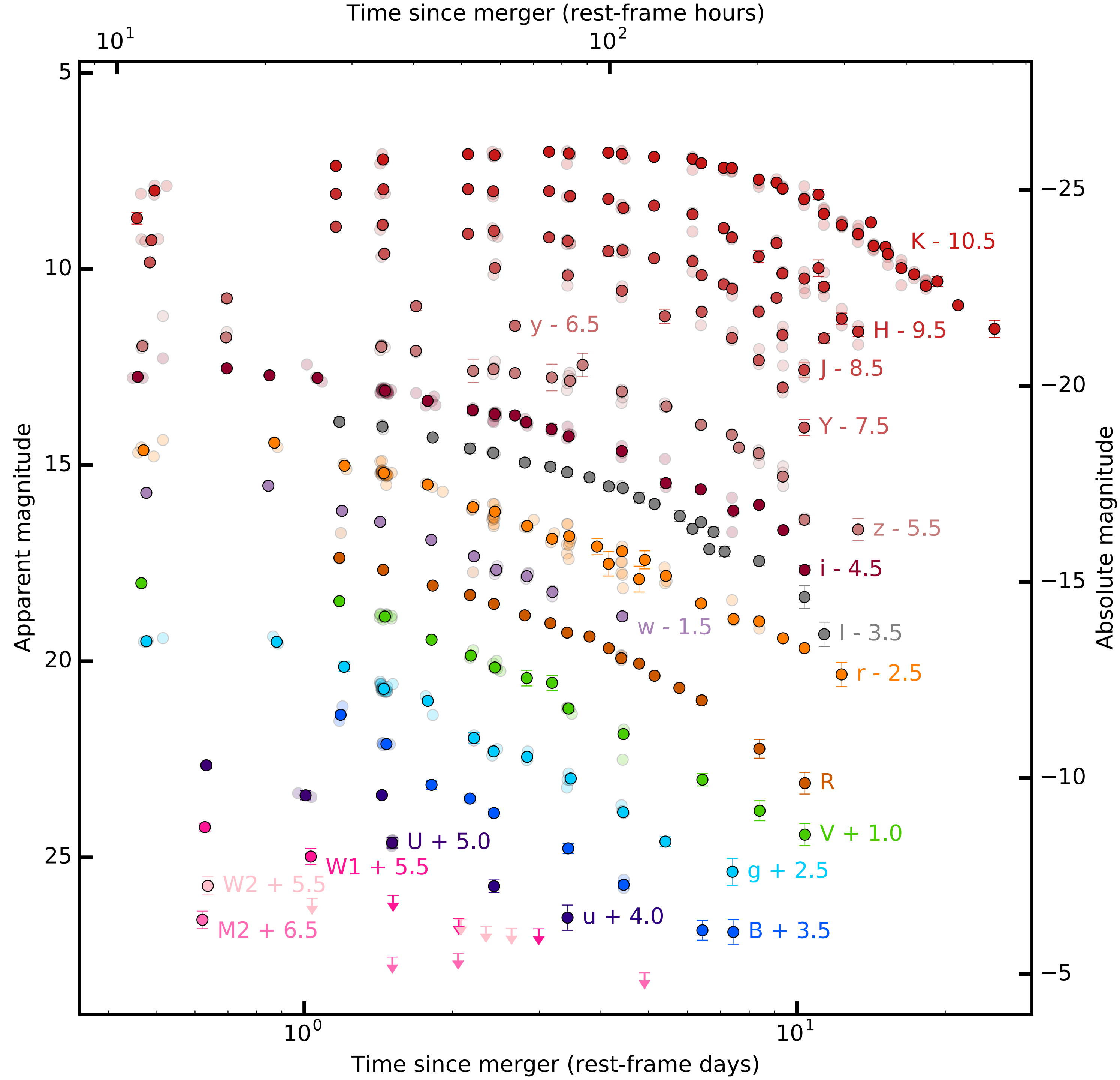
Fastest 'Bright' Transient: The GW170817 Kilonova





Arcavi et al. 2017

Part III:
Neutron Star Mergers

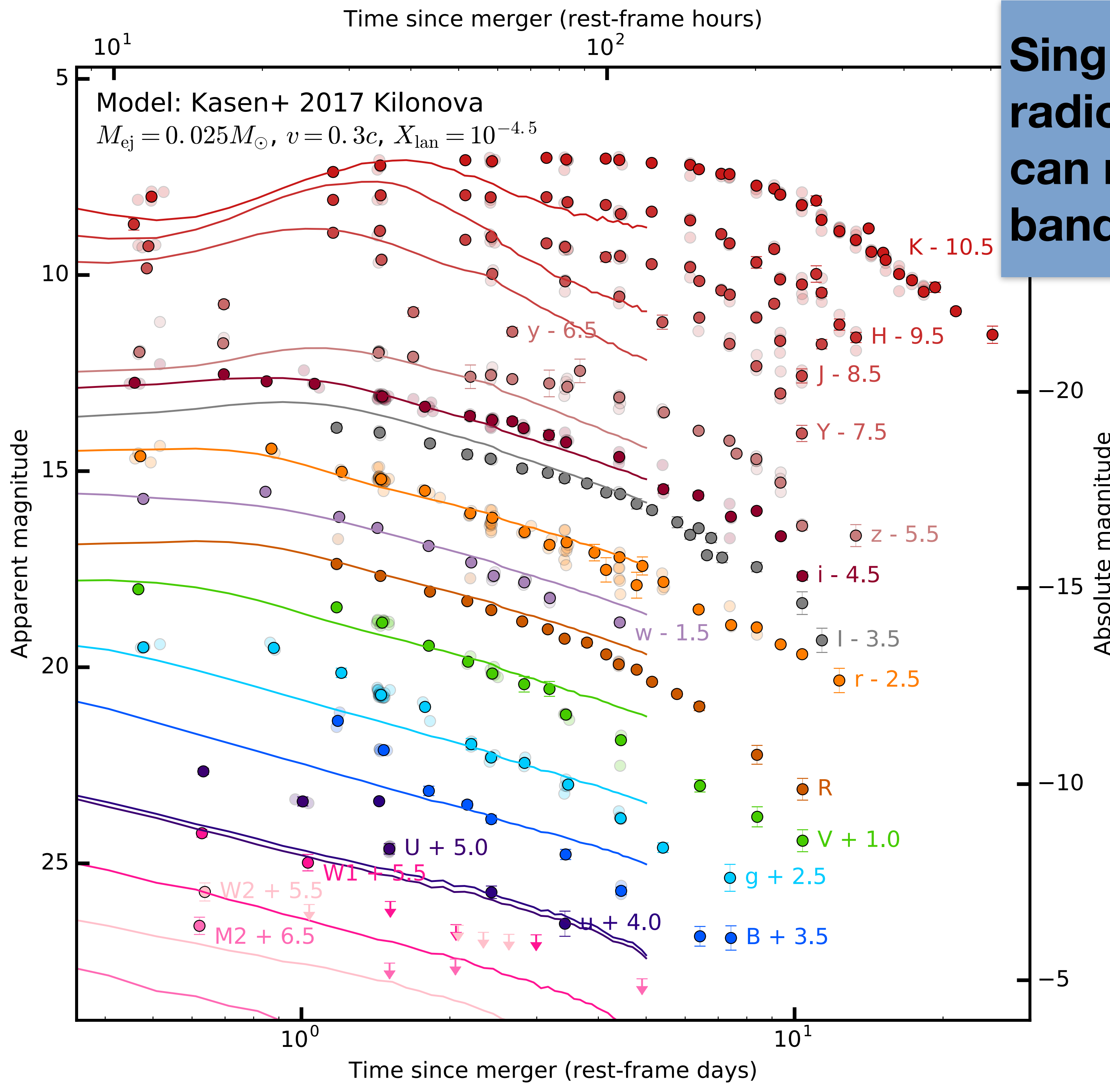


Compilation from:
Arcavi 2018

Data from:
Andreoni et al. 2017,
Arcavi et al. 2017,
Cowperthwaite et al. 2017,
Coulter et al. 2017,
Diaz et al. 2017,
Drout et al. 2017,
Evans et al. 2017,
Hu et al. 2017,
Kasliwal et al. 2017,
Lipunov et al. 2017,
Pian et al. 2017,
Pozanenko et al. 2017,
Shapee et al. 2017,
Smartt et al. 2017,
Tanvir et al. 2017,
Troja et al. 2017,
Utsumi et al. 2017,
Valenti et al. 2017.

Retrieved via:
kilonovae.space

Single component radioactive decay can not explain all bands.

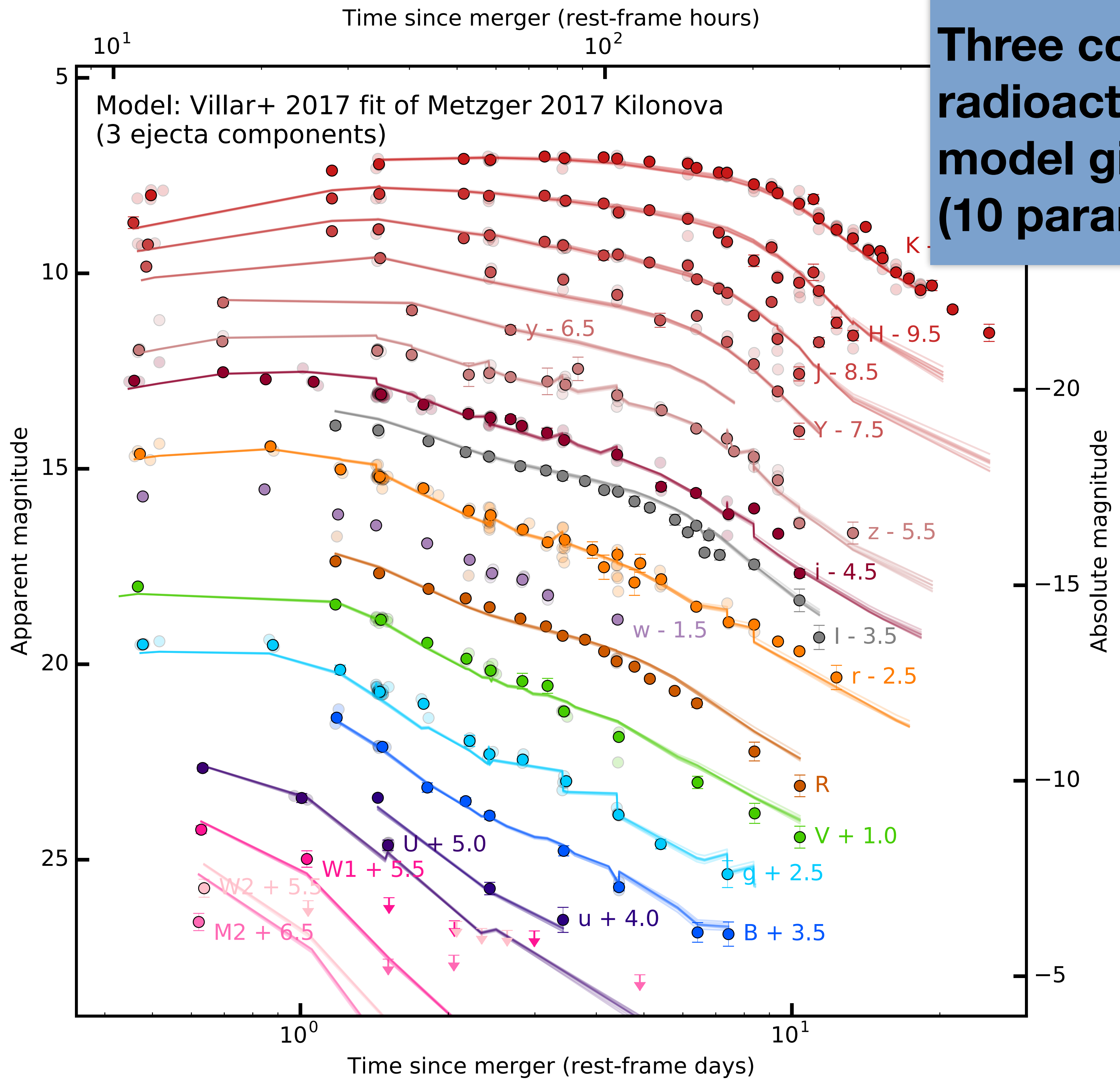


Compilation from:
Arcavi 2018

Data from:
Andreoni et al. 2017,
Arcavi et al. 2017,
Cowperthwaite et al. 2017,
Coulter et al. 2017,
Diaz et al. 2017,
Drout et al. 2017,
Evans et al. 2017,
Hu et al. 2017,
Kasliwal et al. 2017,
Lipunov et al. 2017,
Pian et al. 2017,
Pozanenko et al. 2017,
Shapee et al. 2017,
Smartt et al. 2017,
Tanvir et al. 2017,
Troja et al. 2017,
Utsumi et al. 2017,
Valenti et al. 2017.

Retrieved via:
kilonovae.space

Three component radioactive decay model gives a better fit (10 parameters).



Compilation from:
Arcavi 2018

Data from:
Andreoni et al. 2017,
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Cowperthwaite et al. 2017,
Coulter et al. 2017,
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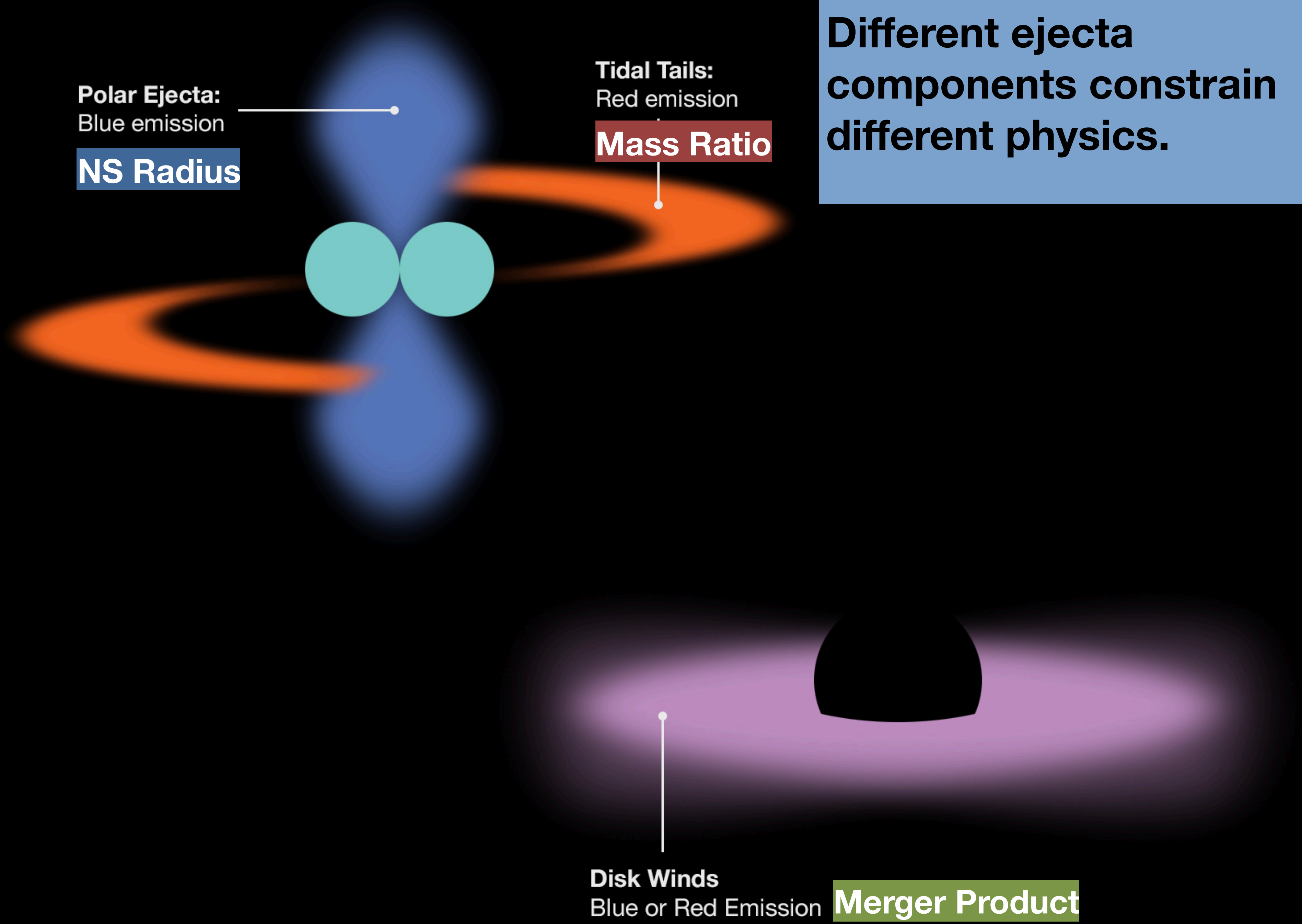
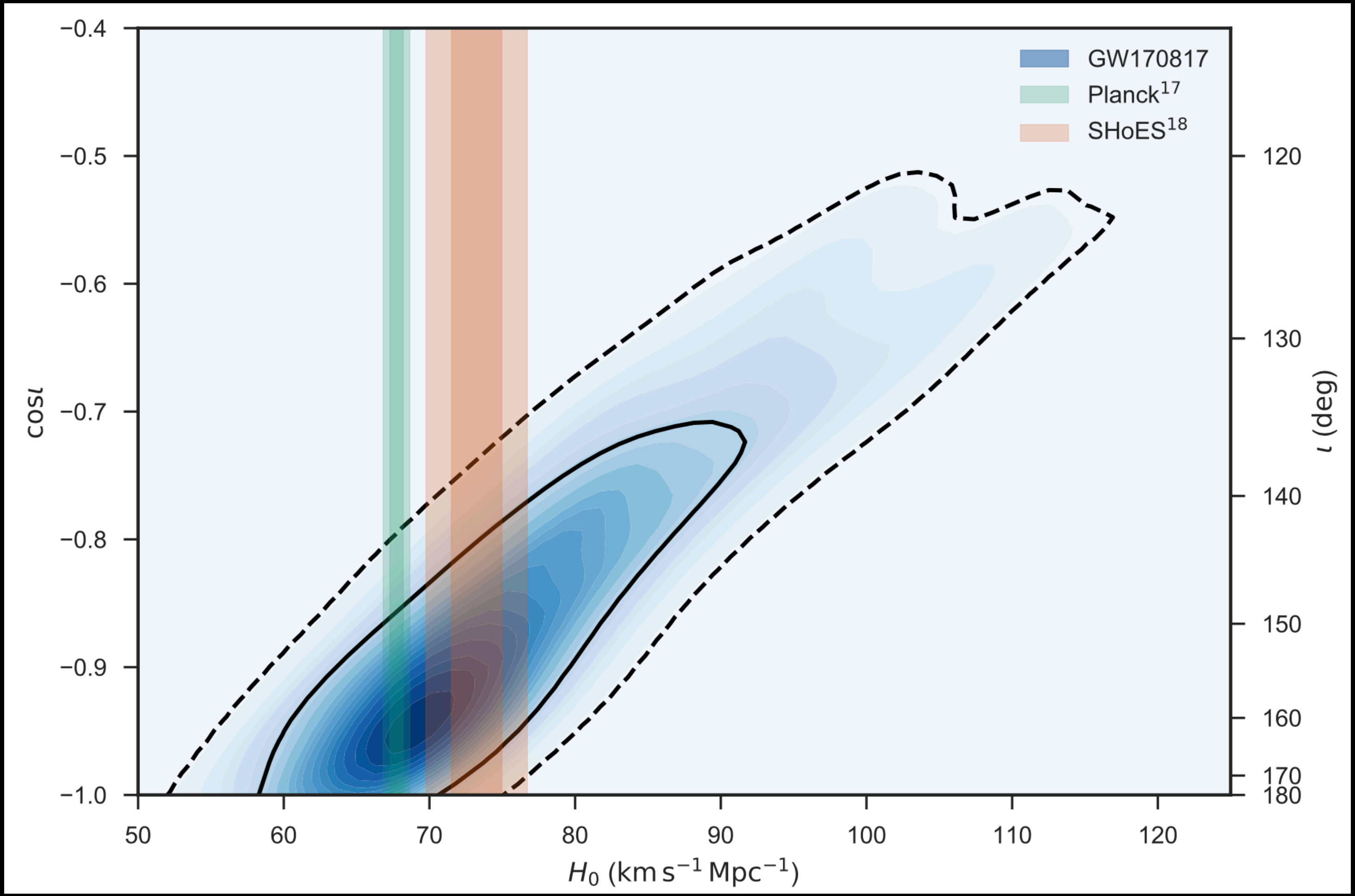
Smartt et al. 2017,
Tanvir et al. 2017,
Troja et al. 2017,
Utsumi et al. 2017,
Valenti et al. 2017.

Retrieved via:
kilonovae.space

Different ejecta components constrain different physics.



Polar Ejecta = Constraint on the Viewing Angle



LIGO & Virgo Collaborations et al. 2017, Nature

Different Models for the Blue → Red Emission

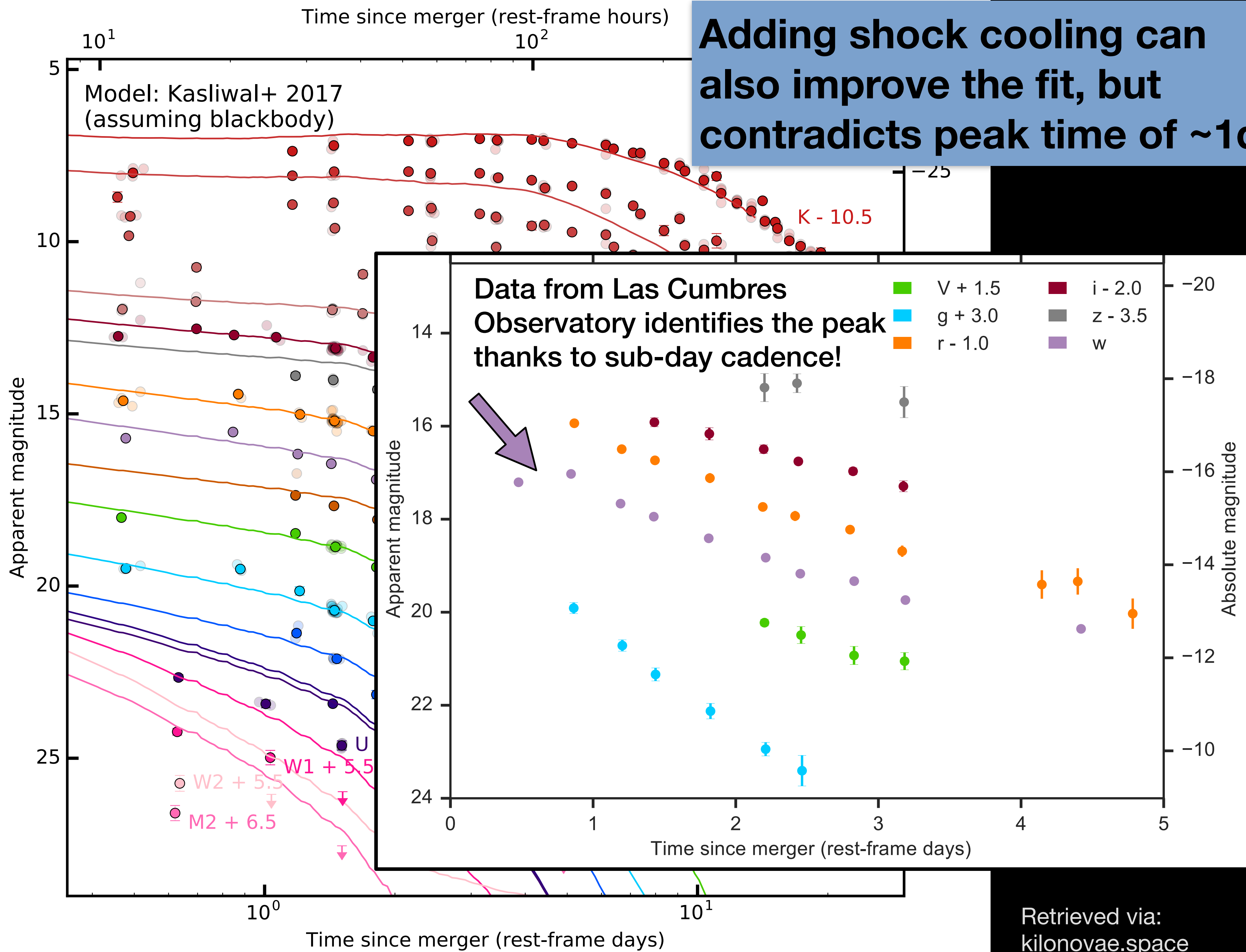
Multi-component radioactive decay
Villar et al. 2017

Single-component radioactive decay
(time-varying opacity) Waxman et al. 2017

Boosted relativistic ejecta
(early blue-emission) Kasliwal et al. 2017, see also Nakar & Piran 2017, Gottlieb et al. 2017

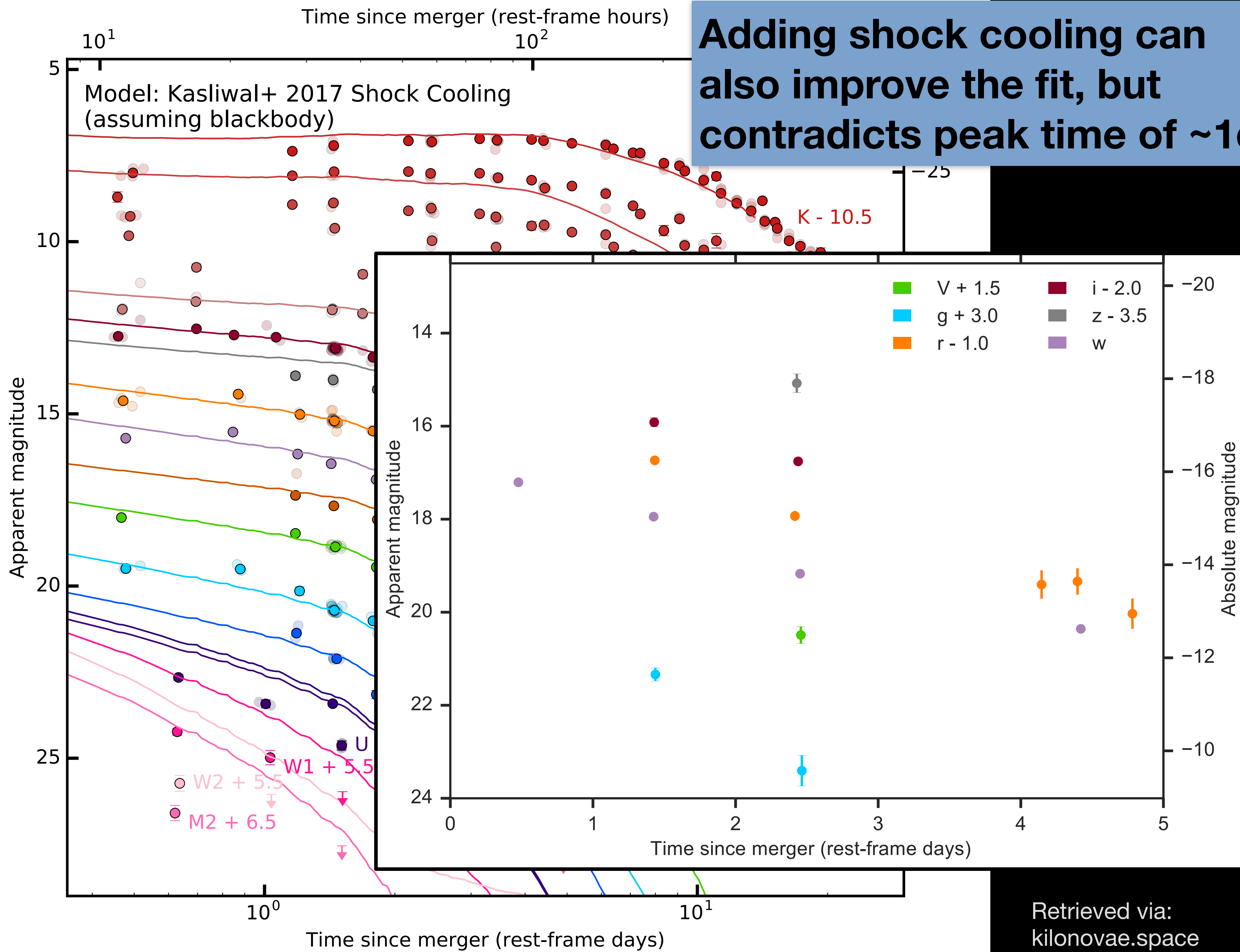
Shock cooling
(early blue-emission) Piro & Kollmeier 2017

Adding shock cooling can also improve the fit, but contradicts peak time of ~1d.



Retrieved via:
kilonovae.space

Adding shock cooling can also improve the fit, but contradicts peak time of ~1d.



Retrieved via:
kilonovae.space

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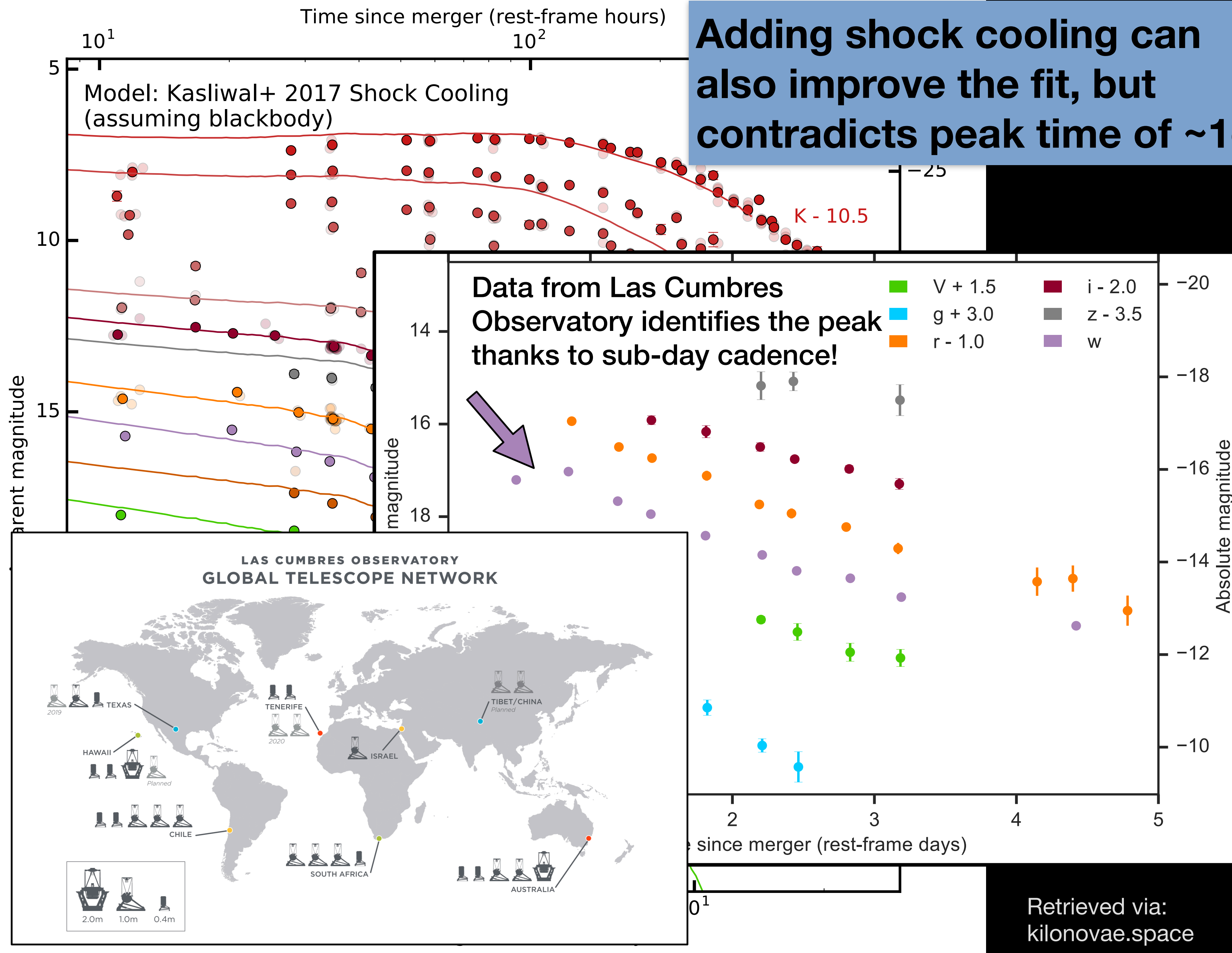

Retrieved via:
kilonovae.space

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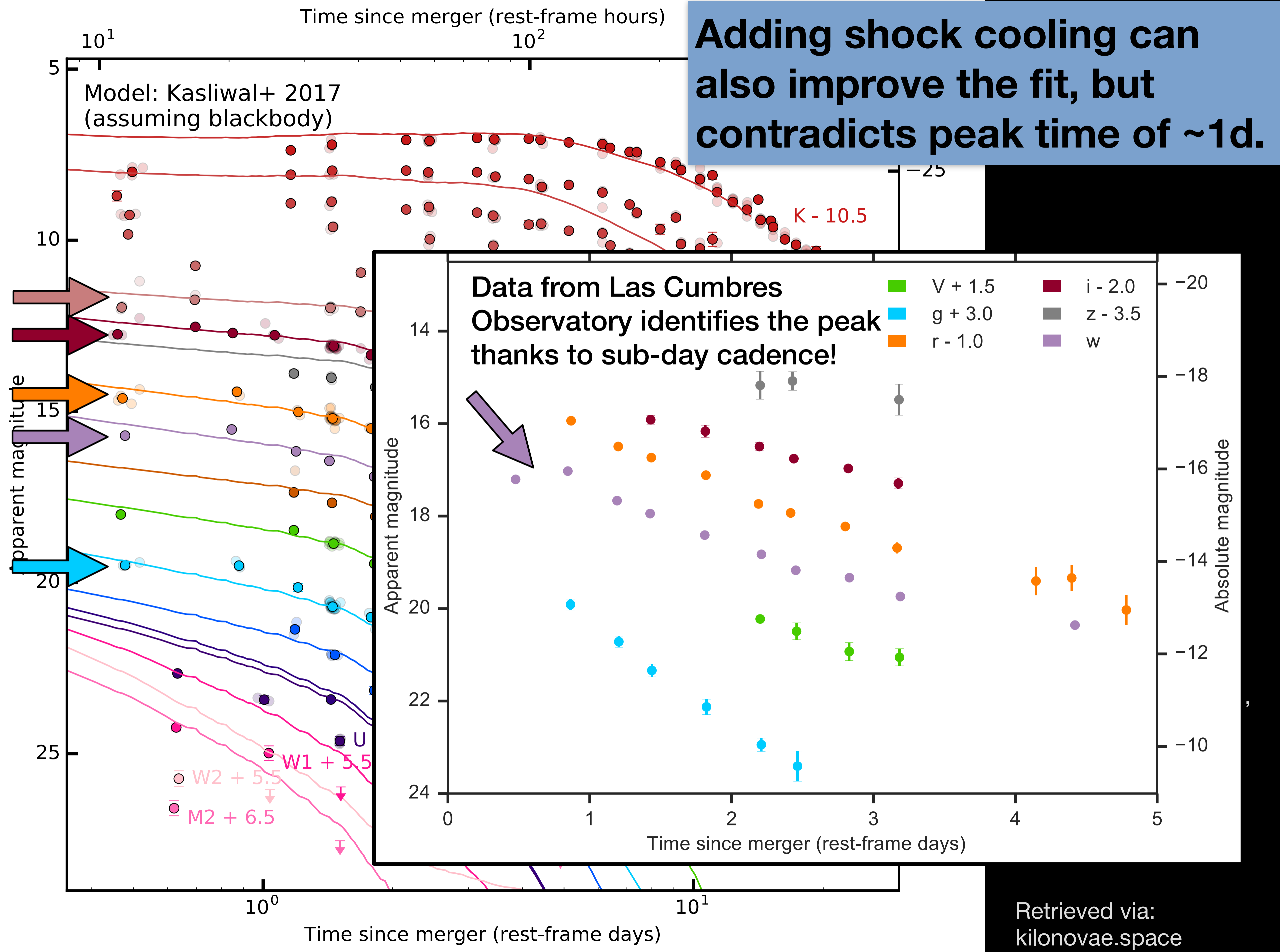
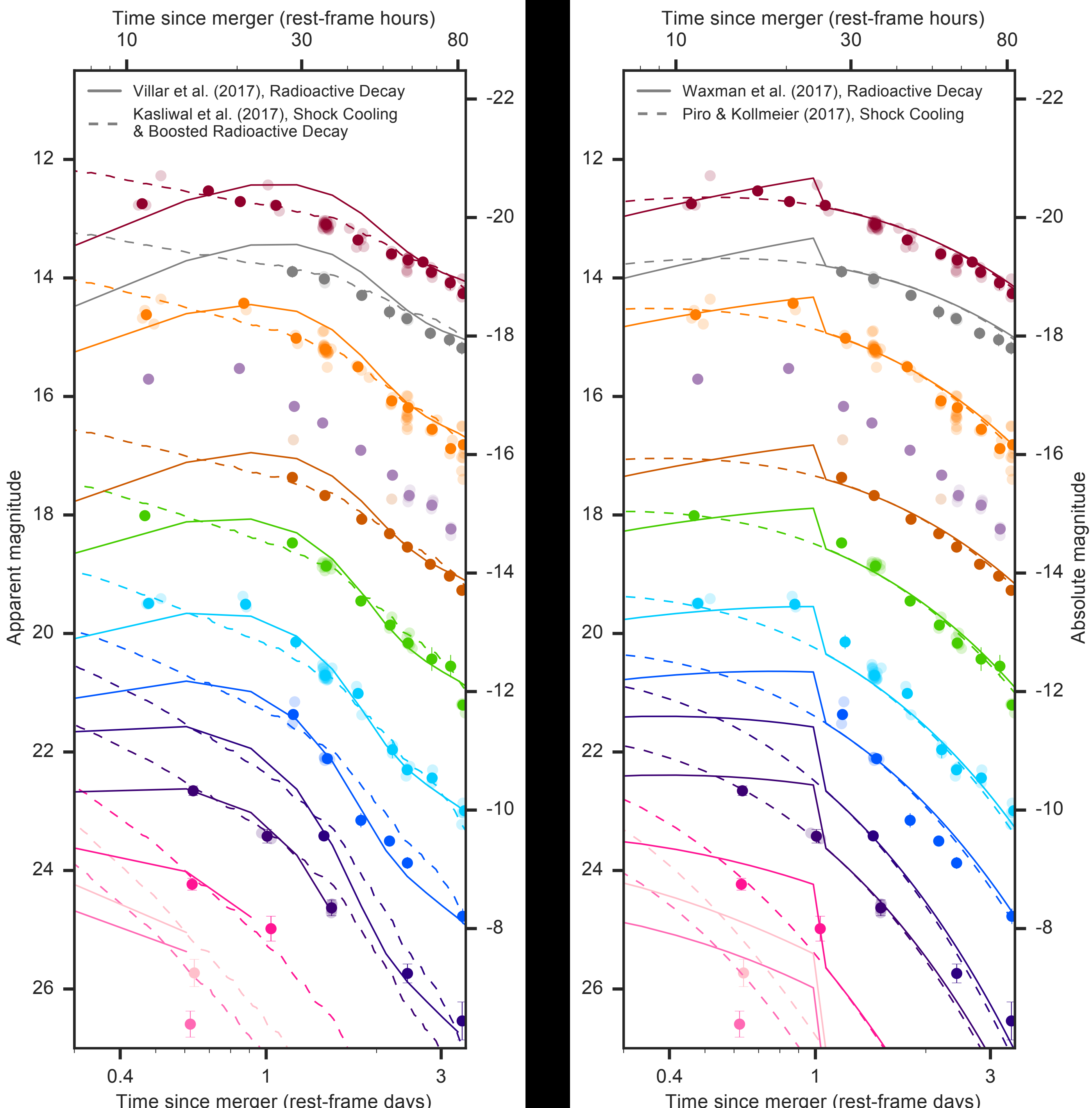
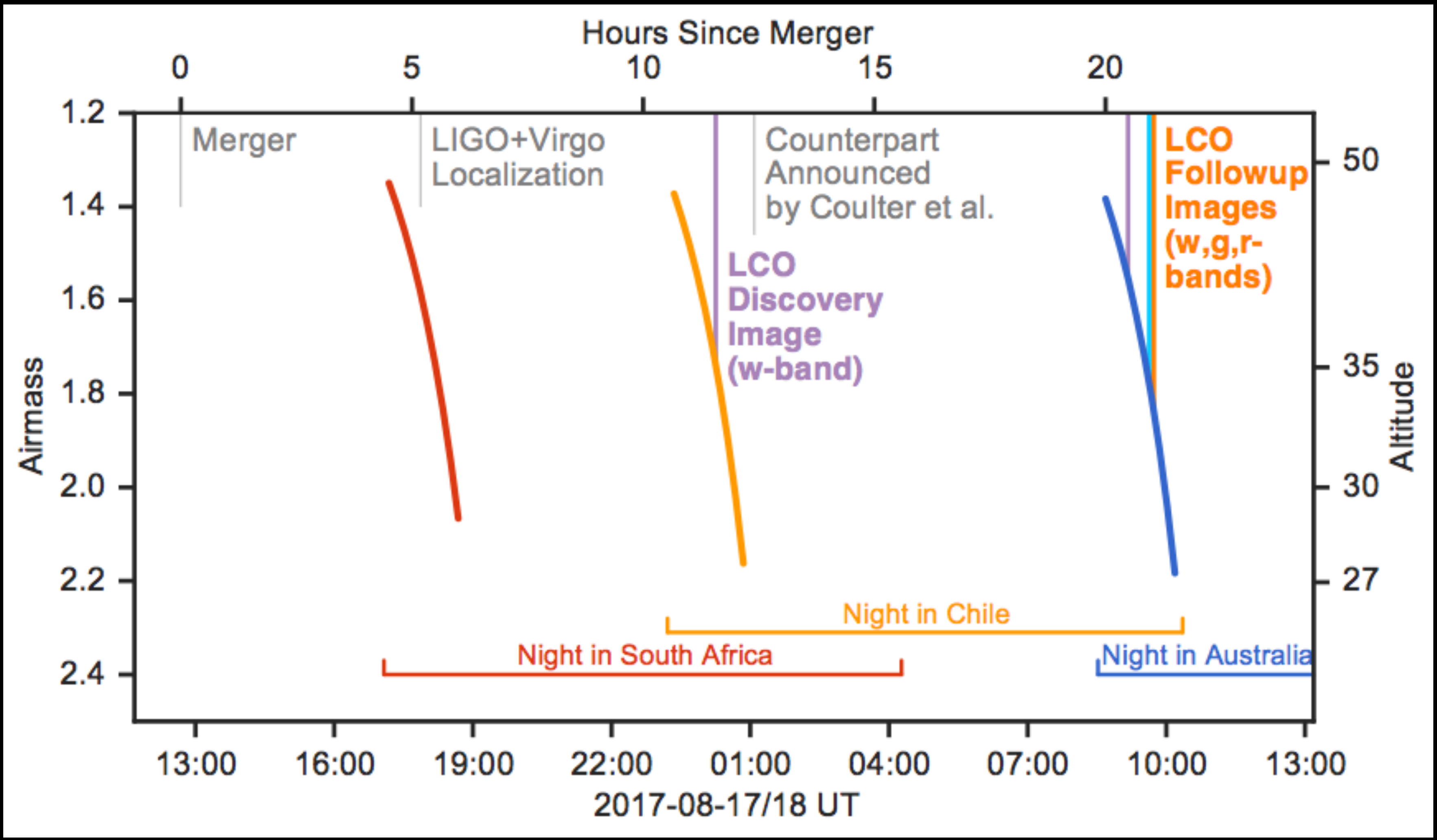


Retrieved via: kilonovae.space


Time since merger (rest-frame hours)
10
30
80
Villar et al. (2017), Radioactive Decay
Kasliwal et al. (2017), Shock Cooling & Boosted Radioactive Decay
Waxman et al. (2017), Radioactive Decay
Piro & Kollmeier (2017), Shock Cooling
Apparent magnitude
12
14
16
18
20
22
24
26
Absolute magnitude
-22
-20
-18
-16
-14
-12
-10
-8
0.4
1
3
Time since merger (rest-frame days)

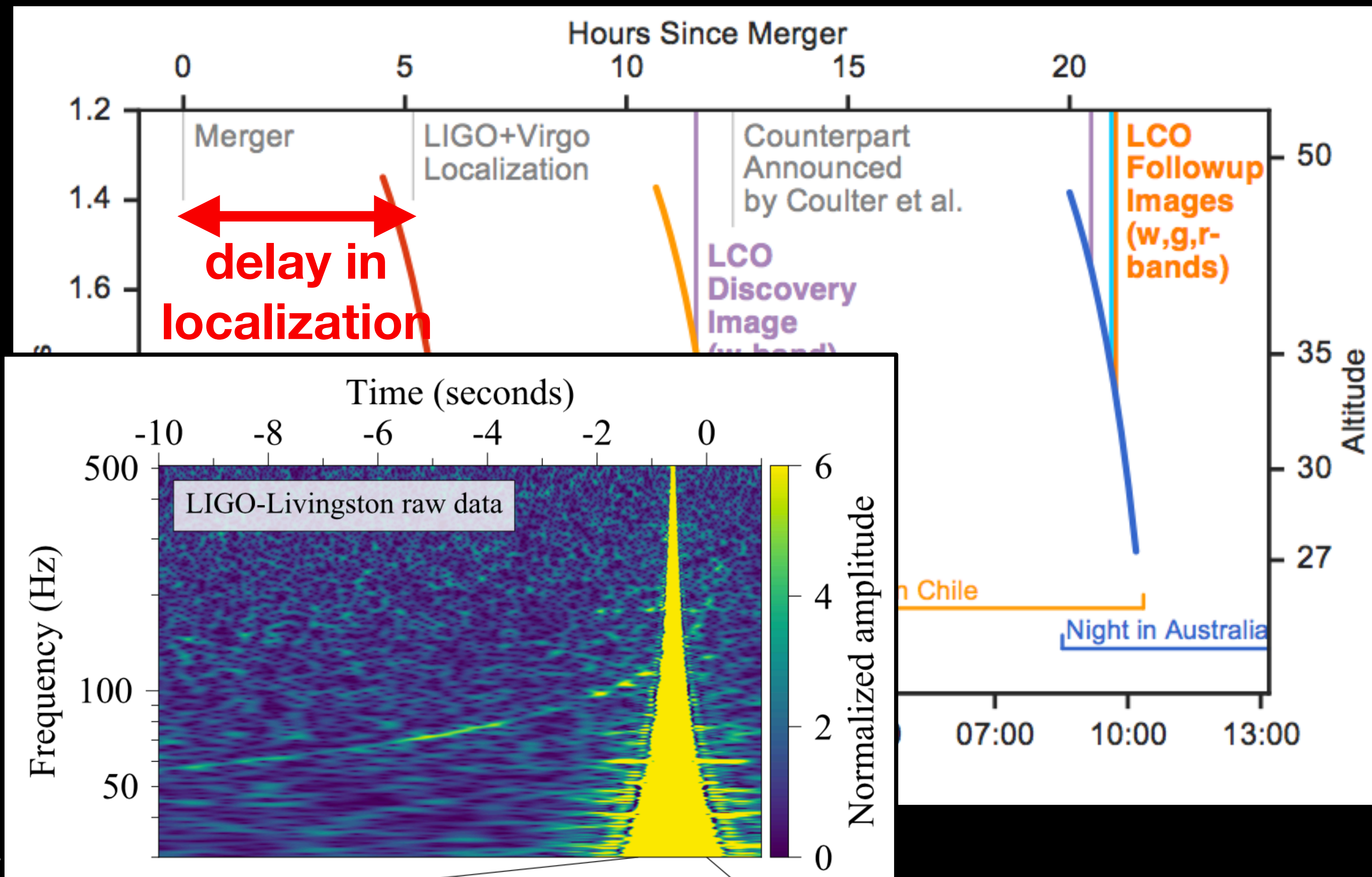
Arcavi 2018

Would Have Solved With GW Localization 1h Earlier

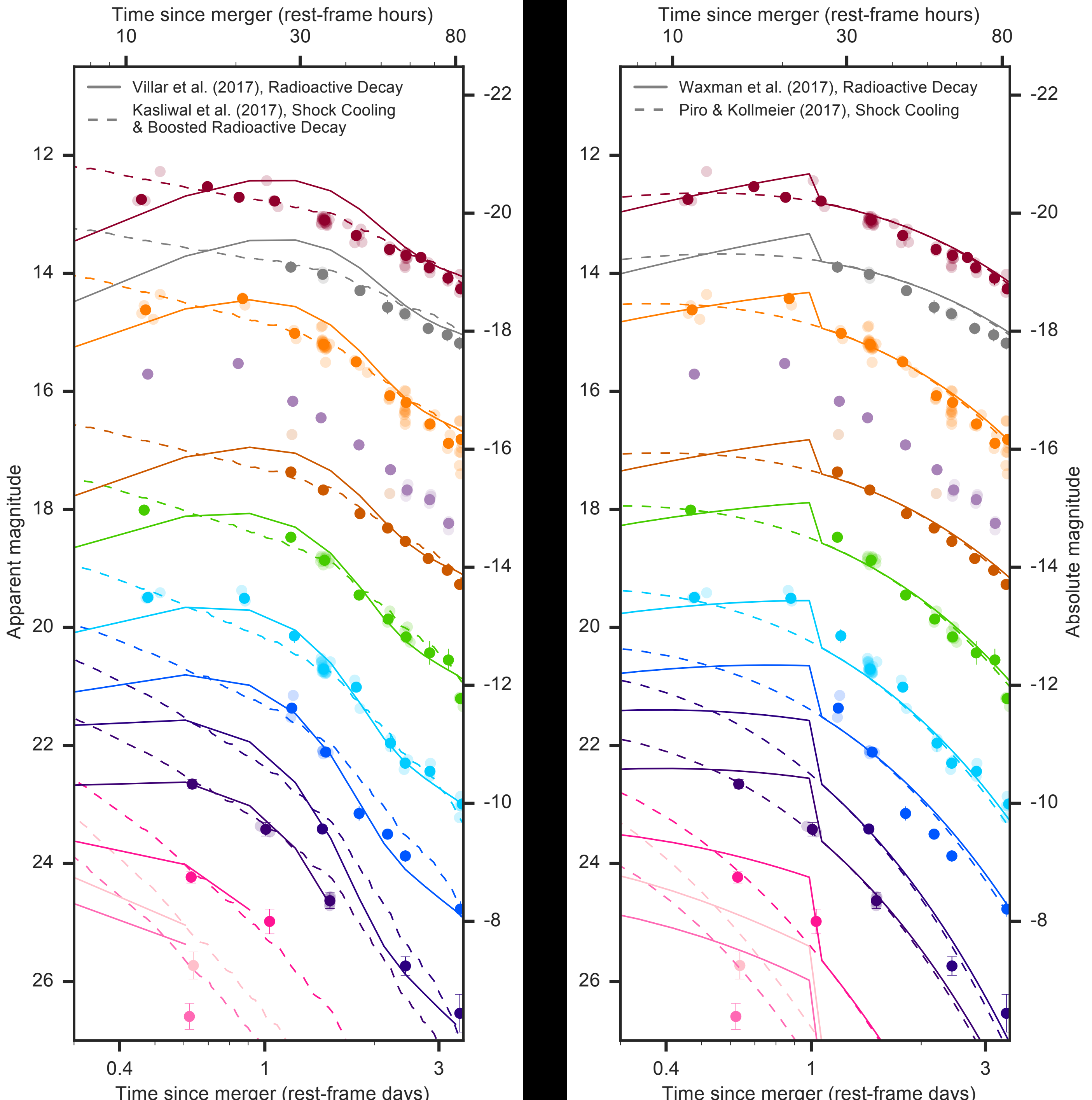


Arcavi et al. 2017a, Nature

Would Have Solved With GW Localization 1h Earlier



Ar


Time since merger (rest-frame hours)
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Villar et al. (2017), Radioactive Decay
Kasliwal et al. (2017), Shock Cooling & Boosted Radioactive Decay
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Waxman et al. (2017), Radioactive Decay
Piro & Kollmeier (2017), Shock Cooling
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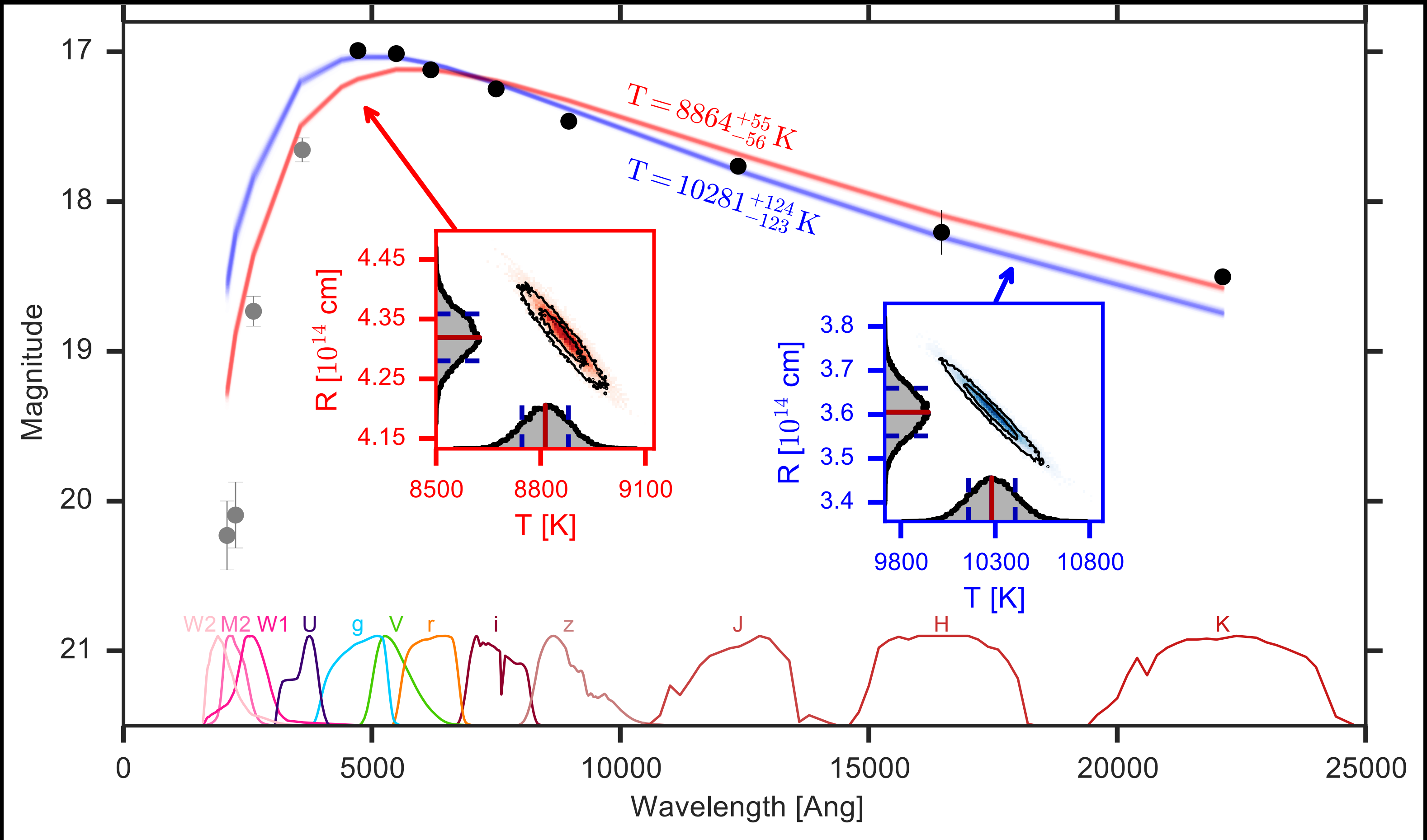
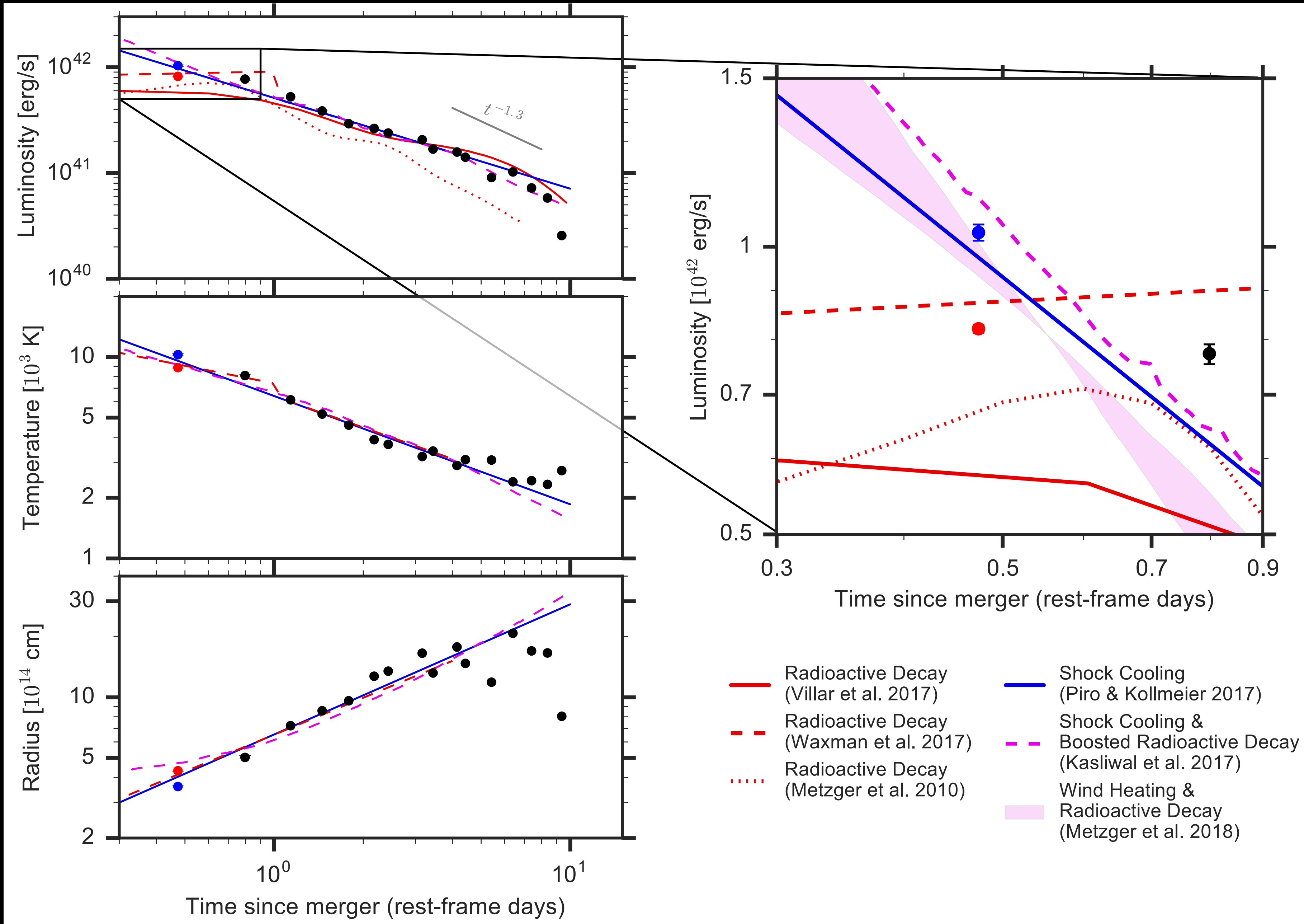
-22
-20
-18
-16
-14
-12
-10
-8
Absolute magnitude
0.4
1
3
Time since merger (rest-frame days)

Arcavi
2018

UV - Optical Discovery Time Difference Was Critical



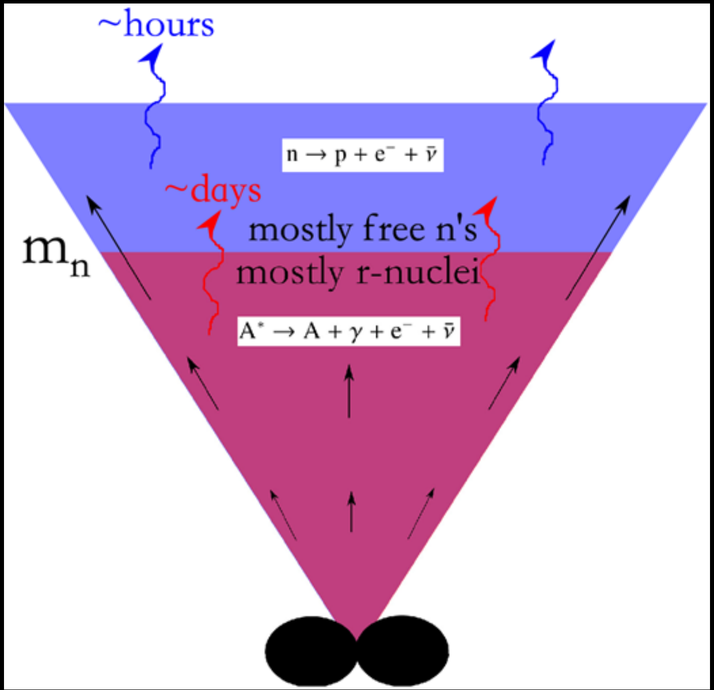
Arcavi 2018

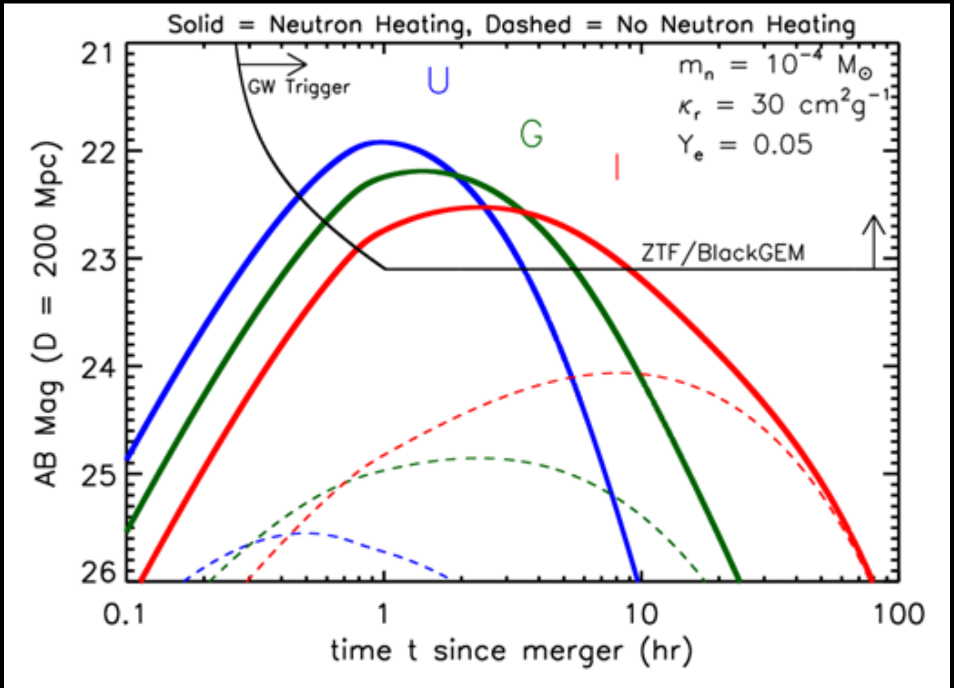


Luminosity [erg/s]
10^{42}
10^{41}
10^{40}
$t^{-1.3}$
Temperature [10^3 K]
10
5
2
1
Radius [10^{14} cm]
30
10
5
2
10^0
10^1
Time since merger (rest-frame days)
1.5
1
0.7
0.5
Luminosity [10^{42} erg/s]
0.3
0.5
0.7
0.9
Time since merger (rest-frame days)
Radioactive Decay (Villar et al. 2017)
Radioactive Decay (Waxman et al. 2017)
Radioactive Decay (Metzger et al. 2010)
Shock Cooling (Piro & Kollmeier 2017)
Shock Cooling & Boosted Radioactive Decay (Kasliwal et al. 2017)
Wind Heating & Radioactive Decay (Metzger et al. 2018)

Arcavi 2018

Predicted One-Hour Time Scale Blue Emission



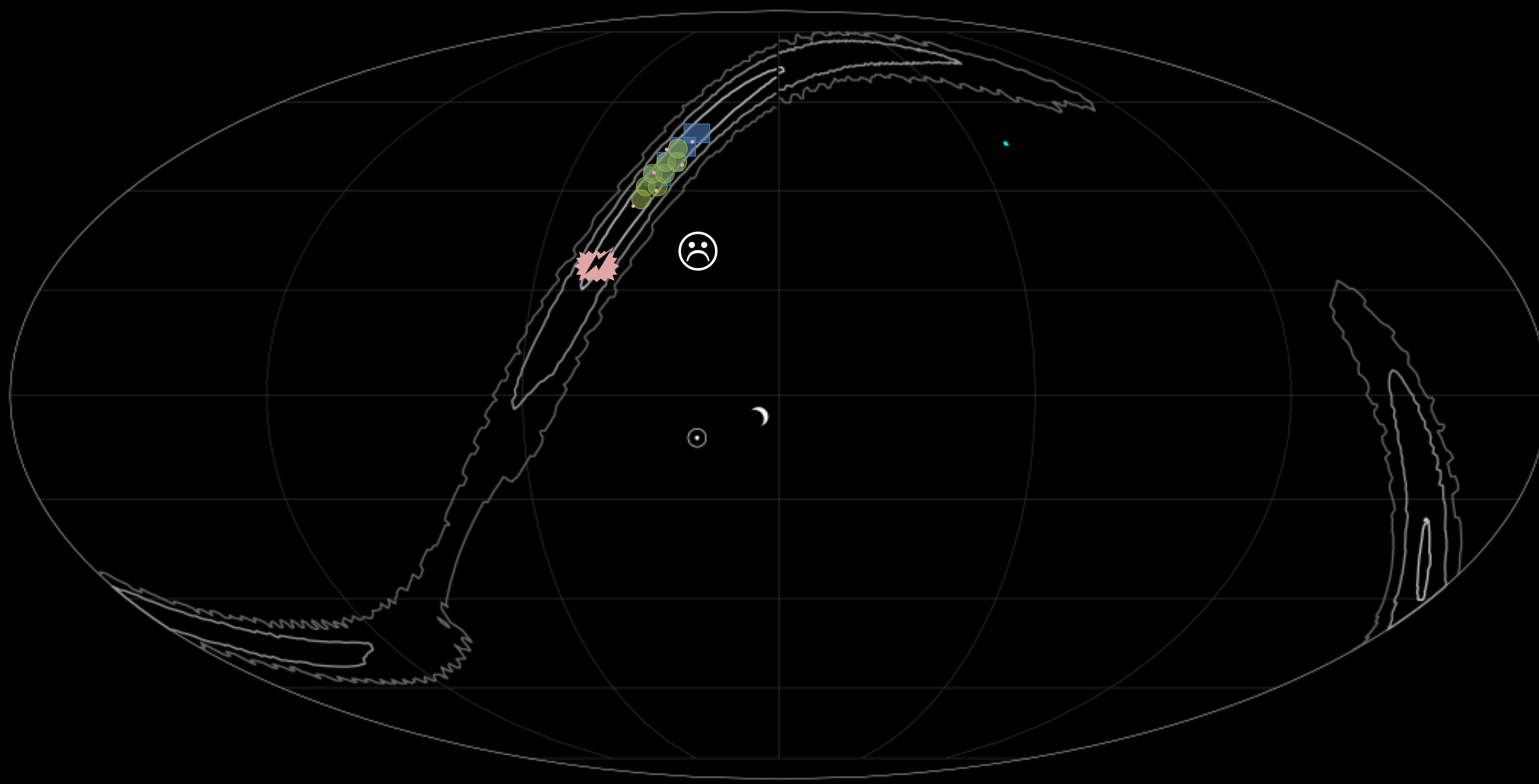


Metzger et al. 2015

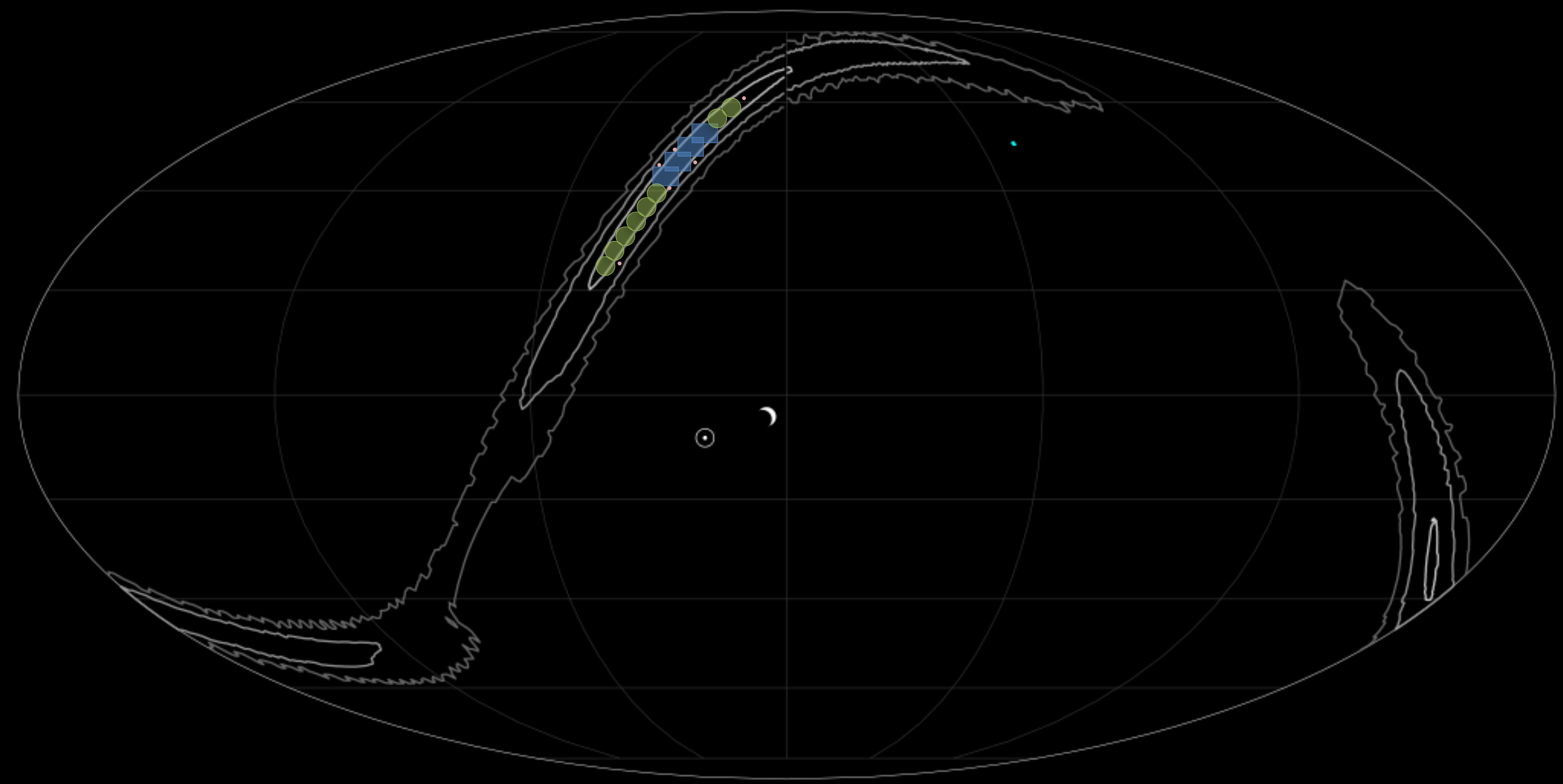
Need a Tool for Coordinating Global GW Followup

LIGO

VIRGO



Need a Tool for Coordinating Global GW Followup



The “Treasure Map”

Voluntary reporting of observations planned and then update to executed

See where other people are searching and plan your observations accordingly

Reporting of candidates and classifications for community vetting with minimal overlaps

Constant updates on brightness and color helps inform additional followup

Allows real-time involvement of amateur observers, citizen scientists, theorists…

http://treasuremap.space

Additional Information in GW Alerts Will Help

Could a localization improve after a preliminary alert or were detectors off?

Could the preliminary / initial mass uncertainty evolve to NS territory?

Is one of the components < 2 solar masses?

In addition to allowing for more rapid discovery, will allow for more efficient telescope use (current EM followup strategies not sustainable, will need to be more selective in the future)

Part III Summary

The source of the early blue emission of GW170817 remains unclear: Radioactive decay from low opacity ejecta, from boosted high velocity ejecta, shock cooling?

This is important: Various ejecta components potentially constrain NS EOS, nucleosynthesis, jet launching, cocoon forming, inclination angle (→ Hubble Constant).

Early data critical! Distinguishing between emission models requires optical-UV observations starting **few hour/s** after merger (10 hours is too late) with **sub-day** cadence.

Must coordinate to find events early!
LVC can help with additional information in alerts.