Systematic Modeling Uncertainties of Kilonova Property Estimation

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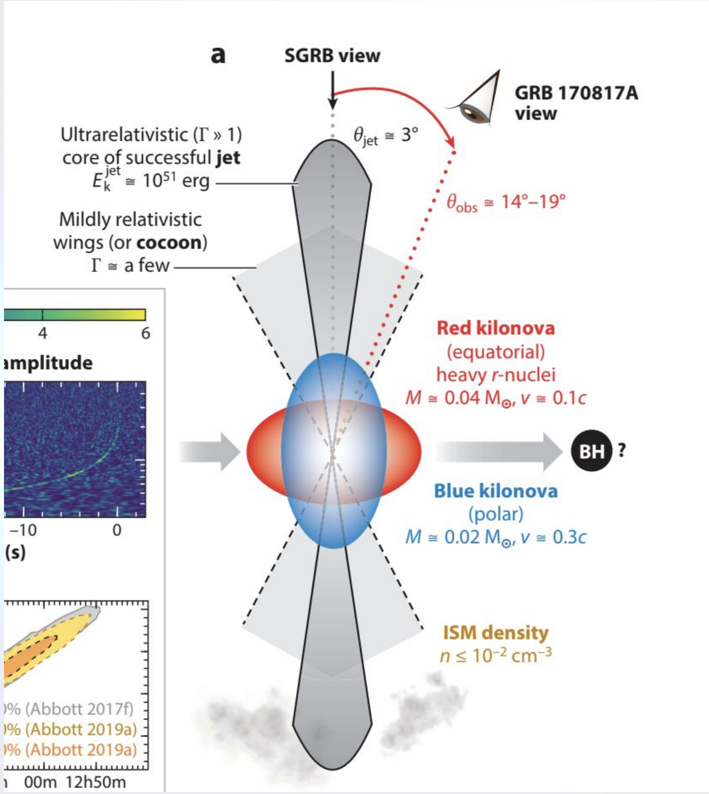
QR Code to paper!

Background

- Fast-evolving UV/Optical/IR transient powered by radioactive decay of *rapid neutron capture* (r-process) elements
- Only confirmed r-process source!
- BNS Merger or NS-BH Merger (?)
- Two components
  - Red Kilonova ➔ Equatorial, low Y_e
  - Blue Kilonova ➔ Polar, high Y_e
- **What is the contribution of KNe to r-process enrichment of the universe?**



GW170817/AT2017gfo Figure 1

Margutti & Chornock 2021

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But how sure are we *really* about KN models?

- While error may be small within a model, what is the error of the model itself?
- We have to make *many* decisions to assume:
  - Density profile
  - r-process Heating Rate
  - Composition
  - Thermalization Efficiency
  - Atomic Data
  - More!

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Lanthanides

- Valence f-shell electrons cause high opacities at optical/UV
- IR emission is a signature of r-process that produced lanthanides and will have the greatest impact on the spectral evolution
    - Blue KN → No/little lanthanides
    - Red KN → Lanthanides
- X_{lan} = mass fraction of lanthanides

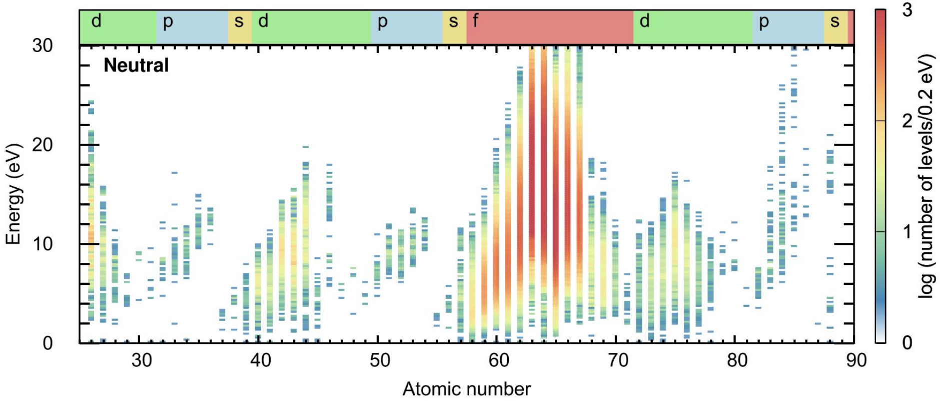

Figure 3
Tanaka+2020

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Atomic Datasets

Atomic Dataset HULLAC

Tanaka+2020

Simulated structure, use $31 \leq Z \leq 70$

Hebrew University Lawrence Livermore Atomic Code (HULLAC)

Atomic Dataset ATOMIC

Fontes+2020

Opacity tables, use $58 \leq Z \leq 70$

Another Theoretical Opacity Modeling Integrated Code (ATOMIC)

$31 \leq Z \leq 57$ HULLAC data

Atomic Dataset Autostructure

Kasen+2017

Simulated structure, $58 \leq Z \leq 70$

Autostructure

Associate elements $31 \leq Z \leq 57$ to lower mass equivalents with cmfgen data

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Energy Injection and Thermalization

- r-process material radioactively decays and emits beta/alpha particles, neutrinos, fission fragments, γ-rays
- What fraction of the energy actually heats the ejecta?
  - Thermalization Efficiency *f*
- Global vs Local approach
  - E.g Barnes+2016, Rosswog+2017

Local

$$f_j(\mathbf{r},t) = \frac{\ln(1+2\eta^2)}{2\eta^2}$$

$$2\eta^2 = \frac{2A_j}{t\rho(\mathbf{r},t)}$$

Global

$$f_{\rm tot}(t) = 0.36\left[e^{-at} + \frac{\ln(1+2bt^d)}{2bt^d}\right]$$

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Model Setup

- Sedona Radiative Transfer Code (Kasen+06)
- 1D, dynamically solves for gas state and opacities
- $M \in [0.001, 0.01, 0.1]\ M_\odot$
- $v_k \in [0.1, 0.3]\ c$
- $\log_{10}(X_{lan}) \in [-9, -4, -2]$

If you want more details about the simulation setup, ask me afterwards!

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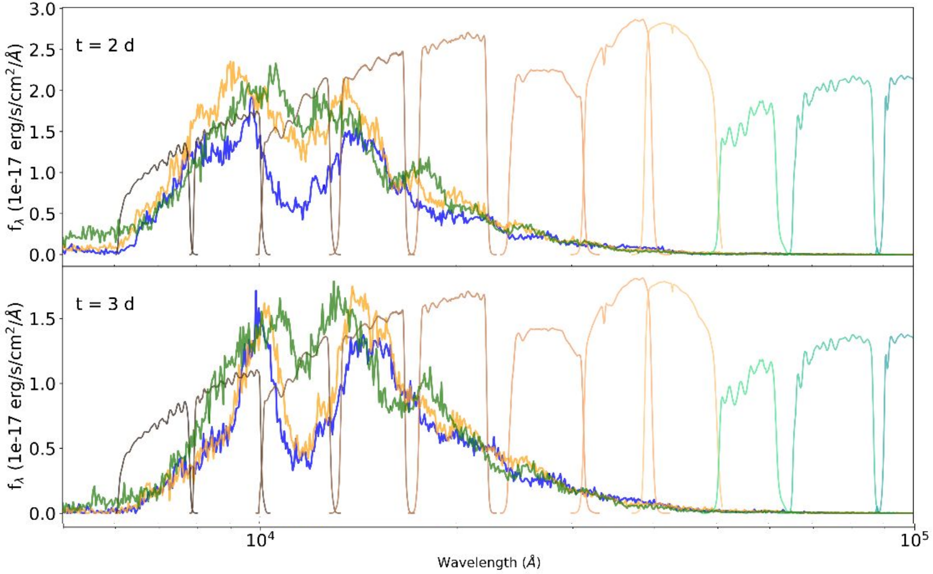
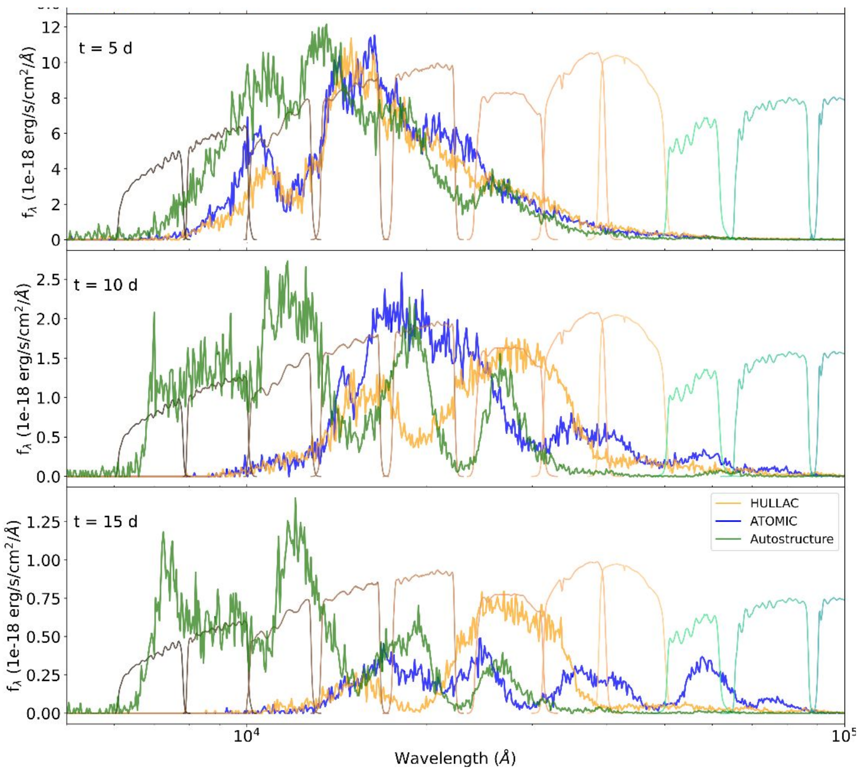
Theory: Example Spectra - 0.01 $M_\odot$, v = 0.1c, $\log_{10}(X_{lan}) = -2$



(Brethauer+24)



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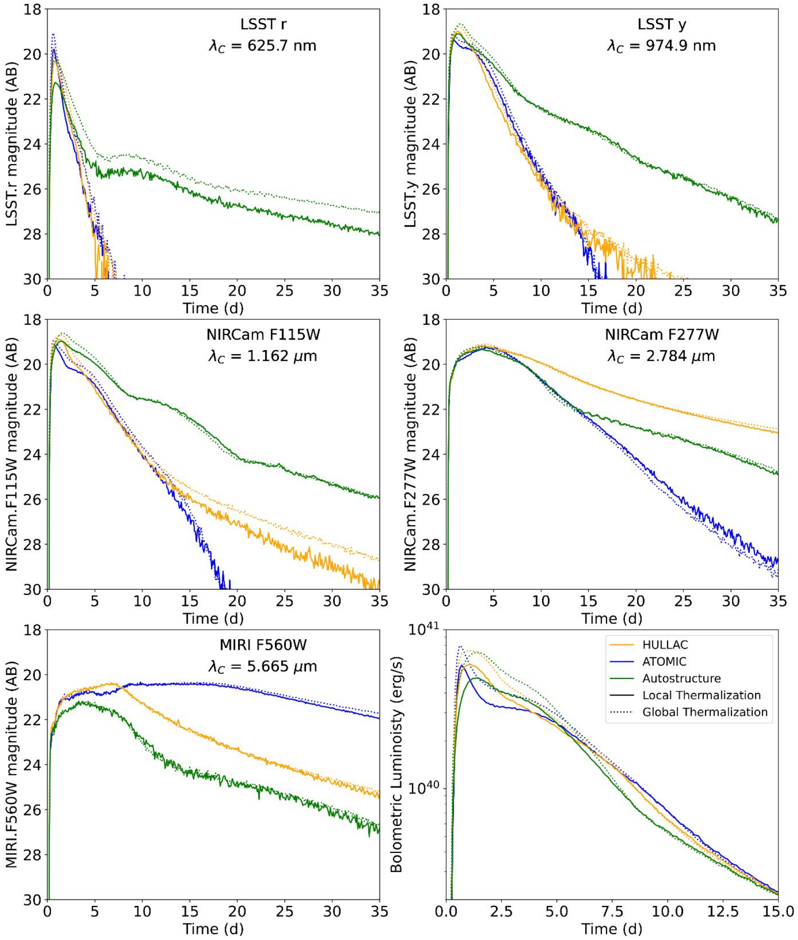
Theory: Observables

- Color and decay rate are most severely impacted by Atomic Dataset for high X_{lan}
  - Bluest filters most affected
  - Color scatter can be different by 1.5 to 2 mags
  - > 1 mag/day difference in decay rate, scatter drops below ~0.1 for *z* and *y* band only
  - In IR, time of peak range of ≳5 days
  - NIR/MIR mags vary dramatically
    - ATOMIC brighter in MIR by >2.5 mags
    - Autostructure is fainter by > 2 mags
- Spectrum of Atomic Data from reddest to bluest
  - ATOMIC → HULLAC → Autostructure



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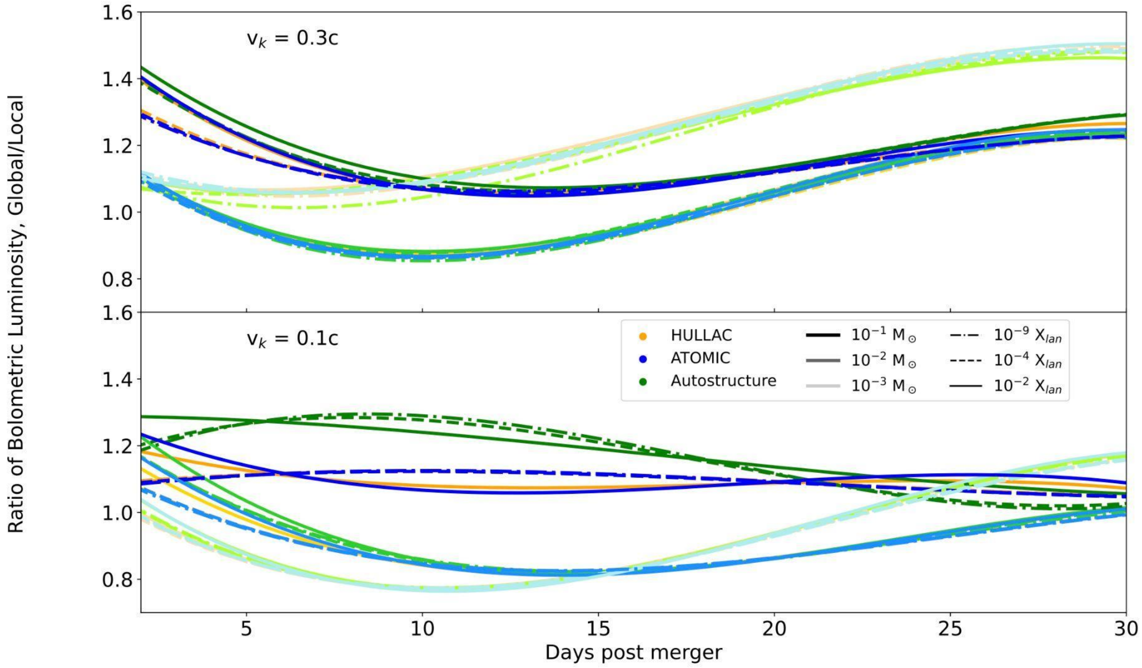
Theory: Thermalization Prescription Offset

- Thermalization Prescription scales spectra up and down
- Global Prescription brighter in bolometric luminosity by 20-50%
- Roughly correlates to 20-50% systematic offset in mass estimate



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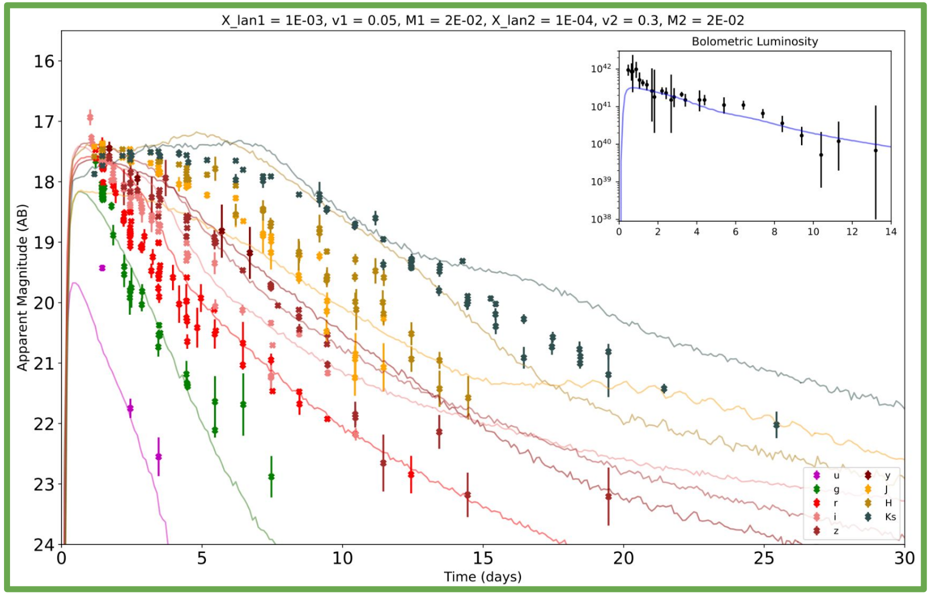
Observation: Given some Data, What Models Fit?

- Two approaches
  - 2-component fit on GW170817 LC data
  - Inter-dataset fit of LC data
- Finer Grid
  - M ∈ [1, 2, 3, 4, 5] x 10^{-2} $M_\odot$
  - v_k ∈ [0.05, 0.1, 0.2, 0.3] c
  - $\log_{10}(X_{lan})$ ∈ [-9, -5, -4, -3, -2]
- Iterative Higher Resolution Fitting



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Observation: Model Matching of GW170817

Table 1. "Best-fitting" model matching ejecta parameters from our χ^2 fitting of GW170817 data. Uncertainties are based on grid spacing.

Dataset	M_1 (10^{-2} $M_\odot$)	v_1 (c)	$\log_{10}X_{lan\,1}$	M_2 (10^{-2} $M_\odot$)	v_2 (c)	$\log_{10}X_{lan\,2}$	Total Lanthanide Mass ($M_\odot$)	χ^2
HULLAC	$2.5^{+0.13}_{-0.13}$	$0.05^{+0.01}_{-0.01}$	$-3.25^{+0.13}_{-0.13}$	$1.5^{+0.13}_{-0.13}$	$0.3^{+0.025}_{-0.025}$	-9^{+2}_{-2}	1.5×10^{-5}	1.12
ATOMIC	$2^{+0.13}_{-0.13}$	$0.05^{+0.01}_{-0.01}$	$-3.75^{+0.13}_{-0.13}$	$2^{+0.13}_{-0.13}$	$0.2^{+0.013}_{-0.013}$	-9^{+2}_{-2}	4×10^{-6}	1.26
Autostructure	$2^{+0.13}_{-0.13}$	$0.05^{+0.01}_{-0.01}$	$-3^{+0.13}_{-0.13}$	$2^{+0.5}_{-0.5}$	$0.3^{+0.05}_{-0.05}$	$-4^{+0.5}_{-0.5}$	2.2×10^{-5}	0.319

- Total mass conserved
- X_{lan} varies by 3/4 order of magnitude in lanthanide rich, 5 in lanthanide poor!
- Velocity not as impacted

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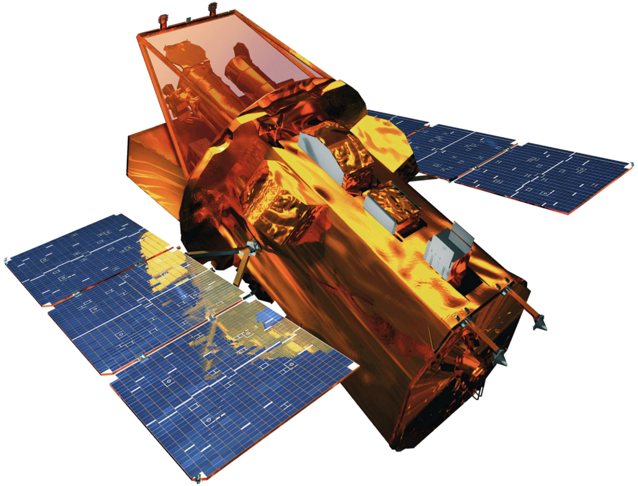
Role of Swift with Kilonovae

- Answering long-standing questions requires Swift:
  - Does free neutron decay play an important role in KNe?
  - What causes discrepancy between early time optical data and models?*
  - What is the connection between LGRBs and KNe?



*Stay tuned over the next couple months!

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Conclusions

- Atomic Data variations can give varying KN ejecta parameters:
    - Typically 25-40% offset in mass, can be > 300%
    - X_{lan} varies by an order of magnitude in lanthanide rich, can be >5 for lanthanide poor
- Thermalization Prescription affects mass estimates by 20-50%
- BNS merger lanthanide contribution uncertain by a factor of 6
- Light curve quantities like color and decay rate are *highly* dependent on Atomic Dataset
    - Colors vary by 1.5 mags
    - IR magnitudes vary by ≳4 mags
- Rapid Swift observations will unveil critical information

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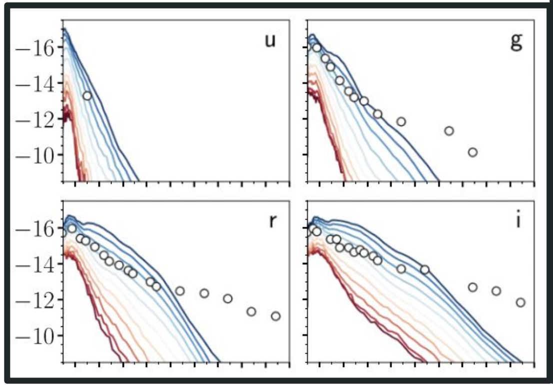
Bonus Plots

Early Time Discrepancy

- Current simulations have trouble with replicating the long-lasting g/r band of GW170817
- Questions to answer:
  - Is there missing physics that needs to be incorporated?
  - Is there a geometry/density profile that can recreate g/r band?
  - Can varying composition resolve the discrepancy?
- Stay tuned in the coming months!*



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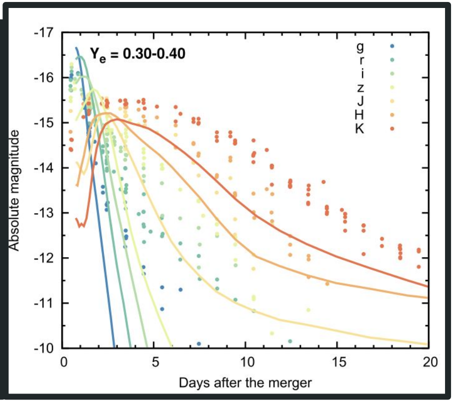

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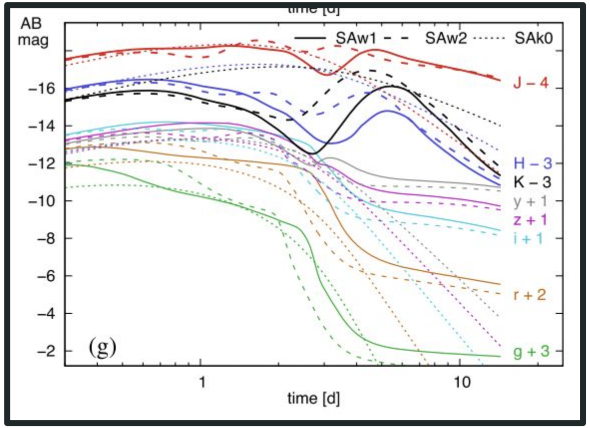
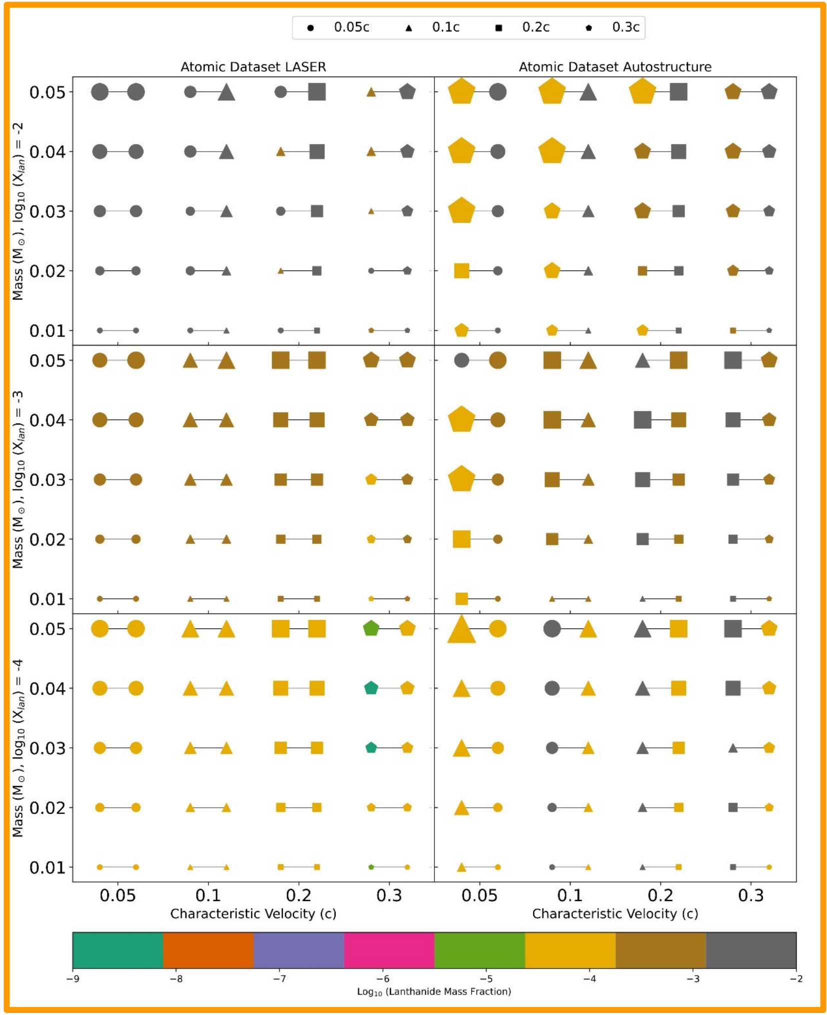
Examples of light curves from various groups that show a significant deviation in g/r band compared to AT2017gfo



Wollaeger+18

Observation: Inter-dataset Fitting

- Autostructure struggles to fit other datasets accurately
- HULLAC & ATOMIC match well but have some scatter:
  - Typical 1 order of magnitude offset in X_{lan}
  - Mass offset of 25-40%, though can be >300%
  - Offset highest at high X_{lan}
  - Evolution of error in velocity and X_{lan}



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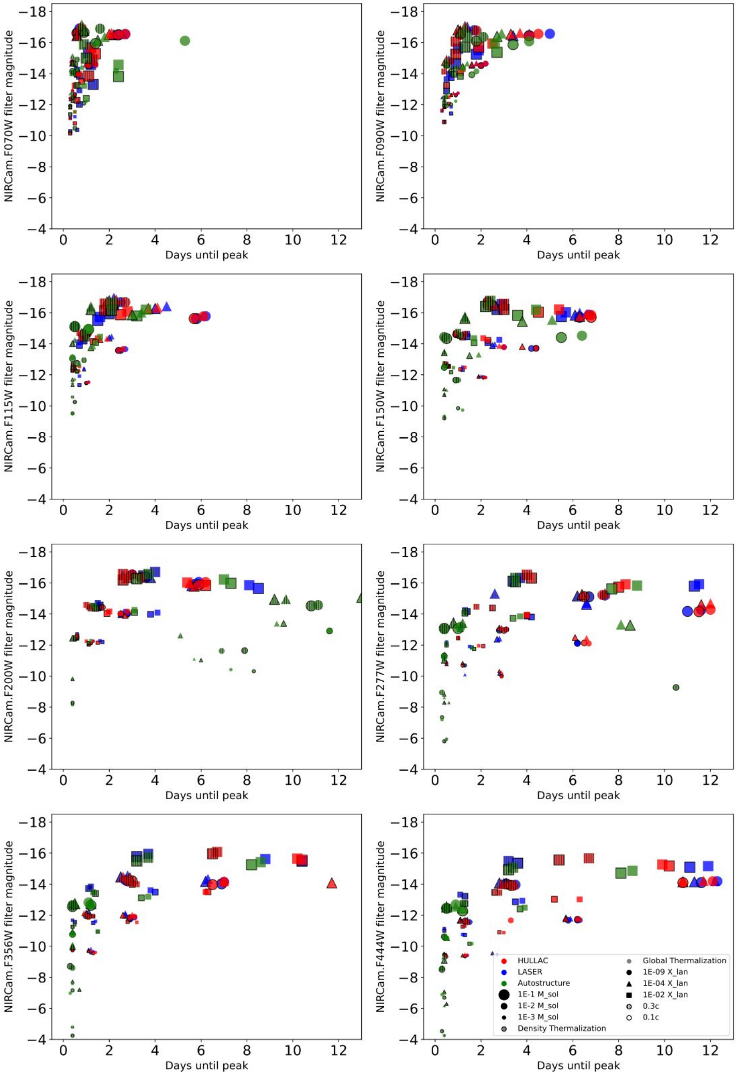
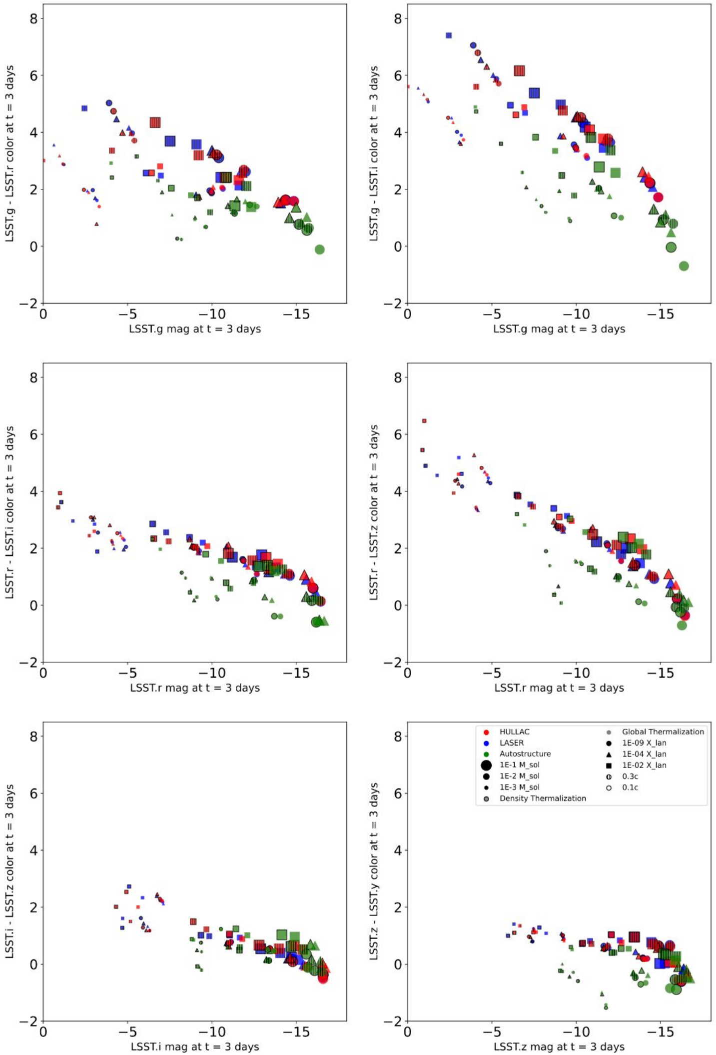
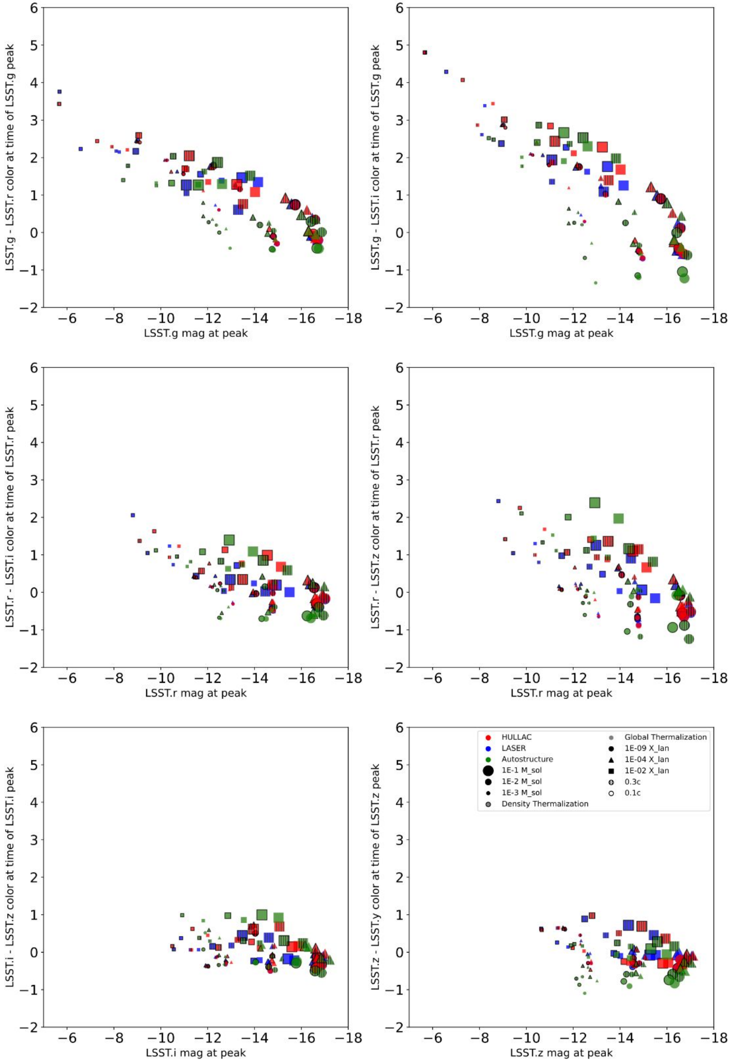
JWST Filter Peaks



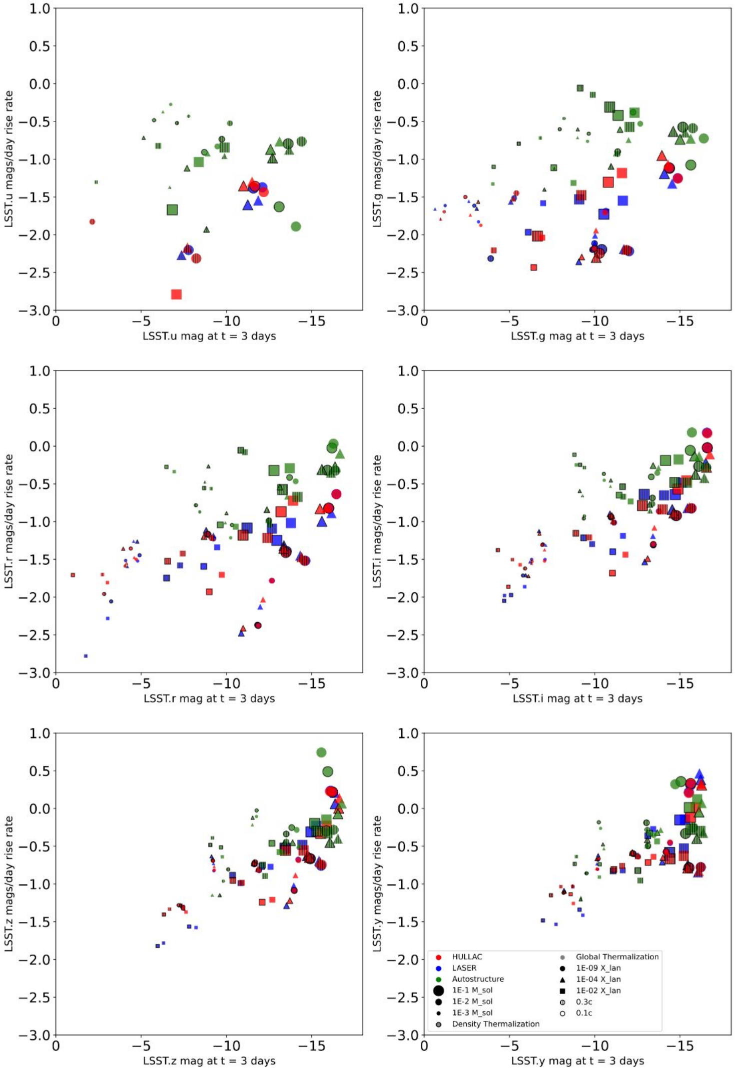
LSST Colors t = 3 days



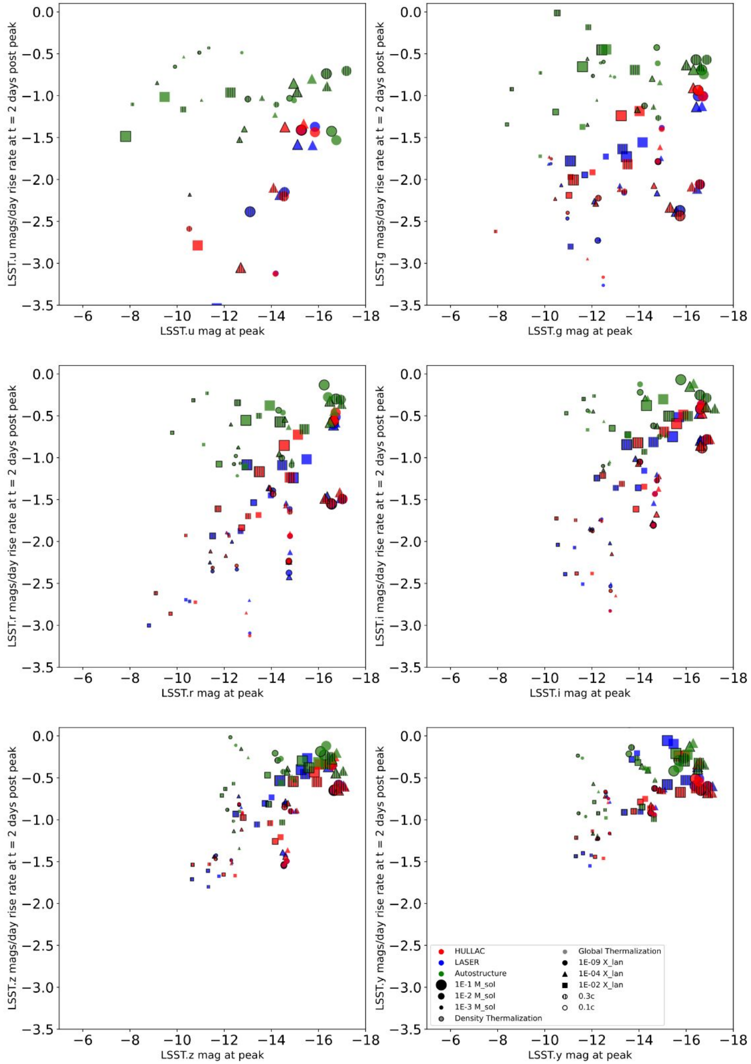
LSST Colors t = peak + 2 days



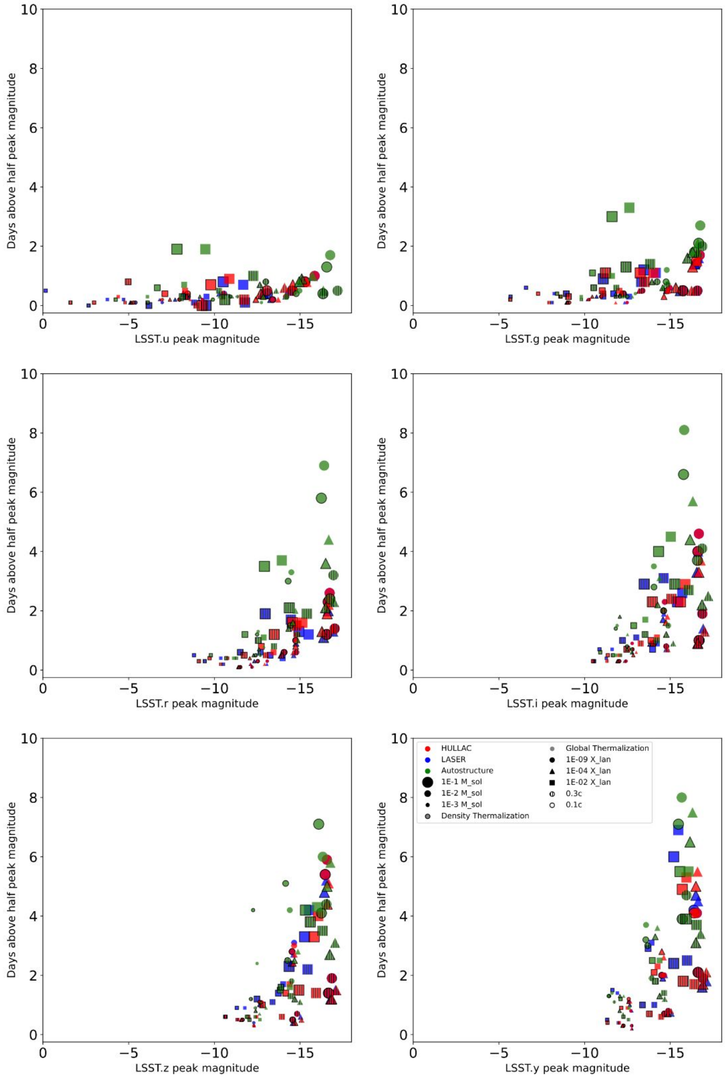
LSST Rise Rate t = 3 days



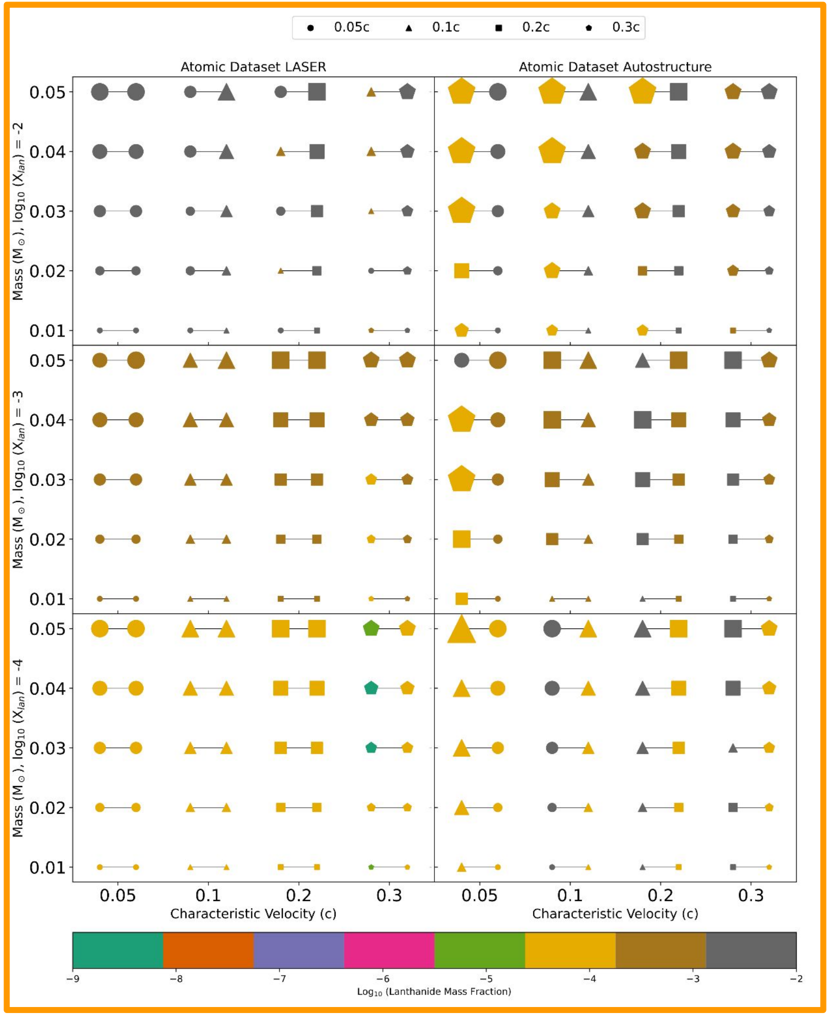
LSST Rise Rate t = peak + 2 days



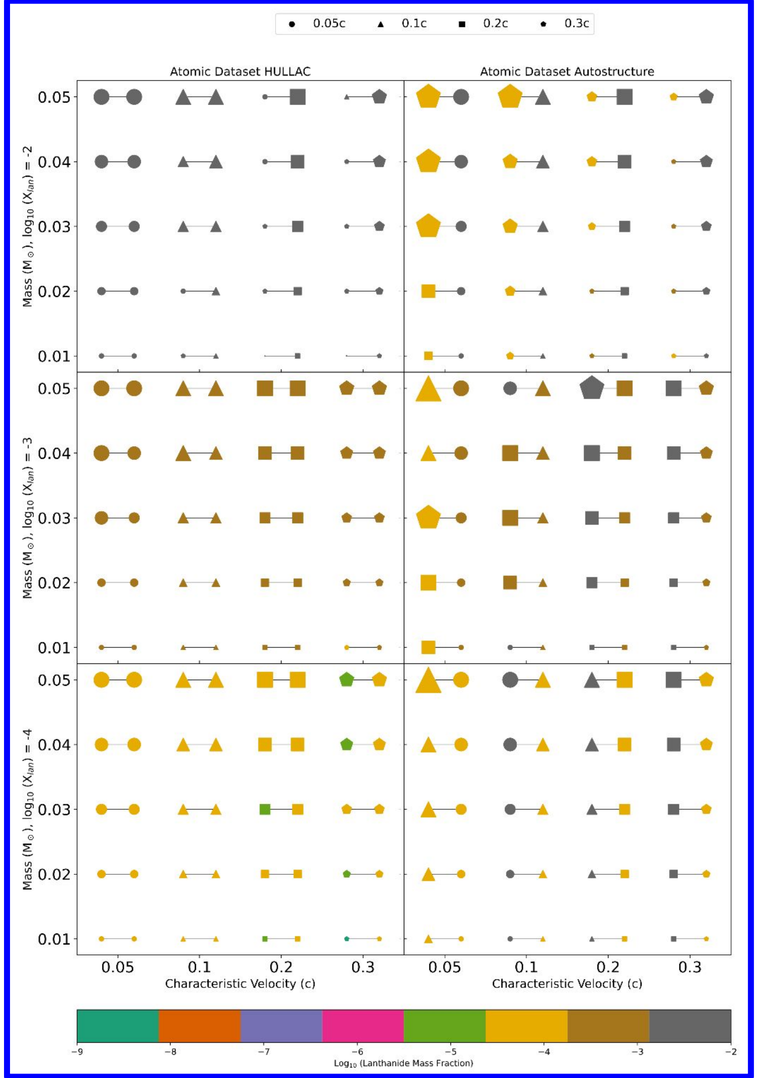
LSST Time Above Half Max



Fitting HULLAC



Fitting LASER



Fitting Autostructure