Understanding kilonovae with a future UV satellite

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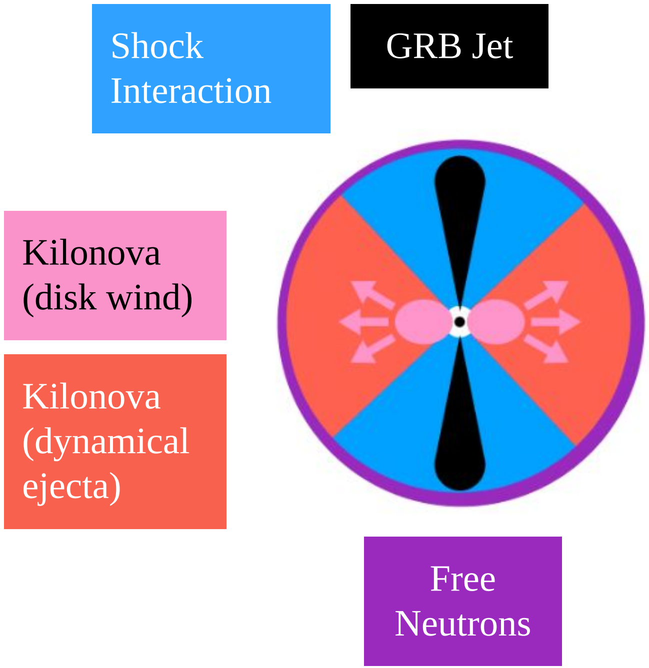
Radiation mechanisms from BNS merger

1. Kilonova: radiation from ejecta heated by radioactive decay of elements formed by r-process
2. Shock: radiation from shock heated material (e.g. jet-ejecta interaction)



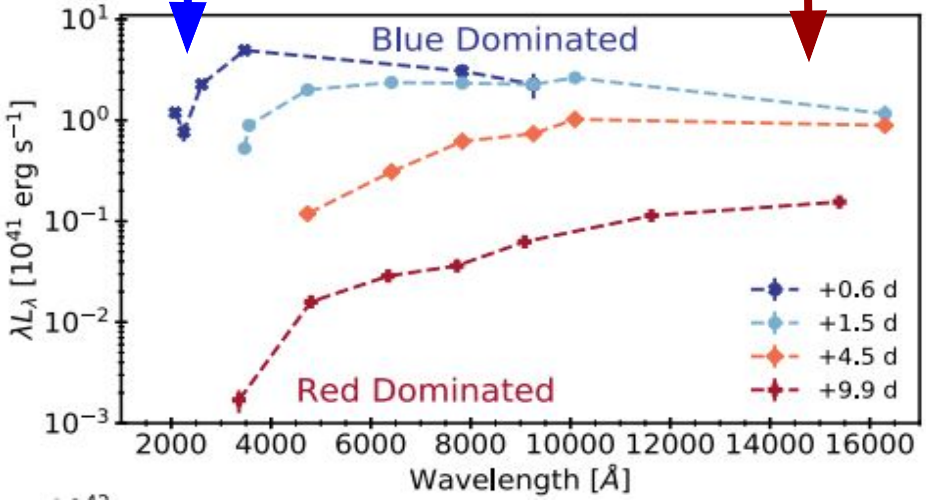
AT2017gfo (GW170817)

Blue component

UV, Optical

Red component

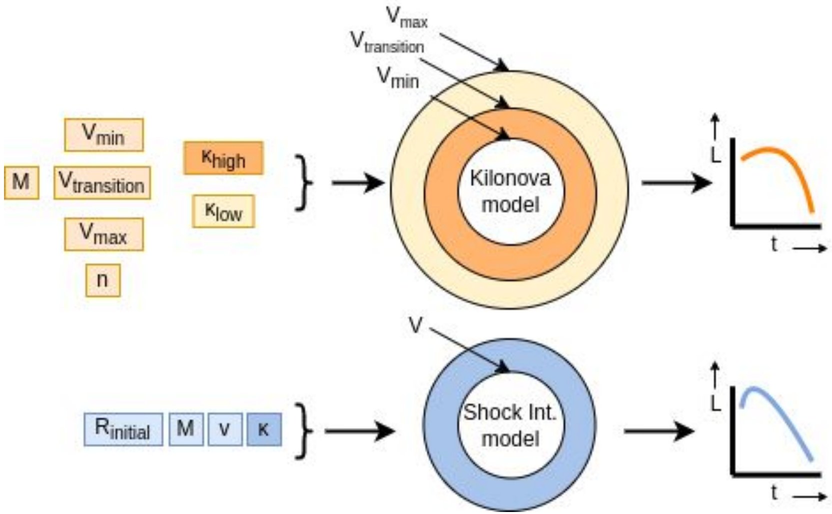
Optical, IR

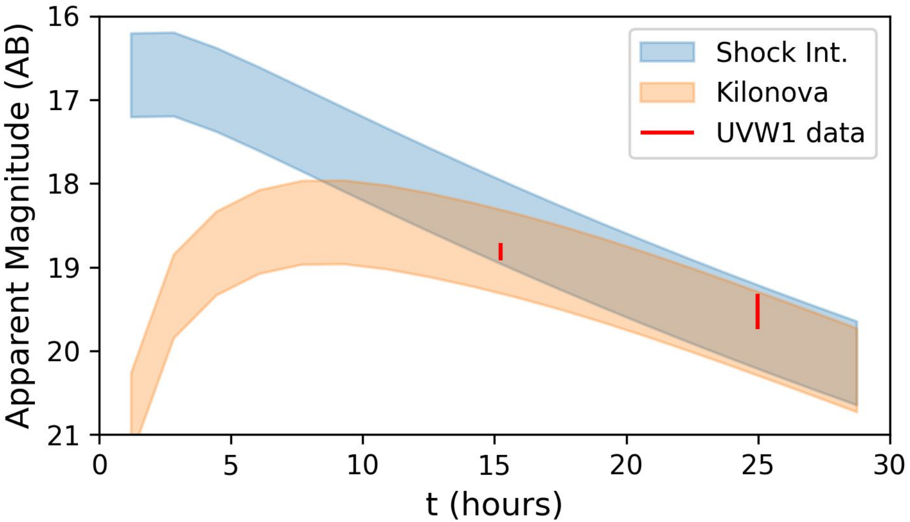


Cowperthwaite+ 2017

Likely two components, unclear if blue component = kilonova

Comparing kilonova vs shock cooling origin





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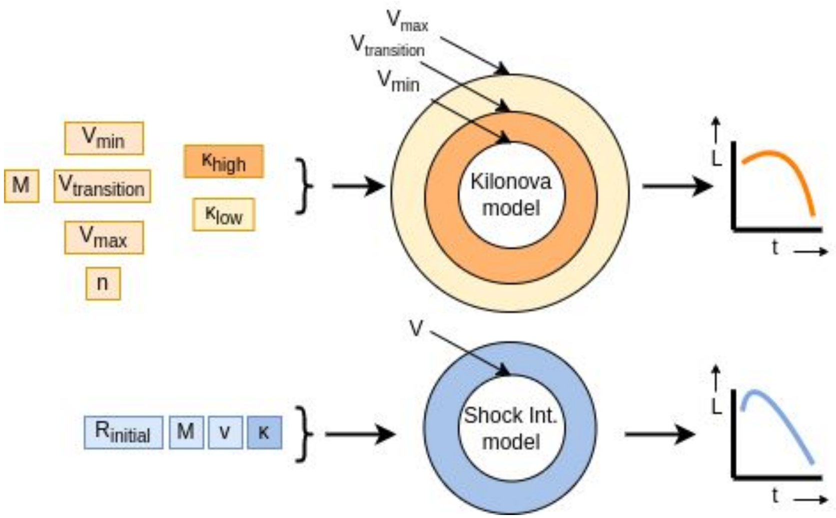
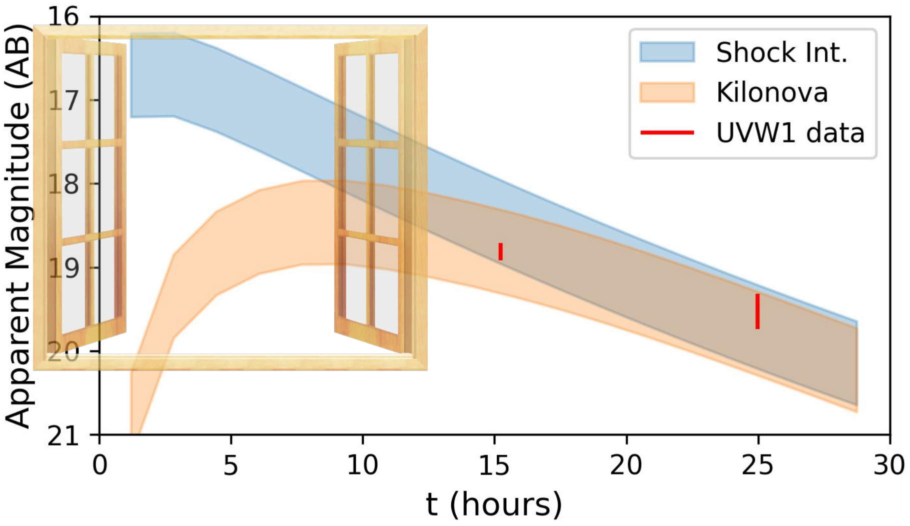


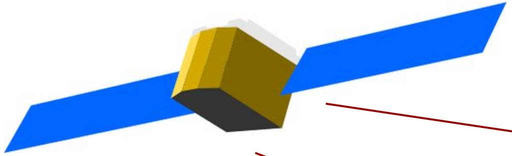


Aim of proposed UV missions: rapid UV follow-up of GWs

Goals

- **Model selection:** Can UV distinguish early physics driving the radiation?
- **Parameter estimation:** Can UV constrain model parameters?
- **Characterize:** how rapid should follow-up be?
- **Methodology to achieve goals**: Bayesian analysis with *simulated data* from *Dorado* mission concept

Instrument:
Dorado



- wide-field UV follow-up of GW alerts
- This mission not funded, but analysis results still interesting for other missions:

	Launch	5σ (AB) (15 minute exp.)	Response time	Ω (deg2)
Dorado	**-**	**20.8**	**~30 minutes**	**50**
Ultrasat	2025?	22.3	~30 minutes	200
UVEX	2028?	25	~3 hr	12

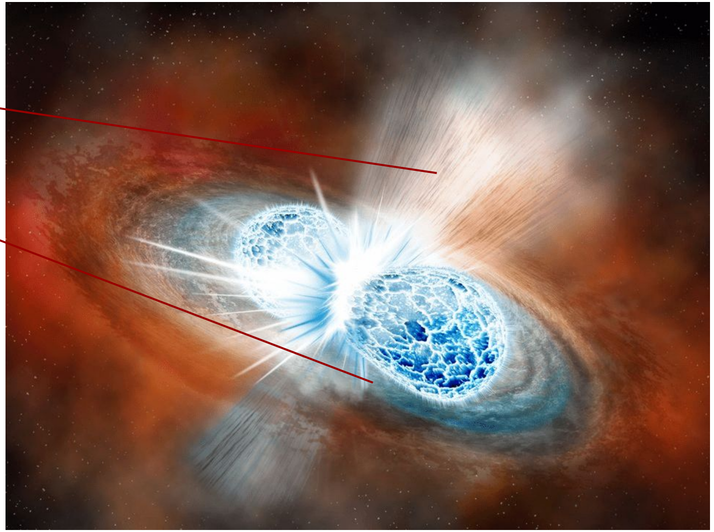
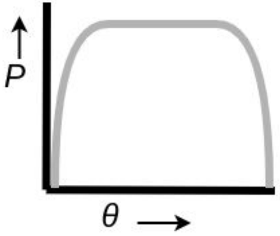


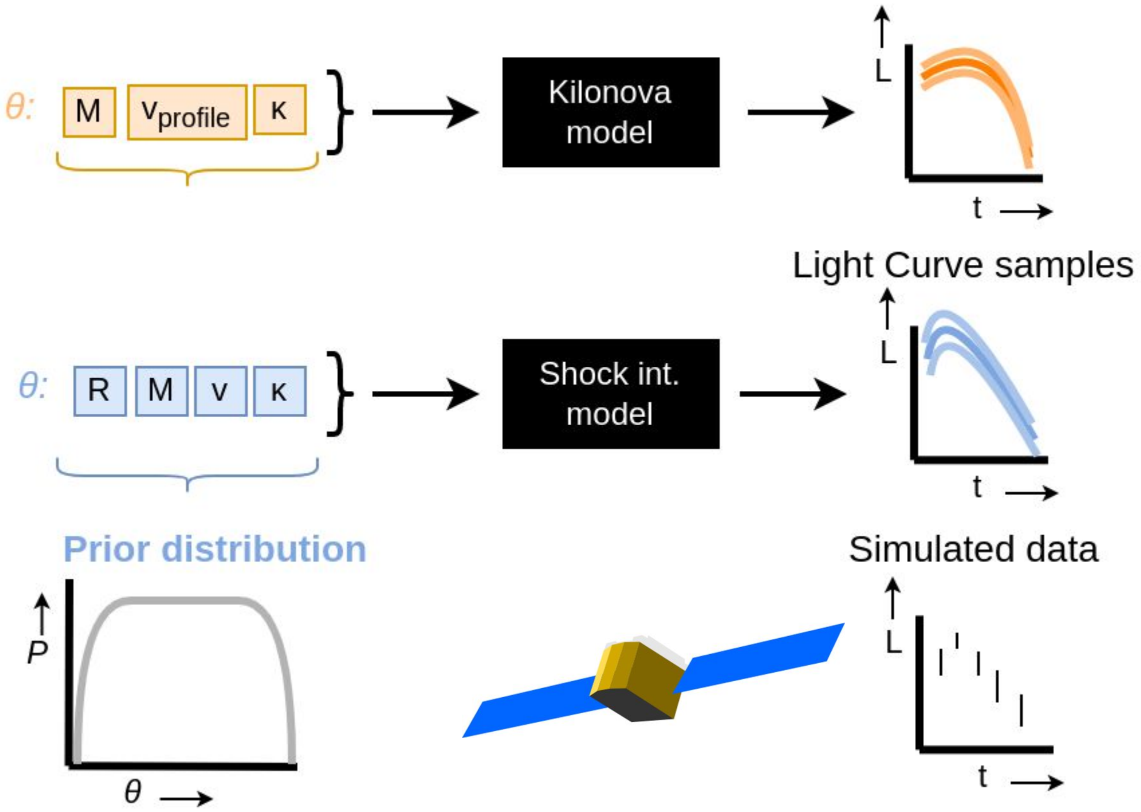
Illustration: Robin Dienel (Carnegie Institution for Science)

Methodology: Bayesian Analysis

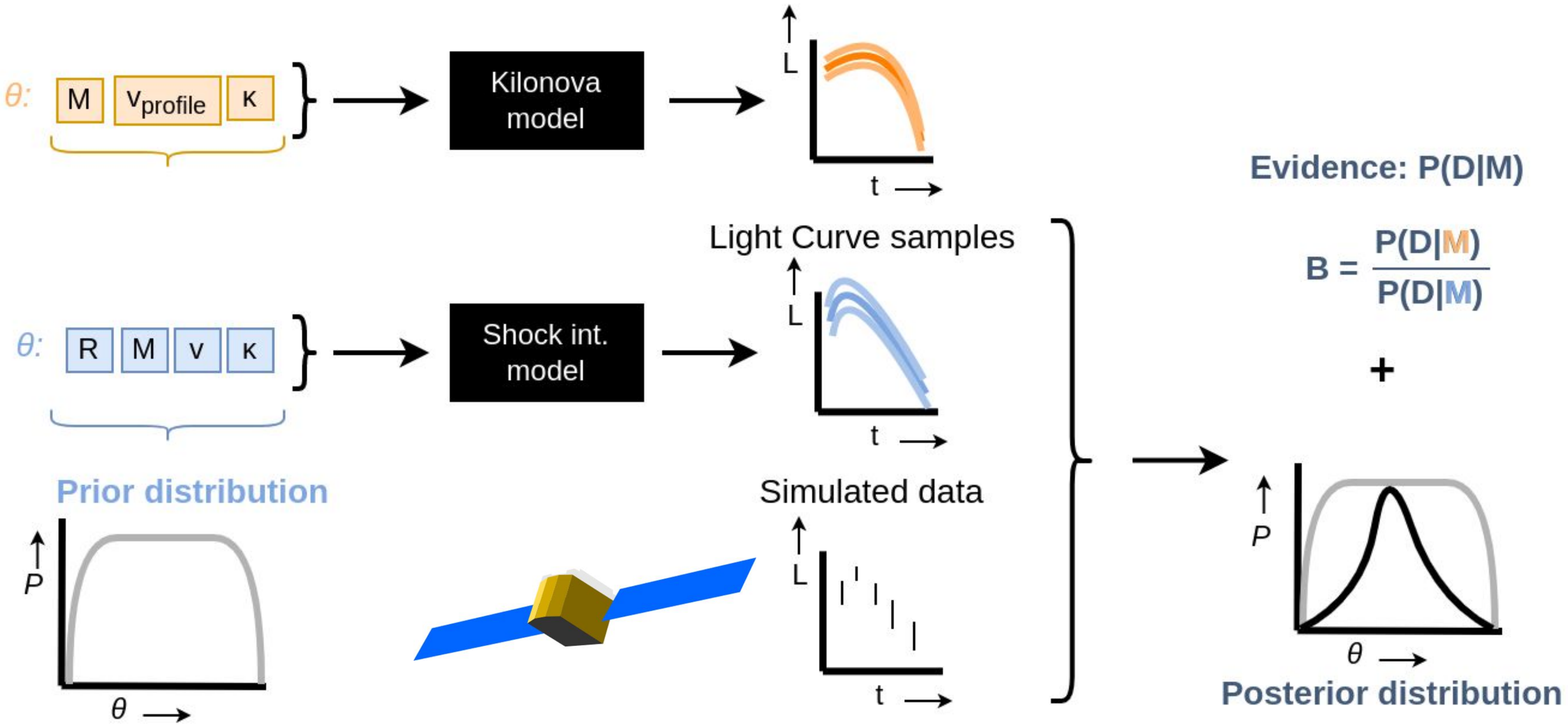
Prior distribution



Methodology: Bayesian Analysis



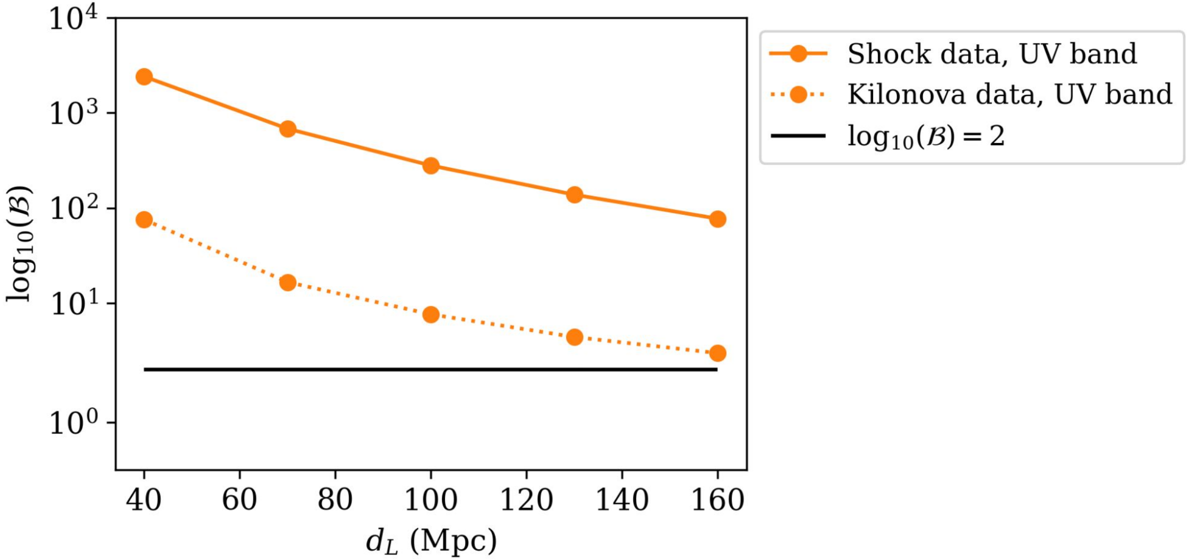
Methodology: Bayesian Analysis



Simulation Results

UV band vs optical (r) band

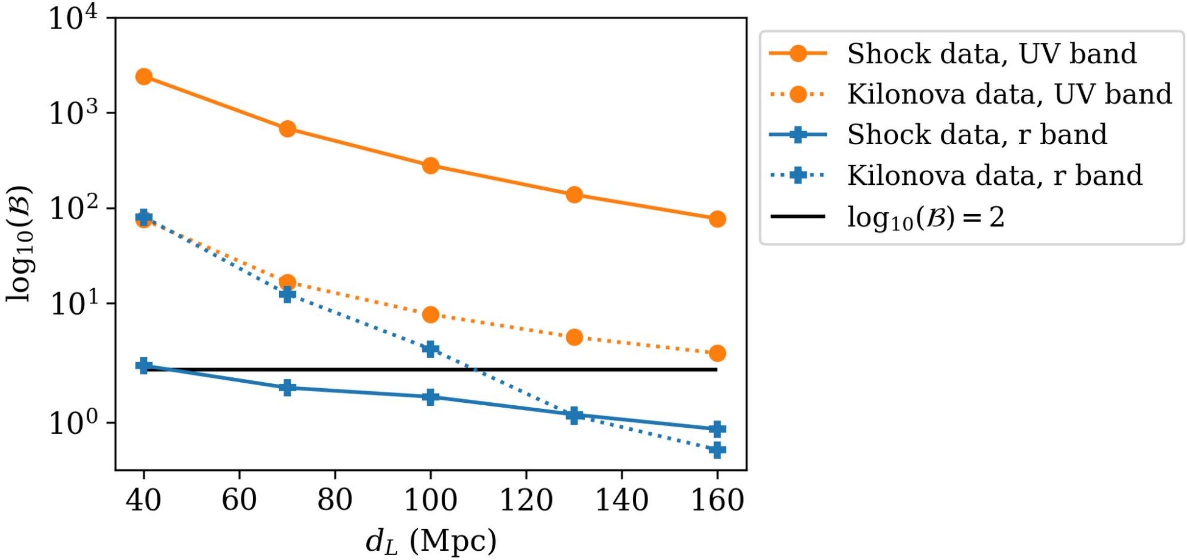
Dorsman et al. 2023



UV significant contributor to distinguishing physics of blue component

UV band vs optical (r) band

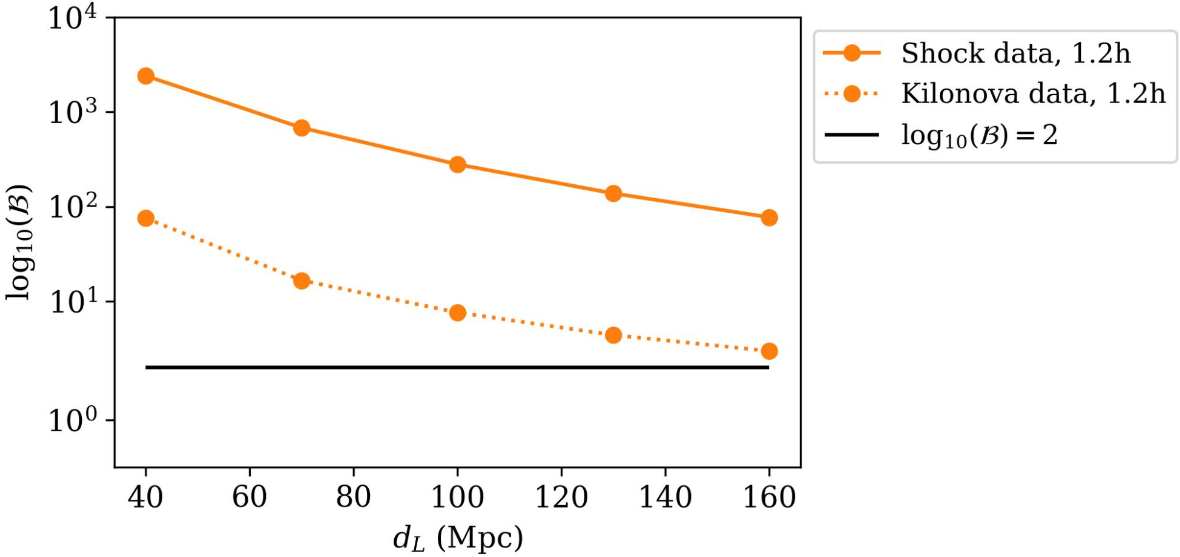
Dorsman et al. 2023



UV significant contributor to distinguishing physics of blue component

Observation starting time

Dorsman et al. 2023



Be on time with UV data! ~3 hrs if Dorado-like sensitivity

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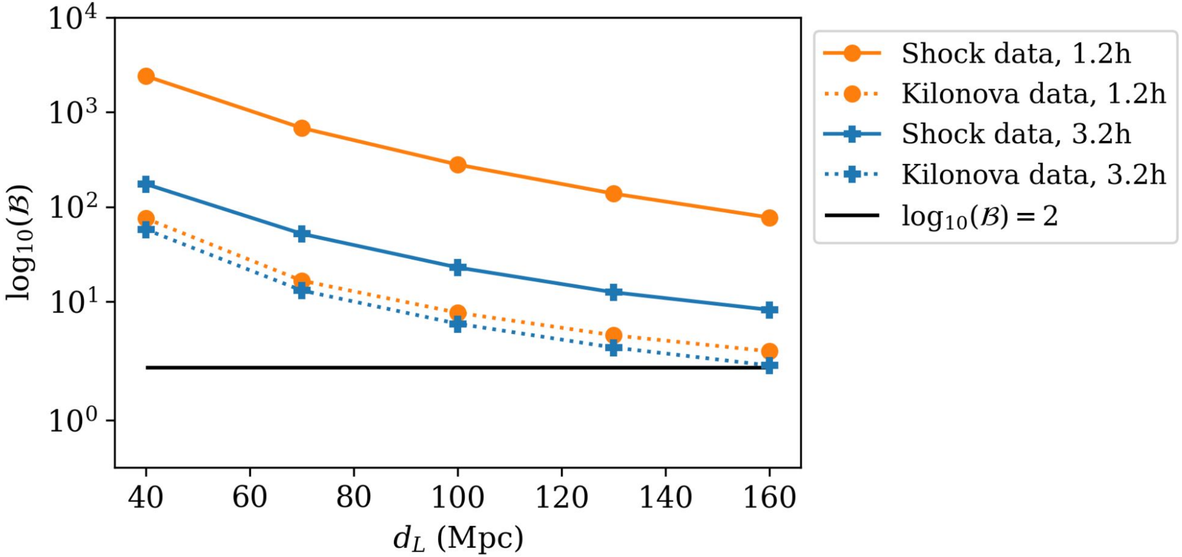

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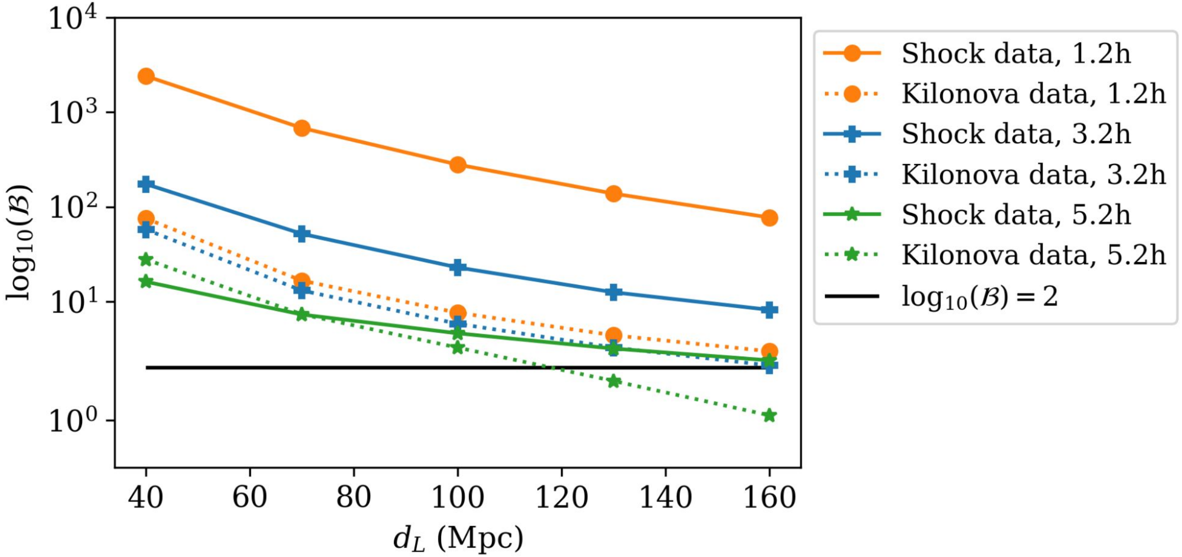

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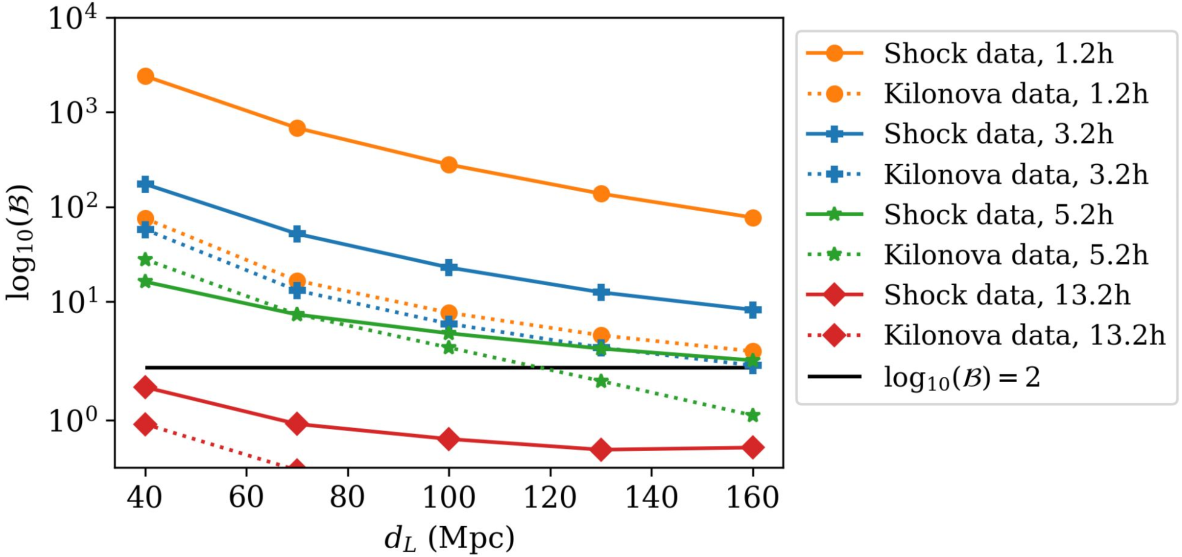

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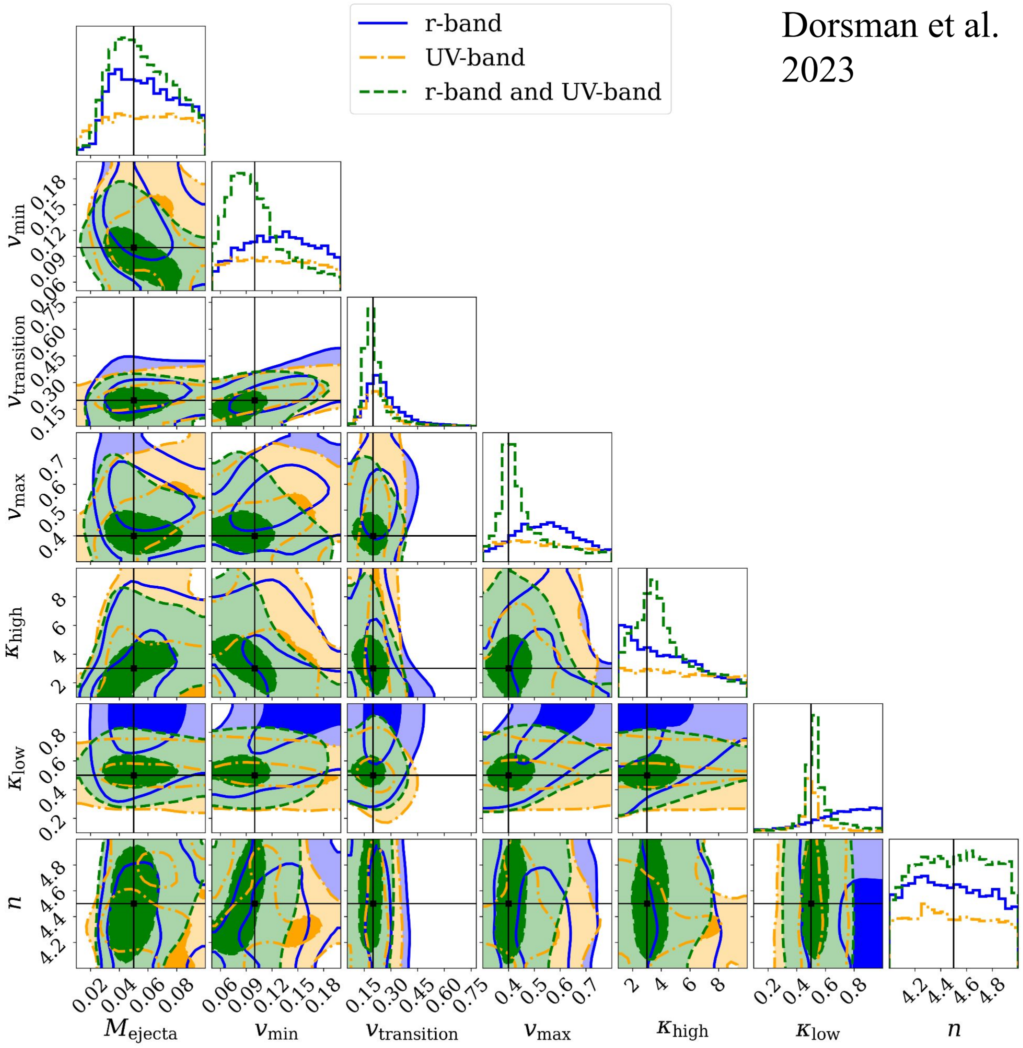
Comparing bands

- Improved constraints with uv+r data

Dorsman et al. 2023



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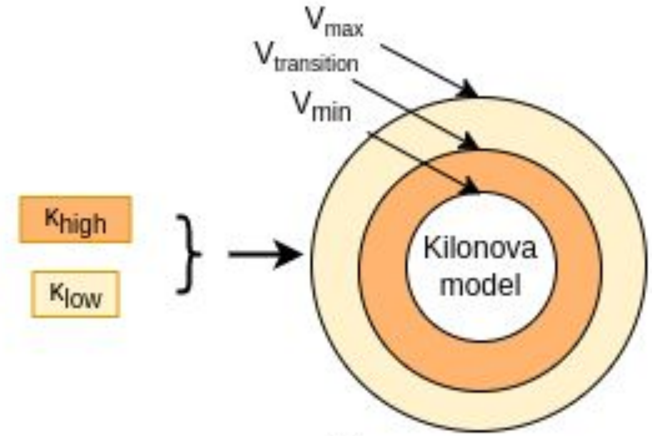
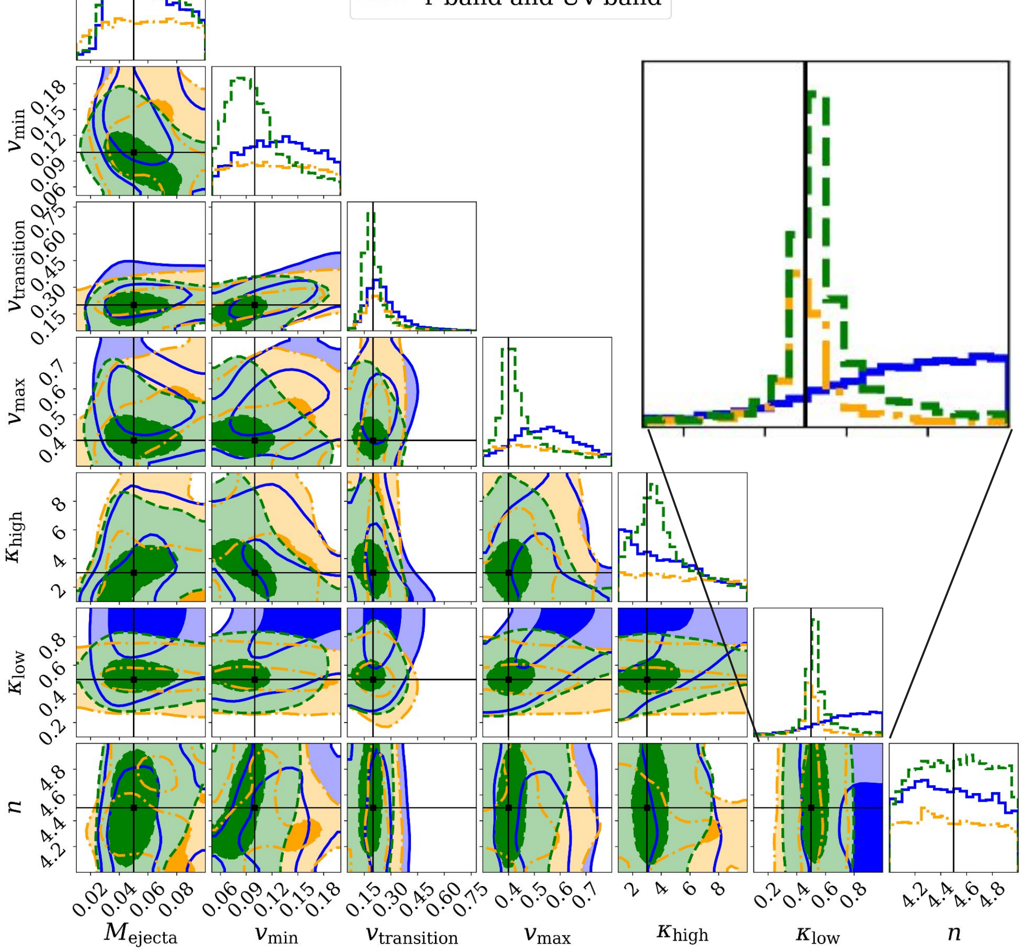
Comparing bands

- Improved constraints with uv+r data
- UV data constrains k_{low},$v_{transition}$



Dorsman et al. 2023



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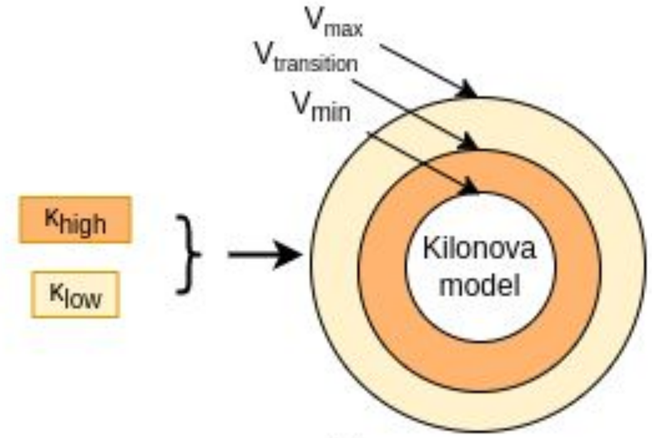
- UV data constrains k_{low}, $v_{transition}$



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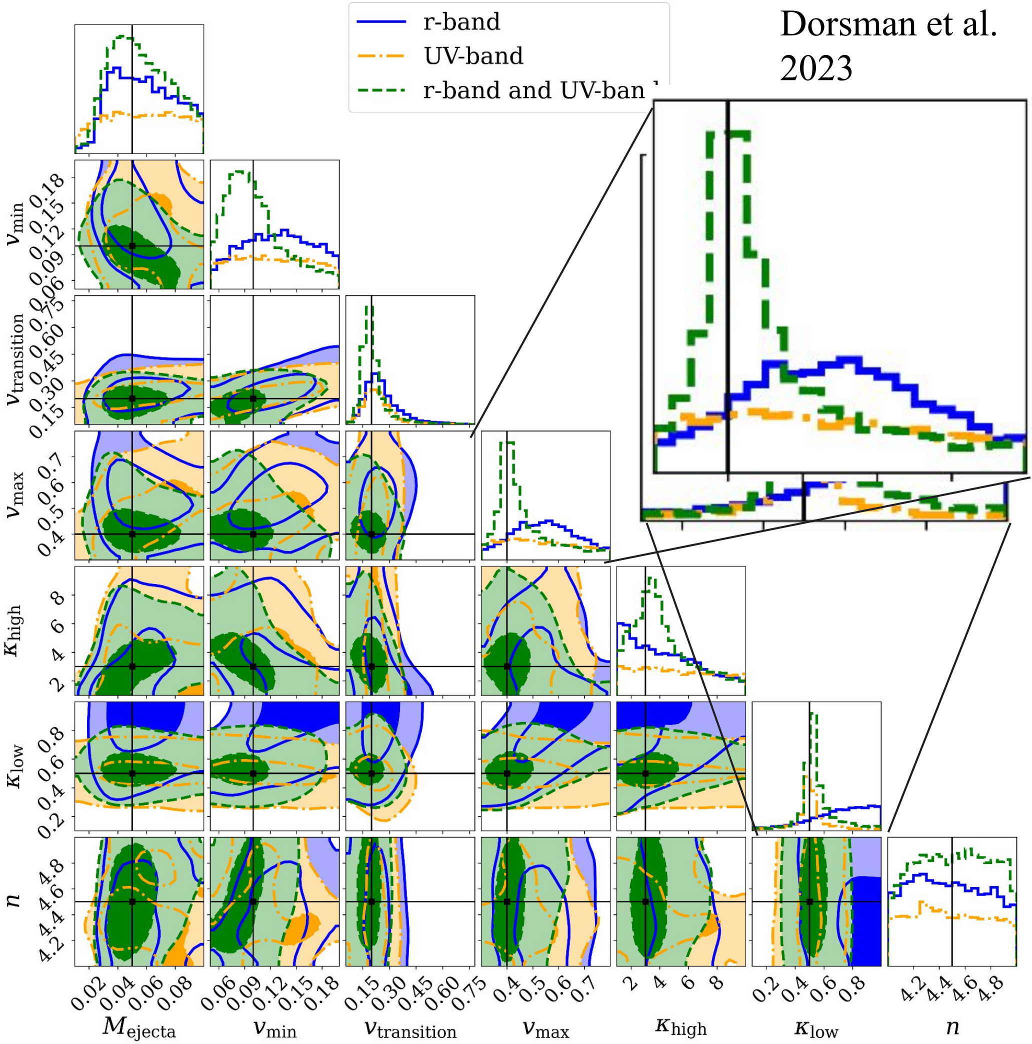

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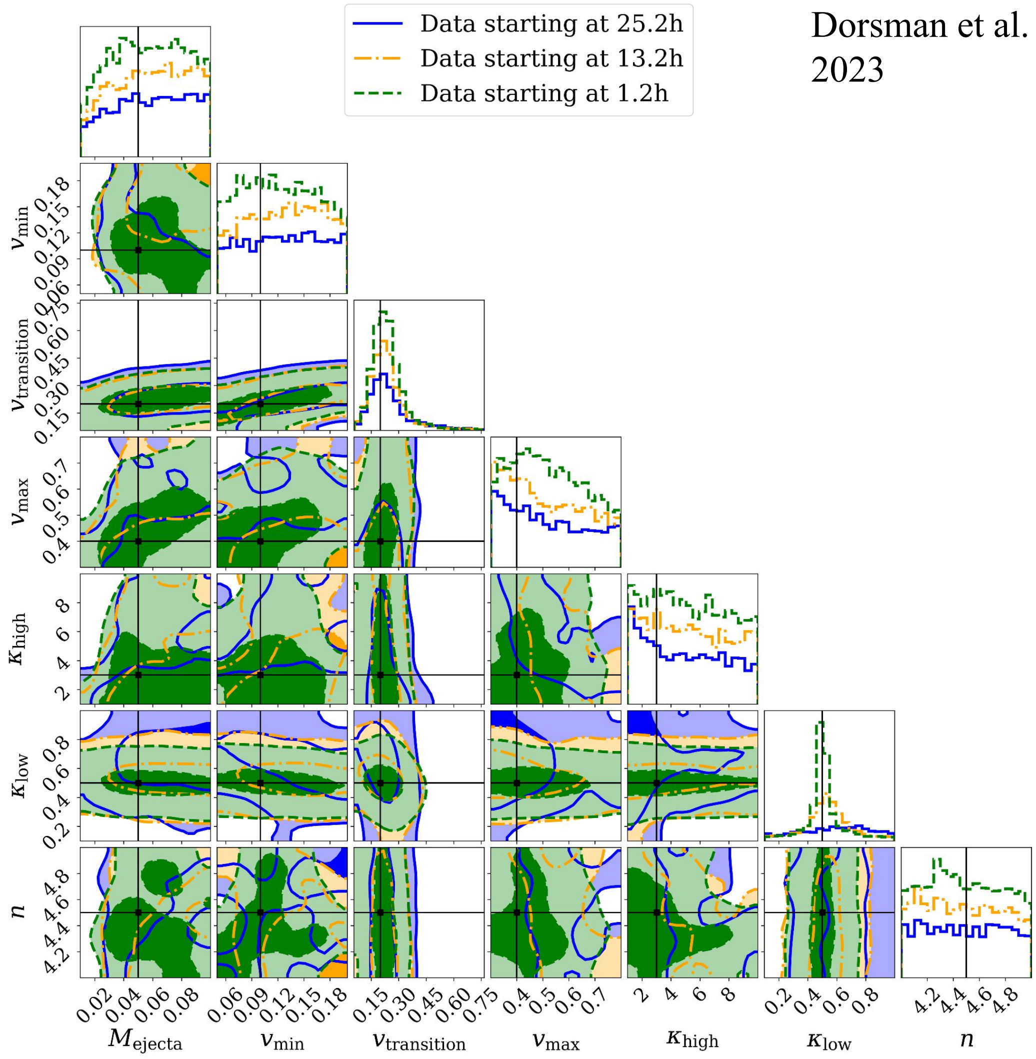
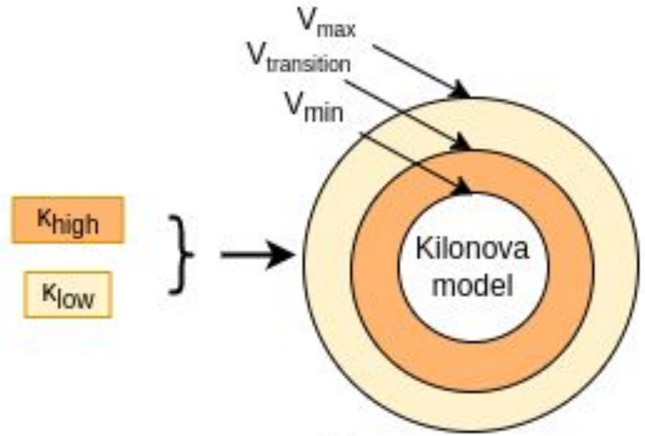
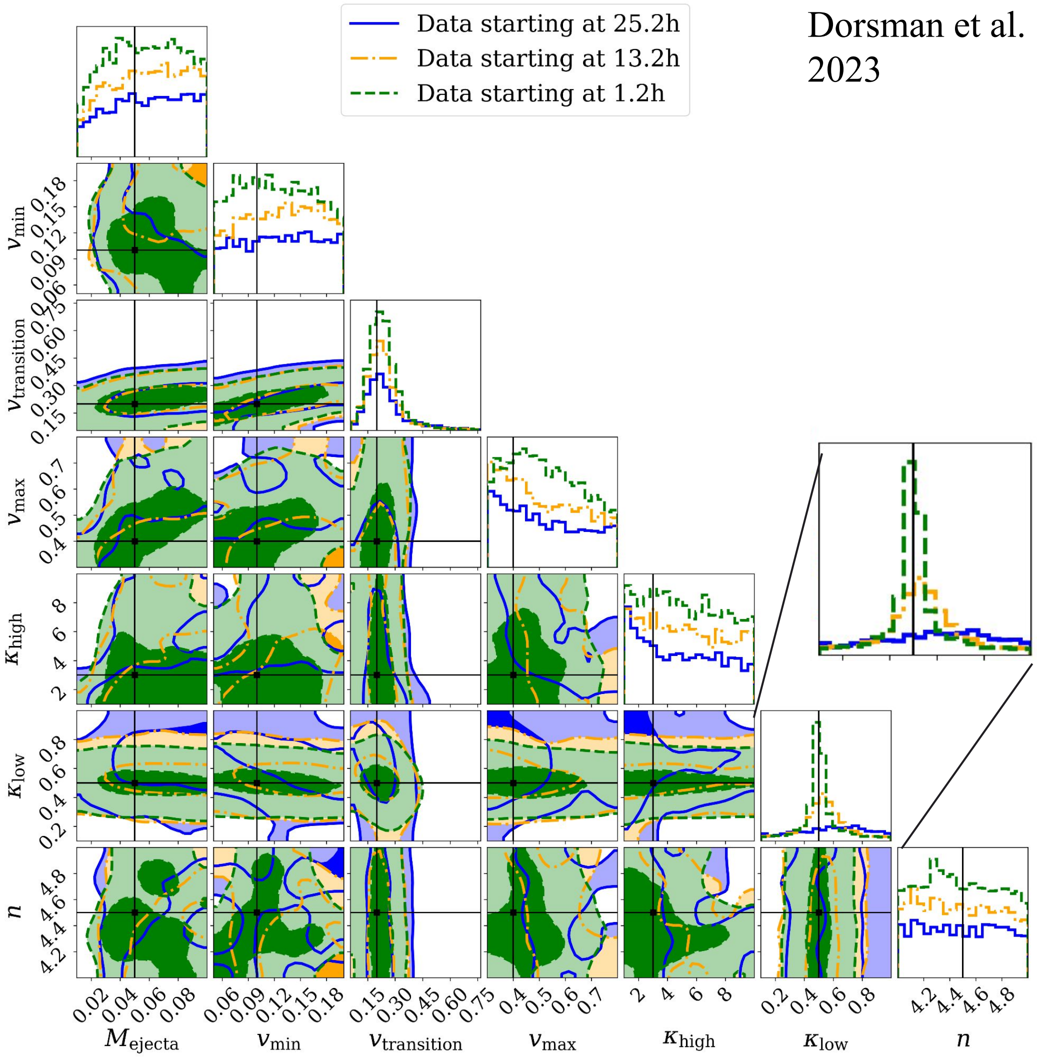
Dorsman et al. 2023



Observation starting time

- k_{low} best constrained for t < 13.2h





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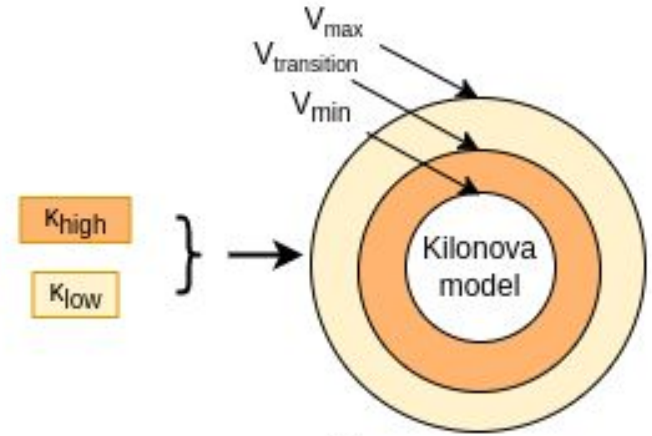
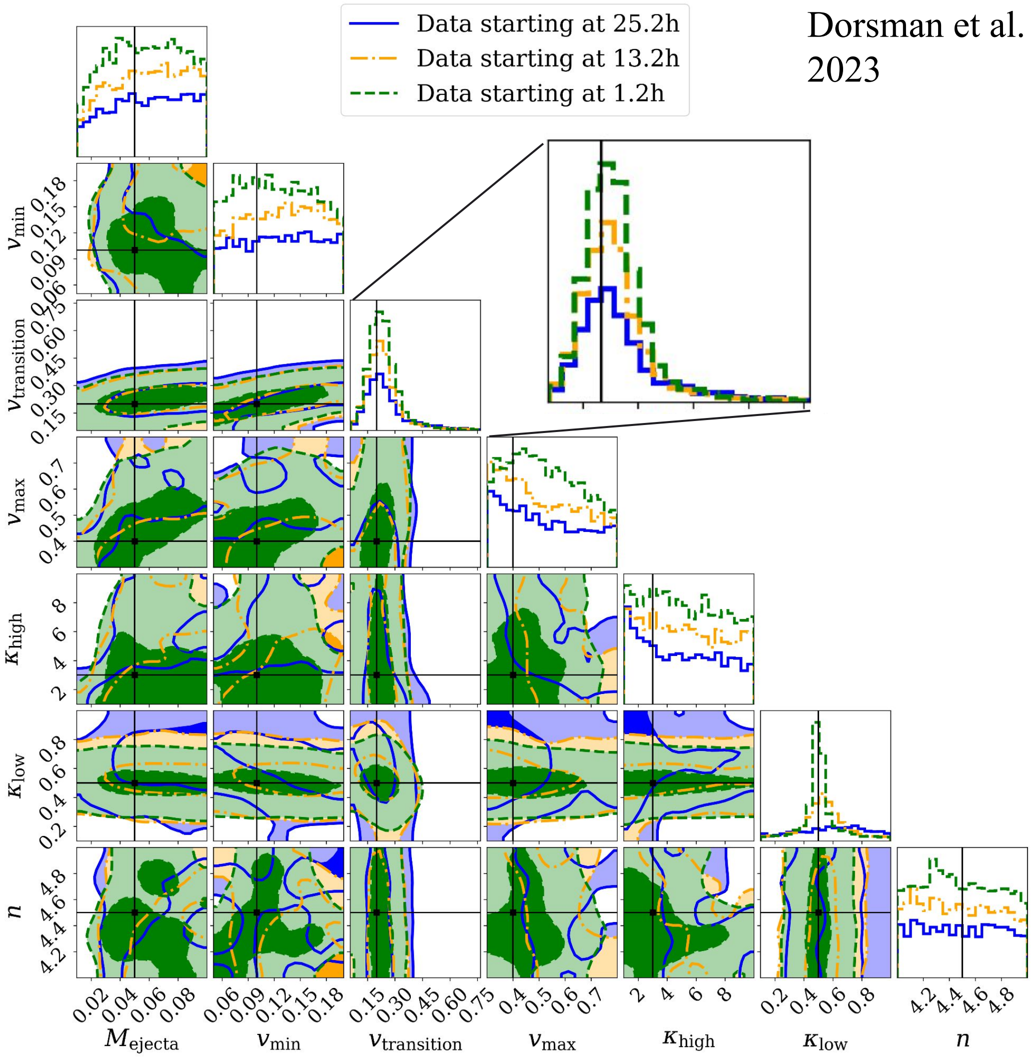
Observation starting time

- k_{low} best constrained for t < 13.2h
- $v_{transition}$ still constrained at t = 25.2h





Dorsman et al. 2023

Discussion

- Simulations biased, assuming AT2017gfo
- Only one event+localization from BNS merger library analyzed
- Different satellites not studied yet (orbit & sensitivity)
- Different light curve models not studied yet (e.g. inclination dependency, free neutron precursor)
    - Redback code by Nikhil Sarin

Conclusions

- UV significant contributor to distinguish for early driving physics
- Start observing within ~3 hours for confident model selection
- Constrain models using multiwavelength observations
- This analysis is limited, but code is open source!

Open source:

- https://github.com/Basdorsman/kilonova-bayesian-analysis
- b.dorsman@uva.nl

Thank you!

Special thanks to:

- Geert Raaijmakers
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- Samaya Nissanke
- Leo Singer
- Mansi Kasliwal
- Tony Piro
- Eric Bellm
- Dieter Hartmann
- Kenta Hotokezaka,
- Kamilė Lukošiūtė
- and whole the *Dorado Team*!

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Extra slides:

Detections since AT2017gfo

- GW -> At2017gfo took 11 hours to detect in optical, 15 hours to detect in UV
- GW -> High confidence NSBH mergers GW200105 and GW200115, no em counterpart found
- Long GRB 211211A maybe kilonova counterpart? (e.g. Rastinejad+ 2022). Multiwavelength lightcurve roughly agrees with AT2017gfo @ 350 Mpc. Maybe NSBH? (Zhu+ 2022) Maybe WDNS? (Yang+ 2022)

We still are eagerly awaiting more smoking gun GW+EM detections!

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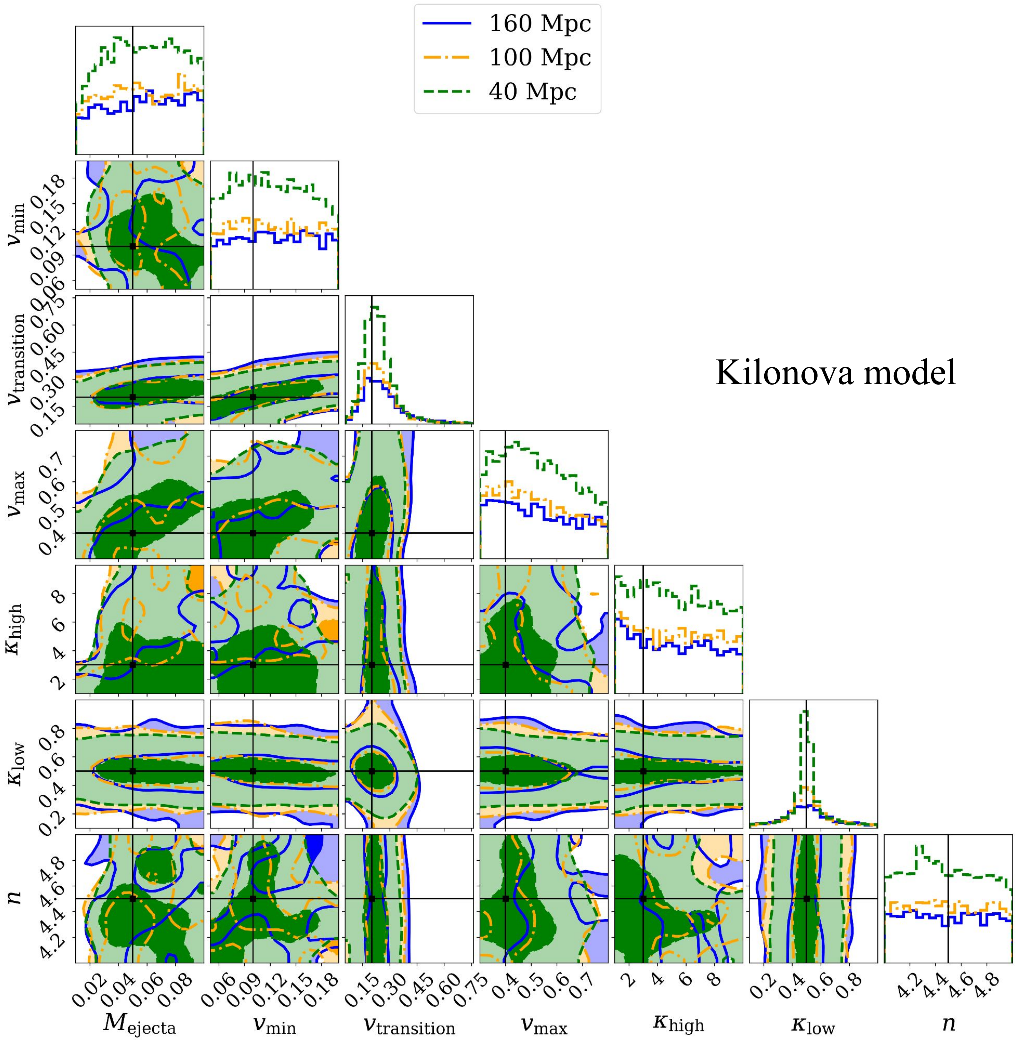
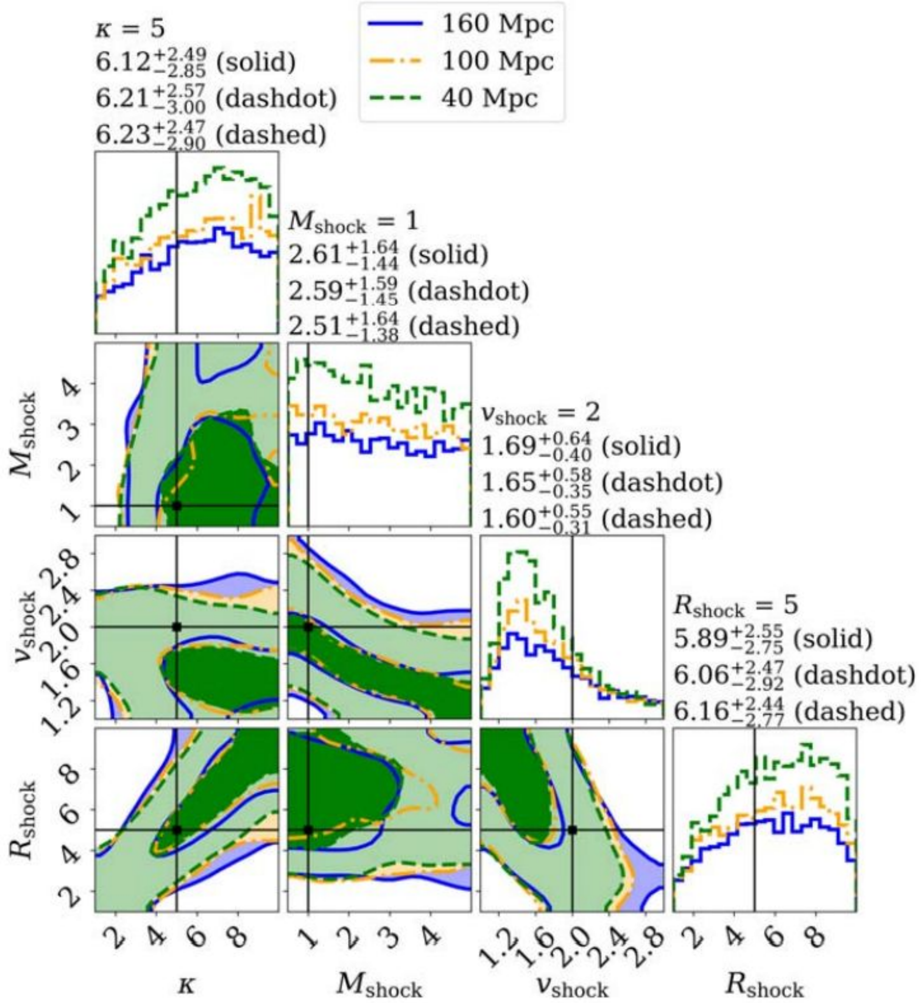
Comparing distances

- No constraints in shock model: contains parameter degeneracies

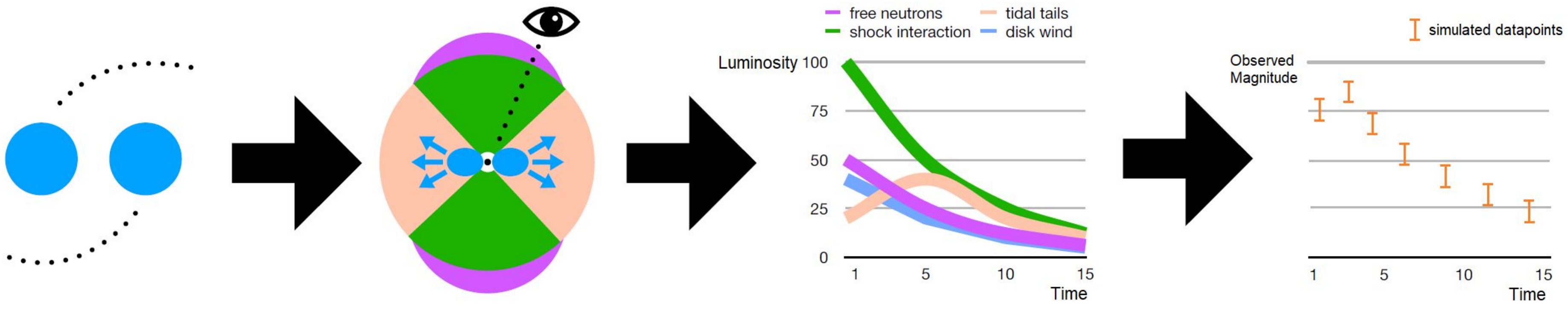
- UV constraints distance dependent in kilonova model



Parameter estimation shock model

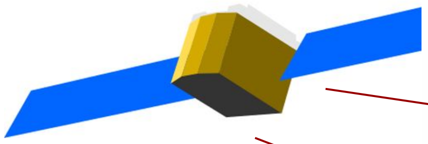


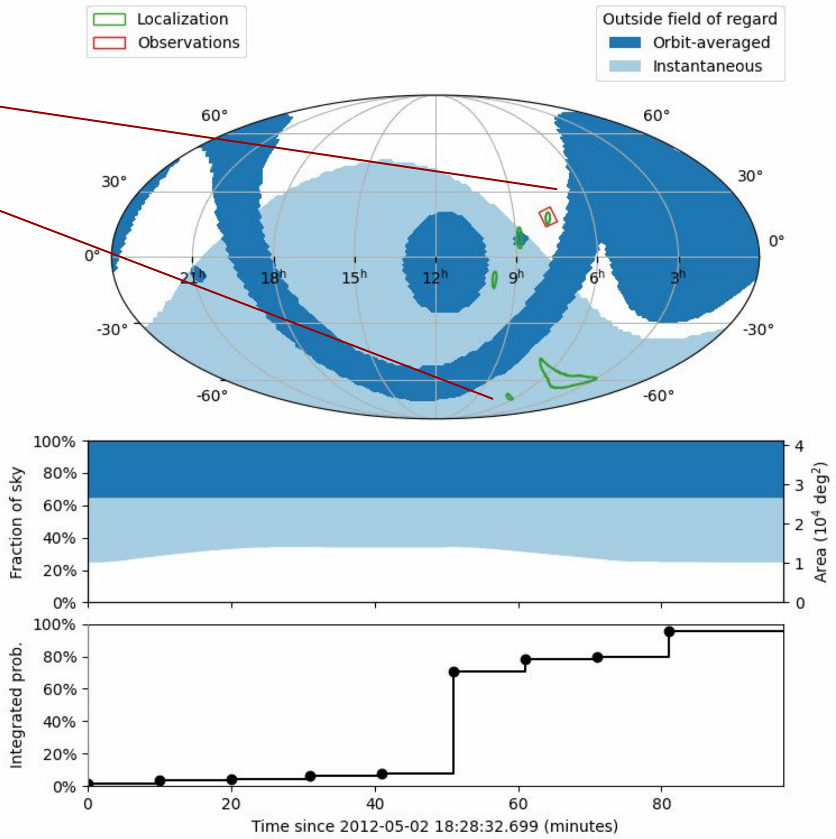
Observation simulation pipeline



Binary parameters	Outflow parameters	Light curve	Photometry
E.g. Masses, spins, distance and inclination angle	E.g. M_{ejecta}, v, κ. (Fitted to numerical simulations)	Kilonova/Shock Interaction models	Error bars, visibility constraints

Simulate Observations





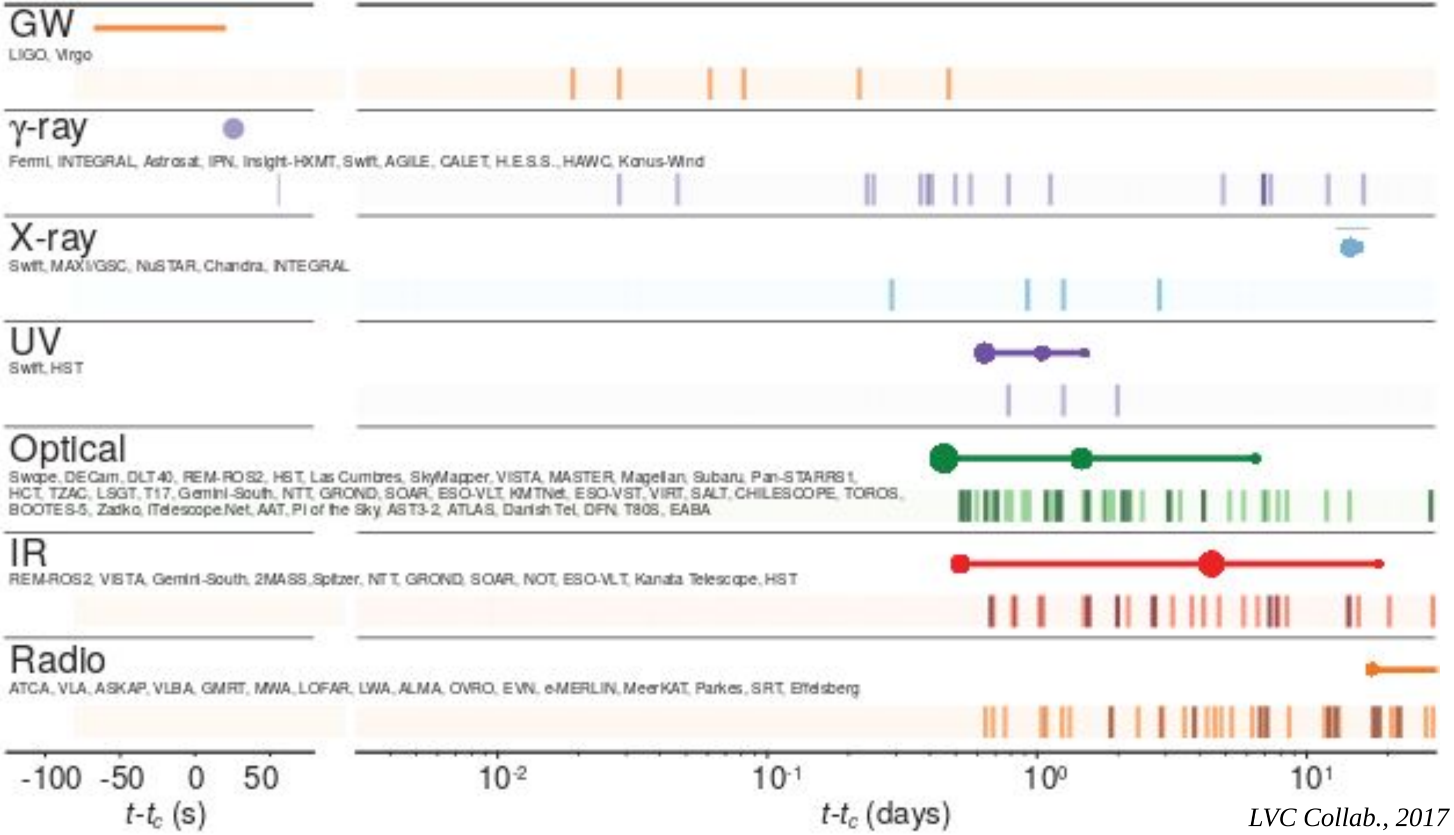
- Simulation of BNS mergers for O5 (Singer et al. 2021)
- Generate optimized observation plan for a representative event

Image sourced from: https://github.com/nasa/dorado-scheduling

Methods

1. Simulation of BNS mergers for O5 (Singer et al. 2021)
2. Generate optimized observation plan (github.com/nasa/dorado-scheduling)
3. Mapping binary parameters to outflow parameters via analytical formulae calibrated to numerical simulations. (Raaijmakers et al. 2019)
4. Kilonova heating rate code (Hotokezaka & Nakar 2020), shock interaction code (Piro & Kollmeier 2018)
5. Simulated photometry (github.com/nasa/dorado-sensitivity)
6. Bayesian analysis (Dorsman et al. 2023)

FIRST Multi-messenger Detection of a BNS merger



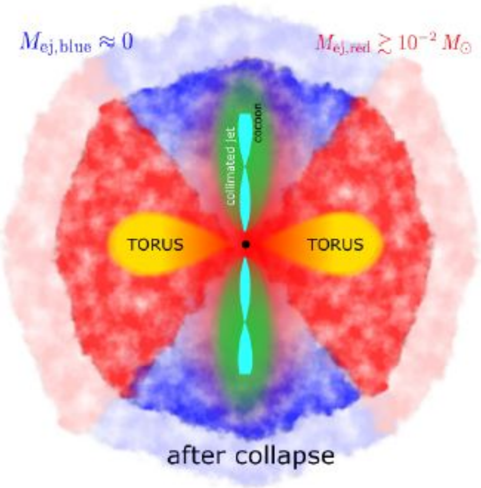
LVC Collab., 2017

Watershed moment, start of GW-multimessenger era for astronomy

Fiducial models and prior distributions

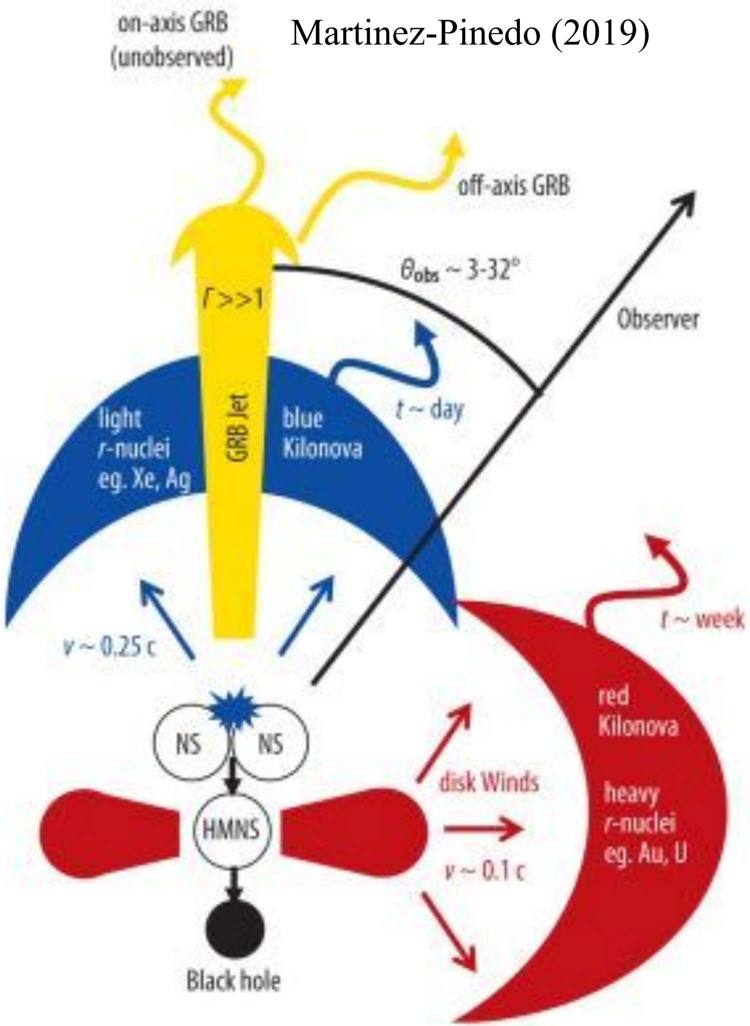
Parameter (Unit)	Description	Prior density	Injected value
	'Default' ['Lower early opacity'] Nucleosynthesis Powered Model		
M_{ej} ($M_\odot$)	Ejecta mass	U(0.01, 0.1)	0.05
v_{min} (c)	Minimum ejecta velocity	U(0.05, 0.2)	0.1
v_{max} (c)	Maximum ejecta velocity	U(0.3, 0.8) [U(0.21, 0.8)]	0.4 [0.23]
n_{ej}	Power law index of ejecta density distribution	U(3.5, 5)	4.5
$v_{transition}$ (c)	Transition velocity between high and low κ	U(v_{min}, v_{max})	0.2
κ_{high} (cm^2/g)	Effective grey opacity for $v \leq v_{transition}$	U(1, 10)	3
κ_{low} (cm^2/g)	Effective grey opacity for $v \geq v_{transition}$	U(0.1, 1) [U(0.01, 0.1)]	0.5 [0.04]
	Shock Interaction Powered Model		
M_{sh} ($M_\odot$)	Shocked ejecta mass	U(0.005, 0.05)	0.01
v_{sh}[c]	Shocked ejecta velocity	U(0.1, 0.3)	0.2
R (10^{10} cm)	Initial shock radius	U(1, 10)	5
κ_{sh} (cm^2/g)	Effective grey opacity of shocked ejecta	U(0.1, 1)	0.5

Extra: GW170817 schema

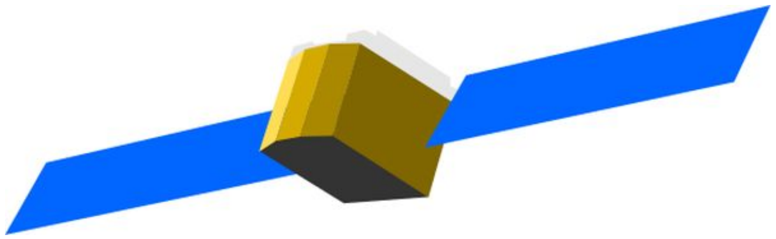


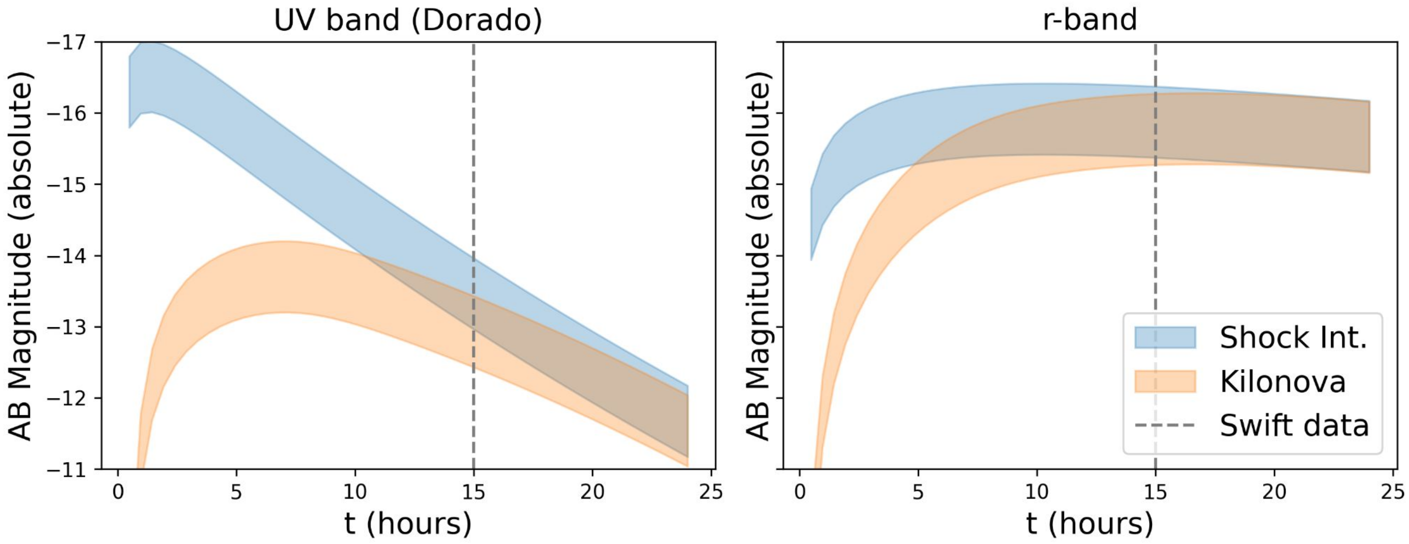
Gill+ (2019)

Martinez-Pinedo (2019)



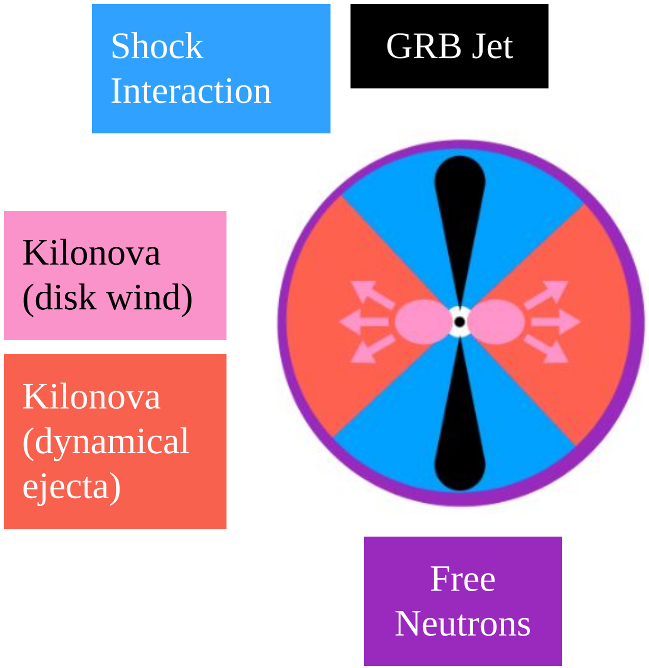
Extra: Dorado



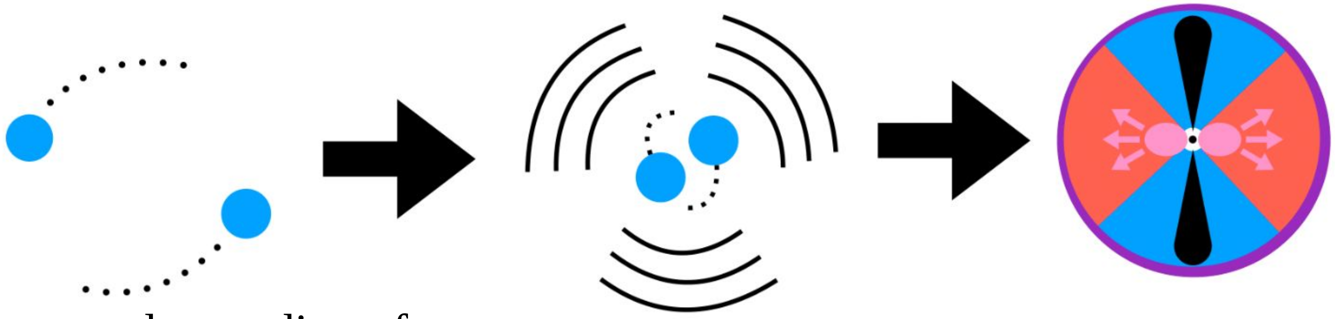


Kilonovae and other EM signatures of BNS mergers

1. Kilonova:
    - (Quasi) Isotropic Radiation powered by radioactive decay from elements produced via r-process (Li & Paczyński 1998)
2. Other EM counterparts:
    - GRB jet (e.g. Catz & Canel 1996, Dokuchaev& Eroshenko 1996)
    - Radiating shock heated ejecta (e.g. Kasliwal+ 2017)
    - Free neutron precursor (Metzger 2015)



Binary neutron star mergers, what are they good for?



Test our understanding of:

- GR strong gravity regime
- GRB jet physics
- Expansion history of the Universe
- Stellar & BH Population
- Binary evolution
- Heavy element formation
- NS EoS

***"Einstein's richest laboratory"* - Baiotti & Rezzolla (2017)**

Bayesian Analysis: Model Selection (1)

- Two models, M_A and M_B:

$$\text{Prior ratio} = \frac{P(M_A)}{P(M_B)}$$

- Default prior: 50/50.
- Probability ratio is *updated* by the Bayes' factor:

$$\text{Posterior ratio} = \mathcal{B}_B^A \frac{P(M_A)}{P(M_B)} = \frac{P(M_A|D)}{P(M_B|D)}$$

Bayes' factor tells us how new data updates probability