Astrophysics with joint analysis of multi-messenger observations

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7th KAGRA International Workshop

Institute for Gravitational Research

Academics


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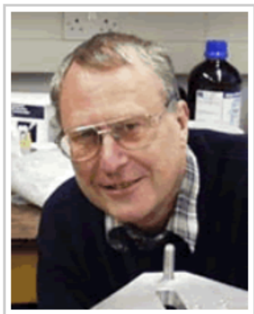
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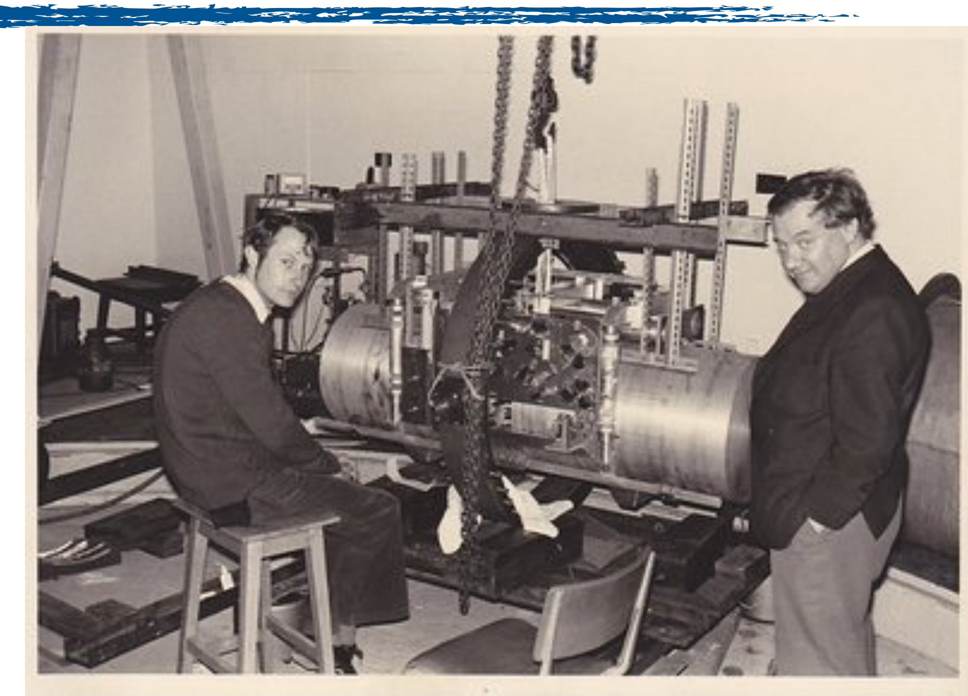
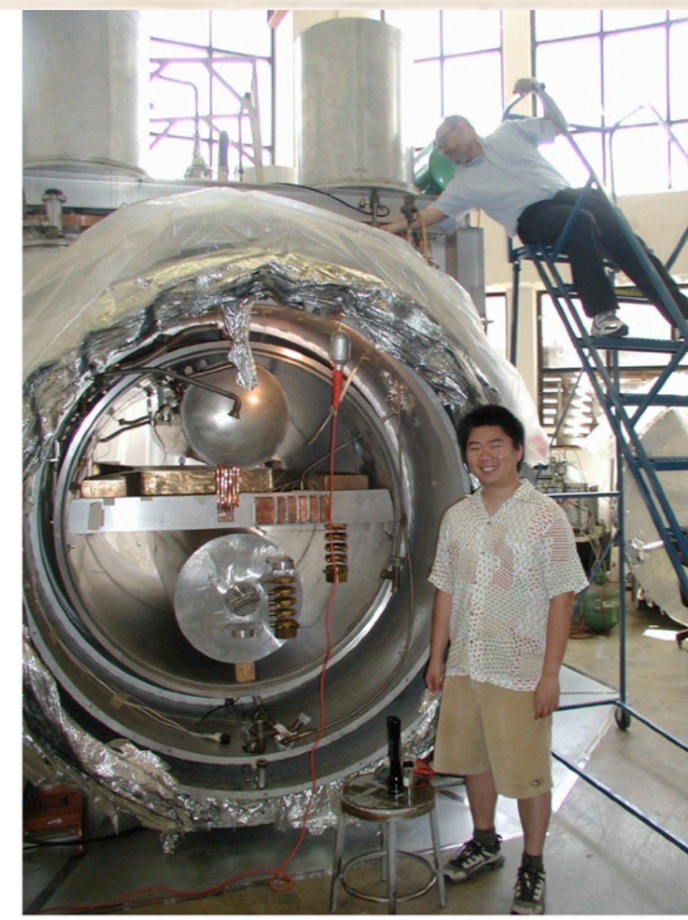


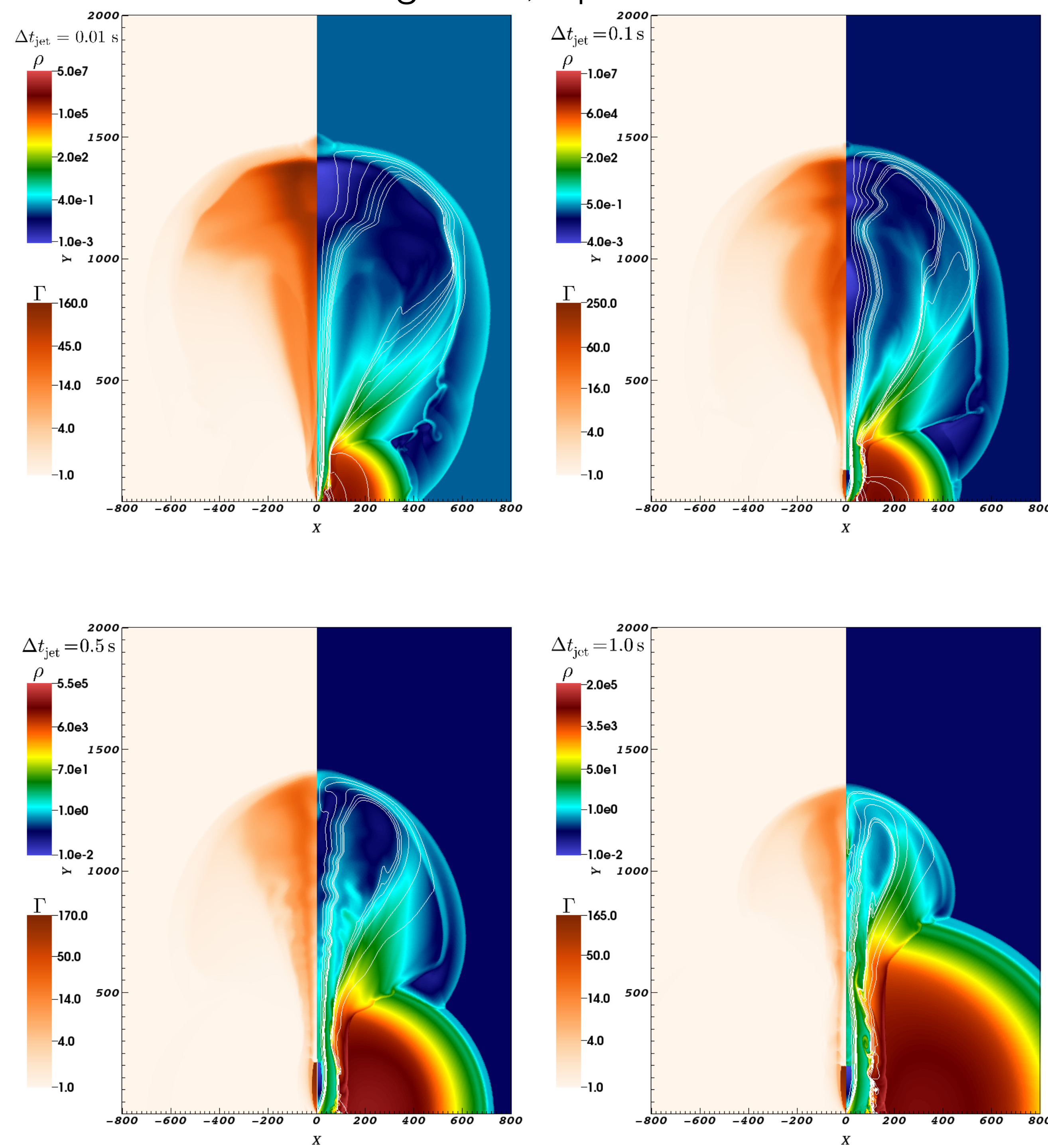


- The Institute for Gravitational Research (IGR) consist of over 70 members: 13 academic staff, ~20 postdocs/research fellows, ~40 PhD students plus support staff

Outline

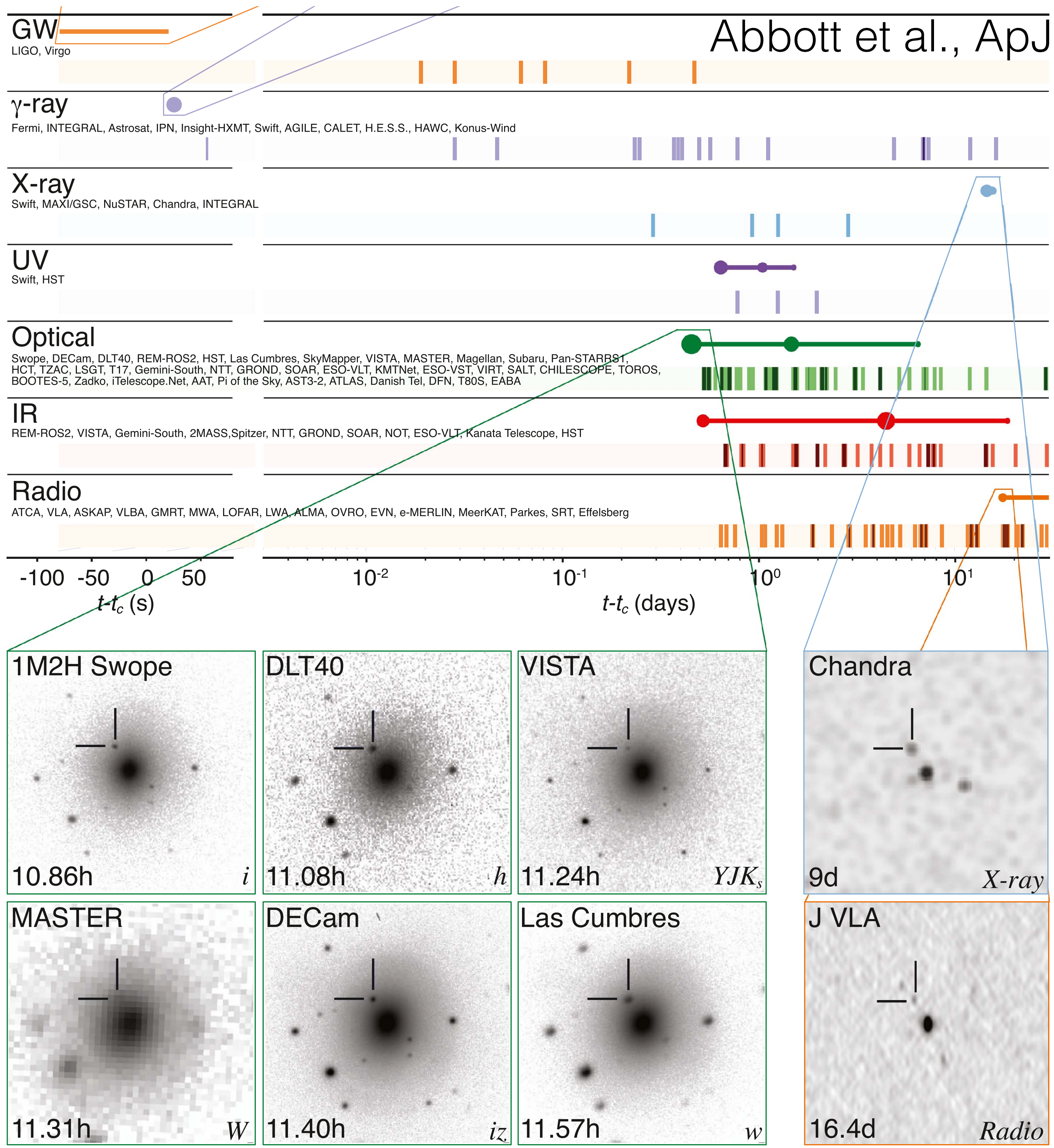
- Brief introduction
- Short gamma-ray burst (sGRB) jet structure inference via joint analysis with gravitational wave observations
- Inferring kilonova parameters including BNS merger time
- Additional collaborations presented in talks by
  - En-Tzu Lin: X-ray afterglow joint analysis
  - Surojit Saha: autoencoders for kilonova light curves

Geng et al., ApJL 2019



Multi-messenger astronomy with GW170818

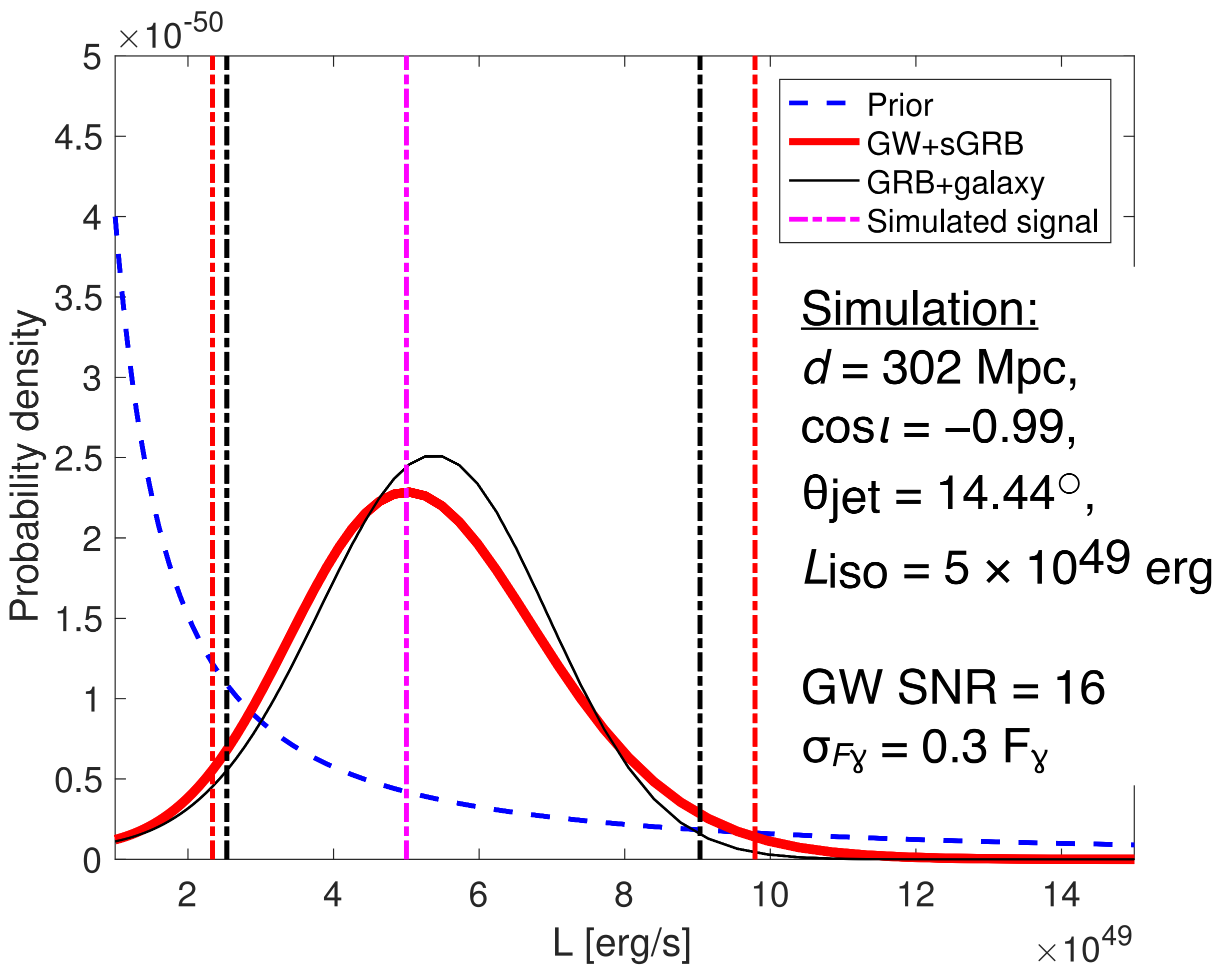
Abbott et al., ApJL 848(1) 2017



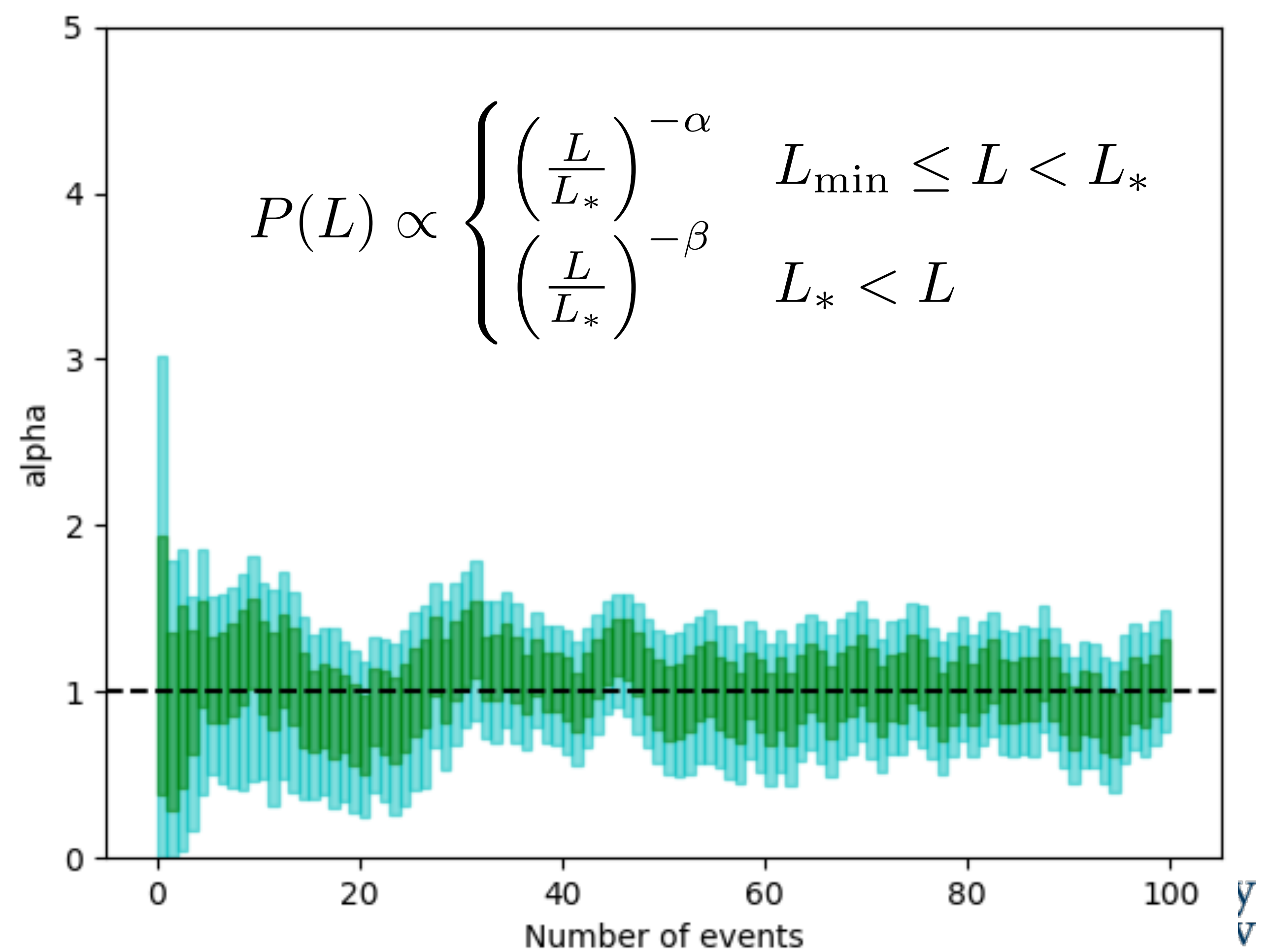
Joint GW-GRB inference

- We previously showed that, for joint short GRB-BNS detection, we can obtain the short GRB intrinsic luminosity using GW information: Fan, Messenger & Heng PRL (2017) arXiv:1706.05639
- We have also demonstrated that the short GRB luminosity function can be accurately determined from a population of joint short GRB-GW observations of BNS mergers

Fan, Messenger & Heng PRL (2017) arXiv:1706.05639

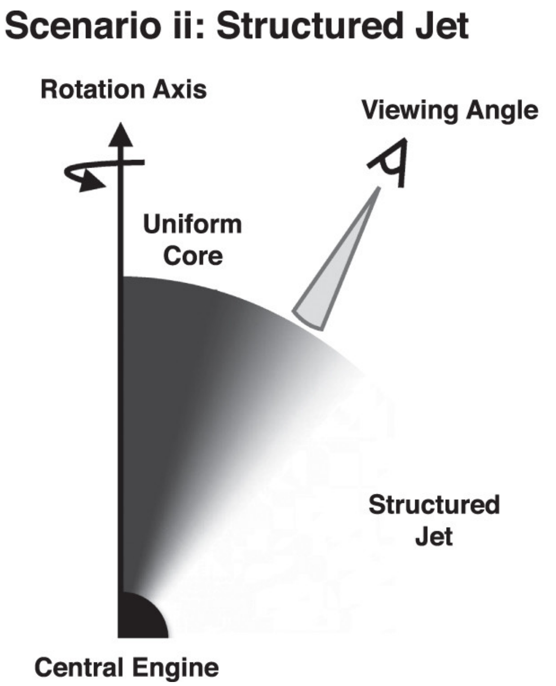


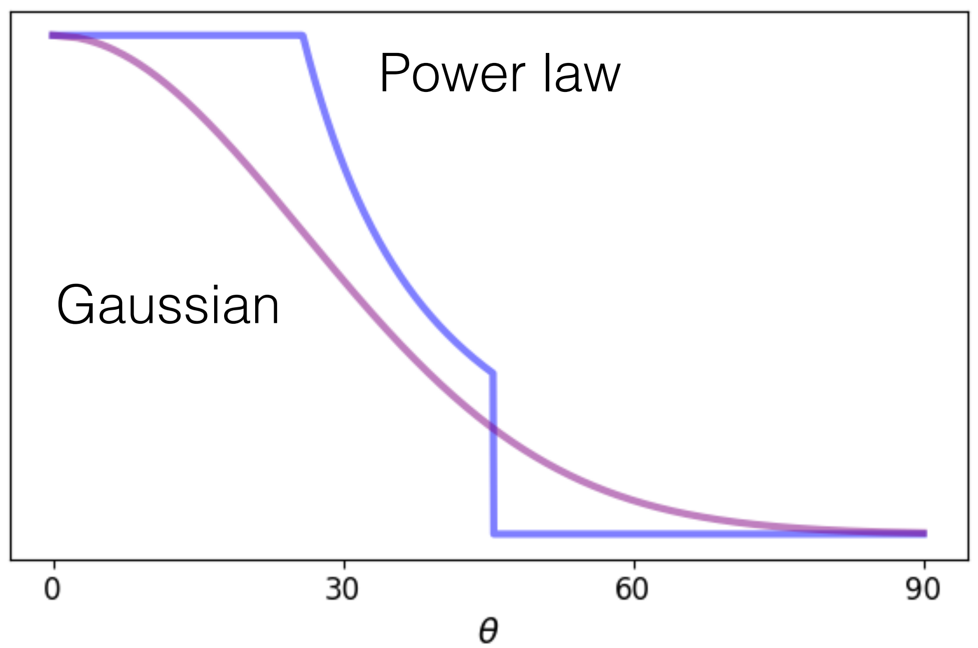
C. McIsaac et al, in prep



Inferring sGRB jet structure

- We can combine the information from population of GW observations of BNS with the corresponding GRB observation to see to investigate the GRB jet structure
- To demonstrate this, we consider two **observed** structured jet models:
  - Gaussian jet (GL)
  - Power law (PL)
- We simulate a BNS merger population and draw their corresponding GRB luminosities based on the assumed jet structure model
- Details of hierarchal Bayesian analysis in F. Hayes *et al.*, ApJ 891 (2020)



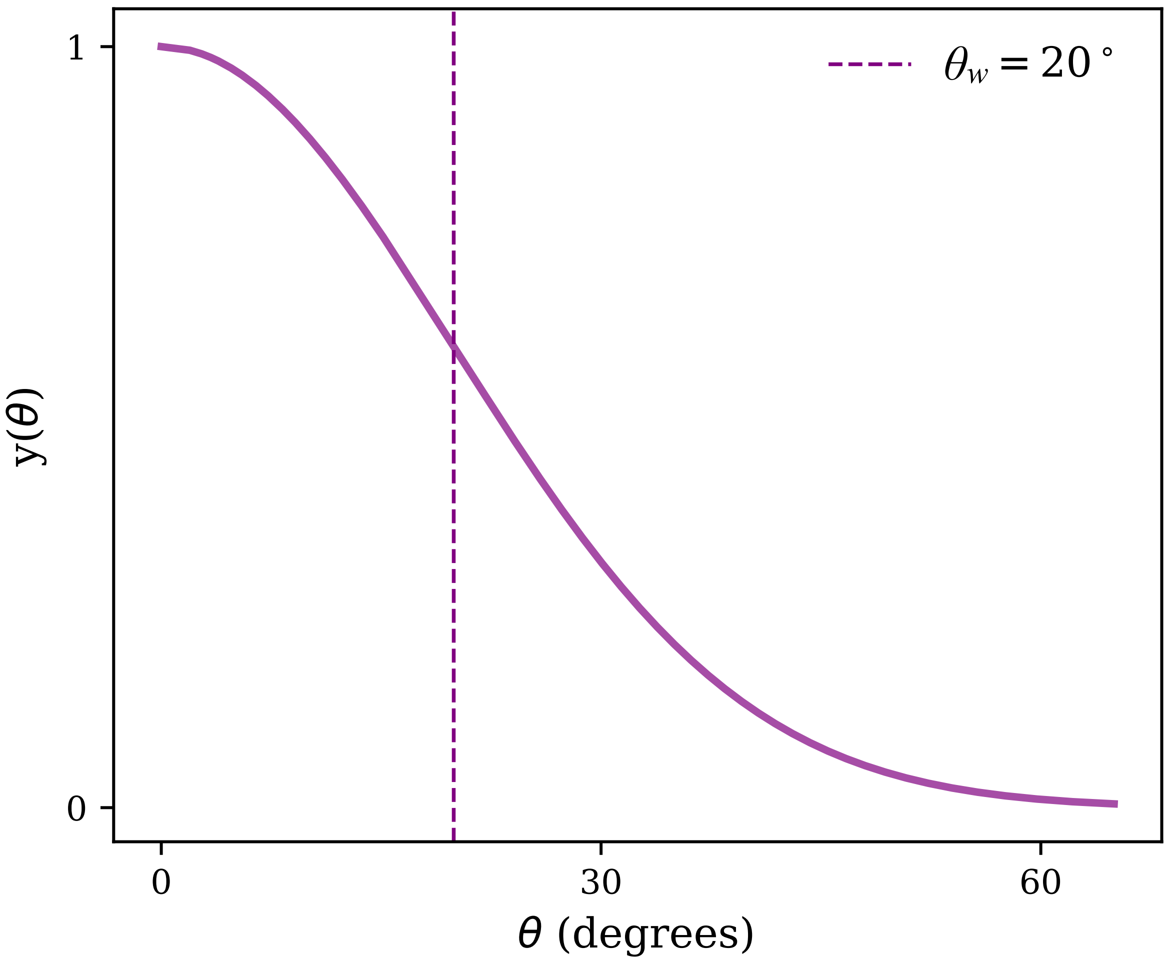


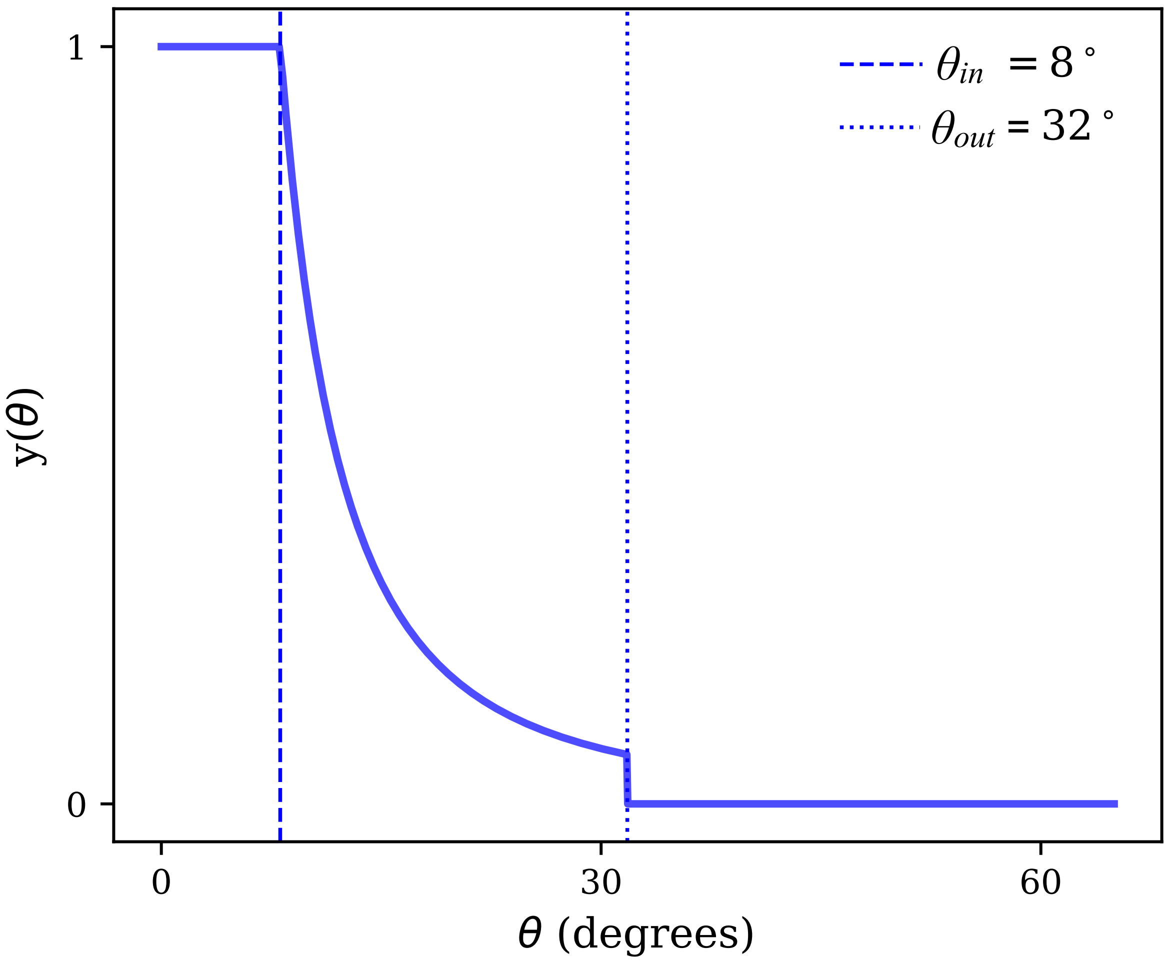
Jet structure models

$$y(\theta) = e^{-\frac{1}{2}\left(\frac{\theta}{\theta_w}\right)^2}$$

$$y(\theta) = \begin{cases} 1 & \text{if } 0 \le \theta \le \theta_{in}, \\ \left(\frac{\theta}{\theta_{in}}\right)^{-k} & \text{if } \theta_{in} < \theta \le \theta_{out}, \\ 0 & \text{if } \theta_{out} < \theta. \end{cases}$$

Fix $k = 2$ for this analysis.





Bayesian model selection

- Bayes' theorem where for desired model, M_A, and some observational data, D, we have

$$\overbrace{p(M_A|D,I)}^{\text{posterior}} = \frac{\overbrace{p(D|M_A,I)}^{\text{likelihood}} \times \overbrace{p(M_A|I)}^{\text{prior}}}{\underbrace{p(D|I)}_{\text{evidence}}}$$

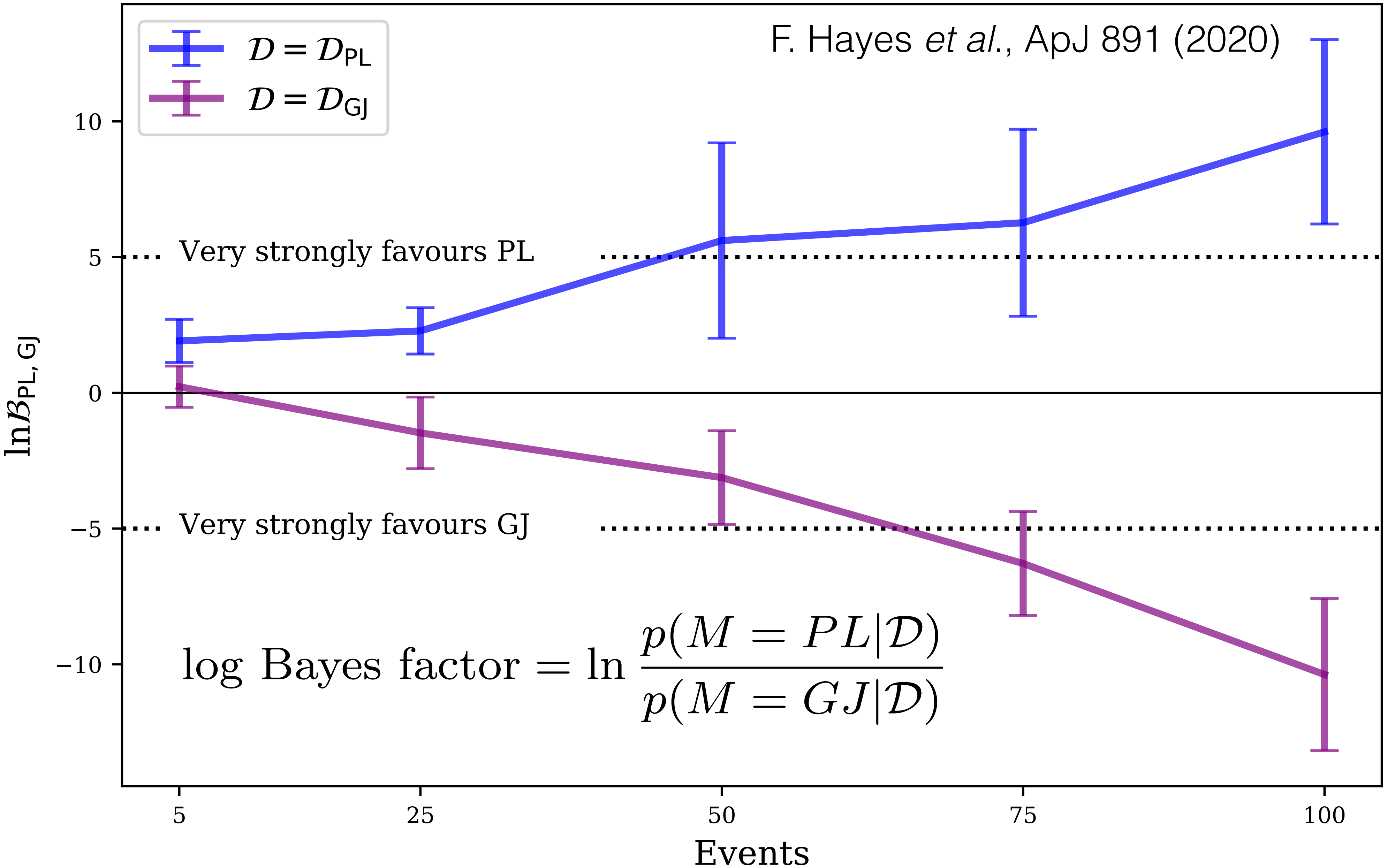
- The posterior probability represents the state of our knowledge of the model ("the truth") in light of our observed data
- If we have a competing model or hypothesis, we use the ratio of the posterior probabilities for each model

$$\frac{p(M_A|D,I)}{p(M_B|D,I)} = \underbrace{\boxed{\frac{p(M_A|I)}{p(M_B|I)}}}_{\text{prior odds}} \times \underbrace{\boxed{\frac{p(D|M_A,I)}{p(D|M_B,I)}}}_{\text{Bayes factor}}$$

- If Bayes factor > 1, M_A is preferred. If Bayes factor < 1, M_B is preferred

Model comparison

- We calculate the Bayes factor for two datasets, each with 100 BNS detections
  - Dataset D_{GJ} - universe of sGRBs with Gaussian jet structures
  - Dataset D_{PL} - universe of sGRBs with power-law jet structures



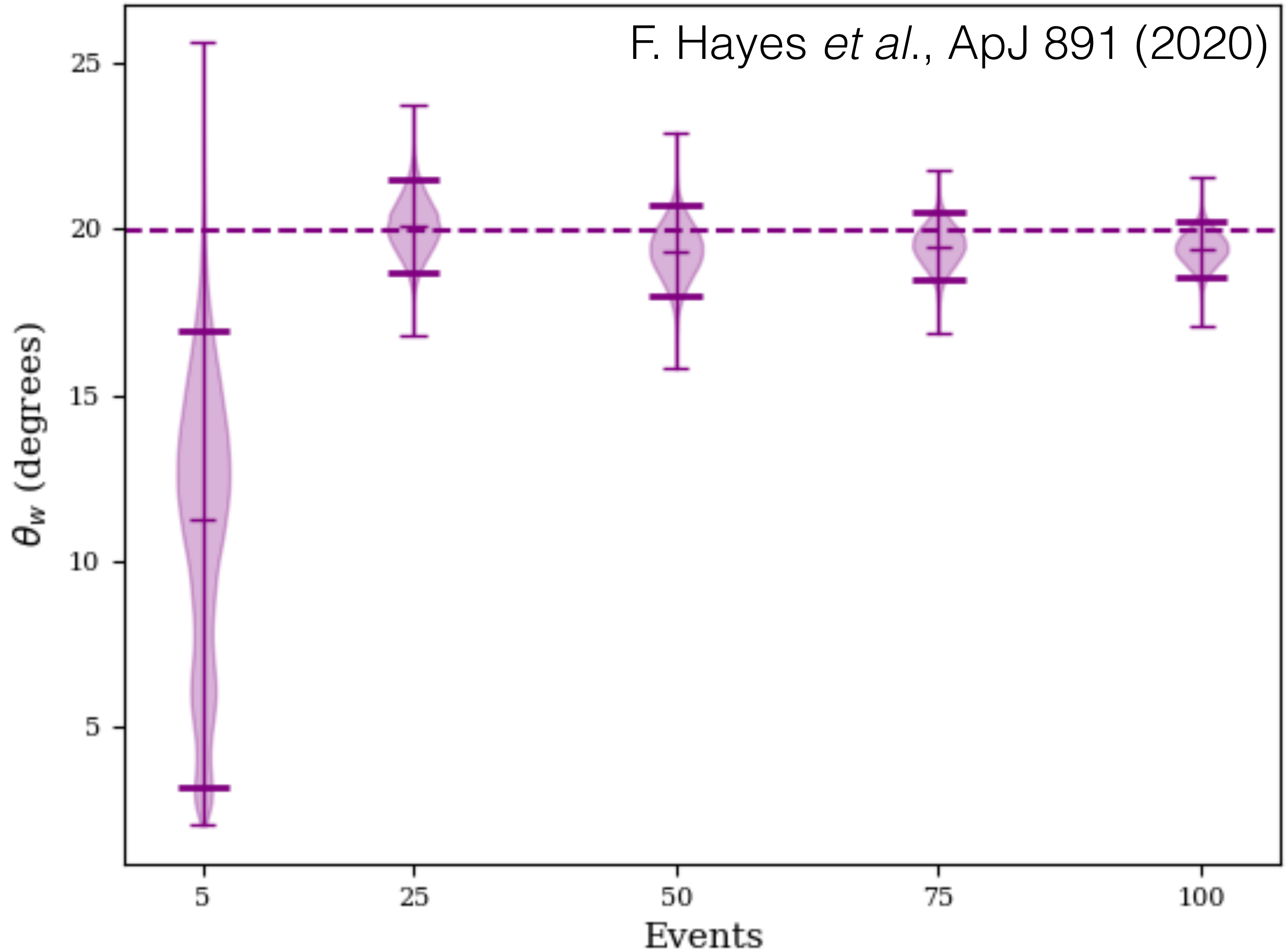
$$\text{log Bayes factor} = \ln \frac{p(M = PL|\mathcal{D})}{p(M = GJ|\mathcal{D})}$$

Events = BNS detections where sGRB observations were also possible but sGRB detection not necessary

Parameter estimation

- We can also estimate the jet structure parameters using the correct model

$$p(\theta_M|\mathbf{f},\mathbf{h}) \propto \prod_{i=1}^{N}\left[\int \overbrace{\mathcal{L}(f^i,h^i|\theta_v^i,r^i,y,\epsilon_0^i,\theta_M)}^{likelihood}\overbrace{p(\theta_M)p(\epsilon_0^i)}^{priors}\,d\epsilon_0^i\right]$$



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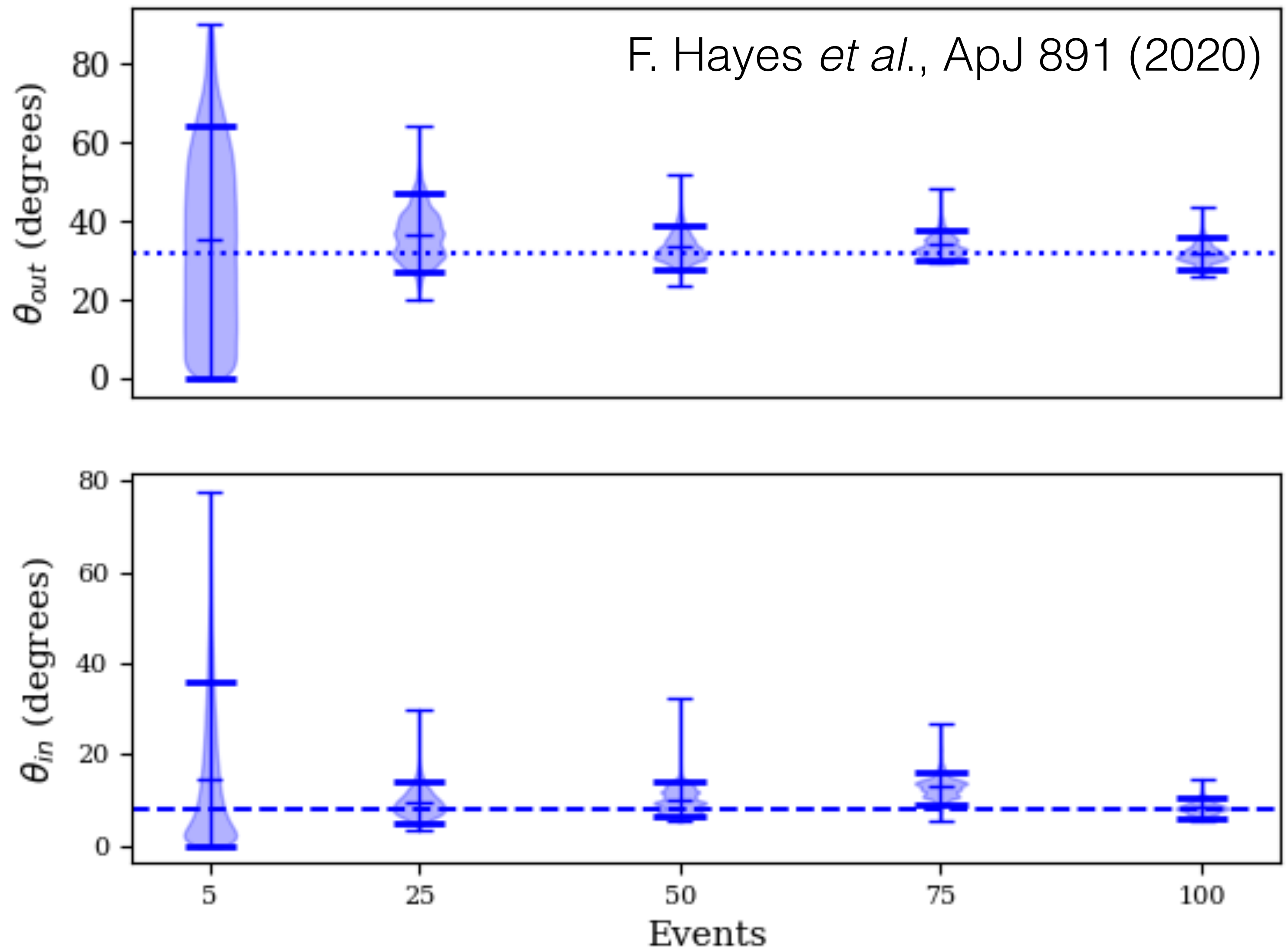


Events = BNS detections where sGRB observations were also possible but sGRB detection not necessary

Rates-based inference

- Gravitational wave observations have provided us with an estimate of the rate of BNS and NSBH mergers.
- Can we combine these rates with the rate of sGRBs to learn about the jet structure?
  - Selection effects are included when calculating BNS and NSBH rates from GW observations
  - Selection effects for sGRB rate are a little tricky since it is also a function of the jet structure
- Previous work assuming top-hat jets: Williams *et al*., ApJ 858 (2018)
- For structured jets, we base our analysis on the formalism laid out by K. Mogushi *et al*., ApJ 880 (2019)
- We construct a likelihood which is a Poisson distribution with the number of observed sGRBs, N_{obs}, as the distribution mean
- Aim to evaluate Bayes factor comparing different jet structure models; can also obtain jet structure model parameters

Rates-based inference

- The number of observed sGRBs is related to a redshift dependant sGRB rate $R_{GRB}(z)$ by

$$N_{\rm obs}(\theta_M) = T\hat{F}R_0 \int_0^{z_{\rm max}} \int_{-1}^{1} \int_{L_{\rm th}(\theta_M, z, \cos\theta)}^{\infty} \frac{R_{\rm GRB}(z)}{1+z} \frac{dV(z)}{dz} \mathcal{N}(L) dz d(\cos\theta) dL$$

- The effect of the jet structure enters via a luminosity threshold used to determine detection

$$L_{\rm th}(\theta_M, z, \cos\theta) = 4\pi d_L(z) k(z) F_{\rm min} \frac{y_{M,0}}{y_M(\theta)}$$

- Also,

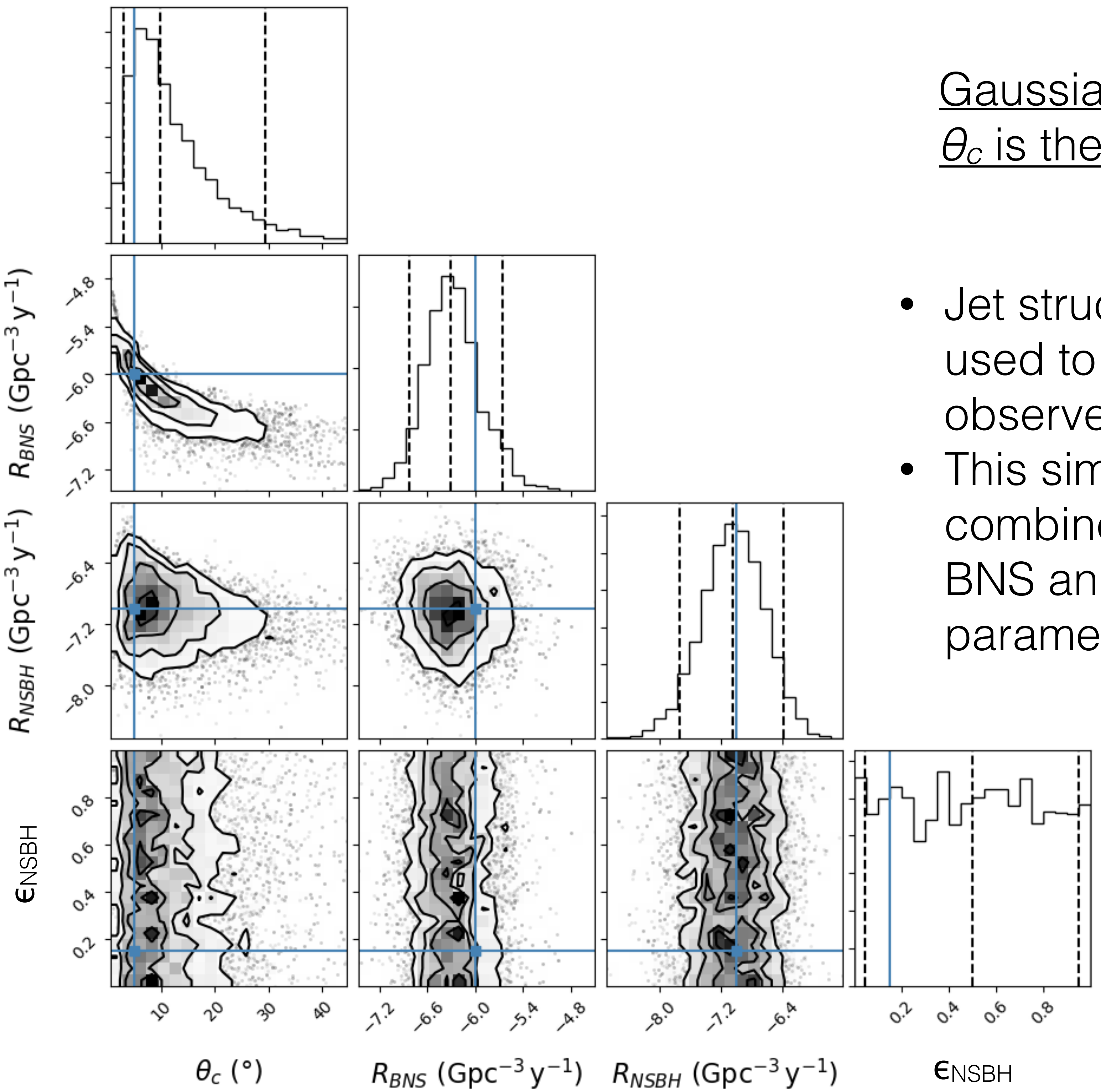
$$R_0 = \epsilon_{\rm BNS} R_{\rm BNS} + \epsilon_{\rm NSBH} R_{\rm NSBH}$$

- where ϵ_{BNS} is fraction of BNS mergers that produce a GRB and similarly for eNSBH
  - assume ϵ_{BNS} = 1, ϵ_{NSBH} is unknown (typically 0.1-0.3)
- BNS/NSBH rates taken from GWTC-1

$N(z,\cos\theta,L)$: sGRB number density
z: redshift
θ: viewing angle
L: intrinsic luminosity
L_{th}: luminosity threshold
$R_{GRB}(z)$: normailised sGRB rate where $R_{GRB}(0) = 1$
R_0: sGRB rate at $z = 0$
T: observation duration
$\hat{F}$: time-averaged detector response
V: redshift volume
$y_M(\theta)$: jet structure for model M
yM,0:
θ_M: jet structure model parameters
d_L: luminosity distance
k: k-correction factor
F_{min}: minimum flux required for detection

Rates-based inference

- Test case with simulated number of observed sGRBs for validation

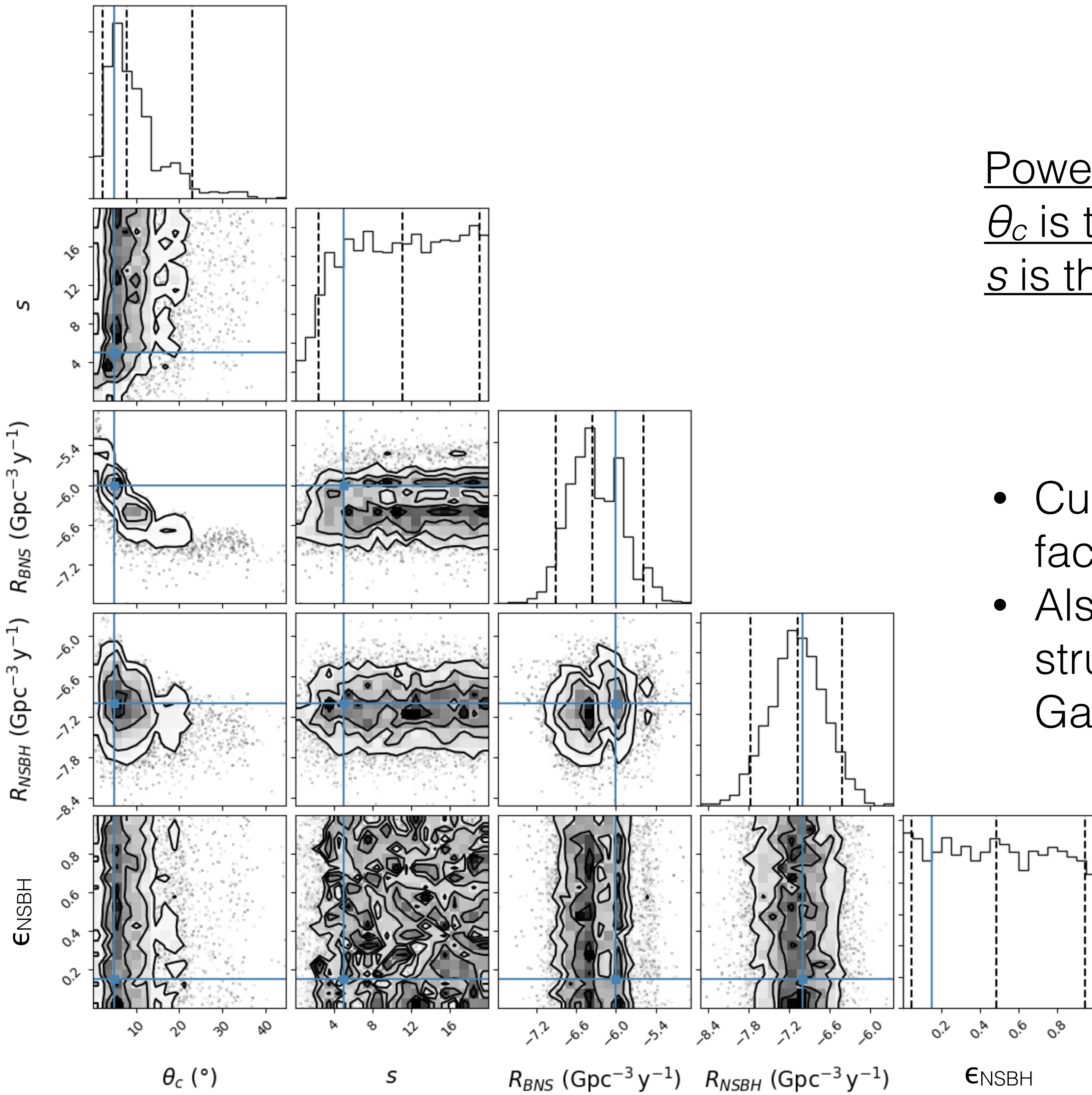


<u>Gaussian jet structure where θ_c is the width of the gaussian</u>

- Jet structure function and rates used to simulate the number of observed sGRBs
- This simulated value is combined with GW priors on BNS and NSBH rates to obtain parameter posteriors

Rates-based inference

- Test case with simulated number of observed sGRBs for validation



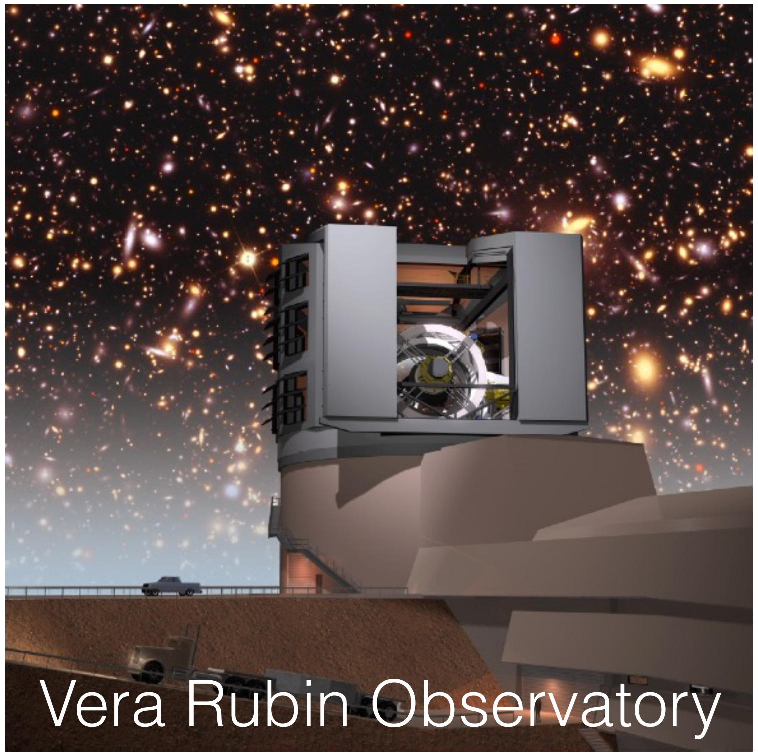
Power law jet structure where θ_c is the width of the core and s is the slope of the power law

- Currently calculating Bayes factors for model comparison
- Also considering other jet structure models (double Gaussian)

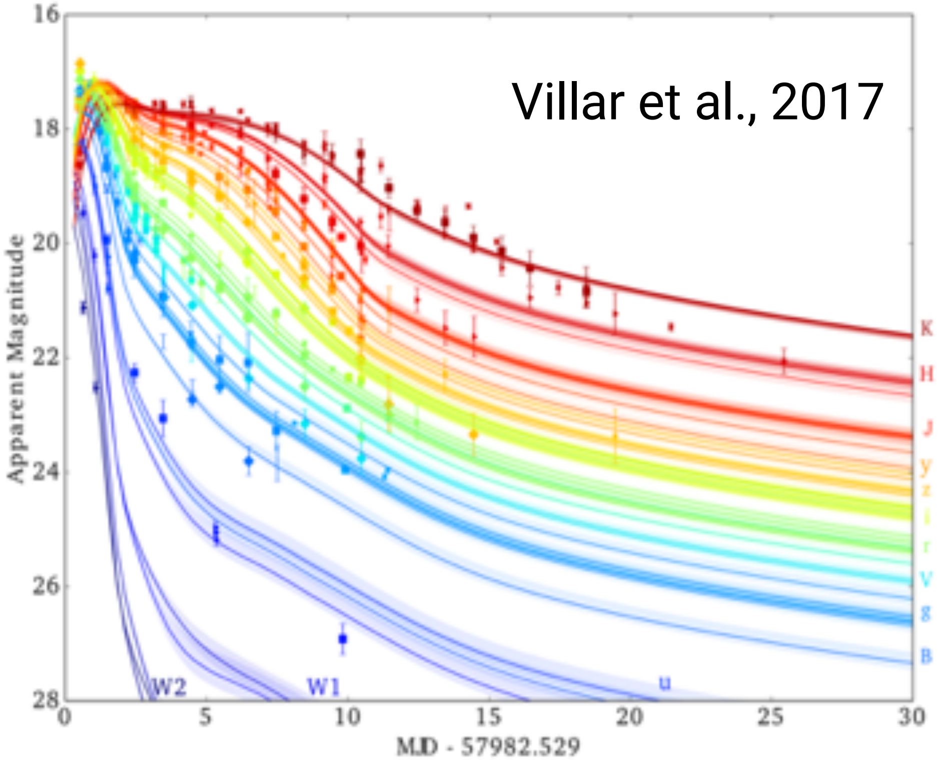
Kilonovae

- We expect a number of BNS to be subthreshold (edge-on) or single detector events - an associated EM counterpart could confirm one of these detections as an event.
- We expect a number of untriggered kilonova detections associated with such subthreshold or one detector events. (Setzer *et al.*, 2019)
- Depth and field of view of LSST searches make it ideal for serendipitous kilonova discoveries

L. Datrier *et al.*, in prep.

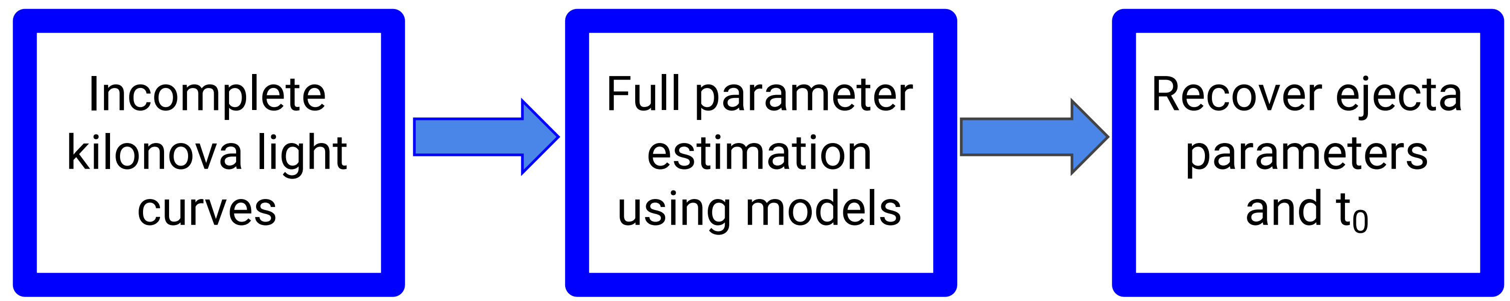


credit: lsst.org



Methdology

- We use the 2017 Kasen models to simulated observed light curves, and try to recover model parameters for varying cadences
- Two components (red, blue) with 3 ejecta parameters each:
  - Ejecta velocity
  - Ejecta mass
  - Lanthanide fraction

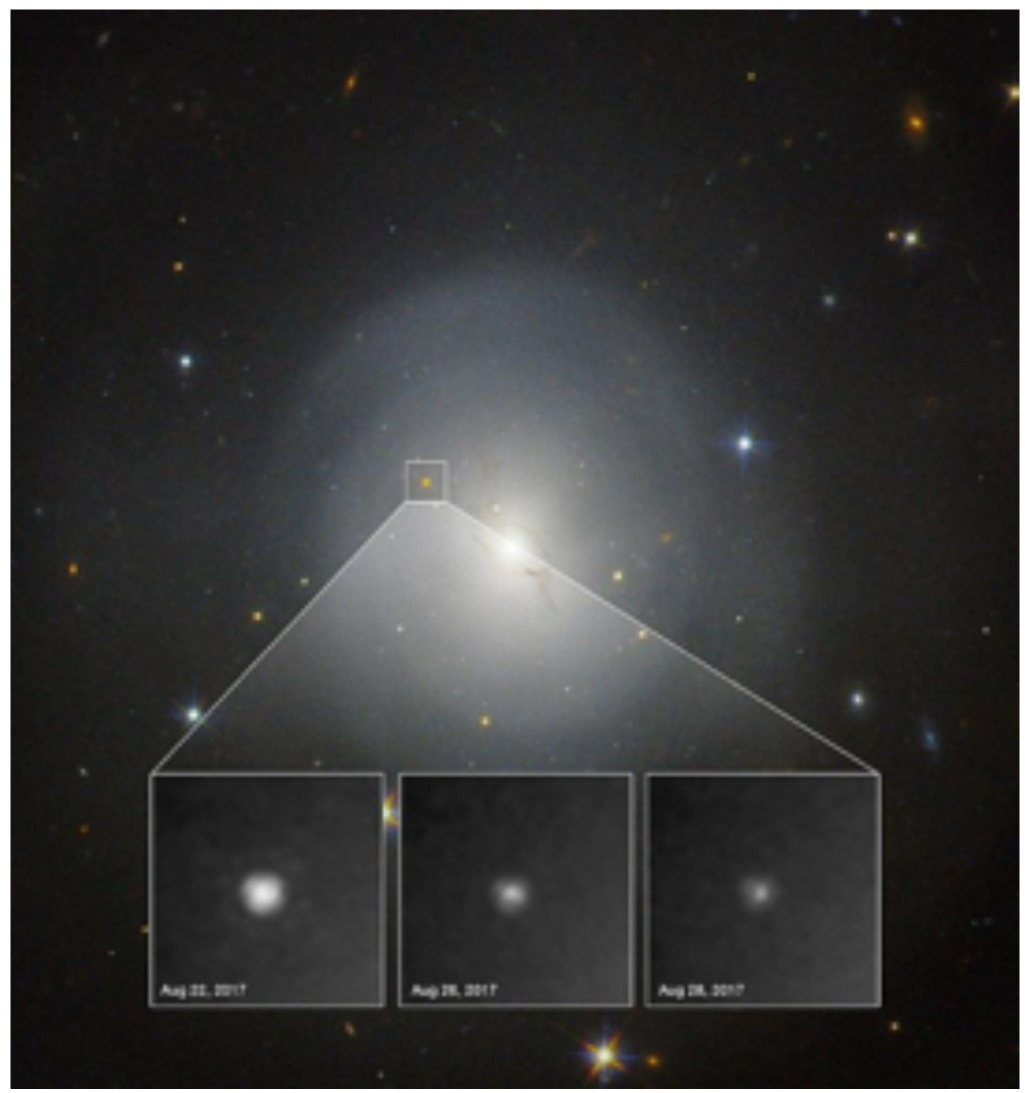


L. Datrier *et al.*, in prep.

- 1 magnitude uncertainty on models
- Models on evaluated on a grid - expanded with Gaussian Process Regression.
- Simulate apparent magnitude for different types of kilonovae from time resolved spectra, focusing at g,r,i bands
- Use LSST single exposure magnitude limits to determine when light curve is no longer detectable
- Consider different cadences and observing start times (time of first observation in days most-merger)

Test with AT2017gfo

- Full parameter estimation on truncated AT 2017 gfo light curves for g,r,i DECam data.
- Start of observations t = 1.45 days after merger
- Recovered t = $1.21^{+1.14}_{-0.82}$ days



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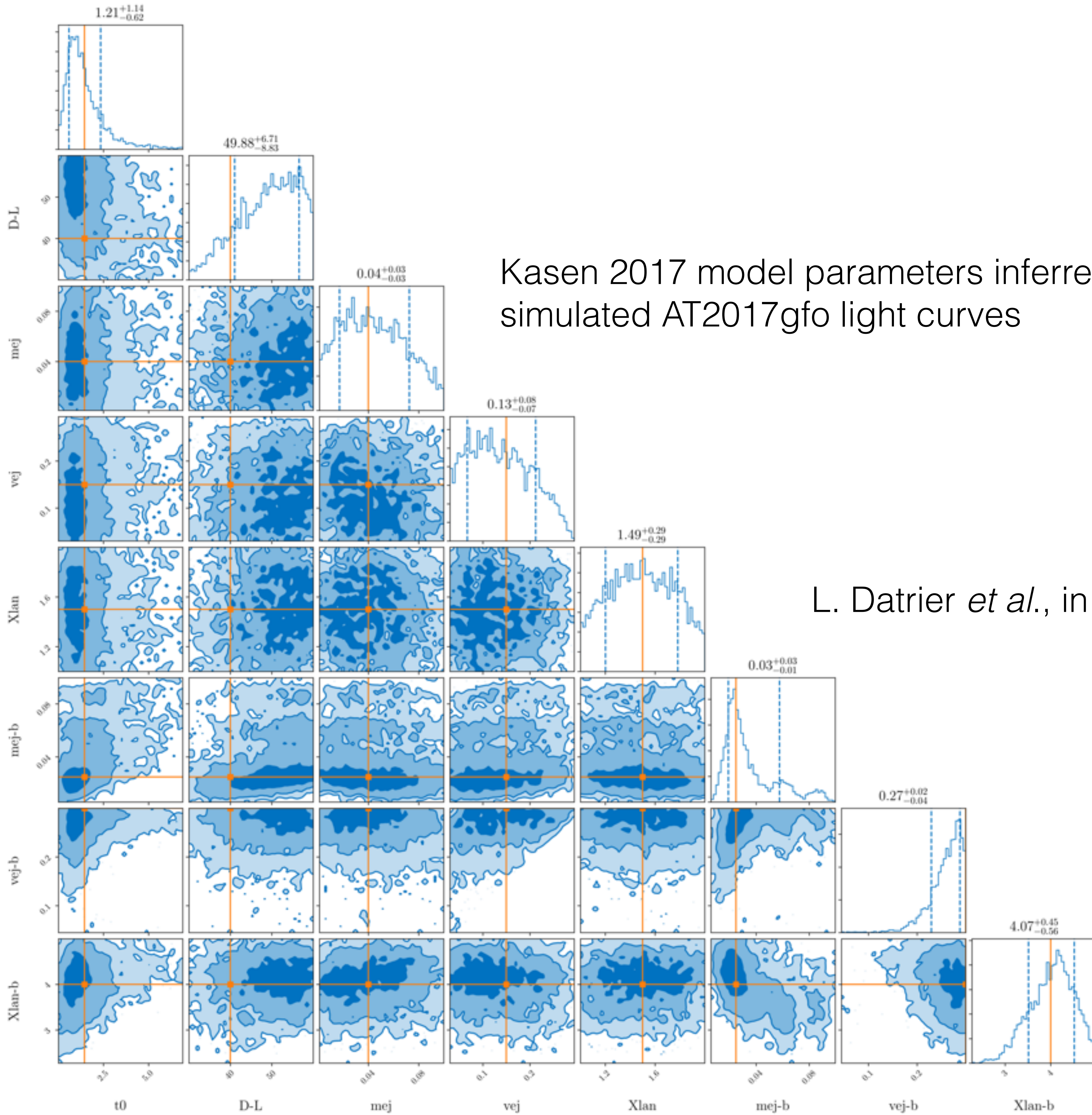

Kasen 2017 model parameters inferred from simulated AT2017gfo light curves

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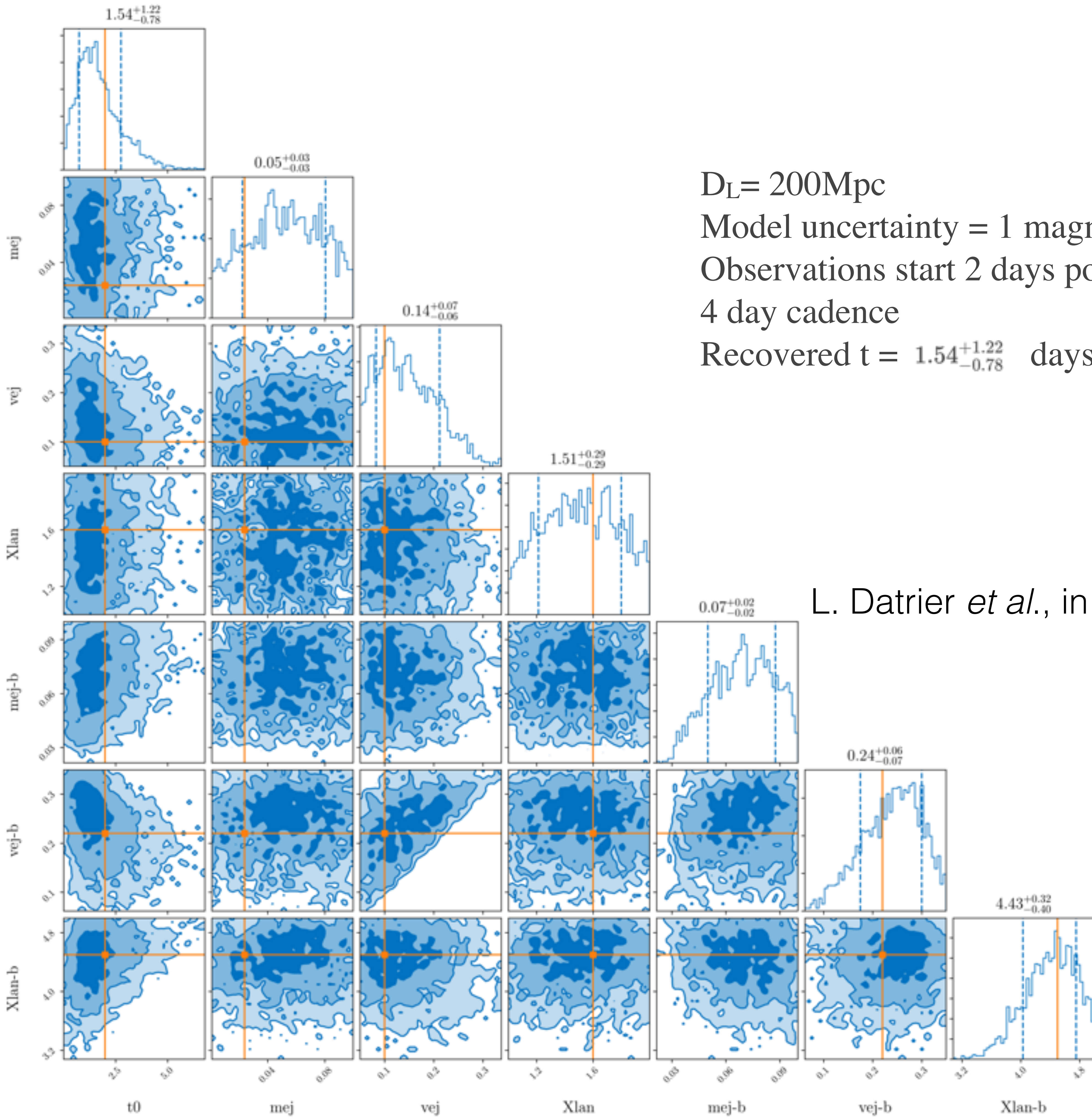

D_L= 200Mpc
Model uncertainty = 1 magnitude
Observations start 2 days post merger (t_0)
4 day cadence
Recovered t = $1.54^{+1.22}_{-0.78}$ days

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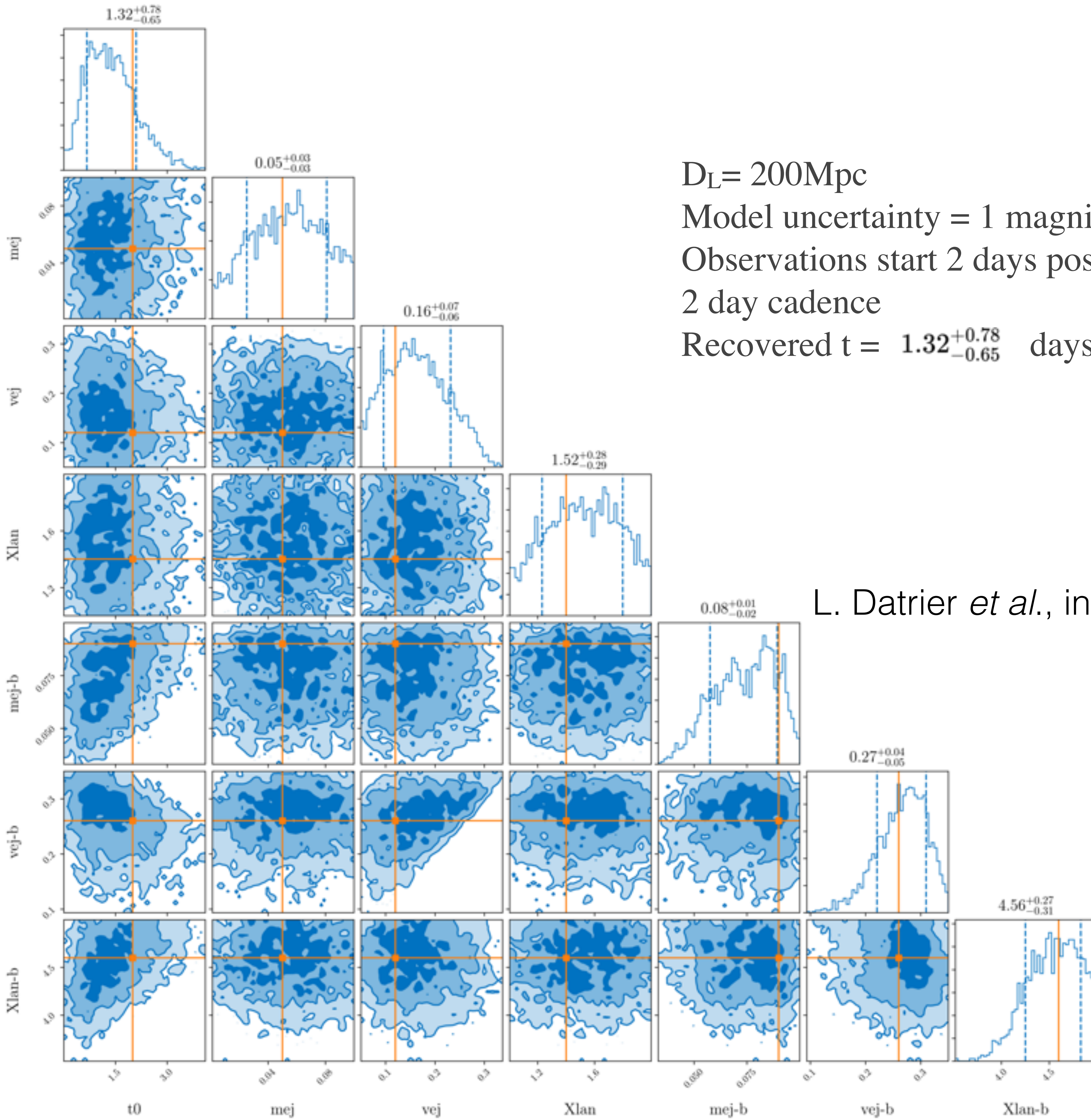

D_L= 200Mpc

Model uncertainty = 1 magnitude

Observations start 2 days post merger (t_0)

2 day cadence

Recovered t = $1.32^{+0.78}_{-0.65}$ days

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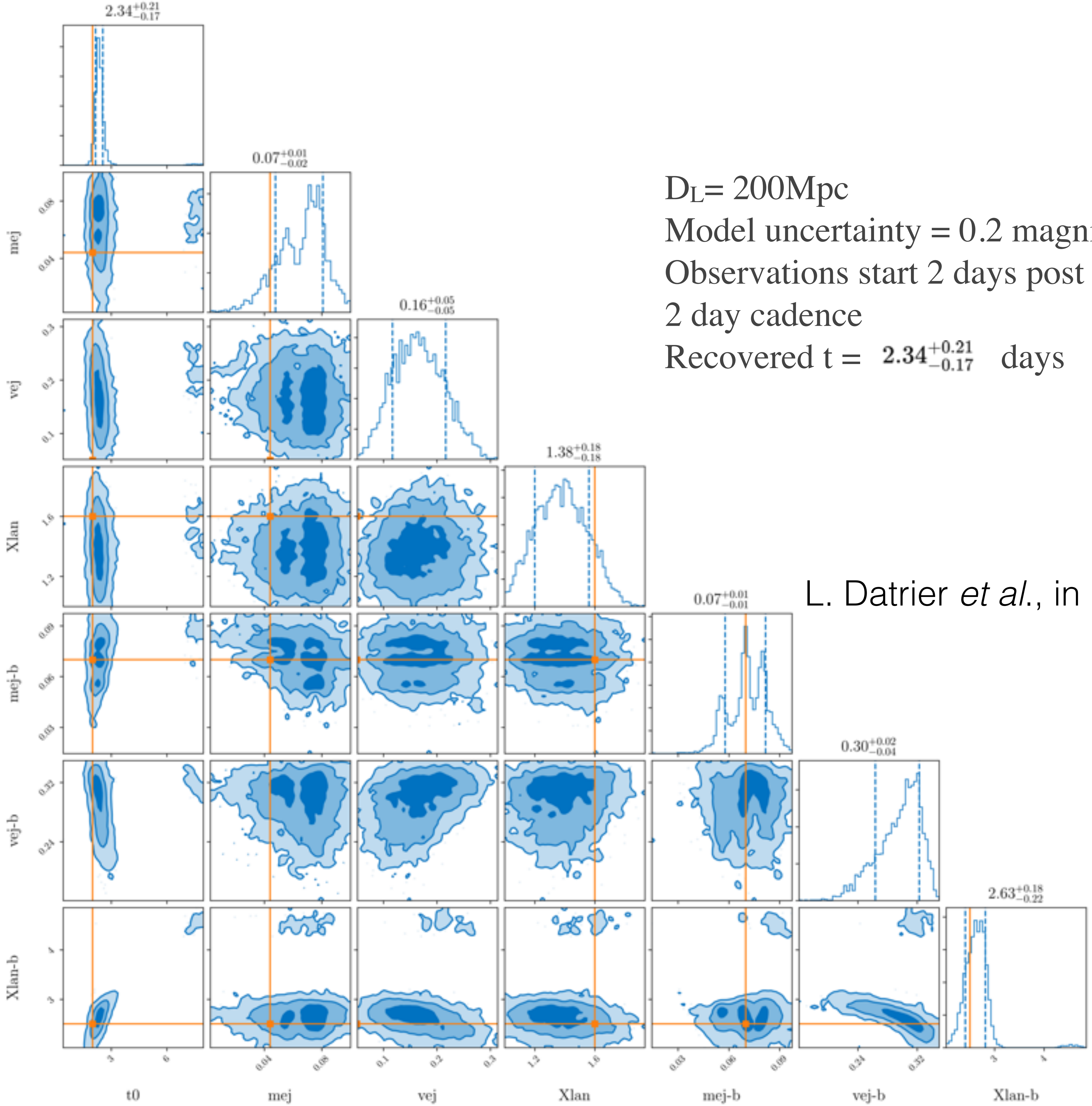

D_L= 200Mpc
Model uncertainty = 0.2 magnitude
Observations start 2 days post merger (t_0)
2 day cadence
Recovered t = $\mathbf{2.34^{+0.21}_{-0.17}}$ days

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Summary

- Multi-messenger analysis of joint observations can uncover astrophysical insight which may not be accessible otherwise
  - population of GRB-GW observations will allow us to probe jet strucure
  - joint analysis of GRB, GW, X-ray,… observations will improve parameter estimation for individual events

- Kilonova model uncertainties have a significant impact on the ability to determine the merger time
  - Other factors include number of observing bands, kilonova brightness,…

- Multi-messenger analysis can also improve inference on distance, inclination,… and lead to better interpretation (eg. cosmology)

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