

GPU-accelerated Bayesian inference for diffracted gravitational wave signals

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Motivation

- Established PE pipelines (Bilby, LALInference, PyCBC) are **CPU-based**
- Computationally expensive ($O(\text{days})$ with 16 CPUs)
- Problem with the ever increasing rate of GW detections
- Problem of analyzing deep backgrounds of simulated signals to assess lensing significance

Credits: LIGO-Virgo-KAGRA Collaboration

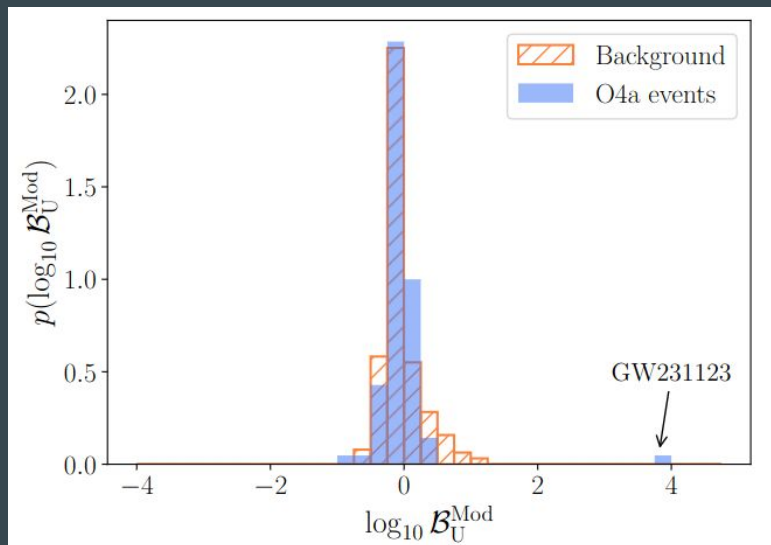
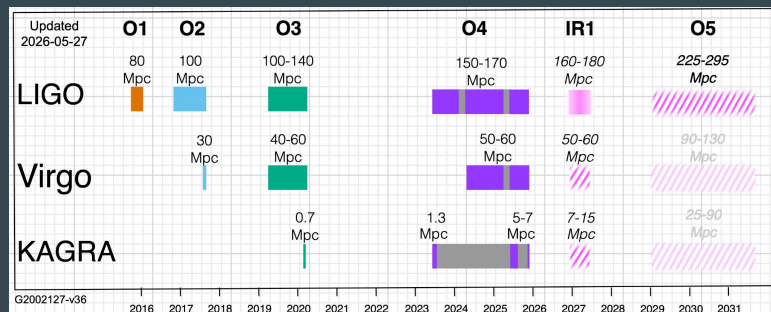


Figure taken from [1]

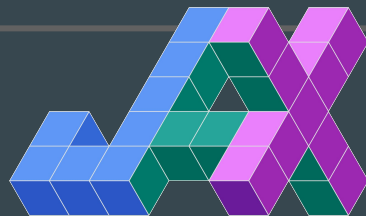
Addressing these challenges

- **GPU-based** PE pipelines have been developed to accelerate the inference process
- Example 1: **Jim** [2,3]
 - exploits the JAX-based automatically differentiable gravitational waveforms to achieve GPU-accelerated likelihood calls
 - Can achieve PE in minutes
- Example 2: **Dingo** [4]
 - makes use of neural posterior estimation
 - Once trained, PE in seconds
 - Dingo-lensing [5] $\rightarrow$ large-scale backgrounding ($O(1e5)$)
 - necessity of training on particular simulated scenario + risk of out-of-training data [6]
 $\rightarrow$ Prevents Bayes factor computations

In this work

- We implement the **amplification factor** of a **point-mass lens** in Jim
- We call this framework **Jim-lensing**
- We run Bayesian inference under the point-mass lens hypothesis in, on average, 17 minutes while retaining similar accuracy to **Gravelamps** [7], a state-of-the-art lensing pipeline used in LVK

- Free open-source software package designed to perform Bayesian inference rapidly and accurately
- Leverages JAX, enabling high-speed array computation through GPUs
- Has support for different sampling methods
- Here we use the **Blackjax-ns** sampler [8], performing nested sampling in batched and vectorized way
- In particular, the “acceptance-walk” sampling method [9]



Point-mass lens amplification factor

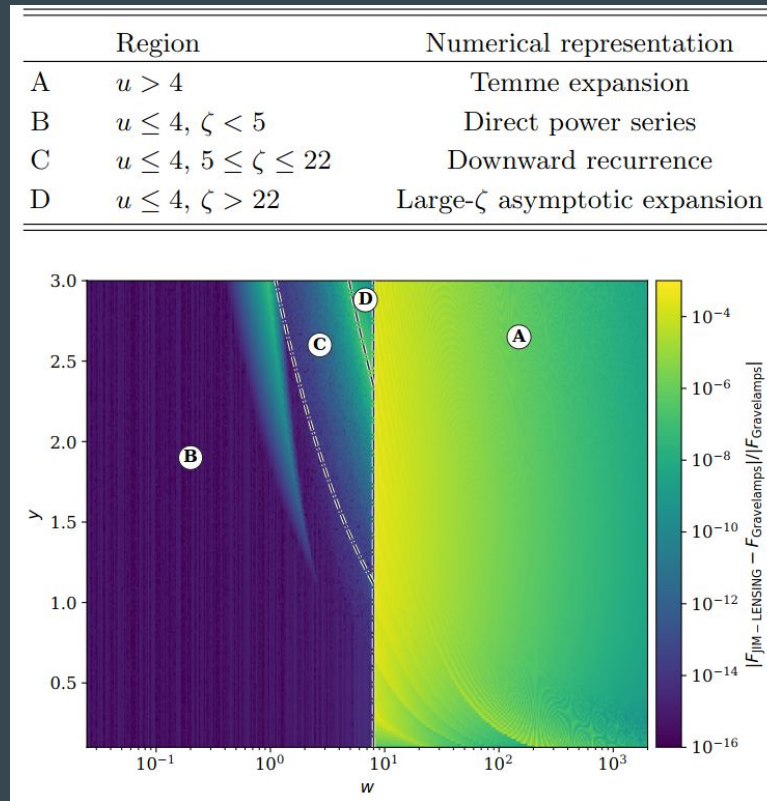
- Lensed waveform and unlensed waveform related by **amplification factor**

$$\tilde{h}^L(f) = F(f) \tilde{h}^U(f)$$

- Analytically solvable only for a few simple lens models
- For point mass:
$$F(w, y) = \exp \left[\frac{\pi w}{4} + \frac{iw}{2} \left(\ln \frac{w}{2} - 2\phi_m(y) \right) \right] \Gamma \left(1 - \frac{iw}{2} \right) {}_1F_1 \left(\frac{iw}{2}, 1; \frac{iwy^2}{2} \right)$$
- Confluent hypergeometric function of the first kind with complex input not implemented in JAX
- Employ numerical strategy used in [10,11].

Point-mass lens amplification factor

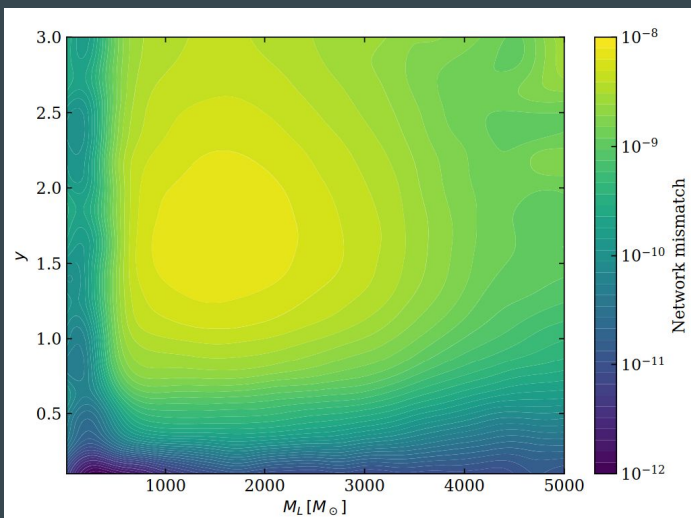
- Divide (w,y) -plane into different regions based on the values of $u=w/2$ and $\zeta = wy^2/2$
 - Relative difference with Gravelamps does not exceed $1e-3$
- immeasurable differences in parameter estimation



Jim-lensing

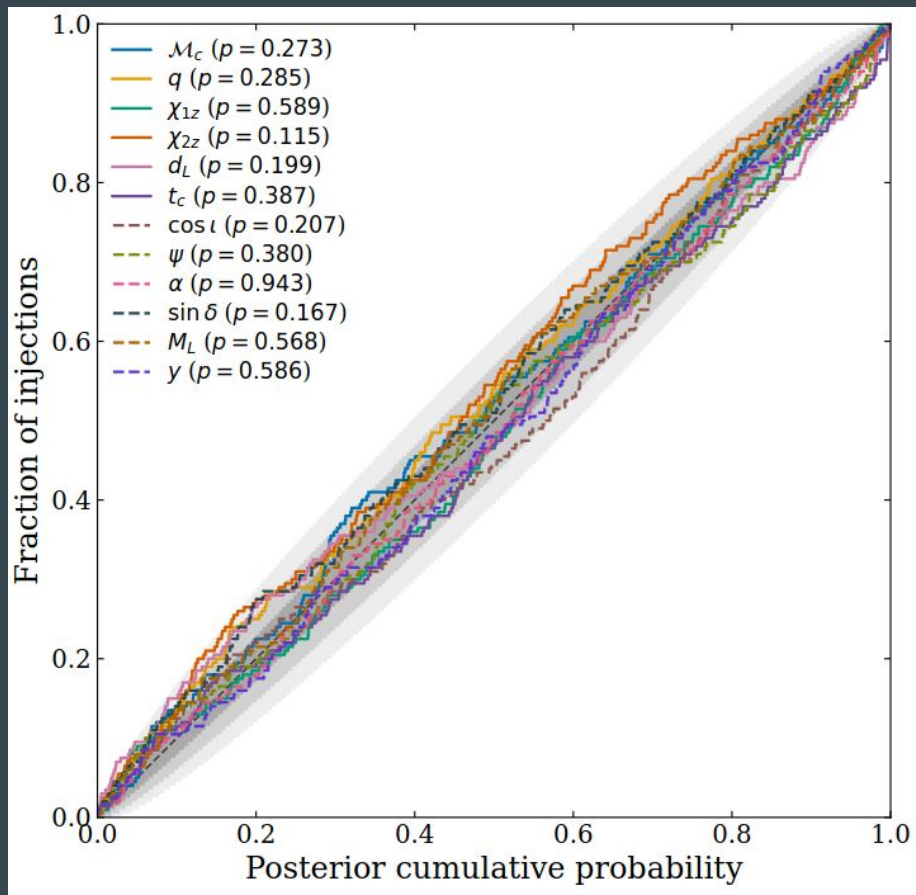
- We implement a point-mass lensed waveform generator in Jim
- Mismatch study with IMRPhenomD, $f_{\min} = 20\text{Hz}$, $f_{\max} = 1024\text{Hz}$ and H-L-V
- Maximum mismatch is below $1e-7$

Parameter	Prior
$\mathcal{M}/M_{\odot}$	$\mathcal{U}(20, 50)$
q	$\mathcal{U}(0.5, 1.0)$
χ_{1z}, χ_{2z}	$\mathcal{U}(-0.8, 0.8)$
d_L/Mpc	$p(d_L) \propto d_L^2, [100, 1250]$
t_c/s	$\mathcal{U}(-0.1, 0.1)$
ϕ_c	$\mathcal{U}(0, 2\pi)$
ι	$p(\iota) \propto \sin \iota, [0, \pi]$
ψ	$\mathcal{U}(0, \pi)$
α	$\mathcal{U}(0, 2\pi)$
δ	$p(\delta) \propto \cos \delta, [-\pi/2, \pi/2]$
$M_{L,z}/M_{\odot}$	$\mathcal{U}(10, 5000)$
y	$\mathcal{U}(0.1, 3.0)$



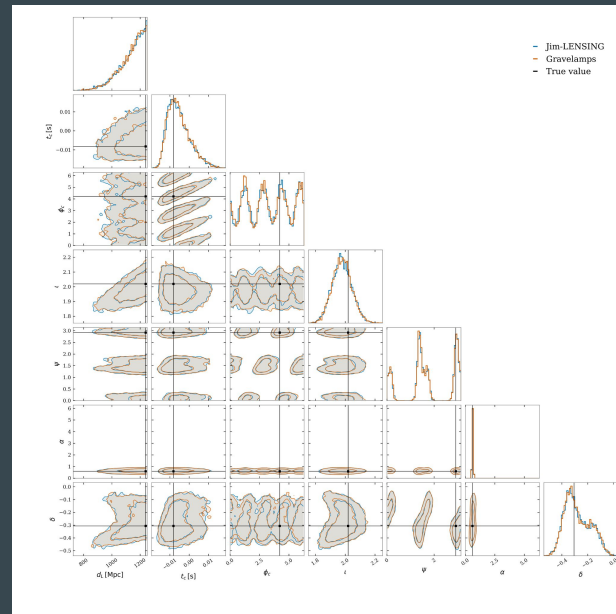
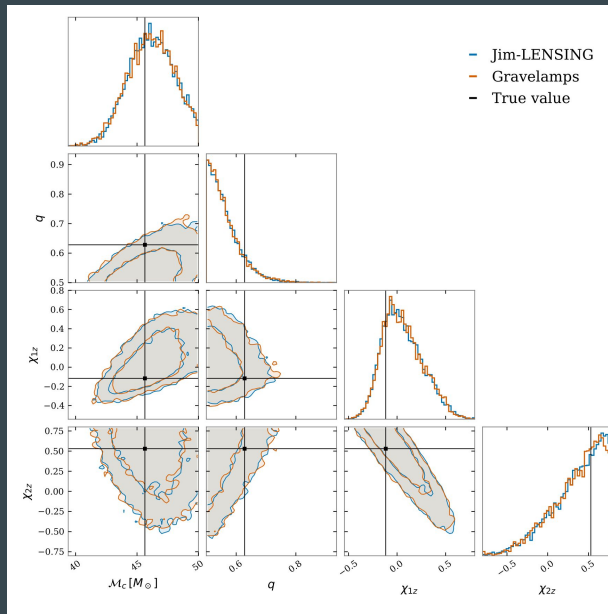
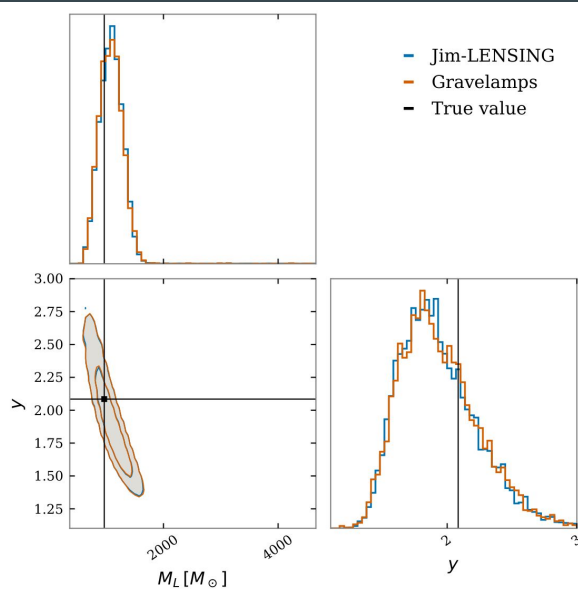
Percentile-percentile plot

- We inject 200 signals in gaussian noise and recover with same prior
- Compute the marginalized posterior percentiles of the true value
- For an unbiased method they should be distributed uniformly
- CDF of these gives the P-P plot $\rightarrow$ trend along diagonal
- Test uniformity with KS-test $\rightarrow$ combined p-value = 0.32



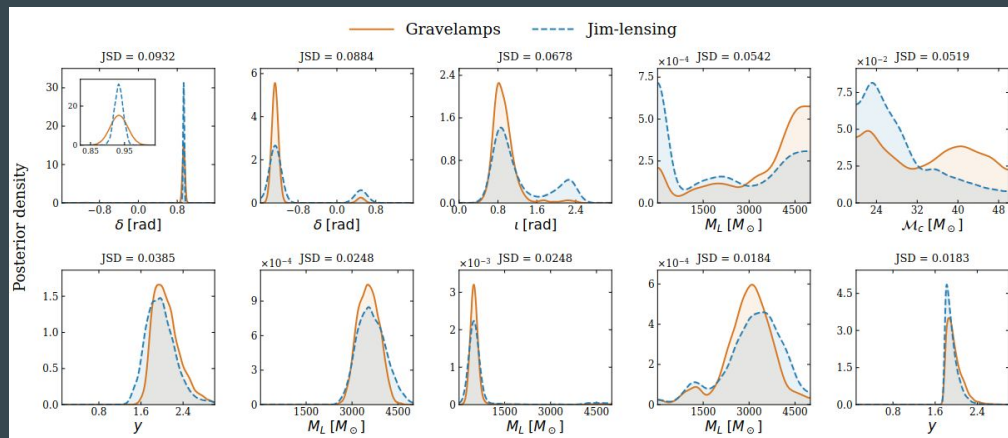
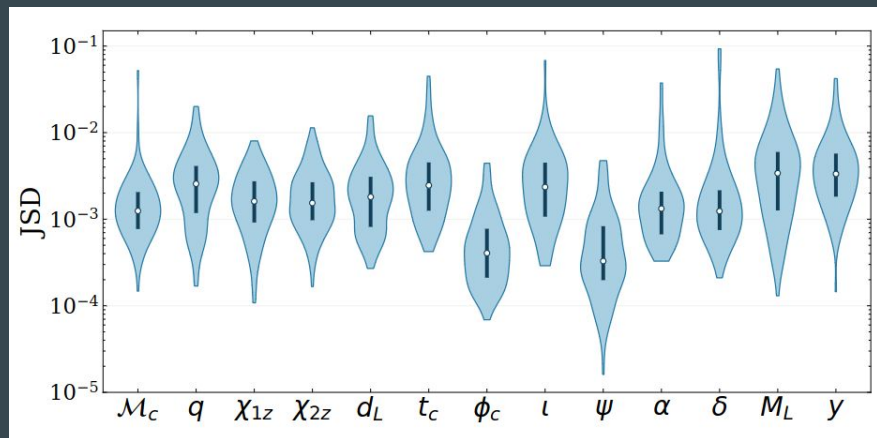
Posterior comparison

- We also recover the 100 P-P plot injections with Gravelamp



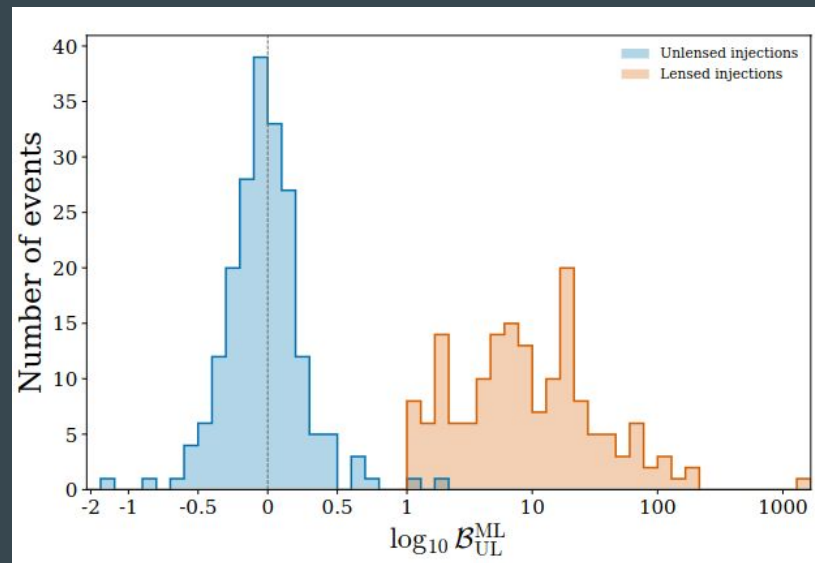
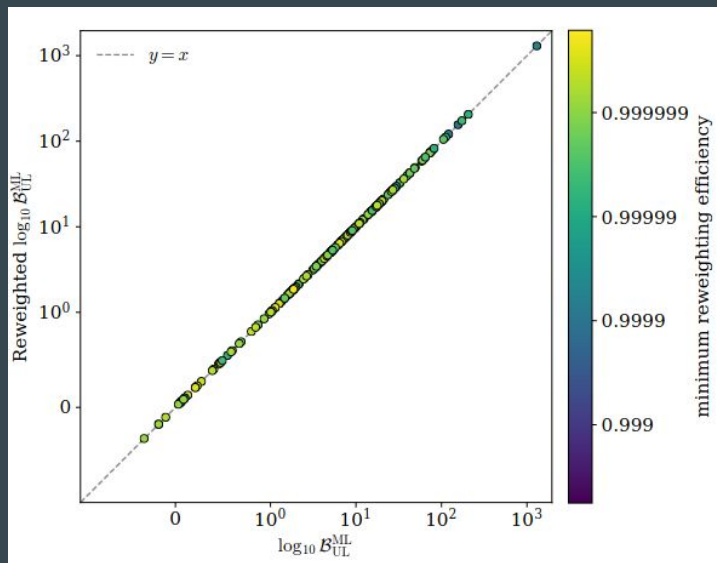
Jensen-Shannon divergence

- To quantify the difference between the posteriors, we compute the JSD (min=0 max=ln2)
- More than 50% of JSD values < 0.002 $\rightarrow$ statistically insignificant
- Most JSD values < 0.017 $\rightarrow$ values obtained by Jim reanalysis of GW150914 [2]
- Few posteriors have JSD > 0.017 $\rightarrow$ posteriors remain comparable



Bayes factor recovery

- We compute the Bayes factor for 200 lensed and 200 unlensed injections drawn from astrophysical prior
- We reweight the Bayes factors of the lensed injections with Gravelamps and only keep those that are higher than 10
- Background: similar numbers as LVK lensing paper
- Foreground: Bayes factors remain above 10

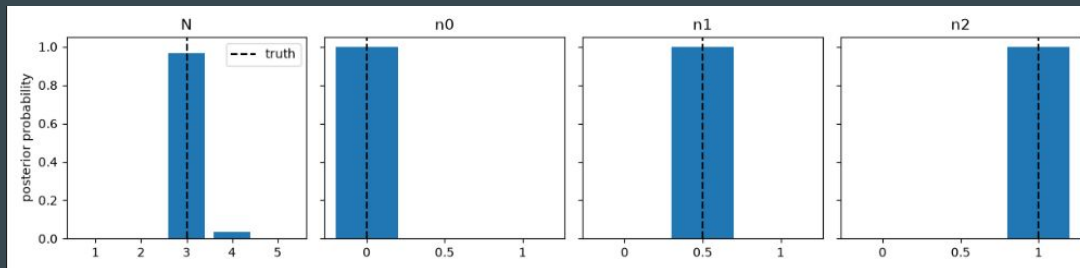


Outlook

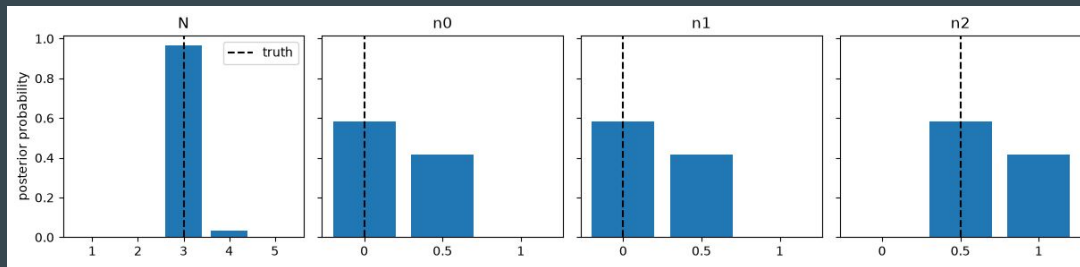
- Speeding up by tweaking sampler settings + parameter marginalization
- Forthcoming implementation of JAX-compatible versions of modern waveforms will enable Jim-lensing to reach parity with current LVK lensing analyses
- Other lens models that allow for an analytic expression (or a power-series expression) can be implemented analogously

Preliminary result for phenomenological lens model

- Recently we implemented a phenomenological lens model
- Model-agnostic, sum of overlapping geometric optics images (number of images is variable)
- Preliminary results:



Type I - II - III system



Type I - I - II system

Thank you for your attention!

References

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2. <https://github.com/kazewong/jim>
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11. <https://github.com/ghow-astro/GLoW>