NORTHWESTERN UNIVERSITY

CIERA

Rapid Compact Binary Coalescence Parameter Estimation in the Advanced LIGO Era

Chris Pankow (CIERA / Northwestern University)
Patrick Brady (CGCA / University of Wisconsin-Milwaukee)
Richard O'Shaughnessy (CCRG / Rochester Institute of Technology)
Evan Ochsner (CGCA / University of Wisconsin-Milwaukee)
Hong Qi (CGCA / University of Wisconsin-Milwaukee)

LIGO-G1601044

Based on PRD 92 (023002) / 1502.04370v1
AMR gridding paper to be submitted to CQG

Gravitational Waves: From Detection to Follow-Up

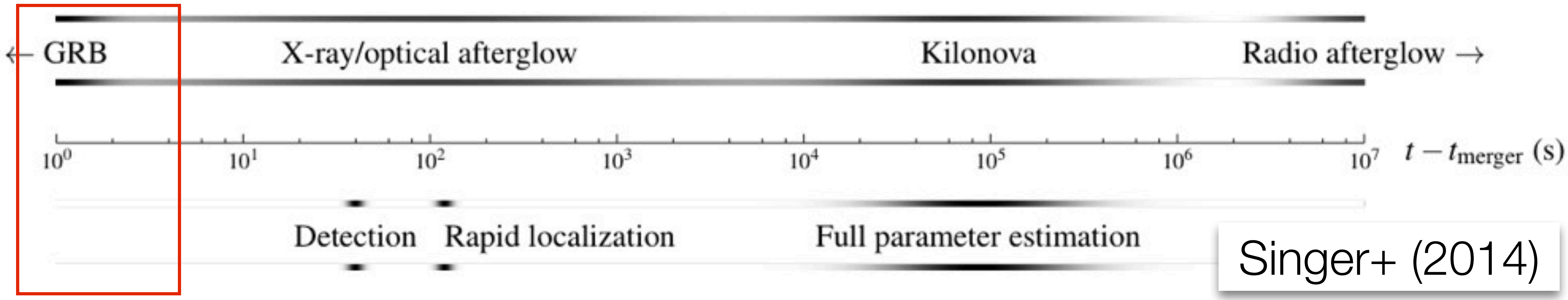


Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.

- NSBH / BNS sources main candidate for joint observations between GW and EM facilities
- GW detection could inform how we observe with EM and vice-versa
  - Early coincidence and informed follow up of EM+GW candidates already in play (talk by ***M. Cho***)
- Discovery opens up rich field of astrophysics associated with joint GW + EM emission and modeling (GRBs, kilonovae, SNe, etc...)

Gravitational Waves: From Detection to Follow-Up

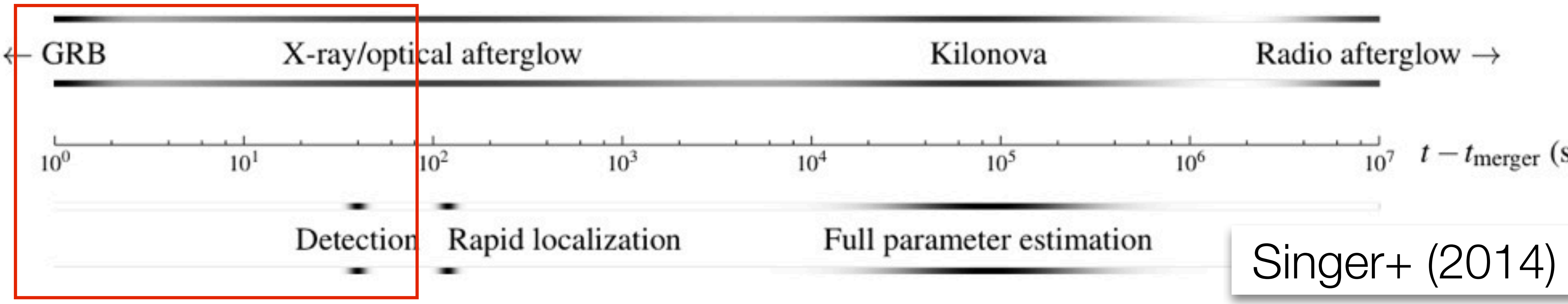
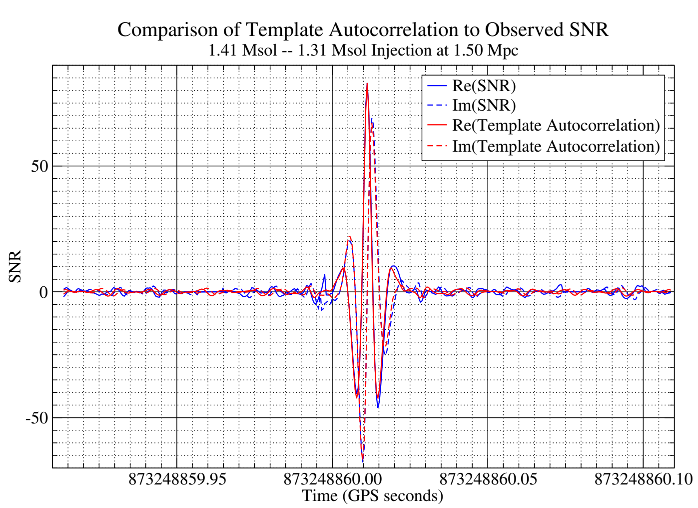
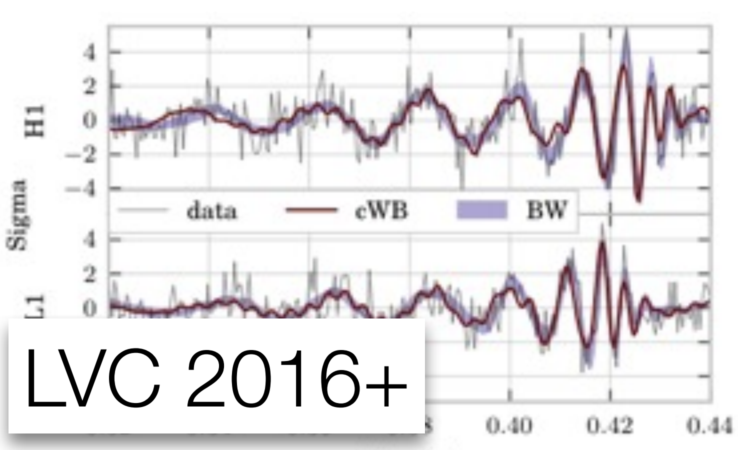


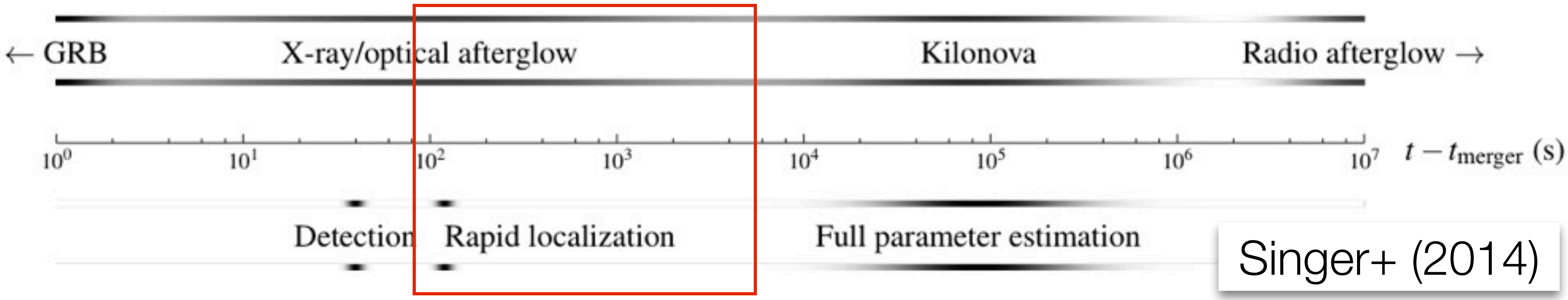
Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.





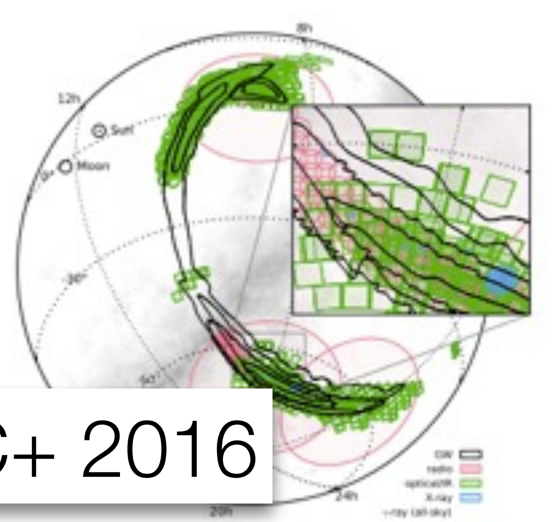
- Low latency searches **produce candidate** event times **in O(min)**
    - **Large template banks** to search a **wide space of parameters** (mass/spins)
    - **Great for detection**, not so great for parameter estimation: **No modeled facility for sky localization, distance estimation is poor**

Gravitational Waves: From Detection to Follow-Up

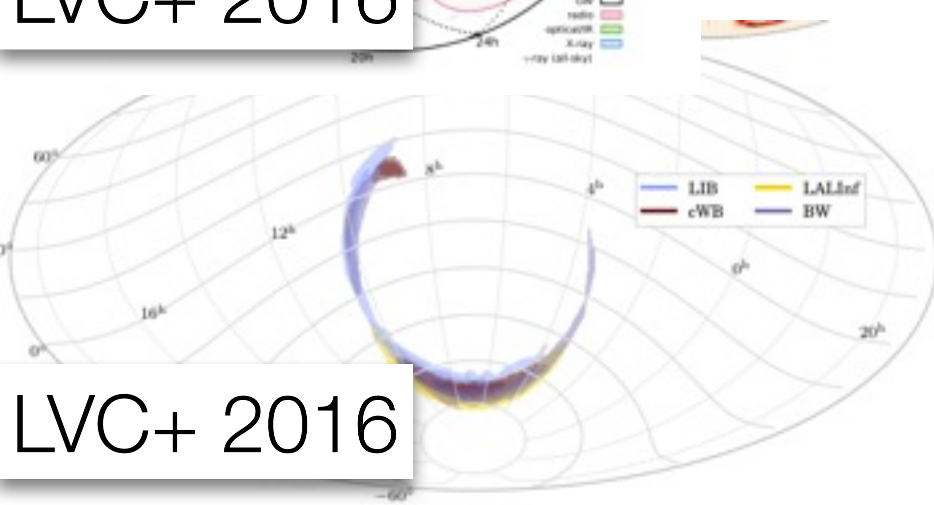


Singer+ (2014)

Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.



LVC+ 2016



LVC+ 2016

- Some very fast schemes to produce posterior distributions on the sky → **astronomers point telescopes**
    - Fold in a few more parameters, **may not account for other masses or spin configurations**
    - Are we dealing with a **"EM-bright" source**? Is it **inclined towards us**? Redshift?

Gravitational Waves: From Detection to Follow-Up

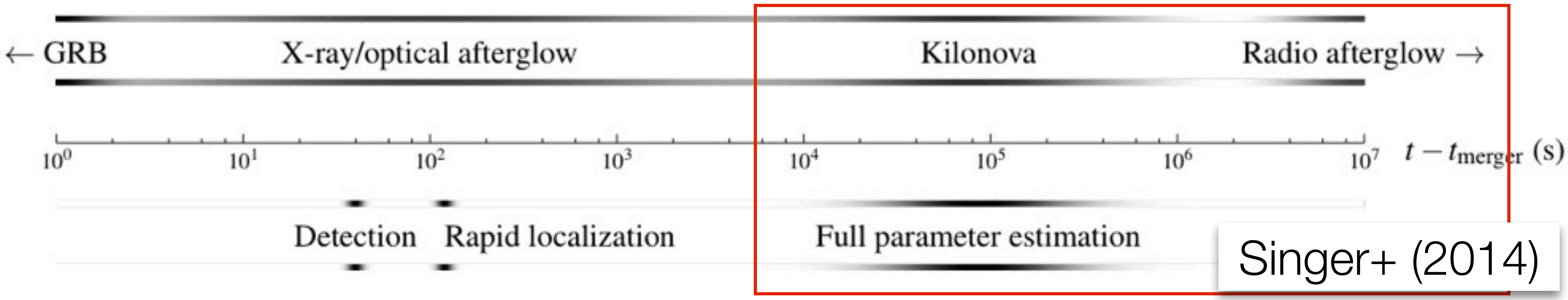


Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.

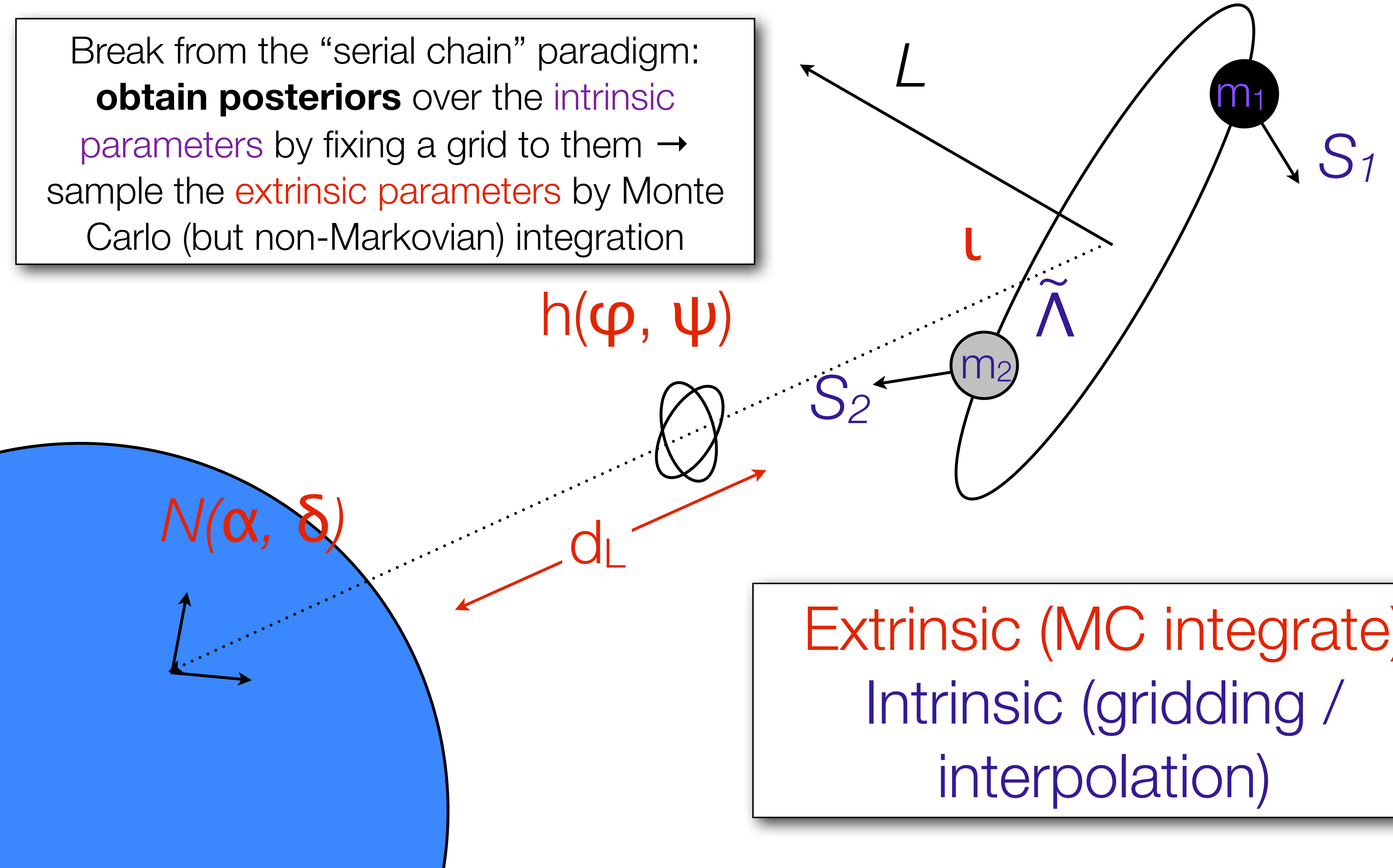
- GW sky position posteriors are **wide**, need a highly coordinated effort for best observing strategy → fast and confirmed localization **can boost detection confidence** in NSBH or BNS GW candidate and **better populate light curves**

- **Full parameter estimation in O(days)**: but we may have already **lost the optical afterglow (GRB)** ... also will have **technical challenges** with half hour long **BNS in 2018**

- ***Need to do basic parameter estimation (masses/distance/inclination) in O(min) to better facilitate optical follow up***

System Parameterization

Break from the "serial chain" paradigm: **obtain posteriors** over the intrinsic parameters by fixing a grid to them → sample the extrinsic parameters by Monte Carlo (but non-Markovian) integration



Extrinsic (MC integrate)
Intrinsic (gridding / interpolation)

Rapid PE: Ingredients

- At fixed intrinsic parameters, the likelihood has a novel formulation which only requires **one** waveform generation (h), and **one** set of precomputed inner products over a **spherical harmonic mode decomposition** (l,m) of the **measured** (ρ) and **optimal** ($\bar{\rho}$) signal to noise ratio → reconstruct the likelihood at arbitrary extrinsic parameters with a few multiplications and adds

$$\tilde{s}(f) = \tilde{h}(f) + \tilde{n}(f)$$

$$\ln \mathcal{L} \propto \rho - \frac{1}{2}\bar{\rho}^2$$

$$\ln \mathcal{L}(\lambda^0, \theta) = \frac{d_{\rm ref}}{d} \Re \sum_k \sum_{l,m} F_k Y^*_{lm} \rho_{k,lm}(\lambda^0)$$
$$- \frac{d^2_{\rm ref}}{4d^2} \sum_k \sum_{lml'm'} |F_k| Y^*_{lm} Y_{l'm'} \bar{\rho}_{k,lm,l'm'}(\lambda^0)$$
$$+ \Re\left(F_k^2 Y_{lm} Y_{l'm'} \bar{\rho}^*(\lambda^0)\right)$$

$$F_k \sim \{\alpha, \delta\} \qquad Y_{lm} \sim \{\iota, \psi, \phi\}$$

Precomputed

$$\rho_{k,lm} = (h_{k,lm} | s)$$
$$\bar{\rho}_{k,lm,l'm'} = (h_{k,lm} | h_{k,l'm'})$$
$$\bar{\rho}^*_{k,lm,l'm'} = (h^*_{k,lm} | h_{k,l'm'})$$

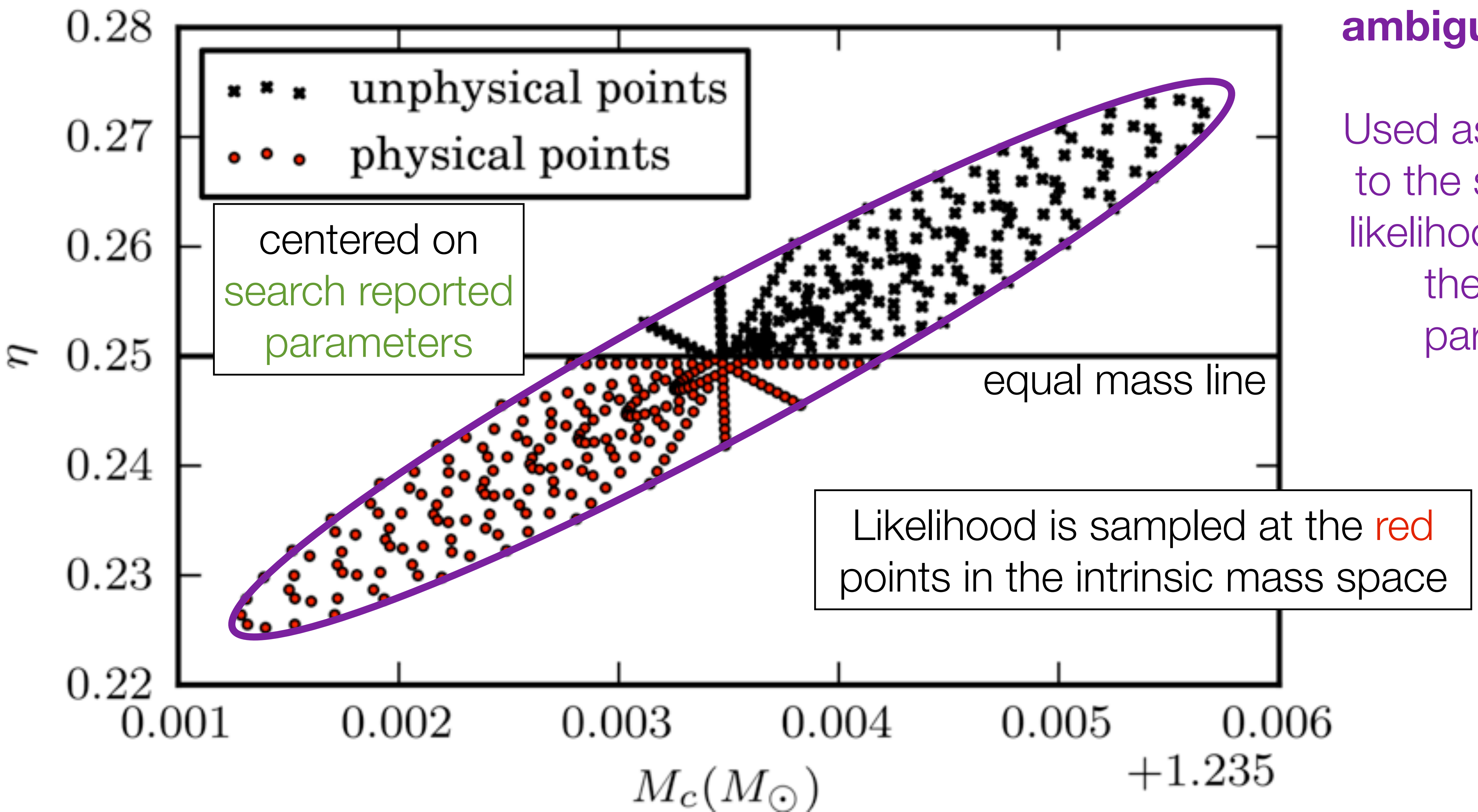
...over *k* instruments...

Intrinsic Parameter Placement (Fisher-matrix)

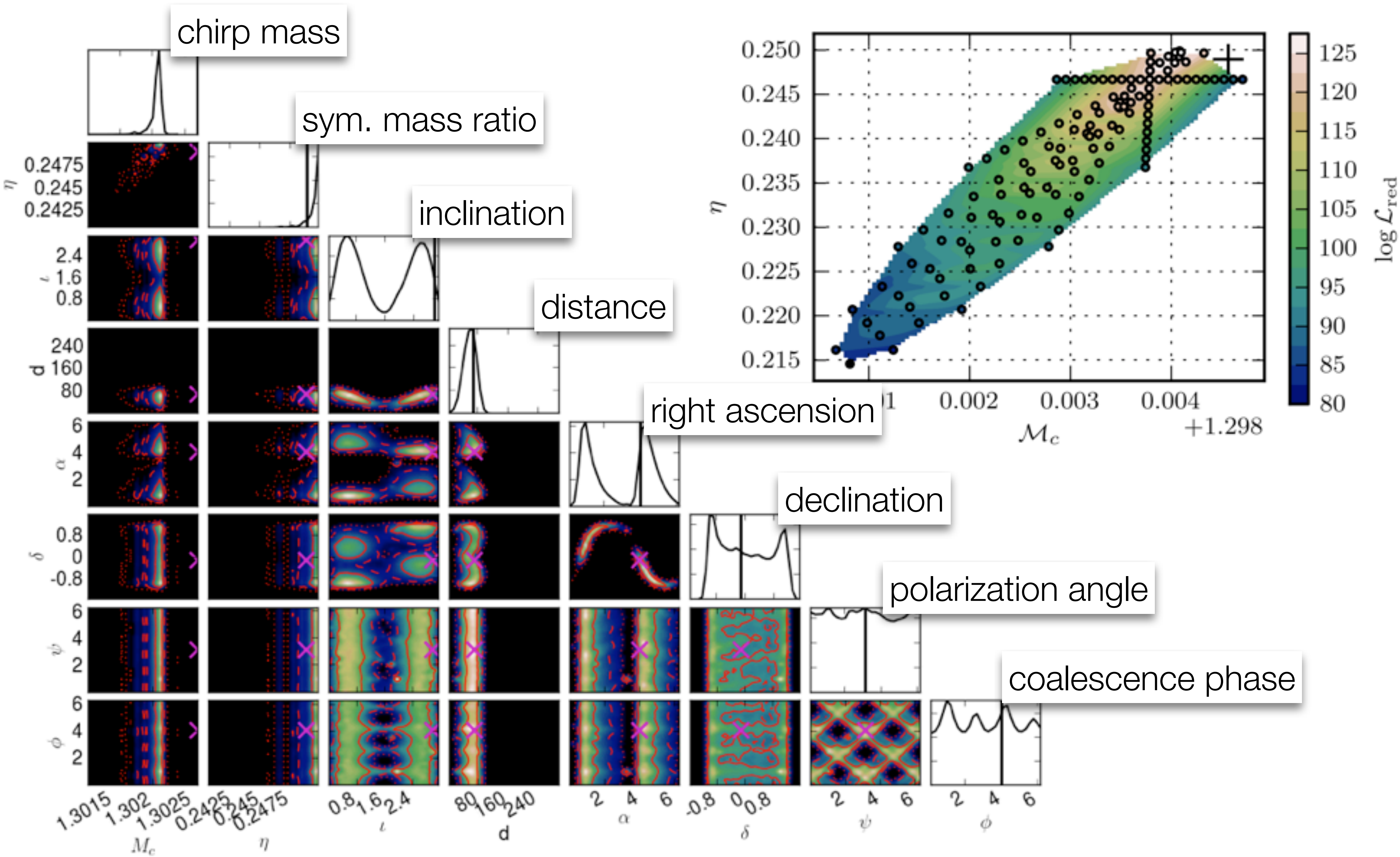
- Low latency searches provide intrinsic parameter measurement (possibly biased or incomplete!) → we use this to guide a strategic placement of the intrinsic grid

Fit to **parameter ambiguity** contours

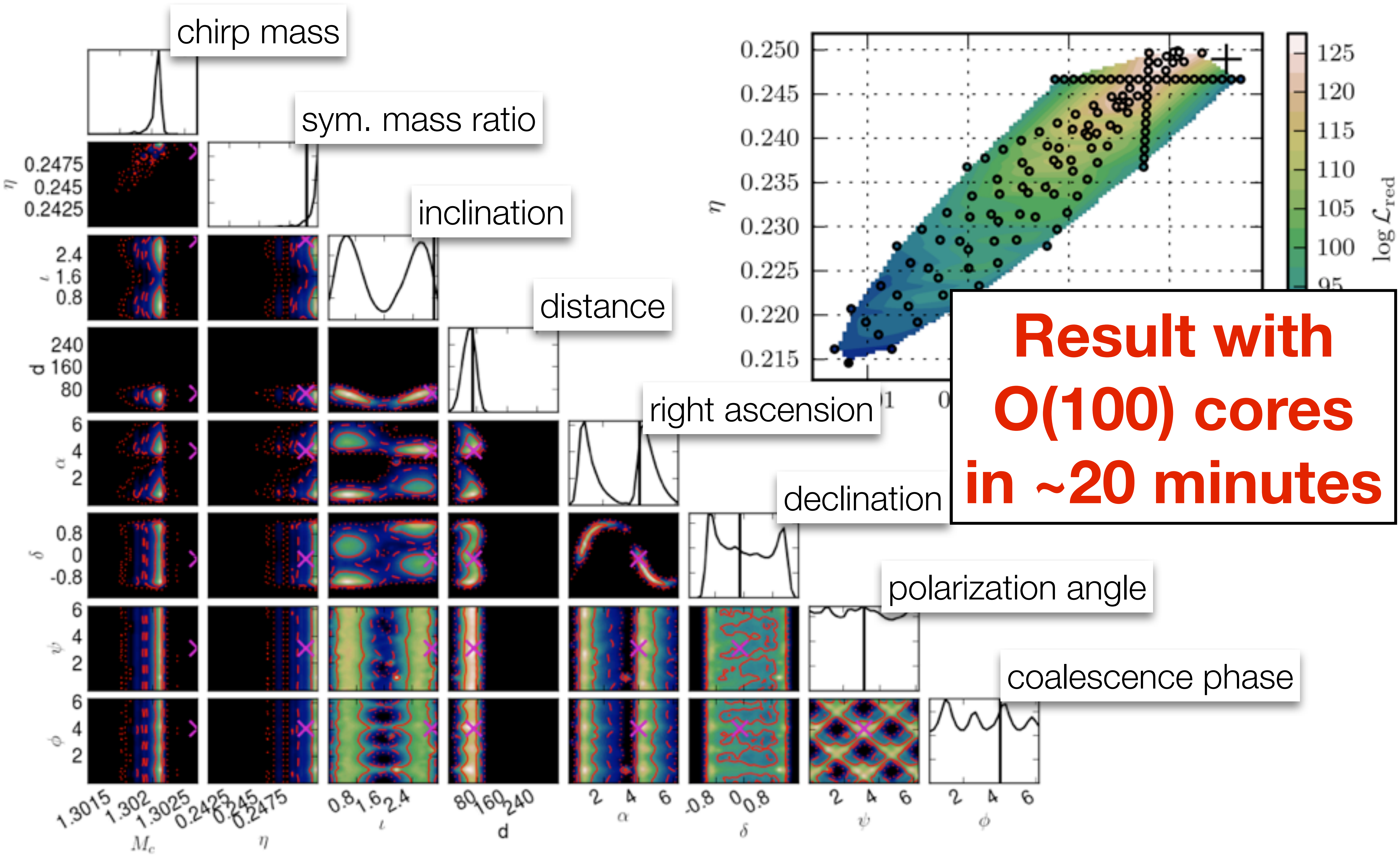
Used as a surrogate to the shape of the likelihood surface in the intrinsic parameters



Parameter Estimation Results: Synthetic BNS Signal in O1



Parameter Estimation Results: Synthetic BNS Signal in O1



Improving Placement / Using Search Information

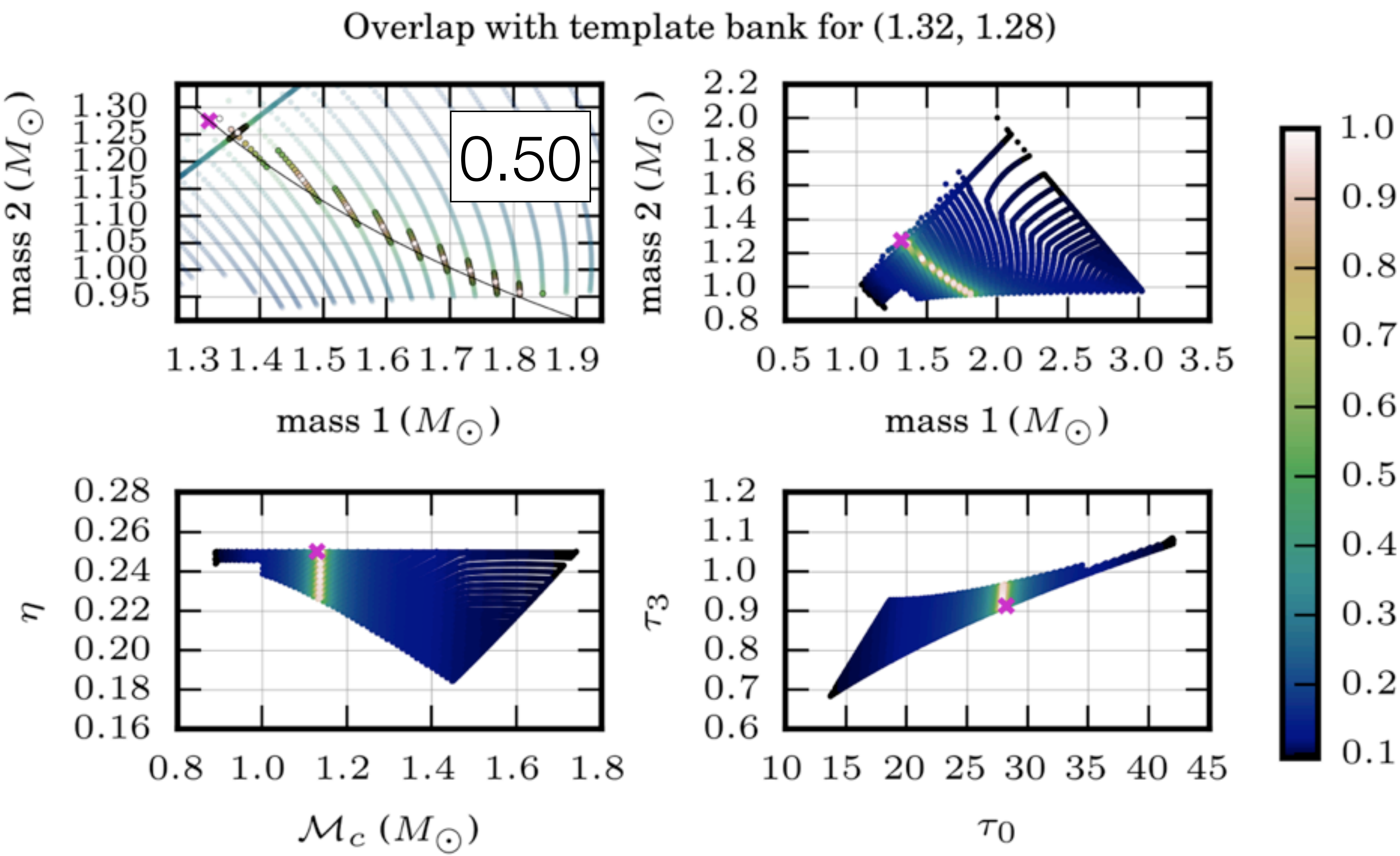
- Initial point selection motivated by Fisher matrix which has limited applicability (inappropriate at low SNR, multimodality in the likelihood function, no clear gridding procedure)

- Template banks of waveforms have ~3% mismatch — very densely oversampled for detection in the intrinsic basis

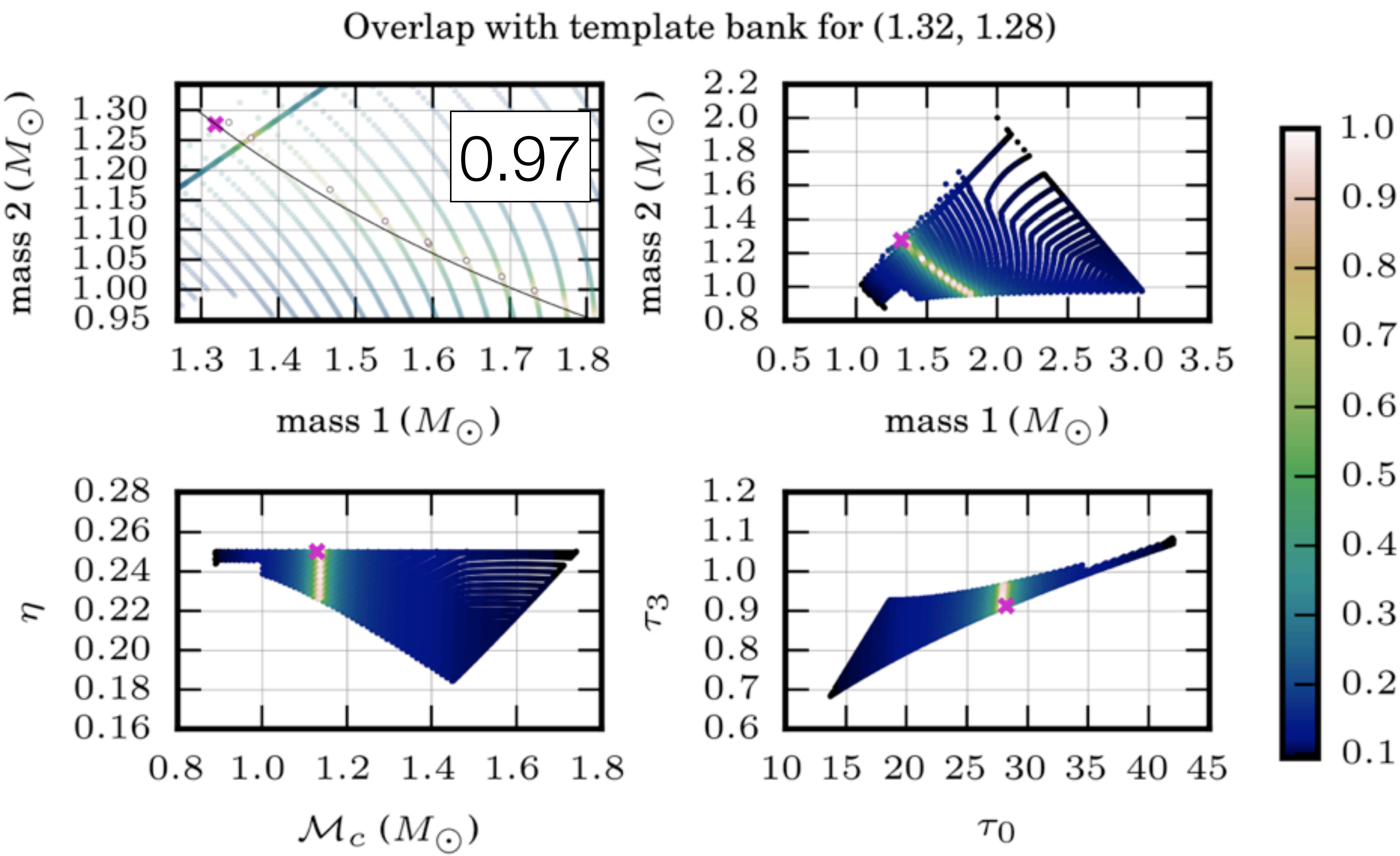
$$\mathcal{O}_{12} = \frac{(h_1|h_2)}{\sqrt{(h_1|h_1)\,(h_2|h_2)}} \sim 0.97$$

- Solution: Use point estimate of mass information from the search and check the search template bank for “relevant templates”

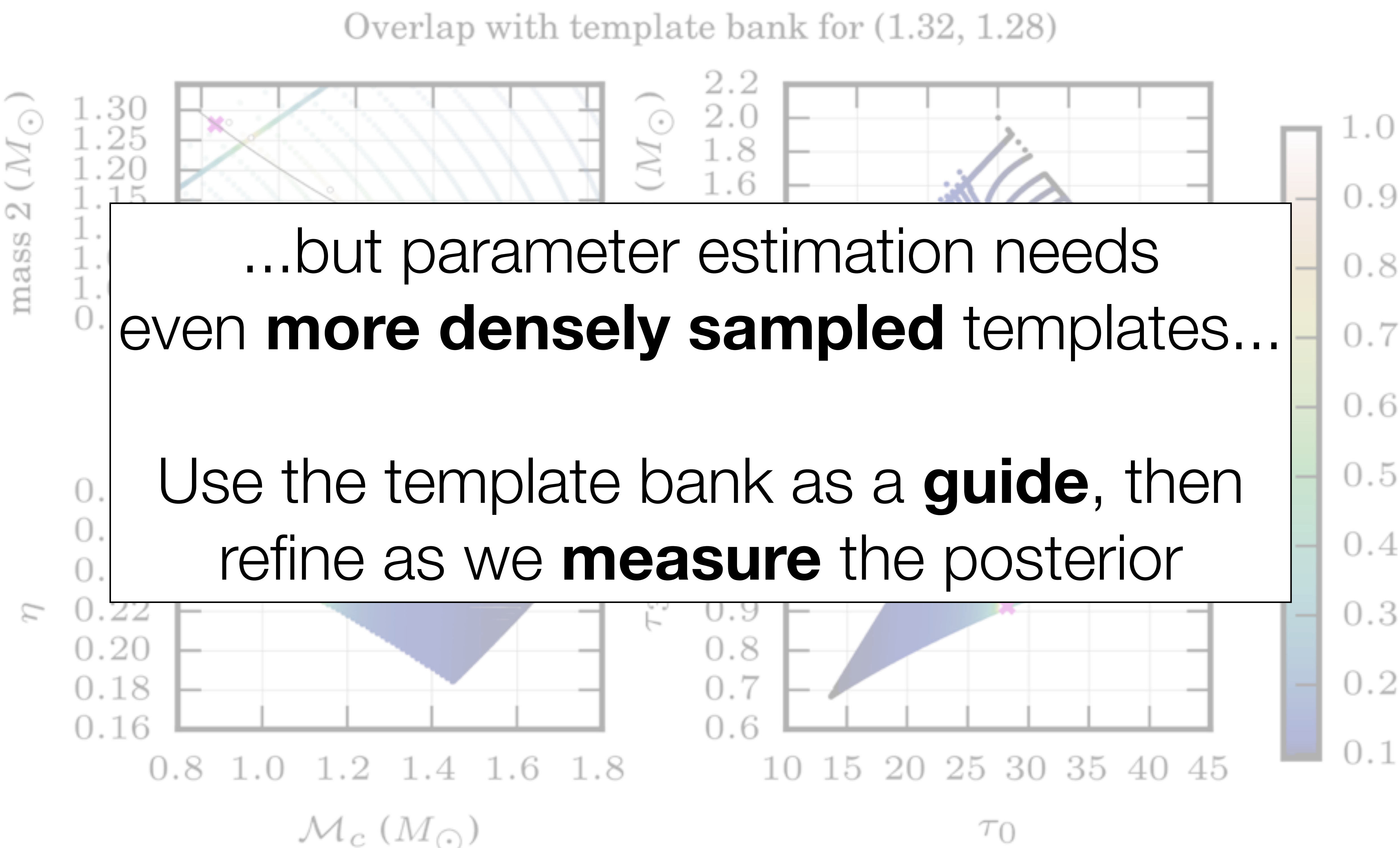
Improving Placement / Using Search Information



Improving Placement / Using Search Information



Improving Placement / Using Search Information



...but parameter estimation needs even **more densely sampled** templates...

Use the template bank as a **guide**, then refine as we **measure** the posterior

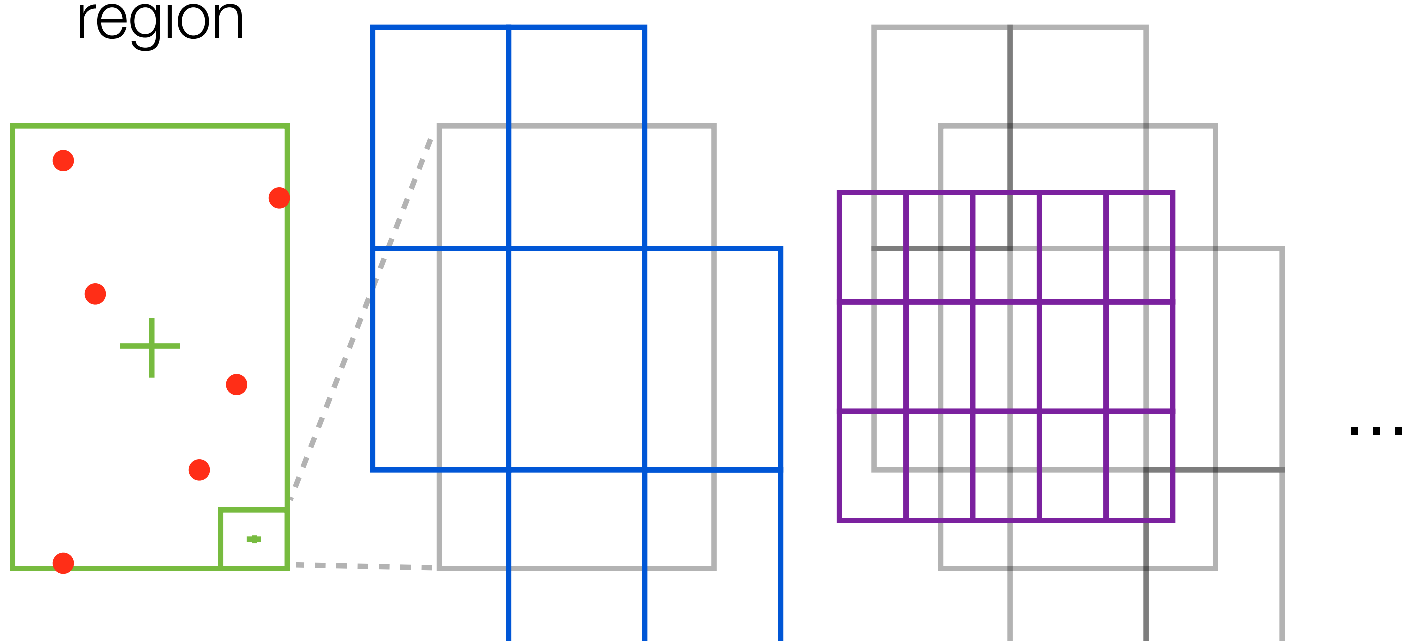
Region Identification and Grid Construction

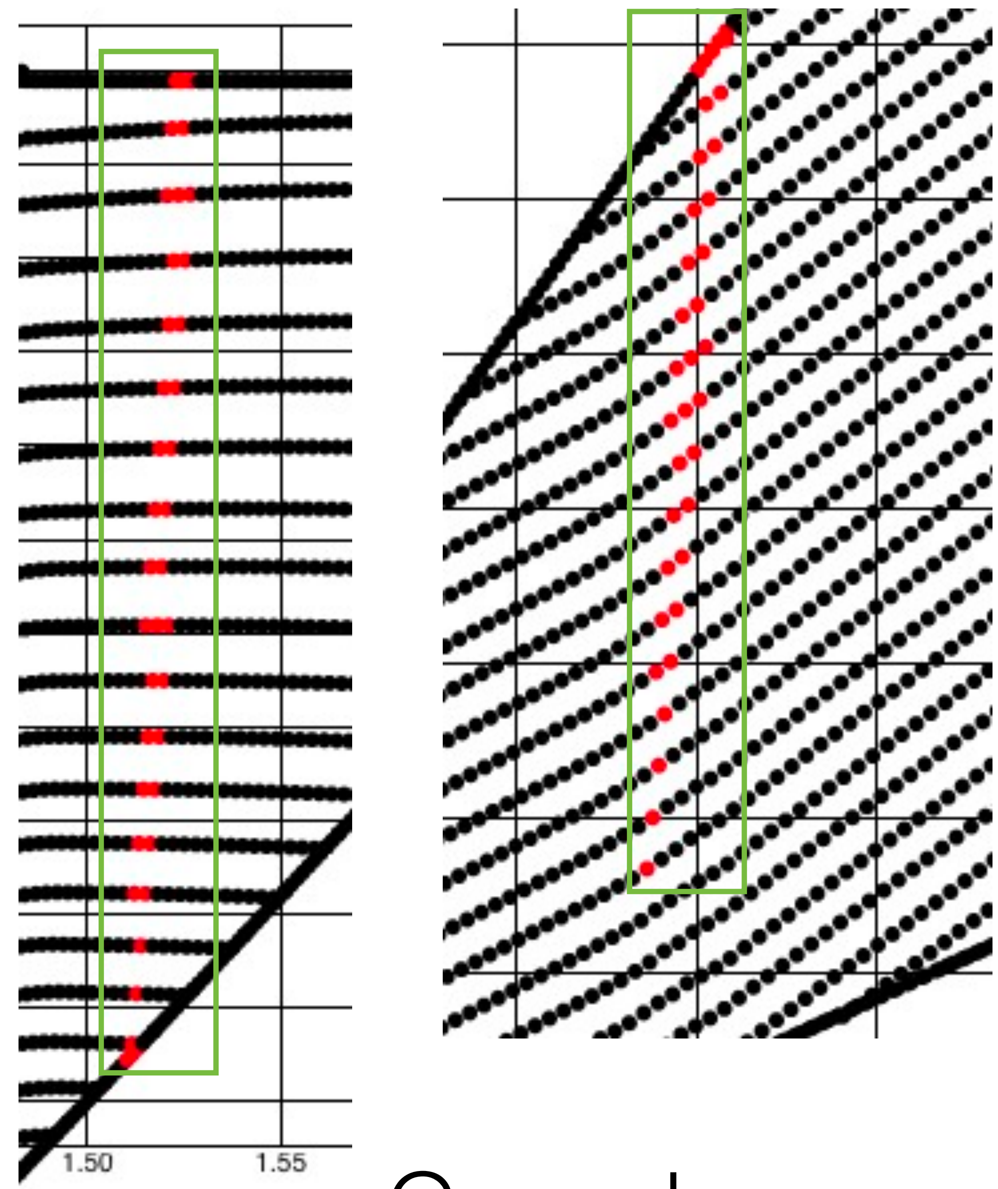
- The same points in M_c / η (left) and τ_0 / τ_3 (right) space — Euclidean "closeness" and overlap "closeness" much more local and apparent here
- Use these to define cells upon which to adapt — Cell can be arbitrarily refined, or not evaluated at all depending on initial overlap or evaluated L_{red} at the point

define initial region

refinement 1

refinement 2



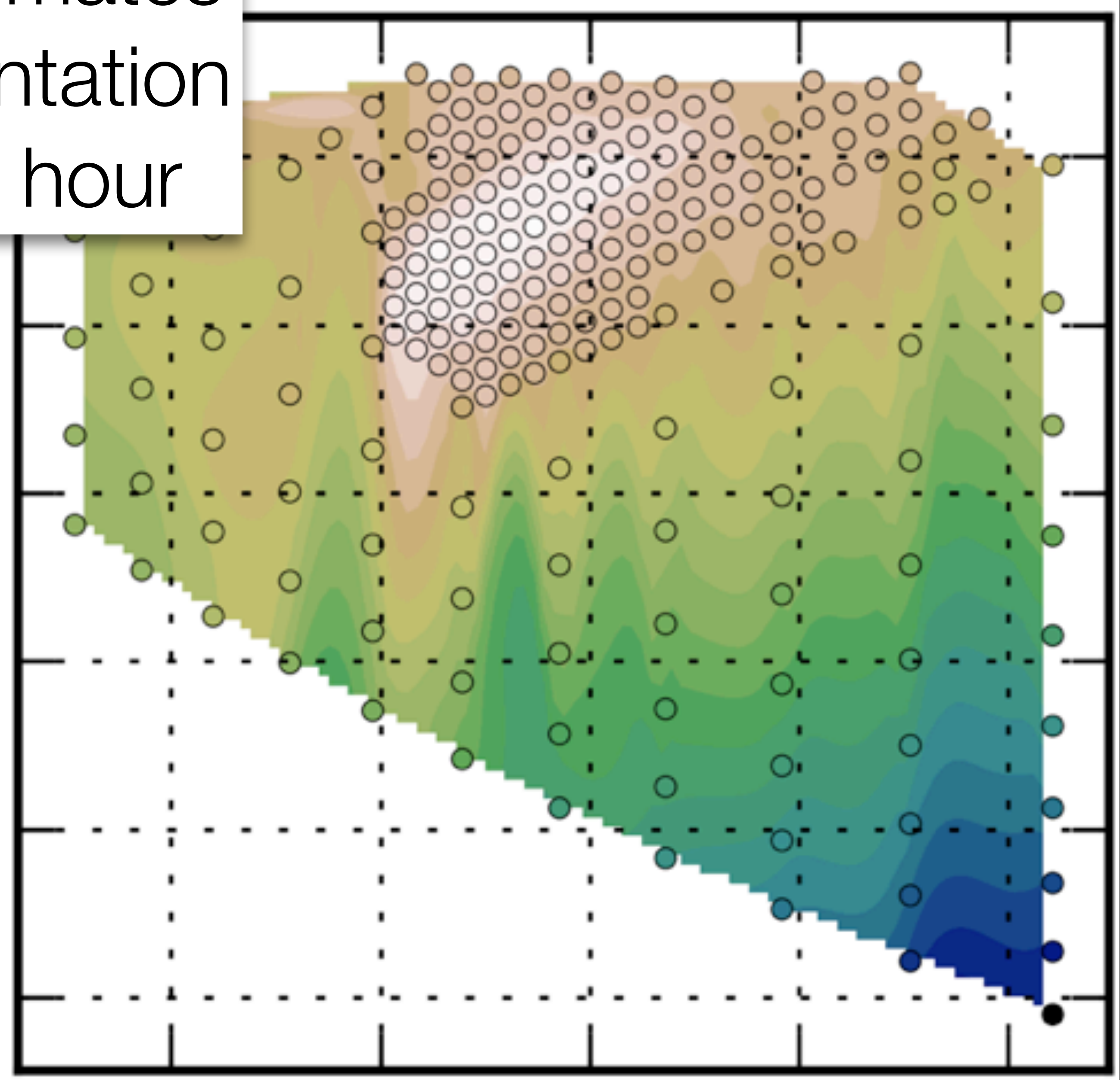


Green box approximates cell "region"

GW150914

mass / spin estimates
and source orientation
in less than an hour

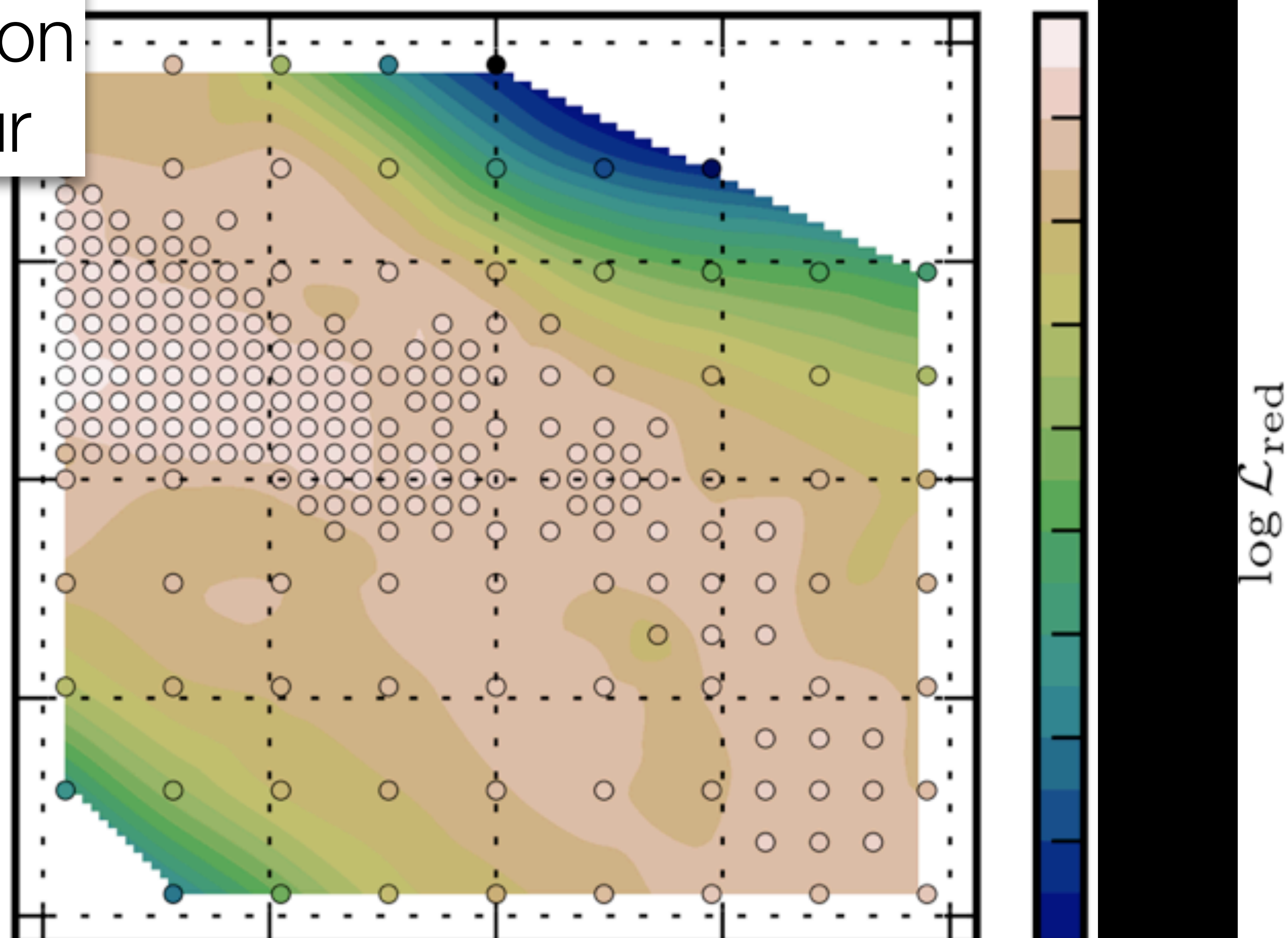
[redacted]



[redacted]

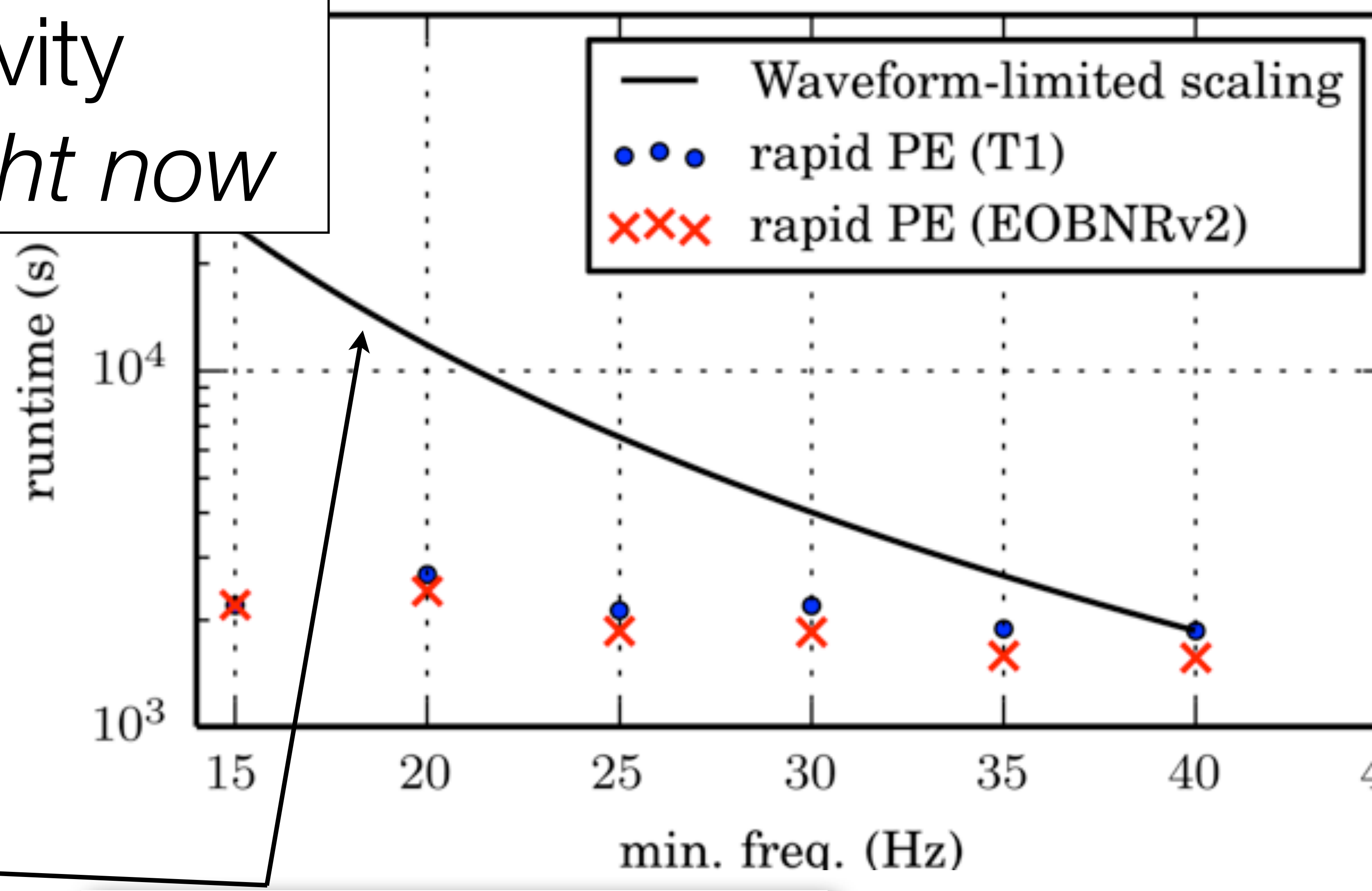
GW150914

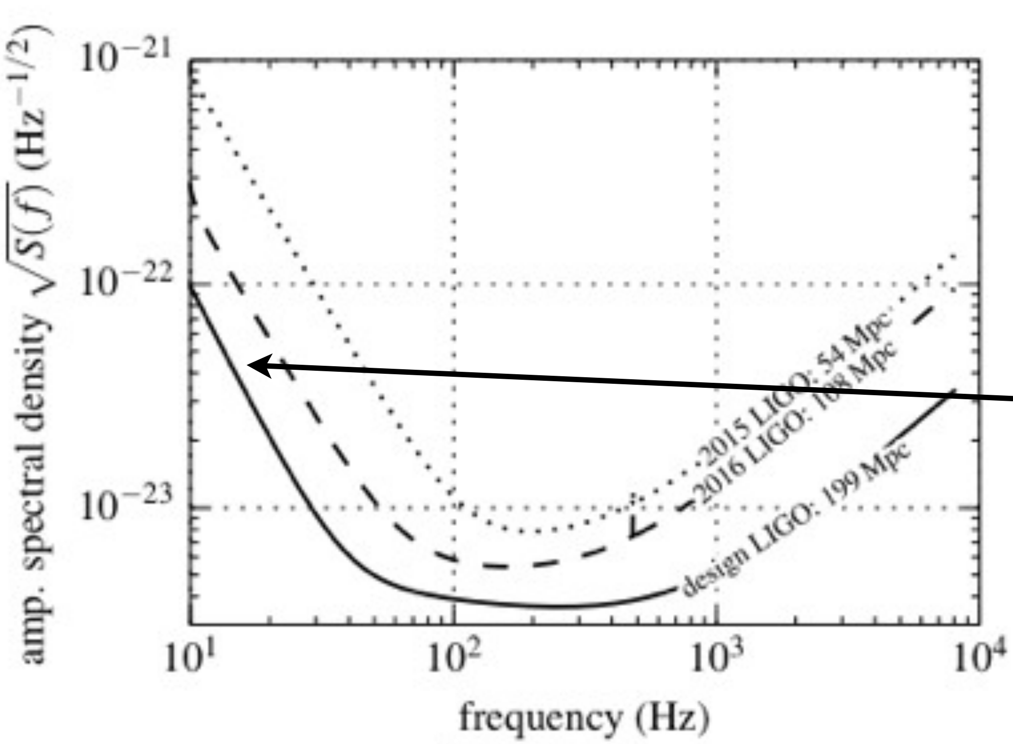
mass / spin estimates
and source orientation
in less than an hour



Scaling to Design Sensitivity Advanced LIGO

We can use any waveform in full design sensitivity advanced LIGO... *right now*





(a) LIGO

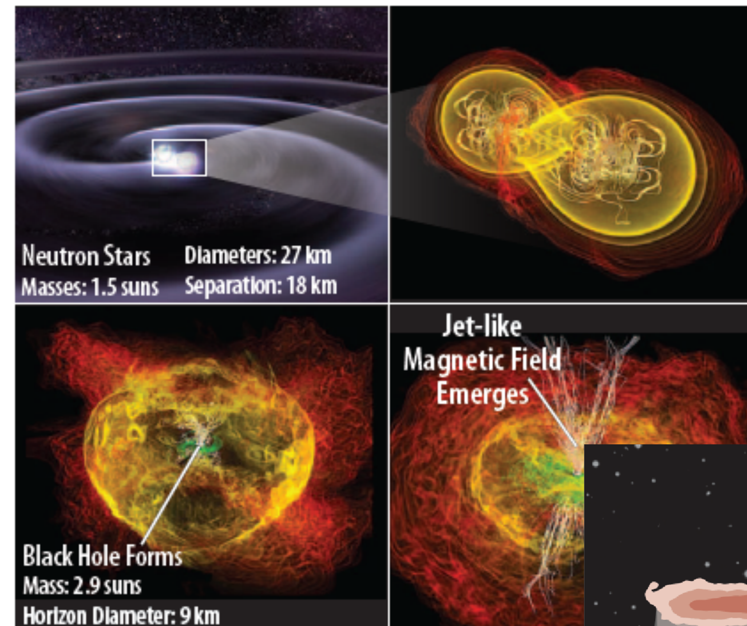
Increasing sensitivity at low frequency
Waveforms "in band" for up to 30 minutes!

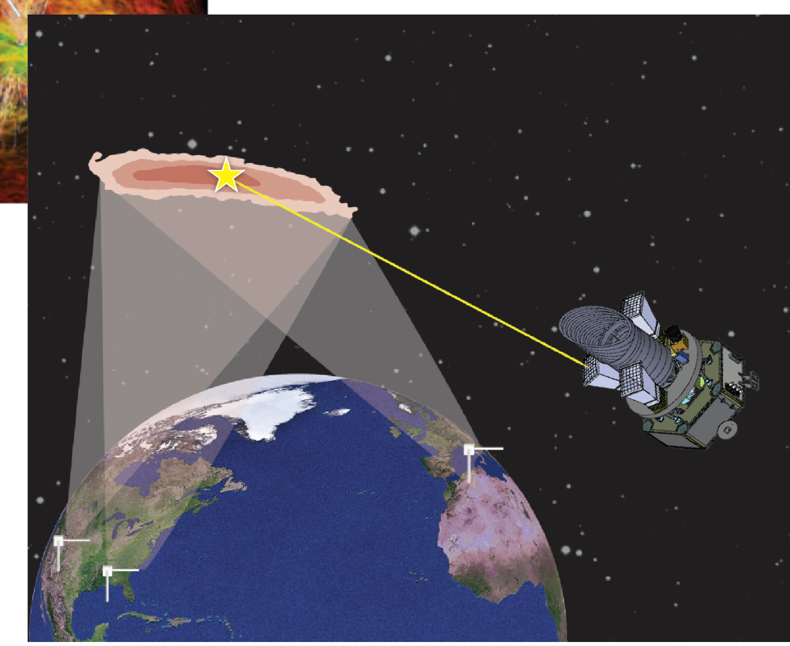
The Upshot

- Minimal parameter estimation (expanding into aligned spin) in **under an hour**
- Gearing up to be running in **near real time response** to LIGO-Virgo triggers in 2nd Observation Run
- **Extensible** and ready for observations **throughout the lifetime** of advanced interferometric instruments (up through 2018+)
- Extensions to **precessing spin** and **use of NR waveforms** has been done (**arxiv: 1606.01262**)
- ***Bring on the NSBH and BNS!***

Explorer for Transient Astrophysics (ETA)

- EM Followup of Gravitational Wave Detections (launch ~2023)
  - Wide-Field Imager (WFI) search for X-ray afterglows (and possibly prompt emission!)
  - IR Telescope search for kilonovae IR emission
  - Gamma-ray Transient Monitor (GTM)
- Early Universe Studies with High Redshift GRBs (out to z ~10 to 12)
  - IRT followup of GTM/ WFI detection
- X-ray Transient Sky
  - Tidal Disruption Events
  - SN Shock Breakouts

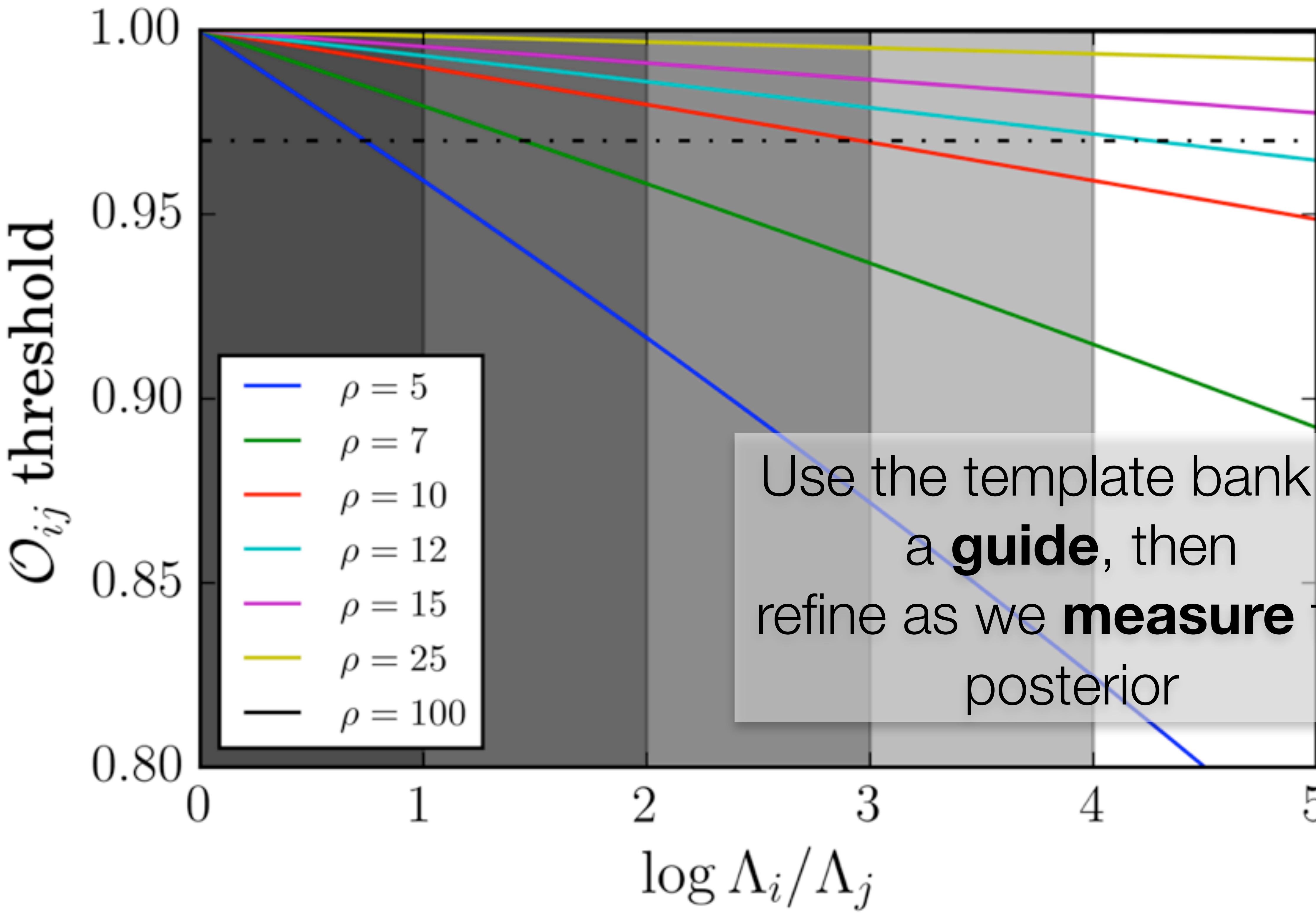




Several per year NS-NS and/or NS-BH

Increase range, confidence of LIGO detections
Precise localization of source (redshift)
Energetics of source
Relative speed of graviton and photon (10^{-17})

Extrapolating the Shape of the Likelihood



Use the template bank as a **guide**, then refine as we **measure** the posterior