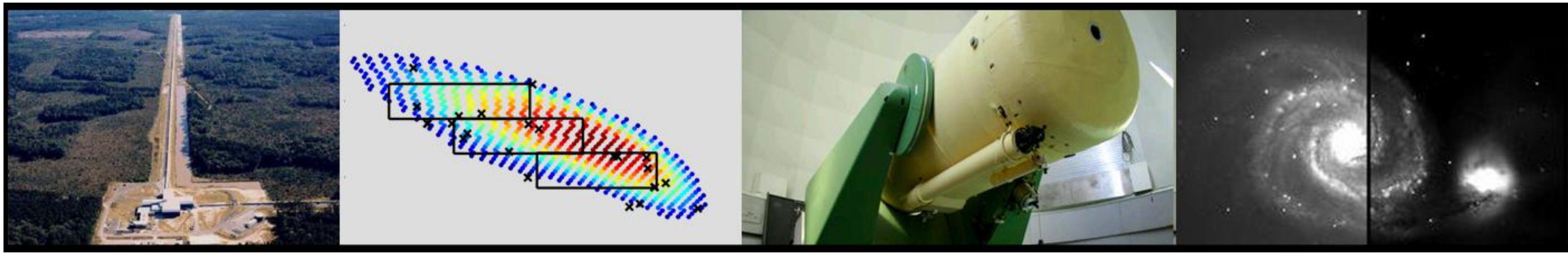


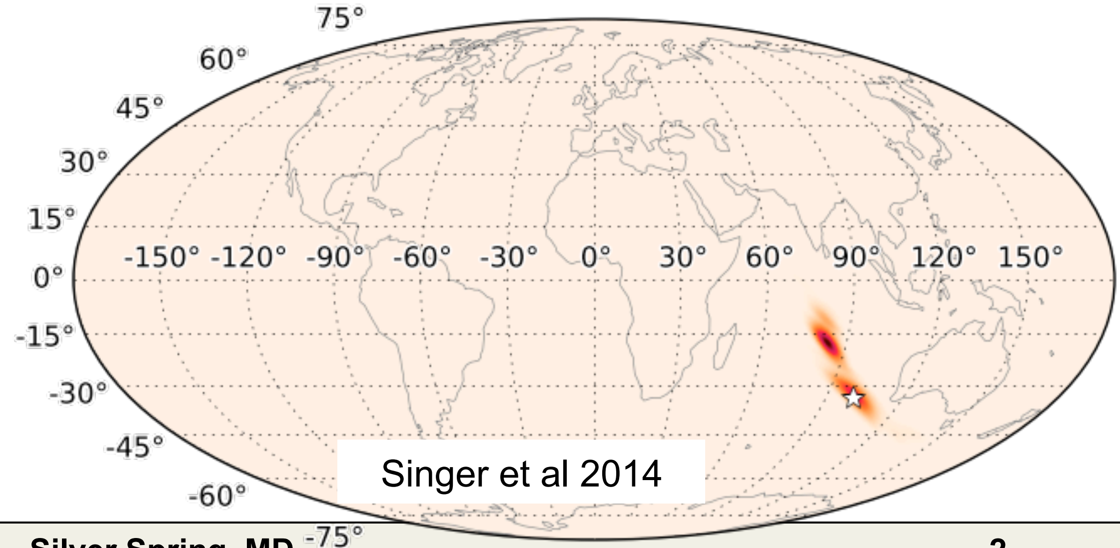
Dawn of GW Astrophysics: Multi-messenger Astronomy

Jonah Kanner
LIGO Lab - Caltech

LIGO-G1500579-v6

First 5 years: 2018-2023

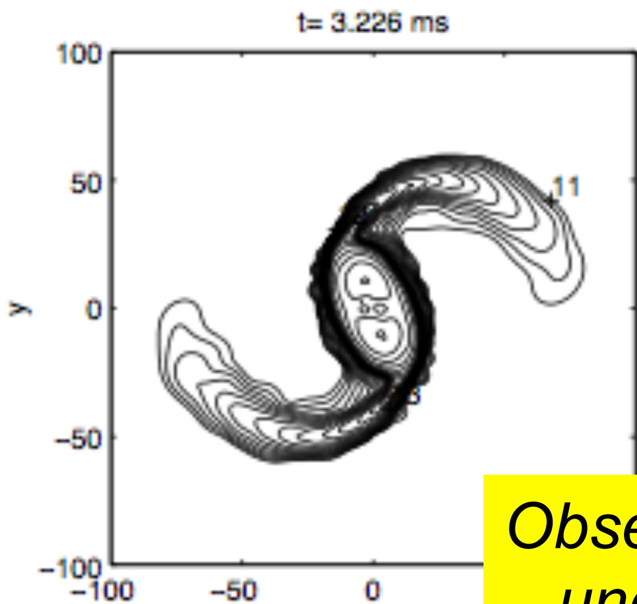
- LIGO + Virgo + Kagra + LIGO India
- 3, 4, or 5 detector network!
  - BNS Range to ~200 Mpc
  - Several to 10's of detections per year
  - Localizations of 10's to 100's of sq. deg.
    - or better!
  - Red-shift measurements for CBC sources



Singer et al 2014

What is the origin of heavy elements?

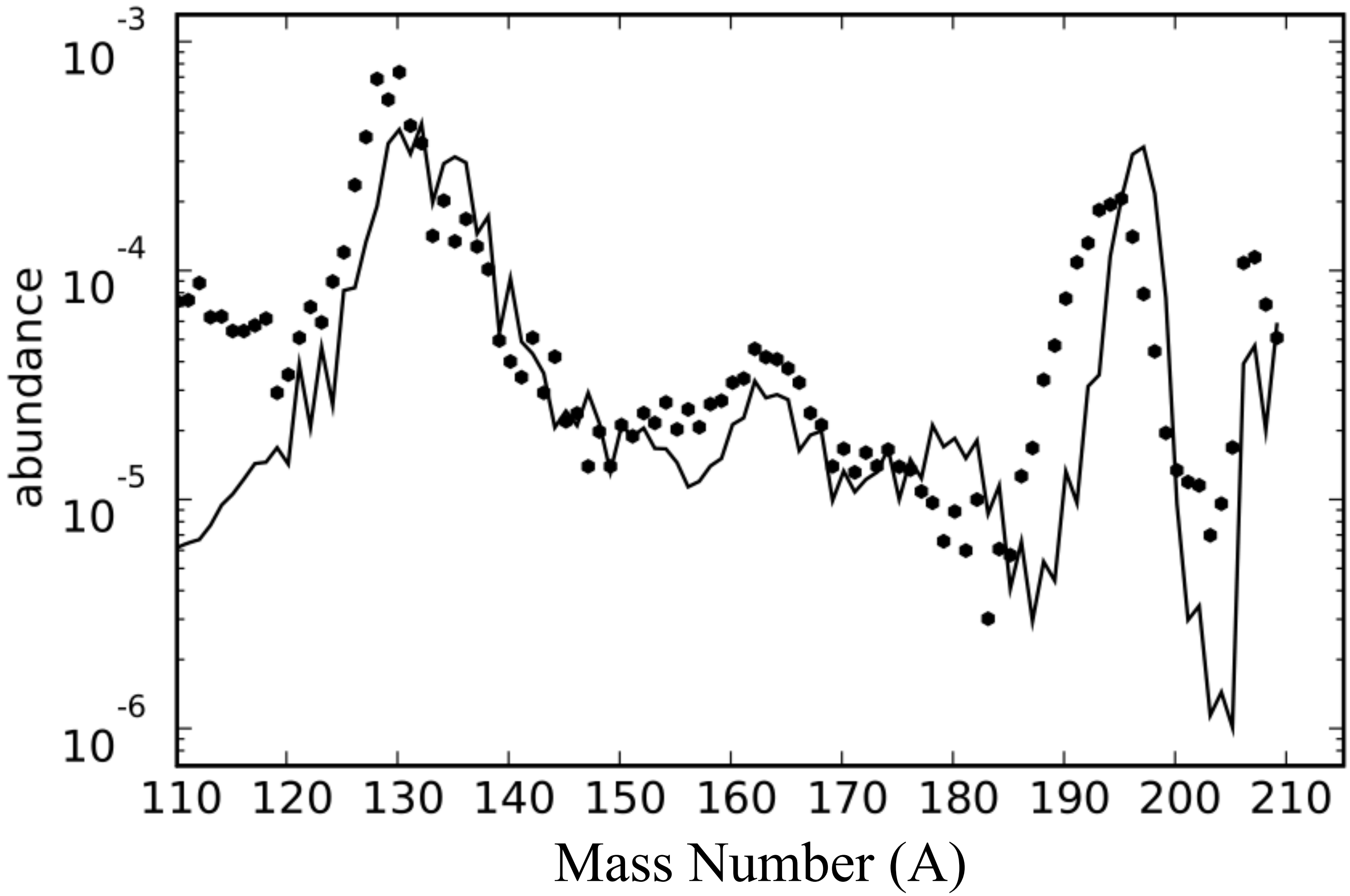
- Abundances of heavy elements (A > 90) not described by stellar processes or SN
- NS-NS / BH-NS merger seem good candidates – **observable as kilonova (~week long EM transient)**



Rosswog et al. 1999

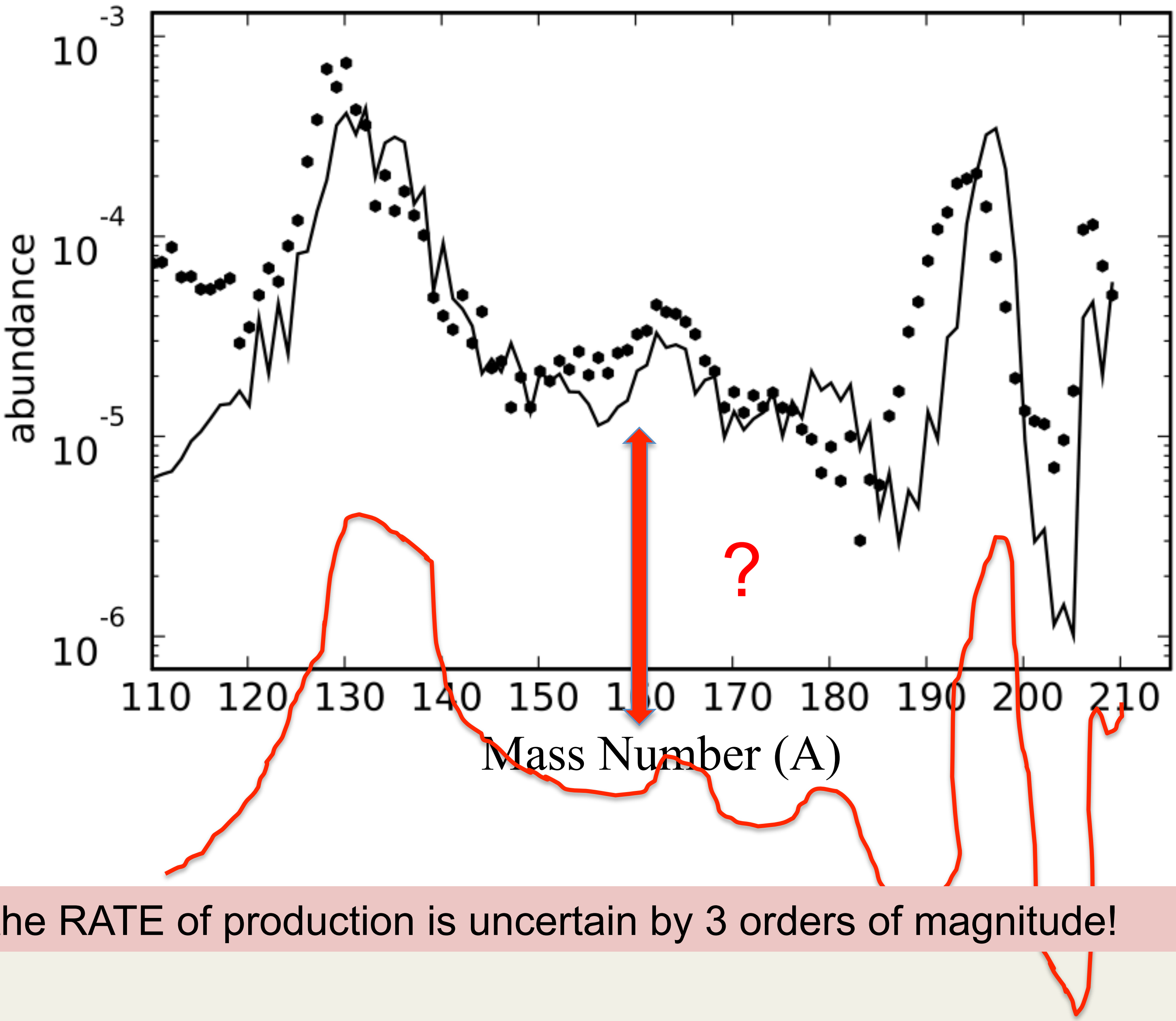
Observing kilonovae could help understand origin of matter!

Metzger et al. 2010



The RELATIVE abundances predicted from NS-NS mergers fits the observed distribution…

Metzger et al. 2010



But the RATE of production is uncertain by 3 orders of magnitude!

Quantify rate of heavy element production

Uncertainties in model include:

- **Rate of compact object mergers**
  - Measured population of LIGO events
- **Amount of ejecta from each merger**
  - Probed by luminosity and time-scale of Kilonova
- **BH-NS, NS-NS, or both** ?
  - Measured by GW parameter estimation

Kilonova + GW observations will provide a ***strong*** *test of this model*

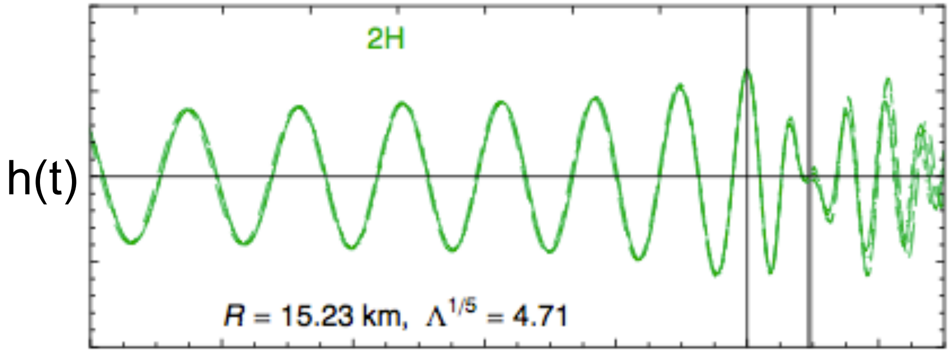
Coincident GRBs

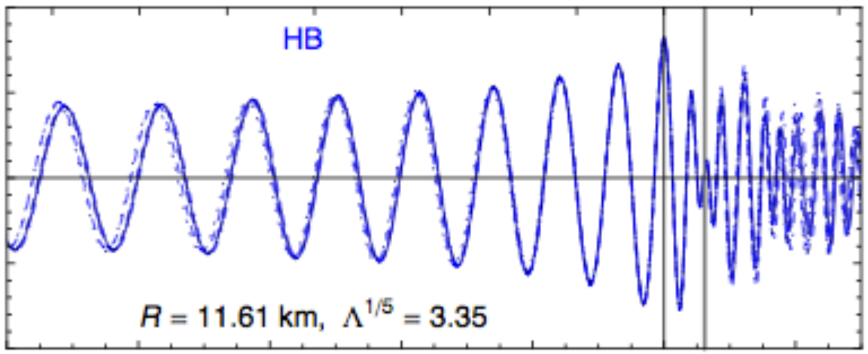
- ~2% of NS-NS mergers will have coincident GRB
  - Could see one or a few in the first few years
    - Never measured a GRB red-shift within LIGO/Virgo horizon
- **Making this connection will probe many science questions**
  - Sources of short GRBs
  - Beaming angles
  - Source population
    - Relationship to host galaxy
    - Mass distribution
    - NS-NS or BH-NS
  - Clues to jet structure / formation
  - Timing between GW and GRB will give clues to source physics, maybe equation of state

Image credit: NASA / Swift / Cruz deWilde.

Neutron Star Equation of State

- **High SNR mergers are key**
- Many possible ways to probe this:
  – Tidal deformation perturbs GW phase
  – Remnant NS post-merger signal peak frequency
  – Amount of mass ejected in Kilonova
    - Measure ejected mass through luminosity/timing
  – Relative timing of GW and GRB signal (?)
  – Existence of GRBs for NS-BH systems





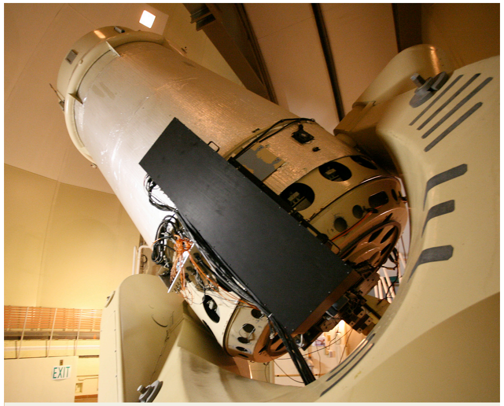
Enabling the Science

GRB all-sky coverage: CubeSats

- Current GRB observatories (Fermi, Swift) may not last through this era
- Space agencies will *probably* continue observing GRBs
  - Many proposed missions
  - SVOM scheduled for 2021
- CubeSats could fill a potential gap
  - All-sky GRB monitoring … in a box!
  - Low cost point
- Proposal in progress from Goddard
  - PI: Jeremy Perkins

Data Mining and Follow-up for big surveys

- Finding a kilonova demands survey in the red or infrared
- Modern/Future surveys should be capable
  - Pan-STARRS, ZTF, **DES, LSST** …
- Data rates will be … big
  - 20 TB per night (LSST)
  - 400 GB per night (DES)
- **False positives will be a major issue**



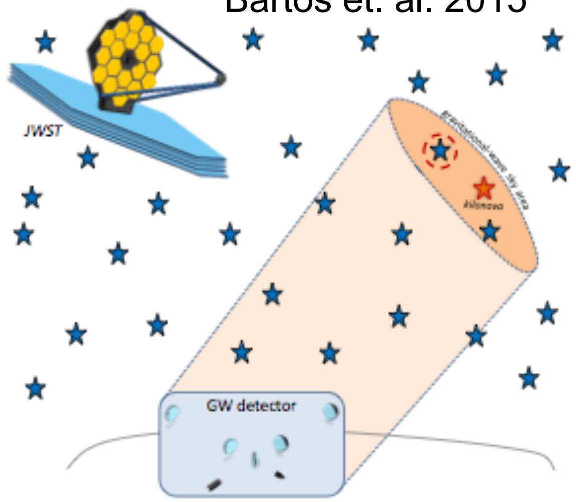
Palomar 60 inch

- May be an opportunity to provide **specialized computing** hardware/software for GW counterparts
- May need resources for kilonova **candidate validation and photometric follow-up**
  - People, telescopes, and/or computers may all be needed
  - Build/re-purpose **a dedicated, ~2 m follow-up instrument?**

Collect / Curate / Validate Galaxy Catalog

- Some facilities may depend on a galaxy catalog to find LIGO counterparts
  - Swift, JWST (?), …
- A validated, public catalog enables:
  - Enhanced LIGO data products
  - Small FOV instruments to seek candidates
  - A range of studies
- Work on this already in progress (e.g. Kasliwal), but **extra resources needed to collect, validate, and curate a catalog**

Bartos et. al. 2015



More Events -> More science

- EM counterpart rate will be a fraction of LIGO BNS rate
  - Coincident GRBs will be ~2% of LIGO BNS rate
  - As a *guess,* observed Kilonovae will be ~10% of LIGO BNS
- Small number of observed EM counterparts:
  < 10 per year
- 30% gain in **LIGO BNS range** would double this!
  - A small change in LIGO sensitivity makes a big difference
- Probably means improving low frequency (20-300 Hz) sensitivity
  - **FOM: BNS Range**

Match GW sensitivity across network

- Search area very sensitive to number of **equally sensitive detectors** in network
  - 2 IFO -> ~400 sq deg
  - 3 IFO -> ~100 sq deg
  - 4 IFO -> ~10 sq deg
- **Improving poorest performing detector** may be best "bang-for-buck" for multi-messenger astronomy if detections are common-place
  - If detections are very few, may be better to improve 2 most sensitive detectors to improve rates

SNR at the merger

- High SNR events help with big questions
  - NS equation of state, parameter estimation, tests of GR
  - Small gains in sensitivity could make a big impact
  - SNR 20 is a lot better than SNR 12
- Lots of interesting science at moment of merger
  - Tidal stretching, NS resonant frequencies, extreme gravity
  - Key for position reconstruction
- Points to improvements at **LIGO high frequency**
  - 1-3 kHz range
  - May also be a key range for galactic events, if we find them!

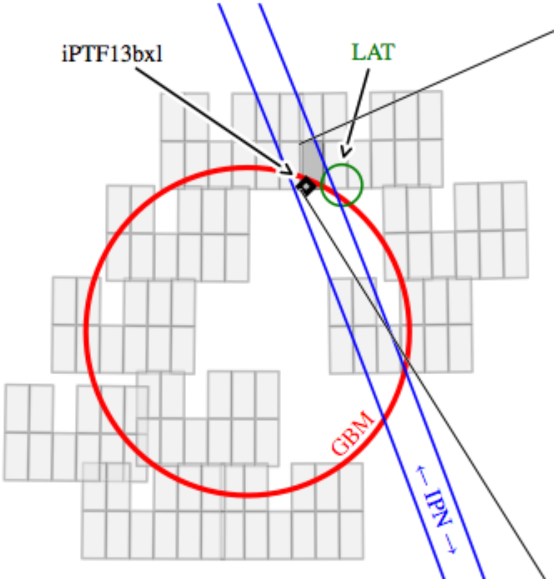
Summary

- **Improving the GW network benefits multi-messenger astronomy**
  - Improve BNS range for more sources
  - Match sensitivity across network for localization
  - Improve high freq. noise for more SNR at merger
- **Could try to patch “holes” in EM landscape**
  - CubeSats to monitor for GRBs
  - Follow-up / Data Mining for large NIR surveys
  - Validate / Curate galaxy catalog

Thank you!

Extra slides

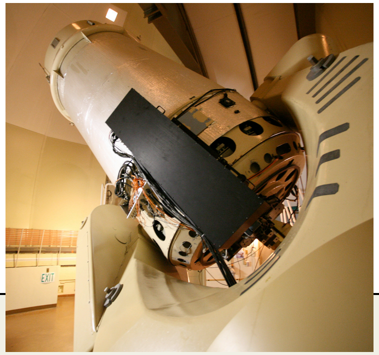
The follow-up bottleneck



70 sq deg survery:
27,000 variable objects

Pass automated cuts:
43 Candidates

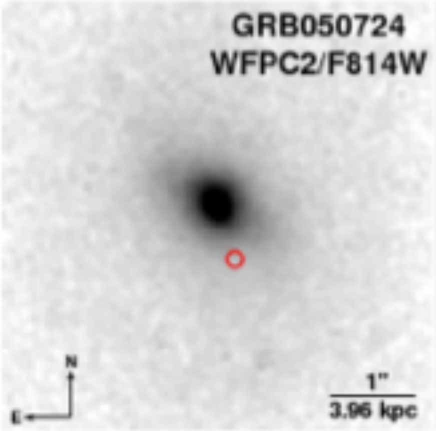
"Inspection" by
graduate student:
7 candidates



"Narrow Field" follow-up:
1 Counterpart + light curve + photometry

Numbers from
Singer et. al. 2013

Host Galaxies



Fong, Berger, & Fox 2010

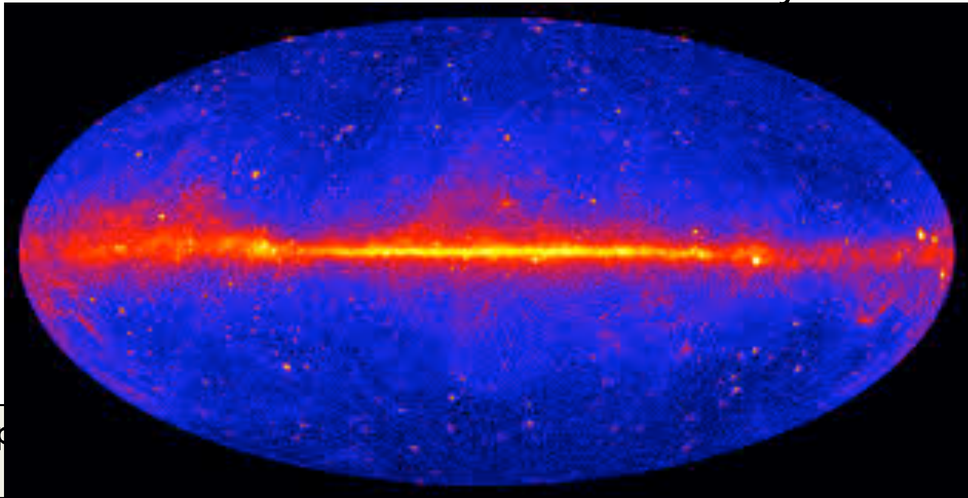
Imagine we find some EM+GW signals:

- **Can localize sources in host galaxy**:
  - What types of galaxies host mergers?
    Does this depend on mass/spin parameters?
  - Tells if binaries trace star formation
    - Is the merger in an area of active star formation?
    - What type of host galaxy?
    - Distinguish NS-NS and NS-BH, which we can't for SGRBs
  - Is the merger well outside the galaxy?
    - Probes time until merger
    - Constrain population synthesis
    - Learn about strengths of kicks from SN – probes SN physics

Possible Surprise: Galactic Sources?

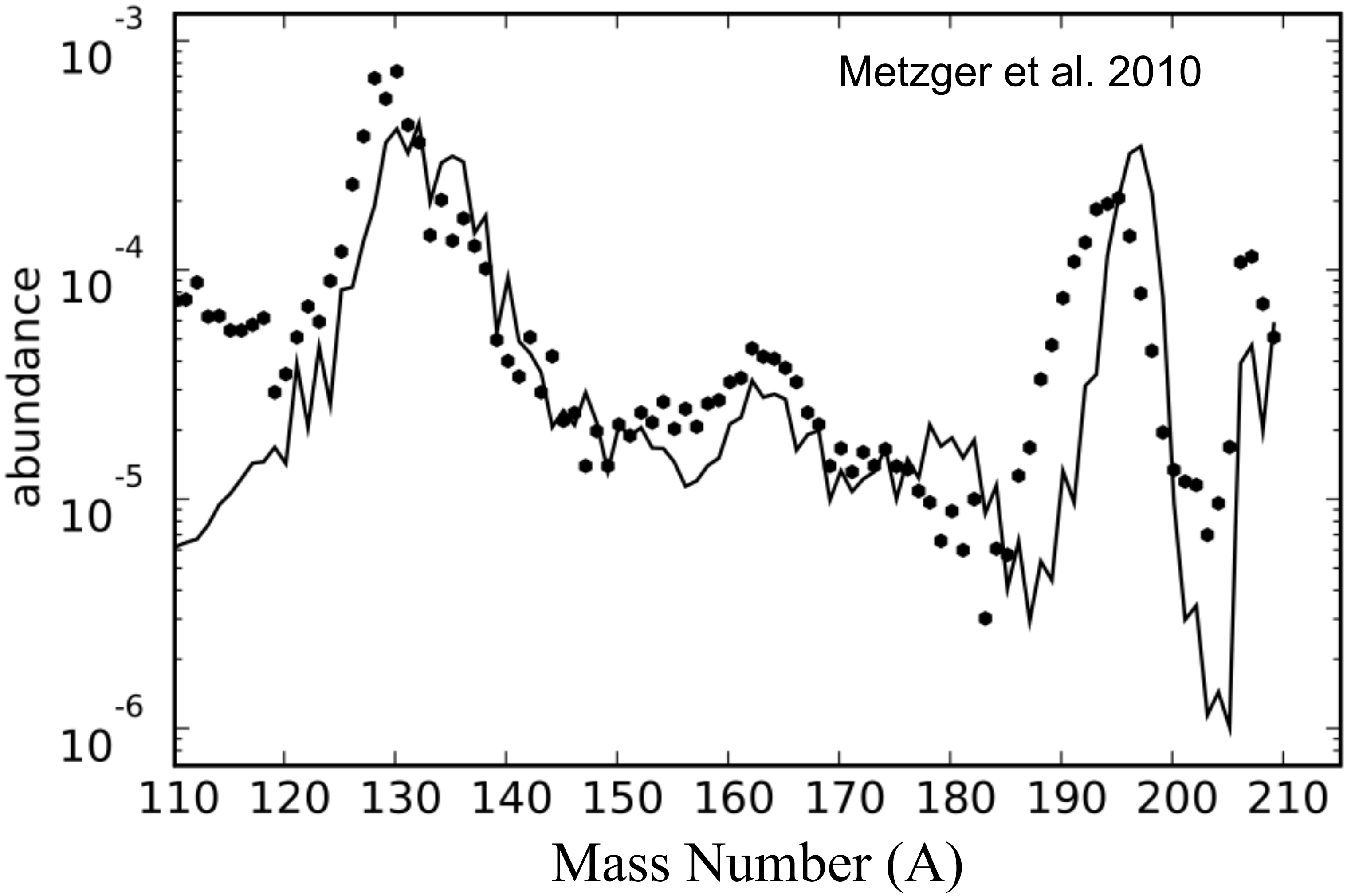
- All EM bands are dominated by galactic sources
  - **Maybe GW will be too?**
- Pulsars, R-modes, neutron star hyper flares …
- Much of this would be at high frequencies
  - NS resonant frequencies around ~1-3 kHz
  - Supernovae have GW content up to ~3kHz

The Fermi LAT sky



Radio Pulses / FRBs ?

- A variety of models suggest radio emission from NS-NS mergers
- There may be a coherent pulse near the time of merger
  - May be a fraction of Fast Radio Bursts (“Lorimer” Bursts)
- Wide field radio arrays may find these in coincidence with GW signal
  - Help understand “coherent” emission
  - Exciting new field of wide field radio astronomy
  - Early sky position may help!



Model based on NS-NS ejecta (solid)
Measured Solar system abundance (dots)
Overall scale of model is normalized to fit observations

The Loudest GW Event

- ~40 events at SNR 8 (250 Mpc)
  → 1 event at SNR 27 (70 Mpc)
- Easy to find counterpart
  - Few possible hosts
  - Bright! Long lived!
- High SNR signal gives many details
  - Better estimate of masses, spins, etc
  - Measure NS Equation of State!
  - Test General Relativity!
  - High resolution image of host galaxy

Some other possible astrophysics targets

- Supernovae,
- Neutrino alerts,
- IMBH,
- measuring the Hubble parameter,
- Dark Matter halos,
- SGRs
- Etc …