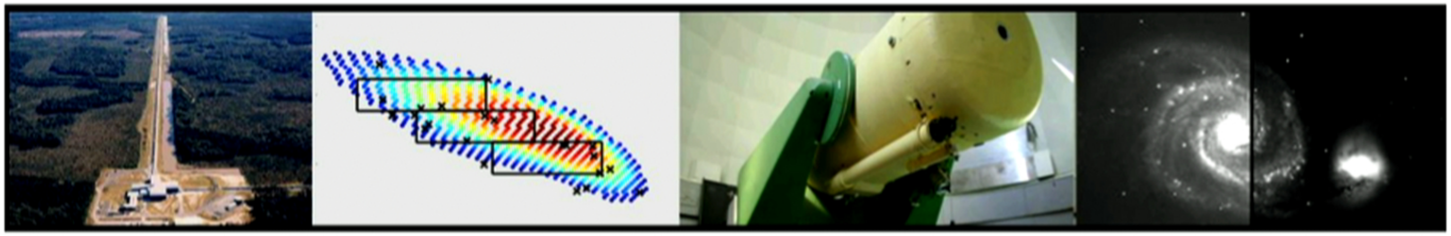
Title: Exploring astrophyiscs with gravitational waves

Date: Oct 22, 2015 01:00 PM

URL: http://pirsa.org/15100052

Abstract: <p>Advanced LIGO has recently started operating, with the promise that discoveries of gravitational wave transients will begin within in the next few years. As astrophysical observatories, LIGO and similar experiments may inform our knowledge of a variety of topics, including heavy element formation, dynamical capture of black holes, and the neutron star equation of state. In this talk, I will highlight recent efforts to quickly identify and distribute transients found with LIGO, and explore some of the astrophysics questions we hope to address.</p>



Exploring astrophysics with gravitational waves

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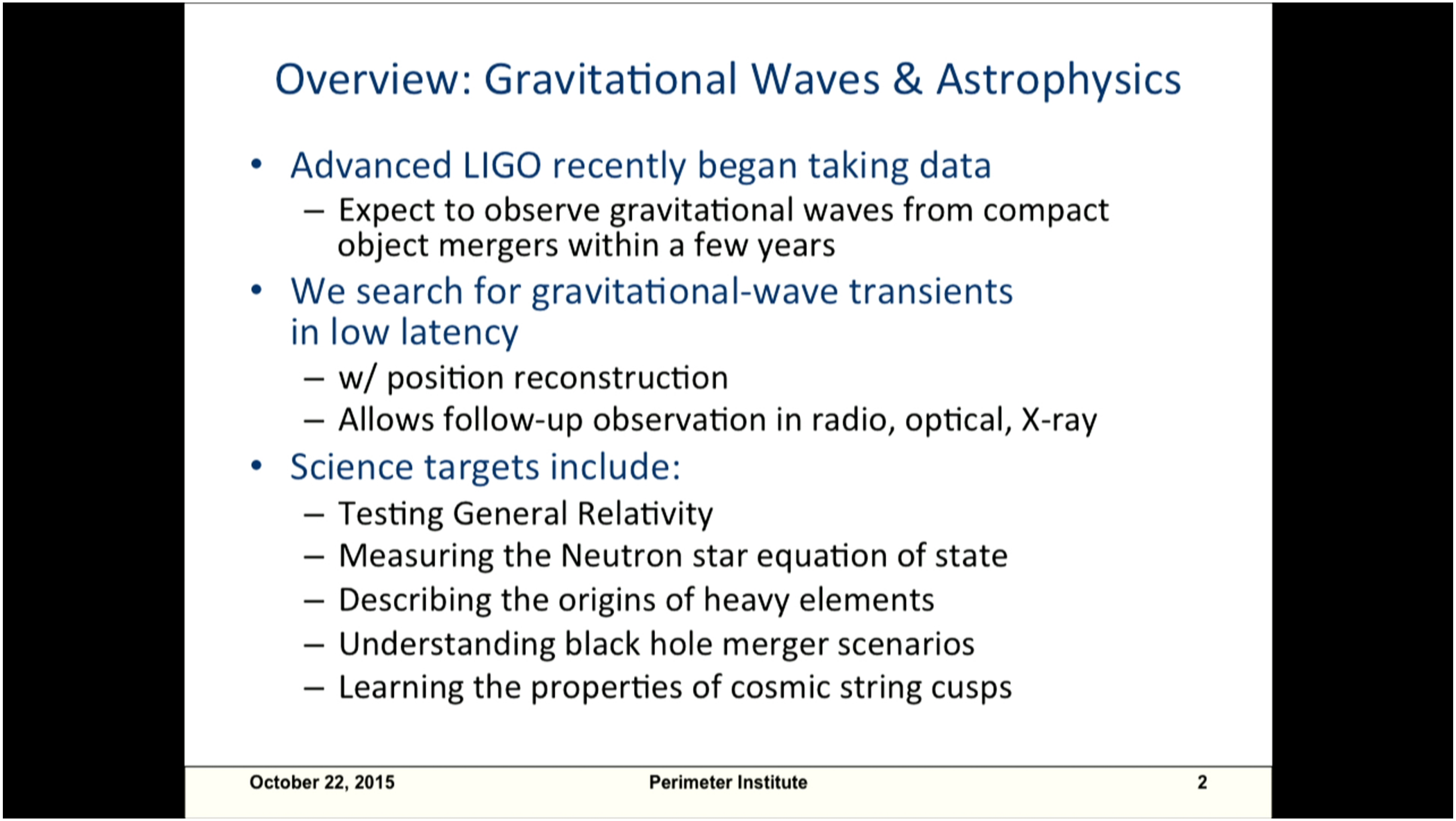
LIGO-G1501258-v2



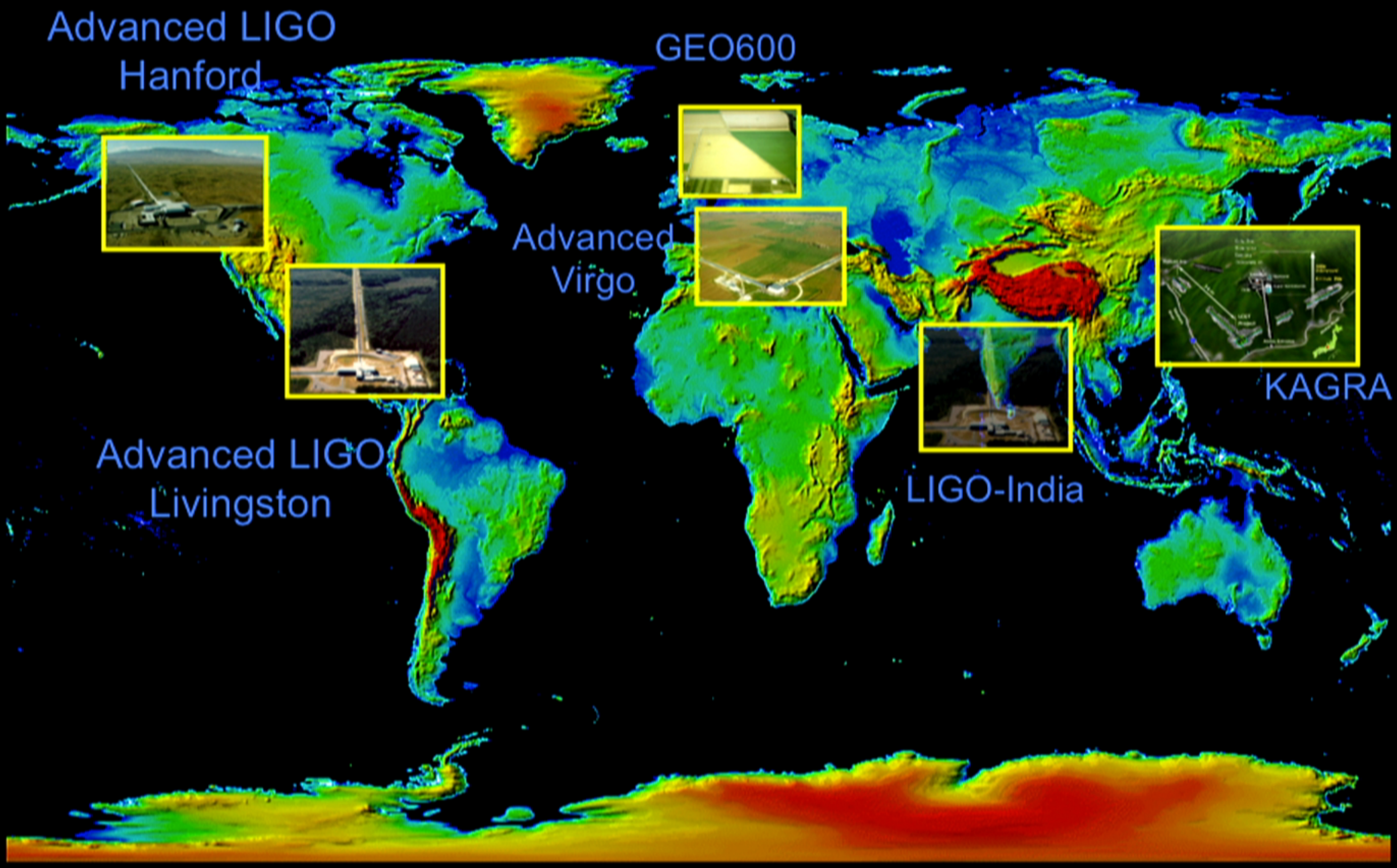
Overview: Gravitational Waves & Astrophysics

- Advanced LIGO recently began taking data
  - Expect to observe gravitational waves from compact object mergers within a few years
- We search for gravitational-wave transients in low latency
  - w/ position reconstruction
  - Allows follow-up observation in radio, optical, X-ray
- Science targets include:
  - Testing General Relativity
  - Measuring the Neutron star equation of state
  - Describing the origins of heavy elements
  - Understanding black hole merger scenarios
  - Learning the properties of cosmic string cusps

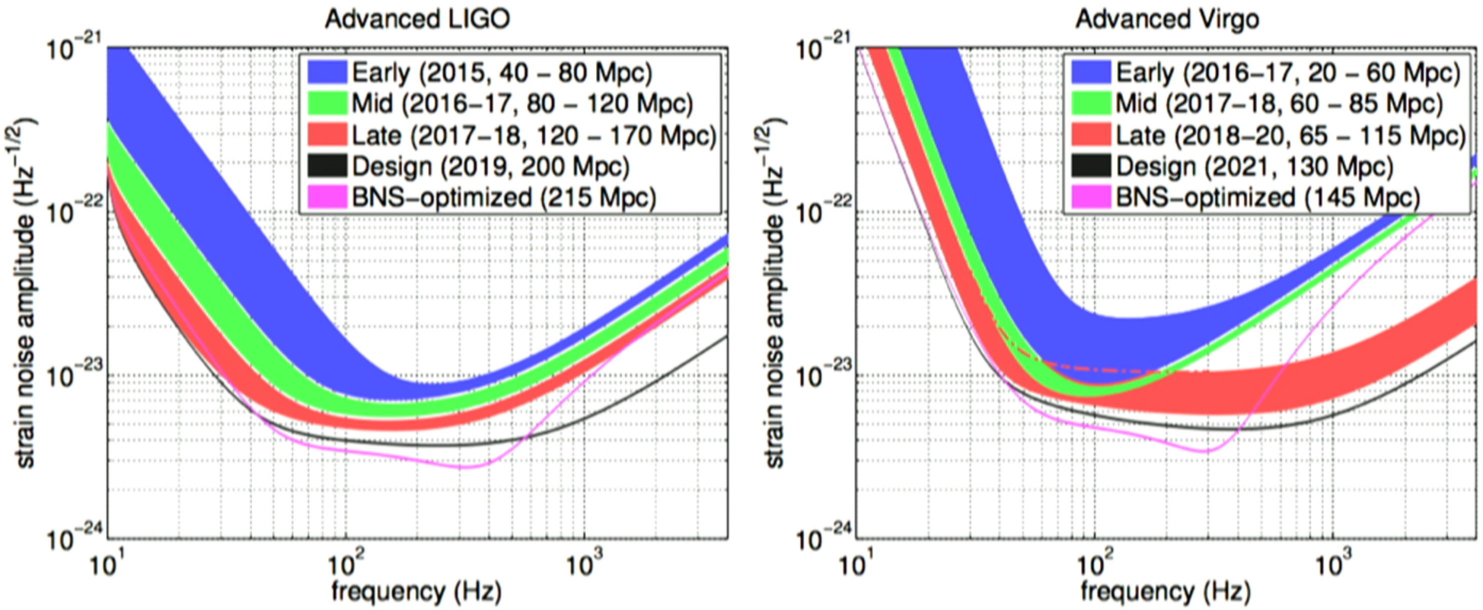
Advanced LIGO

- 4 kilometer gravitational wave detectors
- GW strain ($\Delta L/L$) ~ 10^{-22}
- Detectors in
  Hanford, WA
  and Livingston, LA
  - Partners include GEO, Virgo, and Kagra

The GW Detector Network~2020



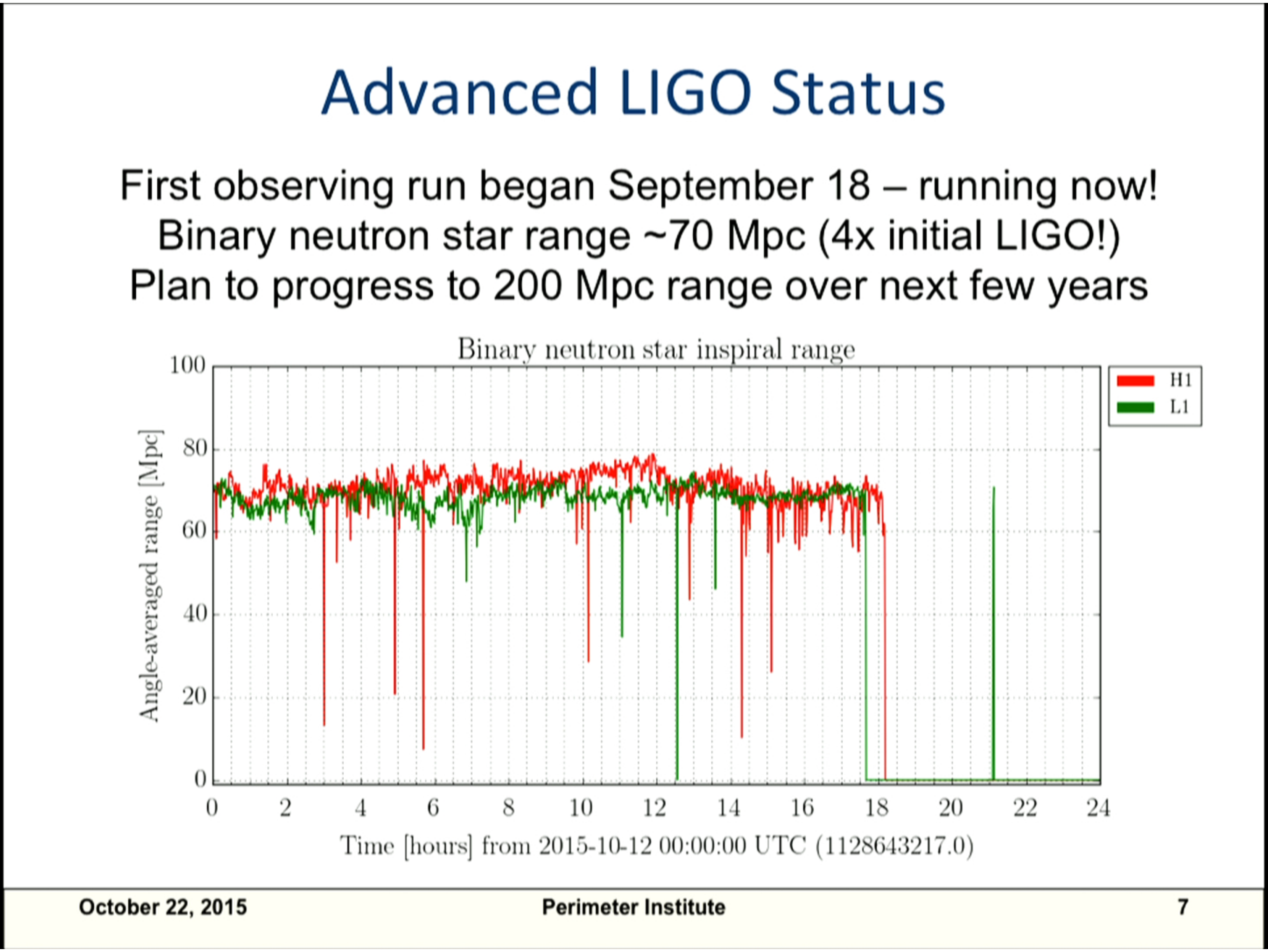
Advanced LIGO/Virgo Possible Timeline



Plan: Sensitivity grows over the next ~5 years

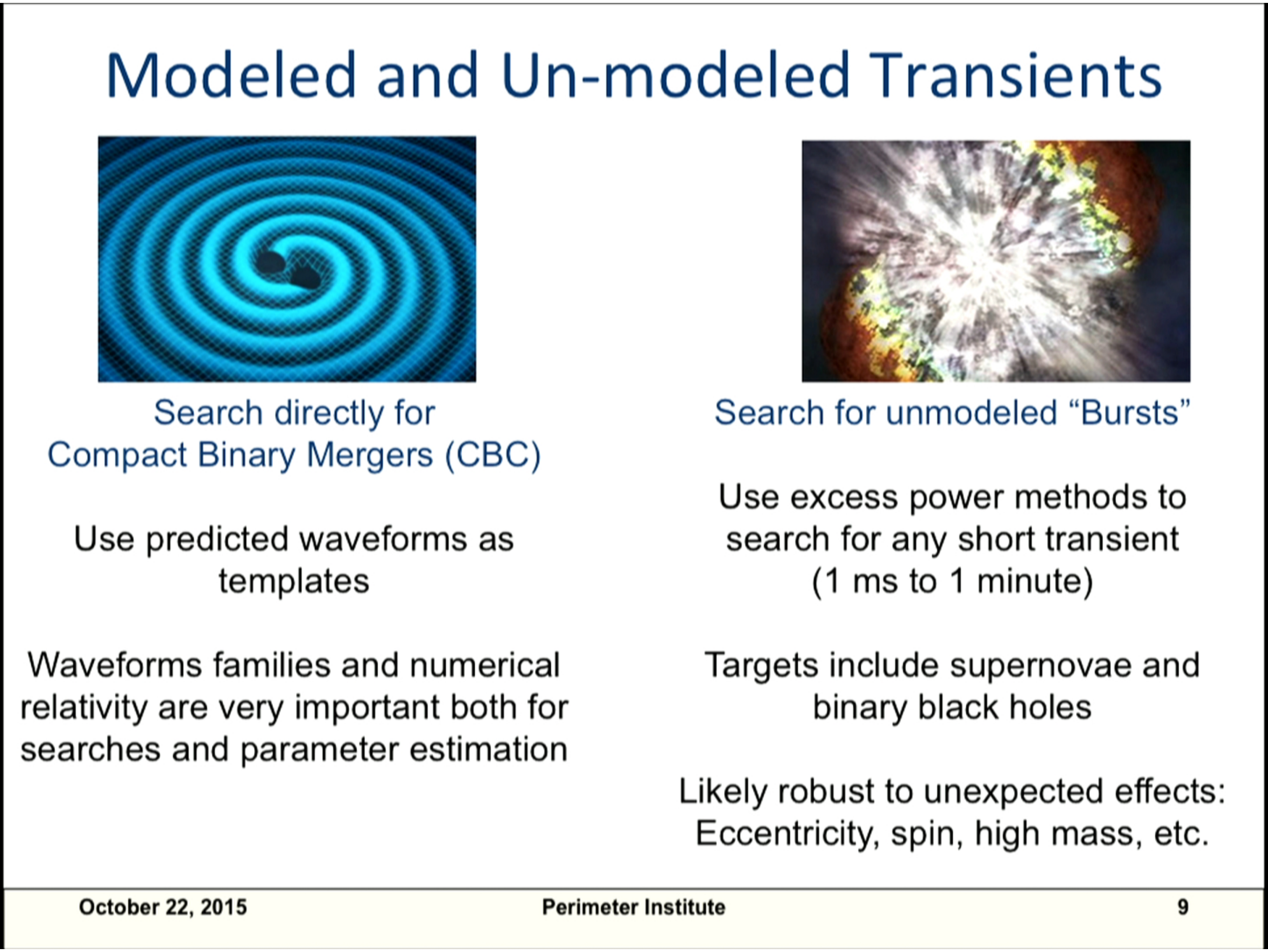
Ranges are sky-averaged distance to which a binary neutron star is visible

Expect ~10’s of binary neutron star mergers per year at design sensitivity



Advanced LIGO Status

First observing run began September 18 – running now!
Binary neutron star range ~70 Mpc (4x initial LIGO!)
Plan to progress to 200 Mpc range over next few years



Modeled and Un-modeled Transients

Search directly for
Compact Binary Mergers (CBC)

Use predicted waveforms as templates

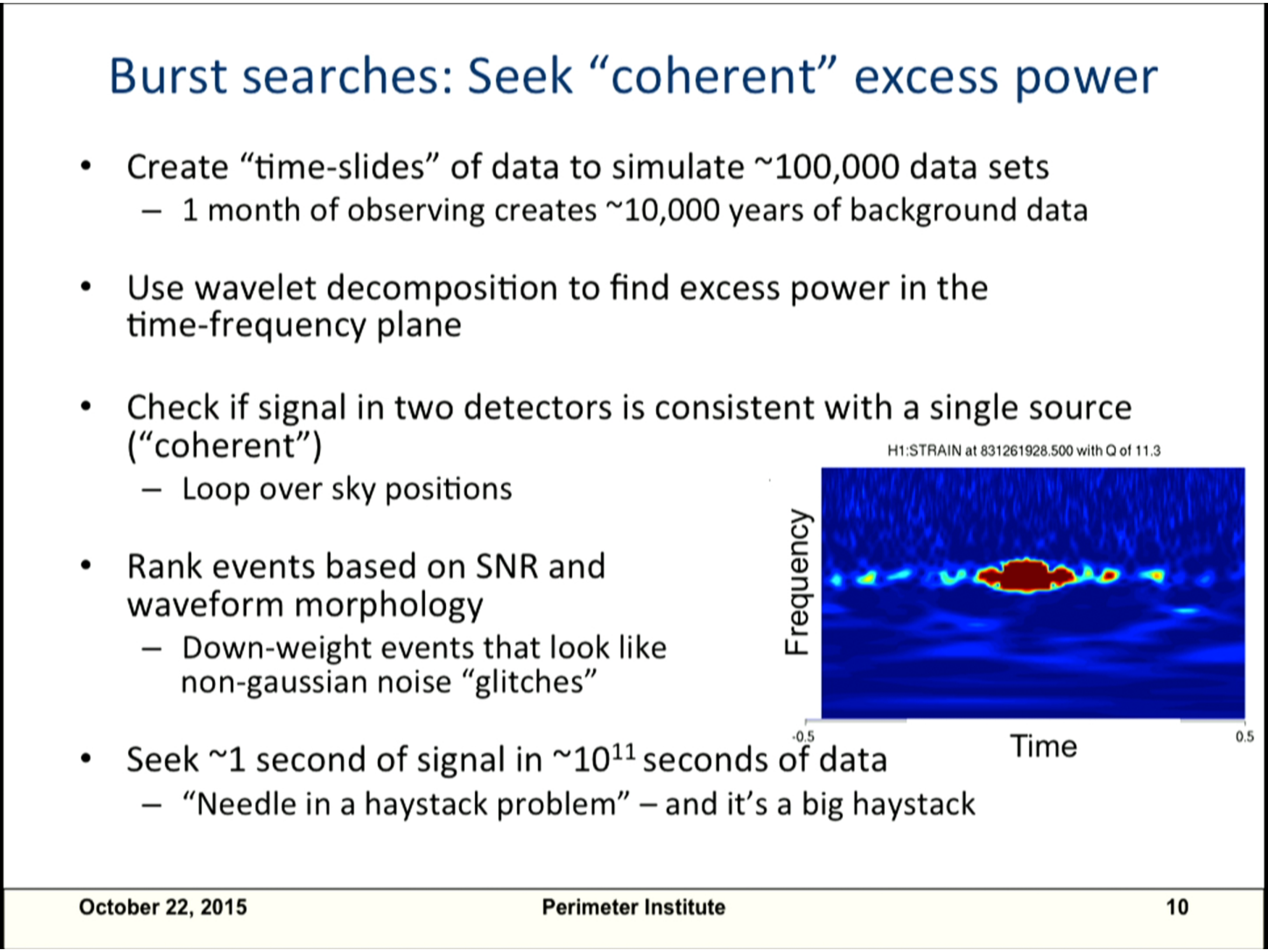
Waveforms families and numerical relativity are very important both for searches and parameter estimation

Search for unmodeled “Bursts”

Use excess power methods to search for any short transient (1 ms to 1 minute)

Targets include supernovae and binary black holes

Likely robust to unexpected effects: Eccentricity, spin, high mass, etc.



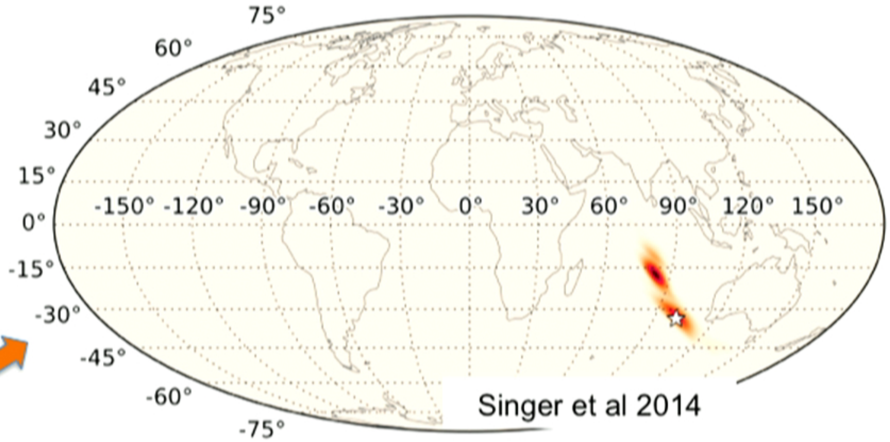
Burst searches: Seek "coherent" excess power

- Create "time-slides" of data to simulate ~100,000 data sets
  - 1 month of observing creates ~10,000 years of background data
- Use wavelet decomposition to find excess power in the time-frequency plane
- Check if signal in two detectors is consistent with a single source ("coherent")
  - Loop over sky positions
- Rank events based on SNR and waveform morphology
  - Down-weight events that look like non-gaussian noise "glitches"
- Seek ~1 second of signal in ~10^{11} seconds of data
  - "Needle in a haystack problem" – and it's a big haystack

Low latency analysis

Transient searches performed in low latency (~10 minutes)

Includes source position estimate



Singer et al 2014

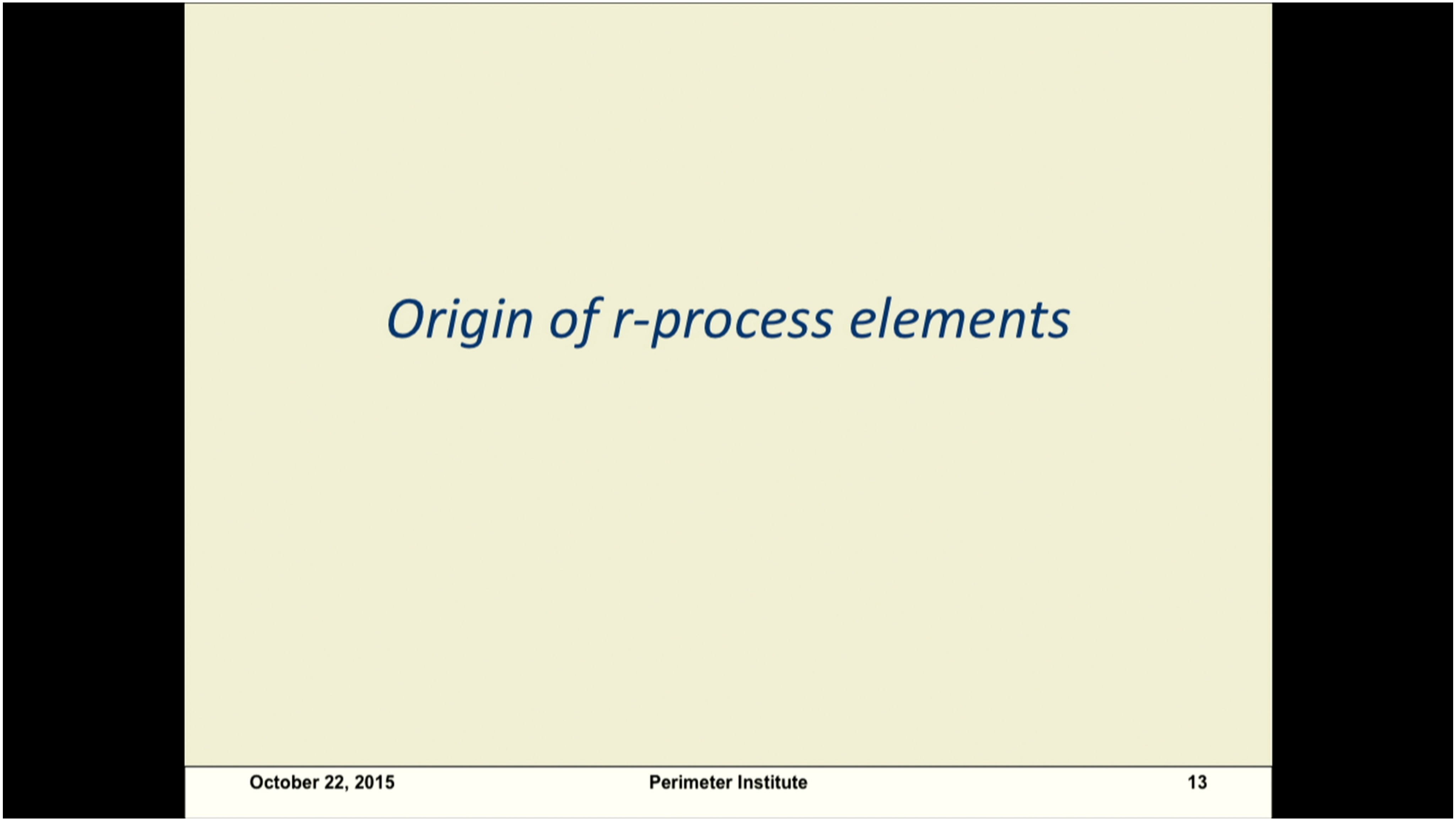
Allows radio, optical, and X-ray observatories to look for counterparts

Access to LIGO data

- Low latency triggers
  - Partner with astronomers to seek EM counterparts
  - Over 60 MOU partners part of this program
- Time series data available through the LIGO Open Science Center (LOSC)
  - https://losc.ligo.org/
  - Data from initial LIGO now public
  - Tutorials, examples, segments, and more
- Any published discoveries will have h(t) data released
  - Run your own analysis
  - Extract source physics, test GR, etc

LIGO Open Science Center

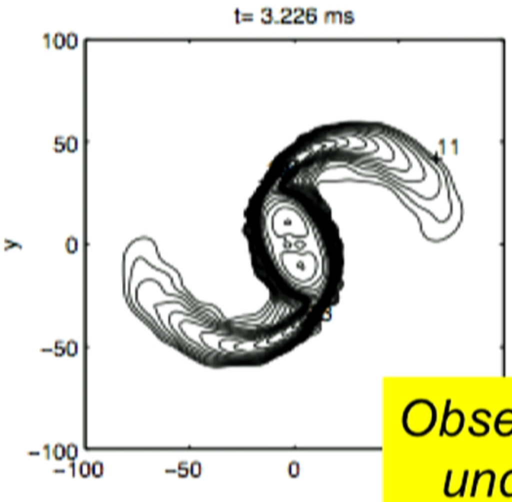
LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.



Origin of r-process elements

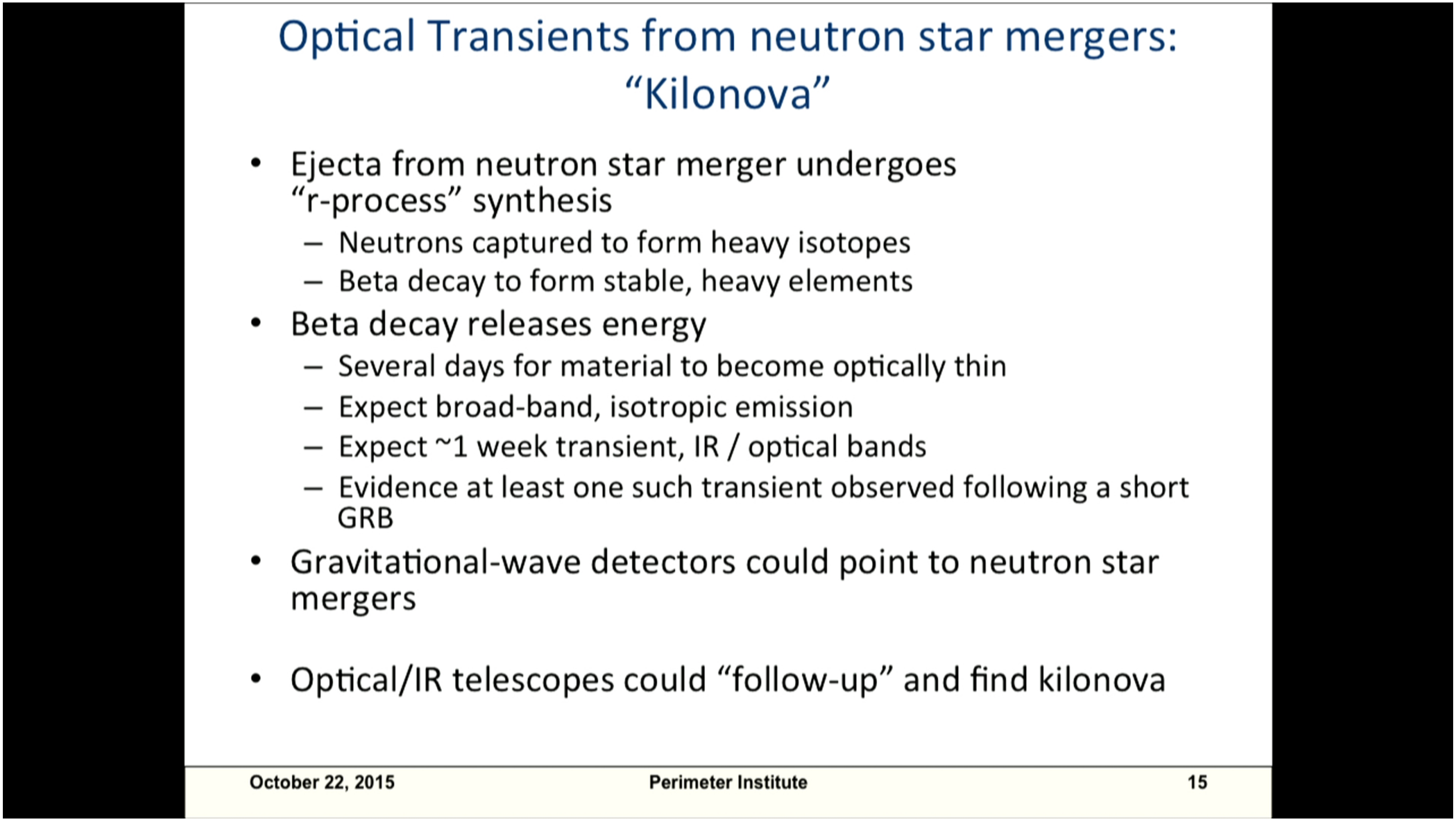
What is the origin of heavy elements?

- 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!



Optical Transients from neutron star mergers: “Kilonova”

- Ejecta from neutron star merger undergoes “r-process” synthesis
  - Neutrons captured to form heavy isotopes
  - Beta decay to form stable, heavy elements
- Beta decay releases energy
  - Several days for material to become optically thin
  - Expect broad-band, isotropic emission
  - Expect ~1 week transient, IR / optical bands
  - Evidence at least one such transient observed following a short GRB
- Gravitational-wave detectors could point to neutron star mergers

- Optical/IR telescopes could “follow-up” and find kilonova

Observed Kilonova Candidate

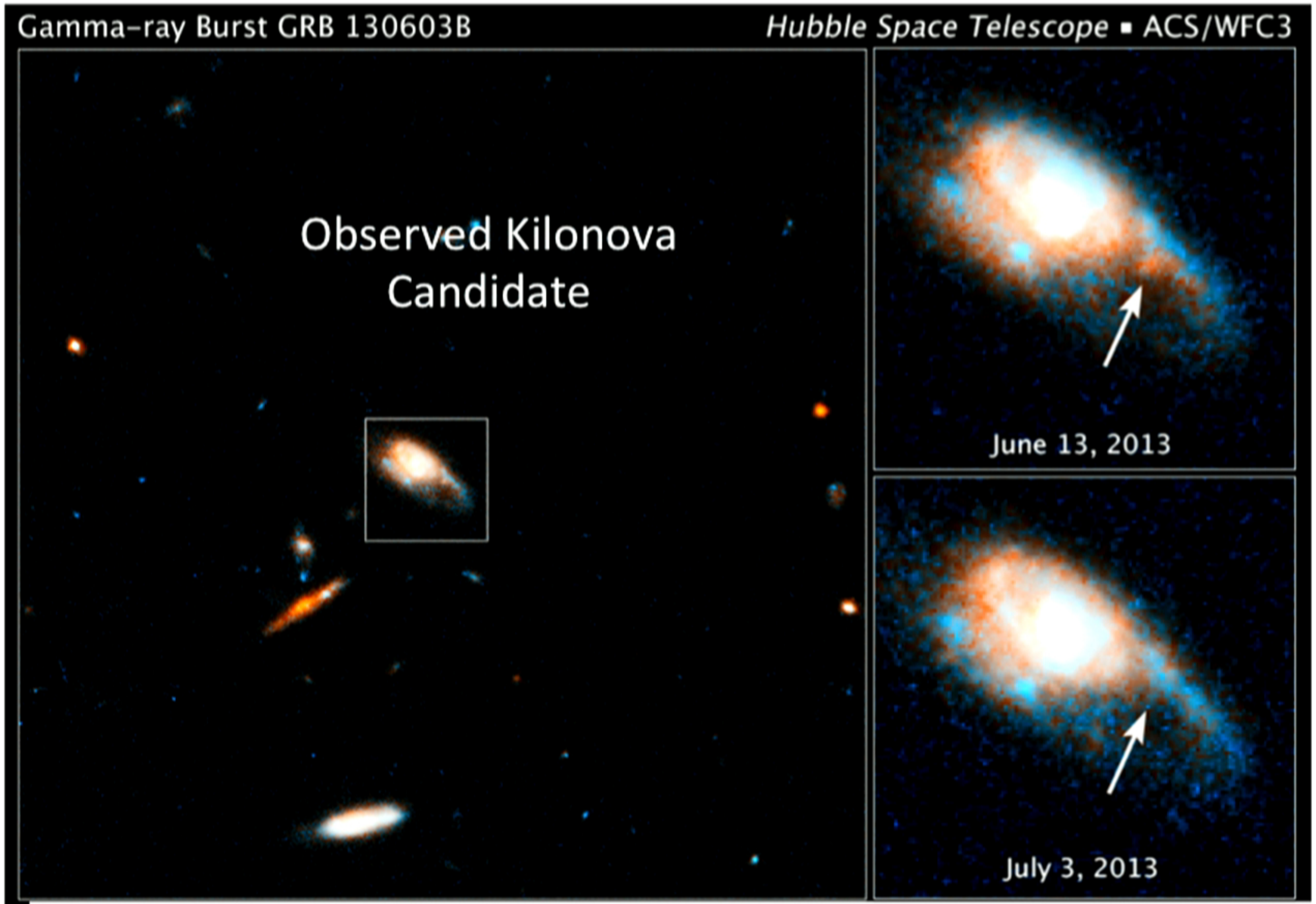
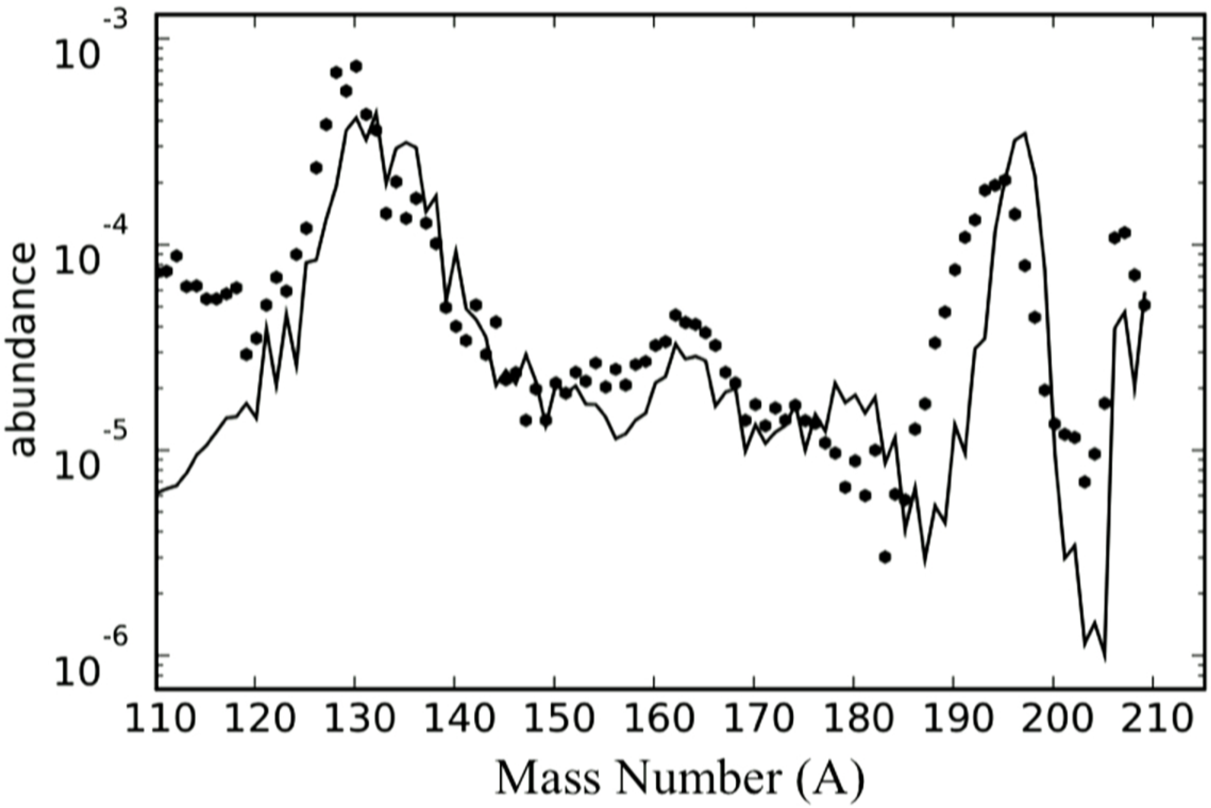


Image: NASA, ESA, N. Tanvir (University of Leicester), A. Fruchter (STScI), and A. Levan (University of Warwick)

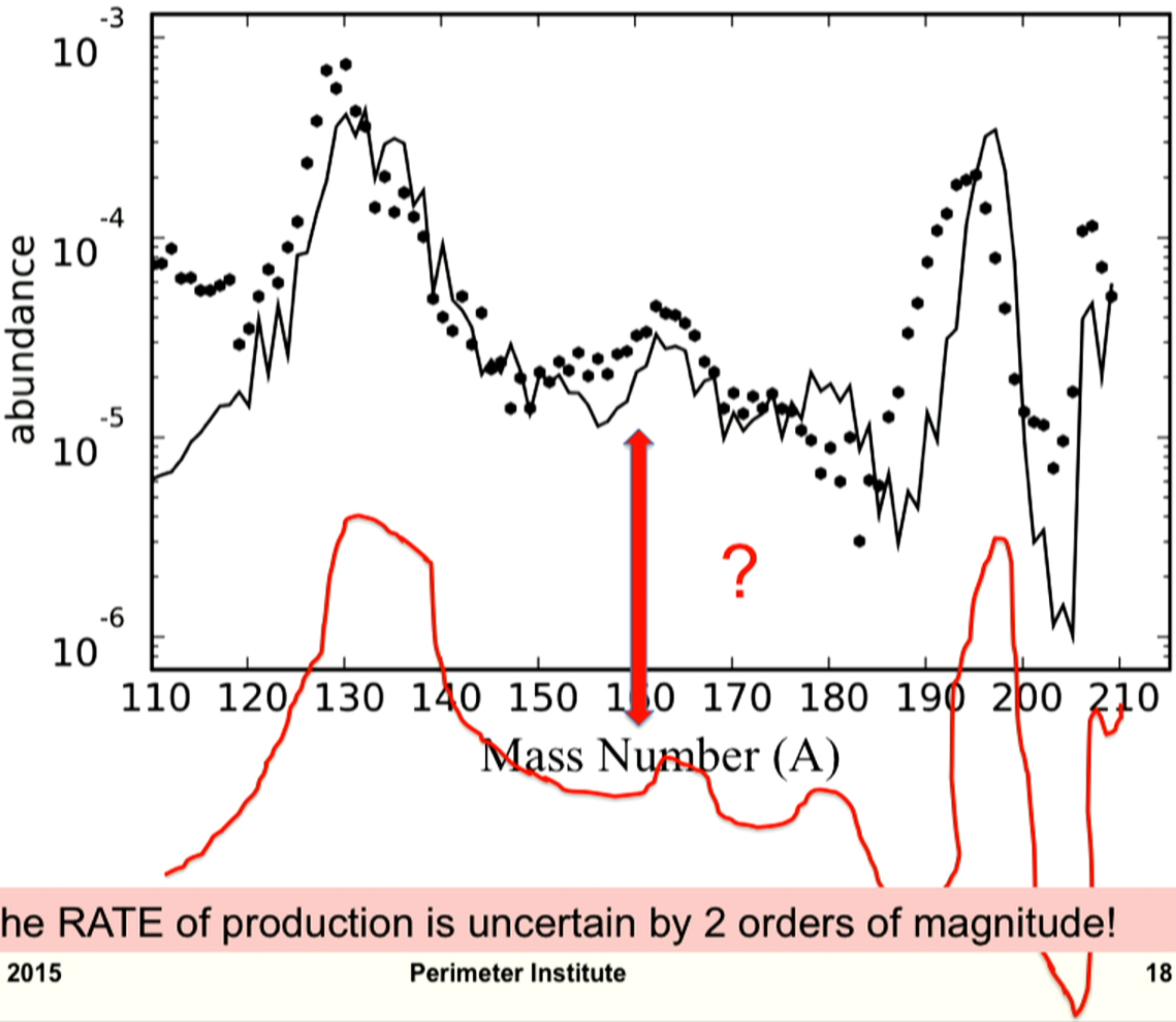
Nature, Volume 500, Issue 7464, pp. 547-549 (2013)

Metzger et al. 2010

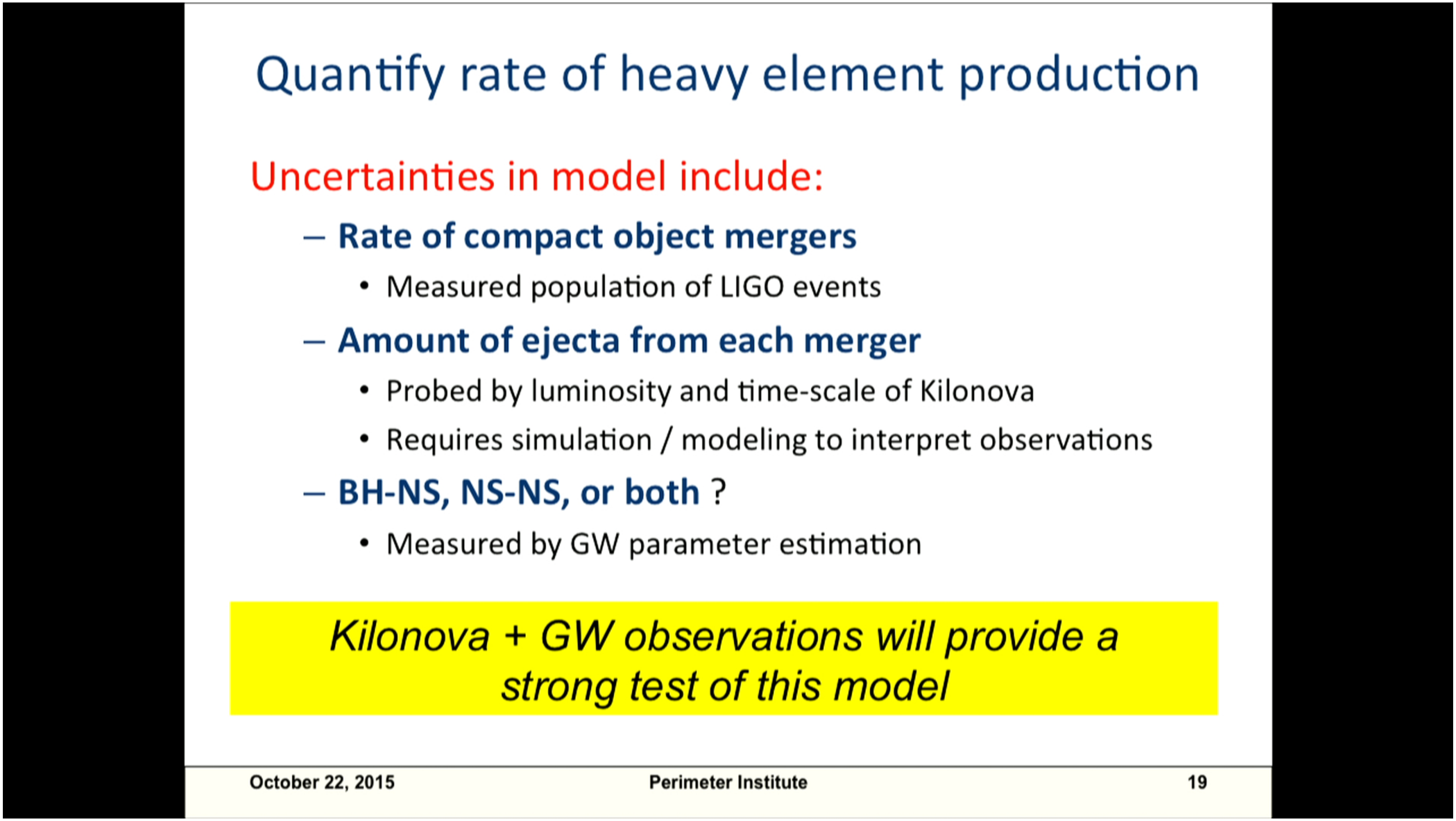


The RELATIVE abundances predicted from NS-NS mergers fits the observed distribution…

Metzger et al. 2010



But the RATE of production is uncertain by 2 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
  - Requires simulation / modeling to interpret observations
- **BH-NS, NS-NS, or both** ?
  - Measured by GW parameter estimation

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

Merger Rate X Mass per merger → Total R-element Mass

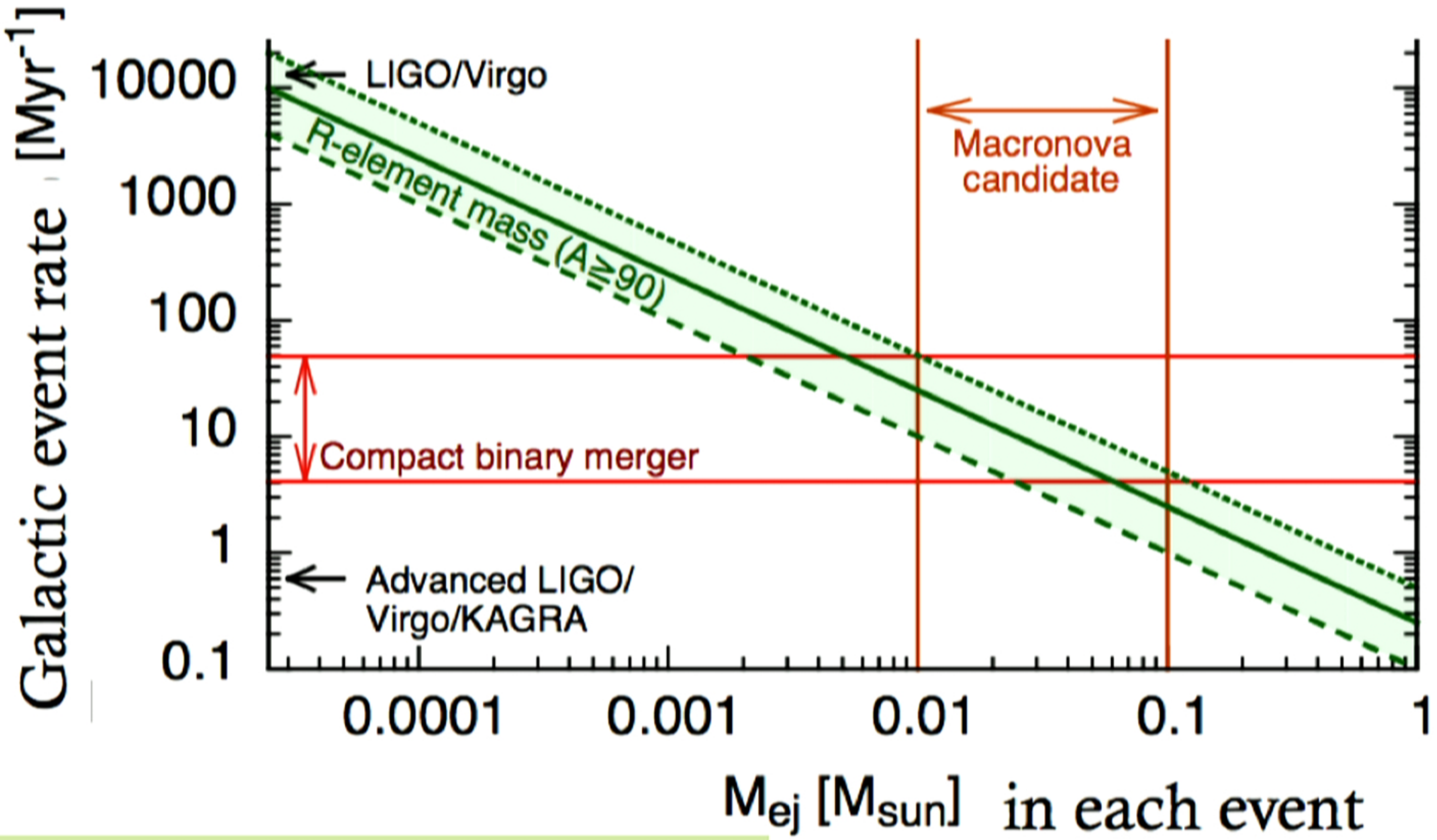
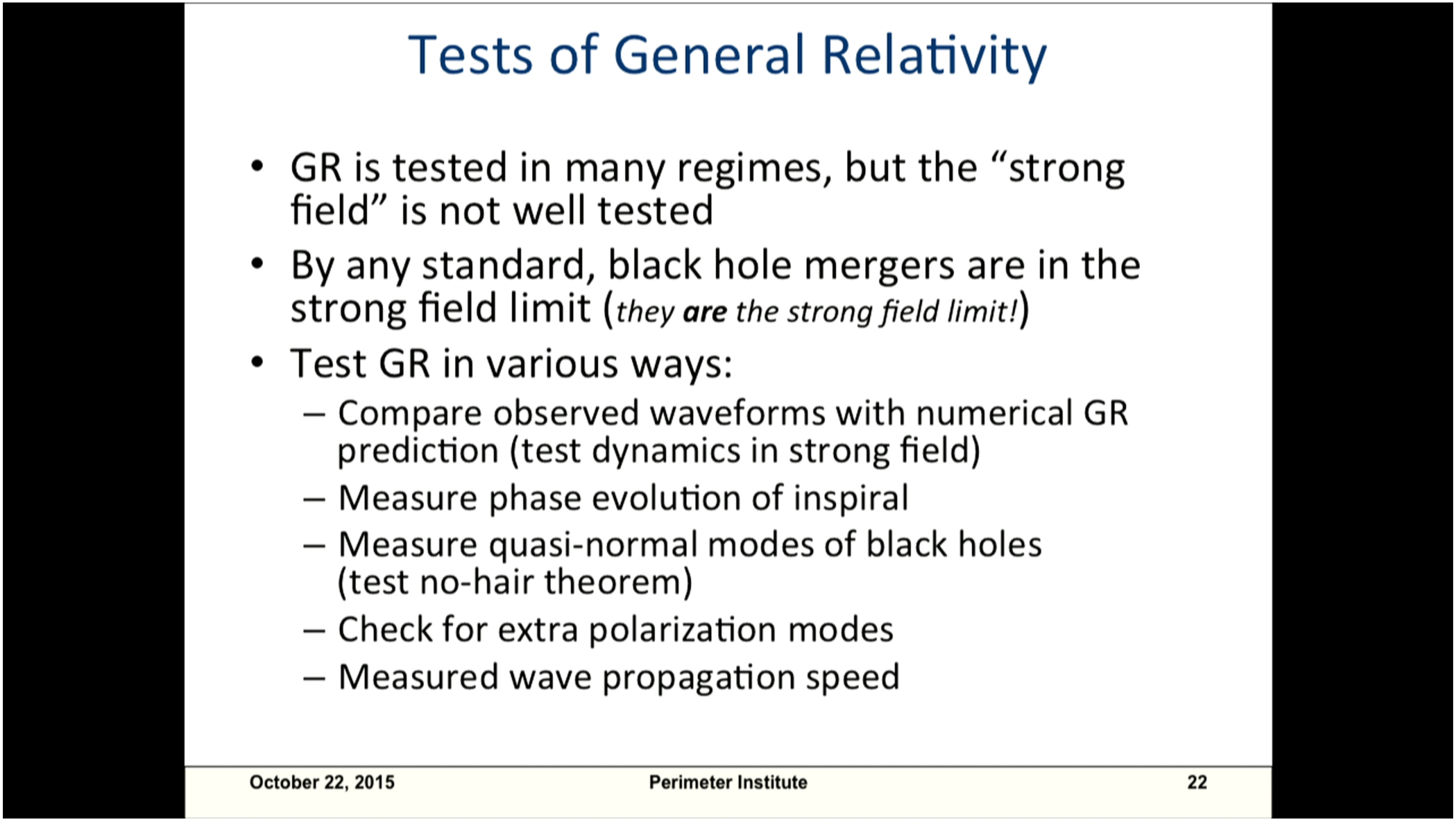


Figure adopted from Hotokezaka et al. 2015



Tests of General Relativity

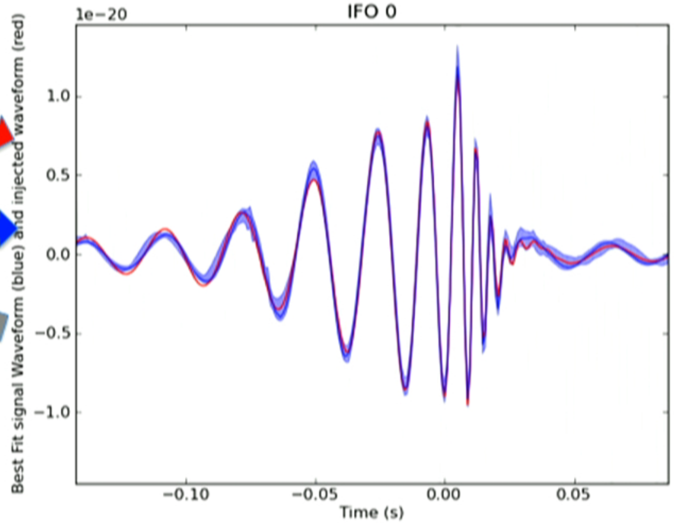
- GR is tested in many regimes, but the “strong field” is not well tested
- By any standard, black hole mergers are in the strong field limit (*they **are** the strong field limit!*)
- Test GR in various ways:
  - Compare observed waveforms with numerical GR prediction (test dynamics in strong field)
  - Measure phase evolution of inspiral
  - Measure quasi-normal modes of black holes (test no-hair theorem)
  - Check for extra polarization modes
  - Measured wave propagation speed

Testing GR Example: Waveform Reconstruction

Red: Simulated Waveform added to data

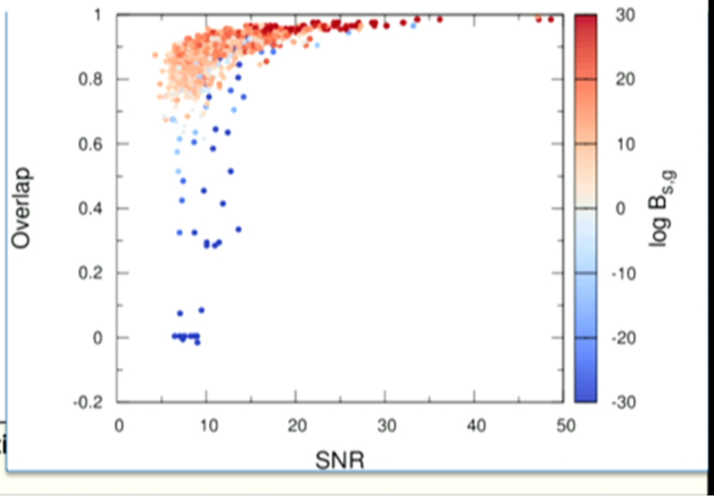
Blue: Recovered waveform with uncertainty

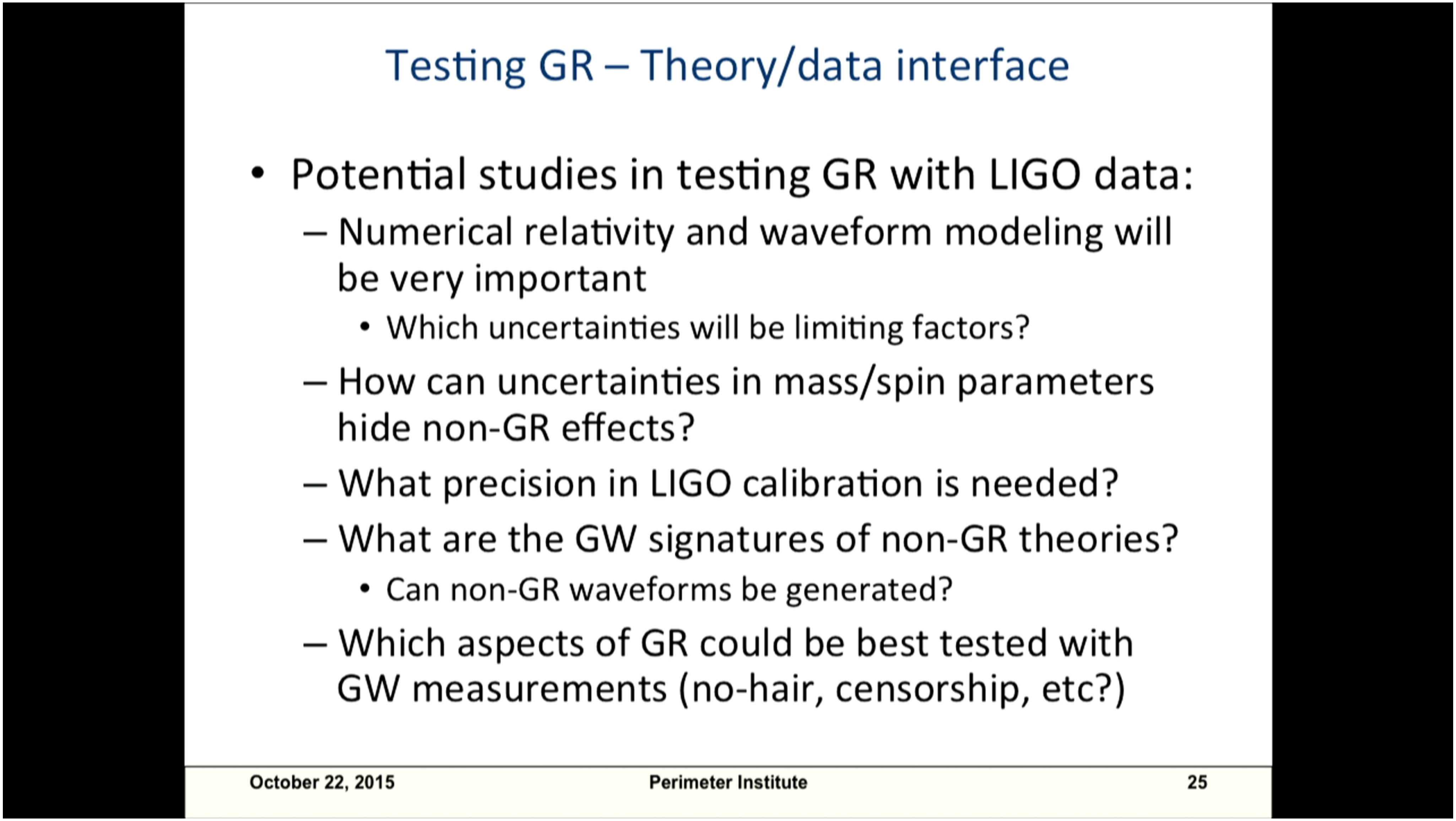
Gray: LIGO data with simulated signal



Extracted waveform can be directly compared with predictions from numerical relativity

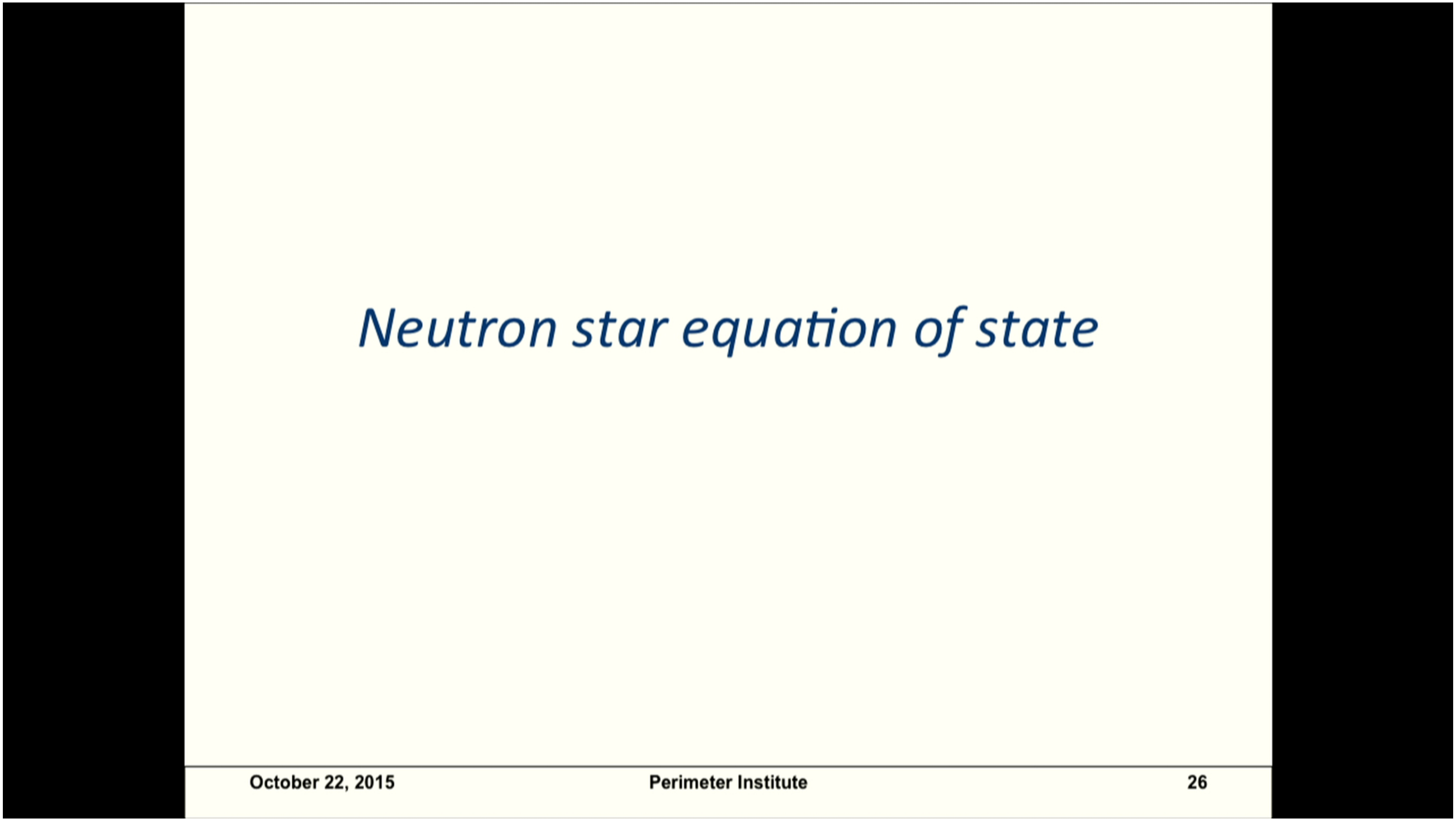
Recover waveforms with ~90% accuracy around network SNR 15



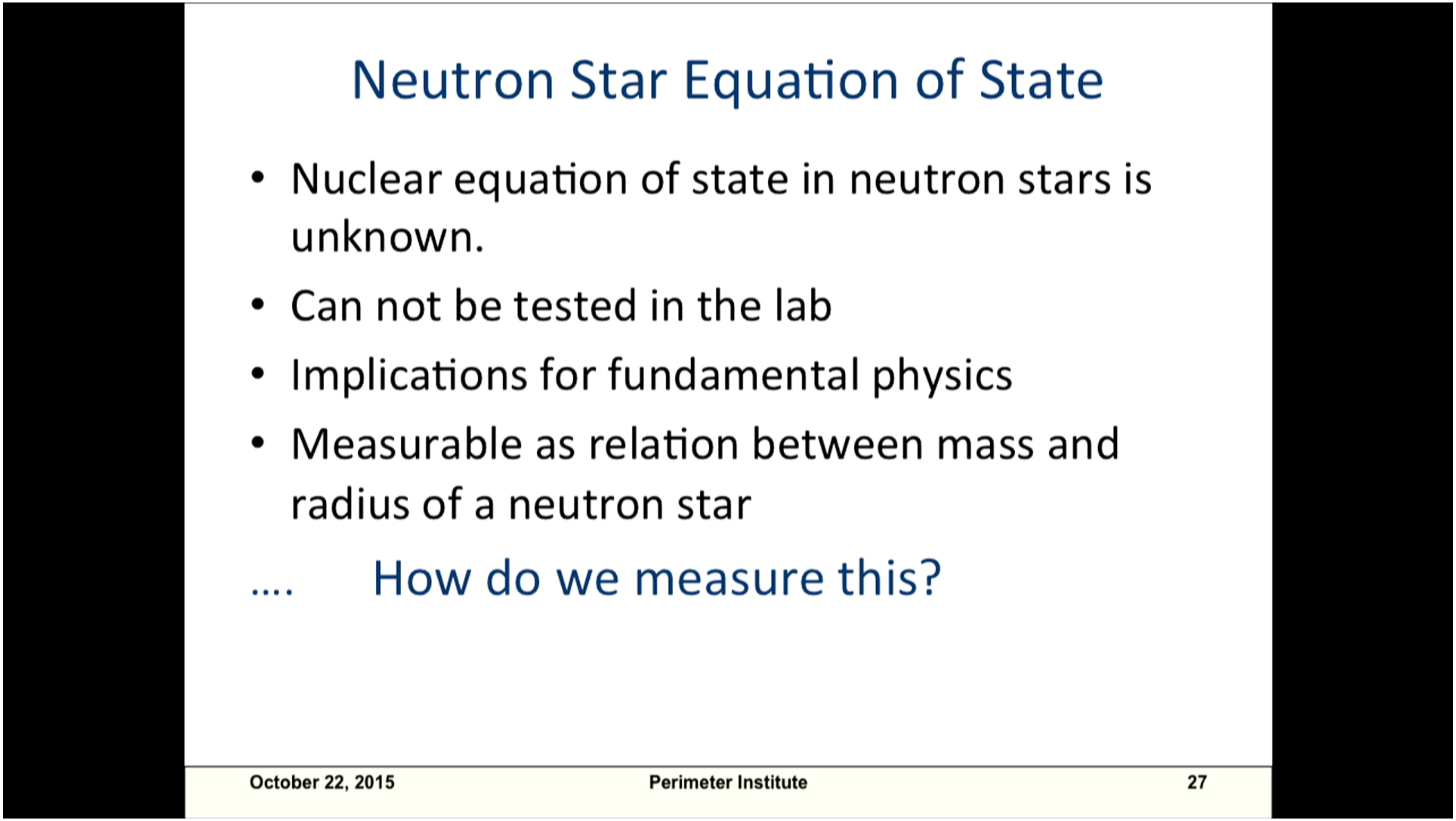


Testing GR – Theory/data interface

- Potential studies in testing GR with LIGO data:
  - Numerical relativity and waveform modeling will be very important
    - Which uncertainties will be limiting factors?
  - How can uncertainties in mass/spin parameters hide non-GR effects?
  - What precision in LIGO calibration is needed?
  - What are the GW signatures of non-GR theories?
    - Can non-GR waveforms be generated?
  - Which aspects of GR could be best tested with GW measurements (no-hair, censorship, etc?)



Neutron star equation of state



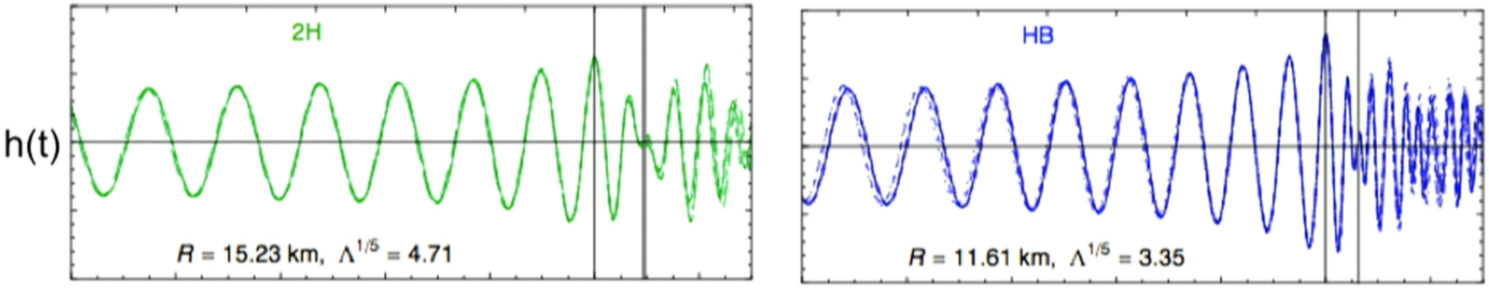
Neutron Star Equation of State

- Nuclear equation of state in neutron stars is unknown.
- Can not be tested in the lab
- Implications for fundamental physics
- Measurable as relation between mass and radius of a neutron star

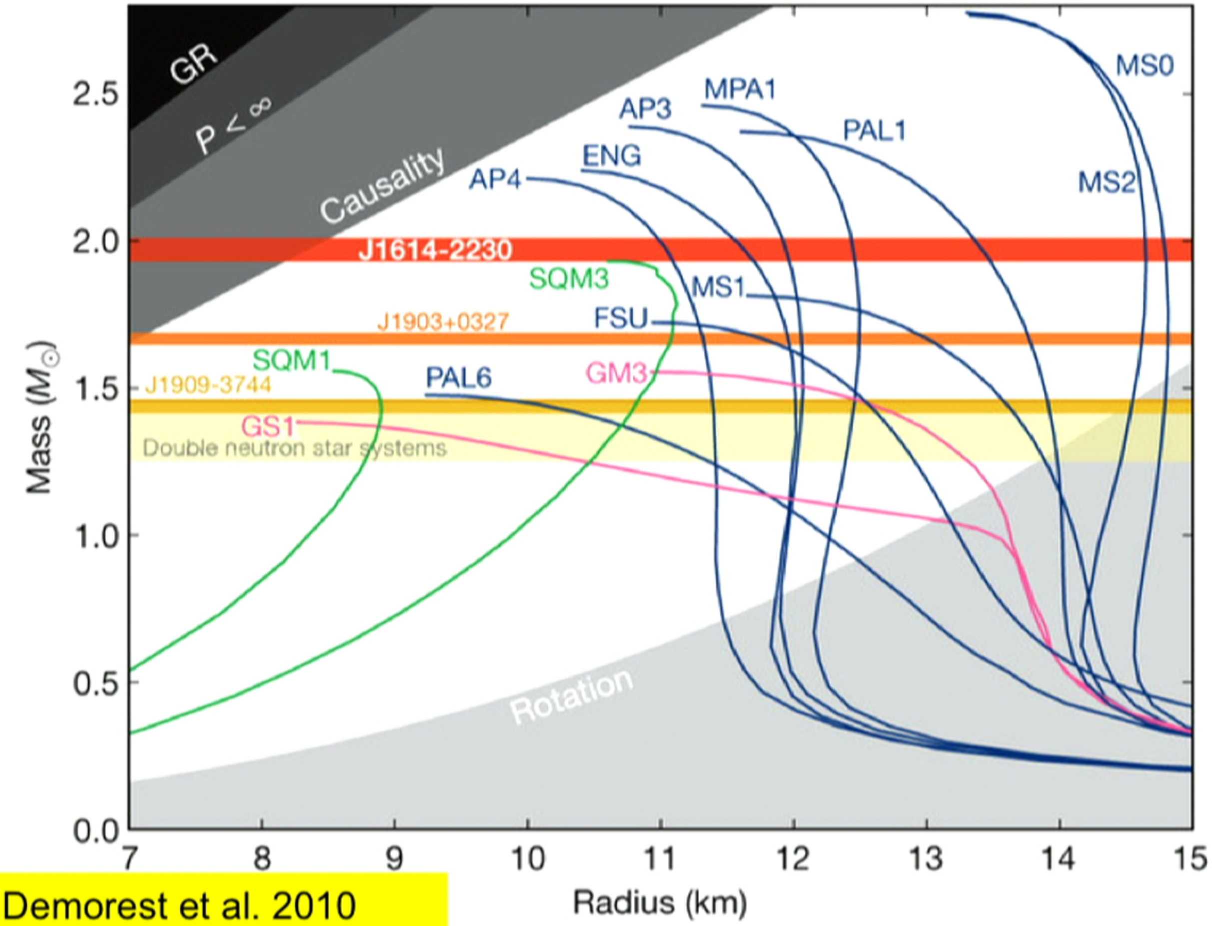
…. How do we measure this?

Measure the neutron star EOS in a binary merger

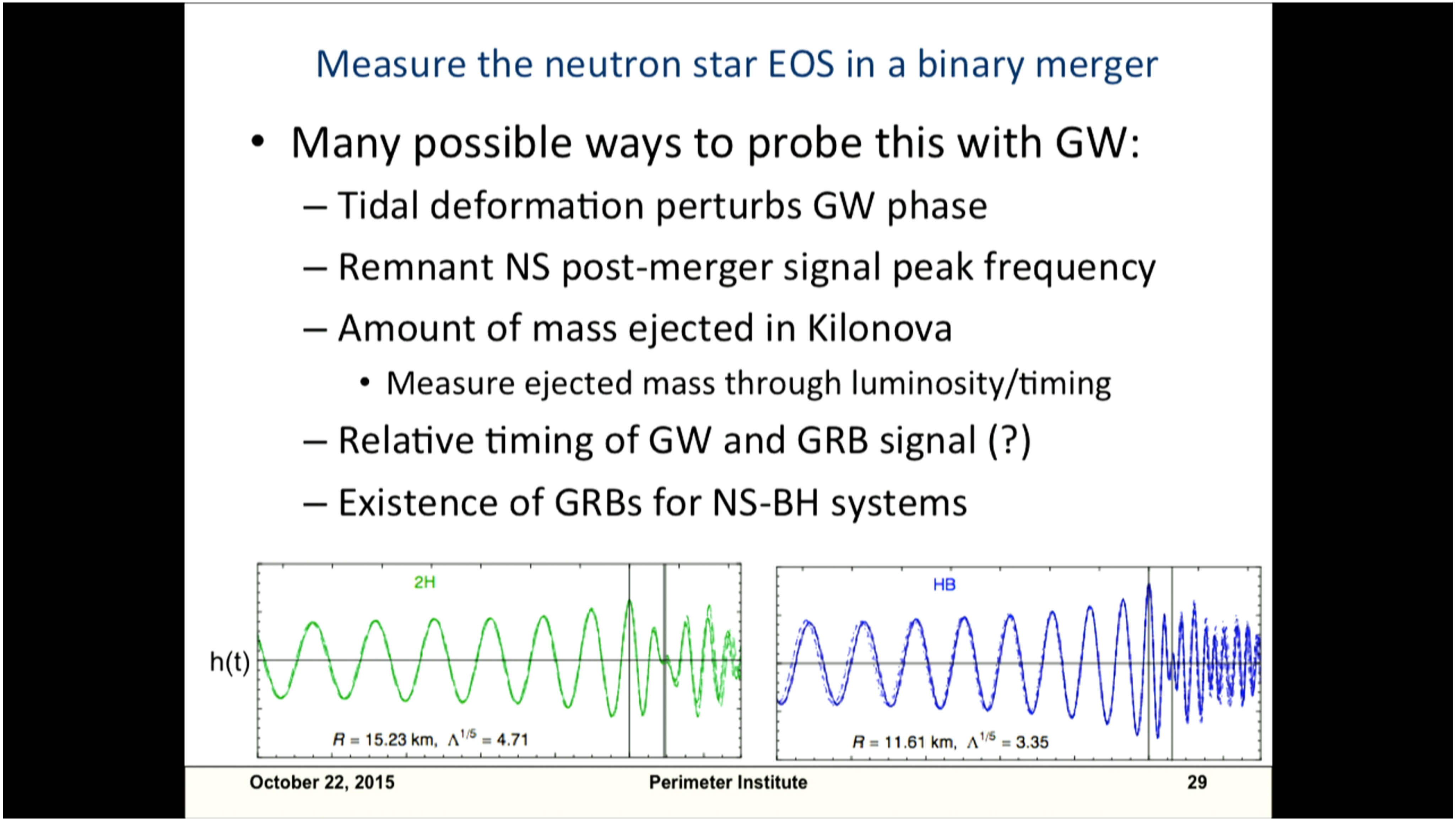
- Many possible ways to probe this with GW:
  - Tidal deformation perturbs GW phase
  - Remnant NS post-merger signal peak frequency
  - Amount of mass ejected in Kilonova
    - Measure ejected mass through luminosity/timing
  - Relative timing of GW and GRB signal (?)
  - Existence of GRBs for NS-BH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



Neutron star EOS defines Mass / Radius relation



P. B. Demorest et al. 2010



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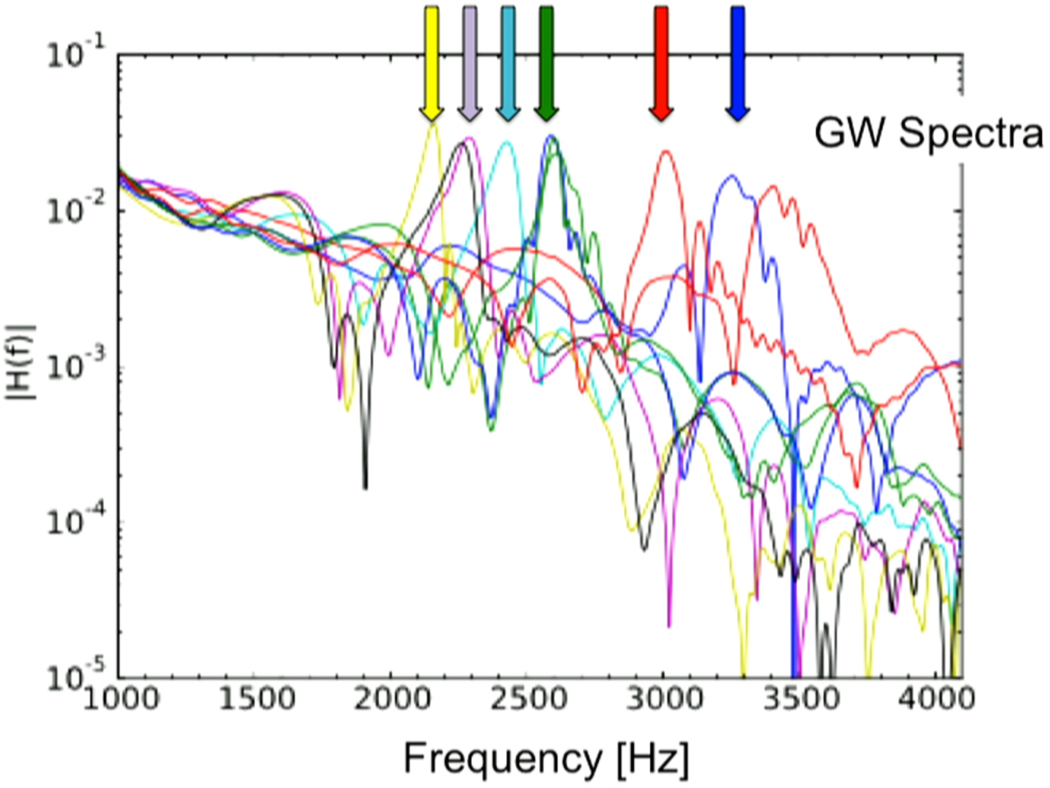
Measuring EOS: Post-merger peak frequency

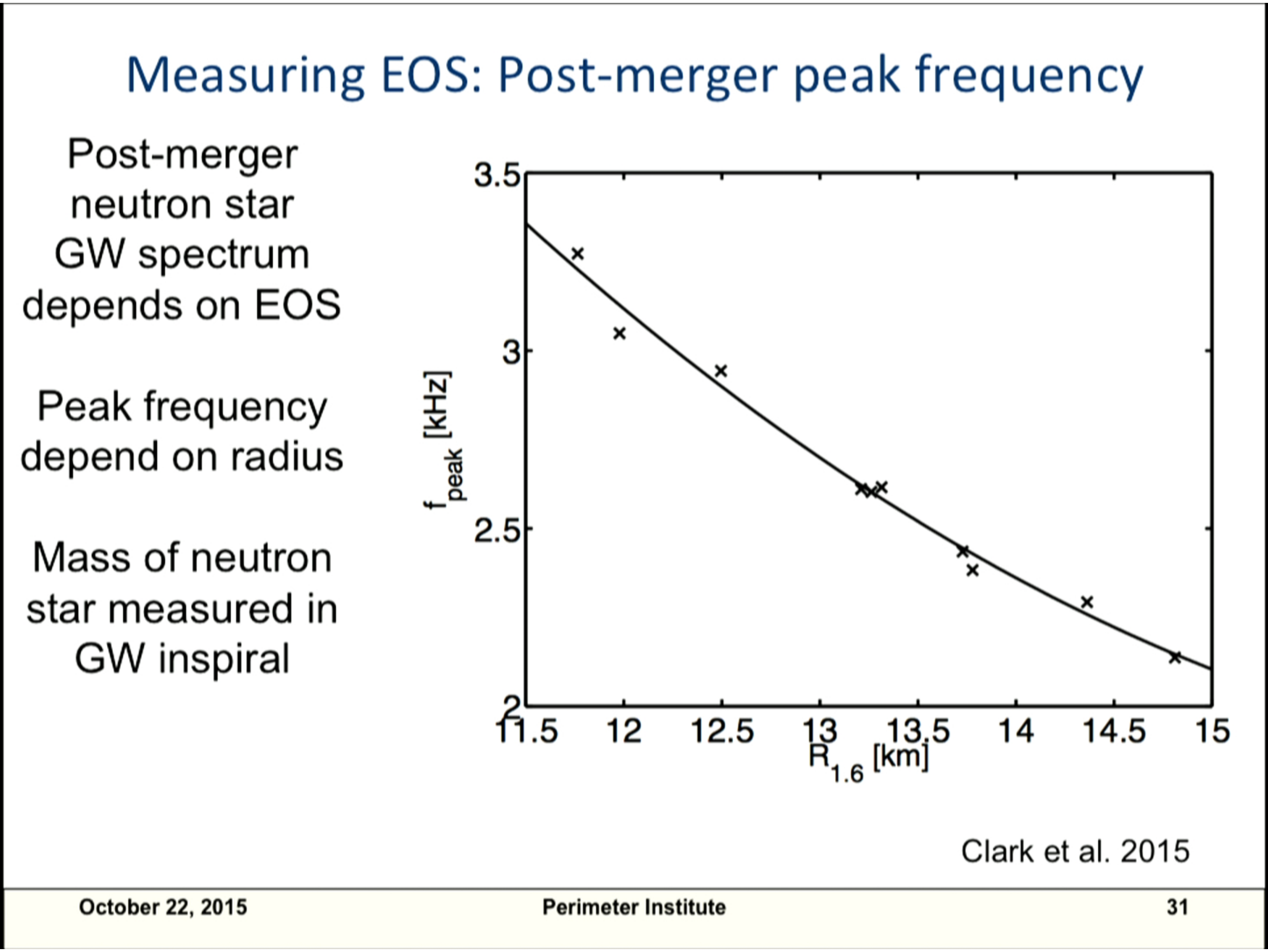
Post-merger neutron star GW spectrum depends on EOS

Peak frequency depend on radius

Mass of neutron star measured in GW inspiral



Clark et al. 2015



Measuring EOS: Post-merger peak frequency

Post-merger neutron star GW spectrum depends on EOS

Peak frequency depend on radius

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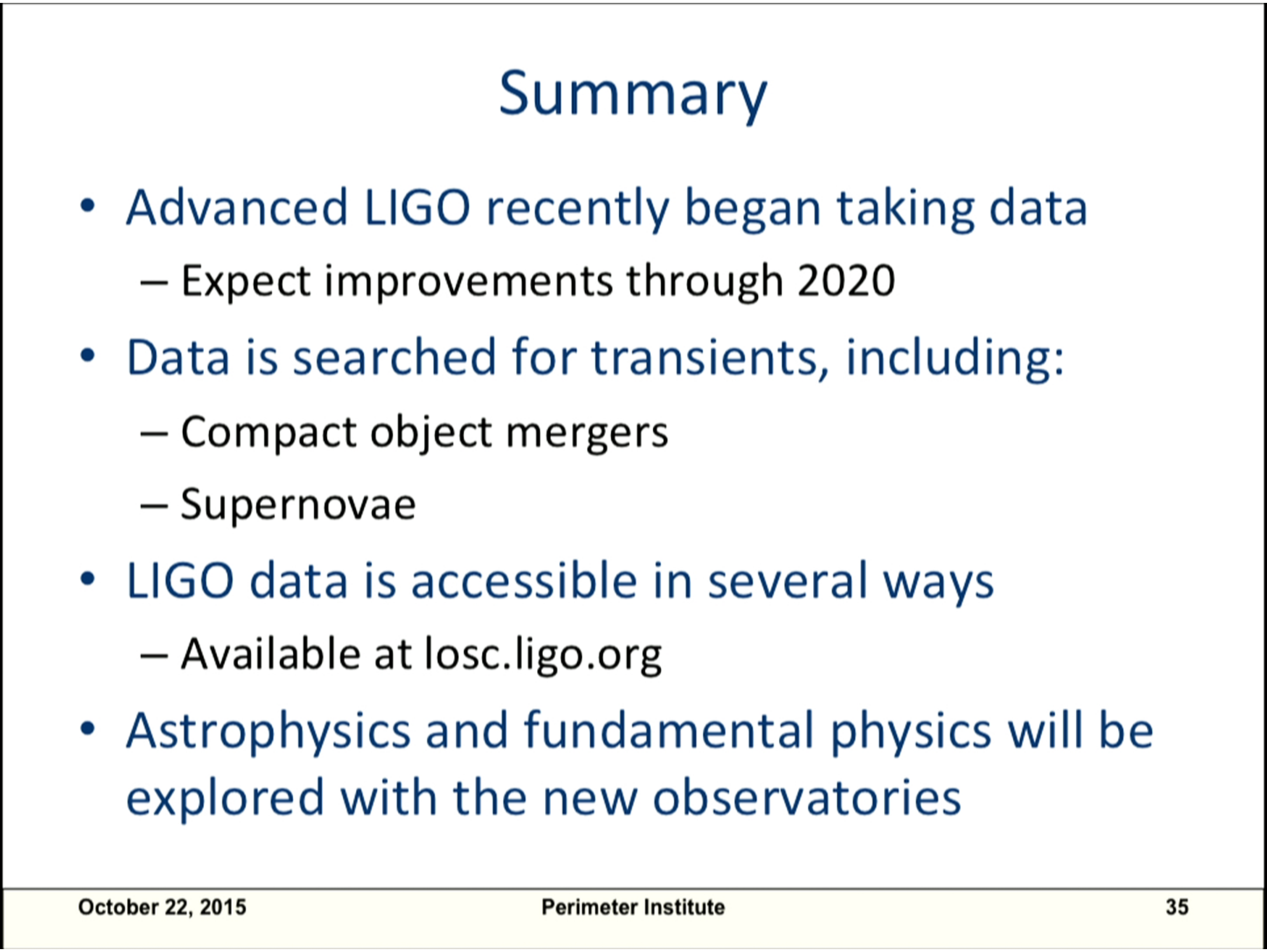

Summary

- Advanced LIGO recently began taking data
  - Expect improvements through 2020
- Data is searched for transients, including:
  - Compact object mergers
  - Supernovae
- LIGO data is accessible in several ways
  - Available at losc.ligo.org
- Astrophysics and fundamental physics will be explored with the new observatories