Future X-ray and GW Measurements of NS M and R

Cole Miller
University of Maryland and
Joint Space-Science Institute

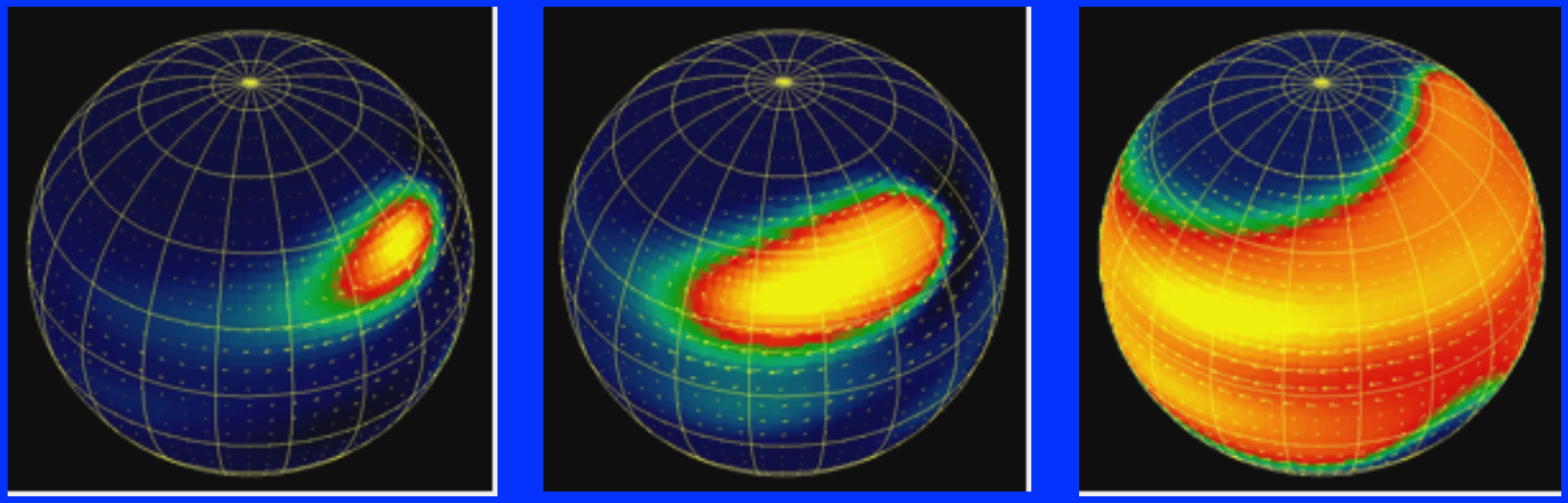
Outline

- A recap
- Estimates from energy-dependent X-ray waveforms
  NICER and LOFT-P
- What can we really do with GW?

Our Story So Far...

- We have to be very careful about systematic errors (Lamb)
- Progress is possible using burst fluxes and spectra, if we select data carefully (Poutanen)
- Waveform fitting is promising; OS looks like an excellent, fast approximation (Morsink)
- In the future, GW could give us completely independent constraints (Read)

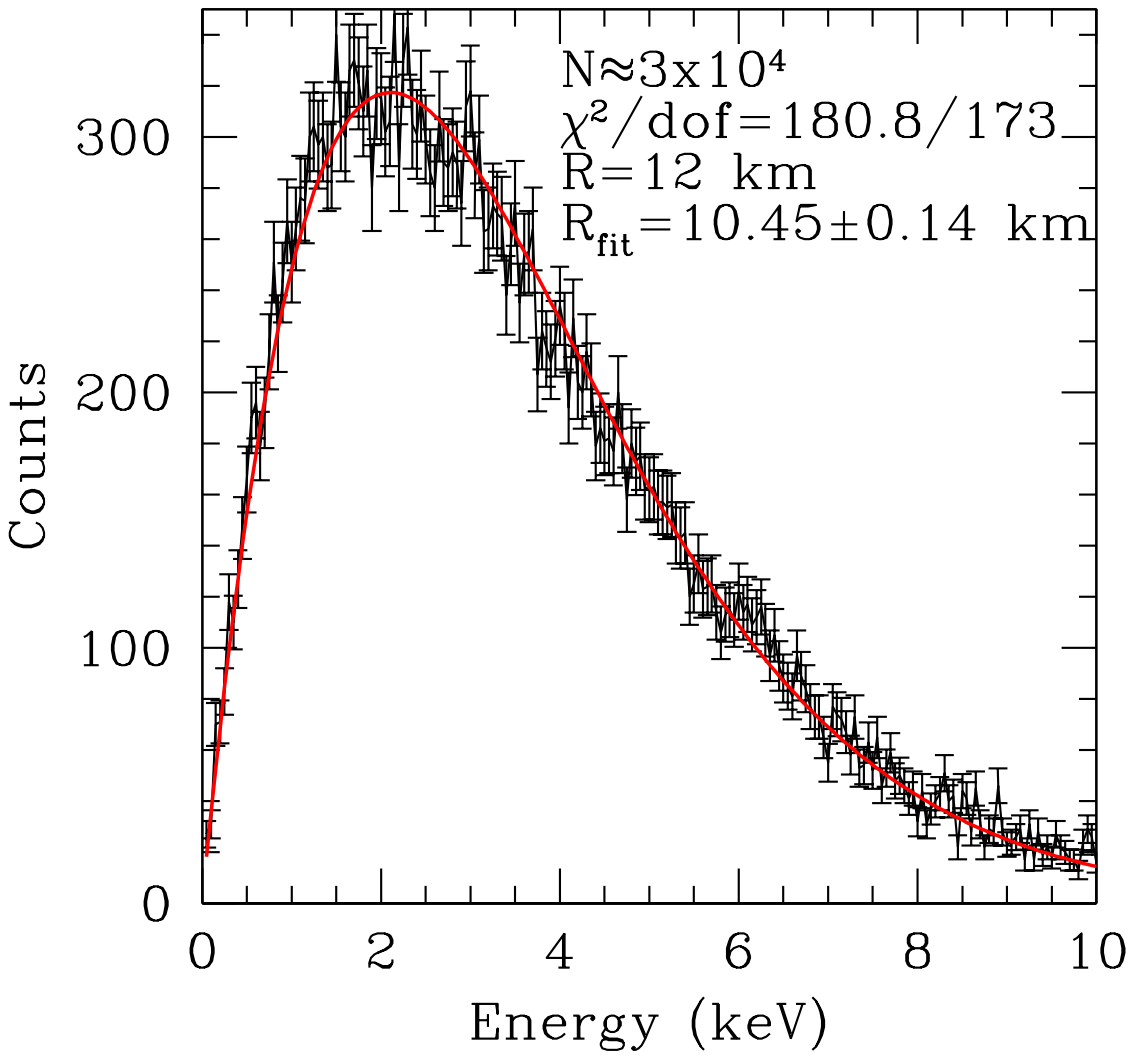
Reminder About Systematics



Sequence of frames from movie by Anatoly Spitkovsky of burning including Coriolis effect

In this model, burning becomes more axisymmetric with time, but latitudinal variations remain

Radius Bias with T Variation



Example of the bias toward low radii from single-temp fits to surface with varying temperature.

Temperature varies smoothly from 2 keV (equator) to 0.2 keV (pole).

Fit is good, but R is 13% low. With narrower T profile, larger correction

Assume perfect energy response, zero N_H

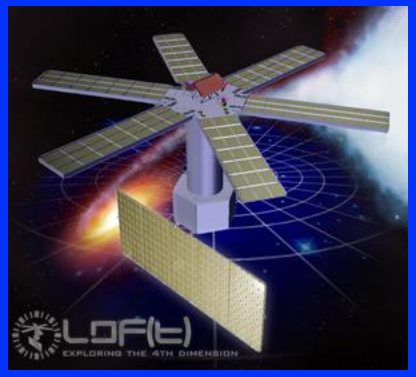
Burst Discussion Questions

- Can we understand spectral contamination enough to model? Note: persistent emission probably changes through burst
- Are there independent ways to constrain the surface emitting fraction (e.g., energy-dependent waveforms)?
- What is needed for the model to be consistent with bursts and thus for inferred masses and radii to be trustworthy?
  Is data selection (Poutanen) sufficient?

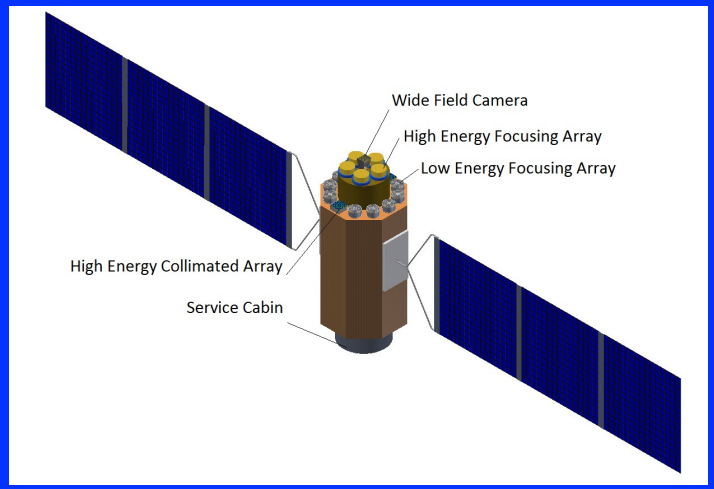
Upcoming and Planned X-ray Timing Missions

- NICER

- LOFT-P



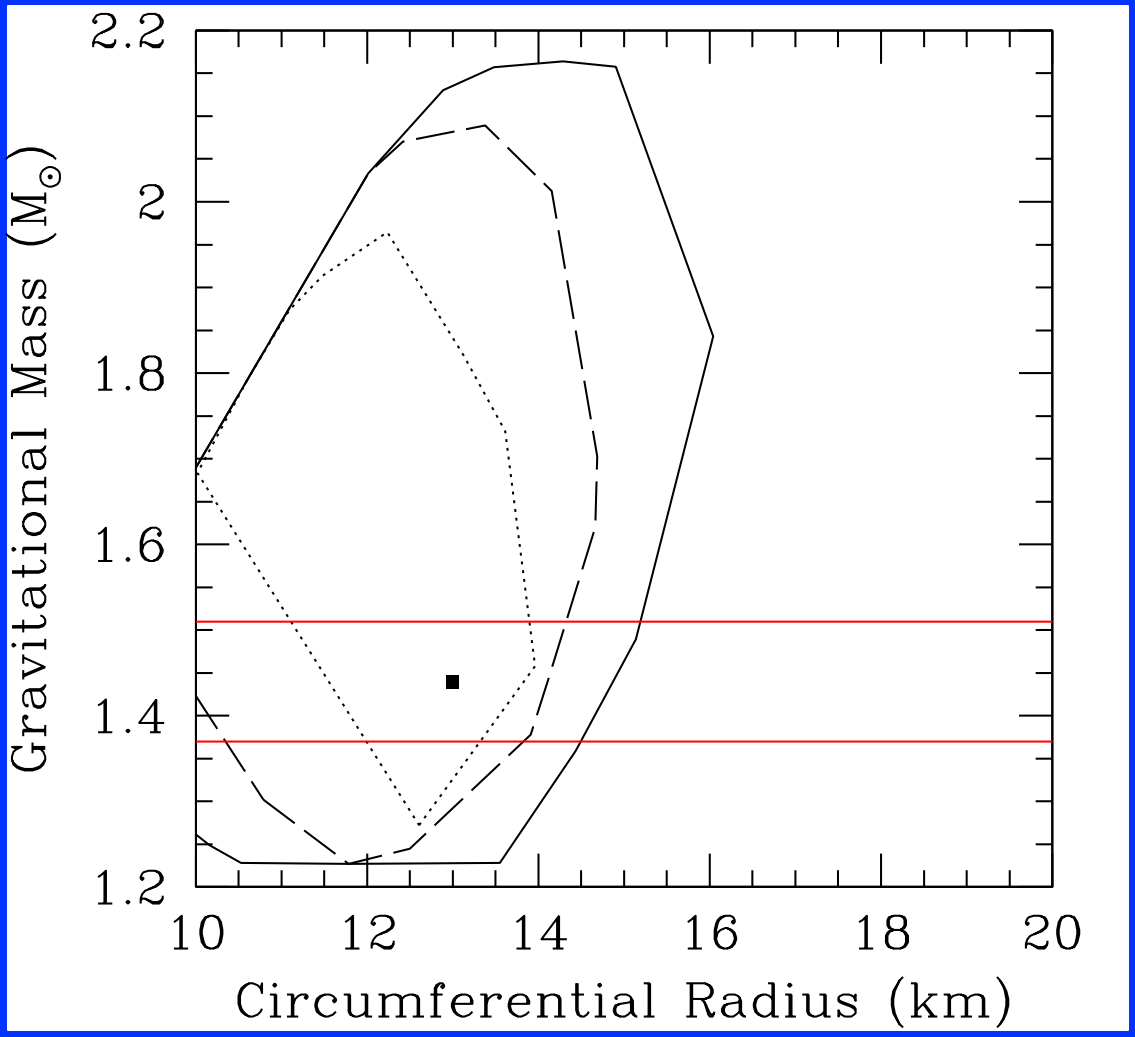
- eXTP



Waveform Fitting: NICER

- Expected launch 1 February 2017
- Will focus on non-accreting neutron stars
- What are the prospects for individual sources?
  4U J0437-4715 (brightest X-ray MSP)
  4U J1614-2230 (1.928+-0.017 M_{sun})

J0437: Prospects with NICER



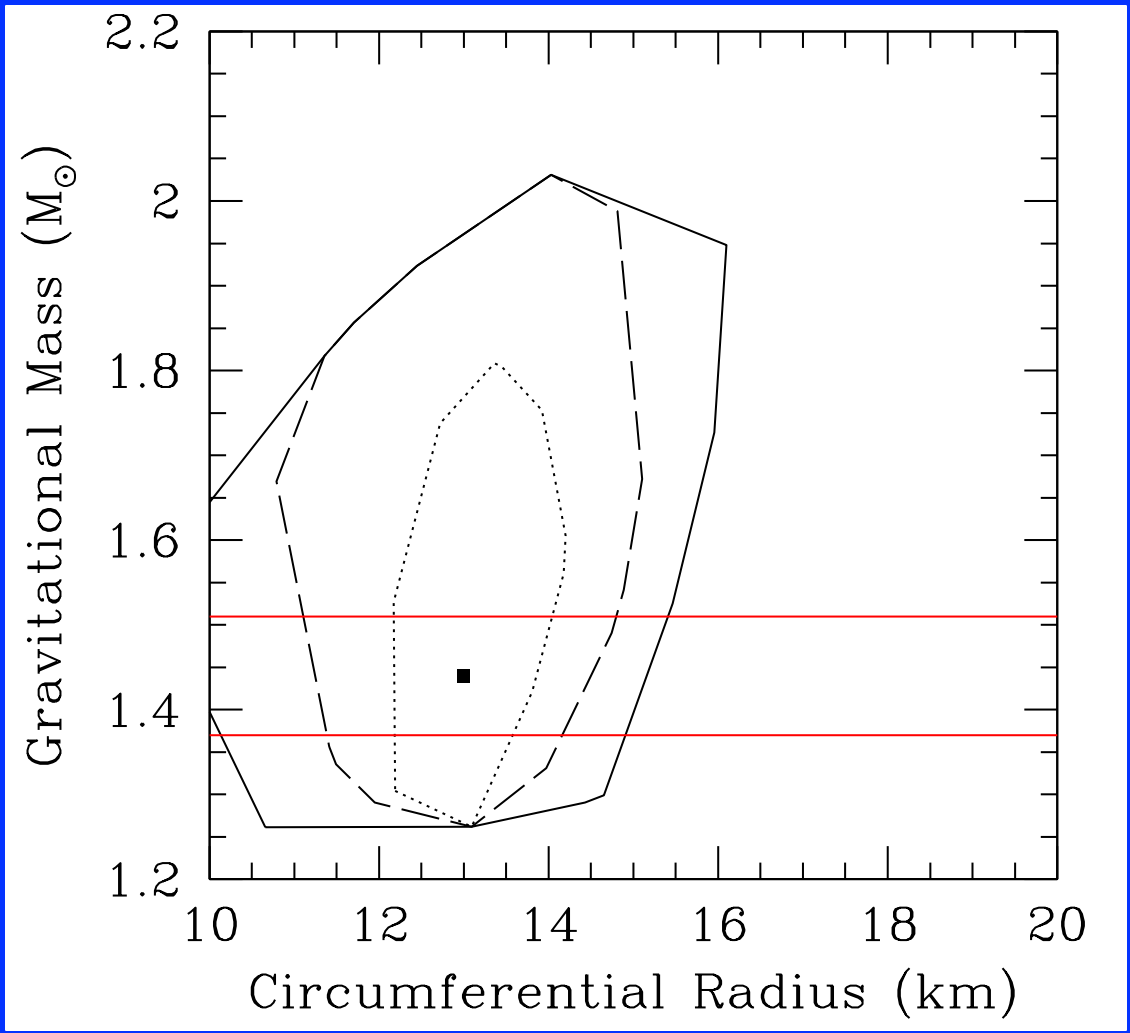
Only temperature at infinity known

Conservative:
6×10^5 photons from spot

4×10^5 photons from unmodulated surface emission

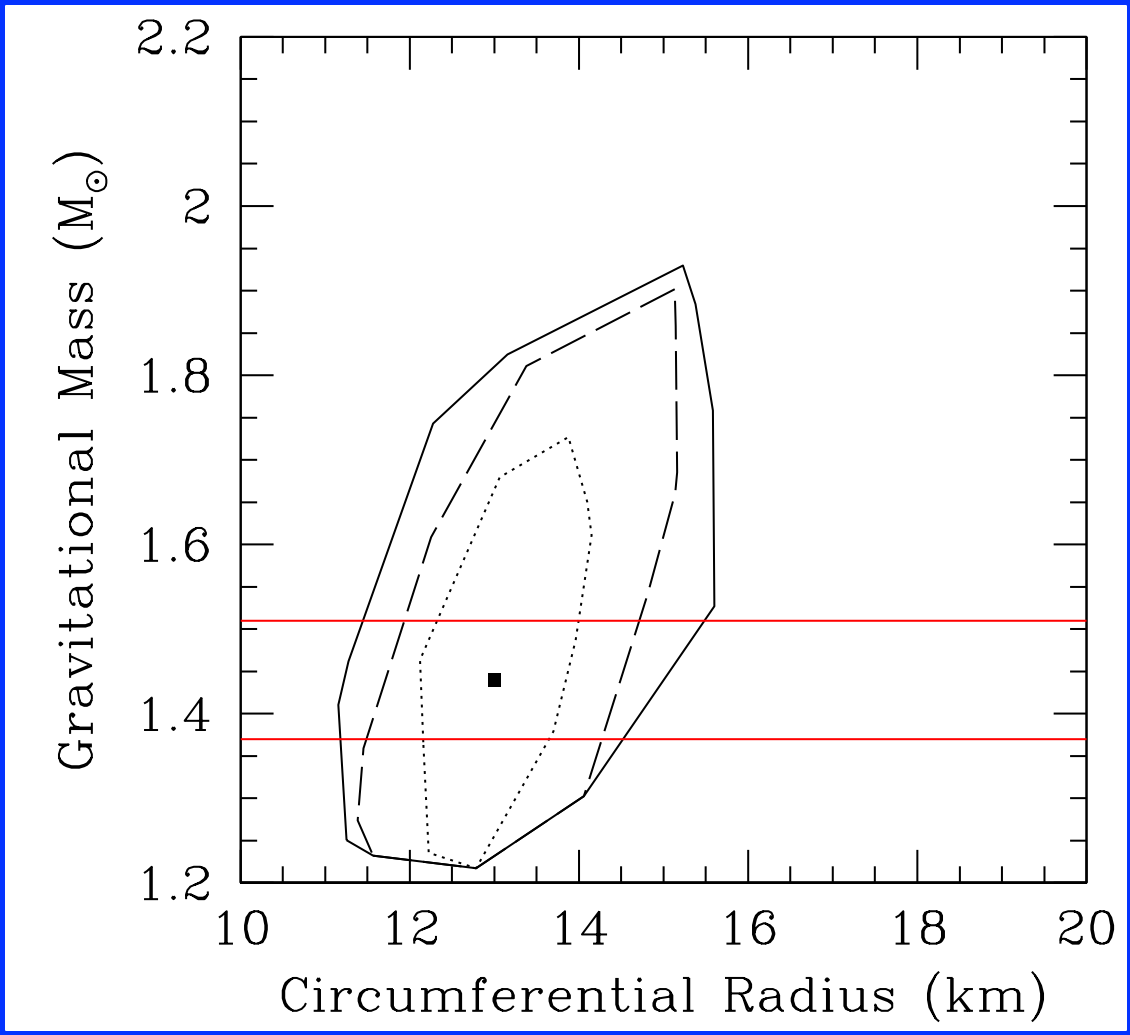
2×10^5 photons from unmodulated power law

J0437: Prospects with NICER



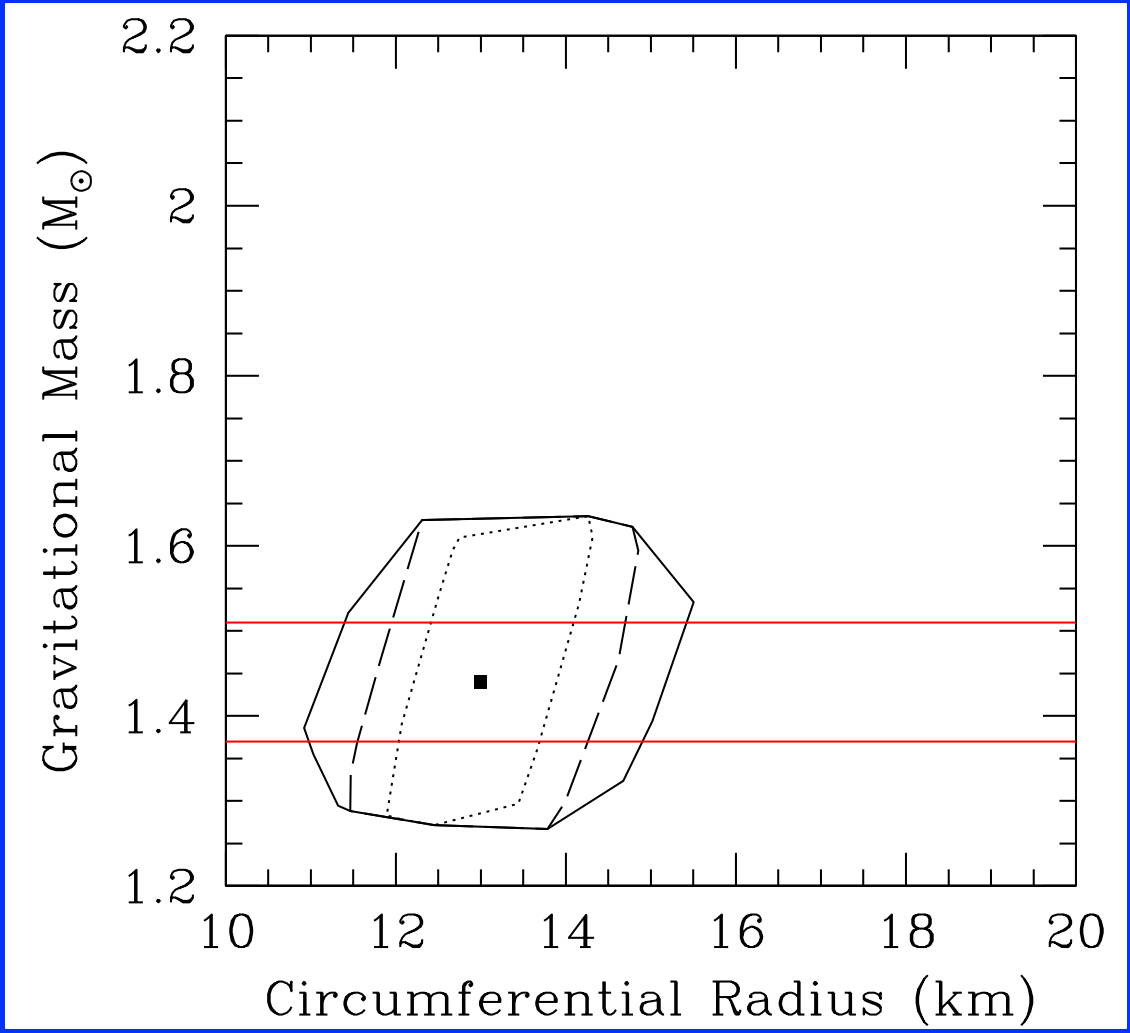
Temperature and observer inclination known

J0437: Prospects with NICER



Temperature, observer inclination, and spot inclination known

J0437: Prospects with NICER



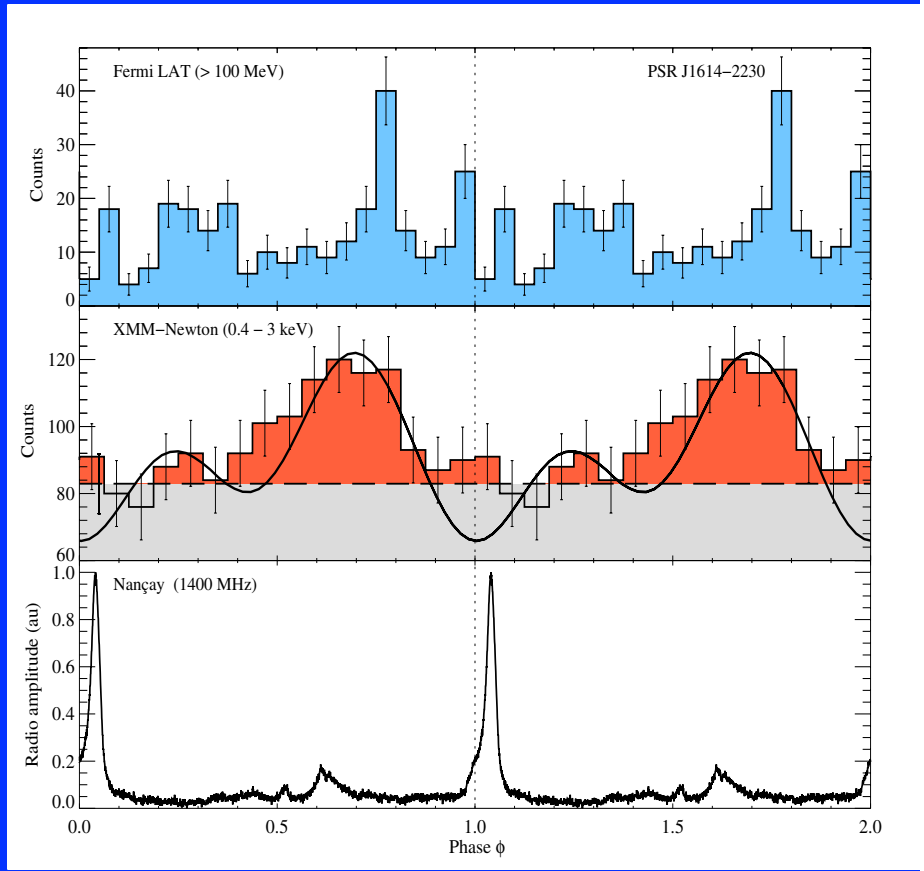
Temperature, observer inclination, and spot inclination known, and mass constrained to 1.25-1.65 M_{sun} (3σ)

4U J1614: A Special Case

- J0437: ~1 NICER count/s.
  J1614: ~0.018 count/s
- Rate is insufficient to get a tight constraint on radius
- However, the apparently large modulation amplitude could place an interesting lower limit on the radius
- Especially interesting because of high M

XMM Data on PSR J1614

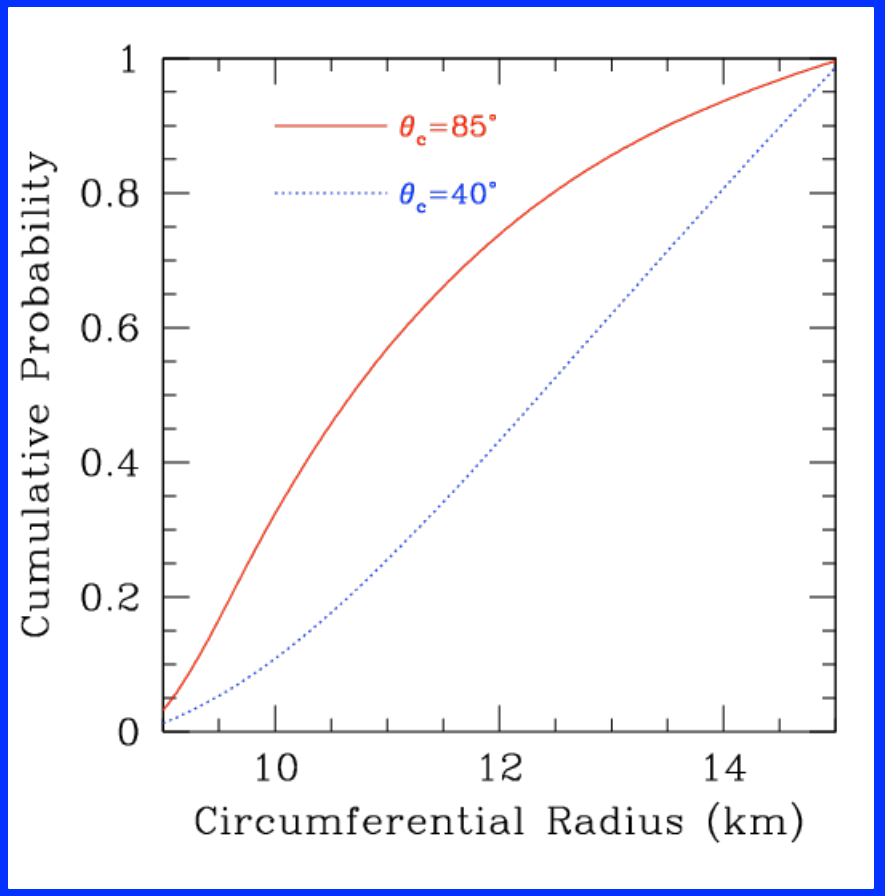
- Total of ~44 ksec
- 1543 counts
- But 1326 are estimated to be background counts
- Strong source modulation
- If M/R too high, mod. frac. too low



Pancrazi et al. 2012

Analysis of XMM Data

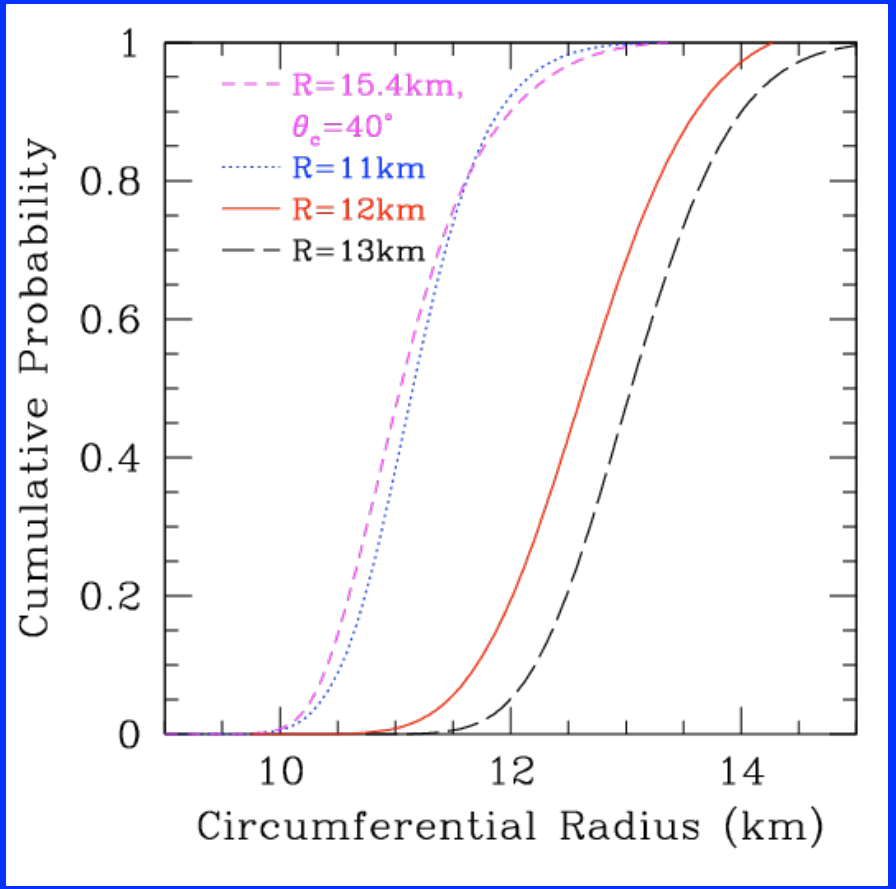
- Can get lower limit to radius for known mass and inclination (~90 deg)
- If spot inclination is 40 deg (from γ-ray), constraint is stronger than if near equator
- Certainly not definitive yet



Miller 2016

Possibilities With NICER Data

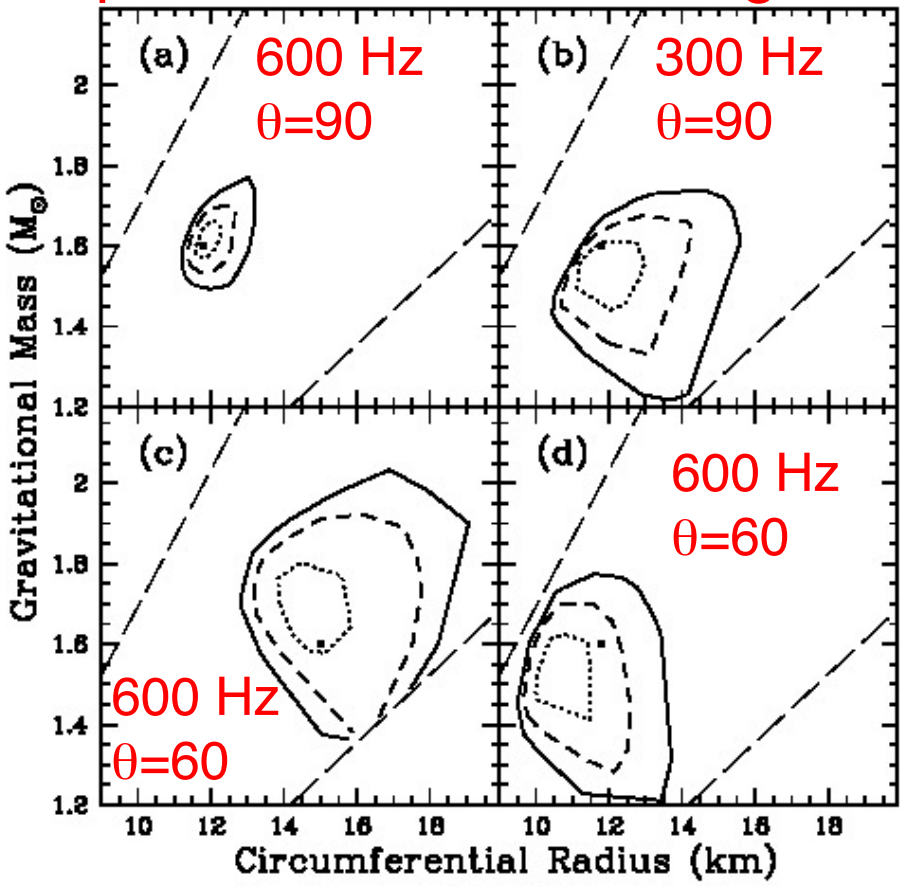
- Strong constraints will be possible, if background is decently measured
- Also showed that incorrect or even *modulated* background will not fool us



Miller 2016

LOFT-P: Bayesian Analyses

10^6 spot counts, 9×10^6 background



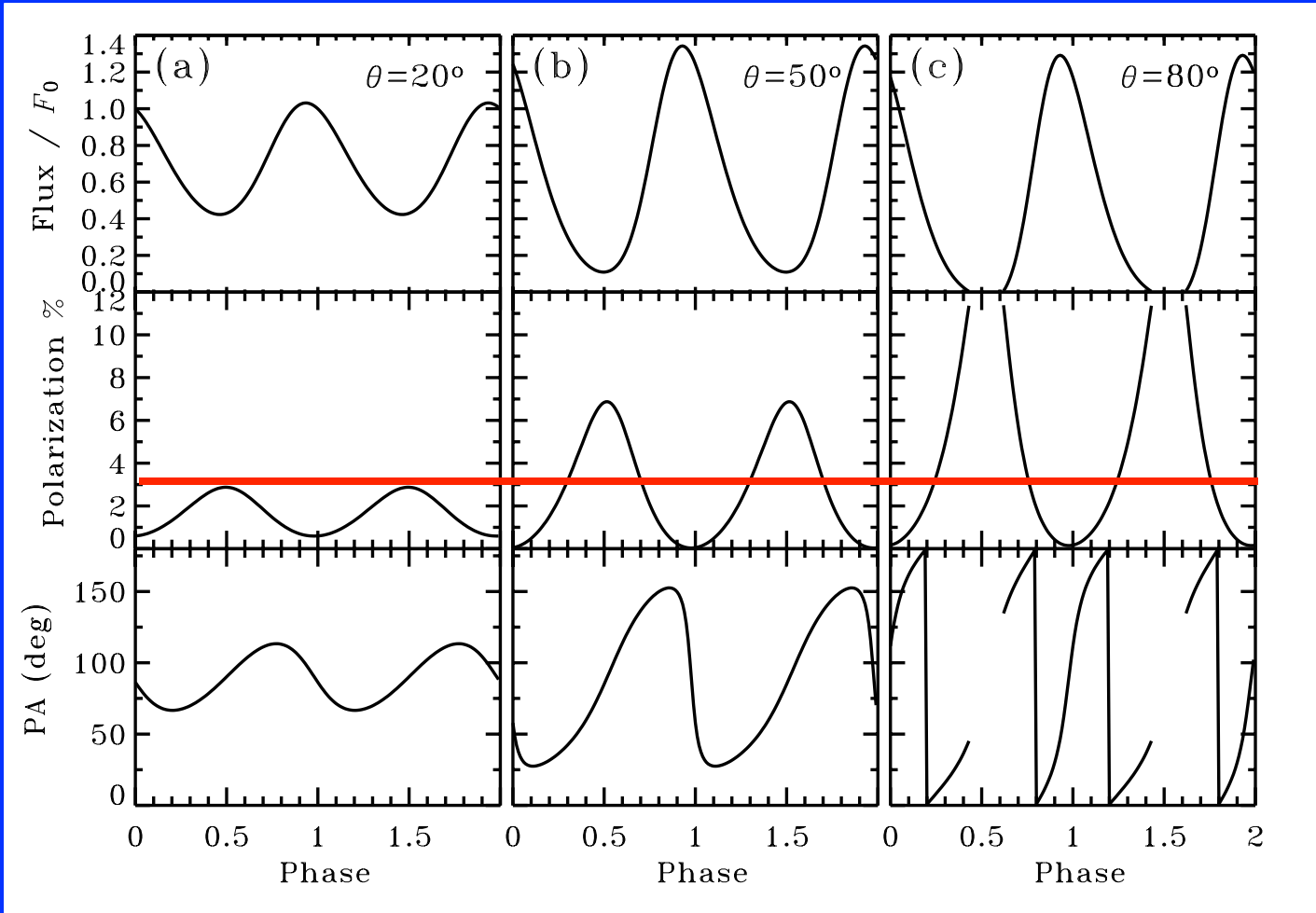
$M=1.6\ M_{sun}$, $R_{eq}=11.8$ km or 15 km

Miller+Lamb 2015
Top left: spot, obs on equator.
3%-7% precision possible in M, R.

Bottom right: data generated w/ temp gradient, fit with const temp. No statistically significant bias.

No simple formula for precision.

eXTP: Info From Polarization



eXTP: ~3% polarization at 10^6 counts

Viironen+Poutanen 2004: M=1.4 Msun, R=10.3 km, i=60 deg, ν=400 Hz
Benefit: gives us critically-needed inclination information!

Questions for Discussion

- Promising so far, but are there other significant systematic errors to explore? Looking into rapid rotation; see Morsink talk as well
- Current data are unconstraining. Optimism for NICER, but will this model be extendable to isolated pulsars with multiple spots and thus extra parameters?

Gravitational Waves

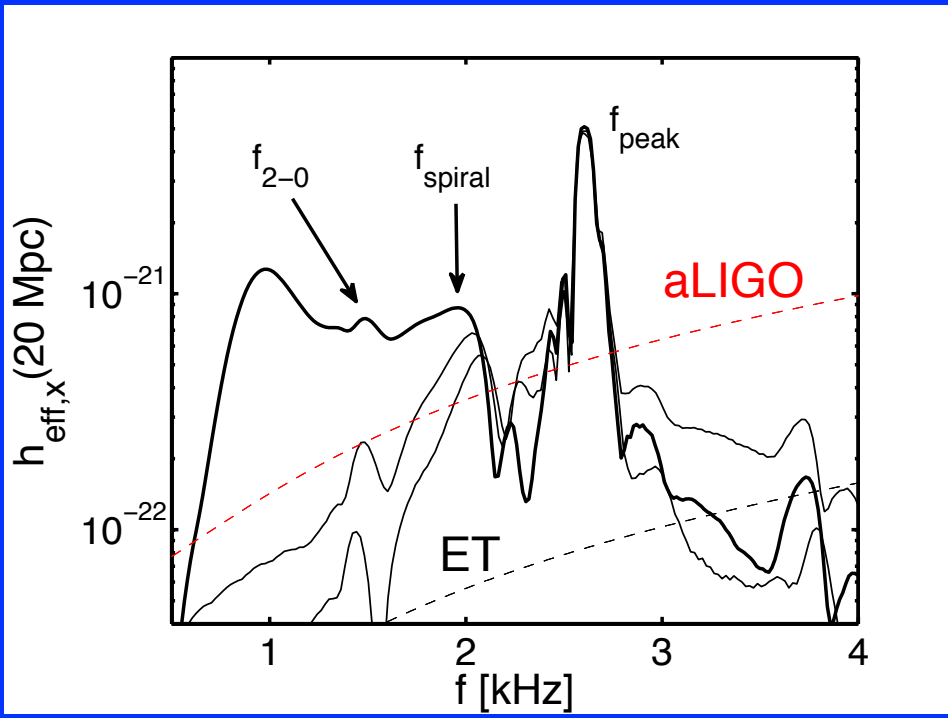
- Nicely covered by Jocelyn!
  Waveforms altered by tides
- Promise is substantial, but:
  Systematic errors from waveforms?
  Reliability of numerical simulations?
- Getting greedy...

Tasks for Numerical Simulations

- Resolve static tides
  Removes energy from orbit, thus less energy is in GW
- Resolve dynamic tides
  Oscillations induced in star
  As Jocelyn said: these could be substantial even if not resonant
- Realistic EOS? Need T-dependence?

Really High SNR: Oscillations!

- Oscillation modes of merged remnant contain huge amounts of info
- Correlation of f_{peak} with $R(1.6M_{sun})$?
- Probably need to wait for Einstein Telescope or luck...



Bauswein et al. 2016

Questions for Discussion

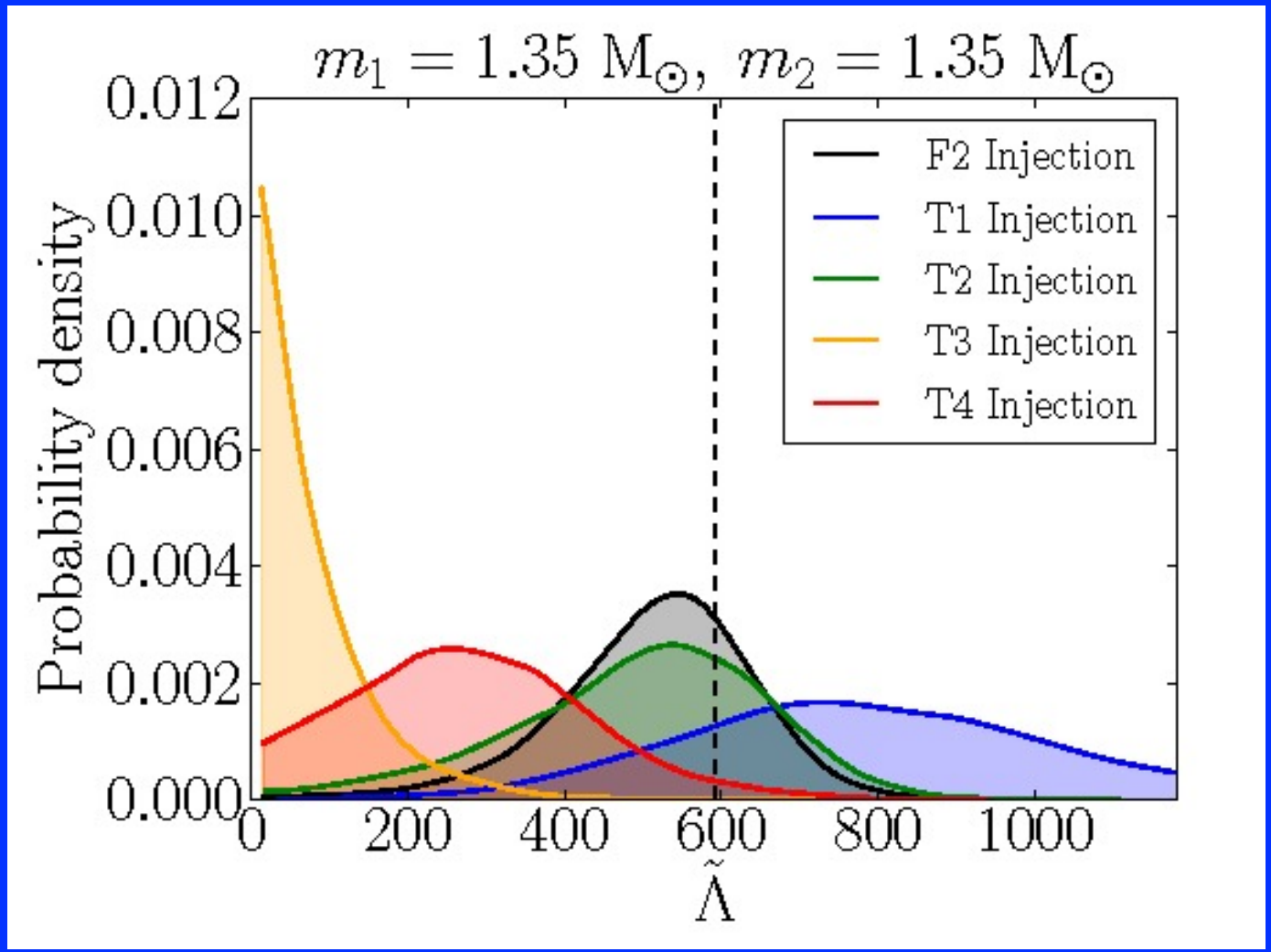
- How long will it take to get the “right” theoretical waveform templates?
- Will observations of other sources (e.g., BH-BH) rule in favor of one template set?
- Will better high-freq sensitivity (e.g., from squeezing) help distinguish empirically between templates?
- Will non-Gaussian noise introduce systematics?
- Systematics from spins? (I. Mandel)

Conclusions

Many methods of radius estimation have been proposed.

To me, it seems that waveform fitting and, in the near future, gravitational wave analysis are most promising. But systematics must be explored carefully!

Systematics in Waveforms



Wade+ 2014
SNR_{net}=32.4
Recover w/ TaylorF2 waveform templates

Dashed vert line is injected tidal param

~equally good statistical fits