Challenges in Measuring Neutron Star Radii

Cole Miller

University of Maryland and

Joint Space-Science Institute

Collaborators: Romain Artigue, Didier Barret, Sudip Bhattacharyya, Stratos Boutloukos, Fred Lamb, Ka Ho Lo

Outline

Key point: all current NS radius estimates are dominated by systematics!

- Estimates from cooling spectra
- Estimates from X-ray burst spectra
- Estimates from X-ray waveforms
- Future estimates from gravitational waves

Idea of talk: I will give a quick overview of each method, then we can discuss ways to estimate/limit the systematic errors in each case.

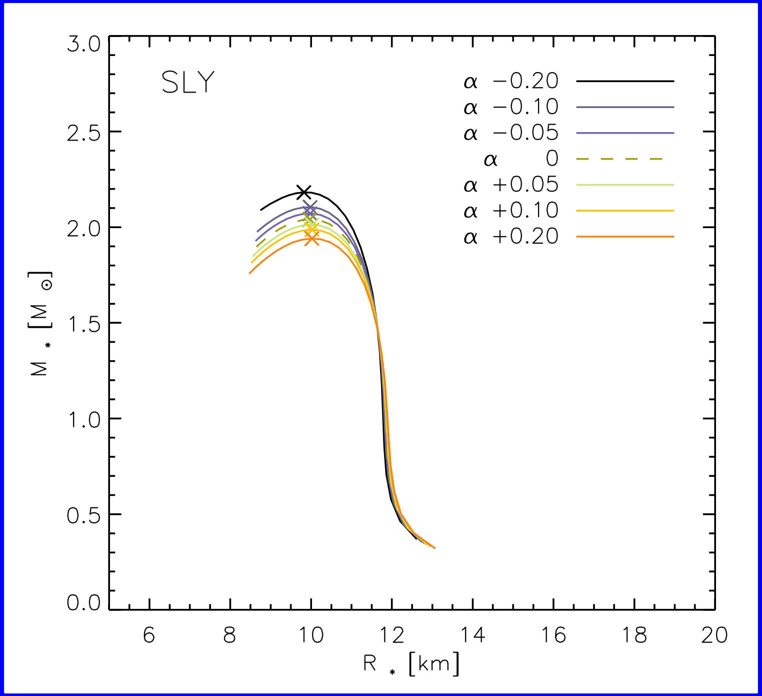
Challenges

- Can we measure NS radii without huge systematic errors?
- What can we do with future X-ray satellites?
- What can we do with gravitational radiation?

Overall point: for most existing methods, there is no *direct* way, using *observations*, that we can tell if the model being used is the correct one. Thus we rely heavily on theoretical confidence, which is not a good situation!

Waveform fitting might be an exception, but we have only begun our detailed analysis to see what effect systematics have.

Alternate Gravity Theories?



Orellana et al. 2013
R^2 gravity

- Keep in mind: strong gravity not tested well
- Actually testing joint hypothesis of EOS, GR
- Just cautionary, though, and LIGO grav waves should test strong GR
- We will assume GR in rest of talk

Measuring stellar radii

- Ordinary star, like the Sun
- Too far for angular resolution
- But can get luminosity L
- If we assume blackbody, $R^2=L/(4\pi\sigma T^4)$
- But for NS, usually gives ~5 km!
- Why? Spectral shape is ~Planck, but inefficient emission
- Need good spectral models
- But data usually insufficient to test

Emission from Cooling NS

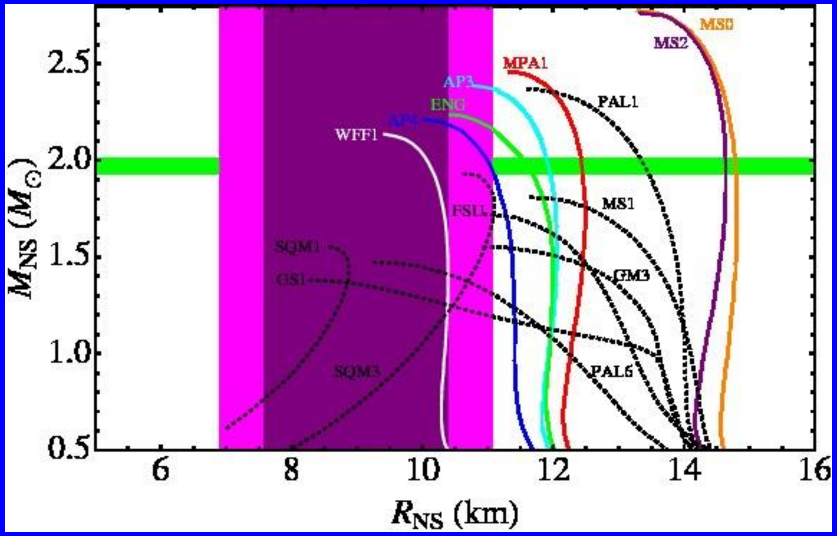
- Old, transiently accreting NS
- Deep crustal heating (e.g., e capture)
- If know average accretion rate, emission provides probe of cooling; can we use to fit radius?
- Predictions of simple model:
  Minimum level of emission
  Spectrum should be thermal
  No variability: steady, slow decay

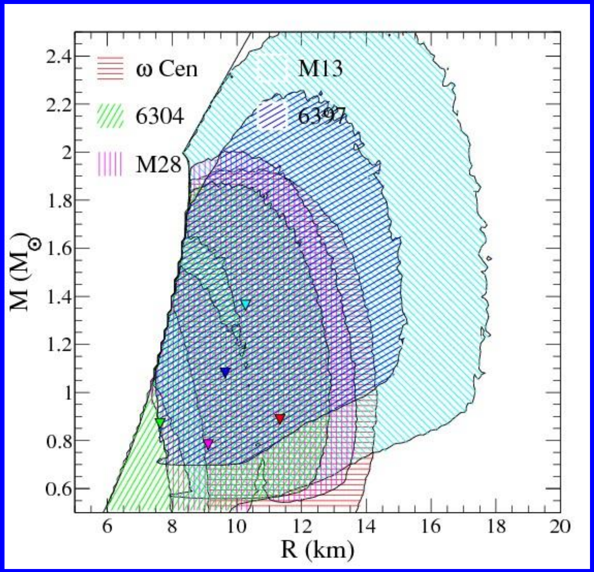
Cooling NS Observations

- But all the predictions fail
  L sometimes below minimum
  Large power law (nonthermal) component
  Significant variability
- Explanations exist, but failure of basic model means we can’t use these observations to get R
- Also: is surface mainly H? He? C? Makes 10s of percent difference to R
- Magnetic field can also alter spectrum
- No guarantee that whole surface emits uniformly
- Again, wide variety of models fit data, thus can’t use data to say which model is correct

Effect on inferred R for qLMXBs

- Top: Guillot+ 2013
  Bottom: Lattimer+Steiner 2014
  Heinke et al. 2014
- Huge differences!
  N_H, d, H vs He atm
  Probably understated; both assume uniform full-surface emission
- Again, can't tell from data alone



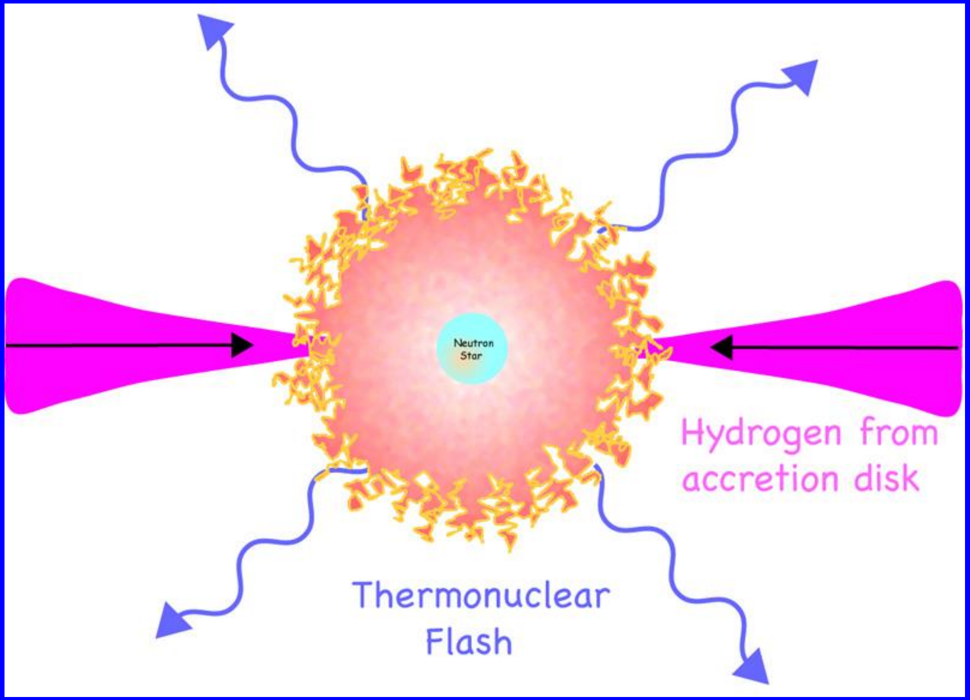


Questions for Discussion

- How many counts are needed to distinguish observationally between H and He atmospheres? To rule out 10^{9-10} G fields, which could affect spect?
- Can nonthermal comp be ruled out?
- Given that fields might be moderately to closely aligned with rotation axis, how well can we rule out temperature gradient on surface?

M and R from X-ray Bursts

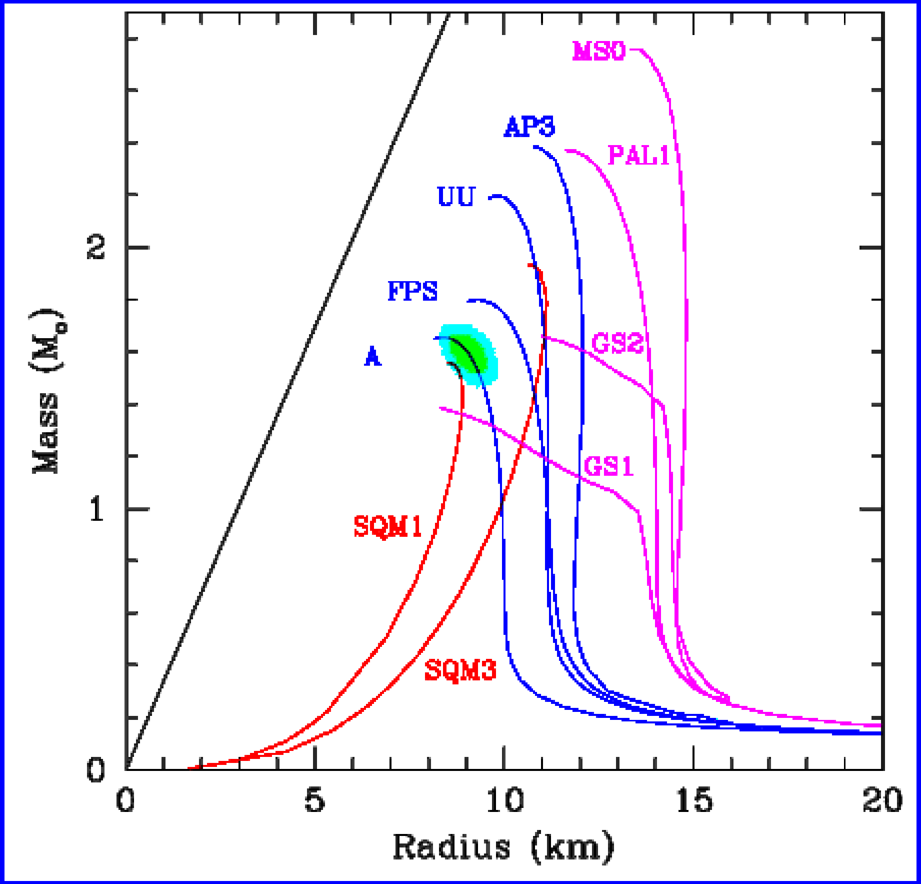
- van Paradijs (1979) method
- XRB: thermonuclear explosions on accreting NS
- Assume known spectrum, emission over whole surf.
- Only with RXTE (1995-2011) are there enough data



http://cococubed.asu.edu/images/binaries/images/xray_burst3_web.jpg

4U 1820 Bursts: Soft EOS?

Guver et al. 2010; known dist (globular)



Uses most optimistic assumption: no systematics, only statistical uncertainties

But small errors are misleading; only ~10^{-8} of prior prob. space gives M, R in real numbers! (Guver et al., Steiner et al.)

Also, spectral model is terrible fit to best data!

- Are there models that fit well? What do they say about uniformity of surface emission?

Fits Using New Models

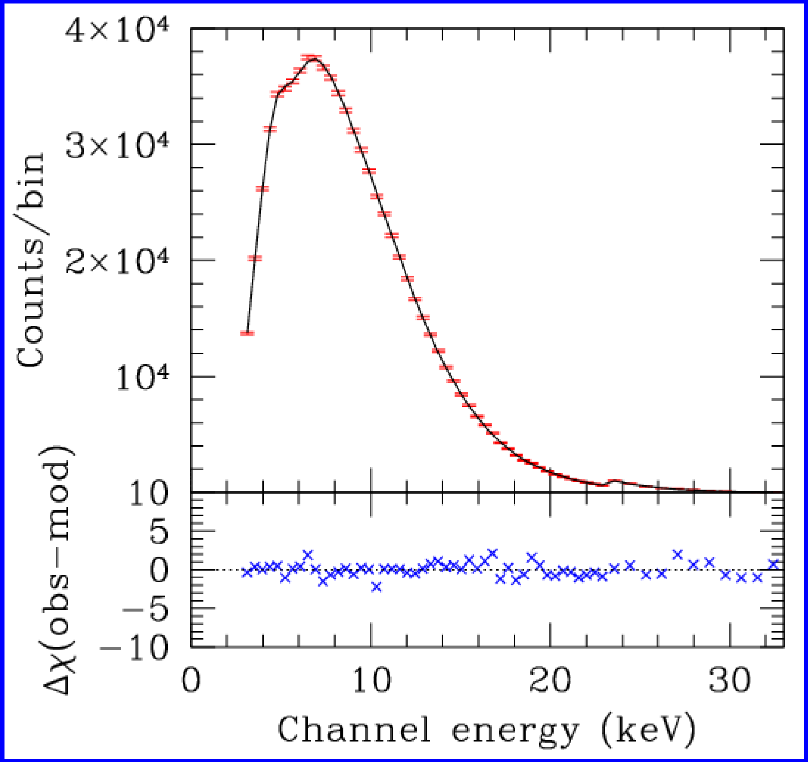
Yes! New models from Suleimanov et al. do seem to fit the data quite well.

This model has $F=0.95F_{Edd}$
Best fit: χ^2/dof=42.3/48
Best B-E fit: χ^2/dof=55.6/50

For full 102-segment data set, best fit has χ^2/dof=5238/5098
B-E best: χ^2/dof=5770/4998

Fits are *spectacularly* good!
Much better than B-E, so further info can be derived.
~20 million counts needed

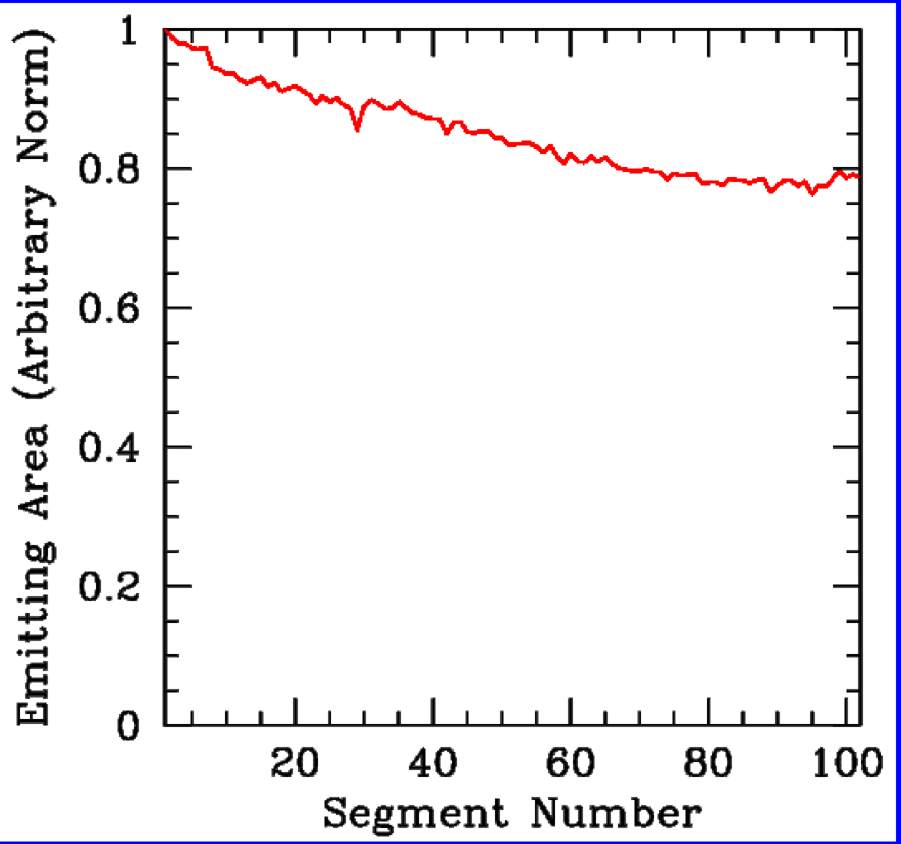
64-second segment at peak temperature; 1820 superburst



Boutloukos, Miller, Lamb 2010
Pure He, log g = 14.3, $F=0.95F_{Edd}$
Model from Suleimanov et al. 2010

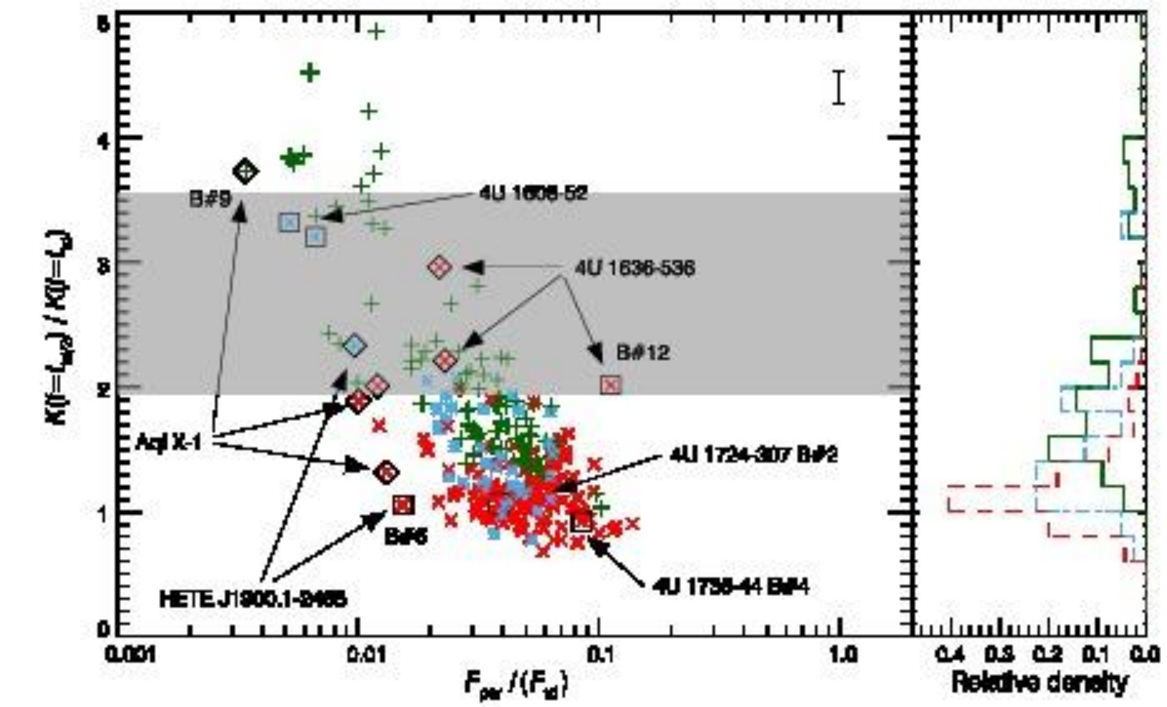
Use of New Models

- So is it a simple matter of using the new models, with the van Paradijs method?
- Unfortunately, no
- Fitted emitting area changes systematically (even assuming g, z constant, so photospheric radius is constant)
- Constrain z given g
- With next-gen instruments, might constrain both g and z from spectra, leading to M and R



Inferred relative emitting areas, for 102 16-s segments near the peak of the 1820 superburst: Miller et al., in prep

Few Bursts Follow Model



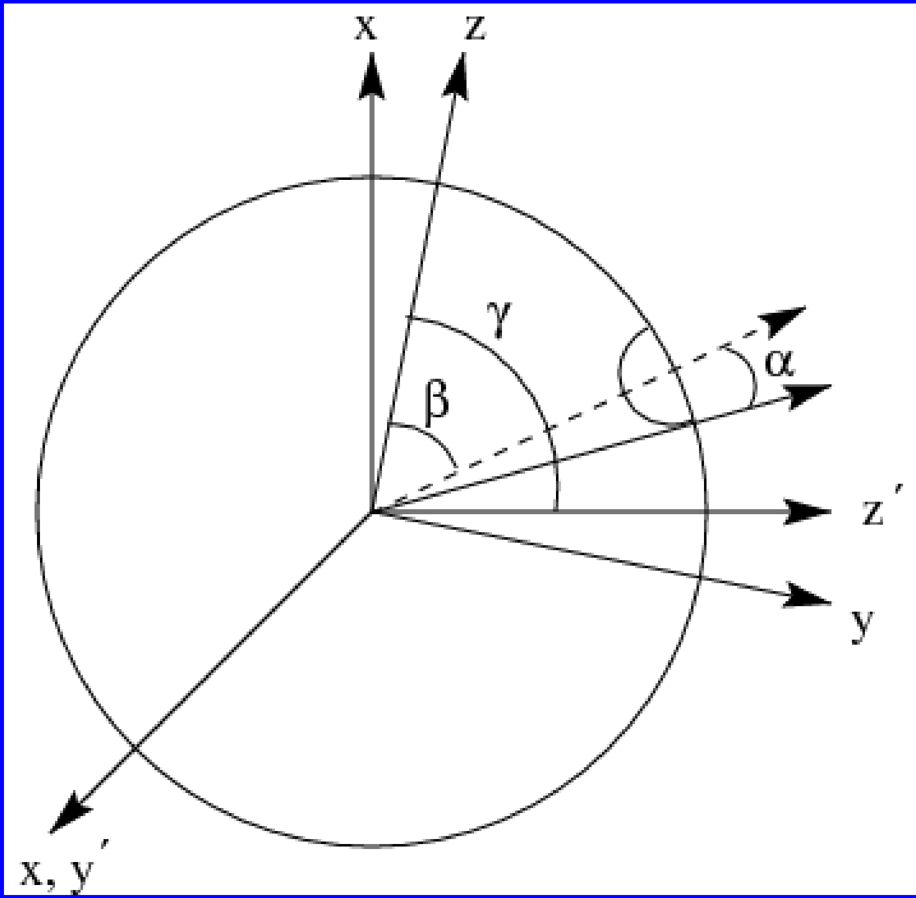
- Kajava+ 2014. Grey band follows model
- Bursts with $F_{persistent}/F_{burst}$>0.03, and bursts not in hard state, don't follow model
- Some of the rest don't either

Questions for Discussion

- Can we understand spectral contamination enough to model? Note: can’t assume persistent emission continues unchanged through burst
- Are there independent ways to constrain the surface emitting fraction (e.g., energy-dependent waveforms)?
- Can this approach be rescued?

Ray Tracing and Light Curves

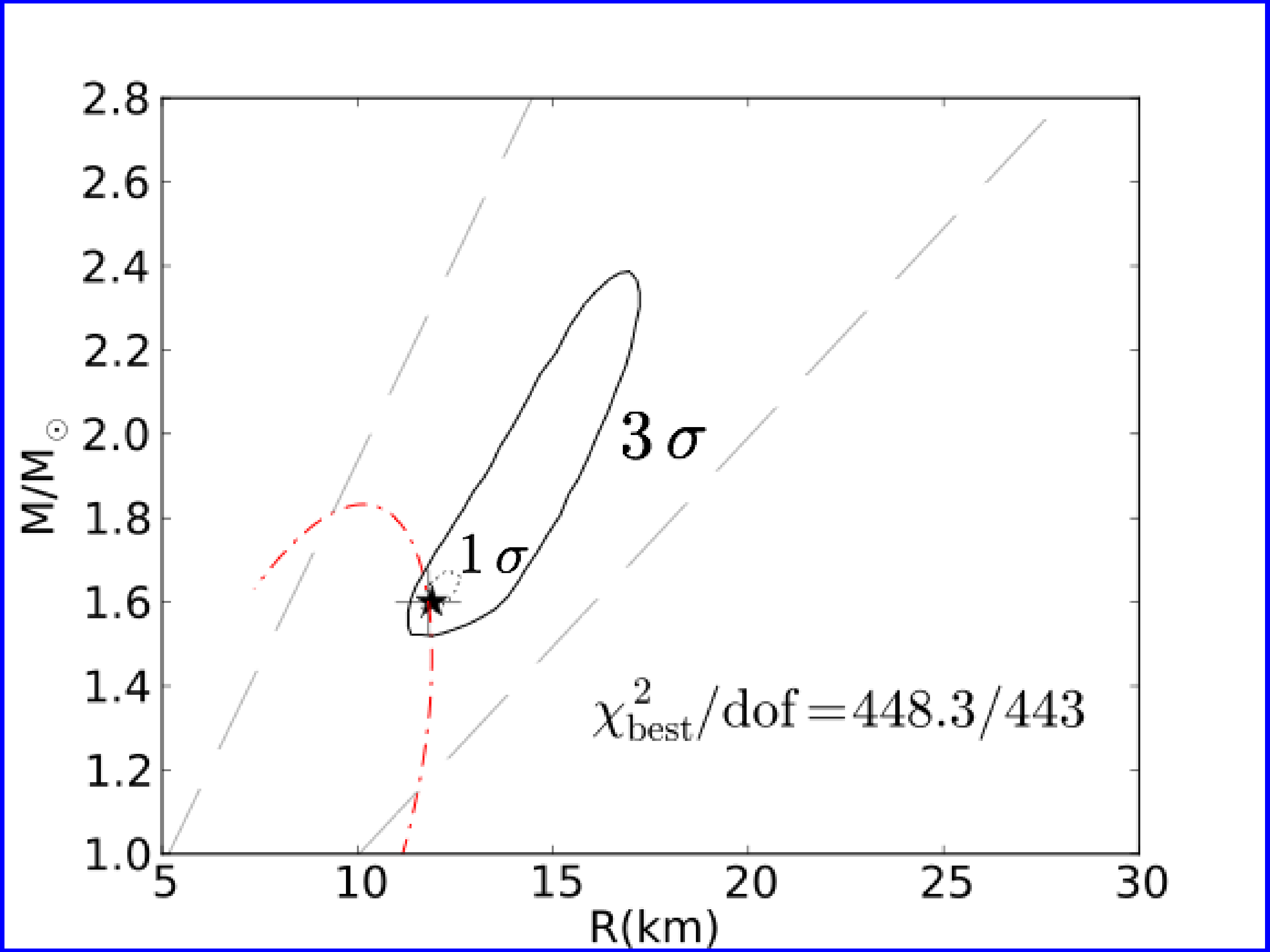
- Rapidly rotating star 300-600 Hz v_{surf}~0.1-0.2c
  SR+GR effects
- Light curve informative about M, R
  Miller & Lamb 1998
  Bogdanov+ 07, 08, 12
  Many others...
- Must deal carefully with degeneracies
- Will now focus on our results from Lo et al. 2013
  Miller+Lamb 2014 (synthetic data only!)



Weinberg, Miller, and Lamb 2001

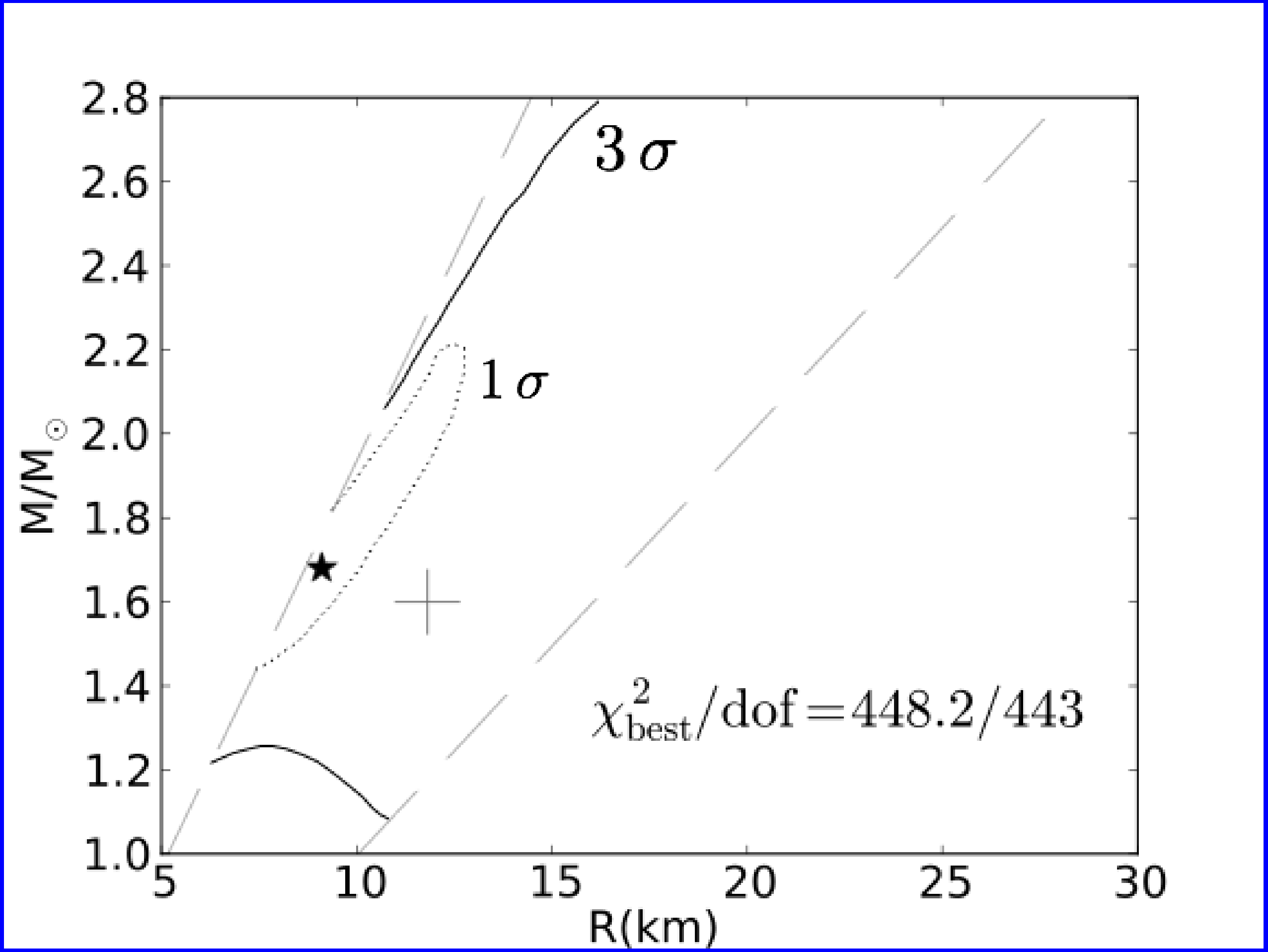
High inclinations allow tight constraints on M and R

Spot and observer inclinations = 90˚ , high background



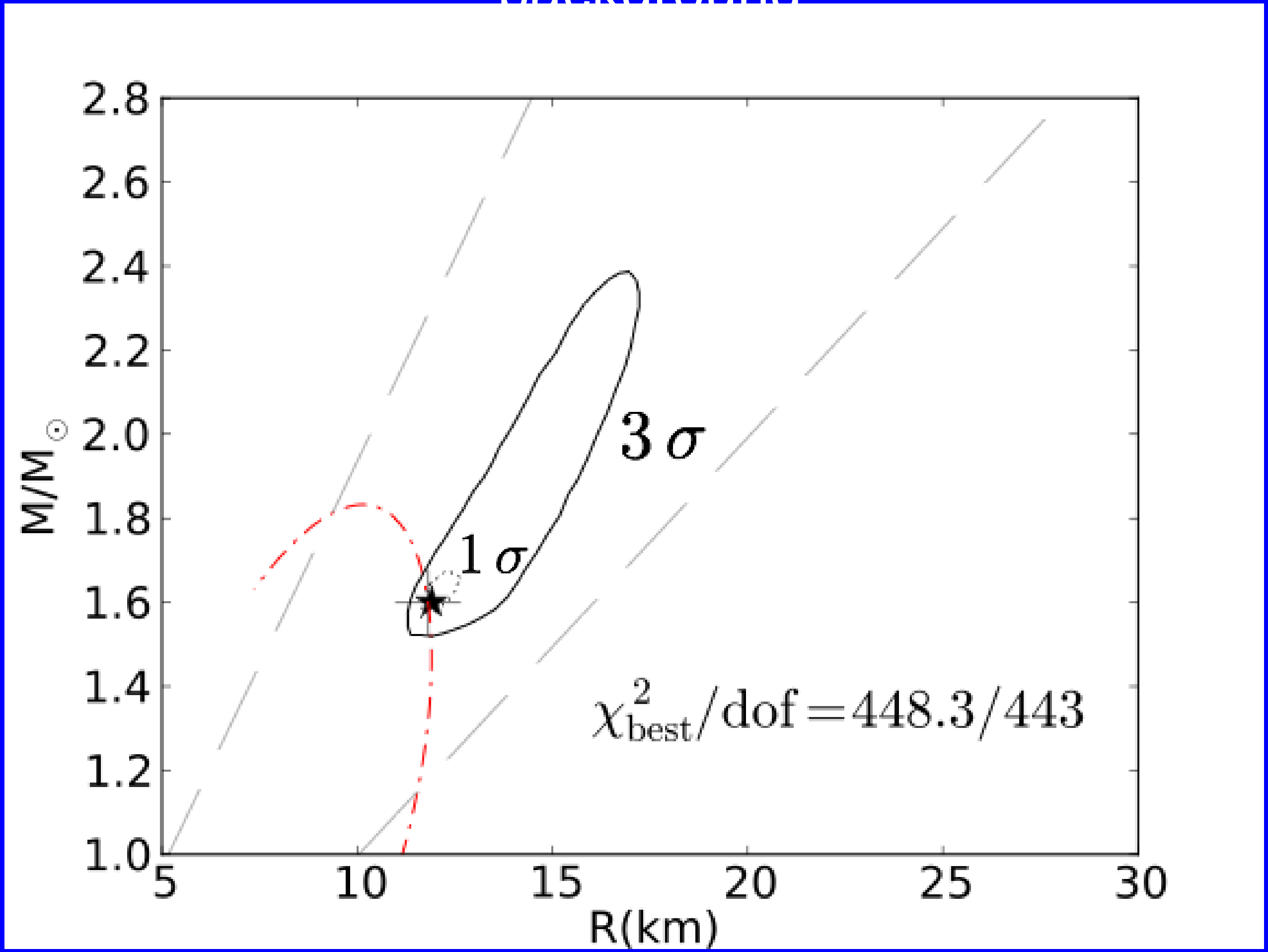
Low inclinations produce looser constraints

Amplitude similar to the previous slide, but low spot and observer inclinations, low background



Independent knowledge of the observer's inclination can increase the precision

spot and observer inclinations = 90° , high background



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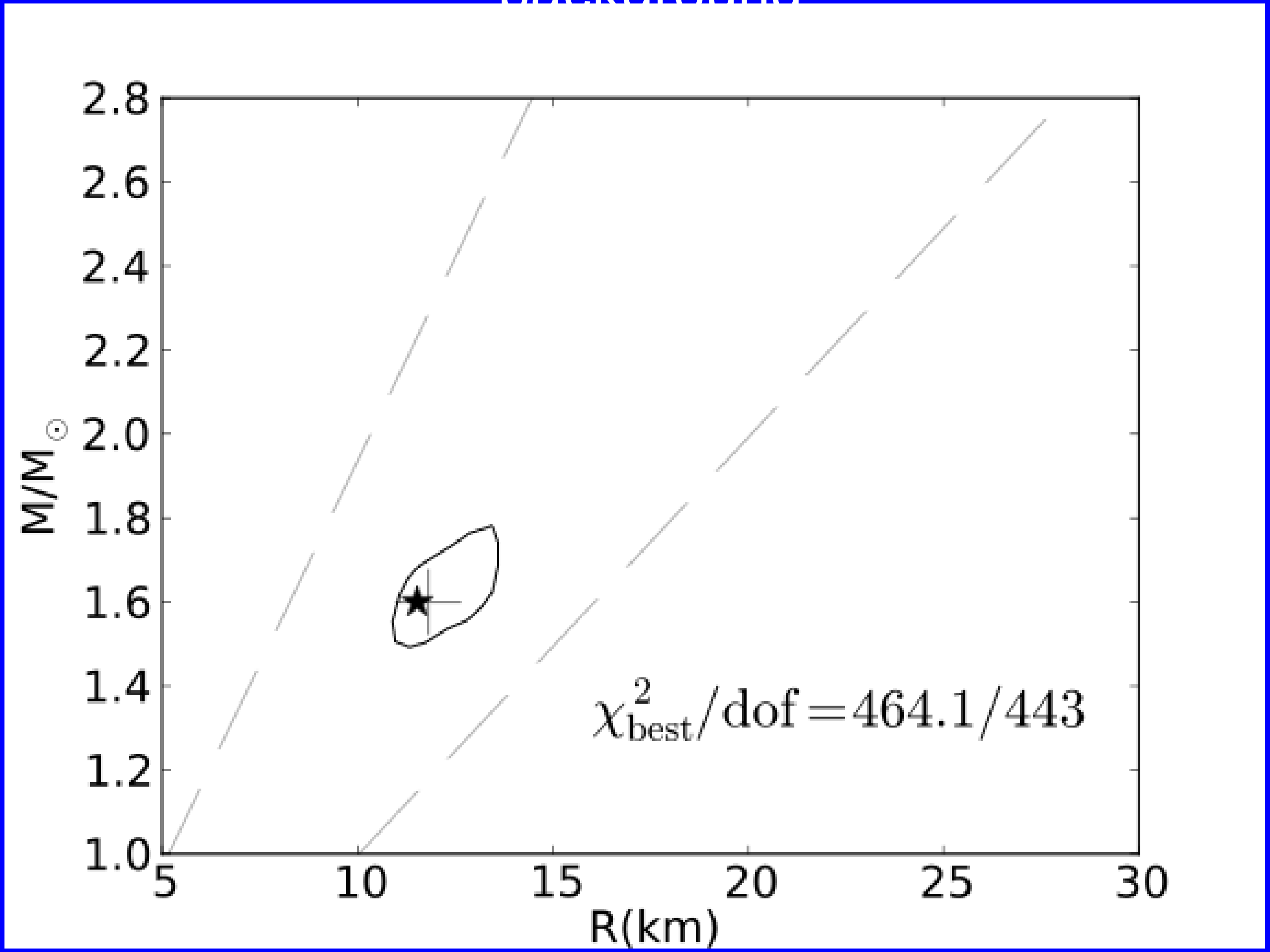
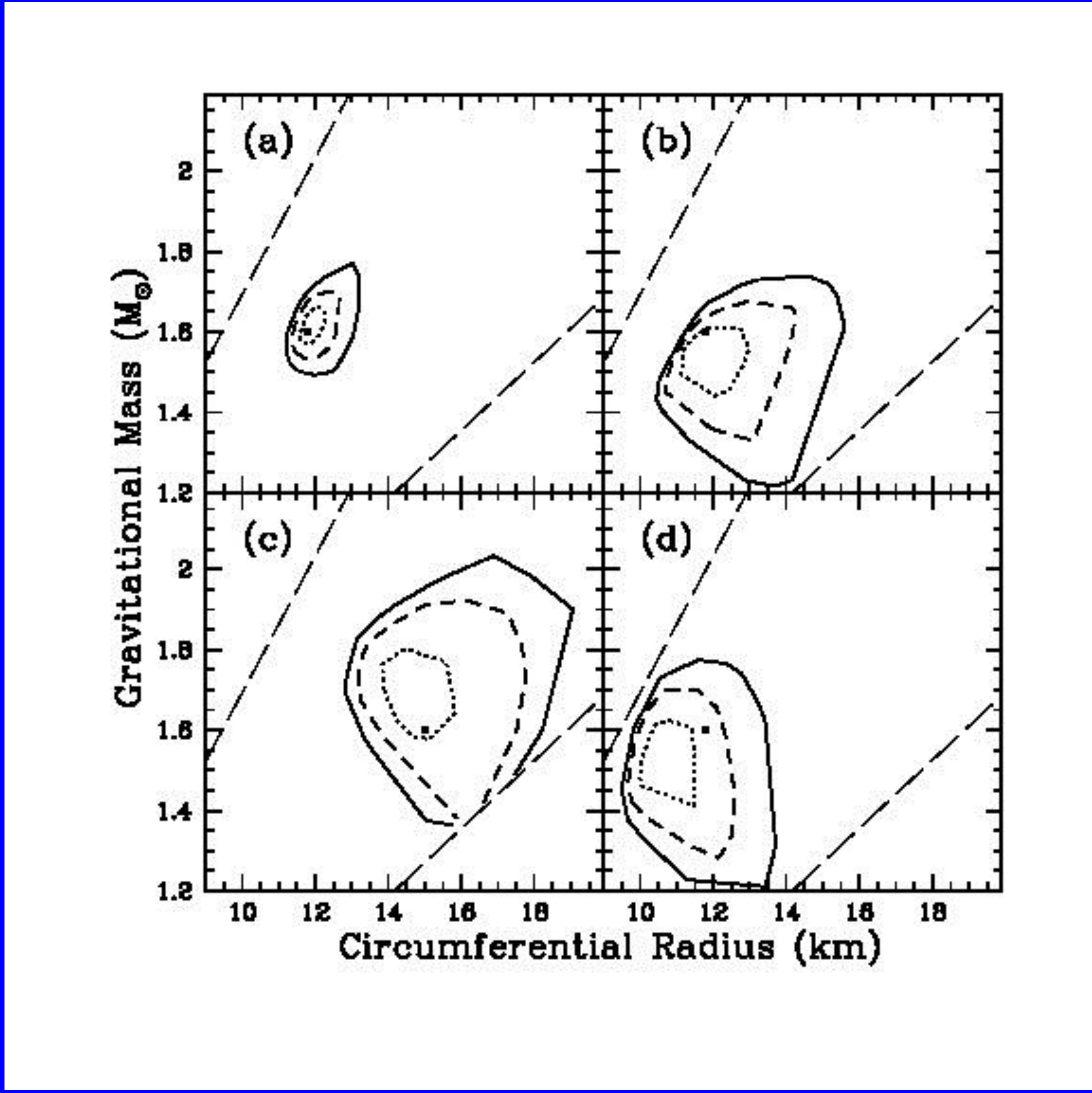


Systematic Deviations?

- A key, encouraging aspect of this model is that in addition to the 3-7% precisions possible with 10^6 photons from the spot, currently examined systematics aren't as problematic as in other methods
- Different spot shape, spectrum, beaming pattern, temperature gradients
- Don't find (1) good fit, (2) apparently tight constraints, (3) significant bias

Oblate Schwarzschild



Miller+Lamb 2014
Top left: spot, obs on equator.
3-7% precision possible in M, R.

Bottom right:
data generated w/ temp gradient, fit with const temp.
Minimal bias.

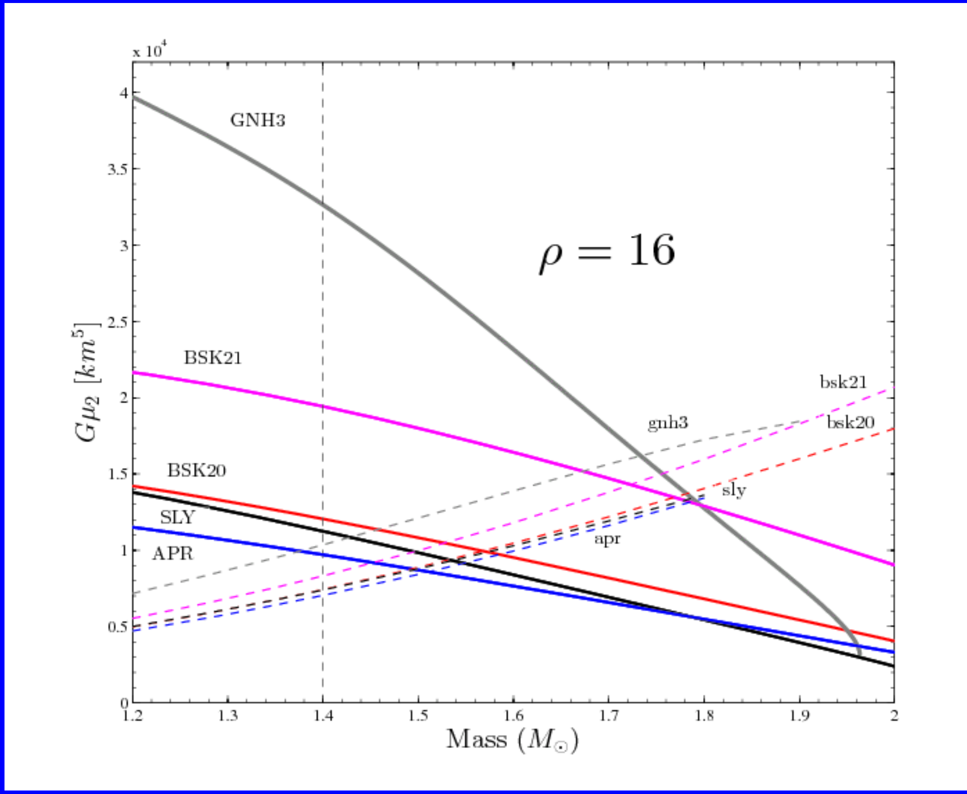
Questions for Discussion

- Promising, so far, but are there other significant systematic errors to explore? Put in ATP proposal to examine frame-dragging and other effects
- ~10^6 counts from spot needed for good constraints; seems practical for NICER, but will this model be extendable to isolated pulsars with different beaming patterns?

Phase Accumulation from GWs

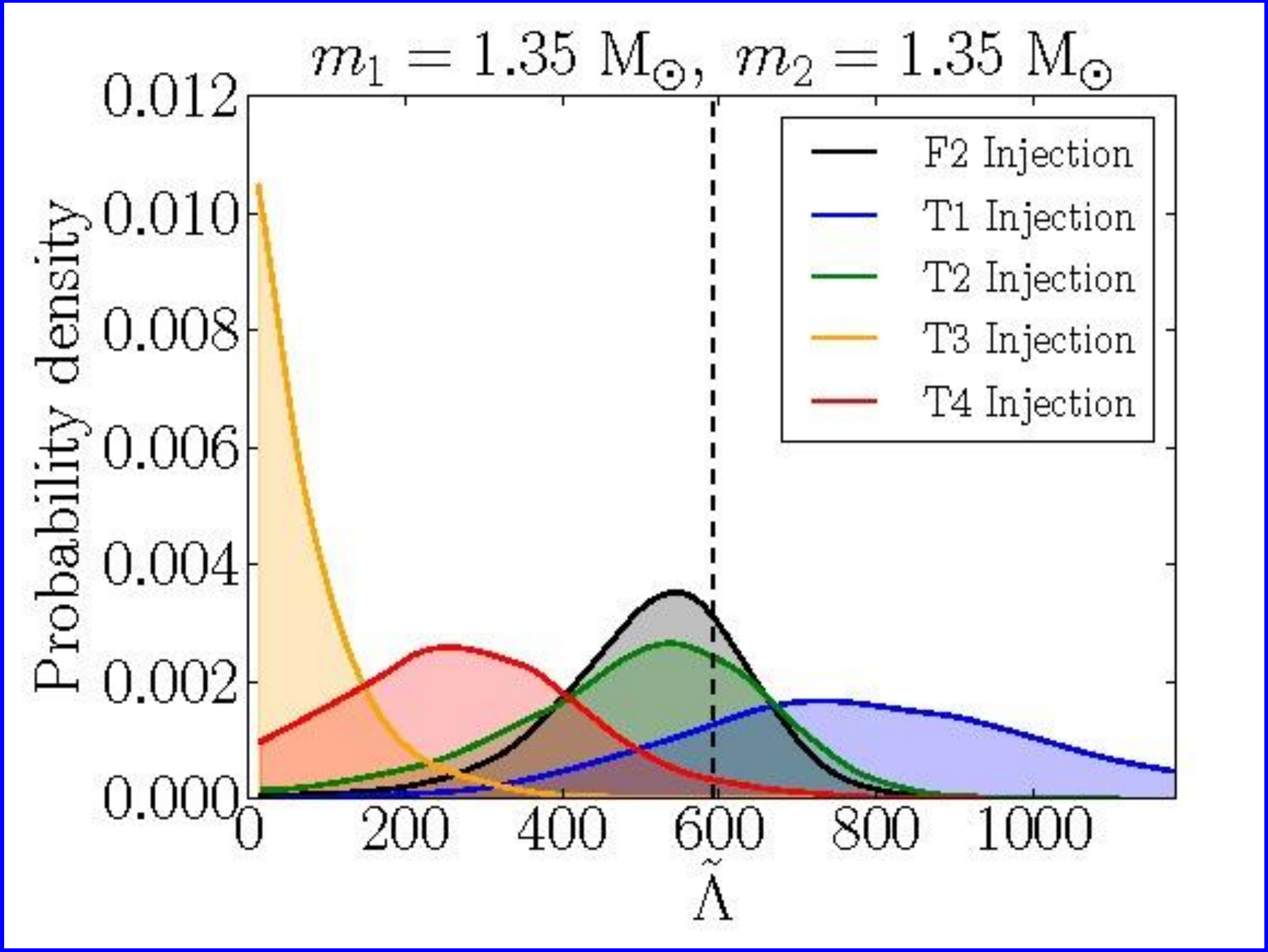
- aLIGO/Virgo: >=2015
- Deviation from point mass in NS-NS inspiral: accumulated tidal effects
- For aLIGO, can measure tidal param (Del Pozzo+ 2013: distinguish R~11, 13 km with 15 events?)
- Recent analytics confirmed by numerical relativity (Bernuzzi et al. 2012)
- High-freq sensitivity key

  High-freq modeling, too



Damour et al., arXiv:1203.4352

Systematics in Waveforms



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

Dashed vert line is injected tidal param

~equally good fits for all templates

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 spin? (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!

Open question: how can we best combine astronomical information with laboratory measurements (e.g., ^{208}Pb skin thickness)?