Neutron Star Constraints on Cold High-Density Matter

Cole Miller

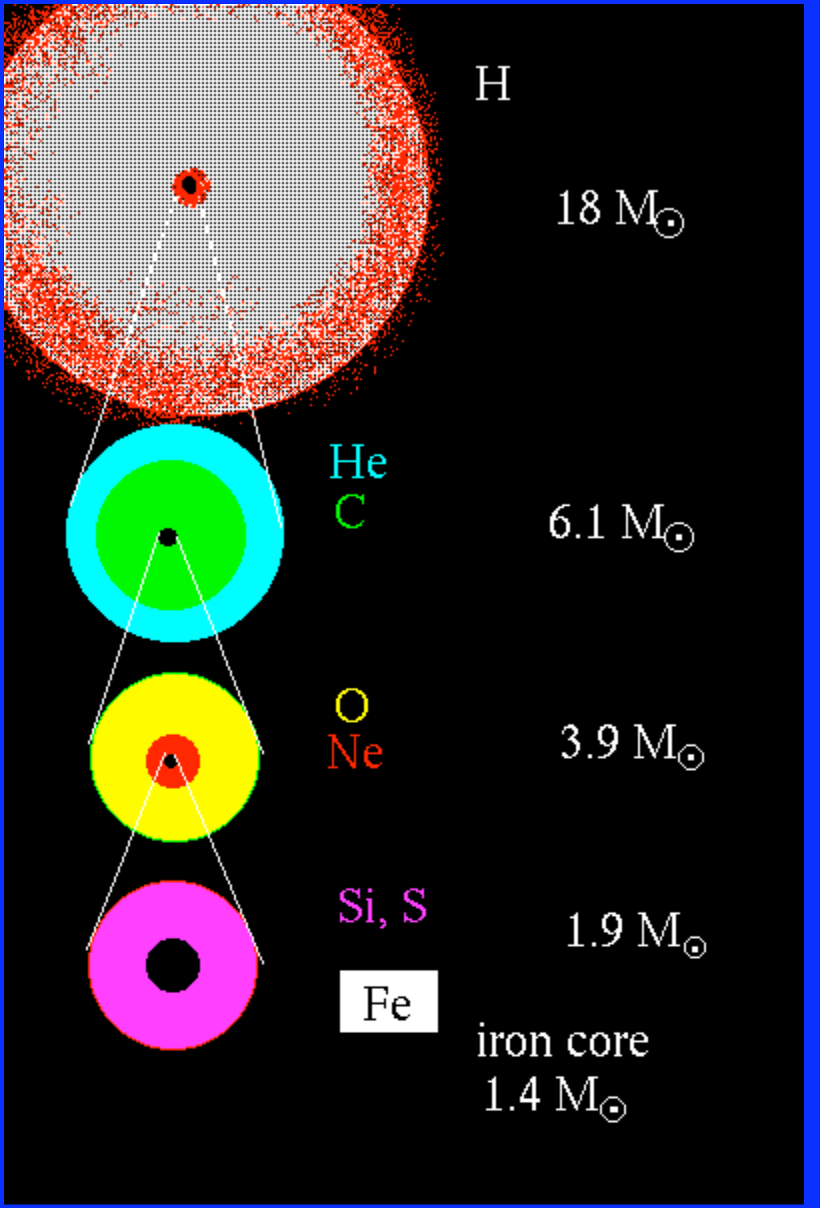
University of Maryland

Outline

- The life of a neutron star
- NS mass estimates
  In binary neutron star systems
  In other binaries
  In other ways
- Light curves and NS radius estimates
- Equation of state or theory of gravity?
- The promise of gravitational waves

Initial Mass of NS

- Core collapse
  Baryonic mass>1.35M_s
  Grav mass>1.2M_s
- Unknown amount of fallback (in some cases leads to BH, collapse)
- How much matter can accrete afterwards?



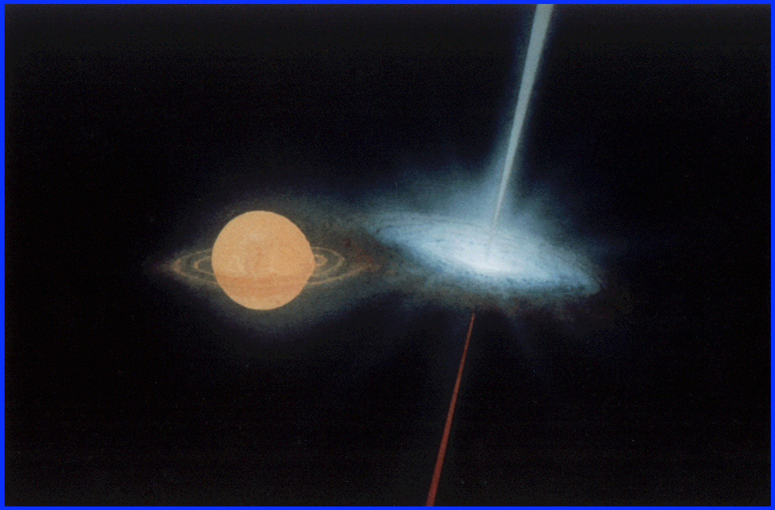
http://hera.ph1.uni-koeln.de/~heintzma/Integral/bilder/snt8.gif

The Eddington Limit

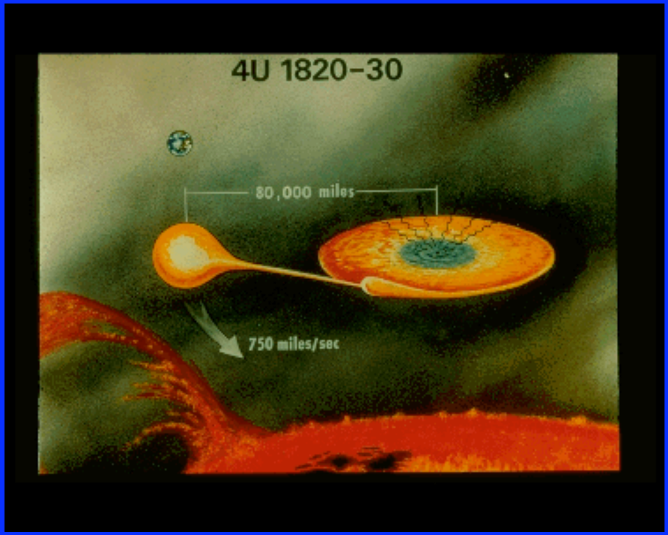
- Limit on accretion rate, when radiation acceleration equals gravitational accel
  $M/(dM/dt) \sim 4 \times 10^7$ yr
- Applicable for photon luminosity
  Hypercritical applies for neutrino
- But works well for mass transfer from a stellar companion
- What is reasonable total mass accreted?

Mass Transfer Binaries

- ISM accretion minimal
- Two types, comp mass
- High mass: wind transfer, $T<10^7$ yr
  Path for double NS
  $\Delta M<0.1\ M_s$
- Low mass: Roche lobe overflow, $T\sim10^{7\text{-}9}$ yr
  WD-NS, MS-NS
  ΔM up to $\sim$0.5-1 M_s



http://astronomy.nmsu.edu/nicole/teaching/ASTR110/lectures/lecture25/pics/SS433.gif



http://lheawww.gsfc.nasa.gov/users/white/xrb/4u1820_small.gif

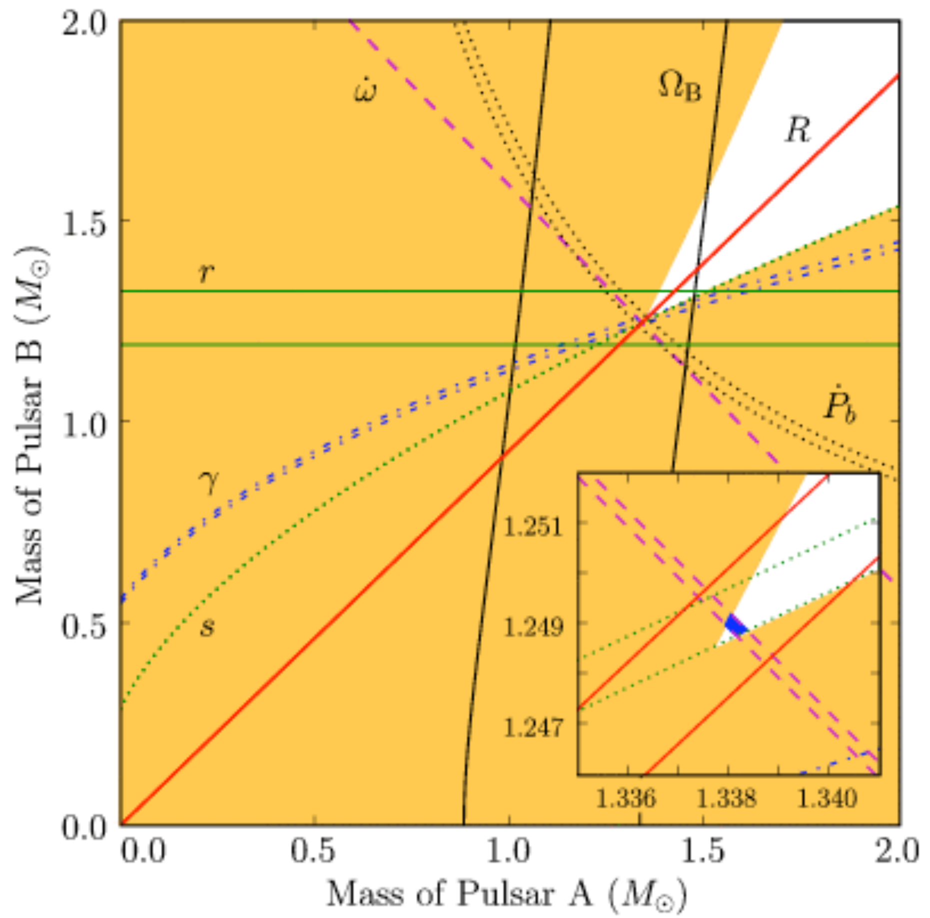
Net Result:

Mass of NS can be from about
1.2 M_s to NS maximum.
Note: rotation can increase maximum,
but no confirmed rate is high enough
to change M_{max} significantly.

How can we determine masses?

Binary Orbits

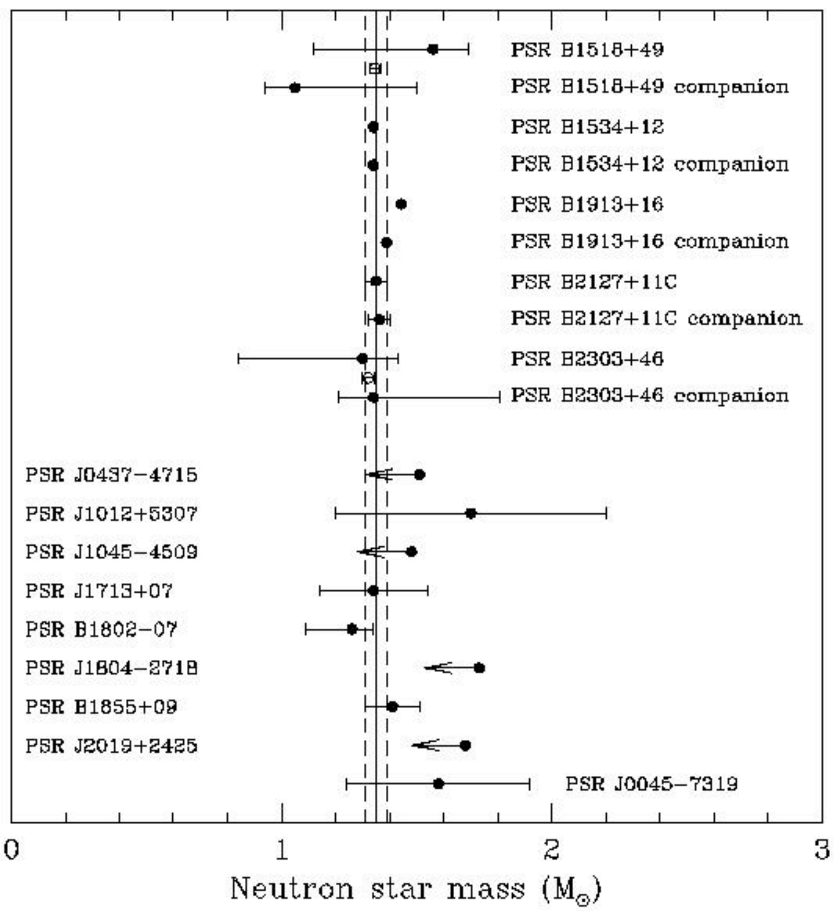
- Mass function:
  $M_{min}=v^3P_{orb}/(2\pi G)$
- Post-Keplerian params can break degeneracy
  Pericenter precession
  Shapiro delay
  Orbital decay
- For double NS, no complicating factors
  Very precise masses!
  Measure I in future?



Breton et al. 2008

Double NS Masses

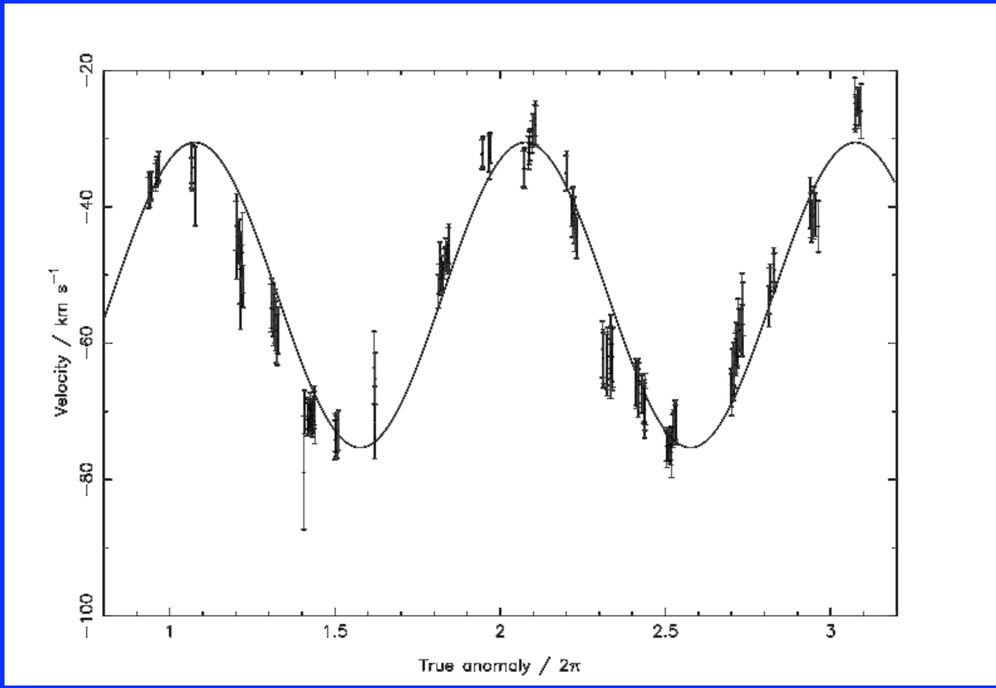
- Very tightly clustered $M=1.35+-0.1\ M_s$
- Close to formation mass ($\Delta M<0.1\ M_s$)
- Does this indicate a very low upper limit on masses?
- Or are formation conditions just similar?



http://www.lsw.uni-heidelberg.de/users/mcamenzi/NS_Mass.jpg

NS in Other Binaries: Vela X-1

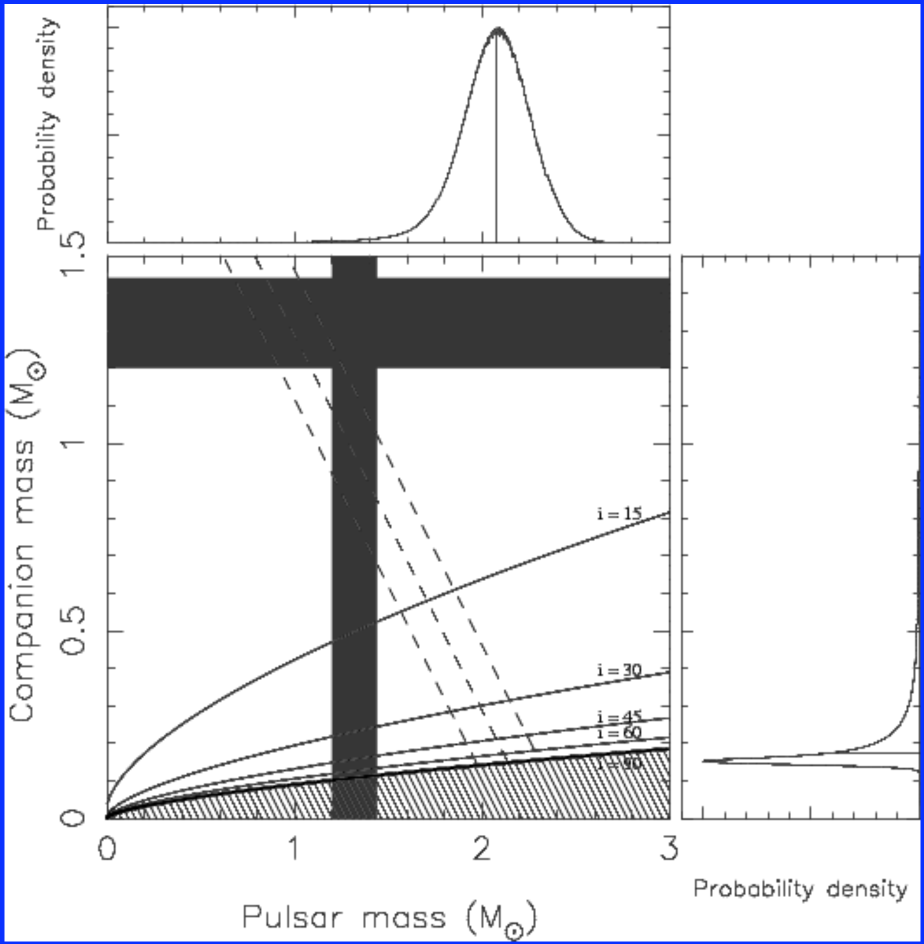
- High-mass normal stellar companion
  Tidal effects!
- Could be progenitor of double NS system
- But mass estimate is 1.75 to 2.01 M_s
- Different formation?
  Or just chance?



Vela X-1, radial velocity curve
Quaintrell et al. 2003

Statistical Argument for High Mass

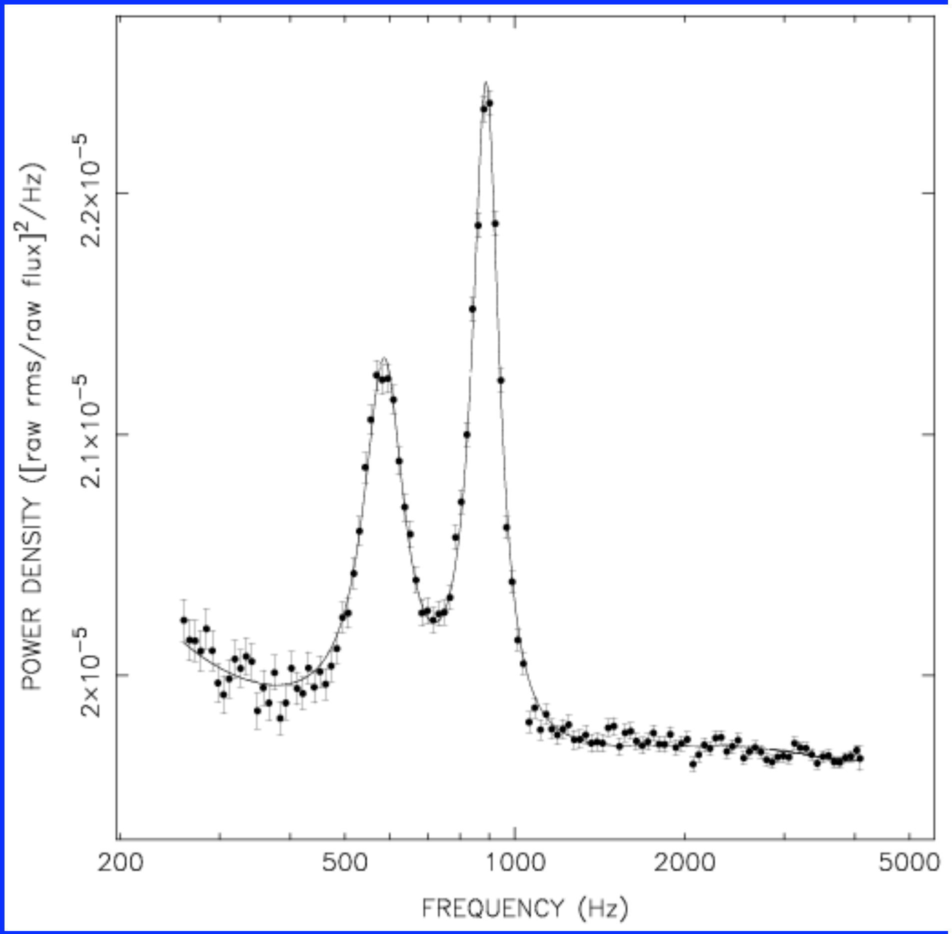
- Globular cluster M5
- Several NS-WD pairs
- Not enough info to know inclinations
  Only lower mass lims
- But, several cases with high lower lims
- $P(M>1.7M_s)>99\%$
  N6440B: $M>2M_s$?
  But is there bias in the inclination angles?



Freire et al. 2008

A Longer Shot: Quasi-Periodic Oscillations

- X-ray intensity from NS LMXBs varies quasi-periodically
- Best model: upper peak close to orbital frequency at some special radius
- Some evidence for ISCO $M \sim 2M_s$?



Sco X-1 (van der Klis et al. 1996)

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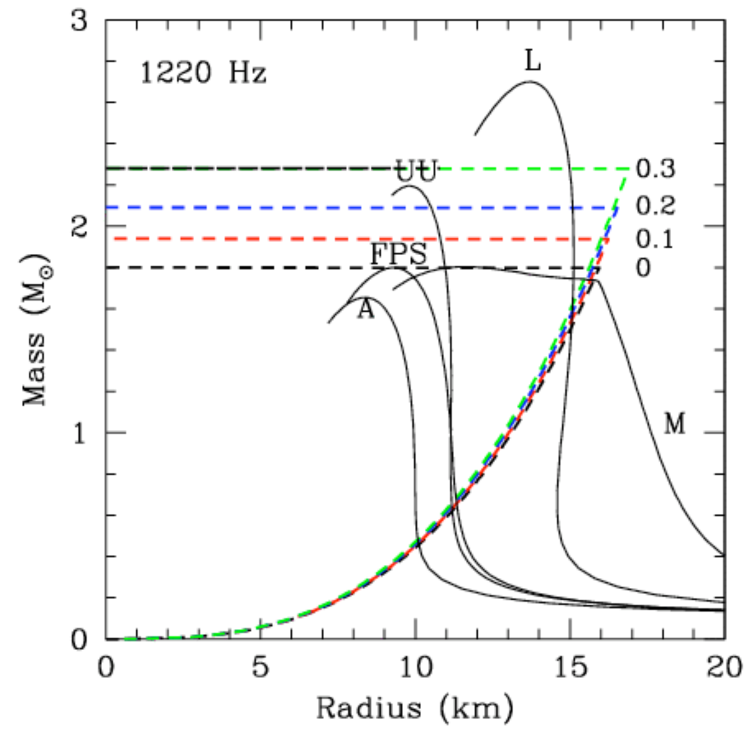


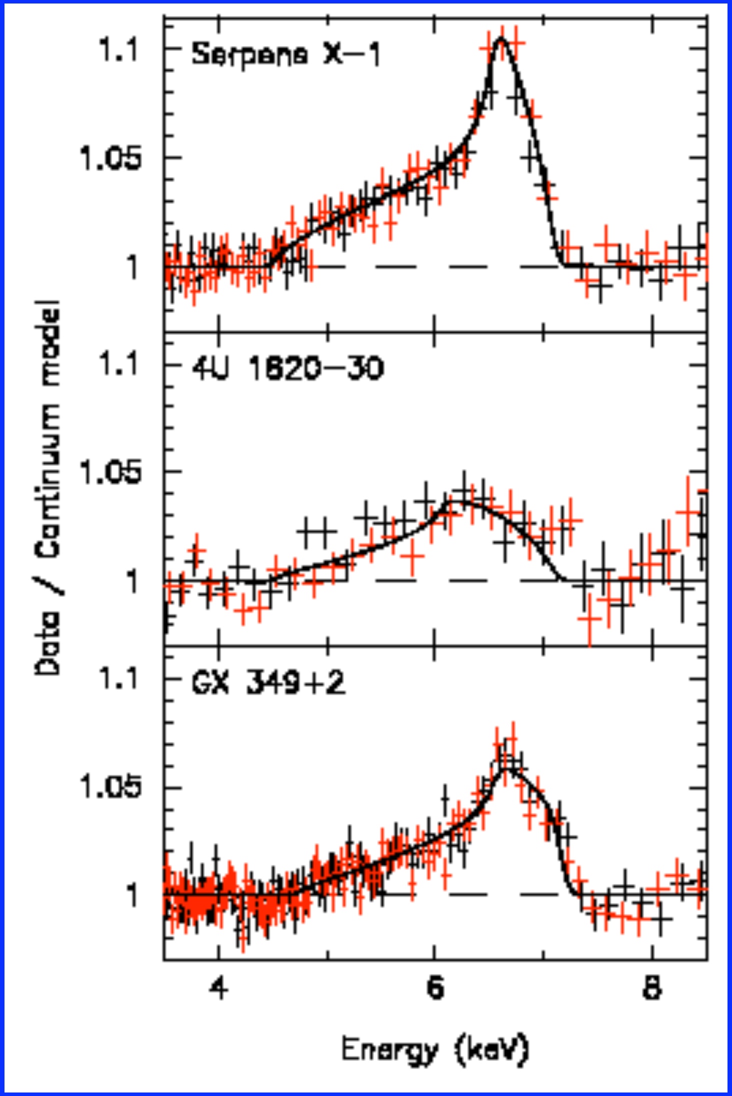
M-R constraints: Miller et al. 1998

Complementary Constraints

- In principle, measurement of speed would add greatly to information
- Modulo minor frame-dragging effects:
  $f \sim (GM/r^3)^{1/2}$
  $v \sim (GM/r)^{1/2}$
- Would combine to give independent constraints on mass, orbital (not stellar) radius
  With frame-dragging, constrain a/M
- How can speed be measured?

Broad Iron Lines

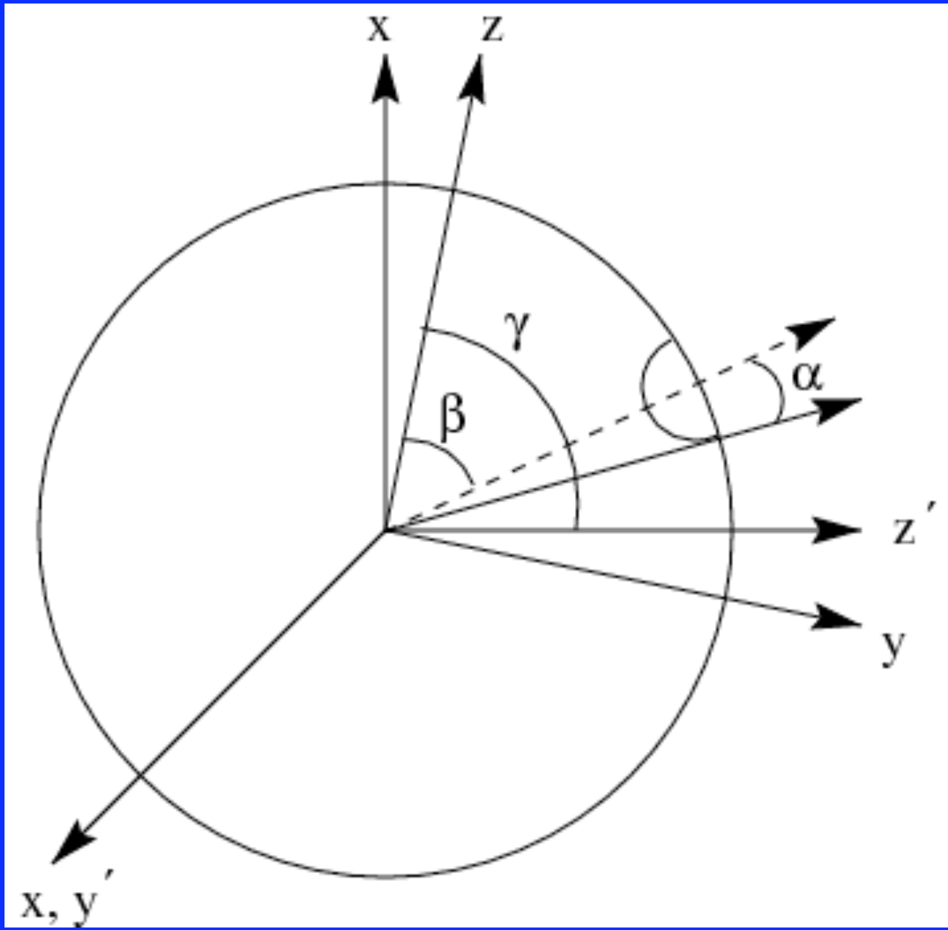
- Iron fluorescence lines are seen from many BH
- Profile affected by Doppler, grav. redshifts, and inclination
- Recently seen from several NS sources
- Constrains spin and speed
- Do not yet have single source with simultaneous QPOs, good line data



Cackett et al. 2007

Ray Tracing and Light Curves

- Rapidly rotating star
  300-600 Hz
  v_{surf}~0.1c
  SR+GR effects
- Light curve informative about M, R
  Miller & Lamb 1998
  Bogdanov et al. 2007,8
  Many others...



Weinberg, Miller, and Lamb 2001

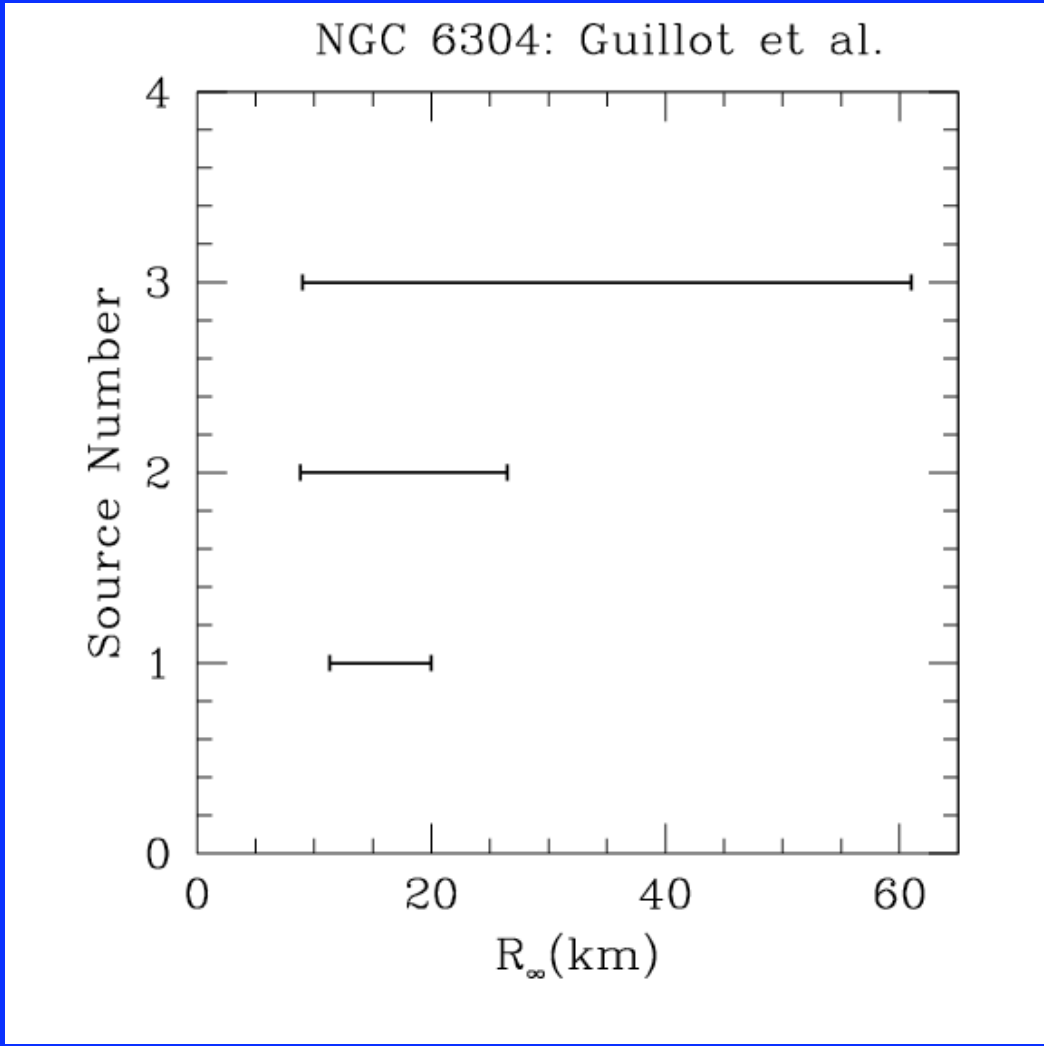
Caveats and Status of Ray Tracing

- One might think spot shape matters, but for small spots shape is irrelevant
  Broad view of surface, plus light deflection
- Beaming pattern does matter some; choose electron scattering or isotropic emission
- Current constraints are not restrictive, but future large-area instruments might get radius to 5% or better

Emission from Cooling NS

- Old, transiently accreting NS
- e capture releases energy deep in crust (E. Brown talk)
- In principle, continuum fit gives radius for quiescent low-mass X-ray binaries (qLMXBs)
- Distance uncertainty; mitigated if source is in globular cluster

Radii from qLMXB in Globular?

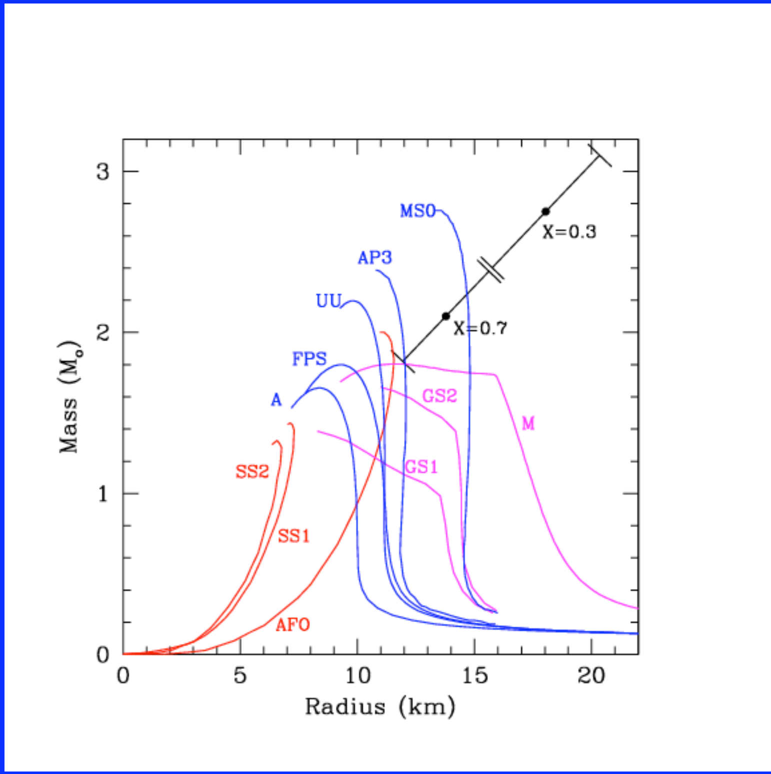


Just statistical errors.
Assumes perfect distance knowledge.
Fixes mass of star at 1.4 M_s
Fixes spectral model (pure hydrogen, no mag field)
For best source (#1), 49% of emission in power law; what causes this?

Continuum spectra not great for constraints!

Data assembled from Guillot, Rutledge et al. 2008

EXO 0748 Bursts: Hard EOS?



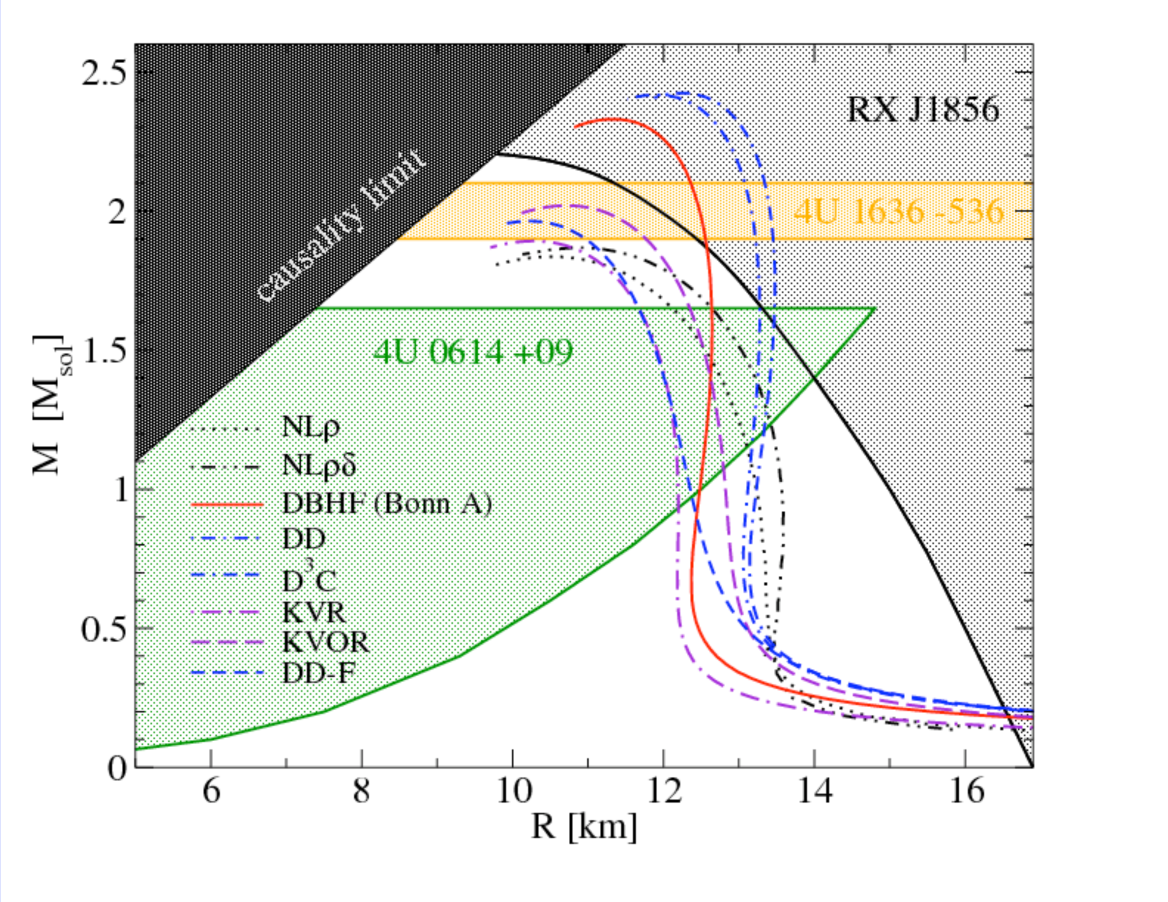
Ozel 2006

Is the mass robustly >$2M_s$?

No. Too many uncertainties.

- Method: van Paradijs   (implemented by Ozel)
- Combine redshift, L_{Edd}, etc. to get M, R
- Interesting, but many complications: Redshift uncertain; L_{Edd} not const; surface emission modeling not clear. Much uncertainty left.

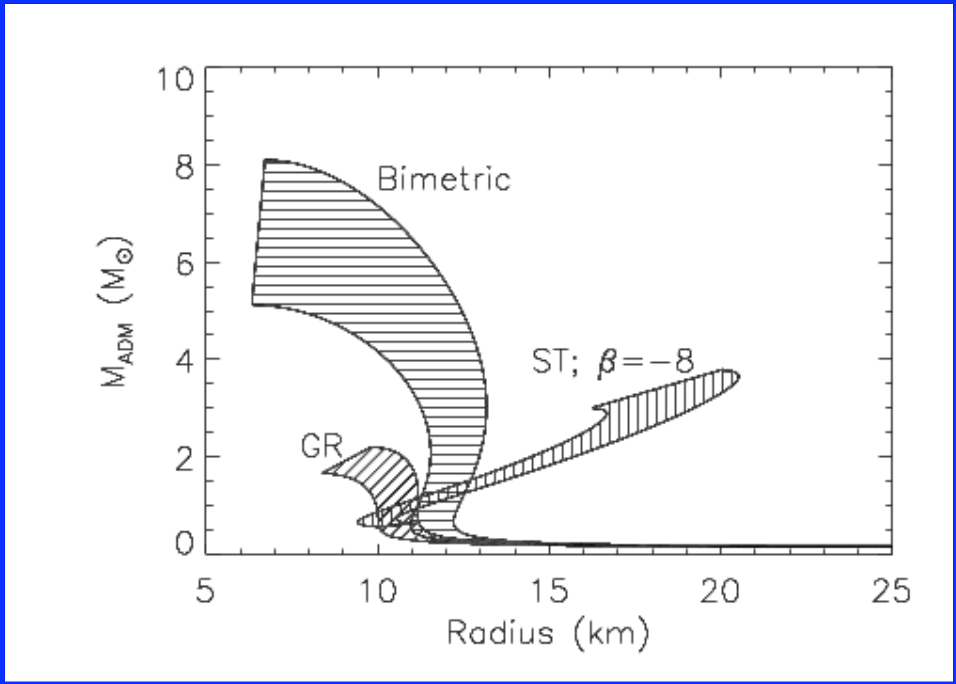
Current Constraints



Again consistent with a nucleonic hard EOS.

Klahn et al. 2006. Combines ISCO, QPO constraints, and thermal radius estimates. Beware of systematics!

Alternate Gravity Theories?

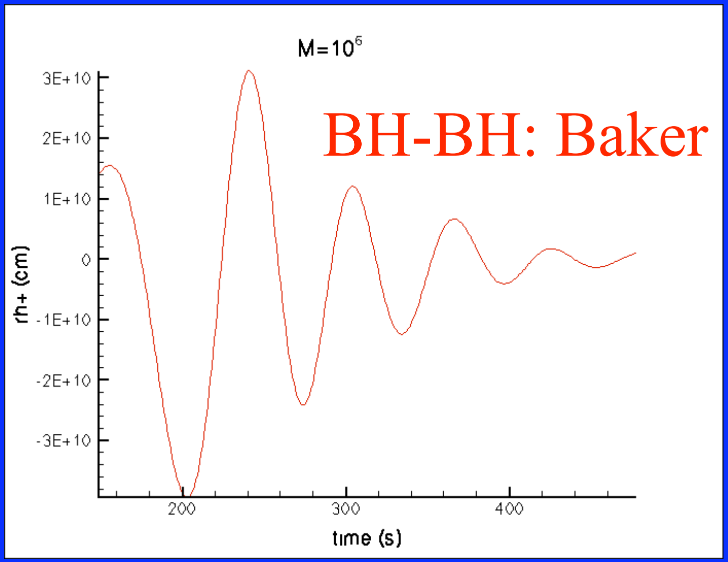


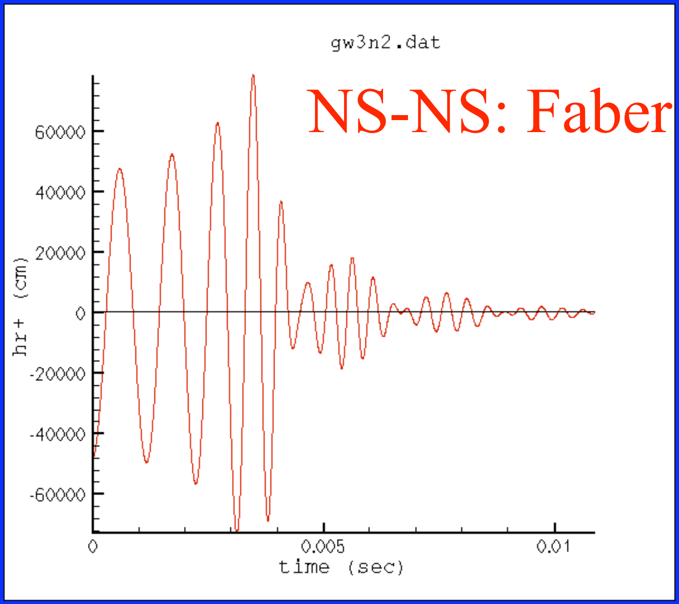
DeDeo & Psaltis 2003

- Keep in mind: strong gravity not tested well
- Therefore, really testing joint hypothesis of EOS and gravity
- Just cautionary, though, and LIGO grav waves will test strong GR very nicely

The Future: Gravitational Waves

- AdLIGO~2013-2018
- Tens of NS-NS/yr
  ?? of BH-BH, BH-NS
- Get NS masses
  High masses?
- Radius from NS disruptions
- Strange star: different waveforms





Mass and Radius from GW

- For DNS observed with AdLIGO, S/N=10:
  Total mass to 1%
  Mass ratio to 10% (5% for 1.5:1 ratio)
  Expect tens of such pairs per year
  A few per year at S/N>20
- Radii not as clear currently
  Simulations need realistic EOS!
  Reason to expect $\Delta R/R<10\%$

Conclusions

- NS masses >1.7 M_s established pretty well
- Radii still very much up in the air: all current methods suffer from systematics
- Most robust near future method?
  If $M>2M_s$ established, that will do it
  Otherwise, I like light curves; simple and robust, just not enough photons now
  Need large-area X-ray timing, IXO!
- In <10 years, GW obs very important