Why neutrino emission is critical for astronomical constraints on dense matter

Andrew W. Steiner (UTK/ORNL)

March 23rd, 2018

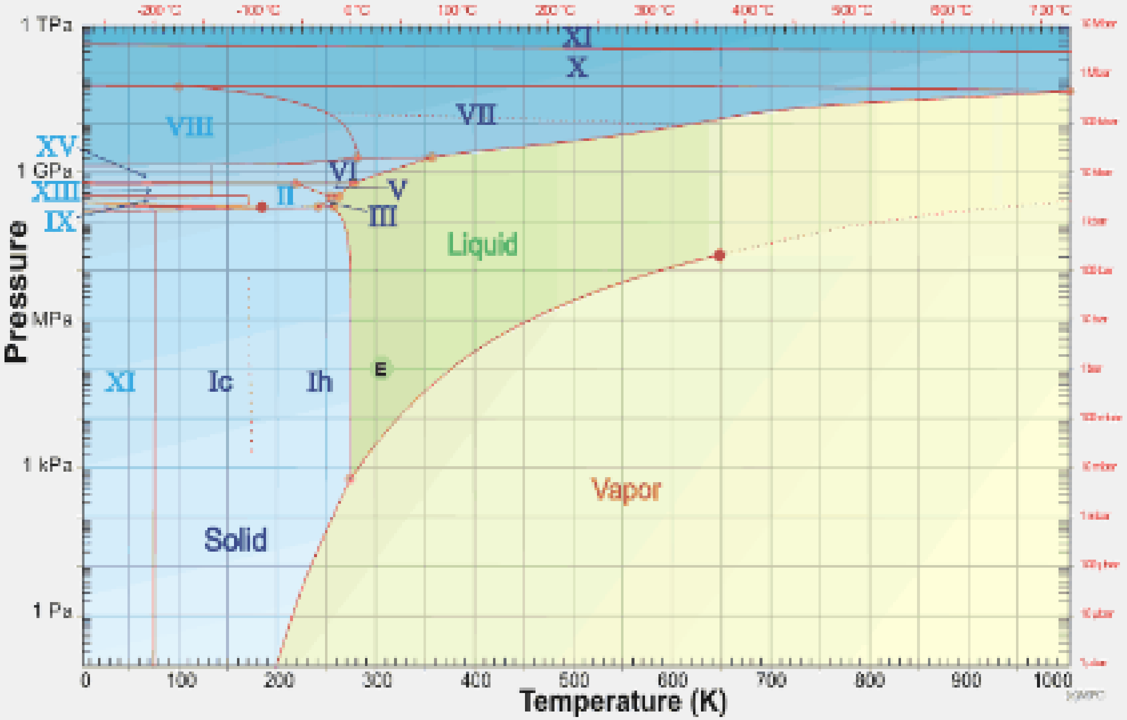
Work in this talk completed in collaboration with: Arash Bahramian, **Spencer Beloin**, Slavko Bogdanov, **Xingfu Du**, Farrukh Fattoyev, Stefano Gandolfi, **Sophia Han**, Craig Heinke, Wynn C. G. Ho, Jeremy W. Holt, Jim Lattimer, Chengkui Li, Will Newton, Dany Page, Madappa Prakash, and Sanjay Reddy.

Outline

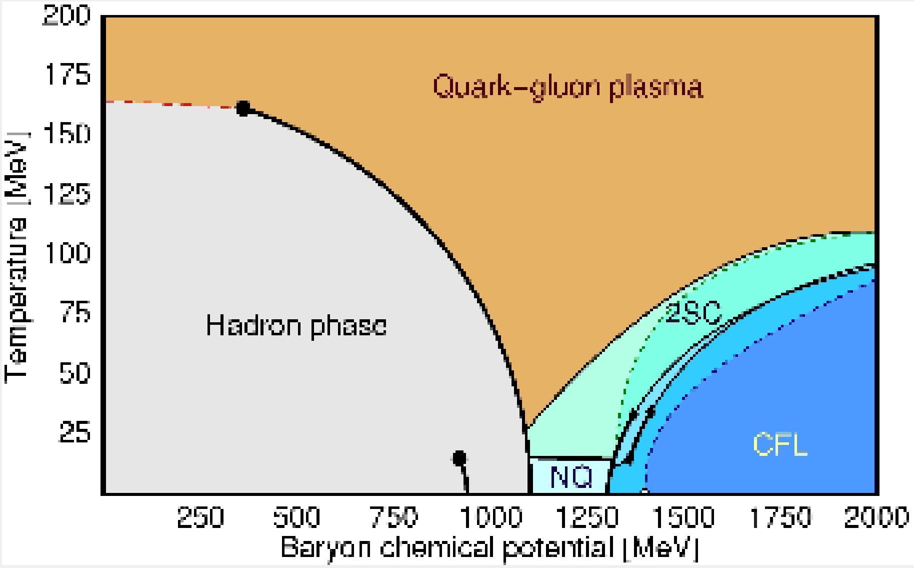
- QCD and neutron stars
- EOS of dense matter
- X-ray and LIGO observations
- Bayesian inference nightmare data analysis problems
- Merger simulations, new EOS, ν interactions
- Beyond the EOS: neutron star cooling and composition

The QCD phase diagram

- QCD: The theory which describes the interactions of nucleons and quarks



http://www.lsbu.ac.uk/water/phase.html

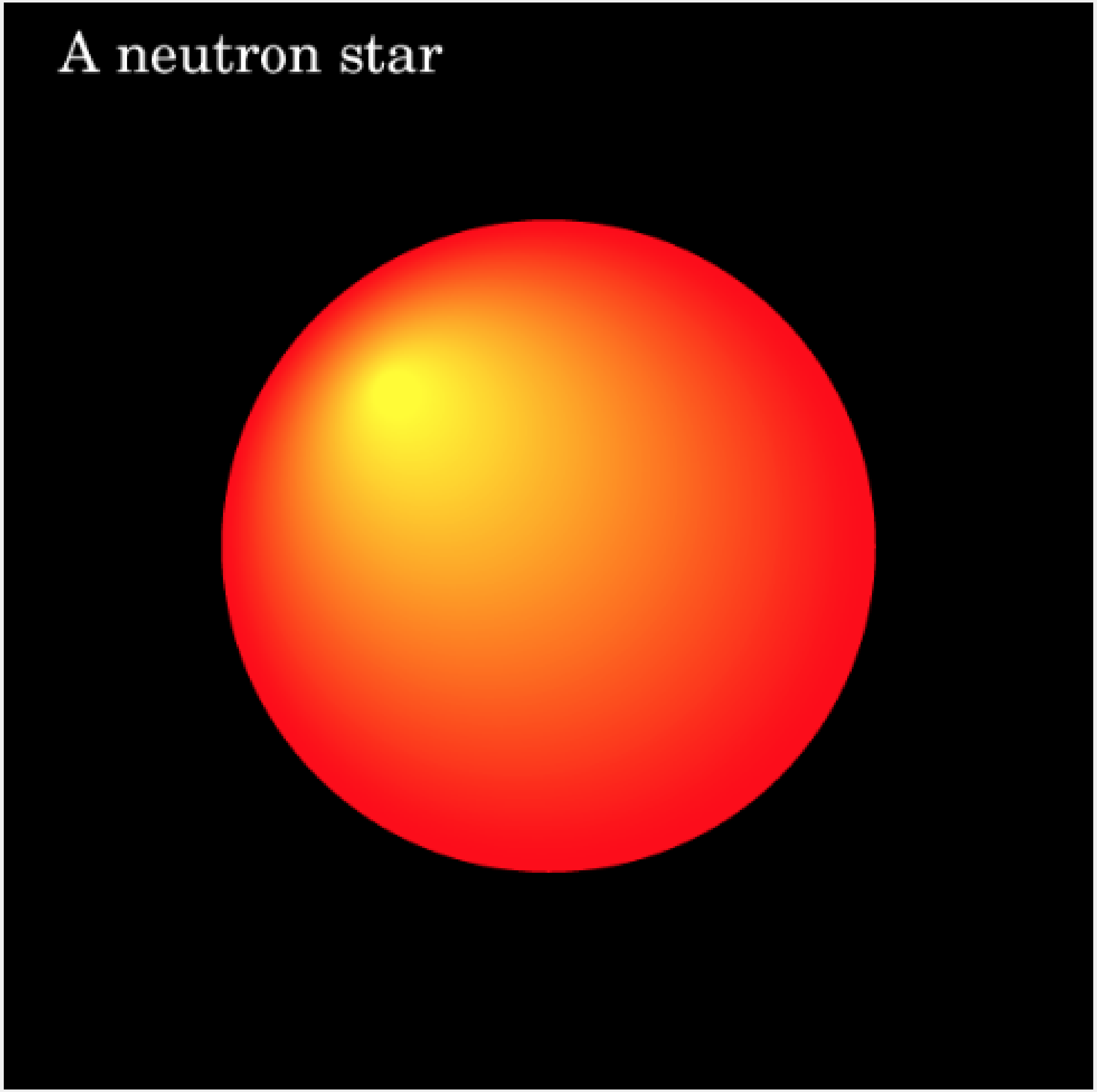


Rüster et al. (2006)

- Heavy-ion collisions and lattice QCD sensitive primarily to high T, low μ regions

- Electromagnetic and gravitational wave observations of neutron star-related phenomena are the **best** probe of cold, dense (and non-perturbative) QCD.

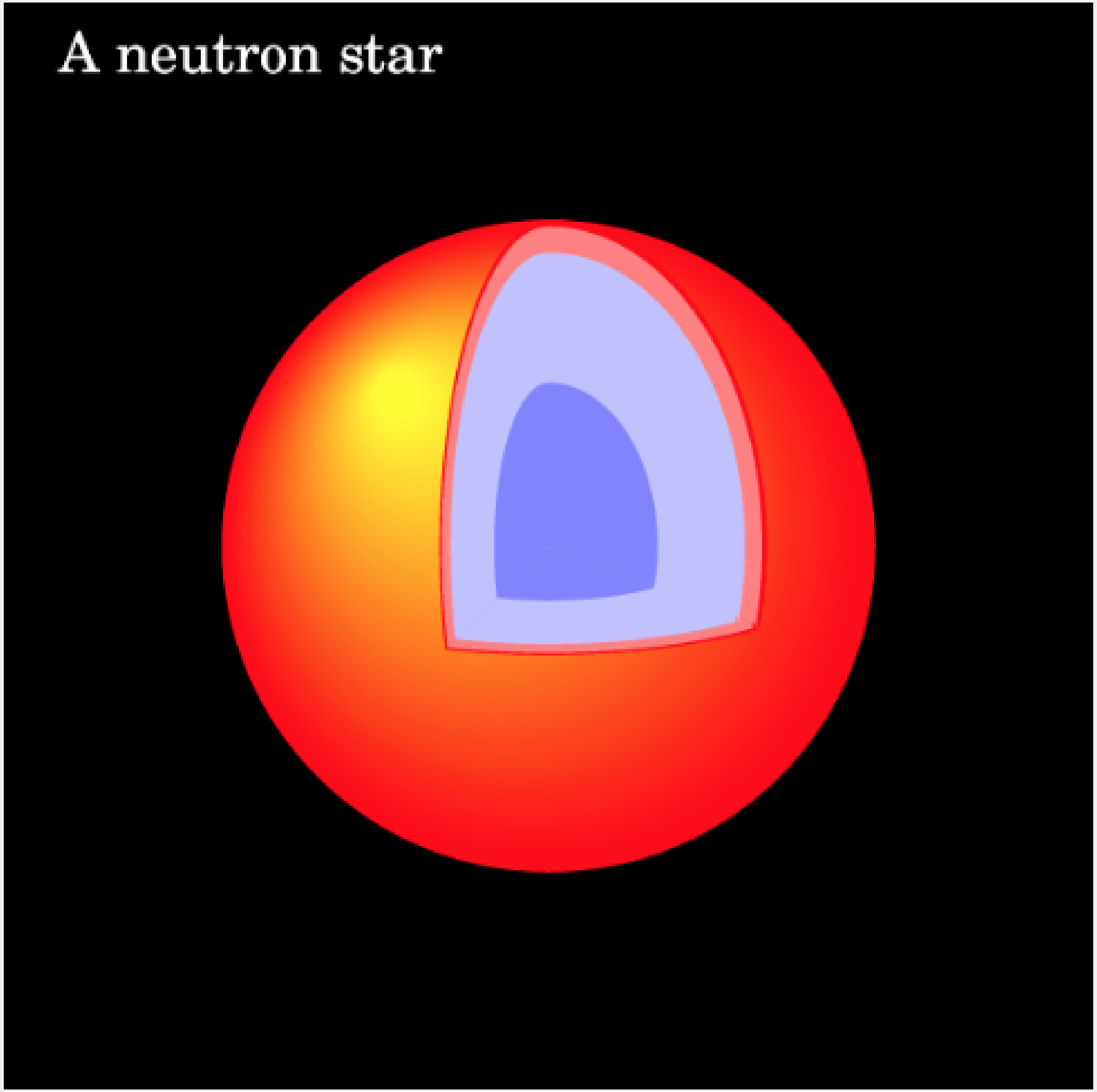
Neutron Star Composition



- Spherical nucleus with 10^{57} nucleons

Inspired by D. Page; open source (python)

Neutron Star Composition



- Spherical stars
- Much like the earth: solid crust and fluid core

Inspired by D. Page; open source (python)

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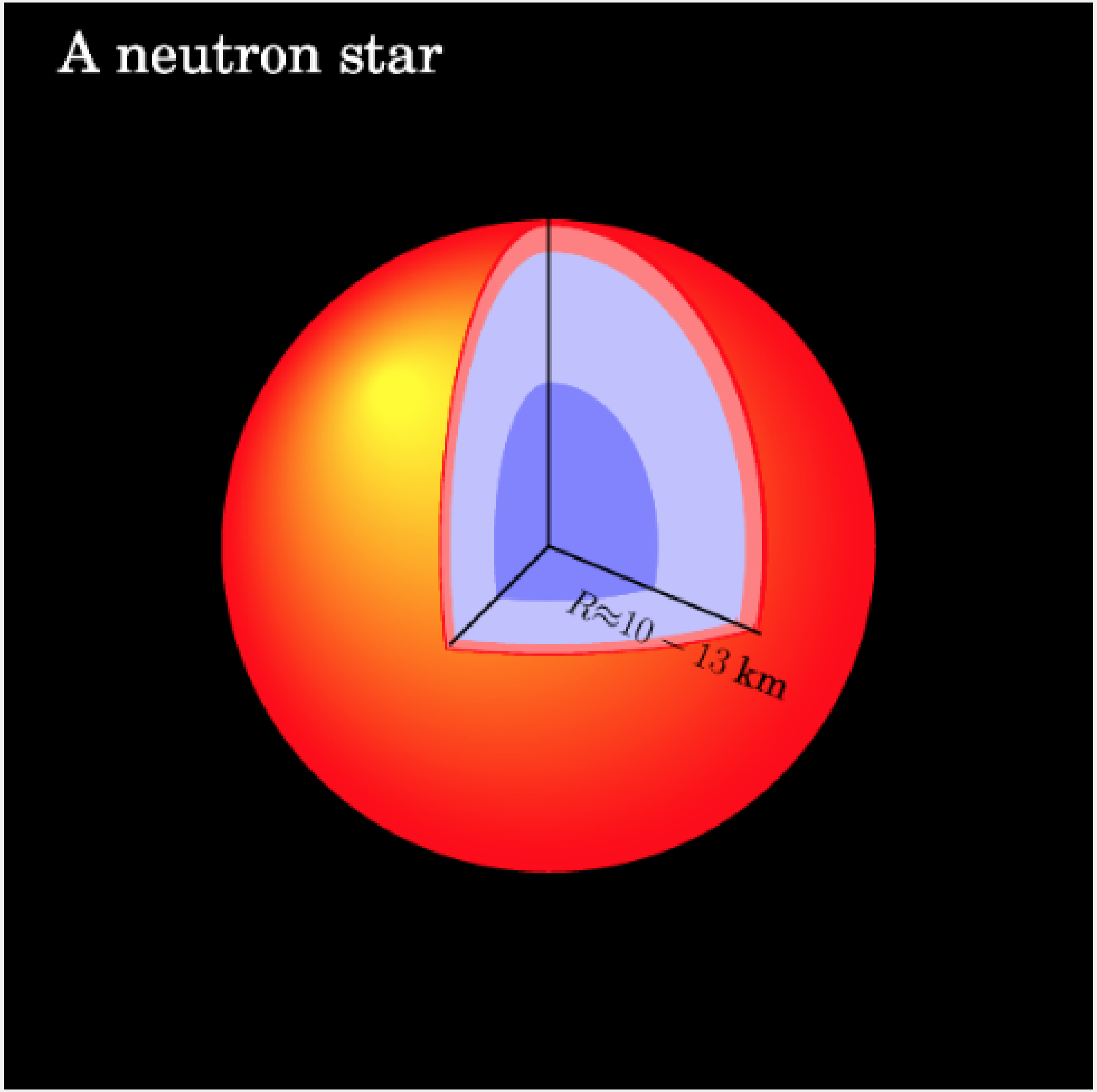

- Spherical stars
- Much like the earth: solid crust and fluid core
- Size of Chicago, mass of the sun

Inspired by D. Page; open source (python)

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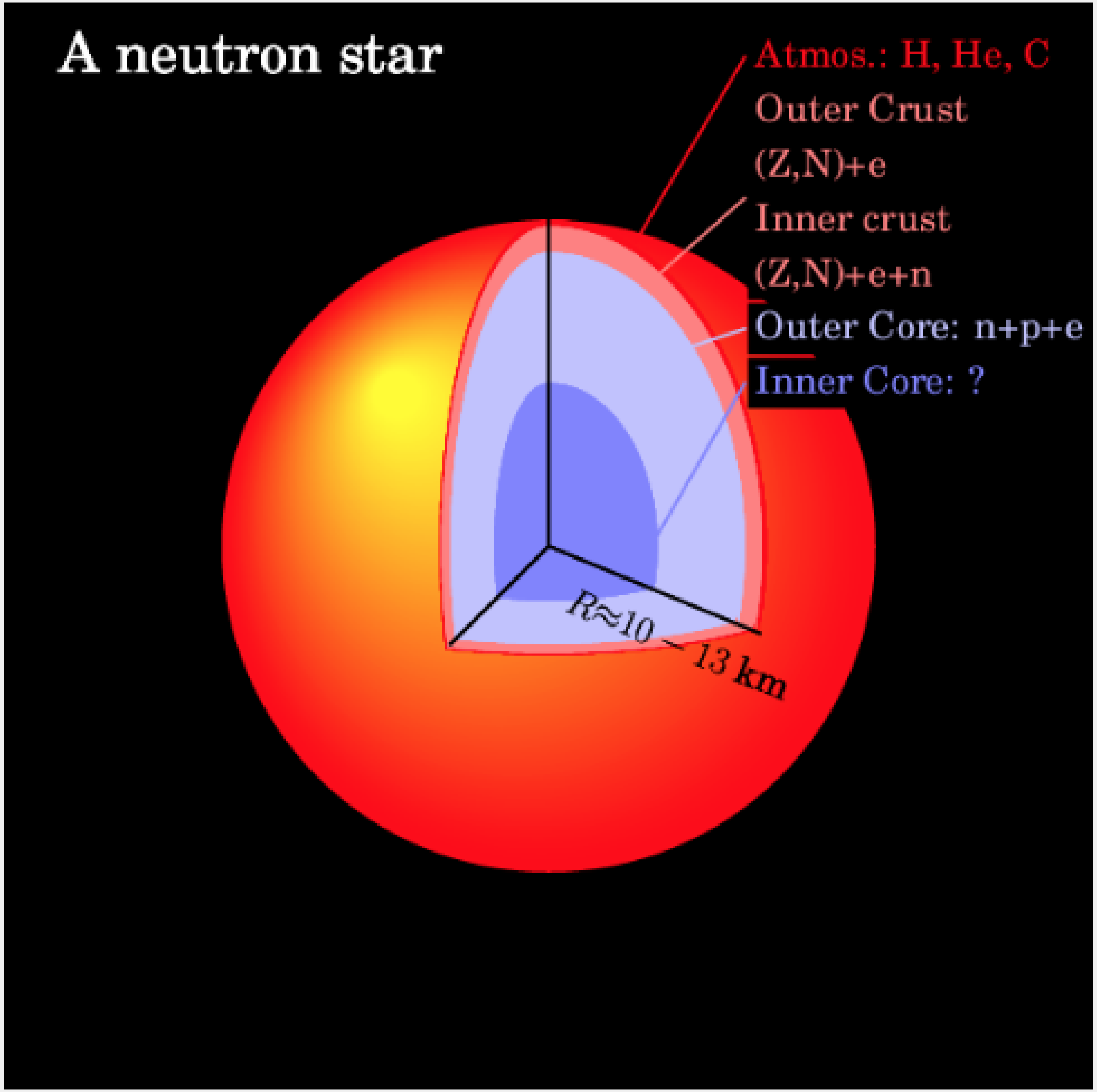
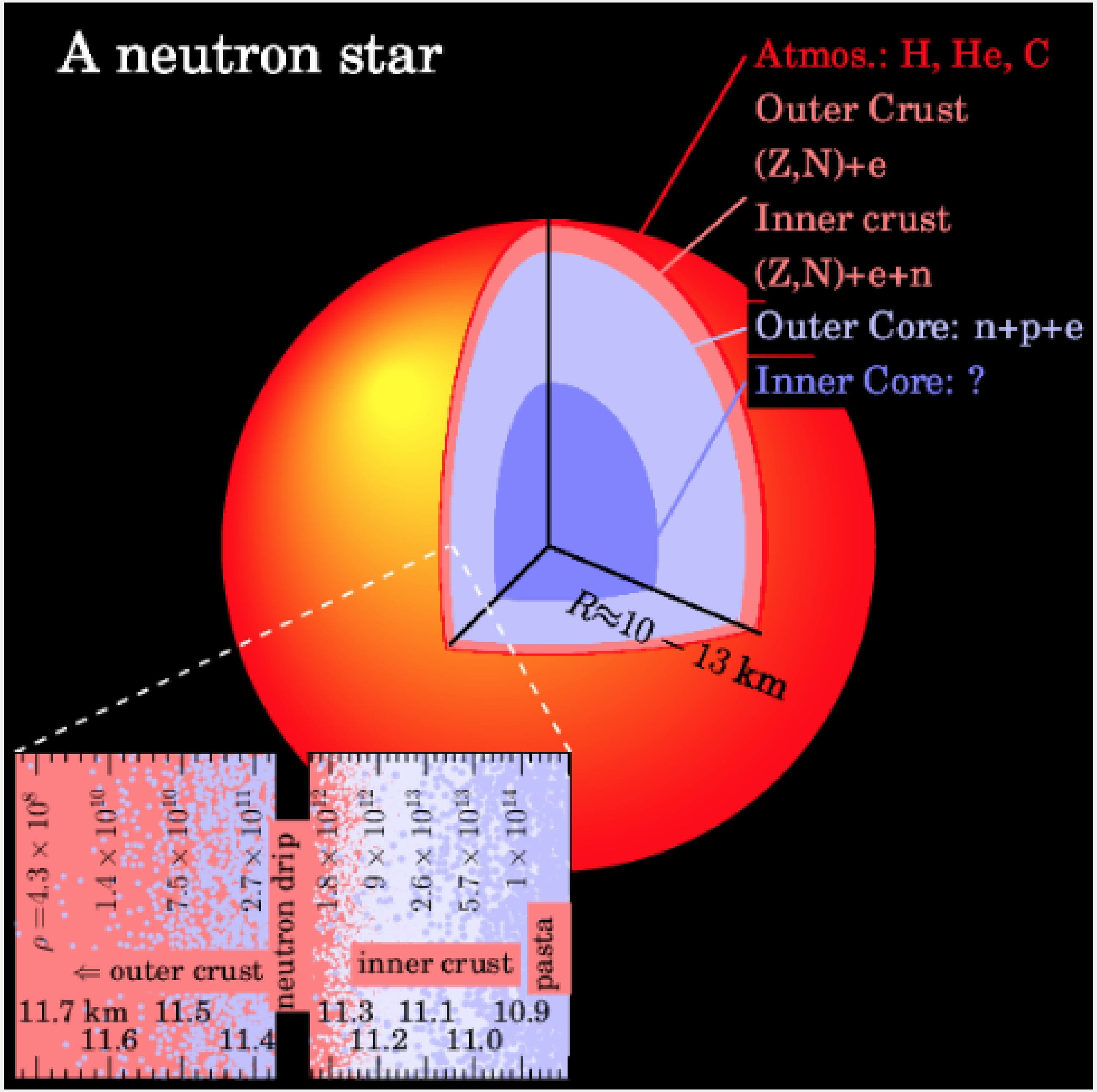


- Outer crust: of neutron-rich nuclei
- Inner crust: neutron-rich nuclei embedded in a sea of quasi-free superfluid neutrons
- Outer core: fluid of neutrons, protons, and electrons
- Inner core: hyperons? Bose condensates? deconfined quark matter?

Inspired by D. Page; open source (python)

Neutron Star Composition



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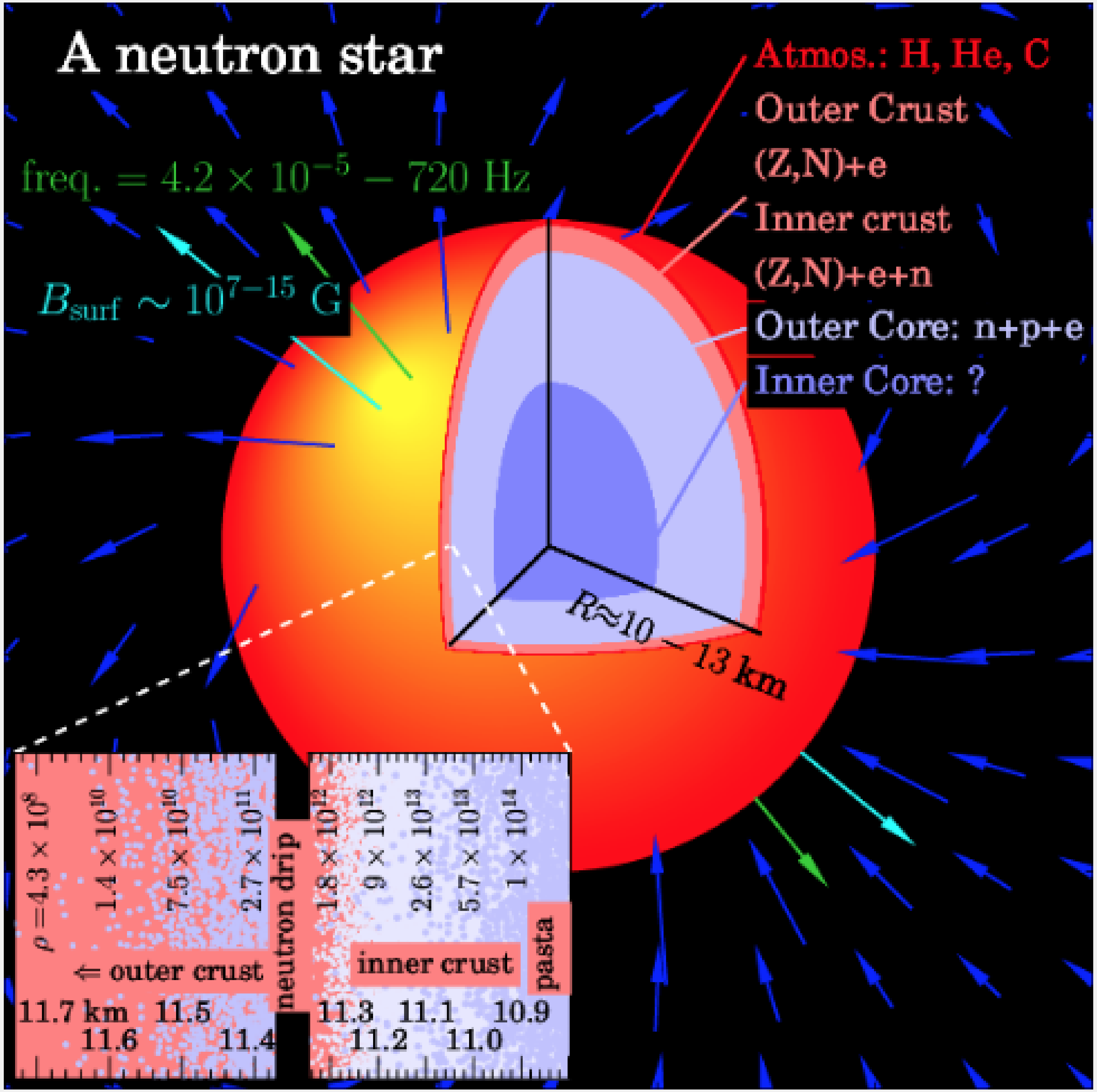

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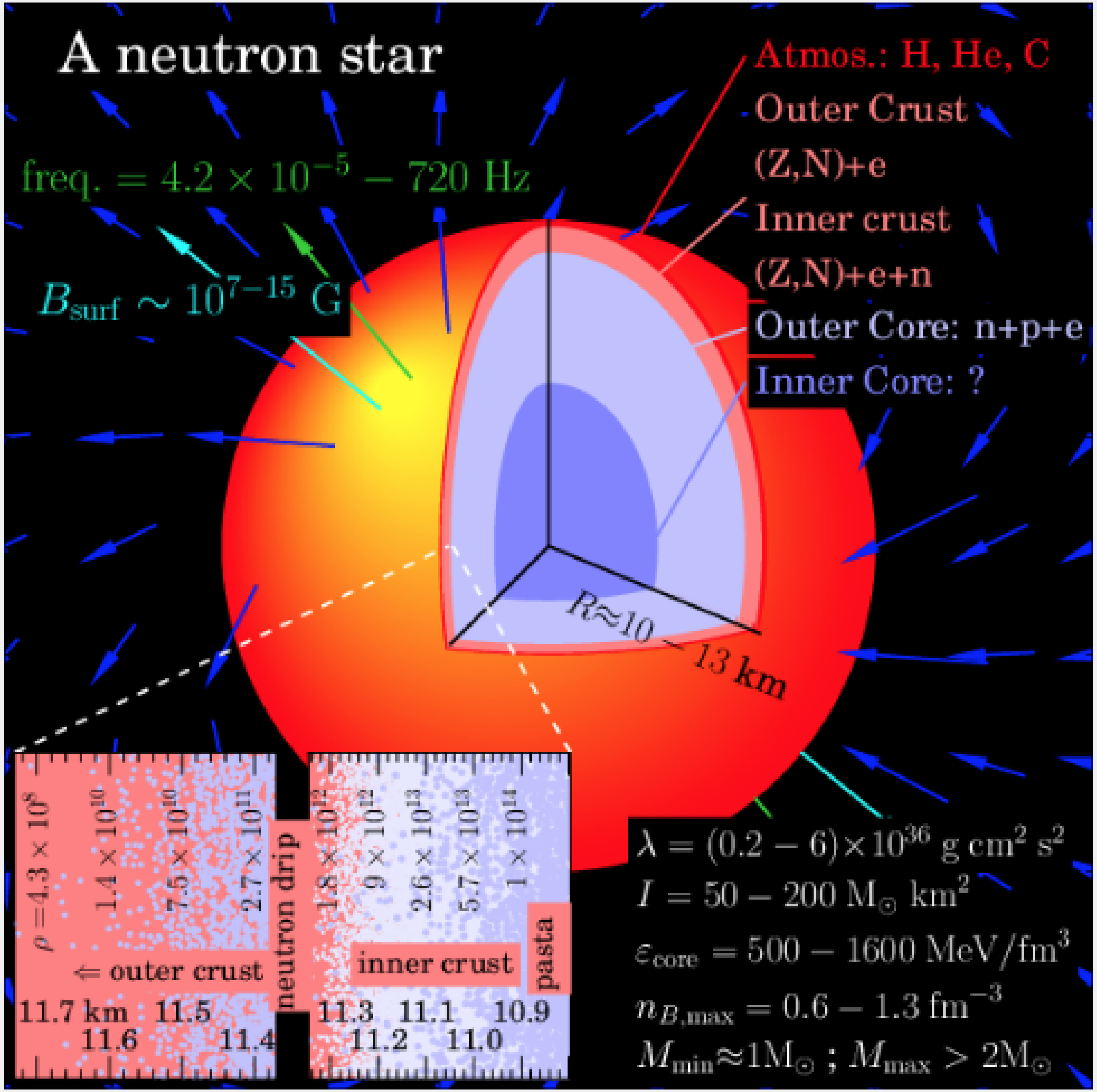
- Magnetic fields and rotation

Inspired by D. Page; open source (python)

Neutron Star Composition



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What are the correct degrees of freedom for the effective field theory which describes dense matter?

Inspired by D. Page; open source (python)

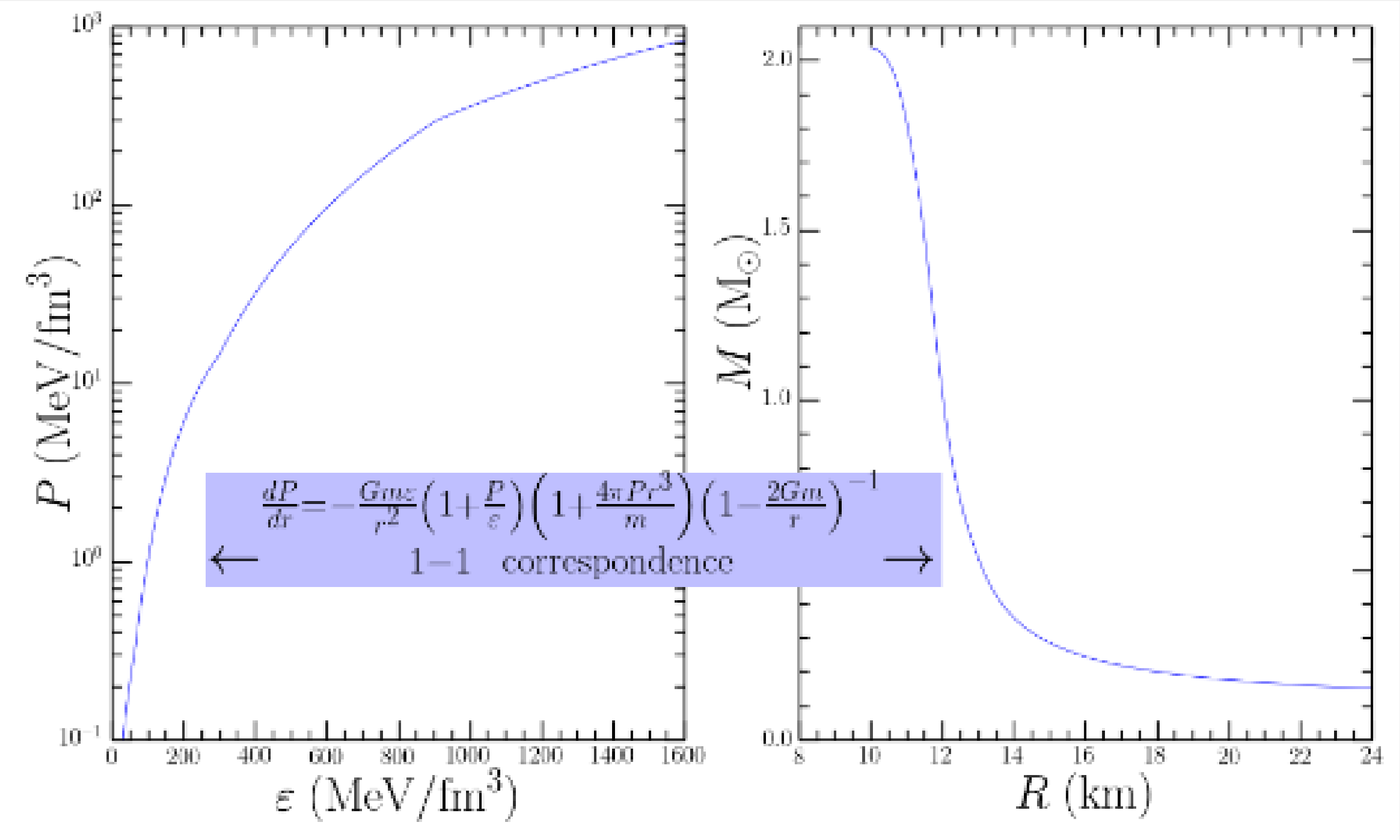
Neutron Stars as Glue

Neutron stars provide the glue between astronomical observations, gravitational wave observations, nuclear experiments, nuclear theory, large-scale astrophysical simulations, statistics, computational science...

Neutron Star Masses and Radii and the EOS

- Neutron stars (to better than 10%) all lie on one universal mass-radius curve

  (Largest correction is rotation)



$$\frac{dP}{dr} = -\frac{Gm\varepsilon}{r^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi P r^3}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}$$

← 1–1 correspondence →

- Two 2 $M_\odot$ neutron stars

  Demorest et al. (2010), Antoniadis et al. (2013)

- As of 2007, neutron star radii ranged from 8-16 km

  Lattimer and Prakash (2007)

- Now 10-13 km is more likely

  Steiner, Lattimer, and Brown (2013) and update in Steiner et al. (2018)

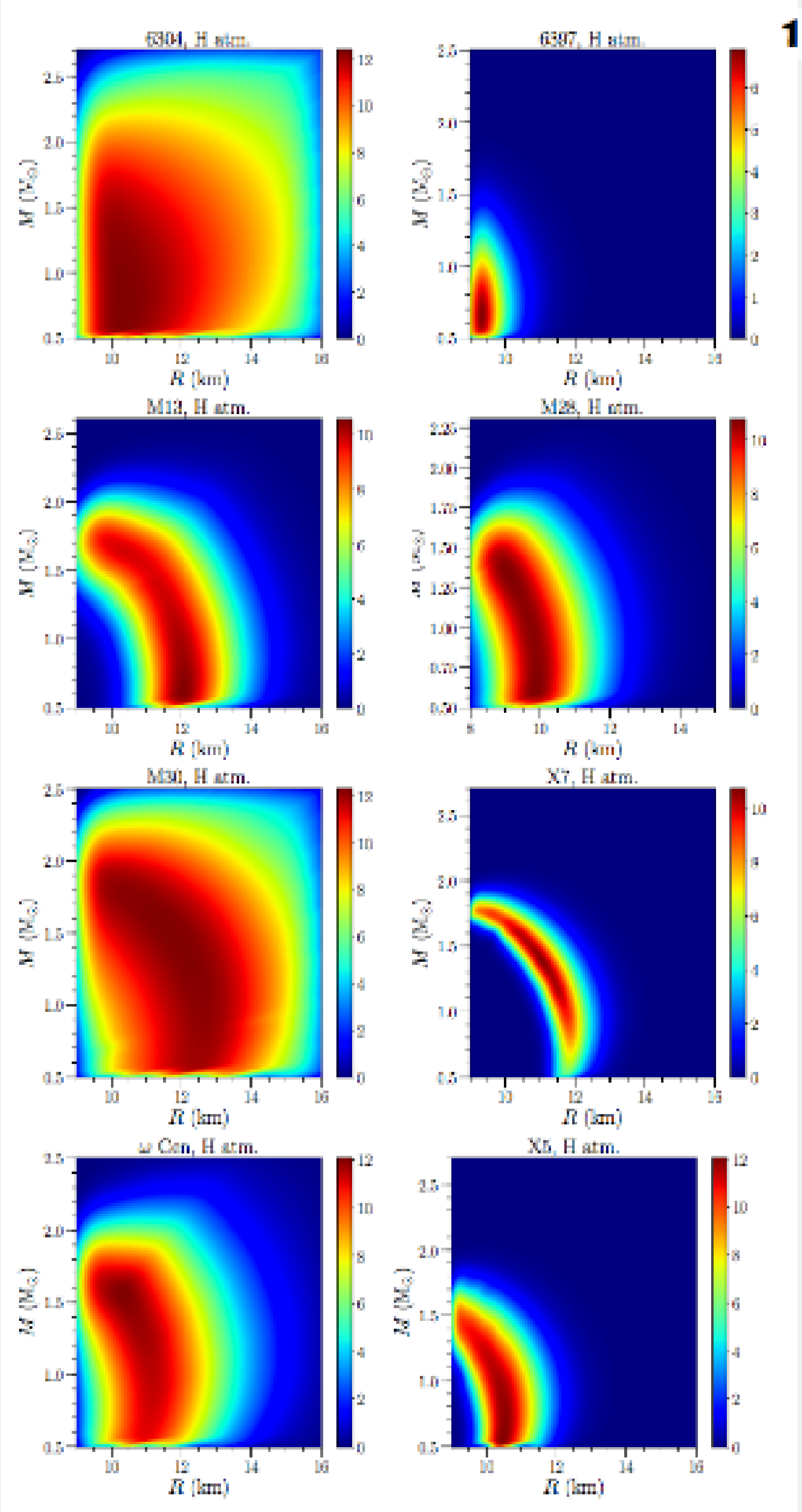
Quiescent Low-mass X-ray Binaries

- Blackbody-like spectrum of X-rays

$$F = (\sim 1) \times T_{\rm eff}^4 \left(\frac{R_\infty}{D} \right)^2$$

e.g. Rutledge et al. (1999)

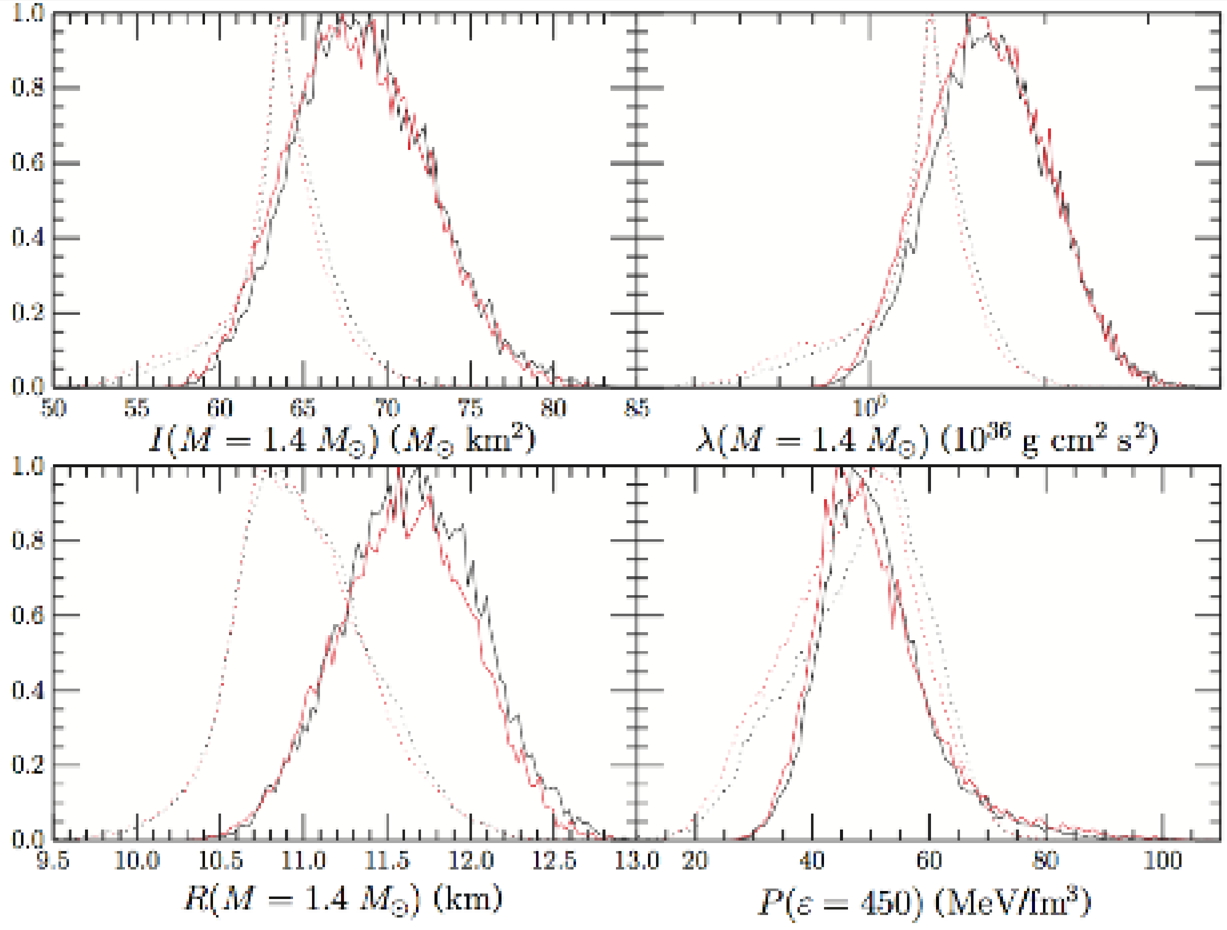
- Tackling systematic uncertainties is an important priority for us:
    - Distance uncertainty
    - X-ray absorption
    - Atmosphere composition, H or He
    - Uneven temperature distribution
    - Phase transitions at high density
    - Neutron star maximum mass
    - X5 is an eclipsing binary
- Some evidence for $R_{1.4} < 12$ km



Steiner et al. (2018)

2015: Predictions for LIGO

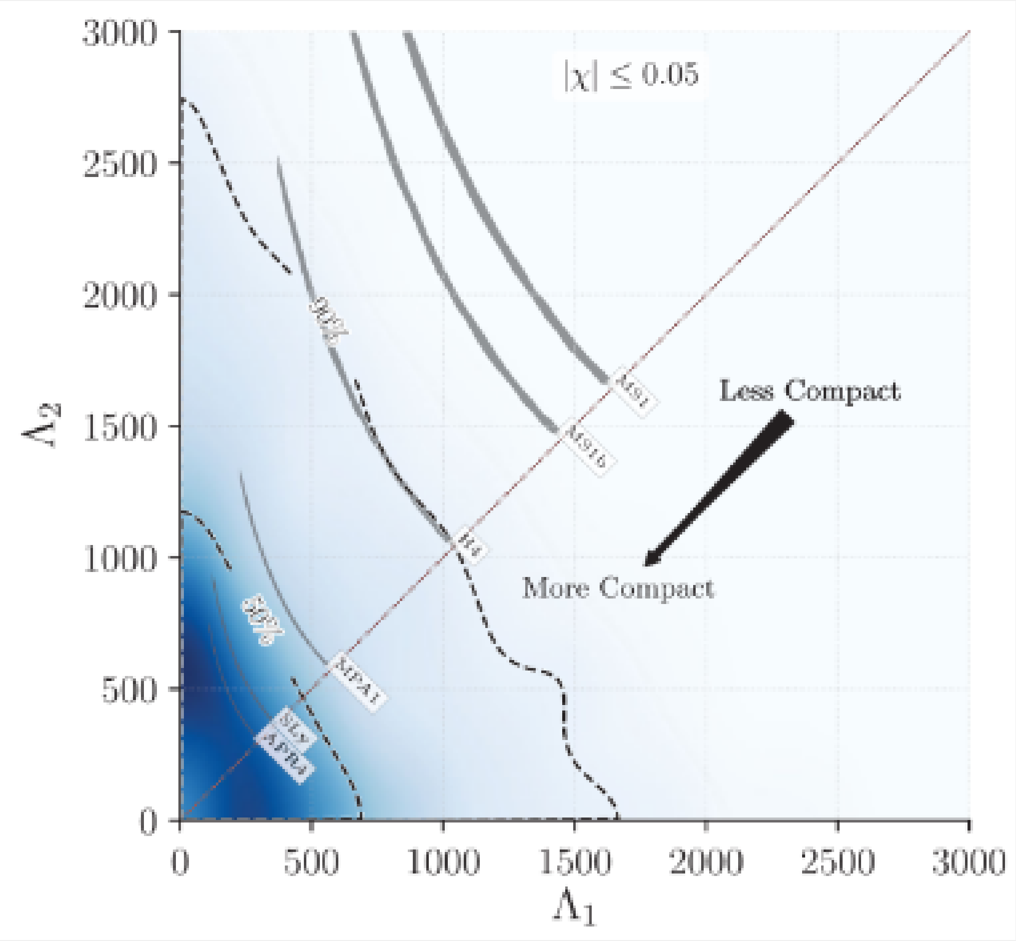
- Use X-ray data to compute I and λ

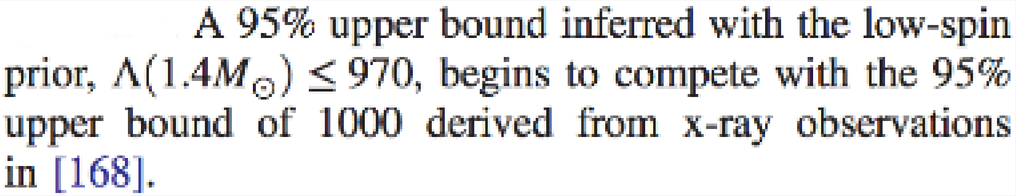


Steiner, Gandolfi, Fattoyev, Newton (2015)

- Transforming to a dimensionless version Λ, the upper limit in these predictions is about $\Lambda \sim 1000$

LIGO Result and the GW 170817 Merger





A 95% upper bound inferred with the low-spin prior, $\Lambda(1.4M_\odot) \leq 970$, begins to compete with the 95% upper bound of 1000 derived from x-ray observations in [168].

Abbott et al. (2017) citing Steiner, Gandolfi, Fattoyev, Newton (2015)

- Glass half full interpretation: LIGO confirmed our prediction
- Glass even more half full interpretation: **Gravitational wave detectors may eventually be better at measuring neutron star radii than X-ray satellites**

Bayesian Inference vs. χ^2 fitting

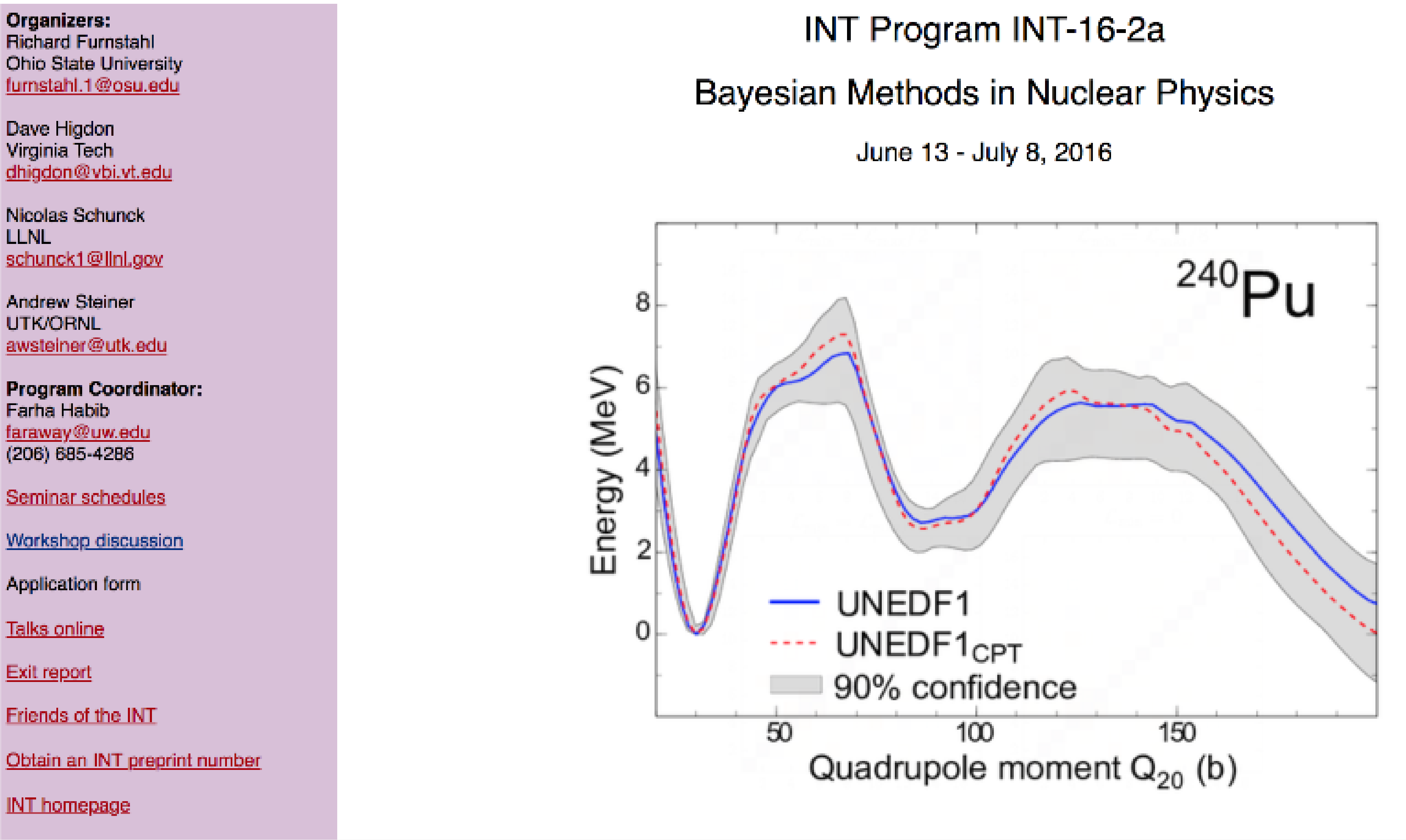
$$\chi^2 = \sum_i \left[\frac{(\mathrm{data})_i - (\mathrm{model})_i}{(\mathrm{err})_i} \right]^2$$

- Maximize the likelihood: $\mathcal{L} = \exp(-\chi^2/2)$ with respect to model parameters
- Not unique when uncertainties in independent variable are large
- Bayes theorem: $P[\mathcal{M}_i|D] \propto P[D|\mathcal{M}_i]P[\mathcal{M}_i] = \mathcal{L} \times \mathrm{prior}$
- Determine parameters through marginalization, i.e.

$$P(\mathcal{M}_i^0) = \int \delta(\mathcal{M}_i - \mathcal{M}_i^0) P[D|\mathcal{M}_i] P[\mathcal{M}_i] \, d\mathcal{M}$$

- Integrals can be computationally demanding
- Reproduces traditional χ^2 fit in the appropriate limits

Bayesian Inference at the INT



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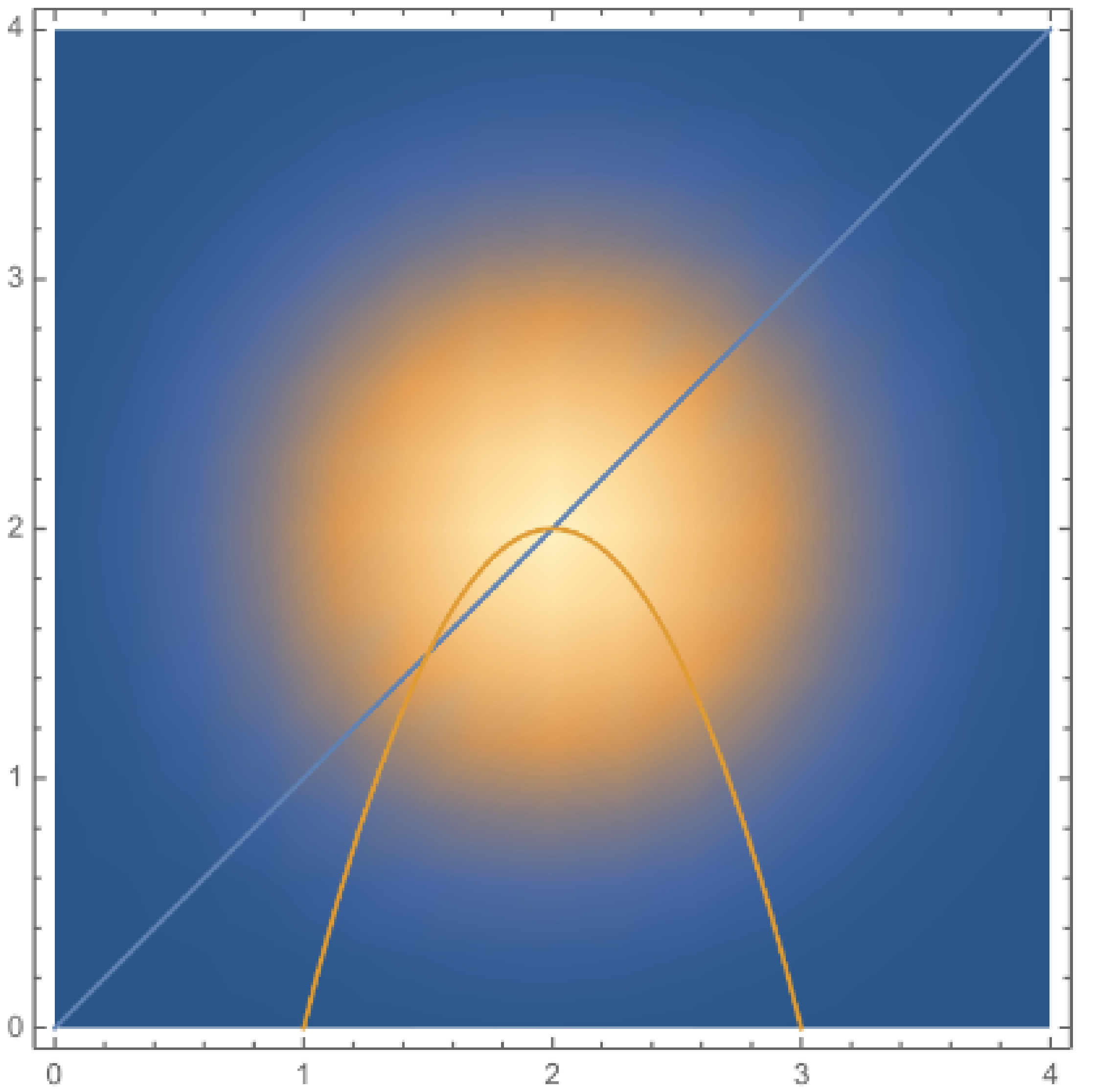
Bayesian Methods in Nuclear Physics

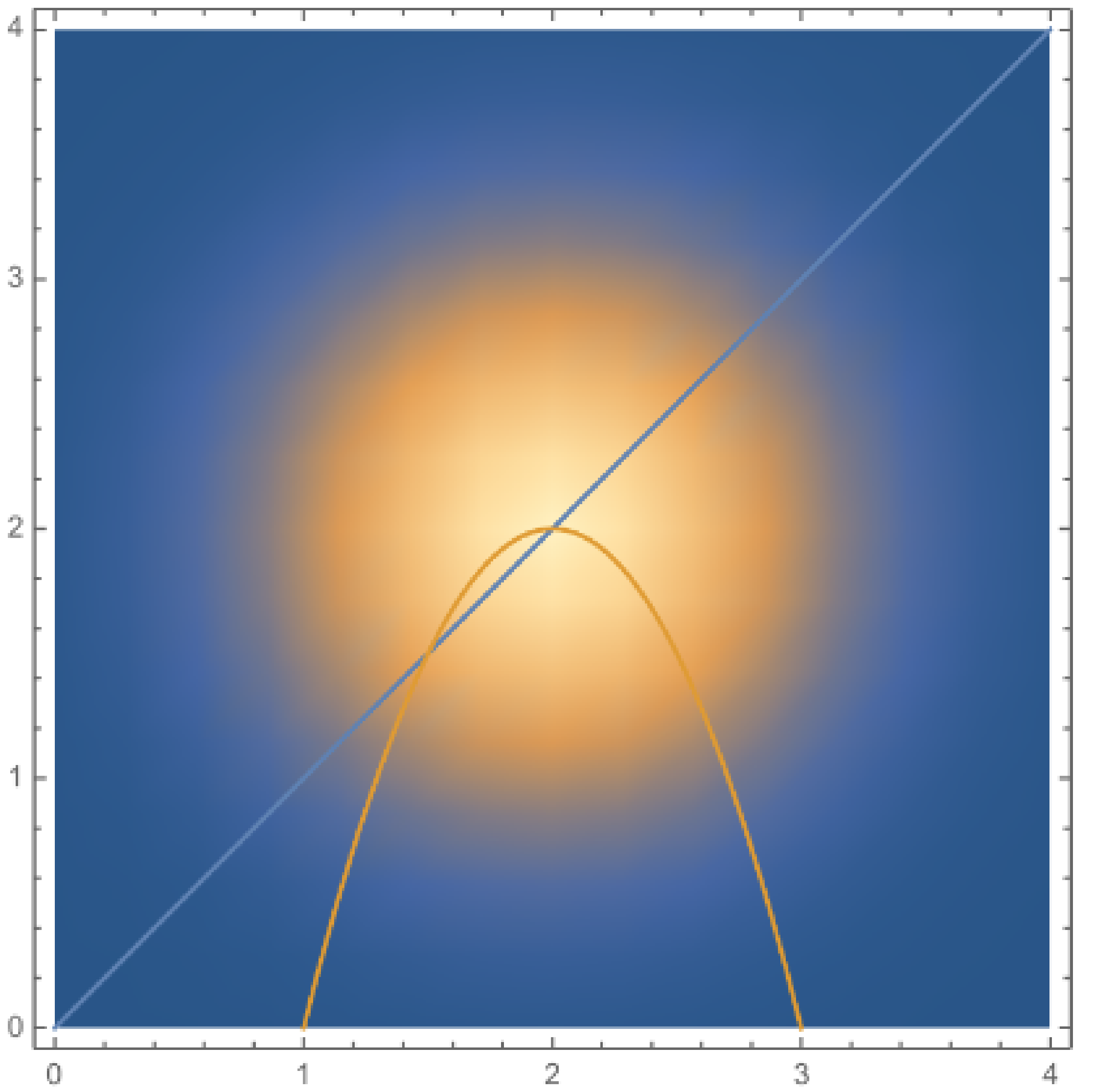
June 13 - July 8, 2016

Fitting Data to Curves



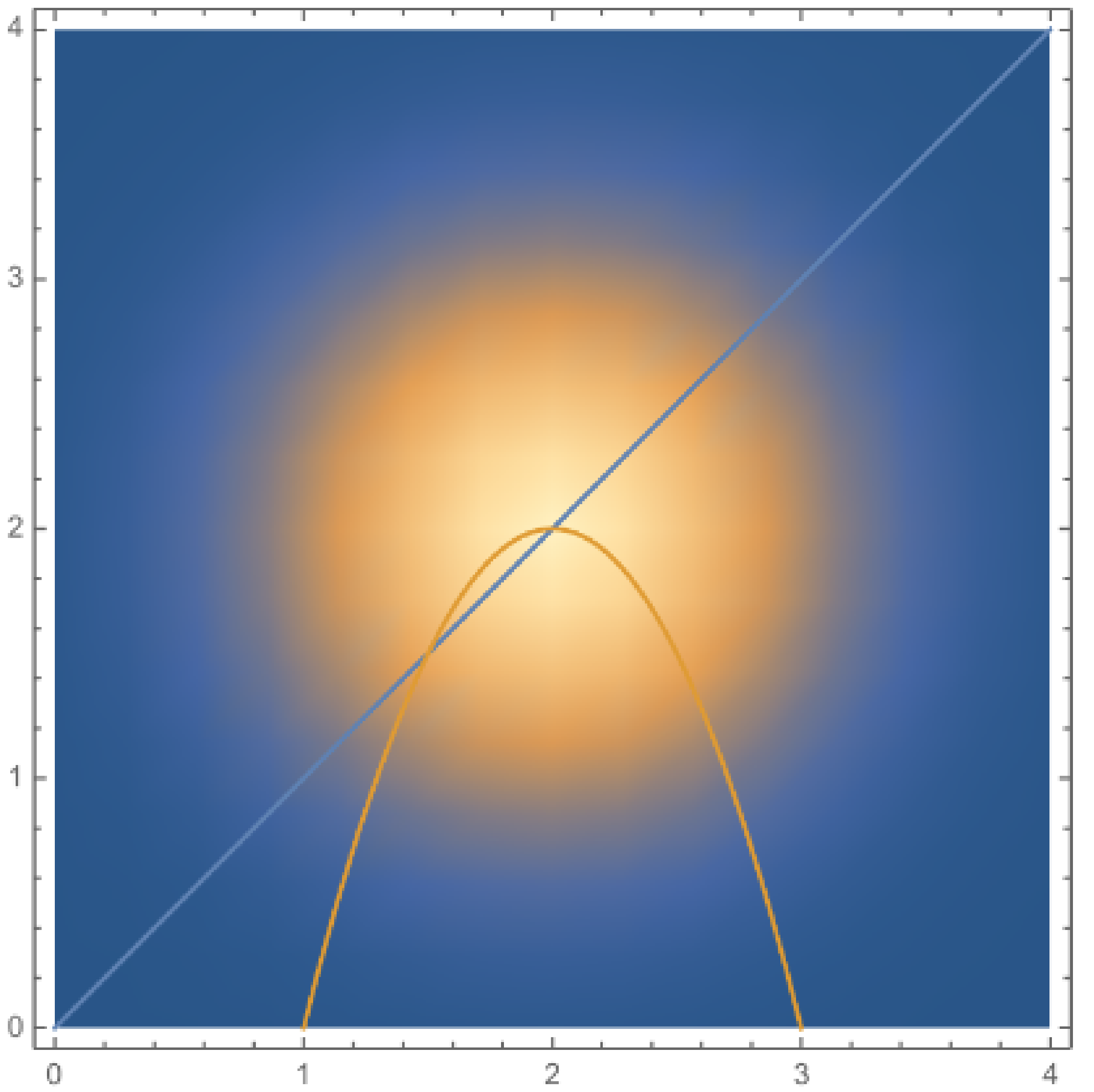
- Which curve best fits the data point?

Fitting Data to Curves



- Which curve best fits the data point?
- You could decide that they both fit equally well, but then what is $\langle y \rangle$?

Fitting Data to Curves



- Which curve best fits the data point?
- What kind of information do you need to specify to unambiguously decide between the two curves?

When Bayesian Inference Needs Differential Geometry

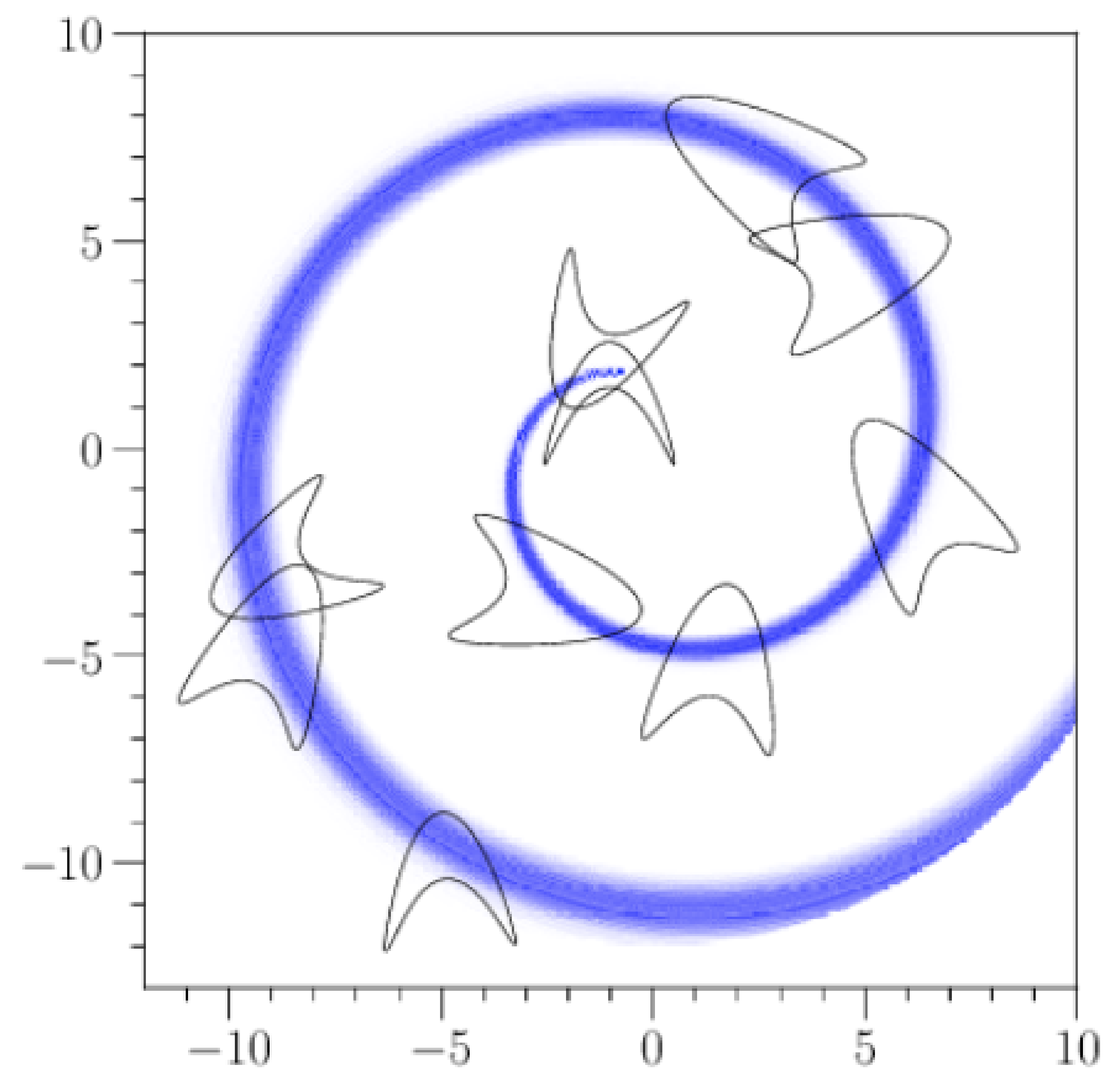
- The analysis of neutron star data is a special case
- Model exists in a lower-dimensional space where the data is in higher-dimensional space
- Requires embedding, e.g. one-dimensional model in two-dimensional data space

$$P(D|M) \propto \int_{c_i(\{p\})} \left\{ \prod_{i=1}^{N} \left[d\lambda_i \left| g_{jk\,i} \frac{dx_i^j}{d\lambda_i} \frac{dx_i^k}{d\lambda_i} \right|^{1/2} \right] M_i(\lambda_i) \mathcal{D}[x_i^1(\lambda_i), x_i^2(\lambda_i)] \right\}$$

where c_i are curves determined by parameters p, λ_i parameterizes the curve, g_{jk} specifies the metric on the 2D space, $M_i(\lambda_i)$ allows the model to depend on the parameterization of the curve and $\mathcal{D}$ is the data or the result of a previous inference

- Easily generalizable to higher dimension embeddings (requires determinant of the metric)

Nightmare Data Analysis Problem



- Non-Gaussian data, model curves are not bijections
- Very complicated problems easily handled with proper specification of the likelihood

Toward Exascale Astrophysics of Mergers and Supernovae (TEAMS)

a DOE SciDAC supported collaboration

Nuclear Astrophysics at the Exascale

Our collaboration aims to study the astrophysical events responsible for the production of many of the heaviest of the chemical elements using realistic simulations containing the most complete physics available. This complexity will require these simulations run on the world's most advanced supercomputers.

Merger simulations need microphysics

- **Future LIGO data will require substantial theory input to fully interpret**
- EOS and differential neutrino scattering and absorption cross sections
- From T=0 to 150 MeV
- From $\rho = 10^5$ to 10^{15} g/cm^3
- From $N \sim Z$ to $N \gg Z$
- Neutrino trapping, thus $\mu_{\nu_e} > T$

Merger simulations need good EOSs

- EOS microphysics
    - Connection to the scattering length in dilute nucleonic matter
    - Reproduce nuclear masses and charge radii
    - Ab-initio theory provides the best description of
        - Neutron matter "near" the saturation density
        - Finite-temperature properties of nucleonic matter
    - Matter beyond the saturation density
    - Nuclear structure in dense matter environment

Merger simulations need good EOSs

- EOS microphysics

  Pure phenomenology; Du, Steiner, and Holt (2018)

  - Connection to the scattering length in dilute nucleonic matter

    Virial expansion

  - Reproduce nuclear masses and charge radii

    Skyrme models with parameters described by a posterior distribution determined by a fit to nuclear masses and charge radii

  - Ab-initio theory provides the best description of

    - Neutron matter "near" the saturation density

      QMC results from S. Gandolfi

    - Finite-temperature properties of nucleonic matter

      Chiral interaction + Kohn-Luttinger-Ward perturbation series

  - Matter beyond the saturation density

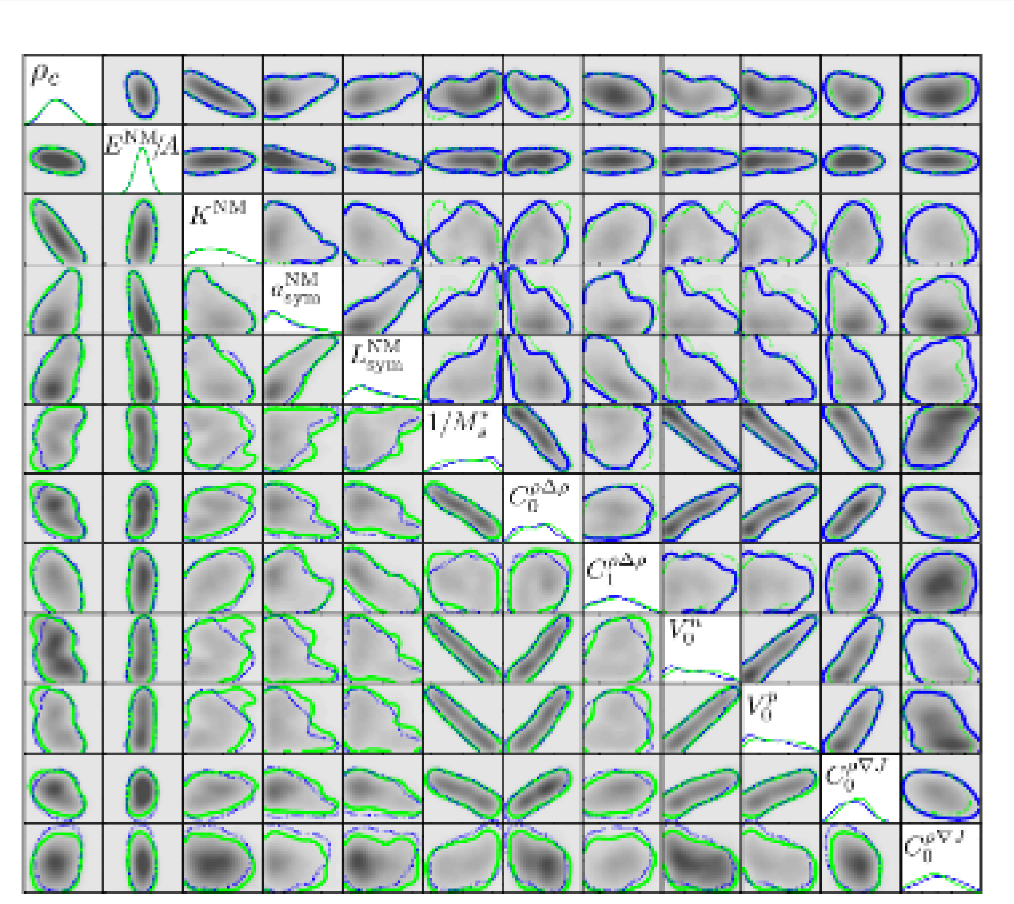
    Neutron star observations (add heavy-ion collisions later)?

  - Nuclear structure in a hot and dense environment

    In progress...

Using NUCLEI Posterior Distributions

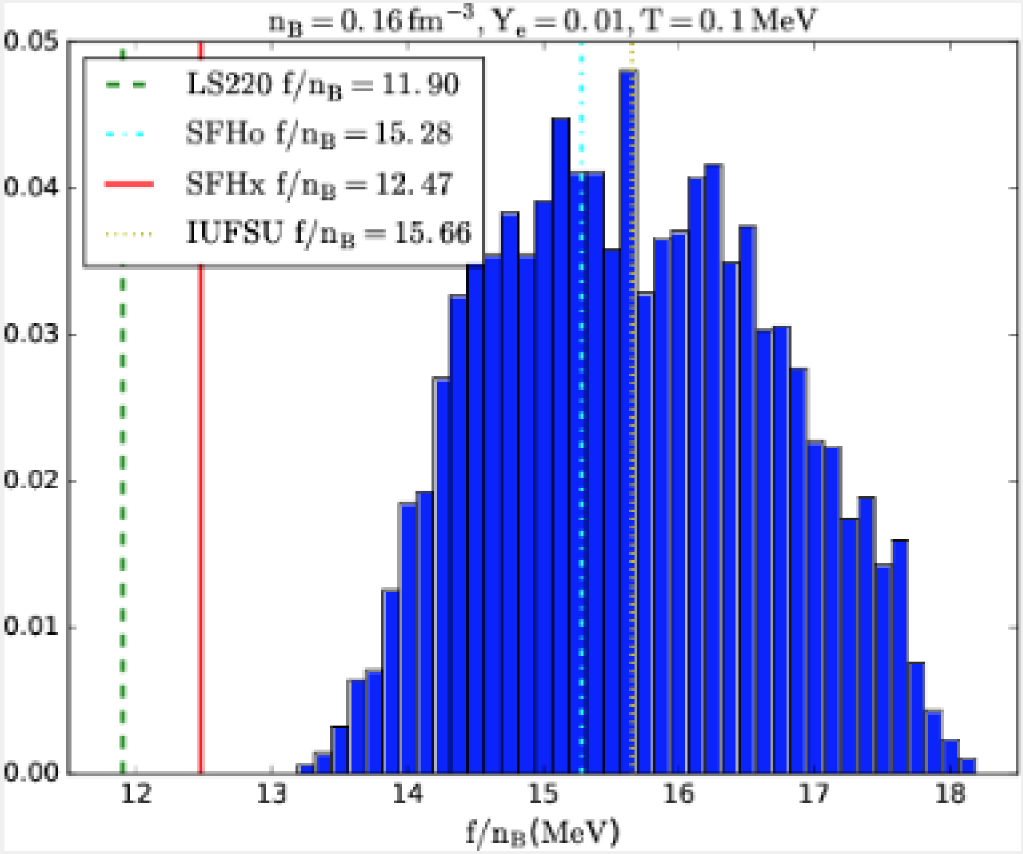
- Bayesian inference applied to
    - nuclear masses (deformed and spherical
    - charge radii
    - Odd-even staggering
    - Fission isomer energies
- Generates a posterior distribution of Skyrme parameters



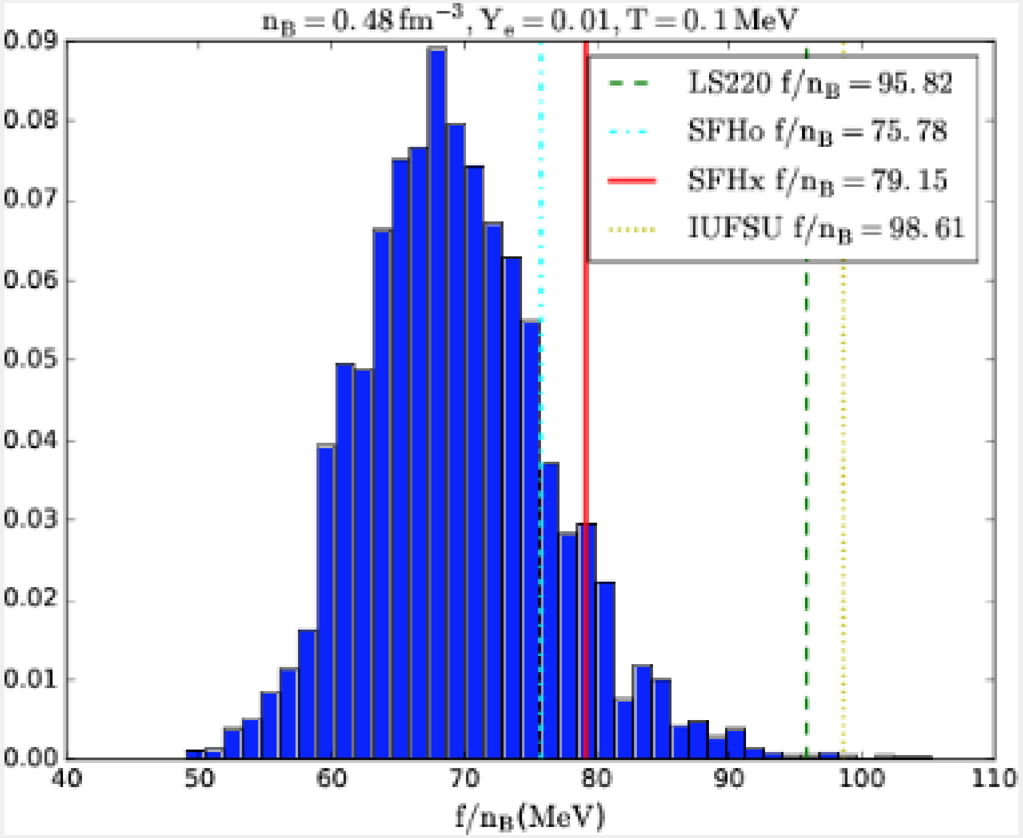
Kortelainen et al. (2014); McDonnell et al. (2015)

- We ignore the isovector parts of the interaction because they are poorly constrained (e.g. violates Tews, Lattimer, Ohnishi, and Kolmeitsev (2017) limit)
- Many models must be removed because nucleon effective masses diverge at a density inside neutron stars
- Recent work by Bogner et al. (2018) goes beyond Skyrme

Equation of State with Uncertainty Quantification



Probability distribution for the energy of the neutron matter at saturation



Probability distribution for the energy of the neutron matter at three times saturation

Du, Steiner, and Holt (2018)

- Give up self-consistency in order to match experimental and observational data
- Generate a full posterior distribution of equations of state
- Full range of (n_B, Y_e, T)

From EOS to neutrino interactions

- Theoretical calculations of the cross sections

  Varying degrees of difficulty

- Consistency with EOS

  Important, see e.g. Roberts and Reddy (2012)

- Self-consistency (all connected to the same underlying Hamiltonian)?
- Uncertainty quantification

  Extremely difficult to do well

- Implementation (next most difficult)
  - Difficult to get an army of software engineers; not exciting work
  - Simulation codes are diverse in design
  - Simulation codes tend to be closed

    Excellent progress by Evan O'Connor and Luke Roberts

Some required cross sections

- Annihiliation: $e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

  "easy"

- Scattering: $\nu + \{n, p, e, \mu, (N, Z)\} \to \nu + \{n, p, e, \mu, (N, Z)\}$ and absorption: $\nu_e + n \leftrightarrow p + e$ and $\nu_e + (Z, N) \leftrightarrow (Z + 1, N - 1) + e$ and variants

  Reddy et al.

  Can one just tabulate weak response, $S(q, \omega)$ along with the EOS?

- Brehmsstrahlung: $n + n \to n + n + \nu + \bar{\nu}$ and variants

  Old OPE; EFT results e.g. Schwenk, Jaikumar, and Gale (2004); Recent work by Fischer (2016) and Bartl et al. (2016).

- $\nu + \nu \to \nu + \nu$

  Very difficult because of flavor transformation

Beyond the Neutron Star EOS

- Multi-messenger astronomy may eventually determine the neutron star EOS

- Next: neutron star composition and nucleonic superfluidity

- Cooper pair neutrino emissivity: $n + n \rightarrow (nn) + \nu + \bar{\nu}$

  e.g. Steiner and Reddy (2009)

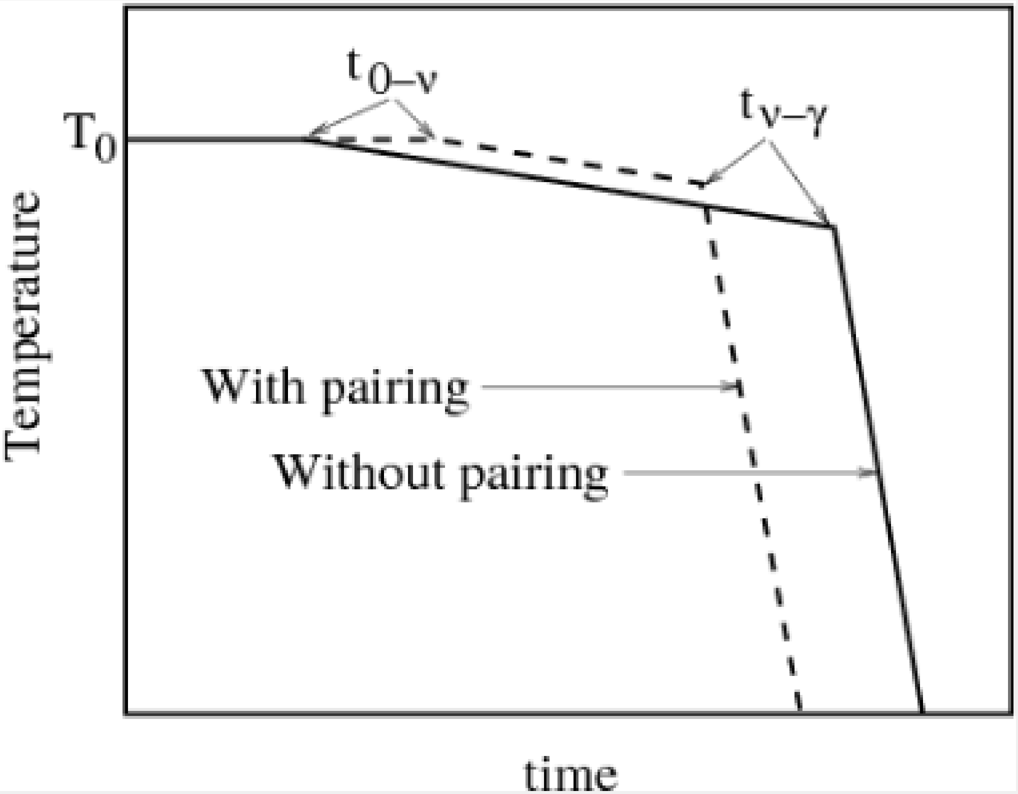
- Can dominate the cooling for low-mass stars

Thermal Emission from Isolated Neutron Stars

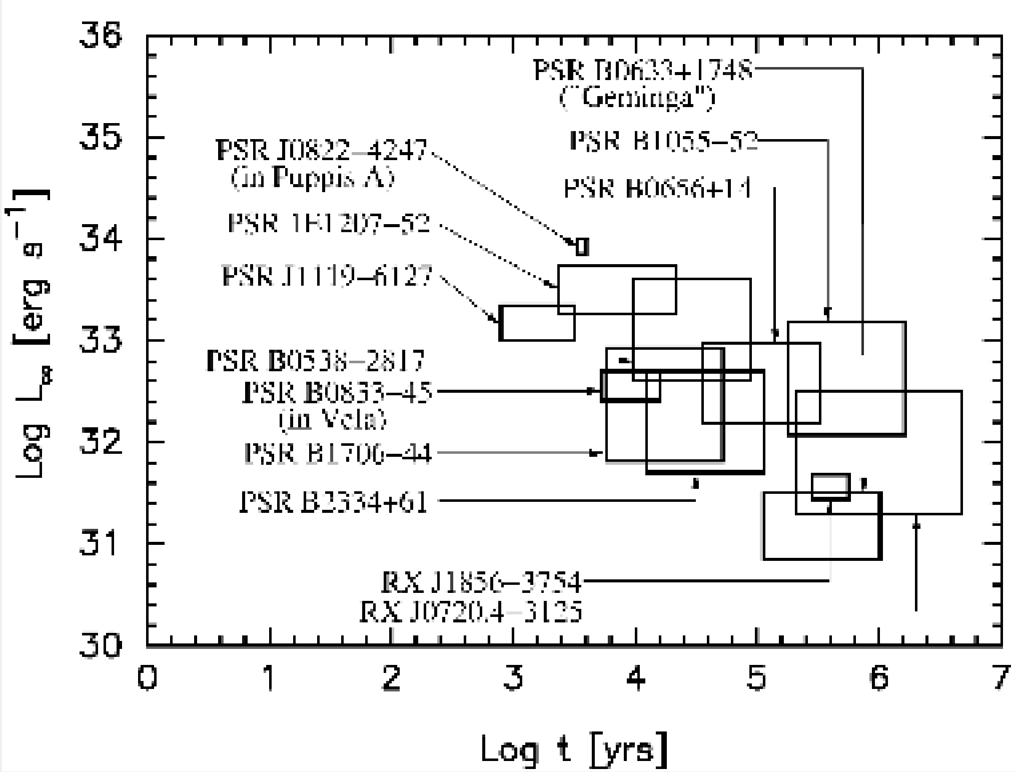
- After ~ 10 years, the star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma \,, \quad L_\gamma \sim T^{2+4\alpha} \,, \quad L_\nu \sim T^8 \text{ (Modified Urca)} \,, \quad C_V \sim CT$$

- Age assumed from spin-down age or associated with a supernova remnant



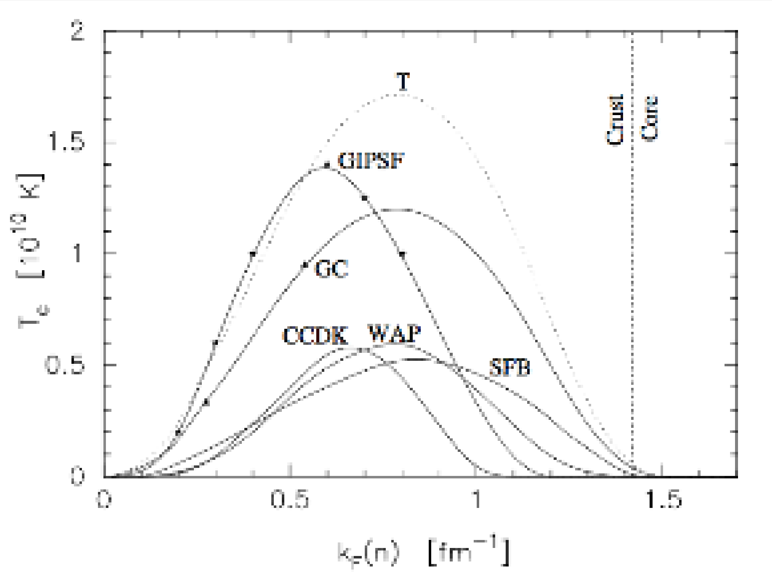
Page, et al (2004)

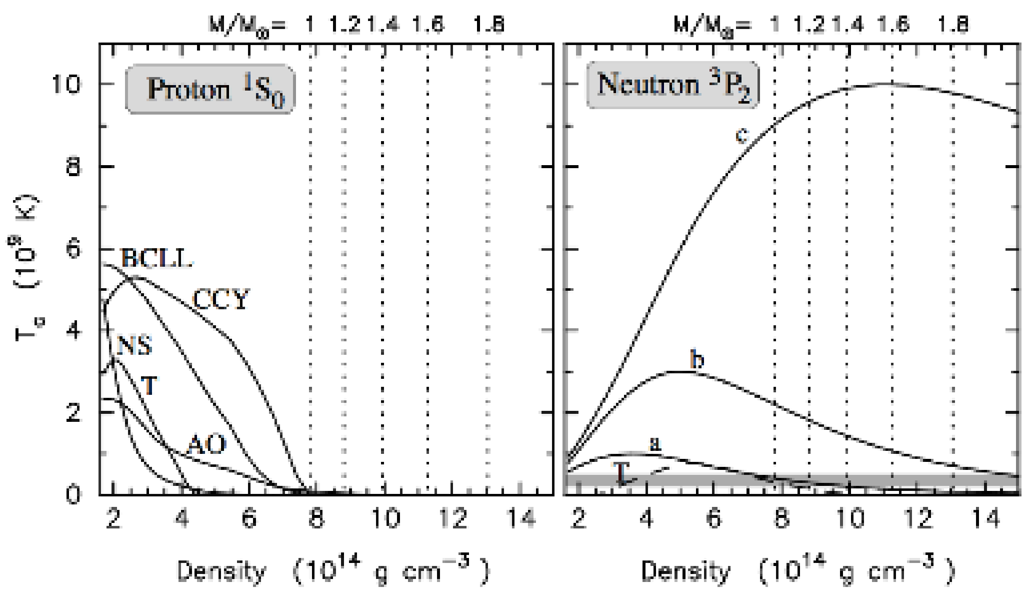


Page, et al (2009)

Neutron Star Superfluidity

(See our review at arxiv:1302.6626)



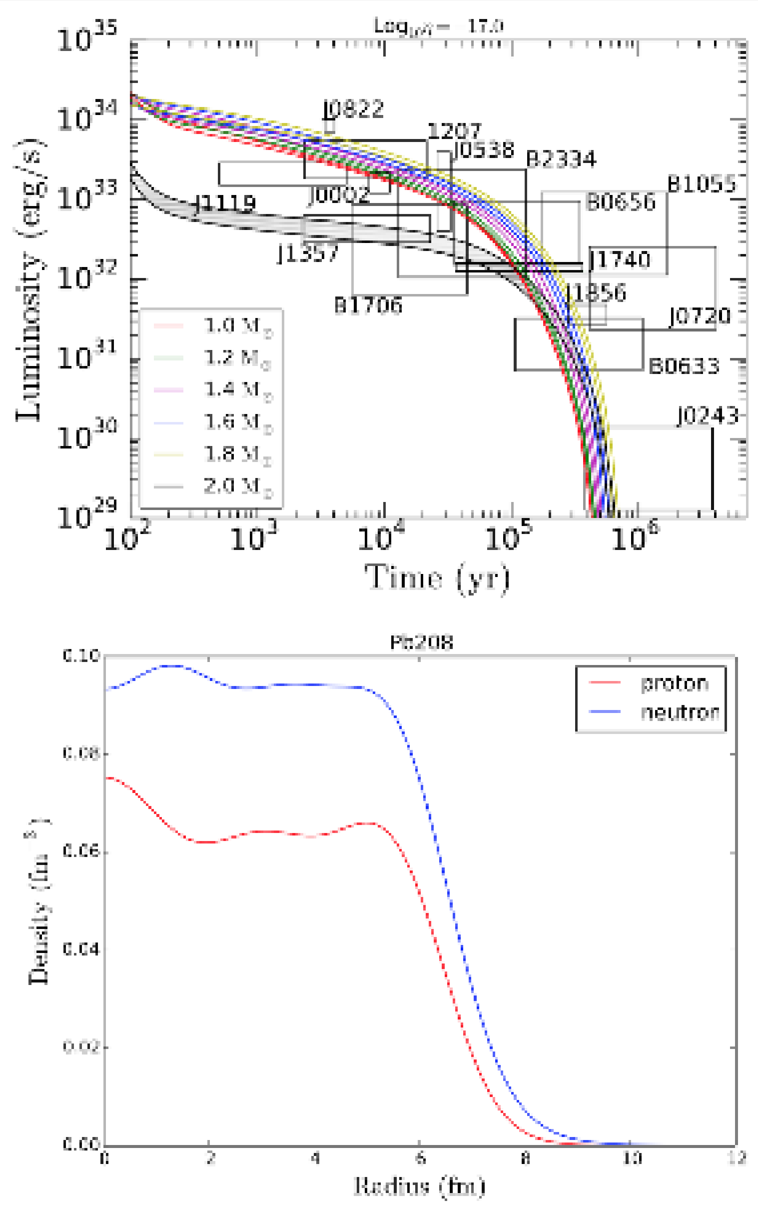


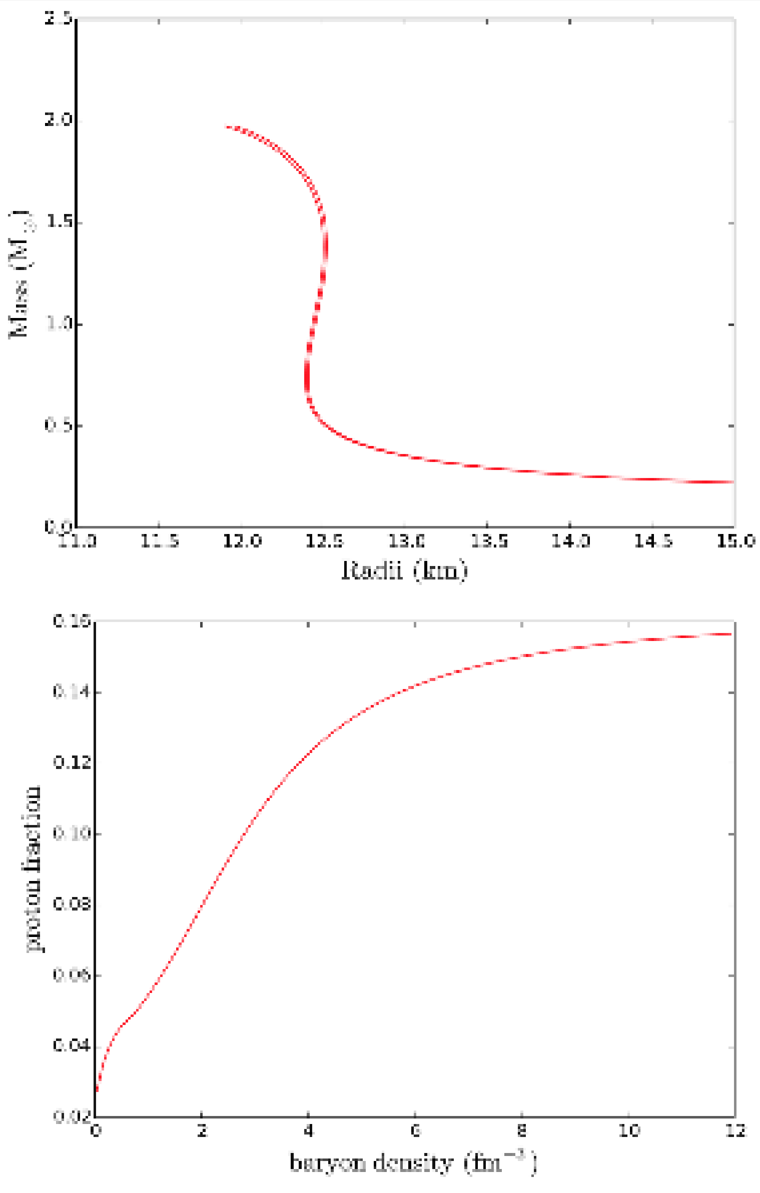
- For older neutron stars, presume crust is fully paired
- Parameterize T_C instead of Δ

$$T_C(k_F) = T_{C,\mathrm{max}}\, e^{-(k_F-k_{F,\mathrm{peak}})^2/2/(\Delta k_F)^2}$$

- Applied to proton $^1S_0$ and neutron $^3P_2$ gaps

Large Scale Inference for Composition





Beloin, Han, and Steiner (in prep.)

- Use one (RMF) model to describe $R(m)$, $T(t)$, and nuclei - 60 parameters
- Completing inference results in in **composition information** in addition to EOS constraints

Large Scale Inference for Composition

- What makes this possible is that not all of the 60 parameters impact all of the data
  - 25 parameters, one for every neutron star mass
  - 10 EOS parameters
  - 19 parameters for neutron star envelope/atmosphere composition
  - 6 gap parameters
- Use likelihood described above with trivial metrics
- Not yet connected to ab-initio theory (work in progress)

Summary

- Continue to constrain the EOS of dense matter with combinations of theory, experiments, and multi-messenger observations
- How to improve our use of Bayesian inference
- New EOS for supernovae and mergers, from theory experiments, and observations
- Going beyond the EOS to determine composition with neutron star cooling