Title: Experimental Probes of Vacuum Energy

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Abstract: <p>The vacuum energy changes when cosmological phase transitions take place, or in environments with high temperatures or chemical potentials. The propagation of primordial gravity waves is affected through the trace anomaly, and eras where the vacuum energy dominates can lead tofeatures in the gravity wave spectrum. High density phases of QCD in neutron stars, where the vacuum is rearranged, are also a novel probe: The mass-radius relationships for neutron stars is sensitive to the equation of state appearing in the Einstein equations, which may depend on new dynamics associated with vacuum energy. Such observations could potentially rule out large classes of explanations for the smallness of the currently observed cosmological constant.</p>

Experimental Probes of Vacuum Energy

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Dark Energy, CC, and QFT

- Simplest model for dark energy is a cosmological constant
- The observed current value of the cosmological constant is very small:

$$\Lambda \sim (10^{-3}\mathrm{eV})^4$$

- Generally expect that microscopic origins of CC involve the vacuum energy of QFT
- CC problem: Why is it so small? Not $(100\ \mathrm{GeV})^4$, or even $(M_{Pl})^4$?
- Since it is so small, why isn't it zero?

The Vacuum Energy **Changes**

$$\Lambda_{\rm eff} = \Lambda_{\rm bare} + \sum_i \alpha_i T_{c,i}^4$$

- Vacuum state changes across high T or high density phase transitions: e.g. QCD, EW phase transitions
- If no other dynamics in play: $\Delta\Lambda_{\rm PT} \sim T_{\rm PT}^4$
- **Disturbing**: if we are to obtain current small value, each PT must “anticipate” the upcoming ones
- Before EW: $\Lambda_{>EW} \sim m_W^4$
- After EW: $\Lambda_{<EW} \sim \Lambda_{\rm QCD}^4$

The Changing Vacuum Energy

- At electroweak phase transition:

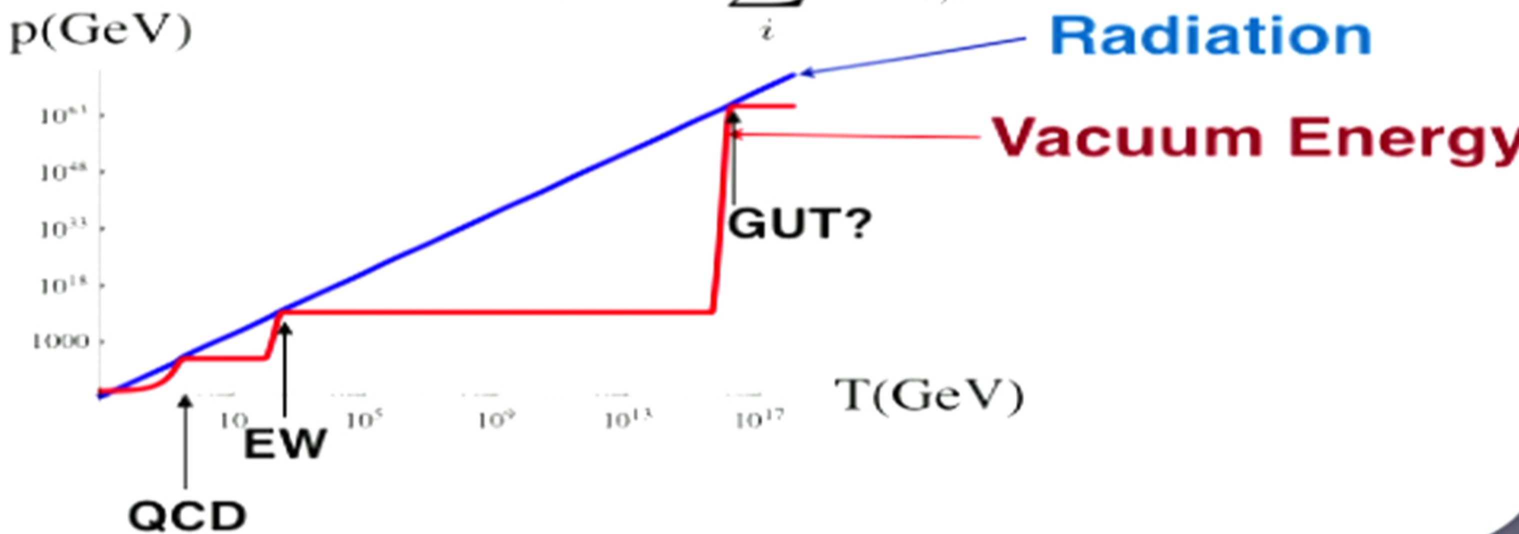
$$\Delta\Lambda_{\rm EW} \sim M_W^4 \text{ so require } \Lambda_{\rm before} + \Delta\Lambda = \mathcal{O}(\Lambda_{\rm QCD}^4)$$

- At each phase transition, QFT adds just the right amount to sum to small current value

- In very early universe plasmas, vacuum energy was huge, although never quite dominated FRW scale factor evolution due to radiation component

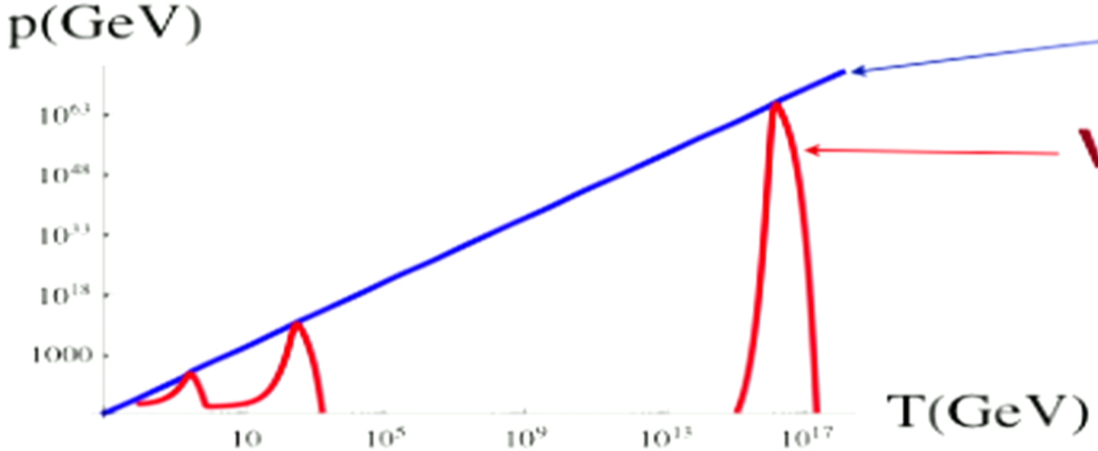
Cartoon of **Standard** Vacuum Energy Evolution:

$$\Lambda_{\rm eff} = \Lambda_{\rm bare} + \sum_i \alpha_i T_{c,i}^4$$



Also anthropic/multiverse picture

Alternative: Adjustment Mechanism



Currently no convincing model from theory, but if there were, it could look like this

Other alternatives: screening - maybe it is always small

Distinguishing Scenarios

- Regardless of plausibility of current alternative scenarios, crucial to test VE **experimentally**
- Want novel probes of gravity + quantum field theory
- If steps are or are not confirmed, refutes large classes of models for dark energy

Goals:

- Propose viable "O(my lifetime)" experimental tests of how/whether QFT vacuum energy enters into Einstein's equations
- Focus on phase transitions associated with significant re-arrangement of field vacuum expectation values
  - $\Delta\Lambda \sim T^4, \mu^4$
- Search out phenomena sensitive to this

Distinguishing Scenarios

- Difficulty: Λ is typically sub-dominant
- Difficulty: Closest phase transitions in SM are weak (2nd order/crossover phenomena)

What do we want?

Phenomena where Λ contributes at O(1) Level

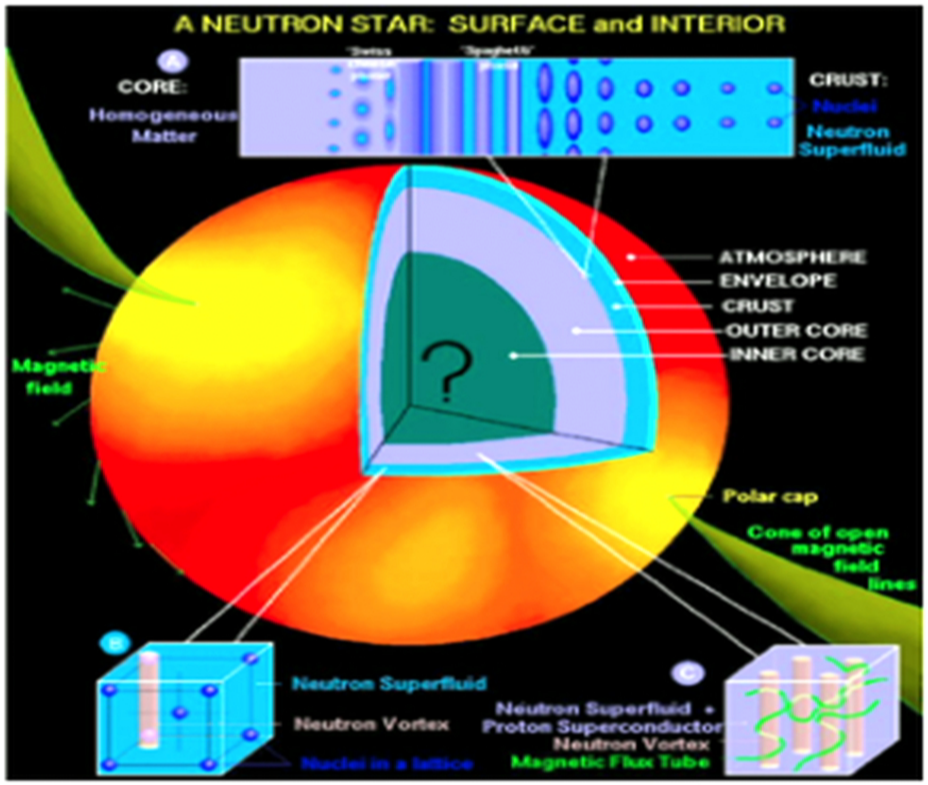
Where can we get it?

Structure of Neutron Stars

Primordial Gravity Waves

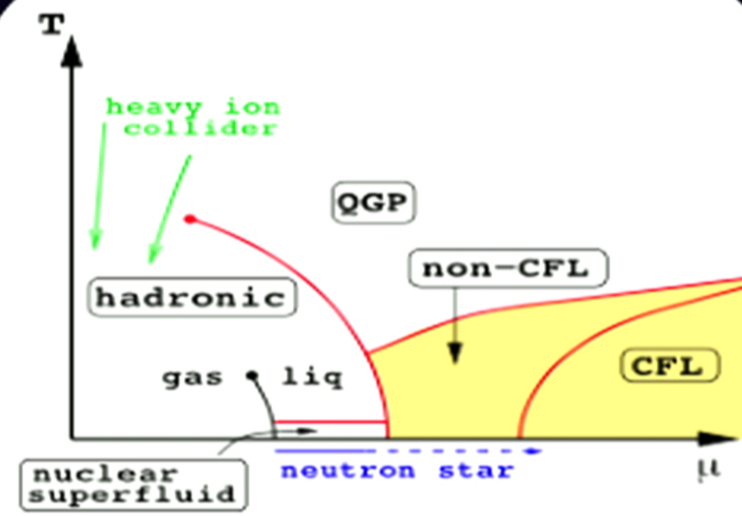
Neutron Stars

From Coleman Miller



Neutron Stars as probe of vacuum energy

- High densities - QCD enters exotic phases
- As chemical potential increases, enter Non-CFL phase and then CFL phase
  - **different condensates than QCD at T=μ=0**



From Alford, Schmitt, Rajagopal, Schaefer 2008

Neutron Stars may straddle phase boundaries

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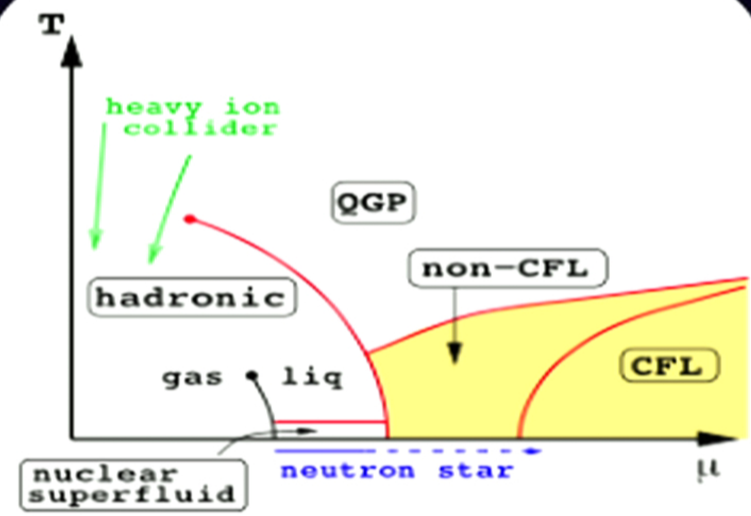

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Neutron Stars may straddle phase boundaries

Neutron stars and VE

- Neutron stars may contain cores of exotic QCD matter where QFT vacuum energy is much larger than background cosmological constant
- equation of state appearing in Einstein's equations determines pressure balance
- M(R) curves (and other properties) of NSs sensitive to vacuum energy contribution to EOS

Similar proposal to test Aether theory:
Kamiab, Afshordi 2011

Toy model for Neutron Stars

- Consider just two regions: inner and outer cores
- Neglect complicated thin skin - crust, envelope, atmosphere (subdominant w.r.t. VE effects)
- Model fluids as polytropic EOS for inner and outer cores with VE component in inner core
- transition between them at critical pressure for phase transition

Neutron Star Balance

- Calculate stable solutions
- Metric: $ds^2 = e^{\nu(r)}dt^2 - (1 - 2GM(r)/r)^{-1}\, dr^2 - r^2 d\Omega^2$
- Einstein Equations (Tolman-Oppenheimer-Volkoff):

$$
\begin{aligned}
M'(r) = &\quad 4\pi r^2 \rho(r)\,, \\
p'(r) = &\quad -\frac{p(r)+\rho(r)}{r^2\,(1-2GM(r)/r)}\left[GM(r) + 4\pi r^3 p(r)\right]\,, \\
\nu'(r) = &\quad -\frac{2p'(r)}{p(r)+\rho(r)}\,,
\end{aligned}
$$

Final equation is EOS input from QFT/experiment:

$$p = p(\rho)$$

Neutron Star M(R)

- Radius determined by point where p(R)=0
- Inner core radius determined by $p(r_{inner})=p_{crit}$
- match solution across jump in EOS:

$$\begin{array}{llll} p = p_{(-)}(\rho)\,, & \rho = \rho_{(-)}\,, & p \geq p_{cr}\,, & r \leq r_{cr} \\ p = p_{(+)}(\rho)\,, & \rho = \rho_{(+)}\,, & p < p_{cr}\,, & r \geq r_{cr} \end{array}$$

- Assume 2nd order/crossover (no surface tension)

$$M(r), \nu'(r), p(r) \text{ all continuous}$$

Two Step Equation of State

Inner Core: polytropic EOS **plus vacuum energy**
(Bag parameter - already in EOS for modern NS fits)

$$p_{(-)}(\rho) = p_f(\rho) - \Lambda = K_- \rho_f^{\gamma_-} - \Lambda$$
$$\rho_{(-)} = \rho_f + \Lambda$$

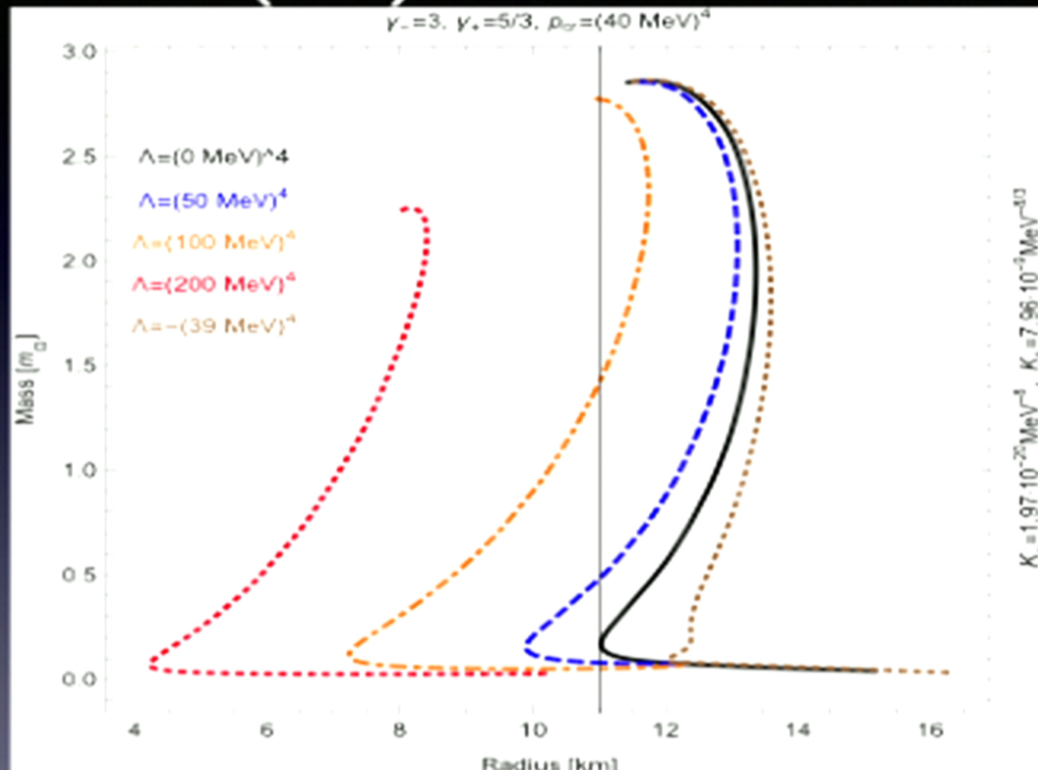
Outer Core: polytropic EOS **without vacuum energy**

$$p_{(+)}(\rho) = p_f(\rho) = K_+ \rho_f^{\gamma_+}$$
$$\rho_{(+)} = \rho_f \, .$$

Choose EOS parameters in-line with NS reviews (e.g. Lattimer '12)

Limits on Vacuum Energy Term:
too large +: negative partial pressure for non-CFL QCD
too large -: no equilibrium solutions

M(R) Curves

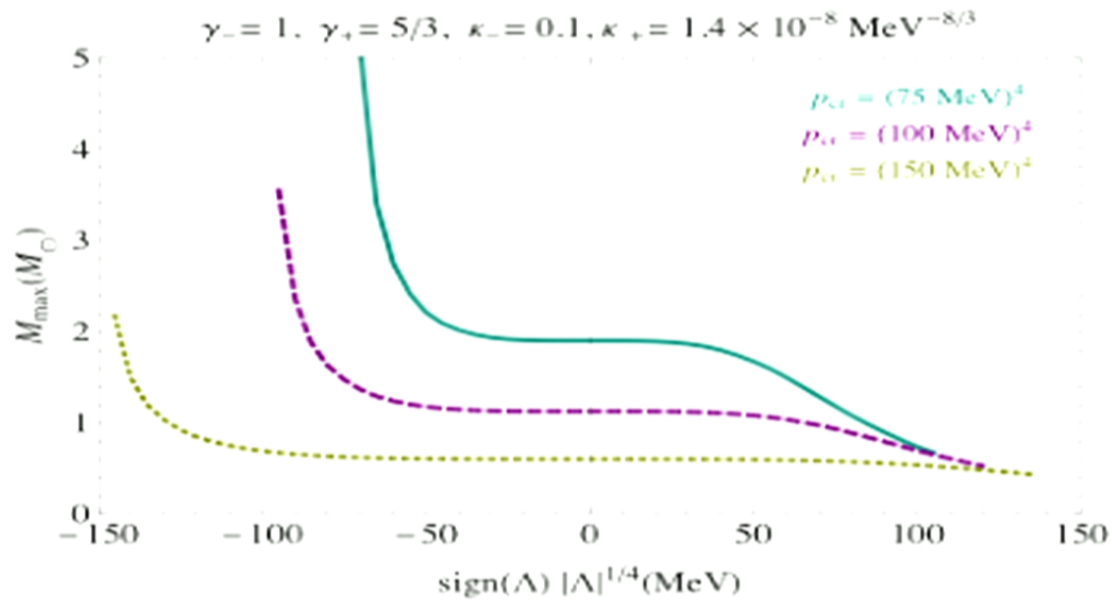


With external **theory input** of Equations of state: distinguish between scenarios with/without gravitating vacuum energy

Mass limit

- Vacuum energy can have large effect on **maximum mass** of neutron stars
  - varies by up to 20% for various EOS
  - some evidence of super-critical NSs
- sensitive to different possibilities for **currently unknown** EOS

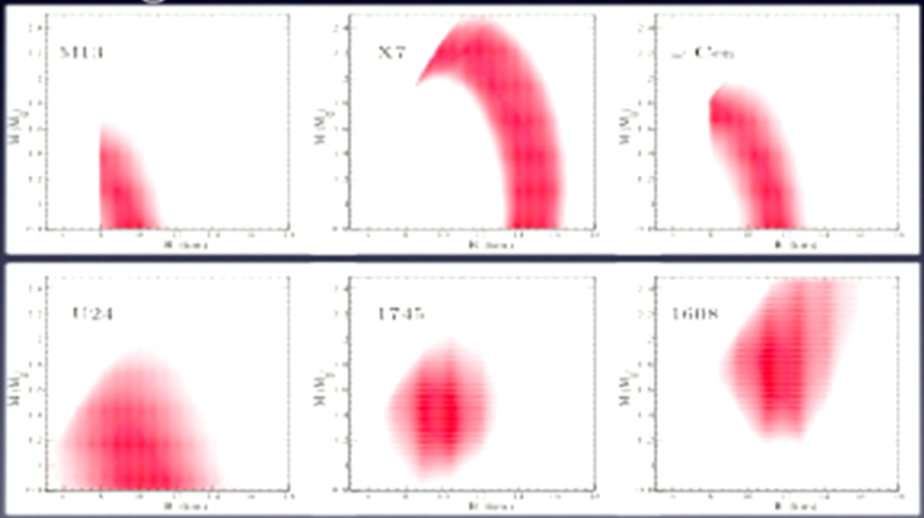
Mass limits



Effect of varying critical pressure for phase transition and vacuum energy contribution to fluid pressure

Experimental probes

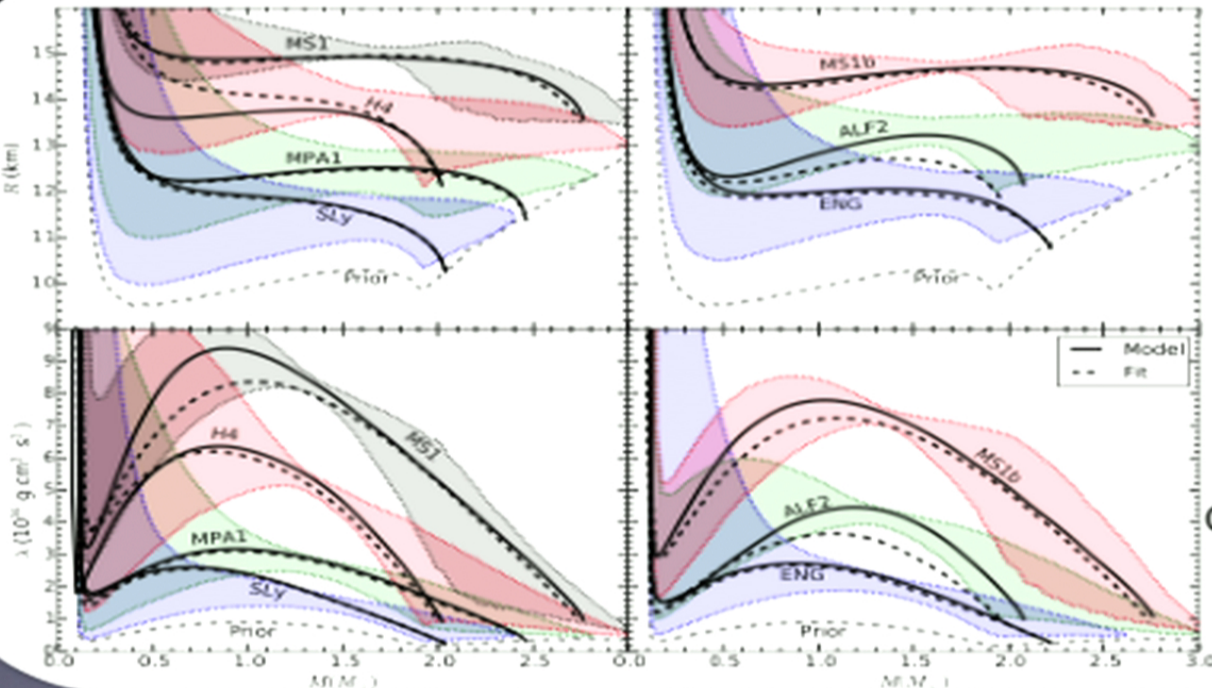
- Most current measurements of R come from studying luminosity profiles of accreting neutron stars



  - extract M in binaries
  - Uncertainties in R are large (~20-30%)

Future Probes

Advanced LIGO reach (Lackey and Wade 2014 for LIGO)



M(R)

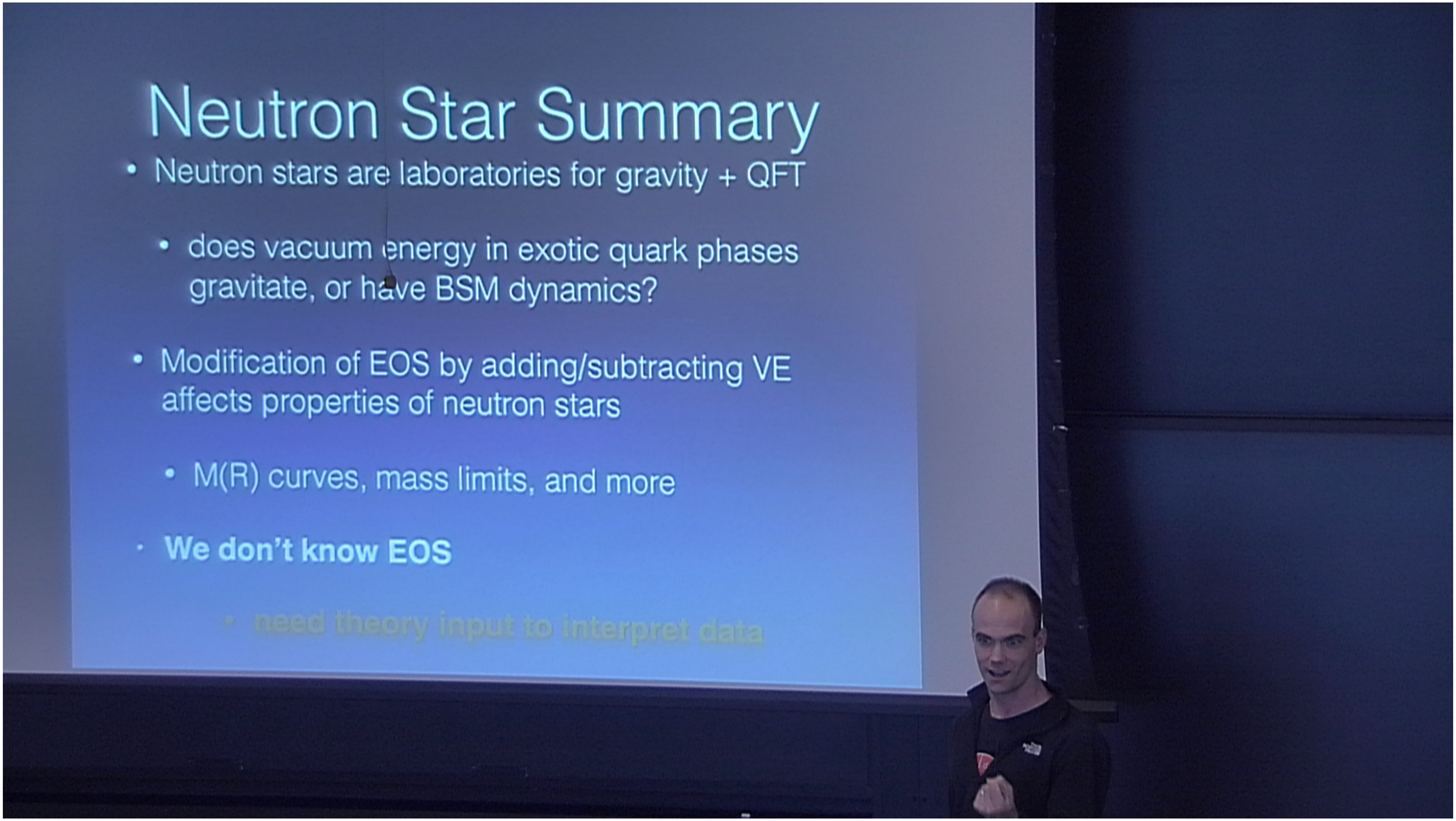
Tidal deformability

Various hypothetical equations of state (black lines)

10% in R given M @ 95% CL (colored envelopes)

Neutron Star Summary

- Neutron stars are laboratories for gravity + QFT
  - does vacuum energy in exotic quark phases gravitate, or have BSM dynamics?
- Modification of EOS by adding/subtracting VE affects properties of neutron stars
  - M(R) curves, mass limits, and more
- **We don't know EOS**
  - **need theory input to interpret data**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Primordial Gravity Waves

Metric perturbations sourced during inflation propagating in expanding FRW:

$$ds^2 = a(\tau)^2 \left(d\tau^2 - (\delta_{ij} + h_{ij})dx^i dx^j\right)$$

Consider transverse traceless tensor metric perturbations:

$$h_{ij} \text{ with } h^i_i = \partial_k h^k_i = 0$$

Note we use conformal time. Relations to co-moving time:

$$dt = a(\tau)d\tau \qquad \frac{da}{d\tau} \equiv a' = a\dot{a} = a^2 H$$

Einstein Eq: $\frac{a''}{a} = a^2\left(\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2\right) = \frac{4\pi G_N}{3} T^\mu_\mu$

Propagation of GWs

Work with rescaled modes: $\chi_k = a h_k$

Evolution Equation:

$$\chi_k'' + \left(k^2 - \frac{a''}{a}\right)\chi = \chi_k'' + \left(k^2 - \frac{4\pi G}{3}a^2 T^\mu_\mu\right)\chi = 0$$

Roughly two scenarios:

$$k^2 \gg \frac{a''}{a}$$

Simple plane waves:

$\sqrt{\langle\chi^2\rangle}$ constant

$$\sqrt{\langle h^2\rangle} \propto \frac{1}{a}$$

Mode Damps

$$k^2 \ll \frac{a''}{a}$$

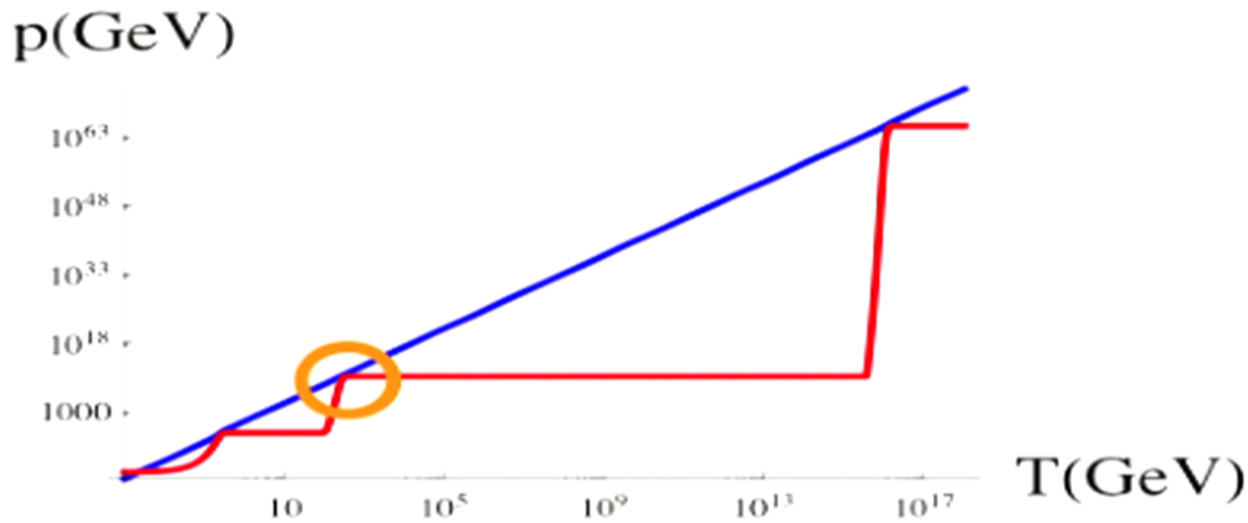
Frozen Mode:

$$\frac{\chi''}{\chi} \approx \frac{a''}{a}$$

$$\chi \propto a$$

$h \approx$ constant

Typical Transition



Radiation domination
PT happens
radiation domination again

Number of rel. deg. of freedom drops

Spectral Steps and Peaks

During radiation Domination:

$$\Omega_h(k > k_{eq}) \propto k^2 a^2(\tau_{hc}) \propto a^4(\tau_{hc}) H_{hc}^2 \propto g_*^{-\frac{1}{3}}$$

If we assume entropy conservation across the phase transition, we generate step:

$$\frac{\Omega_b}{\Omega_a} = \left(\frac{g_*^b}{g_*^a}\right)^{1/3}$$

A typical phase transition generates a step with **subfeatures** that depend on details of EOS across phase transition

$$\xi = \frac{\rho_\Lambda}{\rho_R} \qquad \Omega \propto (1+\xi) g_*^{-1/3}$$

Peak in spectrum from VE

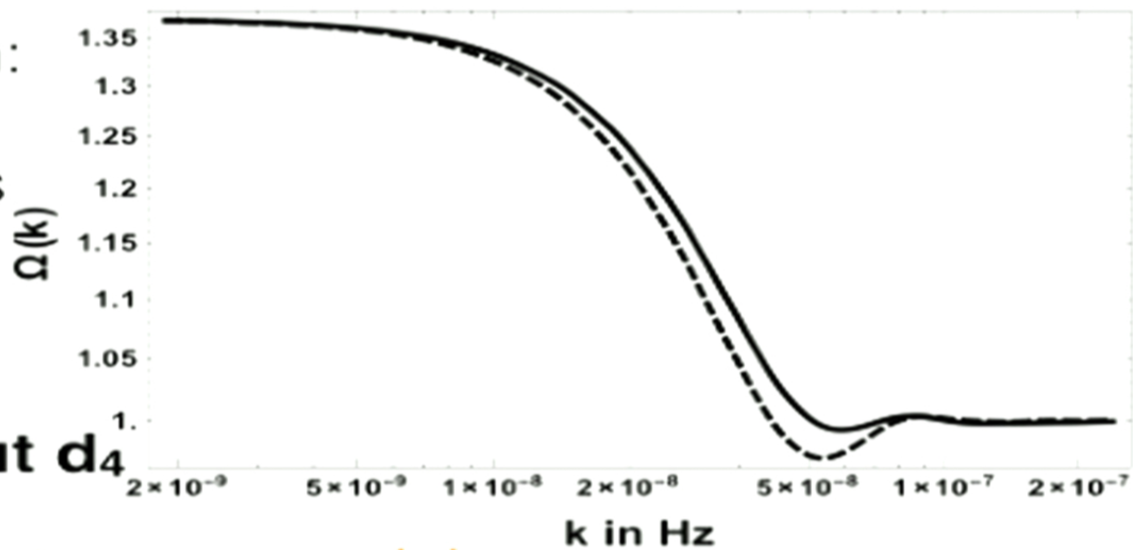
The QCD Step

Recall GW's sensitive to trace:

$$\Theta = T^{\mu}_{\mu} = T^4\left(1-\frac{1}{(1+e^{(T-c_1)/c_2})^2}\right)\left(\frac{d_2}{T^2}+\frac{d_4}{T^4}\right)$$

d_4 is a VE term:
lattice data
gives numerics

Change d_4:
Solid = SM
Dashed=max out d_4



Not very promising -
Electroweak is similar
Large step washes out peak

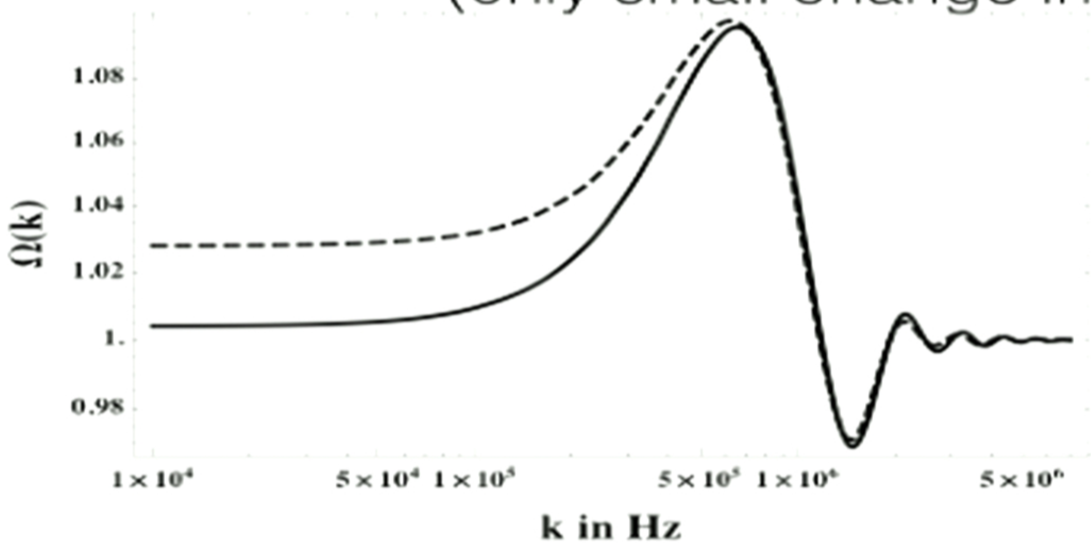
Making a peak

Consider **hypothetical** high scale PT

High scale global SU(N) symmetry breaking

many dof become massless goldstones

(only small change in g_*)



Vacuum energy term creates peak

Similar results from classes of Peccei-Quinn U(1) breaking

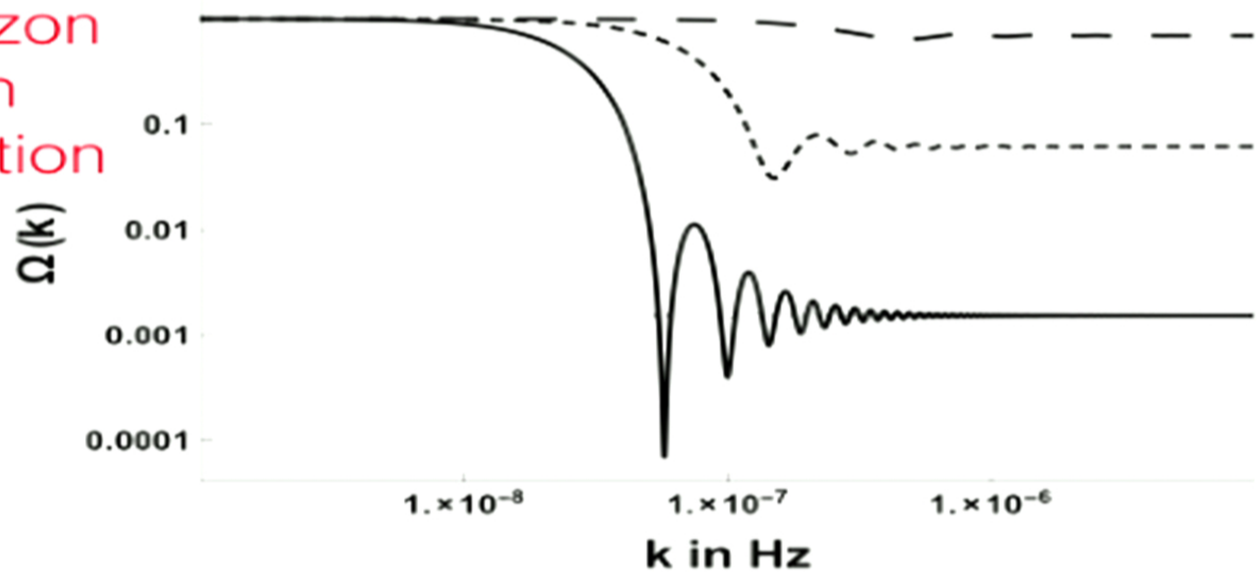
More Exotic Possibilities?

Some CC adjustment mechanisms may drastically modify cosmic history across PT's.

I.e. a slow adjustment mechanism generates a mini-inflationary period after a PT

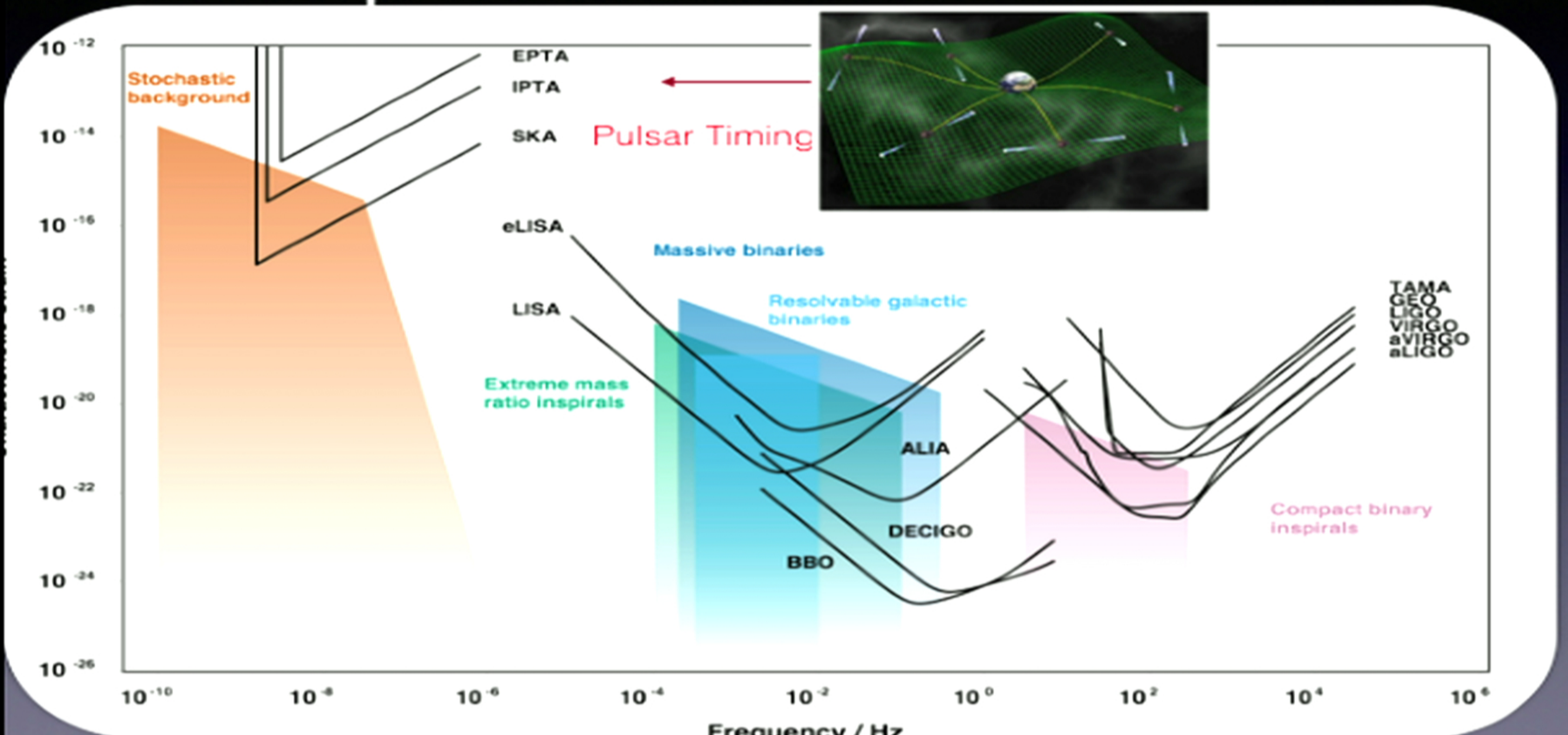
Modes inside horizon before transition damped like radiation

$$r \sim (a_0/a_f)^4$$



Step size dependent on relaxation time

Experimental Probes



Conclusions

- Part of our **standard** picture of particle physics:
  - **Vacuum energy changes across phase transitions**
- Neutron stars - Vacuum energy is a significant fraction of total mass
  - deviations in M(R), other physical quantities
  - **motivates theory pursuit of EOS, precision measurements of neutron stars**
- Gravitational waves:
  - dynamics could have dramatic effect (inflation or peak at high scale PT)
  - need complete picture of EW physics (anticipating more Run II data!)
  - **provides additional strong motivation for GW experimental programs**