

# **Experimental Tests of Vacuum Energy**

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with**

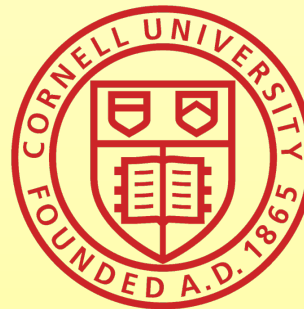
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# The Evolution of vacuum energy

- The cosmological constant is **very small** today

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

- Expectation is that **microscopic origin** of cc is **vacuum energy** of quantum field theory
- Why** is it so **small** vs.  $(TeV)^4$ ,  $M_{Pl}^4$
- If it is so small **why** is it **not** zero?
- Is it **always very small** (ie. is there an adjustment mechanism)?

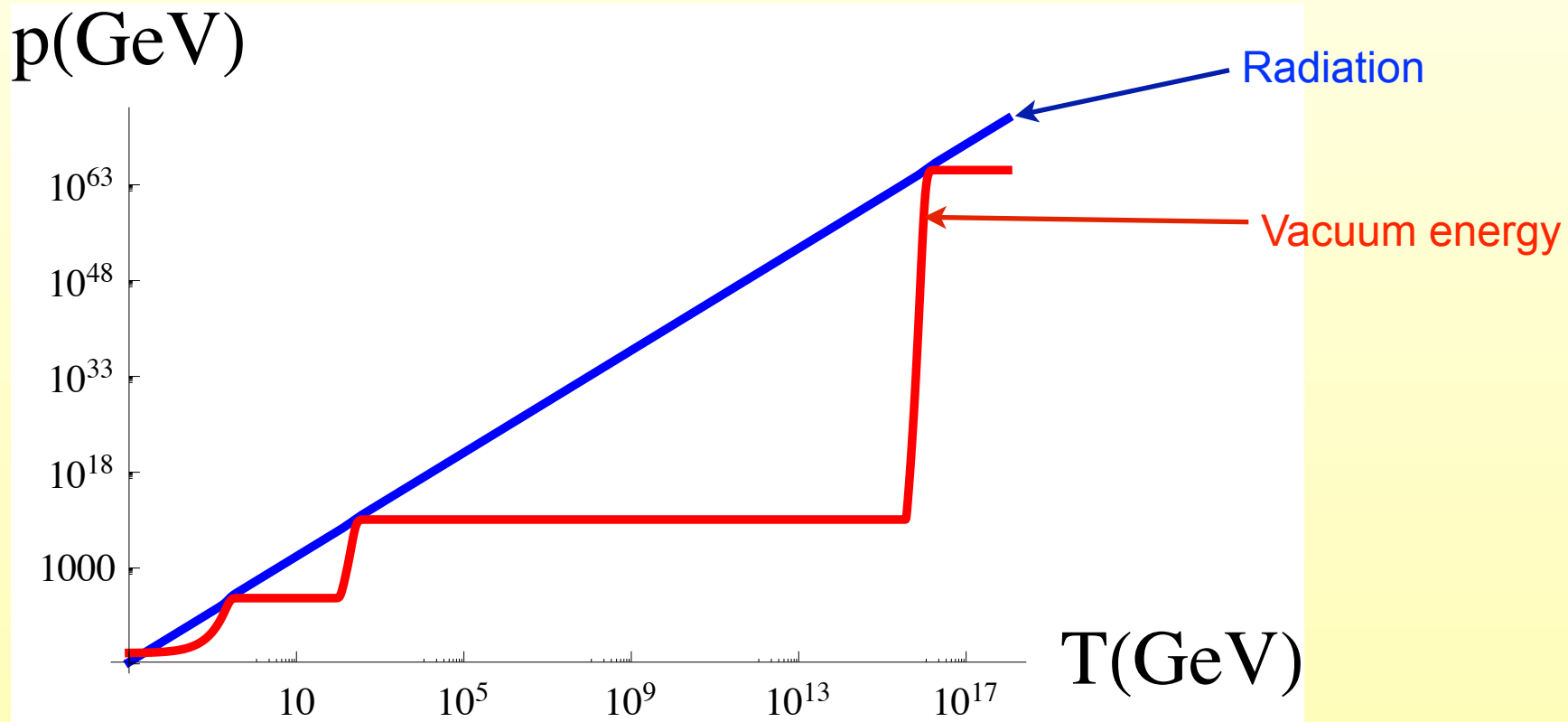
# The Evolution of vacuum energy

- If CC result of microphysics, in traditional picture cc should undergo a **series of jumps** at every phase transition
- Expectation  $\Delta\Lambda_i \propto T_{c,i}^4$
- Want CC to **NOT** dominate **AFTER** phase transition (otherwise Universe accelerates **too early**)
- CC **AFTER PT** should be of order of  $T_c$  of **NEXT** phase transition
- eg. before EWPT  $\Lambda \sim M_W^4$

## The Evolution of vacuum energy

- $\Delta\Lambda \sim M_W^4$  so tuning  $\Lambda + \Delta\Lambda \sim \mathcal{O}(\Lambda_{QCD}^4)$
- At one phase transition Universe already “knows” where the next phase transition will be
- At least QCD, EW PT, potentially also SUSY and/or GUT phase transition (if SUSY changes GUT expectations)
- In previous history  $\Lambda$  was much larger than now, but never dominated previously!

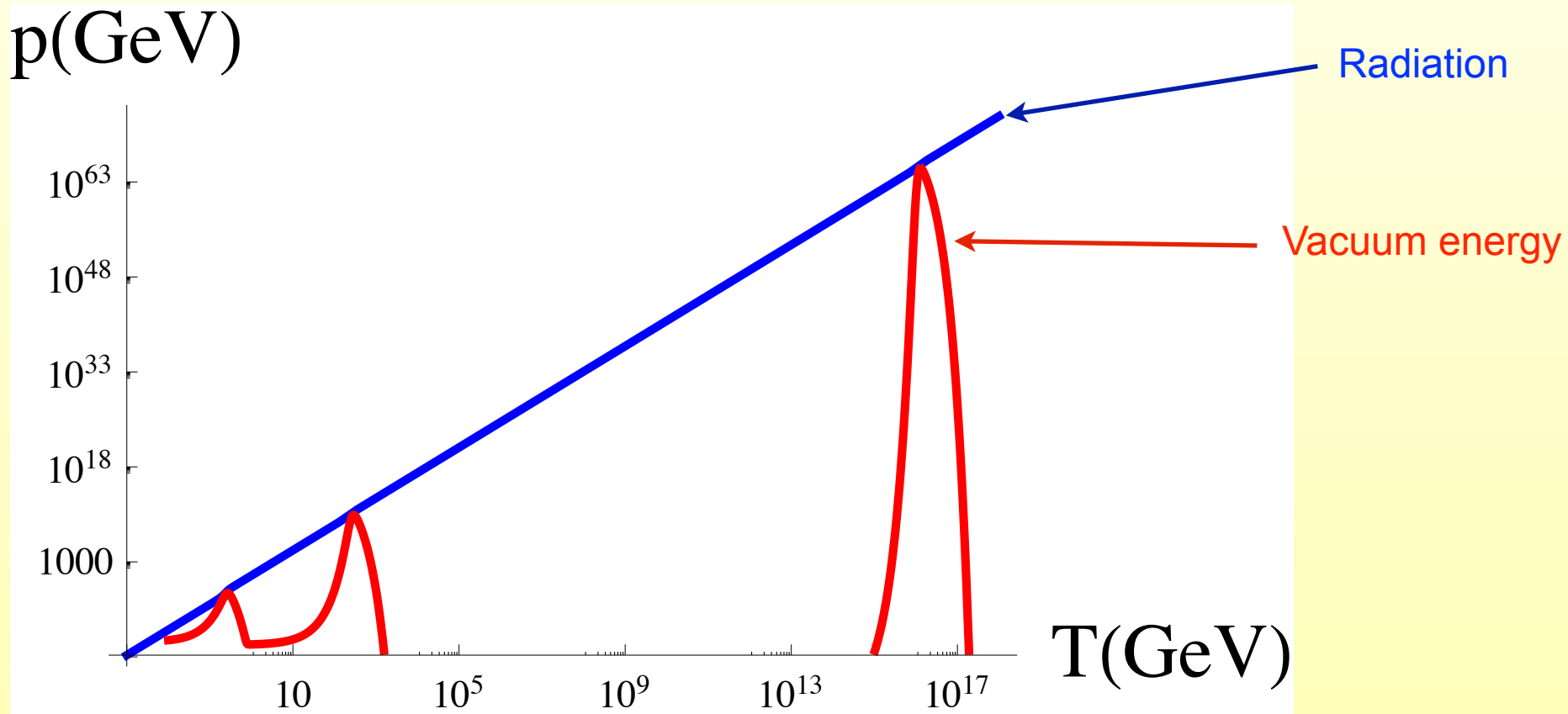
# A simple sketch of the evolution of $\Lambda$



## The Evolution of vacuum energy

- $\Lambda$  goes through **steps** during phase transitions
- Whenever  $\Lambda$  would start to dominate a **new phase** transition happens
- $\Lambda$  is **always subleading** even though it was **much bigger** than it currently is - **challenging** to find experimental tests of this picture
- Size of step of order  $(T_c^{(i)})^4$
- Amount of tuning given by  $(T_c^{(i+1)})^4$

# Alternative evolution of $\Lambda$ : with adjustment



## Alternative evolution of $\Lambda$ : with adjustment

- $\Lambda$  is always small except around PT's
- When PT starts  $\Lambda$  starts growing
- Adjustment mechanism kicks in and drives  $\Lambda$  small again
- Will have its own timescale  $\Delta t_{adj}$
- Heights will depend on details of adjustment, PT

## Steps or adjustment?

- **Important goal**: to determine experimentally which of these pictures is right one
- If steps: lends **more credence** to anthropic arguments
- If **adjustment** need to find **mechanism**
- Difficulty:  $\Lambda$  **always** sub-dominant
- **Last** of these transitions occurred at  $\Lambda_{QCD}$  :  
Above CMB, BBN, etc. **Not much precision results**  
from that period

## Steps or adjustment?

- Further complication: **neither** EW nor QCD PT **first order** (at least in SM with 125 GeV Higgs) - no gravitational waves produced from bubble collisions...

- **NEED:**

Effect where leading radiation's contribution strongly suppressed



Primordial gravitational waves

System where vacuum energy  $\mathcal{O}(1)$  fraction of total energy



Neutron star

## Goal

- Establish **experimentally** that **vacuum energy** of microscopic physics is actually what show up **in Einstein eq** - or there is an adjustment mechanism
- Only care about PT's that actually **change VEVs** of fields
- For **example** recombinations at  $z \sim 1100$  is a PT where  $e^+p \rightarrow H$ , with binding energy 13.6 eV
- Decrease of energy density of matter, but **not a change** in vacuum energy - this energy density gets diluted with expansion, while  $v_e$  does not

# 1. Propagation of primordial gw's

- Tensor perturbations  $h_{ij}$  transverse traceless

$$h_i^i = 0, \text{ and } \partial_k h_i^k = 0$$

- Perturbation of metric in expanding Universe

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

- Usually conformal time  $\tau$  is used  $a(\tau)d\tau = dt$   
where expansion equation

$$a' = a\dot{a} = a^2 H, \quad \frac{a''}{a} = a^2 \left( \frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} \right) = \frac{4\pi G}{3} a^2 T_\mu^\mu$$

# Propagation of primordial gw's

- Einstein equation:  $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 0$
- Expand in modes:  $h_{ij} = \sum_{\sigma=+,-} \int \frac{d^3k}{(2\pi)^3} \epsilon_{ij}^{(\sigma)} h_k^{(\sigma)}(\tau) e^{ikx}$
- Rescaled modes:  $\chi_k \equiv a h_k$
- Satisfy **very simple** equation:

$$\chi_k'' + \left(k^2 - \frac{a''}{a}\right) \chi_k = \chi_k'' + \left[k^2 - \frac{4\pi G}{3} a^2 T_\mu^\mu\right] \chi_k = 0$$

- Interpretation: if  $k^2 > \frac{a''}{a}$  just **free plane wave** for  $\chi$
- But actual mode is  $\chi/a$  getting **damped** by  $1/a$

## Propagation of primordial gw's

- Interpretation: if  $k^2 < \frac{a''}{a}$  then equation  $\frac{\chi''}{\chi} = \frac{a''}{a}$

has solution  $\chi \propto a$  and actual mode  $\chi/a$  is frozen

- If mode outside damping horizon set by  $\frac{a''}{a}$  it is frozen. Once it enters horizon it is damped by  $1/a$

- Key:  $\frac{a''}{a} = \frac{4\pi G}{3} a^2 T^\mu_\mu$

- For pure conformal radiation  $T^\mu_\mu = 0$  while for general radiation strongly suppressed

## Propagation of primordial gw's

- For **example** for  $SU(N_c)$  with  $N_f$  flavors effect of trace anomaly in thermal field theory:

$$\epsilon \equiv 1 - 3w = \frac{5}{6\pi^2} \frac{g^4}{16\pi^2} \frac{(N_c + \frac{5}{4}N_f)(\frac{11}{3}N_c - \frac{2}{3}N_f)}{2 + \frac{7}{2} \frac{N_c N_f}{N_c^2 - 1}}$$

- For example for QCD:  $\epsilon \sim 6 \cdot 10^{-3}$
- Total expression for **damping** term:

$$T_{\mu}^{\mu} = \epsilon \rho_{rad} + 4\Lambda$$

# Propagation of primordial gw's

- Effective **damping horizon** for gravitational waves

$$\frac{2\pi}{D_{gw}^2} = \frac{4\pi G}{3} a^2 T_\mu^\mu \sim \frac{4\pi G}{3} a^2 (\epsilon \rho_{rad} + 4\Lambda + \rho_{mat})$$

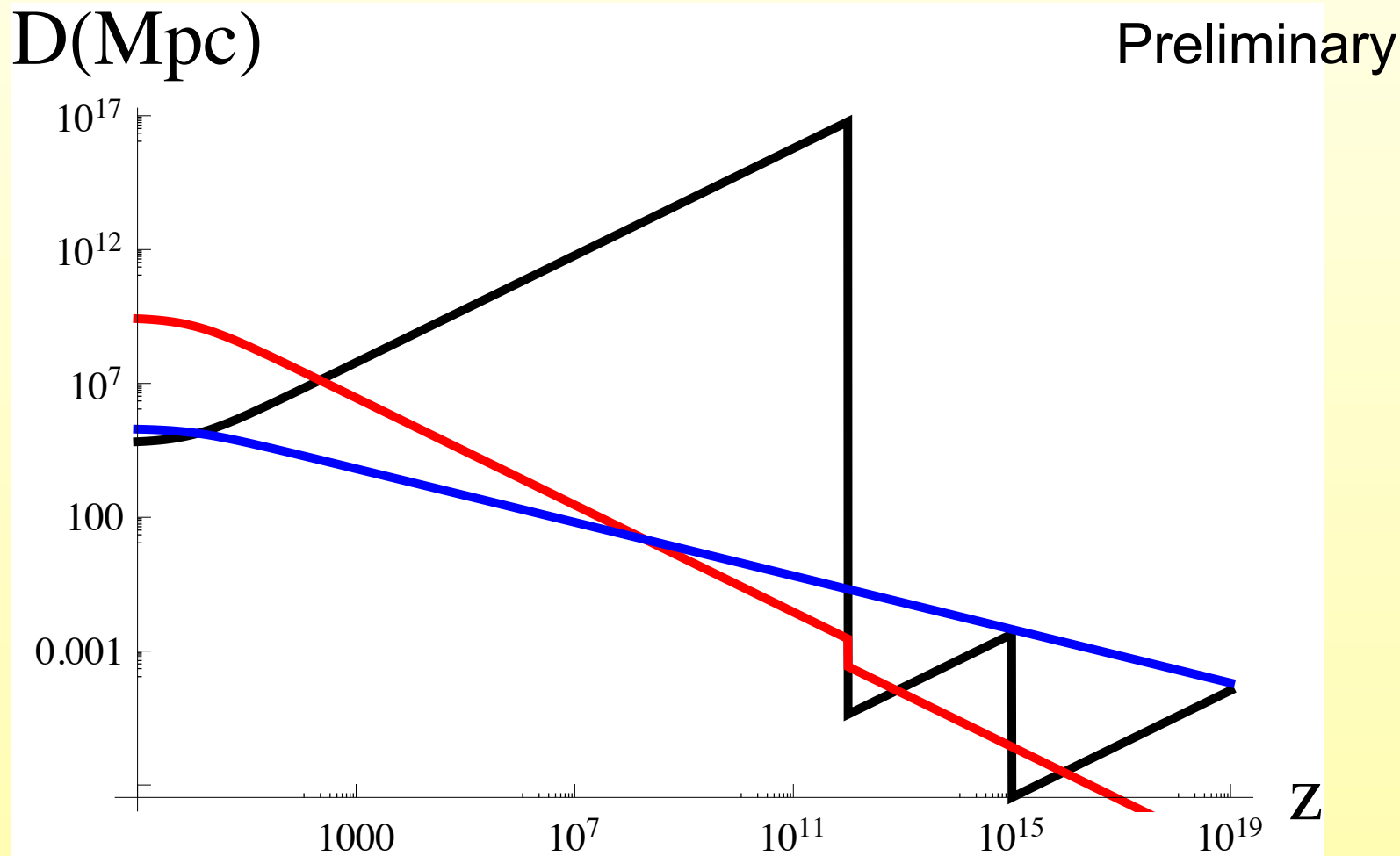
- Wavelength **smaller** will be **damped** by  $1/a$
- Wavelength **longer** will be **frozen**
- Simplest to write in terms of **scale factor**  $a$  (or redshift):

$$D_{gw}^{(rad)} = \sqrt{\frac{3}{4\pi G} \frac{a}{\sqrt{\epsilon \rho_{rad}^0}}}$$

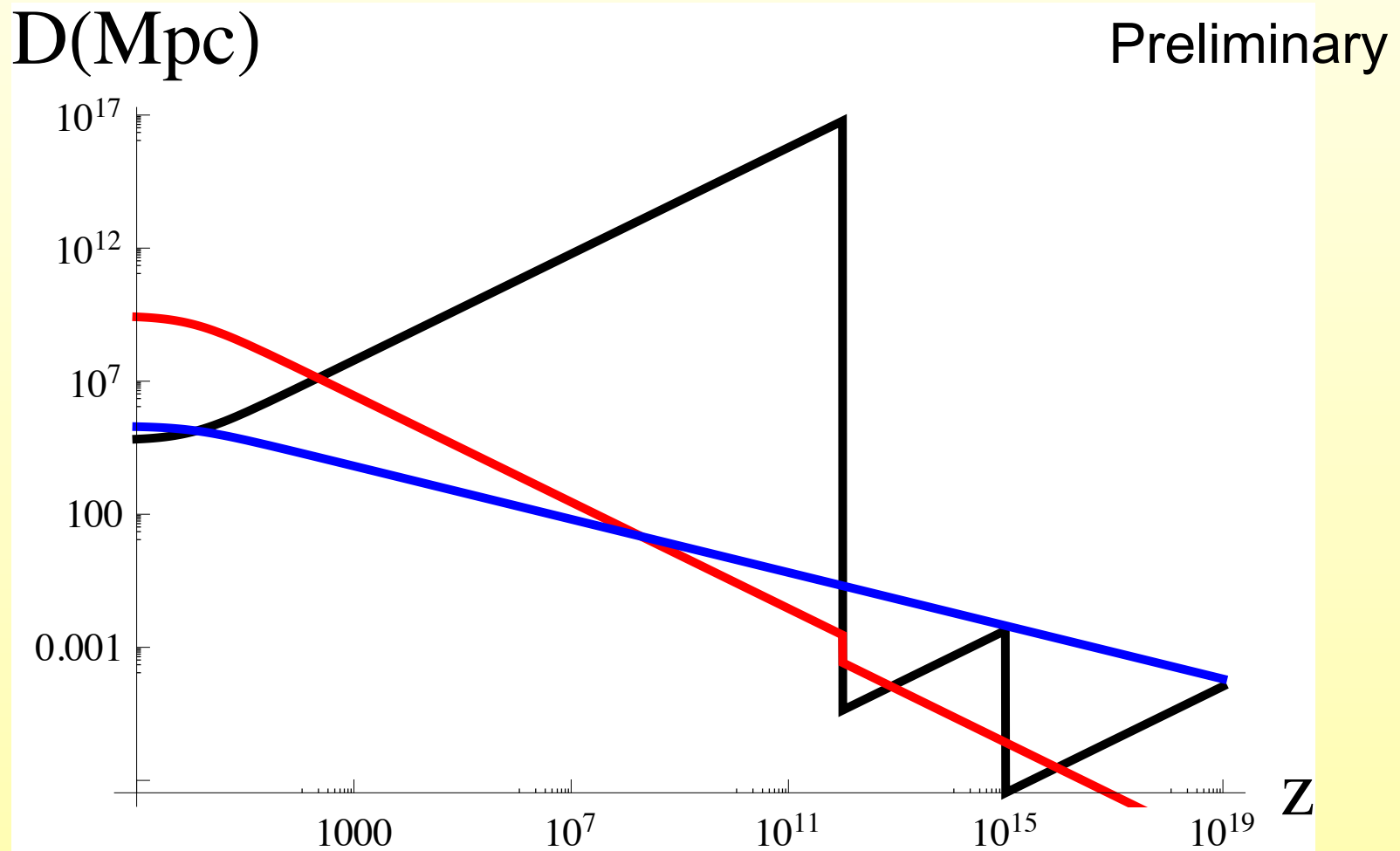
$$D_{gw}^{(\Lambda)} = \sqrt{\frac{3}{4\pi G} \frac{1}{2\sqrt{\Lambda}a}}$$

$$D_{gw}^{(mat)} = \sqrt{\frac{3}{4\pi G} \frac{a^{\frac{1}{2}}}{\sqrt{\rho_{mat}^0}}}$$

# The damping horizon for gravitational waves



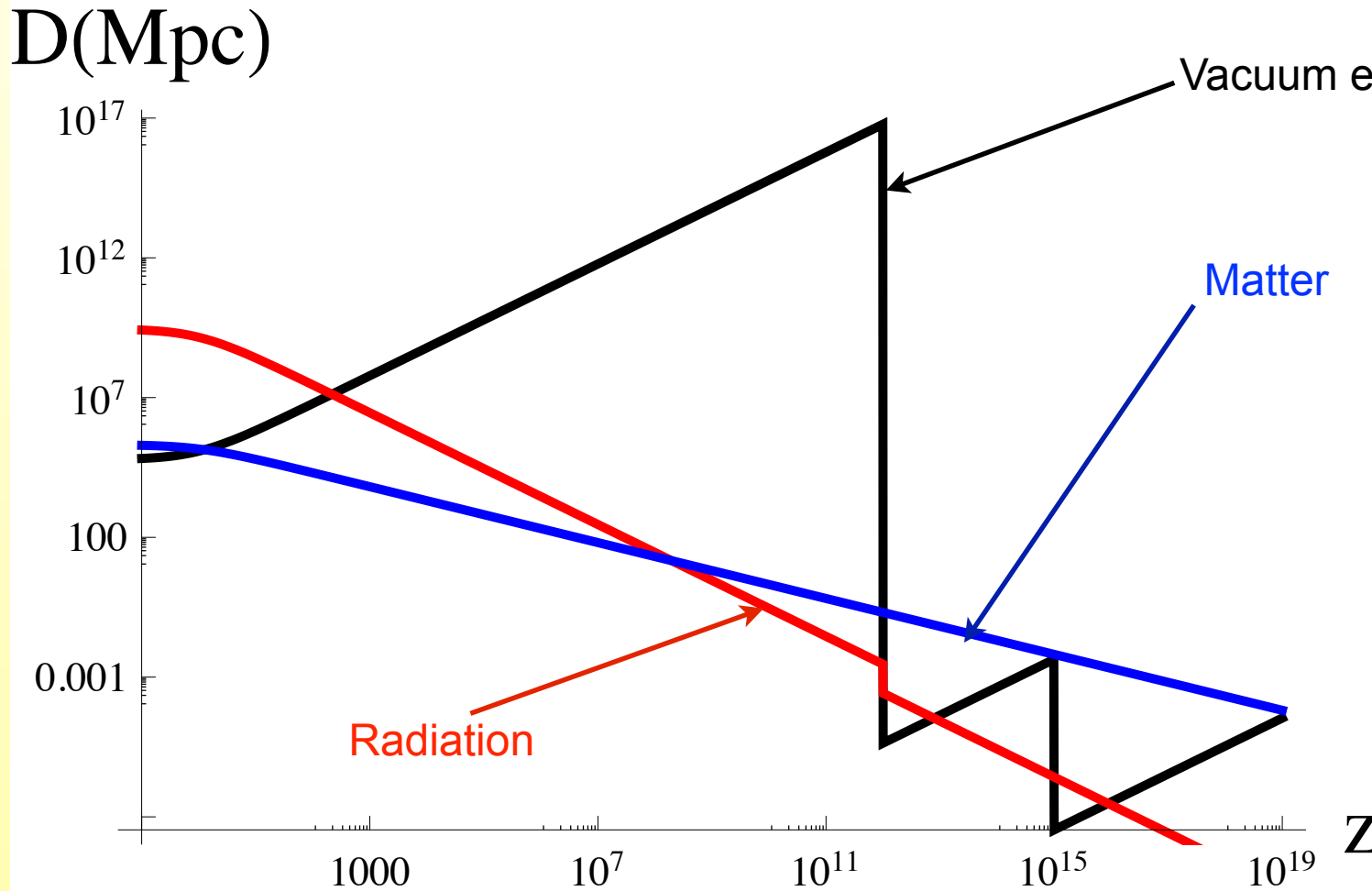
# The damping horizon for gravitational waves



Smallest damping horizon wins

# The damping horizon for gravitational waves

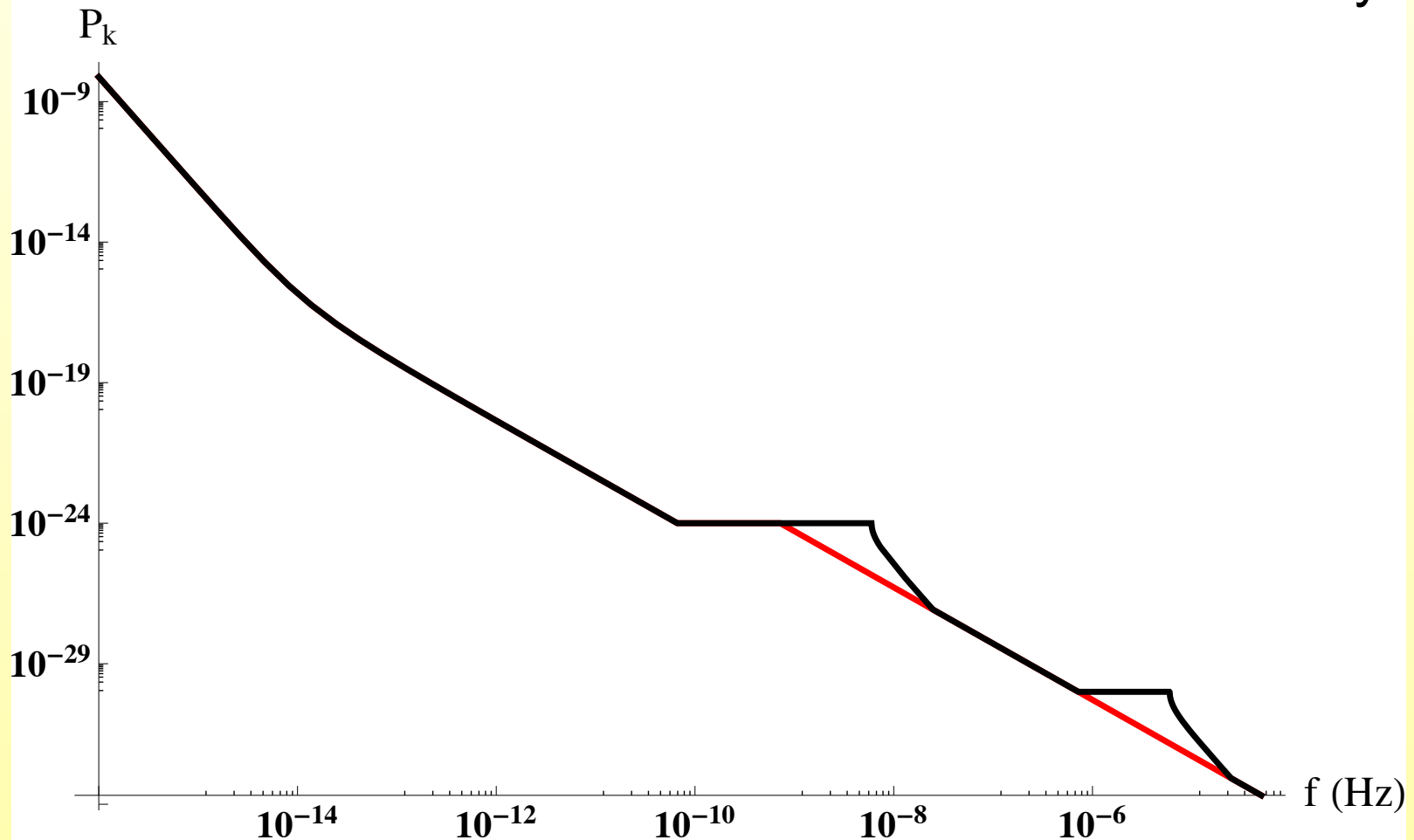
Preliminary



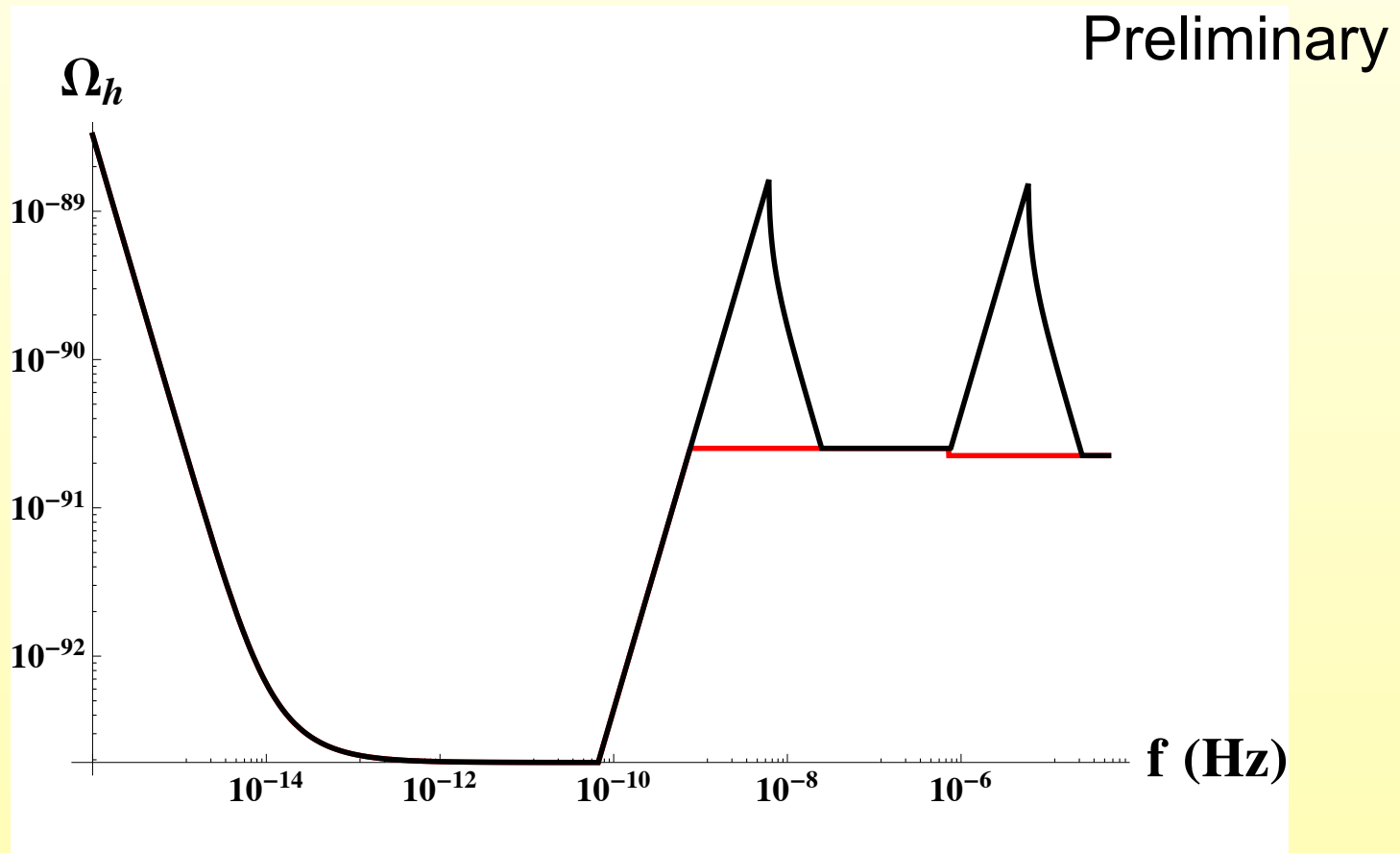
Smallest damping horizon wins

# The spectrum of initially scale invariant primordial gravitational waves

Preliminary

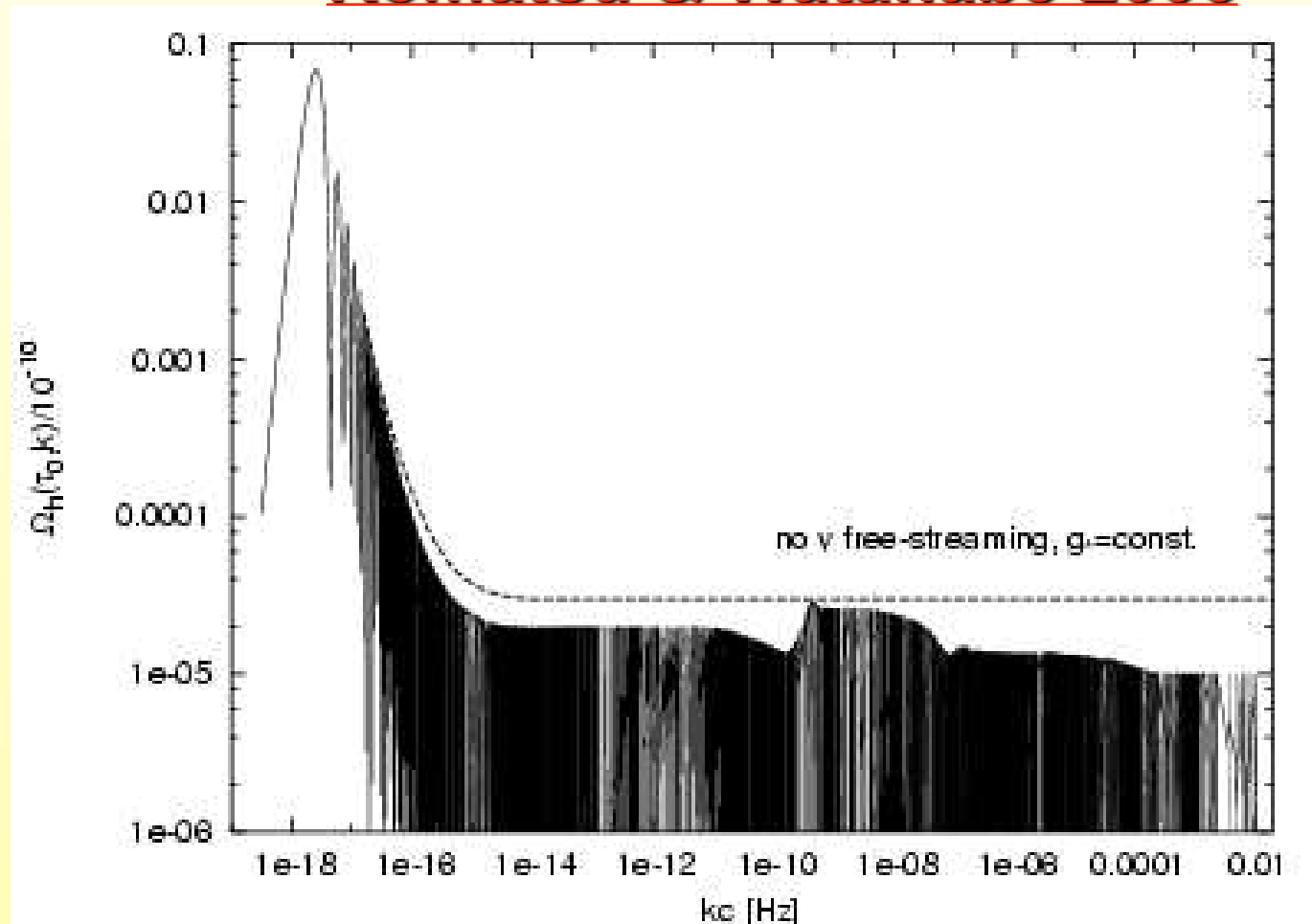


# The energy distribution of initially scale invariant primordial gravitational waves



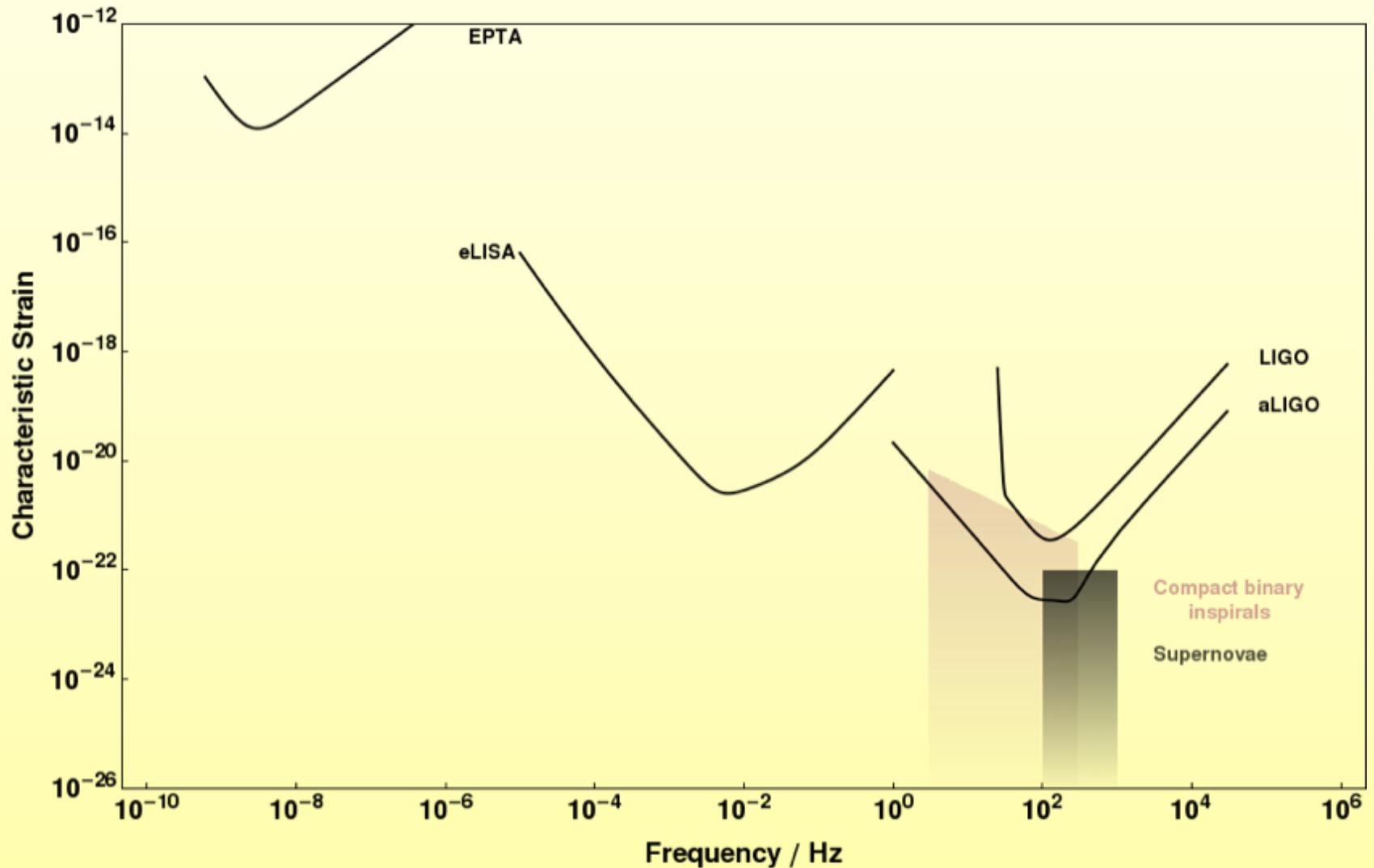
Large peaks should be present due to EW and QCD PT's

# Comparison plot from traditional calculation Komatsu & Watanabe 2006



Much smaller peaks due to just the PT's  
Main point: CC will dominate quite a bit earlier

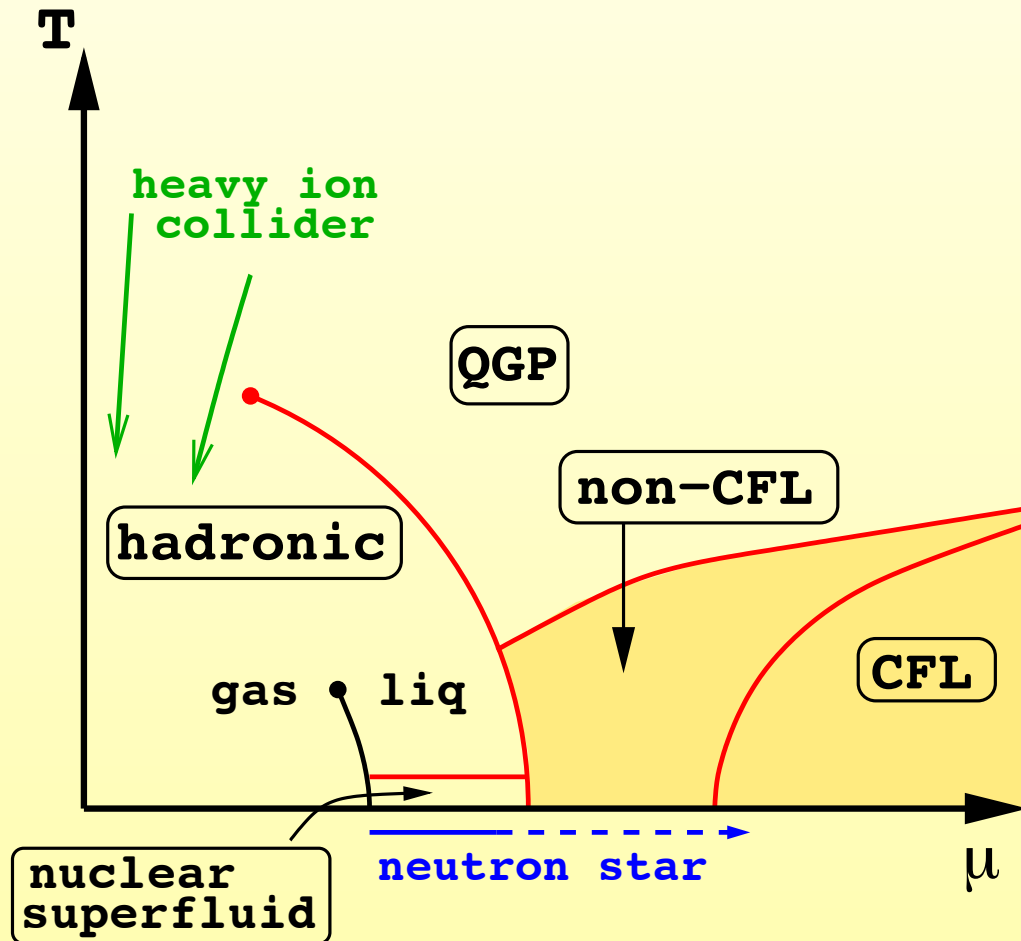
# Sensitivity of future experiments



## 2. Neutron stars for testing vacuum energy

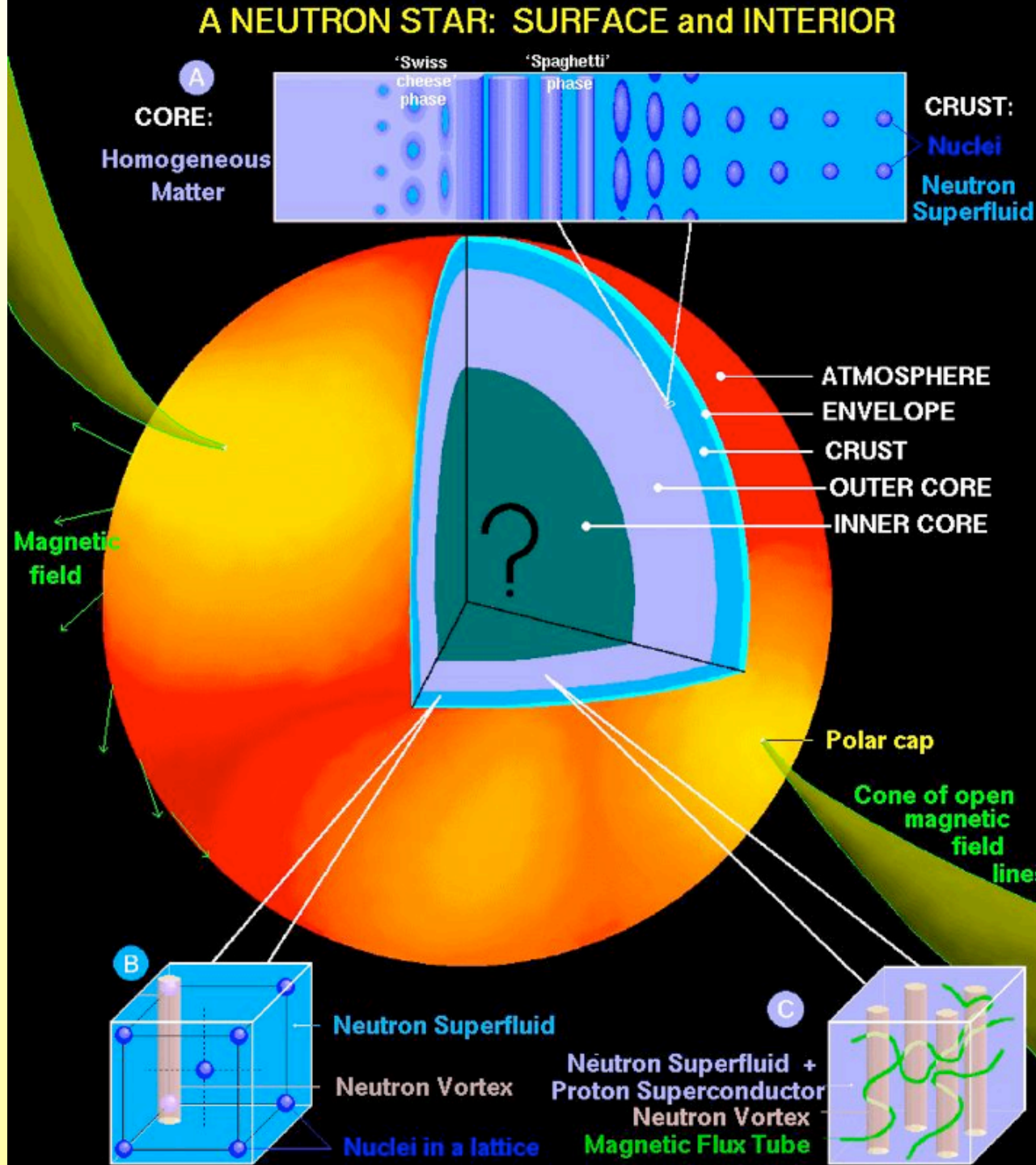
- Need a system which is in different phase of matter
- QCD at large densities probably has those phases: at low  $T$  but large chemical potential CFL phase, and non-CFL phase, both with VEVs different from QCD condensates
- Core of neutron star may have this unconventional QCD phase
- If adjustment mechanism at play, expect to cancel effect of additional cc in the core. Will modify the structure and  $M(R)$  relation of ns's

# The phases of QCD



From Alford, Schmitt, Rajagopal, Schaefer  
2008

# Neutron Stars



From Coleman Miller

# Toy model for neutron stars

- Will just consider **two phases**, inner and outer core
- **Neglect** crust, envelope, atmosphere...
- Take **simple** polytropic **EOS's** for inner and outer cores
- Match them up at **critical pressure** for phase transition
- Add **vacuum energy** in **inner** core (and compare to case w/o vacuum energy)

# Toy model for neutron stars

- At zero temperature, gravitational pressure balanced by pressure of fluid. Metric:

$$ds^2 = e^{\nu(r)} dt^2 - (1 - 2GM(r)/r)^{-1} dr^2 - r^2 d\Omega^2$$

- Einstein eq's (aka Tolman-Oppenheimer-Volkoff eq):

$$M'(r) = 4\pi r^2 \rho(r) ,$$

$$p'(r) = - \frac{p(r) + \rho(r)}{r^2 (1 - 2GM(r)/r)} [GM(r) + 4\pi r^3 p(r)] ,$$

$$\nu'(r) = - \frac{2p'(r)}{p(r) + \rho(r)} ,$$

# Toy model for neutron stars

- Radius determined by position of vanishing pressure  $p(R)=0$

- Assume phase transition happens at  $p_{crit}$

- Two different EOS's

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

- Junction condition:  $\nu'(r), M(r)$  continuous, thus  $p(r)$  also cont.

# Toy model for neutron stars

- For inner core use polytropic with cc:

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

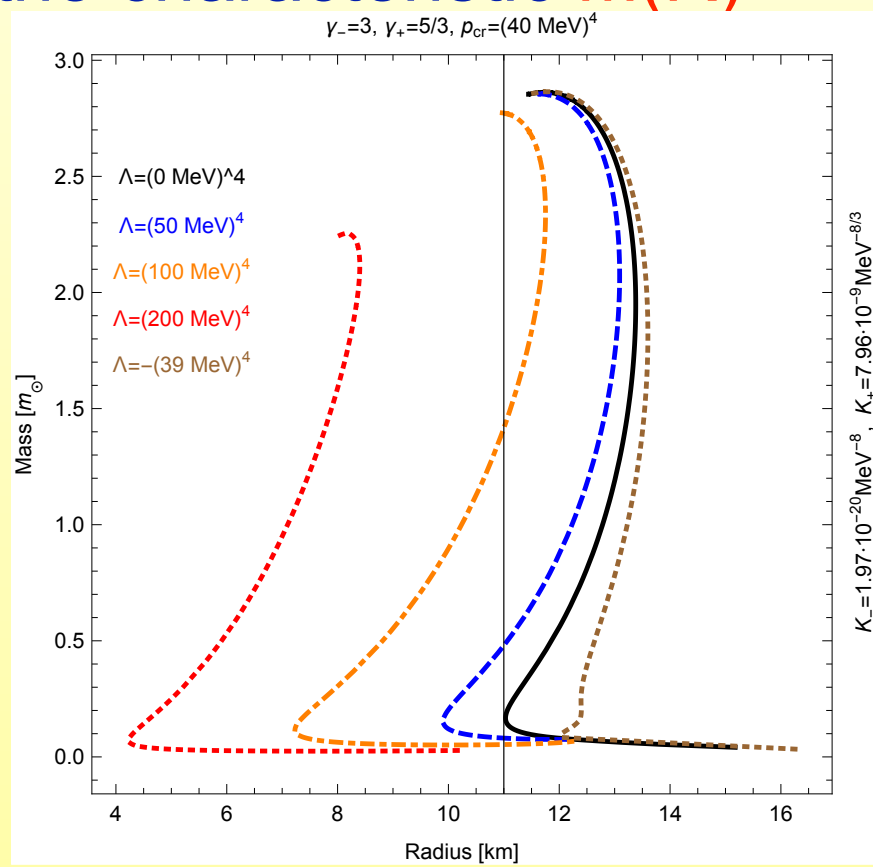
- For outer core just polytropic

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

- The value  $\gamma_+ = 5/3$  reproduces the small pressure limit of a Fermi fluid
- The cc can not be too large negative:  $\Lambda > -p_{cr}$   
Otherwise partial pressure of QCD fluid negative

# Toy model for neutron stars

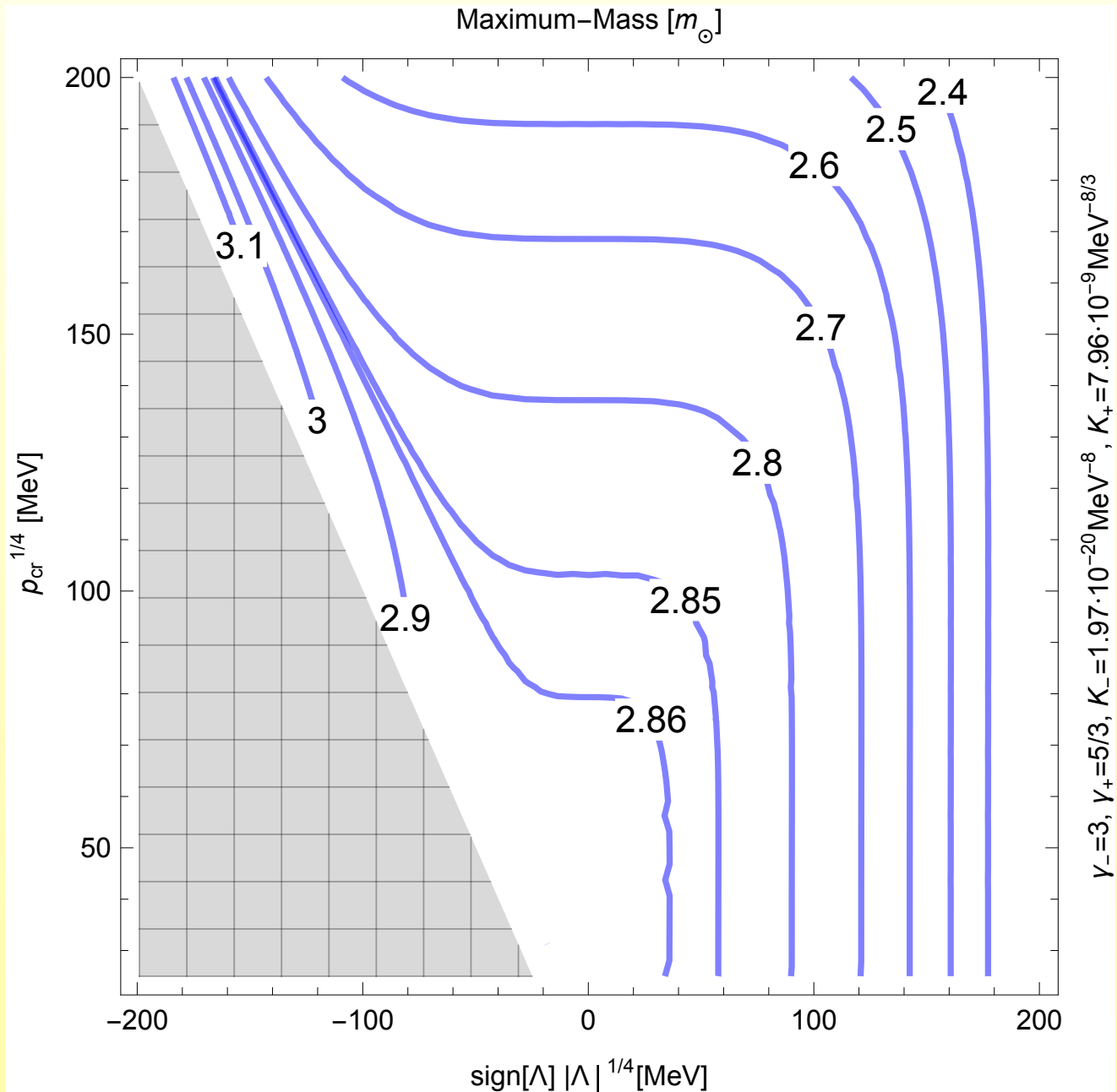
- Likely also a thermodynamic **upper bound** to satisfy  $dG = 0$  for Gibbs free energy in equilibrium between phases. Will **limit upper value** of  $\Lambda$  to few  $\cdot 100$  MeV
- Checked nicely **reproduce** the characteristic  **$M(R)$**  curves for neutron stars



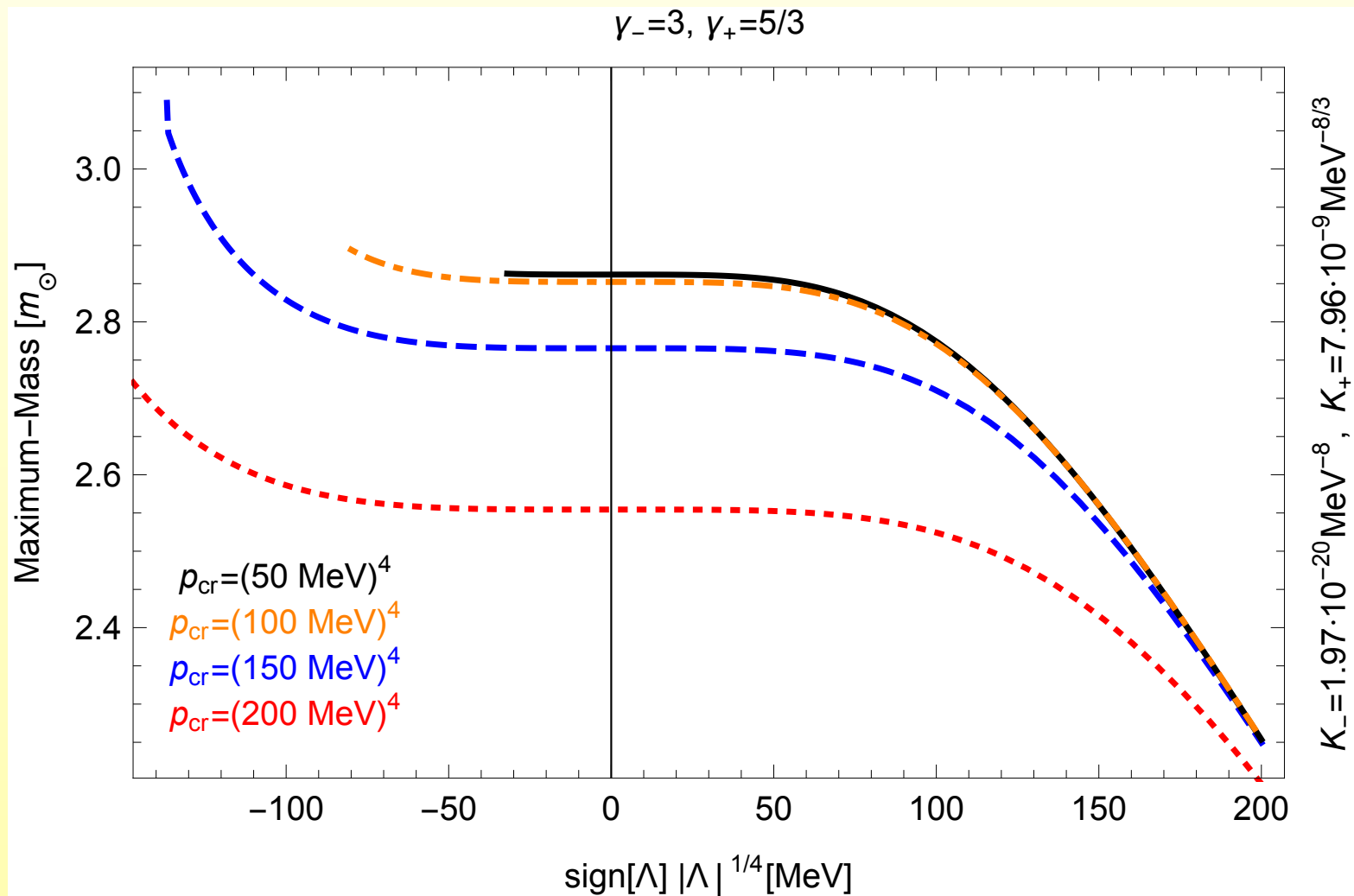
## Toy model for neutron stars

- Check effect of changing  $\Lambda$  on  $M(R)$  curve
- Depending on parameters maximal mass can change by as much as 20%
- But depends very strongly on equations of state parameters, critical pressure...

# Sensitivities of NS's to vacuum energy



# Sensitivities of NS's to vacuum energy



## Summary

- An important part of our standard picture of cosmology & particle physics: **cc should change** during PT's
- Never dominates - how could we check **experimentally?**
- Look for **effect** where radiation is **suppressed**:  
Primordial gravitational waves - predict larger peaks in energy density spectrum
- Look for systems where **vacuum energy** is sizeable fraction  
Neutron stars - should cause measurable deviation in maximal mass of NS's