Inflation meets neutrinos

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Bambi Meets Godzilla (1969) [1:30]

1903.02036, PRD99(2019)
with P. Denton and I. Oldengott

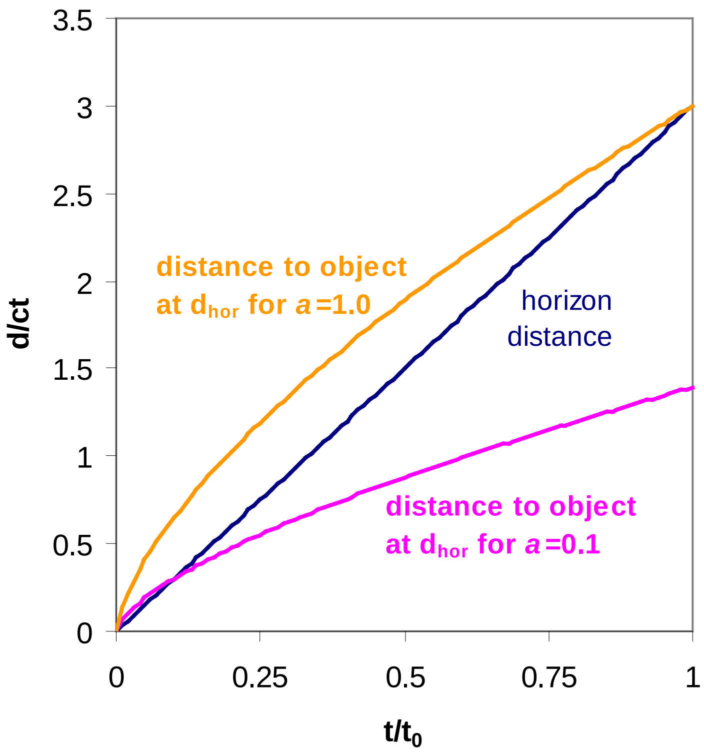
Corfu 19 -- CA15108

Unsolved issues in the standard model

- Horizon problem
  Why is the CMB so smooth ?
- The flatness problem
  Why is the Universe flat ? Why is $\Omega \sim 1$?
- The structure problem
  Where do the fluctuations in the CMB come from ?
- The relic problem
  Why aren't there magnetic monopoles ?

Outstanding Problems

- Why is the CMB so isotropic?
  - consider matter-only universe:
    - horizon distance $d_H(t) = 3ct$
    - scale factor $a(t) = (t/t_0)^{2/3}$
    - therefore horizon expands faster than the universe
      - "new" objects constantly coming into view
  - CMB decouples at $1+z \sim 1000$
    - i.e. $t_{CMB} = t_0/10^{4.5}$
    - $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
    - now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
    - but horizon distance now is $3ct_0$
    - so angle subtended on sky by one CMB horizon distance is only $10^{-1.5}$ rad ~ 2°
  - patches of CMB sky >2° apart should not be causally connected



Outstanding Problems

- Why is universe so flat?
  - a multi-component universe satisfies

$$1-\Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$$

and, neglecting Λ,

$$\left(\frac{H(t)}{H_0}\right)^2 = \frac{\Omega_{\mathrm{r0}}}{a^4} + \frac{\Omega_{\mathrm{m0}}}{a^3}$$

  - therefore
    - during radiation dominated era $|1 - \Omega(t)| \propto a^2$
    - during matter dominated era $|1 - \Omega(t)| \propto a$
    - if $|1 - \Omega_0| < 0.06$ (WMAP) ... then at CMB emission $|1 - \Omega| < 0.00006$
  - we have a fine tuning problem!

Outstanding Problems

- Where is everything coming from ?

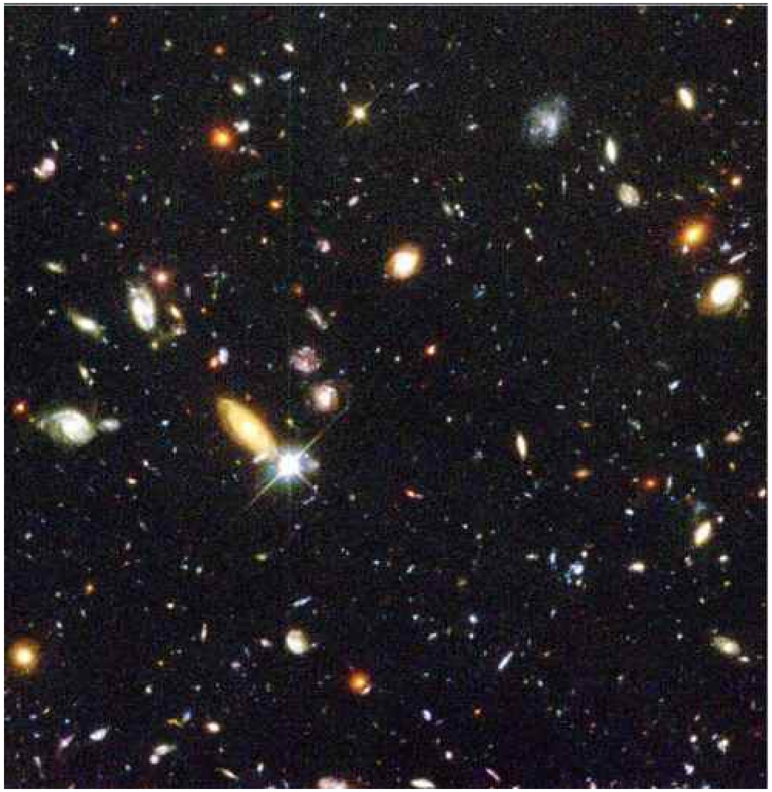
Models like ΛCDM nicely explain how the fluctuations we can observe in the CMB grew to form galaxies.

They can also reproduce the observe large scale distribution of galaxies and clusters.

BUT .. why are there fluctuations in the first place ?

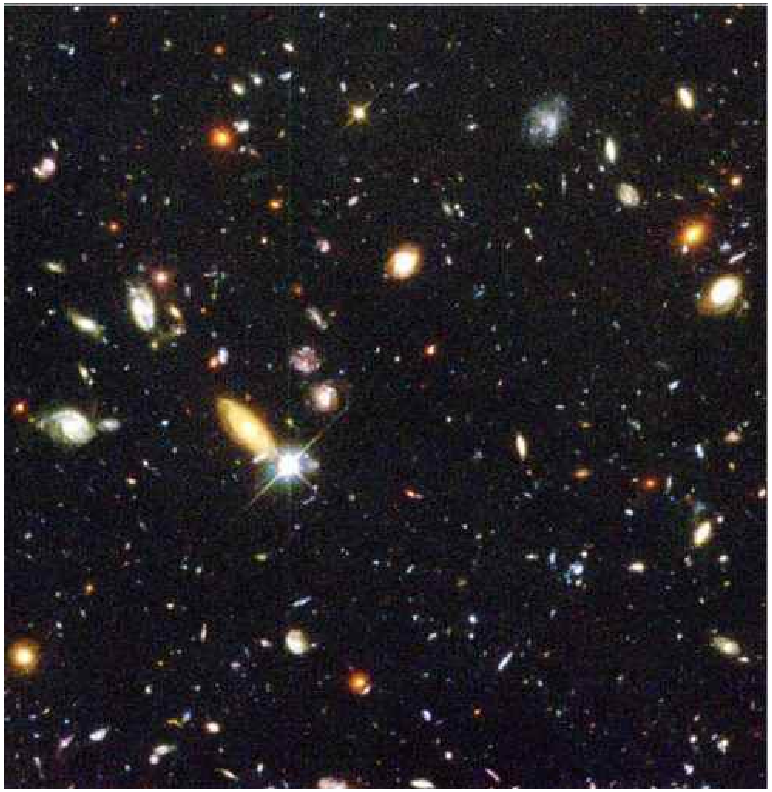
Outstanding Problems

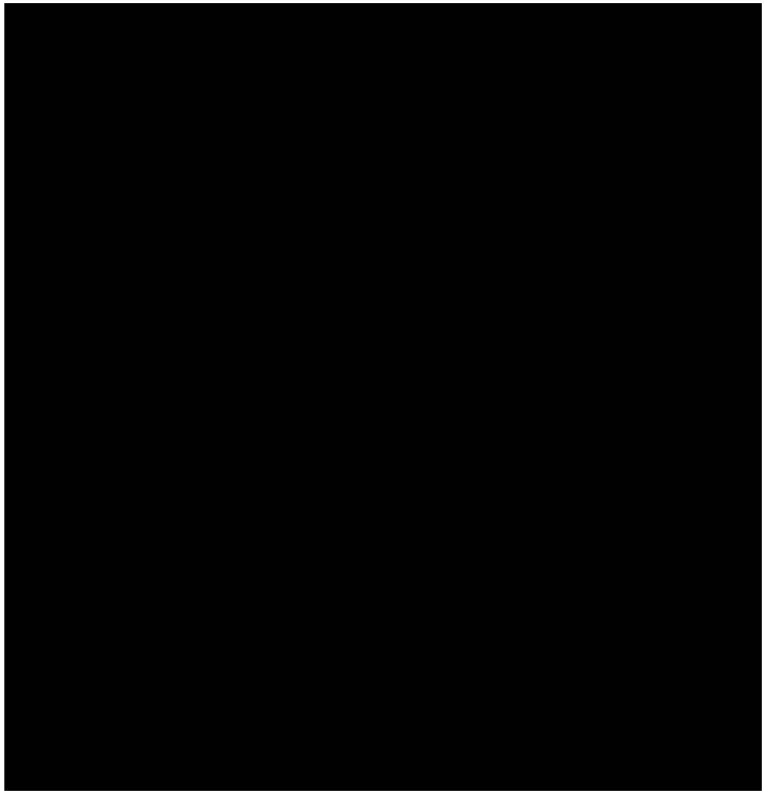
- Where is everything coming from ?



Outstanding Problems

- Where is everything coming from ?





Outstanding Problems

- The monopole problem
  - big issue in early 1980s
    - Grand Unified Theories of particle physics → at high energies the strong, electromagnetic and weak forces are unified
    - the symmetry between strong and electroweak forces 'breaks' at an energy of ~10^{15} GeV ($T \sim 10^{28}$ K, $t \sim 10^{-36}$ s)
      - this is a phase transition similar to freezing
      - expect to form 'topological defects' (like defects in crystals)
      - point defects act as magnetic monopoles and have mass ~10^{15} GeV/c^2 (10^{-12} kg)
      - expect one per horizon volume at $t \sim 10^{-36}$ s, i.e. a number density of 10^{82} m^{-3} at 10^{-36} s
      - result: universe today completely dominated by monopoles (not!)

The concept of inflation

The idea (A. Guth and A. Linde, 1981): Shortly after the Big Bang, the Universe went through a phase of rapid (exponential) expansion. In this phase the energy and thus the dynamics of the Universe was determined by a term similar to the cosmological constant (vacuum energy).

Why would the Universe do that ?

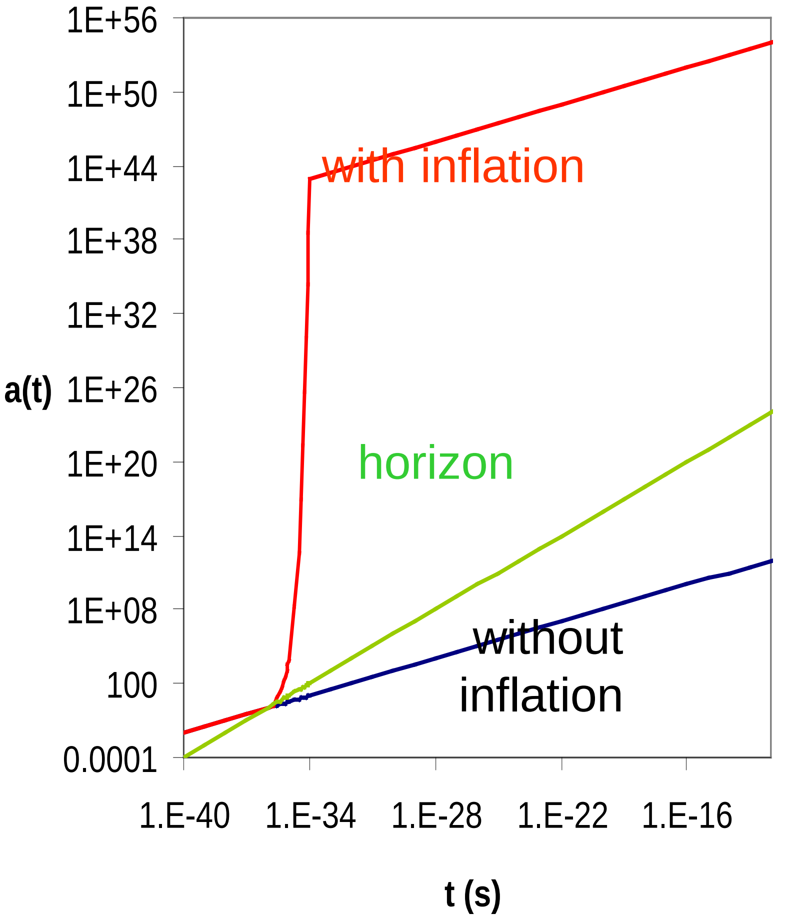
Why does it help ?

Inflation and the horizon

- Assume large positive cosmological constant Λ acting from t_{inf} to t_{end}

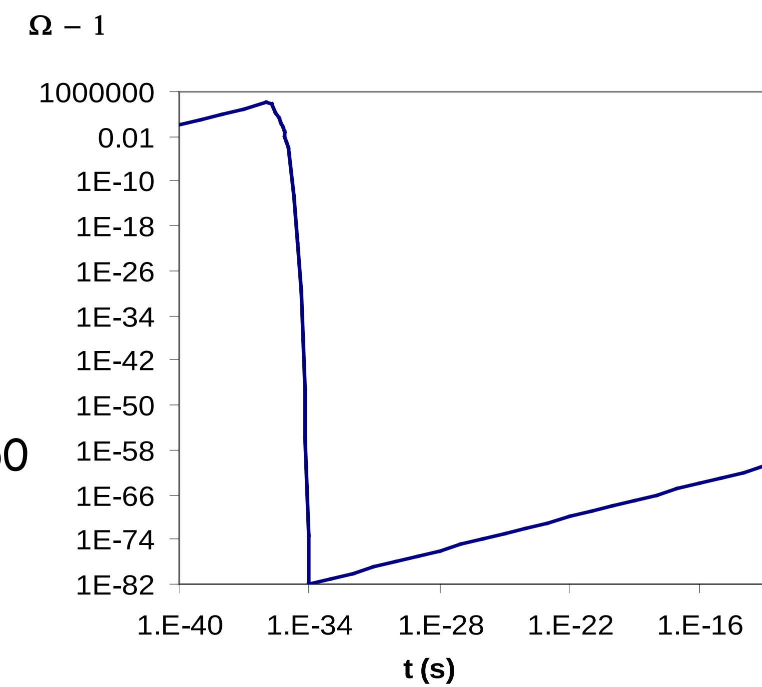
- then for $t_{inf} < t < t_{end}$
  $a(t) = a(t_{inf}) \exp[H_i(t - t_{inf})]$
  - $H_i = (\frac{1}{3}\Lambda)^{1/2}$
  - if Λ large a can increase by many orders of magnitude in a very short time

- Exponential inflation is the usual assumption but a power law $a = a_{inf}(t/t_{inf})^n$ works if $n > 1$



Inflation and flatness

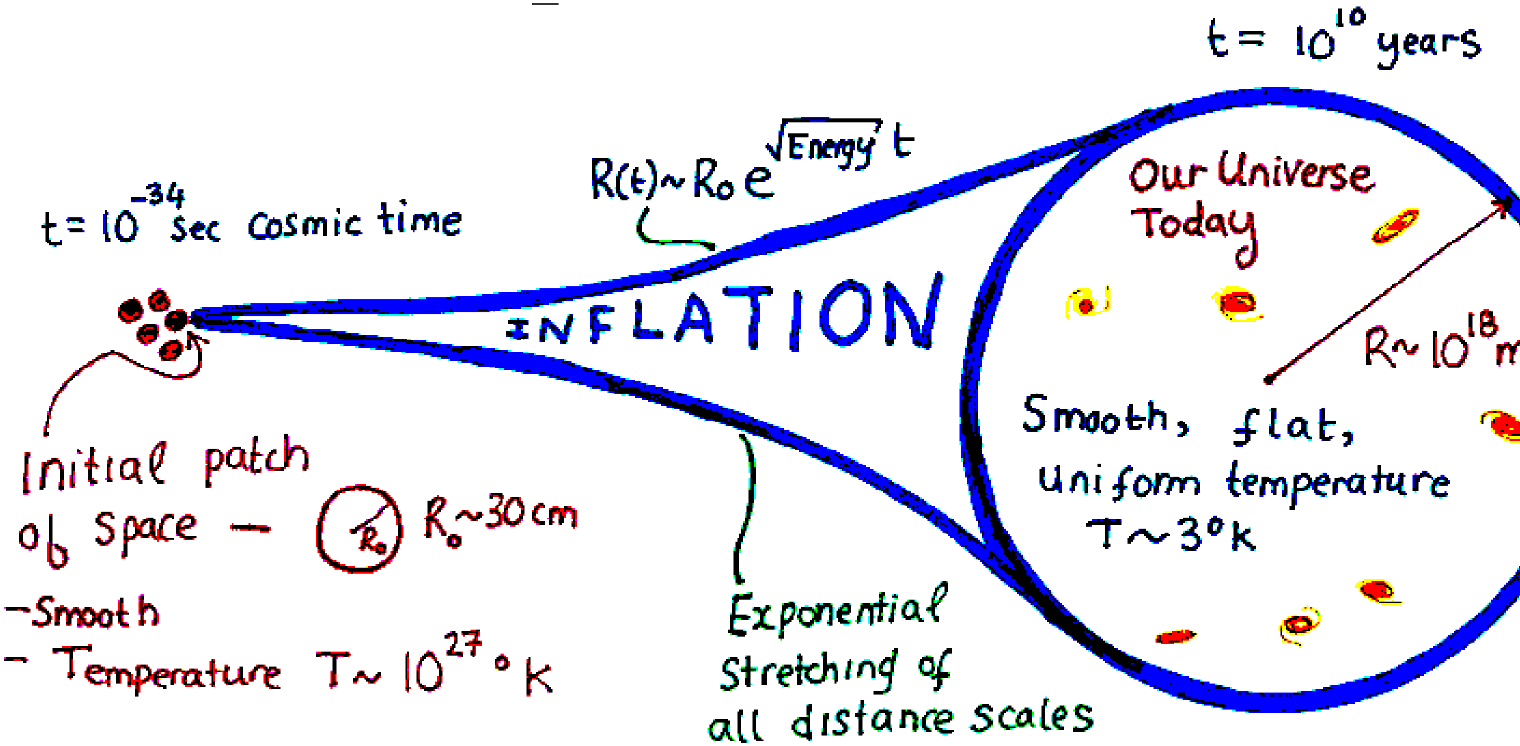
- We had
$$1-\Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$$
  - for cosmological constant *H* is constant, so $1 - \Omega \propto a^{-2}$
  - for matter-dominated universe $1 - \Omega \propto a$
- Assume at start of inflation $|1 - \Omega| \sim 1$
- Now $|1 - \Omega| \sim 0.06$
  - at matter-radiation equality $|1 - \Omega| \sim 2 \times 10^{-5}$, $t \sim 50000$ yr
  - at end of inflation $|1 - \Omega| \sim 10^{-50}$
  - so need to inflate by $10^{25} = e^{58}$



Inflation and the structure problem

- Before inflation: quantum fluctuations
- Inflation amplifies quantum fluctuations to macroscopic scales
- After inflation macroscopic fluctuations (as can be observed in the CMB radiation) provide the seeds from which galaxies form.

Inflation and the relic problem



What powers inflation?

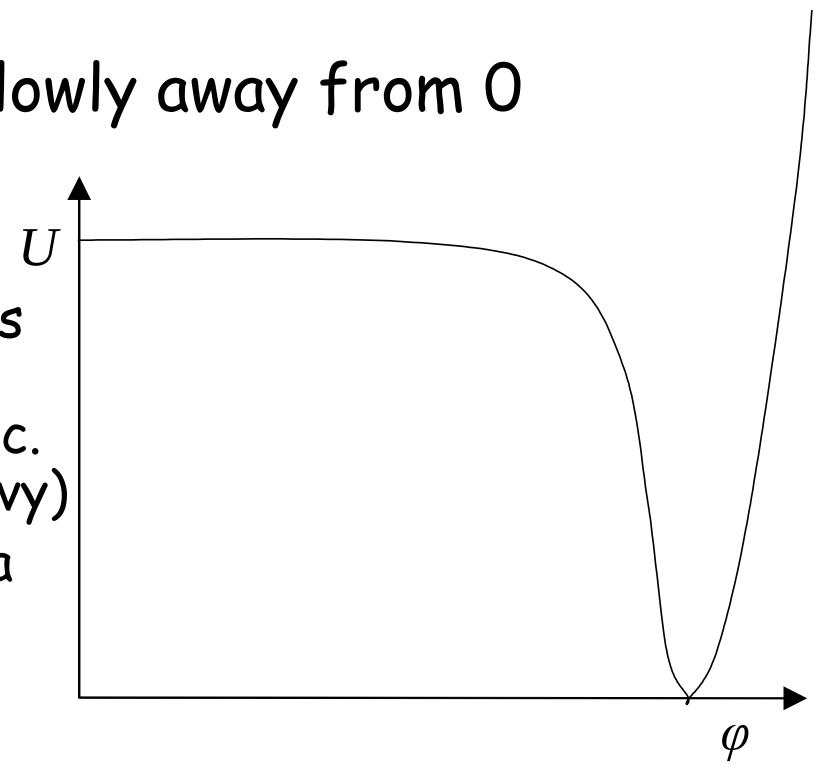
- We need $H_{inf}(t_{end} - t_{inf}) \geq 58$
  - if $t_{end} \sim 10^{-34}$ s and $t_{inf} \sim 10^{-36}$ s, $H_{inf} \sim 6 \times 10^{35}$ s^{-1}
  - energy density $\rho_\Lambda \sim 6 \times 10^{97}$ J m^{-3} $\sim 4 \times 10^{104}$ TeV m^{-3}
    - cf. current value of $\Lambda \sim 10^{-35}$ s^{-2}, $\rho_\Lambda \sim 10^{-9}$ J m^{-3} ~ 0.004 TeV m^{-3}
- We also need an equation of state with negative pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\rho + 3P\right)$$

accelerating expansion needs $P < 0$

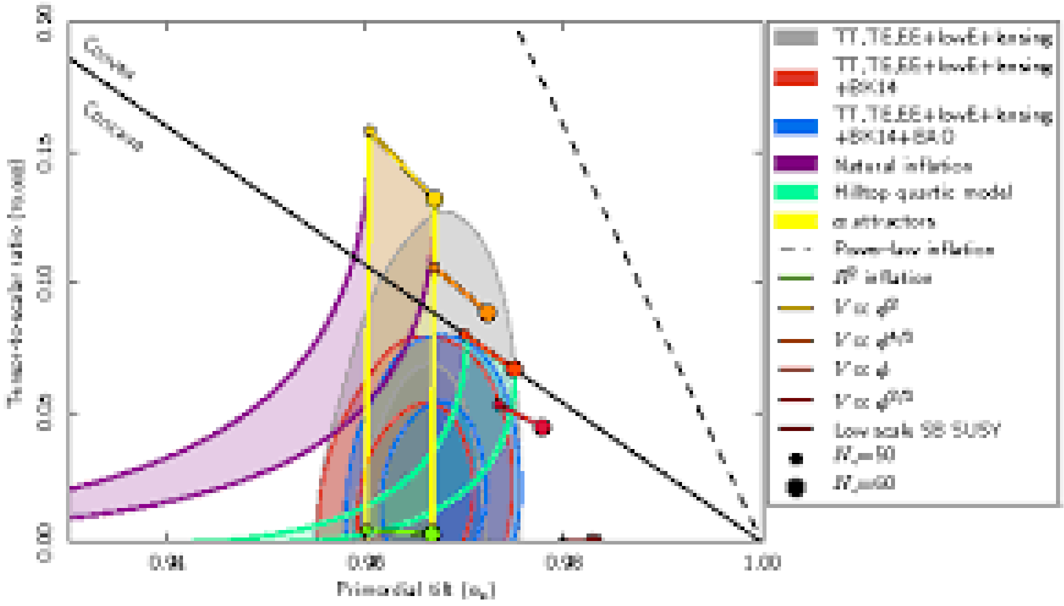
Inflation with scalar field

- Need potential U with broad nearly flat plateau near $\varphi = 0$
  - metastable false vacuum
  - inflation as φ moves very slowly away from 0
  - stops at drop to minimum (true vacuum)
    - decay of inflaton field at this point reheats universe, producing photons, quarks etc. (but not monopoles – too heavy)
    - equivalent to latent heat of a phase transition



Inflation is not a model but a framework

- predict two types of perturbations
- scalar and tensor, which turn into density (matter) and gravitational waves



eV^2 sterile neutrinos suggested by LSND, MiniBooNE, Source anomalies, RAA, new SBL reactors...

),

Incompatible with Neff from CMB and BBN
and neutrino mass from CMB+

New (non standard) neutrino interactions ?

The following are all connected through new ν interactions:

- CMB
- BBN
- Precision decay measurements
- H_0 tension
- Inflation models
- IceCube (astrophysics)

$$L \supset g_{\alpha\beta}\, \overline{\nu_\alpha}\, \nu_\beta\, \varphi$$

Sometimes called secret interactions

Beyond new interactions/propagation effects:

Neutrino decay: $m_\varphi < m_\nu$

A. Acker, S. Pakvasa, J. Pantaleone

PRD 45 (1992)

Neutrino mass generation: $\langle\varphi\rangle \neq 0$

Y. Chikashige, R. Mohapatra, R. Peccei

PLB 98 (1981)

:

$$G_{eff} = \frac{1}{\sqrt{4\pi}} \frac{g^2}{m_\varphi^2}$$

- **Perturbativity**: $g < 1$

- **SN1987A**: neutrinos aren't absorbed by CνB:

$G_{eff} < 10^8$ GeV^{-2} E. Kolb, M. Turner PRD 36, 2895 (1987)

- *Z*-**decay**: $G_{eff} \sim 10^{-5}$ GeV^{-2} for $m_\varphi < 80$ GeV

M.Bilenky, A. Santamaria hep-ph/9908272

- **Mediator brem**: Kaon/tau decays:

$g < \{0.003, 0.01, 0.3\}$ for $m_\varphi < \{0.5, 0.5, 2\}$ GeV

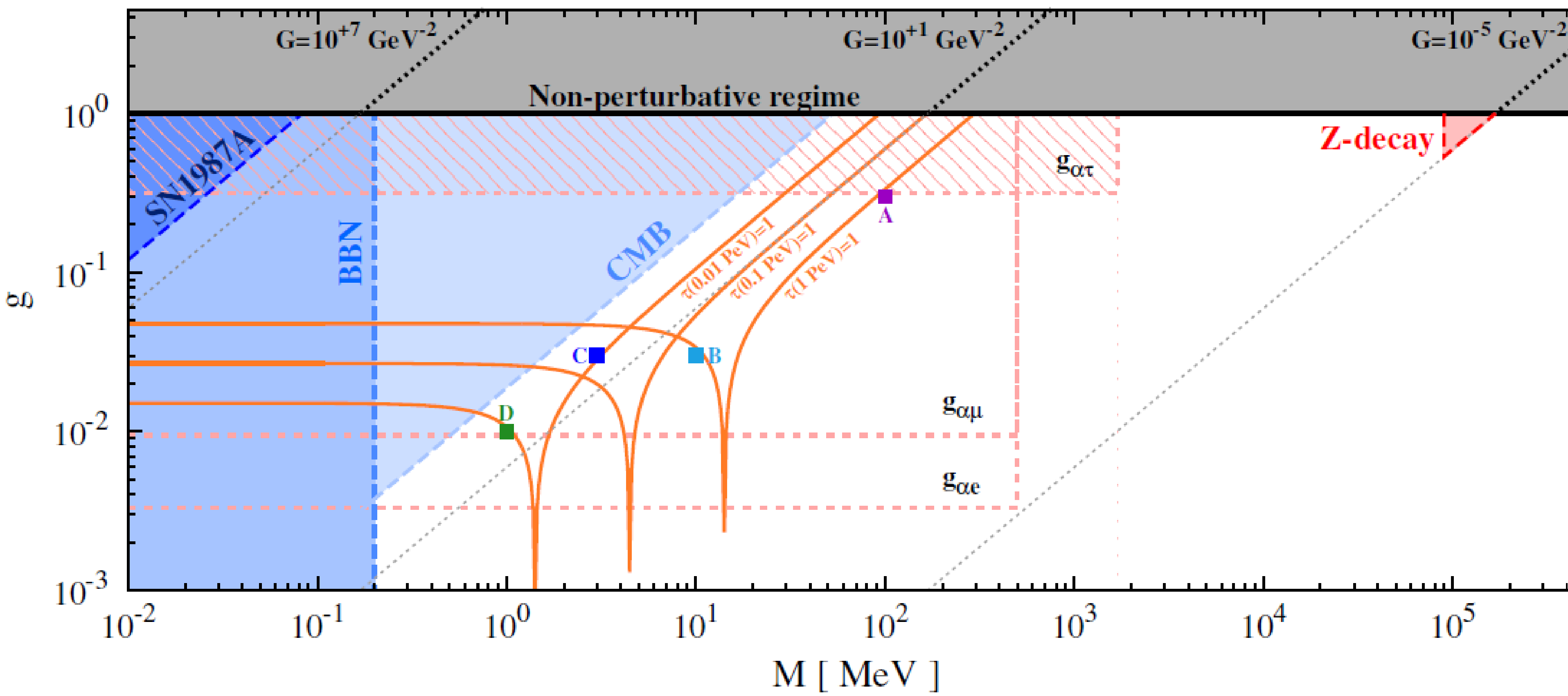
A. Lessa, O. Peres hep-ph/0701068

- **BBN/CMB**: Thermal mediator $\rightarrow \Delta N_{eff}$: $m_\varphi > 0.2$ MeV Ahlgren, T. Ohlsson, S. Zhou 1309.0991

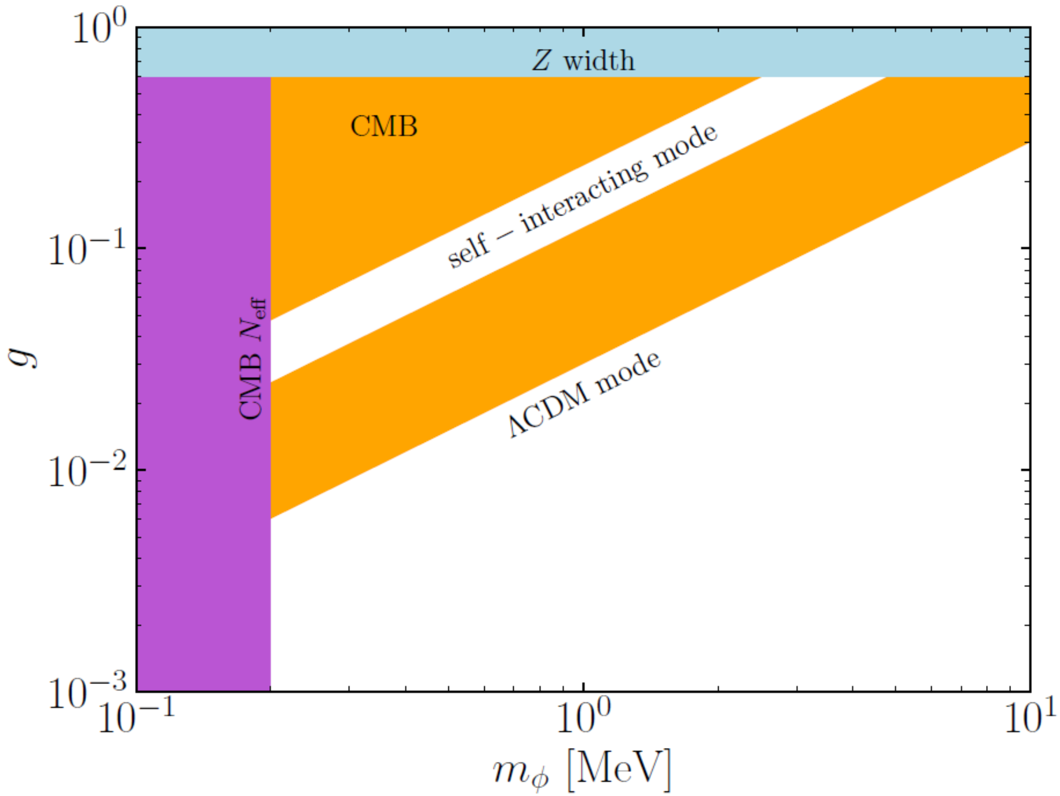
- **CMB**: Neutrinos should be free-streaming until $z \sim 2 \times 10^5$: $G_{eff} < 100$ GeV^{-2}

F. Cyr-Racine, K. Sigurdson 1306.1536

1903.023


G=10^{+7} GeV^{-2}
G=10^{+1} GeV^{-2}
G=10^{-5} GeV^{-2}
Non-perturbative regime
SN1987A
BBN
CMB
Z-decay
gατ
gαμ
gαe
τ(0.01 PeV)=1
τ(0.1 PeV)=1
τ(1 PeV)=1
A
B
C
D
g
M [MeV]

Standard picture with neutrinos compared to no neutrinos:



•Fr ... n plasma,

•Pu ... amplitude

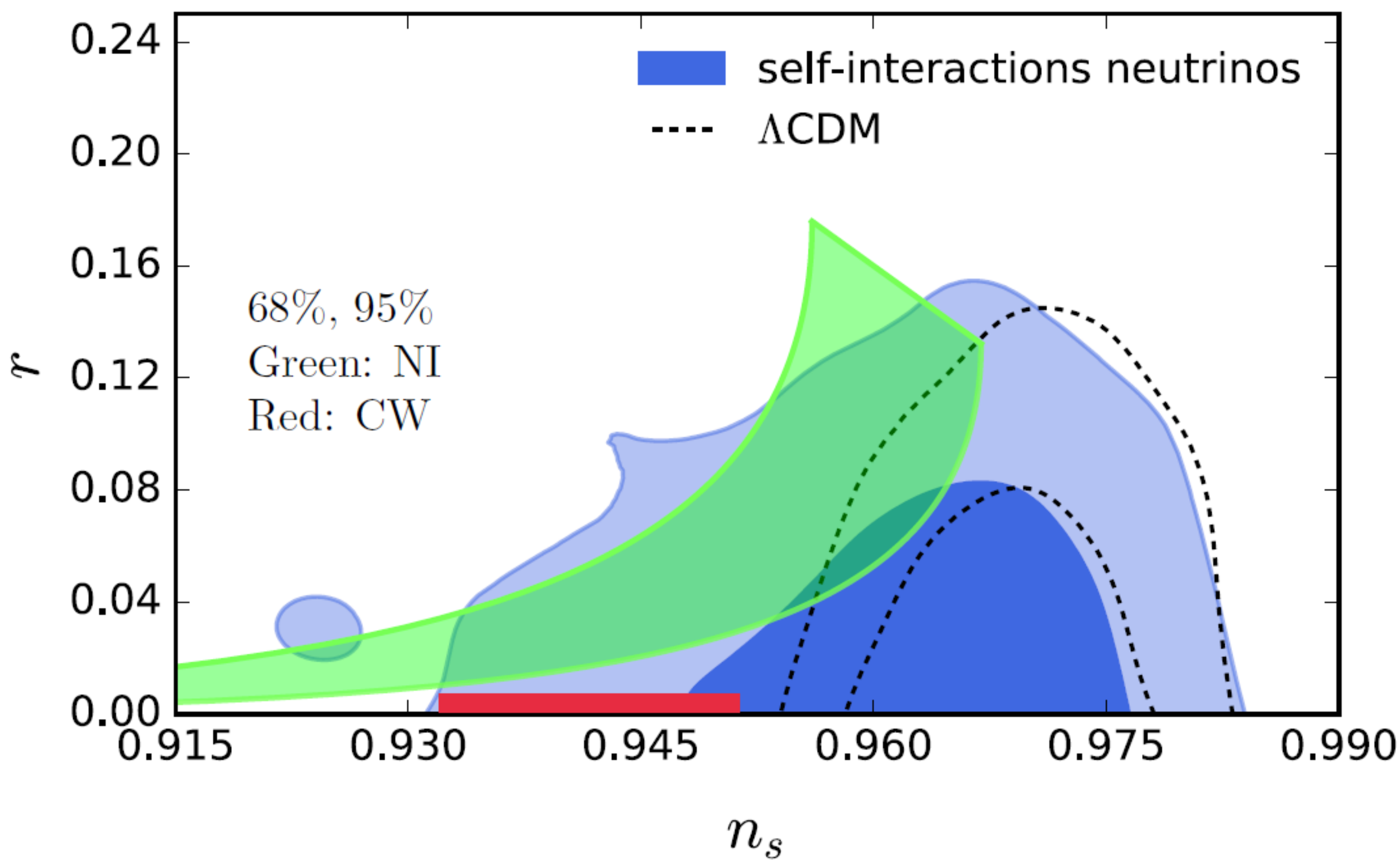
•Ir

A r ... n the data.

Th ... ,dec ~ 8300

...ngott, et al. 1706.02123

C. Kreisch, F. Cyr-Racine, O. Dor´e 1902.00534



self-interactions neutrinos
ΛCDM
68%, 95%
Green: NI
Red: CW
r
0.24
0.20
0.16
0.12
0.08
0.04
0.00
0.915
0.930
0.945
0.960
0.975
0.990
n_s

CνB Scattering

In the same fashion as the Z-burst at $E_\nu \sim 10^{14}$ GeV. . .

T. Weiler PRL 49 234 (1982)

HE ν's scatter off CνB leading to a dip due to NSI

A. Difranzo, D. Hooper 1507.03015

I. Shoemaker, K. Murase 1512.07228

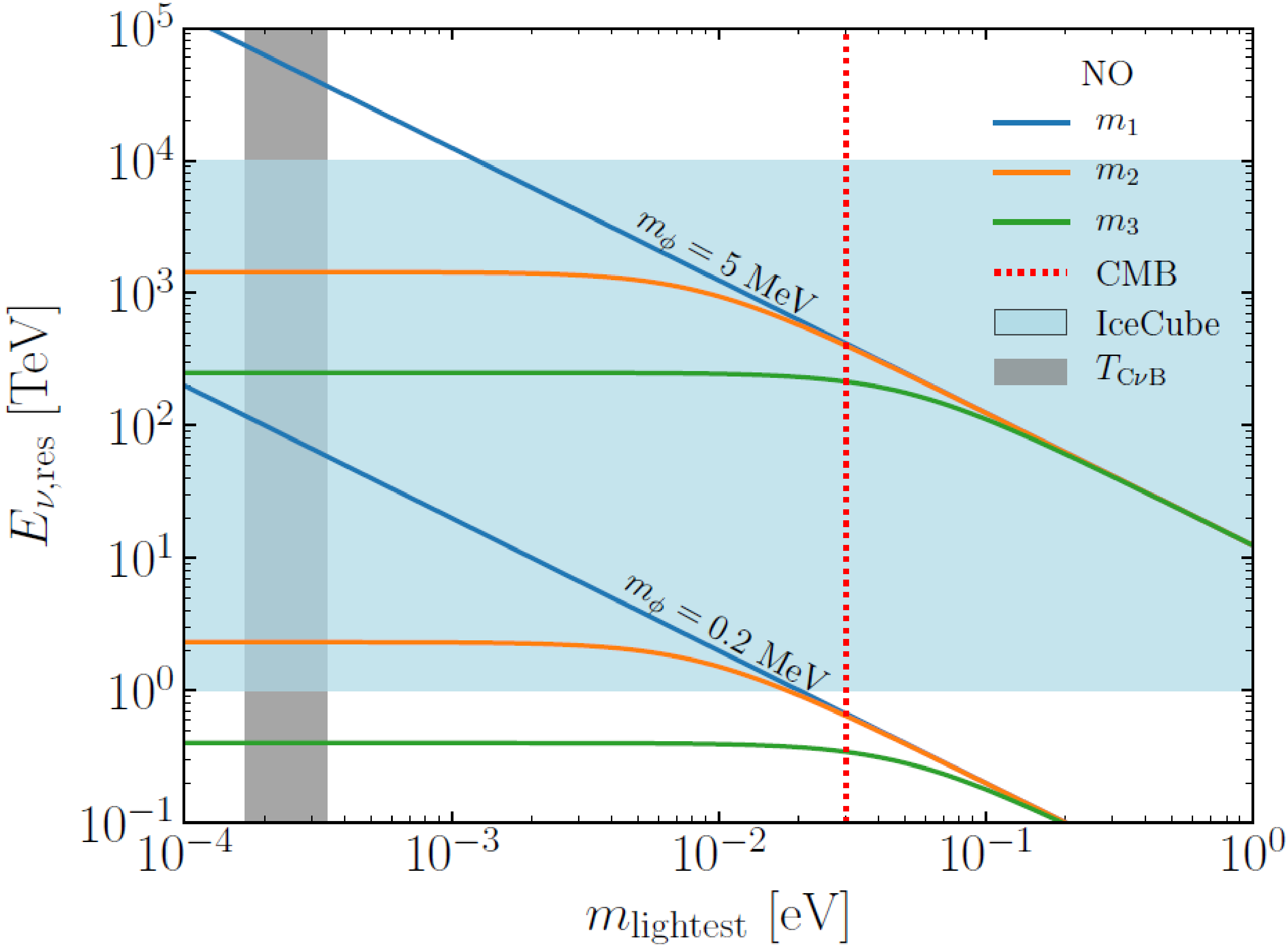
Assuming $p_\nu < m_\nu$

$$E_{\nu_i}^{\rm res} = \frac{m_\varphi^2 - m_{\nu_i}^2}{2m_{\nu_i}} \approx \frac{m_\varphi^2}{2m_{\nu_i}}$$

Hint of a dip at $E_\nu \sim 500$ TeV?

Dip identification requires: assuming a known astrophysical spectrum!

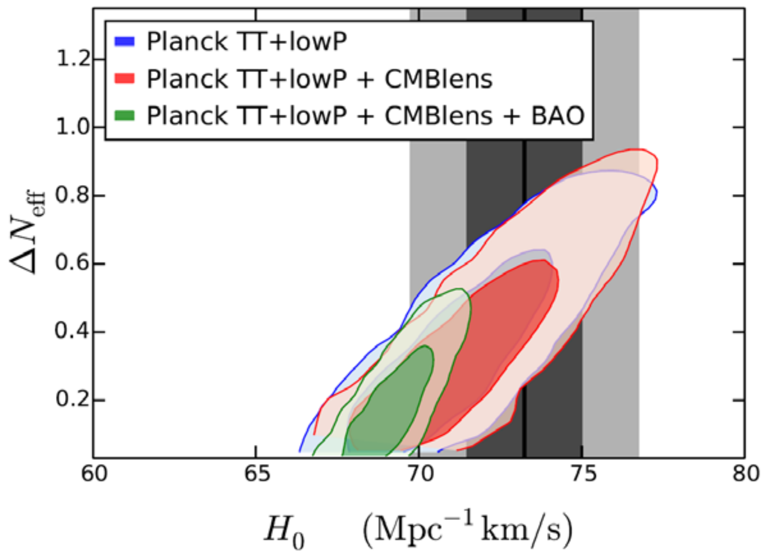
IceCube resonant absorption

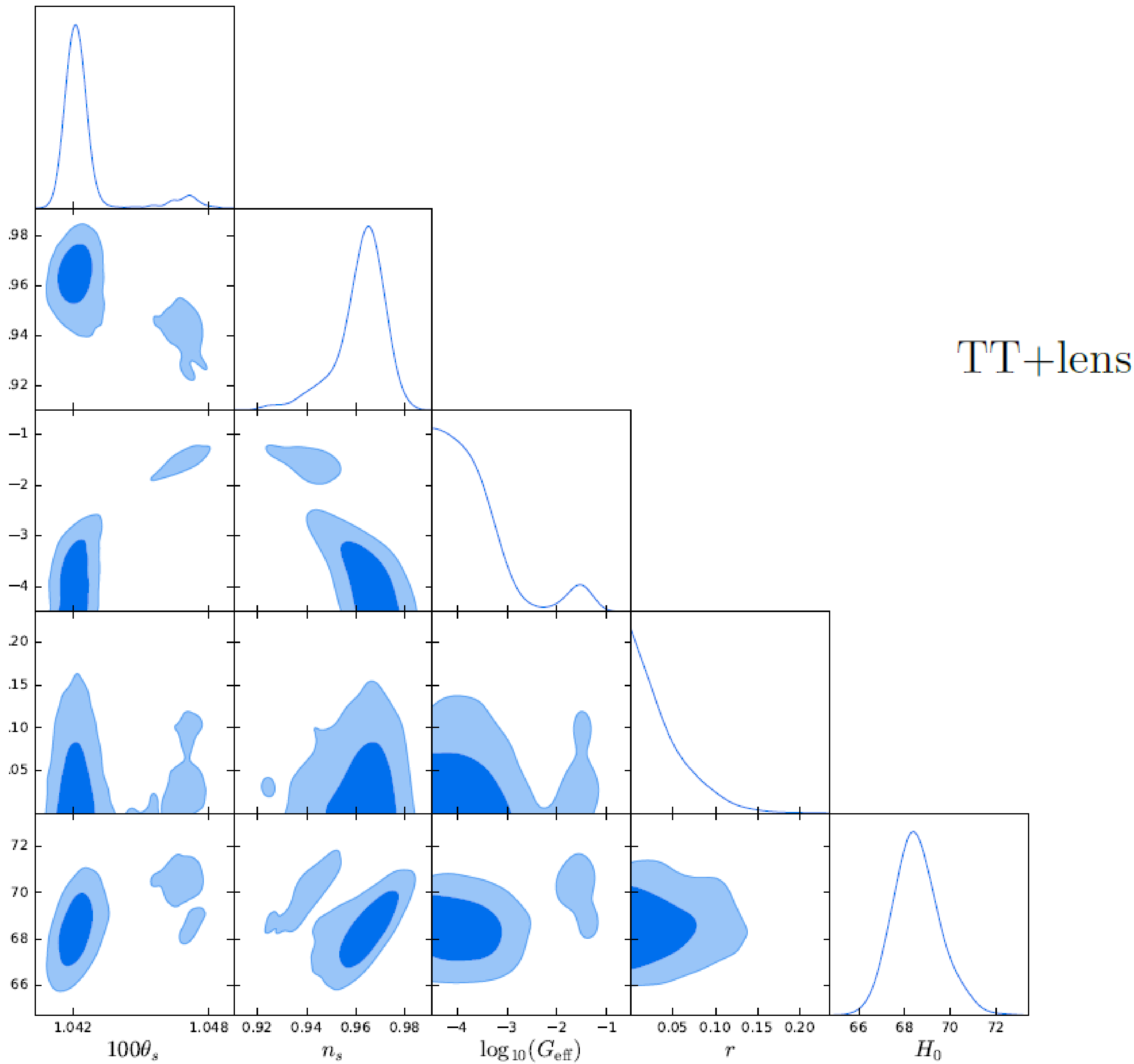


Riess et al (2016) vs CMB fit

H_0 = 73.24 ± 1.74 km/s/Mpc

H_0 = 67.8 ± 0.9 km/s/Mpc




TT+lens
1.042
1.048
.98
.96
.94
.92
0.92
0.94
0.96
0.98
−1
−2
−3
−4
.20
.15
.10
.05
0.05
0.10
0.15
0.20
72
70
68
66
$100\theta_s$
n_s
$\log_{10}(G_{\rm eff})$
r
H_0

Conclusions

Constraints on inflation/ΛCDM need to account for new ν interactions

Natural and Coleman-Weinberg inflation are allowed

Testable by IceCube (ish)

H_0 and sterile **tensions** with CMB may be **alleviated**

Lots of constraints but some parameter space left