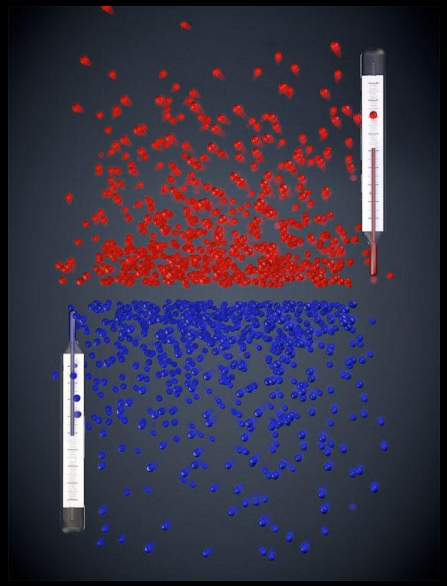
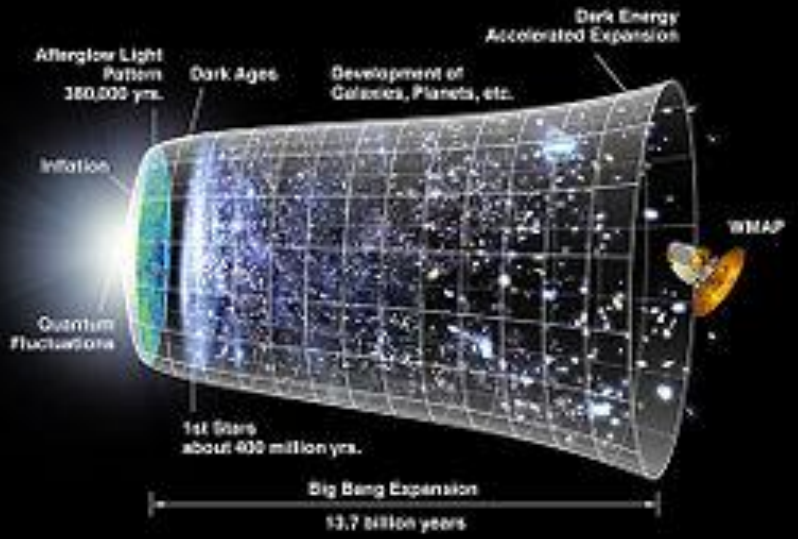
Cosmology With Negative Absolute Temperatures

José P. P. Vieira

COSMO 15

11th September 2015





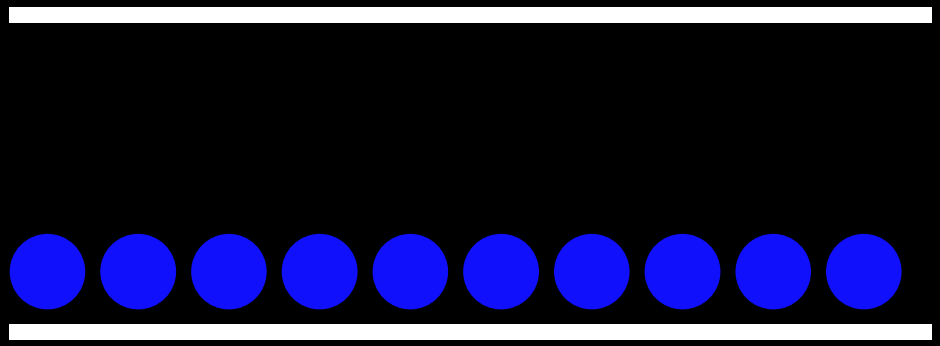
University of Sussex

Science & Technology Facilities Council

What do you mean T<0?

$$\frac{1}{T} = \left(\frac{\partial S}{\partial U} \right)_V$$

$$S = k_B \ln \Omega$$



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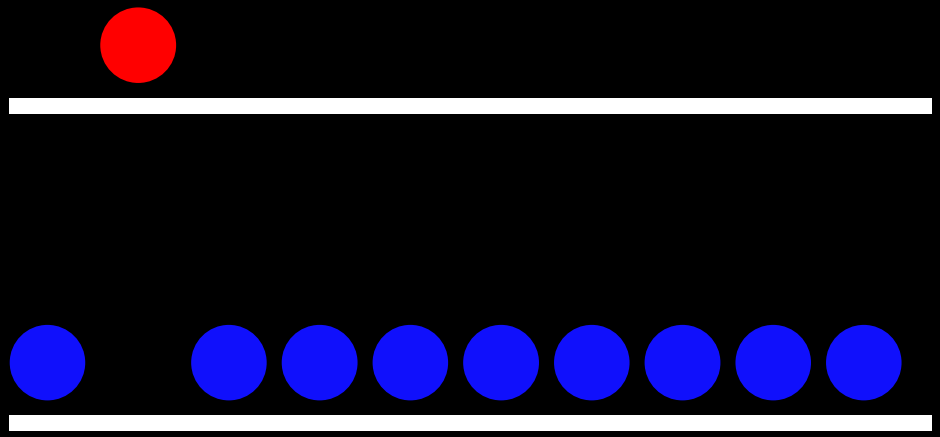

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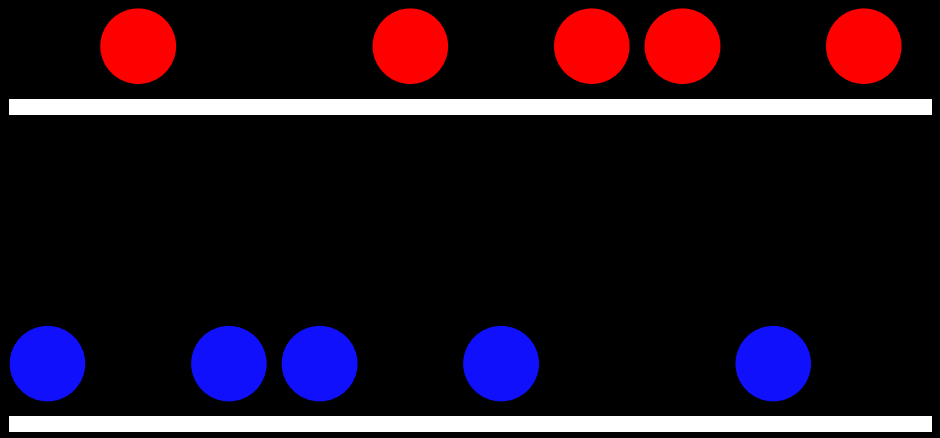

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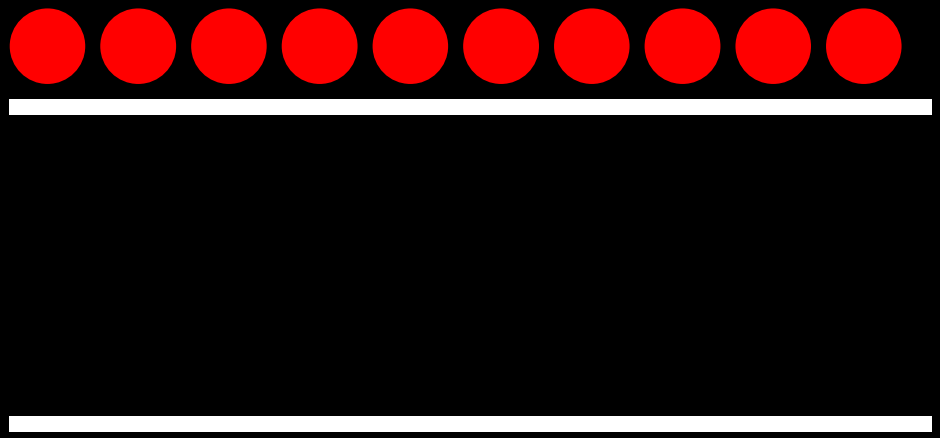

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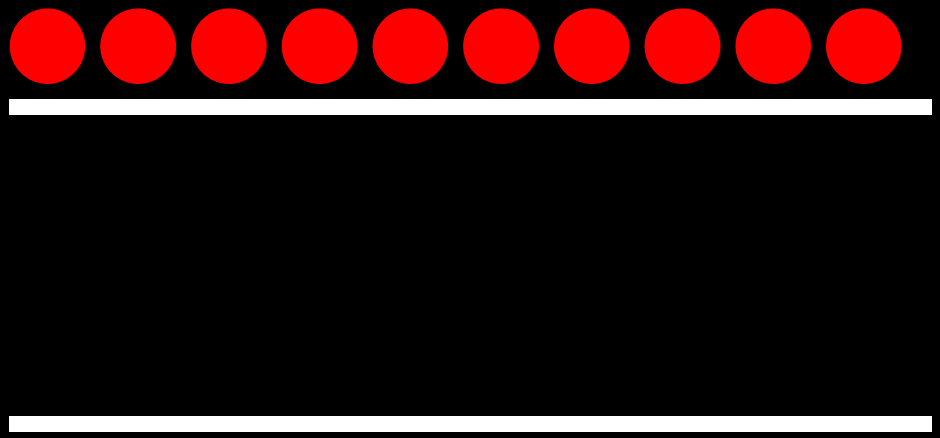

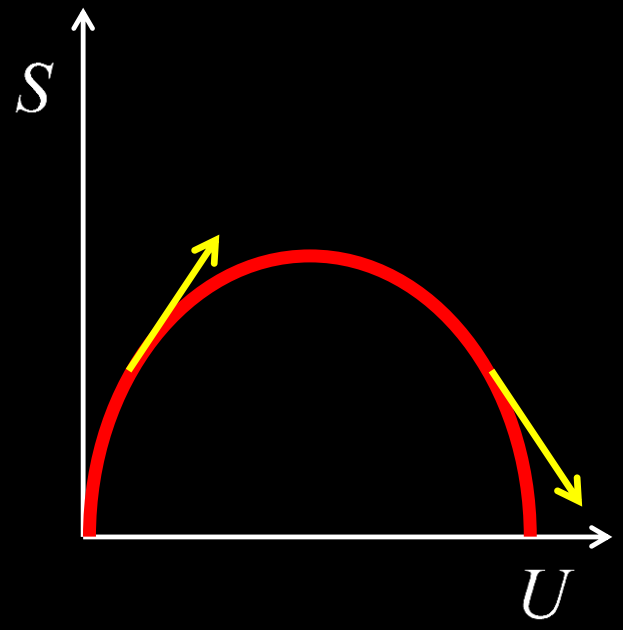

Some landmarks in NAT

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- 1951 – LiF at -1K

  Purcell & Pound, *Phys. Rev., 81:279-280*

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- 2012 – T<0 with motional degrees of freedom

  Braun et al, *Science 339(6115)*

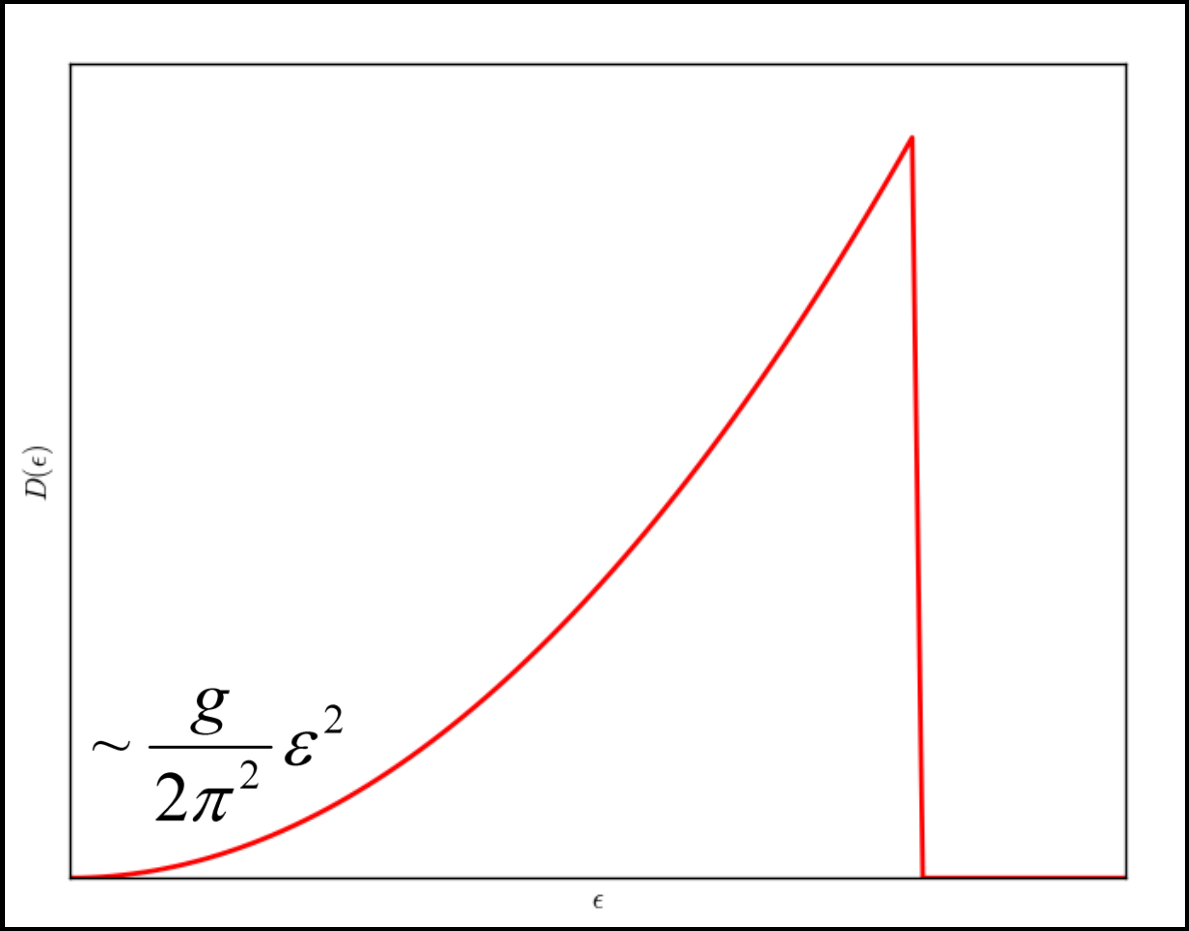
Why do we care?

$$dU = TdS - PdV$$

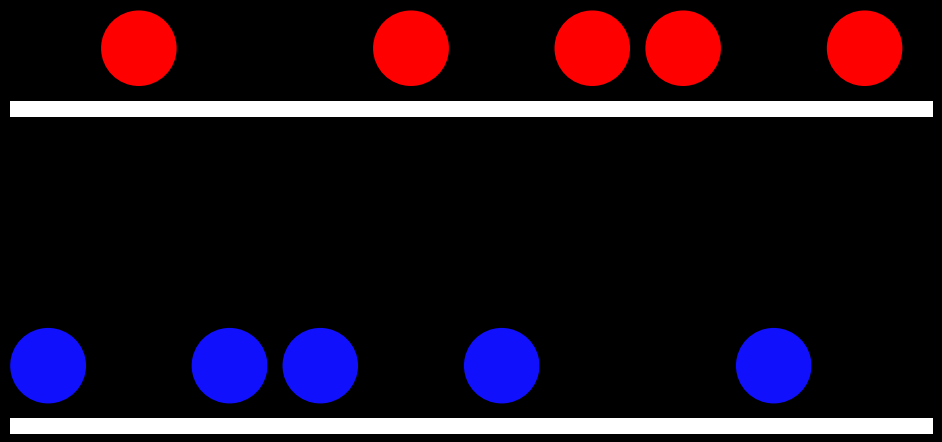
$$\left(\frac{\partial S}{\partial V}\right)_U = \frac{P}{T} \geq 0$$

$$T < 0 \Rightarrow P < 0$$ → Inflation?

Cosmology with an energy cut-off?



Making use of holes



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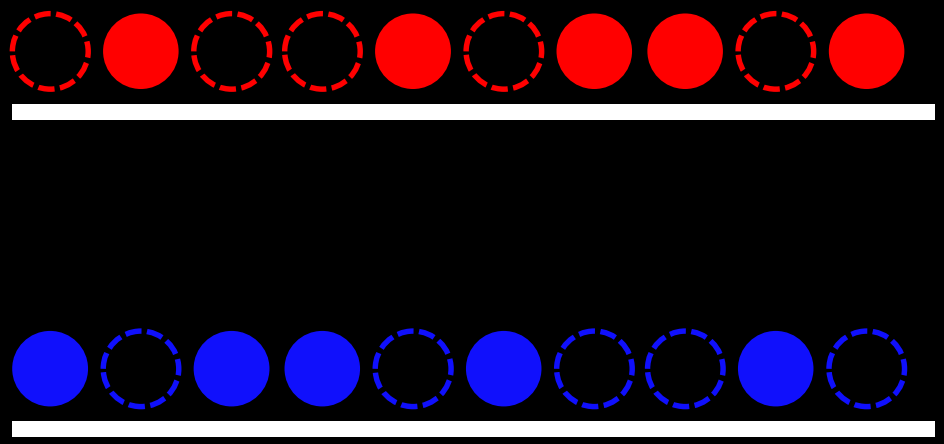

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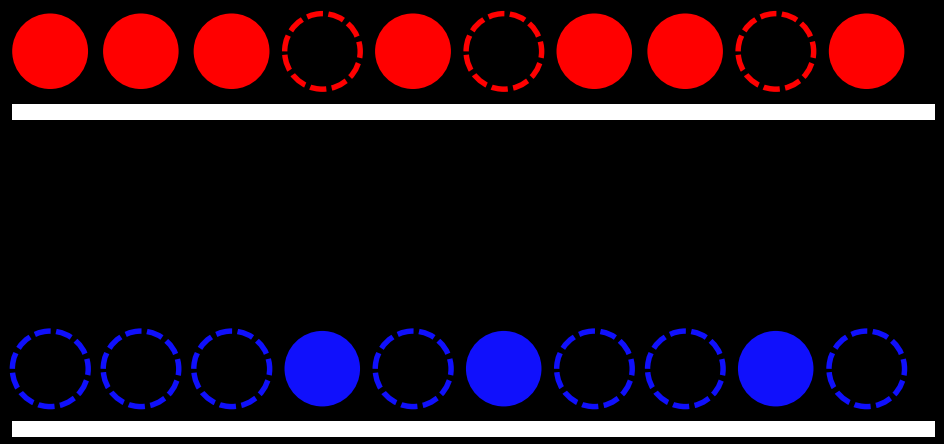

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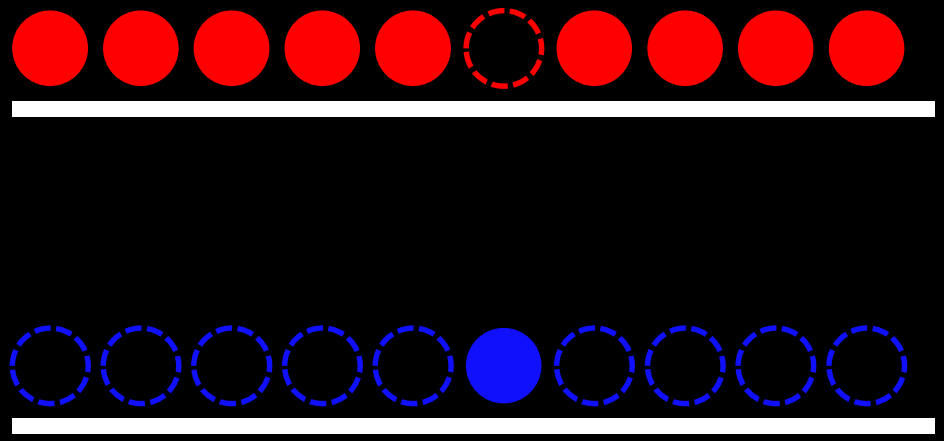
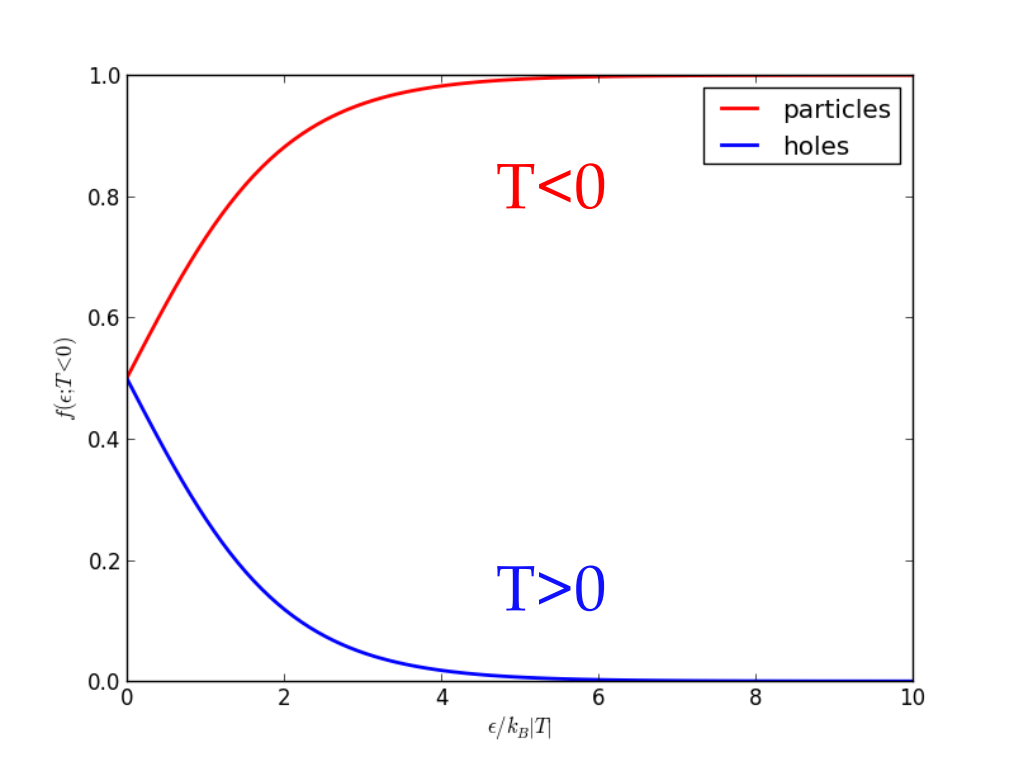


Making use of holes

$$f(\varepsilon;T) = 1 - f(\varepsilon;-T)$$
$$\rho(T) = \rho_{\max} - \rho(-T)$$
$$P(T) = -\rho_{\max} - P(-T)$$



Hole dynamics

Low-temperature holes may behave like

radiation

$$w = -\frac{1}{3}\left(4\frac{\rho_{\max}}{\rho} - 1\right)$$

matter

$$w = -\frac{\rho_{\max}}{\rho}$$

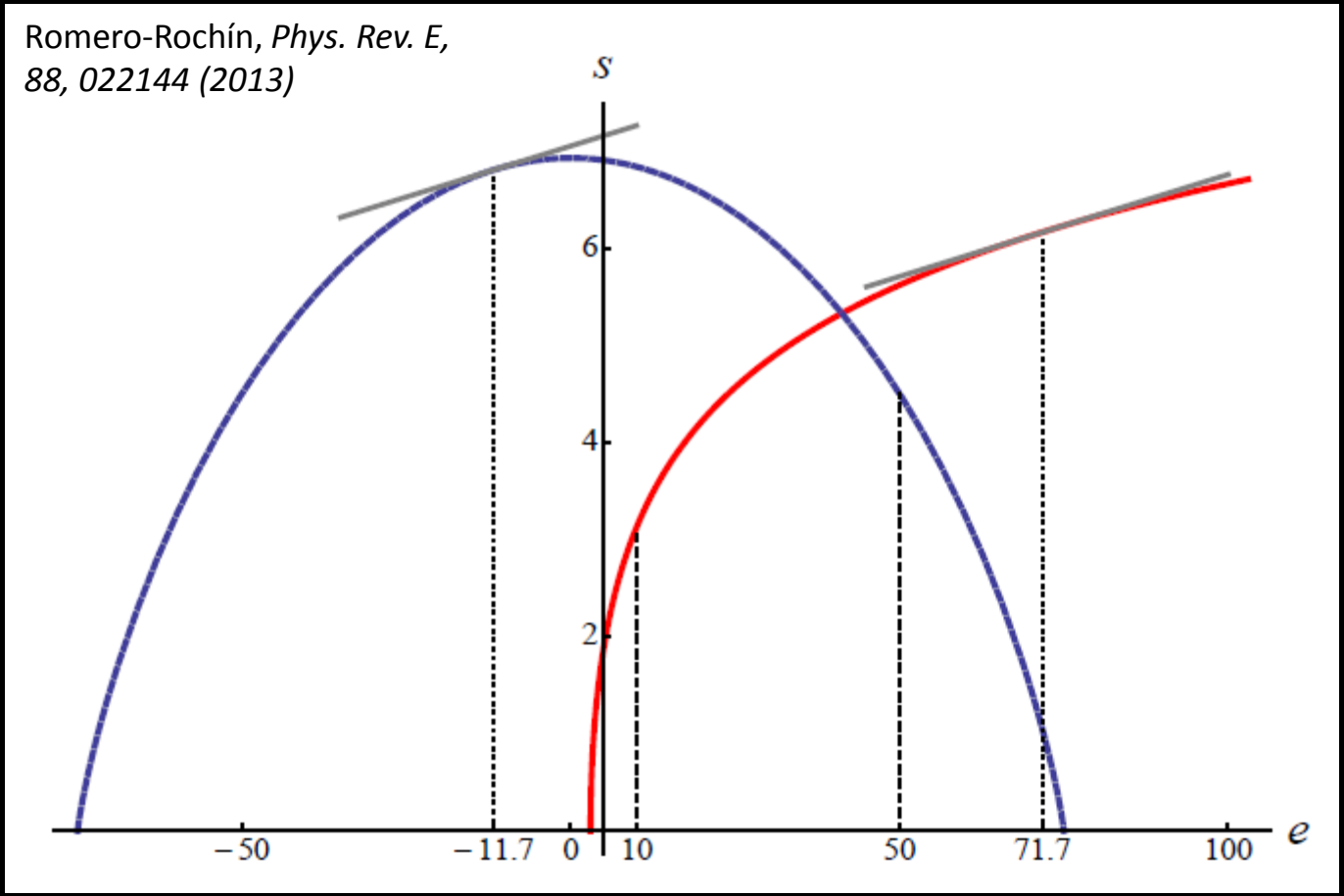
$$\frac{d\ln\rho}{dt} = -3H(1+w) \geq 0$$

Full of holes?

$$\#\, e-foldings = -\frac{1}{3}\int_{\rho_i}^{\rho_f} \frac{d\rho/\rho}{1+w} = \begin{cases} \frac{1}{4}\ln\left[\frac{1-\rho_i/\rho_{\max}}{1-\rho_f/\rho_{\max}}\right] \\ \frac{1}{3}\ln\left[\frac{1-\rho_i/\rho_{\max}}{1-\rho_f/\rho_{\max}}\right] \end{cases}$$

Full of holes?

Romero-Rochín, *Phys. Rev. E, 88, 022144 (2013)*



In conclusion

- If a component of the Universe is allowed to be at $T<0$:

accelerated expansion with $w\approx-1$ naturally arises

(inflation? dark energy? Big Crunch averted?)

BUT...

In Conclusion

- Where could the cut-off come from?
  Quantum gravity (discrete spacetime)?

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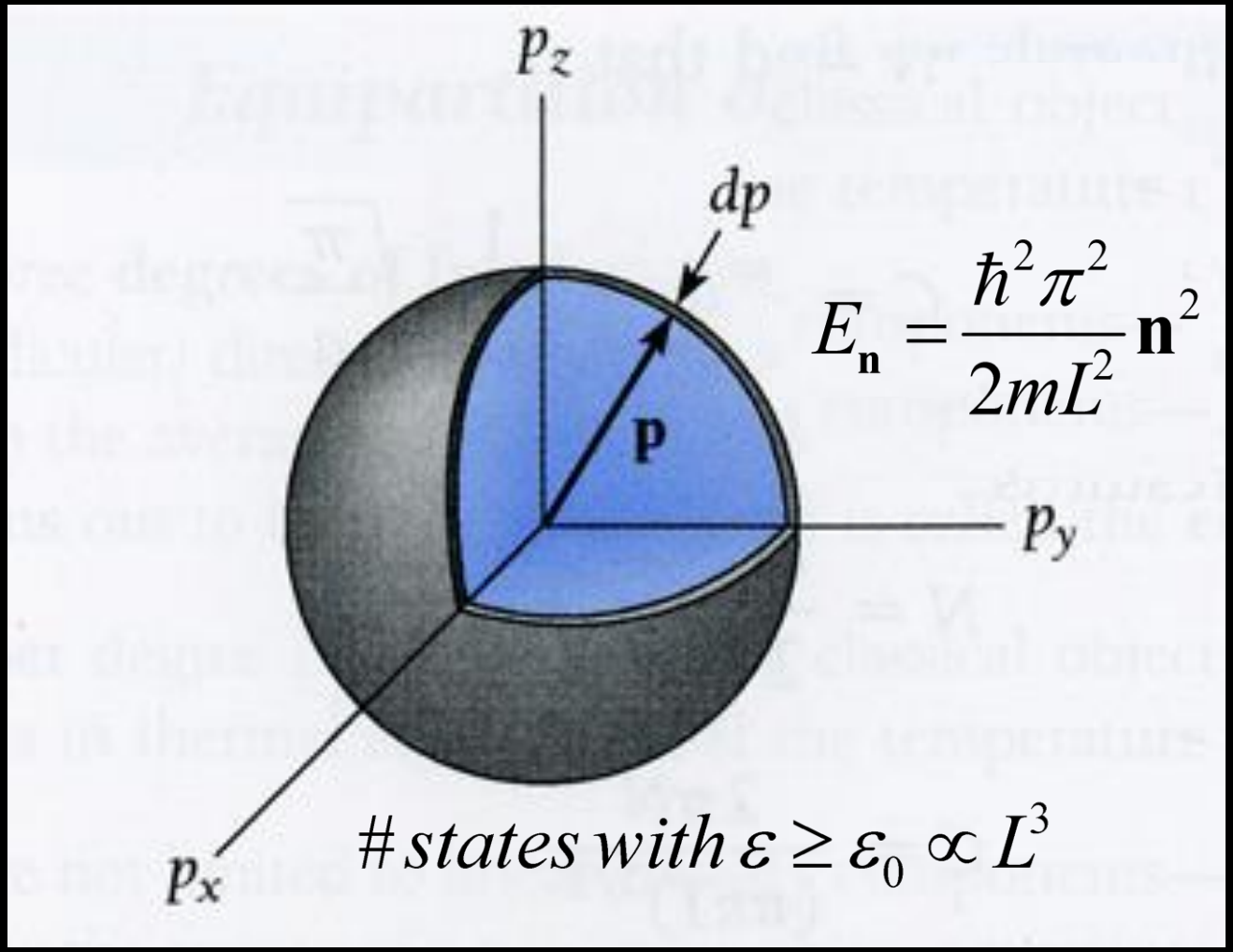
  Quantum gravity (discrete spacetime)?

- What is the microscopic origin of $P<0$?
  Modified Heisenberg uncertainty?
  Could thermalisation at high temperatures be forbidden?

- How would inflation end?
  ”Temperon” decay?
  Thermalisation with bosons?

The End

Cosmology with an energy cut-off?



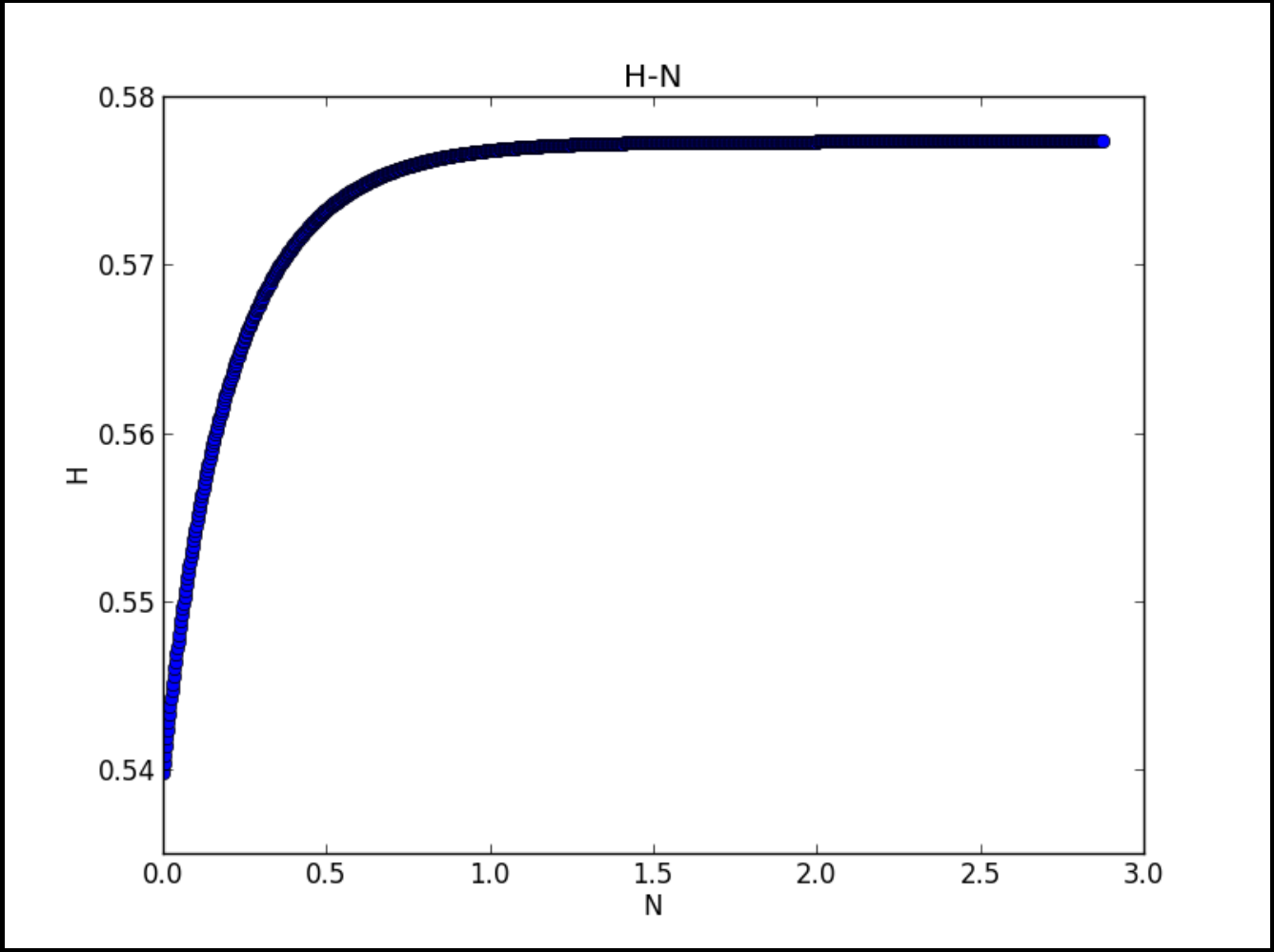
Thermodynamic Formulas

$$f(\varepsilon;T,\mu)=1-f(\varepsilon;-T,\mu)$$
$$\rho(T,\mu)=\rho_{\max}-\rho(-T,\mu)$$
$$n(T,\mu)=n_{\max}-n(-T,\mu)$$
$$P(T,\mu)=2\mu n_{\max}-\rho_{\max}-P(-T,\mu)$$

$$P(T,\mu)=\mu n(T,\mu)-\left(\frac{\partial F}{\partial V}\right)_{T,n}$$

$$\frac{F}{V}=-k_B T\int f(\varepsilon;T,\mu)\ln\left(1+e^{-\frac{(\varepsilon-\mu)}{k_B T}}\right)d\varepsilon$$

Thermodynamic Formulas



Gibbs-Hertz Entropy

Loris Ferrari (2015)
arXiv:1501.04566v3

$$S_B(E) = \ln\left[\sum_u \delta_{H(u),E}\right]$$

$$S_G(E) = \ln\left[\sum_u \Theta(E - H\{u\})\right]$$