GRAVITATIONAL ATOMS

SDU UNIVERSITY OF SOUTHERN DENMARK

CP3

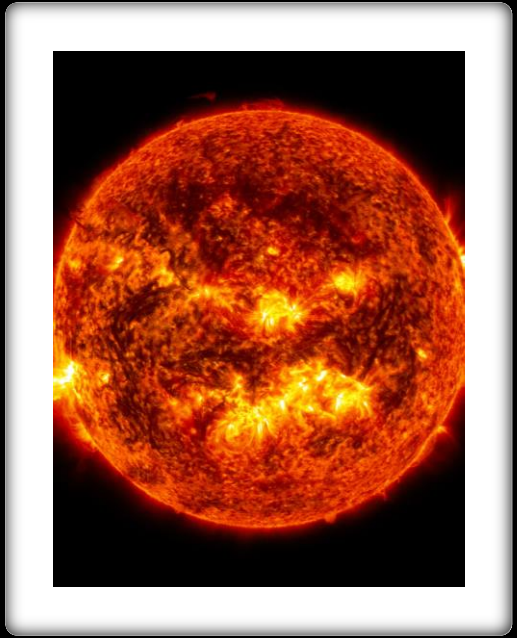
Niklas G. Nielsen, Andrea Palessandro, Martin S. Sloth

PATRAS 2019. Freiburg, Germany.

CLASSICAL

CLASSICAL

CLASSICAL



QUANTUM?

GRAVITATIONAL BOUND STATES IN THE UNIVERSE

GRAVITATIONAL ATOMS? NO WAY!

- Gravity is weak, $\mathrm{m/q} \ll m_p$, for visible particles. Gauge forces dominate at microscopic scales. Gravitational atoms of ordinary particles cannot exist.
- Even if $q = 0$, elementary particles are usually too light to form gravitational bound states. Bohr radius is $r_B = (\alpha_G m)^{-1}$, where $\alpha_G = m^2/m_p^2$, therefore

$$r_B = \frac{m_p^2}{m^3}$$

For electrons, $m = 0.5$ meV, and $r_B \sim 10^5 \times$ radius of the observable universe

For the Higgs boson, $m = 125$ GeV, and $r_B \sim 1$ light year

These atoms could not withstand tidal forces in galaxies or even Hubble expansion.

HOWEVER…

- Postulate the existence of a heavy particle X in a dark sector for which gravity is strong, $\mathrm{m_X/q_X} \gg m_p$.
- This does not violate WGC, as the conjecture only requires one particle in the spectrum satisfying $\mathrm{m}/q < m_p$.
- In the semiclassical limit, gravity is described by a central inverse square law potential $V(r) = \alpha_G/r$, with $\alpha_G = m_X^2/m_p^2$. Same as theory of positronium with the trivial replacement $\alpha_E \rightarrow \alpha_G$.
- The mass m_X controls both the charge and the inertia of the atom. Only one free parameter.
- Atom will not collapse to a black hole, since $m_X < m_p$ and $r_B > r_S = m_X/m_p^2$.

MINIMAL MODEL

1. X has only standard gravitational interactions. In particular $q_X = 0$ (no self-interactions) and $\xi_X = 0$ (minimal coupling). Dark sector maximally decoupled from visible sector.
2. X is a scalar particle without internal quantum numbers. We expect a natural mass $m_X \sim m_p$.
3. Gravitational atoms are created near the end of inflation. Lower bound on their number density is given by production from gravitational scattering in the thermal plasma of the SM.

Contrary to ordinary atoms, these gravitational BS are not stable by any global symmetry, and they decay to radiation.

Decay rate: $\Gamma = C\,\alpha_G^5 m_X$, $C \sim 0.1$.

MINIMAL MODEL

- Lifetime: $\tau_X \sim m_p^{10}/m_X^{11}$. Huge powers of the mass.

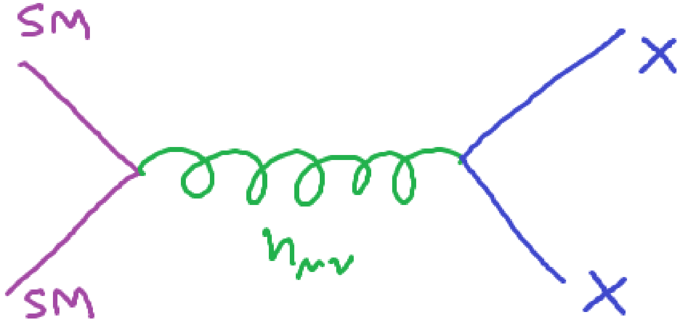
1. If $m_X < 10^{-6} m_p$, $\tau_X \gg$ age of the universe. Gravitational atoms stable on cosmic timescales. They give rise to showers of UHE cosmic rays.
2. If $m_X > 10^{-6} m_p$, gravitational atoms decay early in the history of the universe and produce gravitational waves.

- Bounds on the mass:

1. Disruption of BS due to tidal forces in galaxies: $m_X > 10^{-8} m_p$.
2. Disruption of BS due to cosmic expansion: $r_B < H^{-1} \Rightarrow m_X > \left(H\, m_p^2\right)^{\frac{1}{3}}$. Depends on Hubble rate H.

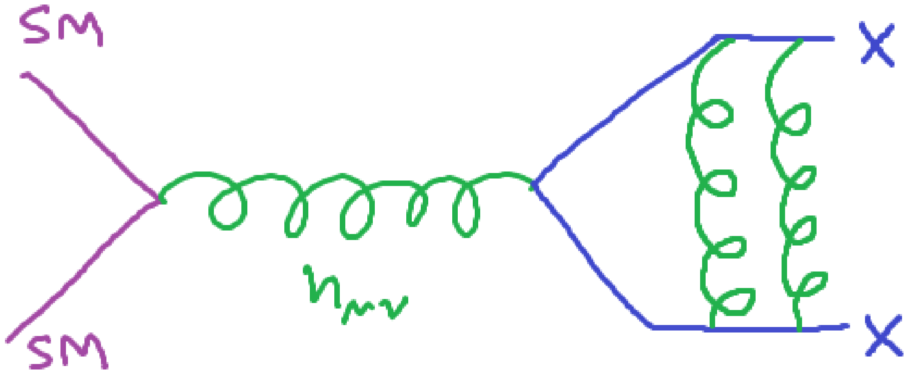
PRODUCTION MECHANISM

Production by thermal scattering after reheating. Always present: lower bound on the abundance



$$n_X = N\frac{\kappa^2 m_X^4 T_{rh}^2}{2^7 m_p^3 \pi^2} e^{-\frac{2m_X}{T_{rh}}}$$

$$\frac{n_B}{n_X} = \frac{m_X^6}{m_p^6}\sqrt{\pi\frac{m_X^3}{T_{rh}^3}}$$



$$n_B = N\frac{\kappa^2 m_X^{11}\sqrt{m_X T_{rh}}}{2^7 m_p^9 \pi^{3/2}} e^{-\frac{2m_X}{T_{rh}}}$$

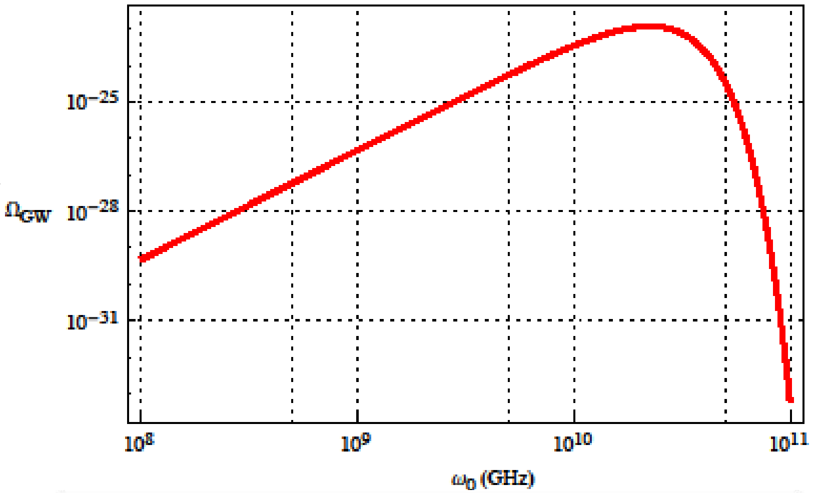
GRAVITATIONAL WAVE SIGNAL

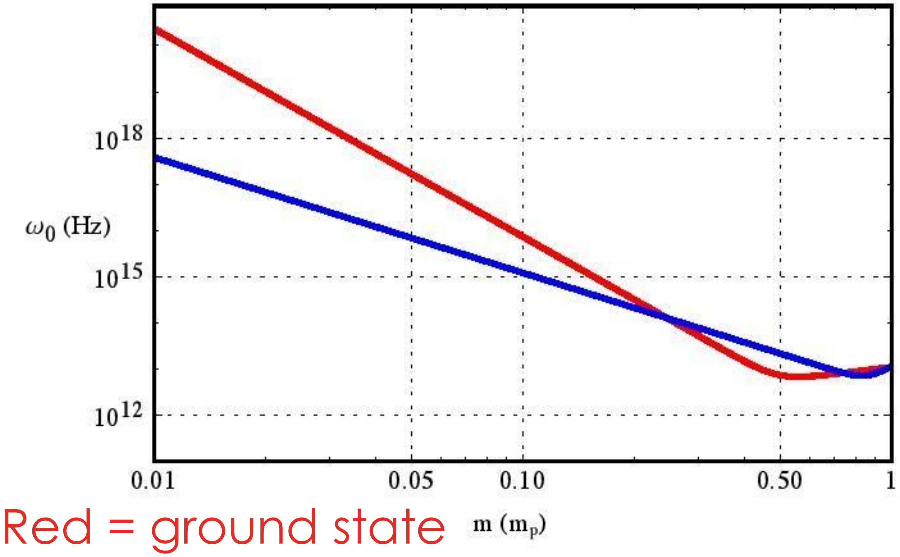
- Gravitational atoms created close to reheating with number density n_B.
- If atoms are near Planckian, $m_X \sim m_p$, they decay immediately after being produced, sourcing a highly energetic, isotropic, and nearly monochromatic gravitational wave signal.
- Peak frequency of the signal is $\omega_0 = 2\, m_X \frac{T_0}{T_{rh}} \sim \frac{T_0}{T_{rh}}$. Bound on T_{rh}: $T_{rh} \leq 10^{-3} m_p \Longrightarrow \omega_0 \geq 10^{13}$ Hz.
- Rapid Hubble expansion: $m_X > \left(T_{rh}^2 m_p\right)^{1/3}$.
- The general formula valid for any mass is

$$\omega_0 = 2 m_X \frac{T_0}{T_{rh}} \frac{\left(1+\frac{T_{rh}^2}{\Gamma}\right)}{F\left(\frac{\sqrt{\Gamma m_p}}{T_{rh}}\right)} \geq 10^{13}\text{Hz}$$

$$F(x) = 1 + e^{x^2} \frac{\sqrt{\pi}}{2x} \text{Erfc}(x).$$

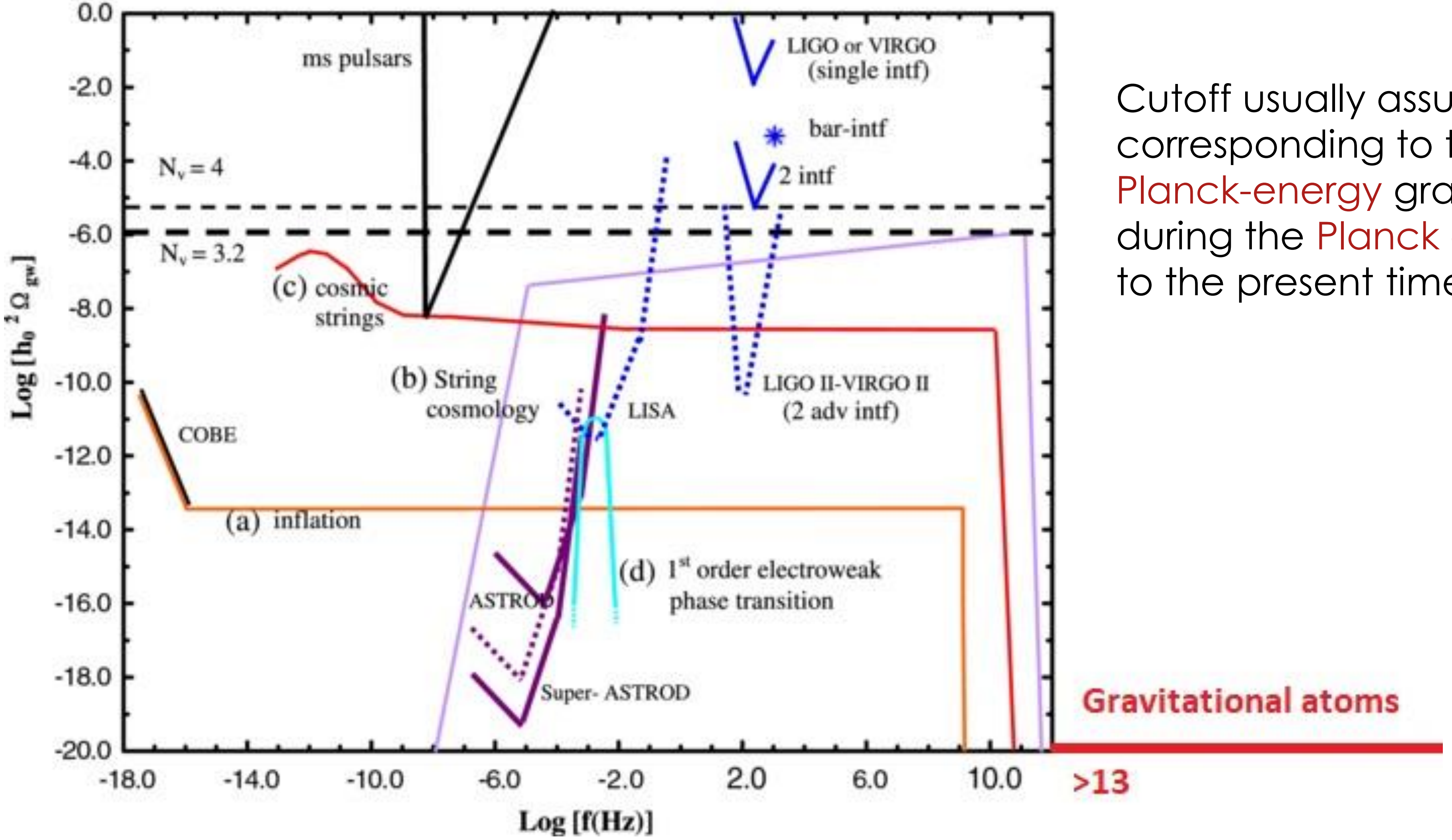
$m_X \sim 0.01\, m_p$, $T_{rh} \sim 10^{-3} m_p$





Red = ground state
Blue = first excited state

PRIMORDIAL GW SPECTRUM



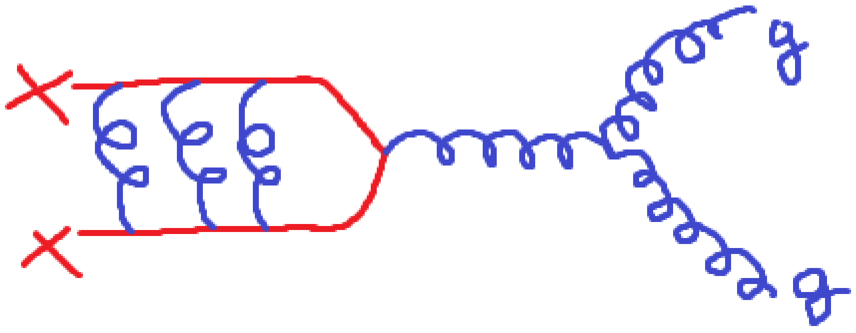
Cutoff usually assumed at 10^{11} Hz, corresponding to the frequency of a Planck-energy graviton produced during the Planck era, and redshifted to the present time.

CONCLUSIONS

- No fundamental reason why gravitational atoms should not exist.
- Minimal scenario with only gravitationally interacting particles extremely constrained. Only two parameters, m_X and T_{rh}. Very predictive scenario.
- Rare (unique?) source of isotropic gravitational waves with a peak in the spectrum at such high frequencies ($\omega_0 \geq 10^{13}$ Hz).
- $\omega_0 \geq 10^{13}$ Hz only if Einstein gravity holds up to the Planck scale + ΛCDM. Sensitive to Planck-scale physics.

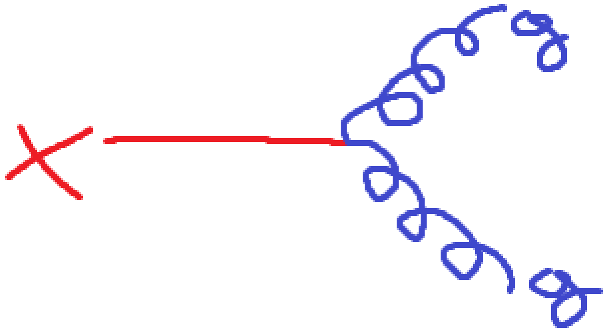
THANK YOU!

GRAVITATIONAL ATOMS OR MASSIVE PARTICLES?



$$\Gamma = \frac{41}{128\,\pi^2}\alpha_G^5 m_X$$

Monochromatic, isotropic signal if $m_X \sim m_p$.



Forbidden at tree level. Loop suppressed?

BOLTZMANN EQUATION

$$\dot{n}_B = -3Hn_B + <\sigma v>_{SM\to B} n_{SM}^2 + <\sigma v>_{X\to B} n_X^2 + <\sigma v>_{G\to B} n_G^2 - \Gamma_{SM} n_B - \Gamma_G n_B$$

$<\sigma v>_{SM\to B}$: creation by SM annihilations
$<\sigma v>_{X\to B}$: creation by recombination of X particles
$<\sigma v>_{G\to B}$: creation by graviton annihilations (graviton triple vertex)
Γ_{SM}: decay to SM particles
Γ_G: decay to gravitons

Atoms can be created in two regimes:

1. $n_{SM} \gg n_X$. Free X particles and X-atoms created by freeze-in from the SM plasma
2. $n_X \gg n_{SM}$. Gravitational atoms created by scattering of X in the non-equilibrium dark plasma (similar to recombination)

GRAVITATIONAL WAVE SPECTRUM

$$\frac{d\rho_{G,0}}{d\omega_0} = T_0^3 \frac{\Gamma_G}{\Gamma} \frac{n_{B,i}}{T_{rh}^3} \frac{\kappa^2 \Gamma m_p}{T_0^2} \frac{\omega_0^2}{m_B^2} \exp\left[\frac{\kappa^2}{2} \frac{\Gamma m_p}{T_{rh}^2} \left(1 - \frac{T_{rh}^2}{T_0^2} \frac{\omega_0^2}{m_B^2}\right)\right]$$

ω_0: frequency today

T_0: temperature today, T_{rh}: reheating temperature

Γ_G: decay rate to gravitons, Γ: total decay rate

m_B: mass of the bound state

$$\kappa = \left(\frac{45}{4\,\pi^3 g_{rh}}\right)^{\frac{1}{4}} \approx 0.25$$

Spread of the spectrum: $\delta \sim m_B \sqrt{\frac{T_0^2}{\Gamma m_p}} \ll \bar{\omega}_0 = m_B T_0 / T_{rh}$ in the high mass regime. Monochromatic signal.

EARLY MATTER DOMINATION

- Redshift factor increases if in its early stages of evolution the universe expands faster than in the radiation dominated phase: early matter domination.
- Early matter-dominated phase is present in most string theory models of the early universe
- If matter-domination lasts until BBN, the minimum frequency is

$$\omega_0 = m_B \frac{T_0}{T_{BBN}} \left(\frac{T_{BBN}^2}{\kappa^2 H_i m_p} \right)^{2/3} \sim 10^7 \text{ Hz}$$

for $H_i \sim 10^{-6} m_p$ (non-observation of tensor modes in the CMB).