LOOKING FOR ULTRALIGHT SCALARS WITH LVK BINARIES

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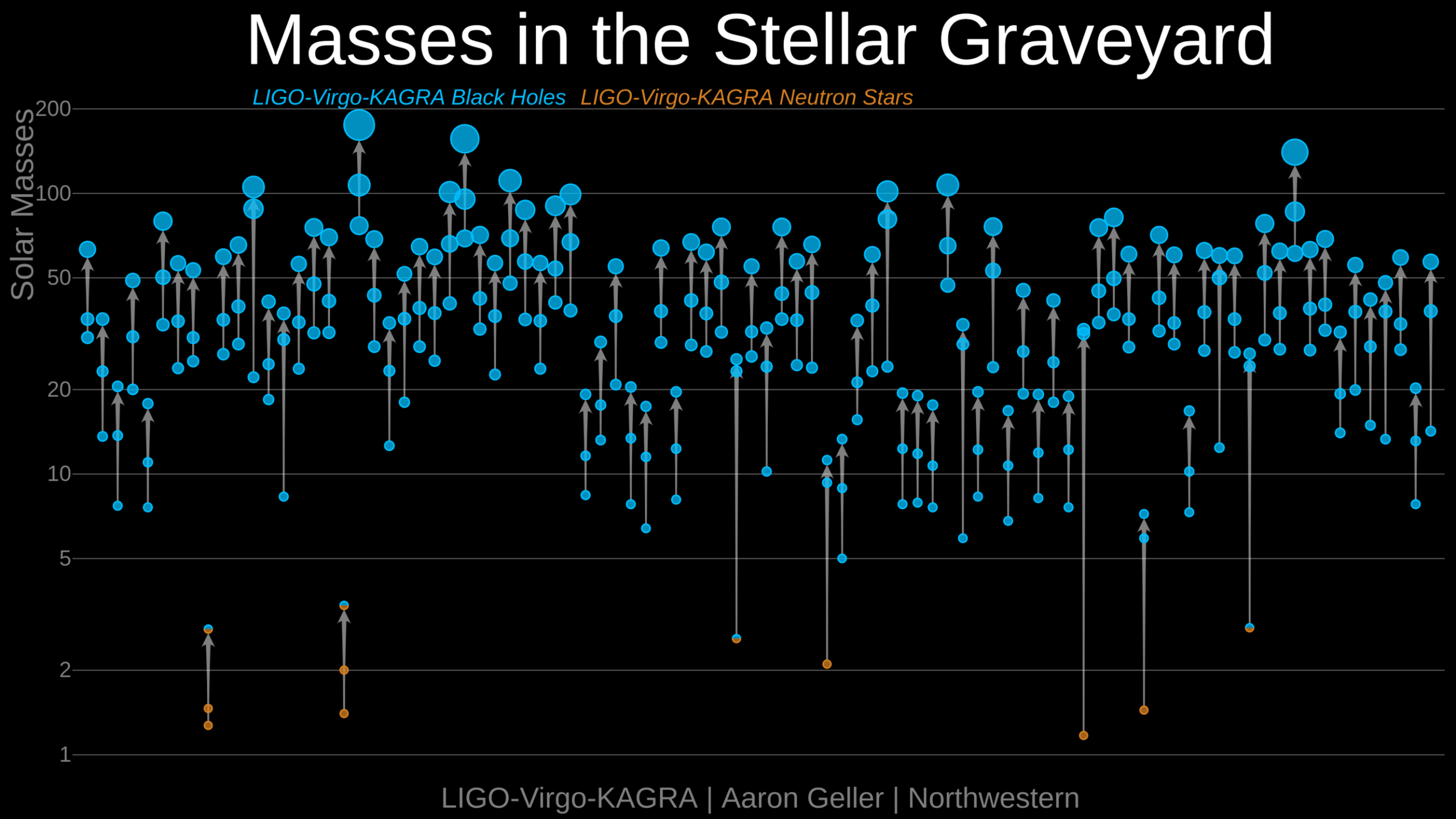
New horizons for Psi (Lisbon, IST)

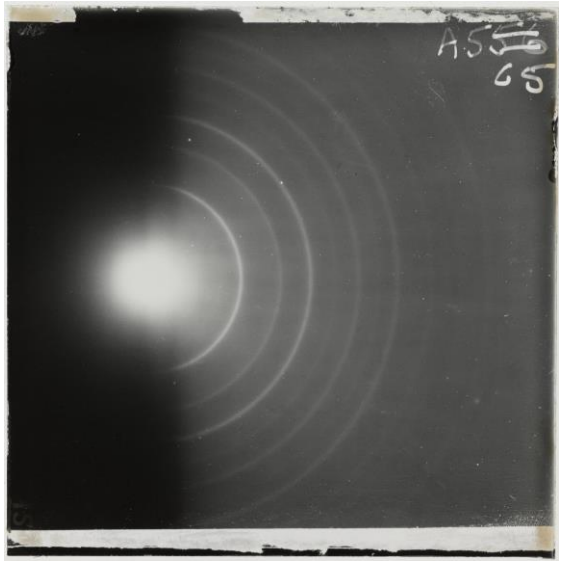
Masses in the Stellar Graveyard



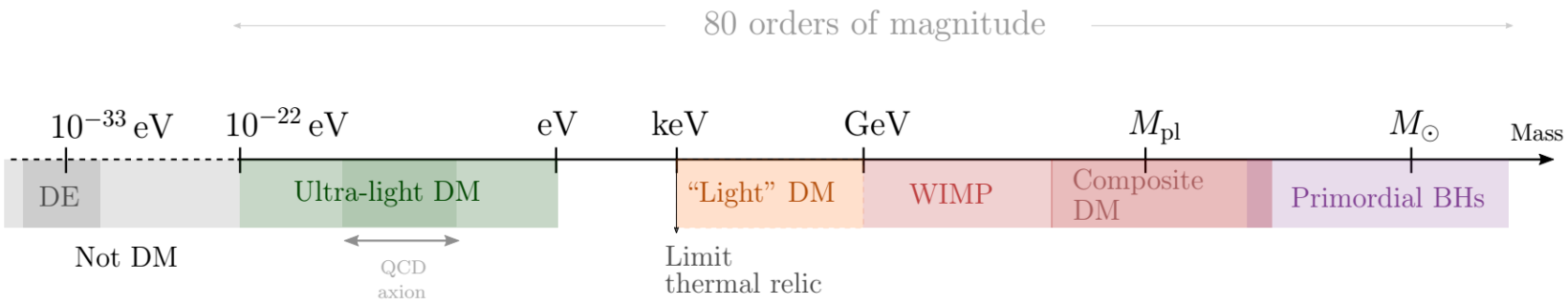
How light is "ultralight"?

Wave vs Particle

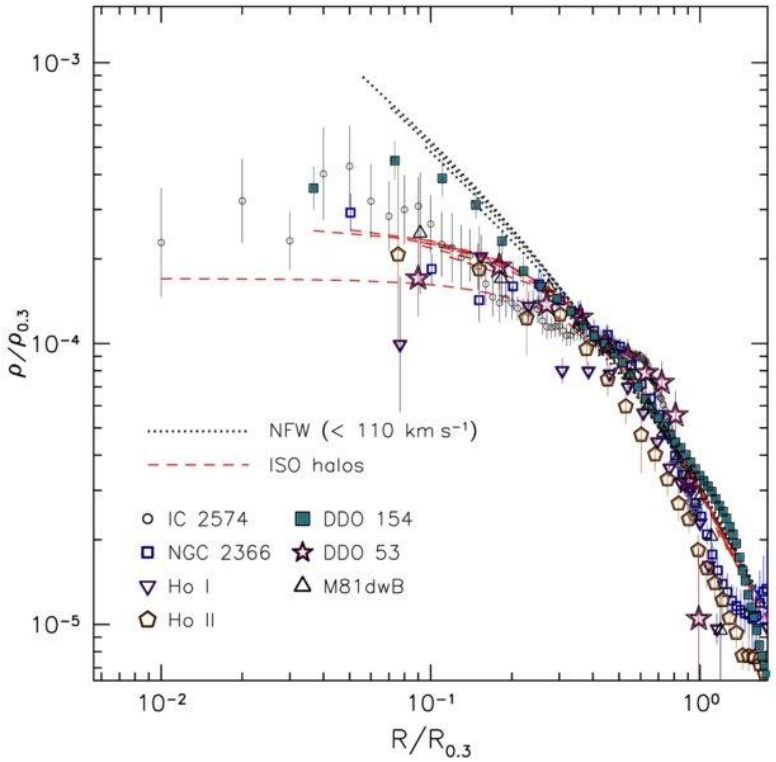
$$\lambda_{dB} \equiv \frac{2\pi}{m_\psi v}$$



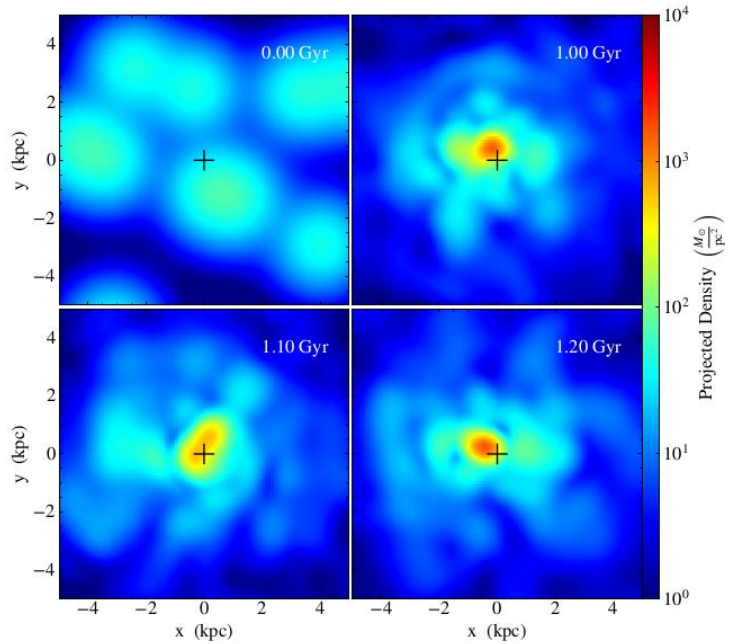
G.P. Thomson (1927)

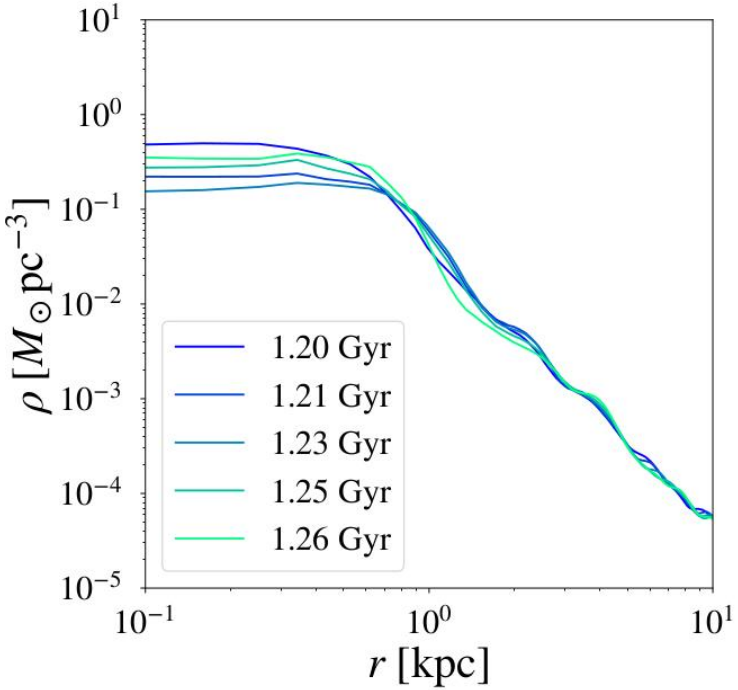


PARTICLE DM VS SMALL-SCALE OBSERVATIONS



Oh, *et al.* [1011.0899]

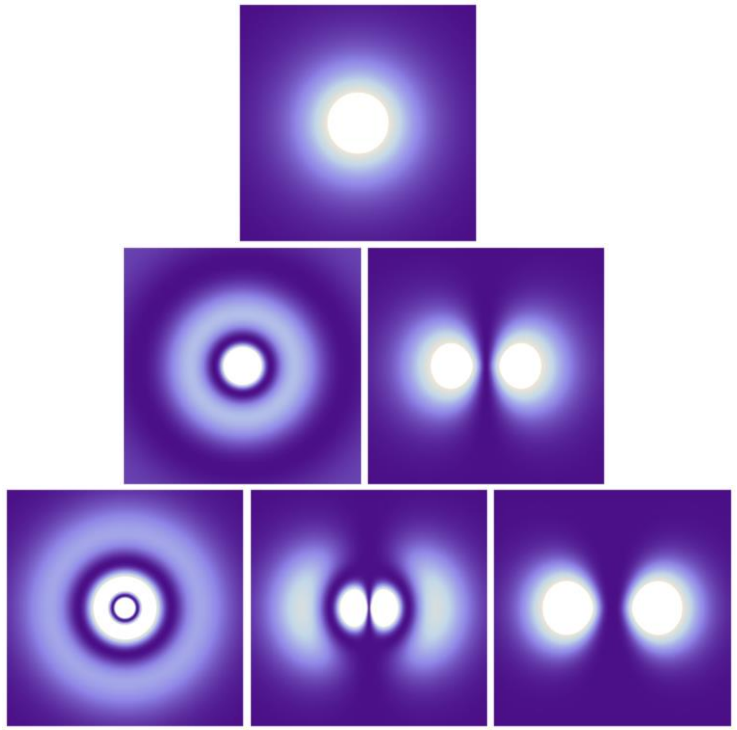




Hui, *et al.* [2101.11735]

$$\lambda_{\rm dB} \sim 0.5\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m_\psi}\right)\left(\frac{250\,{\rm km/s}}{v}\right)$$

GRAVITATIONAL CHEMISTRY (THE ATOM)



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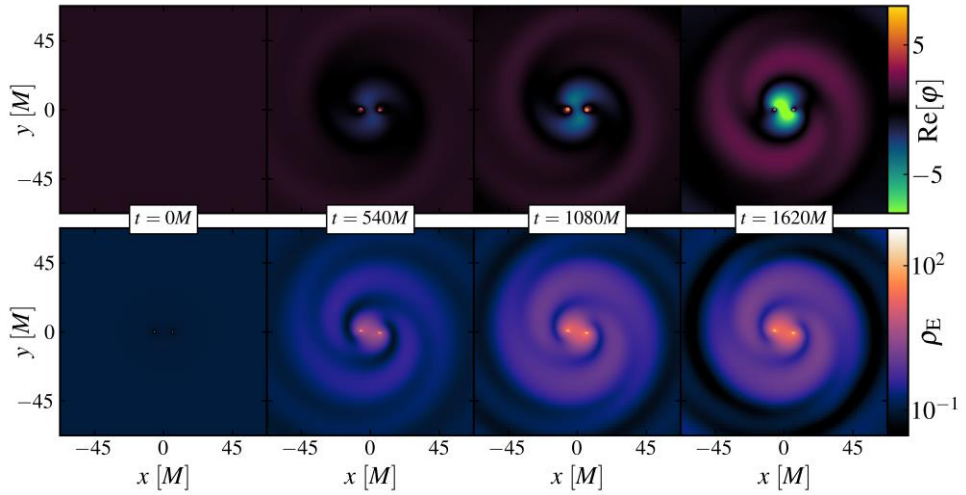
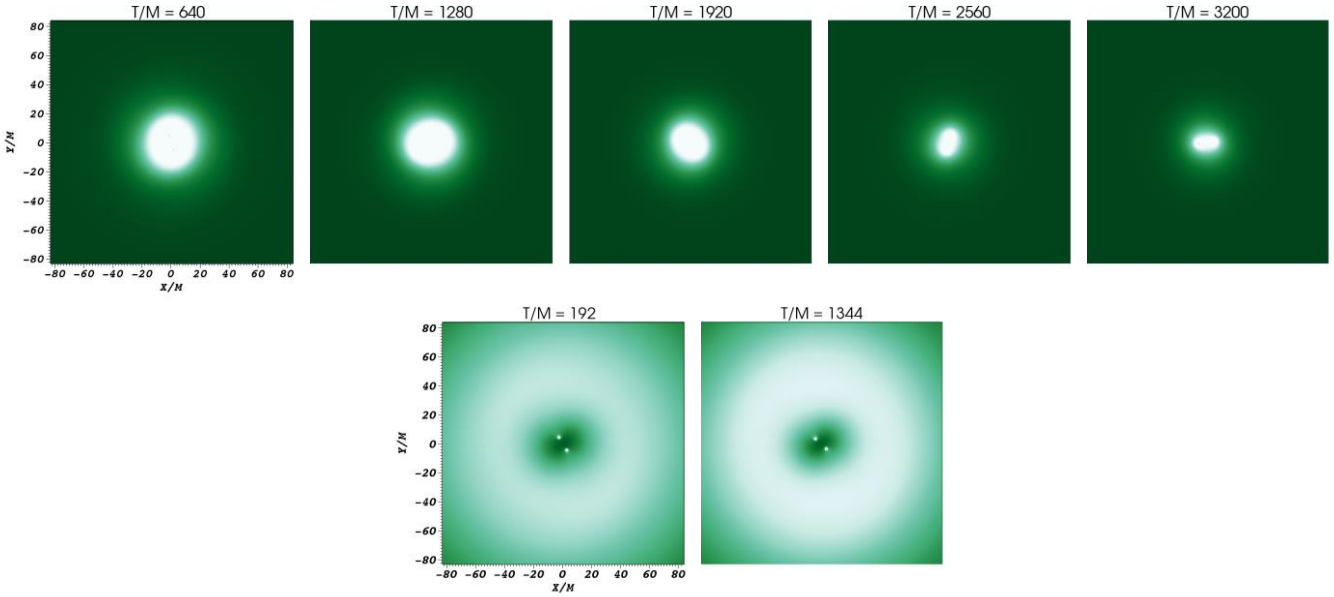
$$\lambda_{dB} \gtrsim \left(\frac{r_g}{20 M_\odot}\right)\left(\frac{10^{-10}\,\mathrm{eV}}{m_\psi}\right)$$

GRAVITATIONAL CHEMISTRY (THE MOLECULE)



Bamber, *et al.* [2210.09254]



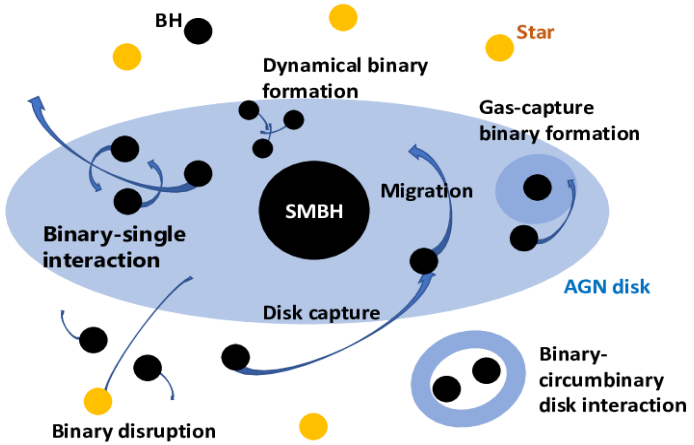
Ikeda, *et al.* [2010.00008]

$$\lambda_{dB} \gtrsim \left(\frac{R}{12\times2\times10M_{\odot}}\right)\left(\frac{10^{-11}\,eV}{m_{\psi}}\right)$$

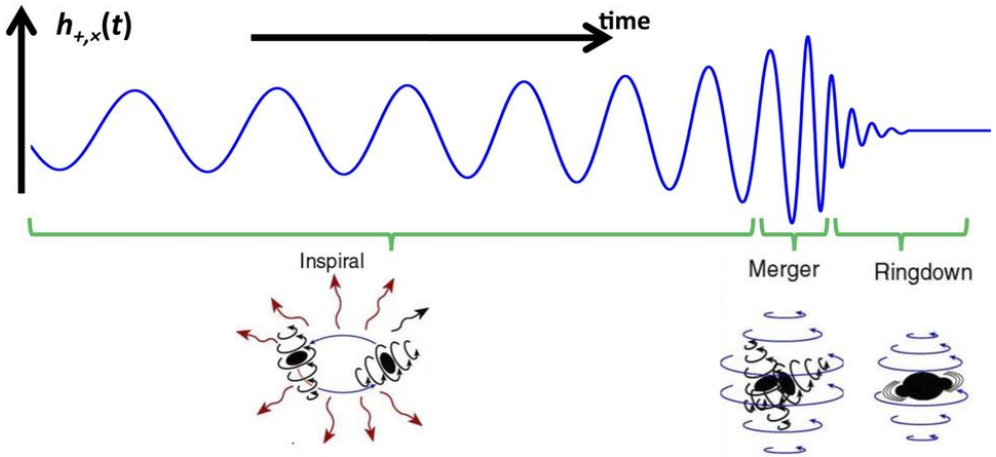
CAN WE DO (GRAVITATIONAL) CHEMISTRY WITH GWS?

BUT... FIRST, A (NOT SO) SLIGHT DETOUR

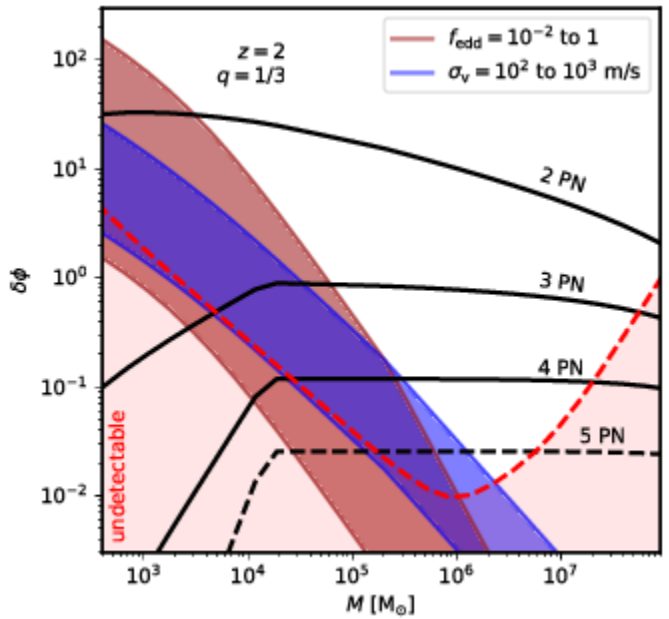
THE ENVIRONMETS WHERE COMPACT BINARIES LIVE IN



Tagawa, Haiman, Kocsis [1912.08218]



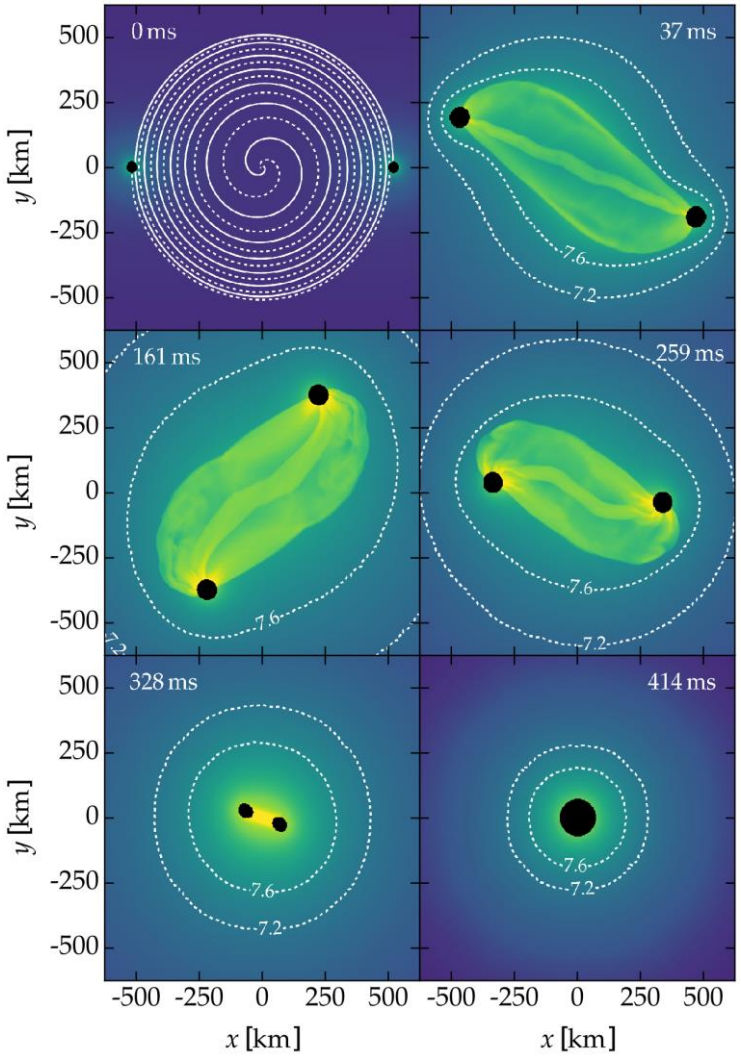
Favata/SXS/Thorne

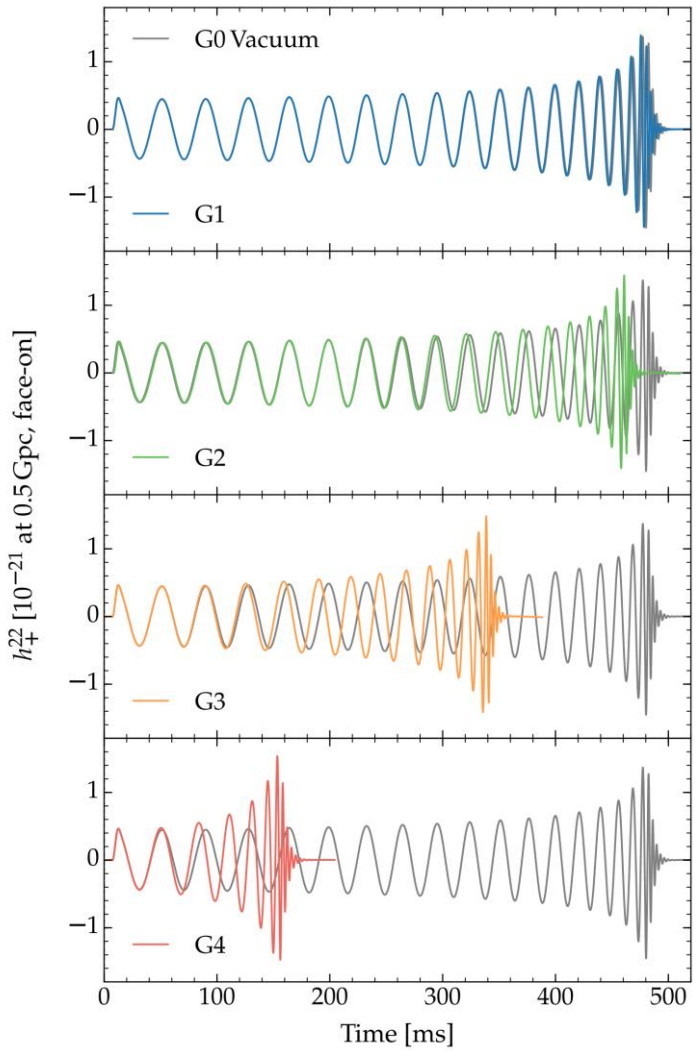


Zwick, Capelo, Mayer [2209.04060]

"If the goal is to maximise the science yield of future missions, the community could be better served by shifting the focus from the source of GWs to its surroundings"

HOW EMPTY IS THE *VACUUM* OF LVK SOURCES? (THE NR WAY)





Fedrow *et al.* [1704.07383]

HOW EMPTY IS THE *VACUUM* OF LVK SOURCES? (THE PHENOM WAY)

$$\tilde{h} = A(f)e^{i\Phi(f)}$$

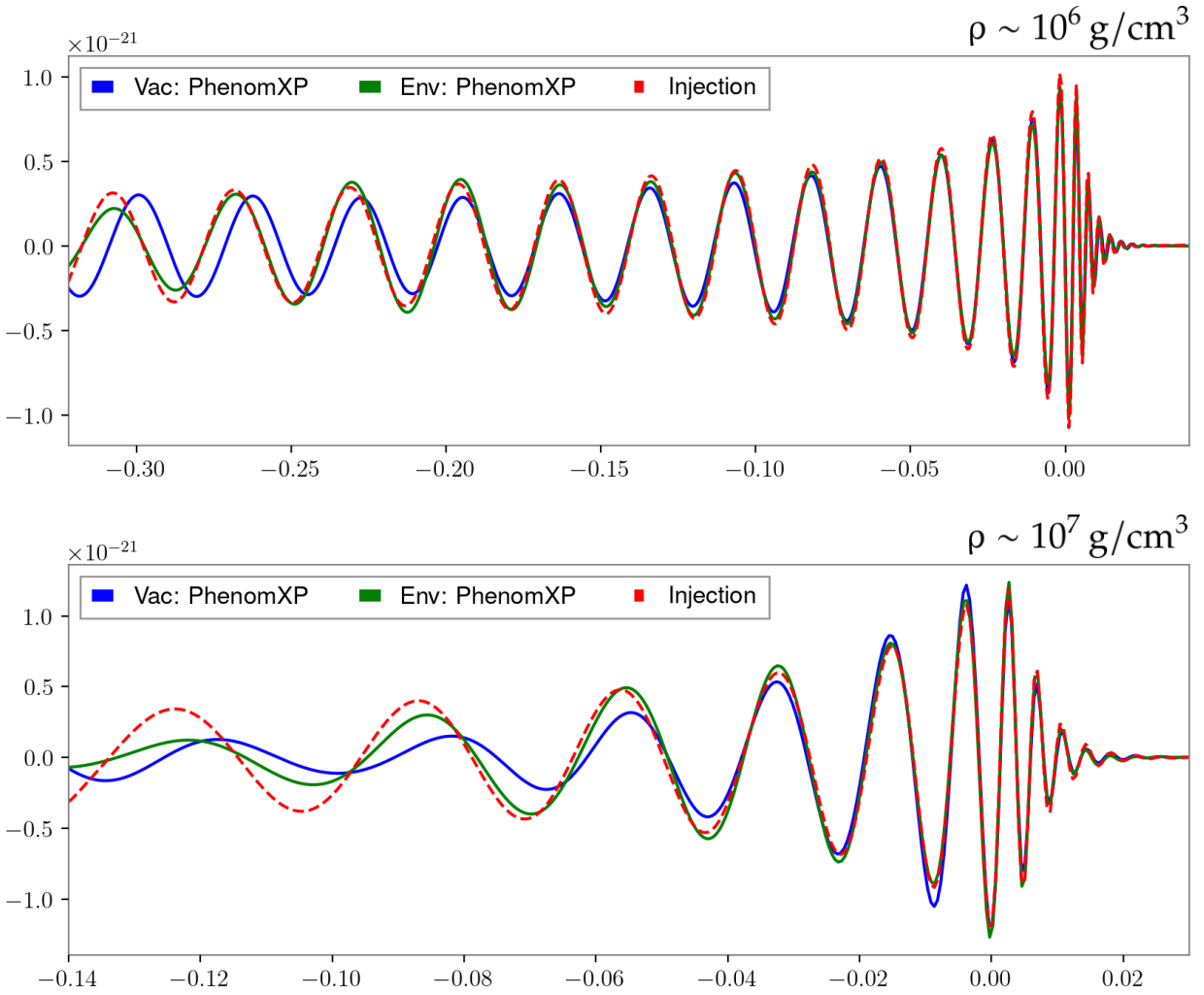
where $A \approx \frac{h[t(f)]}{2\sqrt{\dot{f}}}$ and $\Phi \approx 2\pi f t_c - \varphi_c - \frac{\pi}{4} - 2\pi \int_f^\infty df' \left(\frac{f - f'}{\dot{f}}\right)$

$$\dot{L} = \tau_{gw} + \tau_{df}$$

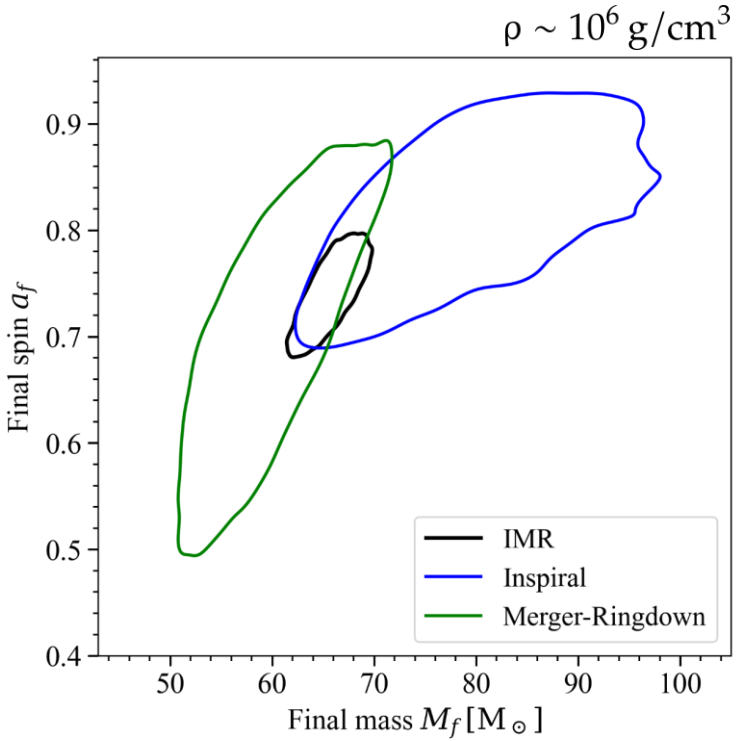
where $\tau_{df} \approx \frac{4\pi\rho_\psi M^2}{(\pi M f)^{\frac{1}{3}}} I_{df}(\cdot, q_2, Mf)$ and $\dot{m}_i = \rho_\psi A_i I_{acc}(\cdot, q_2, Mf)$

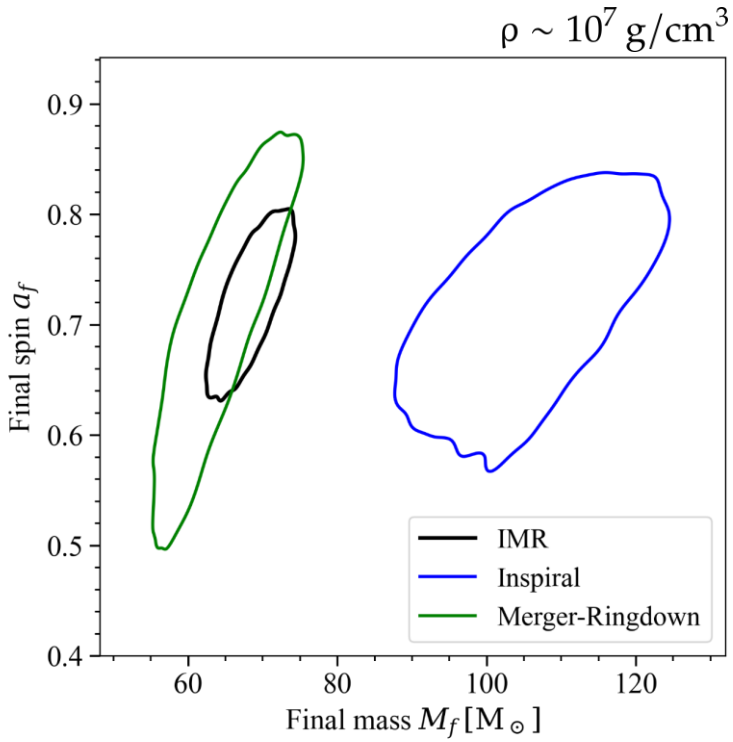
HOW EMPTY IS THE *VACUUM* OF LVK SOURCES? (NR VS PHENOM)

$I_{df}(Mf) = 1$ and $I_{accr}(Mf) = (4\pi Mf)^{-1}$ (Hoyle-Lyttleton)

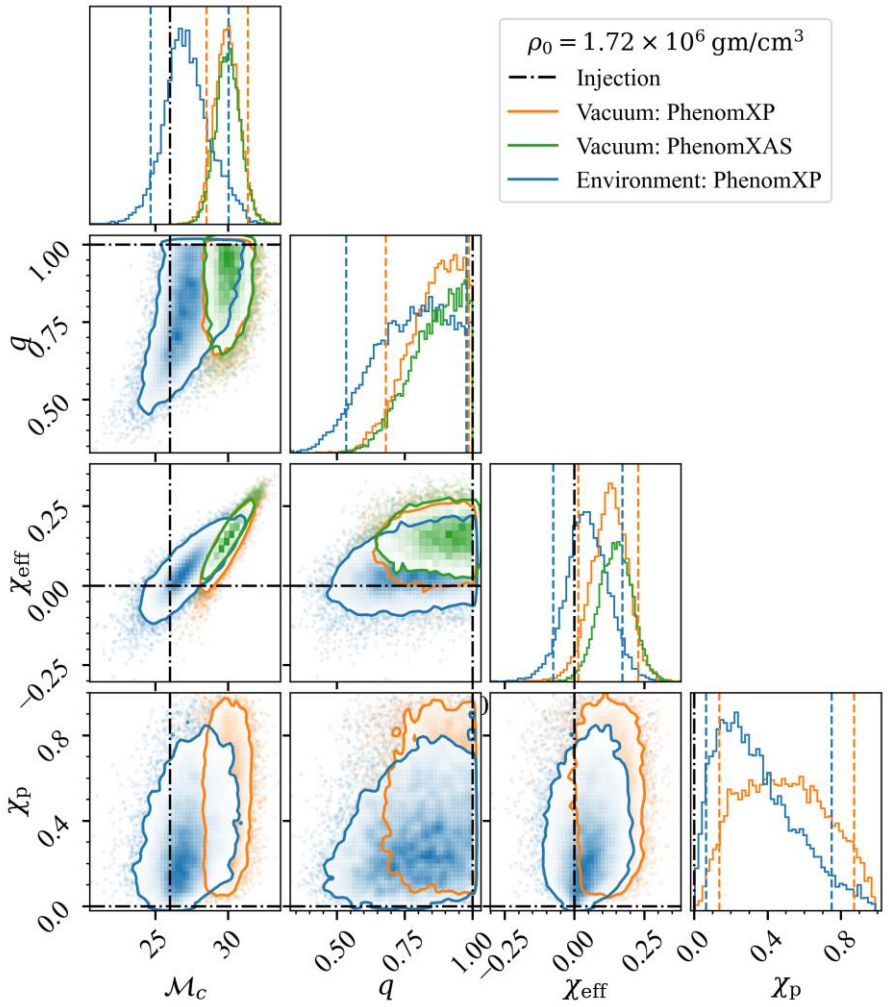


HOW EMPTY IS THE *VACUUM* OF LVK SOURCES? (NR VS PHENOM)

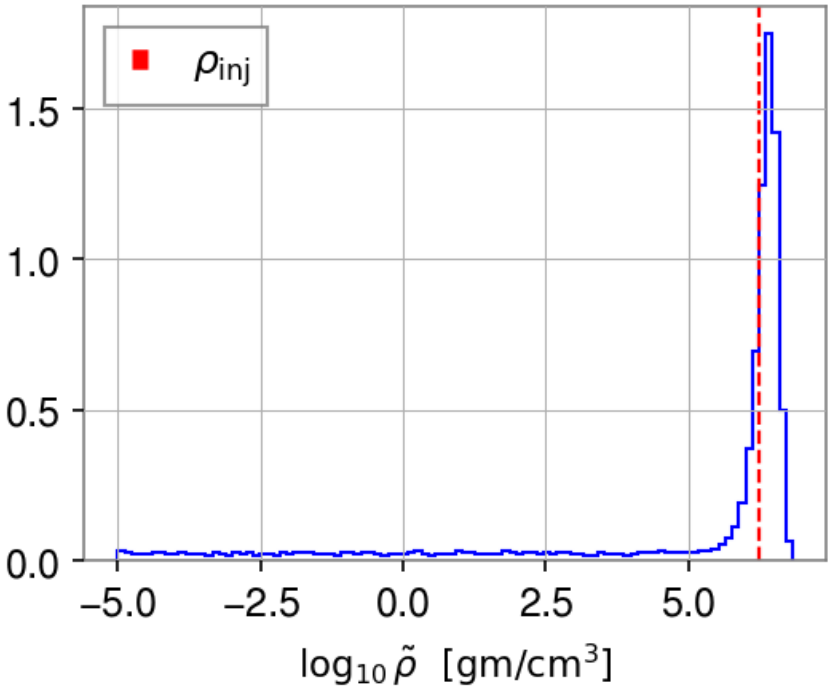




HOW EMPTY IS THE *VACUUM* OF LVK SOURCES? (NR VS PHENOM)

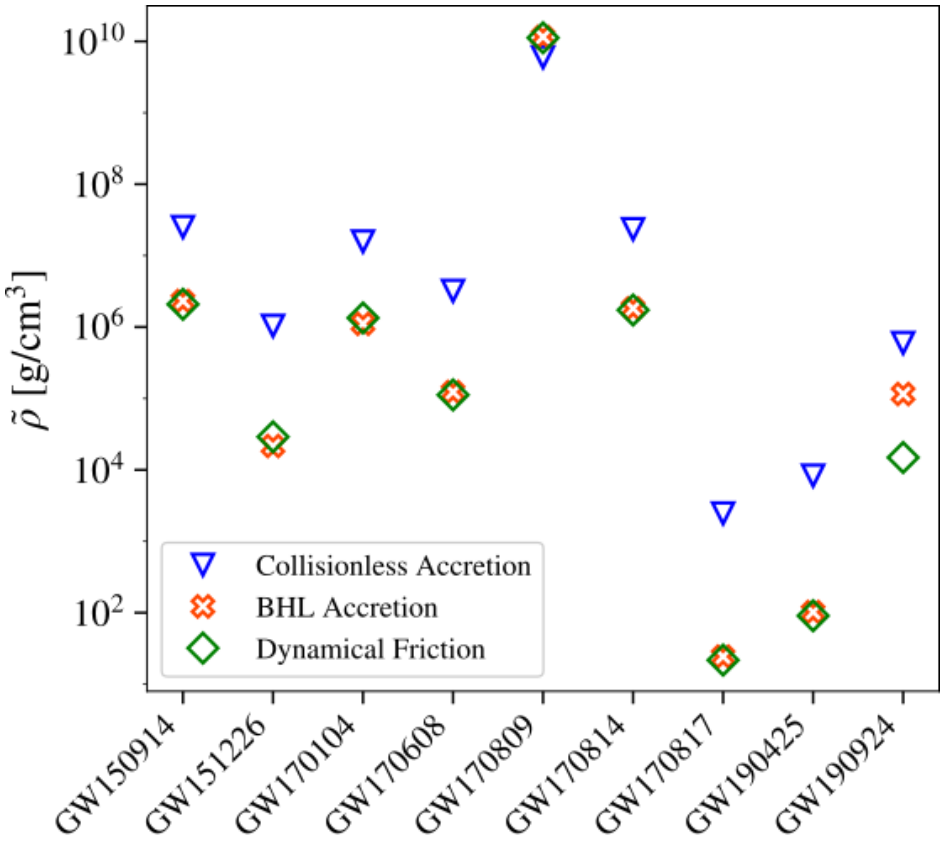


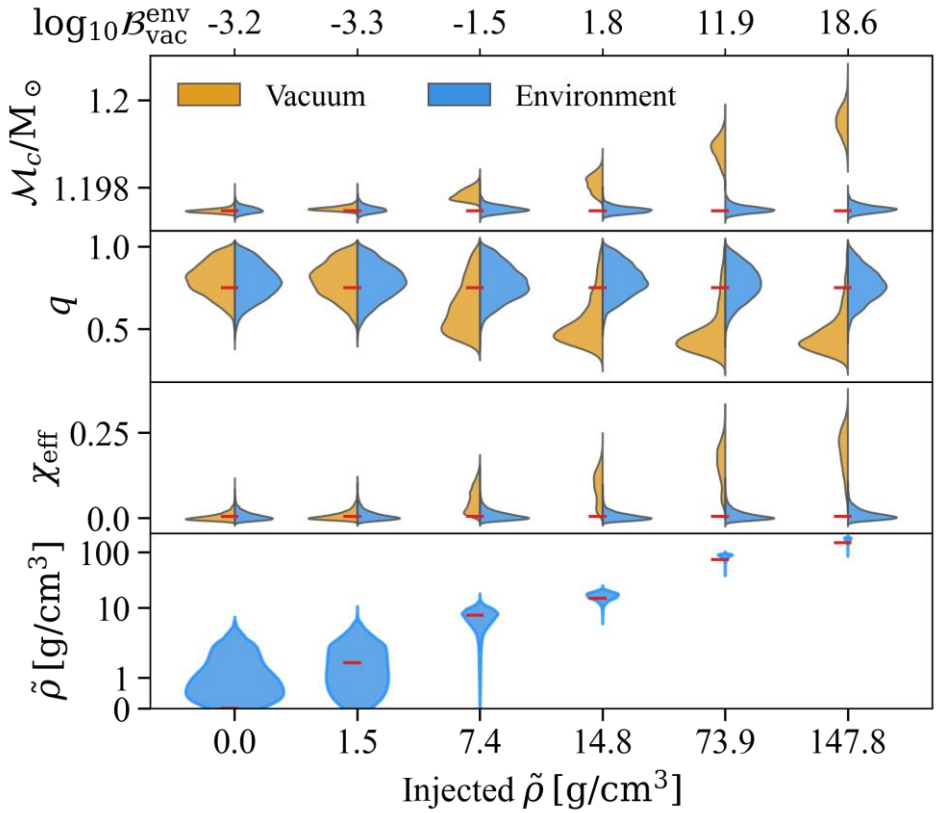
$\log_{10} \mathcal{B}^{\rm env}_{\rm vac} \approx 2.5$



HOW EMPTY IS THE *VACUUM* OF LVK SOURCES?

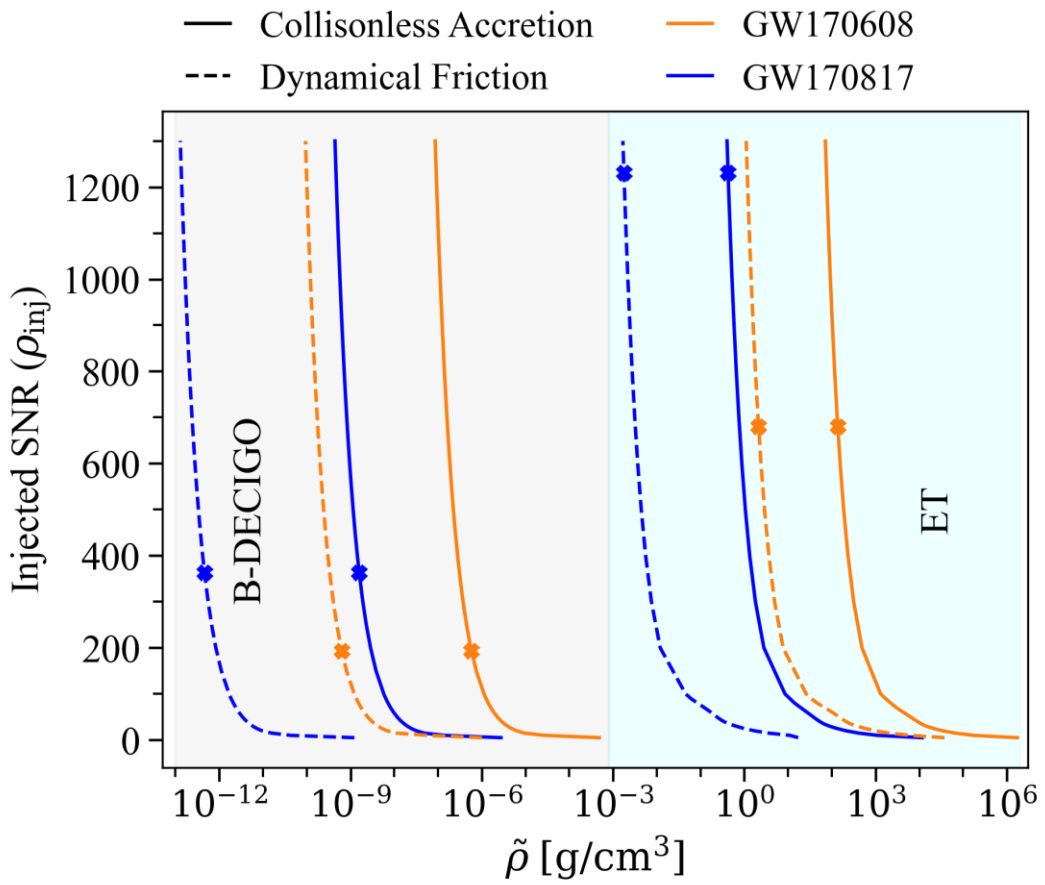
Santoro, *et al.* [2309.05061]





... AND WITH NEXT-GEN. INTERFEROMETERS?

Santoro, *et al.* [2309.05061]



$$\rho_{\rm fragm}\,[{\rm g/cm^3}] \gtrsim 10^{7}$$

$$\rho_{\rm thin}\,[{\rm g/cm^3}] \lesssim 10^{-1}(10^5 M_\odot/m_3)^{7/10}$$

$$\rho_{\rm thick}\,[{\rm g/cm^3}] \lesssim 10^{-8}(10^5 M_\odot/m_3)$$

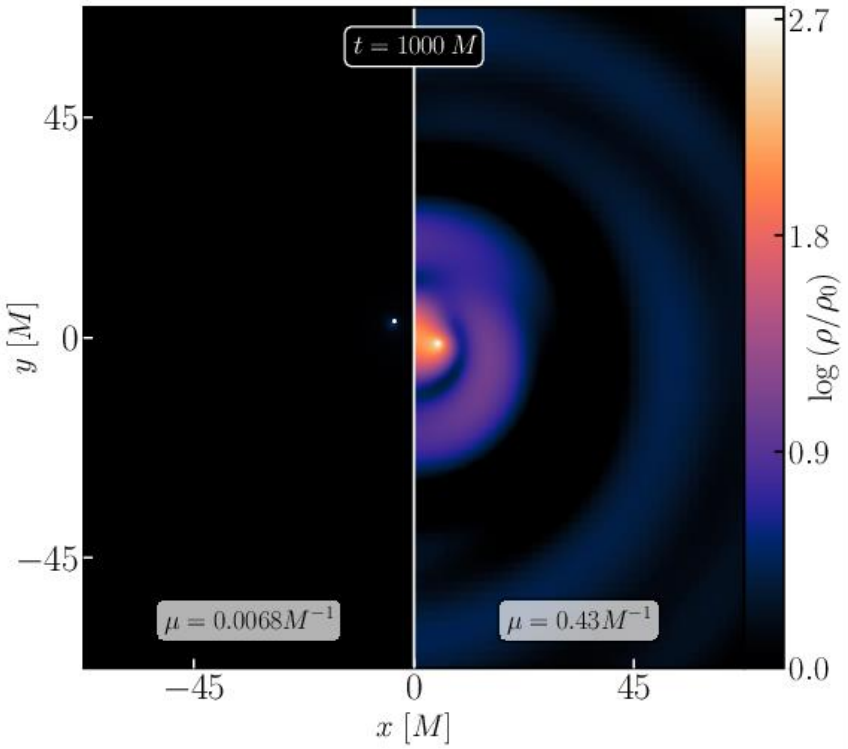
$$\rho_{\rm SR}\,[{\rm g/cm^3}] \lesssim 10^{-1}(10^5 M_\odot/m_3)^2$$

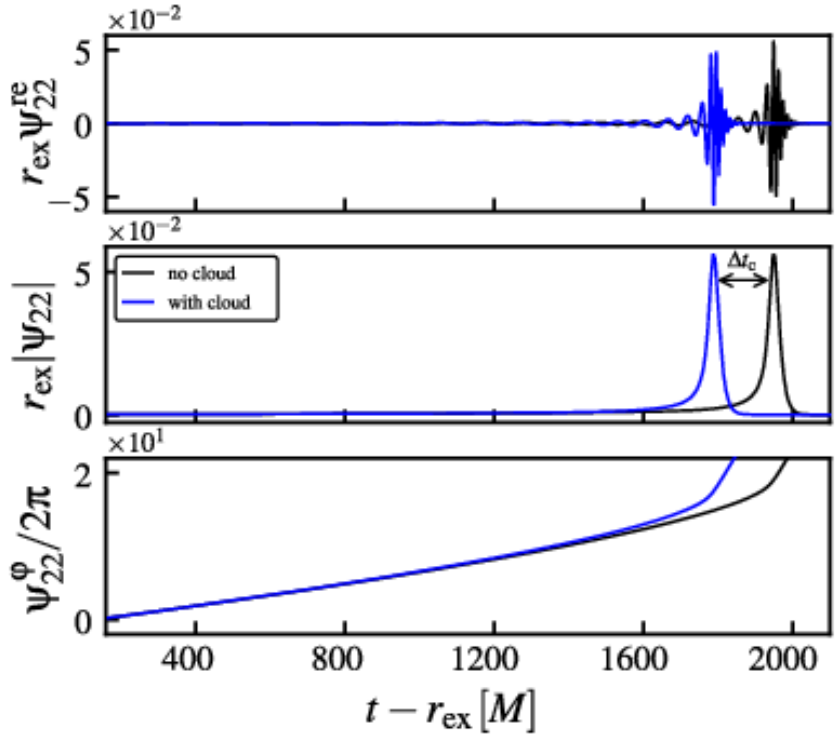
$$\rho_{\rm spikes}\,[{\rm g/cm^3}] \lesssim 10^{-6}$$

$$\rho_{\rm solit}\,[{\rm g/cm^3}] \lesssim 10^{-19}$$

So, but... how about the ψ?

HOW BINARIES COALESCE IN SCALAR ENVIRONMENTS? (THE NR WAY)





Aurrekoetxea, et al. [2311.18156]

HOW BINARIES COALESCE IN SCALAR ENVIRONMENTS? (THE PHENOM WAY)

$$\left[\Box_\eta - m_\psi^2(1-2\Phi)\right]\psi(x) = 0$$

with $$\Phi = -\frac{M}{r}\left\{1 + \sum_{\ell_*\geqslant 1}\sum_{m_*\leqslant \ell_*} Y^*_{\ell_* m_*}(\theta_{2*},\varphi_{2*})Y_{\ell_* m_*}(\theta,\varphi)F_{\ell_* m_*}(r)\right\}$$

$$F_{\ell_* m_*} \equiv \frac{4\pi\alpha}{2\ell_*+1} q_2\left[1+(-1)^{\ell_*}q_1 q_2^{\ell_*-1}\right]\left(\frac{r_{2*}}{r}\right)^{\ell_*} \sim (R/\lambda\!\!\!^{-}_{\rm dB})^{\ell_*}$$

$$\Longrightarrow \quad I_{\rm df} = (\cdots)$$

$$I_{\rm accr}(\nu_i \gg m_\psi M_i) \approx 1$$

HOW BINARIES COALESCE IN SCALAR ENVIRONMENTS? (CONSTRAINTS)

$$\text{GW150914}\ [M_1 \sim 36M_\odot,\ M_2 \sim 29M_\odot,\ M_f \sim 62M_\odot,\ \text{SNR} = 24] \implies \log_{10}\rho[\text{g/cm}^3] \approx 6.6$$

$$\text{GW151226}\ [M_1 \sim 14M_\odot,\ M_2 \sim 7.5M_\odot,\ M_f \sim 21M_\odot,\ \text{SNR} = 13] \implies \log_{10}\rho[\text{g/cm}^3] \approx 4.6$$

$$\text{GW170608}\ [M_1 \sim 12M_\odot,\ M_2 \sim 7M_\odot,\ M_f \sim 18M_\odot,\ \text{SNR} = 12] \implies \log_{10}\rho[\text{g/cm}^3] \approx 4.3$$

$$\rho \sim 10^7\ \text{g/cm}^3\ \frac{q_\phi}{0.1}\left(\frac{\alpha_1}{0.05}\right)^6\left(\frac{10M_\odot}{M_1}\right)^2$$

TAKEAWAY

- Environmental effects may be observable by near-future GW detectors
- Current data from LVK may already be used to constrain the presence of scalar enviroments
- Better (semi)analytic waveforms might be needed (NR injections vs Phenom)
- Better modelling of binary history would be needed to probe the existence of ultralight bosons