Title: Matter-Gravity Entanglement in Quantum Gravity

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Series: Quantum Gravity

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Abstract: Quantum gravity may be viewed as a bipartite matter-geometry system. Evolution of matter-geometry entanglement entropy is an interesting question for issues such as the emergence of QFT on curved spacetime from quantum gravity: emergence would require initial states to evolve to product states. We study this question in a cosmological model. We give numerical evidence that matter-geometry entanglement entropy increases indefinitely (with respect to a relational time) for apparently arbitrary initial states. This result raises the question of whether matter and geometry remain entangled in a large Universe.

Matter-Geometry Entanglement in QG

Viqar Husain
(with Suprit Singh - to appear soon)

1. Some QG questions
2. Evolution of S_{ent}: simple models
3. Evolution of S_{ent}: cosmology with matter
4. Next steps

1. Some QG questions
2. Evolution of S_{ent}: simple models
3. Evolution of S_{ent}: cosmology with matter
4. Next steps

– So far most (non-string) work in QG has focused only on gravity/geometry

... not much work on matter in spin foams, CDT, LQG. Big gap.

With matter, QG may be viewed as a geometry-matter bipartite system with Hilbert space

$$\mathcal{H} = \mathcal{H}_G \otimes \mathcal{H}_M$$

Entanglement entropy S_{ent} of static or evolving states derived by tracing a state over geometry or matter states.

QG questions

- What is the physical Hilbert space?

- Are solutions of the WDW equation with matter always entangled states?

- With respect to some time variable, how does S_{ent} evolve?

- "Derivations" of QFT on curved space spacetime from WDW starts with a product state:

$$\Psi[q, \phi] = \psi[q, q_0]\ \xi[\phi, q_0]$$

q_0 are peaking parameters for the gravity state ψ.

Can product states arise dynamically from QG?

We studied the evolution of

$$S_{\text{ent}} = -\text{Tr}(\rho_A \log \rho_A),$$

$$\rho_A = \text{Tr}_B(\rho_{AB}).$$

for three systems with various initial states ρ_{AB}:

– spin-spin

– spin-oscillator (Jaynes-Cummings model)

– scalar cosmology with dust clock

spin-spin model:

$$H = \sigma_z^{(1)} \otimes \mathsf{I}^{(2)} + \mathsf{I}^{(1)} \otimes \sigma_z^{(2)} + g(\sigma_+^{(1)}\sigma_-^{(2)} + \sigma_-^{(1)}\sigma_+^{(2)}).$$

An exact solution of the TDSE is

$$|\psi\rangle = \cos(gt)|01\rangle - i\sin(gt)|10\rangle$$

spin-spin model:

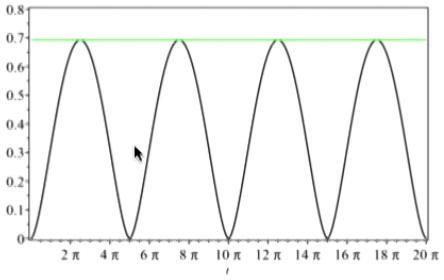
$$H = \sigma_z^{(1)} \otimes \mathrm{I}^{(2)} + \mathrm{I}^{(1)} \otimes \sigma_z^{(2)} + g(\sigma_+^{(1)}\sigma_-^{(2)} + \sigma_-^{(1)}\sigma_+^{(2)}).$$

An exact solution of the TDSE is

$$|\psi\rangle = \cos(gt)|01\rangle - i\sin(gt)|10\rangle$$

For this solution

$$S_{ent} = -\cos^2(gt)\ln[\cos^2(gt)] - \sin^2(gt)\ln[\sin^2(gt)]$$



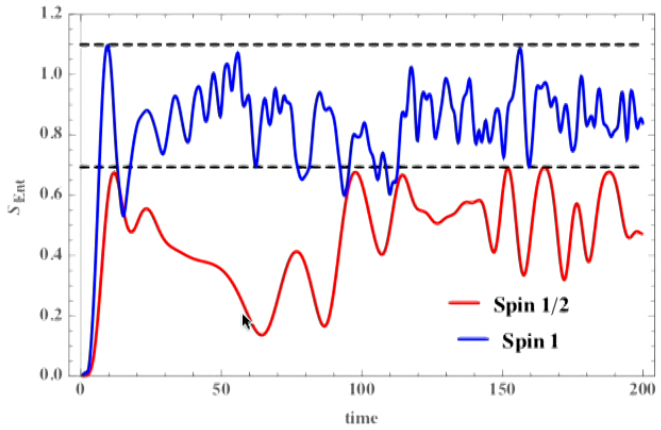
Easily generalized to higher spin with similar behaviour – might be desirable for emergence of QFT on a background from QG.

Spin-Oscillator:

$$H = a^\dagger a \otimes \mathbb{I} + \mathbb{I} \otimes \sigma_z + g\left(a^\dagger \otimes \sigma_- + a \otimes \sigma_+\right)$$

Truncate oscillator matrices to study evolution.
For an initial product state

$$\psi \sim e^{-\alpha x^2}|0\rangle$$



– dotted lines are maximum possible entanglement entropies $\ln 2$ and $\ln 3$.
– there are dips in entropy, but no recurrence of product states.
– for higher spin s entropy oscillates close to maximum value $\ln(2s+1)$.

Cosmology with scalar and dust

$$S = \int d^4x\, \sqrt{-g}R - \int d^4x\, M\sqrt{-g}\left(g^{ab}\partial_a T\partial_b T + 1\right) + \int L(\phi)$$

Canonical action:

$$S = \int d^3x\, dt\, \left(\pi^{ab}\dot{q}_{ab} + p_T\dot{T} + p_\phi\dot{\phi} - N\mathcal{H} - N^a\mathcal{C}_a\right),$$

$$\begin{aligned}
\mathcal{H} &\equiv \mathcal{H}_G + \mathcal{H}_D + \mathcal{H}_\phi \\
&= \frac{1}{\sqrt{q}}(\pi^{ab}\pi_{ab} - \frac{1}{2}\pi^2) - \sqrt{q}{}^{(3)}R + \frac{p_\phi^2}{2\sqrt{q}} + \frac{1}{2}\sqrt{q}q^{ab}\partial_a\phi\partial_b\phi \\
&\quad + \mathrm{sgn}(M)\; p_T\sqrt{1 + q^{ab}\partial_a T\partial_b T}, \qquad (1) \\
\mathcal{C}_a &\equiv -D_b\pi^b{}_a + p_T\partial_a T + p_\phi\partial_a\phi \qquad (2)
\end{aligned}$$

Use dust time: $T = t$, and solve the Hamiltonian constraint
This gives

$$S_{GF} = \int d^3x\, dt\, \left(\pi^{ab}\dot{q}_{ab} + p_\phi\dot{\phi} - H_P - N^a\mathcal{C}_a\right),$$

Physical Hamiltonian:

$$H_P = \frac{1}{\sqrt{q}}(\pi^{ab}\pi_{ab} - \frac{1}{2}\pi^2) - \sqrt{q}{}^{(3)}R + \frac{p_\phi^2}{2\sqrt{q}} + \frac{1}{2}\sqrt{q}q^{ab}\partial_a\phi\partial_b\phi.$$

Reduction to cosmology: phase space $(a, \phi; p_a, p_\phi)$.

$$H_P = -\frac{p_a^2}{24a} + \frac{p_\phi^2}{2a^3}$$

After a canonical transformation ($p = p_a/\sqrt{12a}$, $x = 4a^{3/2}/\sqrt{3}$)

$$H_P = \frac{1}{2}\left(-p^2 + \frac{p_\phi^2}{x^2}\right).$$

Quantization: 2 particle Hilbert space $\mathcal{H}_x \otimes \mathcal{H}_\phi$.

TDSE for $\psi(x, \phi, t)$:

$$i\,\dot{\psi} = \frac{1}{2}\left(\partial_x^2 - \frac{1}{x^2}\partial_\phi^2\right)\psi$$

Solve this equation numerically...

Numerical scheme: a modification of the ADI (Alternating Direction Implicit) method for 2d diffusion.

$$\psi(x, \phi, t) \to U_{ij}^n$$

n is time step.

Divide one time step Δt into two: $n \to n^* \to n+1$

$$\begin{aligned} U^* &= U^n + \frac{1}{2}\left(\delta_x^2 U^* - \frac{1}{x_n^2}\delta_\phi^2 U^n\right) && \text{implicit in x} \\ U^{n+1} &= U^* + \frac{1}{2}\left(\delta_x^2 U^* - \frac{1}{x_n^2}\delta_\phi^2 U^{n+1}\right) && \text{implicit in } \phi \end{aligned}$$

δ^2 is discretization of second derivative.

Scheme is unconditionally stable.
Probability conservation is very good 10^{-6} with $\Delta t = 0.01$, $\Delta x = \Delta\phi = 0.05$.

Results:

Evolution starting form product state:

$$\psi_0(x, \phi) = \exp[(x - x0)^2/\sigma + (y - y0)^2/\sigma + ip_0 y]$$

p_0 is initial expansion momentum.

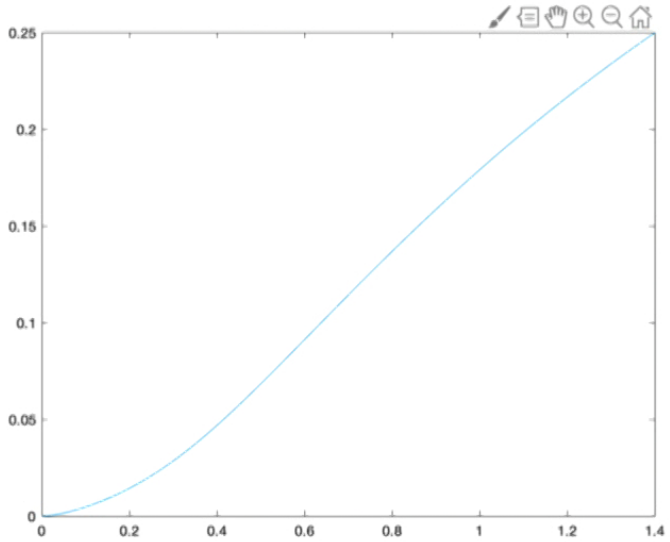
These states evolve to squeezed states:

– spreading in ϕ slows as Universe expands due to $1/x^2$.

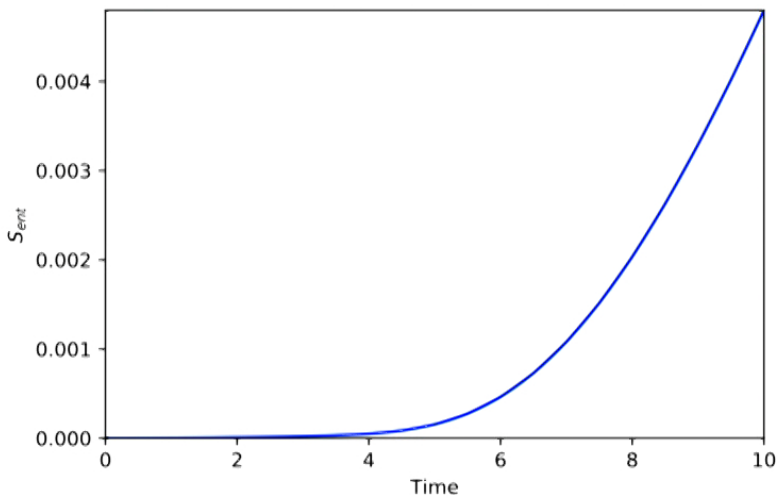
– spreading in x (scale factor) becomes dominant.

Typical increase in entanglement entropy...

For initial momentum $p_0 = 2.5$:

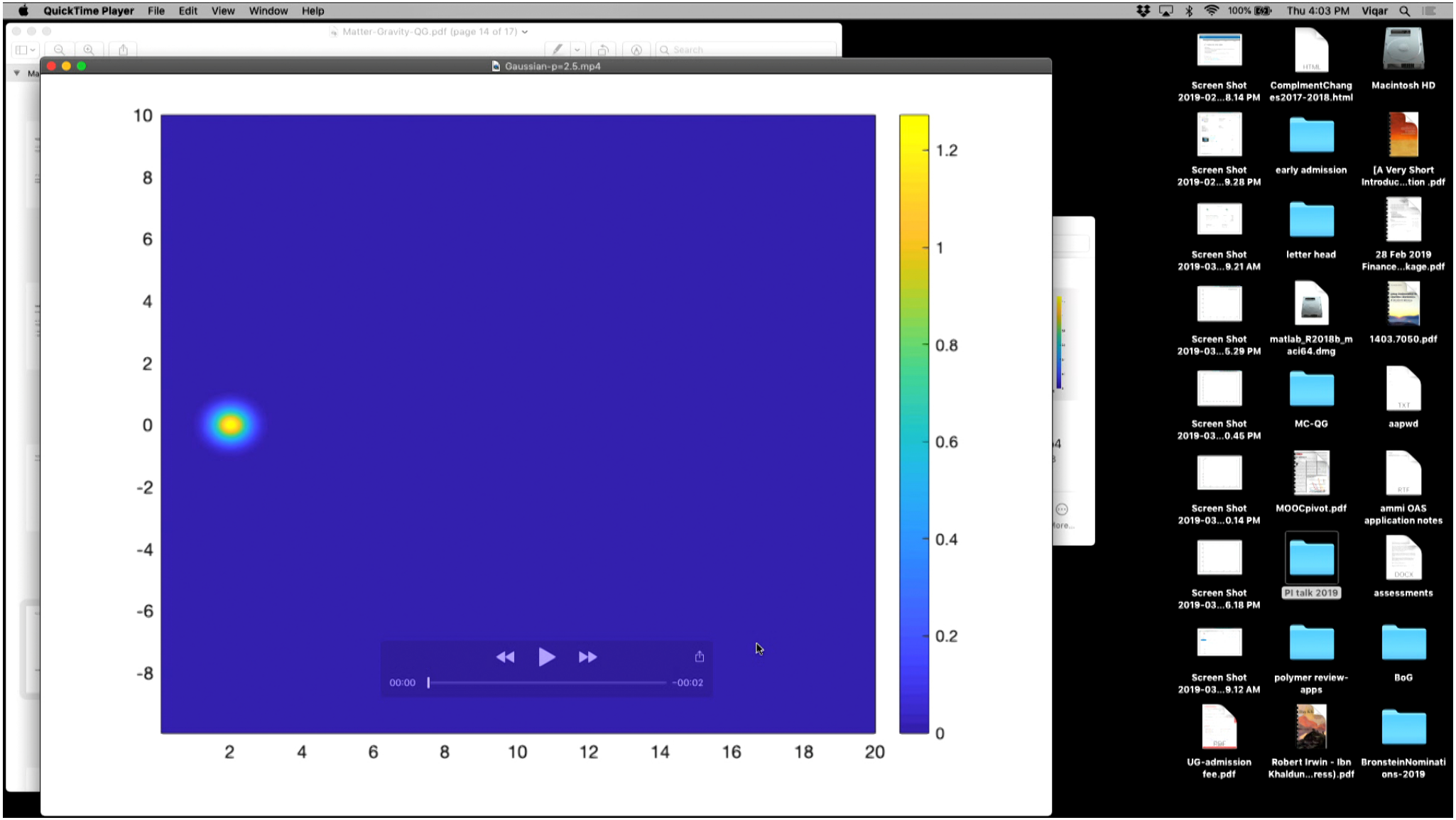


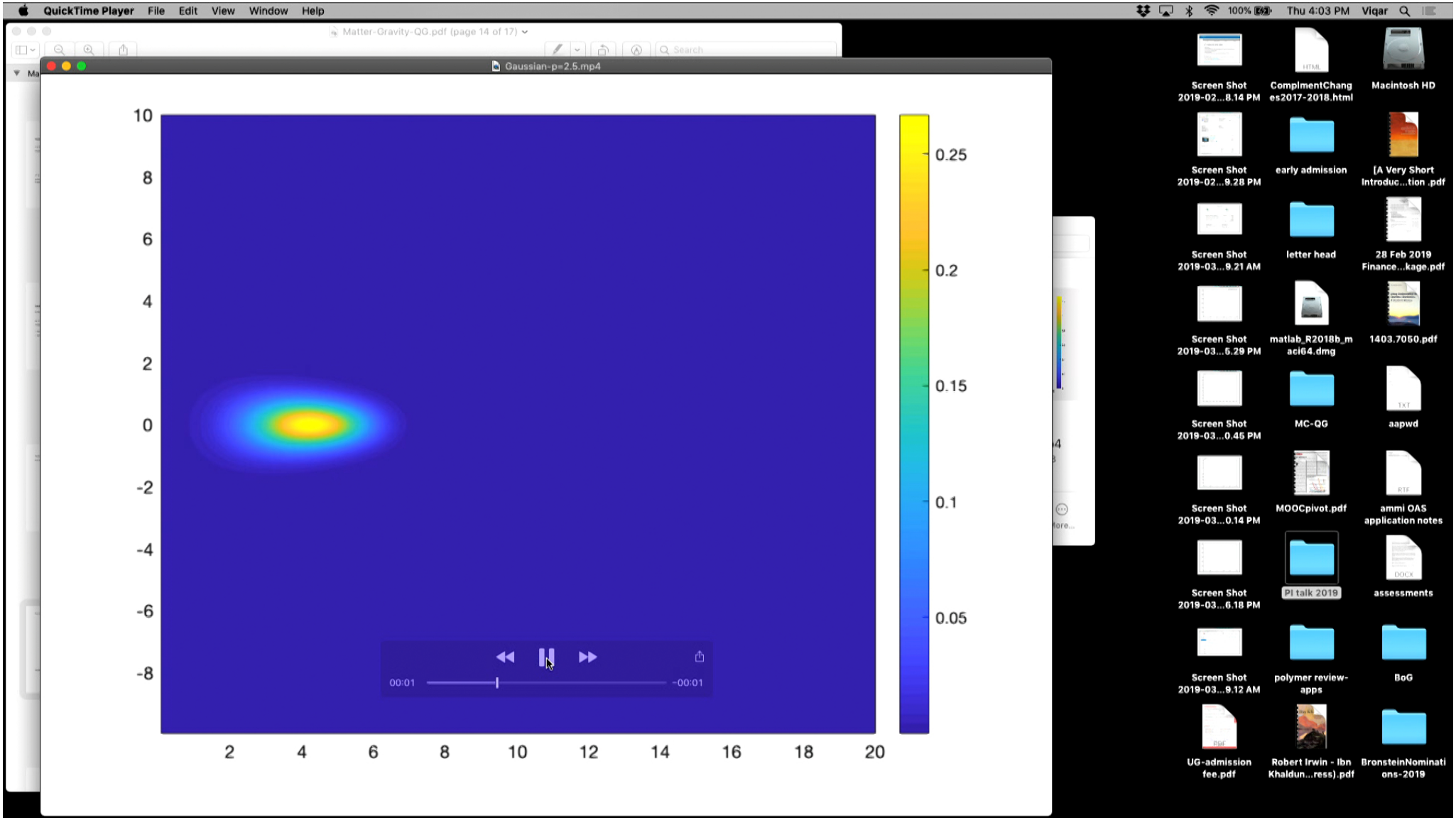
For initial momentum $p_0 = 1.0$:

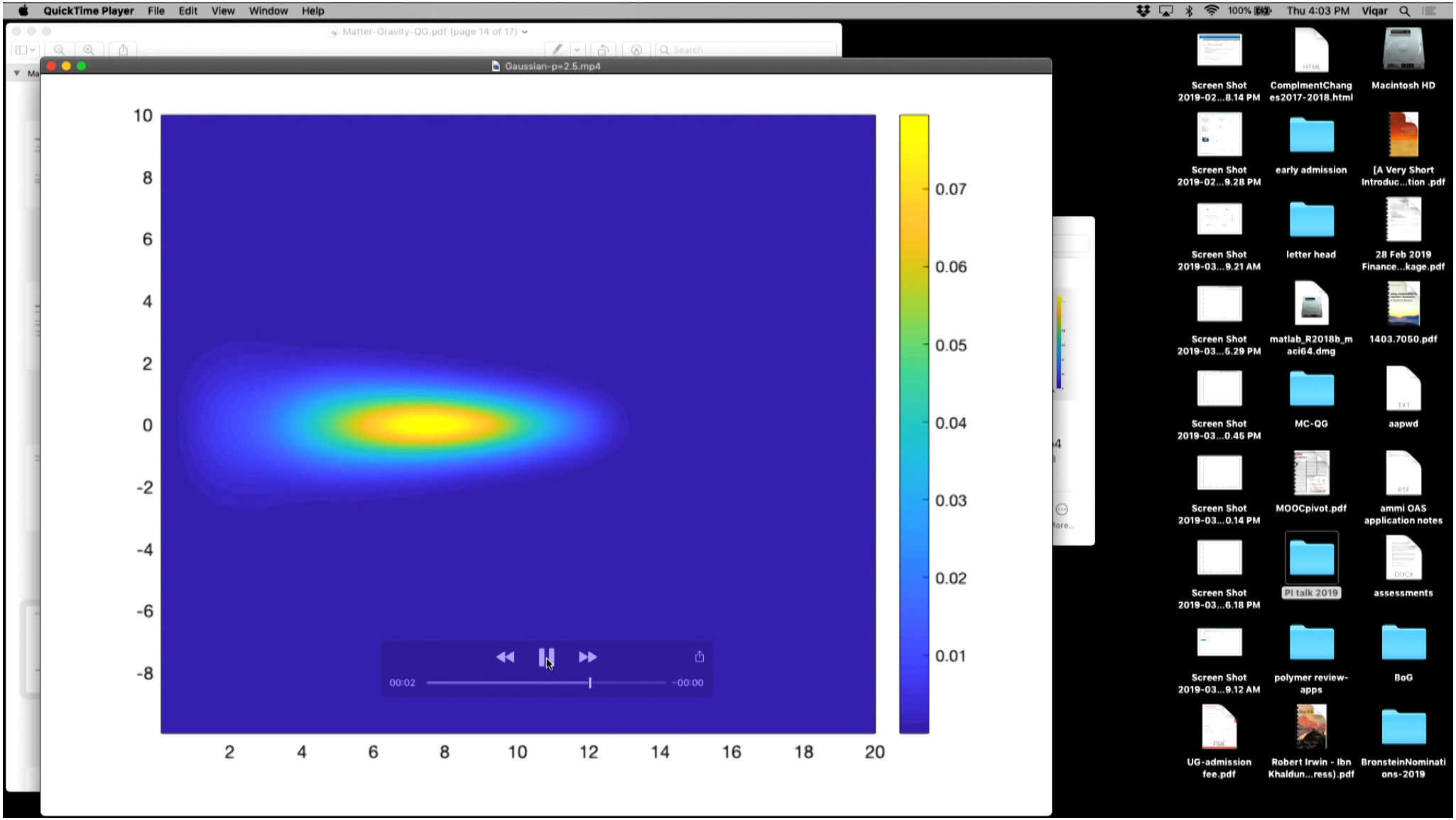


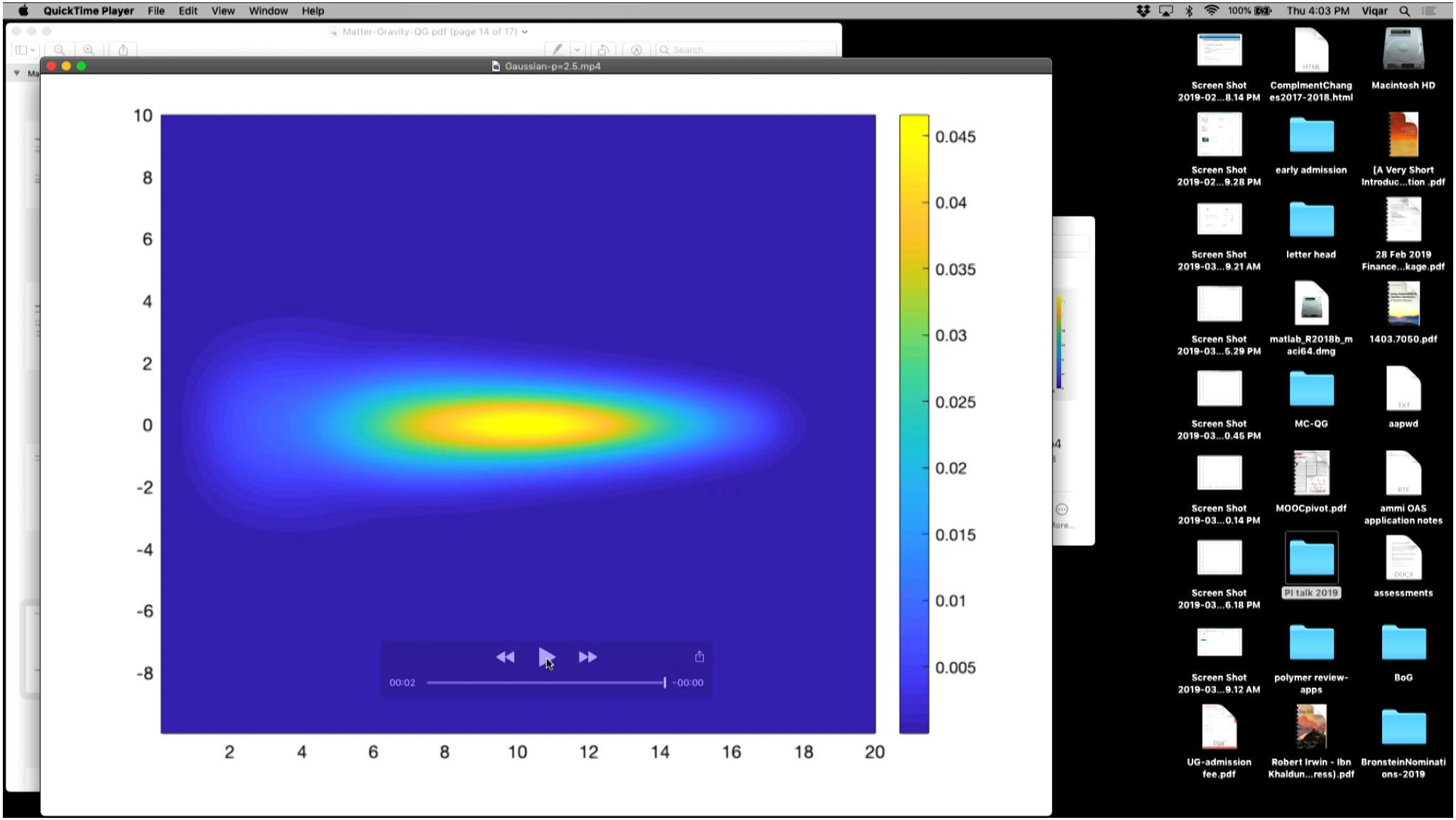
Similar behaviour with a variety of states, including initially entangled states:

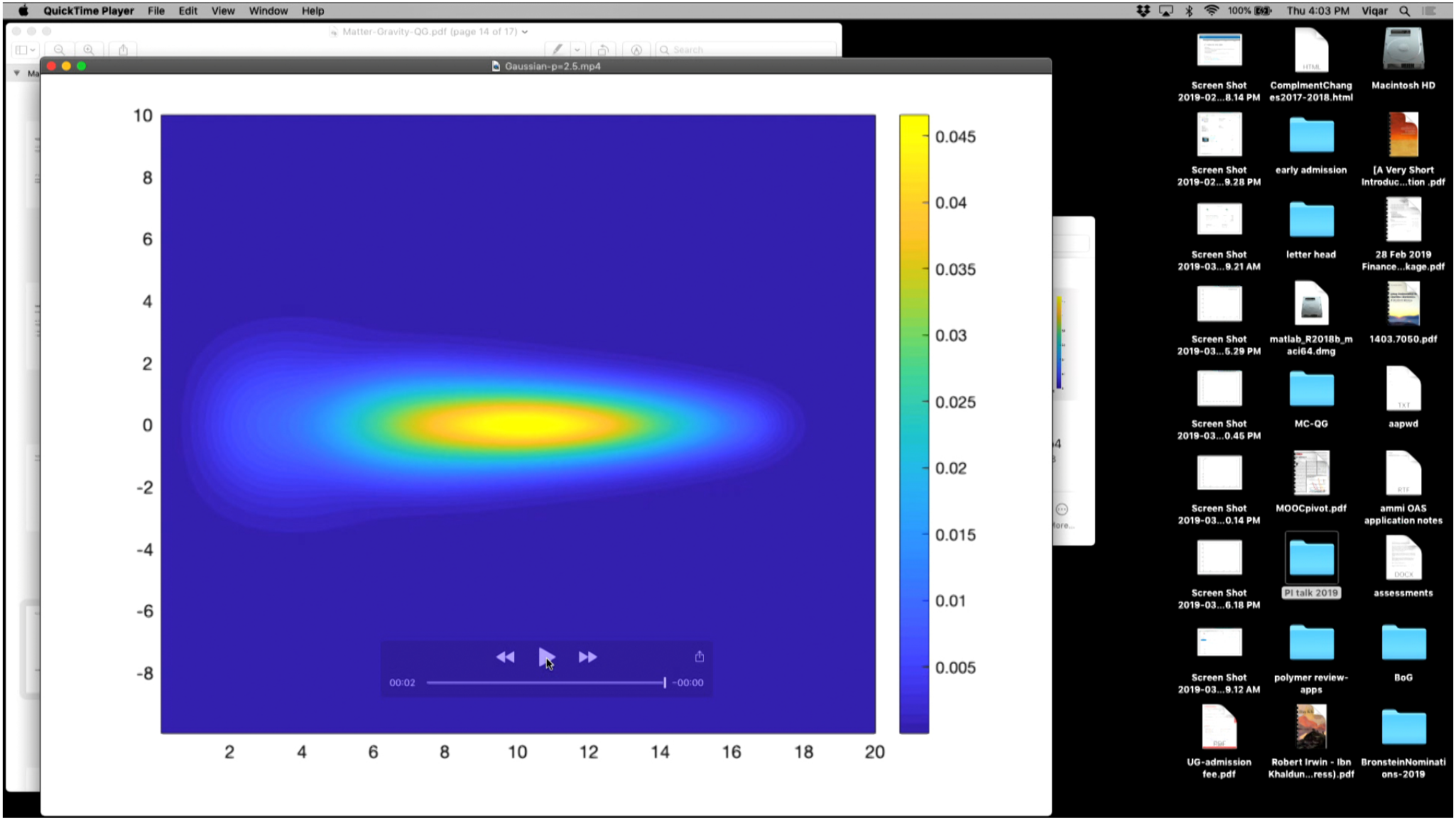
$$\psi_0(x,\phi) = \exp\left\{-[(x-x_0)+(\phi-\phi_0)]^2/w - w[(x-x_0)-(\phi-\phi_0)]^2\right\}$$

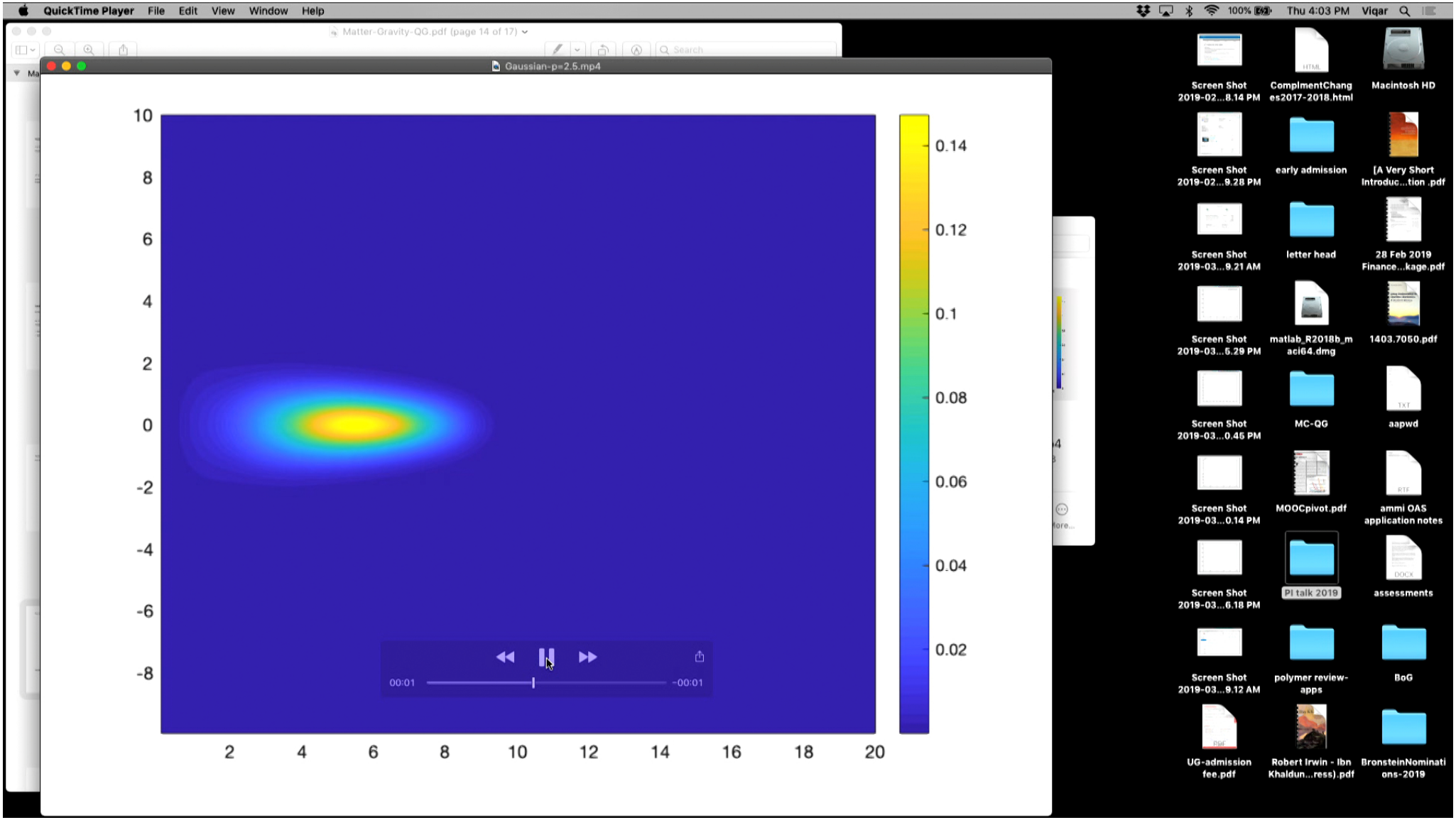

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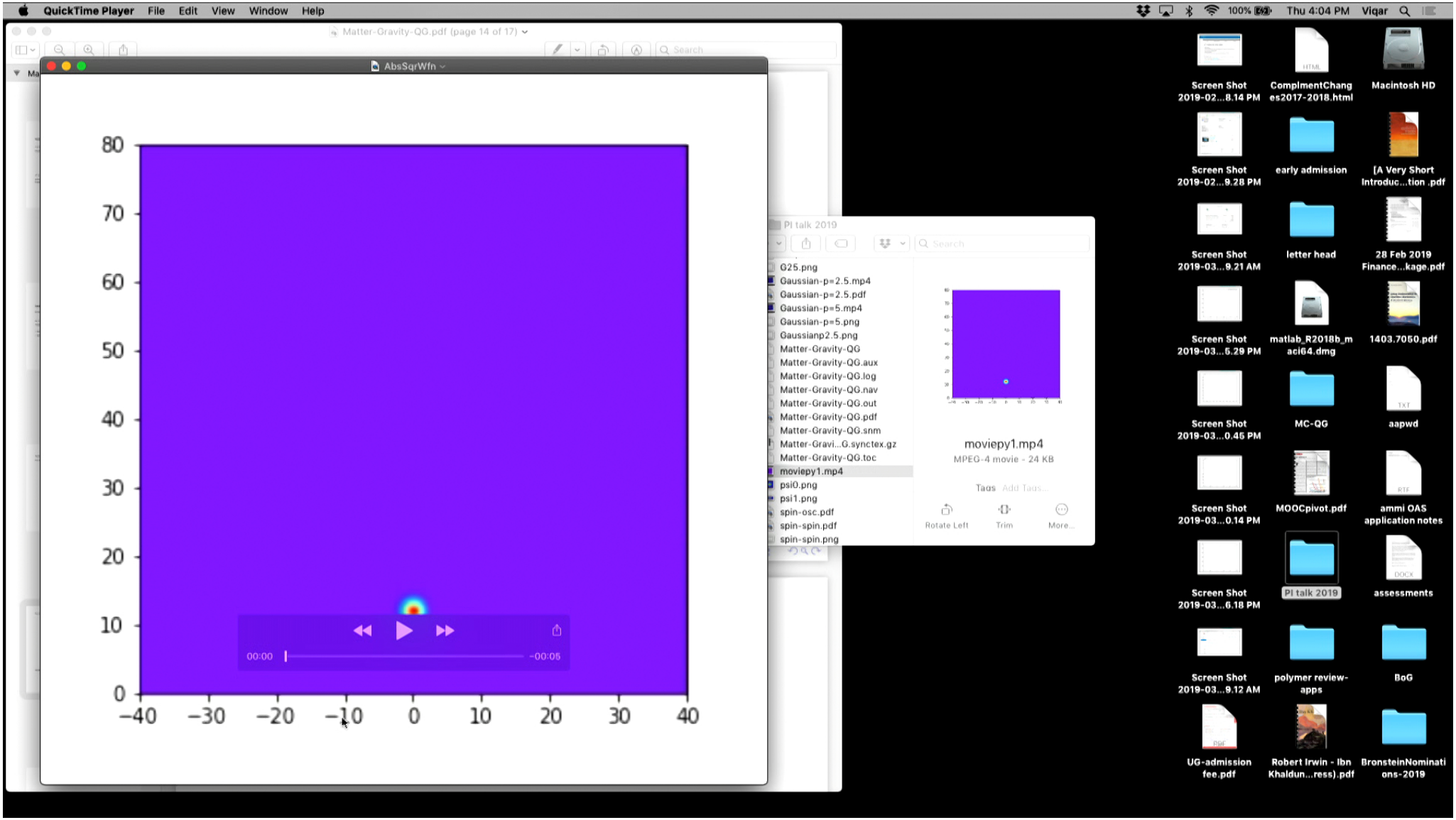

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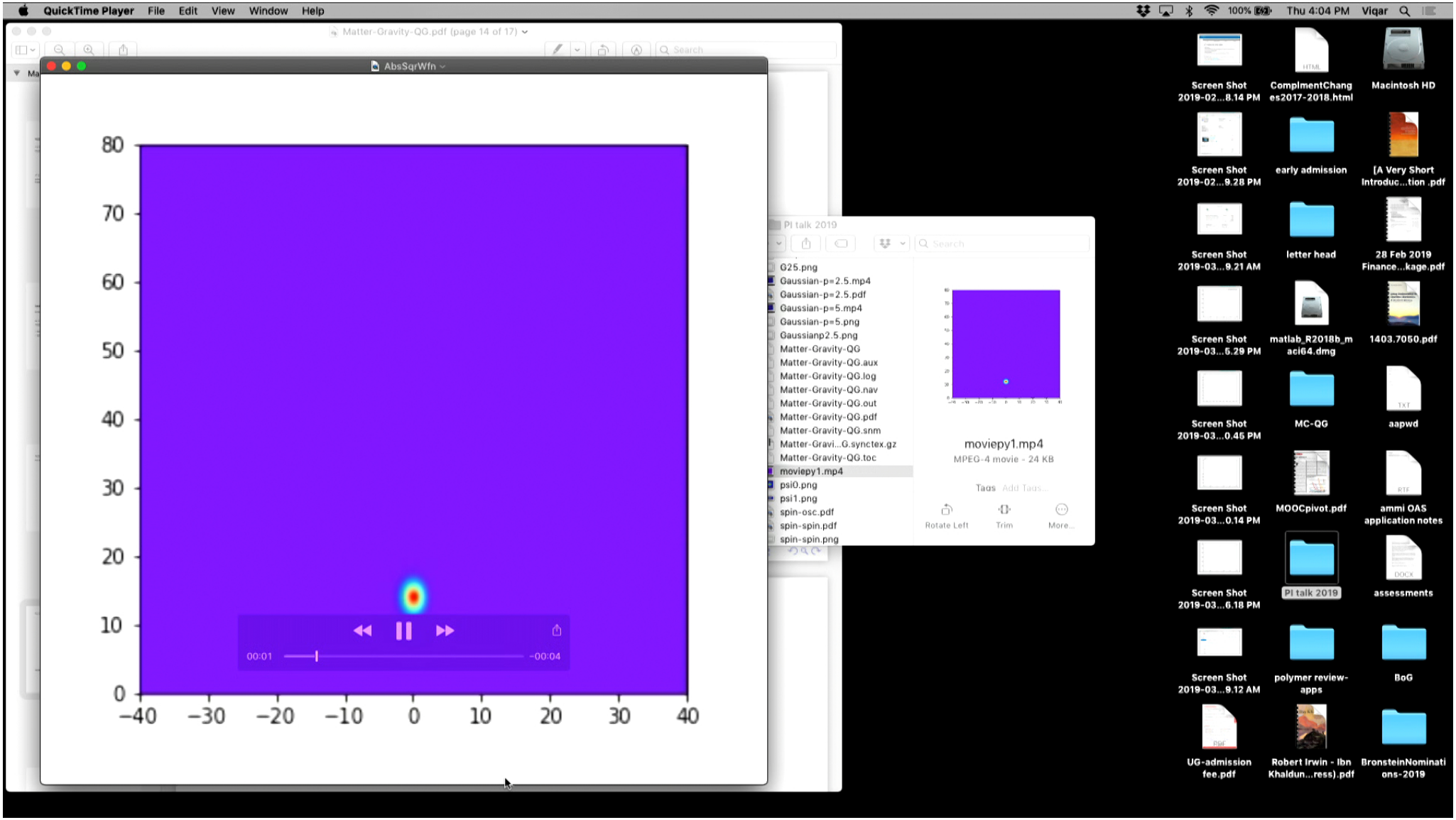

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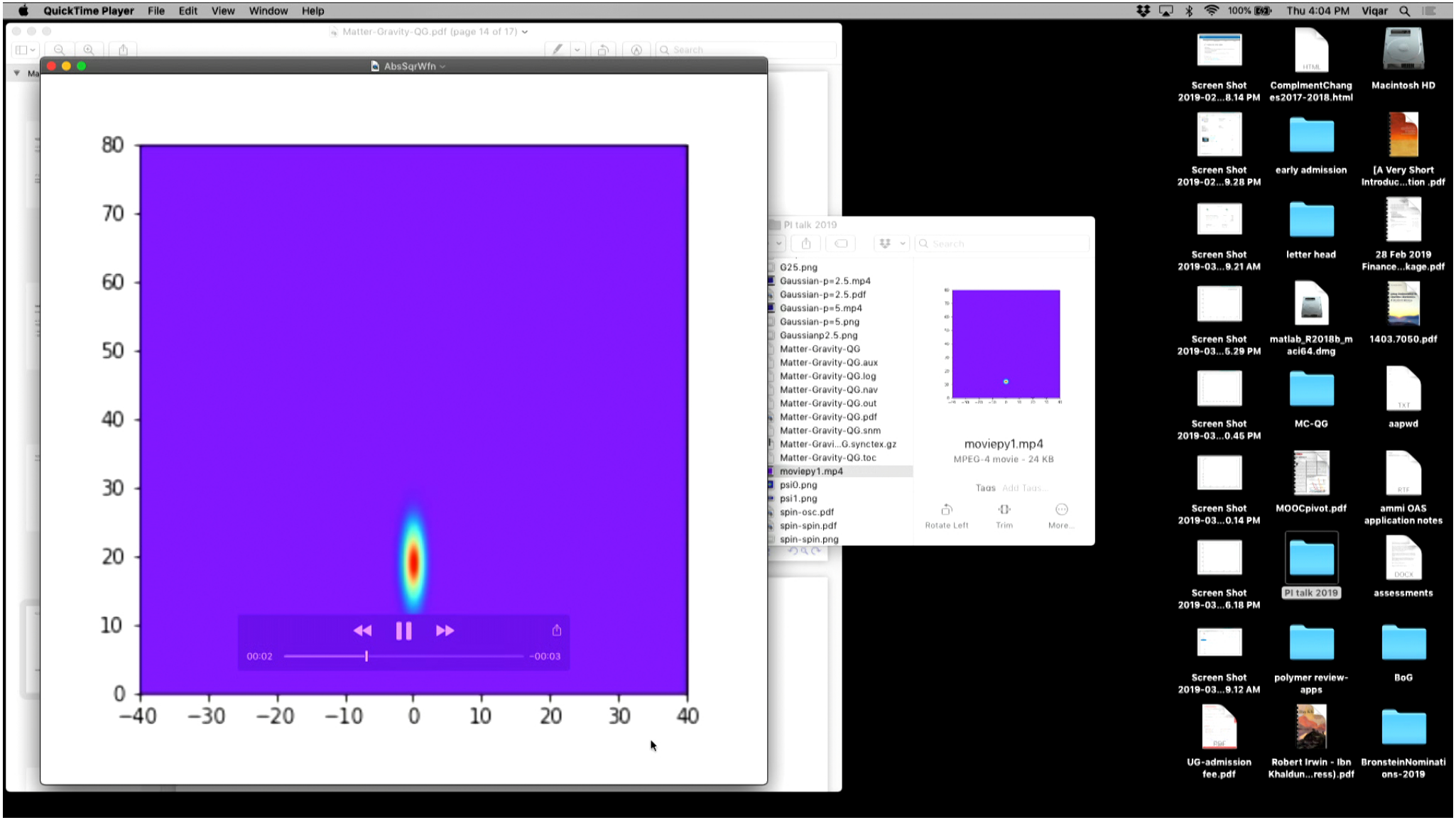

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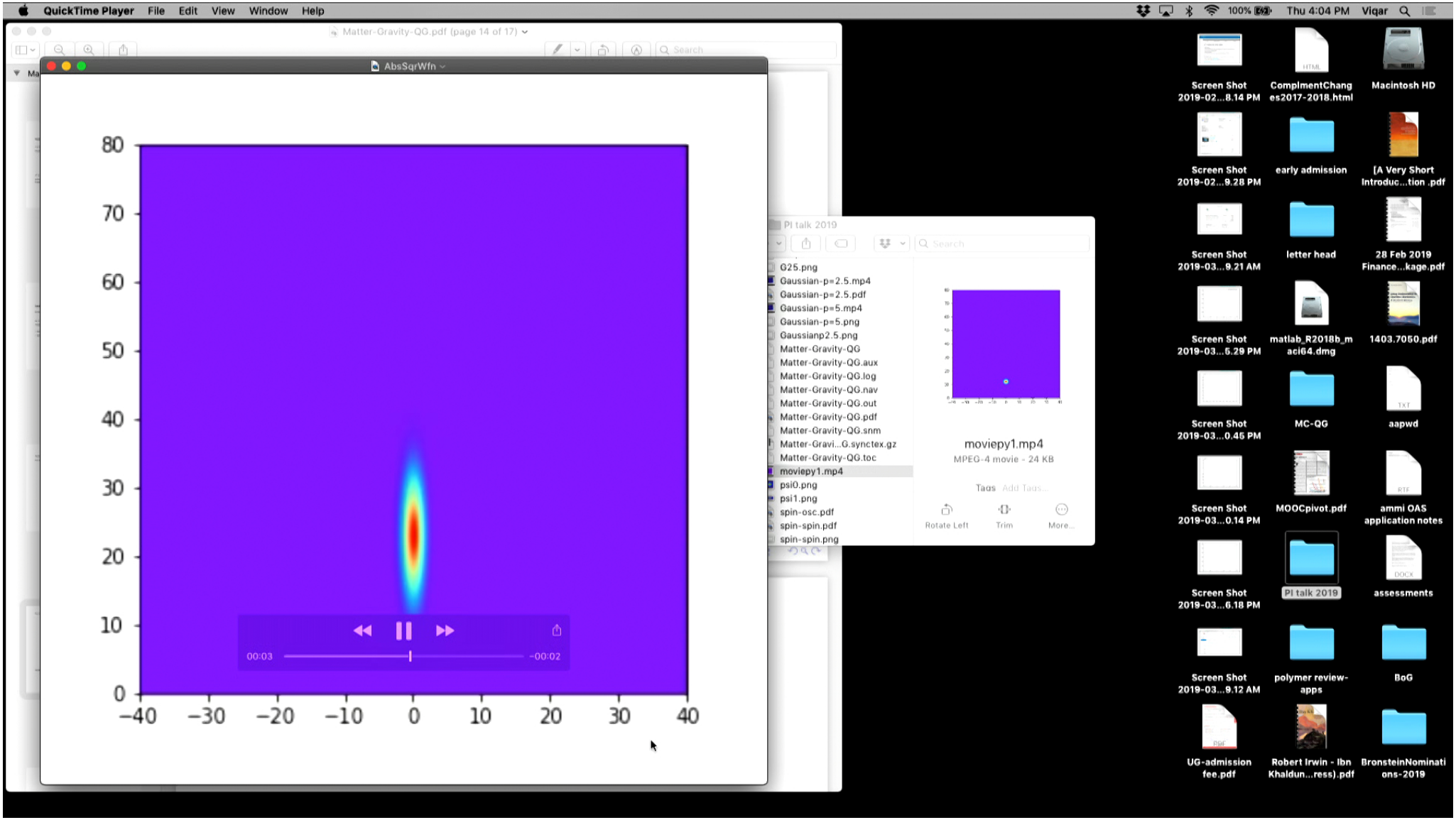

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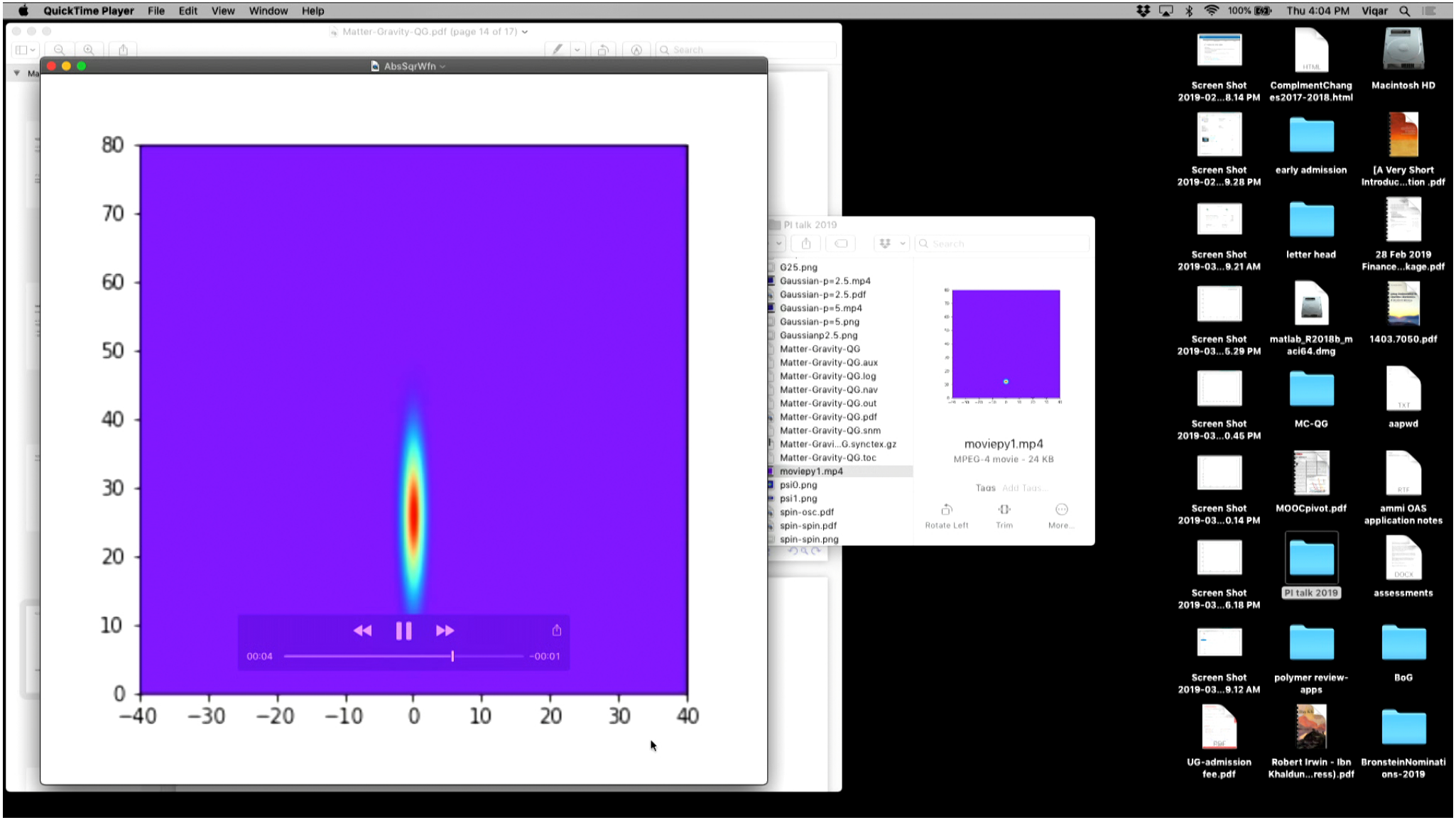

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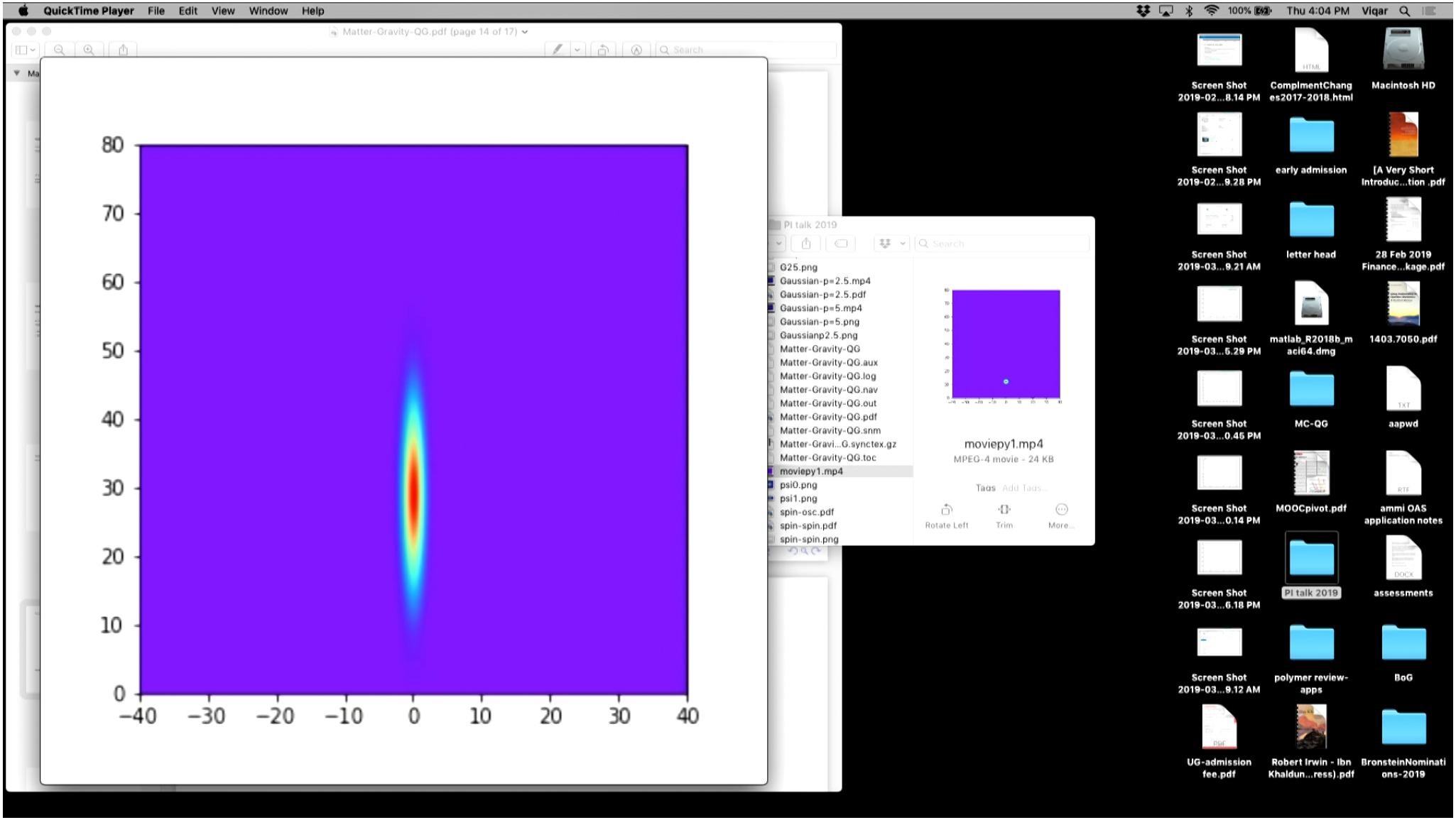

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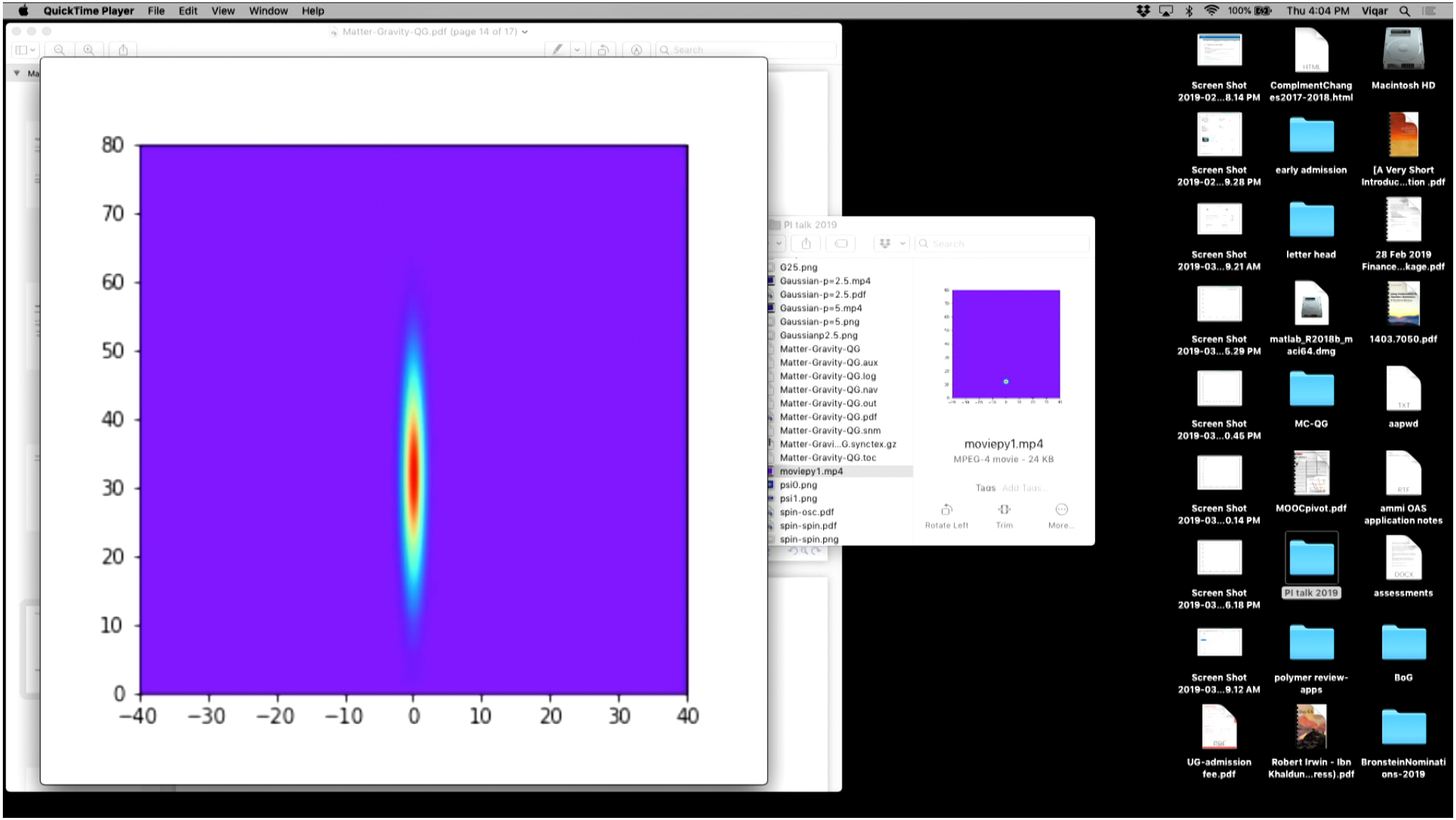

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Main result:

Computational evidence that matter-geometry entanglement entropy increases as the Universe expands.



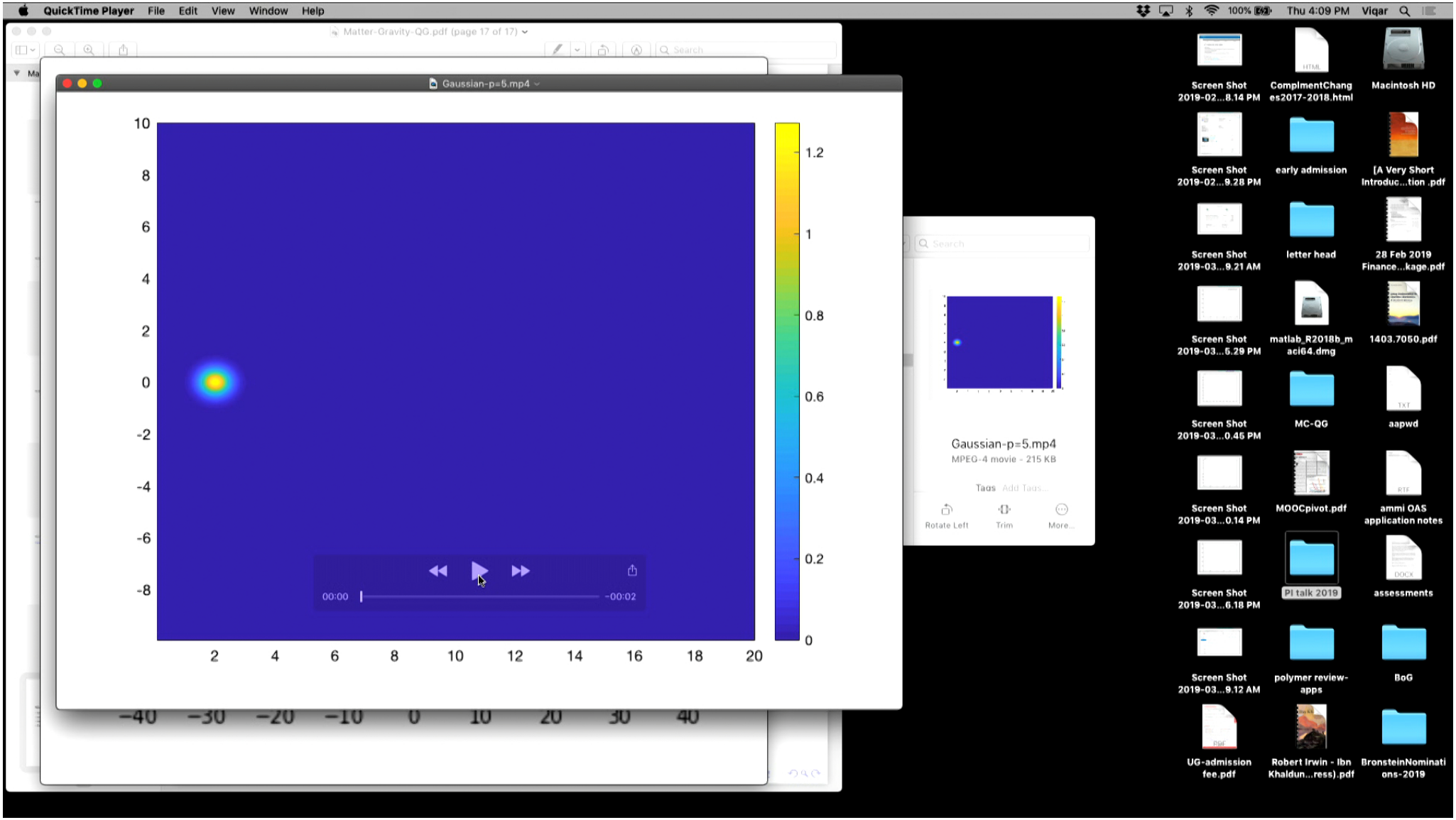
Next steps:

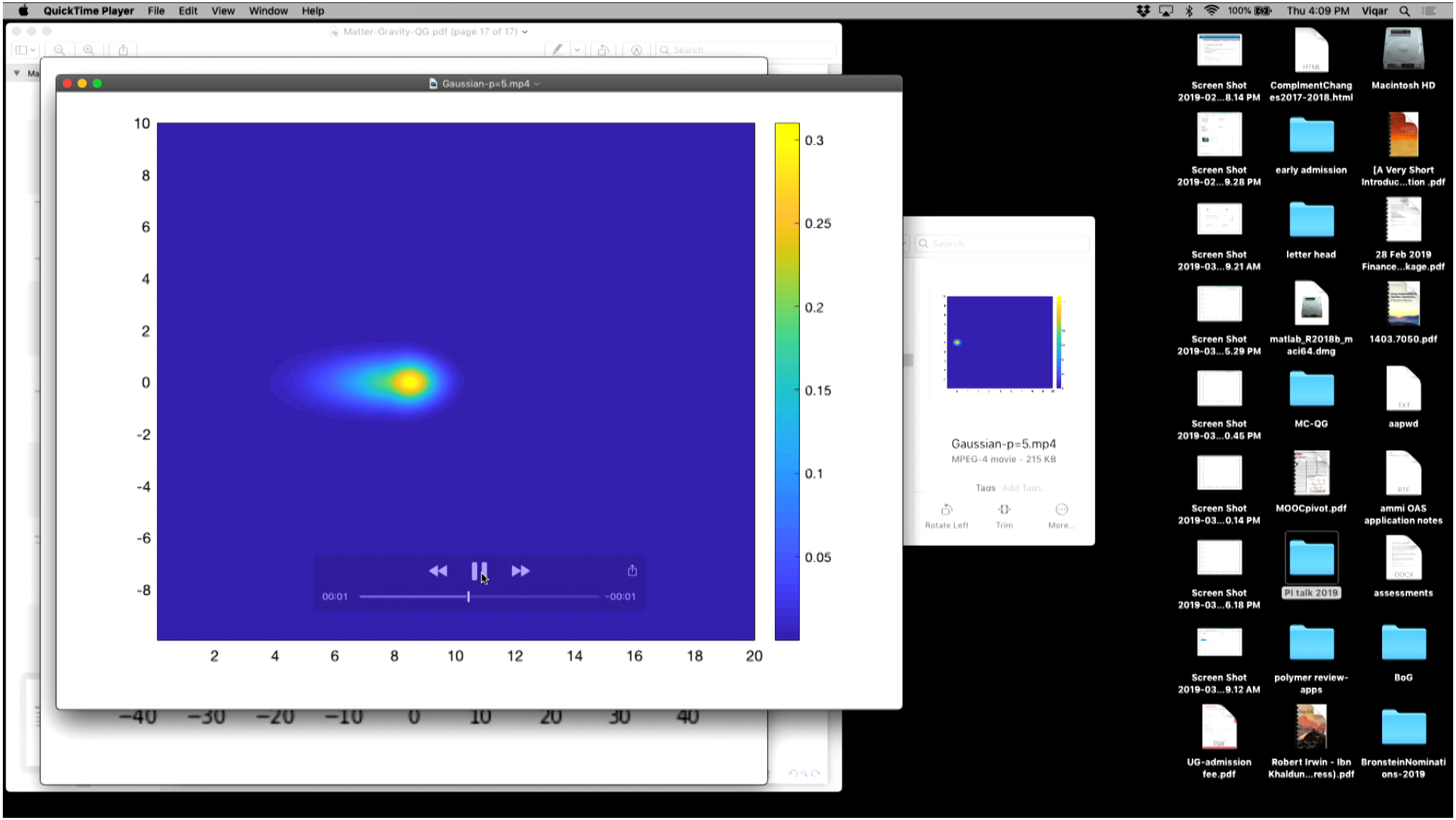
– Gather more evidence: longer evolution times, bigger grids.

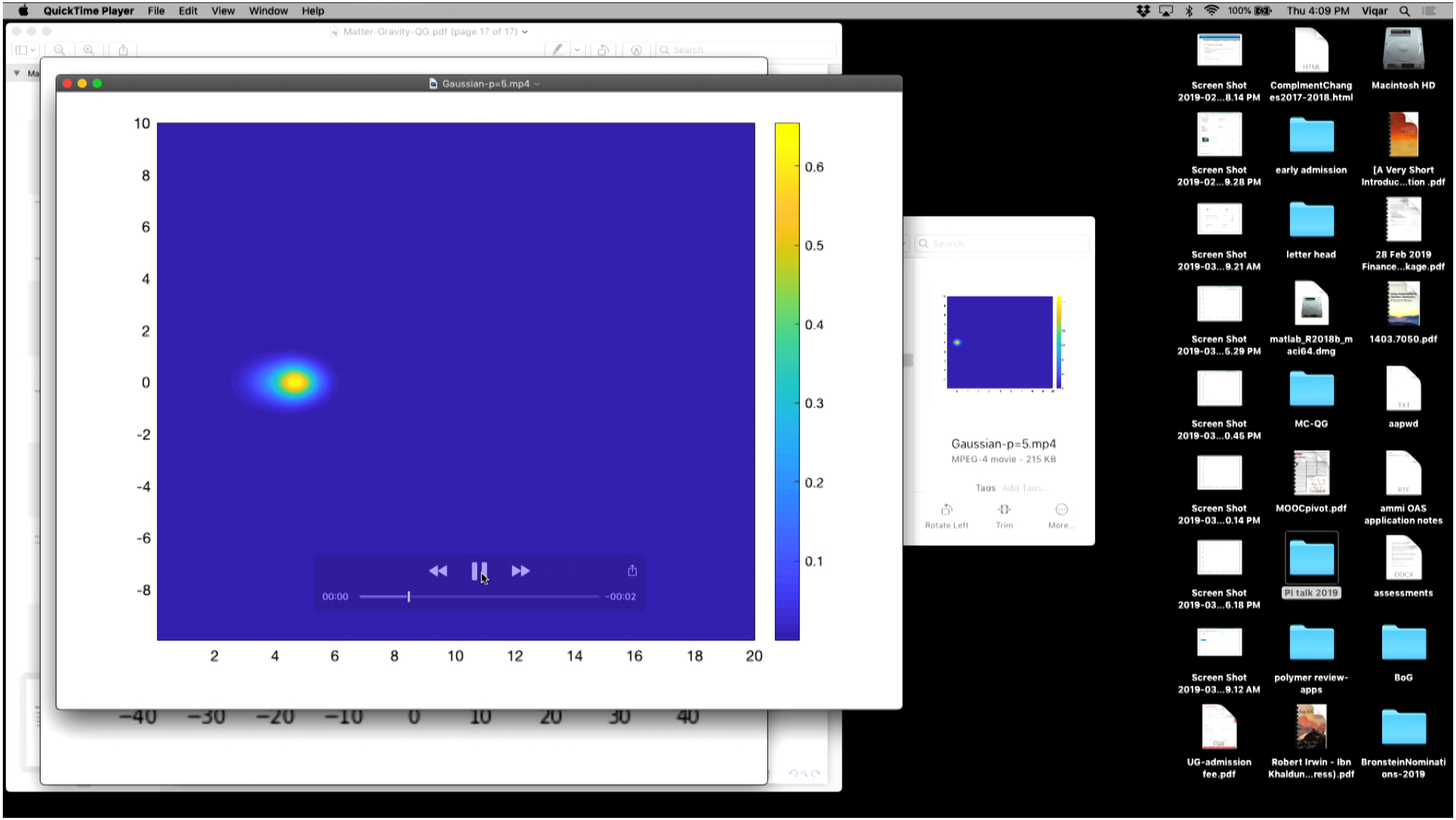
– Larger models

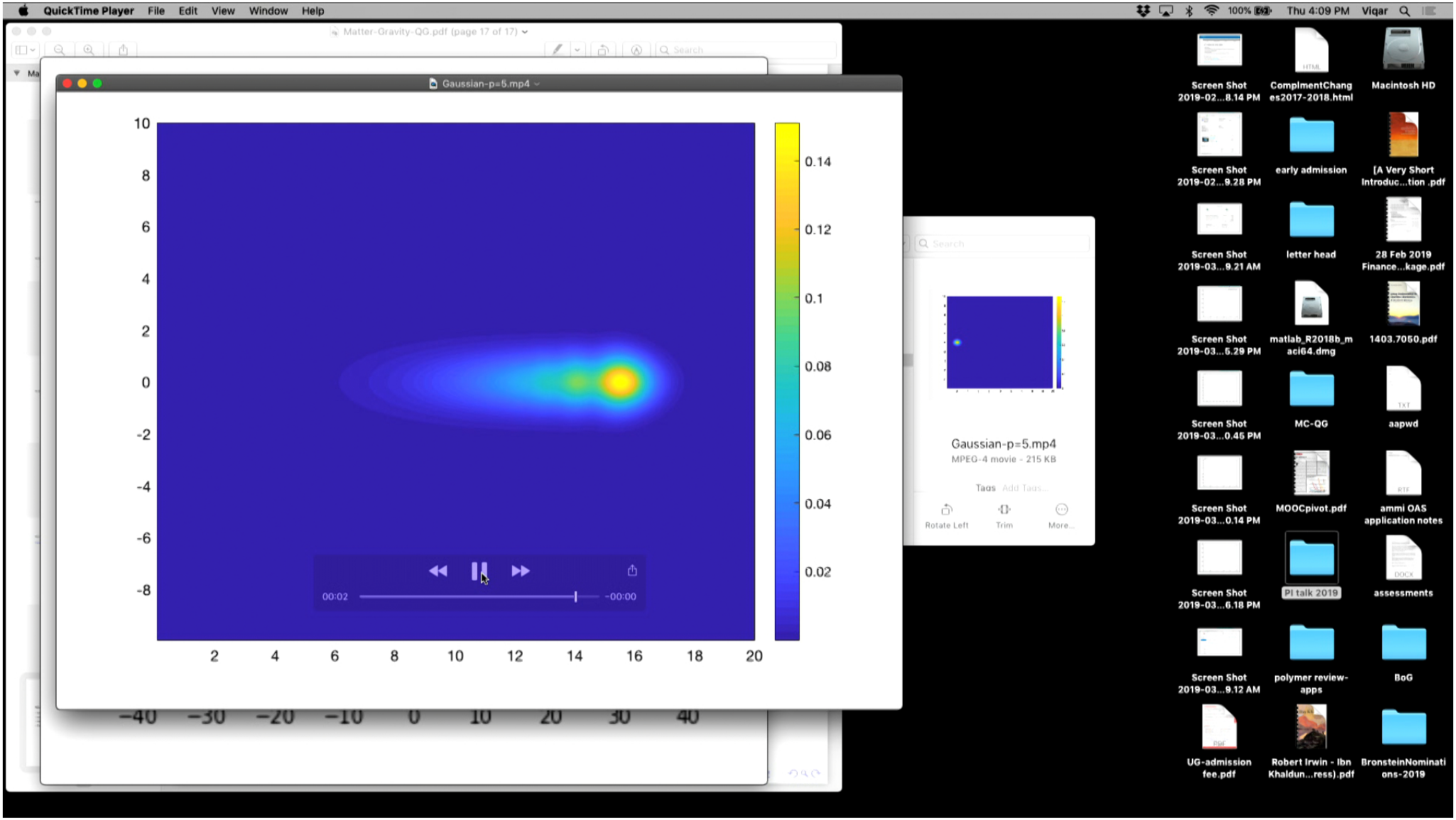
– Other time choices

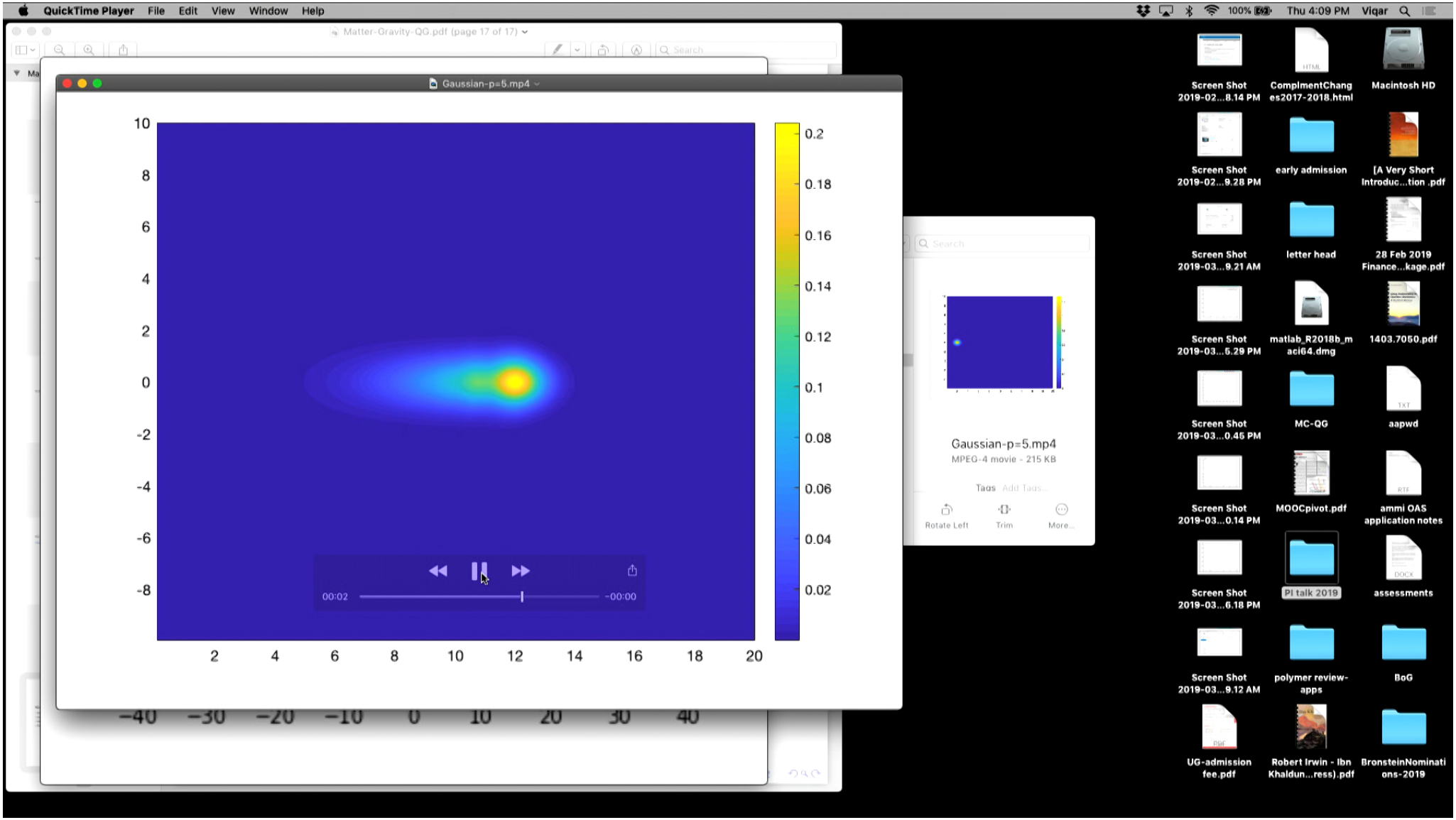
– Physical consequences of matter-geometry entanglement?

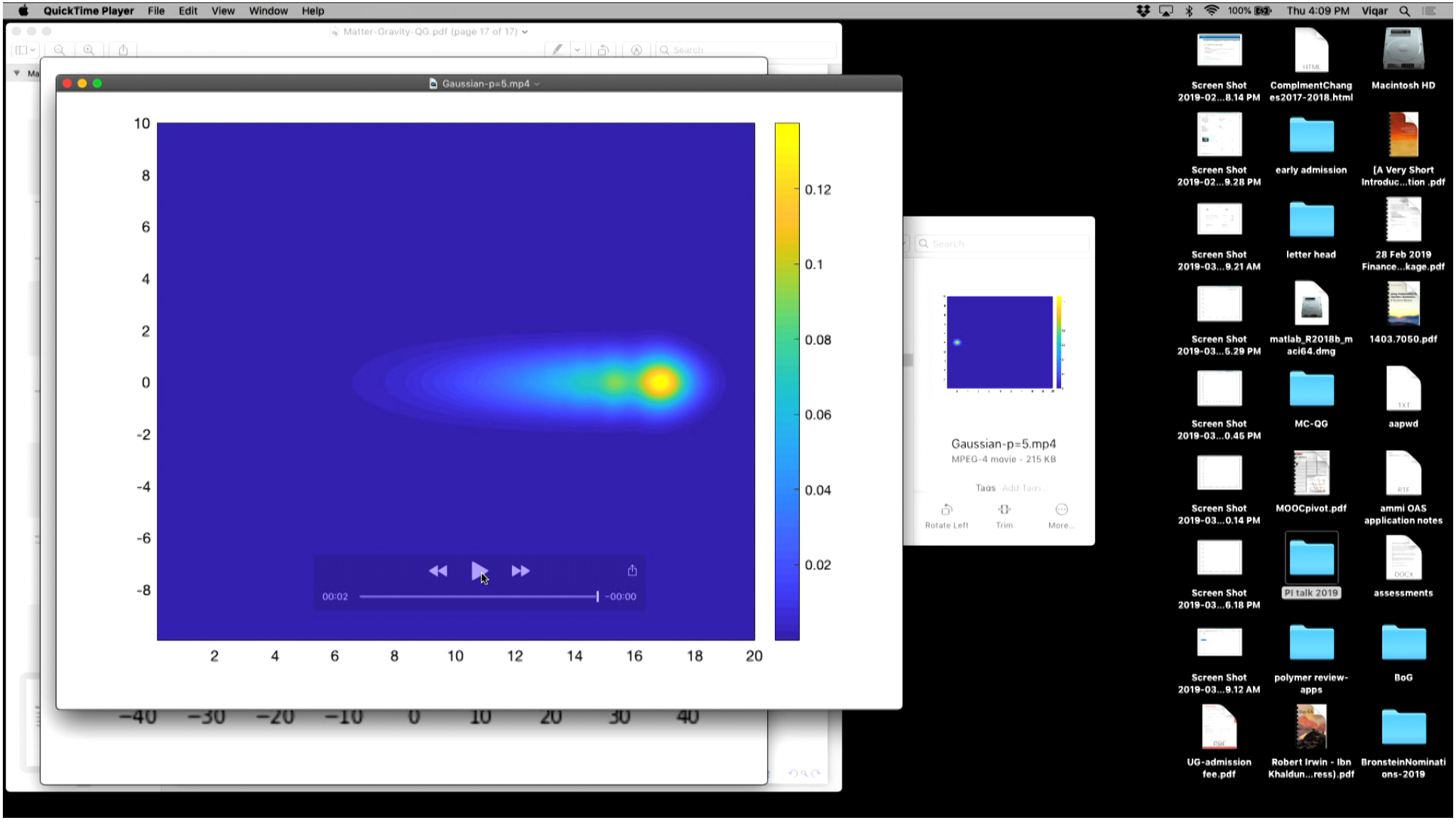

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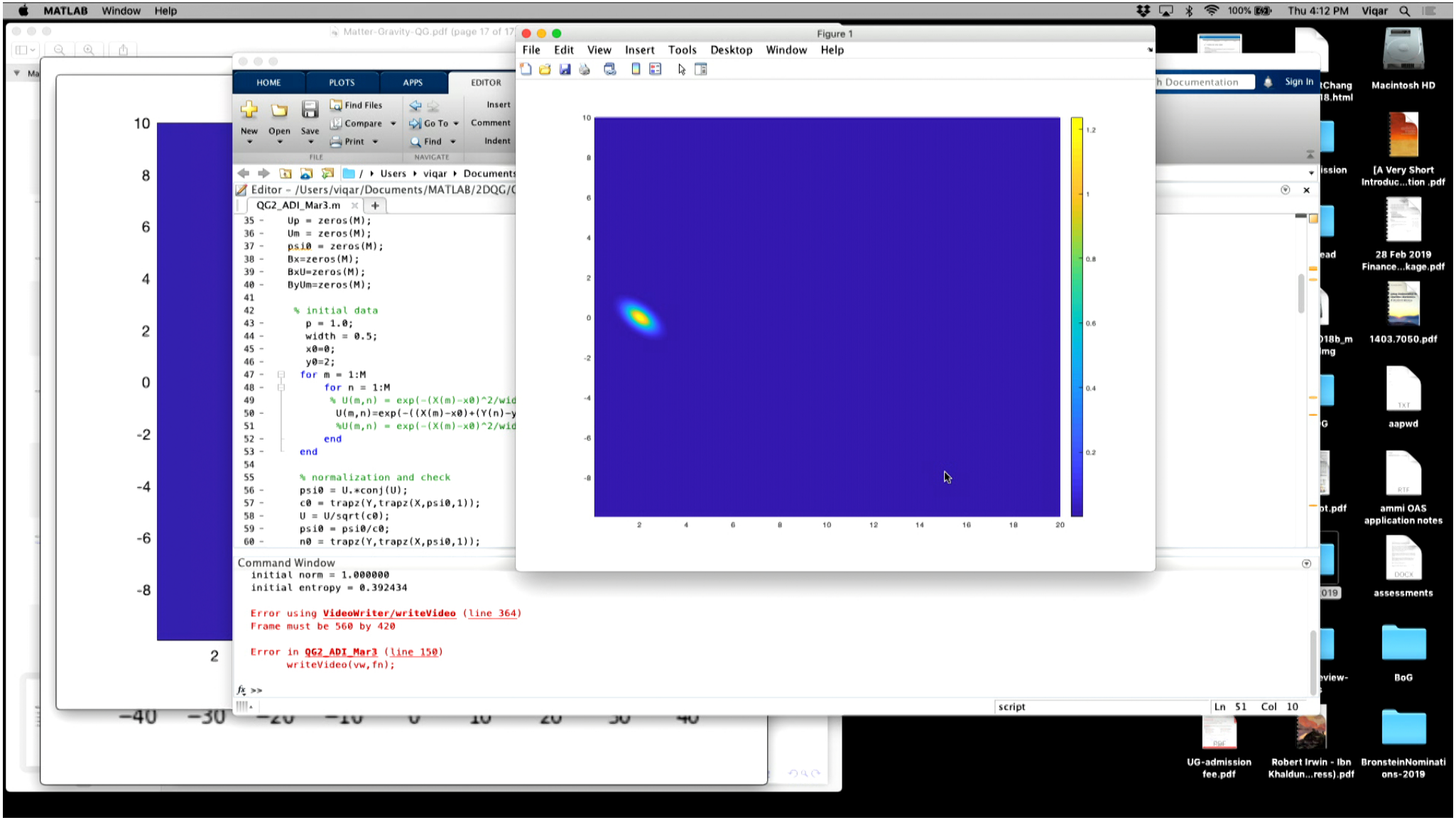

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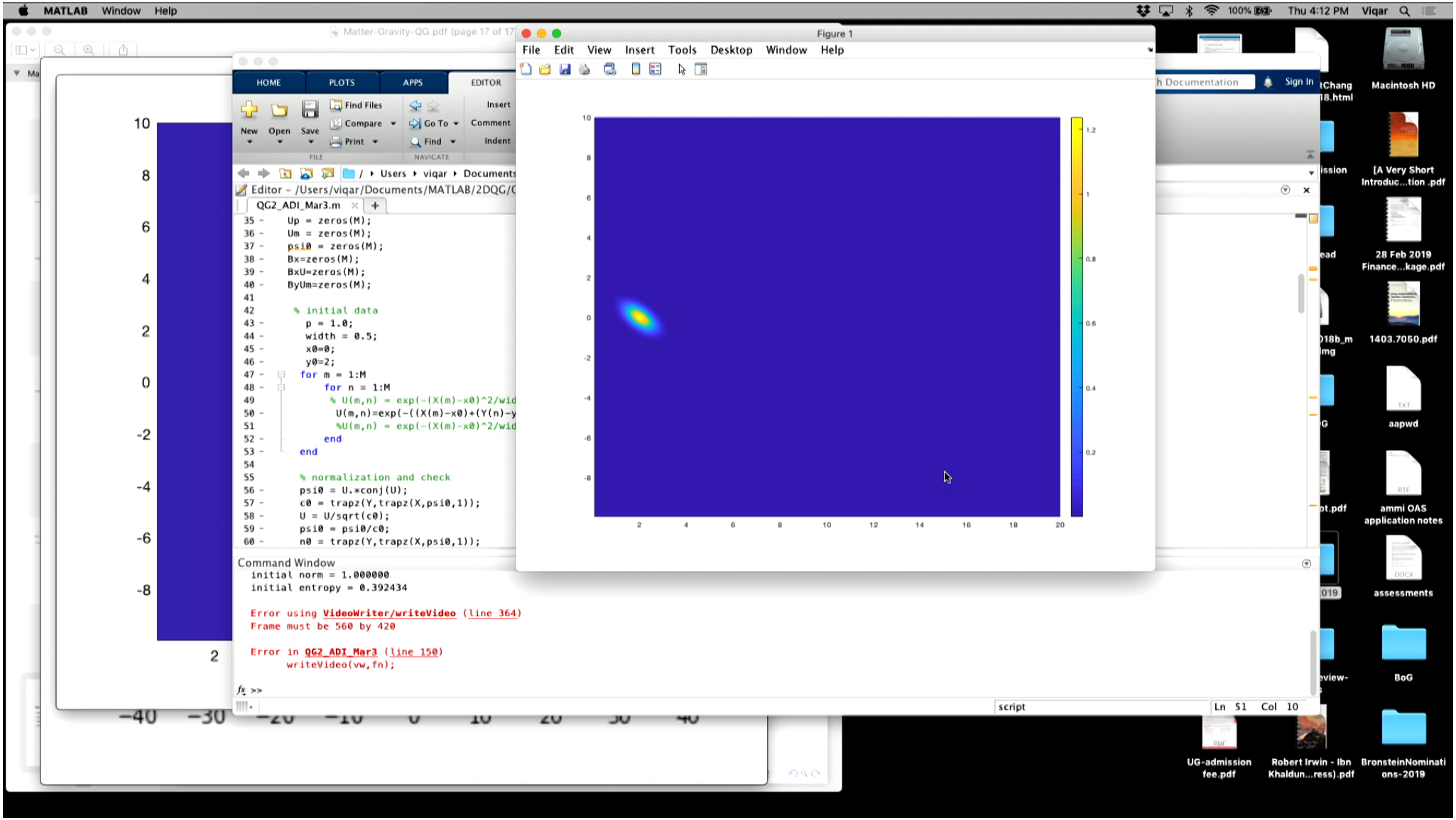

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