Supermassive Black Holes from Superconducting Cosmic Strings

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Workshop in Honour of Brandon Carter, IAP, July 4 - 6 2022

Work in collaboration with B. Cyr and H. Jiao,
`arXiv:2202.01799`

What I am not talking about

S. Brahma, RB, S. Laliberte, arXiv:2206.12468

Emergent metric space-time from BFSS matrix model

- Starting point: BFSS matrix model in a high temperature state.
- Theory of 10 Hermitean $N \times N$ matrices A_μ, $N \to \infty$ limit.
- **Emergent continuous and infinite time** from A_0 matrix.
- **Emergent continuous and infinite space** from A_i matrices
- Phase transition: $S0(9) \to SO(3) \times SO(6)$, only three dimensions become macroscopic.
- **Emergent spatial metric** $g_{ij}(t) = A(t)\delta_{ij}$: spatially flat.
- Thermal fluctuations → scale-invariant spectra of density fluctuations and gravitational waves. (S. Brahma, RB and S. Laliberte, arXiv:2107.11512).

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Supermassive black holes from superconducting cosmic strings

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- Black Holes: one focal point of Brandon’s research.
- Superconducting cosmic strings: another focal point of Brandon’s research.
- This talk: Combination of these two interests of Brandon.
- Loops of superconducting cosmic strings can seed direct collapse black hole formation at high redshifts.
- → explanation for the origin and abundance of observed high redshift super-massive black holes.

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Outline

Plan

High Redshift Super-Massive Black Holes: Challenge for Standard ΛCDM Paradigm

- Black holes with masses $M > 10^9 M_\odot$ observed at redshifts $z > 6$.
- Accretion bounded by Eddington rate.
- $\rightarrow$ high mass nonlinear seeds required at early times.
- Standard ΛCDM model: probability of such nonlinear seeds exponentially suppressed.

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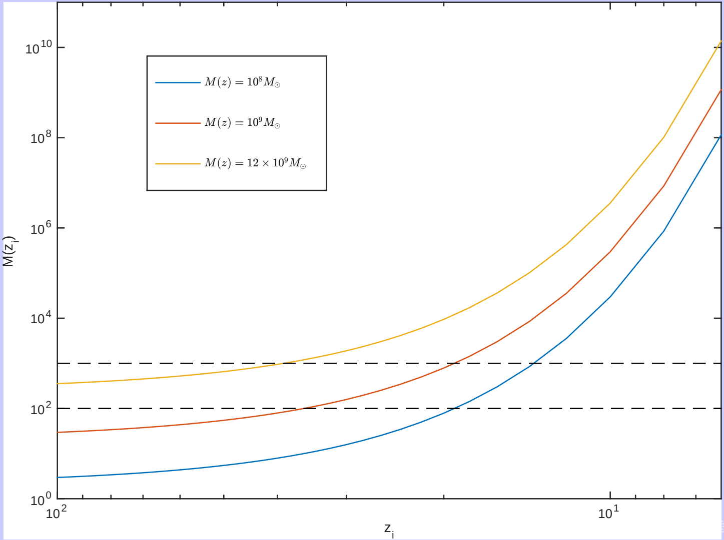
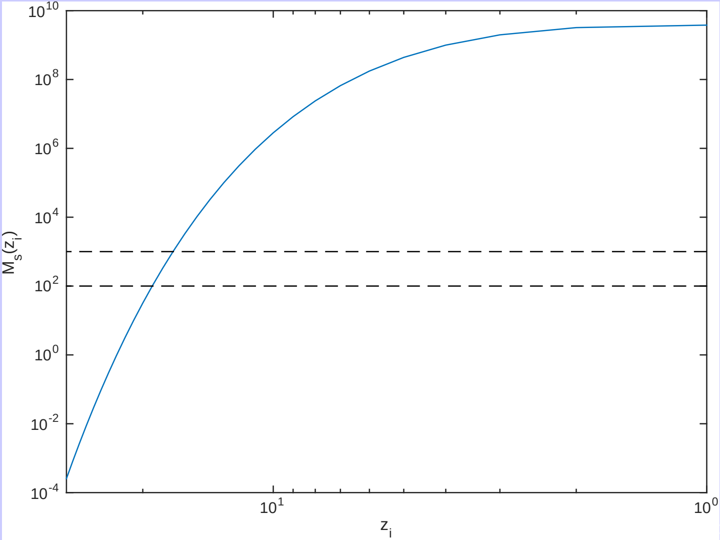
Required Seed Mass (Eddington Accretion)



Abundance of nonlinear overdensities in standard ΛCDM model



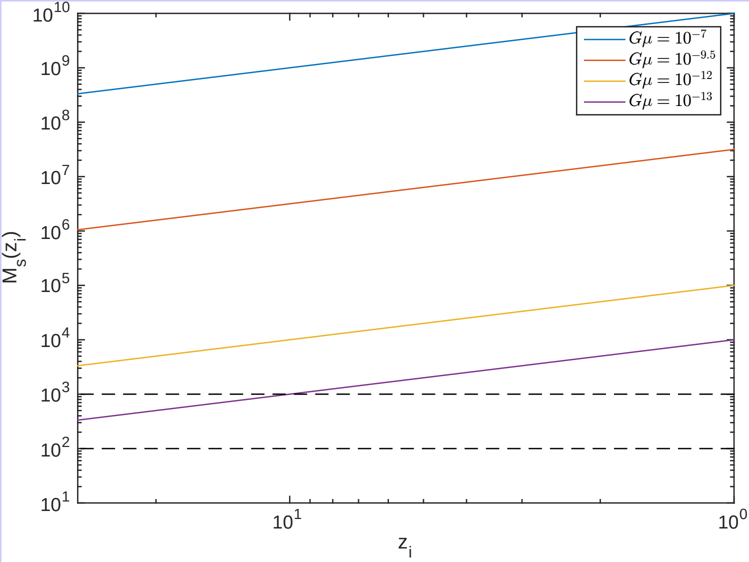
Cosmic Strings to the Rescue

T. Kibble, J. Phys. A **9**, 1387 (1976); Y. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).

- Assume: theory which describes our matter has cosmic string solutions.
- → scaling distribution of strings at all times.
- **Cosmic string loops → nonlinear perturbations at high redshifts.**
- → more massive seeds which have more time to grow.
- → solution of the supermassive black hole mystery.

Abundance of nonlinear overdensities due to cosmic strings

S. Bramberger, R.B., P. Jreidnin and J. Quintin, arXiv:1503.02317



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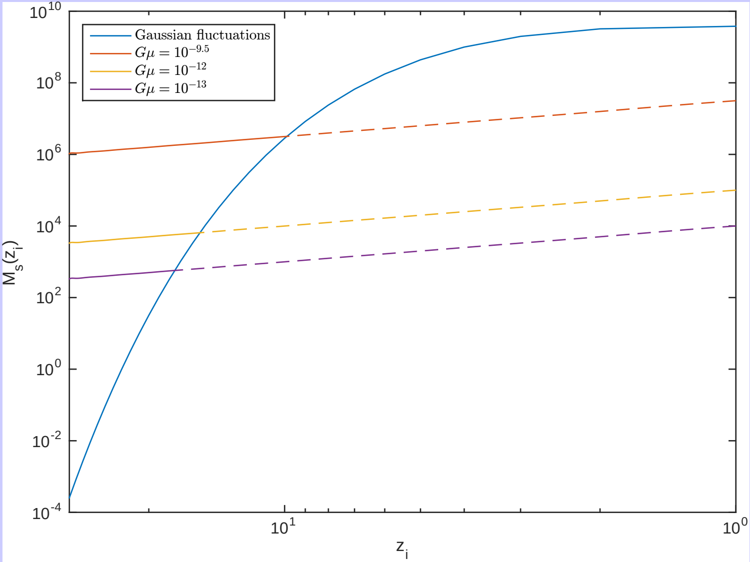

New Challenge

- Nonlinear seeds of sufficient mass is a necessary but not a sufficient criterion for black hole formation.
- The mass needs to collapse to within its Schwarzschild radius.
- In general a collapsing cloud will fragment → no black hole formation.
- Presence of Lyman-Werner radiation can prevent the fragmentation.
- Superconducting cosmic strings produce Lyman-Werner radiation.
- Superconducting cosmic string loops → direct collapse black hole formation.

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- Cosmic string = linear topological defect in a quantum field theory.
- 1st analog: line defect in a crystal
- 2nd analog: vortex line in superfluid or superconductor
- Cosmic string = line of trapped energy density in a quantum field theory.
- Trapped energy density → gravitational effects on space-time → important in cosmology.

Relevance to Particle Physics I

- Cosmic string solutions exist in many particle physics models beyond the “Standard Model".
- In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.
- Seeing a cosmic string in the sky would provide a guide to particle physics beyond the Standard Model!
- Cosmic strings approach a **scaling solution**: the statistical properties of the string network is independent of time if all length are scaled to the Hubble radius.
- Scaling solution is independent of the string tension.
- String network consists of **long strings** and **string loops**.

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Relevance to Particle Physics II

- Cosmic strings are characterized by their tension μ which is associated with the energy scale η at which the strings form ($\mu \sim \eta^2$).
- Searching for the signatures of cosmic strings is a tool to probe physics beyond the Standard Model at energy ranges complementary to those probed by the LHC.
- Cosmic strings are constrained from cosmology: $G\mu \leq 1.3 \times 10^{-7}$ otherwise a conflict with the observed acoustic oscillations in the CMB angular power spectrum (Dvorkin, Hu and Wyman, 2011).
- String loops oscillate and emit gravitational waves.
- Constraints as low as $G\mu < 10^{-10}$ follow from pulsar timing constraints on the amplitude of the spectrum of stochastic GW background.
- Existing upper bound on the string tension rules out large classes of "Grand Unified" models.

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Relevance to Cosmology

Strings can produce many good things for cosmology:

- String-induced mechanism of baryogenesis (R.B., A-C. Davis and M. Hindmarsh, 1991).
- Explanation for the origin of primordial magnetic fields which are coherent on galactic scales (X.Zhang and R.B. (1999)).
- Seeds for high redshift supermassive black holes (S. Bramberger, R.B., P. Jreidini and J. Quintin, 2015; R.B., B. Cyr and H. Jiao, 2021).
- **Origin of globular clusters** (A. Barton, R.B. and L. Lin, 2015; R.B., L. Lin and S. Yamanouchi, 2015).
- Origin of fast radio bursts (R.B., B. Cyr and A. Iyer, 2017).
- Global 21-cm absorption signal (EDGES) (R. Thériault, J. Mirocha and R.B. 2021)

Cosmic string scaling solution

- At any time t there will be a network of “infinite" strings with curvature radius $\sim t$, ~ 1 per Hubble volume.
- At any time t there will be a distribution of string loops with radii R

$$n(R, t) \,=\, N R^{-5/2} t_{eq}^{1/2} t^{-2} \quad \gamma G\mu t < R < \alpha t$$

- $R_c = \gamma G\mu t$: gravitational radiation cutoff. Loops with $R < R_c$ negligible.

Superconducting Strings

E. Witten, Nucl. Phys. B249, 557 (1985)

- In many models, cosmic strings can carry currents → superconducting cosmic strings.
- Bosonic and Fermionic superconductivity.
- In Grand Unified Models cosmic string superconductivity is generic.
- In superconducting string models there is an additional parameter characterizing the string network, the **current I**.
- “Maximal" current I_c: for $I > I_c$ electromagnetic radiation dominates → cutoff R_c on loop distribution changes..

Note: Brandon Carter pioneered a large body of work on superconducting cosmic strings, e.g. on vorton formation (B. Carter, Int. J. Theor. Phys. 36, 2451 (1997)).

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Plan

1. Observational Challenge
2. Cosmic String Review
3. Super-Massive High Redshift Black Holes from Superconducting Cosmic Strings
4. Globular Clusters from Cosmic Strings
5. Conclusions

Challenge

- **Primordial black holes**: Hubble scale nonlinearities form a black hole because the Schwarzschild radius equals the radius of the overdensity.
- ΛCDM model of cosmology $\rightarrow$ nonlinearities form at late times and on scales much smaller than the Hubble radius. $\rightarrow$ Schwarzschild radius is parametrically smaller than the radius of the overdensity..
- Insufficient to have nonlinear fluctuations: Need to demonstrate that the mass collapses to inside the Schwazschild radius.
- In general, a collapsing gas cloud will fragment, form stars and never lead to a super-massive black hole (only stellar mass black holes).

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Direct Collapse Black Hole Criteria

To allow a gas cloud to collapse into a super-massive black hole the following criteria must be satisfied:

- **Sufficient mass condition**: $M_b > 10^5 M_{\odot}$ to form a super-massive black hole.
- **Atomic cooling threshold condition**: Collapse without fragmentation → $T_{vir} > 10^4 K$.
- **No heavy metal condition**: presence of heavy metals woud allow cooling → fragmentation.
- **No molecular hydrogen**: would lead to cooling and fragmentation → requires presence of a Lyman-Werner background of $J > J_c \sim 10^{-44} \mathrm{GeV}^3$.

Realizing the Direct Collapse Black Hole Criteria I

B. Cyr, H. Jiao and RB, arXiv:2202.01799, MNRAS, in press

Sufficient mass condition at redshift $z < z_{rec}$:

$$M_b(z) = \frac{\Omega_b(z)}{\Omega_M(z)} \beta \mu R \frac{1 + z_{eq}}{1 + z} > 10^5 M_\odot$$

$$\rightarrow R_c < R < \alpha t_{eq}$$

There is a range of loop radii for which the condition is satisfied.

Atomic cooling condition:

Spherical collapse → kinetic energy at collapse → converted to virial temperature.
Result: atomic cooling condition satisfied whenever the mass condition is met.

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Realizing the Direct Collapse Black Hole Criteria II

Lyman-Werner condition

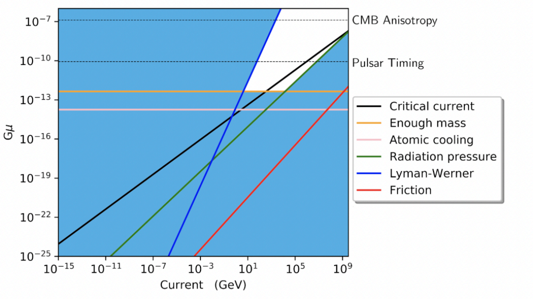
$$\frac{dP}{d\omega} = \kappa I^2 R^{1/3} \omega^{-2/3}$$

Assumption: radiation remains confinred in overdense region → can compute the density of photons with $10\mathrm{eV} < E < 13\mathrm{eV}$

→ there is a range of currents $I < I_c$ for which the condition is satisfied.

Parameter Space Region

B. Cyr, H. Jiao and RB, arXiv:2202.01799, MNRAS, in press



Lessons

There is a range of the cosmic string parameter space for which the direct collapse black hole criteria can be satisfied.

- For $G\mu \sim 10^{-10}$ the mean separation of loops forming SMBH will be $d_g \sim 10^{2/3}\mathrm{Mpc}$
- $\rightarrow$ reasonable number density of SMBH (M. Volonteri).

Intermediate Mass Black Holes from Cosmic String Loops?

RB, B. Cyr, and H. Jiao, arXiv:2103.14057

- Consider $G\mu$ chosen to get the correct abundance of SMBH.
- $dn/dM \sim M^{-2}$ for $M_c < M < M_{SMBH} \rightarrow$ abundance of seeds which *might* lead to BH formation.
- $M_c \sim M_\odot$
- $\rightarrow$ seeds in the *mass gap region* present in great abundance.

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- Globular cliusters: **oldest** and **most dense** star clusters, distributed in the **halo.**
- Cosmic string loops: **oldest** and **most dense** nonlinear regions, distributed in the **halo** of ΛCDM fluctuations.
- **Question**: Could string loops be the seeds of globular cliusters?

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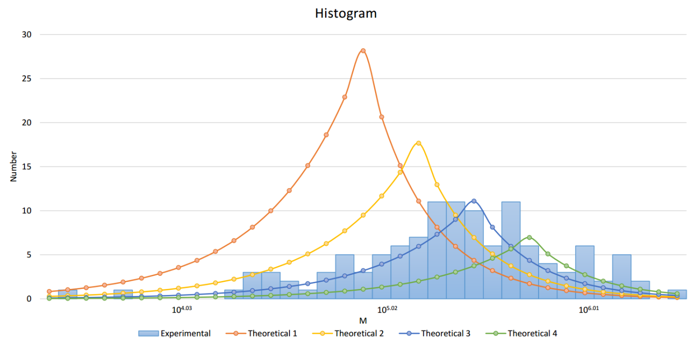
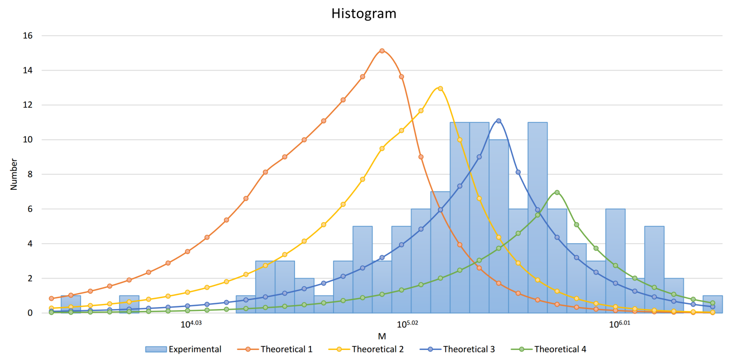
Abundance of globular cluster seeds due to cosmic strings

A. Barton, RB and L. Lin, arXiv:1502.07301



Effect of Cosmic String Velocities

L. Lin, S. Yamanouchi and RB , arXiv:1508.02784



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Conclusions

- For $G\mu \sim 10^{-10}$ loops of superconducting cosmic strings can seed the observed abundance of high redshift super-massive black holes.
- Specifically: direct collapse black hole criteria can be satisfied in a range of cosmic string parameter space.
- String loops → other interesting consequences for cosmology.