Supermassive Stars: evading (*temporarily*!) the inevitable with Dark Matter

Dark Matter and Black Holes

IPMU, Japan, December 2, 2025

Image credit: *Science News*

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two tantalizing "problems"

- **Dark Matter**

- **Black Holes**:

supermassive BHs at very high redshift z>10

maybe (??) light black holes, $M < 2.5\ M_{sun}$,
that conventional astrophysics cannot make (really?)

utterly disturbing: JWST evidence for SMBH at z=17 & 25 ??

A. Matteri, A. Ferrara, A. Pallottini, "Beyond the first galaxies primordial black holes shine", arXiv:2503.18850

Little Red Dots, etc., etc.

We have a **Supermassive Black Hole** (SMBH) problem:

--- SMBHs with masses > 10^4 solar masses are there at high redshift ($z > 10$), when the universe is only $\sim$ 400 Myr in age!

--- Do these form via mergers of smaller mass black holes? Hard to start from ~ 1 solar mass black hole "seeds".

--- Are there higher mass seed black holes? Where do these come from?

--- Does Dark Matter play a role, either facilitating the formation of high mass seeds, or facilitating mergers ("last parsec" problem)?

--- There is (a hint of) evidence of gravitational radiation from SMBH mergers in the nano-Hz band from the *pulsar timing array* experiments, specifically *nanoGrav*.

The particles of the Standard Model and composites of them
like neutrons, protons, nuclei, atoms, etc.,
that is, “Ordinary Matter”, currently comprises only ~ 5 percent of the total mass-energy content of the universe!

But that is ~ 20% of all the slowly moving “stuff”.

What is the other ~80% ????

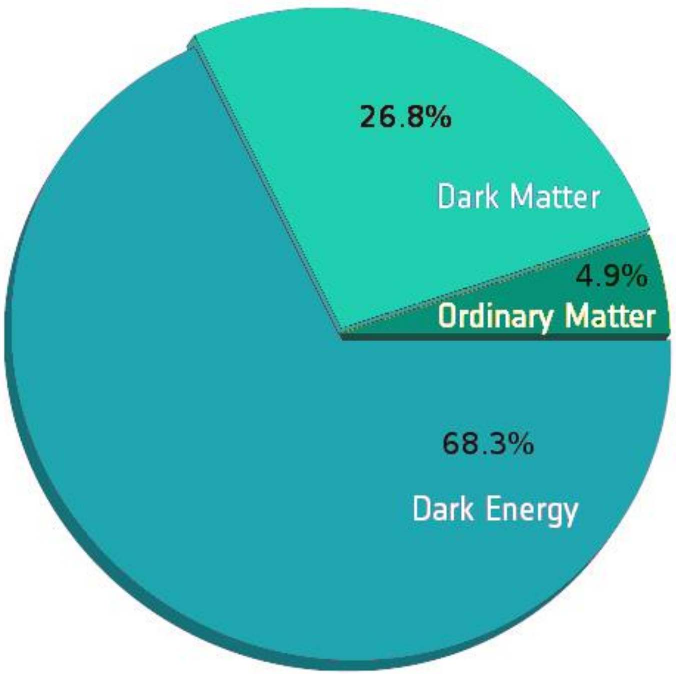


Image credit: DARWIN experiment

It may be characteristic human hubris to assume this other 80% does nothing but gravitate and/or affects only large scale structure.

Let's first tackle the early supermassive black hole (SMBH) problem with purely **Standard Model** physics

(1) Supermassive stars are wonderful progenitors for SMBHs
and their inevitable collapse may leave
characteristic gravitational wave signatures

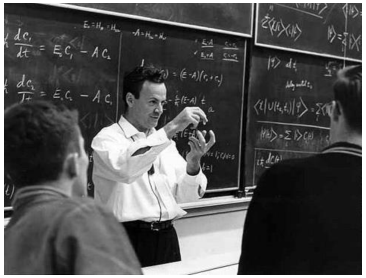
(2) A big issue: **How do they form**?

Stellar Evolution

Driven by the Weak Interaction and Gravitation

The **Weak Interaction**, and sometimes the nuclear burning it facilitates, sets up self gravitating configurations for instability whenever the pressure support for the star is from particles moving near the speed of light the star is "**trembling on the verge of instability**"

MASS in $M_\odot$	**Main Seq. Entropy per baryon** s/k_B	**Collapse Entropy per baryon** s/k_B	**degenerate core mass** in $M_\odot$	**Instability Mechanism**	**Fraction of rest mass radiated as neutrinos**	**Neutrino Trapping / Thermal equilibrium**
10 to ~ 100	**~ 10**	**~ 1**	**~ 1.4**	**Electron capture / NSE Feynman-Chandrasekhar G.R. instab.**	**~ 10%** of collapsing core mass	**Yes**
~ 100 to ~ 10^4	**~ 100**	**~ 100**	**NONE**	$e^\pm$ **pair instability**	**~ 10%** C/O burning core	**Yes**
~ 10^4 to ~ 10^8	**~ 1000** no main seq.	**~ 1000**	**NONE**	**Feynman-Chandrasekhar G.R. Instability**	**~ 1%**	**No**



Supermassive Stars $M > 10^4\,\mathrm{M}_\odot$

- Structure completely Newtonian

- Stability determined by small nonlinear correction from General Relativity

Baryons supply (most of) the mass; Photons supply (most of) the pressure!

$*$ "gas pressure" $P_\mathrm{g} = N k_\mathrm{b} T = \frac{\rho\, N_A}{\mu}\, k_\mathrm{b} T$ where $\mu =$ "mean molecular weight"

nuclear burning will increase this, lower β and so drive the star ***closer*** to instability

$*$ radiation pressure $P_\mathrm{r} = \frac{\pi^2}{15}\, T^4$

$*$ ratio of gas pressure-to-radiation pressure $\beta \equiv P_\mathrm{g}/P_\mathrm{r}$

$*$ pressure-averaged adiabatic index: $\langle\Gamma_1\rangle \approx 4/3 + \beta/6$ (for small β)

If the gas-to-radiation pressure ratio falls low enough that

$$\langle\Gamma_1\rangle < 4/3 + \mathcal{O}(r_\mathrm{s}/r)$$

collapse ensues

where $r_\mathrm{s} = 2GM$

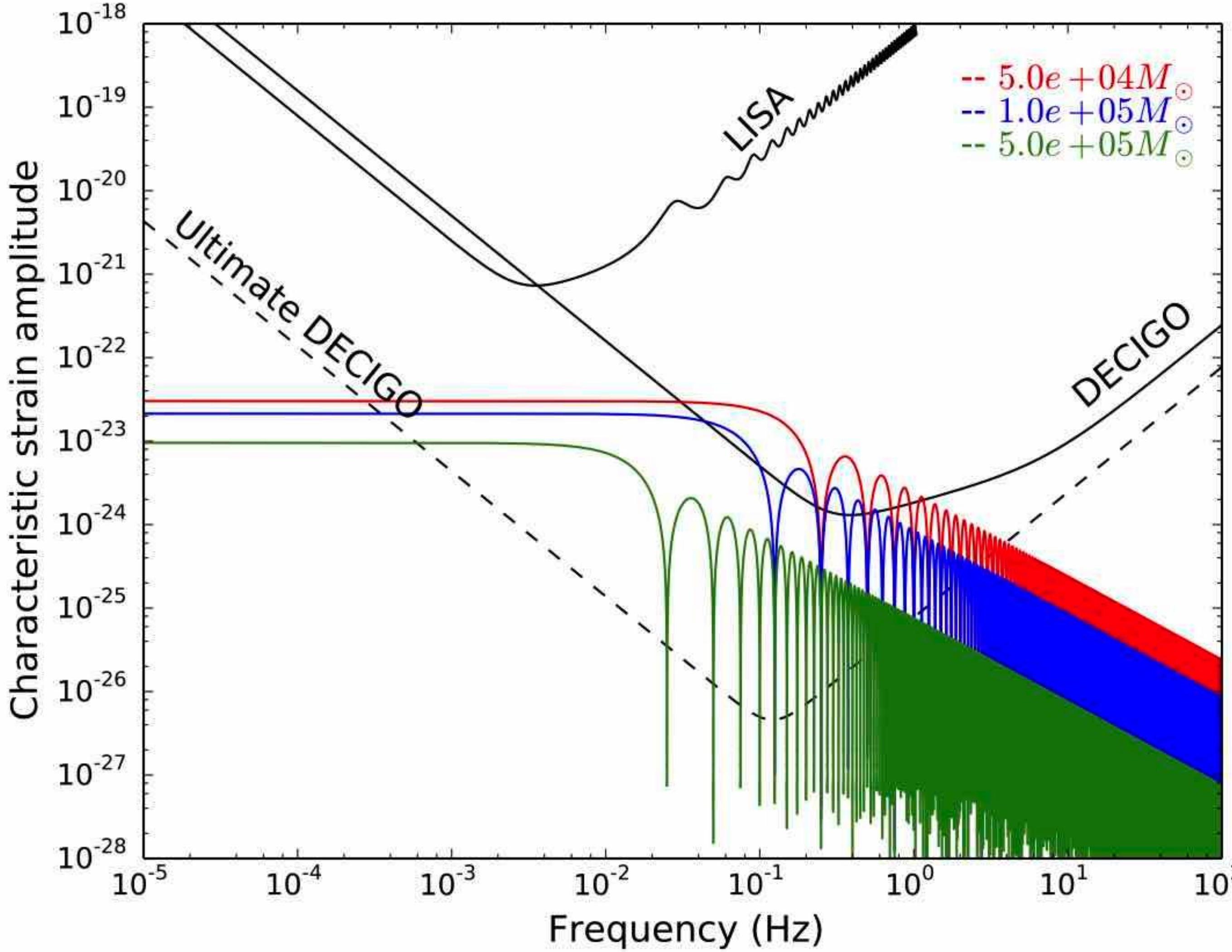
With collapse to a black hole, **~1%** of the star's *rest mass* could be radiated as neutrinos.

Since the neutrino emissivity is proportional to ***nine powers of temperature***, T^9, most of these neutrinos are produced immediately before a trapped surface (black hole) is formed.

If this shell of (neutrino) radiation is slightly asymmetric, there will be a gravitational radiation pulse.

Jung-Tsung Li, GMF, C. T. Kishimoto , *Phys. Rev.* D **98**, 023002 (2018)

gravitational wave burst signal (strain) in DECIGO, LISA, etc.,
for various assumed supermassive stars core masses at black hole formation



Jung-Tsung Li, GMF, C. T. Kishimoto , PRD **98**, 023002 (2018)

Wonderful, but wait . . . how do you form a SMS????

A primordial gas cloud:
Need to cool the gas through molecular hydrogen formation,
but hard to get H_2 at high redshift in SM physics . . .
and cooling can lead to fragmentation of the gas cloud.

Grow a lower mass star by accretion:
Must accrete quickly (super-Eddington),
on a timescale short compared to the weak interaction-driven
stellar evolution timescale.

Stellar "collisions" in a cluster build up a SMS:
Either via tidal disruptions, or the whole cluster of stars collapses
via the GR instability (Zeldovich 1968)

OK, all problematic,
so let’s turn to the ***dark side***

Beyond Standard Model (BSM) Physics

Example:

Dark Matter could facilitate SMBH production and mergers:

P. Bierman & A. Kusenko, *Phys. Rev. Lett.* **96**, 091301 (2006).

sterile neutrino decay-catalyzed H_2 production;

plus recent A. Kusenko work on SMBH production via PBHs

Dark Matter in these objects could ***stabilize them*** (at least for a bit!)

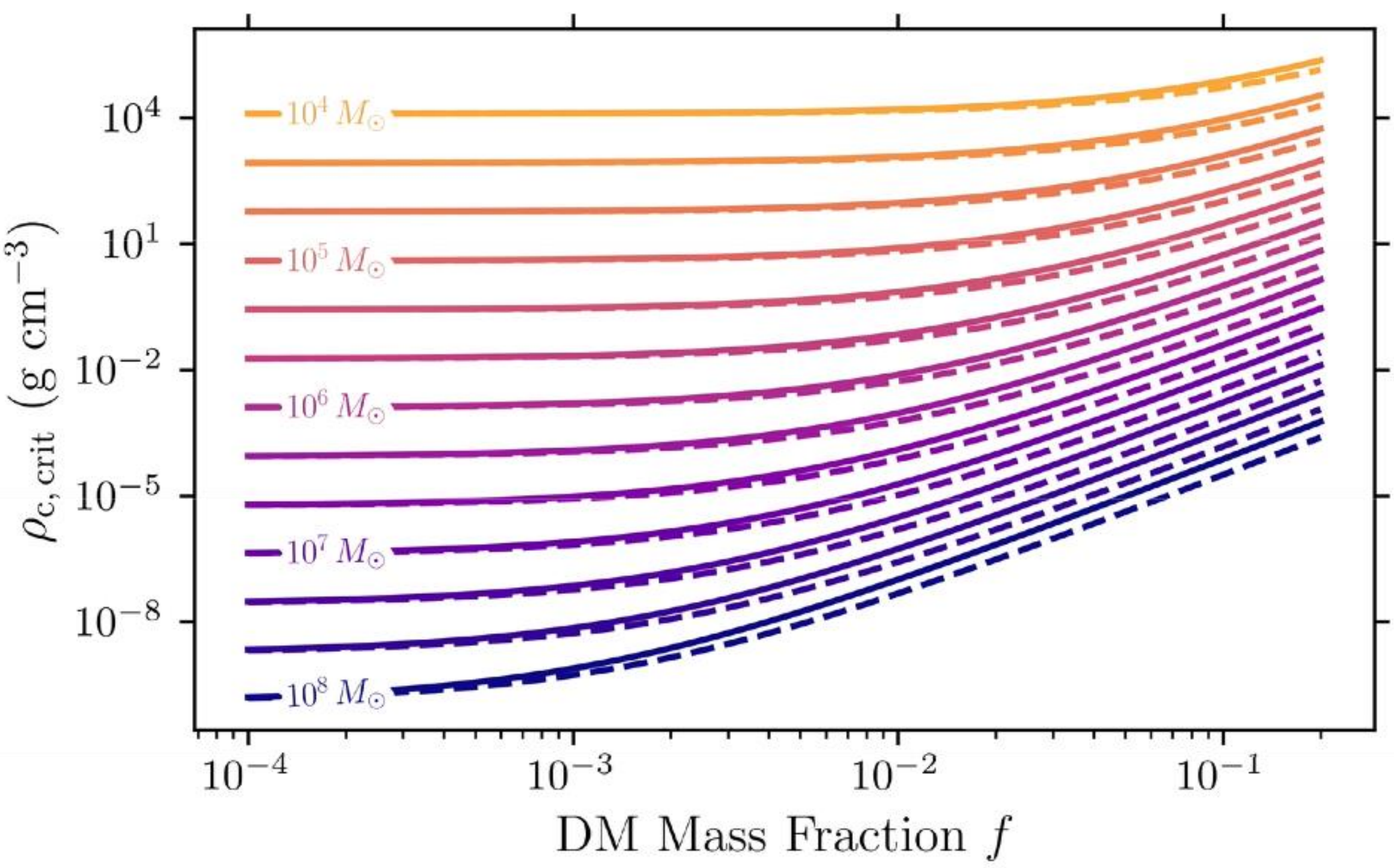
A significant Dark Matter content (~ 0.1% or more by mass)
could delay GR instability and allow a supermassive star
to proceed in hydrogen burning and neutrino energy losses,
where it would otherwise collapse before burning.

G.C. McLaughlin & GMF, *The Astrophysical Journal* **456**, 71 (1996).
G.S. Bisnovatyi-Kogan, *The Astrophysical Journal* **497**, 559. (1998).
K. Kehrer & GMF, "*Dark Matter and General Relativistic Instability in Supermassive Stars*", arXiv:2406.13887

L. Haemmerle, *Astronomy & Astrophysics*, (2024). -- hylotropic configurations where a supermassive core undergoes rapid accretion
M. Begelman, MNRAS **402**, 673 (2010)

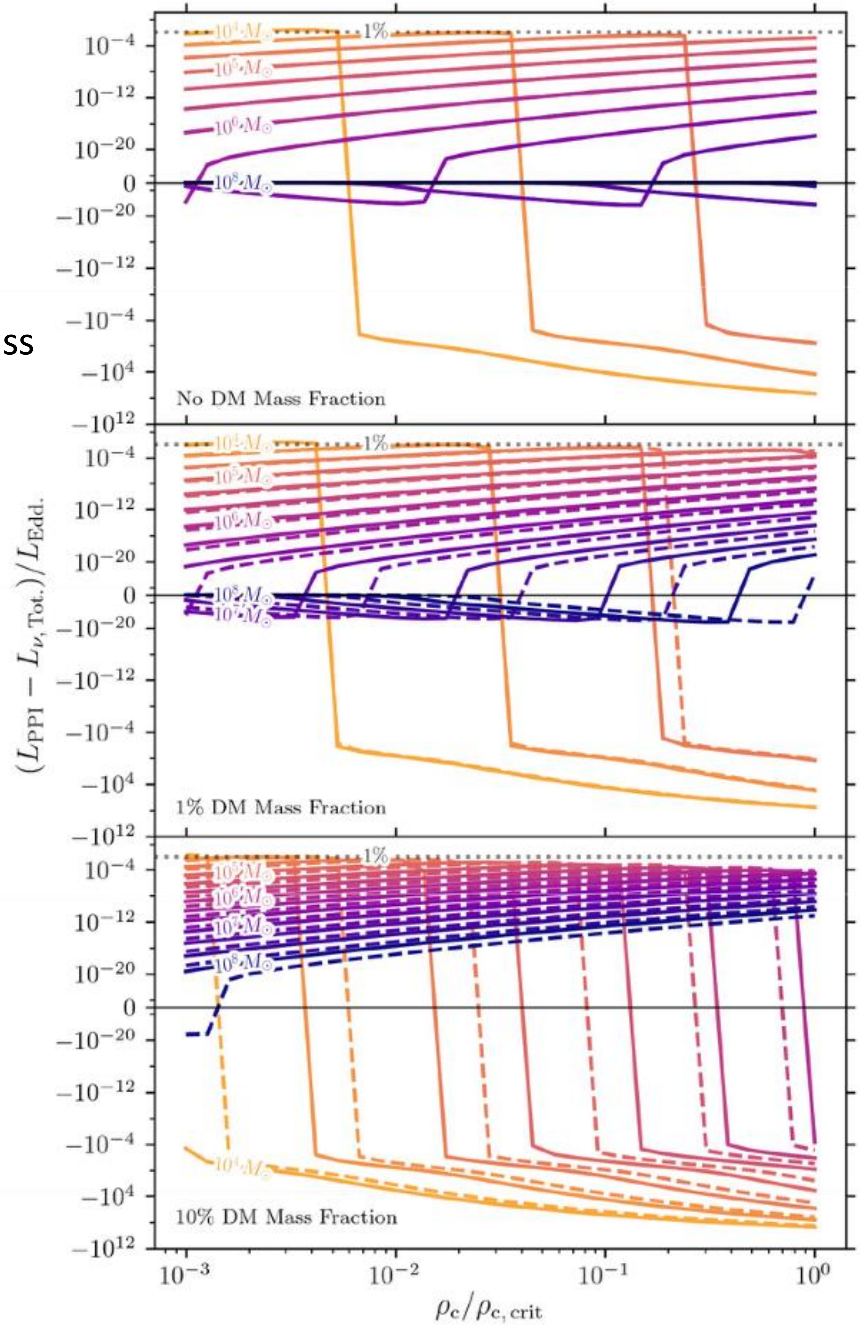
See Also:
S. Butler, A. Lima, T. Baumgarte, S. Shapiro, *Monthly Notices of the Royal Astronomical Society* **477**, 3694 (2018)

even a *modest* (?) amount of Dark Matter in the supermassive star can increase its stability, increasing by orders of magnitude in some cases the critical density required. For the onset of the Feynman-Chandrasekhar instability



K. Kehrer & GMF, "*Dark Matter an General Relativistic Instability in Supermassive Stars*", arXiv:2406.13887 *Physical Review* D **110**, 083035 (2024)

Supermassive stars that would have collapsed before the onset of nuclear burning, may experience stable hydrogen burning and significant loss of entropy through neutrino emission if they contain significant amounts of dark matter.



K. Kehrer & GMF,
"*Dark Matter an General Relativistic Instability in Supermassive Stars*", arXiv:2406.13887
Physical Review D **110**, 083035 (2024)

“Dark Stars”

What if Dark Matter in stars could annihilate or decay,
depositing energy/entropy? – *could completely change the evolution of the star*

K. Freese, T. Rindler-Daller, D. Spolyar, M. Valluri,
Reports on Progress in Physics **79**, 066902 (2016)

It has even been suggested that the recent JWST observation of a source at redshift z=10.5 suggests a supermassive dark star with mass > 10^6 solar masses

C. Ilie, J. Paulin, K. Freese, *Proceedings of the National Academy of Sciences*, **120**, e2305762120 (2023).
https://www.pnas.org/doi/pdf/10.1073/pnas.e2305762120

When will they suffer the general relativistic instability,
and collapse to a supermassive black hole?

arXiv:2511.08578

Early Formation of Supermassive Black Holes via Dark Star Gravitational Instability

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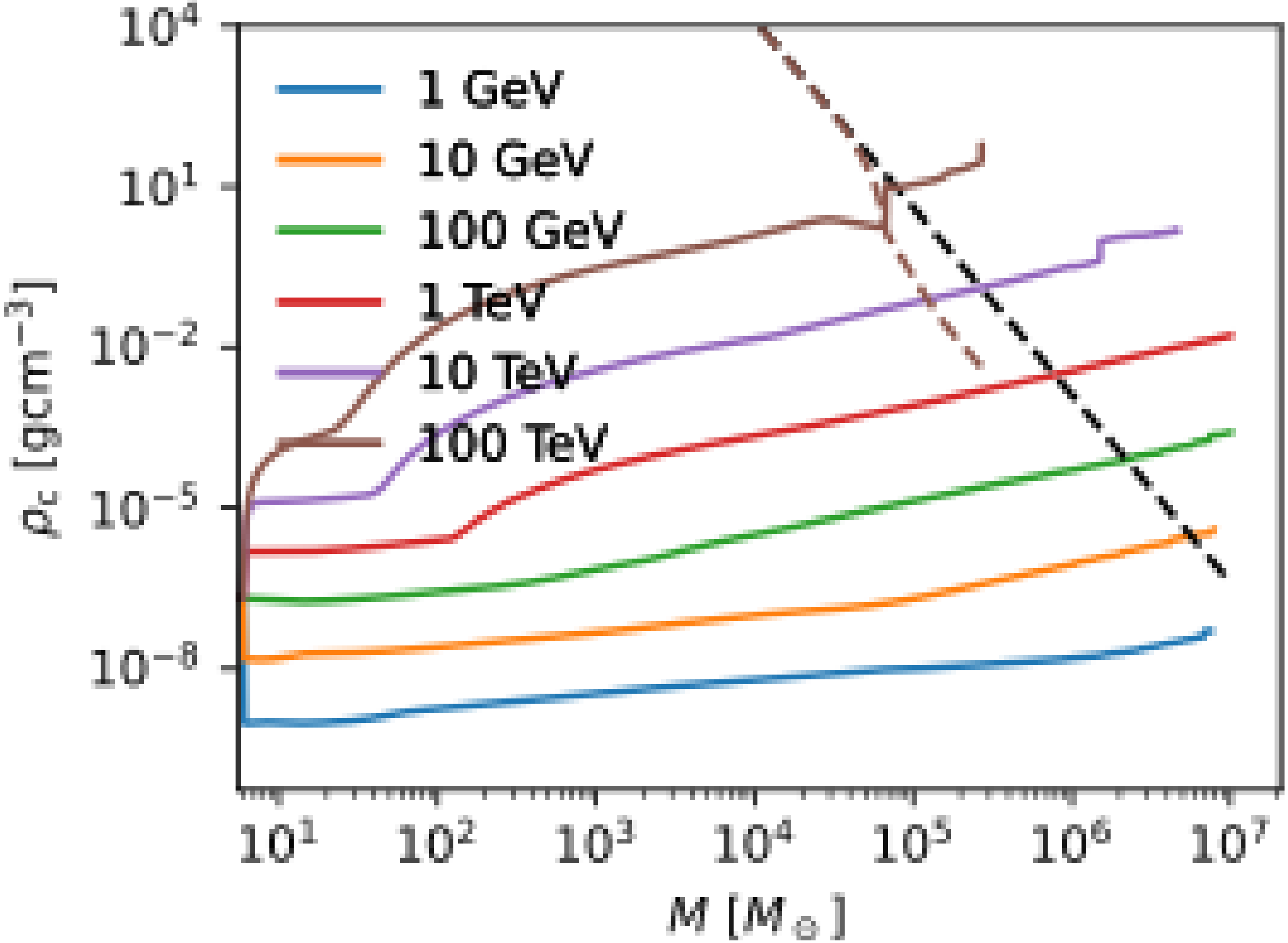
(Dated: November 24, 2025)

We show that dark stars, which are dark-matter-powered stars in the early universe, can grow by accretion to masses in the range $\mathcal{O}(10^4) - \mathcal{O}(10^7)\ M_\odot$ before the general-relativistic Feynman-Chandrasekhar instability causes their dynamical collapse to black holes. These accreting dark star configurations avoid standard stellar nuclear- and weak-interaction evolution that would lead to their demise long before they reached this supermassive size. Remarkably, this mechanism for supermassive black hole (SMBH) genesis is relatively robust to initial dark star mass, formation epoch, accretion rate and its history. The SMBHs produced this way can serve as seeds for even larger SMBHs ($\gtrsim 10^9\ M_\odot$) that have been discovered at high redshift.

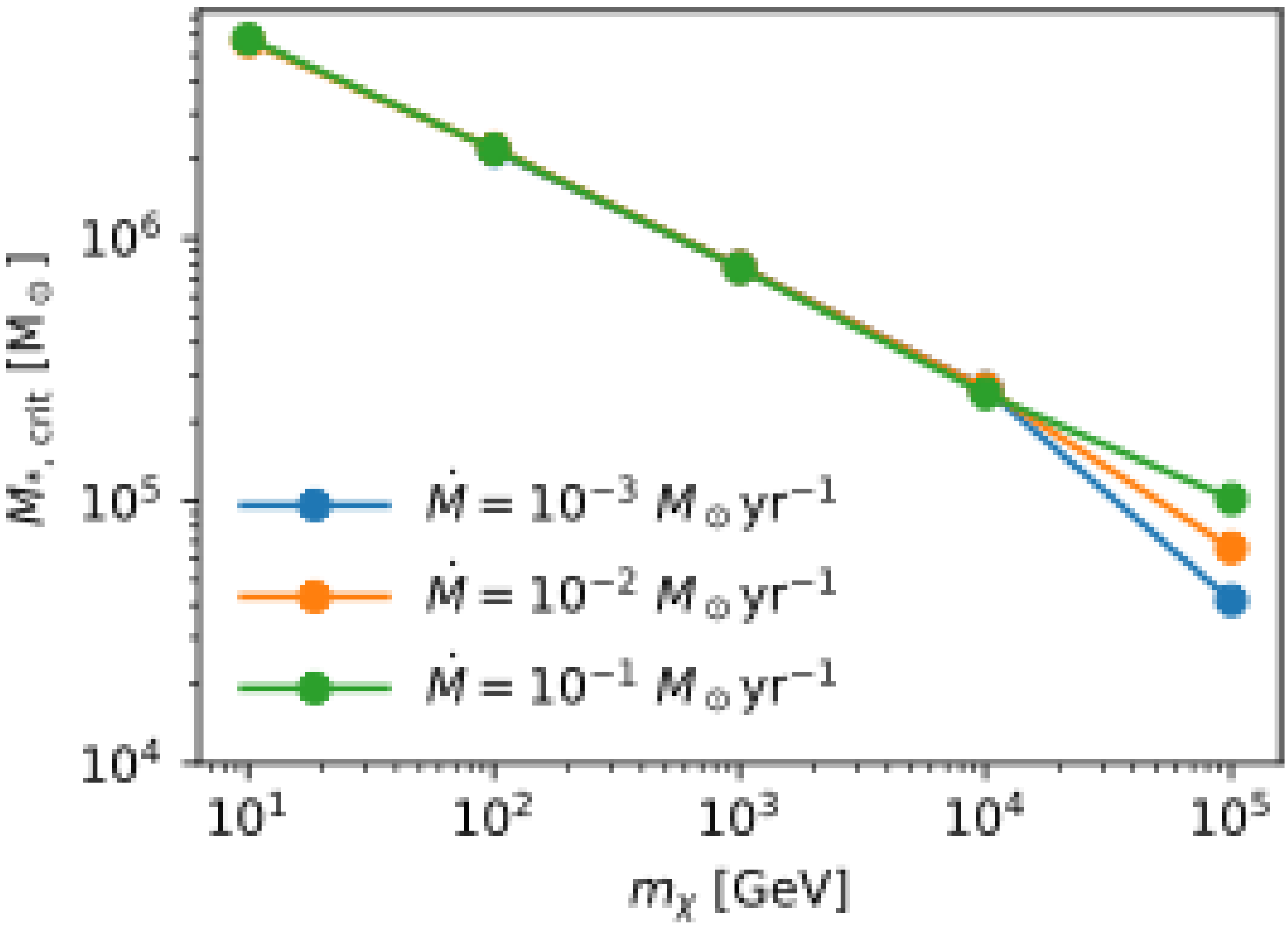
This scheme can get around the formation problem and evade weak interaction-driven destruction by keeping the star “puffy” and ”cool”.

Can start with a solar mass scale star and build up by accretion



Evolutionary tracks for DSs labeled by dark matter particle mass.
Dashed line shows where GR instability/collapse sets in.

arXiv:2511.08578



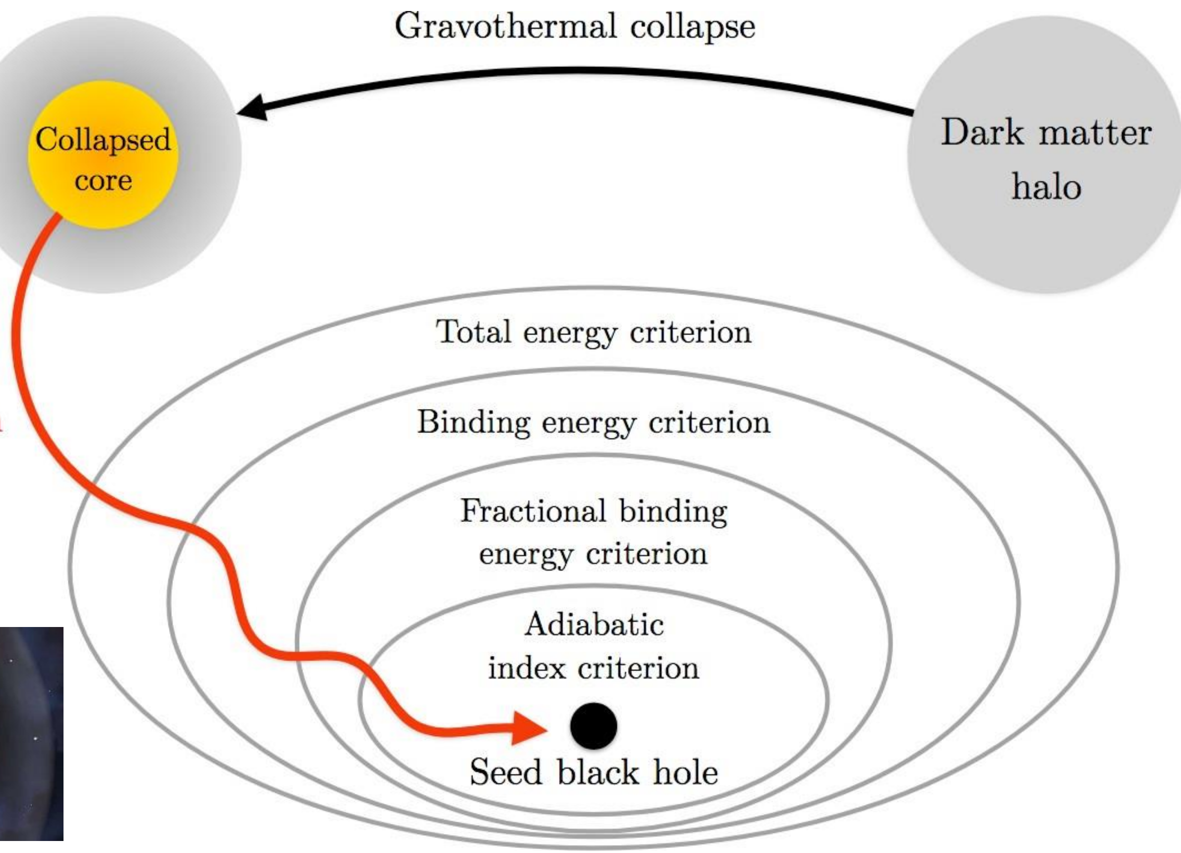
arXiv:2511.08578

Mass of object at the GR instability point (roughly final BH mass)
for various assumed mass accretion rates as a function of dark matter particle mass, m_χ

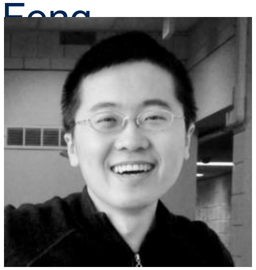
other kinds of dark mater . . .

Haibo Yu and his group:

Self-Interacting Dark Matter (SIDM): *Seeding Supermassive Black Holes*



Wei-Xiang Feng



Yi-Ming Zhong

Truncated Maxwell-Boltzmann distribution

$$\begin{cases} (e^{-\epsilon/kT} - e^{-\epsilon_c/kT})d^3p(\epsilon) & (\epsilon \leq \epsilon_c) \\ 0 \quad (\epsilon > \epsilon_c), \end{cases}$$

Central 3D velocity dispersion>0.57c

Find GR configurations using the Tolman-Oppenheimer- Volkov (TOV) equation; Check GR instability criteria

Feng, HBY, Zhong (ApJ Letters 2021, JCAP 2022)