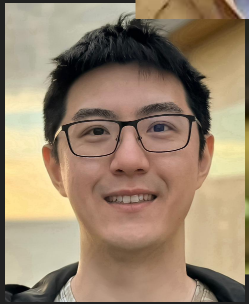
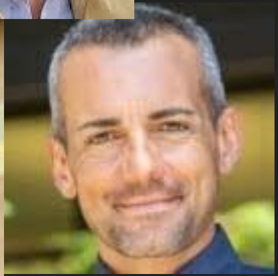
Black holes from Fermi ball collapse

Zachary S.C. Picker (UCLA)

with Alexander Kusenko, Yifan Lu, and Stefano Profumo (UCSC)





Roadmap

Early structure formation in the dark sector

- Fermi balls
  - Fermi ball collapse
    - Fermi ball interactions
      - Fermi balls in the late universe

Early structure formation in the dark sector

Dark matter model

- Two component model
- Heavy fermion and light scalar
- 3 free parameters: fermion mass, scalar mass, coupling *y*

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - (m_\psi - y\varphi)\right)\psi + \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 - V(\varphi).$$

Mediates attractive Yukawa force
$\Rightarrow$ ‘Yukawa length scale’ is 1/scalar mass

$$F = y^2 \frac{e^{-m_\varphi/r}}{r^2}$$

Dark matter model

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- Inspired by asymmetric dark sector
  - See Flores, Lu, Kusenko 23 for full worked model
- We choose bad ‘standard asymmetric’ parameters:
  - m_ψ > TeV, m_φ < eV

Dark matter model

- Two component model
- Heavy fermion and light scalar
- ~~3~~ ~4 free parameters: fermion mass, scalar mass, coupling *y*, fermion asymmetry
  - Fixed by f_{DM}

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - (m_\psi - y\varphi)\right)\psi + \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 - V(\varphi).$$

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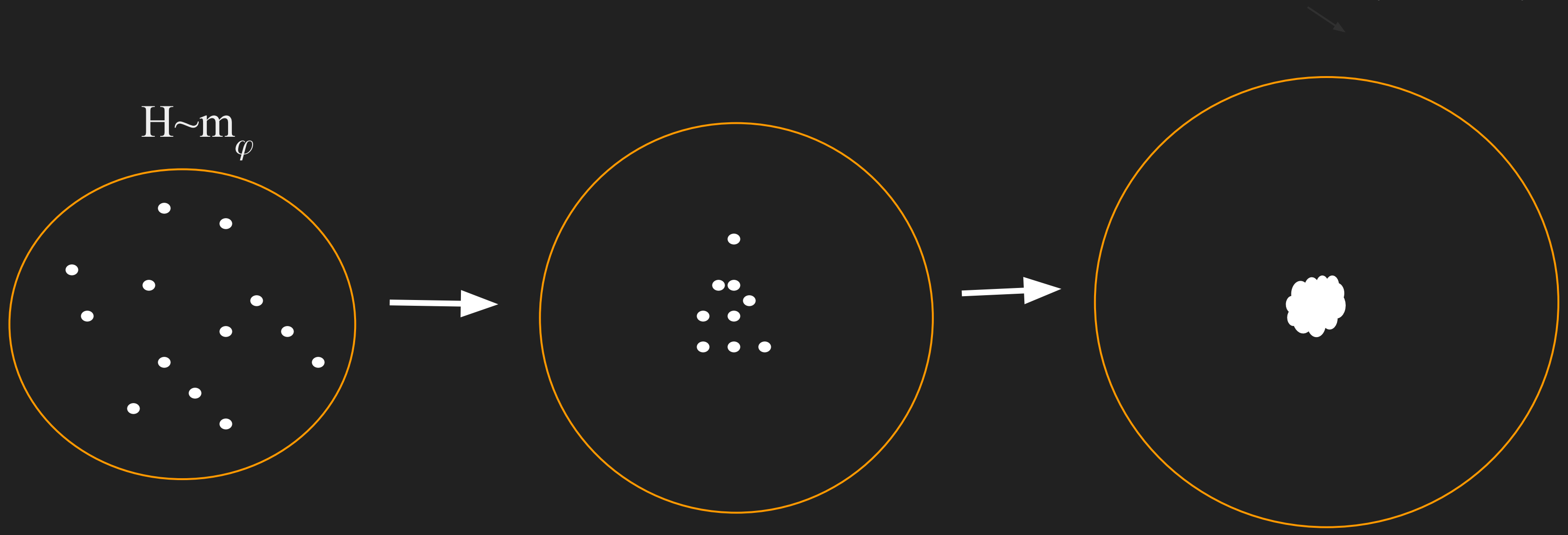
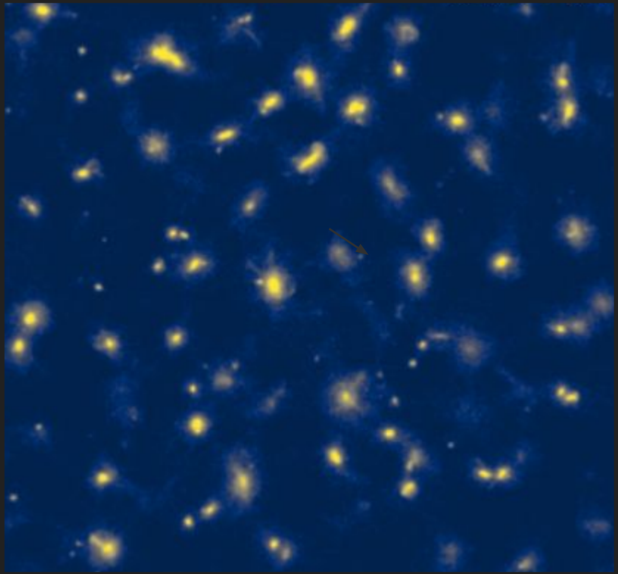
Yukawa structure formation

- New medium-range force allows for early structure formation
  - Up to Yukawa length scales in early universe
  - Halo mass completely tunable

(need to account for fermion asymmetry)



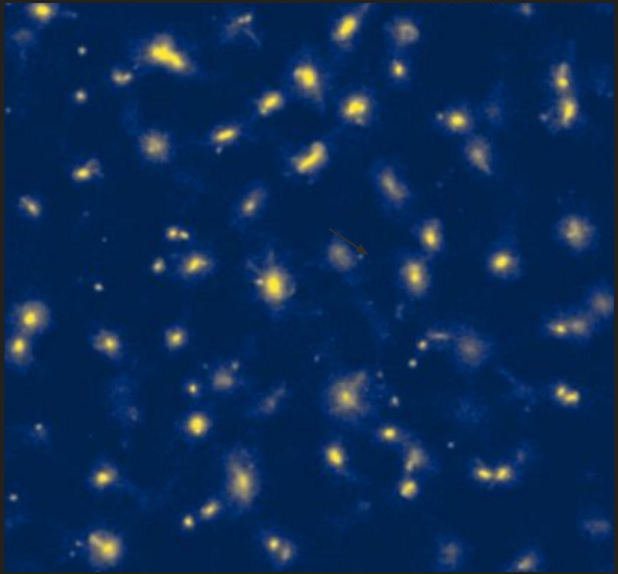
Yukawa structure formation



Simulations: Domenech, Inman, Kusenko, Misao Sasaki (2023)

Yukawa structure formation

- Significant phenom:
  - ‘Fireball’ baryogenesis
    - (Flores, Kusenko, Pearce, White 2022)
  - Gravitational waves
    - (Flores, Kusenko, Sasaki 2022)



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Yukawa structure formation

- Significant phenom:
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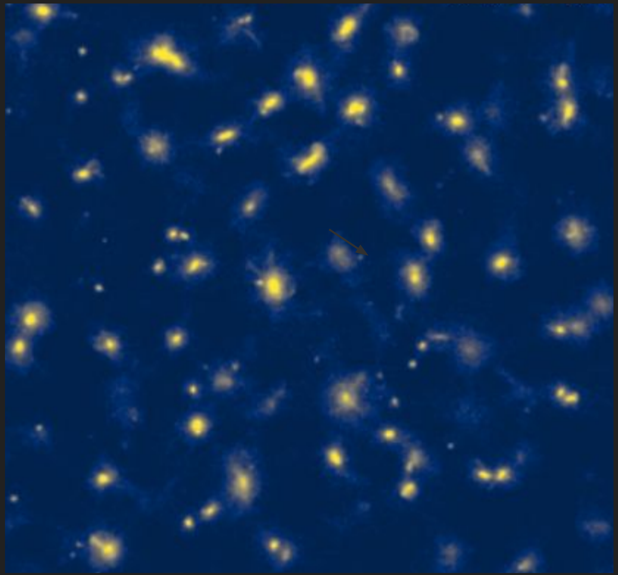
    - (Flores, Kusenko, Sasaki 2022)

- Form PBHs directly
  - Flores, Kusenko 2021
  - Flores, Lu, Kusenko 2023

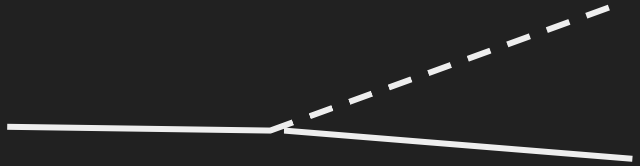


Simulations: Domenech, Inman, Kusenko, Misao Sasaki (2023)

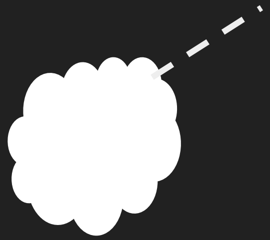
Fermi balls and PBHs

The fate of the halos

- Halos can cool via scalar radiation
  - Flores, Kusenko 21
- Stable, nontopological solitons can form — Fermi balls
  - Fermi degeneracy pressure



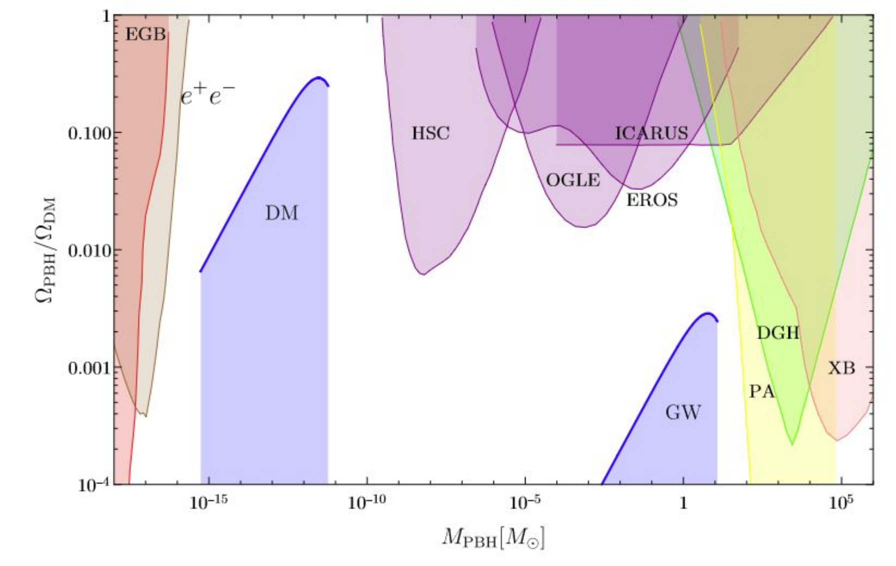
Scalar brehmsstrahlung cooling



Surface cooling

The fate of the halos

- Halos can cool via scalar radiation
    - Flores, Kusenko 21
- Stable, nontopological solitons can form — Fermi balls
    - Fermi degeneracy pressure
- If Fermi degeneracy is not strong enough, they collapse immediately to PBHs



Flores, Kusenko 2021

The fate of (these) Fermi balls

- Act ~like cold dark matter…
  - Still have Yukawa force!
- They *could* grow by mergers or accretion
  - Even today…

Could they collapse to a black hole?

eg chandrasekhar/Tolman-Oppenheimer-Volkoff (TOV) limits?

Fermi balls ~dark equivalent of neutron stars/white dwarfs

Fermi balls ~dark equivalent of neutron stars/white dwarfs

- Old idea: other ways to form
  - Nugget synthesis (eg nuclear synthesis)
  - Phase transition (eg quark nuggets)
- (some) relevant papers:
  - Lee, Pang 1987, 1992
  - Grosso, Franciolini, Pani, Urbano 2023
  - Xie 2024
  - Gresham, Lou, Zurek 2017
    - Use mean field theory to study the exact Fermi ball solution
    - Analytically + numerically compute equations of state

Fermi ball stages

	Mass and Radius	Long range forces	Collapse?
'Nugget'	$R \sim N^{-1/3}$ $M \sim N$	✔	□□
'Sub-saturation'	$R \sim N^{2/3}$ $M \sim N^{2/3}$	✔	□
'Saturation'	$R \sim N^{1/3}$ $M \sim N$	□	✔

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Either it begins as a black hole, or not ☹️

Re-examine the dark matter model

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - (m_\psi - y\varphi)\right)\psi + \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 - V(\varphi).$$

Potential term:

- Scalar field needs additional potential to be renormalizable: $V(\varphi) = \lambda\phi^4$

$\Rightarrow$ new repulsive force when we have: $1 \gtrsim \lambda \gg (m_\varphi / y m_\psi)^2$

($\Rightarrow$ new free parameter λ …)

New Fermi ball equations of state

Drastic effect:

Repulsive force can ‘kick in’ sooner than degeneracy pressure

New Fermi ball equations of state

Drastic effect:

Repulsive force can ‘kick in’ sooner than degeneracy pressure

Valiantly rederived (analytically & numerically) by Yifan Lu:

- Radius $\propto N^{1/3}$
  Mass $\propto N$
  - (more technically…they reach ‘saturation’ almost immediately)
- Adding more fermions increases mass more quickly than radius

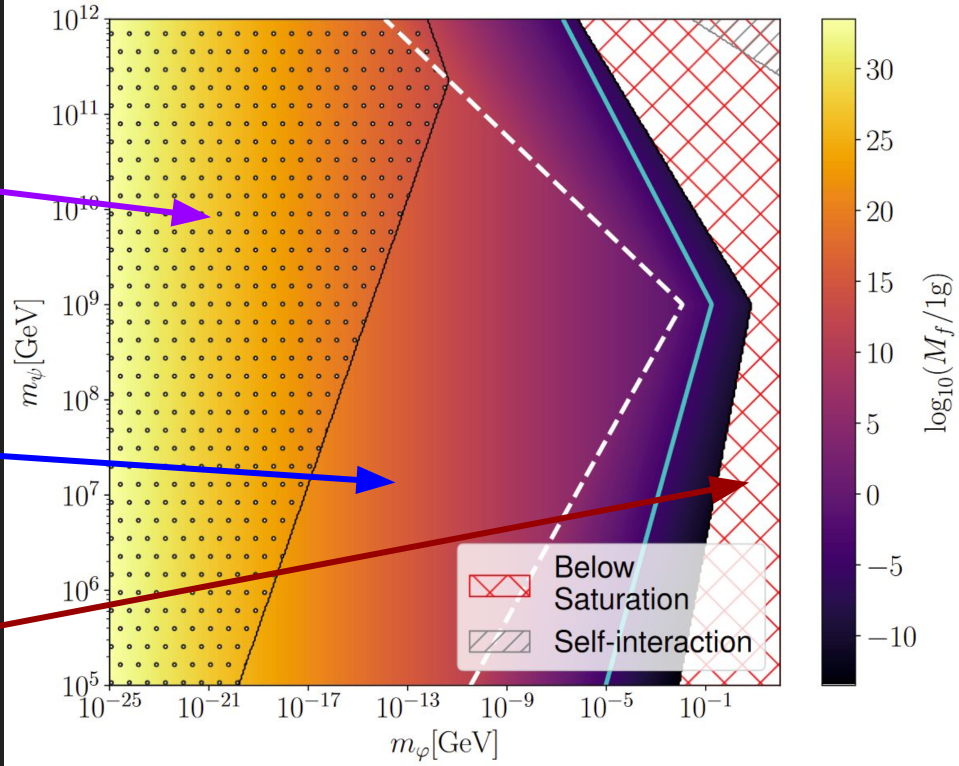
$\Rightarrow$ By adding more fermions, you *can* cause it to collapse to a black hole

~New primordial black hole formation mechanism

Black holes are formed (~whale to solar size here)

Fermi balls are formed

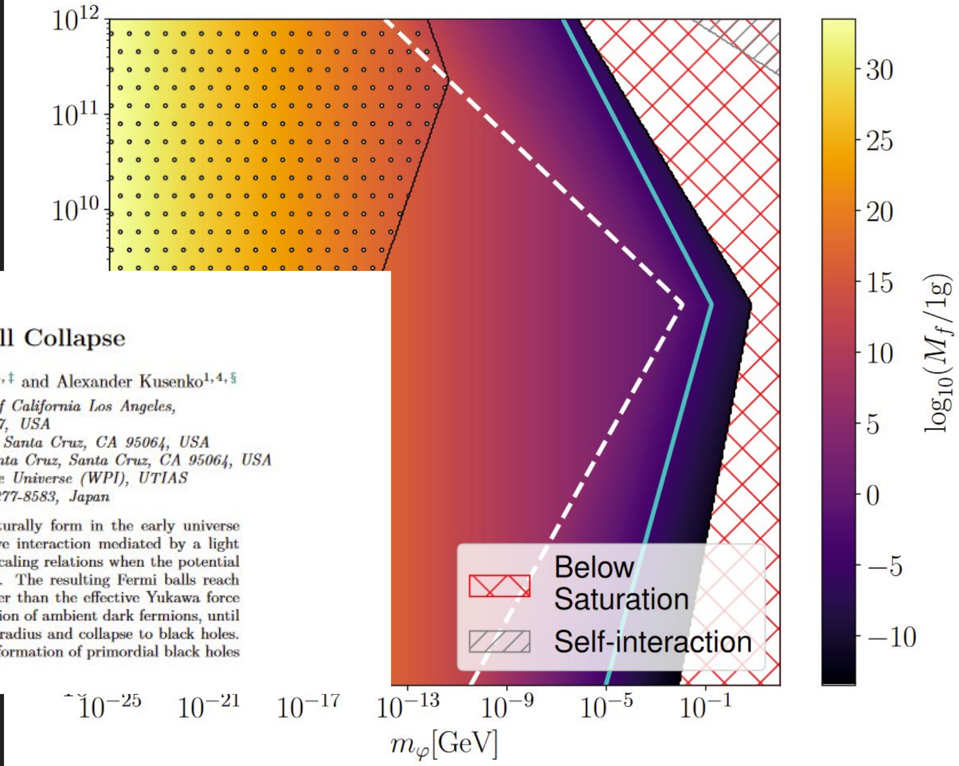
'sub-saturated' Fermi balls (non-analytic)

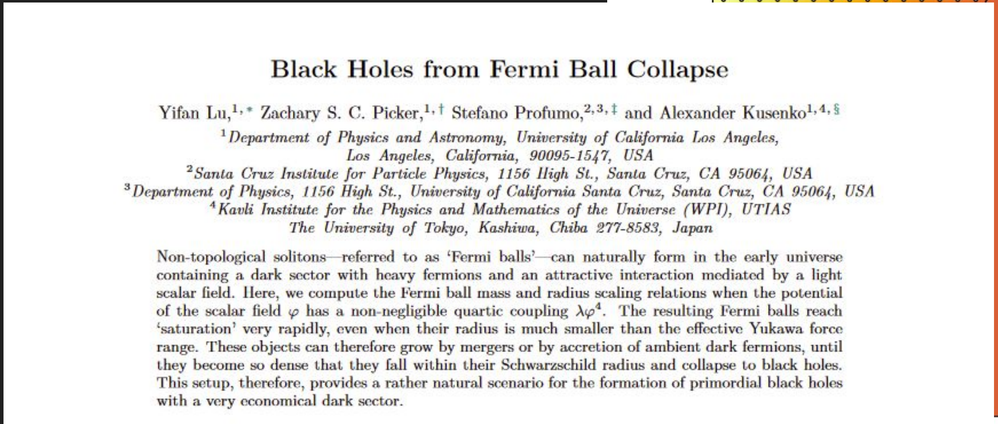


(y=5e-2, λ=1e-2, asymmetry -> all DM)

New primordial black hole formation mechanism

Paper is finished ✓





Black Holes from Fermi Ball Collapse

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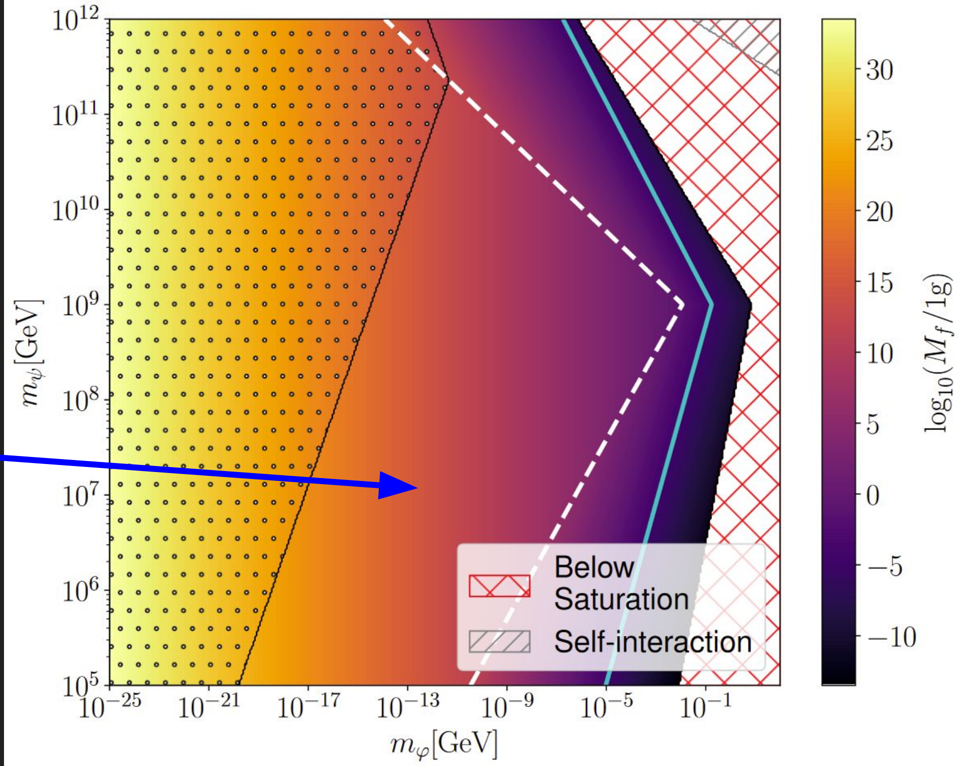
[2] *Santa Cruz Institute for Particle Physics, 1156 High St., Santa Cruz, CA 95064, USA*
[3] *Department of Physics, 1156 High St., University of California Santa Cruz, Santa Cruz, CA 95064, USA*
[4] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

Non-topological solitons—referred to as 'Fermi balls'—can naturally form in the early universe containing a dark sector with heavy fermions and an attractive interaction mediated by a light scalar field. Here, we compute the Fermi ball mass and radius scaling relations when the potential of the scalar field φ has a non-negligible quartic coupling $\lambda\varphi^4$. The resulting Fermi balls reach 'saturation' very rapidly, even when their radius is much smaller than the effective Yukawa force range. These objects can therefore grow by mergers or by accretion of ambient dark fermions, until they become so dense that they fall within their Schwarzschild radius and collapse to black holes. This setup, therefore, provides a rather natural scenario for the formation of primordial black holes with a very economical dark sector.

(y=5e-2, λ=1e-2, asymmetry -> all DM)

New primordial black hole formation mechanism

What happens to these guys over cosmological times?



(y=5e-2, λ=1e-2, asymmetry -> all DM)

Fermi balls in late times

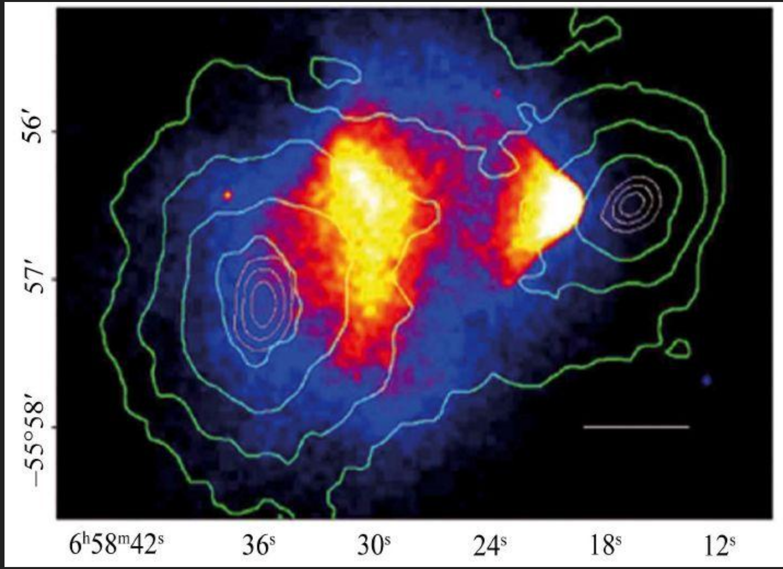
Fermi ball - Fermi ball interactions

- Saturated Fermi ball size is *now* smaller than Yukawa length
  - Can have Fermi ball self interactions

Self interaction constraints:

$\sigma/m < 1\ cm^2/g$

(Easily satisfied)



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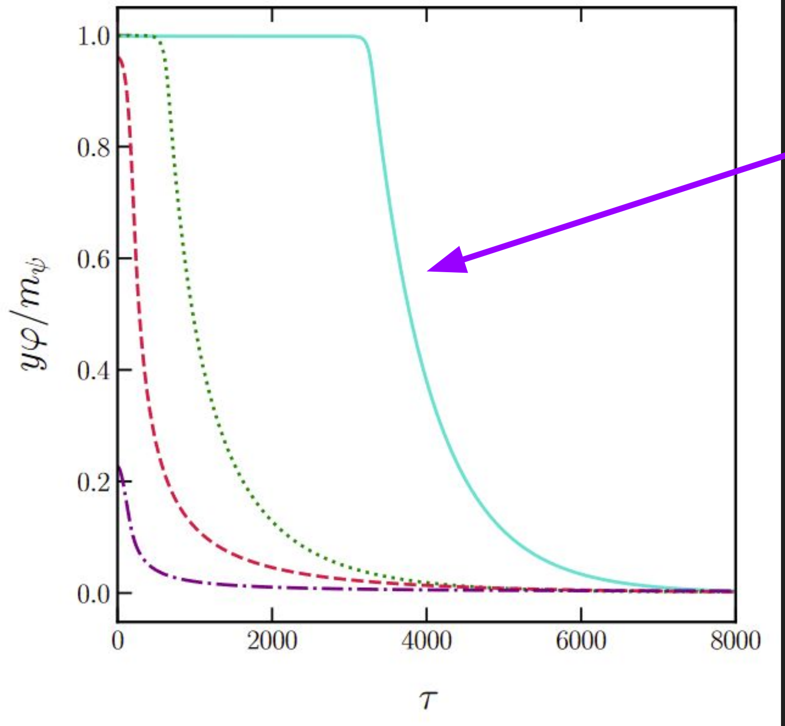
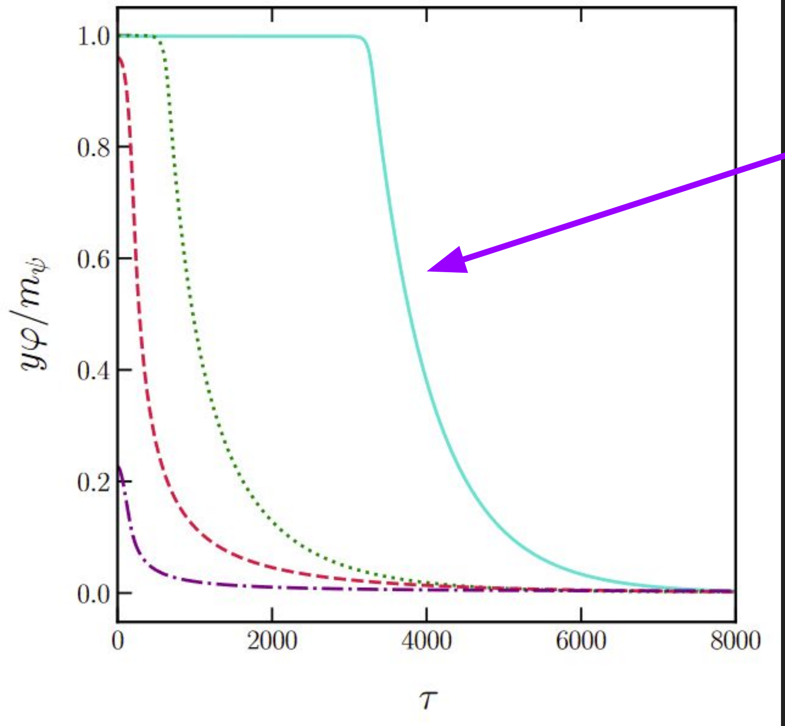


$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \lambda\varphi^3 = 0$$

Unreliable numerically…

Fermi ball - Fermi ball interactions



$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \lambda\varphi^3 = 0$$

Needed for interaction energy:

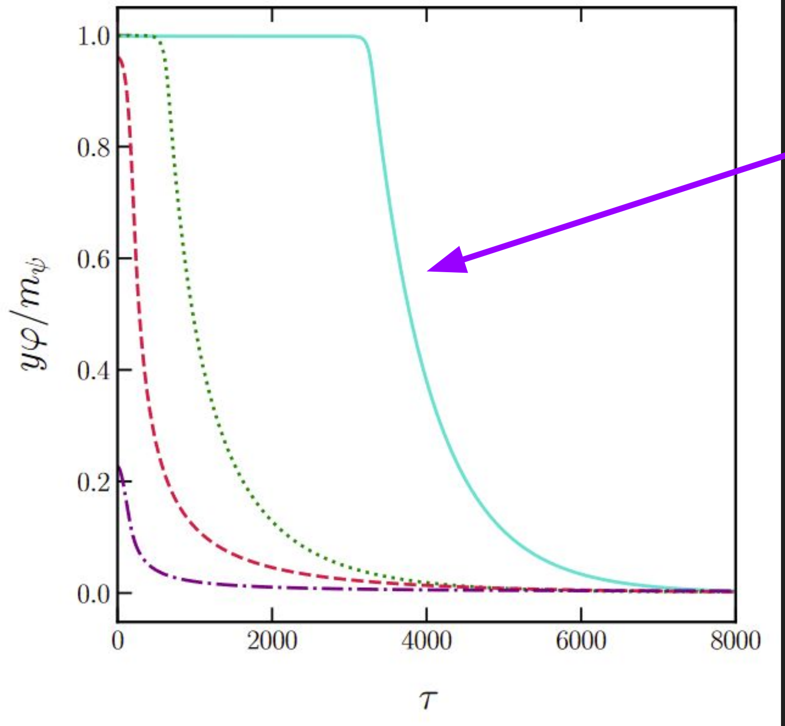
$$E(r) = -\int y\varphi(r)\,\langle\bar{\psi}\psi\rangle\, d^3x$$

Can only estimate upper and lower bounds:

$$F_{\rm low} \simeq \left(\frac{243}{16\pi^2}\right)^{1/3} \frac{y^{2/3}\lambda^{-1/6}}{r^2}\left(N_1^{2/3} + N_2^{2/3}\right)$$

$$F_{\rm high} \simeq 3\frac{y}{r^2}\left(N_2^{1/3}N_1^{2/3} + N_1^{1/3}N_2^{2/3}\right) ,$$

Fermi ball - Fermi ball interactions



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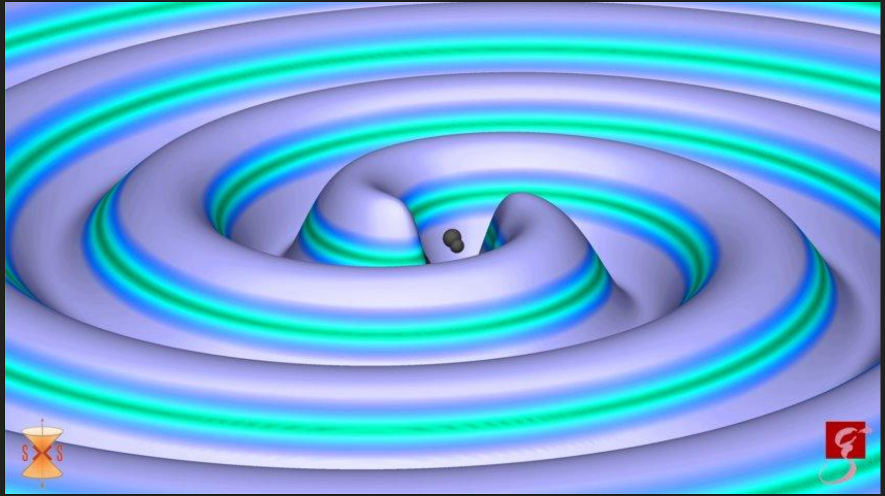
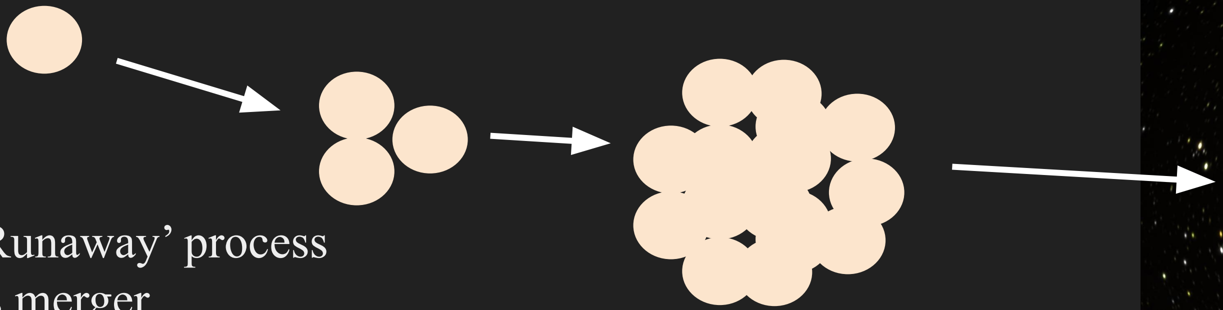
Fermi ball interactions

- Fermi balls still have 'short' range force between them
  - Binary is formed if they pass close enough (~cm - km usually)
  - Analogous to binary BH capture but with scalar radiation
  - Almost immediately merge
- Inelastic mergers



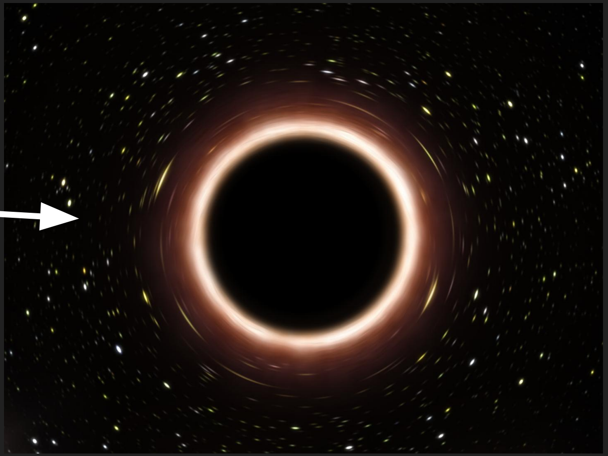
S. Ossokine, A. Buonanno, T. Dietrich

Late forming black holes



‘Runaway’ process as merger cross-section increases

Sink towards galactic center as they grow



Late forming black holes

Two futures

Late forming black holes

Two futures

Fermi ball - black hole conversion

- Not too many mergers until a BH is formed
- Merger timescale is sufficiently small

All Fermi balls become BHs before today

Late forming black holes

Two futures

Fermi ball - black hole conversion

- Not too many mergers until a BH is formed
- Merger timescale is sufficiently small

All Fermi balls become BHs before today

Rare black hole formation

- Many mergers required
- Merger timescale is very long

Black holes form occasionally near galactic center

Late forming black holes - phenom

Two futures

Fermi ball - black hole conversion

- Possible constraints from DM halo contraction

Late forming black holes - phenom

Two futures

Fermi ball - black hole conversion

- Possible constraints from DM halo contraction

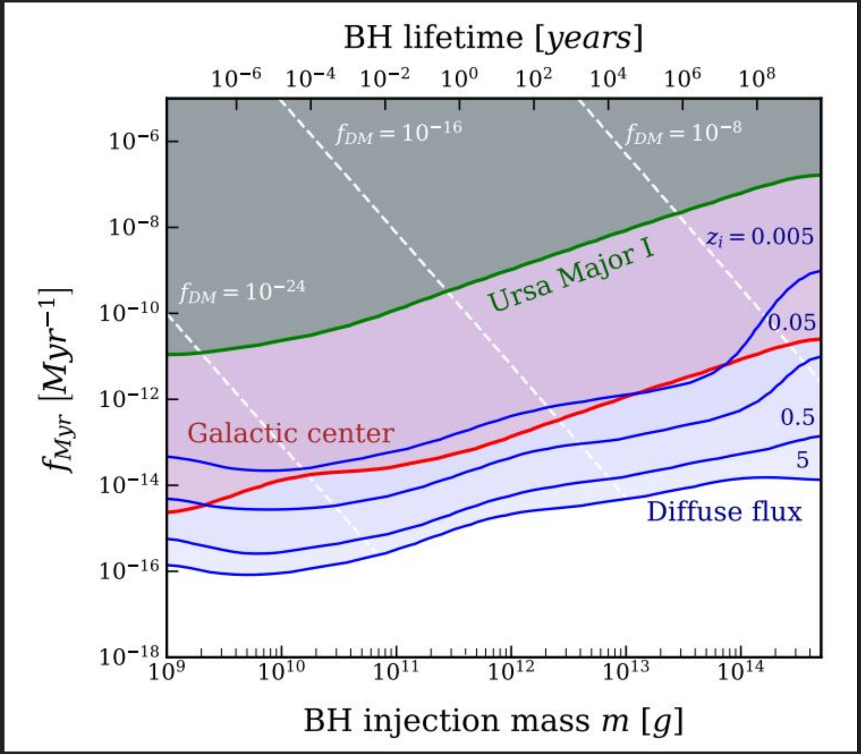
Rare black hole formation

- Tiny black holes could be evaporating today
  - (Impossible otherwise)
- Solar system capture

Black holes evaporating today

Constraints on late forming, evaporating BHs

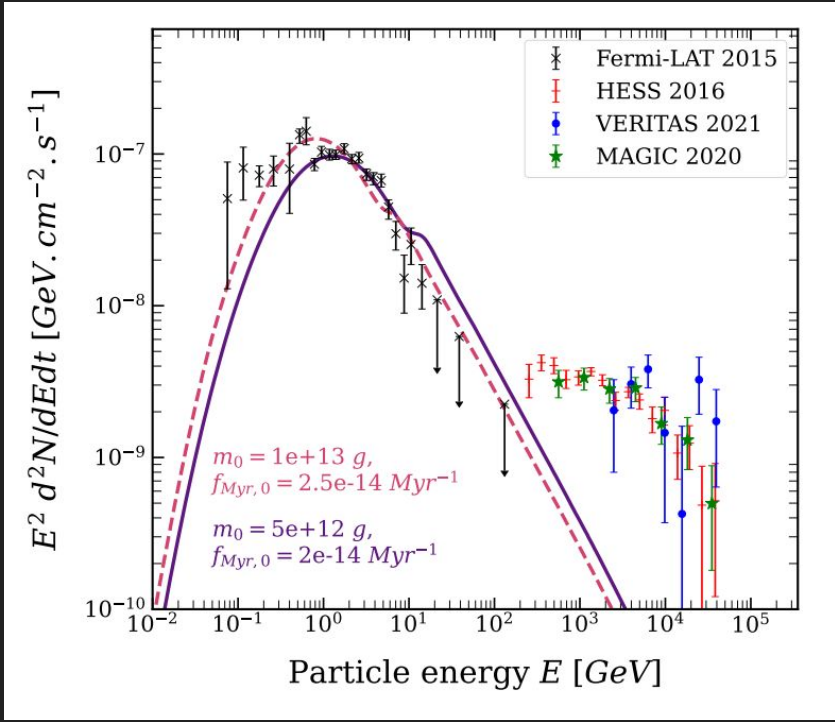
ZSCP, Kusenko 23



Particle excesses in the galactic center

- A small amount of evaporating black holes could explain the GeV excess
  - ZSCP, Kusenko 23

- ~1e13 g black holes
- ~1 explosion per second in galaxy



Particle excesses in the galactic center

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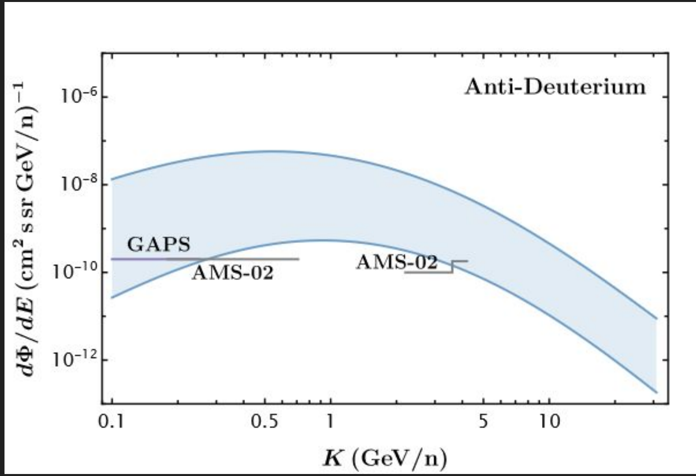
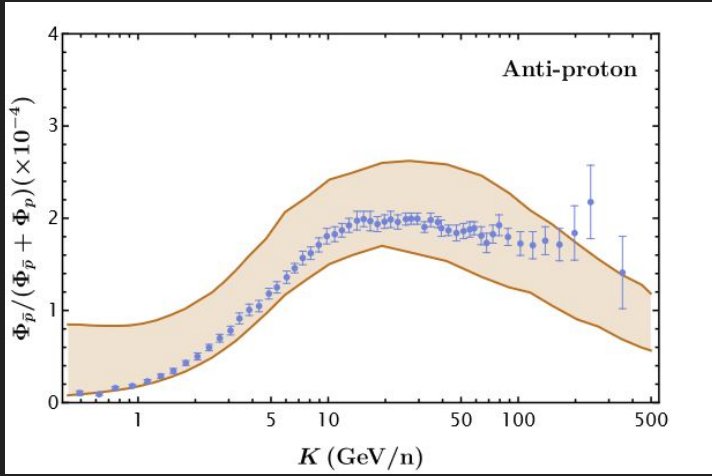
- Additional particle excesses
  - Potential anti-proton, anti-Helium events in AMS
  - Korwar, Profumo 24





Results under construction

- We can estimate the formation rate of late PBHs
  - Need b~km
  - ⇒ ~10-100 in solar orbit
- Direct relation between initial parameters and late time phenomenology
  - Scalar mass, fermion mass, yukawa coupling (and lambda)

Conclusions

- Interacting dark sector can form structures early
- Structures collapse to Fermi balls or PBHs
  - Derived detailed Fermi ball behaviour
- Fermi balls may continue merging today

Explicit scenario for late forming, exploding black holes

Thanks!