The Fate of the Fermi Balls: Late-forming black holes

Zachary S.C. Picker (UCLA)

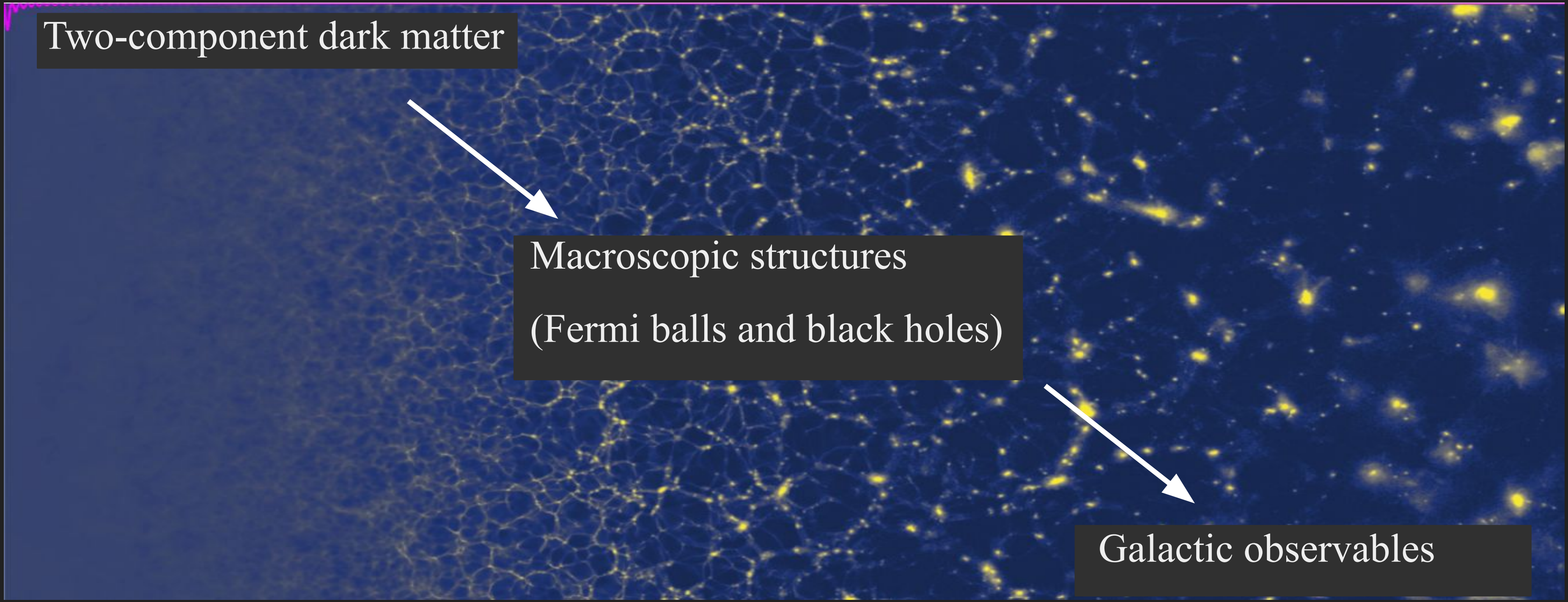
PACIFIC 2024

The Fate of the Fermi Balls: Late-forming black holes

Zachary S.C. Picker (UCLA)
PACIFIC 2024

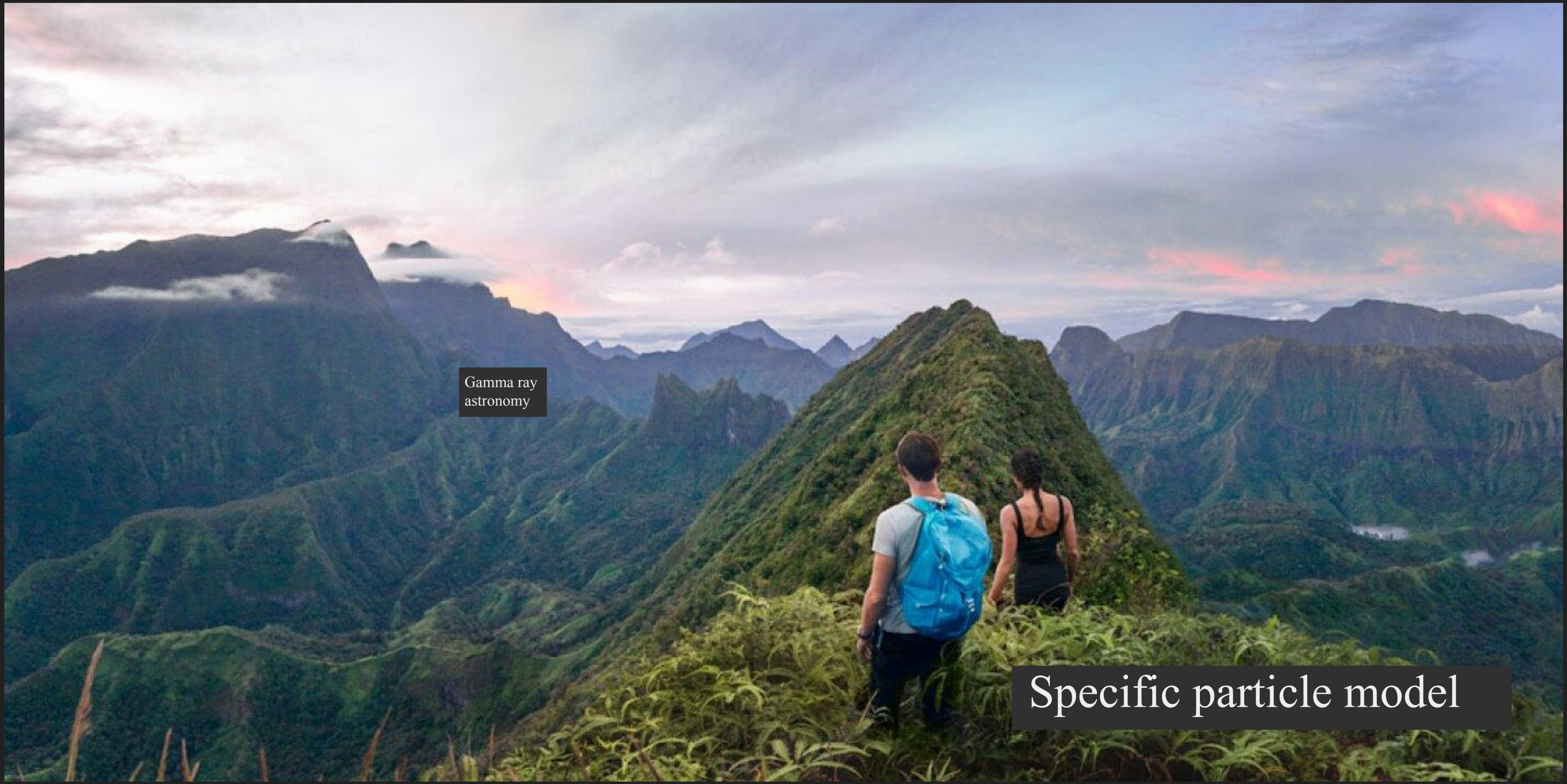
with Alexander Kusenko, Yifan Lu, and Stefano Profumo

Particle physics — Medium physics — Astrophysics/cosmology



Domenech, Inman, Kusenko, Misao Sasaki (2023)

A narrow ridge…



Small scale: Yukawa force dark matter

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
⇒ ‘Yukawa length scale’ is 1/scalar mass

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

Dark matter model

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

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

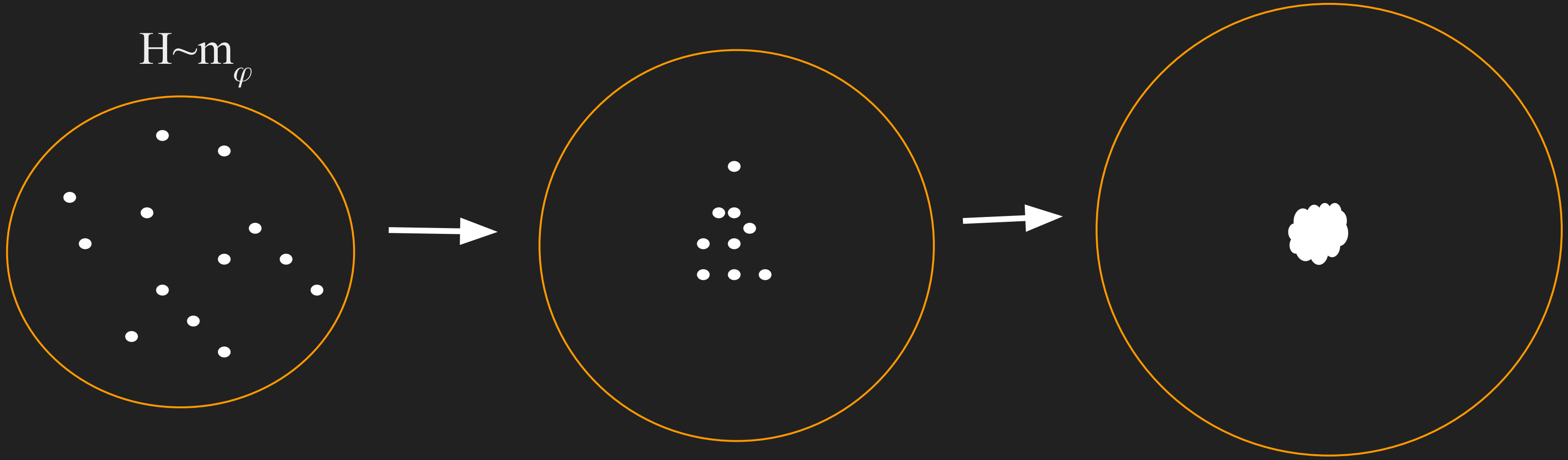
- Inspired by asymmetric dark sector
  - See Flores, Lu, Kusenko 23 for full worked model

Yukawa structure formation

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

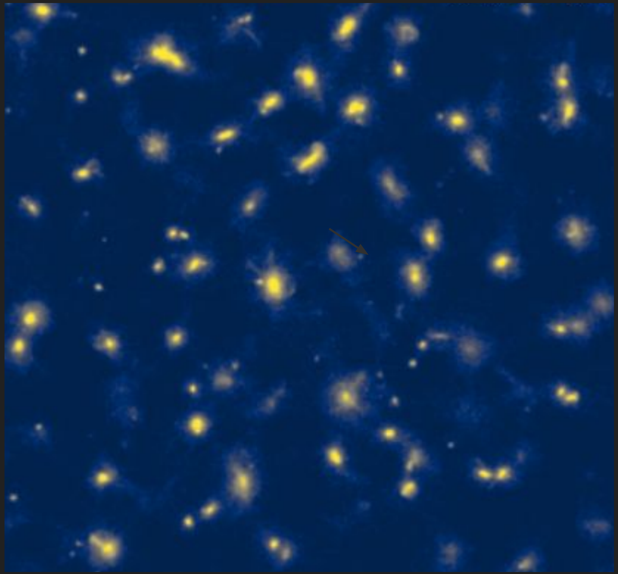
(may need to account for fermion asymmetry)

$H \sim m_\varphi$



Yukawa structure formation

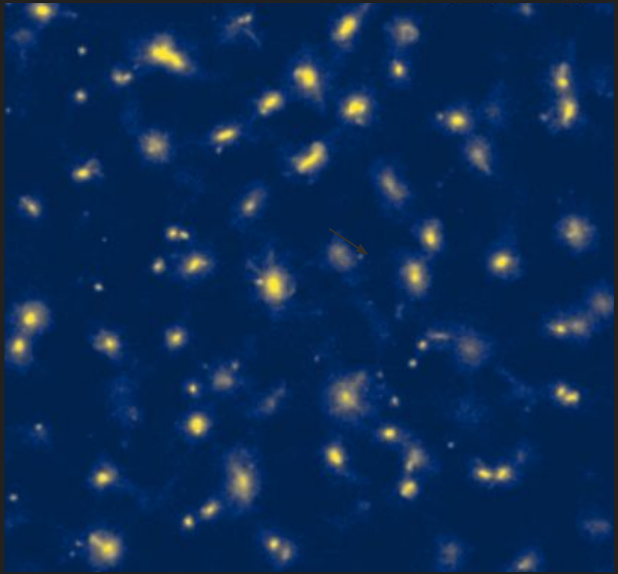
- Significant phenom:
  - Form PBHs directly
    - (Flores, Kusenko 2020, Flores, Lu, Kusenko 2023)
  - ‘Fireball’ baryogenesis
    - (Flores, Kusenko, Pearce, White 2022)
  - Gravitational waves
    - (Flores, Kusenko, Sasaki 2022)



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

Yukawa structure formation

- Significant phenom:
  - Form PBHs directly
    - (Flores, Kusenko 2020, Flores, Lu, Kusenko 2023)
  - ‘Fireball’ baryogenesis
    - (Flores, Kusenko, Pearce, White 2022)
  - Gravitational waves
    - (Flores, Kusenko, Sasaki 2022)



What happens to these halos?

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

Medium scale: Fermi balls and black holes

Fermi balls

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

~dark equivalent of neutron stars/white dwarfs

Fermi balls

- 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

Fermi balls

- 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

The fate of (these) Fermi balls

- Act ~like cold dark matter…
- They *could* grow by merging with each other

Could they collapse to a black hole?

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

The fate of (these) Fermi balls

- Act ~like cold dark matter…
- They *could* grow by merging with each other

  Because their mass + radius is set by the degeneracy pressure, they both scale the same (R, M $\propto$ $N^{2/3}$ where we care)

- ⇒ Black holes do not* form
  - *Reach 'saturation' at Yukawa length
  - *TOV equations (i.e., including gravity) needed once masses are very large

Either it begins as a black hole, or not

Small scale: Yukawa force dark matter
(Again)

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

($\Rightarrow$ new free parameter λ …)

Medium scale: Fermi balls and black holes (Again)

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

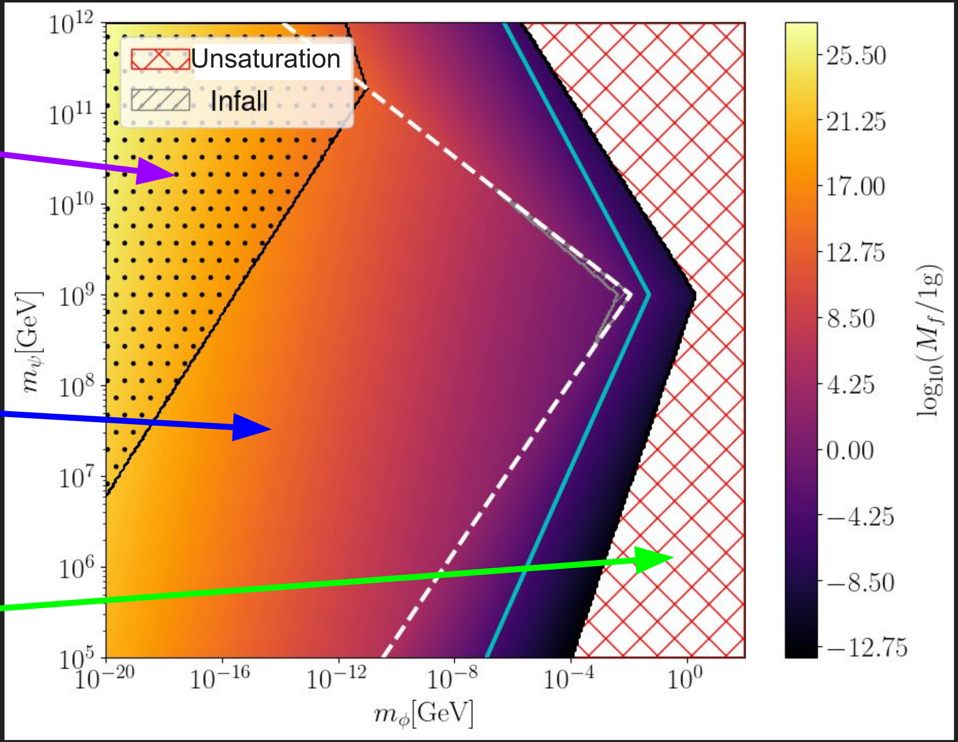
$\Rightarrow$ By adding more fermions, you *can* cause it to collapse to a black hole

~New primordial black hole formation mechanism

Black holes are formed immediately (~whale to planet size here)

Fermi balls are formed

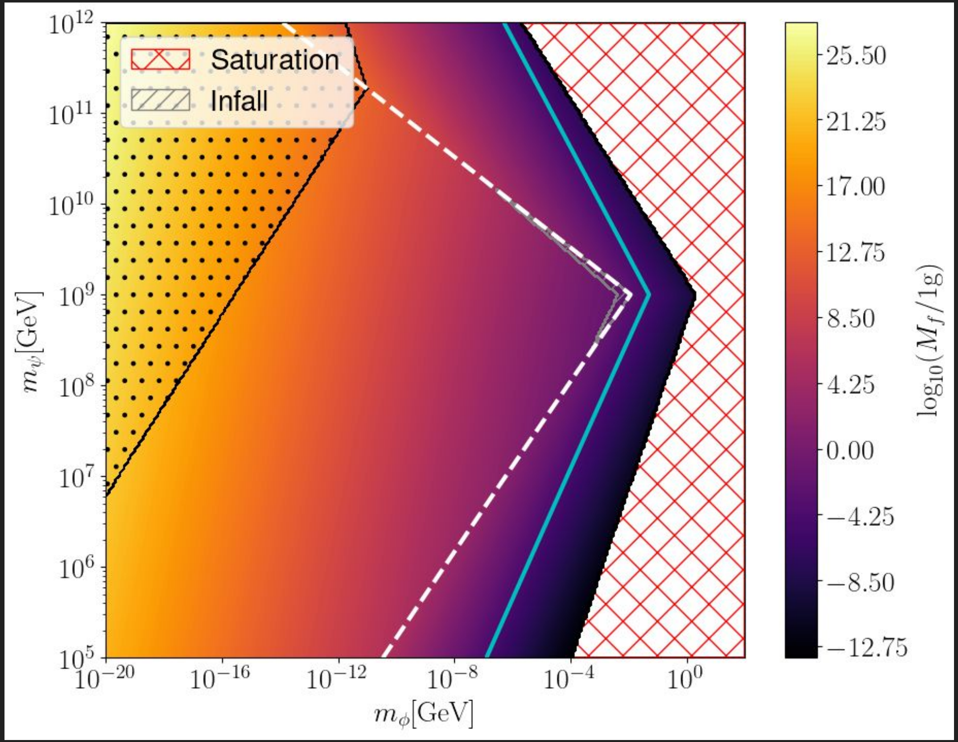
'Unsaturated' Fermi balls (non-analytic)



(y=5e-2, λ=1e-2)

New primordial black hole formation mechanism

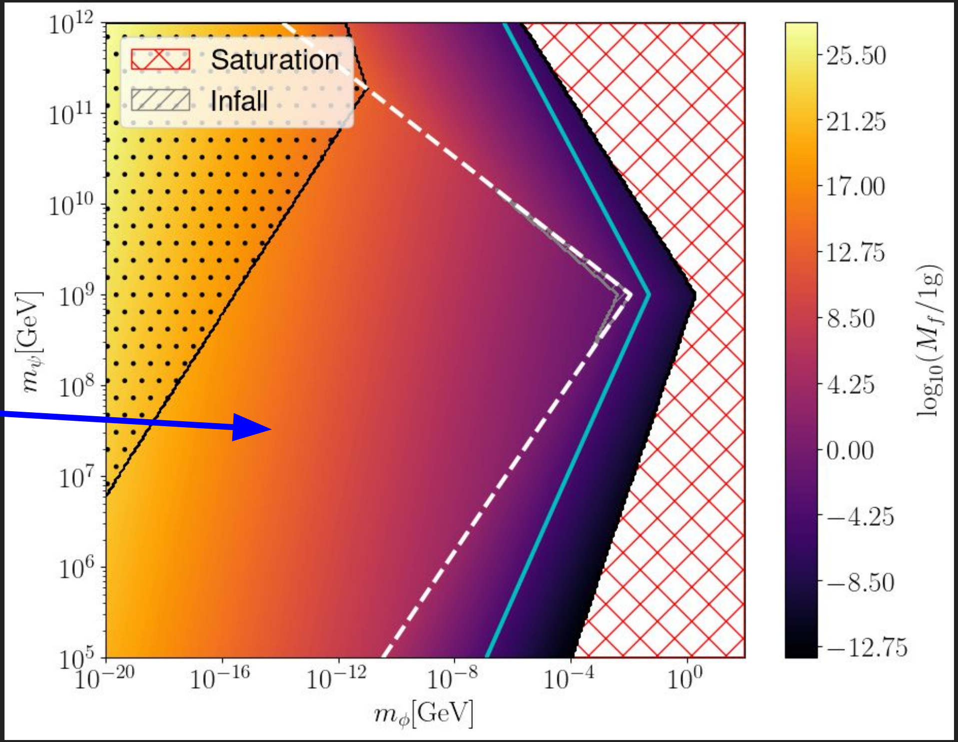
Paper coming… soon



(y=5e-2, λ=1e-2)

New primordial black hole formation mechanism

What happens to these guys over cosmological times?

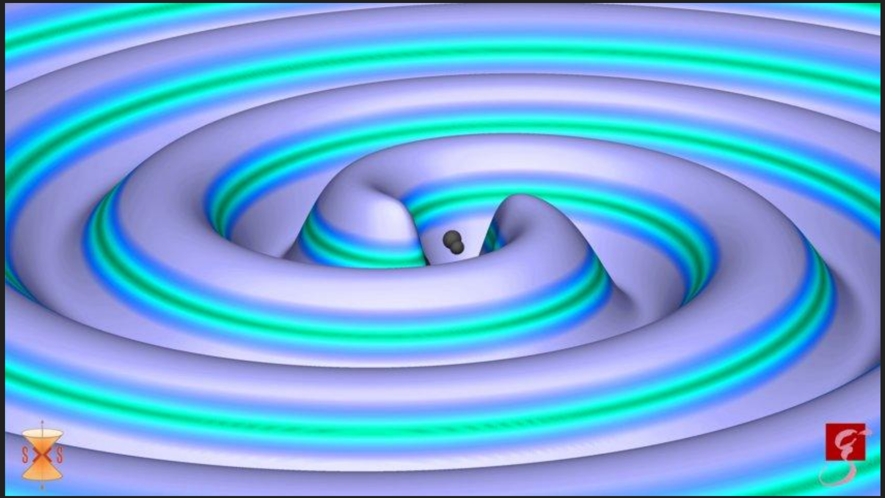


(y=5e-2, λ=1e-2)

Big scale: Fermi ball halos

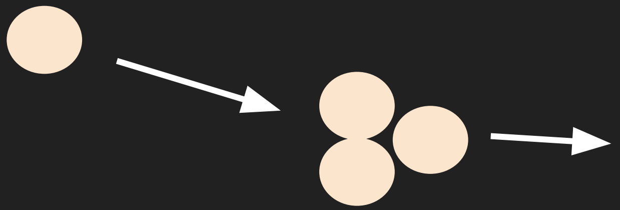
Fermi ball interactions

- 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
- (Usually) no issue from self-interacting dark matter constraints
  - Yukawa length scale << inter-Fermi ball spacing

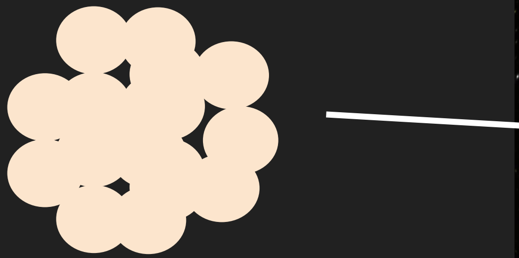


S. Ossokine, A. Buonanno, T. Dietrich

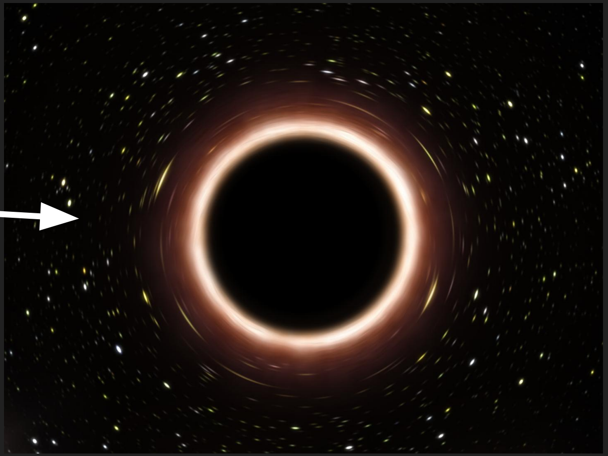
Late forming black holes



‘Runaway’ process as merger cross-section increases



Sink towards galactic center as they grow



Mahon Pool, Maroubra, NSW Australia

Late forming black holes (or ‘microstructure’ black holes)

Two futures

Late forming black holes (or ‘microstructure’ 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 (or 'microstructure' black holes)

Two futures

Fermi ball - black hole conversion

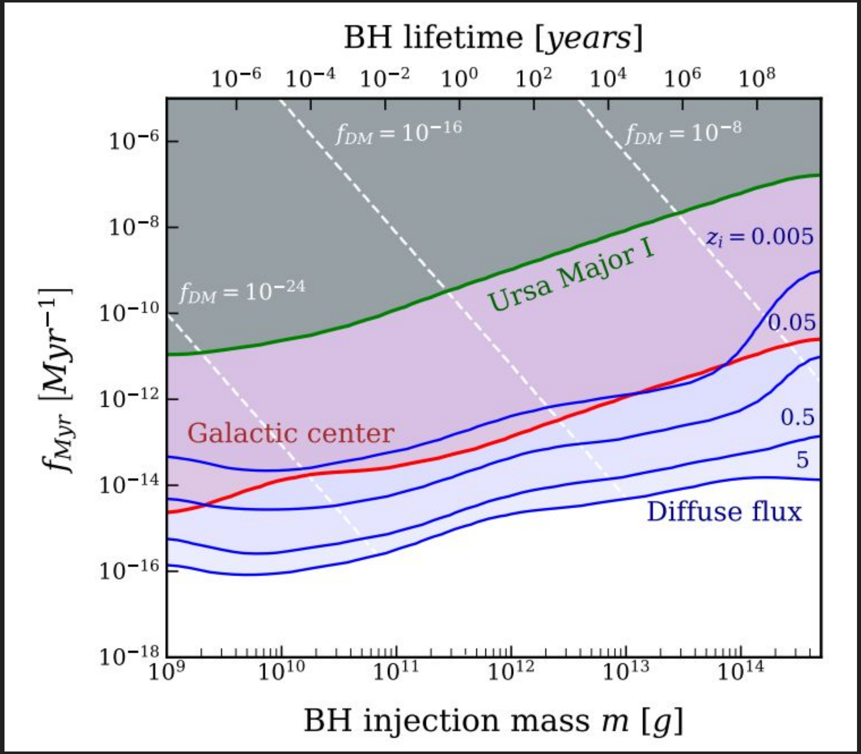
- Need to investigate possible constraints from DM halo contraction

Rare black hole formation

- The black holes could be evaporating today
  - (Impossible otherwise)
- Constraints, but also phenom…

Constraints on late forming, evaporating BHs

ZSCP, Kusenko 23

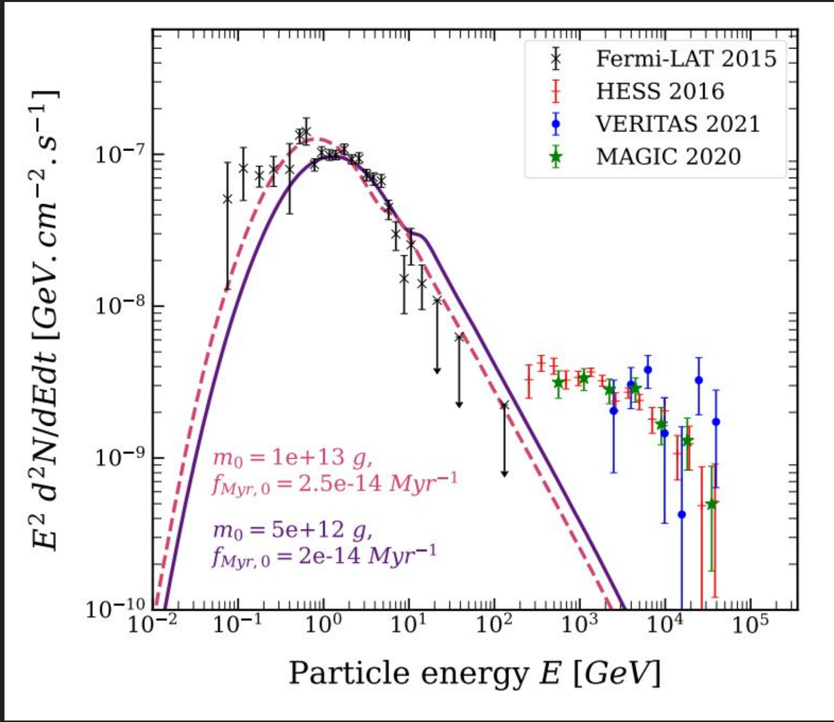


Particle excesses in the galactic center

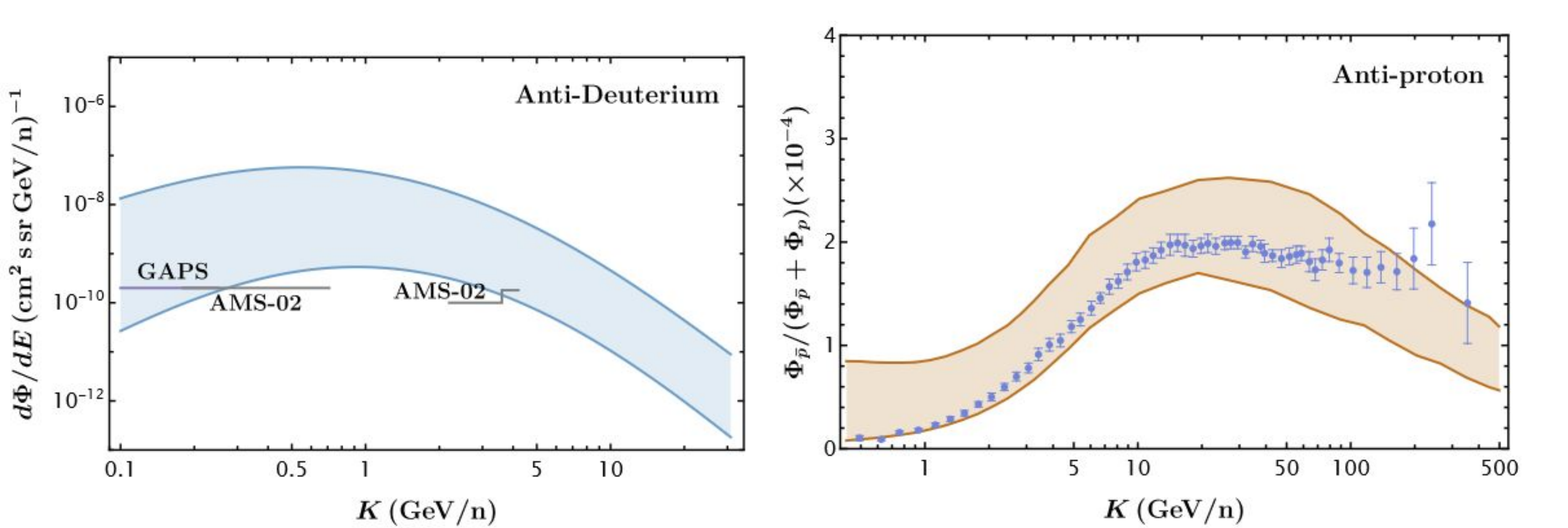
- A small amount of evaporating black holes could explain the GeV excess
  - ZSCP, Kusenko 23

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

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



Particle excesses in the galactic center



Korwar, Profume 24

Results under construction

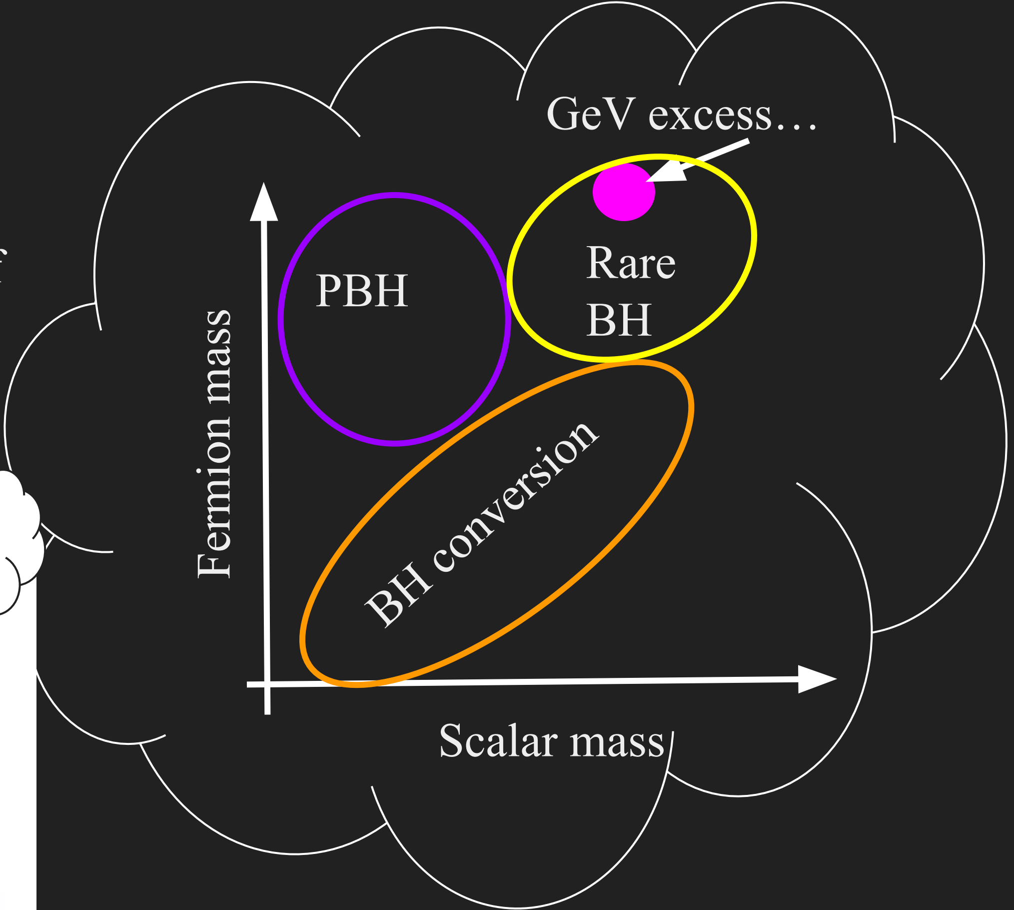
- We can estimate the formation rate of late PBHs
- Direct relation between initial parameters and late time phenomenology
    - Scalar mass, fermion mass, yukawa coupling (and lambda)
    - No real ‘fudge’ steps—but only ~order of mag certainty

Results under construction

- We can estimate the formation rate of late PBHs
- Direct relation between initial parameters and late time phenomenology
    - Scalar mass, fermion mass, yukawa coupling (and lambda)
    - No real ‘fudge’ steps—but only ~order of mag certainty
- I don’t have a plot to show you right now…

Results under construction

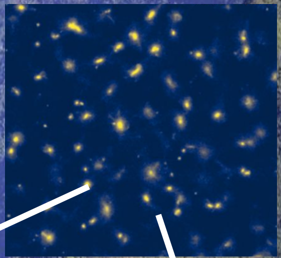
- We can estimate the formation rate of late PBHs
- Direct relation between initial parameters and late time phenomenology
  - Scalar mass, f
    coupling
  - No real ‘fudge
    mag certainty
- I don’t have a pl
  now…



Paper coming also soon…(ideally)

The full storyline

Dark matter with Yukawa force forms structures early



Collapse to PBH or Fermi balls

Fermi balls grow quickly or slowly

Could convert to BHs or evaporate today…