The art of making black holes

Zachary S. C. Picker

Oct. 2023

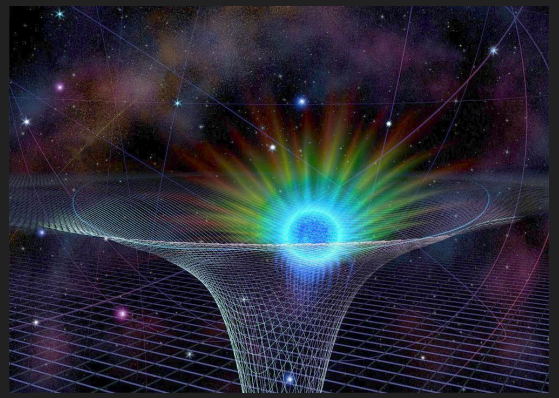
Feat. Alexander Kusenko, Graciela Gelmini, Yifan Lu, Volodymyr Takhistov

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
UC SANTA CRUZ

UCLA
PHYSICS & ASTRONOMY

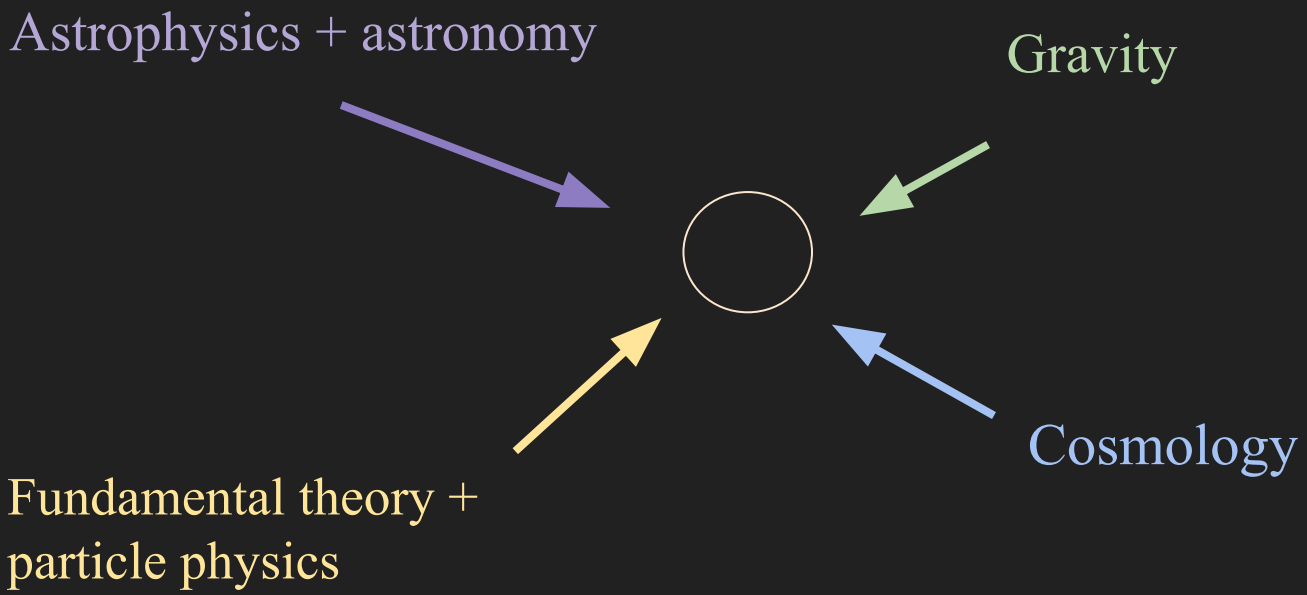
PBH…

1. Hints
2. Phenomenology
3. Origins
4. Forming in late times



The gospel of black holes

The gospel: all roads lead to black holes

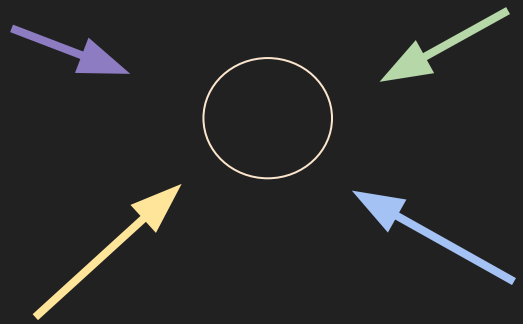


The gospel: all roads lead to black holes

Astrophysics + astronomy

- Dark matter?
- SMBH/galaxy formation?

Gravity



Cosmology

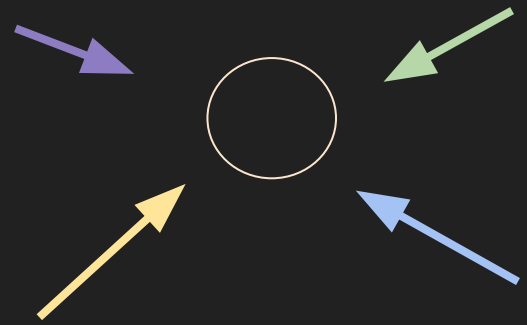
Fundamental theory + particle physics

The gospel: all roads lead to black holes

Astrophysics + astronomy

- Dark matter?
- SMBH/galaxy formation?

Gravity



Cosmology

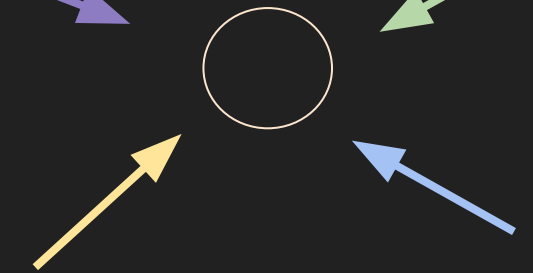
Fundamental theory + particle physics

- BSM (SUSY, GUT, strong-CP,...?)

The gospel: all roads lead to black holes

Astrophysics + astronomy
- Dark matter?
- SMBH/galaxy formation?

Gravity
- GW sources?
- Unification with QFT?



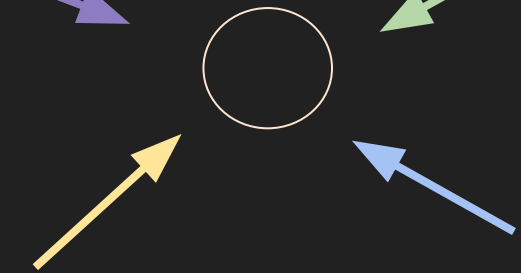
Fundamental theory + particle physics
- BSM (SUSY, GUT, strong-CP,...?)

Cosmology

The gospel: all roads lead to black holes

Astrophysics + astronomy
- Dark matter?
- SMBH/galaxy formation?

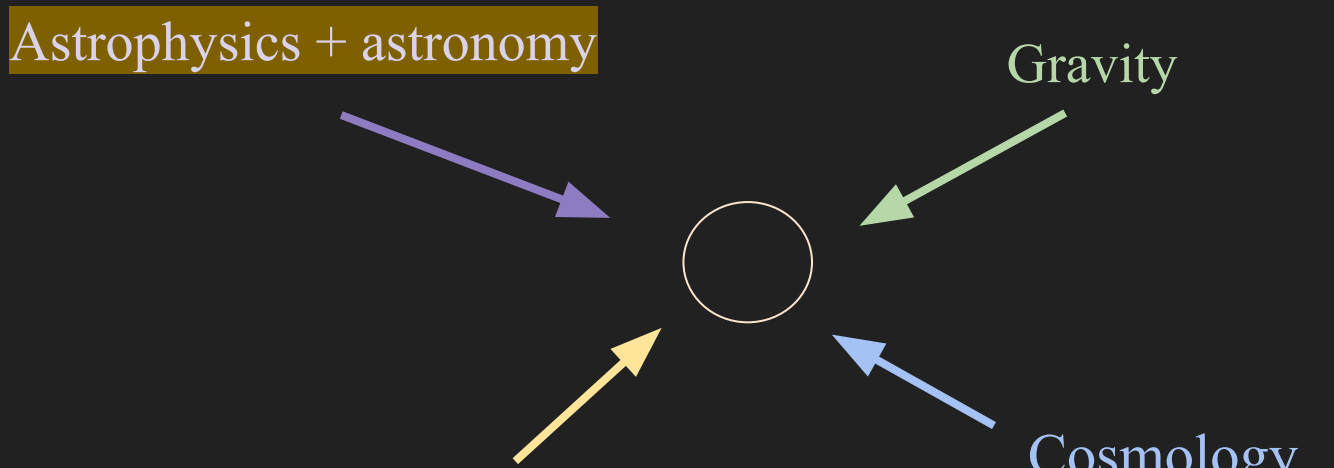
Gravity
- GW sources?
- Unification with QFT?



Fundamental theory + particle physics
- BSM (SUSY, GUT, strong-CP,...?)

Cosmology
- Dark matter?
- Baryogenesis?
- Inflation?

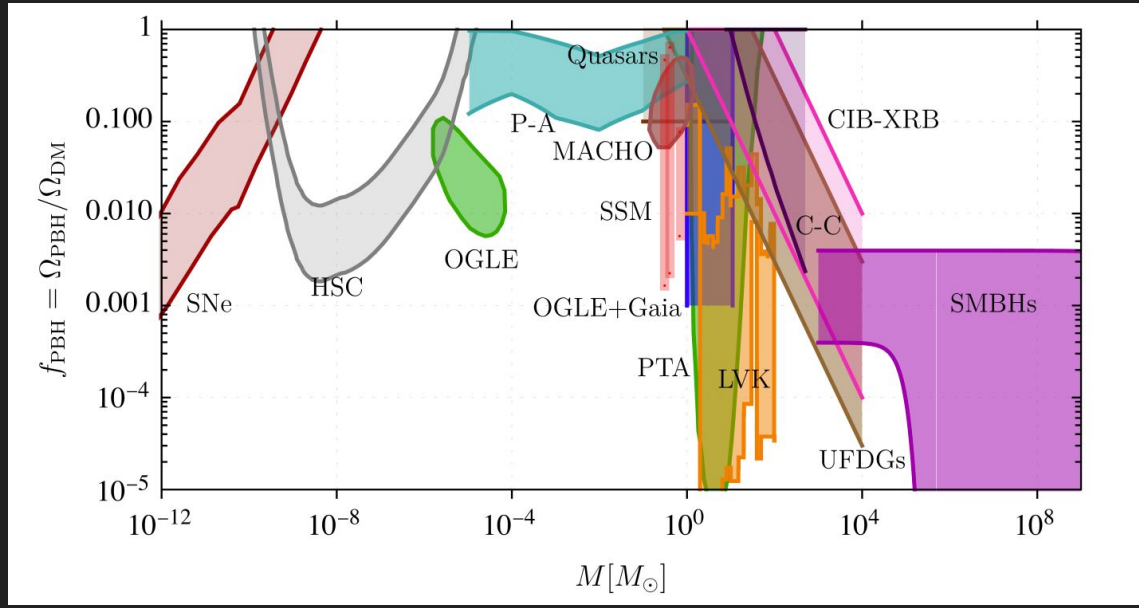
The gospel: all roads lead to black holes



PhD advisors: Archil Kobakhidze + Celine Boehm (Usyd)

PBH Hints

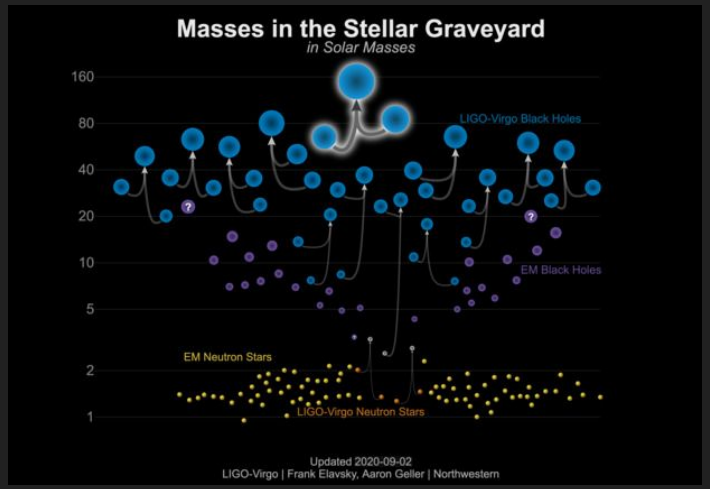
PBH Hints: *A Positivist Perspective,* arXiv:2306.03903

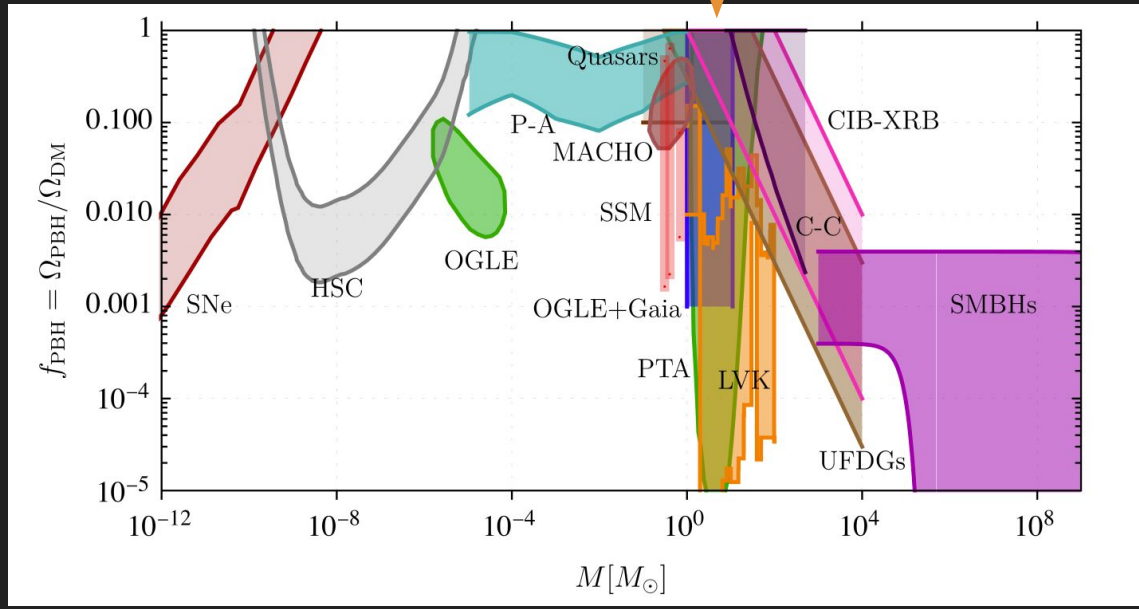


Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

PBH Hints: Ligo-Virgo-Kagra events

- Upper and lower mass gaps
- GW190521:
  85, 64 solar masses
- GW190814:
  23, 2.6 solar masses

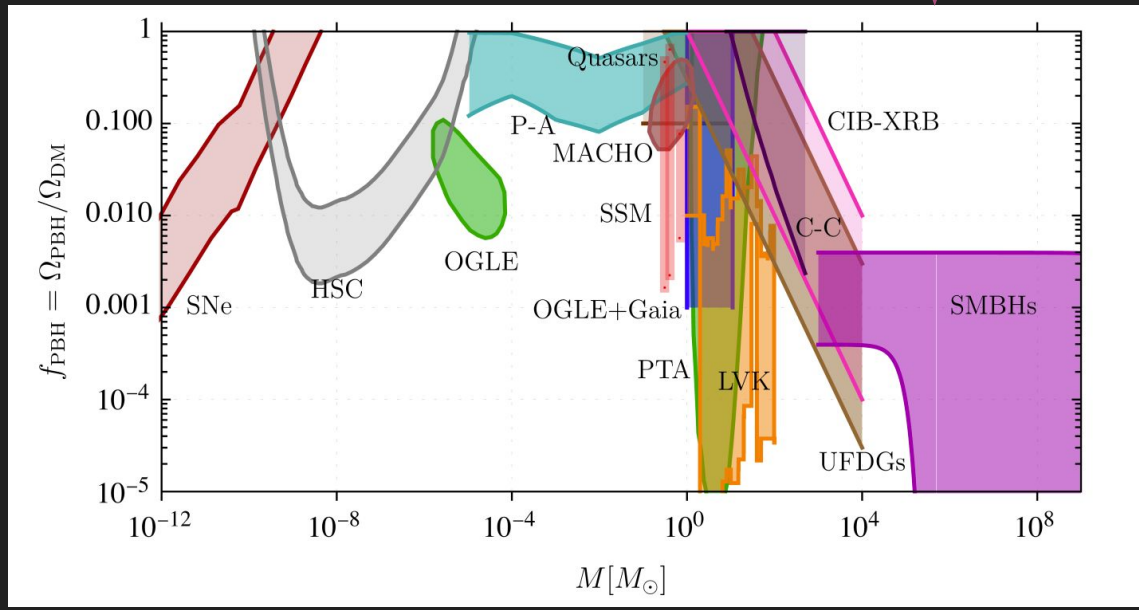




Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

PBH Hints: Structure formation

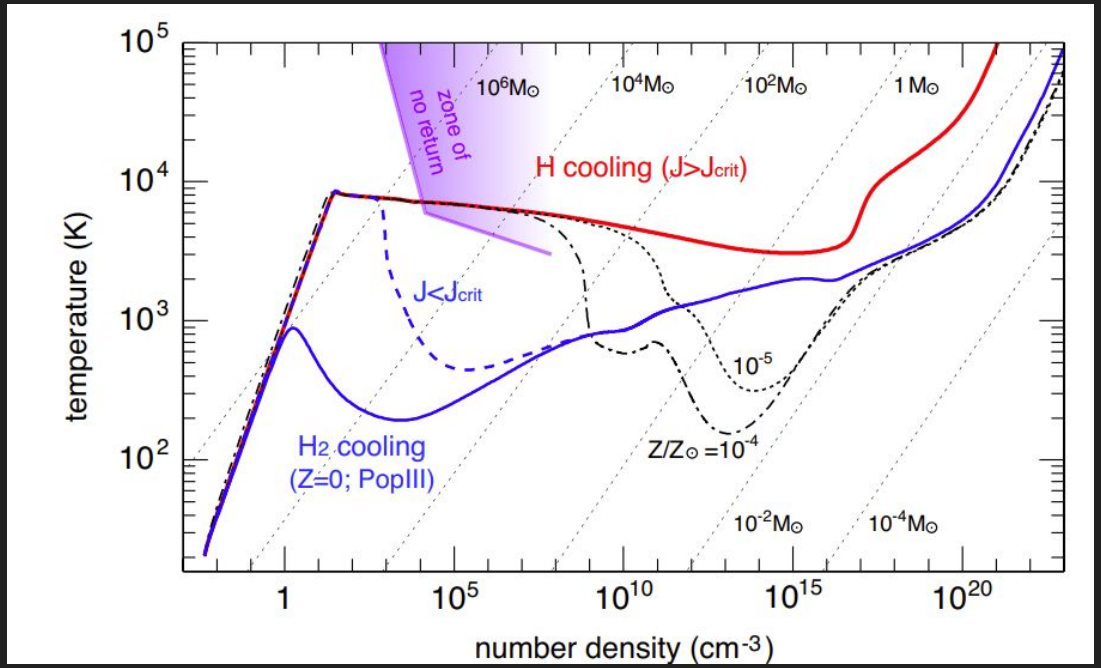
- Seeds of structure formation and early SMBH



Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

PBH Hints: SMBH formation (preliminary)

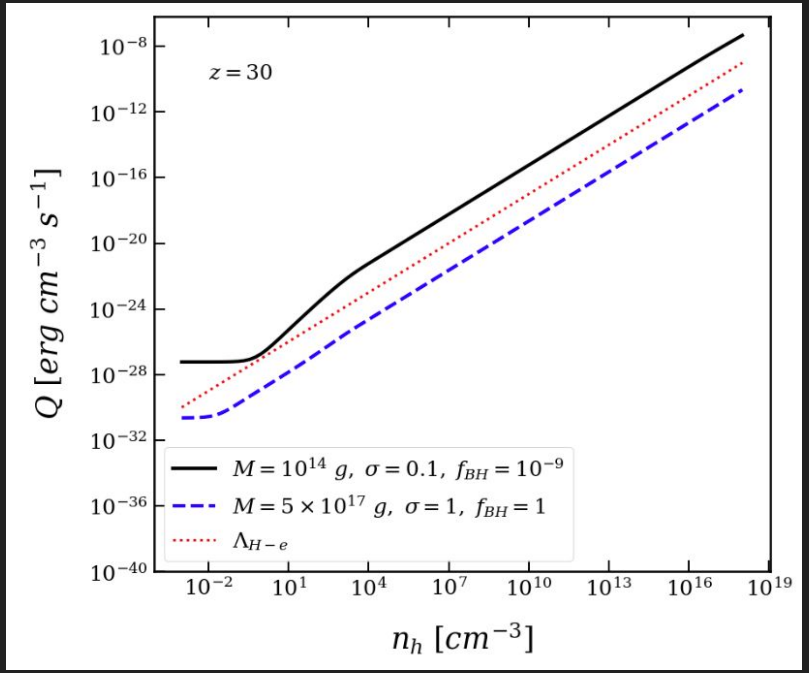
- SMBH formation by mergers may take too long
- Direct collapse to BHs is limited by cooling → fragmentation
- Must keep gas hot enough to avoid molecular cooling



Kohei Inayoshi, Eli Visbal, Zoltan Haiman 2019

PBH Hints: SMBH formation (preliminary)

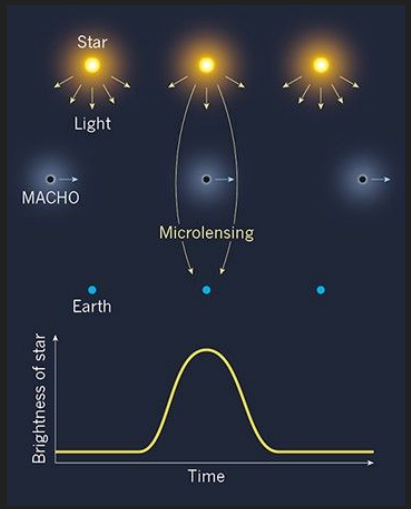
- SMBH formation by mergers may take too long
- Direct collapse to BHs is limited by cooling and fragmentation
- Must keep gas hot enough to avoid molecular cooling
- Hawking evaporation as heat source?
  - (very involved numerically…)

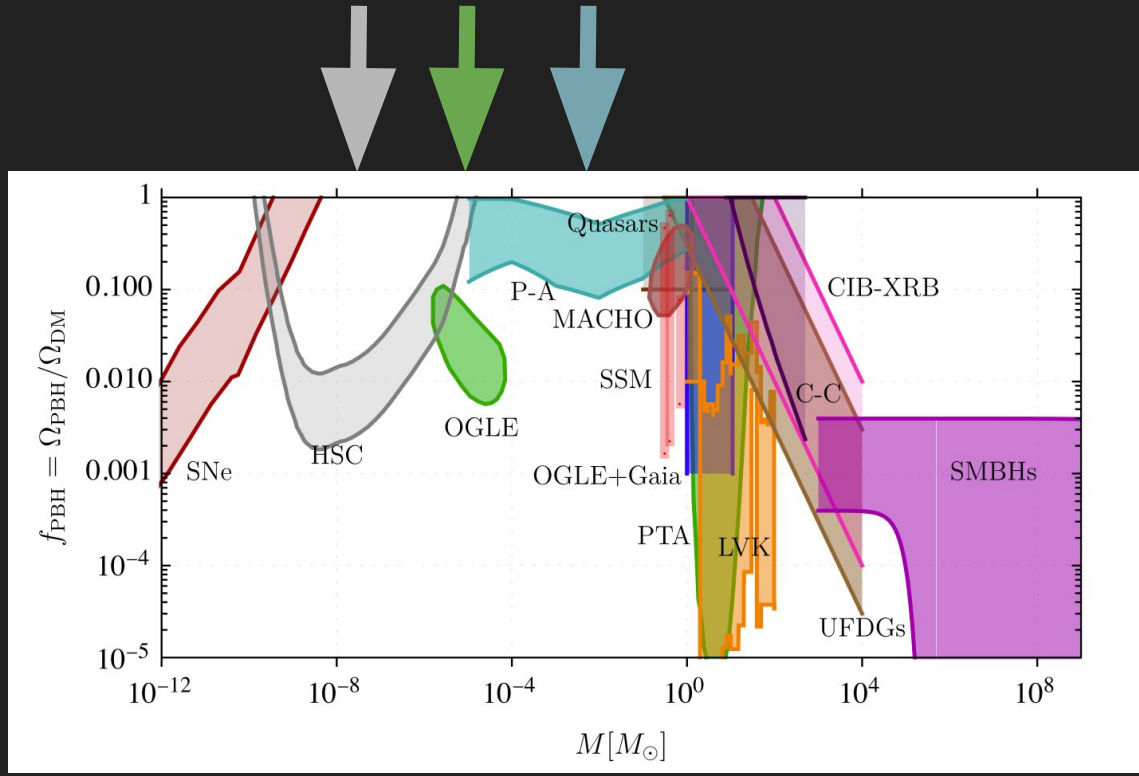


Yifan Lu, ZSCP, Alexander Kusenko 2023 (hopefully)

PBH Hints: Lensing

- Microlensing, quasar lensing
  - Quasar lightcurves? Hawkins 2022
  - OGLE six events? Niikura et al 2019

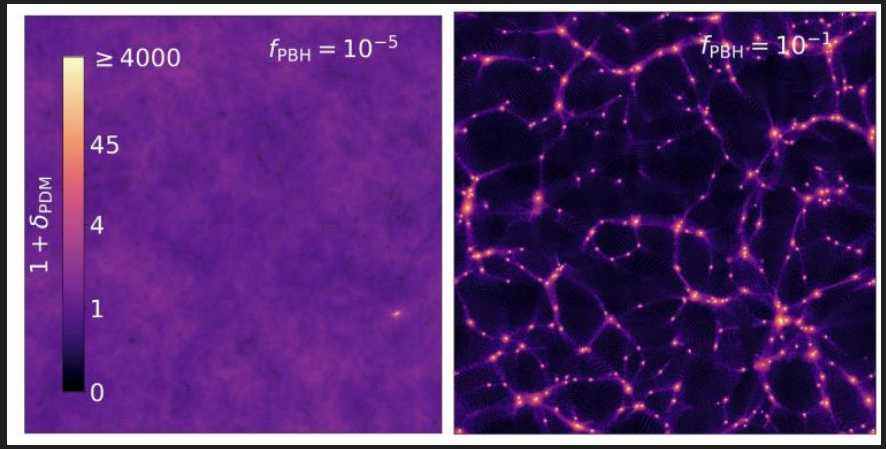




Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

Aside: clustering

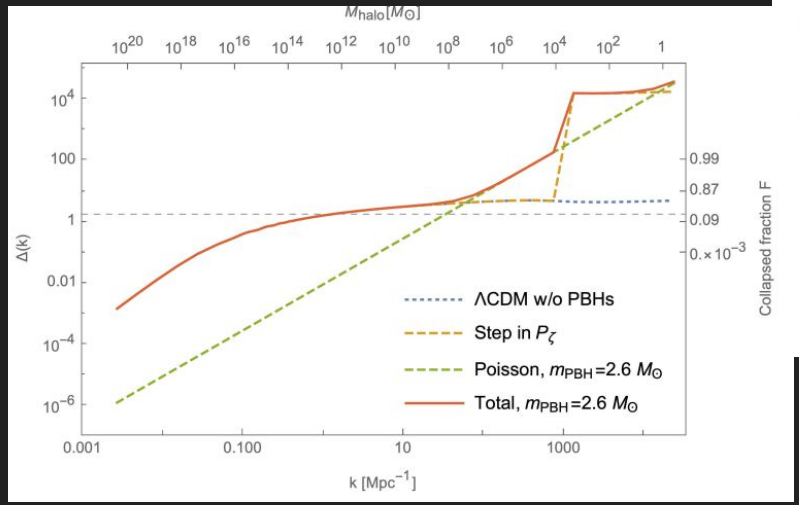
- Poisson fluctuations → clustering
- Affects constraints, structure formation

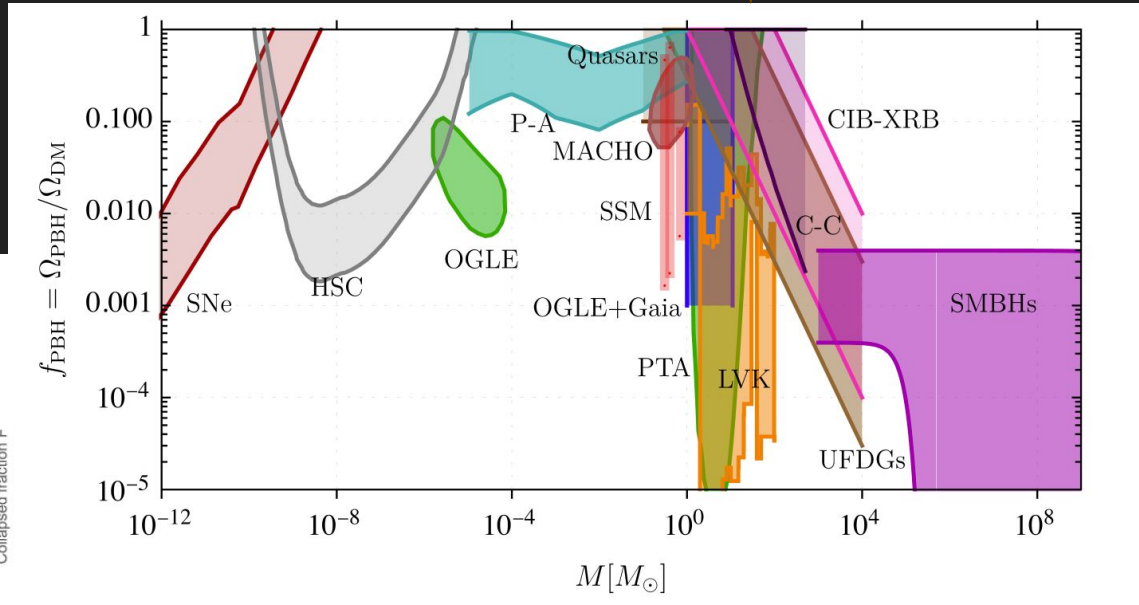


Inman and Ali-Haimoud 2019
Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

PBH Hints: Ultra-faint dwarf galaxies

- PBH clusters naturally agree with the minimum mass/radius of UFDG

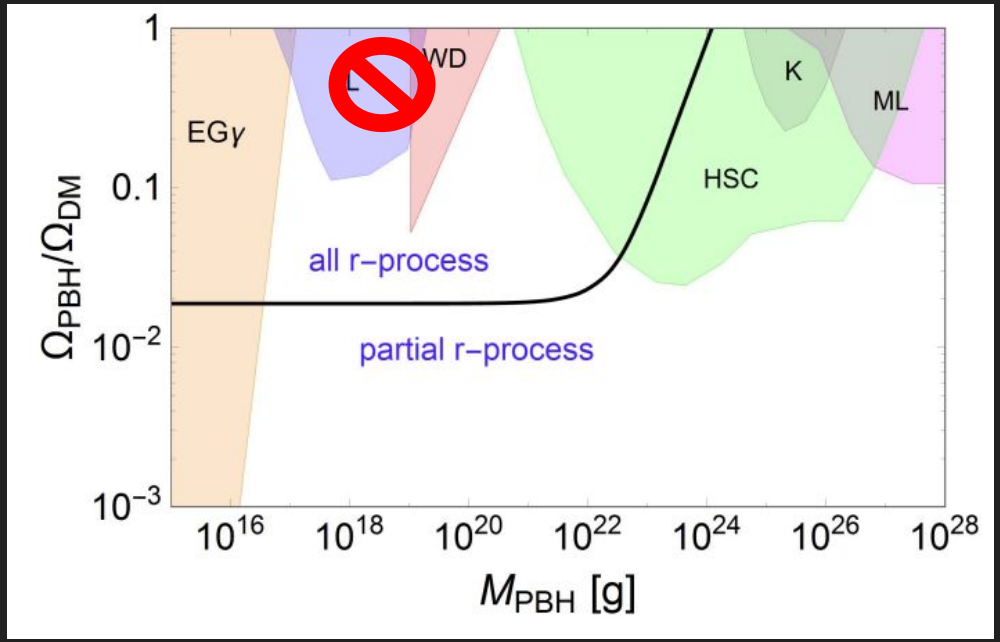




Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

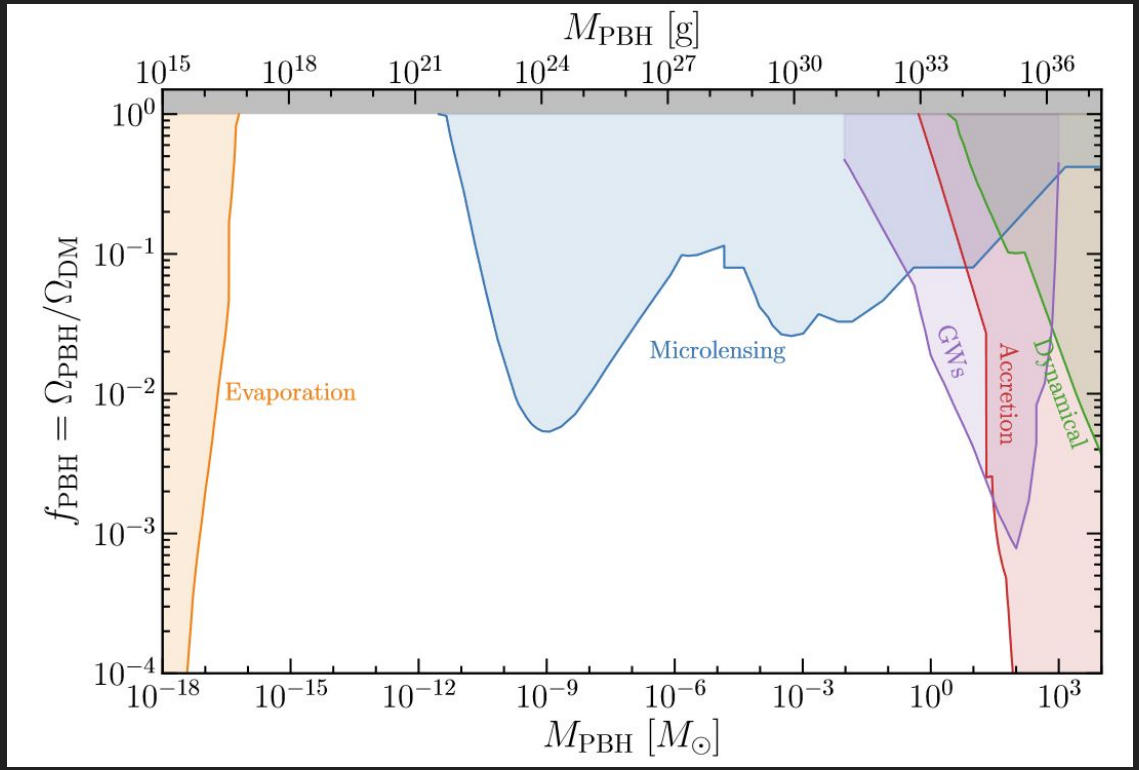
PBH Hints: Missing pulsars, R-process nucleosynthesis, g-objects

- Asteroid-mass PBHs may destroy neutron stars
  - Y. Genolini, P. D. Serpico, P. Tinyakov (2020)
- Unexplained g-objects
  - Flores, Kusenko, Ghez, Naoz



George M. Fuller, Alexander Kusenko, Volodymyr Takhistov (2017)

PBH Hints: dark matter??



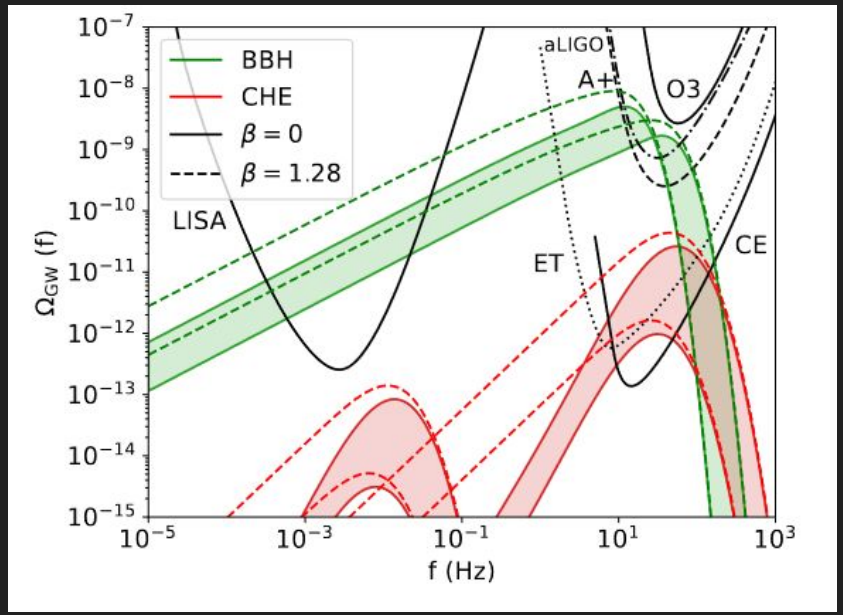
Green and Kavanaugh (2020)

PBH Phenomenology

(i.e. hints we haven’t seen yet)

PBH phenomenology: hyperbolic encounters and GWs

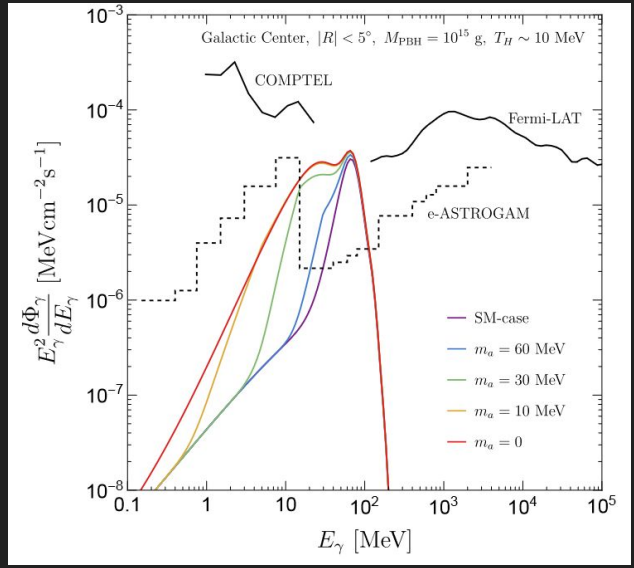
- Burst-like GW signal
- Depends strongly on clustering → depends on PBH formation mechanism, mass distribution
  - ZSCP, Kusenko, Garcia-Bellido (no timeline…)



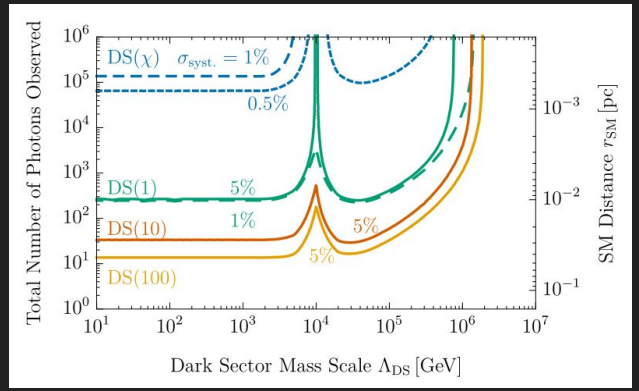
Juan García-Bellido, Santiago Jaraba, Sachiko Kuroyanagi (2022)

PBH phenomenology: Hawking evaporation

- Small PBHs could produce large fluxes of particles
  - Not observed, only used to place constraints currently
  - Korwar, Profumo (2023), Boluna, Profumo, Blé, Hennings (2023)
- Would also produce decaying BSM particles
  - Axions: right and Jho, Kim, Park, Park, Park (2022)

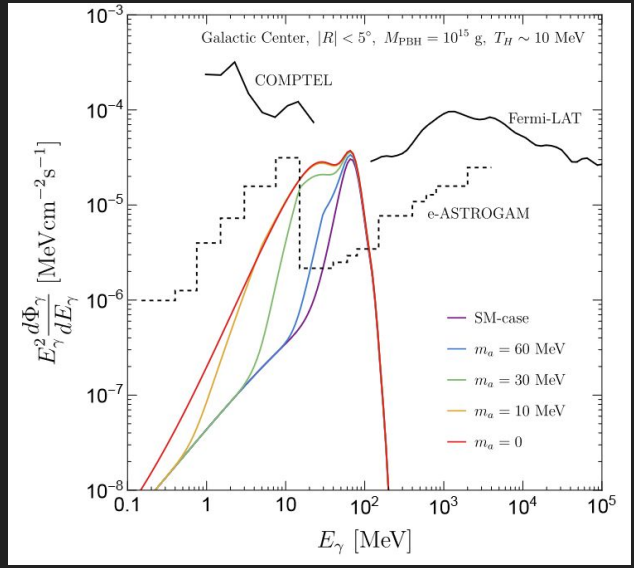


Agashe, Chang, Clark, Dutta, Tsai, Xu (2022)
Baker, Thamm (2021)

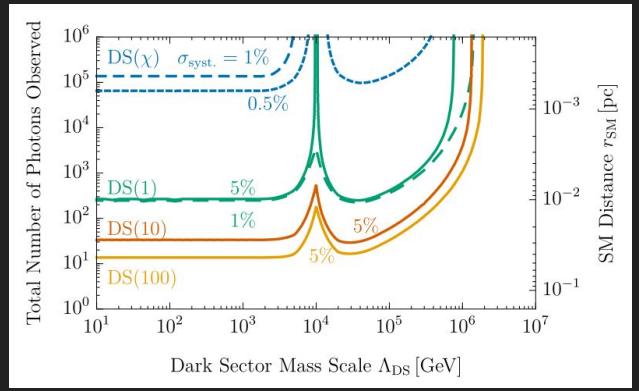


PBH phenomenology: Hawking evaporation

- Small PBHs could produce large fluxes of particles
  - Not observed, only used to place constraints currently
  - Korwar, Profumo (2023), Boluna, Profumo, Blé, Hennings (2023)
- Would also produce decaying BSM particles
  - Axions: right and Jho, Kim, Park, Park, Park (2022)
- Can extend analysis to wider class of short-lived BSM particles
  - ZSCP, Gelmini, Takhistov (hopefully 2023…)

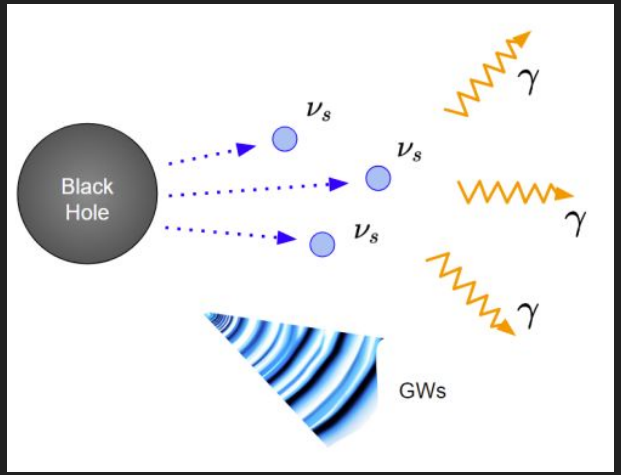


Agashe, Chang, Clark, Dutta, Tsai, Xu (2022)
Baker, Thamm (2021)



PBH phenomenology: early Hawking evaporation

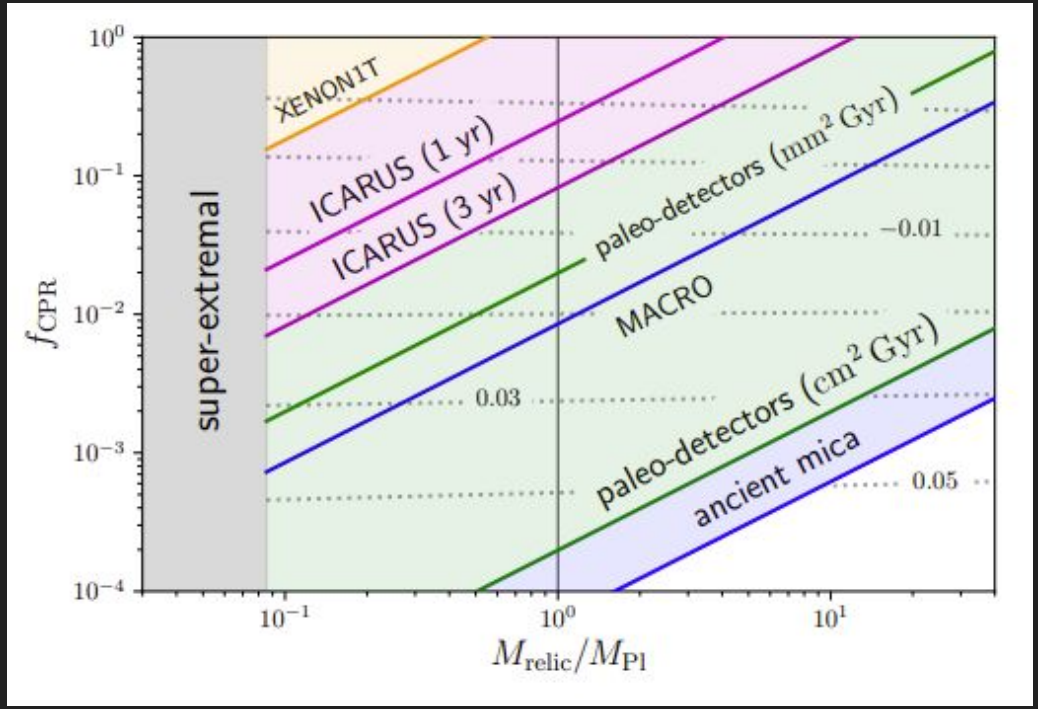
- Alternative DM generation
  - Melanopogenesis: Morrison, Profumo, Yu (2019)
  - Chattopadhyay, Chaudhuri, Khlopov (2022)
  - Sterile neutrinogenesis: Chen, Gelmini, Lu, Takhistov (2023)
- Can create period of early matter domination
  - (the reverse—PBHs from overdensities form much more easily in matter domination…)



Chen, Gelmini, Lu, Takhistov (2023)

PBH phenomenology: Planck relics?

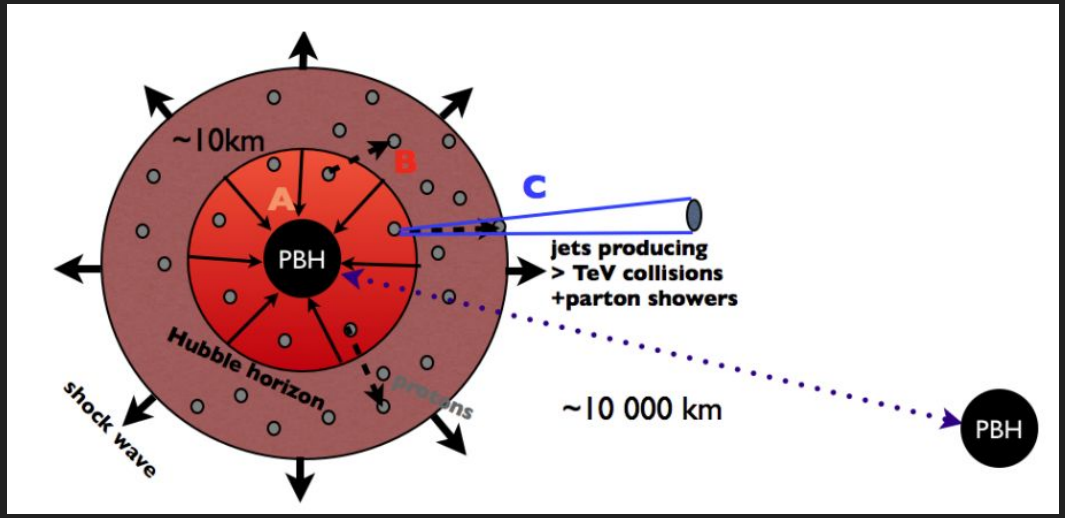
- Hawking evaporation may halt, leaving relics
  - Could be all of the DM
  - MacGibbon (1987), Barrow, Copeland, Liddle (1992)
  - Chen, Adler (2003)
  - Lehmann, Johnson, Profumo, Schwemberger (2019)



Lehmann, Johnson, Profumo, Schwemberger (2019)

PBH phenomenology: baryogenesis

- Hawking evaporation of ultralight black holes
  - Morrison, Profumo, Yu (2019)
  - Hooper, Krnjaic (2022)
  - Gehrmana, Haghib, Sinhaa, Xu (2023)
  - Datta, Ghosal, Samanta (2021)
- PBH ‘hot spots’→ sphalerons turn on
  - See also Flores, Kusenko, Pierce, White (2022)



Garcia-Bellido, Carr, Clesse (2019)

PBH Origins

PBH origins: no comprehensive review exists… yet…

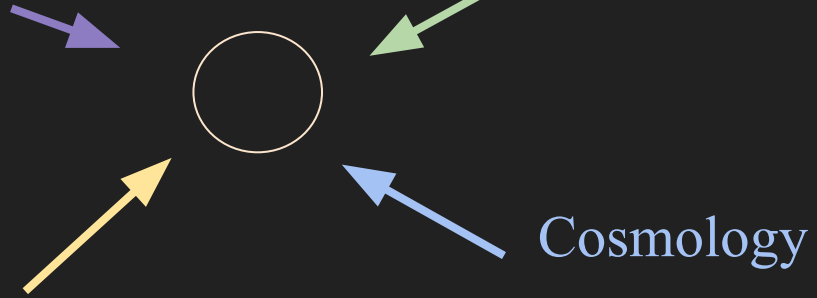
(that I know of)

See however Escriva, Kuhnel, Tada (2023)

PBH origins: New physics → Black holes

Astrophysics

Gravity



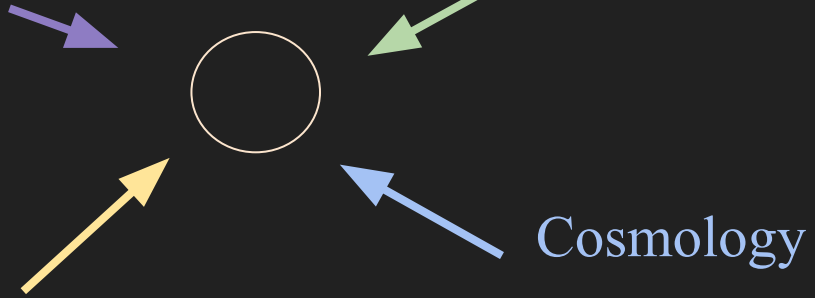
Cosmology

Particle physics

PBH origins: New physics → Black holes

Astrophysics
- Dark sector dynamics

Gravity



Cosmology

Particle physics

PBH origins: New physics → Black holes

Astrophysics
- Dark sector dynamics

Gravity

Cosmology

Particle physics
- Axions + GUTs (topological defects)
- SUSY (Q-balls)

PBH origins: New physics → Black holes

Astrophysics
- Dark sector dynamics

Gravity
- gravity

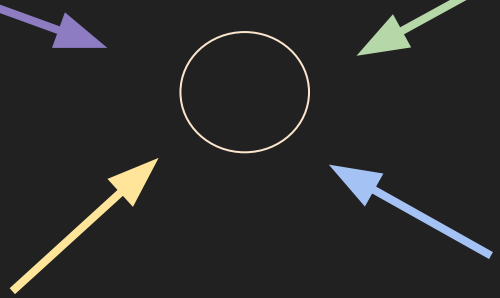
Cosmology

Particle physics
- Axions + GUTs (topological defects)
- SUSY (Q-balls)

PBH origins: New physics → Black holes

Astrophysics
- Dark sector dynamics

Gravity
- gravity

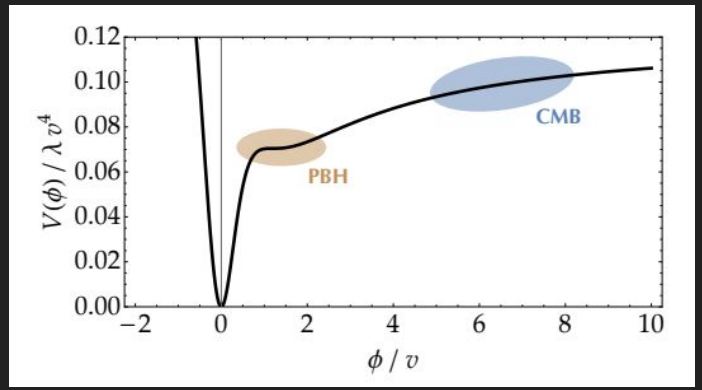


Particle physics
- Axions + GUTs (topological defects)
- SUSY (Q-balls)

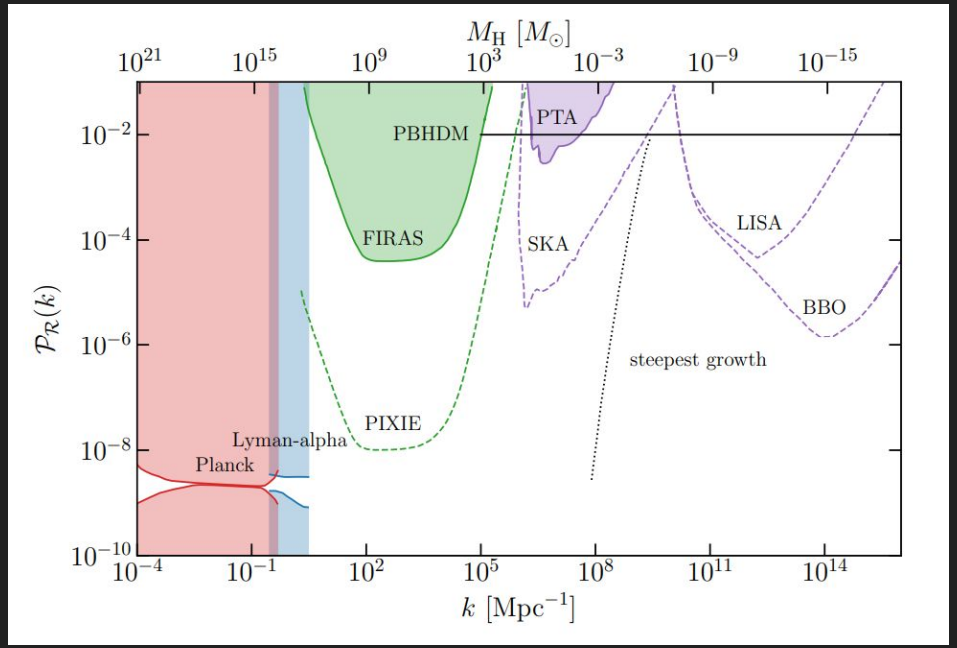
Cosmology
- Inflation
- phase transitions
- Early matter domination

PBH origins: inflation and overdensities

- The ‘classic’ scenario: overdense regions collapse into black holes
- Usually requires some additional inflationary features
  - fine-tuning issues

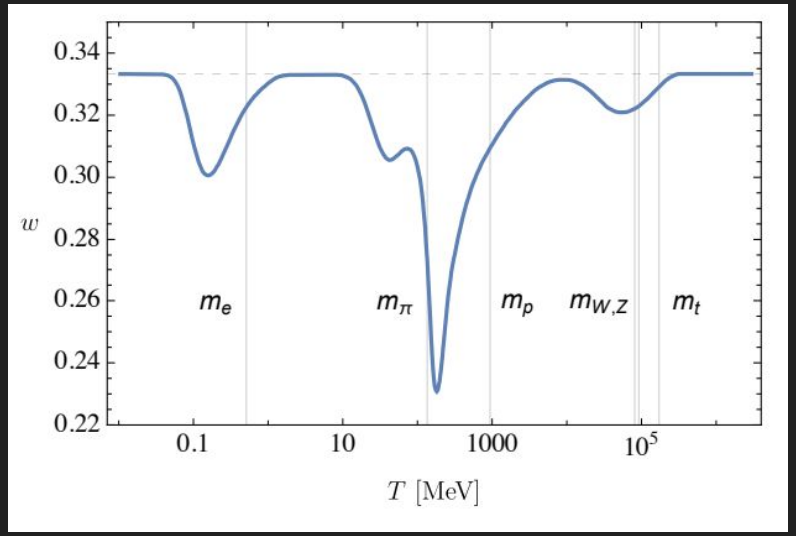


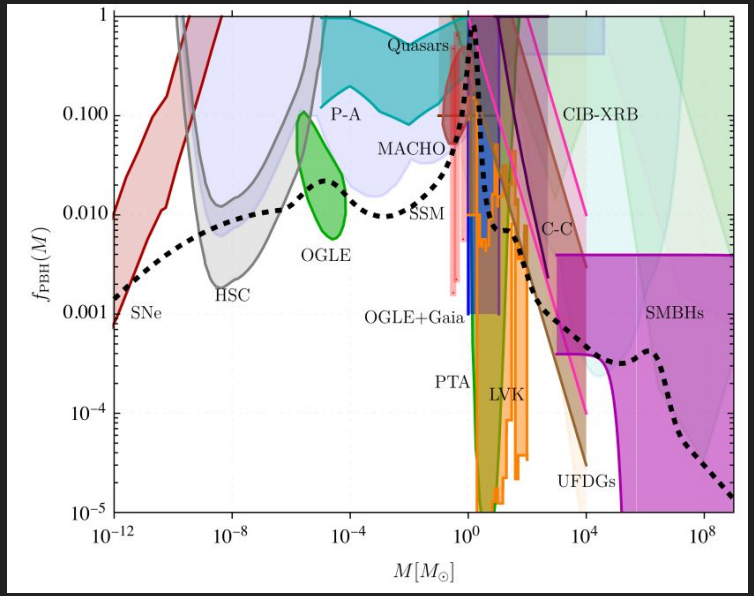
Escriva, Kuhnel, Tada (2023)



Green and Kavanaugh (2020)

PBH origins: enhanced formation

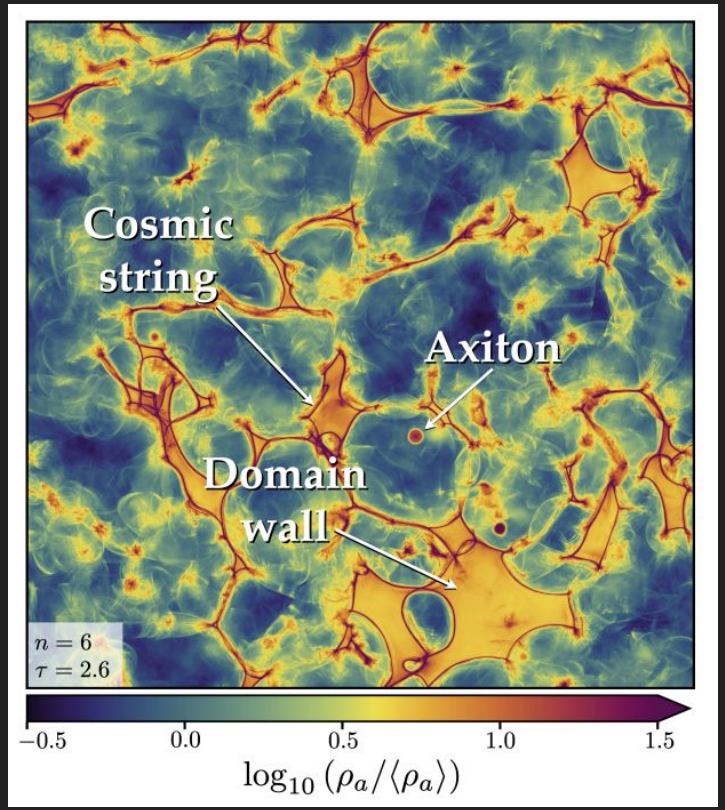




Carr, Clesse, Garcia-Bellido, Kuhnel 2021
Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

PBH origins: cosmic string loops

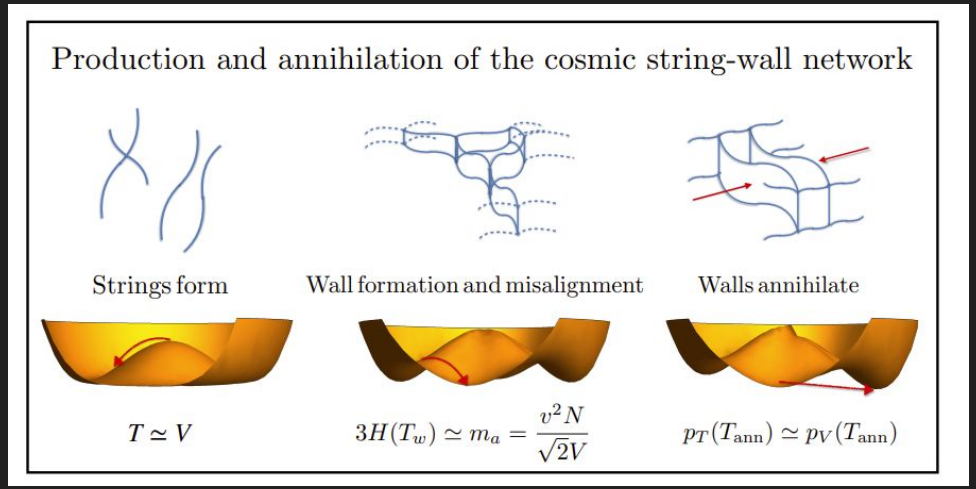
- 1-dimensional topological defects
  - Left behind after some symmetry breaking
  - (eg, in the axion case)
- If a loop is sufficiently small, it could collapse into a black hole
  - Hawking (1989)



O'Hare, Pierobon, Redondo, Wong 2022

PBH origins: domain wall collapse

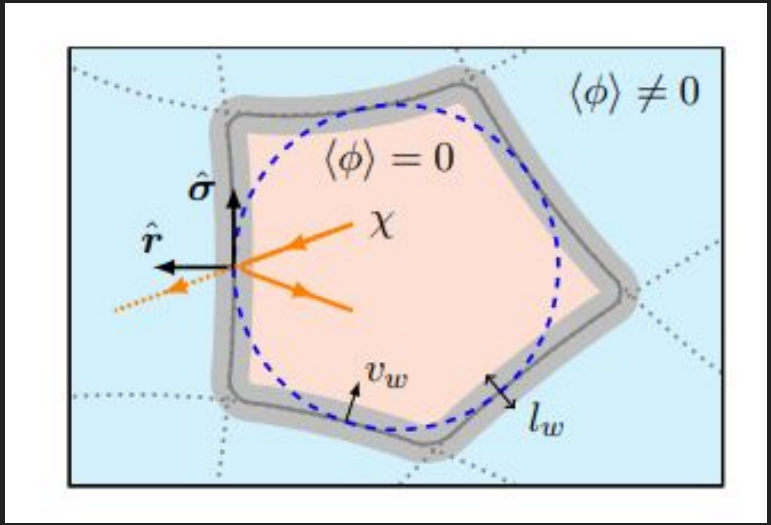
- Domain walls could form in phase transition, or symmetry breaking
- If there are degenerate vacua, bias term needed to collapse network
  - Second order phase transition: Rubin, Khlopov, Sakharov (2000)
  - ‘Catastrogenesis’ production of PBHs from axions/ALP domain walls: Gelmini, Simpson, Vitigliano (2023)
  - D-parity breaking in SO(10) GUT: Mishra, Yajnik (2022)



Gelmini, Simpson, Vitigliano (2023)

PBH origins: bubbles

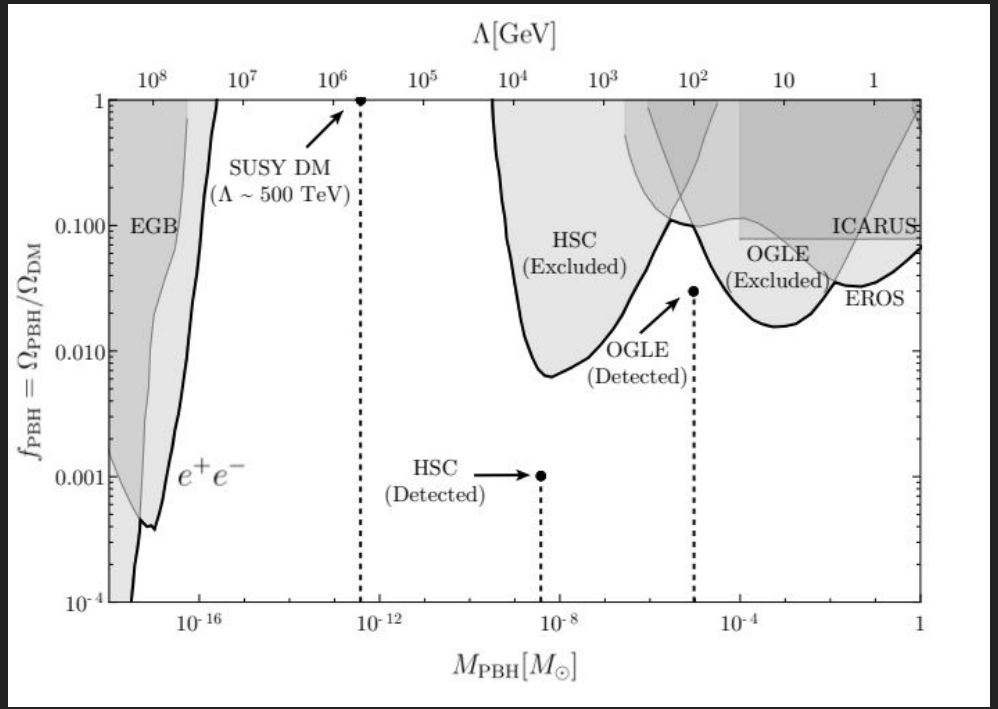
- Bubble collisions
  - Hawking, Moss, Stewart (1982)
  - Khlopov, Konoplich, Rubin, Sakharov (1998)
- Particle trapping between bubbles (i.e. quark nuggets in a dark sector)
  - Baker, Breitbach, Kopp, Mittnacht (2021)



Baker, Breitbach, Kopp, Mittnacht (2021)

PBH origins: Q-Balls and oscillons

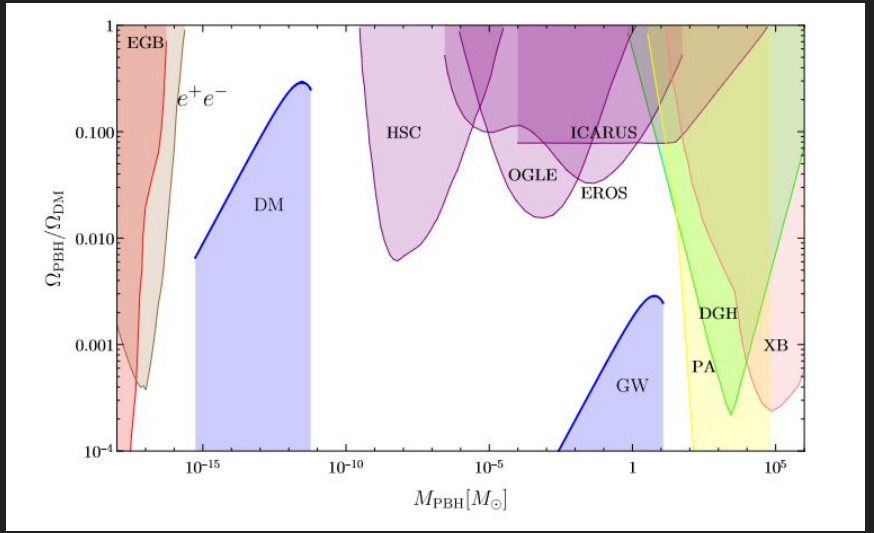
- Q-Balls: Non-topological solitons protected by some quantum number
- Prediction of MSSM (or any scalar field with a flat potential at the end of inflation)
  - Coleman (1985)
  - Kusenko, Shaposhnikov (1997)
  - Cotner, Kusenko (2017)
  - Flores, Kusenko (2022)
- Oscillon (metastable ‘breathing’ configurations)
  - Cotner, Kusenko, Takhistov (2018)



Flores, Kusenko (2022)

PBH origins: dark sector dynamics

- Consider a dark sector with fermion and light scalar field
  - (eg, standard asymmetric dark matter)
- Long-range Yukawa forces can cause structure formation even during radiation domination
  - Generation of fireballs (baryogenesis), gravitational waves, and PBHs
  - Flores and Kusenko 2021

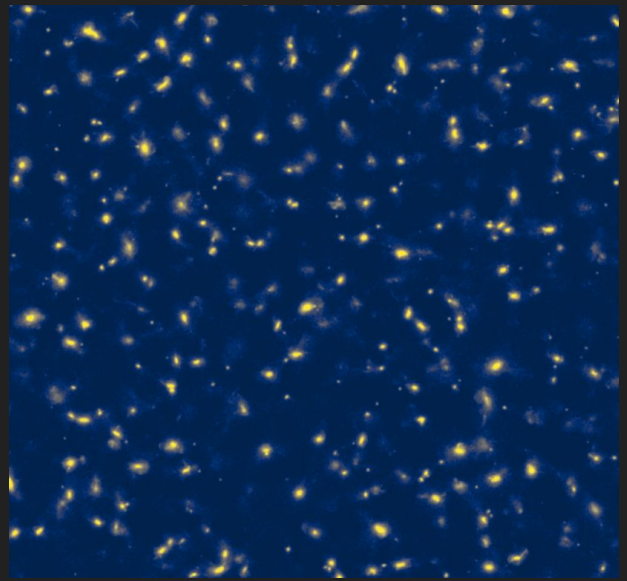


Flores, Kusenko (2021)

Microstructure black holes

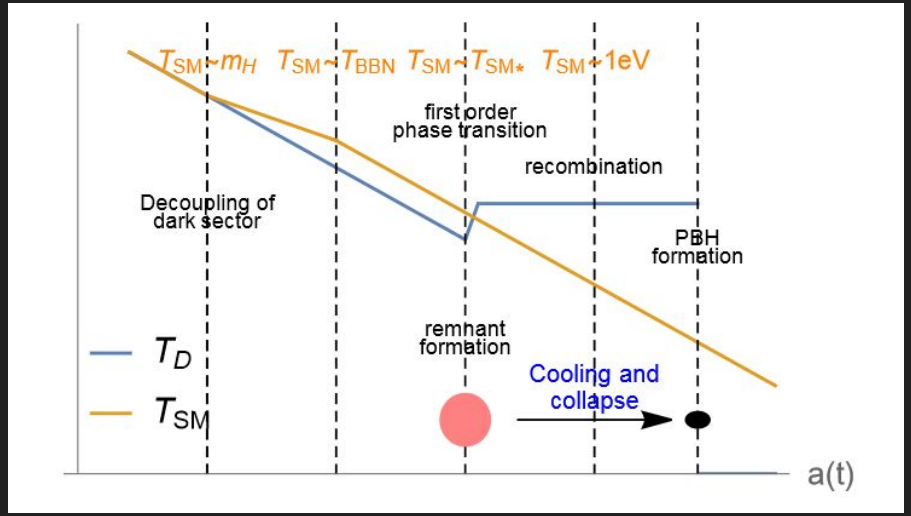
MSBHs: dark structures

- Relatively simple dark sector can lead to dark structures
  - which can later form PBHs
  - Domenech, Inman, Kusenko, Sasaki (2023)
- Fermi Balls (‘dark dwarves’??)
  - Supported by fermi degeneracy pressure
  - Problematic for direct direction…



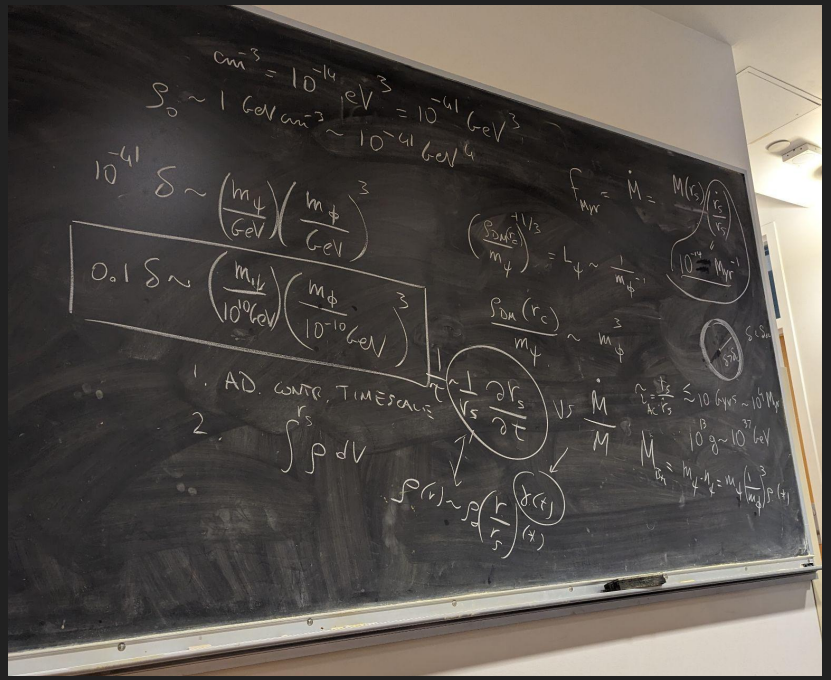
MSBHs: late-time collapse

- Dark sector dynamics can occur on their own timescales
- E.g:
  - Dark phase transition (like nuggets) →
  - → thermal balls → slowly cool →
  - → reach density threshold and collapse
  - Can form intermediate-mass PBHs in late times (or future)
  - Lu, Kuwana, Kusenko (2022)



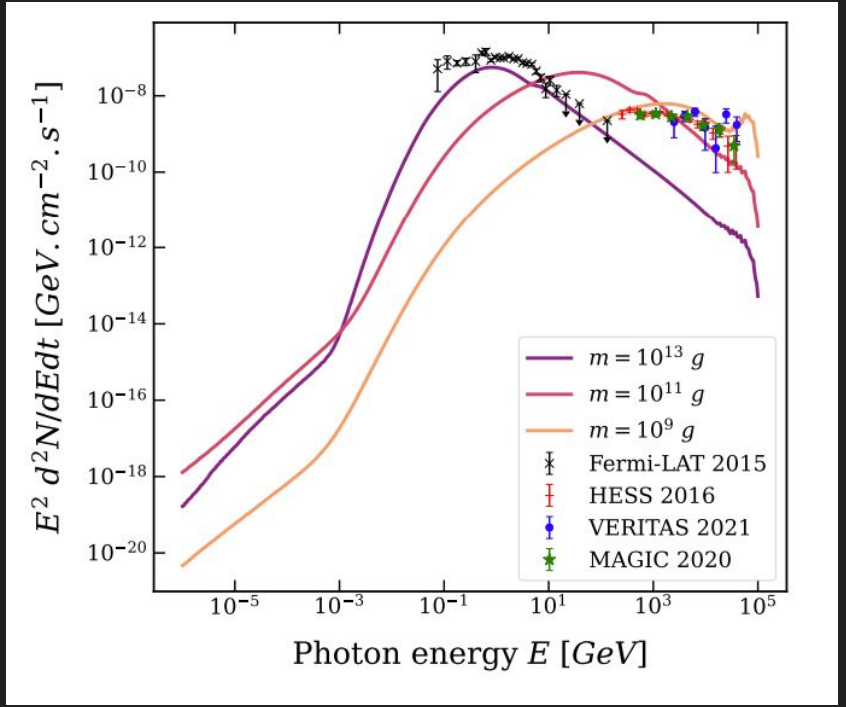
MSBHs: late-time collapse

- Dark sector dynamics can occur on their own timescales
- E.g:
  - Dark phase transition (like nuggets) →
  - → thermal balls → slowly cool →
  - → reach density threshold and collapse
  - Can form intermediate-mass PBHs in late times (or future)
  - Lu, Kuwana, Kusenko (2022)
- Or, e.g.:
  - ‘Galactic pressure cooker’: Profumo, ZSCP, Lu, Kusenko as of ~24 hours ago (if the numbers work out…)



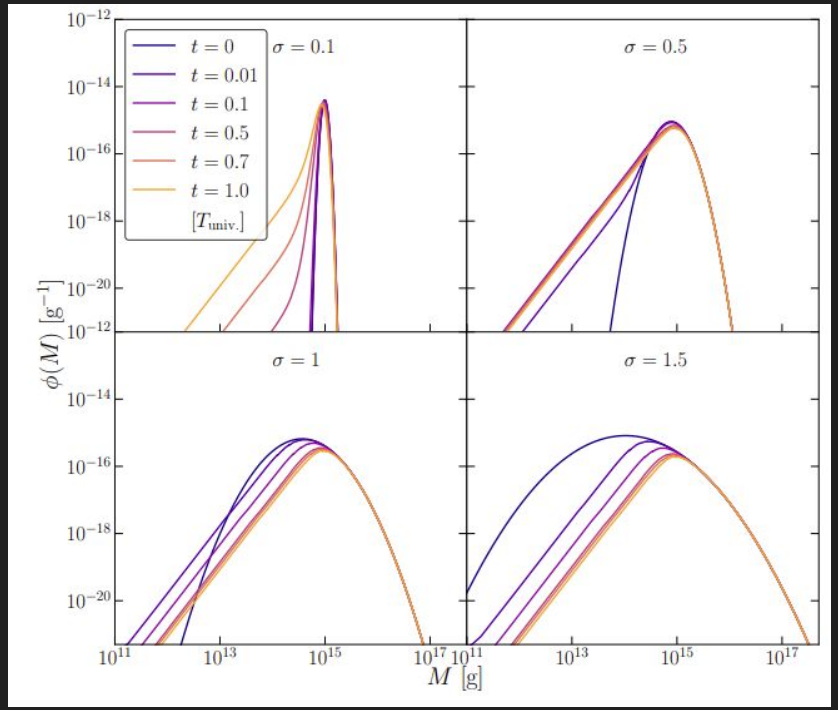
MSBHs: Hawking evaporation

- If late-forming PBHs are very small, they explode immediately



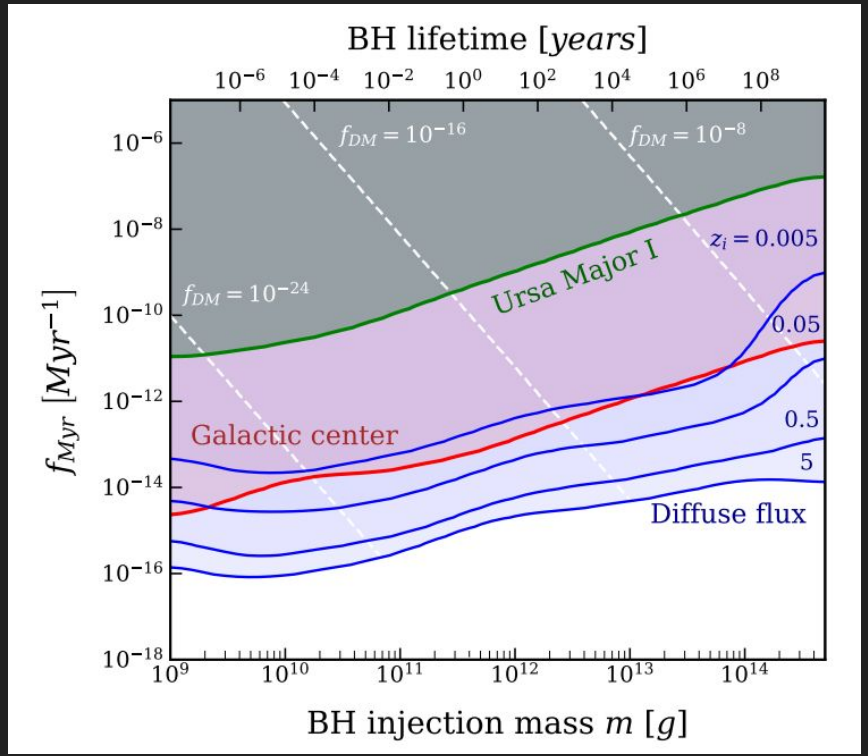
MSBHs: Hawking evaporation

- If late-forming PBHs are very small, they explode immediately
- Smooth PBH mass distributions always give identical spectra for these explosions
  - ‘Triangle distribution’
  - Mosbech, ZSCP (2022)



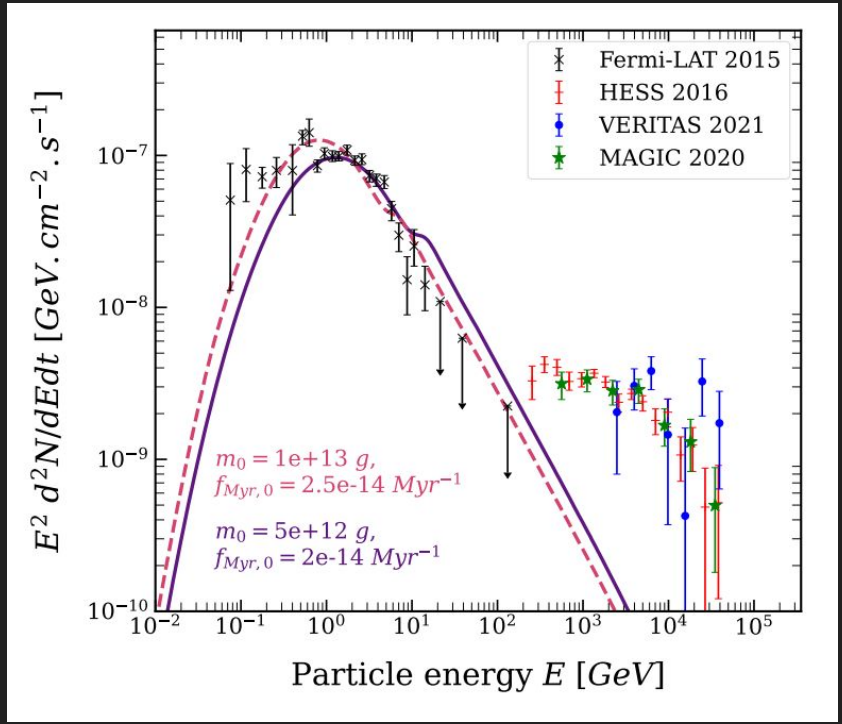
MSBHs: constraints

- First we should check constraints
- f_{Myr} : fraction of dark matter converting to black holes (at mass m) in a Myr period
- Constraints from gamma-ray flux in:
  - Galactic center
  - Extragalactic diffuse emission
  - Dwarf galaxies (Ursa Major I is the dominant constraint)
  - ZSCP, Kusenko (2023)



MSBHs: GeV excess with exploding black holes

- The edge of a constraint is an observation…
- Can match the Fermi-LAT GEV excess quite well
  - Higher energy is well explained by galactic center ‘PeVatron’ accelerating protons
  - ZSCP, Kusenko (2023)



Closing thoughts / revelations

Closing thoughts / revelations

Closing thoughts / revelations

Closing thoughts / revelations

Closing thoughts / revelations

PBHs *could* explain a wide range of astrophysical observations

There are a *lot* of ways to make them besides the ‘usual’, and at widely varying epochs

Even if they don’t comprise all the DM, they still would be interesting

(Hopefully we find them—but only in a few years, when I’m looking for a permanent position)

Closing thoughts / revelations