

Balls, Nuggets,
and Black Holes:
An overview
of macroscopic
dark matter



Zachary S.C. Picker (Queen's U, Kingston)

Outline

1. Introducing myself
 - a. Past, present, and future work
2. ... and Black Holes
 - a. Primordial black hole basics
 - b. Prospects, hints, and constraints
 - c. Formation
3. Balls, Nuggets, ...
 - a. Detection
 - i. Asteroids, rings, and craters
 - b. Specific models
4. Dark sector structure collapse

Outline

1. Introducing myself
 - a. Past, present, and future work
2. ... and Black Holes
 - a. Primordial black hole basics
 - b. Prospects, hints, and constraints
 - c. Formation
3. Balls, Nuggets, ...
 - a. Detection
 - i. Asteroids, rings, and craters
 - b. Specific models
4. Dark sector structure collapse

Intros

How I got here

University of Sydney



Celine Boehm



Archil Kobakhidze

How I got here

University of Sydney



UCLA



Celine Boehm



Archil Kobakhidze



Alex Kusenko



Graciela Gelmini

How I got here

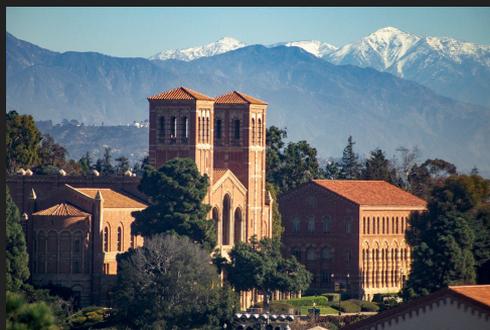
University of Sydney



UCLA



Queen's



Celine Boehm



Archil Kobakhidze



Alex Kusenko



Graciela Gelmini

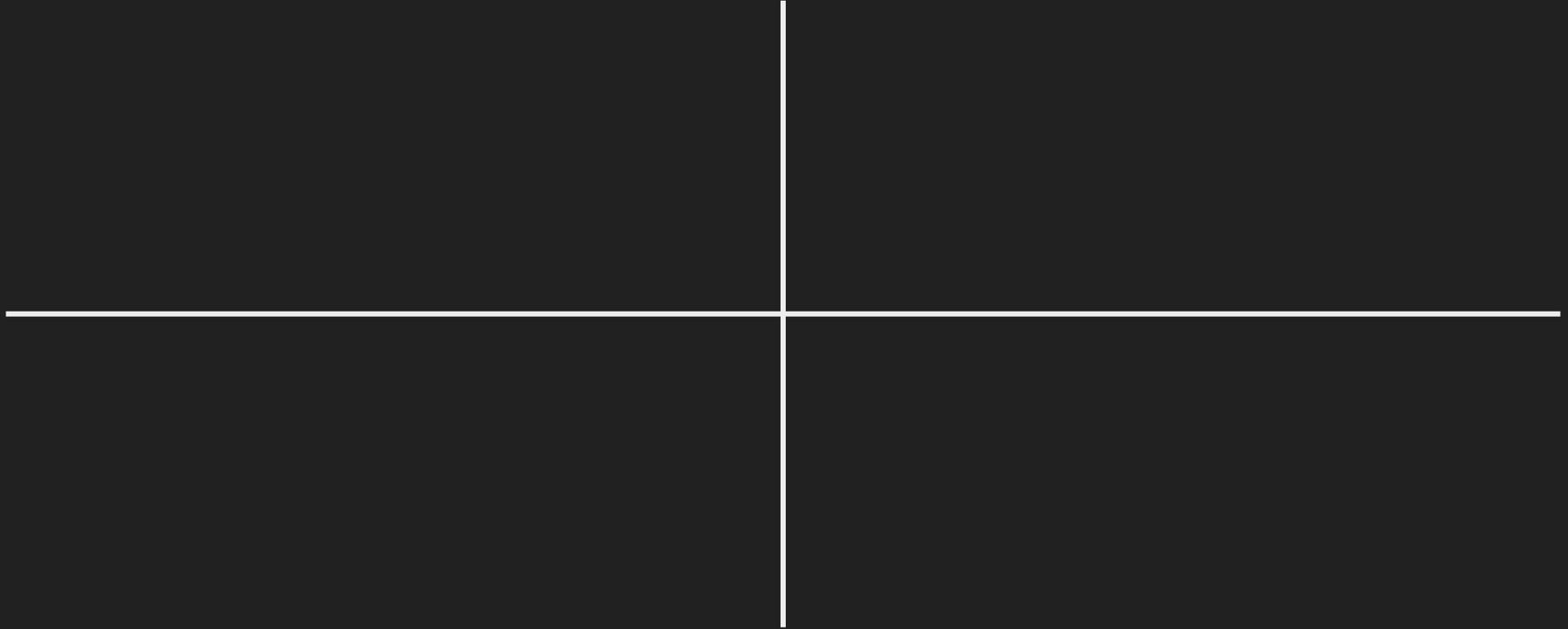


Aaron Vincent



Joe Bramante

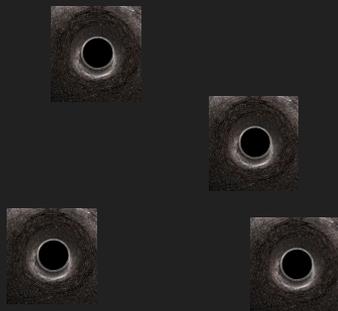
Past Work (not for today)



Past Work (not for today)

Primordial black holes

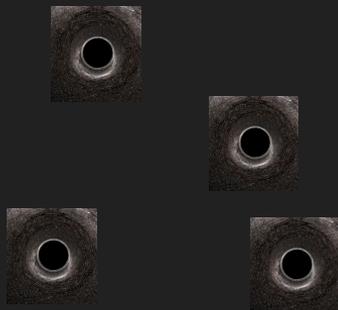
- Black hole metrics beyond Schwarzschild
- Hawking evaporation



Past Work (not for today)

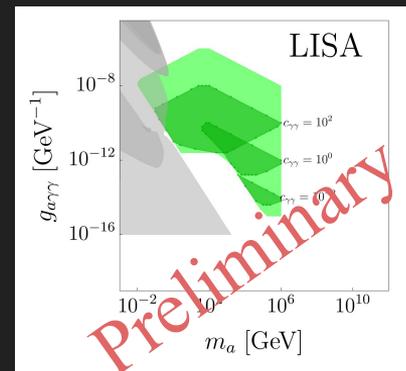
Primordial black holes

- Black hole metrics beyond Schwarzschild
- Hawking evaporation



Axion dark matter

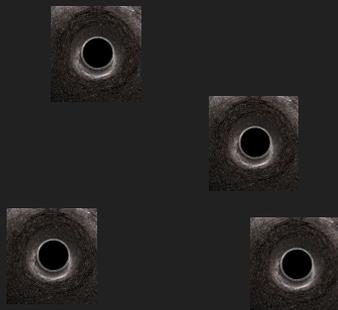
- Multi-axion models
- Domain wall phenom



Past Work (not for today)

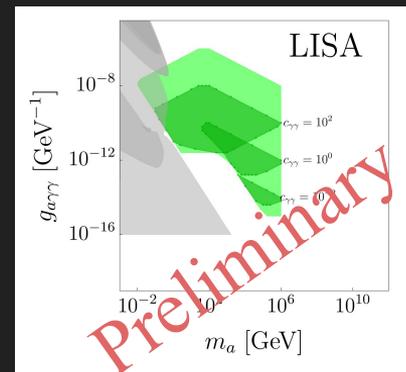
Primordial black holes

- Black hole metrics beyond Schwarzschild
- Hawking evaporation



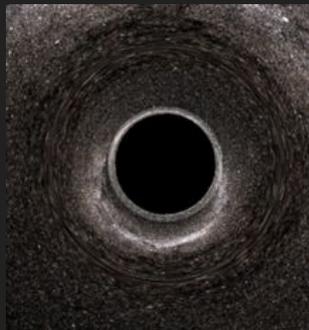
Axion dark matter

- Multi-axion models
- Domain wall phenom



Supermassive black hole formation

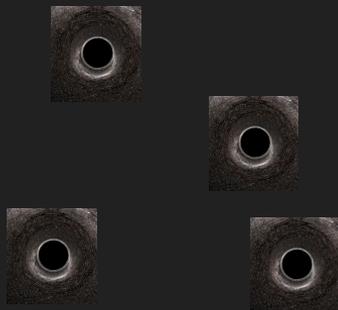
- Direct collapse SMBHs
 - with dark matter of various kinds



Past Work (not for today)

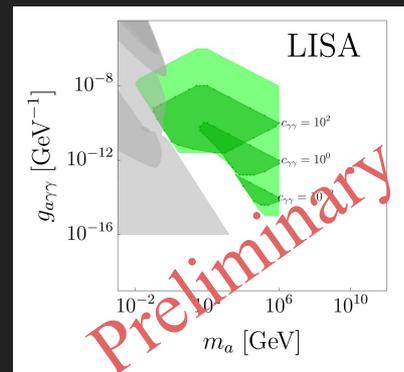
Primordial black holes

- Black hole metrics beyond Schwarzschild
- Hawking evaporation



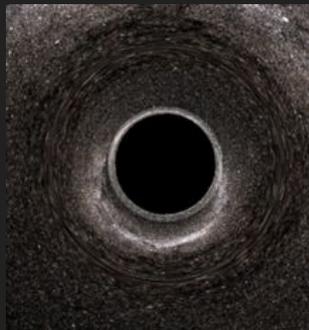
Axion dark matter

- Multi-axion models
- Domain wall phenom



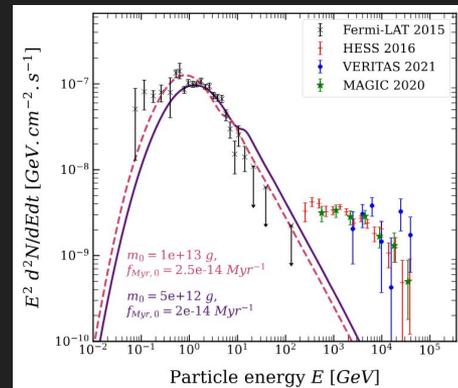
Supermassive black hole formation

- Direct collapse SMBHs
 - with dark matter of various kinds

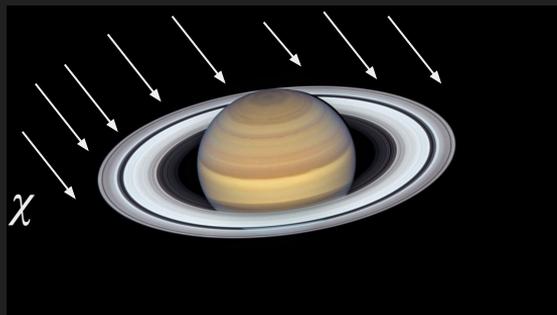


Miscellaneous astroparticle

- Gravitational waves
- GeV excess



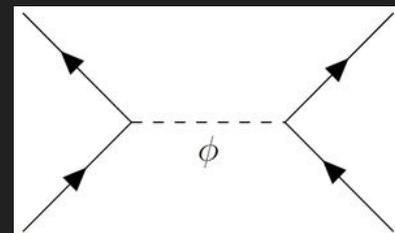
Current-to-future-ish work



Dark matter in Saturn's rings
ft. Celine Boehm, Tarak Maity & Elden Loomes (USyd)

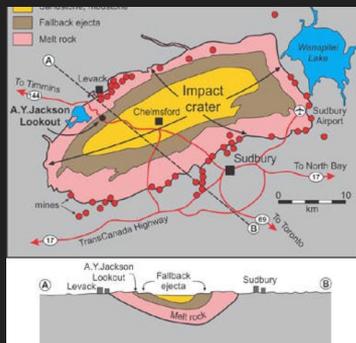
BSM quark nuggets
ft. Yifan Lu (UCLA)

Q

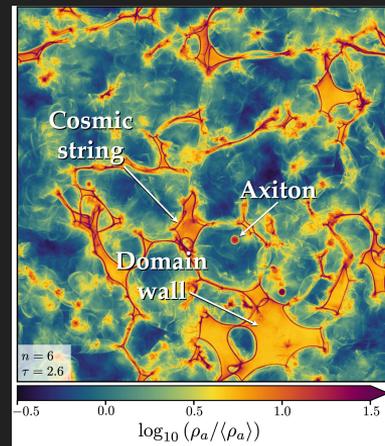


Long-range forces in the early universe
ft. Aaron Vincent, Melissa Diamond (McGill) and Hannah Banks (NYU)

Dark matter impacts and craters
ft. Joe and geologists...?



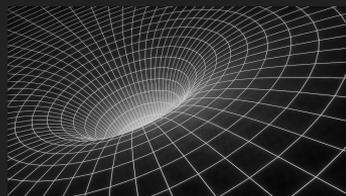
Domain wall collapse
ft. Graciela Gelmini and Jonah Hyman (UCLA)



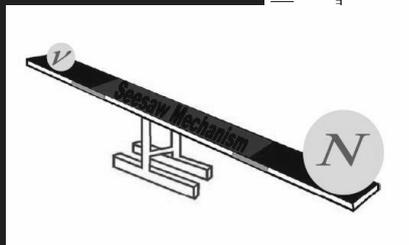
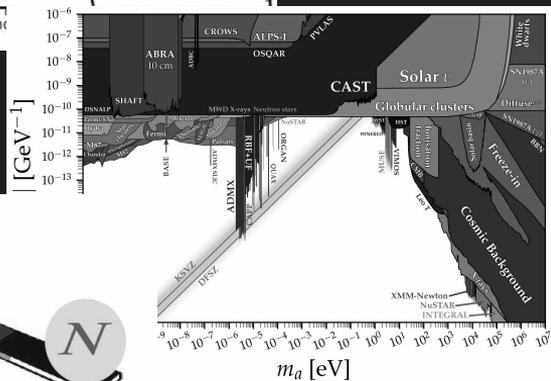
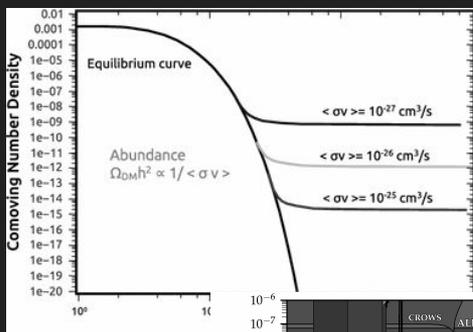
Dark matter

Dark matter

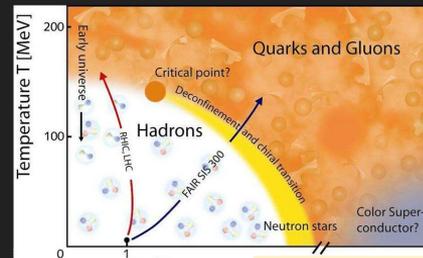
Modified Gravity



Particles



Macroscopic things



...and (Primordial)
Black Holes

Basics

Basics

Primordial black holes:

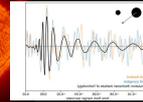
- Did not form from stellar collapse
- Form in early universe*
- Distinguished from supermassive black holes
 - mainly as a matter of sociology
- Simple cold dark matter candidate

No sightings (yet...!)

FAQs: How big is a black hole?



(Planck)



Mass

10^{-5}

10^8

10^{14}

10^{20}

10^{25}

10^{27}

10^{33}

10^{35}

10^{39}

10^{45}

grams

10^{-37}

10^{-24}

10^{-17}

10^{-12}

10^{-7}

10^{-5}

10^0

10^2

10^6

10^{12}

Solar
masses

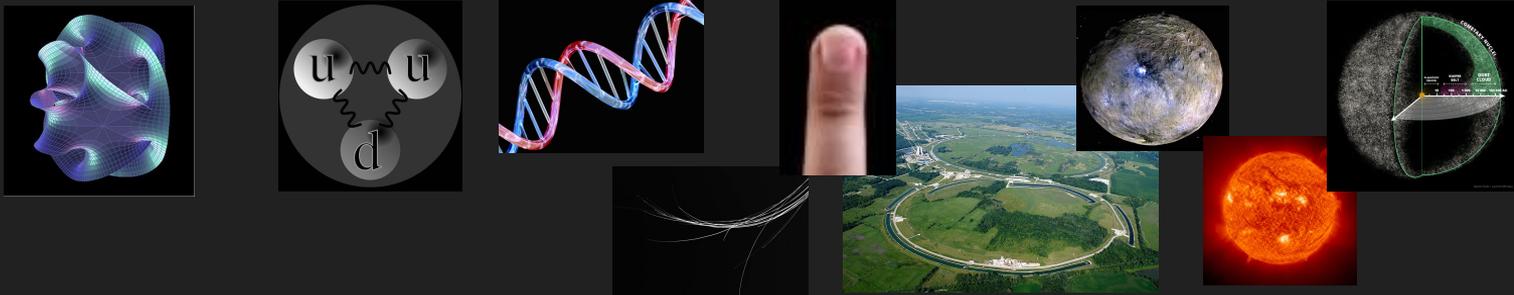
FAQs: How big is a black hole?



(Planck)

| | | | | | | | | | | | |
|------|------------|------------|------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|--------------|
| Mass | 10^{-5} | 10^8 | 10^{14} | 10^{20} | 10^{25} | 10^{27} | 10^{33} | 10^{35} | 10^{39} | 10^{45} | grams |
| | 10^{-37} | 10^{-24} | 10^{-17} | 10^{-12} | 10^{-7} | 10^{-5} | 10^0 | 10^2 | 10^6 | 10^{12} | Solar masses |

| | | | | | | | | | | | |
|----------------|------------|------------|------------|-----------|-----------|--------|--------|--------|-----------|-----------|----|
| Radius =2GM | 10^{-33} | 10^{-19} | 10^{-12} | 10^{-7} | 10^{-2} | 10^0 | 10^5 | 10^7 | 10^{11} | 10^{17} | cm |
| | | | | | | | | | | 0.1 pc | |



Note that black holes become less dense as mass increases!

- $R = 2GM$
 - Normally, $M \sim R^3$

Note that black holes become less dense as mass increases!

- $R = 2GM$
 - Normally, $M \sim R^3$
- Funny fact: the Schwarzschild radius of the universe is the Hubble radius...

$$H^2 = \frac{8}{3}\pi G\rho \quad (\text{Friedman Eq.})$$

$$M_H = \frac{4}{3}\pi R_H^3 \rho \quad (R_H = 1/H)$$

$$\Rightarrow H^2/M_H = 2GH^3 \Rightarrow \boxed{R_H = 2GM_H}$$

FAQs: don't they evaporate?



(Planck)

| | | | | | | | | | | | |
|-----------|------------|------------|------------|------------|-----------|-----------|-----------|-----------|-----------|------------|--------------|
| Mass | 10^{-5} | 10^8 | 10^{14} | 10^{20} | 10^{25} | 10^{27} | 10^{33} | 10^{35} | 10^{39} | 10^{45} | grams |
| | 10^{-37} | 10^{-24} | 10^{-17} | 10^{-12} | 10^{-7} | 10^{-5} | 10^0 | 10^2 | 10^6 | 10^{12} | Solar masses |
| Lifetime* | ? | 10^{-11} | 10^8 | 10^{26} | 10^{41} | 10^{47} | 10^{65} | 10^{71} | 10^{83} | 10^{101} | yrs |

*more to discuss later

7×10^{14} g \leftrightarrow 15 Gigayears

More accurate semi-analytic calc:
Mosbech, ZSCP 2022

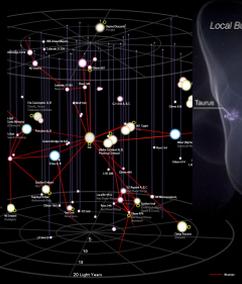
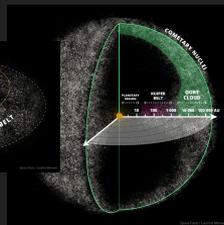
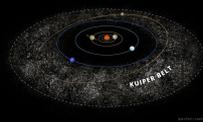
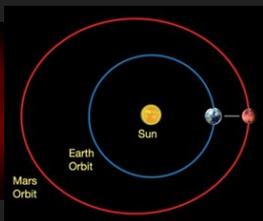
FAQs: how abundant are they? (assuming all of CDM)

Local density is $0.01 M_{\text{sun}} \text{ pc}^3$. There would be one black hole per volume:



(Planck)

| | | | | | | | | | | | |
|--------|------------|------------|------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|---------------|
| Mass | 10^{-5} | 10^8 | 10^{14} | 10^{20} | 10^{25} | 10^{27} | 10^{33} | 10^{35} | 10^{39} | 10^{45} | grams |
| | 10^{-37} | 10^{-24} | 10^{-17} | 10^{-12} | 10^{-7} | 10^{-5} | 10^0 | 10^2 | 10^6 | 10^{12} | Solar masses |
| Volume | 10^{-35} | 10^{-22} | 10^{-15} | 10^{-10} | 10^{-5} | 10^{-3} | 10^2 | 10^4 | 10^8 | 10^{14} | pc^3 |



FAQs: Do they smash into things?

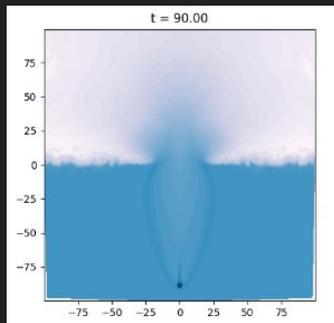
Events are rare, even for very small & more abundant PBHs

Sun

passes
through

Terrestrial bodies

~1m crater
(Yalinewich,
Caplan 2021)



White dwarfs

passes through,
but doesn't
quite ignite carbon
and cause nova

Revisiting constraints on
asteroid-mass primordial black
holes as dark matter candidates

Paulo Montero-Camacho,^{a,b} Xiao Fang,^c Gabriel Vasquez,^{a,b}
Makana Silva,^{a,b} and Christopher M. Hirata^{b,d}

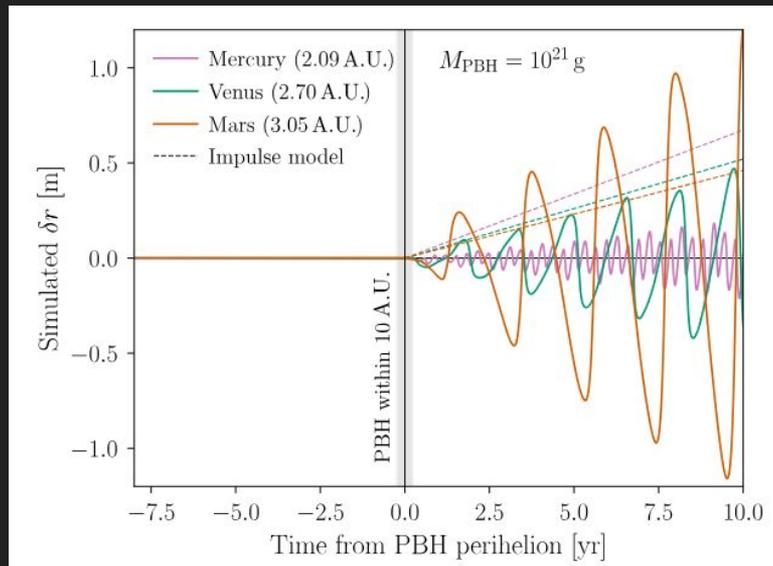
Neutron stars

can capture PBH,
destroy NS...

FAQs: Do they smash into things?

Could detect with solar system

- Decades of precise measurement



Close encounters of the primordial kind: A new observable for primordial black holes as dark matter

Tung X. Tran^{1,*}, Sarah R. Geller^{1,2,3,†}, Benjamin V. Lehmann^{1,‡}, and David I. Kaiser^{1,§}

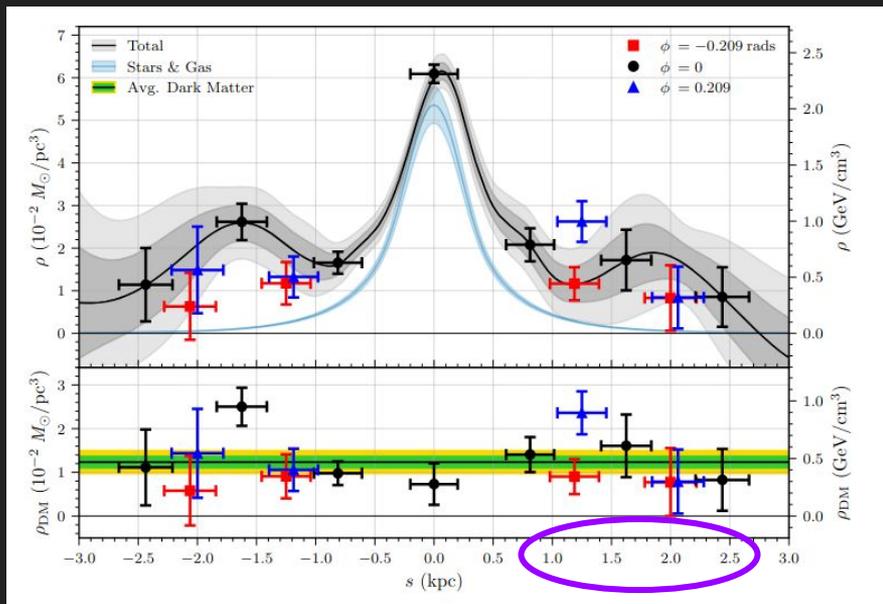
¹Center for Theoretical Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139, USA

²Santa Cruz Institute for Particle Physics, Santa Cruz, California 95064, USA

³Department of Physics, University of California, Santa Cruz, Santa Cruz, California 95064, USA

FAQs: would they be ‘smooth’ enough for CDM?

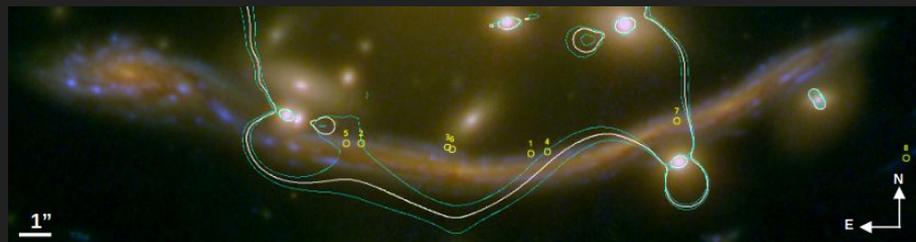
Local stars:



Mapping Dark Matter in the Milky Way using Normalizing Flows and Gaia DR3

Sung Hak Lim, Eric Putney, Matthew R. Buckley, and David Shih
 NHETC, Dept. of Physics and Astronomy, Rutgers, Piscataway, NJ 08854, USA

Lensing (+ microcaustics)



Imaging dark matter at the smallest scales with $z \approx 1$ lensed stars

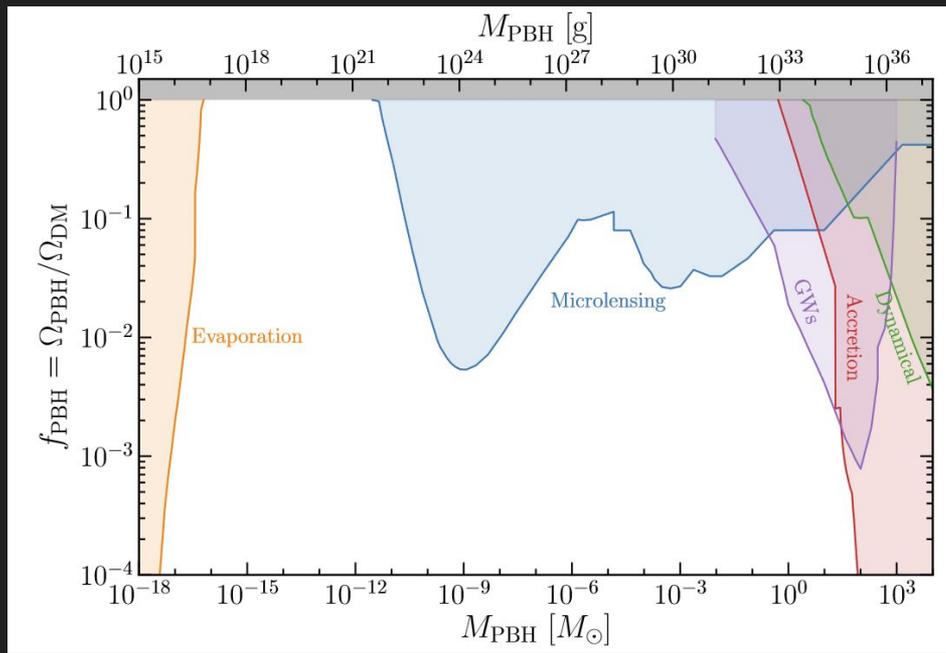
J. M. Diego^{1,*}, Sung Kei Li², Alfred Amruth², Ashish K. Meena³, Tom J. Broadhurst^{3,5,6}, Patrick L. Kelly^{7,8}, Alexei V. Filippenko⁹, Liliya L. R. Williams^{7,8}, Adi Zitrin³, William E. Harris¹⁰, Marta Reina-Campos^{10,11}, Carlo Giocoli^{12,13}, Liang Dai¹⁴, Mitchell F. Struble¹⁵, Tommaso Treu¹⁶, Yoshinobu Fudamoto¹⁷, Daniel Gilman^{18,19}, Anton M. Koekemoer²⁰, Jeremy Lim², J.M. Palencia¹, Fengwu Sun²¹, and Rogier A. Windhorst²²

Limits on Dark Matter Compact Objects implied by Supermagnified Stars in Lensing Clusters

Claudi Vall Müller¹, Jordi Miralda-Escudé^{1,2,3,*}
¹Institut del Cosmos, Universitat de Barcelona, Barcelona, Spain
²Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
³Institut d'Estudis Espacials de Catalunya, Barcelona, Spain

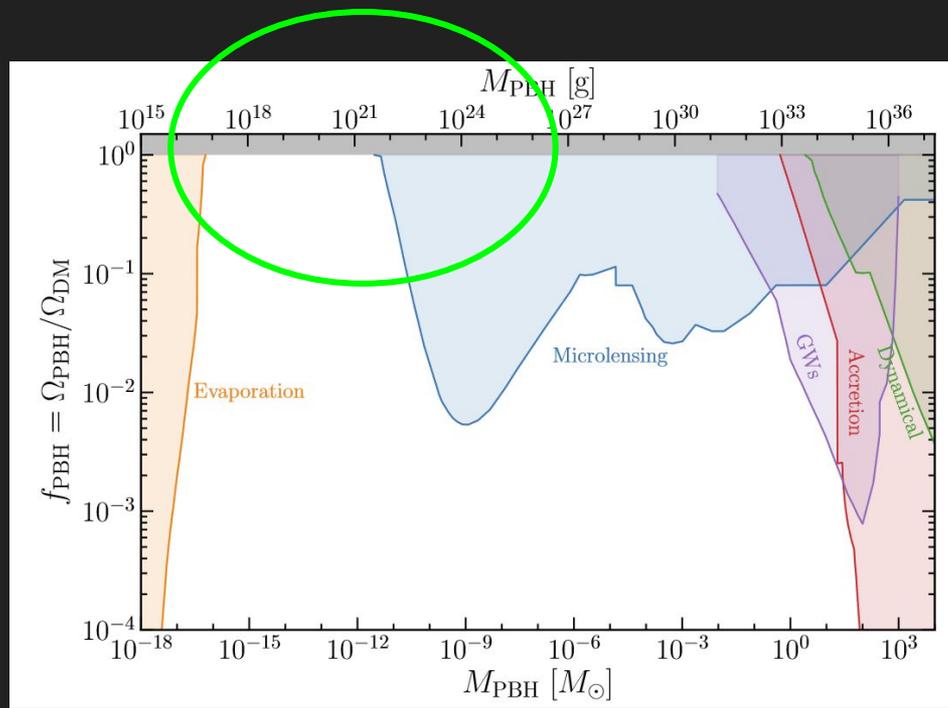
Detection and constraints

Detection and constraints



Detection and constraints

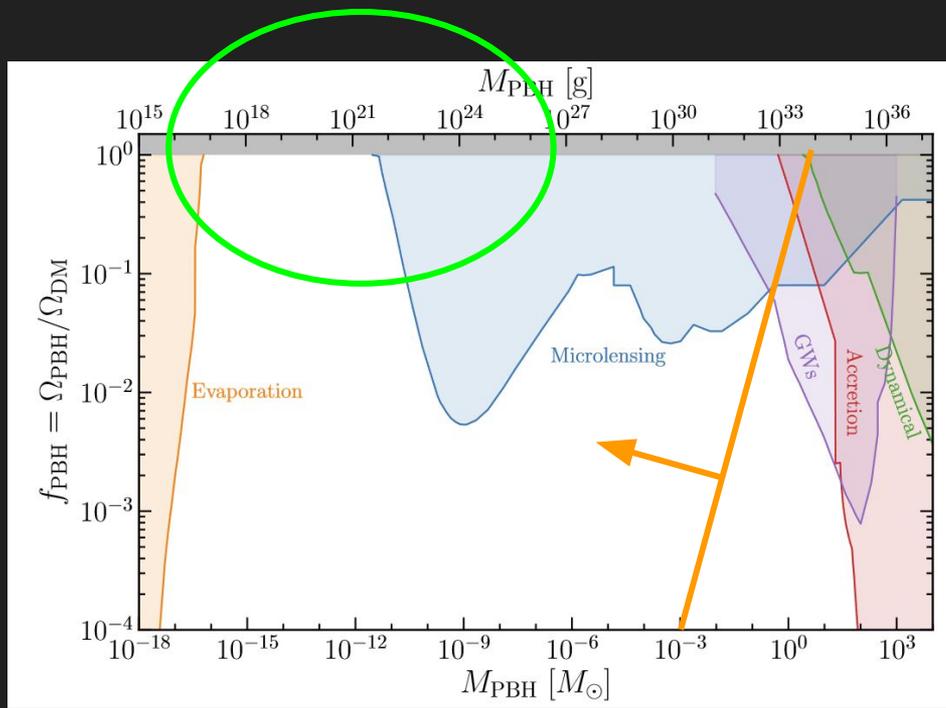
Asteroid mass range



Detection and constraints

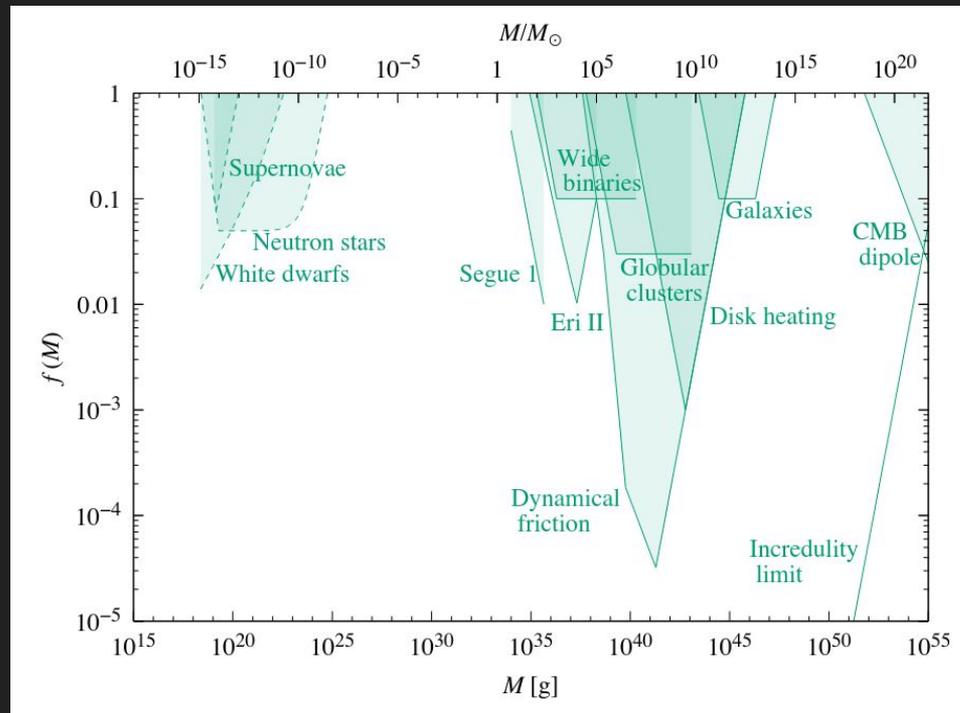
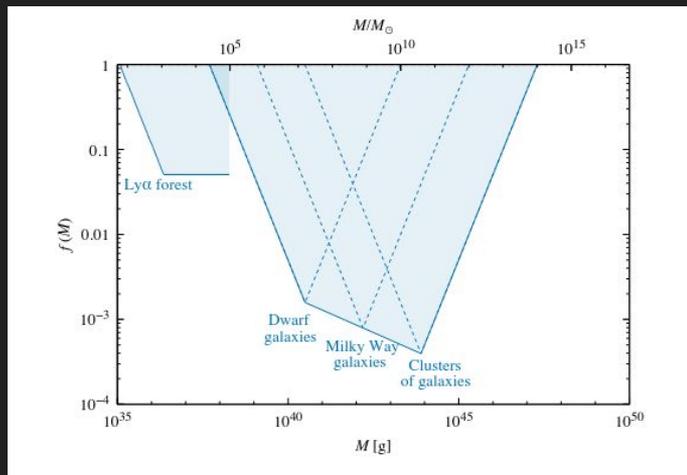
Asteroid mass range

More PBHs than stars!



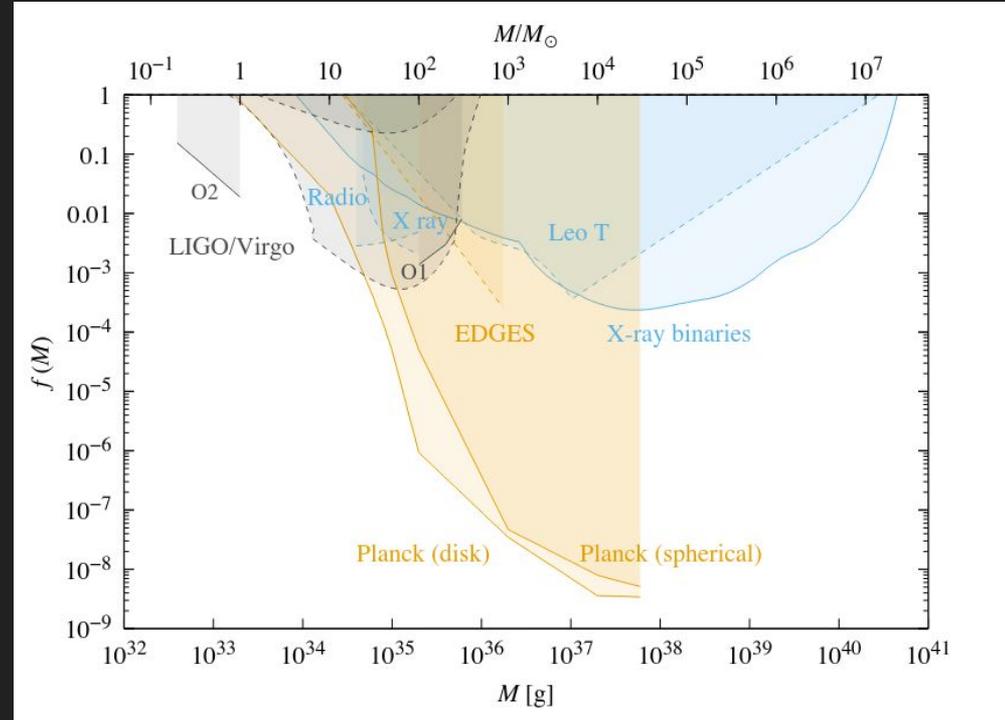
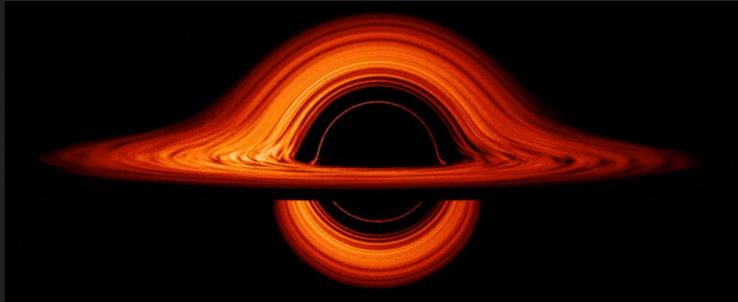
Constraints - dynamical

- Large PBHs can disrupt or destroy large structures
- Could form cosmic structures too early



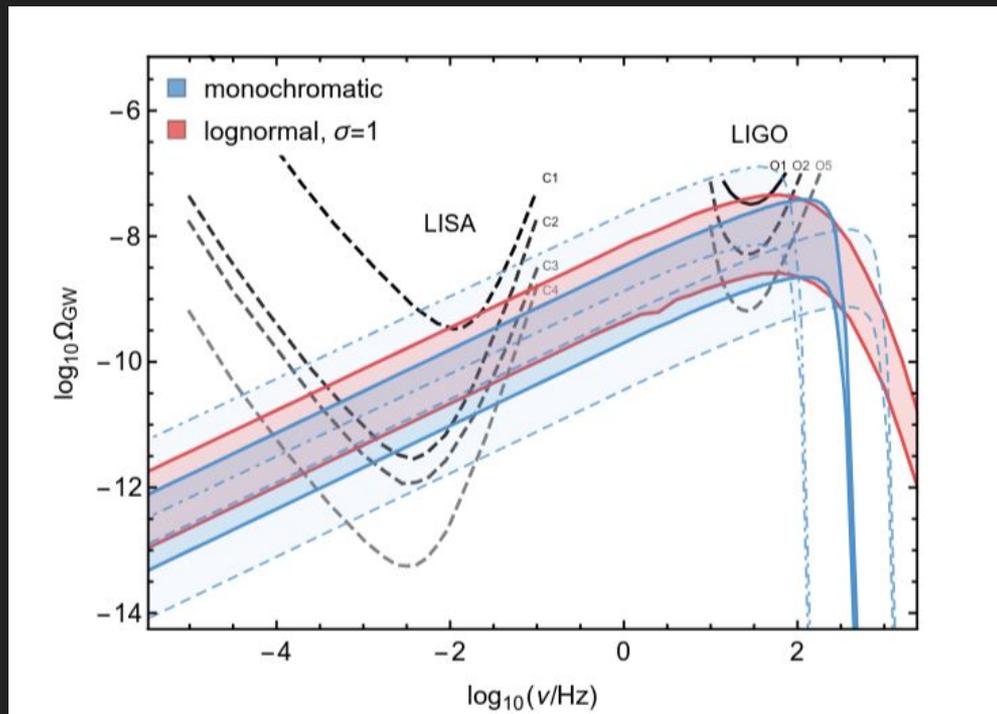
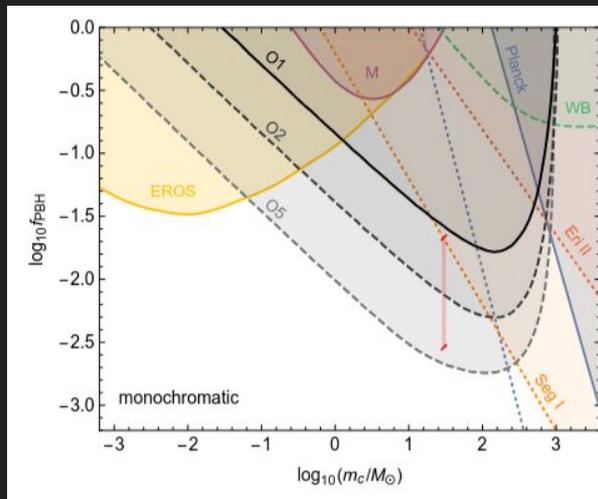
Constraints - accretion

- Accretion onto large PBHs produces radiation
- (Cutoff- accretion timescale must be faster than cosmic expansion)

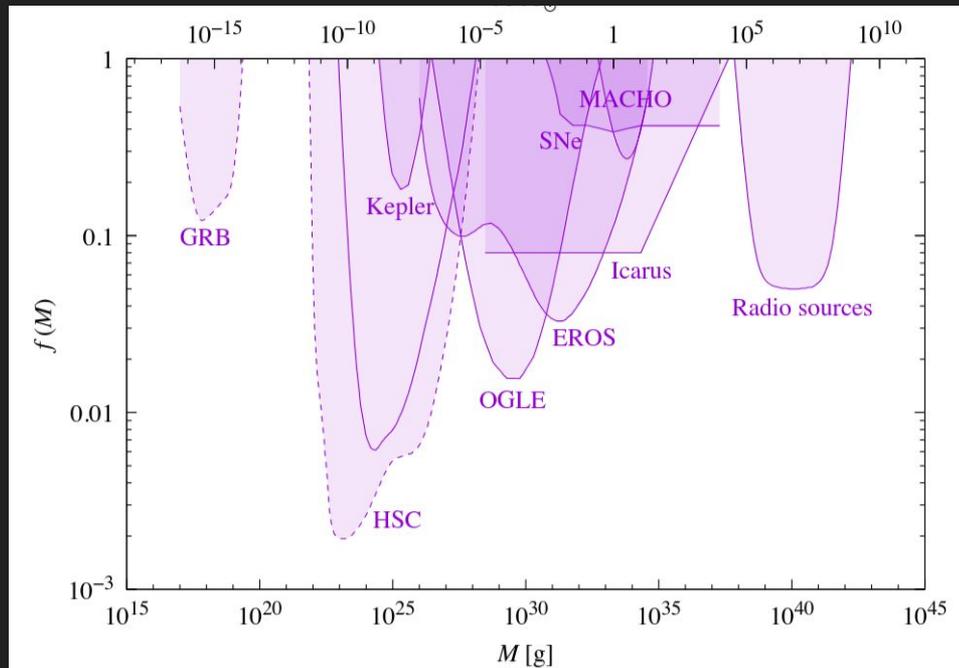
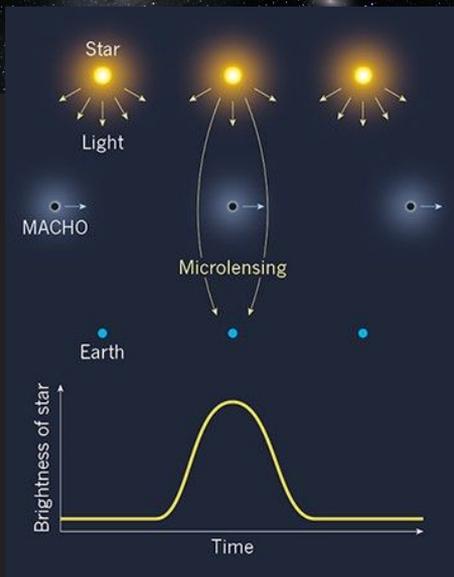


Constraints - gravitational waves

- PBHs readily form binaries in early universe, which could merge today



Constraints - microlensing

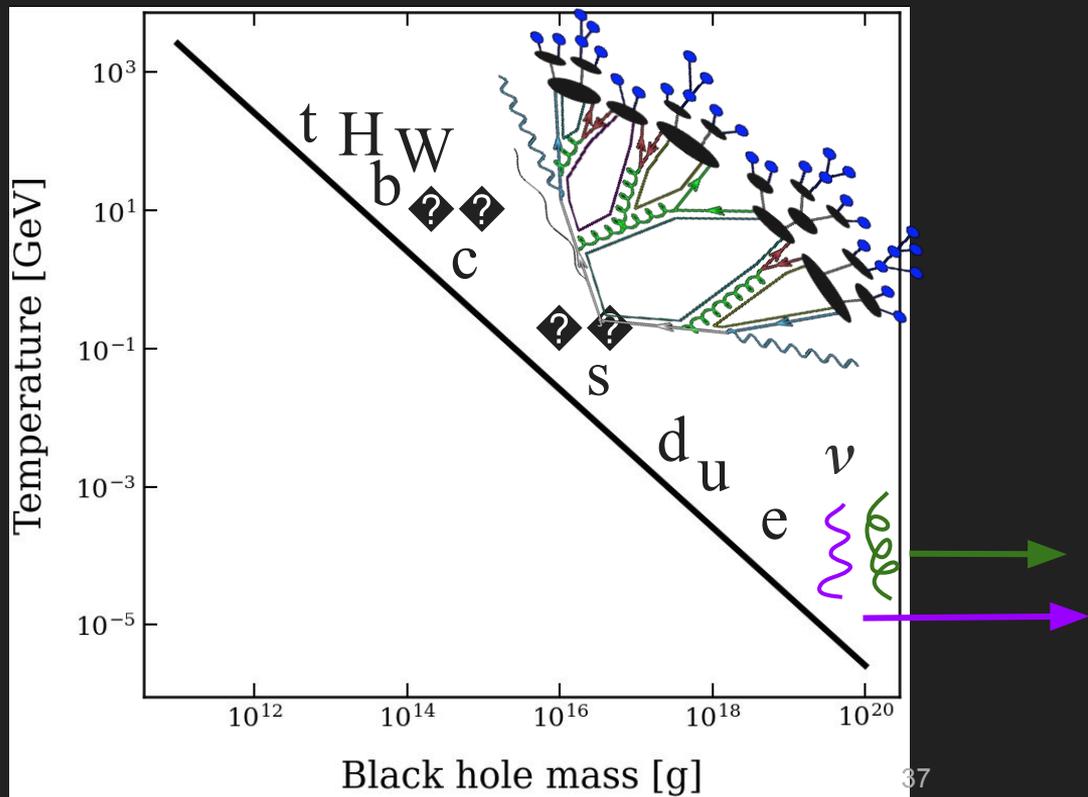


Carr, Kohri, Sendouda, Yokoyama 2021

Constraints - Hawking evaporation

~thermal radiation at temperature
 $T \sim 1/M$

- Higher temps \rightarrow more particle species
- Hadronic jets, etc...



Constraints - Hawking evaporation

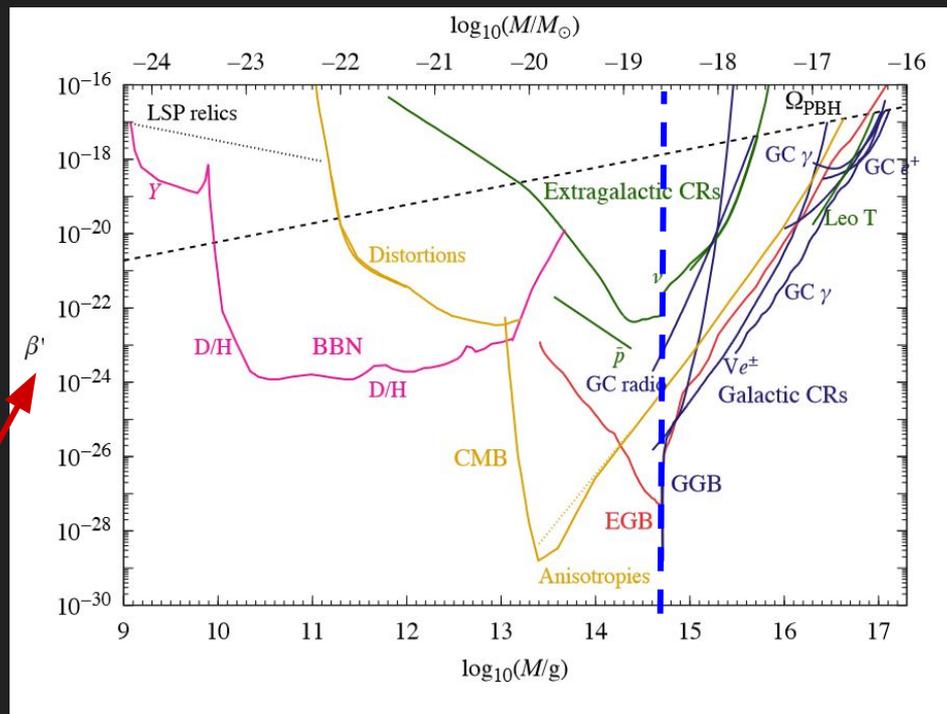
Blue line: evaporates today

Green: extragalactic cosmic rays

Indigo: galactic cosmic rays

Yellow: CMB distortions and anisotropies

Pink: Big bang nucleosynthesis



$\beta' \propto f$ at formation

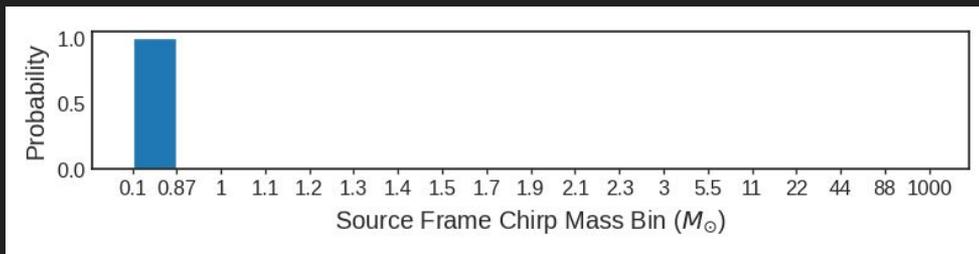
Hints, caveats, and fun things

The community's biggest cheerleaders:

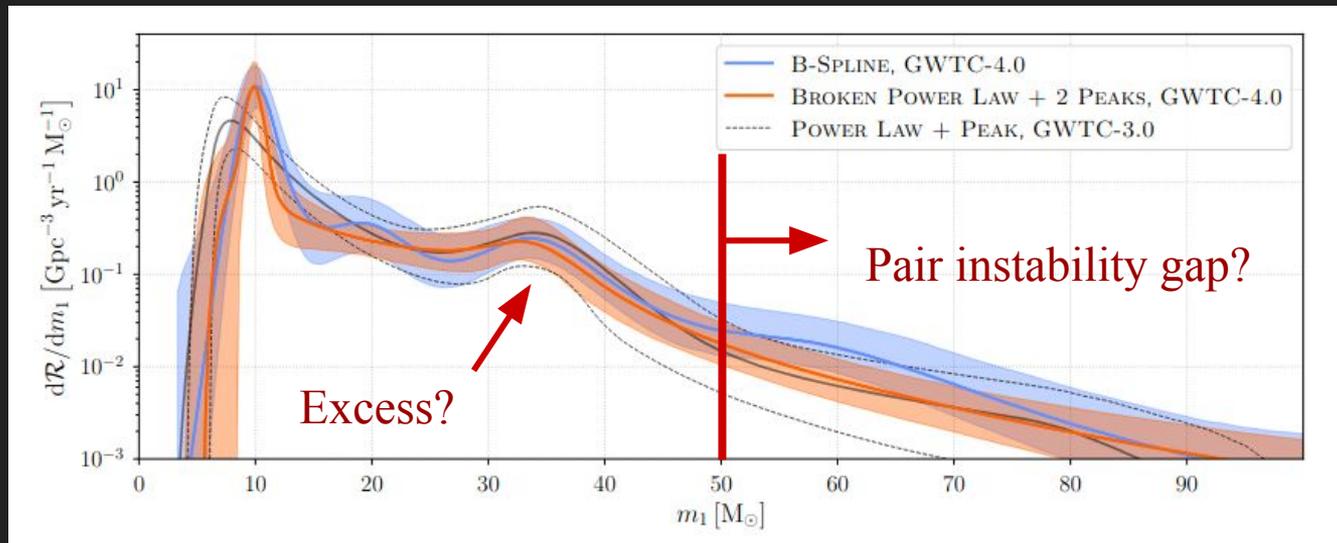
Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,^{1,*} S. Clesse,^{2,†} J. García-Bellido,^{3,‡} M. R. S. Hawkins,^{4,§} and F. Kühnel^{5,¶}

LIGO events...?



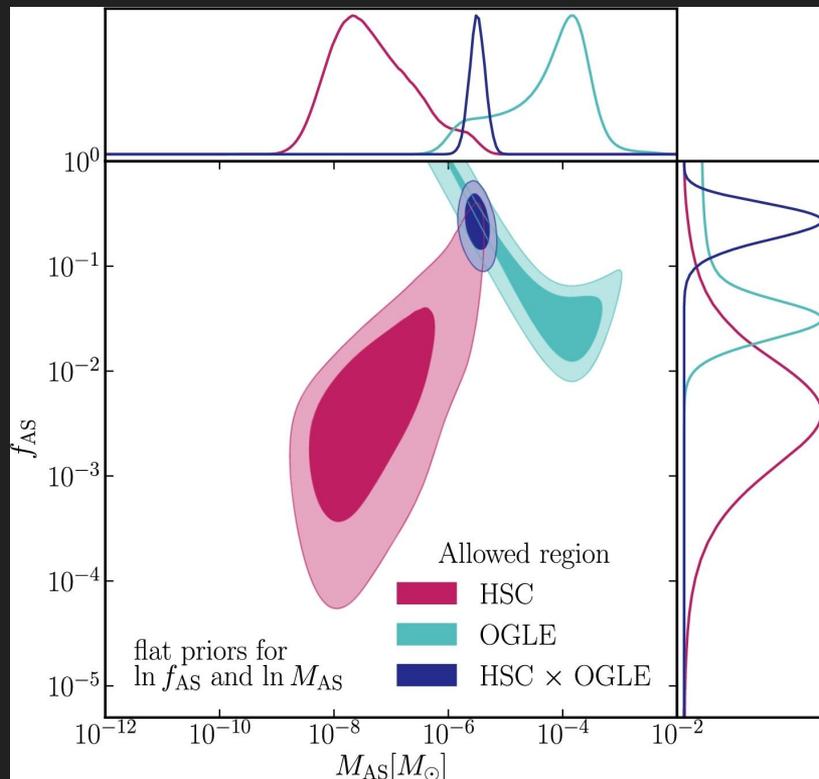
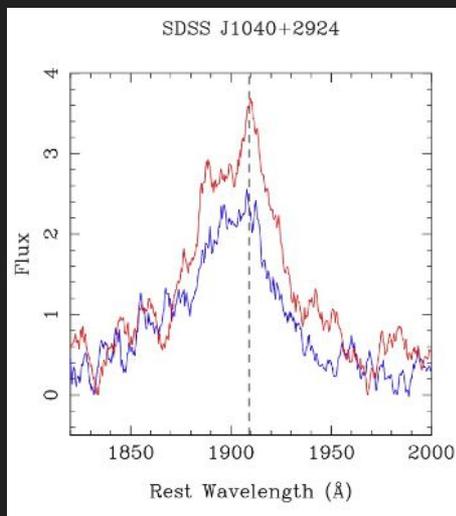
Event: S251112cm (false alarm rate: 1 in 6.2 years...)



LIGO O4 Primary mass distribution

Microlensing events?

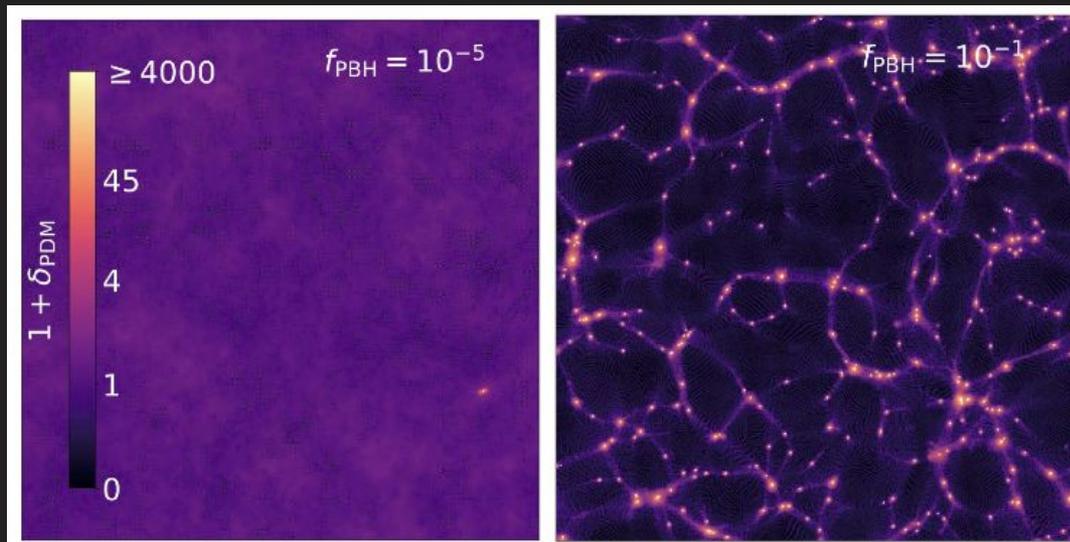
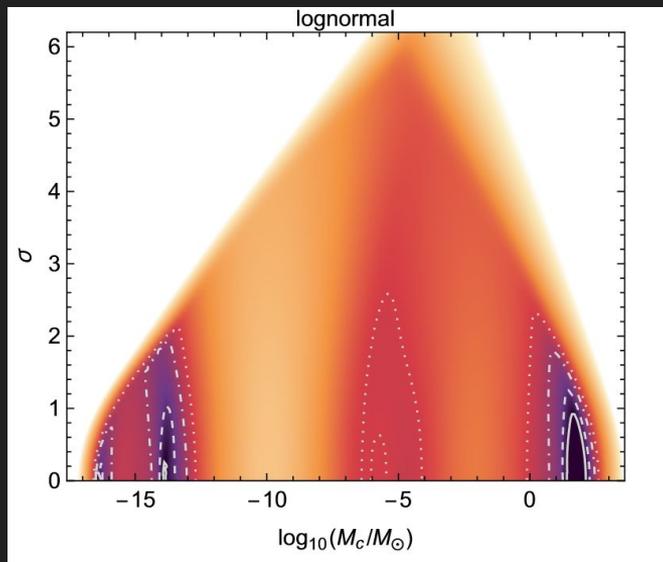
- Actually, public results:
 - OGLE: 6+17 events
 - HSC: 1+? events
- Quasar microlensing?



Sugiyama, Takada, Kusenko 2023
Hawkins 2023

Subtleties

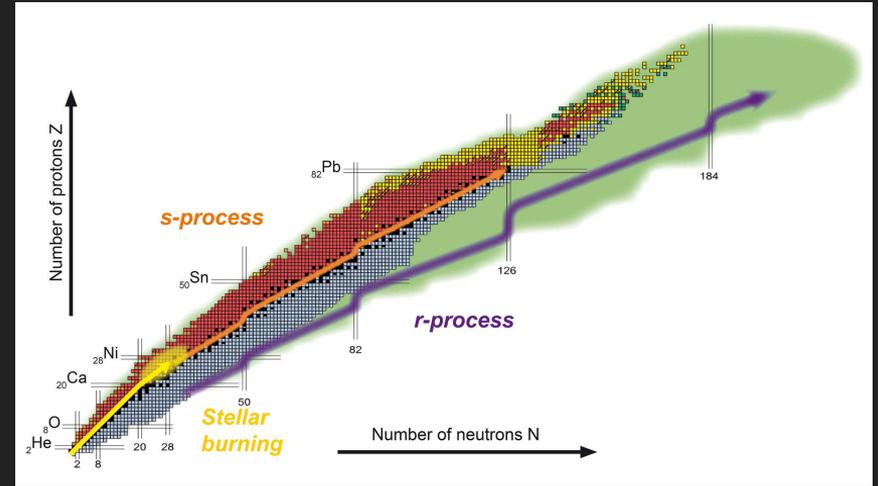
- Clustering
- Extended mass functions



Inman, Ali-Haimoud 2019

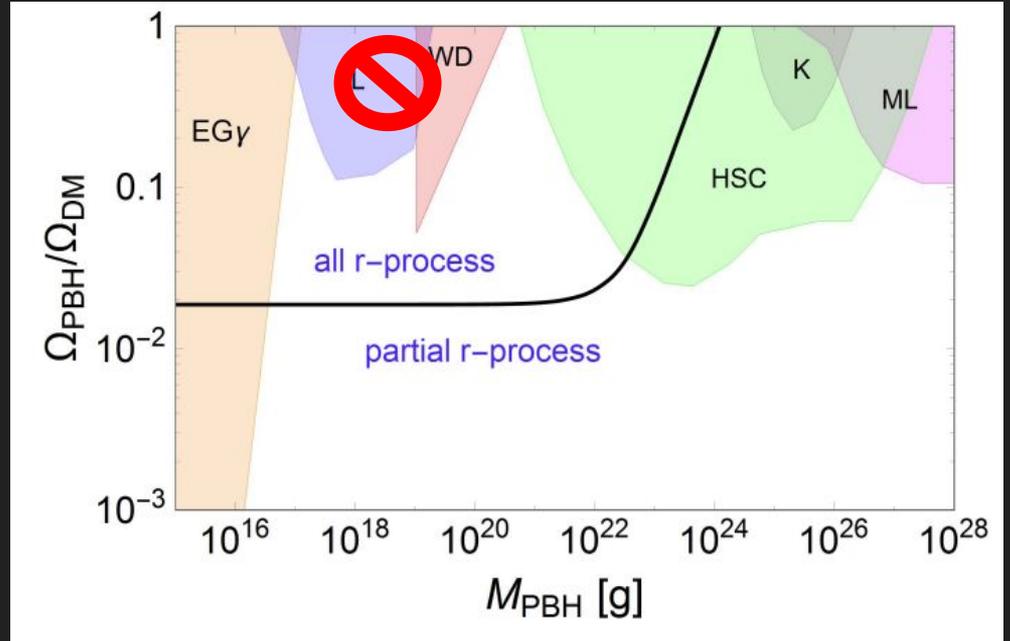
Carr, Raidal, Tenkanen, Vaskonen, Veermae 2019

Neutron star destruction



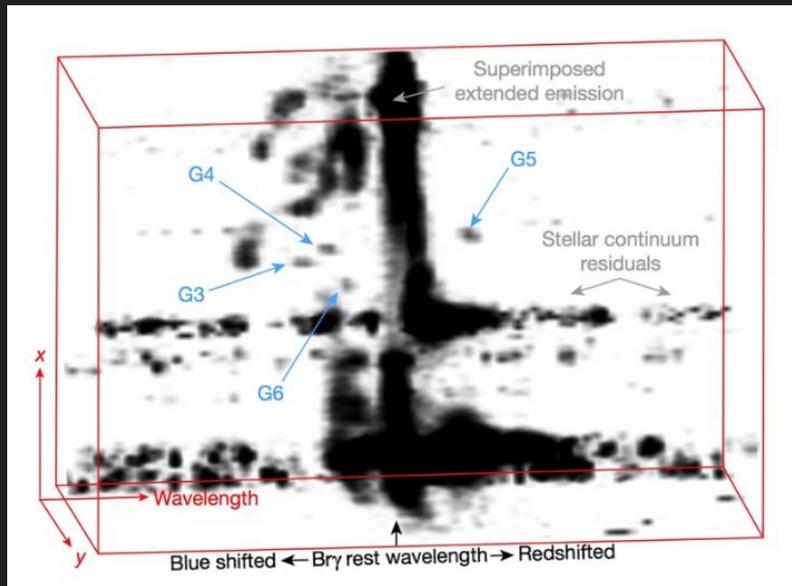
Neutron star destruction

- Not enough R-process nucleosynthesis
 - Too many years since LIGO kilonova 170817
- Could destroy neutron stars in galactic center
 - No GW signal
- Smoking gun: no GW

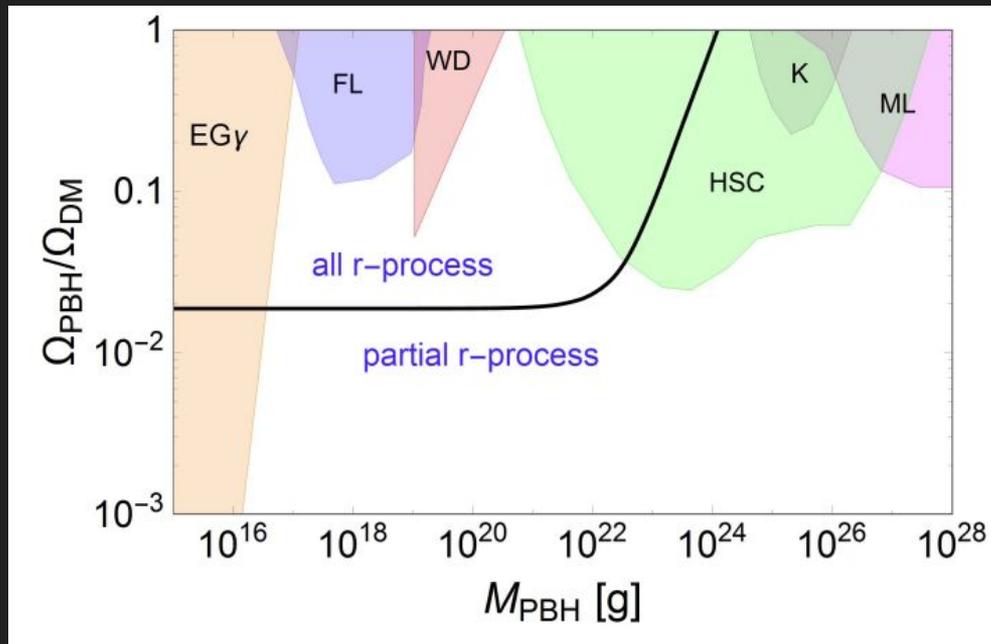


George M. Fuller, Alexander Kusenko,
Volodymyr Takhistov (2017)

Neutron star destruction



Ciurlo et al 2020

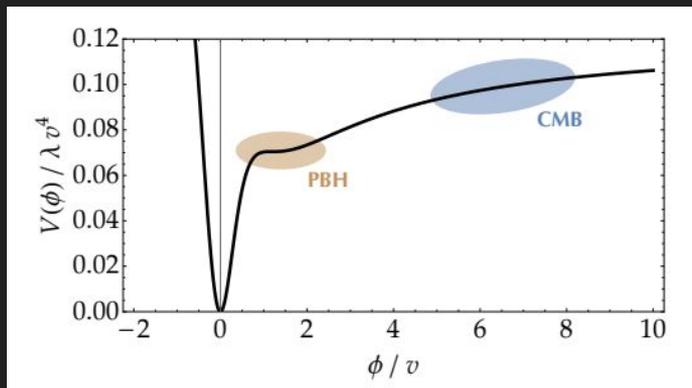


George M. Fuller, Alexander Kusenko,
Volodymyr Takhistov (2017)

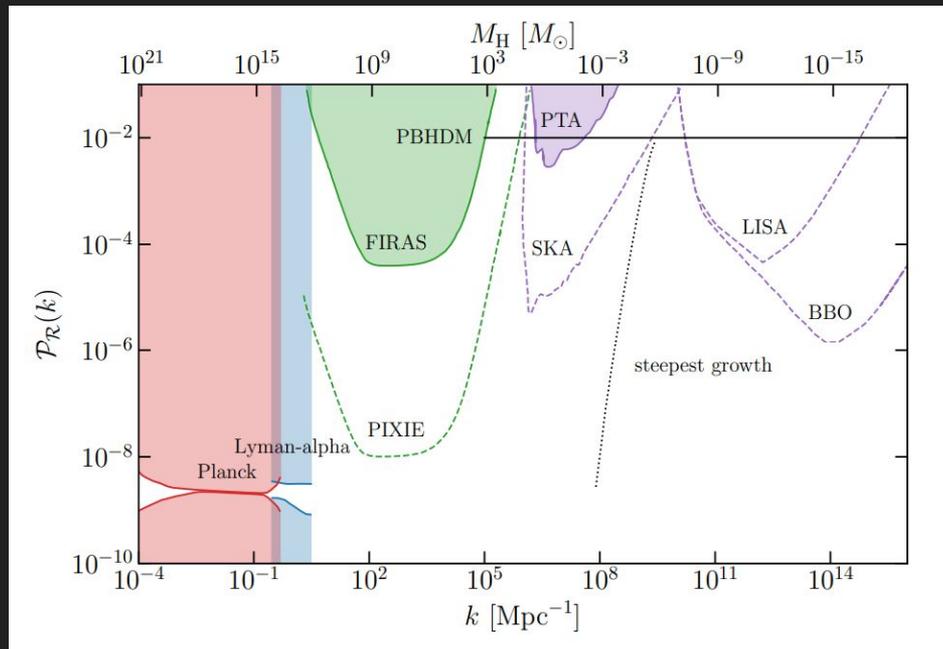
Formation

Inflation

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



Escriva, Kuhnel, Tada (2023)

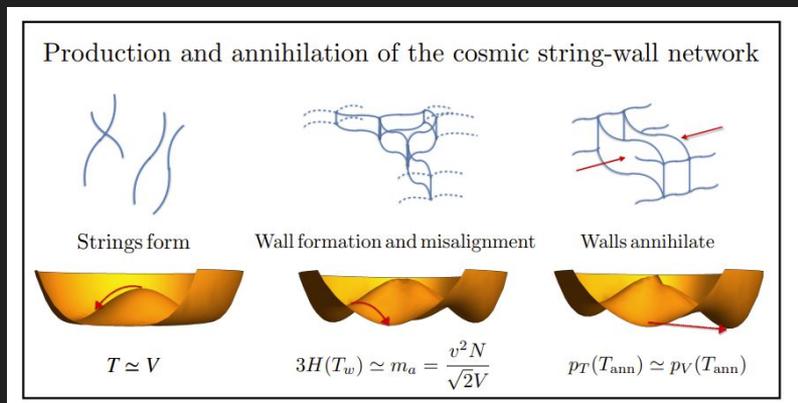


Green and Kavanaugh (2020)

Constraining Primordial Black Hole Formation from Single-Field Inflation

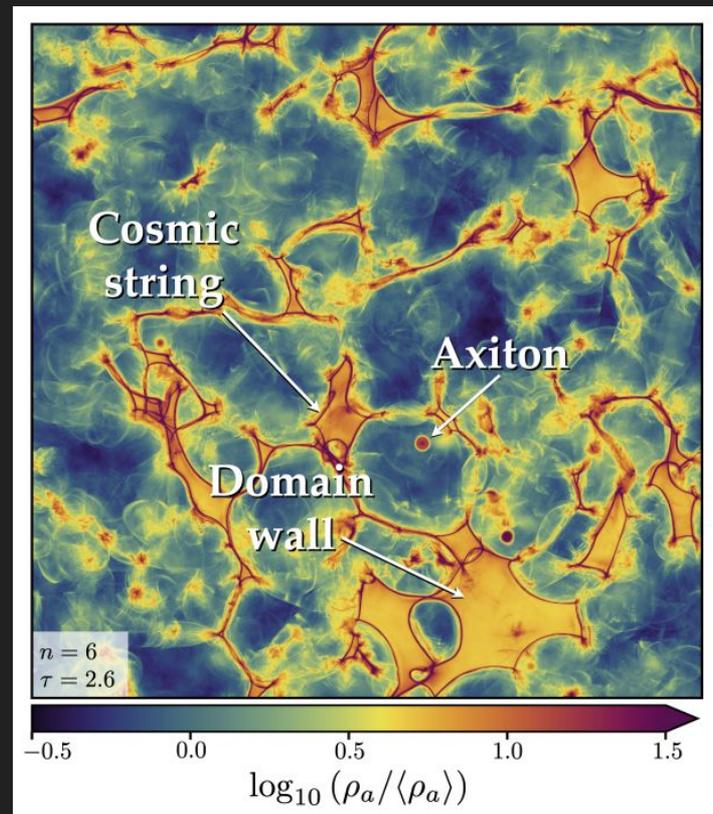
Jason Kristiano^{1,2,*} and Jun'ichi Yokoyama^{3,1,2,4,†}

Topological defects



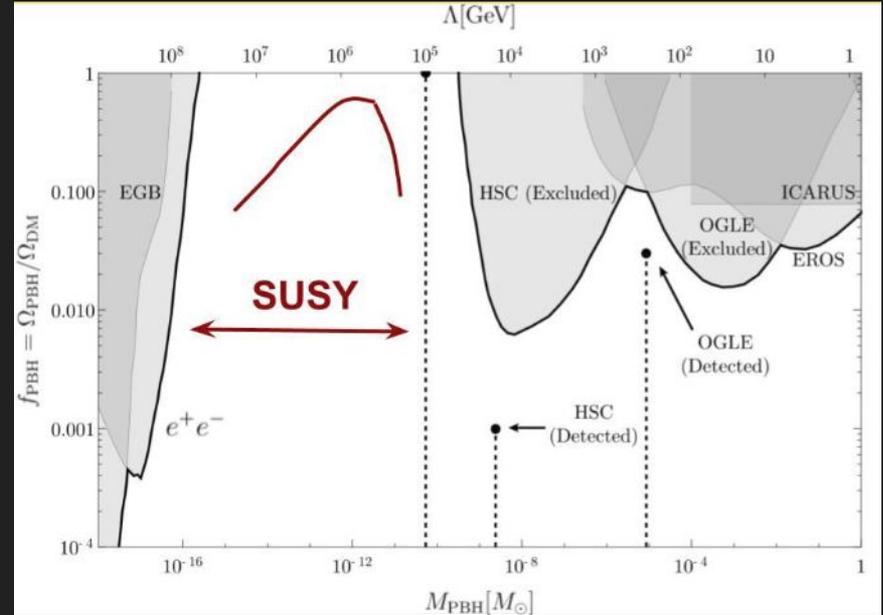
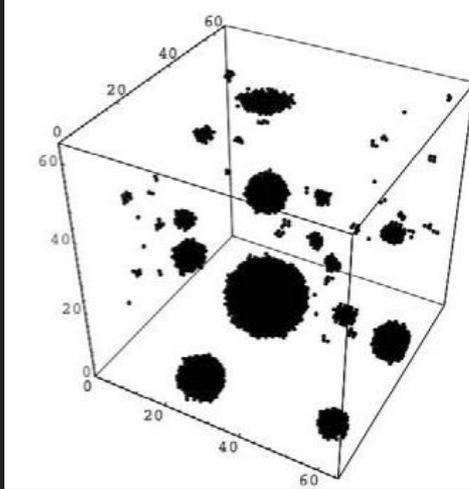
Gelmini, Simpson, Vitigliano 2023

O'Hare, Pierobon, Redondo, Wong 2022



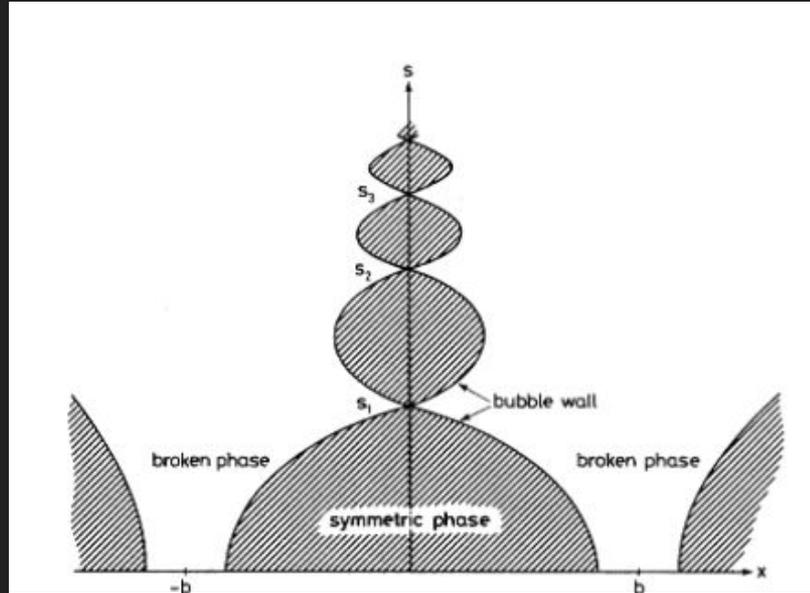
SUSY

- Many flat directions in SUSY
 - Fragment into solitons: Q balls, oscillons
 - Large Poisson statistics → PBH

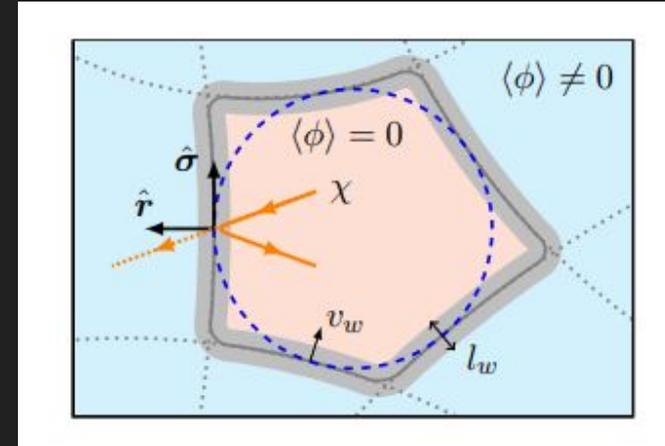


Cotner, Kusenko, Sasaki, Takhistov 2019
Kasuya, Kawasaki

Phase transitions and bubbles

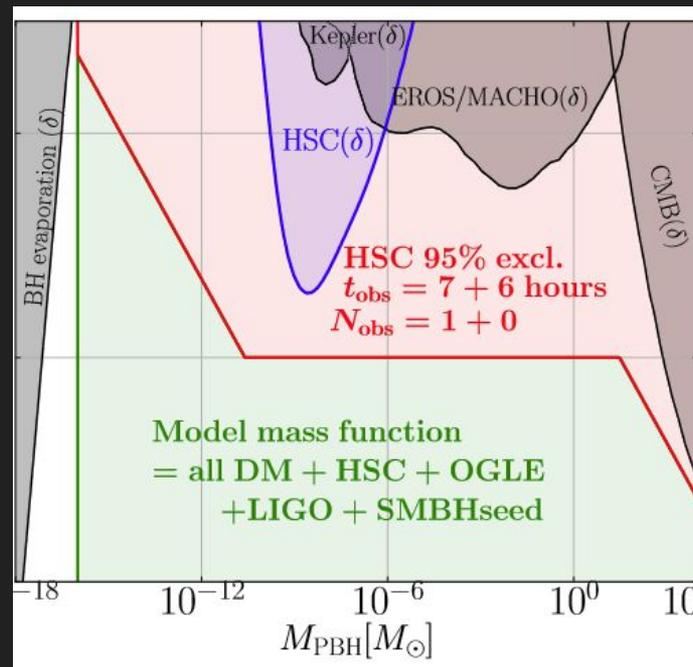
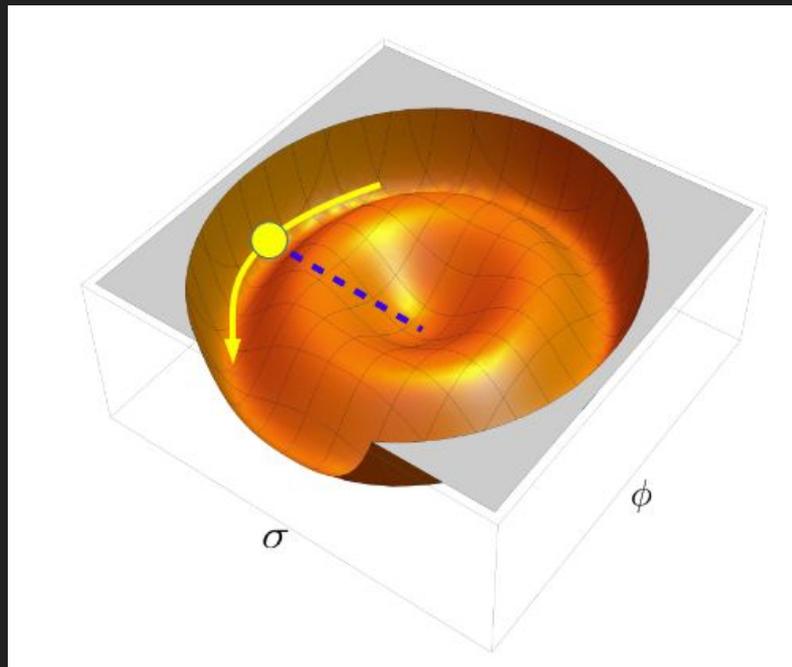


Hawking, Moss, Stewart 1981



Baker, Breitbach, Kopp, Mittnacht (2021)

Multiverse

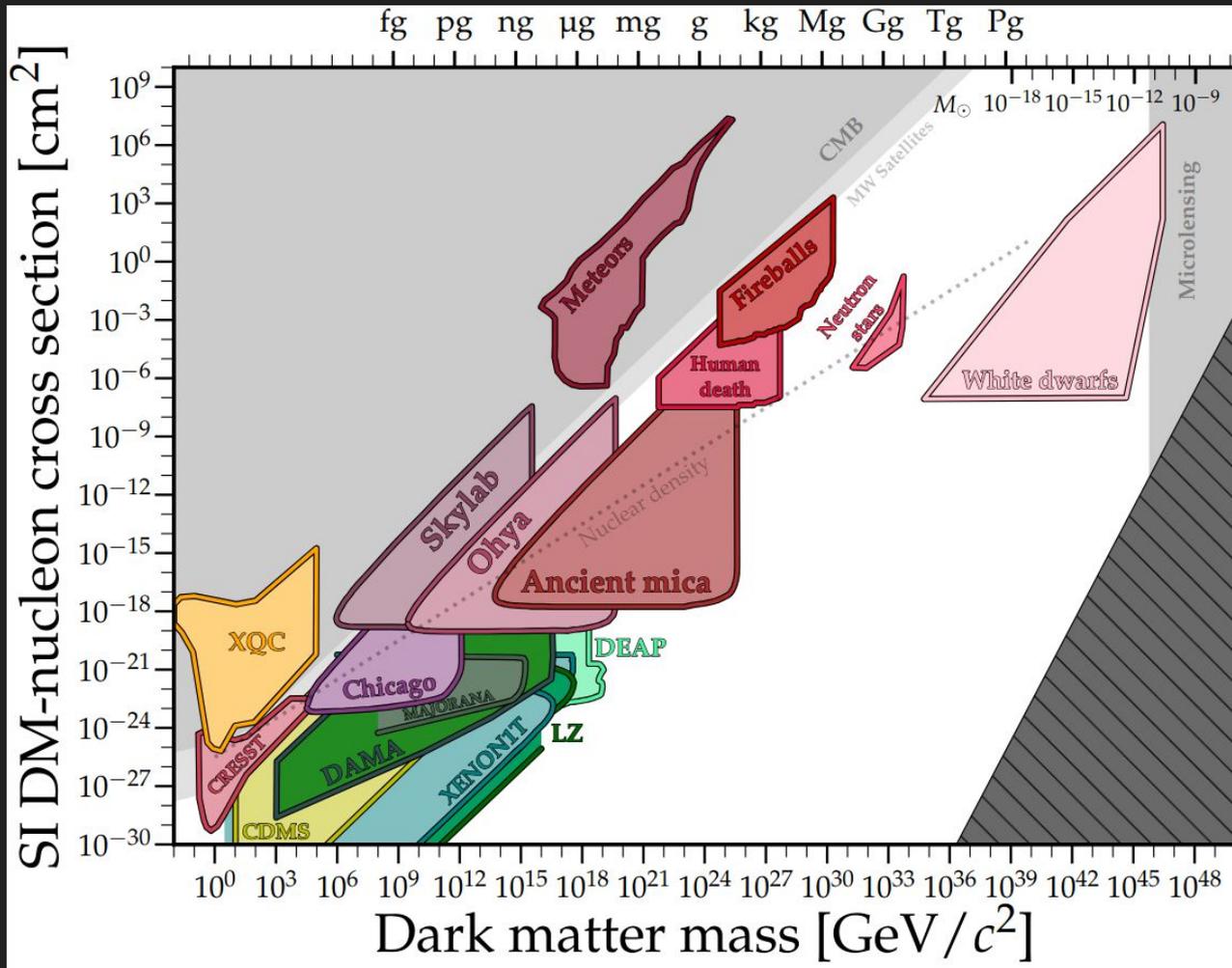


Kusenko, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano (2020)

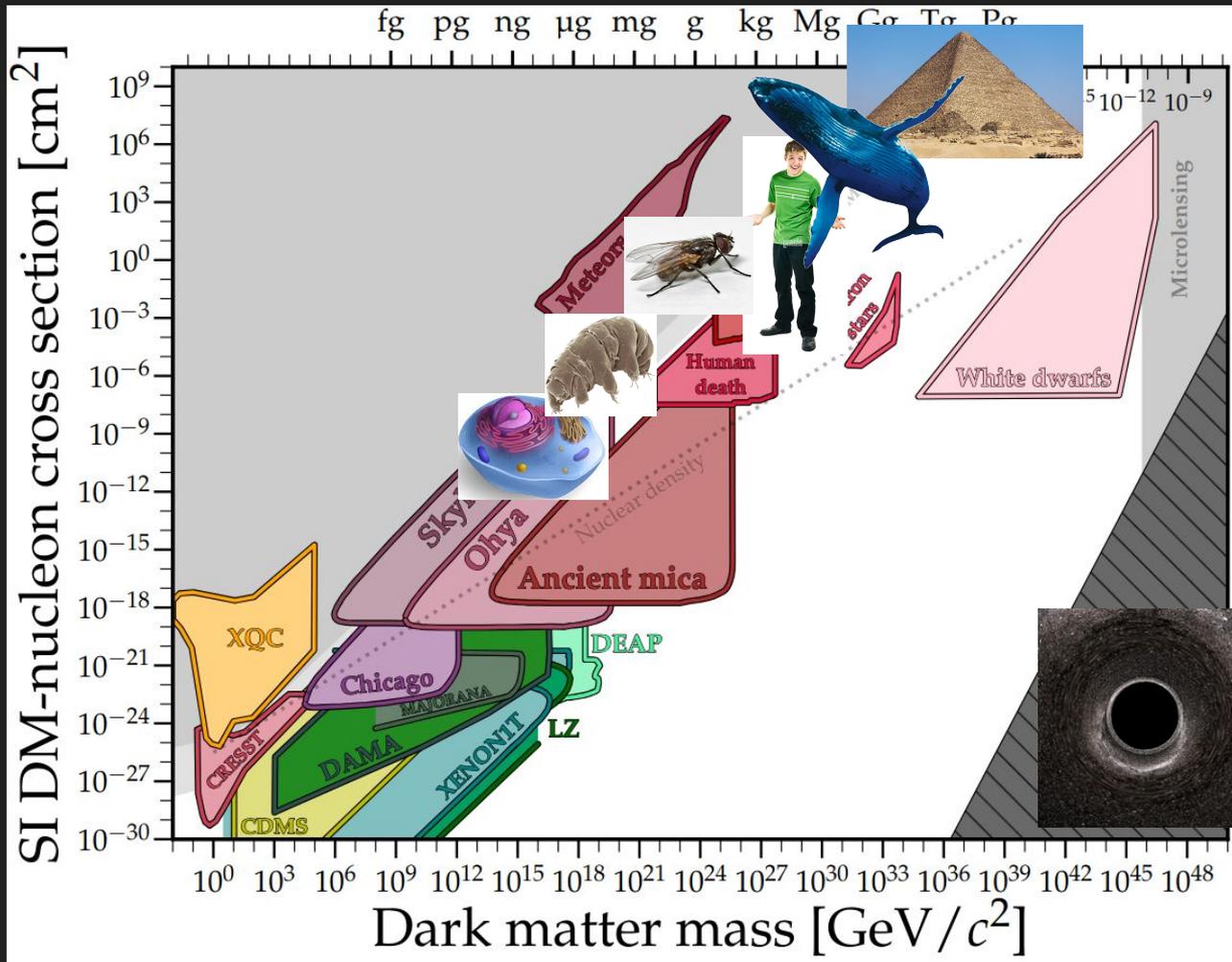
Balls, nuggets,...

Basics

- Dark matter with cross-sections and masses approaching regular stuff

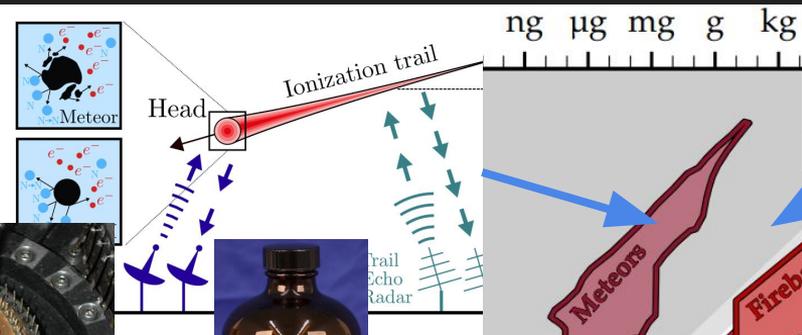
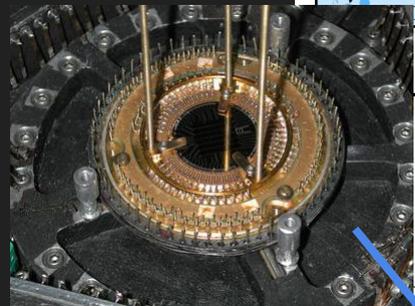


Ciaran O'Hare
github.com/cajo
 hare



Ciaran O'Hare
github.com/cajo
 hare

X-ray calorimetry



neutron



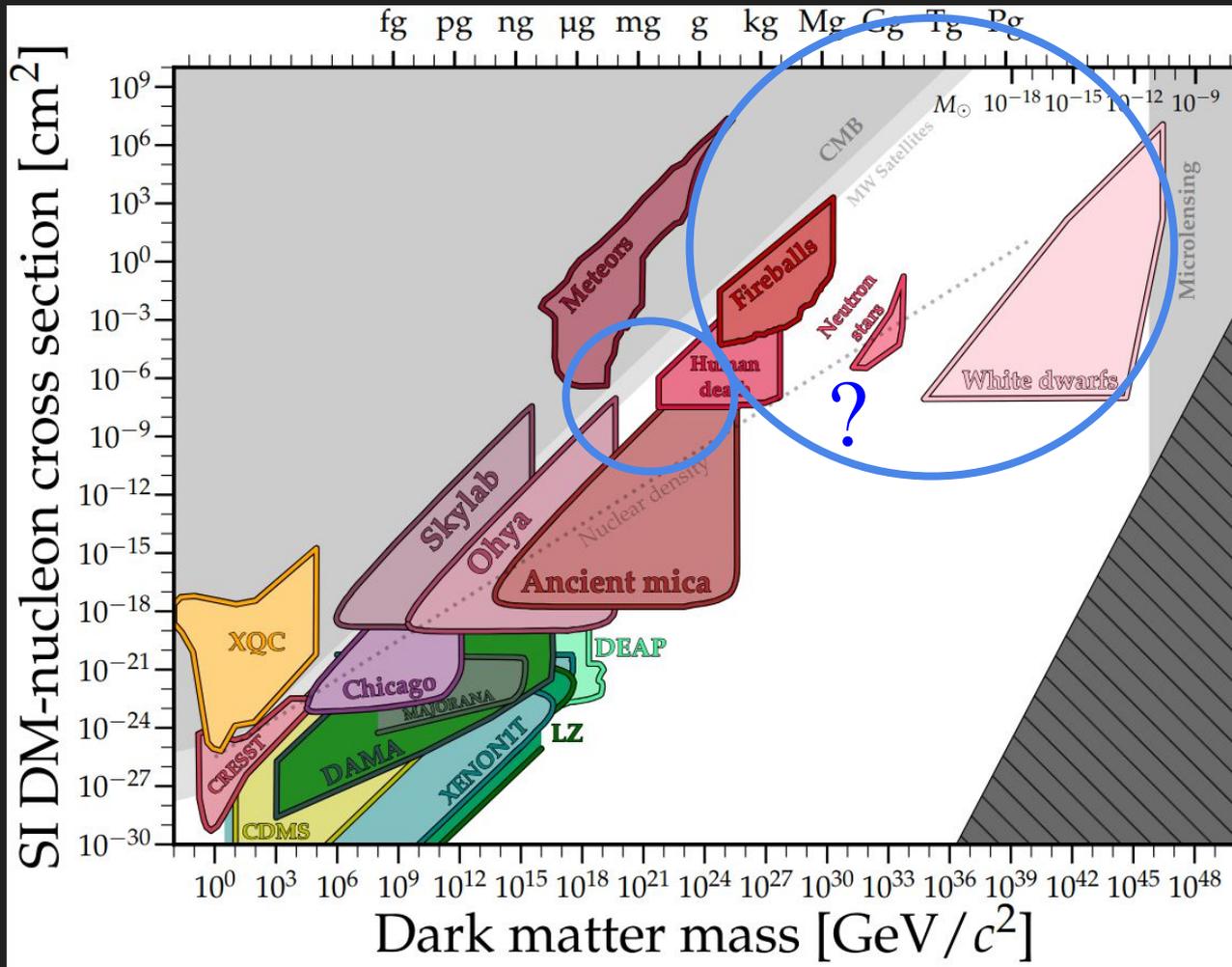
$c^2]$

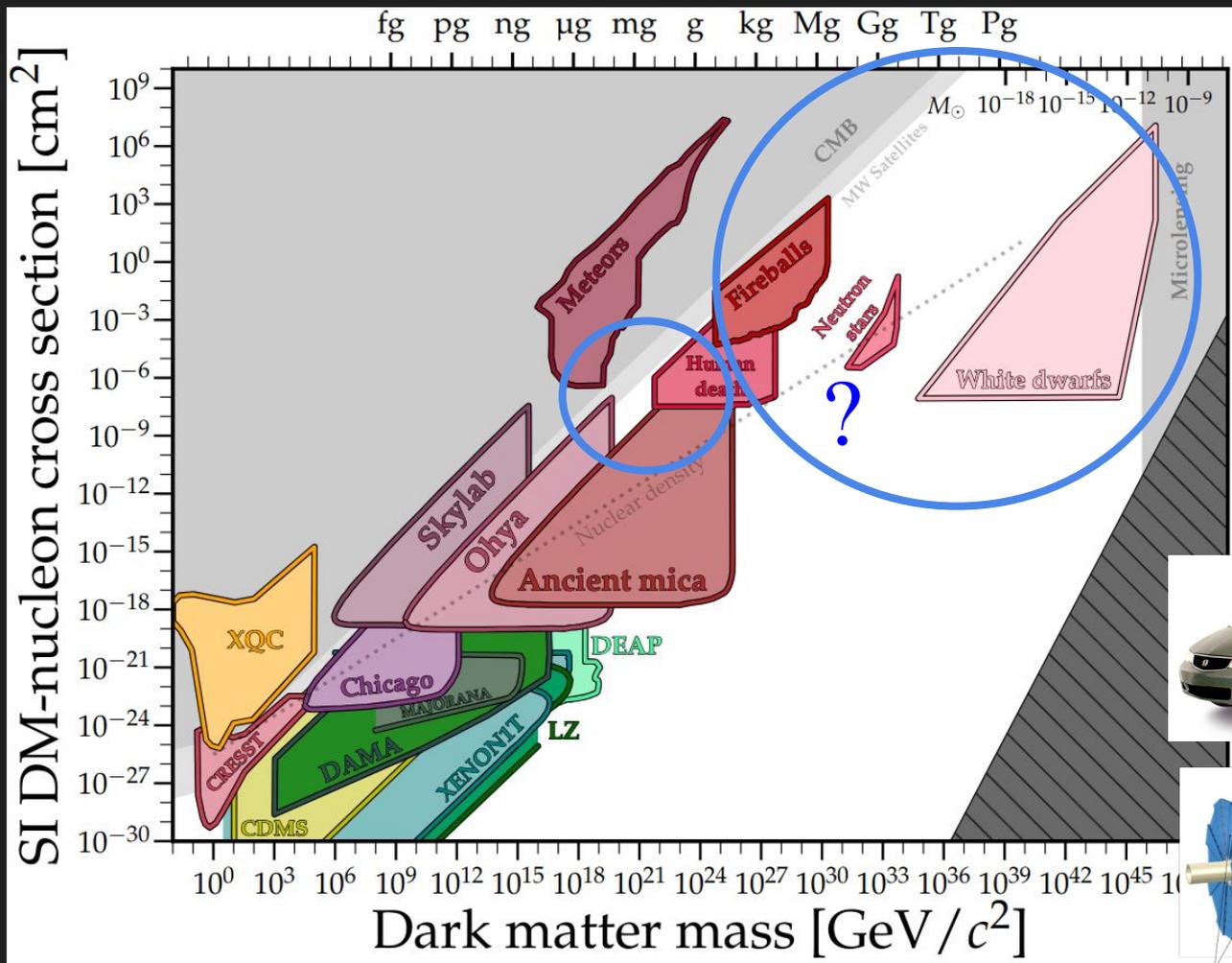


Thermonuclear shell flash

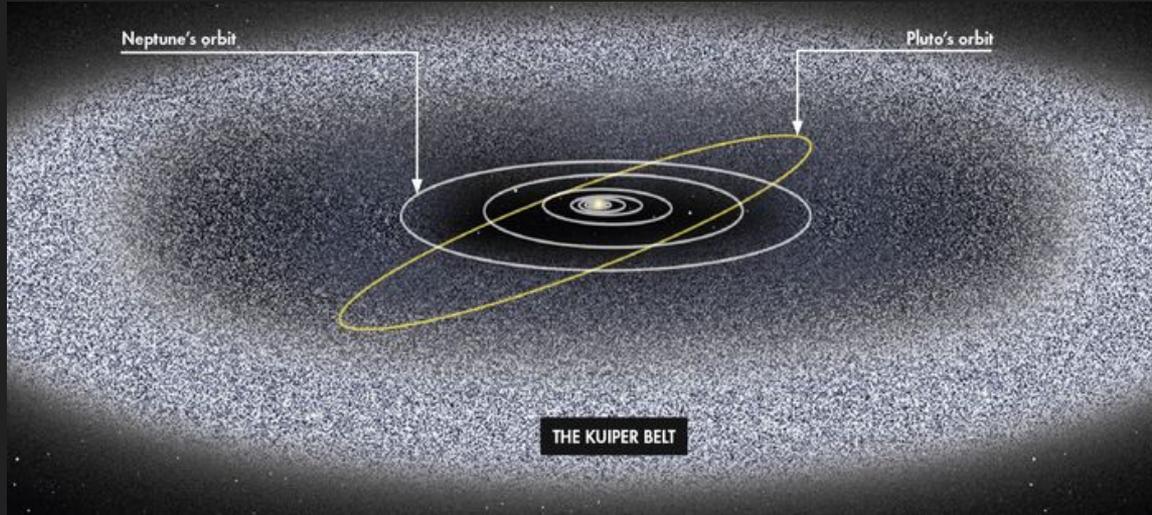


Desert fireball network





Interactions in the solar system

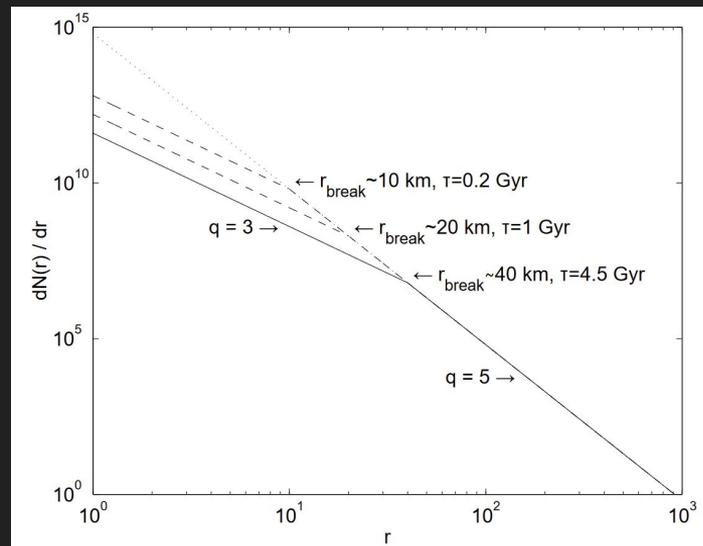


Why look in the solar system?

- Plethora of well-studied objects
 - Asteroids, kuiper belt, etc.
 - Planetary rings
 - Planetary surfaces
 - Moons
- Wide variance of object sizes
- Many objects have been undisturbed for Myr or Gyr
 - Good for dark matter constraints!
- Its fun

Asteroid destruction

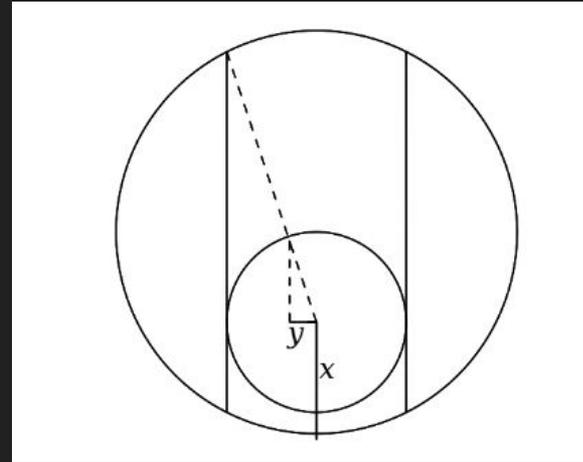
- Asteroids definitely survive until the present day
 - Dark matter should not catastrophically destroy them
- Must know (average) age of asteroid of given size
 - Myr-Gyr
 - Simulations, observations



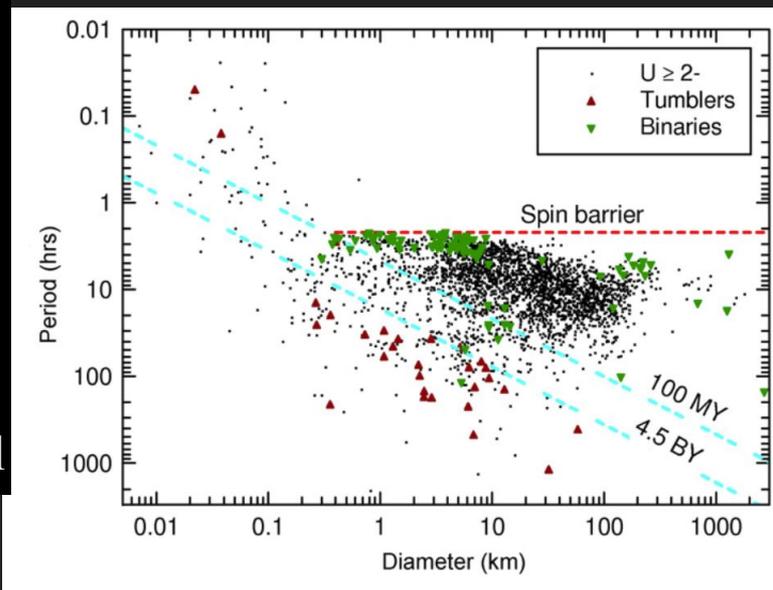
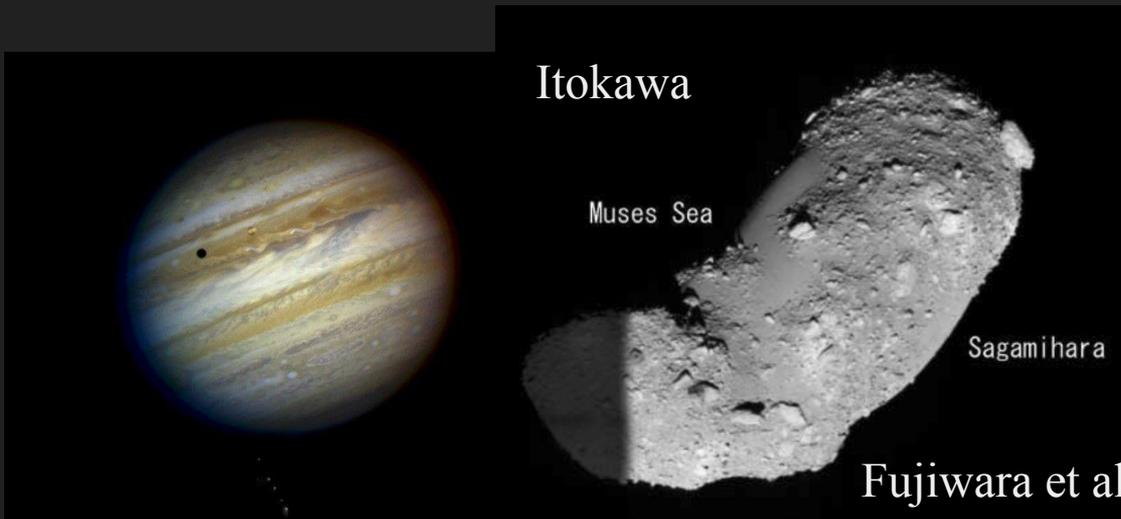
Kuiper belt: Pan and Sari 2004

Asteroid destruction

- Dark matter would plow hole through asteroid
- Estimate how much energy is deposited into the object vs. blasted out



Asteroid compositions - rubble piles

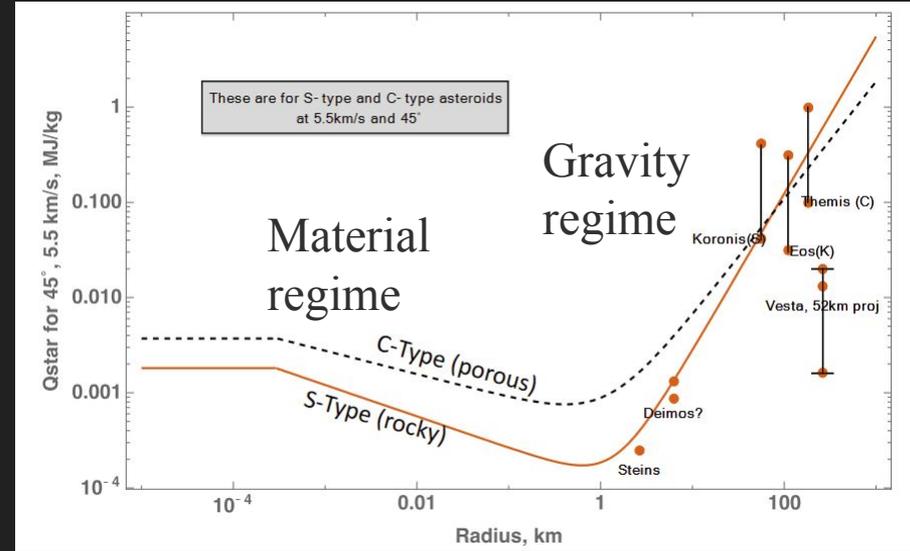
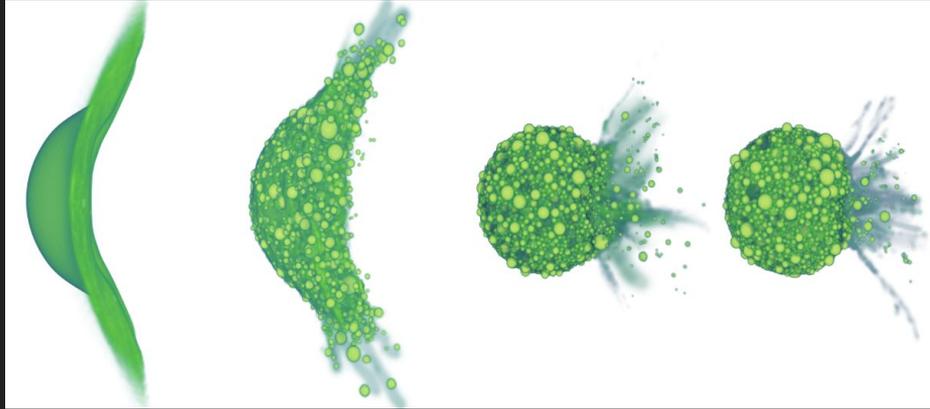


Warner, Harris, Pravec 2009

DART impact on Dimorphos

Asteroid destruction - criteria for catastrophic destruction

Q_* : kinetic energy over target mass

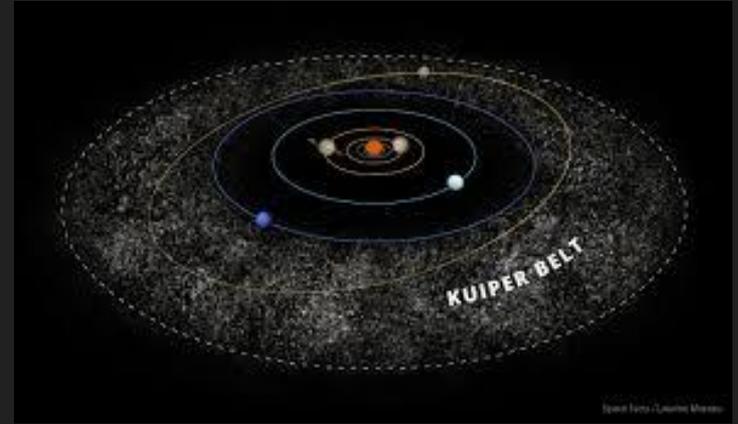


Raducan et al 2024

Holsapple and Housen 2019

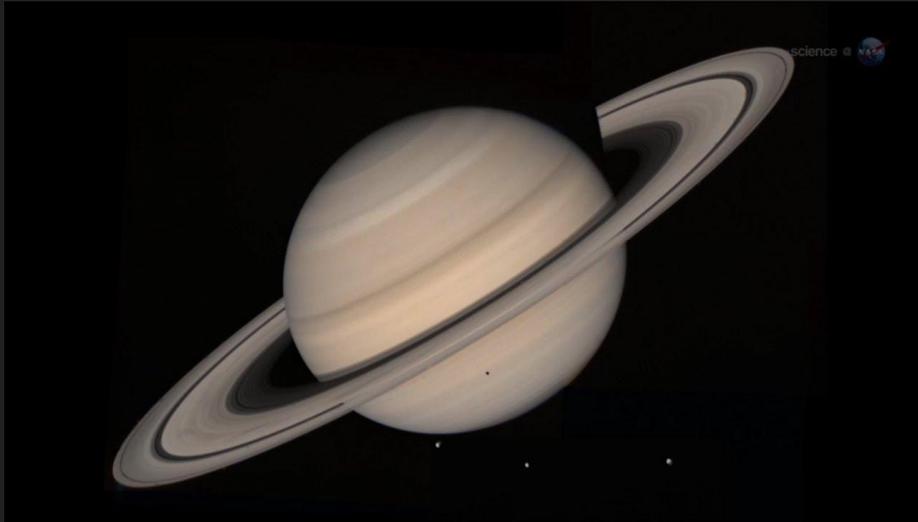
Asteroid 'evaporation'

- Escape velocity is only $\sqrt{2}$ larger than orbital velocity
- A few smaller collisions could add enough velocity to evaporate e.g. Kuiper belt objects
 - (Without destroying them)
 - Already have low orbital speed
- *Not* mass-independent
 - Velocity grows with $\sqrt{\text{number of collisions}}$

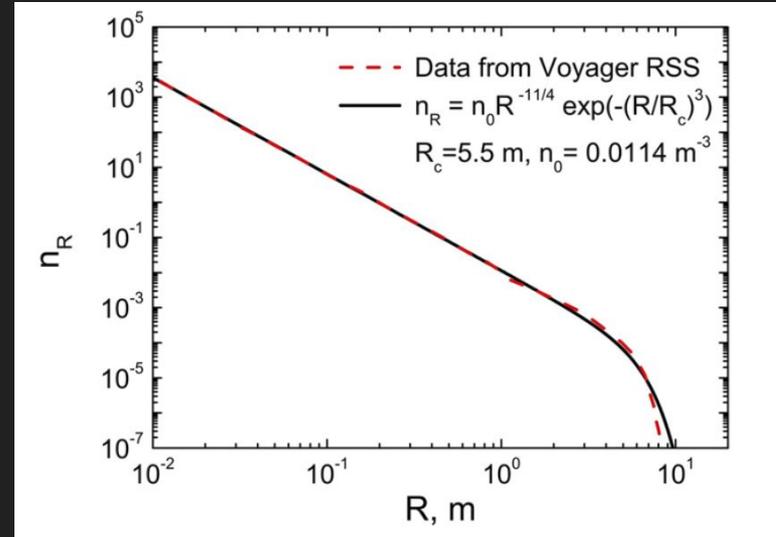


$$\langle \left\| \sum_k \hat{r}_i \right\| \rangle = \sqrt{k}$$

Planetary ring destruction and evaporation (same story)



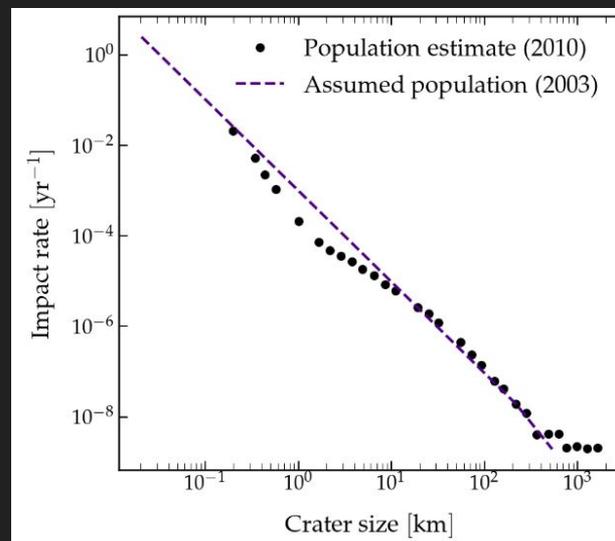
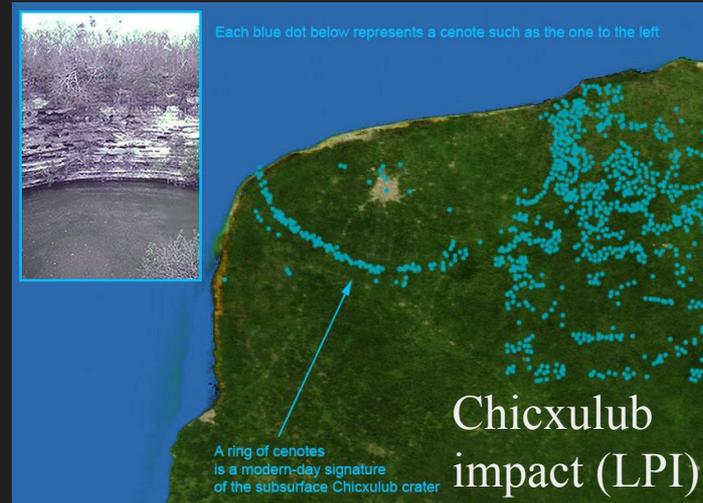
~100 Myr old



Brilliantov et al 2015

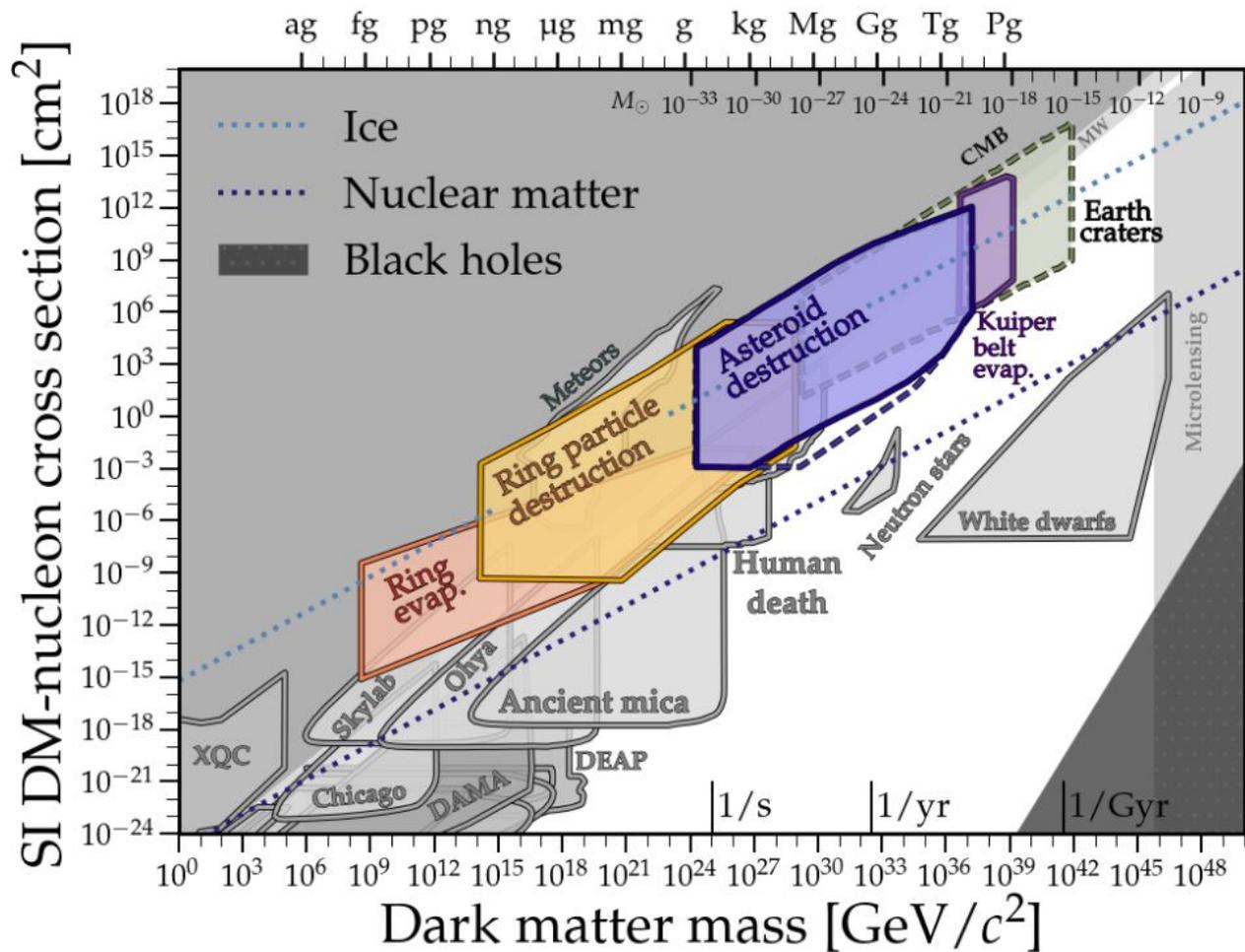
Craters on Earth

- Event rate on Earth can be large
- Potential constraints at smaller mass end
 - Overlap with asteroid destruction constraints
- Higher mass end is more difficult
 - How to distinguish regular crater from DM one?
 - What is the *empirical* cratering rate on Earth?
 - Active geology makes this very difficult... TBC!



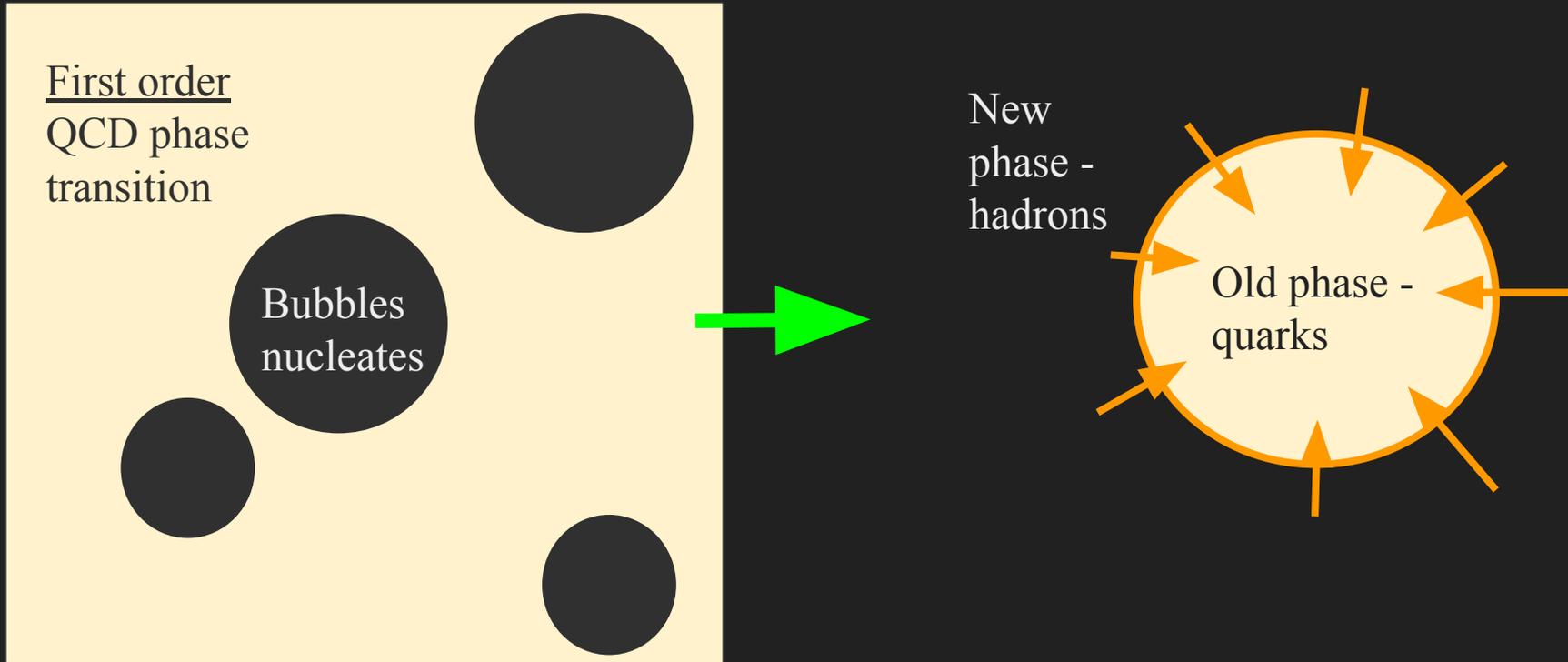
Results

Results



Macroscopic dark matter candidates

Quark nugget formation



Quark nugget stability

The average quark kinetic energy is proportional to μ , so (with a common pressure in the two cases) it is smaller in the three-flavor case by a factor

$$\tilde{\mu}/(\frac{1}{3}\mu + \frac{2}{3}2^{1/3}\mu) = [3/(1+2^{4/3})]^{3/4} \simeq 0.89 .$$

In equilibrium, the energy per quark equals the chemical potential, so the energy per quark in strange-quark matter is less than the energy per quark in zero strangeness quark matter by this factor of 0.89; in this idealization, strange-quark matter is more tightly bound than nonstrange-quark matter by about 100 MeV per baryon. The strange-quark mass will reduce this effect, but it is still plausible that strange quarks lower the energy per baryon of quark matter by 50–70 MeV per baryon. This is somewhat paradoxical, because in nuclear matter strange quarks have the opposite effect.

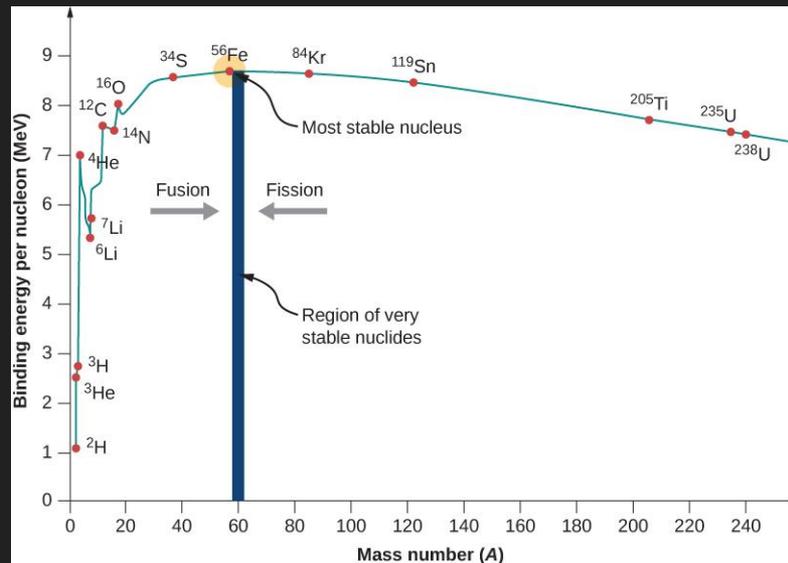
Cosmic separation of phases

Edward Witten*

Institute for Advanced Study, Princeton, New Jersey 08540

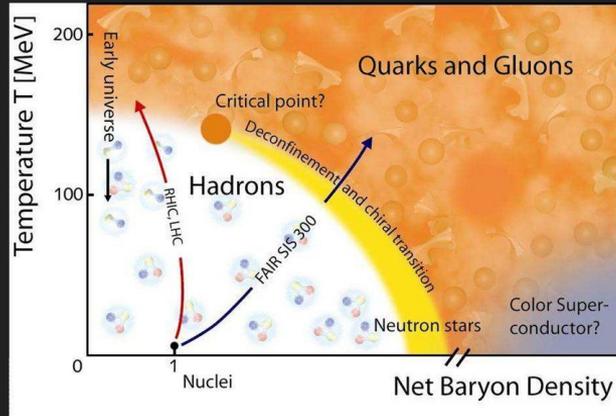
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.



Quark nugget realities

1. QCD crossover transition



2. Evaporation

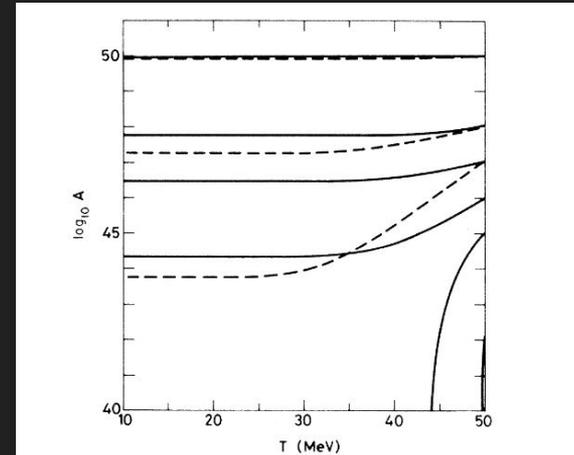
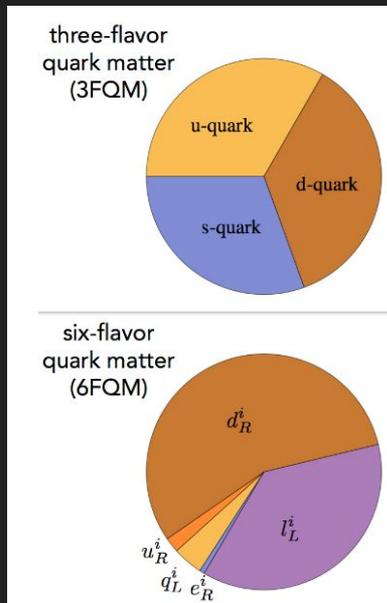


FIG. 4. The baryon number of strange nuggets as a function of the temperature of the Universe. The model for evaporation is described in Sec. IV. Nuggets of different sizes are followed from $T=50$ MeV to evaporation effectively stops at $T \approx 20$ MeV. The solid lines are results for $\alpha_c=0$, dashed lines for $\alpha_c=0.1$, both using $m_s=0$ (see text for further details).

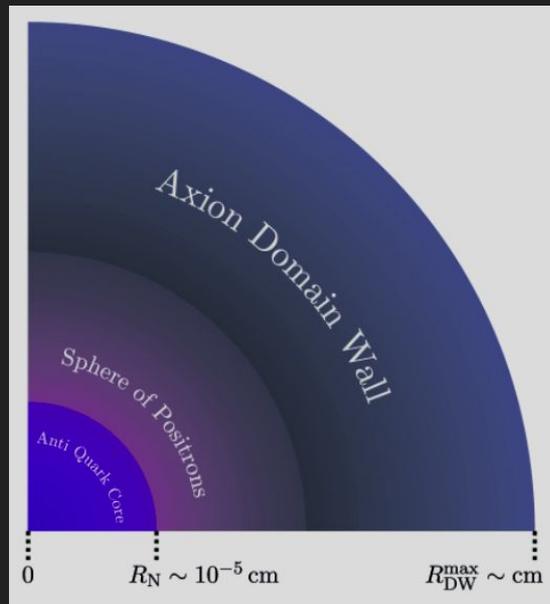
Some recent work

1. QCD before electroweak



Bai, Long 2018

2. Axion quark nuggets?



Sommer et al 2024

Generalizing: Nuggets to balls

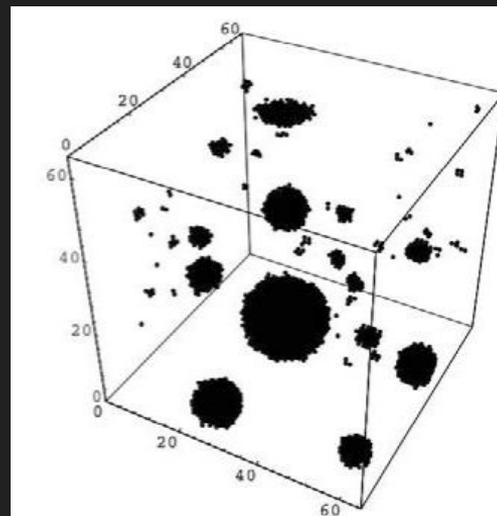
- What is a ball?
- *Nontopological* solitons
 - Stabilized by global symmetry

Q-Balls

Kasuya, Kawasaki :

- Coleman 1985:

there's no long-range force to suppress such fluctuations.) Unfortunately, I have no idea how to estimate the rate of this process. In any event, this alternative does



SOLITOGENESIS:

PRIMORDIAL ORIGIN OF NON-TOPOLOGICAL SOLITONS

Joshua A. Frieman¹, Graciela B. Gelmini², Marcelo Gleiser³, and Edward W. Kolb³

Heavy quarks and strong binding: A field theory of hadron structure*

W. A. Bardeen,[†] M. S. Chanowitz,^{‡§} S. D. Drell,[‡] M. Weinstein,[‡] and T.-M. Yan^{‡||}
Stanford University, Stanford, California 94305

(Received 26 September 1974)

Supersymmetric Q-balls as dark matter

Alexander Kusenko[✉] and Mikhail Shaposhnikov^{**}

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Fermi balls

- Formation
 - Nugget synthesis (eg nuclear synthesis)
 - Phase transition (eg quark nuggets)
 - Yukawa forces (later)
- (some) relevant papers:
 - Lee, Pang 1987, 1992
 - Grosso, Franciolini, Pani, Urbano 2023
 - Xie 2024
 - Gresham, Lou, Zurek 2017

Fermion soliton stars and black holes

T. D. Lee and Y. Pang

Columbia University, New York, New York 10027

(Received 28 October 1986)

Explicit solutions of fermion soliton stars and fermion black holes are given. The former has no horizon and the latter does. The soliton stars are cold, stable, and coherent states of very large mass $M \sim (l_p m)^{-4} m$, with l_p the Planck length, m the mass of the relevant Higgs-type scalar field, and $\hbar=c=1$.

Fermi balls

- Formation
 - Nugget synthesis (eg nuclear synthesis)
 - Phase transition (eg quark nuggets)
 - Yukawa forces (later)



Fermion soliton stars and black holes

T. D. Lee and Y. Pang

Columbia University, New York, New York 10027

(Received 28 October 1986)

Explicit solutions of fermion soliton stars and fermion black holes are given. The former has no horizon and the latter does. The soliton stars are cold, stable, and coherent states of very large mass $M \sim (l_p m)^{-4} m$, with l_p the Planck length, m the mass of the relevant Higgs-type scalar field, and $\hbar = c = 1$.

Forming Fermi balls

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

$$\mathcal{L} = \bar{\psi} (i\not{\partial} - (m_\psi - y\varphi)) \psi + \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 - V(\varphi).$$



Mediates attractive Yukawa force
 \Rightarrow 'Yukawa length scale' is
1/scalar mass

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

Forming Fermi balls

- Two component model
- Heavy fermion and light scalar

Forming Fermi balls

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

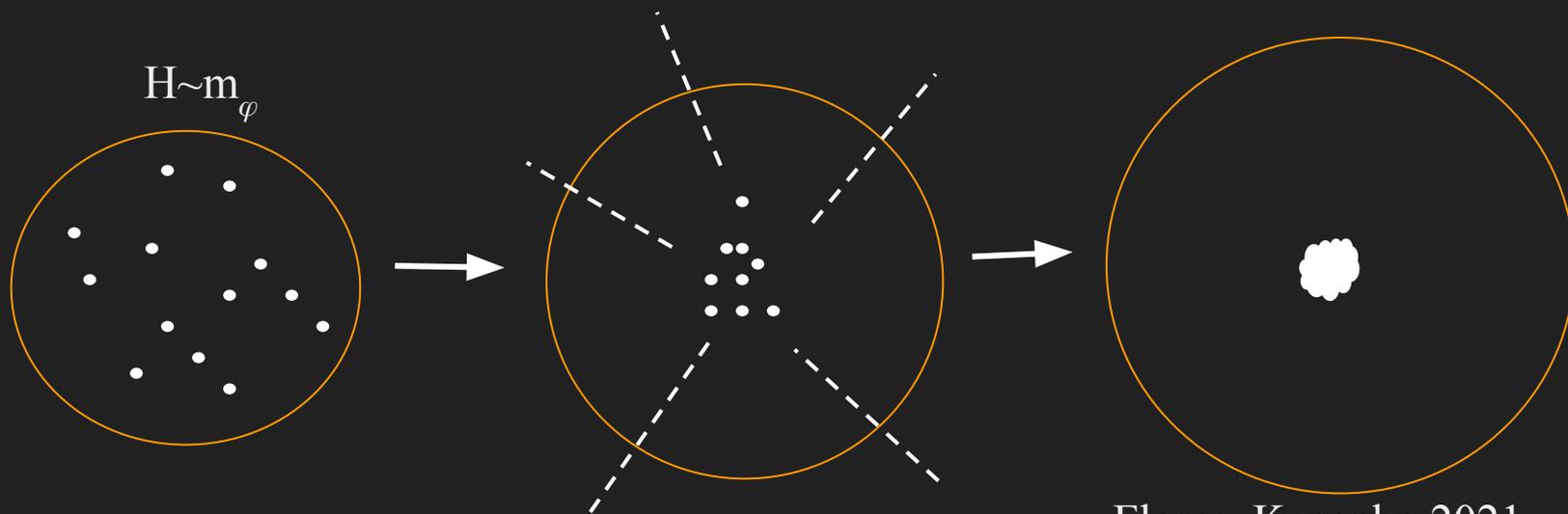
$$\mathcal{L} = \bar{\psi} (i\cancel{\partial} - (m_\psi - y\varphi)) \psi + \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 - V(\varphi).$$

- 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

(need to account for fermion asymmetry)



Flores, Kusenko 2021

Yukawa structure formation

Nonlinear,
screening stuff
starts



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

What happens to the little halos?

- Stable, nontopological solitons can form — Fermi balls
 - Fermi degeneracy pressure

~dark equivalent of neutron stars/white dwarfs

What happens to the little halos?

- Stable, nontopological solitons can form — Fermi balls
 - Fermi degeneracy pressure

~dark equivalent of neutron stars/white dwarfs

Could they collapse to a black hole?

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

Yes

Yes*

The fate of (these) Fermi balls

Gresham, Lou, Zurek
2017

- We have to look closely at their mass-radius relations

Two important regimes: $1/m_\phi \sim R$

Sub-saturation

$$R \propto N^{2/3}, \quad M \propto N^{2/3}$$

Saturation

$$R \propto N^{1/3}, \quad M \propto N$$

The fate of (these) Fermi balls

Gresham, Lou, Zurek
2017

- We have to look closely at their mass-radius relations

Two important regimes: $1/m_\phi \sim R$

Sub-saturation

$$R \propto N^{2/3}, \quad M \propto N^{2/3}$$

Saturation

$$R \propto N^{1/3}, \quad M \propto N$$

- Hard to form black holes:
 - Sub-saturation, they grow proportionately
 - Saturation, longer-range Yukawa forces are lost

Re-examine the dark matter model

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

Potential term:

- Scalar field needs additional potential to be renormalizable:

$$V(\varphi) = -\lambda\varphi^4$$

⇒ new repulsive force

(⇒ new free parameter λ ...)

New Fermi ball equations of state

Drastic effect:

Repulsive force can ‘kick in’ sooner than degeneracy pressure

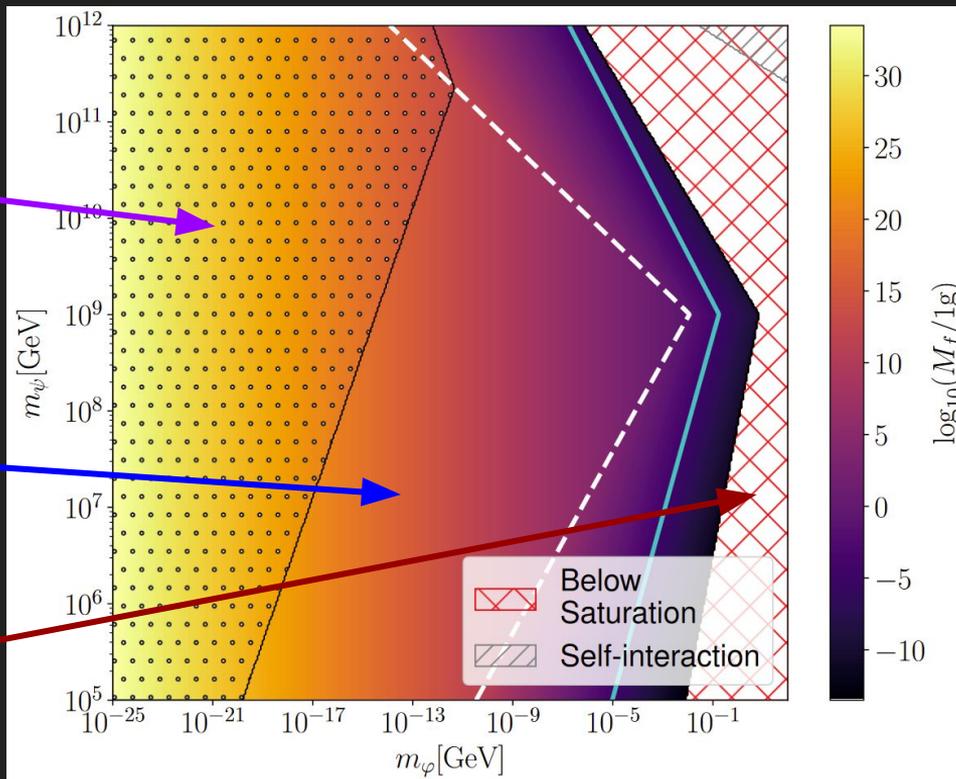
- Radius $\propto N^{1/3}$
Mass $\propto N$
 - (more technically...they reach ‘saturation’ almost immediately because the effective scalar mass is changed)
 - Adding more fermions increases mass more quickly than radius
- ⇒ By adding more fermions, you *can* cause it to collapse to a black hole

~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)



($y=5e-2$, $\lambda=1e-2$, asymmetry \rightarrow all DM)

Conclusions, morals, and partings

Summary

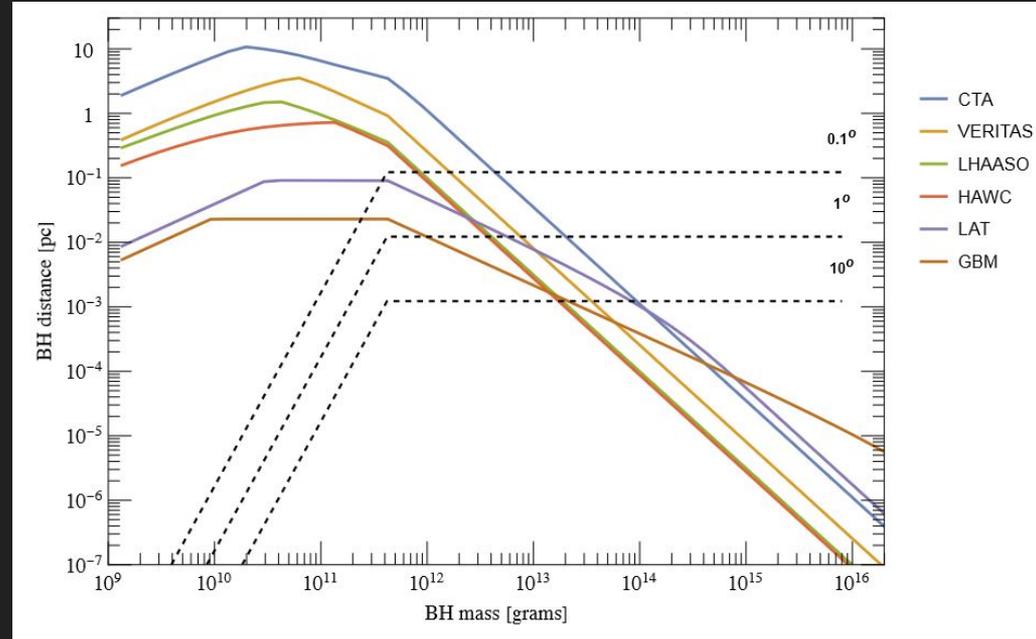
- Macroscopic dark matter is cool
- Primordial black holes
 - Not ruled out, maybe even hints...?
 - Lots of ways to form
- Big composite states
 - Lots of parameter space to test
 - Also easy to form
 - Could have fun signatures: asteroids, rings, craters, etc
 - Could even collapse to black holes
- Come chat with me any time!

Thanks!

Bonus slides

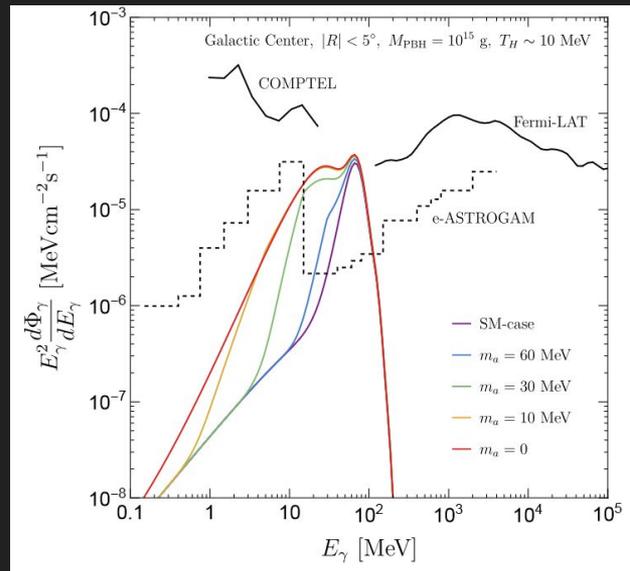
Hawking radiation

- Detection would be extremely exciting

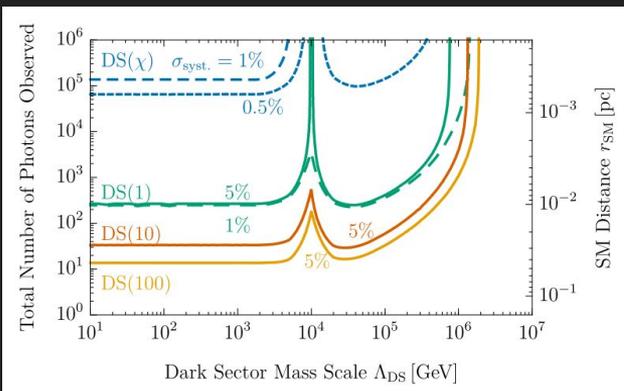


Hawking radiation

- Detection would be extremely exciting
- Decays into *all* particles—probe BSM, dark sectors, etc.



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

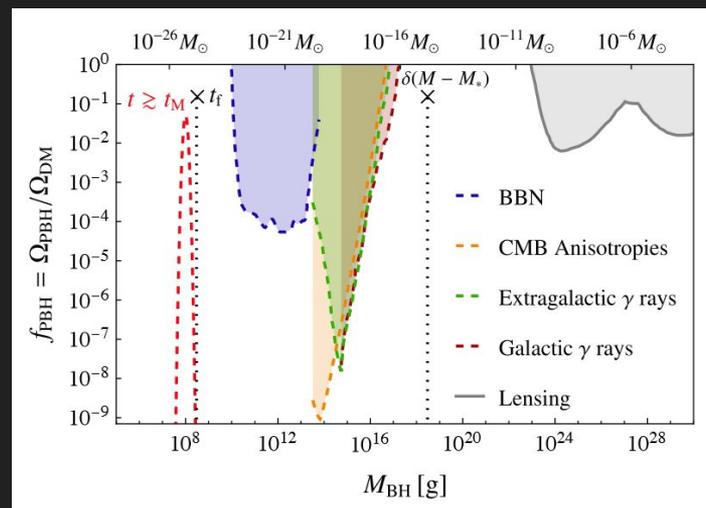
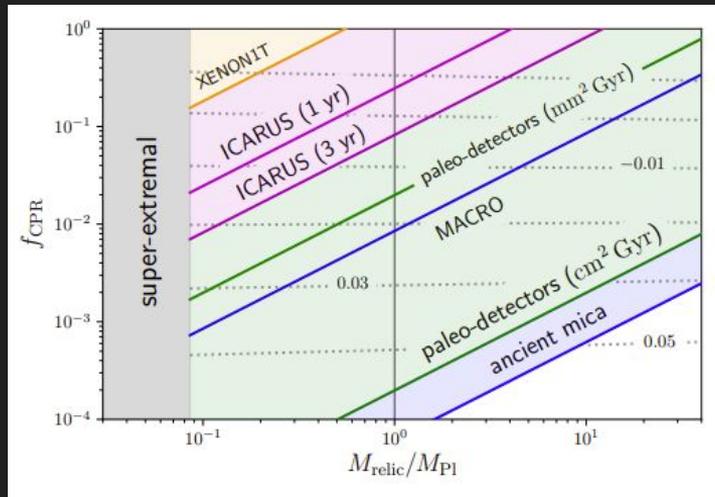


Hawking radiation

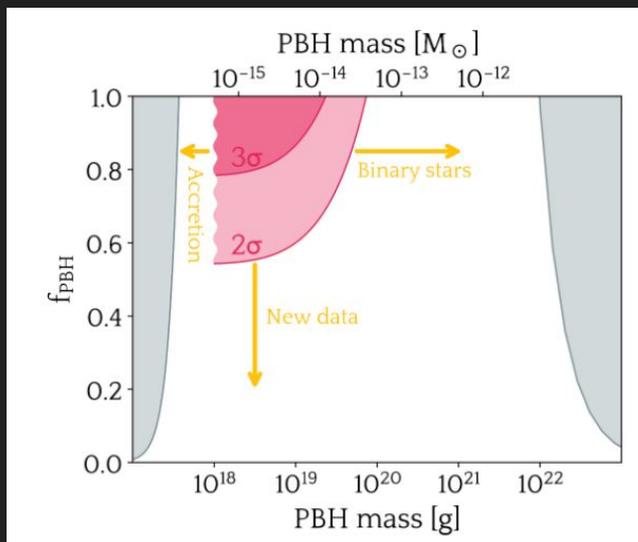
- Detection would be extremely exciting
- Decays into *all* particles—probe BSM, dark sectors, etc.
- Decay could stop early
 - Planck scale?
 - Halfway? (memory burden?)

Lehmann, Johnson, Profumo, Schwemberger 2019

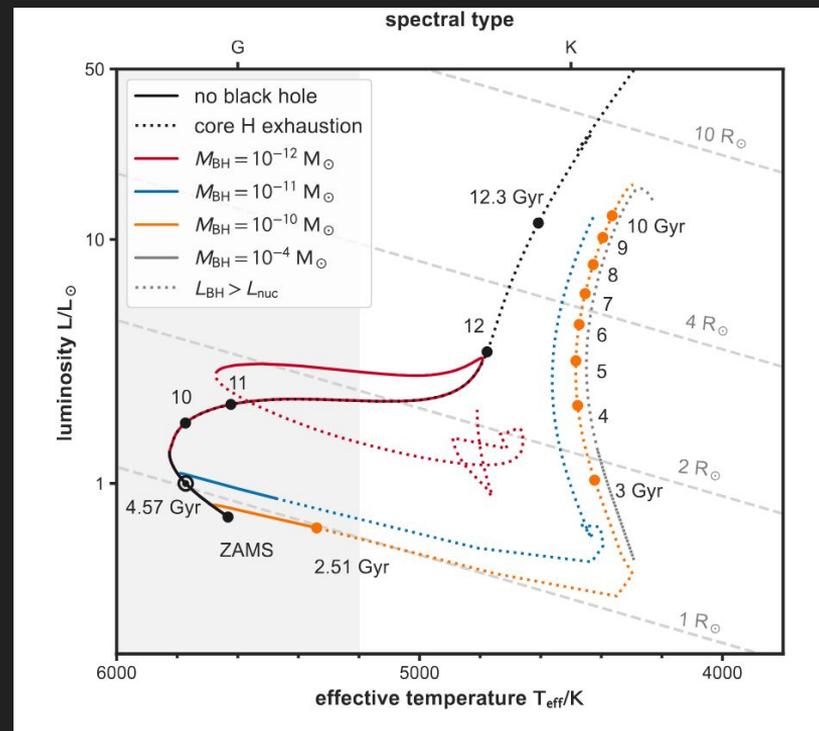
Dvali, Valbuena-Bermudez, Zantedeschi 2024



PBHs in stars...?



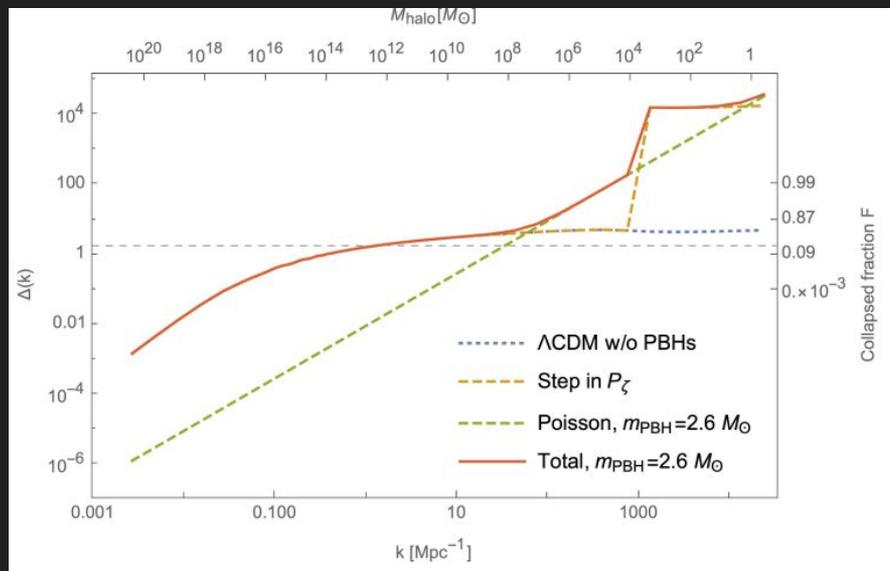
Esser et al 2025 (...+Tinyakov)



Bellinger et al 2023

Constraints - dynamical

- Large PBHs can disrupt or destroy large structures
- Could form cosmic structures too early
- Interesting pheno:
Pbh clusters naturally agree with minimum observed mass/radius of ultra-faint dwarf galaxies

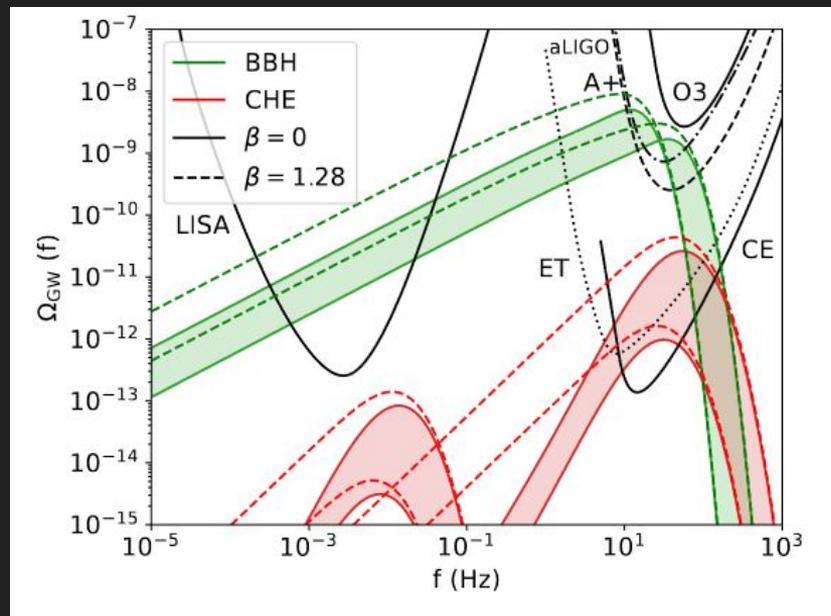


Carr, Clesse, Garcia-Bellido, Hawkins, Kuhnel 2023

Constraints - gravitational waves

Some interesting pheno:

- Should also be many hyperbolic encounters
 - Unique ‘burst’ signal
 - In case PBH clustering prevents binary formation/ survival



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