More Macroscopic Dark Matter

Zachary S.C. Picker

Loosely based on:

- 2411.17074 (Yifan Lu, ZSCP, Stefano Profumo, Alexander Kusenko)
- 2504.07232 (ZSCP)
- Forthcoming:
  - (ZSCP, Lu, Kusenko)
  - (ZSCP, Melissa Diamond, Andrew Buchanen, Joseph Bramante)
  - (Hannah Banks, Diamond, ZSCP, Aaron Vincent)

Macroscopic dark matter

- Possible definition:

‘Dark matter sufficiently massive such that we would not reasonably expect to see it in reasonably-sized direct detection experiments on Earth, in a reasonable time.’

- AKA:
  - Ultraheavy
  - Composite
  - Macros
  - Compact UltraDense Objects
  - …PBHs…

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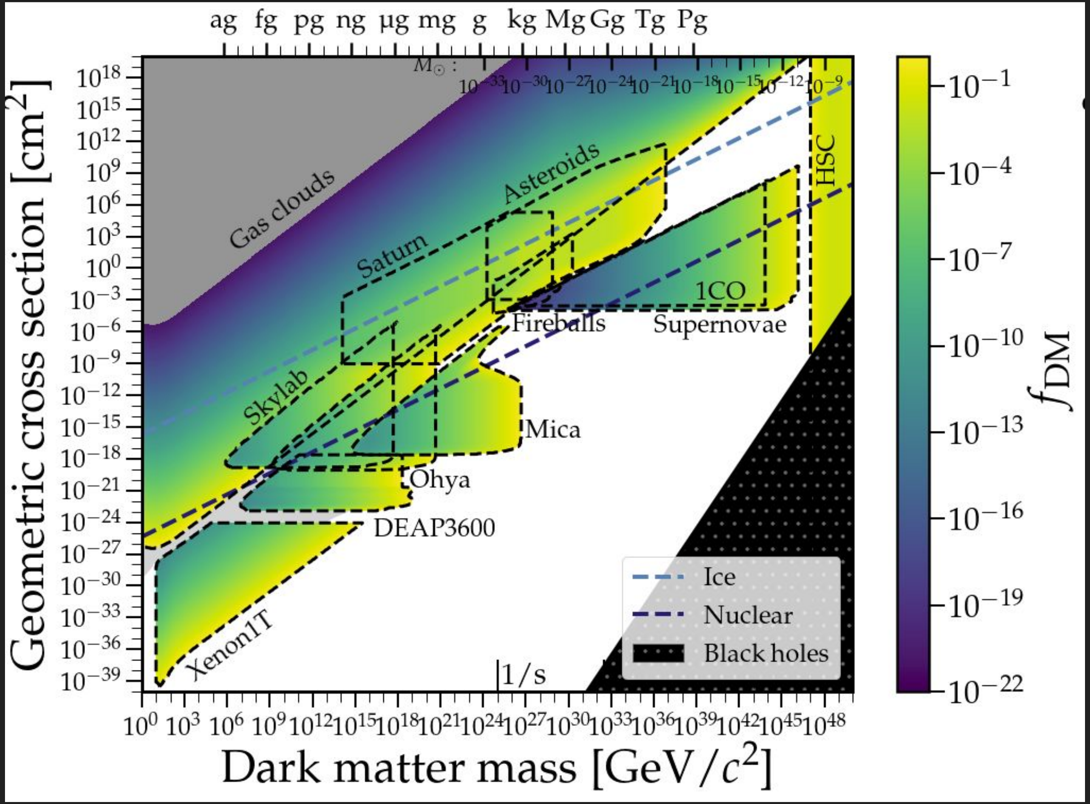
- AKA:
    - Ultraheavy
    - Composite
    - Macros
    - Compact UltraDense Objects
    - …PBHs…
- Two big pheno questions: Formation and Detection

Finding it and forming it

Finding it and forming it

The constraint space (preliminary)

(not exhaustive!!)

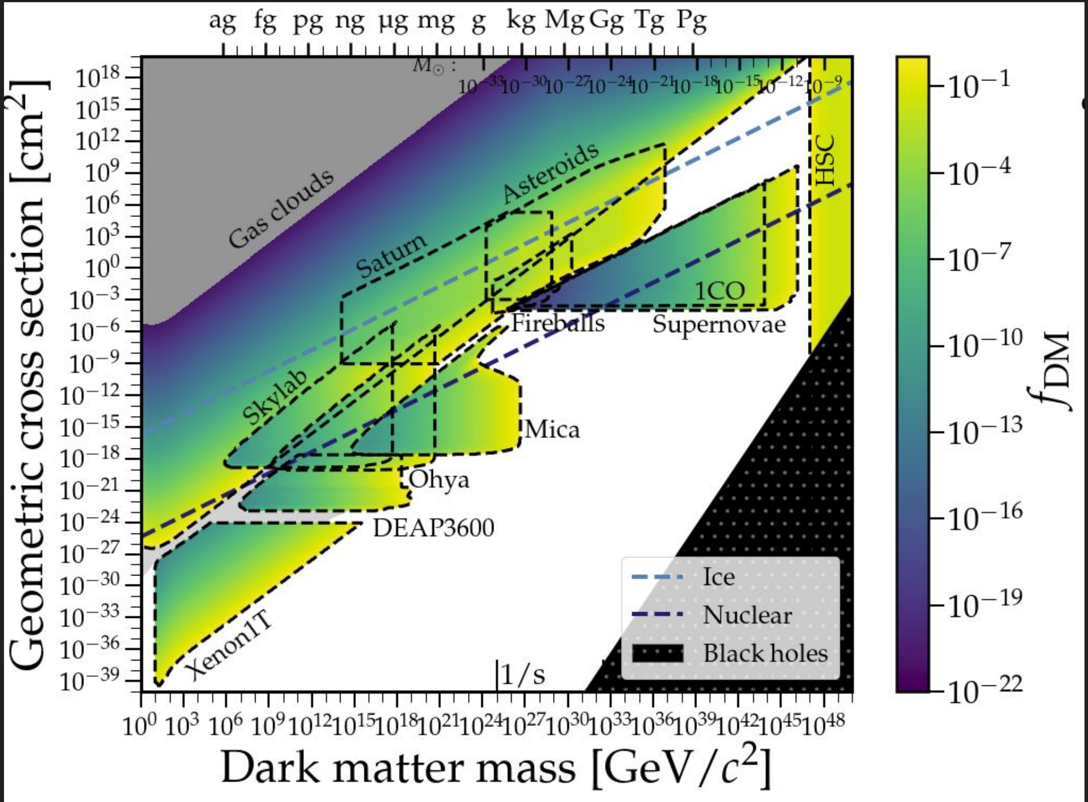


With:
Melissa Diamond
Andrew Buchanen
Joseph Bramante

Copyright slide deleted :)

The constraint space (preliminary)

Developing as (somewhat) friendly public code



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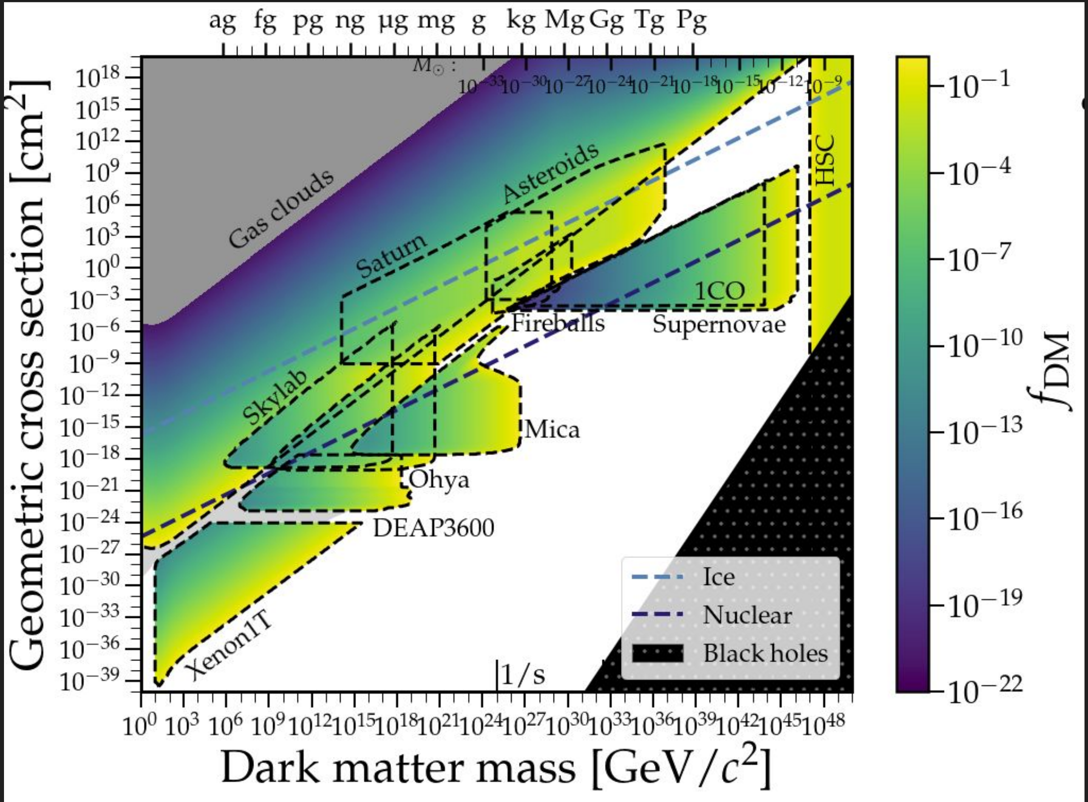
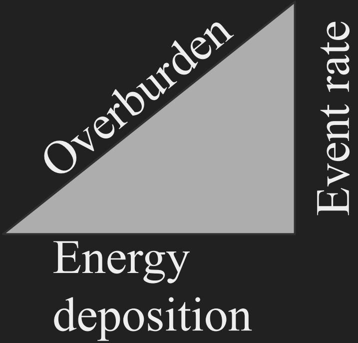
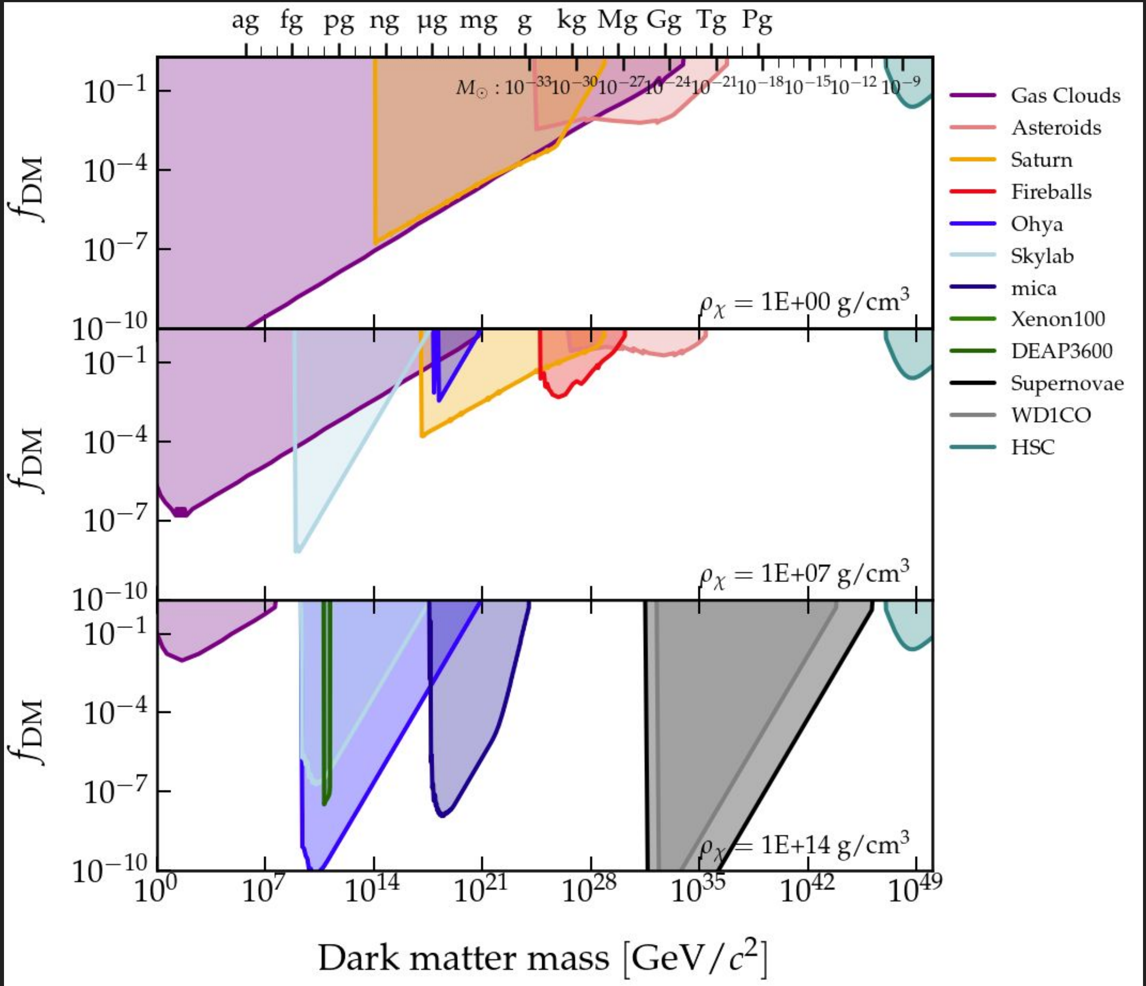




Also possible to make 'PBH-style' plots

- Internal density of macro is fixed
- Primary goal of all this:
  - compute constraints for extended mass functions



Asteroids+Saturn

A dark matter hail:
Detecting macroscopic dark matter with asteroids, planetary rings, and craters

Zachary S. C. Picker[1,*]

[1] *Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California, 90095-1547, USA*

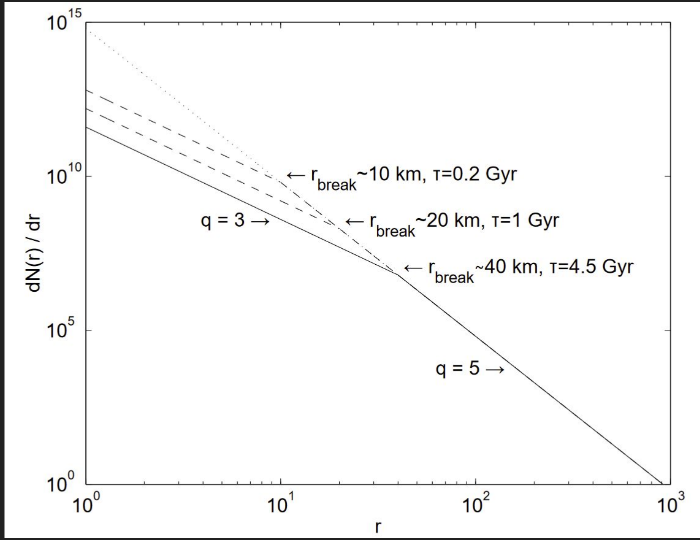
arXiv:2504.07232

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

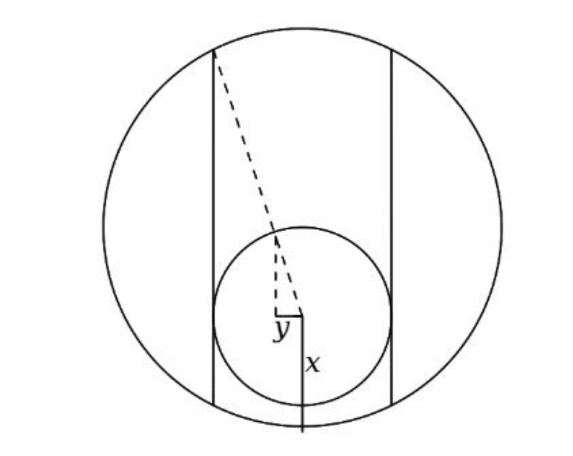
- Asteroids definitely survive until the present day
  - Dark matter should not catastrophically destroy them
- Must know (average) age of asteroid of given size
  - Myr-Gyr
  - Simulations, observations



Kuiper belt: Pan and Sari 2004

Asteroid destruction

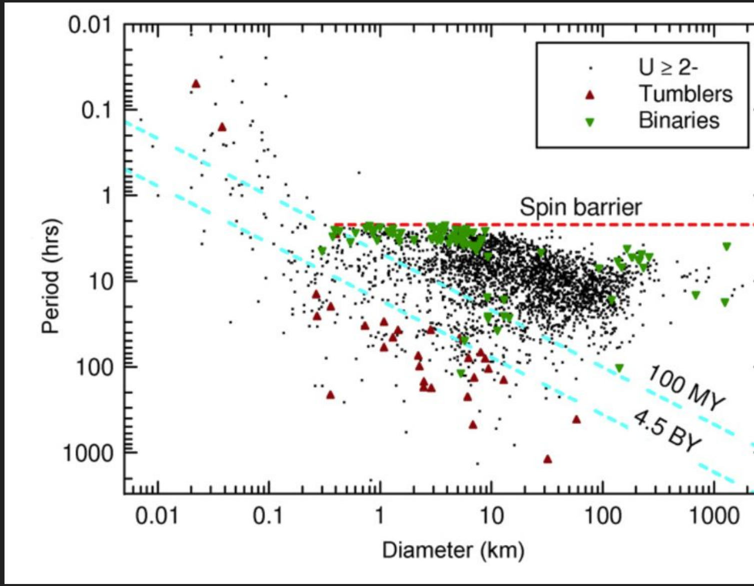
- Dark matter would plow hole through asteroid
- Estimate how much energy is deposited into the object vs. blasted out



Asteroid compositions - rubble piles

Itokawa

Fujiwara et al



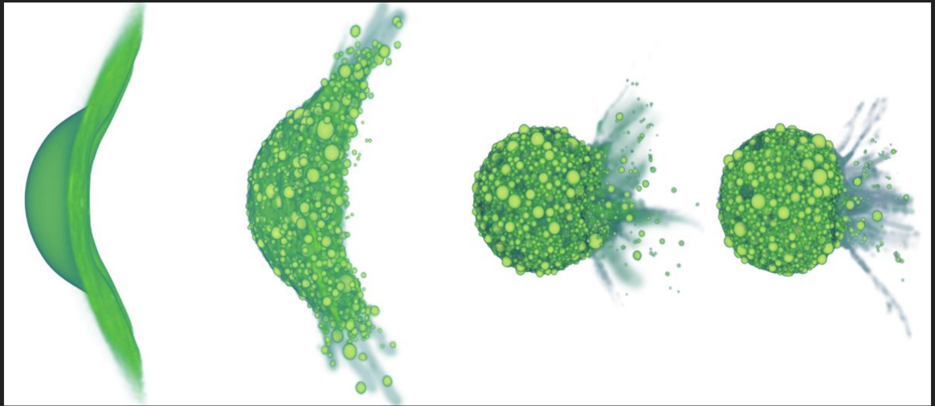
Shoemaker-
Levy 9

Warner, Harris, Pravec 2009

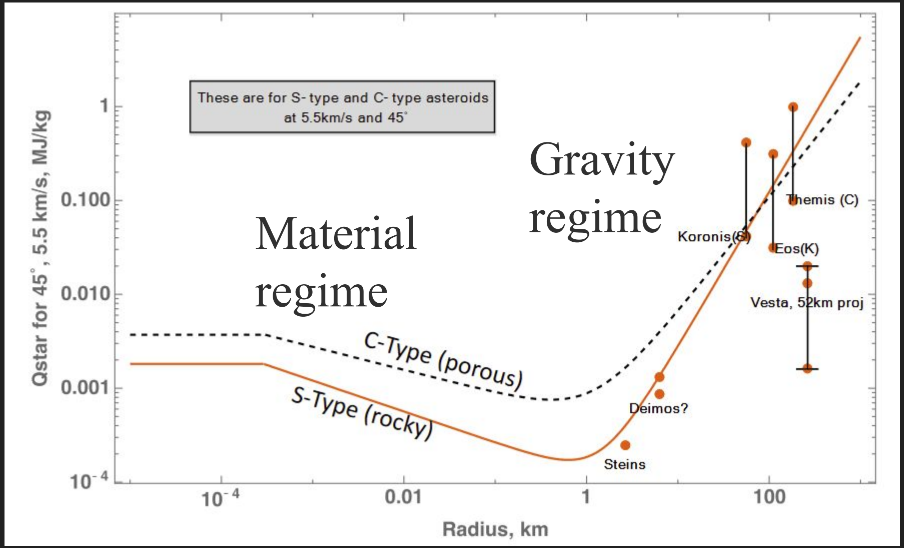
DART impact on Dimorphos

Asteroid destruction - criteria for catastrophic destruction

Q_*: kinetic energy over target mass

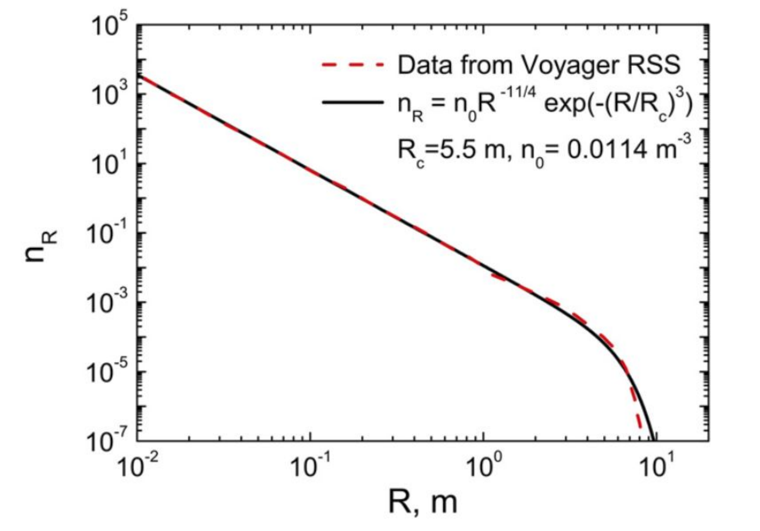


Raducan et al 2024



Holsapple and Housen 2019

Planetary ring destruction and evaporation (same story)



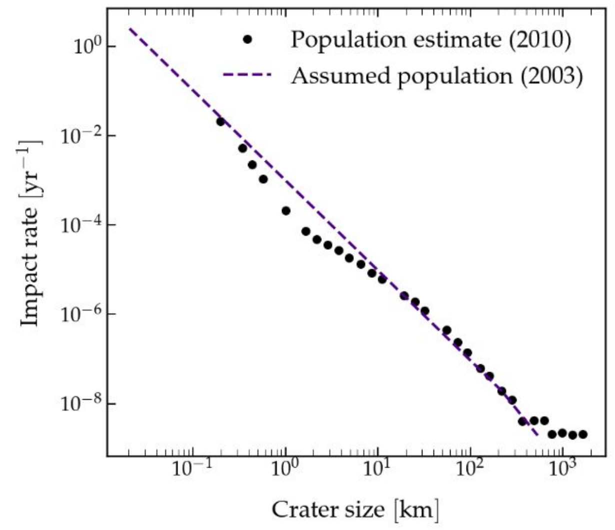
~100-400 Myr old

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!

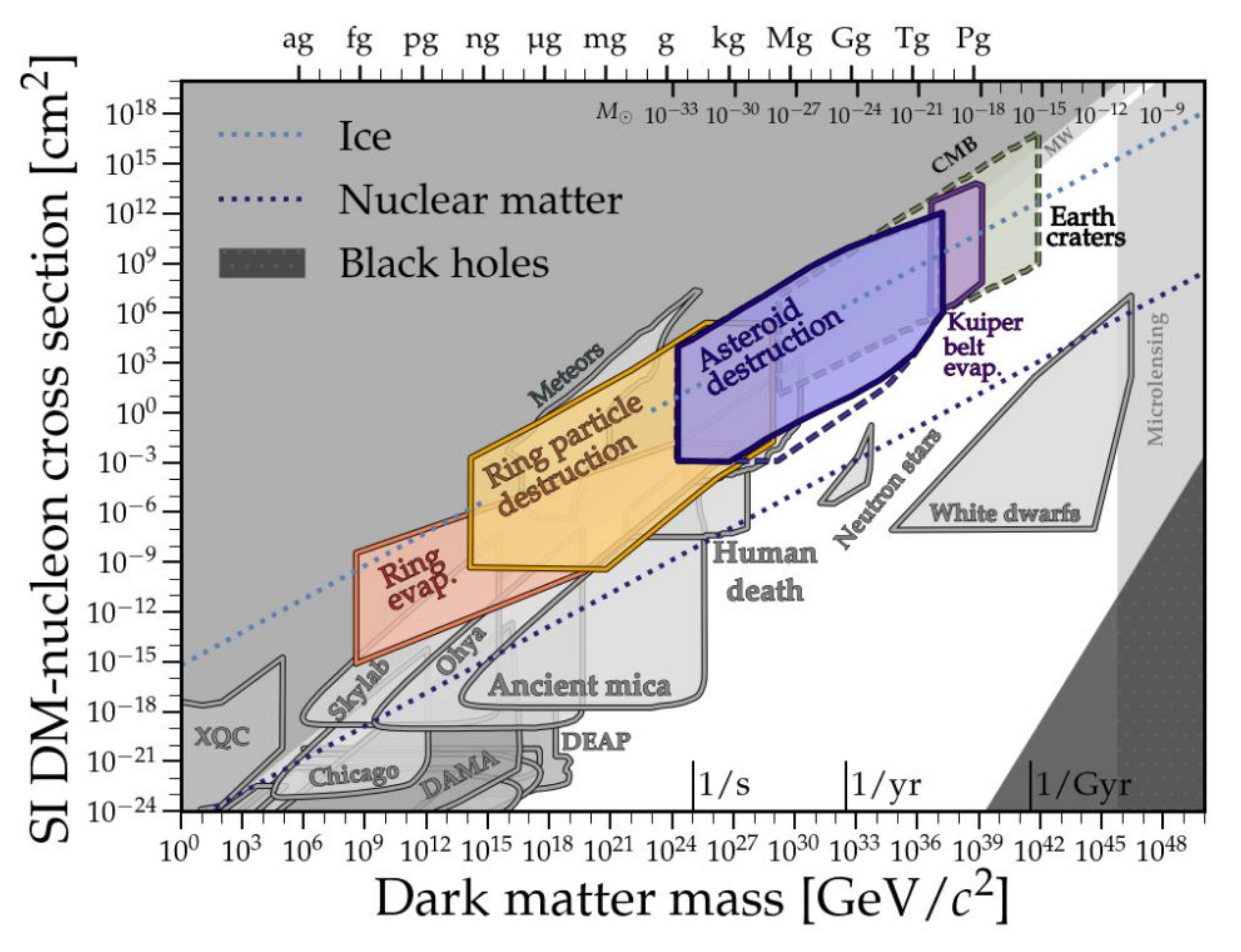
Chicxulub impact (LPI)



Craters elsewhere?

- Moon, Ganymede, Mercury are top 3 candidates
    - Large-ish
    - Geologically inactive
    - (See: Will de Rocco’s Ganymede paper)
- Forthcoming
    - Main complication: cratering simulation/estimates on these surfaces are not trivial

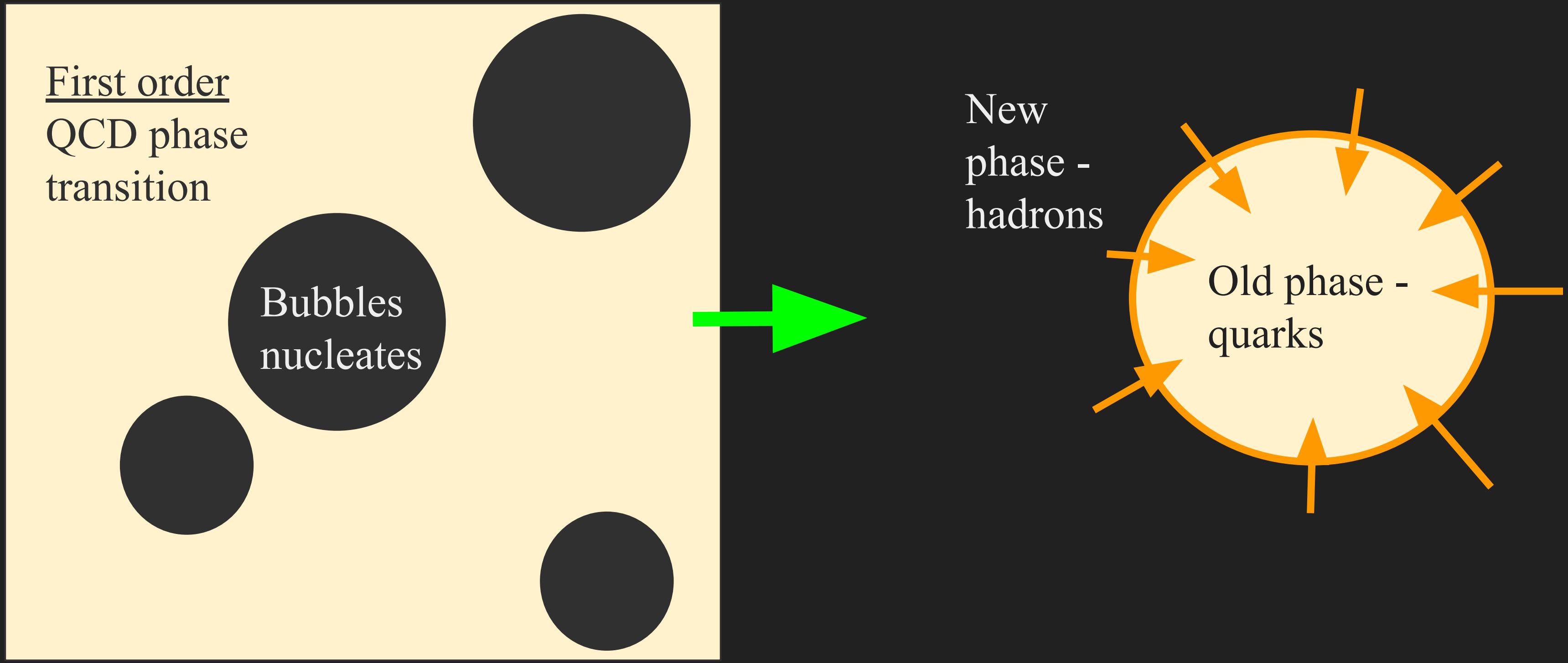
Results



ag fg pg ng µg mg g kg Mg Gg Tg Pg
$M_\odot$ 10^{-33} 10^{-30} 10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9}
Ice
Nuclear matter
Black holes
CMB
MW
Earth craters
Kuiper belt evap.
Asteroid destruction
Meteors
Ring particle destruction
Ring evap.
Neutron stars
White dwarfs
Microlensing
Human death
Ancient mica
Skylab
Ohya
XQC
DEAP
Chicago
DAMA
1/s
1/yr
1/Gyr
SI DM-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]

Finding it and forming it

The canonical example: quark nuggets



Quark nugget stability

PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

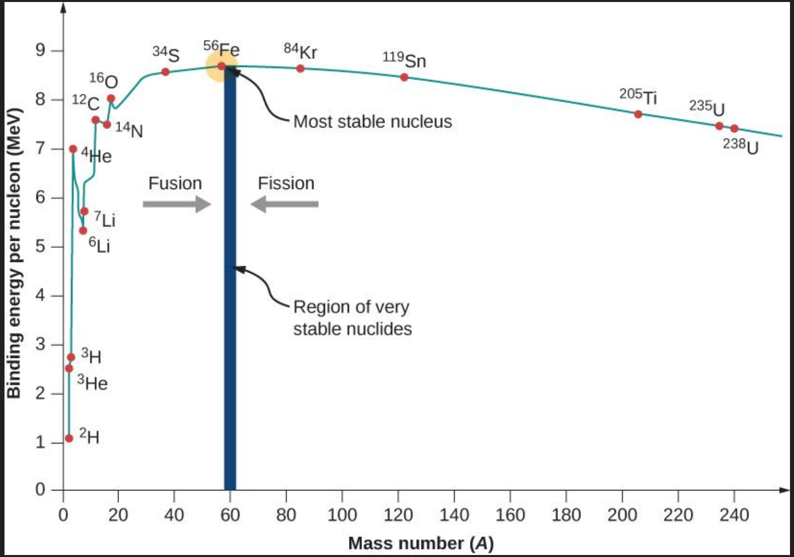
Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

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.

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

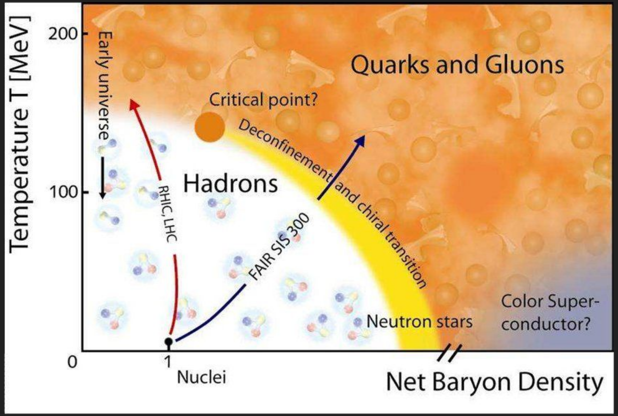
$$\tilde{\mu}/(\tfrac{1}{3}\mu+\tfrac{2}{3}2^{1/3}\mu)=[3/(1+2^{4/3})]^{3/4}\simeq 0.89 .$$

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.



Quark nugget realities

1. QCD crossover transition



Plot: Reinhardt, et al 2016

2. Evaporation

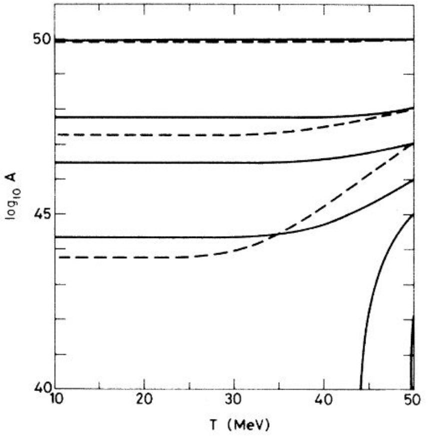
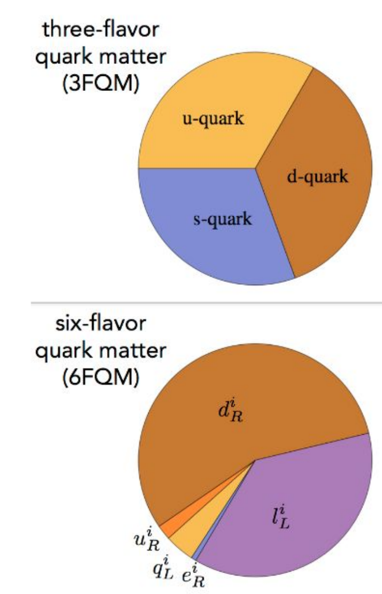


FIG. 4. The baryon number of strange nuggets as a function of the temperature of the Universe. The model for evaporation is described in Sec. IV. Nuggets of different sizes are followed from $T = 50$ MeV to evaporation effectively stops at $T \approx 20$ MeV. The solid lines are results for $\alpha_c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

Madsen, Heidelberg, Riisager 1986

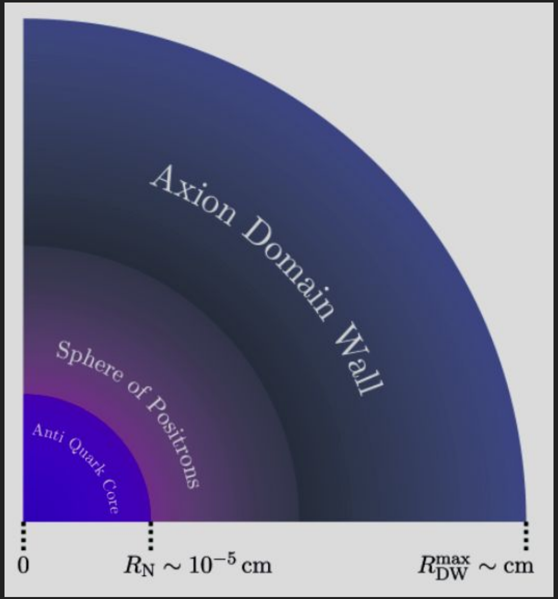
Some recent work

1. QCD before electroweak



Bai, Long 2018

2. Axion quark nuggets?



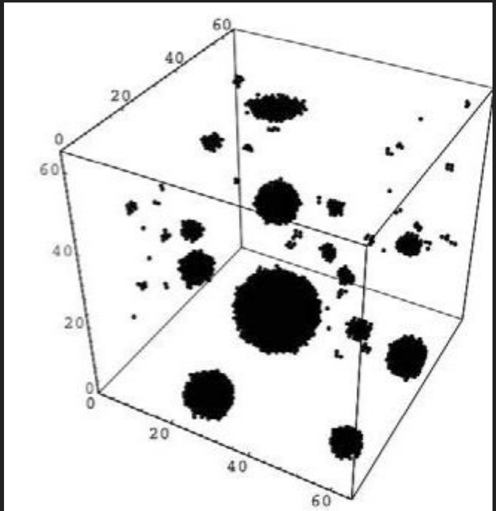
Sommer et al 2024

Generalizing: Nuggets to balls

- What is a ball?
- *Non*topological 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. Frieman[1], Graciela B. Gelmini[2], Marcelo Gleiser[3], and Edward W. Kolb[3]

Supersymmetric Q-balls as dark matter

Alexander Kusenko* and Mikhail Shaposhnikov**

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

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)

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 $\hbar = c = 1$.

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Forming Fermi balls

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

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

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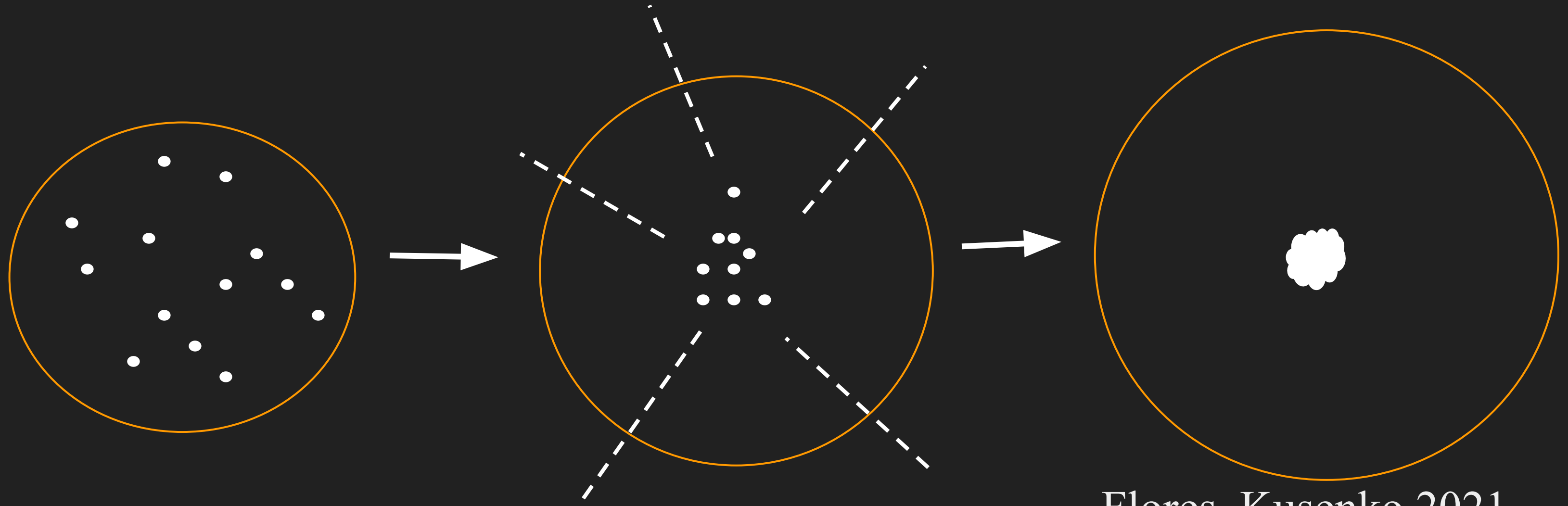
Mediates attractive Yukawa force
⇒ ‘Yukawa length scale’ is 1/scalar mass

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

$$\delta\lambda \simeq \frac{g^4}{2\pi^2}.$$

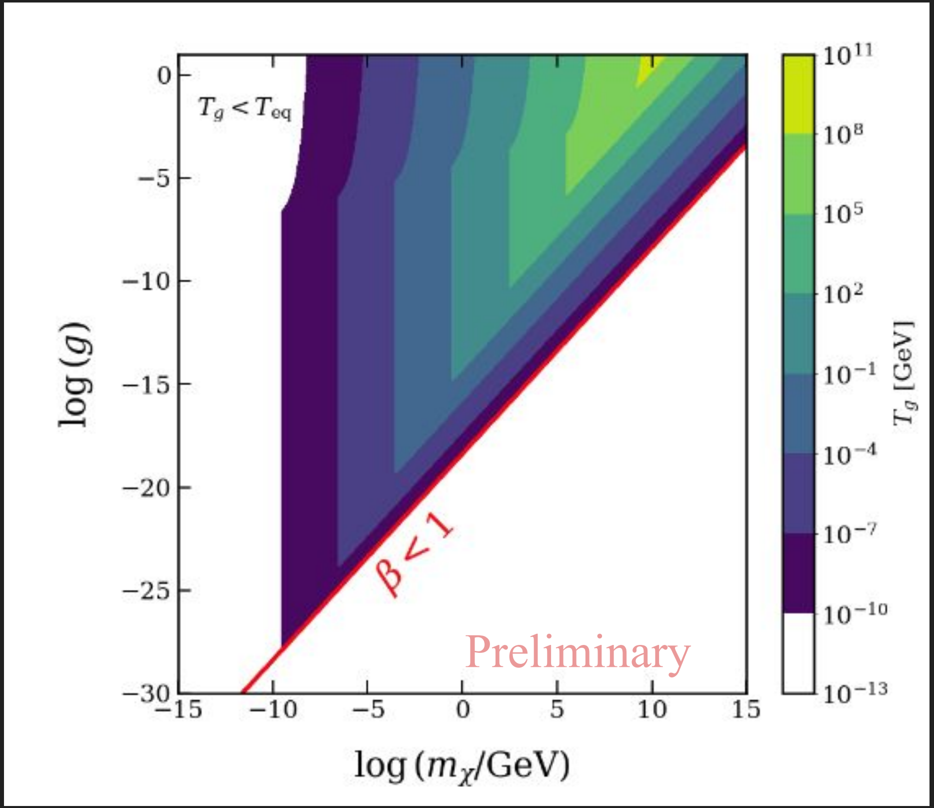
Yukawa structure formation

- Stronger-than-gravity force allows exponentially fast growth of perturbations
  - Earlier than matter-radiation equality
- Halos decouple, turn around, and virialize (as per usual)
- But, they also cool:



Flores, Kusenko 2021

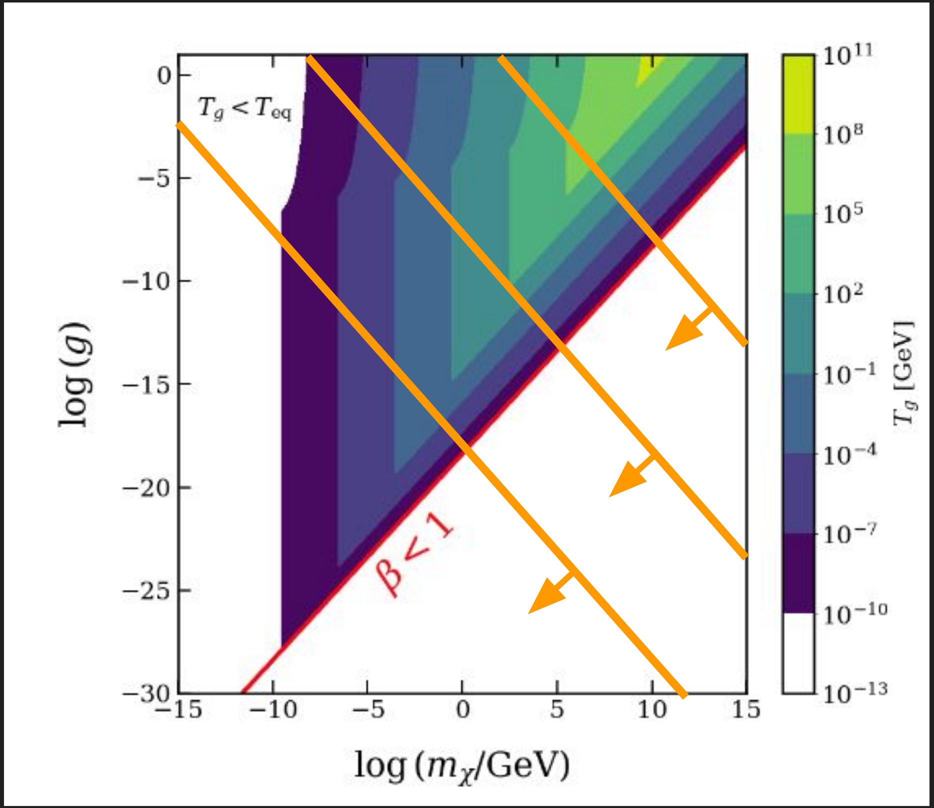
(It’s not just some finely-tuned corner of parameter space, too)



$$\beta \equiv g \frac{m_p}{m_\chi} > 1 \,,$$

$$m_p \equiv M_{\rm Planck}/\sqrt{8\pi}.$$

(It's not just some finely-tuned corner of parameter space, too)



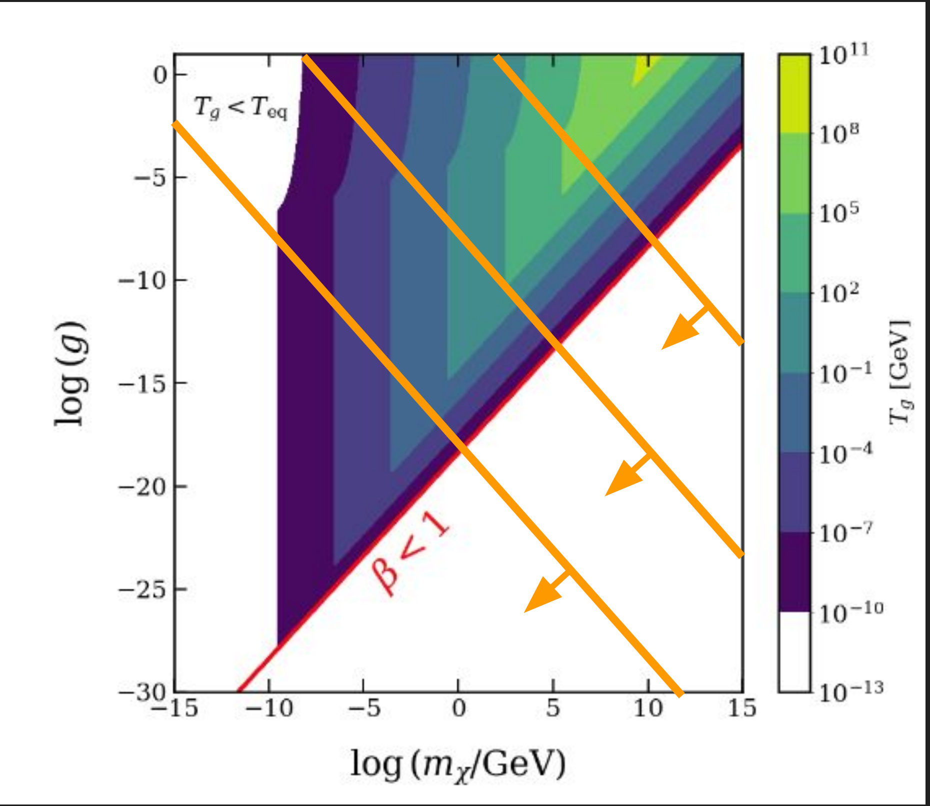
'Natural':

$$\delta m_\phi^2 \simeq \frac{g^2 m_\psi^2}{16\pi^2} \lesssim m_\phi^2$$

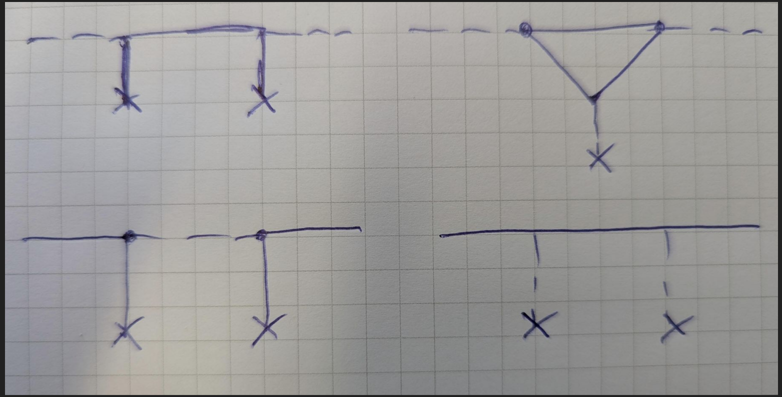
Orange lines are

$$m_\phi = \text{GeV},\ \text{eV},\ 10^{-9}\ \text{eV}$$

(It’s not just some finely-tuned corner of parameter space, too)

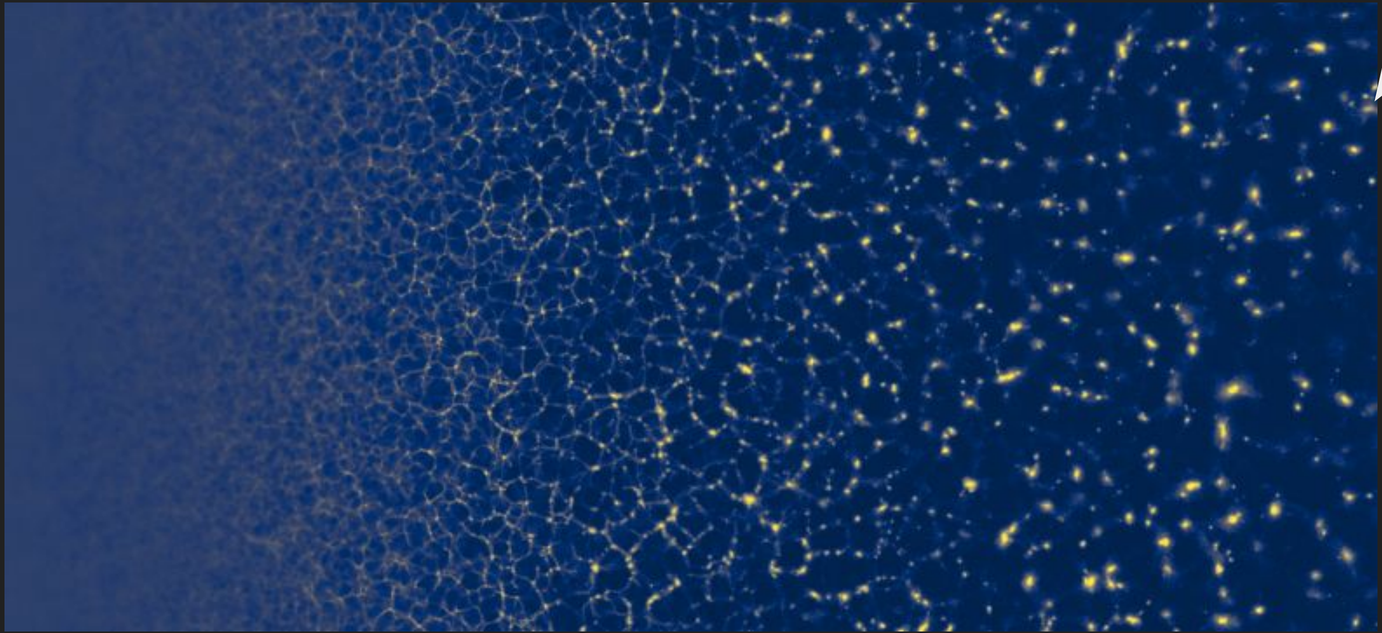


Ongoing work: finite temperature/density corrections (with Hannah Banks, Melissa Diamond, Aaron Vincent)



Finally, some simulations

Nonlinear, screening stuff starts



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

Two possibilities for the structures formed

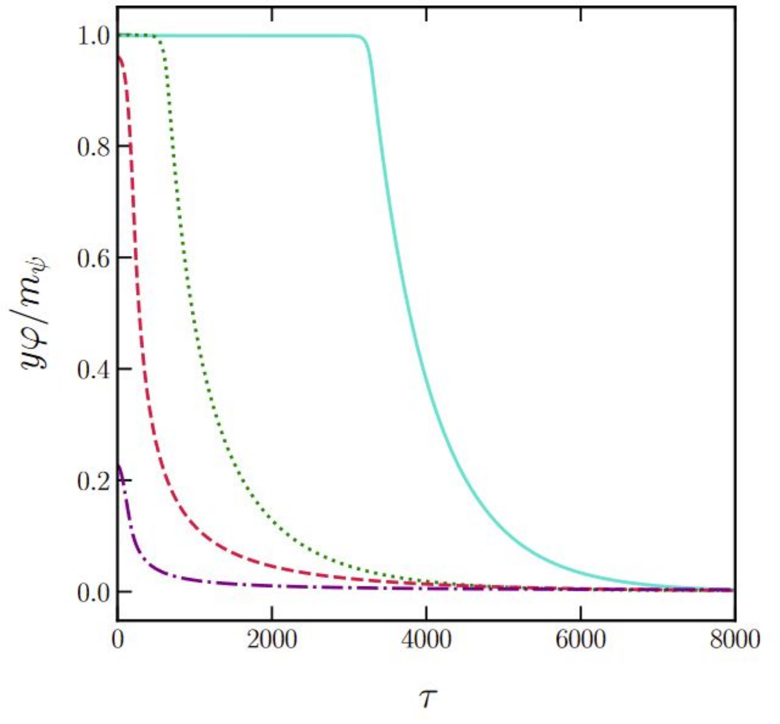
Asymmetry, processed already:
(2411.17074, refs therein)

No asymmetry: (forthcoming: ZCSP, Lu, Kusenko)

Two possibilities for the structures formed

Asymmetry, processed already:
(2411.17074, refs therein)

- Balls are completely stable at degeneracy pressure
- May reach maximum size and form black hole
  - Only when phi^4 is included
- Forces between balls are highly screened

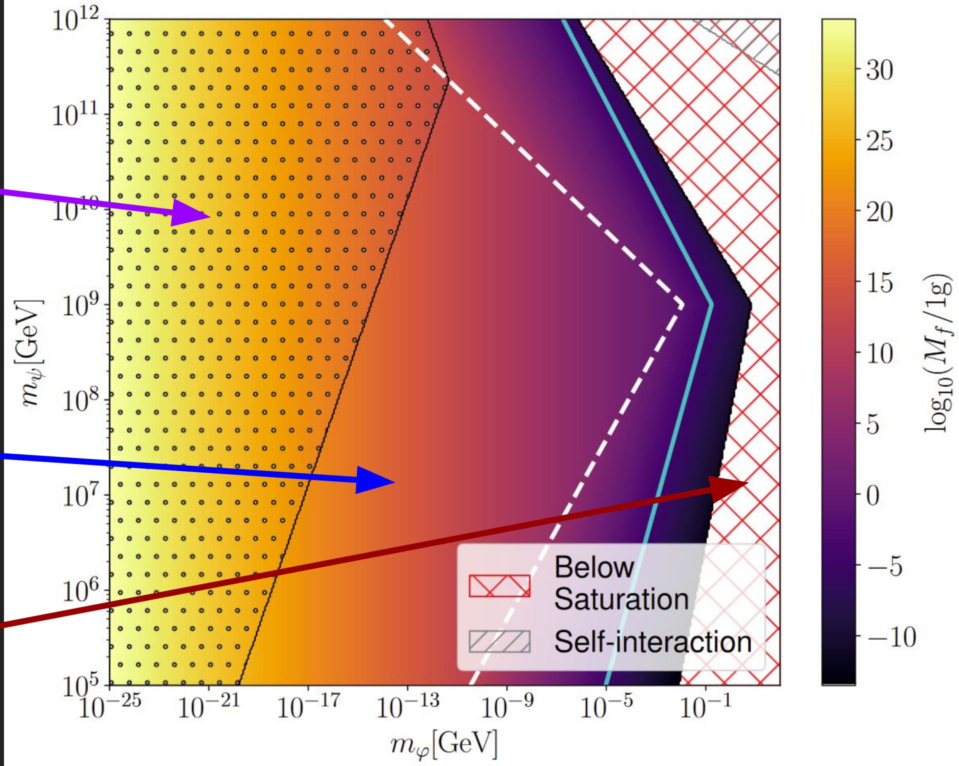


~New primordial black hole formation mechanism

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)

Two possibilities for the structures formed (preliminary)

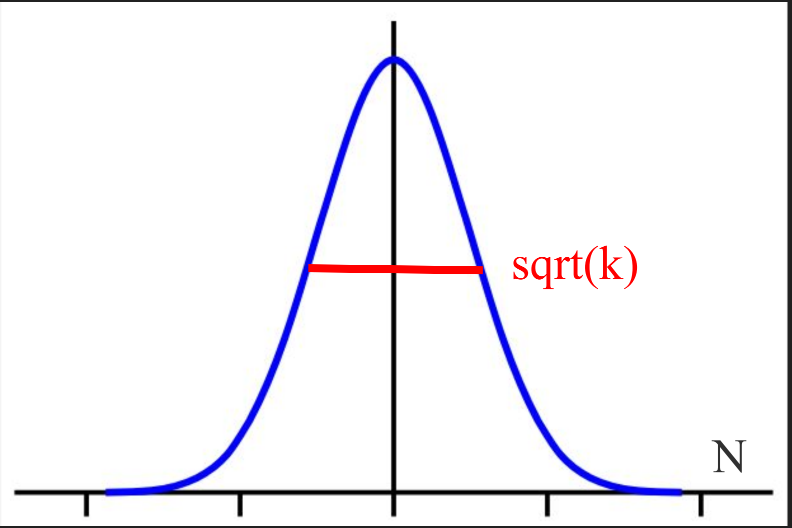
No asymmetry: (forthcoming: ZCSP, Lu, Kusenko)

N

Two possibilities for the structures formed (preliminary)

No asymmetry: (forthcoming: ZCSP, Lu, Kusenko)

- Annihilation provides pressure to counteract cooling
  - Equilibrium is maintained as ‘fuel’ runs out
  - Significant parameter space without catastrophic supernova/unbinding
- Remnants
  - Distribution of Fermi- and anti Fermi-balls
  - ~random walk
  - (this is why I needed the constraint plot…!)



Conclusions

- Macroscopic dark matter: palatable to the PBH crowd??
- Detection:
  - Huge, unconstrained parameter space
  - Can play with fun astrophysical systems
- Formation:
  - Composite states in dark sectors?
  - Not actually that ‘difficult’ to do
  - Complicated but rich pheno
  - (could form PBHs too)

Conclusions

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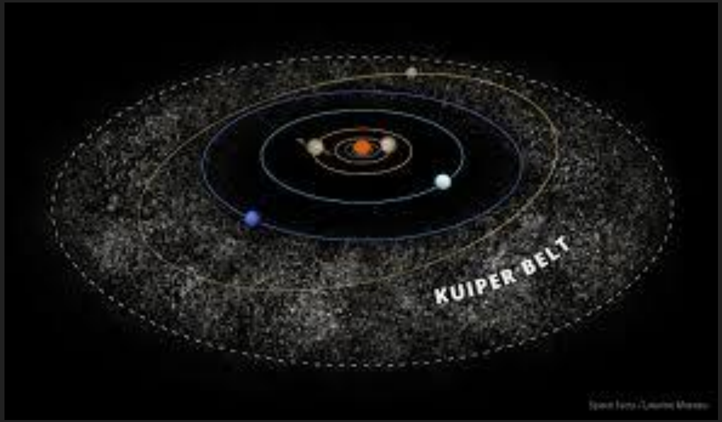
- Formation:
  - Composite states in dark sectors?
  - Not actually that ‘difficult’ to do
  - Complicated but rich pheno
  - (could form PBHs too)
- Not very many people working on this! Let’s do something together…

Thanks!

Bonus

Asteroid ‘evaporation’

- Escape velocity is only √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 √number of collisions



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

The fate of (these) Fermi balls

Gresham, Lou, Zurek 2017

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

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

Sub-saturation

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

Saturation

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

The fate of (these) Fermi balls

Gresham, Lou, Zurek 2017

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

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

  Sub-saturation

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

  Saturation

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

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

Re-examine the dark matter model

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

Potential term:

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

$\Rightarrow$ new repulsive force

($\Rightarrow$ new free parameter λ …)

New Fermi ball equations of state

Drastic effect:

Repulsive force can ‘kick in’ sooner than degeneracy pressure

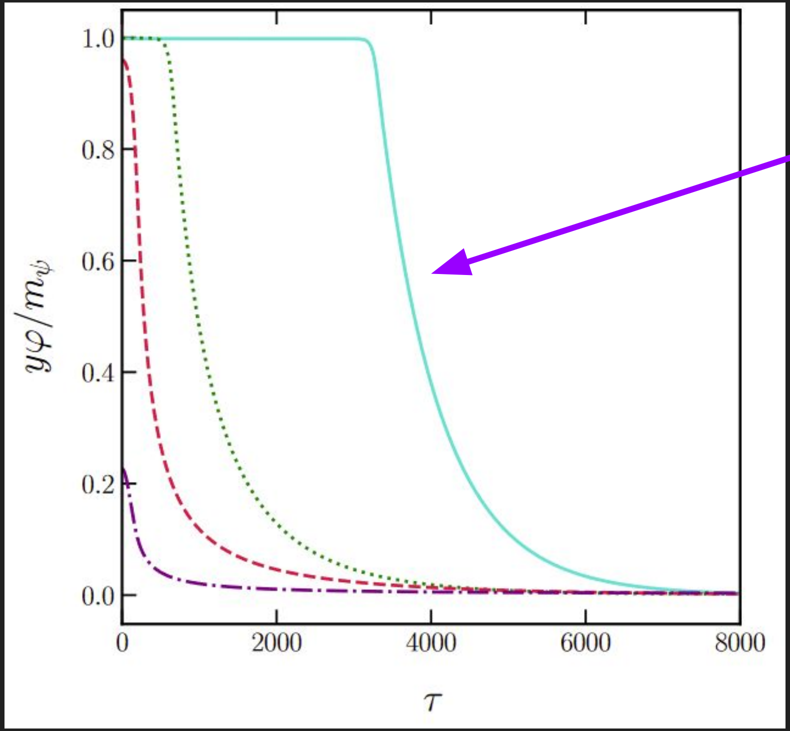
- Radius $\propto N^{1/3}$
  Mass $\propto N$
  - (more technically…they reach ‘saturation’ almost immediately because the effective scalar mass is changed)
- Adding more fermions increases mass more quickly than radius

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

Fermi ball - Fermi ball interactions

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

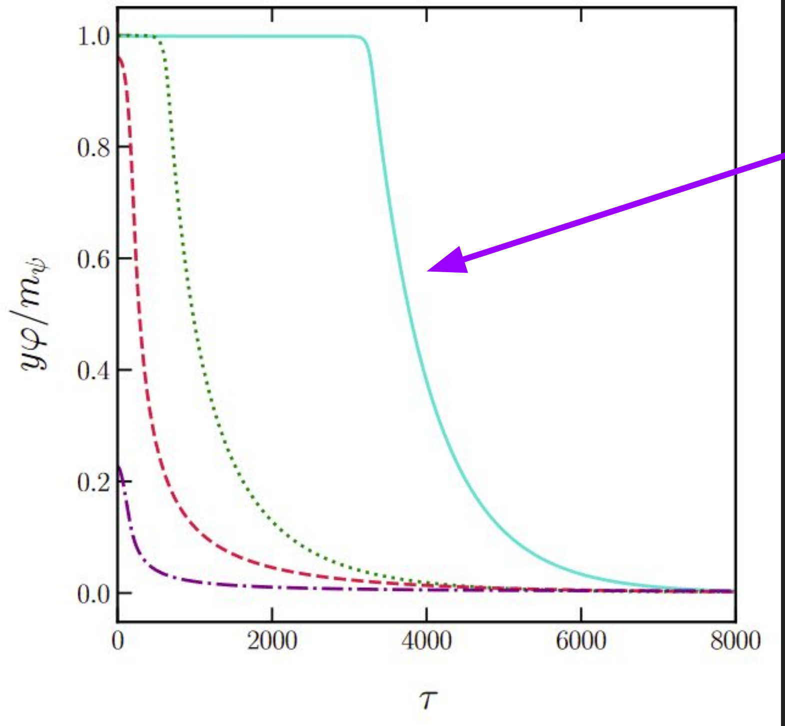
Fermi ball - Fermi ball interactions



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

Unreliable numerically…

Fermi ball - Fermi ball interactions

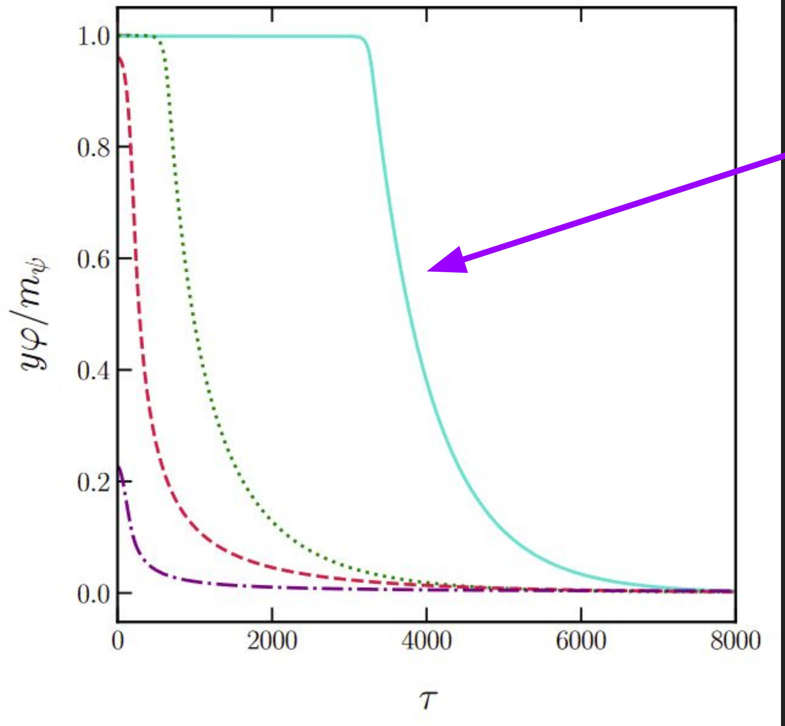


$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \lambda\varphi^3 = 0$$

Needed for interaction energy:

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

Fermi ball - Fermi ball interactions



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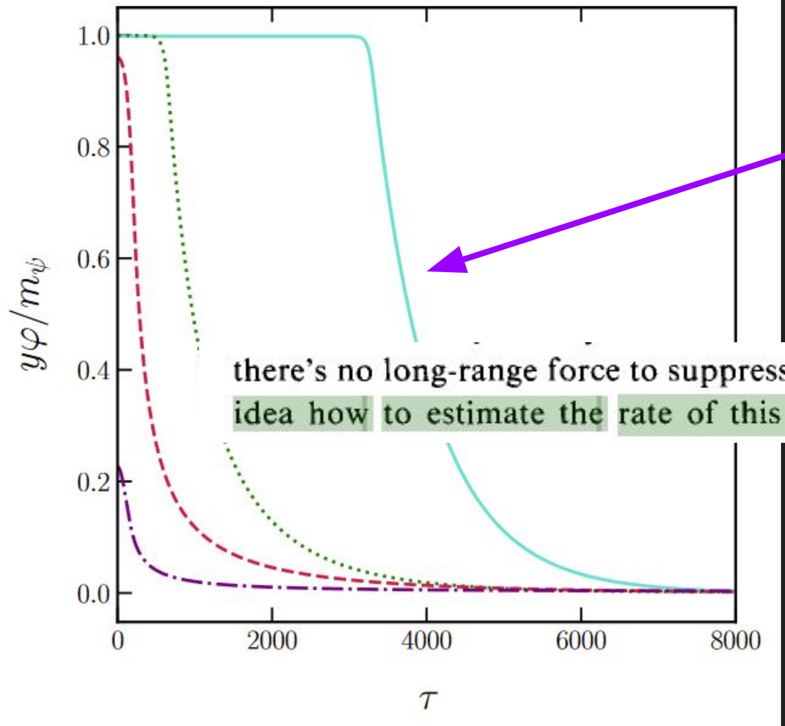

$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \lambda\varphi^3 = 0$$

Needed for interaction energy:

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

Can only estimate upper and lower bounds:

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

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