Supermassive Black Holes from Ultra-Strongly Self-Interacting Dark Matter

ApJ **804**, 131 (2015), arXiv:1501.00017

(with David Spergel and Paul Steinhardt)

Jason Pollack

Workshop on Astrophysics of Dark Matter
Kavli IPMU
October 16, 2015

Outline

I. High-redshift quasars: observations and challenges
II. Ultra-Strongly Self-Interacting Dark Matter
III. Gravothermal Collapse: intuition and physics
IV. SMBHs from uSIDM?
V. Prospects and Future Work

I. High-redshift quasars

- Disclaimer: I am not an expert
- I will try to convince you that there is room for non-standard physics, and am going to highlight the unresolved problems with the standard mechanism to do so.
- As always, it's most likely that the actual resolution will be a better understanding of conventional physics, but it's interesting to speculate…

Observations

- We observe quasars at high redshift ($z \gtrsim 6$–7), with number density $\sim 1\ \mathrm{Gpc}^{-3}$ (e.g. Haiman 2013)
- Interpret as actively accreting SMBHs, $\gtrsim 10^9 M_\odot$
- E.g. ULAS J1120+0641 (Mortlock *et al.* 2011)
  mass $2.0^{+1.5}_{-0.7} \times 10^9\ M_\odot$, $z = 7.085$
- This is only 747 Myr after the Big Bang (using Planck cosmology)! Can we account for SMBHs of this size at this time in the standard picture?

Eddington-limited accretion

- Usual assumption: SMBHs grow by Eddington-limited gas accretion
- Gravitational force balances radiation pressure → exponential growth, with *e*-folding time (Salpeter 1964)

$$t_{\rm Sal} = \frac{\epsilon_r \sigma_T c}{4\pi G m_p} \approx \left(\frac{\epsilon_r}{0.1}\right) 45.1 \ {\rm Myr}$$

(ϵ_r= radiative efficiency—will come back to this later)

- To get to ULAS J1120+0641, need seed black hole mass $\sim 10^3 M_\odot$ by $z \sim 30$
- In general, need to form $10^{2-3} M_\odot$ seeds soon after beginning of baryonic structure formation, then continuous Eddington-limited accretion for $\sim 800 \ {\rm Myr}$

Difficulties in the standard picture

- Can (just) form the required amount of high-redshift quasars within $\Lambda\mathrm{CDM}$ (e.g. Li et al 2007), *if*:
- Baryonic halos cool sufficiently quickly
- Pop III stars have correct mass to form BHs (no fragmentation)
- Early BH seeds accrete gas continuously (no significant gas loss from photoevacuation)
- Central BHs in merging halos merge efficiently
- And…

The radiative efficiency

- Recall that t_{Sal} depends linearly on ϵ_r, the radiative efficiency → resulting SMBH mass is exponentially sensitive to this value!
- ϵ_r depends on black hole spin: from $1-\sqrt{8/9} \approx 0.057$ to $1-\sqrt{1/3} \approx 0.42$ as spin increases from 0 to maximal (e.g. Shapiro 2005)
- If BH is accreting gas, expect it to spin up. So must arrange some way (e.g. frequent mergers) to hold down the value of ϵ_r.

Help from dark matter?

- To the extent that all of these details haven’t yet been worked out, there’s still room for new physics.
- Compared to the standard story, we’d like to provide either more massive seeds or faster SMBH growth—either way, effectively super-Eddington accretion
- To do that, it helps if we use something that doesn’t radiate…

II. Ultra-Strongly Self-Interacting Dark Matter

- Collisionless DM won't help—there isn't enough of it around a central black hole. We need to endow the dark matter with a short-range interaction to allow for heat/mass flow to the center of the halo.
- To move enough material to the center, we'll need lots of scatterings per Hubble time. Expect $\sigma \gg 1 \ \mathrm{cm}^2/\mathrm{g}$. Not just SIDM but uSIDM.
- We can argue over the exact exclusion, but constraints from the Bullet Cluster, etc. definitely rule out a large enough value of σ for our purposes *for the dark matter as a whole.*

Limits on the uSIDM cross-section

- However, there's no constraint if only some fraction $f \lesssim 0.1$ of the dark matter is self-interacting. (Adding a new free parameter, but maybe not a physically unreasonable one.)
- Example: Randall et al 2008 constraints from Bullet Cluster. Find mass-to-light ratio of bullet relative to main cluster is 0.84 ± 0.07. Use assumption that bullet has lost less than 1-.84-.07=23% of its mass to constrain σ. But for f<0.07, can't tell even when if you've lost *all* of the SIDM in the bullet!
- c.f. Boddy et al 2014: hidden sector w/ subdominant uSIDM component. Can get up to $\sigma \sim 10^{11}\ \mathrm{cm^2/g}$. Also some models w/ dominant (standard) SIDM component + subdominant USIDM, w/ $\sigma \simeq 10^5 - 10^7\ \mathrm{cm^2/g}$. Very natural from a particle physics perspective.

III. Gravothermal Collapse

- Recall that gravitationally bound systems have negative specific heat. (Planets speed up as orbits shrink; virial theorem gives $E = -T$)
- Consider inner gravitationally bound system and outer system with positive specific heat (e.g. a globular cluster). Evolution towards equilibrium moves both mass and heat outward. Possibility of a runaway collapse of inner system: “gravothermal catastrophe” (Lynden-Bell and Wood 1968)
- For GR systems, runaway collapse leads to black hole formation via radial instability.

The gravothermal fluid approximation

- To simulate on a computer, coarse-grain + track thermodynamic quantities: $M,\ \rho,\ \nu,\ L$
- Treat DM as ideal gas of point particles in hydrostatic equilibrium, w/ hard-sphere scattering
- Need an expression for the thermal conductivity κ to relate L to ν. Have two length scales: mean free path and Jeans length. Combine in reciprocal:

$$\frac{L}{4\pi r^2} = -\frac{3}{2} ab\nu\sigma \left[a\sigma^2 + \frac{b}{C}\frac{4\pi G}{\rho\nu^2} \right]^{-1} \frac{\partial \nu^2}{\partial r}$$

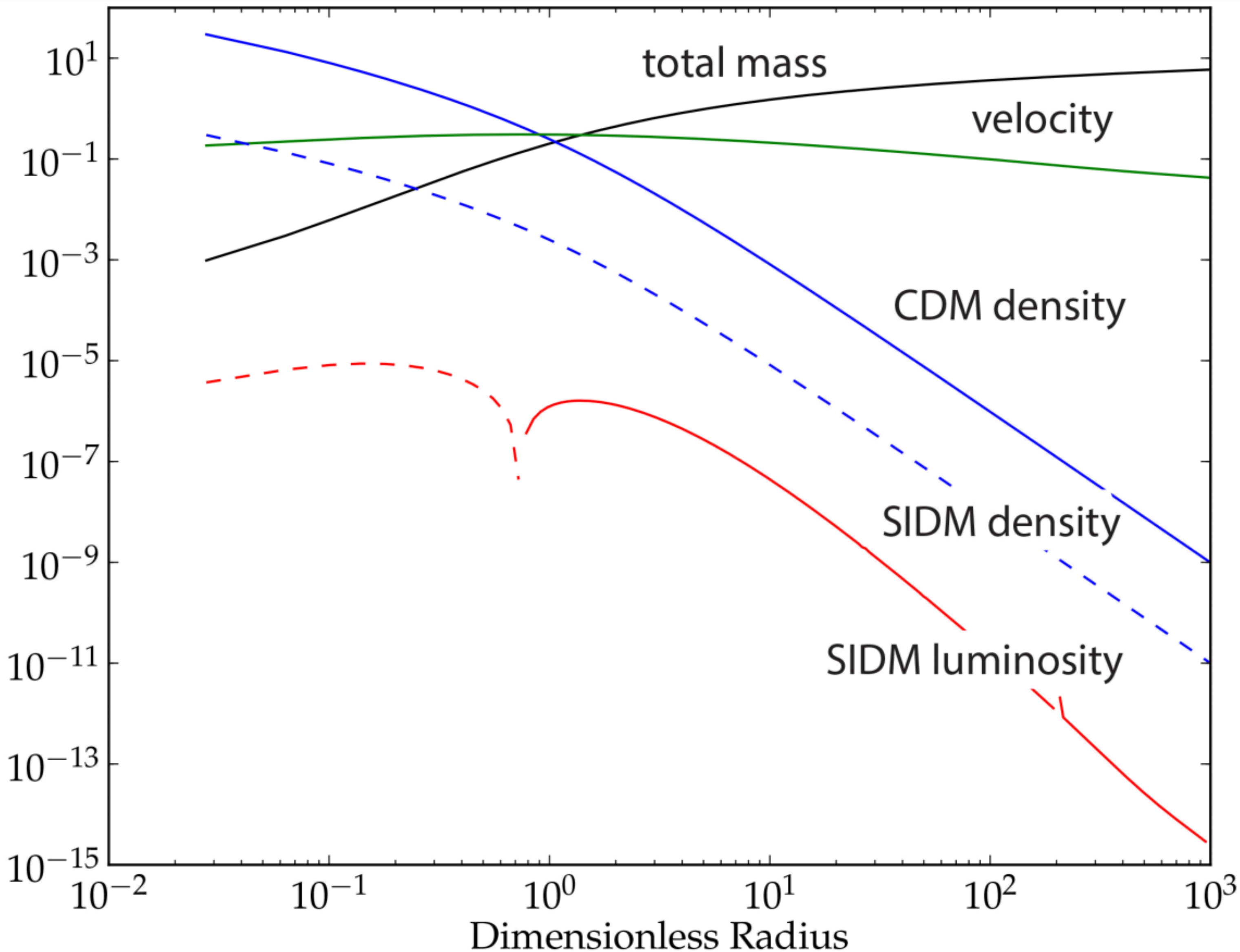
$a = \sqrt{16/\pi}$, $b = 25\sqrt{\pi}/32$ from hard-sphere scattering (transport theory, etc.)

$C \approx 290/385$ from f=1 SIDM N-body simulations (Koda and Shapiro 2011)

Solving the gravothermal fluid equations

- Assume initial NFW profile for both main DM and uSIDM component (i.e. halo formation time is less than characteristic scattering time). Simulate isolated, spherically symmetric halo.
- What if you don't like NFW? We'll see that, as expected for SIDM, initial cusp in central region is evacuated to form a core in ~tens of relaxation times, well before collapse. So expect all non-pathological profiles (cuspy or cored) to have similar qualitative behavior.
- Work with dimensionless quantities: scale out by radius $R_0 = r_s$, mass $M_0 = 4\pi R_0^3 \rho_s$, timescale $t_{r,c}(0) = 1/(f a \rho_s \nu_s \sigma)$ (characteristic relaxation time)

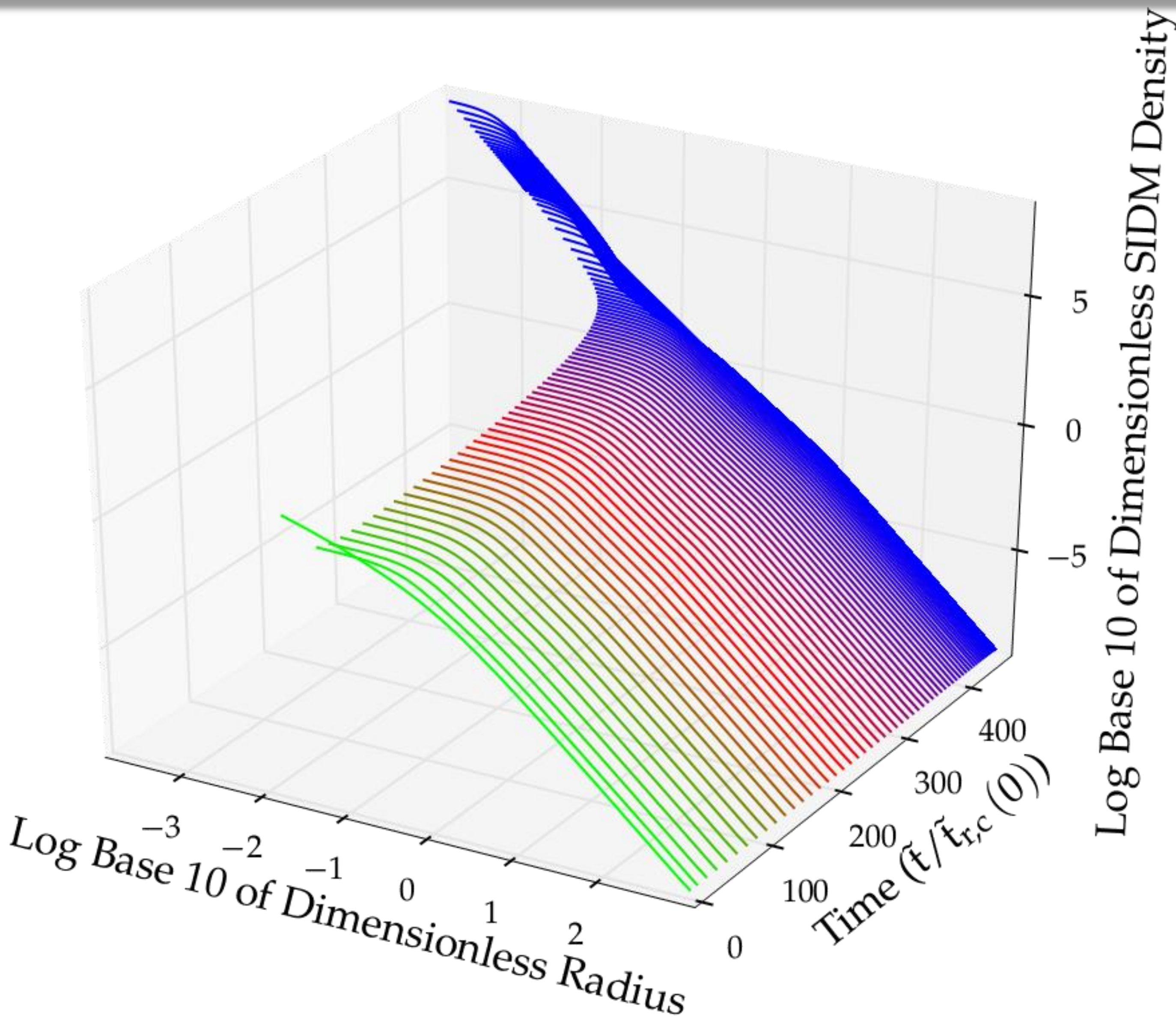
Initial Profile (f=0.01)



Initial Profile (f=0.01)

- Key thing to notice: SIDM luminosity is negative (i.e. outward-pointing) inside the characteristic radius. This indicates mass is flowing out of the central region → core formation.
- Once cusp evacuated, core forms + luminosity becomes positive everywhere, i.e. mass only flows inwards, central density can only increase. Long period of self-similar evolution (c.f. Balberg et al 2002) when core is still in the lmfp regime: core gradually shrinks and increases in density over ~hundreds of relaxation times.

Collapse

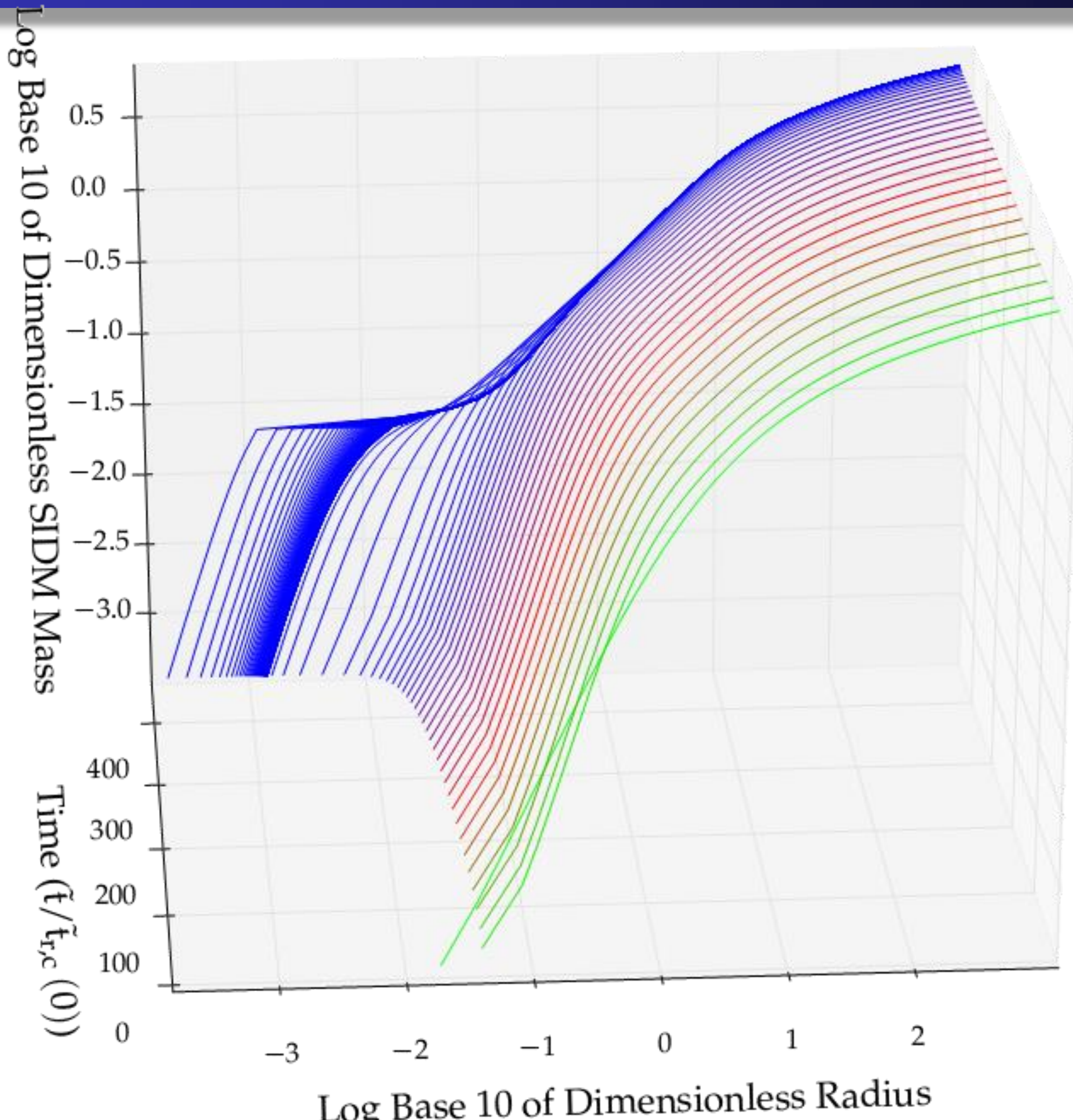


Log Base 10 of Dimensionless SIDM Density
5
0
−5
400
300
200
100
0
Time $(\tilde{t}/\tilde{t}_{r,c}(0))$
−3
−2
−1
0
1
2
Log Base 10 of Dimensionless Radius

Collapse

- When core enters smfp regime, self-similarity is broken: split into smfp inner core and lmfp outer core. Typical interaction in inner core now results in both uSIDM particles remaining within it, so evaporation can only occur from surface → mass loss effectively stops, extremely rapid collapse.
- Because of breakdown of self-similarity, core density becomes singular/fluid approximation breaks down with finite mass still remaining in core. Form central black hole comprising entire inner core (direct collapse + efficient Bondi accretion)

Core Mass



Log Base 10 of Dimensionless SIDM Mass
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
400
300
200
100
0
Time ($\tilde{t}/\tilde{t}_{r,c}(0)$)
−3
−2
−1
0
1
2
Log Base 10 of Dimensionless Radius

IV. Supermassive Black Holes from USIDM

- We find that our isolated NFW halo undergoes gravothermal collapse of its uSIDM component in a time $455.65 t_{r,c}(0)$ to form a black hole of mass $M_{BH} \equiv 0.025 f M_0$.
- To express these quantities in physical units, insert values for uSIDM parameters $\{\sigma, f\}$ and halo parameters $\{M_\Delta, c, z\}$ (virial mass, concentration, redshift of virialization) into expressions for $t_{r,c}(0), M_0$
- We care about the parameter space where halos can form high-redshift SMBHs by a combination of gravothermal collapse + accretion of baryons.

Halo Parameters

- We care about constraining DM properties, so the halo information is nuisance parameters
- In principle, to do cosmology we should specify each of these as functions of mass and redshift (e.g. halo mass function)
- But this is too hard, so we just picked a plausible set of parameter values.
- Focus on reproducing ULAS J1120+0641

  ($M_{SMBH} \approx 2 \times 10^9 M_\odot$ at $z_{obs} = 7.085$)

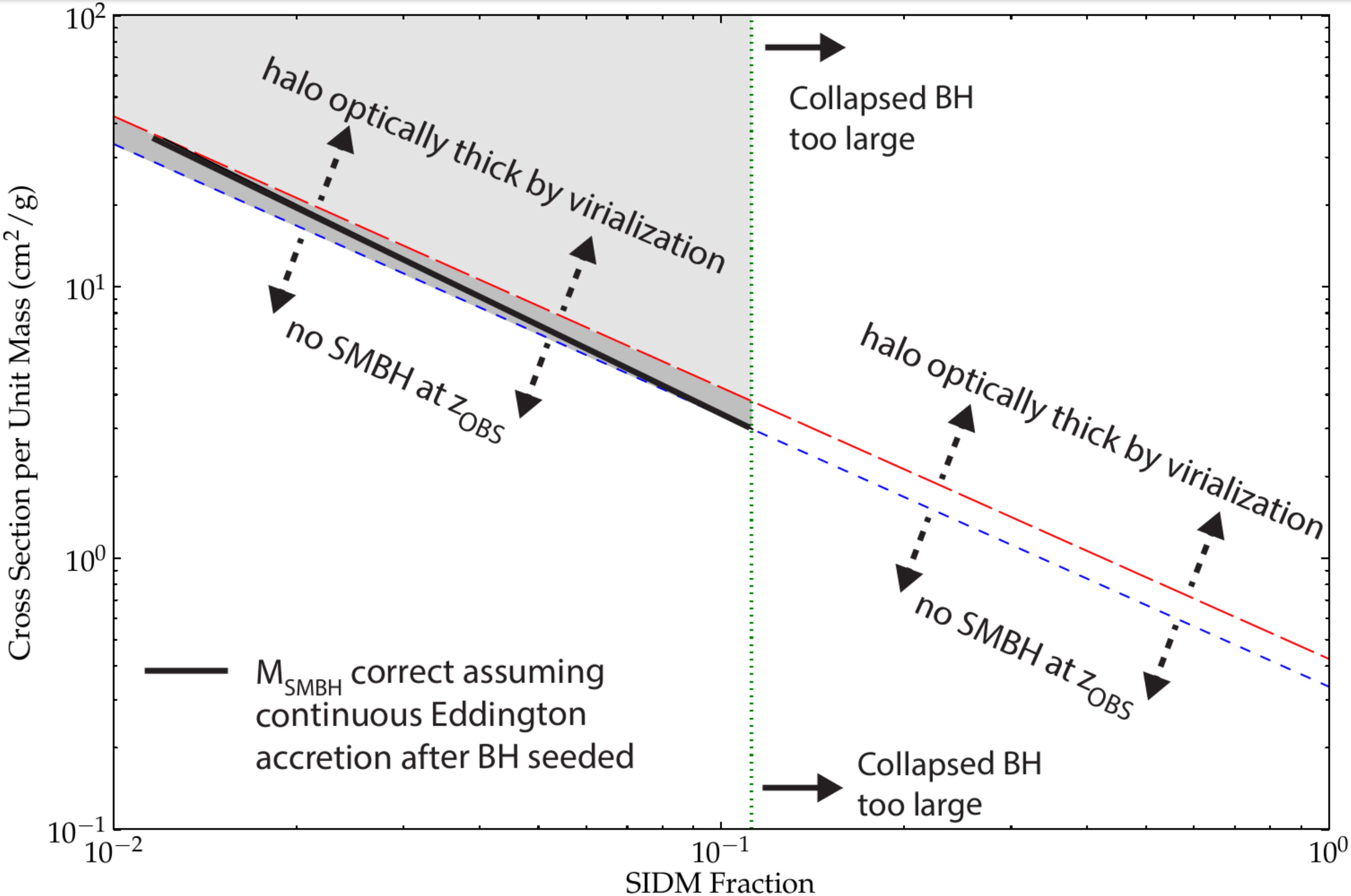
The Model Halo

- Halo mass function is steeply decreasing at large redshifts: take smallest reasonable halo ($M_\Delta = 10^{12} M_\odot$)
- Concentration (recall $r_\Delta \equiv c r_s$): take $c = 9$

  (based on halo catalogs from FIRE simulation)
- Redshift of formation: take $z = 15$ (easy to adjust results to change this, in principle should use IMF)
- Free parameters: size of seed produced (directly sets f), amount of baryonic accretion

  (If assuming continuous Eddington accretion, knowing this reduces $\{\sigma, f\}$ choice to 1d parameter space)

SMBH Parameter Space



Constraints

- SMBH formation by $z_{obs} = 7.085$: upper bound on $t_{r,c}(0)$ → lower bound on σf , here $\sigma f \geq 0.336 \text{ cm}^2/\text{g}$
- Seed BH mass can't exceed observed SMBH mass: concentration-dependent upper bound on f alone, here $f \leq 0.112$
- Recall validity of initial NFW profile requires relaxation time long compared to halo collapse time, i.e. halo is optically thin at r_s . Gives upper bound on σf, here $\sigma f \leq 0.425 \text{ cm}^2/\text{g}$. **Still expect collapse to seed above this**, but results for collapse time and mass might not be valid.

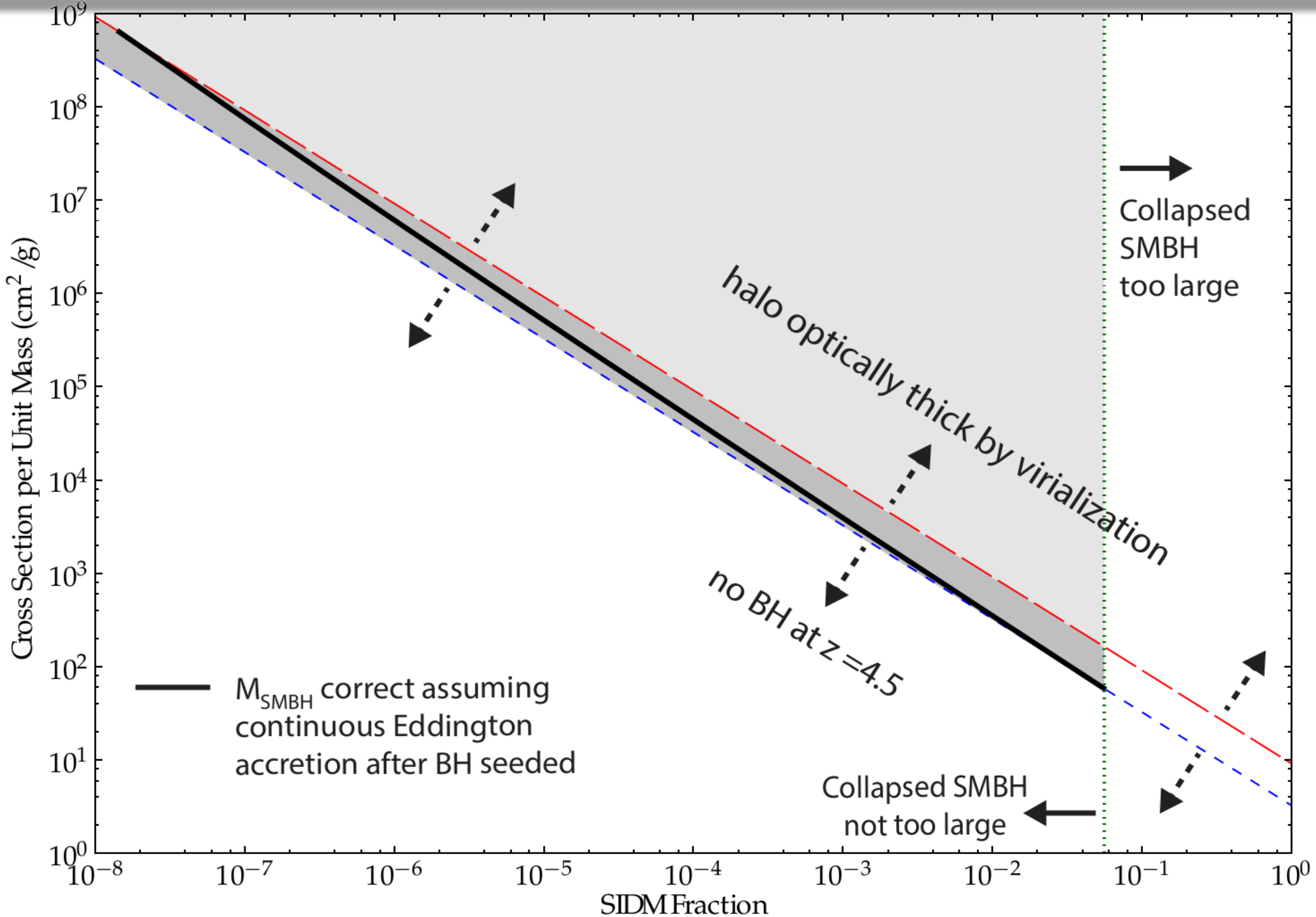
Solving Too Big to Fail with uSIDM?

- If all you have is a hammer…
- We have a novel (to us) way of making black holes. What can we do with them? (M–σ relation?)
- Merging BH binaries emit gravitational waves anisotropically—can receive impulsive kick, expel baryons from center (e.g. Boylan-Kolchin et al 2004)
- For this to have any chance of working, need seed BHs to form ubiquitously in DSph progenitors before mergers. BH formation time shrinks faster than Hubble with z, so this is feasible for halos forming before a (mass-dependent) critical redshift.

TBTF Model Halo

- Repeat the exercise above, now for halo half the size of typical MW dwarf (since must undergo major merger for BH binary). Based off Boylan-Kolchin et al 2012, take $M_\Delta = 10^8 M_\odot$, $z_{obs} = 4.5$. Try for $M_{SMBH} = 10^5 M_\odot$.
- Relaxation time scales as $M_\Delta^{-1/3}$, but ~twice as much time to collapse as SMBH case, so lower bound on σf scaled by $10^{4/3}/2 \approx 10$. Parameter space that solves TBTF is subset of parameter space producing high-z quasars.

TBTF Parameter Space



Prospects and Future Work

- More cosmological information
- Non-isolated halos
- Merger trees
- N-body simulations (interested experts wanted!)
- …
- Other examples of new physics on small length scales? (c.f. galactic center stuff…)

Conclusions

- As we start to consider non-minimal DM models, we should think about multi-component DM/fractional SIDM.
- Constraints on the SIDM cross section fail to apply for $f \lesssim 0.1$. Hence room for extremely large cross sections: uSIDM.
- Just like SIDM/WDM can be distinguished from CDM on small scales, uSIDM can have observational consequences in the very central region of haloes.
- Rich phenomenology appears when haloes evolve for very many interaction times. Gravothermal collapse could just be the tip of the iceberg…

Gravothermal Fluid Equations

$$\frac{\partial M}{\partial r} = 4\pi r^2 \left(\rho^{int} + \rho^{ni}\right)$$

$$\frac{\partial \left(\rho^{int} \left(\nu^{int}\right)^2\right)}{\partial r} = -\frac{GM\rho^{int}}{r^2}$$

$$\frac{\partial \left(\rho^{ni} \left(\nu^{ni}\right)^2\right)}{\partial r} = -\frac{GM\rho^{ni}}{r^2}$$

$$\frac{L^{int}}{4\pi r^2} = -\frac{3}{2} ab\nu^{int}\sigma \left[a\sigma^2 + \frac{b}{C}\frac{4\pi G}{\rho^{int}\left(\nu^{int}\right)^2}\right]^{-1} \frac{\partial \left(\nu^{int}\right)^2}{\partial r}$$

$$\frac{\partial L^{int}}{\partial r} = -4\pi\rho^{int} r^2 \left(\nu^{int}\right)^2 \left(\frac{\partial}{\partial t}\right)_M \ln \frac{\left(\nu^{int}\right)^3}{\rho^{int}}$$

$$0 = \left(\frac{\partial}{\partial t}\right)_M \ln \frac{\left(\nu^{ni}\right)^3}{\rho^{ni}}.$$

Horrible Equations

$$\frac{M_{BH}}{M_\Delta} = \frac{\tilde{M}_{BH}}{\tilde{M}(c)} = \frac{0.025 f}{\ln(1+c) - c/(1+c)}$$

$$t_{r,c}(0) = 1/(a f \rho_s \nu_s \sigma)$$

$$= \frac{1}{a f \sigma}(\frac{K_c^2}{4\pi G^3})^{1/6} \delta_c^{-7/6} \rho_{crit}(z)^{-7/6} M_\Delta^{-1/3}$$

$$= 0.354 \text{ Myr} \times \left(\frac{M_\Delta}{10^{12} M_\odot}\right)^{-1/3} \left(\frac{K_c}{K_9}\right)^{3/2} \left(\frac{c}{9}\right)^{-7/2} \left(\frac{\rho_{crit}(z)}{\rho_{crit}(z=15)}\right)^{-7/6} \left(\frac{\sigma f}{1 \text{ cm}^2/\text{g}}\right)^{-1}$$

$$K_c \equiv \ln(1+c) - c/(1+c) \qquad \delta_c = (\Delta/3)c^3/K_c \qquad \Delta = 18\pi^2 \Omega_m^{0.45}$$