Title: Gravothermal Evolution of Self-Interacting Dark Matter Halos in the Short Mean Free Path Regime - VIRTUAL

Speakers: Sophia Nasr

Series: Cosmology & Gravitation

Date: February 13, 2024 - 11:00 AM

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Abstract: In this talk, I will discuss my exploration of the gravothermal collapse of isolated self-interacting dark matter (SIDM) halos, driven deep into the core-collapsed regime where interactions are frequent. We investigate how elastic collisions influence the central region of SIDM halos as they undergo core collapse. In our numerical findings, we discover a remarkable universality in the behavior of halos, allowing us to predict their evolution deep in the core-collapsed regime. We develop a semi-analytic method to characterize the core properties of the halo in the latest stages of evolution, which is crucial for making predictions of the mass of potential black holes forming at the heart of these dark matter halos.

Zoom link

GRAVOTHERMAL EVOLUTION OF SELF-INTERACTING DARK MATTER HALOS IN THE SHORT MEAN FREE PATH REGIME

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS, FEBRUARY 13, 2024

PRESENTATION OUTLINE

BACKGROUND

- Λ – COLD DARK MATTER (ΛCDM) PARADIGM
- SELF-INTERACTING DARK MATTER (SIDM)
- GRAVOTHERMAL EVOLUTION

RESEARCH

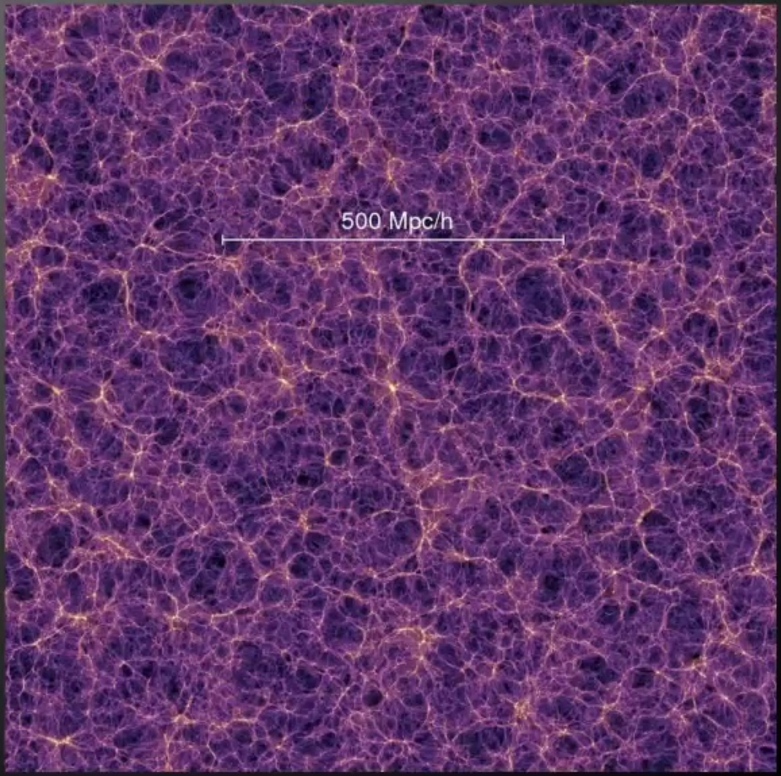
- GRAVOTHERMAL EVOLUTION IN THE LONG MEAN FREE PATH (LMFP)
- NEWFOUND UNIVERSALITY IN THE SHORT MEAN FREE PATH (SMFP) REGIME

CONCLUDING REMARKS

1

CDM SUCCESSES

- COLD DARK MATTER
  - *COLLISIONLESS*
- SUCCESSFUL ON LARGE SCALES
  - COSMIC WEB
    - SIMULATIONS

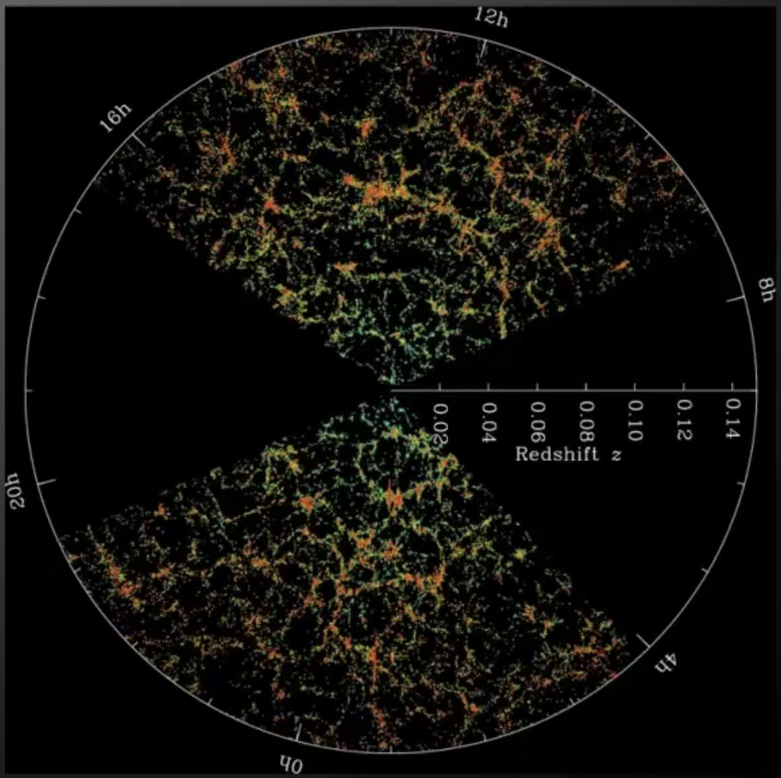


Millennium Simulation

2

CDM SUCCESSES

- ❖COLD DARK MATTER
  - ➢ *COLLISIONLESS*
- ❖SUCCESSFUL ON LARGE SCALES
  - ➢ COSMIC WEB
    - ➢ SIMULATIONS
    - ➢ OBSERVATIONS



M. Blanton and SDSS

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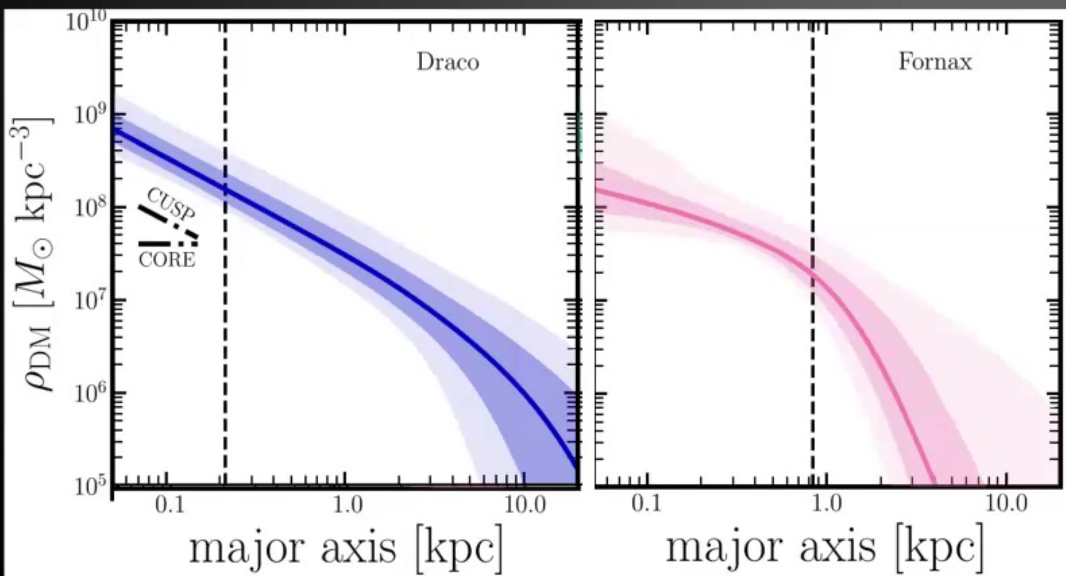
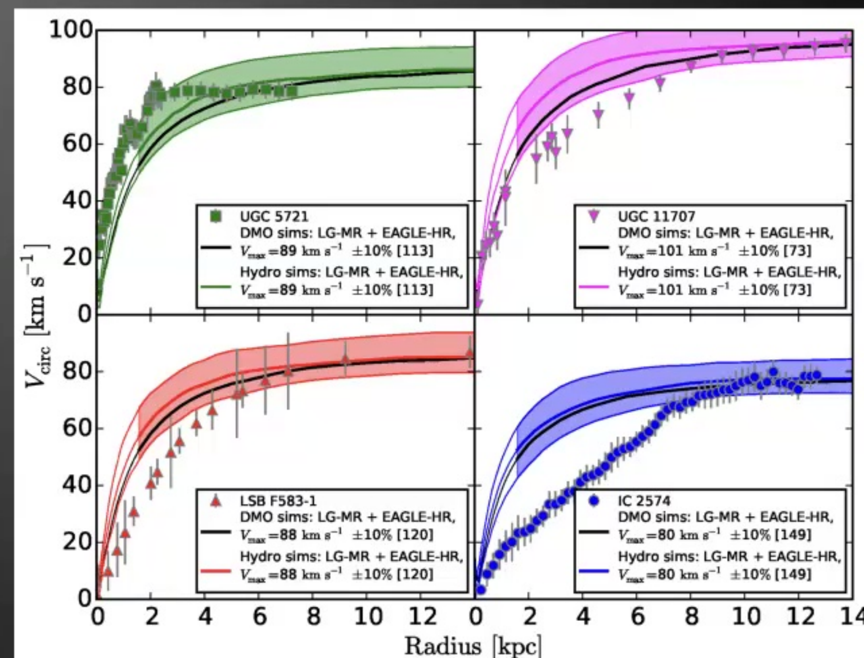
CORE-CUSP AND DIVERSITY PROBLEMS



K. Hayashi, M. Chiba, T. Ishiyama, arXiv:2007.13780 (2020)



K. A. Oman et al, arXiv:1504.01437 (2015)

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

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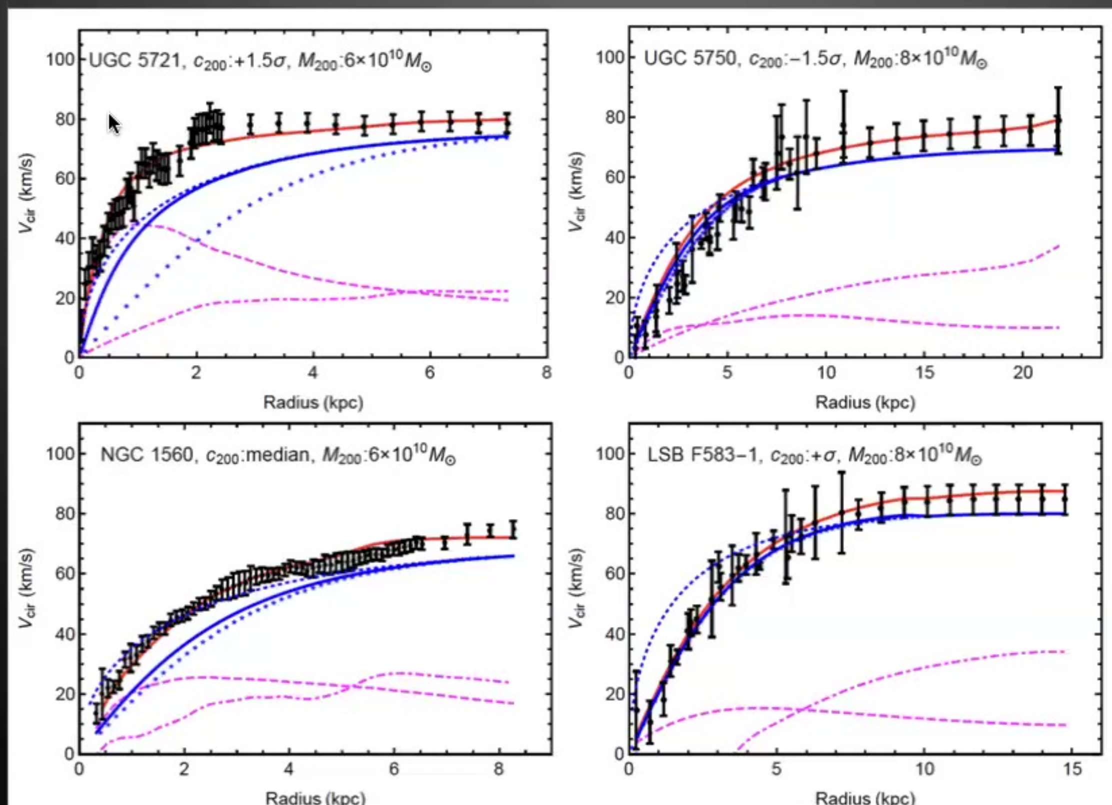
SIDM OVERVIEW

- ❖ONLY MODIFIES INNER HALO → ΛCDM SUCCESSES PRESERVED
- ❖PARTICLE SCATTERING → THERMALIZE CORE
  - ➢ CORE GROWTH → CORE COLLAPSE
- ❖INITIALLY CONSTANT CROSS-SECTIONS
  - SPERGEL & STEINHARDT, arXiv:astro-ph/9909386 (2000)
- ❖VELOCITY-DEPENDENT MODELS
  - ➢ OBSERVATIONS
  - ➢ NATURAL IN LIGHT MEDIATOR MODELS
  - TULIN & YU, arXiv:1705.02358v2 (2017)

DIVERSITY PROBLEM IS NOT A PROBLEM WITH SIDM



Blue solid: SIDM halo
Magenta dashed: stars
Magenta dot-dashed: gas
Magenta long-dashed: bulge
Blue dotted: CDM halo
Blue asterisk: SIDM halo (no stars)
Red: total SIDM fit

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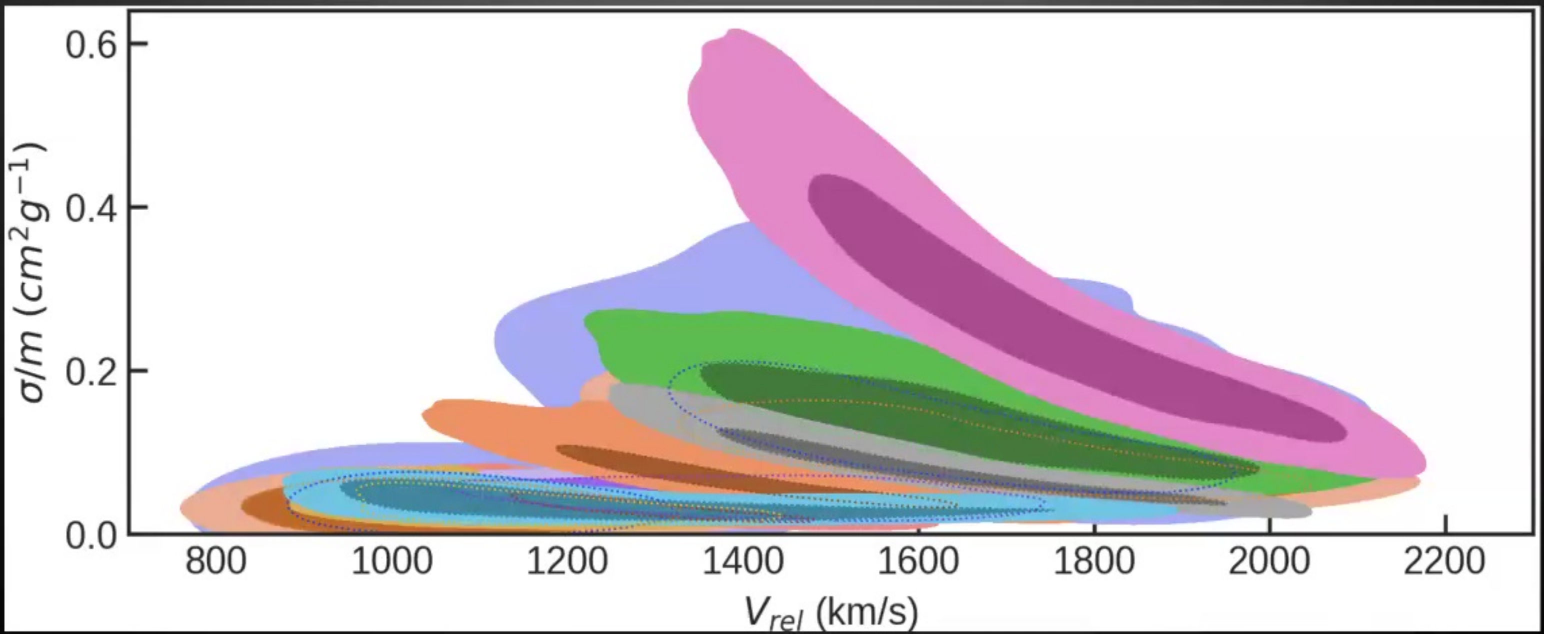
A. Kamada et al, arXiv:1611.02716 (2016)

SIDM CLUSTER SCALE CONSTRAINTS

CLUSTERS REQUIRE $\leq 0.1\ \mathrm{cm^2/g}$



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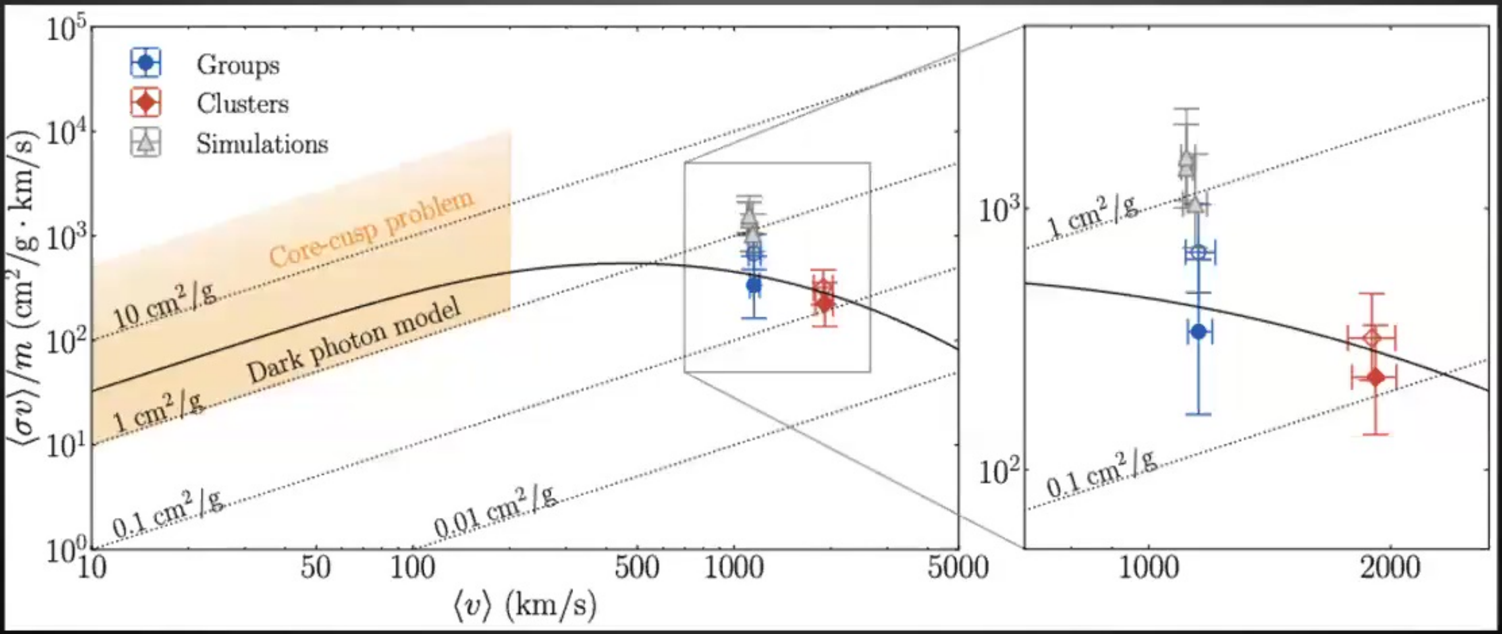
K. Andrade, SGN, et al, arXiv:2012.06611v3 (2021)

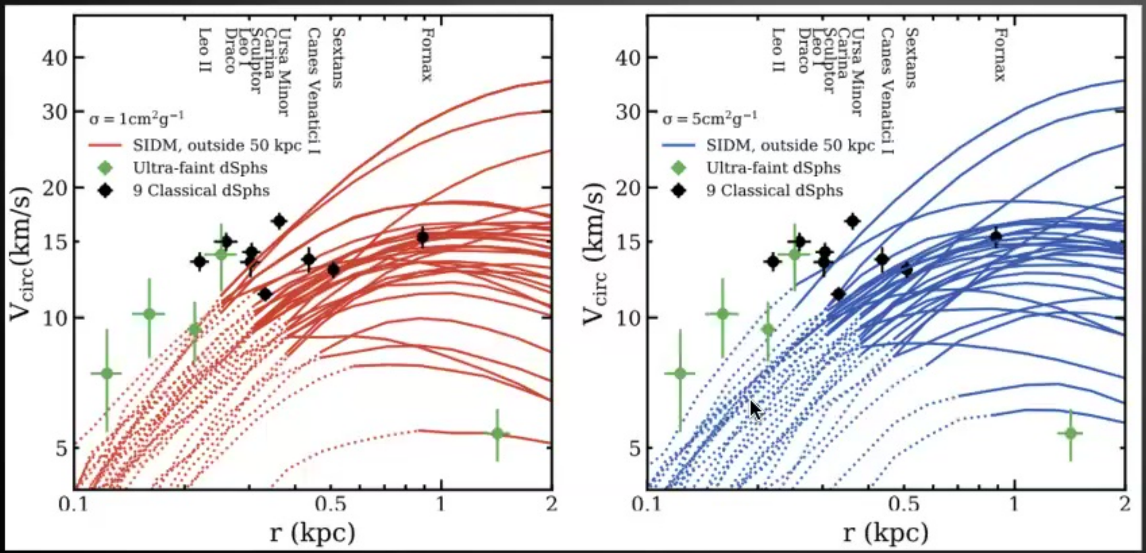
VELOCITY DEPENDENCE OF SIDM

$m_\chi = 15$ GeV
$m_\phi = 11$ MeV



L. Sagunski, SGN, et al, arXiv:2006.12515v1 (2021)

SIDM CORE COLLAPSE



M. Silverman et al, arXiv:2203.10104v2 (2022)

- ❖ DWARFS DENSER THAN SIMULATIONS WITH CROSS-SECTIONS OF 1 AND 5 cm^2/g
- ❖ EVIDENCE OF CORE COLLAPSE
  - ➢ NEED LARGER CROSS-SECTIONS > 50 cm^2/g
  - ➢ REQUIRE VELOCITY DEPENDENT CROSS-SECTION

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GRAVOTHERMAL FLUID EQUATIONS

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

→ MASS CONTINUITY
- ➢ MASS CONSERVATION

$$\frac{\partial(\rho v^2)}{\partial r} = -G\frac{M\rho}{r^2}$$

→ HYDROSTATIC EQUILIBRIUM
- ➢ PRESSURE AND GRAVITY BALANCED

$$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r}$$

→ THERMAL CONDUCTION
- ➢ GOVERNS HEAT FLUX THROUGH HALO

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

→ FIRST LAW OF THERMODYNAMICS
- ➢ RELATES GRADIENT OF HEAT FLUX TO THE ENTROPY

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GRAVOTHERMAL EVOLUTION

- ❖HEAT TRANSPORT FROM WARM OUTER HALO TO COOL CORE
  - ➢ CORE GROWTH
- ❖HEAT TRANSPORT FROM HOTTER INNER CORE TO COOLER OUTER HALO
  - ➢ CORE COLLAPSE
- ❖NEGATIVE HEAT CAPACITY → RUNAWAY COLLAPSE
- ❖"GRAVOTHERMAL CATASTROPHE"
  - LYNDEN-BELL & WOOD, MNRAS (1968) 138, 495
- ❖CORE COLLAPSE → BLACK HOLE
  - BALBERG & SHAPIRO, 2002 (arXiv:astro-ph/0111176)

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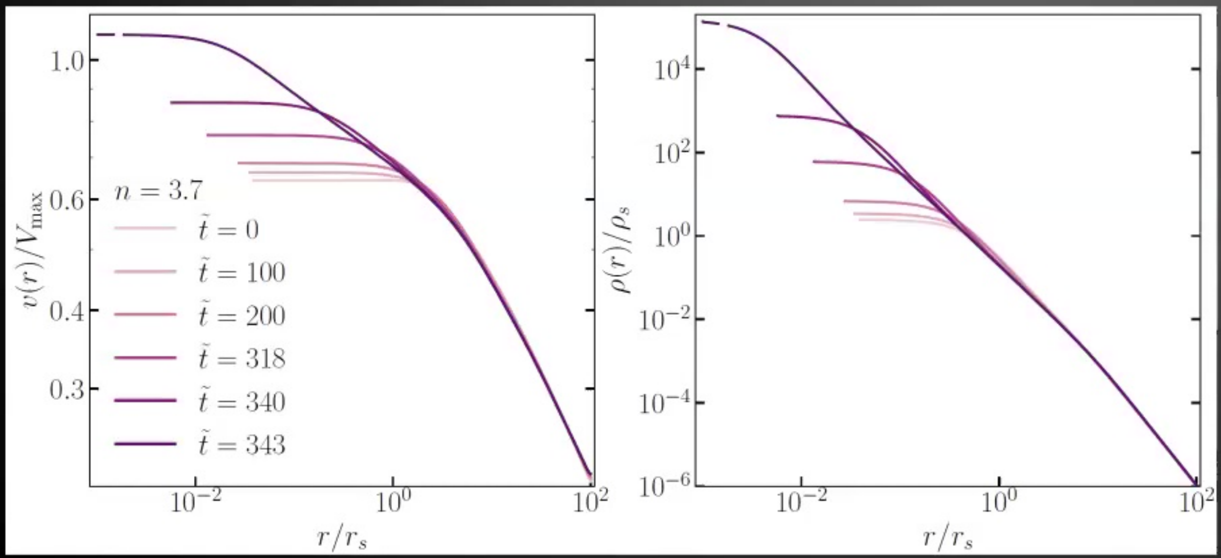
LONG MEAN FREE PATH EVOLUTION



N. Outmezguine, **SGN**, et al, arXiv:2204.06568v1 (2022)

- ❖PARTICLES MAKE MANY ORBITS BEFORE SCATTERING
- ❖CENTRAL DENSITY AND TEMPERATURE GROW
- ❖CORE RADIUS SHRINKS
- ❖SELF-SIMILAR & UNIVERSAL
- ❖BULK OF EVOLUTION IN LMFP

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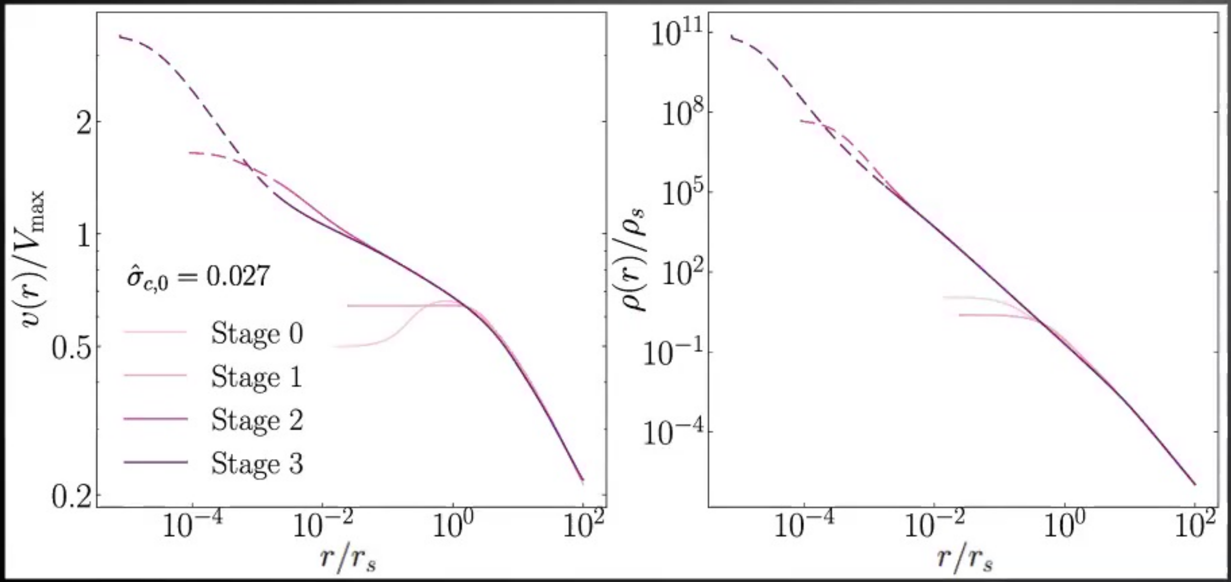
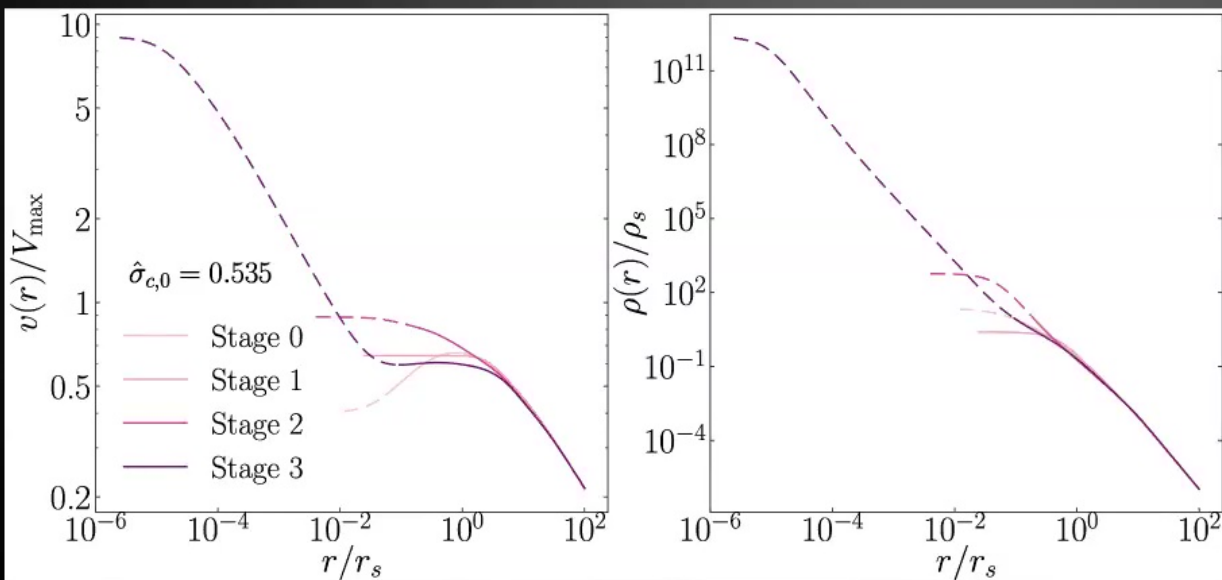
SHORT MEAN FREE PATH EVOLUTION



SGN et al, arXiv:2312.09296 (2023)

- ❖PARTICLES COLLIDE MANY TIMES PER ORBIT
- ❖EXTREME CENTRAL DENSITY AND TEMPERATURE INCREASE
- ❖BLACK HOLE FORMATION WOULD OCCUR IN THIS REGIME

SHORT MEAN FREE PATH EVOLUTION



SGN et al, arXiv:2312.09296 (2023)

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GRAVOTHERMAL EVOLUTION IN THE LONG MEAN FREE PATH REGIME

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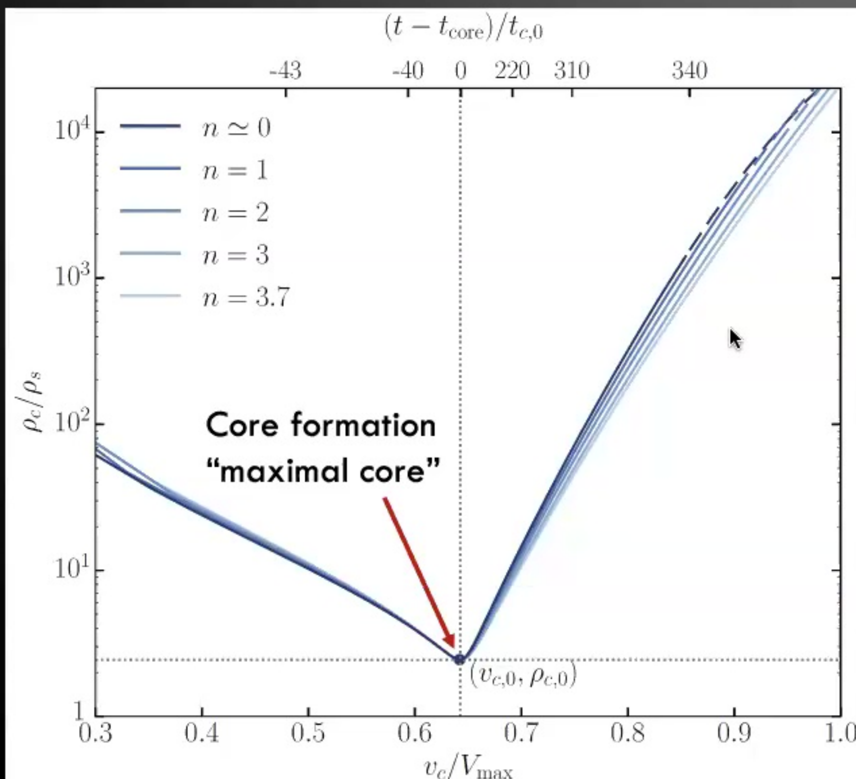
LMFP GRAVOTHERMAL EVOLUTION



N. Outmezguine, **SGN**, et al, arXiv:2204.06568v1 (2022)

- ❖ DEFINITION OF LMFP: $\frac{\kappa_{\rm SMFP}}{\kappa_{\rm LMFP}} > 1$
- ❖ CONDUCTIVITY IN LMFP: $\kappa_{\rm LMFP} \propto \sigma_0 K_p$
- ❖ CORE FORMATION:

$$v_{c,0} = 0.64\, V_{\rm max}, \qquad \rho_{c,0} = 2.4\, \rho_s$$

- ❖ BULK OF EVOLUTION

GRAVOTHERMAL CODE

❖SOLVE DIMENSIONLESS GRAVOTHERMAL EQUATIONS

$$\frac{\partial \tilde{M}}{\partial \tilde{r}} = \tilde{r}^2 \tilde{\rho}, \quad \frac{\partial(\tilde{\rho}\tilde{v}^2)}{\partial \tilde{r}} = -\frac{\tilde{M}\tilde{\rho}}{\tilde{r}^2}, \quad \tilde{L} = -\tilde{r}^2 \tilde{\kappa} \frac{\partial \tilde{v}^2}{\partial \tilde{r}},$$

$$\frac{\partial \tilde{L}}{\partial \tilde{r}} = -\tilde{r}^2 \tilde{\rho} \tilde{v}^2 \left(\frac{\partial}{\partial \tilde{t}}\right)_{\tilde{M}} \log\left(\frac{\tilde{v}^3}{\tilde{\rho}}\right),$$

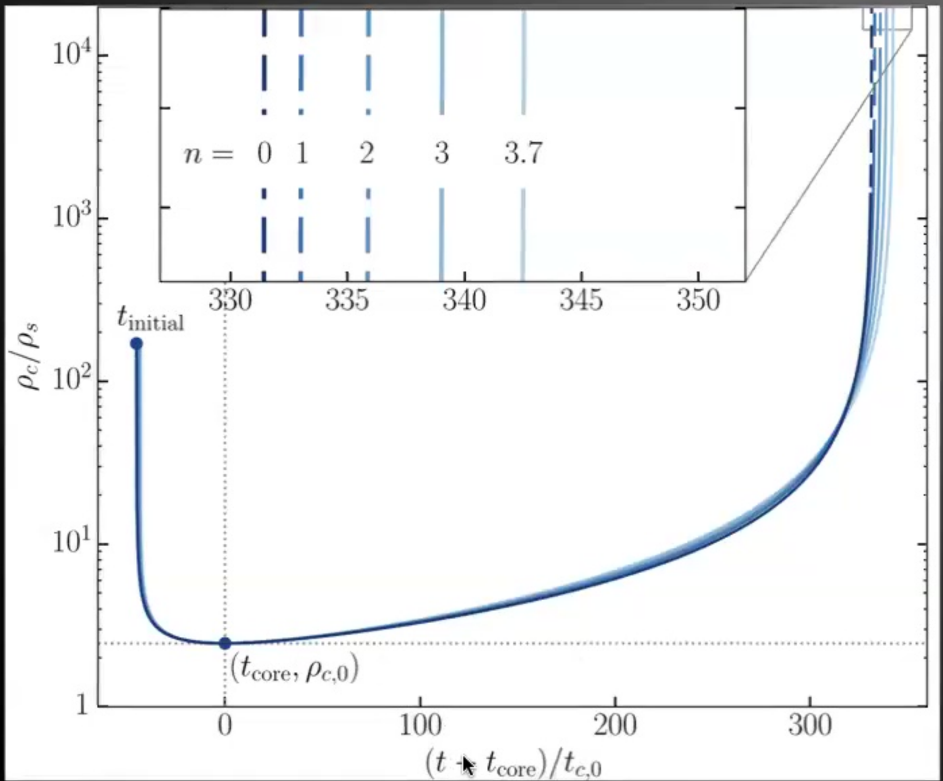
❖VELOCITY DEPENDENCE

$$K_p = \frac{\langle \sigma_{\rm visc} v_{\rm rel}^p \rangle}{\lim_{w\to\infty} \langle \sigma_{\rm visc} v_{\rm rel}^p \rangle}$$

❖DIMENSIONLESS CROSS SECTION

$$\hat{\sigma}^2 = \frac{aC}{b} K_3\left(\frac{1}{\hat{w}}\right) K_5\left(\frac{1}{\hat{w}}\right) \left(\frac{M_N}{4\pi r_N^2}\frac{\sigma_0}{m_{\rm dm}}\right)^2, \quad \hat{w} = \frac{w}{v_N}.$$

LMFP UNIVERSALITY



N. Outmezguine, SGN, et al, arXiv:2204.06568v1 (2022)

❖SCATTERING TIMESCALE:

$$t_{c,0} = \frac{2}{3aC}\left(\rho_{c,0}\frac{\sigma_0}{m_{\text{dm}}}v_{c,0}K_5\left(\frac{v_{c,0}}{w}\right)\right)^{-1}$$

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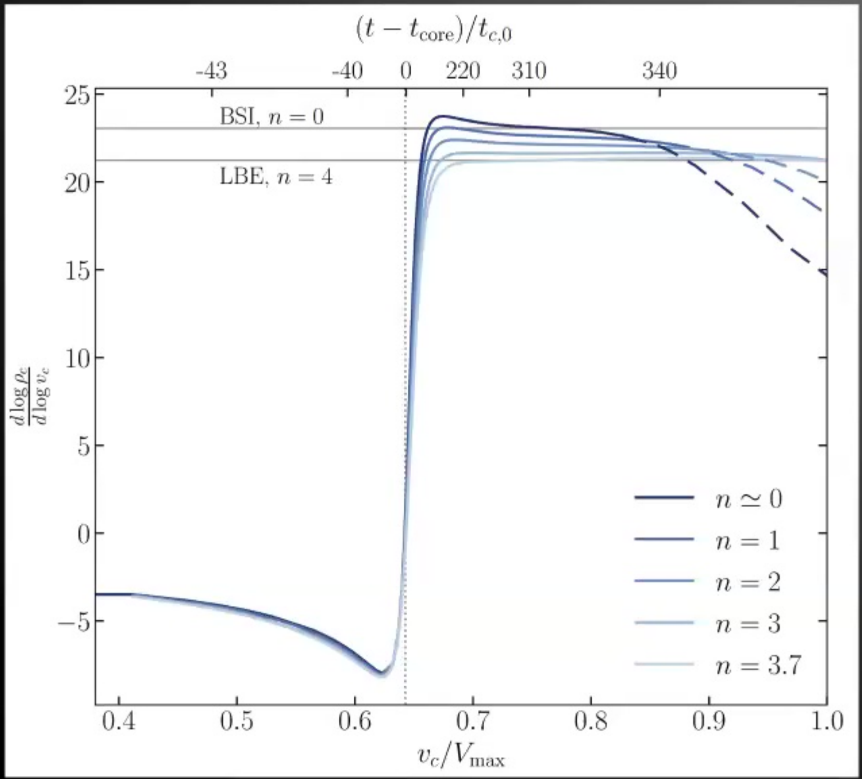
LMFP UNIVERSALITY



N. Outmezguine, **SGN**, et al, arXiv:2204.06568v1 (2022)

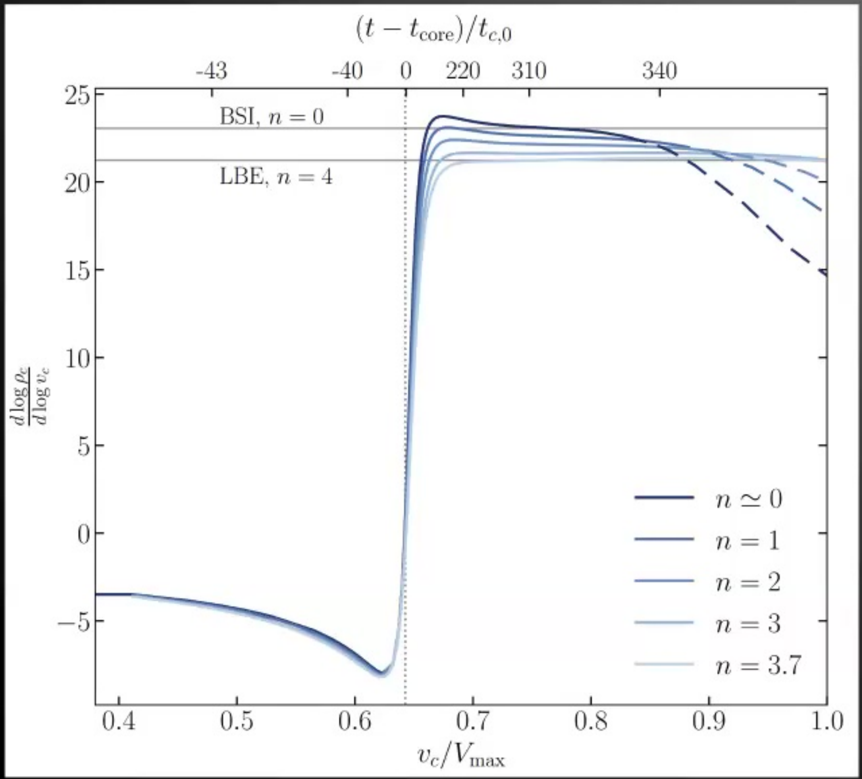
❖COLLAPSE TIMESCALE:

$$\frac{\mathrm{d}\log\tilde{\rho}_c}{\mathrm{d}\log\tilde{v}_c} = \frac{2\alpha}{\alpha - 2}$$

$$\tilde{t}_{\rm coll} = \frac{1}{c_1}\frac{6-\alpha}{(3\alpha-2)-n(\alpha-2)}.$$

$$t_{\rm coll} \sim 335\ t_{c,0}$$

LMFP UNIVERSALITY



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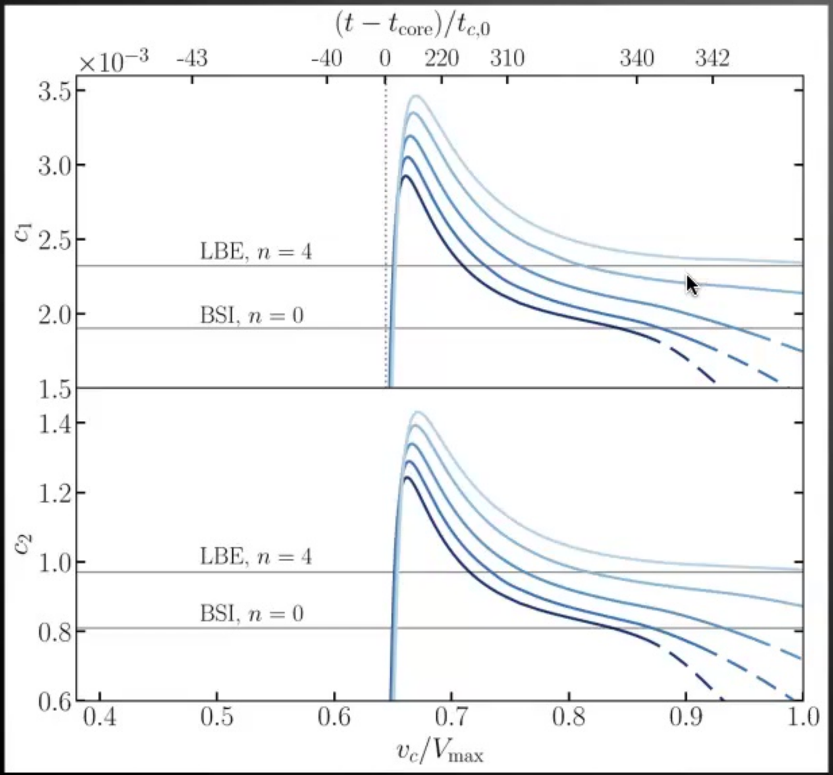
$$\tilde{t}_{\rm coll} = \frac{1}{c_1}\frac{6-\alpha}{(3\alpha - 2) - n(\alpha - 2)}.$$

$$t_{\rm coll} \sim 335\ t_{c,0} \qquad n = -\frac{d\log K}{d\log v_N}$$

LMFP UNIVERSALITY



N. Outmezguine, **SGN**, et al, arXiv:2204.06568v1 (2022)

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$$t_{\mathrm{coll}} \sim 335\, t_{c,0} \qquad n = -\frac{d\log K}{d\log v_N}$$

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RELATING LS TRANSITION TO CORE FORMATION

❖CENTRAL DISPERSION

$$\frac{v_{c,\mathrm{LS}}}{v_{c,0}} \simeq \hat{\sigma}_{c,0}^{-1/\delta} \qquad \delta = 1 - \bar{n} + \frac{\alpha}{\alpha - 2}$$

❖CENTRAL DENSITY

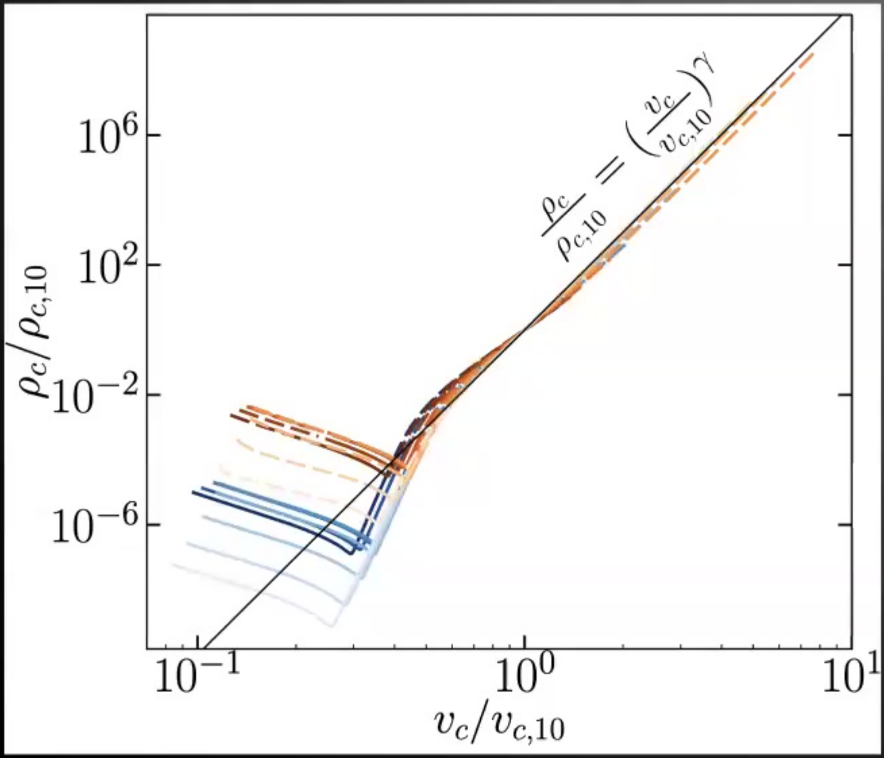
$$\frac{\rho_{c,\mathrm{LS}}}{\rho_{c,0}} \simeq \left(\frac{v_{c,\mathrm{LS}}}{v_{c,0}}\right)^{2\alpha/(\alpha-2)}$$

❖CORE MASS

$$\frac{M_{c,\mathrm{LS}}}{M_{c,0}} \simeq \left(\frac{v_{c,\mathrm{LS}}}{v_{c,0}}\right)^{\frac{6-2\alpha}{2-\alpha}}$$

GRAVOTHERMAL EVOLUTION IN THE SHORT MEAN FREE PATH REGIME: A NEW UNIVERSALITY

SMFP GRAVOTHERMAL EVOLUTION



SGN et al, arXiv:2312.09296 (2023)

❖ DEFINITION OF SMFP: $\frac{\kappa_{\rm SMFP}}{\kappa_{\rm LMFP}} < 1$

❖ CONDUCTIVITY IN SMFP: $\kappa_{\rm SMFP} \propto \left(\sigma_0 K_p\right)^{-1}$

❖ SMFP TIMESCALE: $t_{\rm SMFP} = \frac{\sigma_0 K_{\rm eff}^{(2)}(v_c)\, v_c}{2\pi b G m_{\rm dm}}$

GRAVOTHERMAL METHODS

- SIMILAR TO LMFP
- DIFFERENCES:
  - LMFP, RUTHERFORD SCATTERING $\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi}\left(1 + \frac{v^2}{w^2}\sin^2\frac{\theta}{2}\right)^{-2}$
  - SMFP, MOLLER SCATTERING $\frac{d\sigma}{d\Omega} = \frac{1}{\pi}\frac{\sigma_0 w^4[(3\cos^2\theta + 1)v^4 + 4v^2w^2 + 4w^4]}{(\sin^2\theta v^4 + 4v^2w^2 + 4w^4)^2}$
  - INCREASE IN RESOLUTION
    - 400 SHELLS → 450 SHELLS, PROBED SMALLER RADII

GRAVOTHERMAL METHODS

- SIMILAR TO LMFP
- DIFFERENCES:

Viscosity cross section

- LMFP, RUTHERFORD SCATTERING

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi}\left(1 + \frac{v^2}{w^2}\sin^2\frac{\theta}{2}\right)^{-2}$$

- SMFP, MOLLER SCATTERING

$$\frac{d\sigma}{d\Omega} = \frac{1}{\pi}\frac{\sigma_0 w^4[(3\cos^2\theta + 1)v^4 + 4v^2w^2 + 4w^4]}{(\sin^2\theta v^4 + 4v^2w^2 + 4w^4)^2}$$

- INCREASE IN RESOLUTION
  - 400 SHELLS → 450 SHELLS, PROBED SMALLER RADII

SIDM SCATTERING

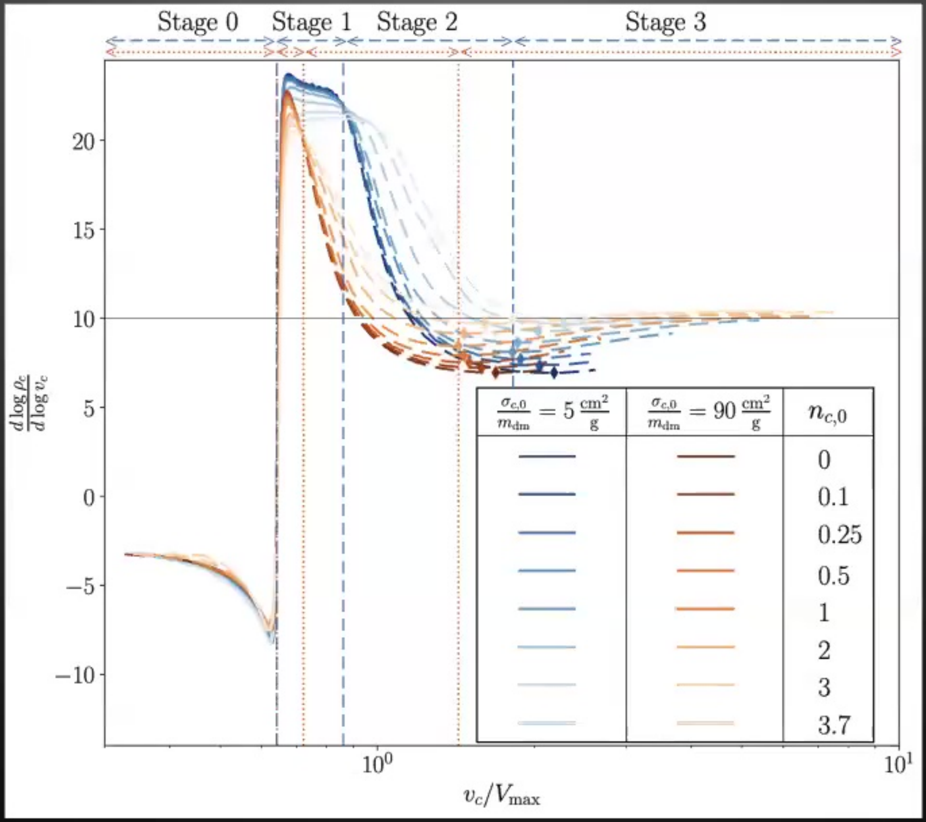
- TRANSFER CROSS SECTION
  - REGULATES FORWARD SCATTERING, BUT ENHANCES BACKWARD SCATTERING

$$\sigma_T = \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

- VISCOSITY CROSS SECTION
  - REGULATES FORWARD *AND* BACKWARD SCATTERING

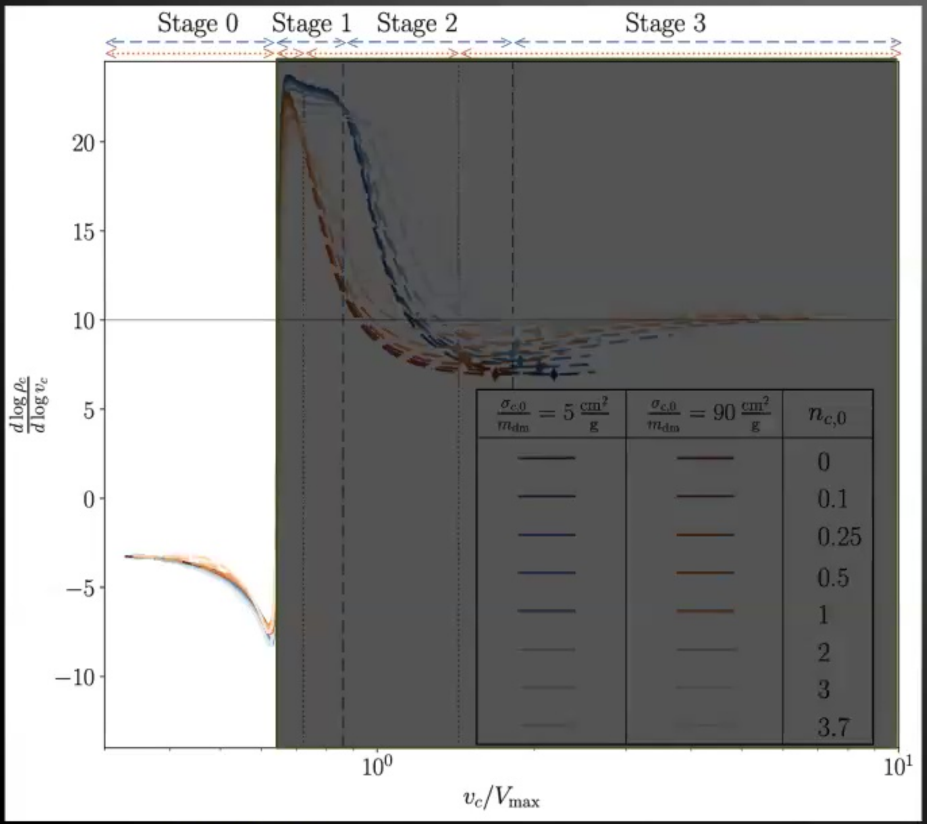
$$\sigma_V = \int d\Omega \sin^2\theta \frac{d\sigma}{d\Omega}$$

STAGES OF EVOLUTION



SGN et al, arXiv:2312.09296 (2023)

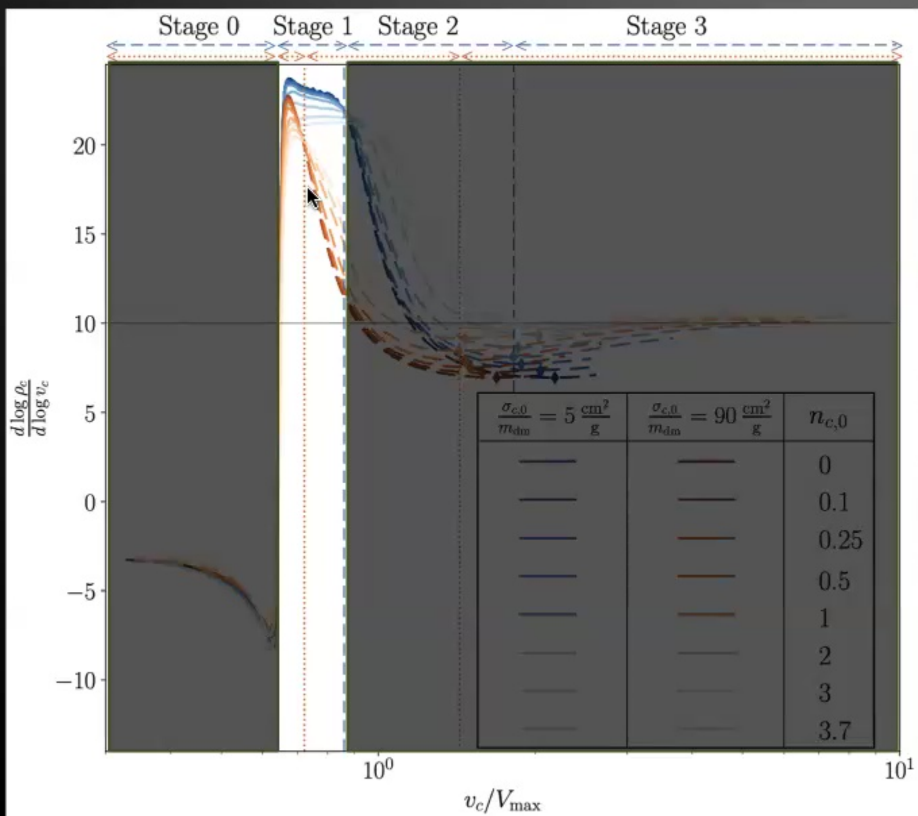
STAGE 0



SGN et al, arXiv:2312.09296 (2023)

- ❖CORE EXPANSION PHASE
- ❖SOLUTION TO CORE-CUSP PROBLEM
- ❖RADIUS INCREASES
- ❖DENSITY DECREASES
- ❖ENDS AT CORE FORMATION

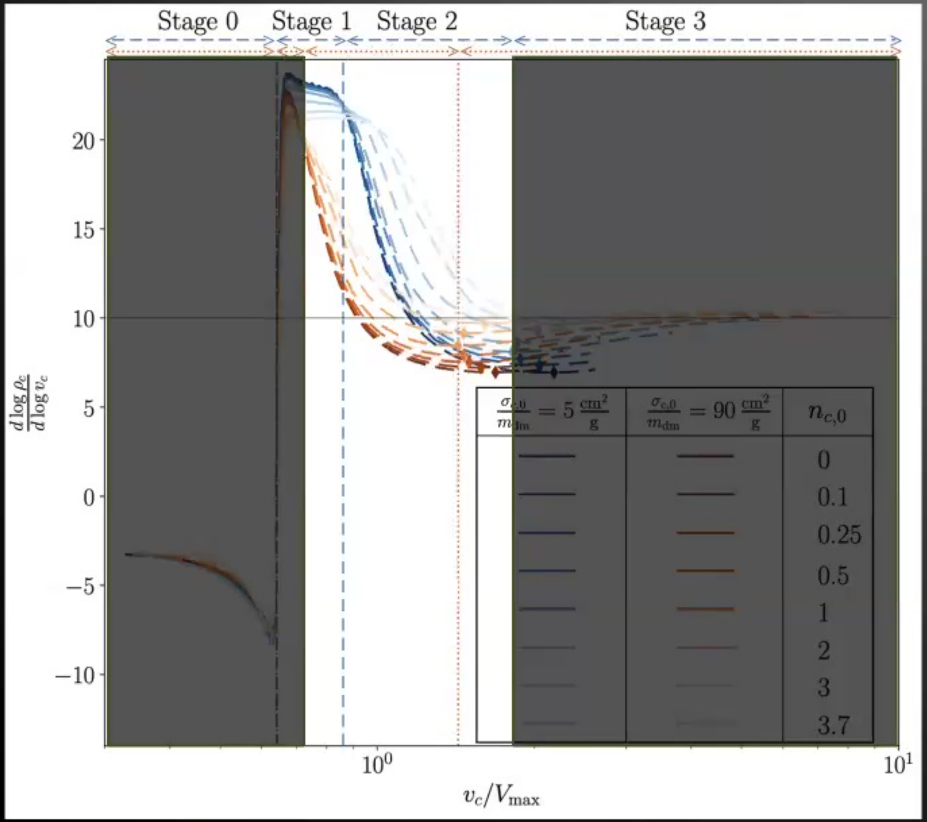
STAGE 1



arXiv:2312.09296 (2023)

- ❖CORE CONTRACTION PHASE
- ❖OCCURS AFTER CORE FORMATION
- ❖RADIUS DECREASES
- ❖DENSITY INCREASES
- ❖ONSET OF LMFP EVOLUTION
  - ❖SELF-SIMILARITY
  - ❖LMFP UNIVERSALITY

STAGE 2



SGN et al, arXiv:2312.09296 (2023)

- ❖UNORGANIZABLE PHASE
- ❖DEPARTURE FROM LMFP SELF-SIMILARITY AND UNIVERSALITY

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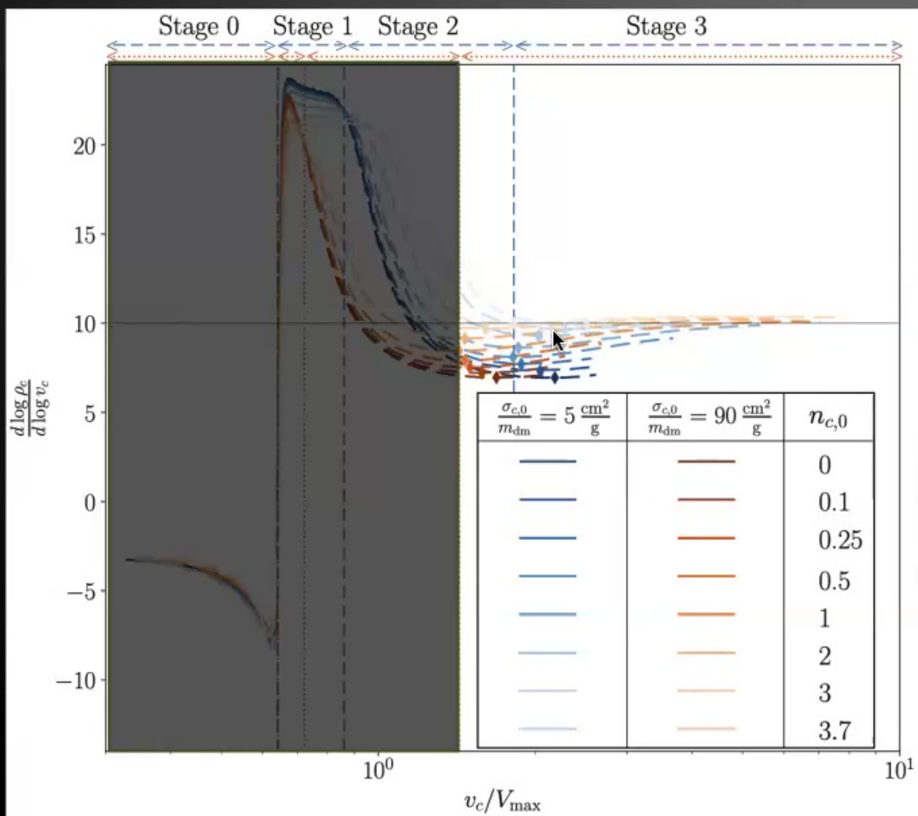
STAGE 3



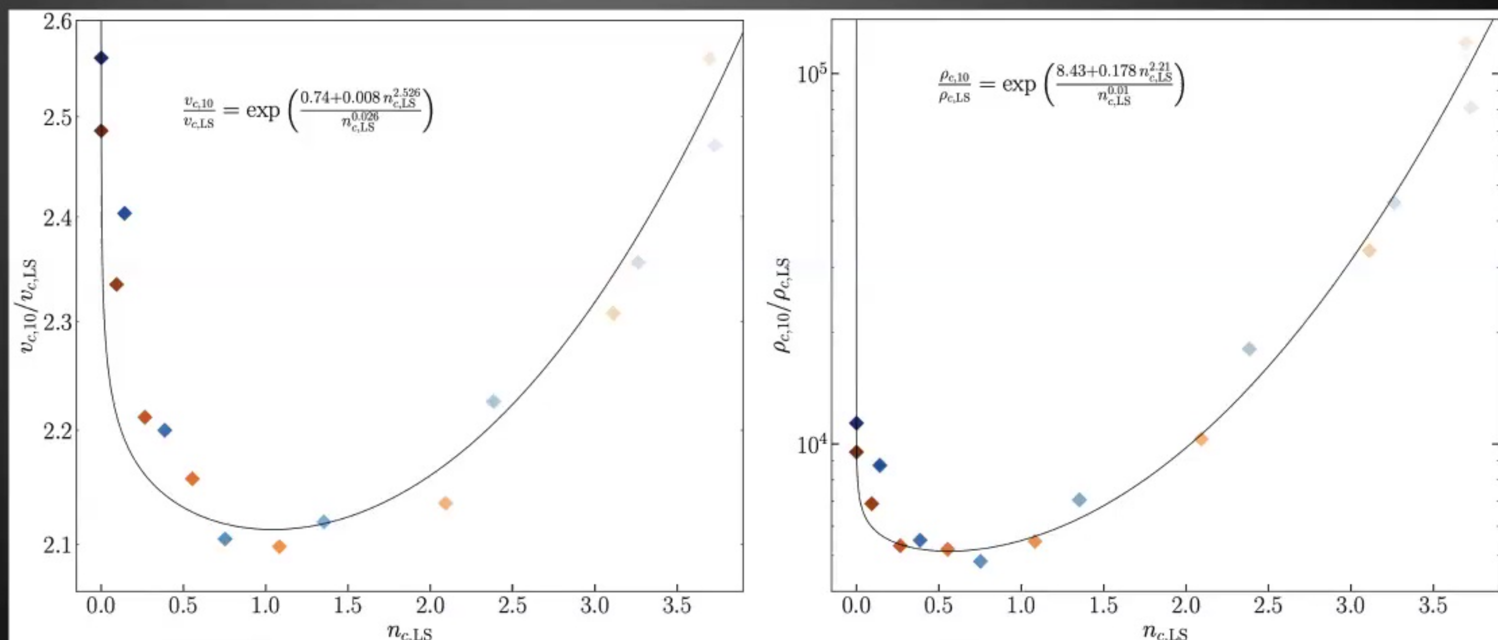
v:2312.09296 (2023)

- ❖CONSTANT THERMAL ENERGY PHASE
- ❖NEW SMFP UNIVERSALITY
- ❖CURVES TEND TO SLOPE

$$\gamma \approx 10 \qquad \frac{d\log \rho_c}{d \log v_c} = \gamma$$

- ❖LS TRANSITION RELATED TO STAGE 3 PARAMETERS → SEMI-ANALYTIC

RELATING LS PARAMETERS TO STAGE 3



$$n = -\frac{d \log K}{d \log v_N}$$

$$\frac{v_{c,\mathrm{LS}}}{v_{c,0}} \simeq \hat{\sigma}_{c,0}^{-1/\delta}$$

$$\frac{\rho_{c,\mathrm{LS}}}{\rho_{c,0}} \simeq \left(\frac{v_{c,\mathrm{LS}}}{v_{c,0}}\right)^{2\alpha/(\alpha-2)}$$

SGN et al, arXiv:2312.09296 (2023)

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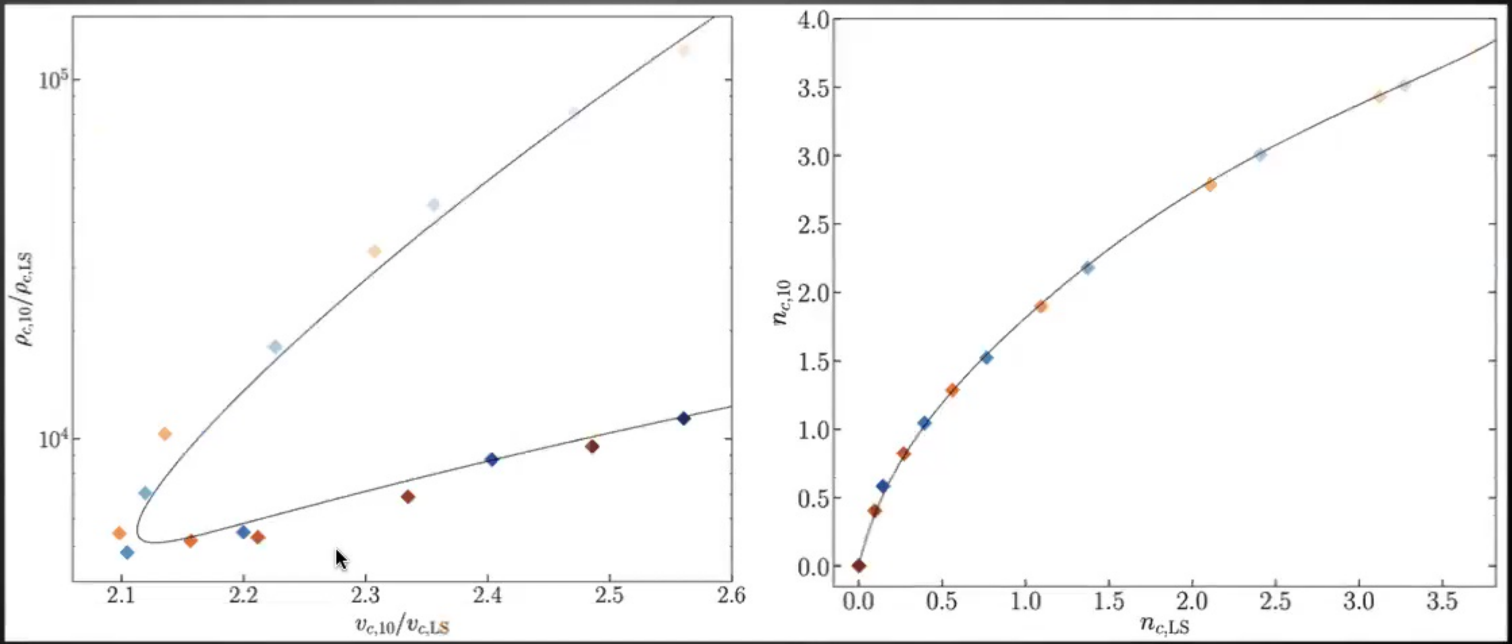
RELATING LS PARAMETERS TO STAGE 3



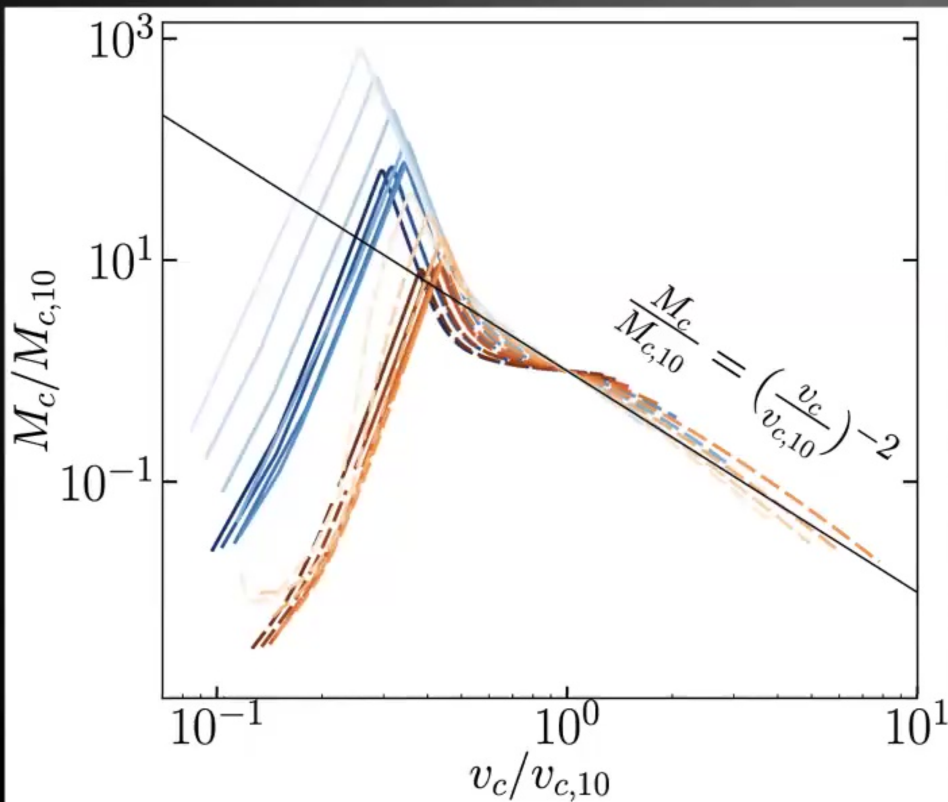
$$n(v_c) \to v_c = f(n)\,,$$

$$\frac{v_{c,10}}{v_{c,\mathrm{LS}}} = \frac{f(n_{c,10})}{f(n_{c,\mathrm{LS}})}\,,$$

$$n_{c,\mathrm{LS}} = n\left[\frac{v_{c,10}}{v_{c,\mathrm{LS}}} f(n_{c,10})\right] \quad , \quad n\,[f(x)] = x$$

SGN et al, arXiv:2312.09296 (2023)

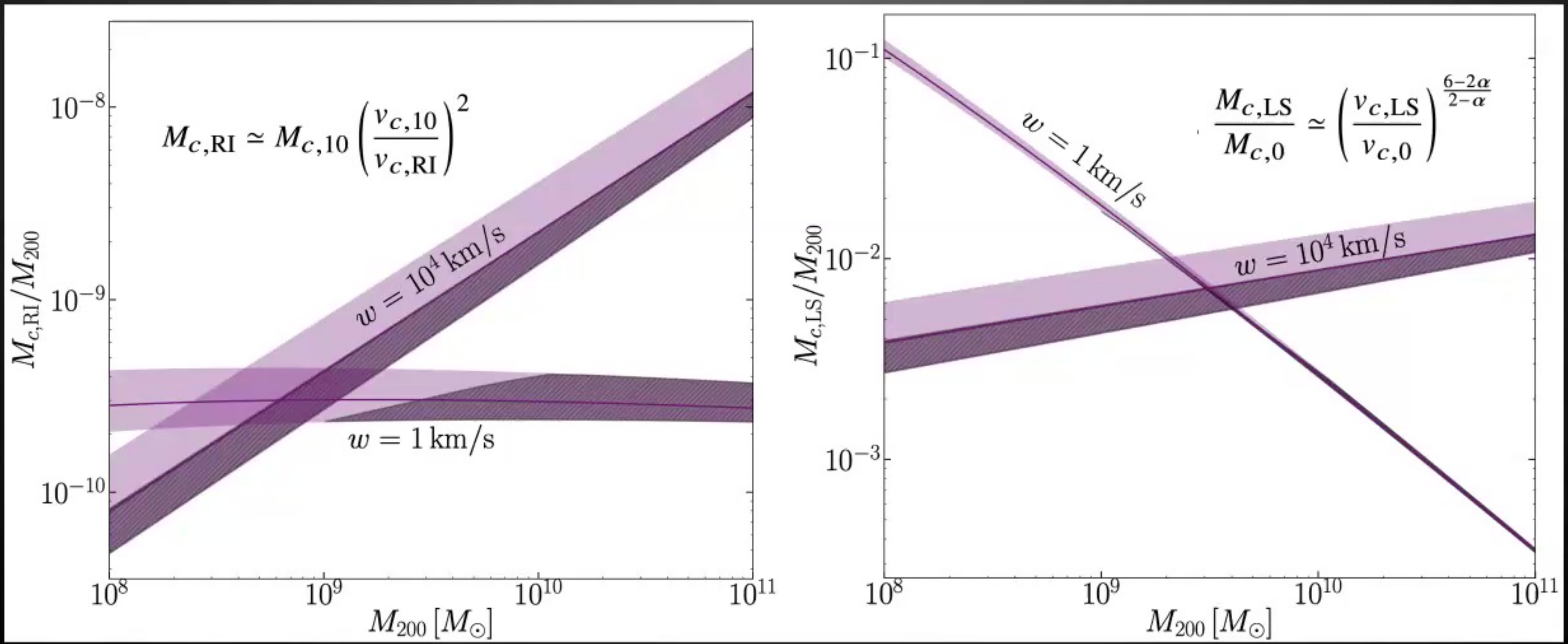
EVOLUTION OF CORE MASS IN STAGE 3



SGN et al, arXiv:2312.09296 (2023)

- ❖SMFP CORE MASS EVOLVES AS v_c^{-2}
- ❖USE TO EXTRAPOLATE TO THE RELATIVISTIC INSTABILITY

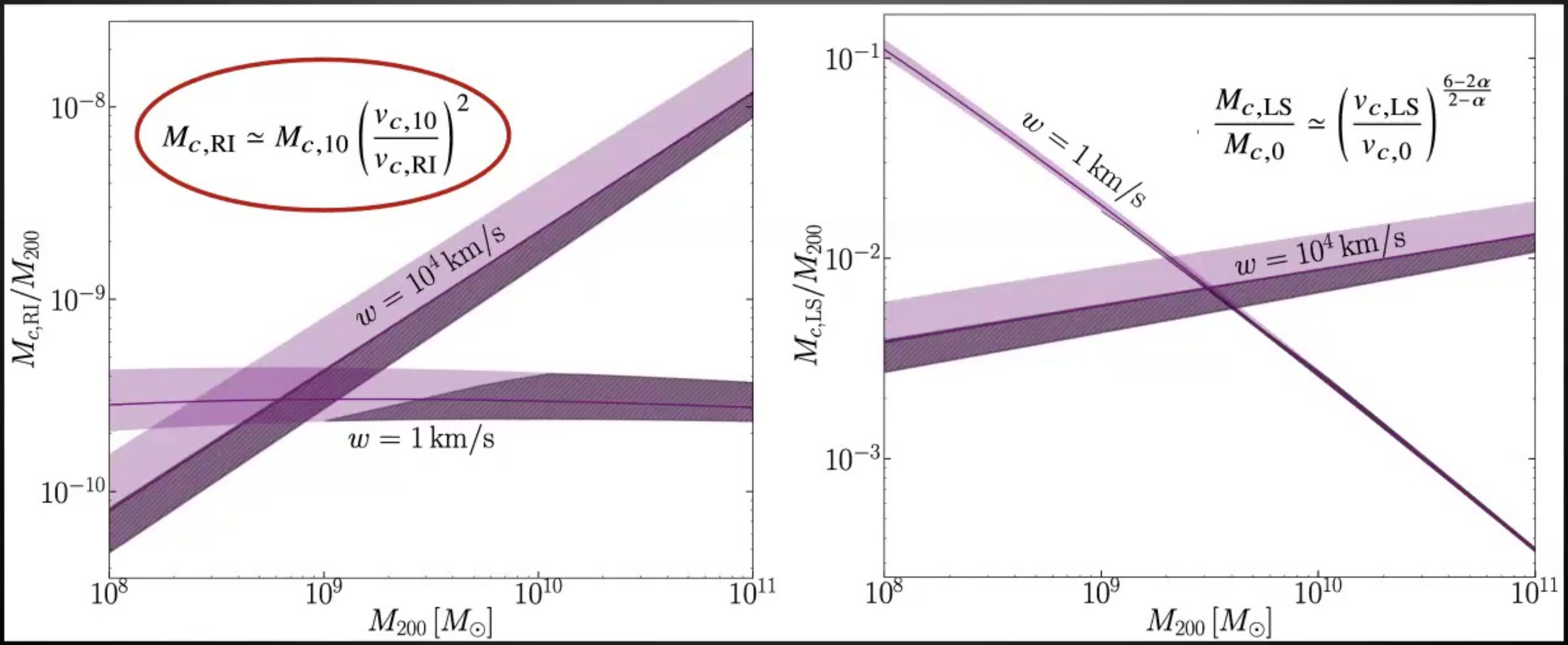
SEMI-ANALYTIC RECIPE FOR CORE MASS LIMITS



SGN et al, arXiv:2312.09296 (2023)

100 cm^2/g at v=20 km/s

SEMI-ANALYTIC RECIPE FOR CORE MASS LIMITS



SGN et al, arXiv:2312.09296 (2023)

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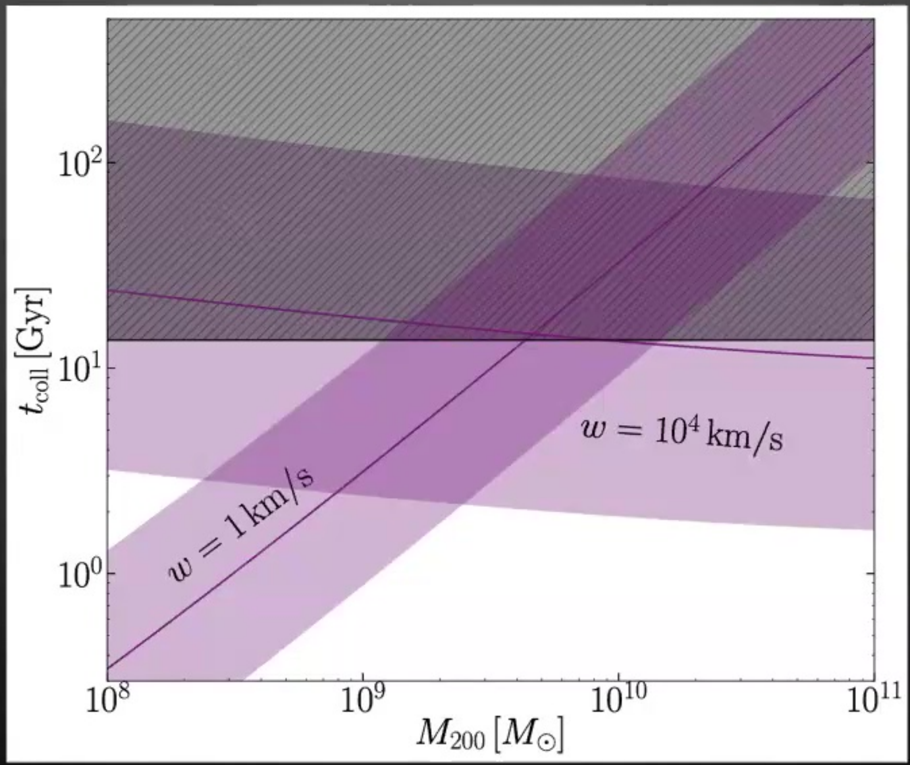
100 $\mathrm{cm^2/g}$ at v=20 km/s

COLLAPSE TIMES



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100 cm^2/g at v=20 km/s

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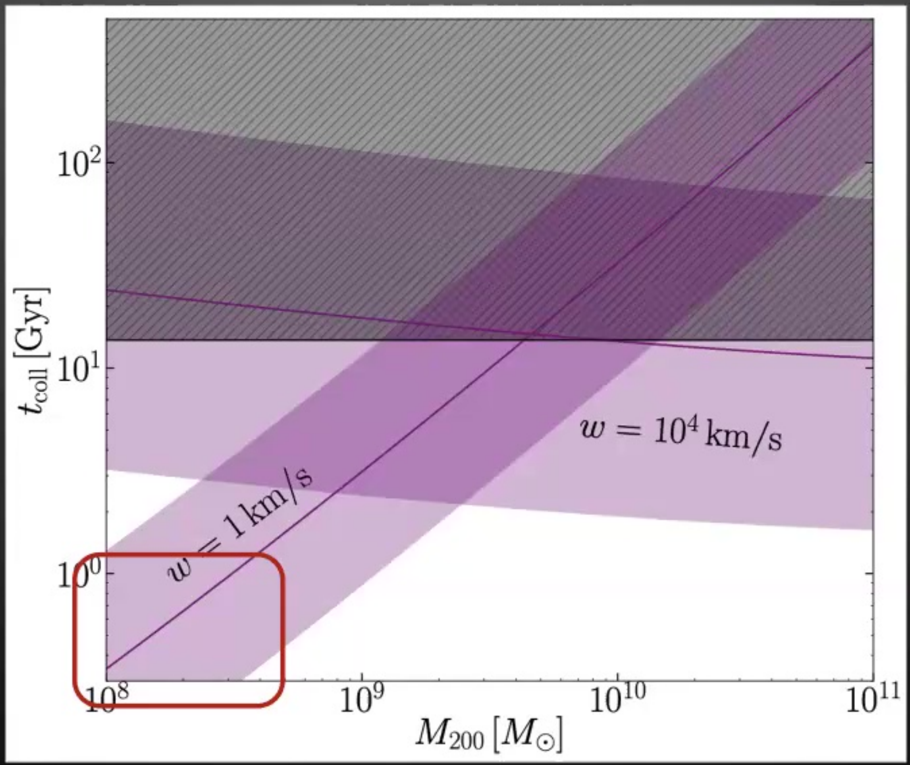
COLLAPSE TIMES



SGN et al, arXiv:2312.09296 (2023)

100 cm^2/g at v=20 km/s

THINGS TO NOTE

- ISOLATED HALOS
- ELASTIC SCATTERING
- BORN APPROXIMATION
- DARK MATTER ONLY
  - BARYONS AND COOLING ACCELERATE COLLAPSE
    - LOOKING INTO COOLING

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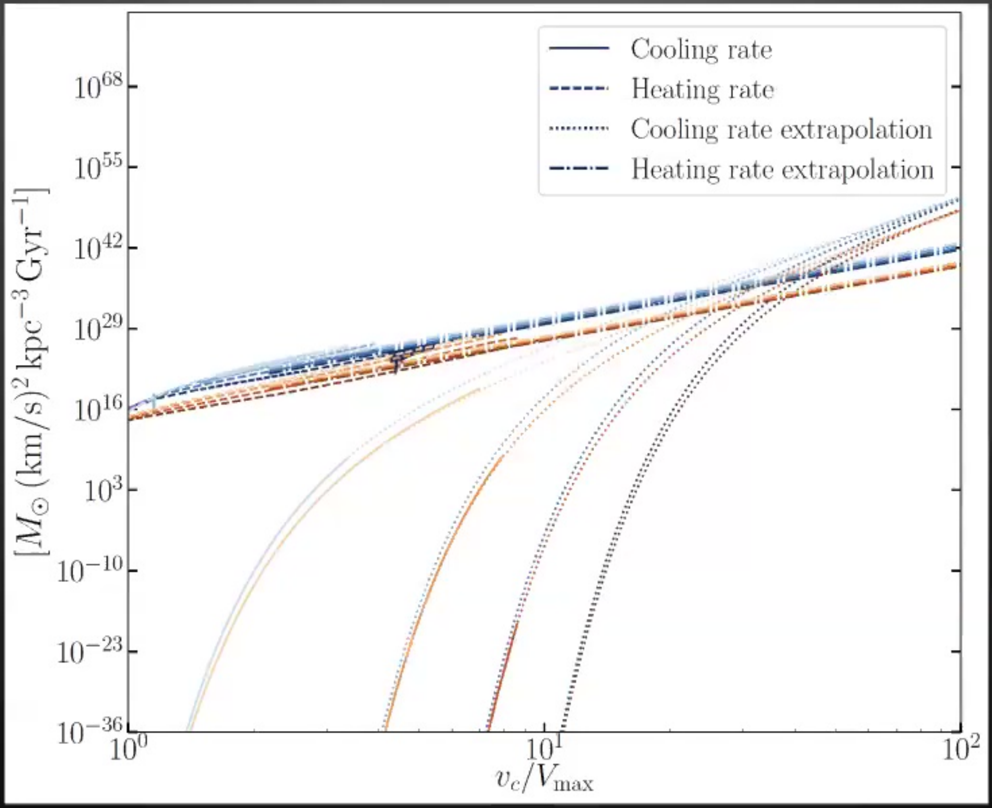
SUMMARY AND KEY TAKEAWAYS

- ❖SIDM IS A VIABLE DARK MATTER MODEL
- ❖LMFP EVOLUTION: SELF-SIMILAR SOLUTION AND UNIVERSAL SOLUTION
- ❖SMFP EVOLUTION: NEWFOUND UNIVERSALITY
- ❖SEMI-ANALYTIC PREDICTION OF STAGE 3 CORE PROPERTIES
  - ❋NO GRAVOTHERMAL CODE NEEDED
  - ❋BETTER BLACK HOLE MASS ESTIMATES

THANK YOU!

QUESTIONS?

HEATING VS COOLING



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