CSST暗物质粒子性质2025会议

暗物质粒子特性及重子反馈的新探针：贫暗物质/重子主导星系

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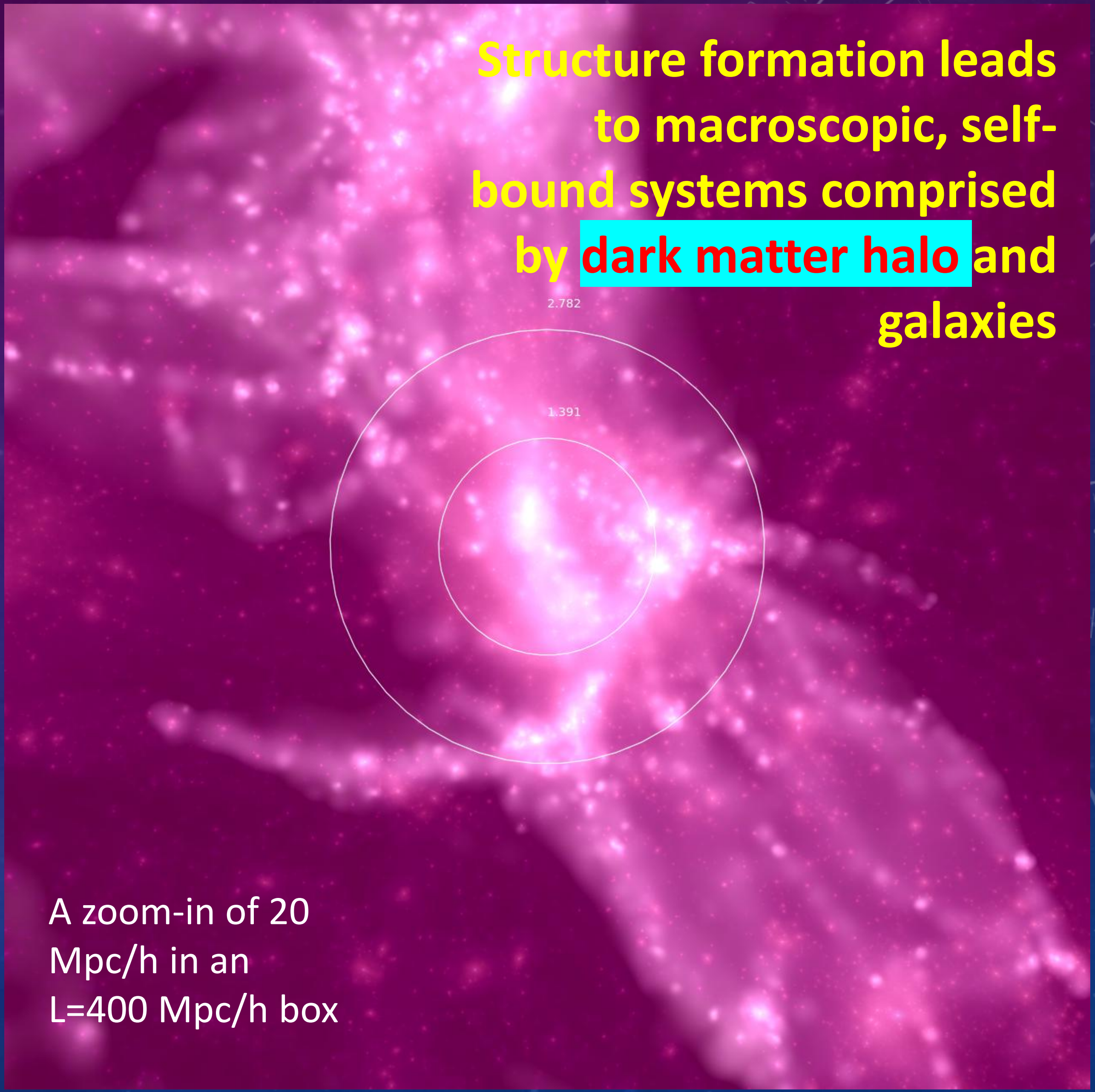
2025年10月26日
江苏，盱眙

Based on
* arXiv:2509.24270 with 王艺颖，范一中，蔡岳霖，卢克宇

Outline

- 暗物质属性寻找的天文窗口
- 观测和模拟中的贫暗物质/重子物质主导星系
- 重子反馈如何影响重子物质的引力束缚
- 星系对撞产生的重子物质主导星系(BDDGs)
- BDDG形成的跷跷板机制：暗晕能量注入



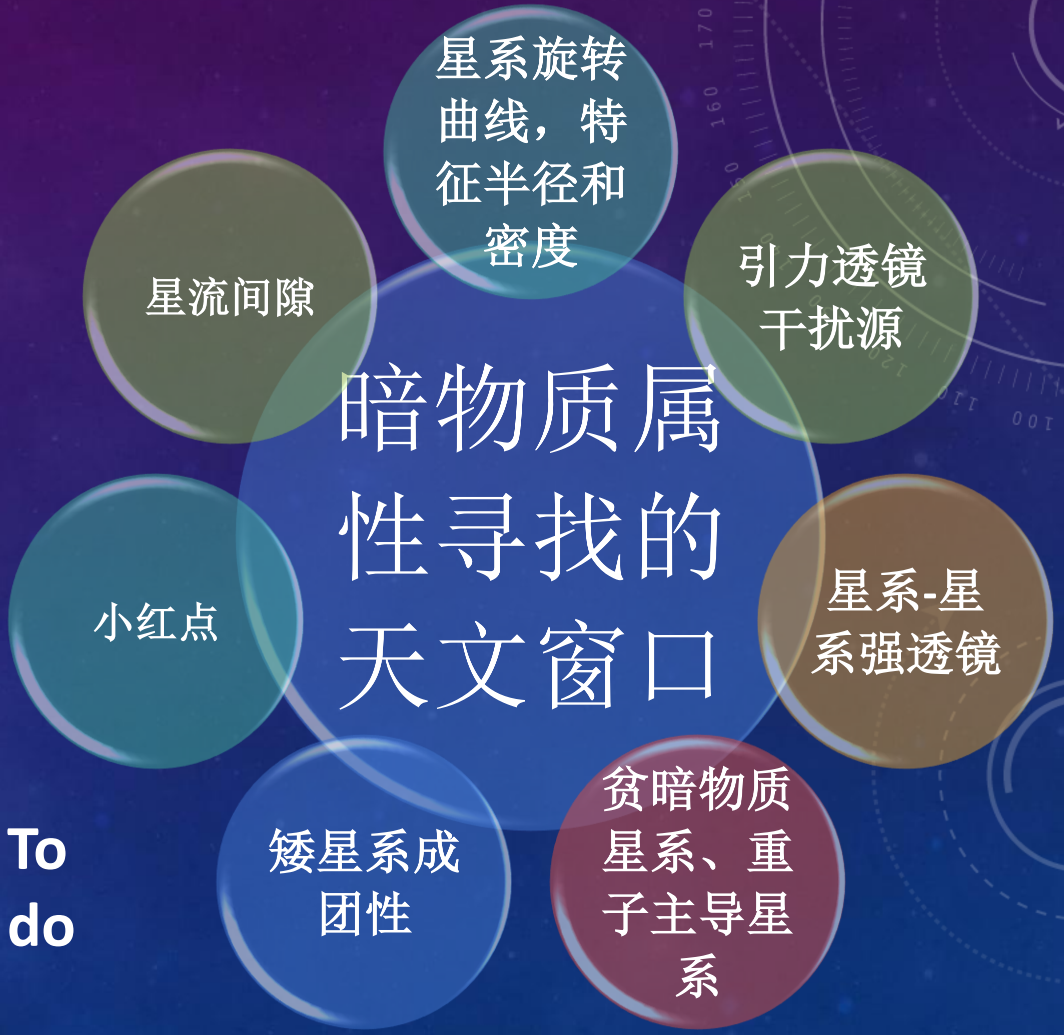
破除底层物理机制可观测效应中的兼并性需要多种观测窗口的协同分析

传统“小尺度危机”的讨论热点

- 核心和尖峰问题
- 过大而不能倒
- 缺失的卫星星系
- 多样性问题

新的小尺度疑难	LCDM	单组份 SIDM	双组分 SIDM（质量分层）
矮星系成团性	✗	✓	✓
强透镜干扰源	✗	✓	✓
星系-星系 强透镜	✗	✗	✓
旋转曲线多样性	🤞	✓	✓
小红点	✗	✓	✓
双黑洞并和	✗ (?)	✓	✓
星流干扰源	(?)	✓	✓

To do



Astrophysical Probes of Dark Matter Properties

Top-down approach

A theory of dark matter

Initial power spectrum & Interaction cross sections

Cosmological simulations

Observable features

- ✓ 自洽并准确
- ■ 技术复杂
- ■ 基于等效理论模拟
- ■ 计算成本高

Bottom-up approach

暗物质弹性散射
- •引力热演化

暗晕/星系的环境和拓扑关联
- •基于图神经网络的参数化模型

新物理效应的参数化预测

非弹性散射
- •加速引力热演化

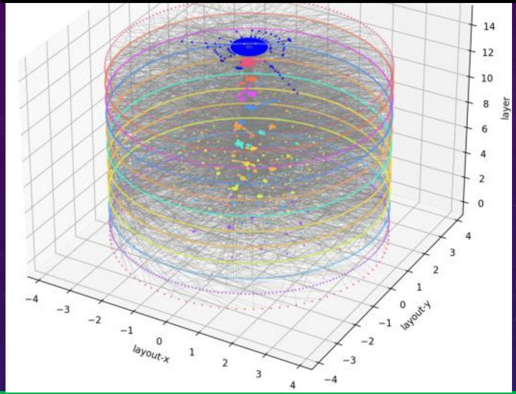
多组分暗物质
- •质量分层引起致密暗晕核心

自加速散射
- •重子引力束缚

- ✓ 分析观测窗口
- ✓ 构建理论图像
- ✓ 实现快速预测
- ■ 需要模拟验证

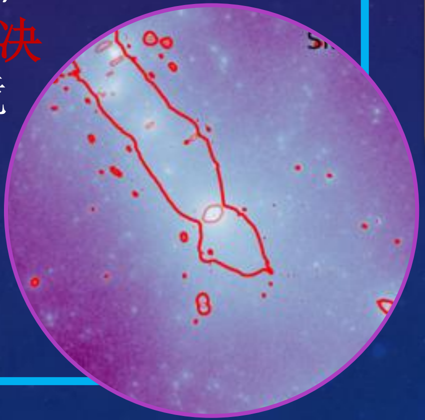
相关工作

跨学科的暗物质属性研究：图论和结构形成



创新提出具有质量分层效应的SIDM模型，解释了长期悬而未决的星系-星系强透镜超出现象

Yang et al. arXiv: 2506.14898 & PRD (2025)



暗物质弹性散射
- 引力热演化

暗晕/星系的环境和拓扑关联
- 基于图神经网络的参数化模型

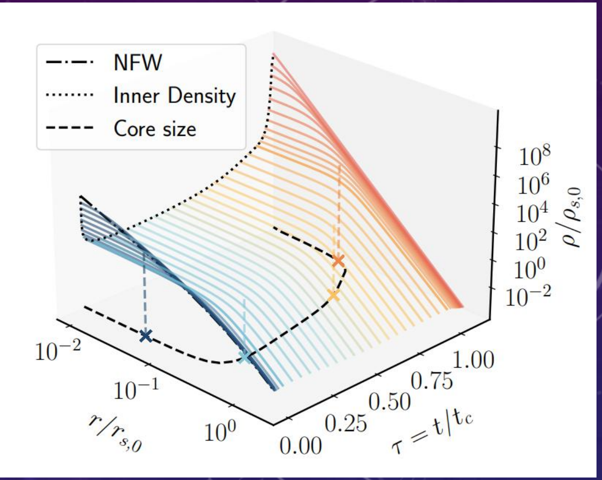
新物理效应的参数化预测

非弹性散射
- 加速引力热演化

多组分暗物质
- 质量分层引起致密暗晕核心

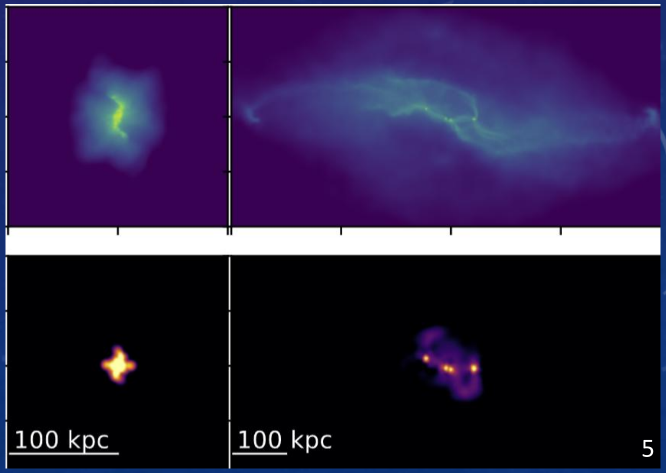
自加速散射
- 重子引力束缚

自相互作用暗晕的参数化模型



https://github.com/DanengYang/parametricSIDM
Yang+2024 JCAP 02 (2024) 032
Yang 2024 PRD 110 (2024) 10, 103044
Yang+2025 PDU 47 (2025) 101807
Hou & Yang + JCAP08 (2025)048

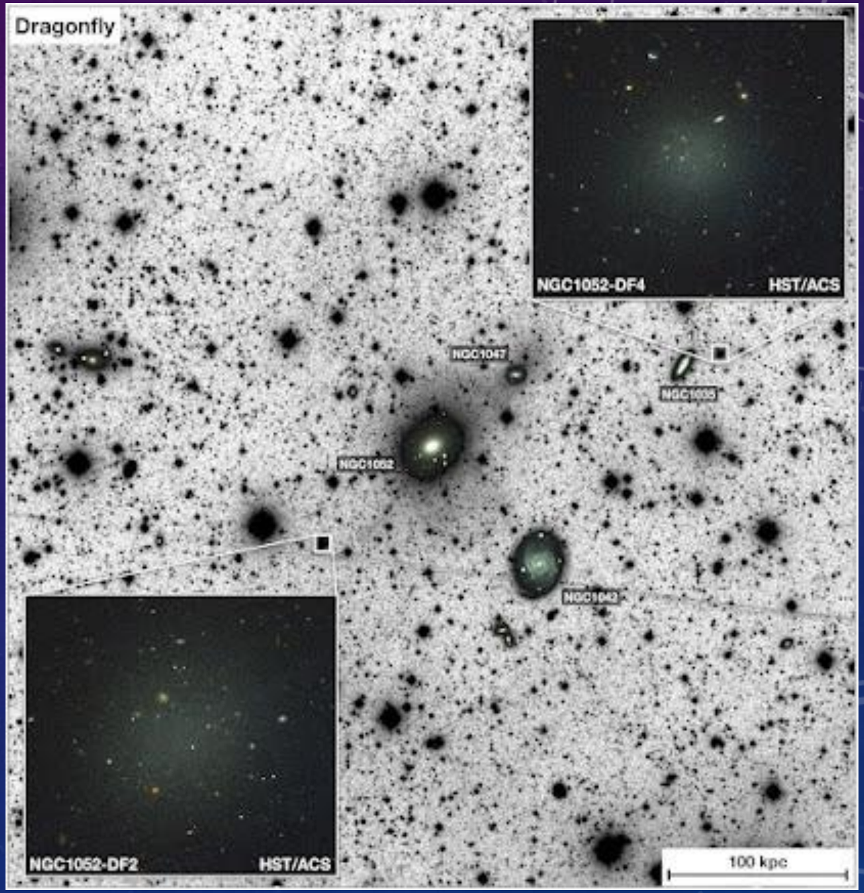
暗物质粒子特性及重子反馈的新探针：贫暗物质/重子主导星系



Wang & Yang et al. 2509.24270

观测和模拟中的贫暗物质/重子物质主导星系

- van Dokkum et al. *Nature* 555, 629–632 (2018), *Nature* 605, 435–439 (2022)
- Guo et al. *Nature Astron.* 4, 246–251 (2019)
- Moreno et al. *Nature Astron.* 6, 496–502 (2022)



van Dokkum et al. 2018

Dark matter deficient galaxies: NGC1052-DF2 & DF4

LCDM predicts that halos hosting **ultra-diffuse galaxies** DF2 & DF4 should be dominated by dark matter

Expect: $M_{DM}/M_{star} \sim 200$

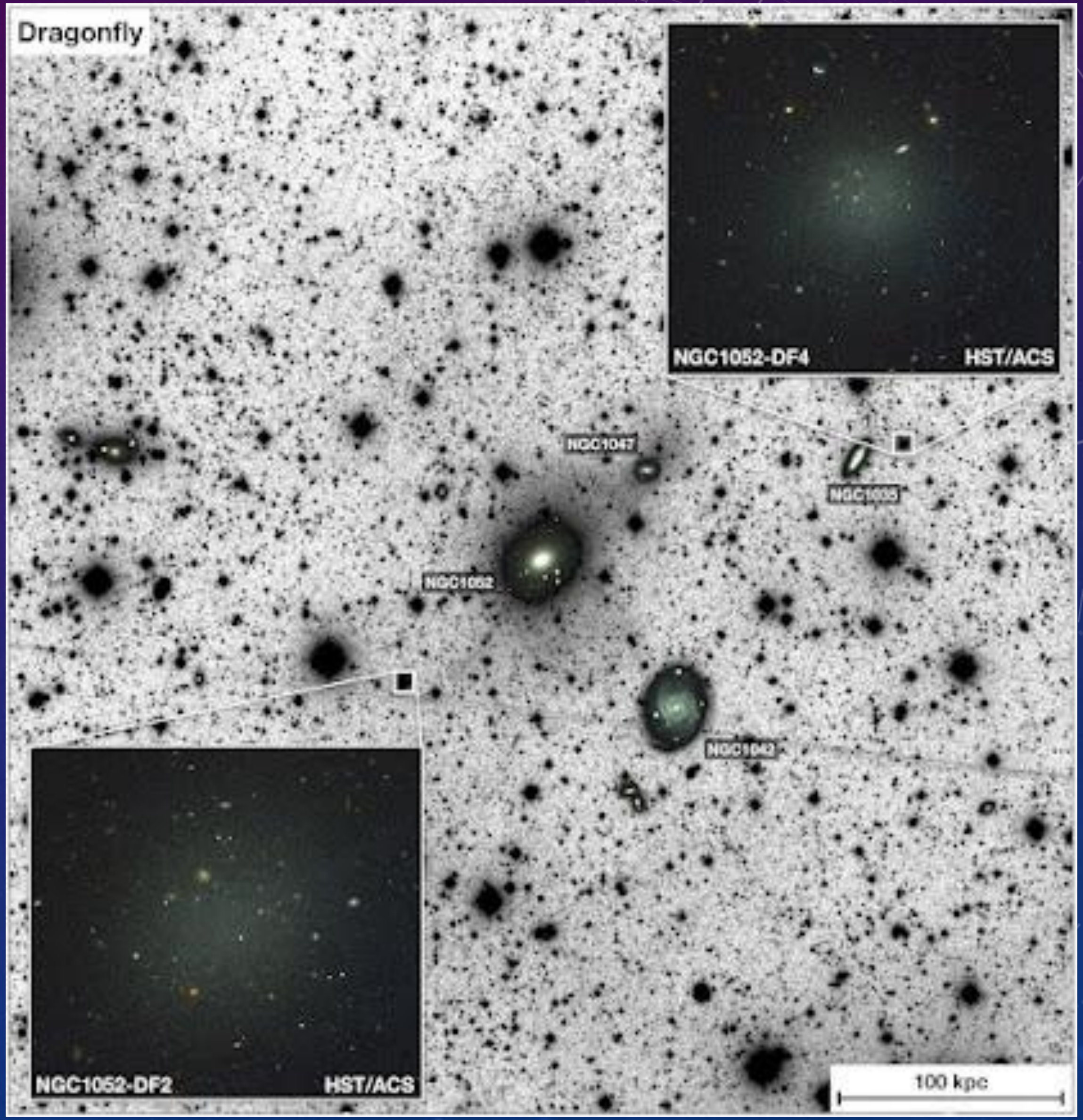
Turns out: $M_{DM}/M_{star} \lesssim 1$

Explaining these observations in LCDM requires at least **-5 sigma from median** （Haslbauer et. al.）

SIDM can alleviate this tension

Yang, Yu, An, PRL, 125:111105

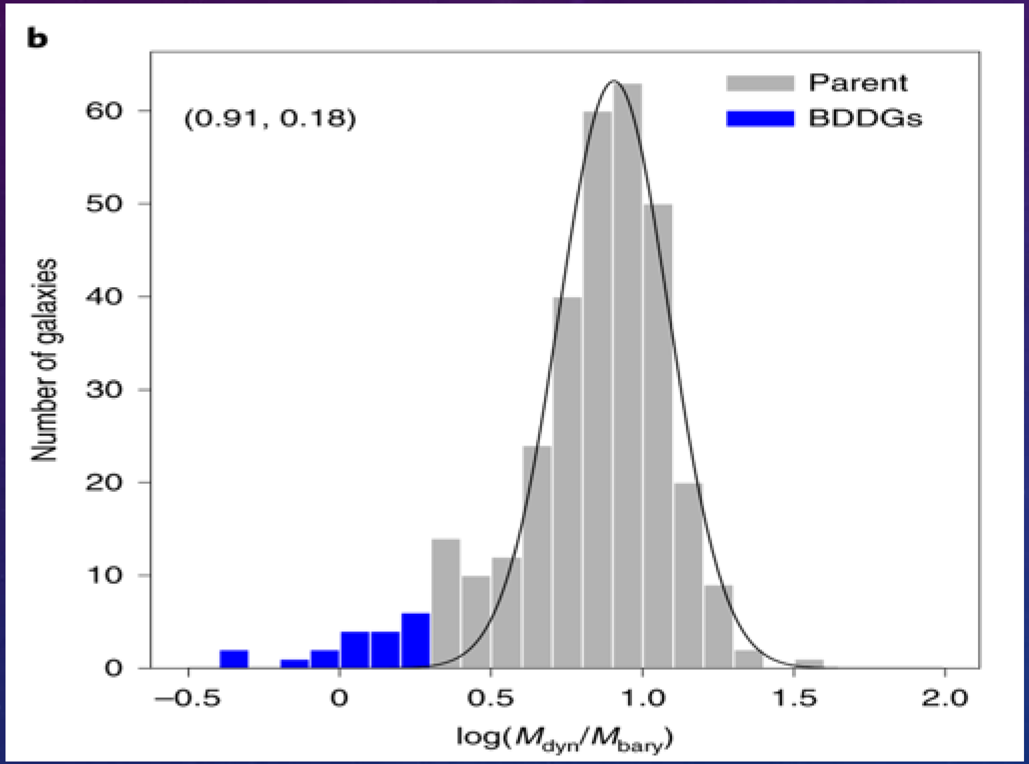
Nature vol. 555, 629-632 (29 March 2018)

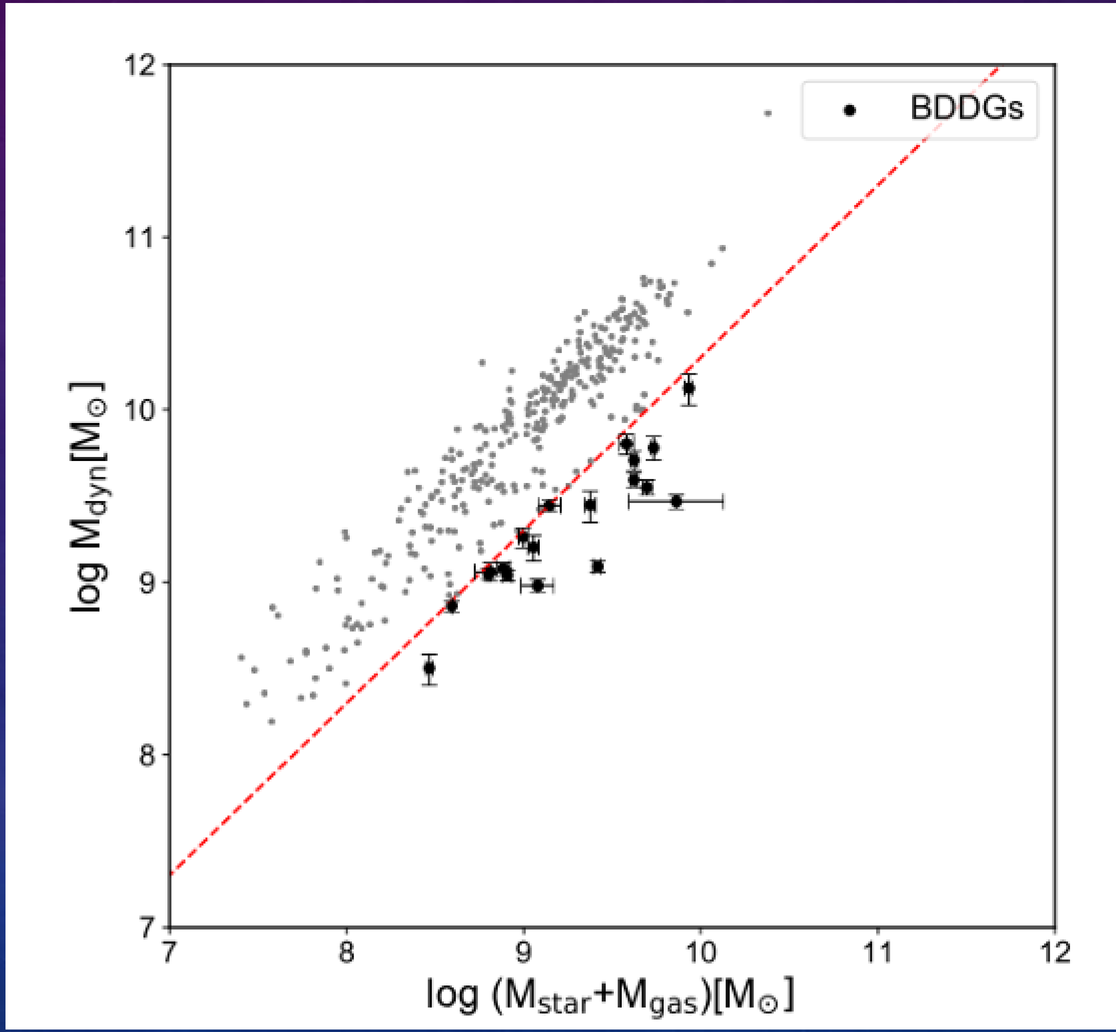


Further evidence of dark matter deficient galaxies

Baryon dominated dwarf galaxies (BDDGs) in Guo et al. 2020 NA

- 19 BDDGs, 14 are isolated
- ALFALFA + SDSS DR7



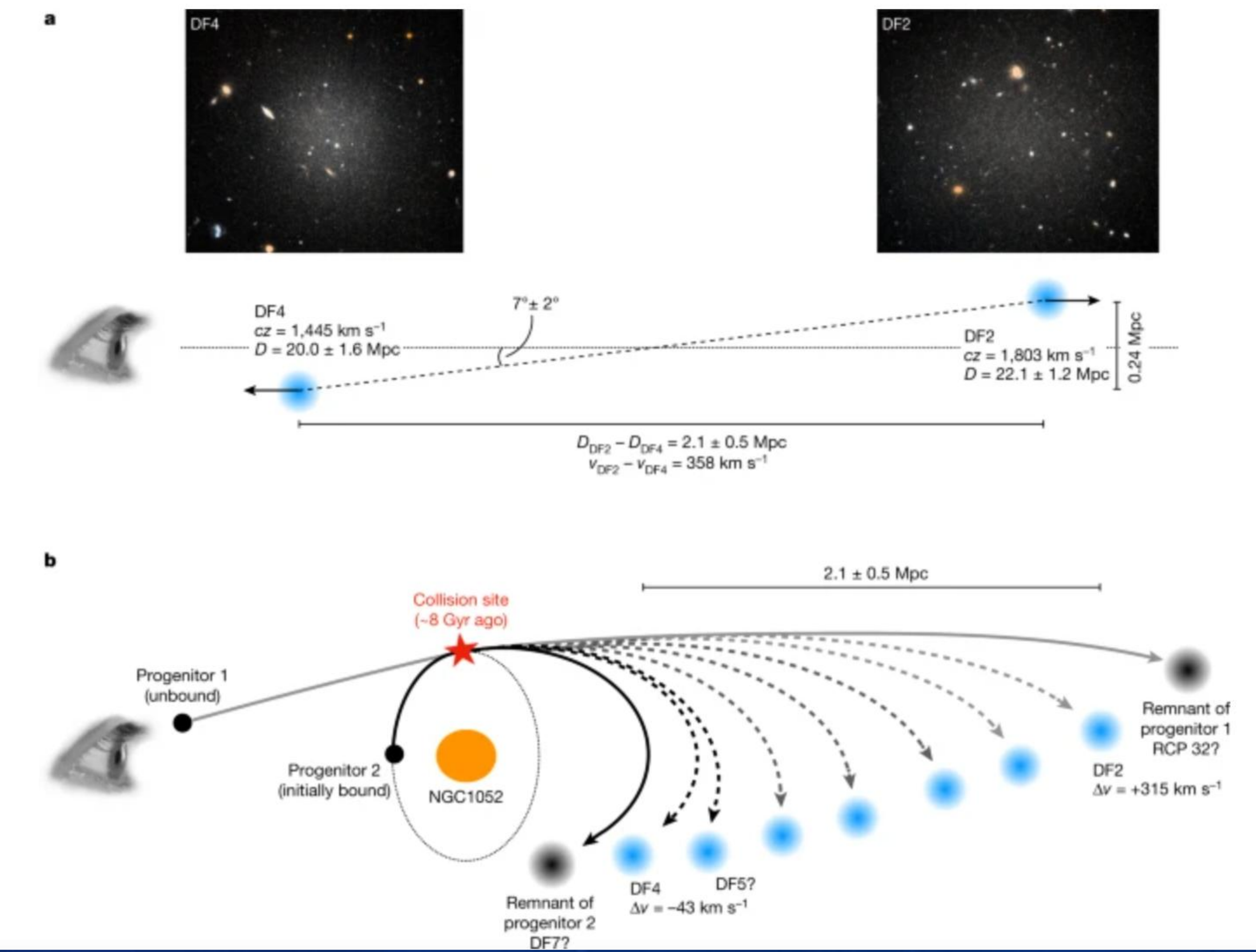


The Collisional Origin of DF2 and DF4

van Dokkum et al.
Nature 2022

A trail of dark-matter-free galaxies from a bullet-dwarf collision

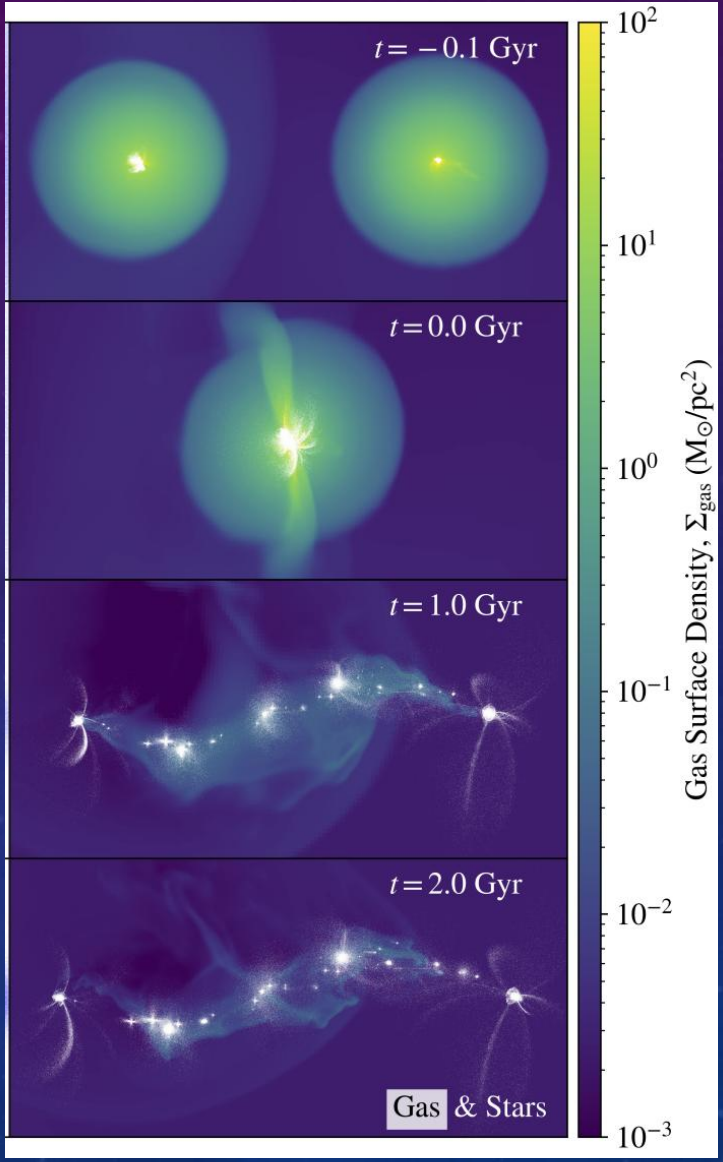
Fig. 1: Geometry of the DF2 and DF4 system.

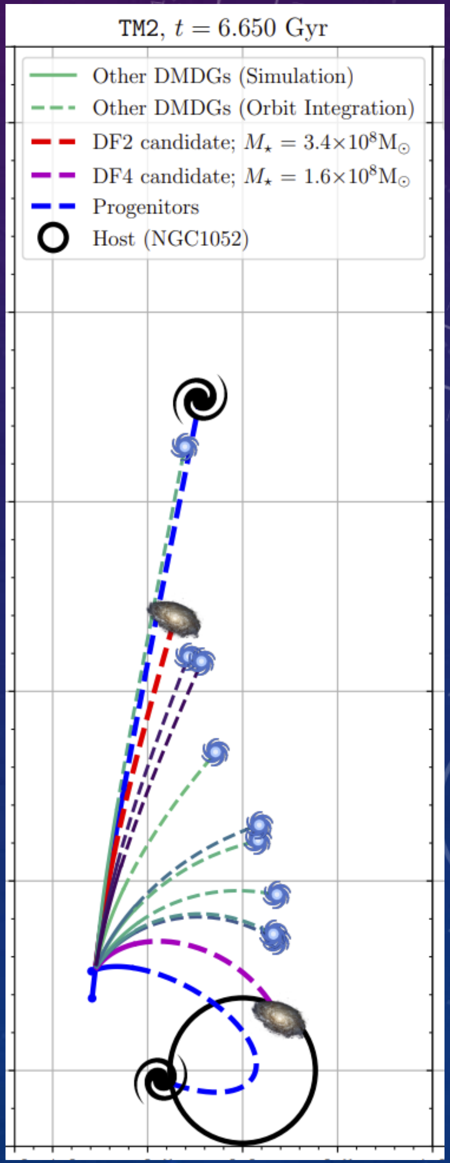


The Collisional Origin of DF2 and DF4

Lee et al. ApJ, 966, 72 (2024)

Reproduce DF2 and DF4 using controlled Hydro/N-body simulations





高气体占比UDG中重子的引力束缚对重子主导星系的形成起到了关键作用

Collisional Baryon-Dominated Dwarf Galaxies: A New Probe of Bursty Feedback and Dark Matter Physics

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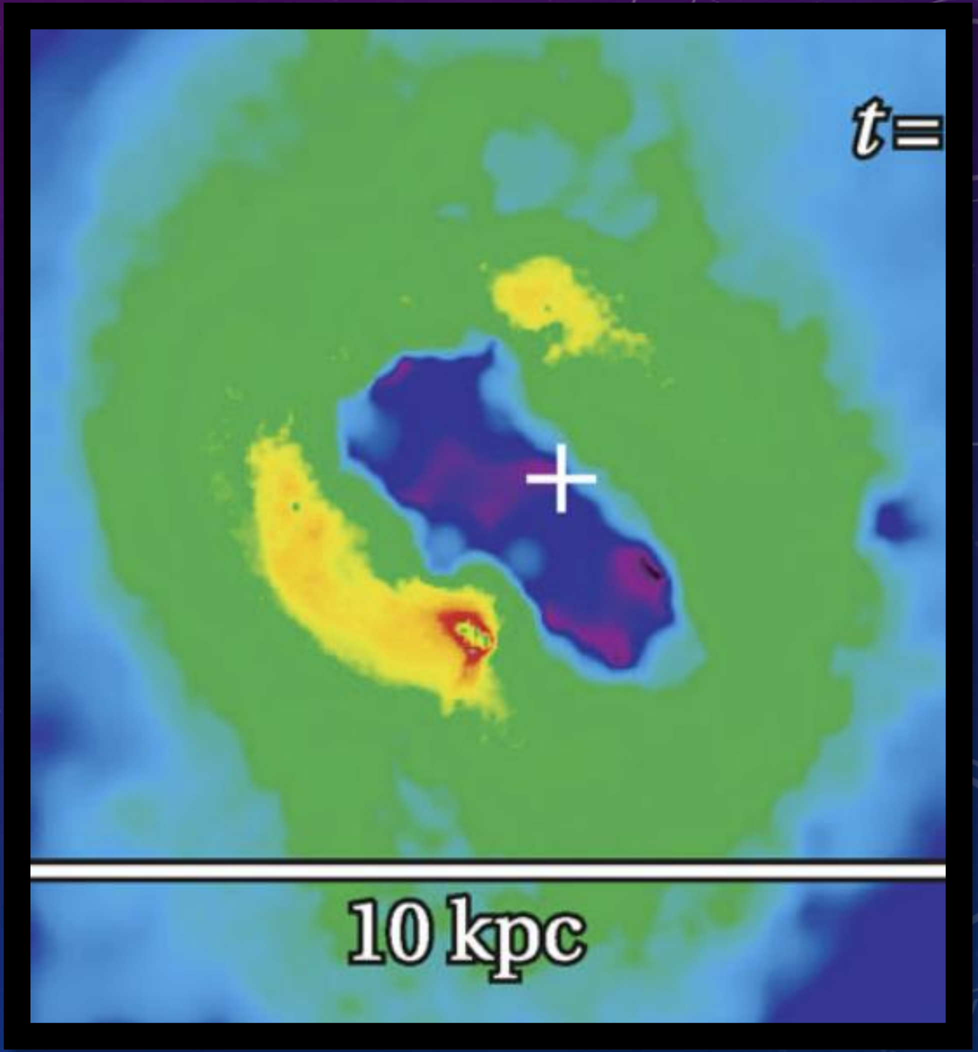
Abstract

High-velocity collisions between gas-rich ultra-diffuse galaxies present a promising formation channel for baryon-dominated dwarf galaxies (BDDGs). Using hydrodynamical simulations, we show that the progenitors' baryonic binding energy, $|E_{\text{bind}}|$, critically controls the outcome. Repeated potential fluctuations, e.g., from bursty feedback, inject energy and reduce $|E_{\text{bind}}|$ by $\approx$ **15%**, yielding fewer but substantially more massive BDDGs. By contrast, elastic self-interacting dark matter produces comparable cores without lowering $|E_{\text{bind}}|$, resulting in negligible effect. This provides a novel way to distinguish between two leading galactic core formation channels, i.e., the baryon feedback and elastic dark matter self-interaction. Among 15 paired simulation runs, 13 show higher BDDG masses in the weakened-binding case, and about two thirds exhibit $>$ **100%** mass enhancements. The simulations also predict systematically lower gas fractions due to sustained post-collision star formation, yielding a clean observational signature. Upcoming wide-field imaging (CSST, LSST), HI surveys (FAST), and kinematic follow-up will be crucial to test this scenario.

重子反馈如何影响重子物质的引力束缚

- 如何产生重子物质主导星系（BDDG）？
- 什么物理过程或物理量对BDDG的产率影响最大?
- 我们能从BDDG的观测中学到什么?



Pontzen et al. 2012 MN

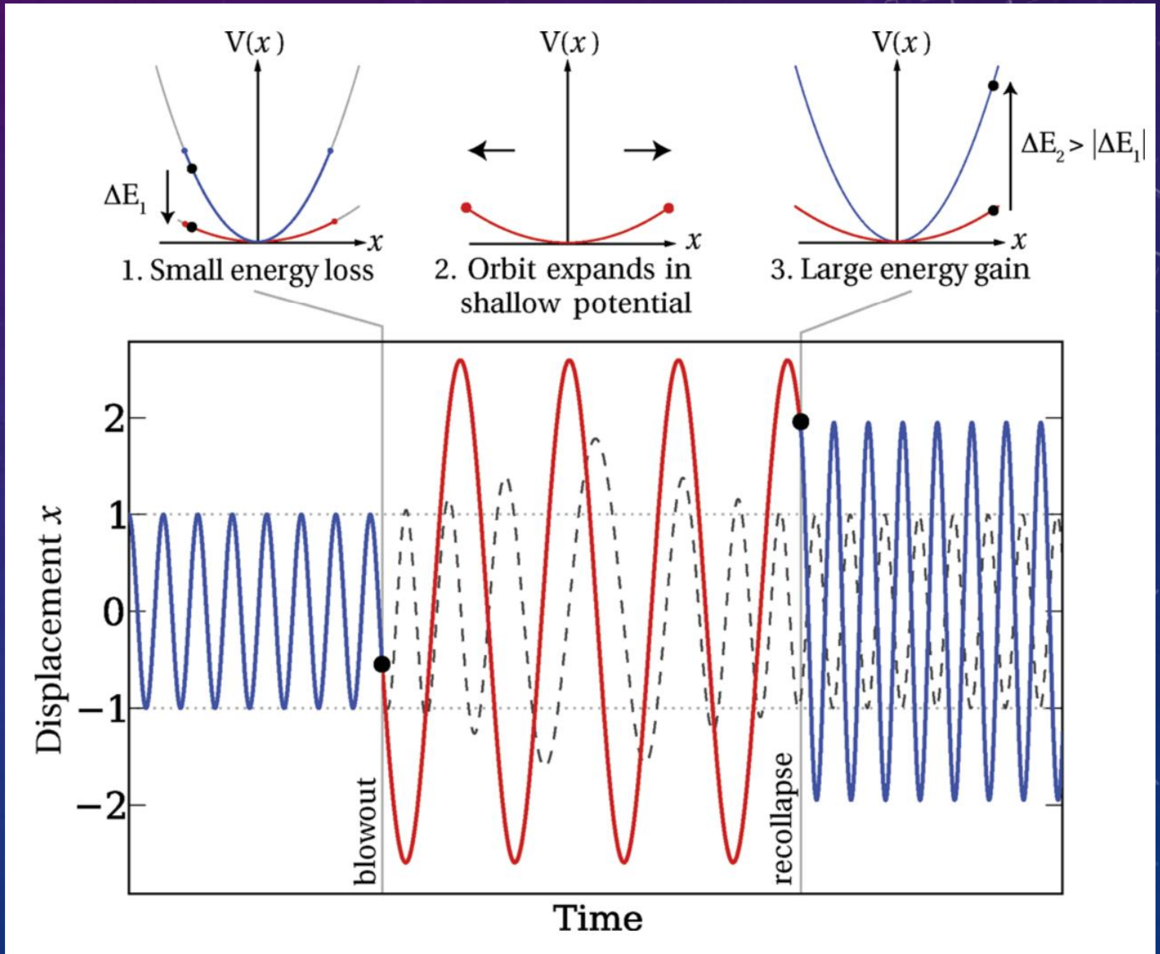
Context: 星系与暗晕的相互影响

How does an oscillating potential inject energy into dark matter particles?

A **sudden** decrease of potential at point 1, which recover instantly at point 3:

The final amplitude of displacement or kinetic energy becomes larger

Gray: if the potential change **adiabatically**, there is no such effect



Analytic model by Pontzen et al. 2012 MN

The challenge to model these accurately…

Deng, Li, et al. 2405.08869 RIGEL

RIGEL: Simulating dwarf galaxies at solar mass resolution with radiative transfer and feedback from individual massive stars

Yunwei Deng[1], Hui Li[1], Boyuan Liu[2], Rahul Kannan[3], Aaron Smith[4], and Greg L. Bryan[5]

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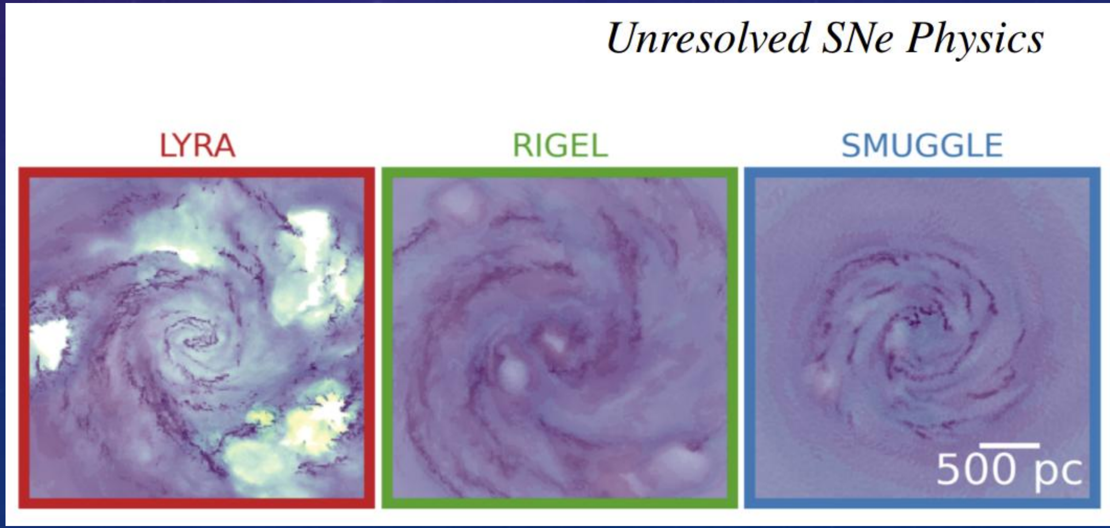
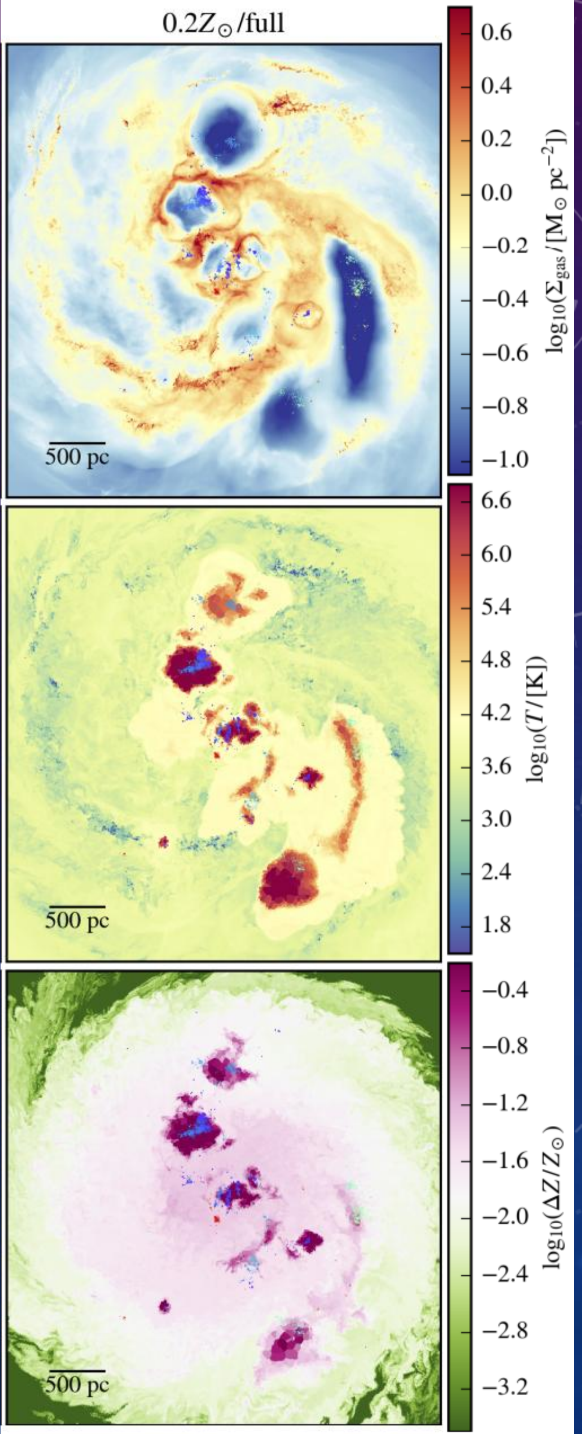
4. Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080, USA
5. Department of Astronomy, Columbia University, New York, NY 10027, USA

The Entangled Feedback Impacts of Supernovae in Coarse- versus High-Resolution Galaxy Simulations

Eric Zhang,[1★] Laura V. Sales,[1] Thales A. Gutcke,[2] Yunwei Deng,[3] Hui Li,[3] Rüdiger Pakmor,[4] Federico Marinacci,[5,6] Volker Springel,[4] Mark Vogelsberger,[7] Paul Torrey,[8] Boyuan Liu,[9] Rahul Kannan,[10] Aaron Smith,[11] and Greg L. Bryan[12]

Zhang et al. 2510.02432
From left to right
t = 250, 450, 650 Myr

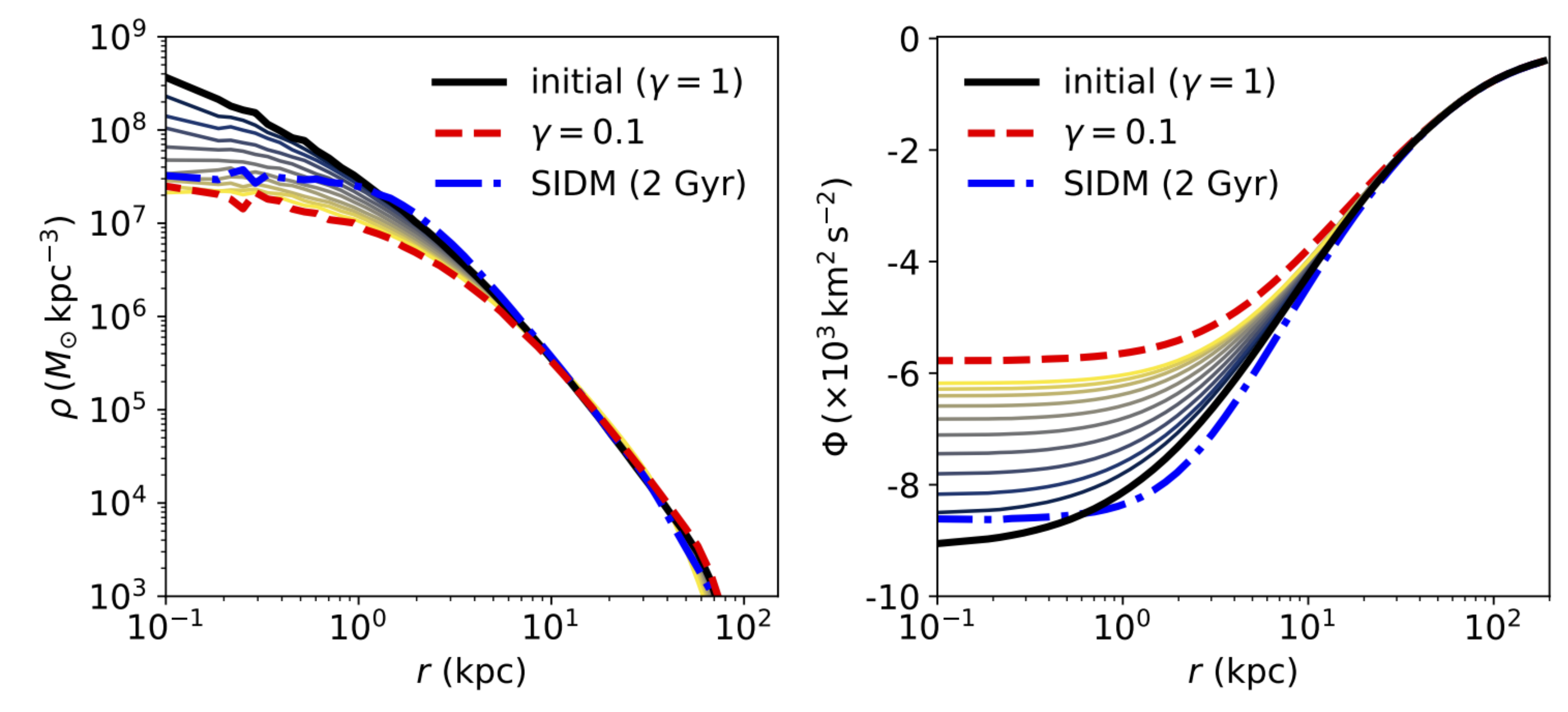


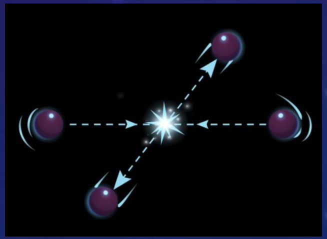


Cored Profiles in Baryon Feedback and Self-Interacting Dark Matter

Cored profiles created by bursty baryon feedback has a shallower potential

Self-Interacting Dark Matter (SIDM) also generate cores, but potential is not significantly changed





Elastic DM scattering

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

γ=1, NFW

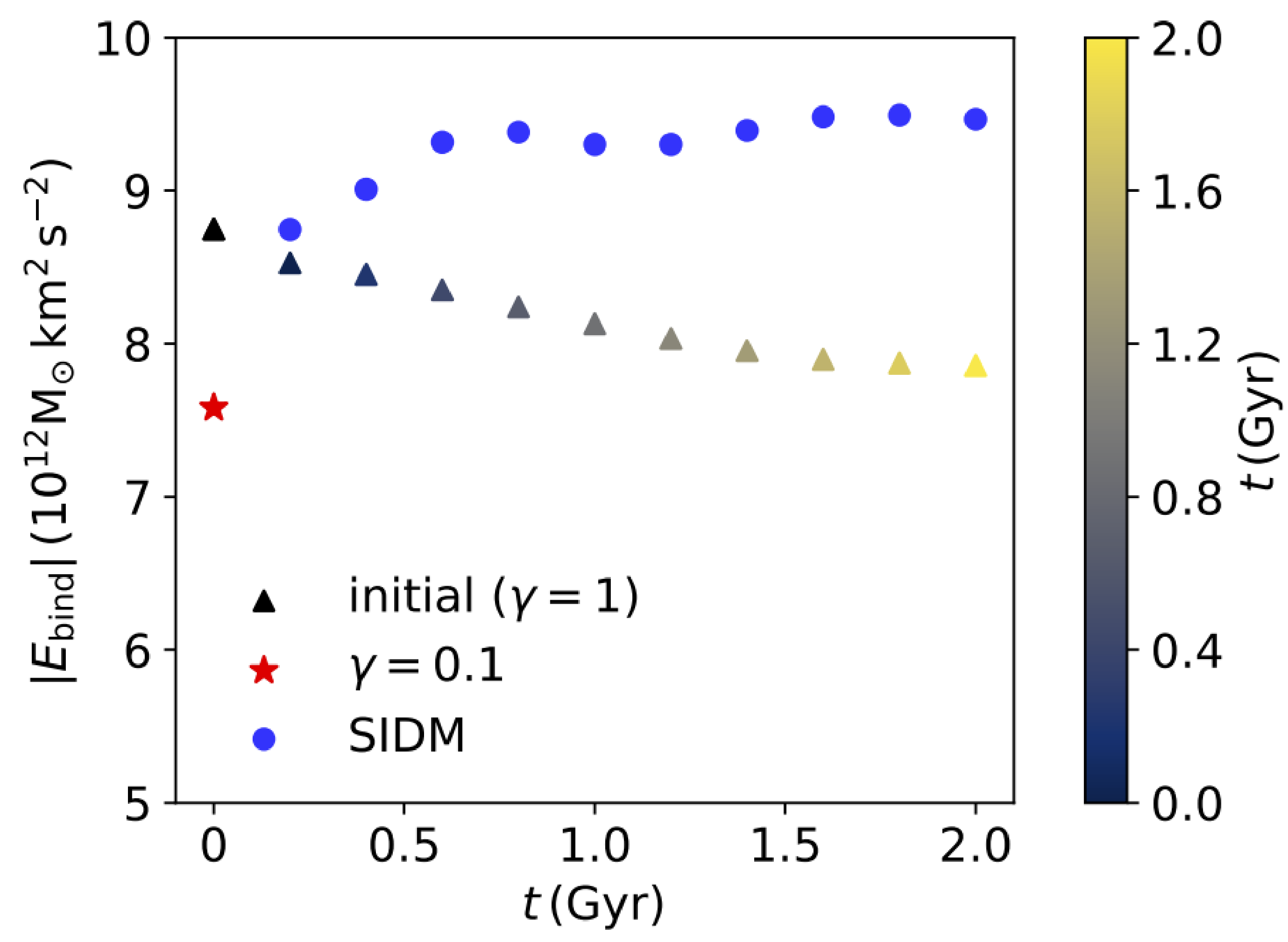
γ=0.1, Core with shallower potential

Cored Profiles in Baryon Feedback and Self-Interacting Dark Matter

Baryon's gravitational binding directly measures the cost to take it outside halos:

$$|E_{\rm bind}| = \int dV\, |\Psi_{\rm tot}(r)|\rho_{\rm gas}(r)$$

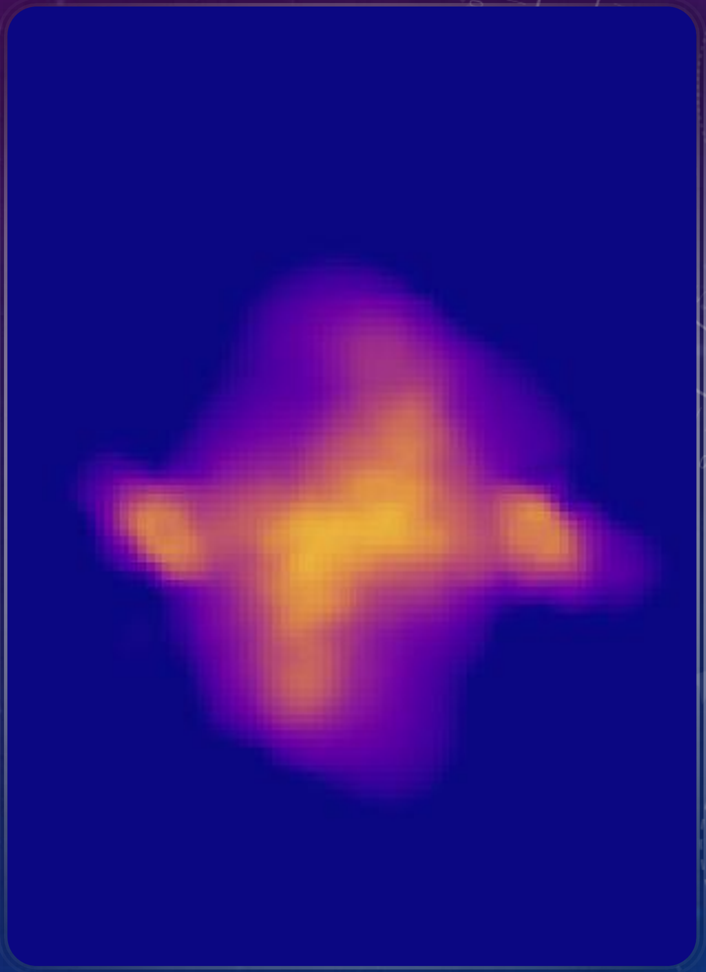
- Bursty potential variation inject energy into the halo, reducing |Ebind| **by ~10%**
- SIDM scattering conserves energy, the relaxation between dark matter and baryons leads to increase in |Ebind|



星系对撞产生的重子物质主导星系(BDDGs)

A crucial observational portal for modern and upcoming telescopes

Previous works (bullet clusters): drag or deceleration
This work: binding energy ⇔ fraction of baryon mass

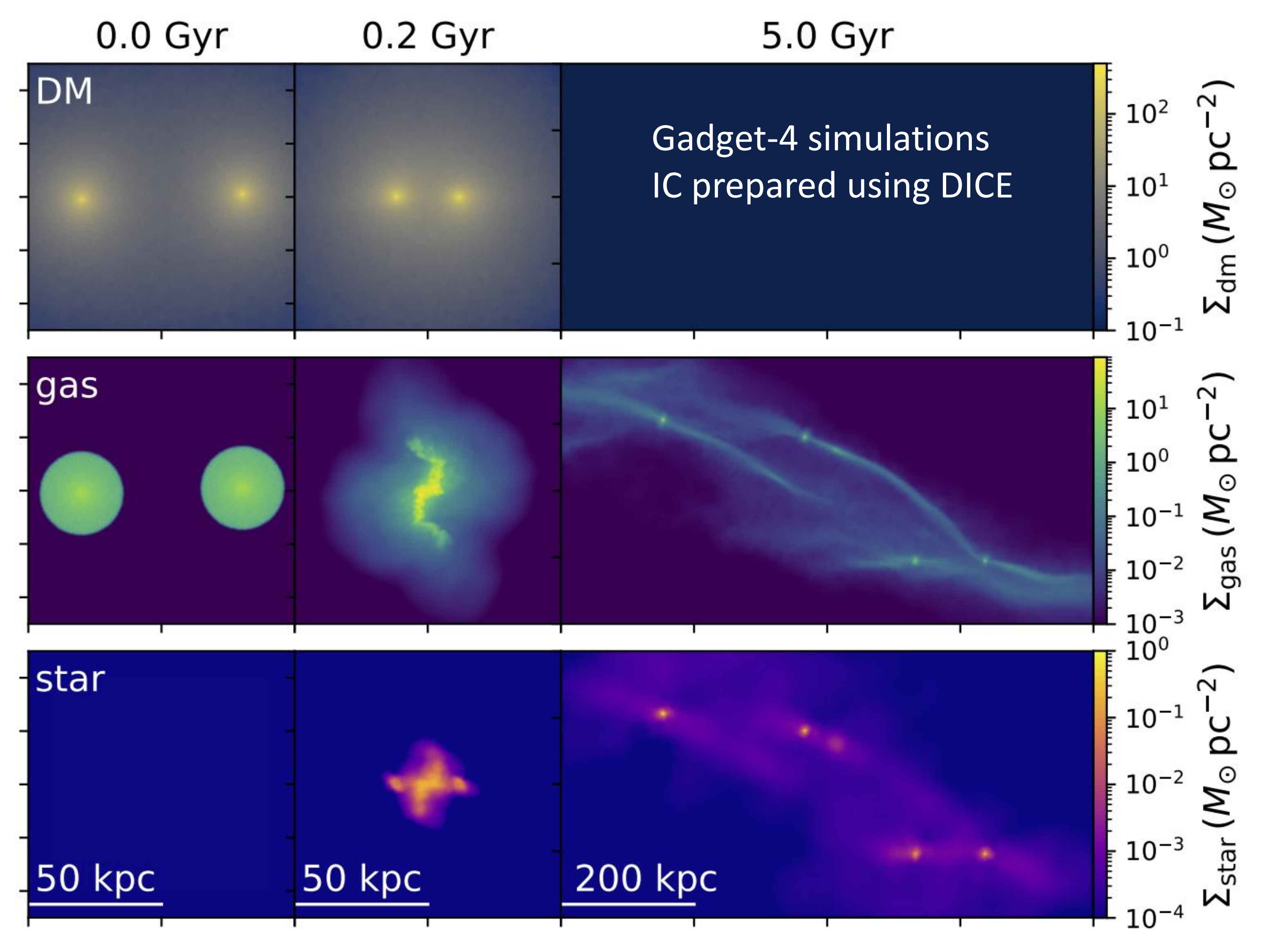


Paired galaxy collision simulations with gamma=1 and 0.1

γ=1, NFW
γ=0.1, Core with shallower potential

Ram-pressure pushes the gas content outside their progenitor halos

- How massive are the BDDGs?
- How many can be produced?
- Under what conditions do we have multiple BDDGs?

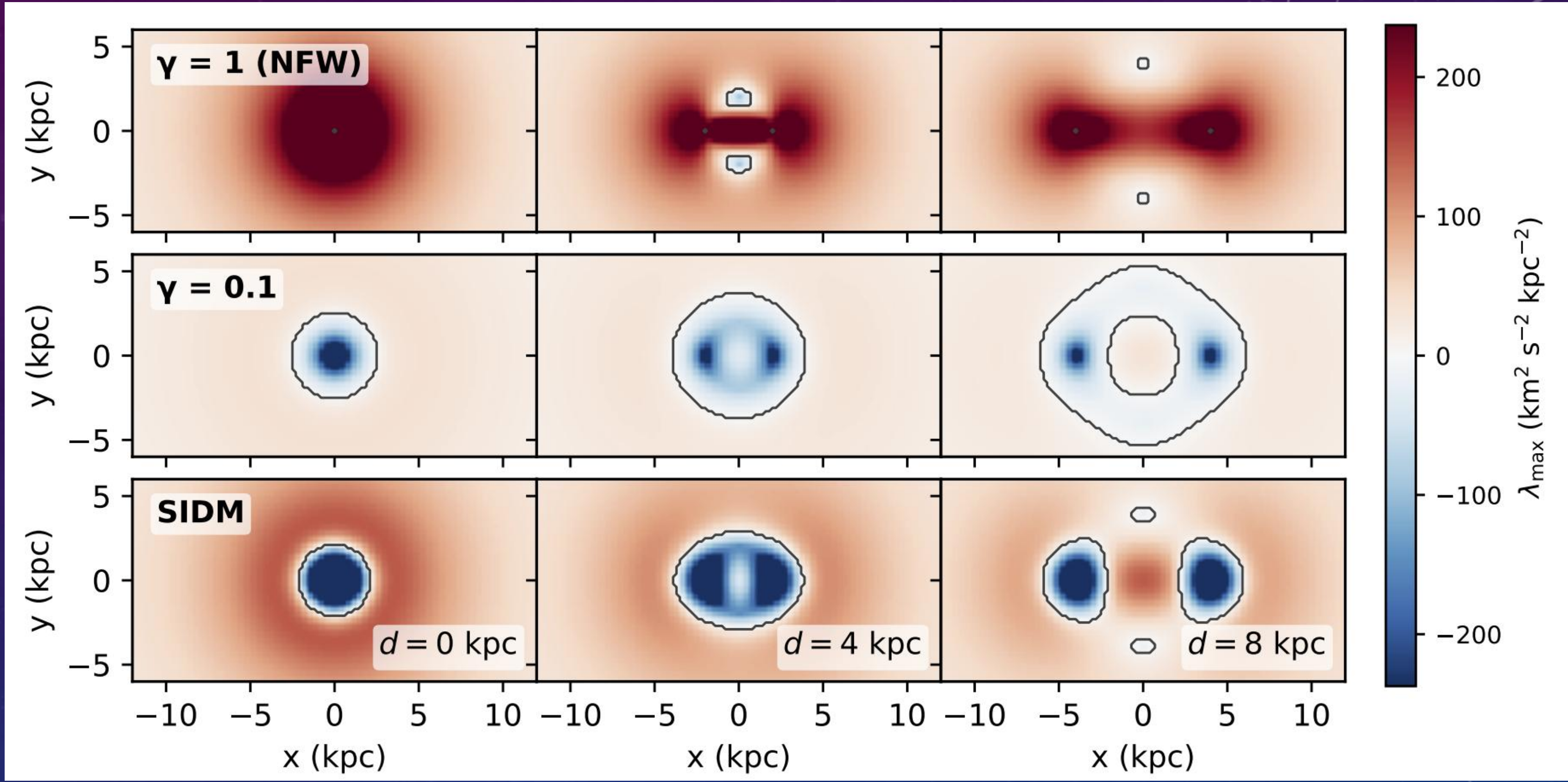


Gas move under a tidal wind of dark matter

The **largest eigenvalue (λ_{max})** of the tidal tensor in the middle plane

$$T_{ij} = \partial_i \partial_j \Phi$$

γ=1: multiple small BDDGs
γ=0.1, single massive BDDG



λ_{max}>0: extensive tide
λ_{max}<0: compressive tide → form more massive BDDG

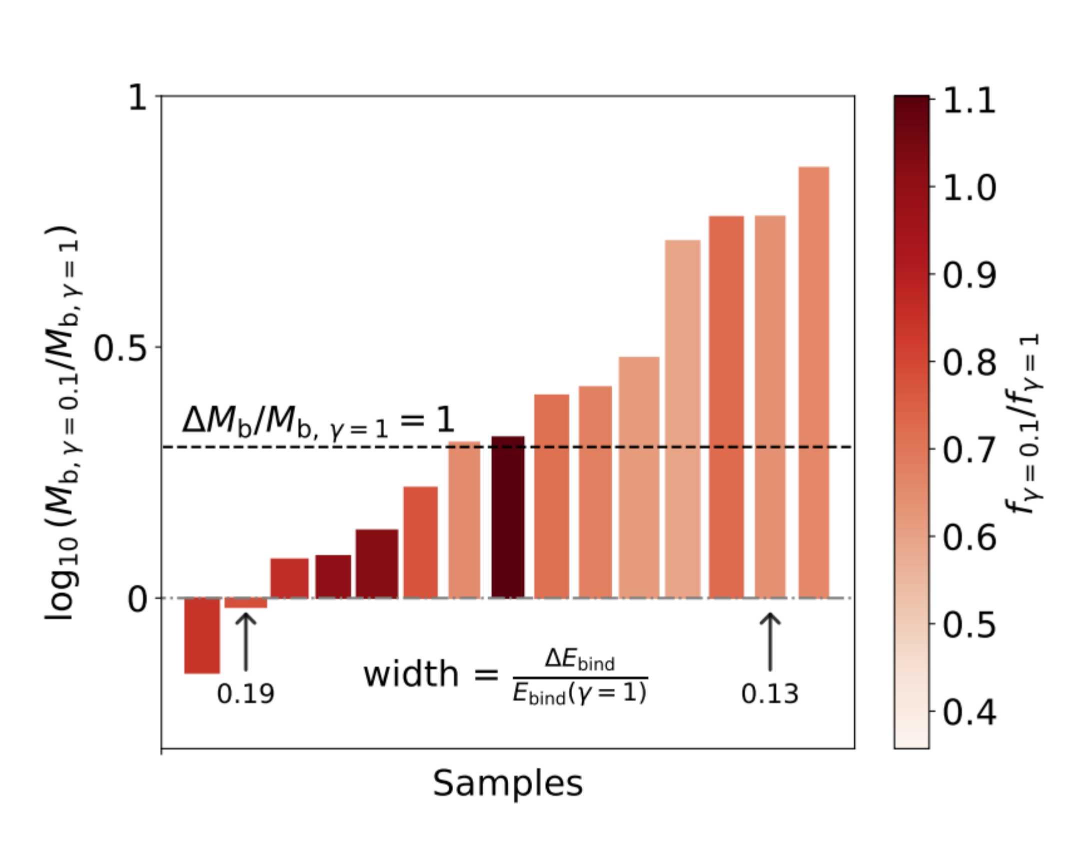
A suite of paired simulation results

Characteristics of the most massive BDDGs in 15 paired simulations

gamma=0.1 case has just ~ 10% lower |Ebind|

9 out of 15 shows enhanced BDDG masses > 100% in the gamma=0.1 scenarios

Almost all cases show smaller gas fraction fgamma=Mgas/(Mgas+Mstar)



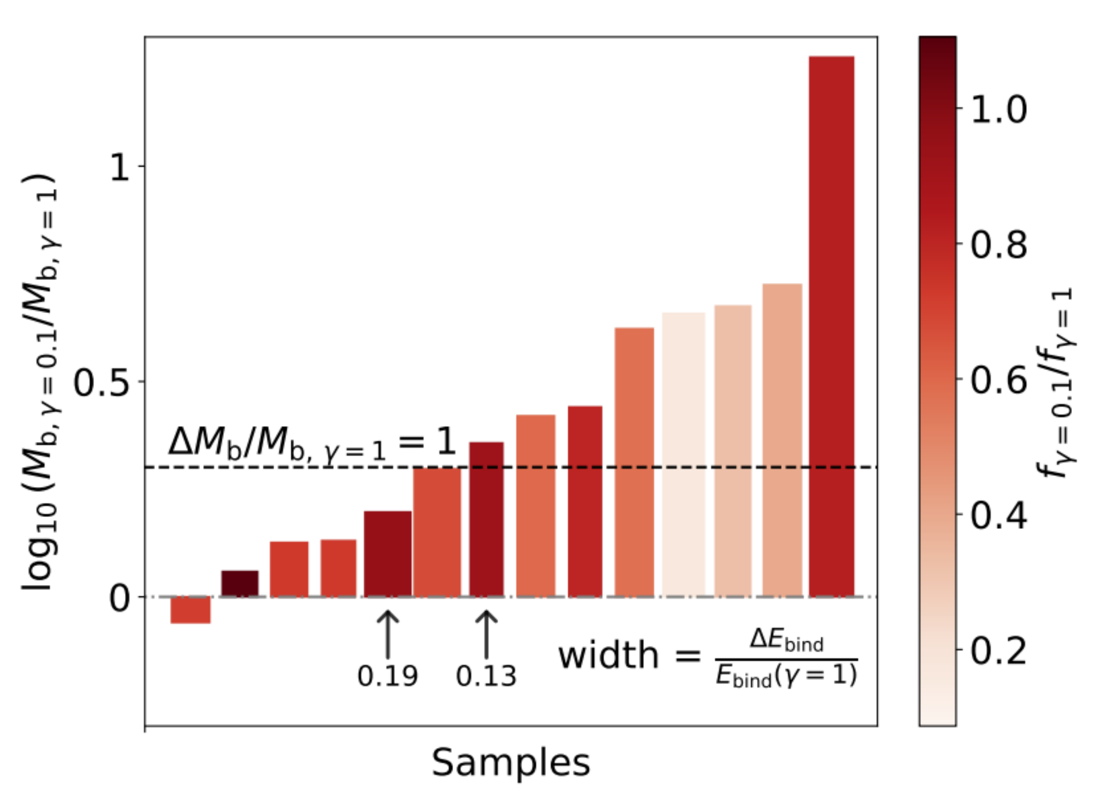
Same results, gas cooling reduced by 50%

If reducing the gas cooling efficiency by 50%...

Most features remain the same
--- 8 out of 14 shows > 100% enhancement

Notably

- More low-mass BDDGs, leading to features look like tidal dwarf galaxies



Post-collision star formation is more efficient in gamma=0.1

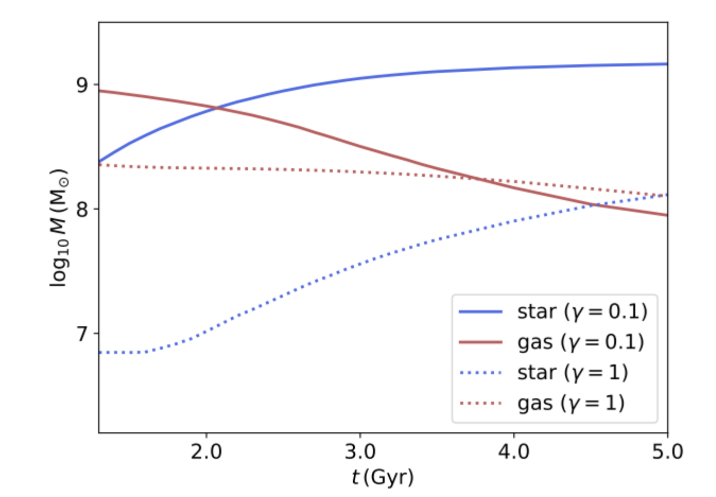
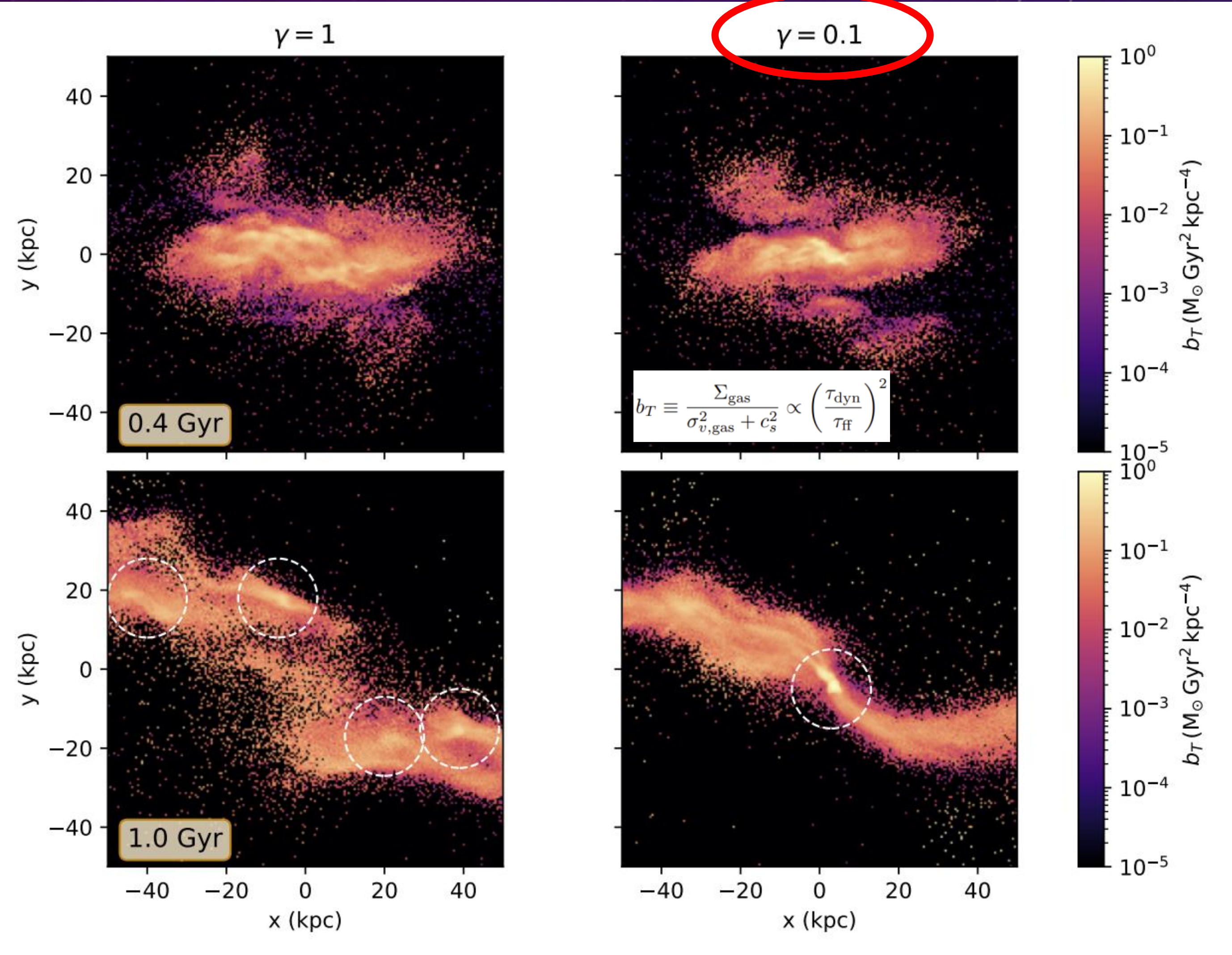
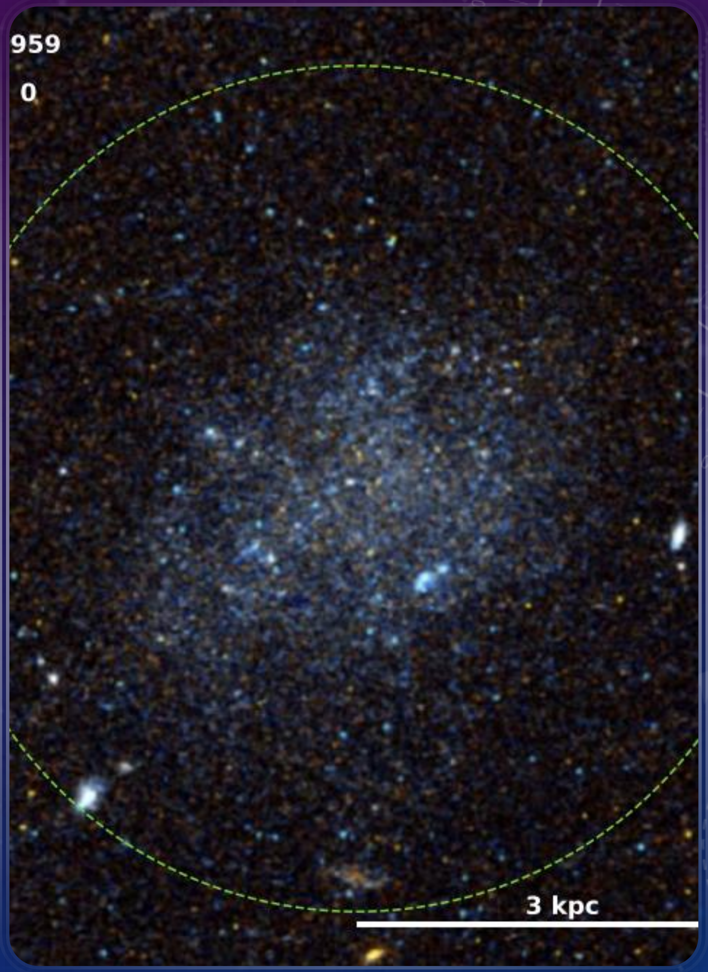


Fig. A2 Post-collision star formation. Mass evolution of the most massive BDDGs in the 2a ($\gamma = 1$) and 2b ($\gamma = 0.1$) simulations. In the weakened binding case ($\gamma = 0.1$), efficient star formation yields a more massive BDDG after the collision, with continued activity beyond 2 Gyr steadily depleting the gas reservoir. For $\gamma = 1$, star formation is much less efficient, leaving a substantial gas fraction even at 5 Gyr. In both scenarios, the total BDDG mass increases only modestly, from 11×10^8 $M_\odot$ (2.3×10^8 $M_\odot$) to 15×10^8 $M_\odot$ (2.6×10^8 $M_\odot$) in the $\gamma = 0.1$ ($\gamma = 1$) case.

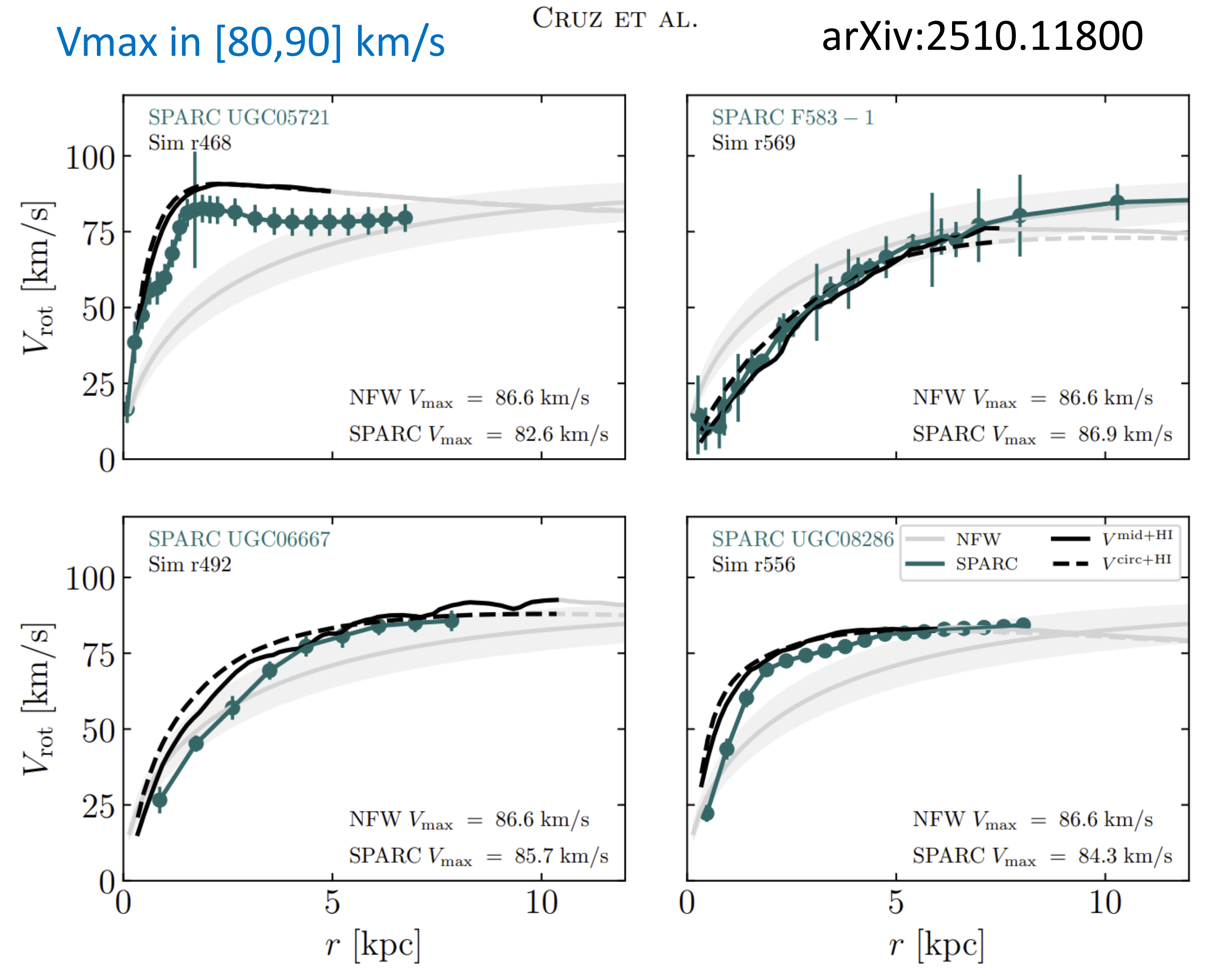


Implementation 1:
The strength of bursty feedback in (isolated) gas-rich UDGs



From Jones et al. 2023 ApJL

The Multifaceted Nature of Baryon Feedback

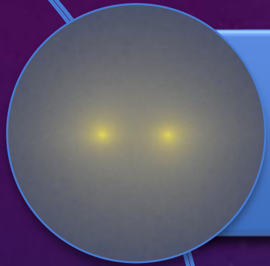


Feedback manifests differently in individual galaxies,

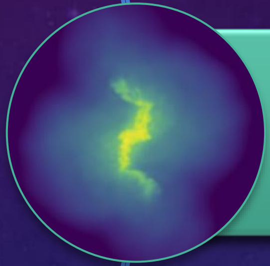
interplay with the hosting dark matter halos,

and potentially explaining the diversity of observed rotation curves.

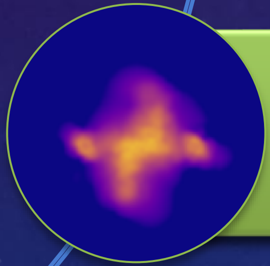
The Multifaceted Nature of Baryon Feedback



The outcome depends on galaxy assembly history



Feedback self-regulates through star formation

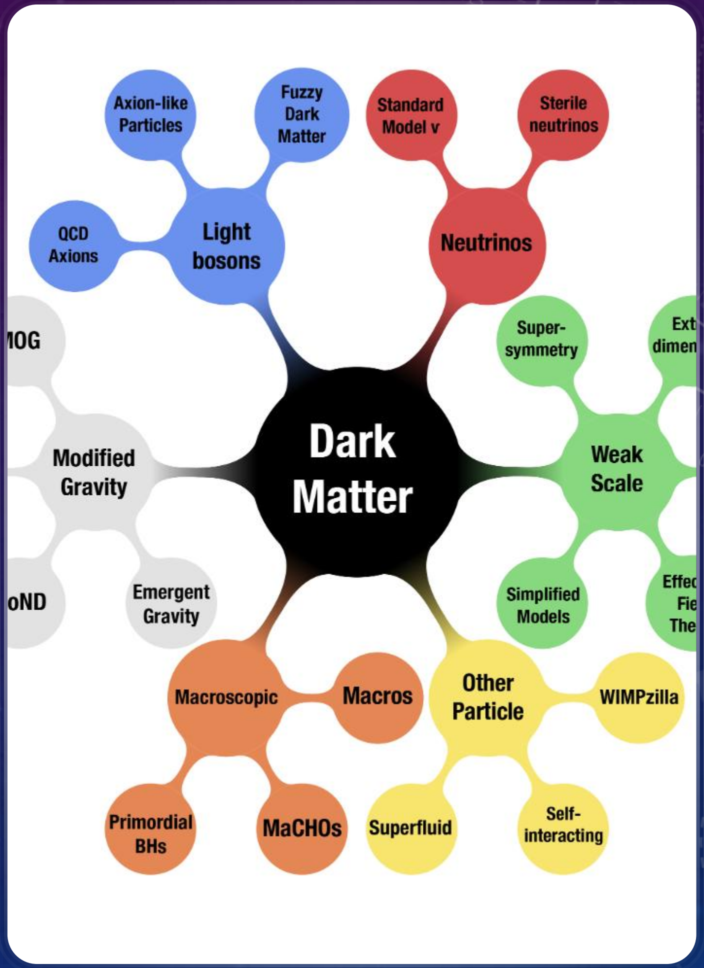


Environmental modulation by gas accretion, tidal and ram-pressure stripping

Gas-rich Ultra-Diffuse Galaxies can have different strength and patterns of baryon feedback

- ***Shallower potential***
- ***Higher spin***
- ***Continuous gas inflow***
- ***Strong bursty feedback***
- ***……***

Implementation 2: Signatures from dark matter physics



(Image: G. Bertone and T. M. P. Tait)

Energy injection through dark sector dynamics

Mechanisms of Energy Injection into Halo

1

Bosenovae

Periodic and Non-adiabatic change of dark matter densities
inject energy into central halo

2

Exothermic self-interacting dark matter

chi1+chi1 -> chi2+chi2, where m2<~m1 and hence more energetic;
the injected kinetic energy should be small to keep chi2 inside halos

3

Dynamical Dark Matter

Multi states/continuum dark matter models
Kinetic redistribution during transitions

4

Cannibal Dark Matter

Mass decrease in n->2 processes; reducing particle number and mass density but heating itself kinetically

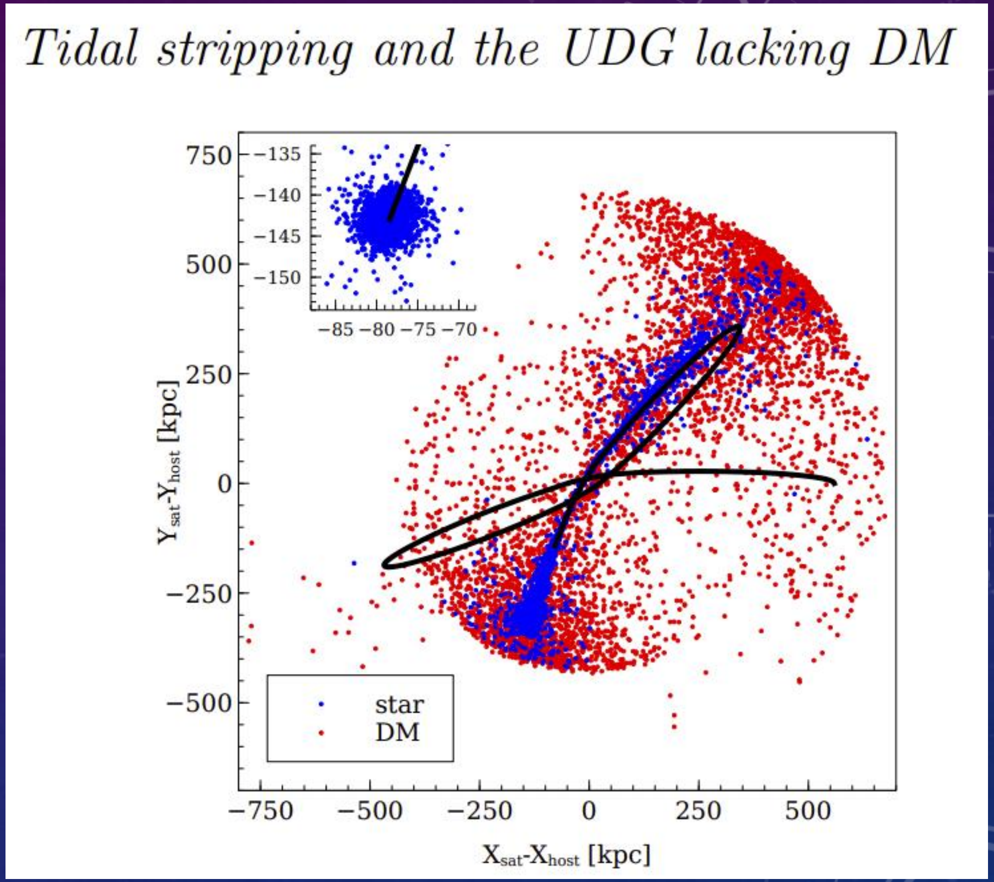
Warm dark matter?

… …

Baryon Dominated Dwarfs in Host halos

Lower mass Tidal Dwarf Galaxies (TDGs) suffer from ram-pressure stripping

Tidally stripped galaxies with gamma=0.1 can become dark matter deficient and still appear as a dwarf galaxy today



Go Ogiya 2018 used the same parametrization of density profile, showing subhalos under strong tidal stripping in gamma=0.1 can explain DF-2

Challenges of Cosmological Simulations for Bursty SN-Feedback

IllustrisTNG / EAGLE / SIMBA

- Gas particle (cell) mass ≈ 10^4–10^5 Msun, softening ≈ 100–300 pc
- Star formation threshold ≈ 0.1 cm^{-3} → gas never reaches true molecular-cloud densities
- Subgrid feedback

FIRE-2 / NIHAO / FABLE zoom-ins

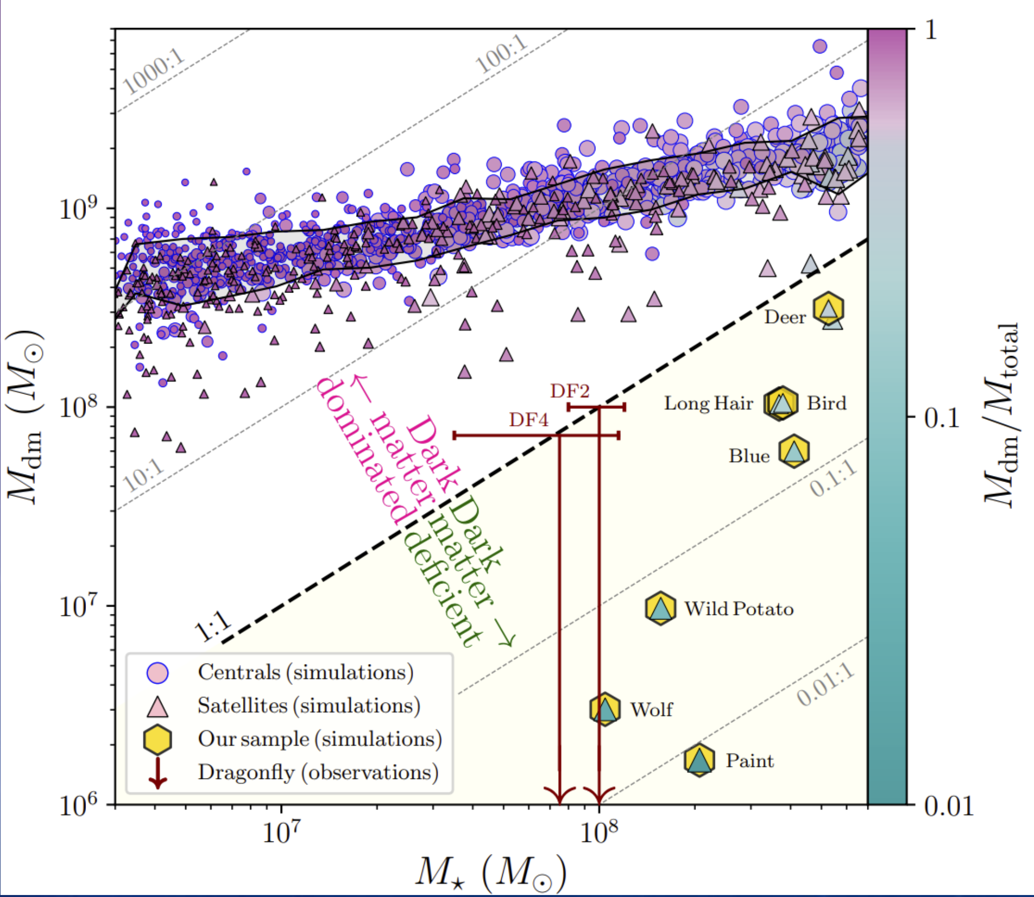
- Gas mass ≈ 10^3 Msun or better, softening ≈ 1–10 pc
- Resolve clustered star formation ($n \gtrsim$ 100–300 cm^{-3}) → naturally bursty SN cycles
- Can drive repeated inflow–outflow events and heat DM cores
- But extremely expensive → small sample sizes, limited cosmological volume

Current models struggle to capture **both cosmological environment and bursty central feedback** simultaneously

Quantify the population of BDDGs in cosmological simulations

Moreno et al. 2022 NA: Galaxies lacking dark matter produced by close encounters in a cosmological simulation

Based on FIRE2 zoom-in simulations



Observations of such systems therefore provide a powerful diagnostic of the energy injection mechanisms. Wide-field surveys (LSST, WFST, CSST, Roman, Euclid) will greatly expand catalogs of low-surface-brightness galaxies, identifying BDDG candidates through diffuse morphologies, old stellar populations, and bright globular clusters. However, optical imaging alone cannot confirm their baryon-dominated nature. Crucially, 21-cm surveys (FAST, MeerKAT, VLA) will provide gas fractions and kinematics, establishing whether baryons alone account for the observed dynamical support. Together, these facilities will enable systematic searches, constrain the frequency of BDDG formation, and map their mass spectrum.

Question:

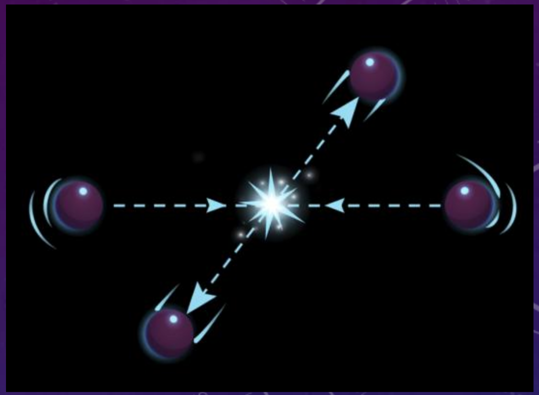
How well can we pre-select a population of potential BDDGs for following up confirmation?

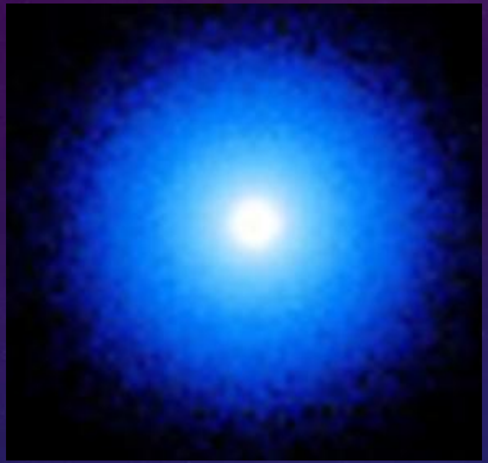
Thanks for your attention!

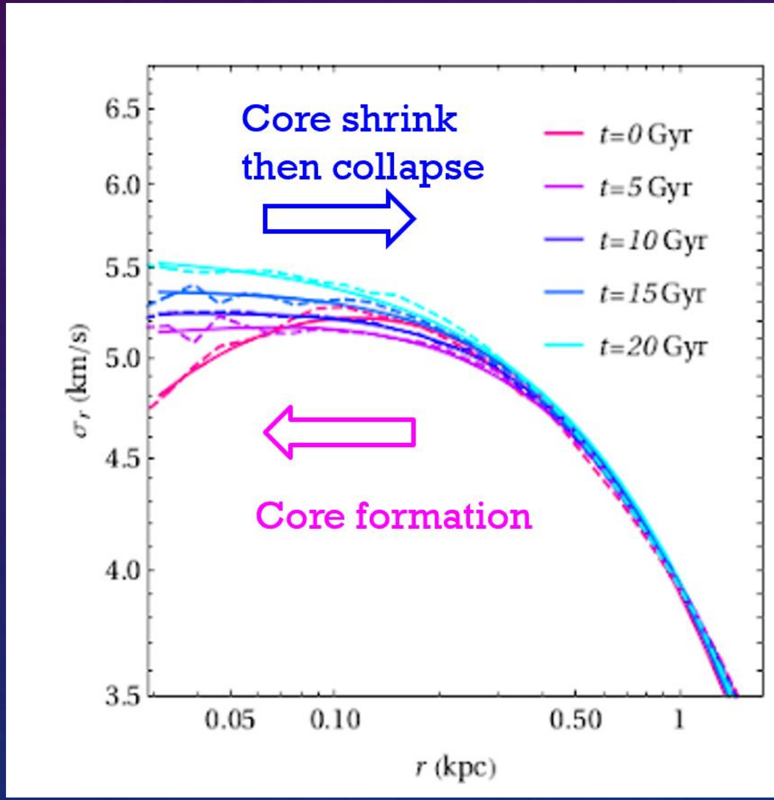
Back up

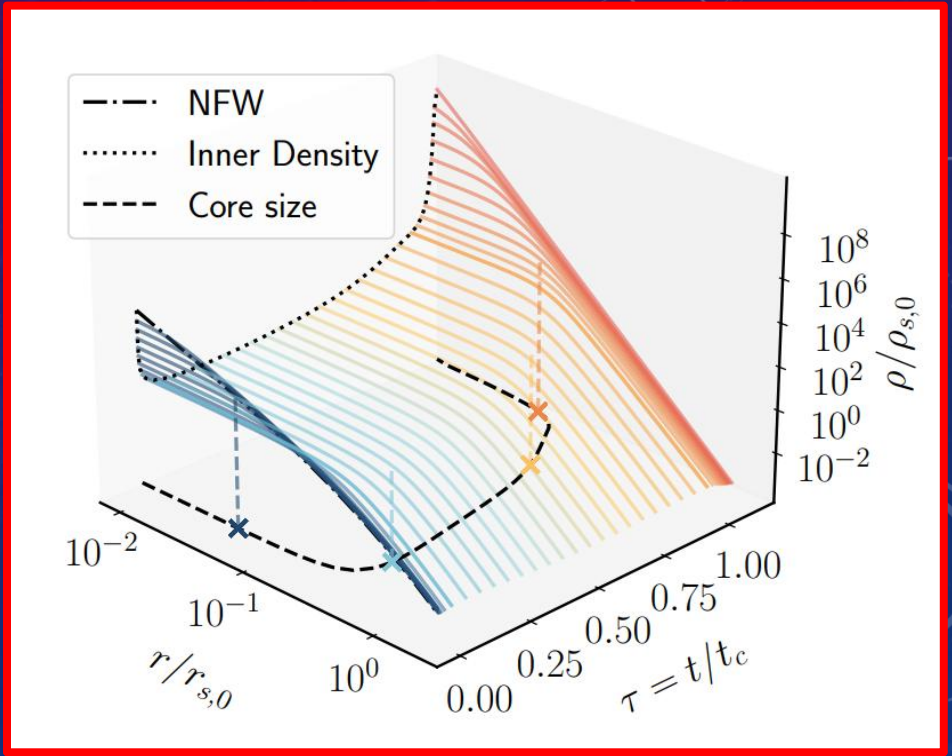
Self-Interacting Dark Matter (SIDM) halos

- Elastic scattering
- Gravothermal evolution (energy transport)
- Core formation
- Core collapse









暗物质晕本身不发光，只能通过其所包含的星系或引力透镜效应来探测

Spergel & Steinhardt 2000, Tulin and Yu 2017 (Review) and many other works

Observational windows

数据很多，问题也很多，我们的理解依然有限

Observational challenges

- Cluster lensing
- Galaxy-Galaxy Strong Lensing (GGSL)
- Strong lensing perturbers
- Little Red Dots
- High-z Super Massive Black Holes
- Galactic rotation curves
- Stellar streams
- Dark Matter Deficient Galaxies (DMDGs)
- Dwarf galaxy clustering
- ……

- Excessive GGSL events
- Overly dense strong lensing perturbers
- Unexpected dwarf clustering
- Diversity problem
- Core cusp problem
- Gaps in stellar streams
- Origin of little red dots
- Final parsec problem of BH binary merger
- Origin of DMDGs
- ……

Models and directions to explore

- Self-Interacting Dark Matter (SIDM)
- MACHO scatterings
- PBH scatterings

Suppressed power spectrum, e.g., Warm dark matter
Enhanced Power Spectrum, e.g., Primordial Black Holes, e.g., Ultra-slow roll inflation

- Dissipative SIDM
- DM-baryon scatterings
- Indirect signatures

Boosted Dark Matter
Atomic Dark Matter
Multi states/continuum dark matter

- Warm dark matter
- Exothermic dark matter
- Dynamical dark matter
- Cannibal dark matter
- Bosenovae
- DM induced baryon feedback

真实世界只有一个，最可能的模型会是什么？