Dark Matter in our galaxy and beyond

New frontiers for DM

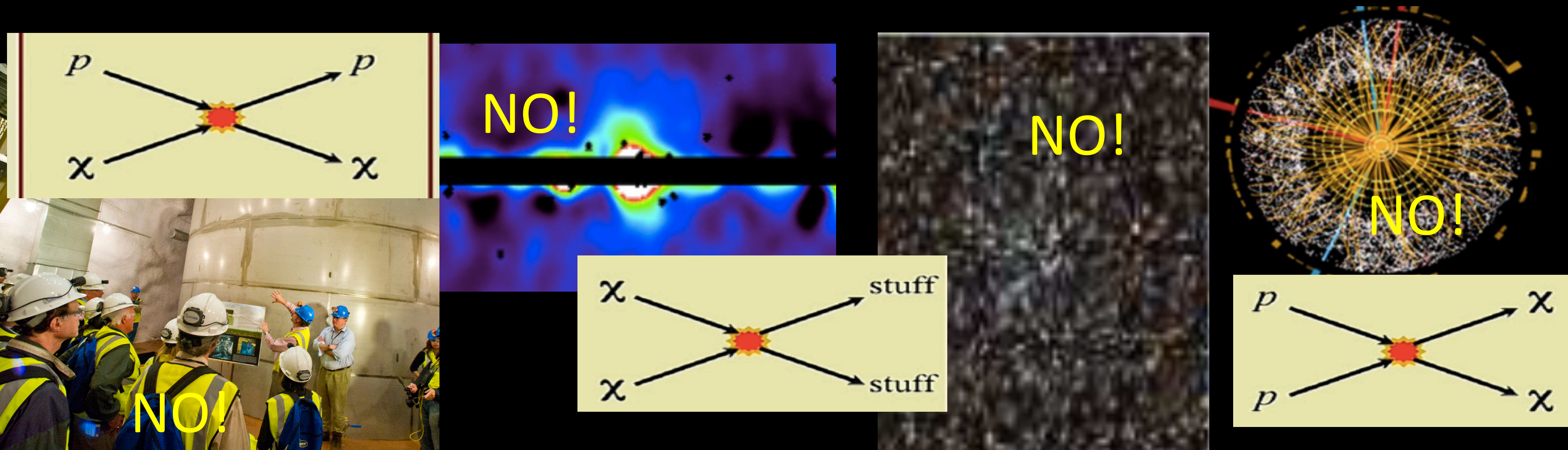
Joe Silk

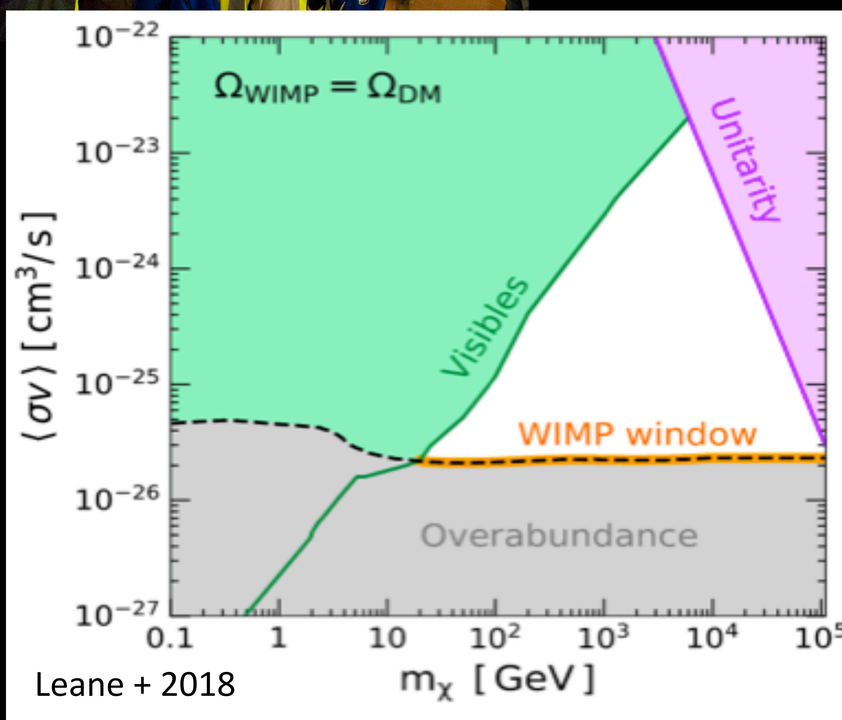
SLAP 2018
Dec 17 2018

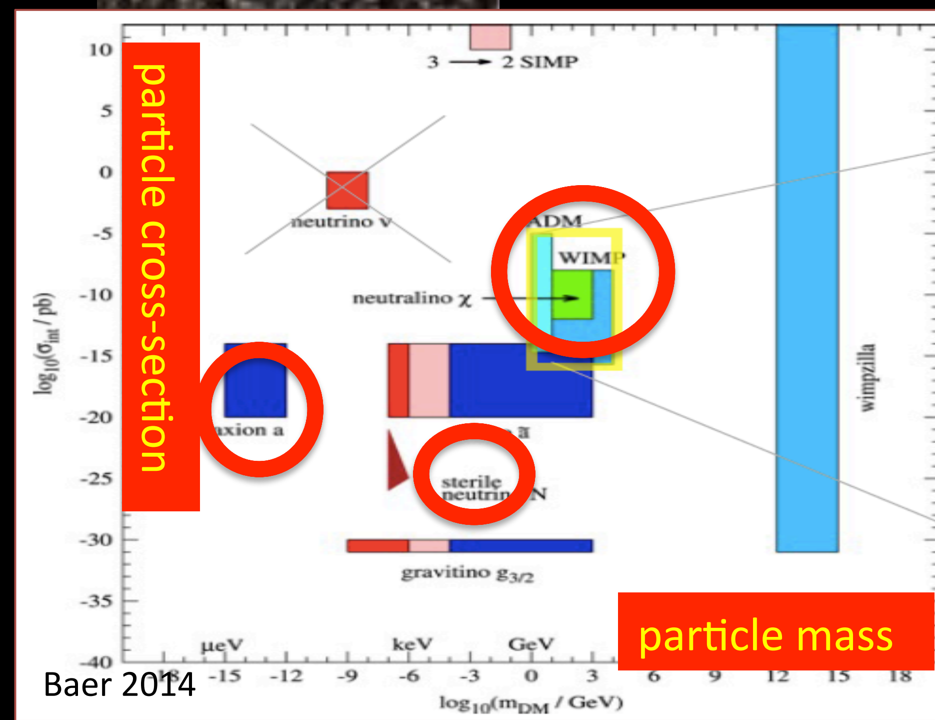
DARK MATTER ISSUES

- No direct or indirect detection of DM
- Beyond SUSY, CDM: sub-GeV, axions…
- Primordial black holes: known physics
- Dwarf galaxy "anomalies" as dark matter probes
- Customized dark matter options: SIDM, scalar DM…
- Distant luminous quasars and massive galaxies
- The Milky Way galaxy as a DM probe

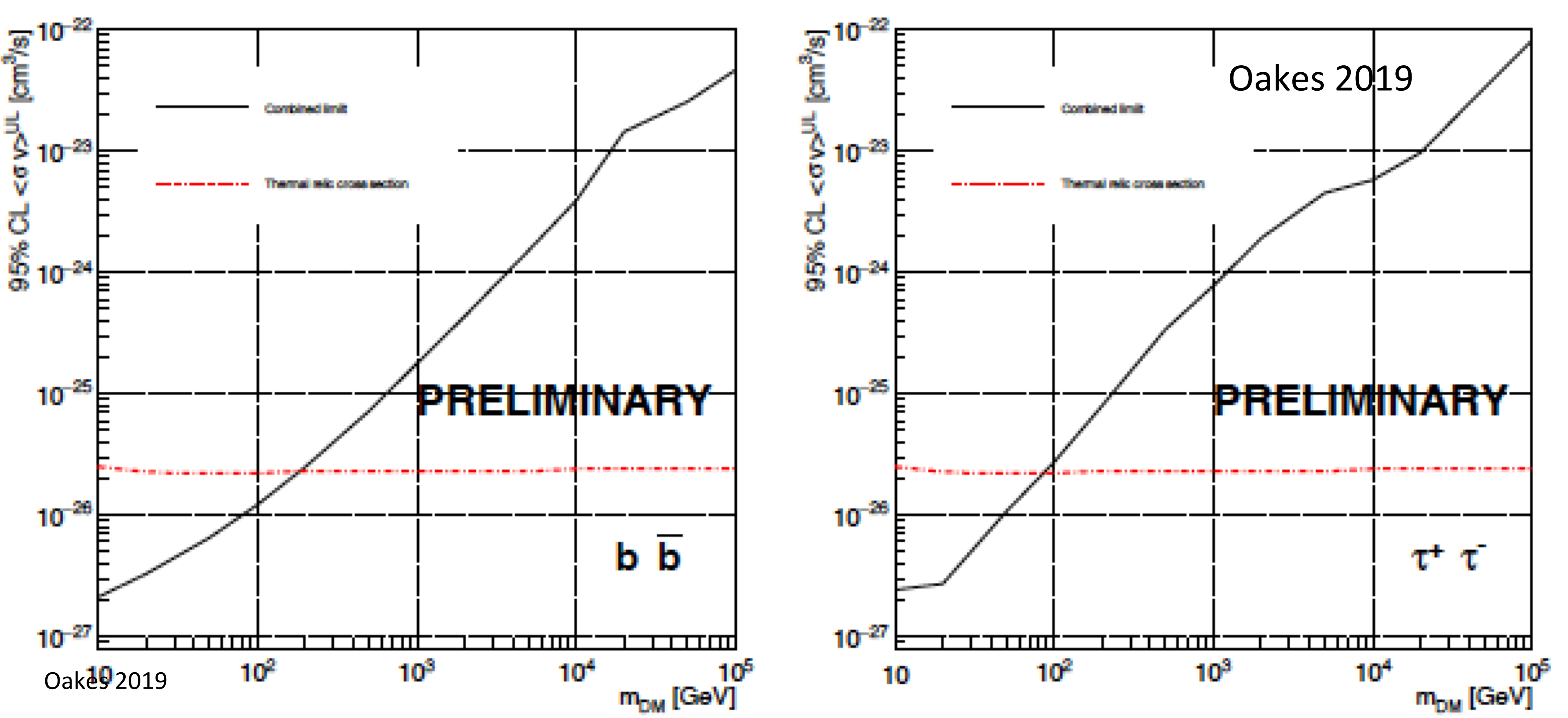
DARK MATTER 2019







Dwarf galaxies: latest γ-ray bound on annihilation



20 dwarfs: allows DM window

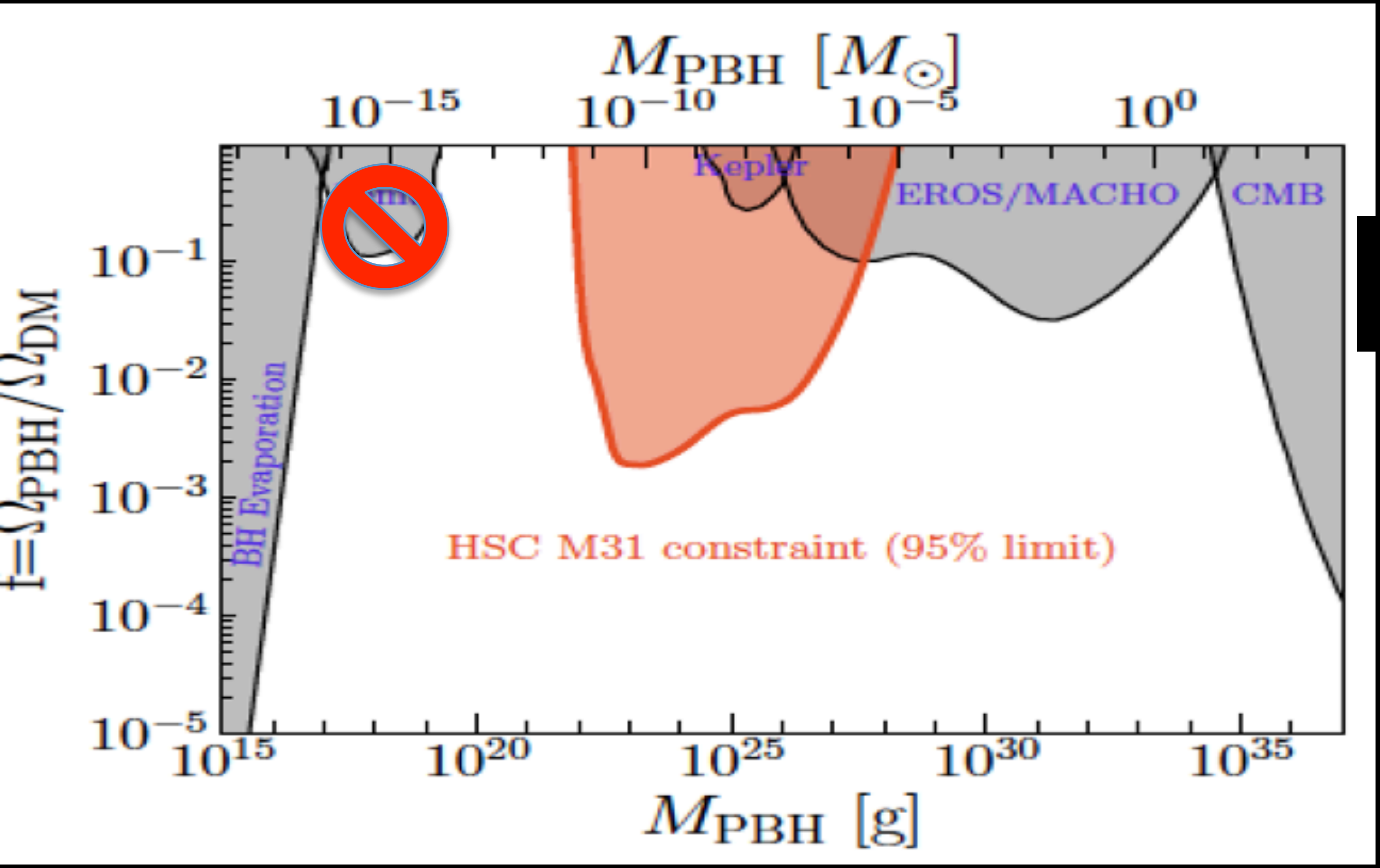
Fermi + HAWC + HESS + MAGIC + VERITAS

DARK MATTER: plan B

γ-rays (GC, M31, dwarfs…) → not ruled out : >100GeV WIMPs

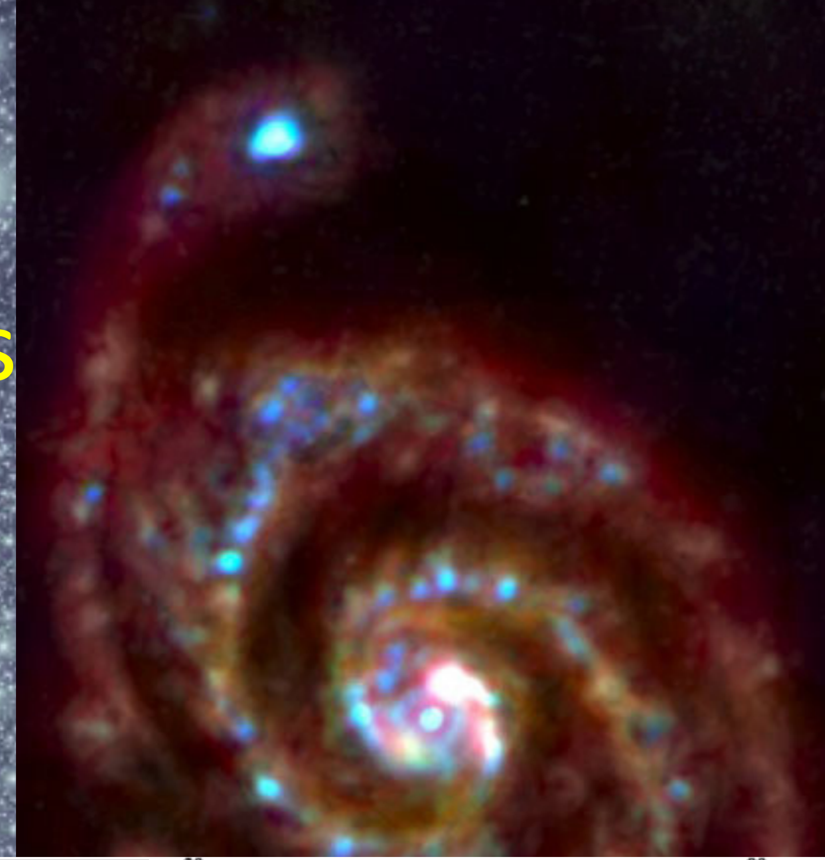
more options: theory, 3.5 keV xray line → subGeV, axions, sterile nus ...

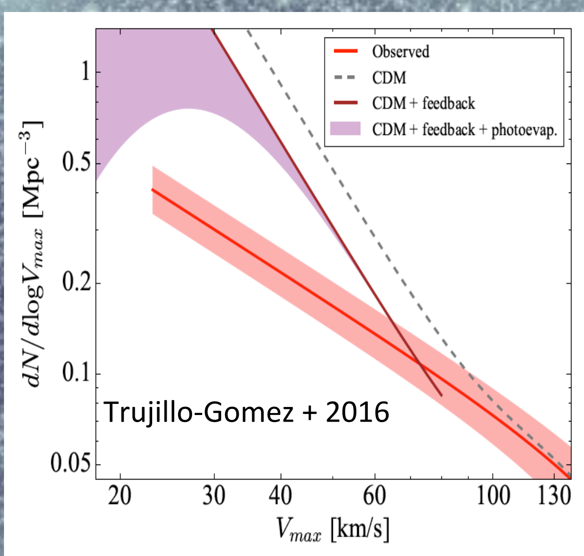
known physics, tuned initial conditions → primordial black holes

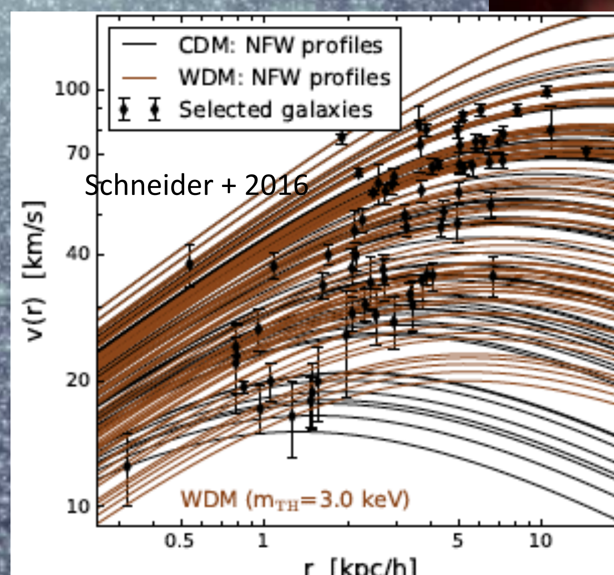


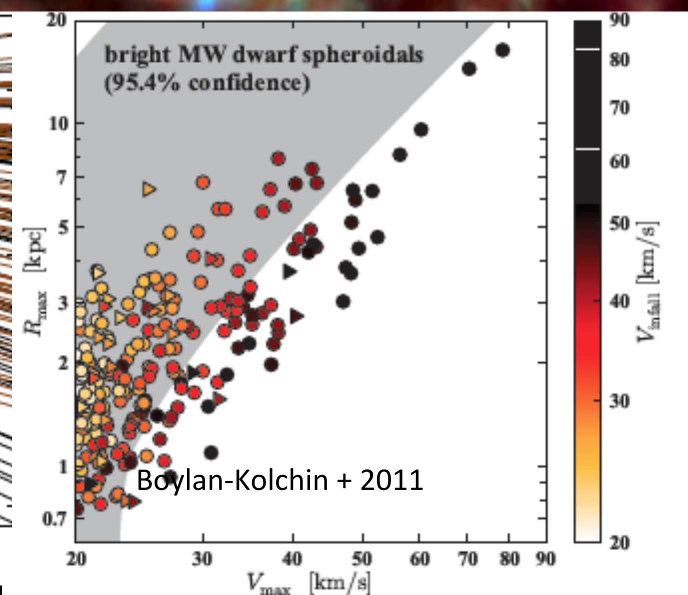
PBH can do it!

three dwarf galaxy issues: numbers, 2big2fail, cores









New physics motivated by dwarf issues

warm dark matter eg sterile neutrino of 7 keV
scalar field dark matter: $\lambda_{\text{de Broglie}}$ ~ dwarf core size
self-interacting dark matter: $\sigma \sim 1\ cm^2/gm$

Can solve some but rarely all of the problems

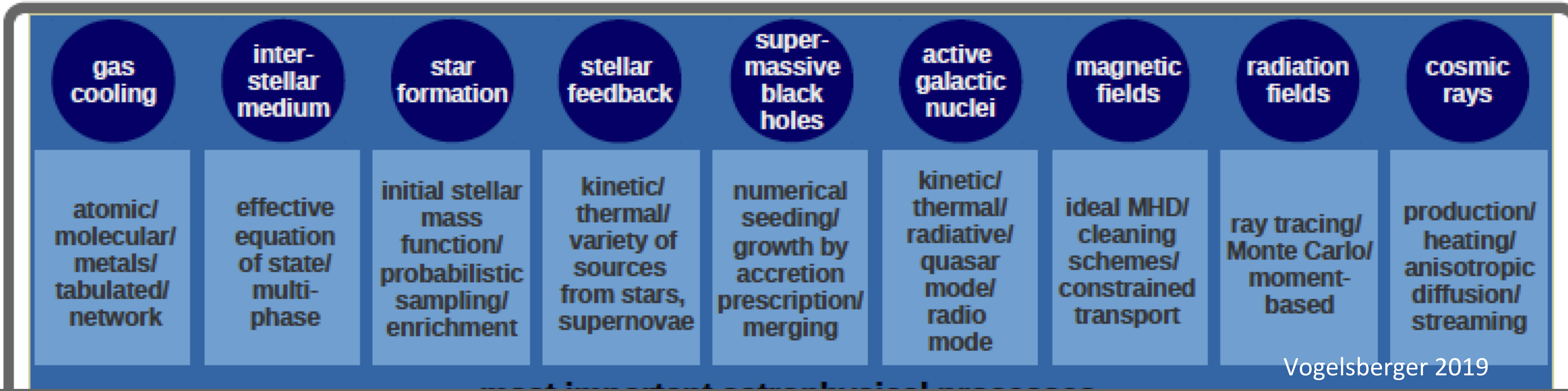
Complex baryonic physics explains all?

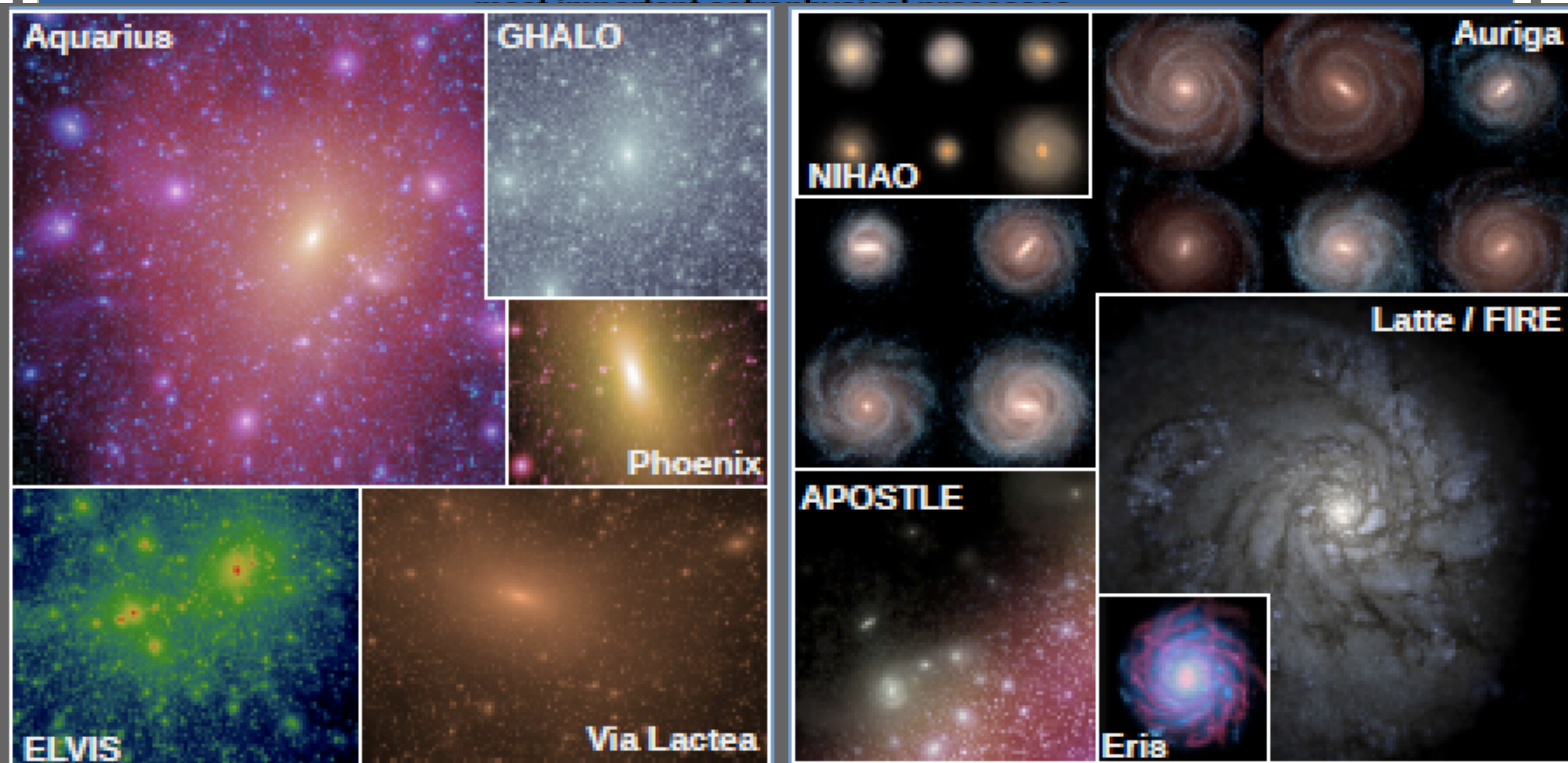
Diversity inevitable with:
Supernova feedback
Environment: ram pressure stripping/tidal heating
Star formation prescriptions
Massive black hole feedback

Resort to numerical simulations

But resolution is limited

how robust are simulations?


gas cooling
inter-stellar medium
star formation
stellar feedback
super-massive black holes
active galactic nuclei
magnetic fields
radiation fields
cosmic rays
atomic/ molecular/ metals/ tabulated/ network
effective equation of state/ multi-phase
initial stellar mass function/ probabilistic sampling/ enrichment
kinetic/ thermal/ variety of sources from stars, supernovae
numerical seeding/ growth by accretion prescription/ merging
kinetic/ thermal/ radiative/ quasar mode/ radio mode
ideal MHD/ cleaning schemes/ constrained transport
ray tracing/ Monte Carlo/ moment-based
production/ heating/ anisotropic diffusion/ streaming
Vogelsberger 2019


Aquarius
GHALO
Phoenix
ELVIS
Via Lactea
NIHAO
Auriga
Latte / FIRE
APOSTLE
Eris

if you don't trust simulations try semi-analytic modelling?

GALACTICUS

Benson 2012

Parameter	Value	Refer
[H_0]	70.2 km/s	§4.2;
[Omega_0]	0.2725	§4.2;
[Omega_DE]	0.7275	§4.2;
[Omega_b]	0.0455	§4.2;
[T_CMB]	2.72548 K	§4.2;
[accretionDisksMethod]	ADAF	§4.3
[adafAdiabaticIndex]	1.444	§4.3
[adafEnergyOption]	pure ADAF	§4.3
[adafRadiativeEfficiency]	0.01	§4.3
[adafViscosityOption]	fit	§4.3
[adiabaticContractionGnedinA]	0.8	§4.8
[adiabaticContractionGnedinOmega]	0.77	§4.8
[barInstabilityMethod]	ELN	§4.7
[blackHoleSeedMass]	100	§3.1.2
[blackHoleWindEfficiency]	0.001	§3.1.2
[bondiHoyleAccretionEnhancementHotHalo]	1	§3.1.2
[bondiHoyleAccretionEnhancementSpheroid]	1	§3.1.2
[bondiHoyleAccretionTemperatureSpheroid]	100	§3.1.2
[coolingFunctionMethod]	atomic CIE Cloudy	§4.5.1
[coolingTimeAvailableAgeFactor]	0	§4.5.5
[coolingTimeSimpleDegreesOfFreedom]	3	§4.5.4
[darkMatterProfileMethod]	NFW	§4.6.1
[darkMatterProfileMinimumConcentration]	4	§3.8.2
[diskOutflowExponent]	2	§4.23
[diskOutflowVelocity]	200 km/s	§4.23
[effectiveNumberNeutrinos]	4.34	§4.4.2
[galacticStructureRadiusSolverMethod]	adiabatic	§4.8
[haloMassFunctionMethod]	Tinker2008	§4.4.6
[haloSpinDistributionMethod]	Bett2007	§4.6.3
[hotHaloOutflowReturnRate]	1.26	§3.2.2
[imfSalpeterRecycledInstantaneous]	0.39	§4.12
[imfSalpeterYieldInstantaneous]	0.02	§4.12
[imfSelectionFixed]	Salpeter	§4.12
[isothermalCoreRadiusOverVirialRadius]	0.1	§4.10

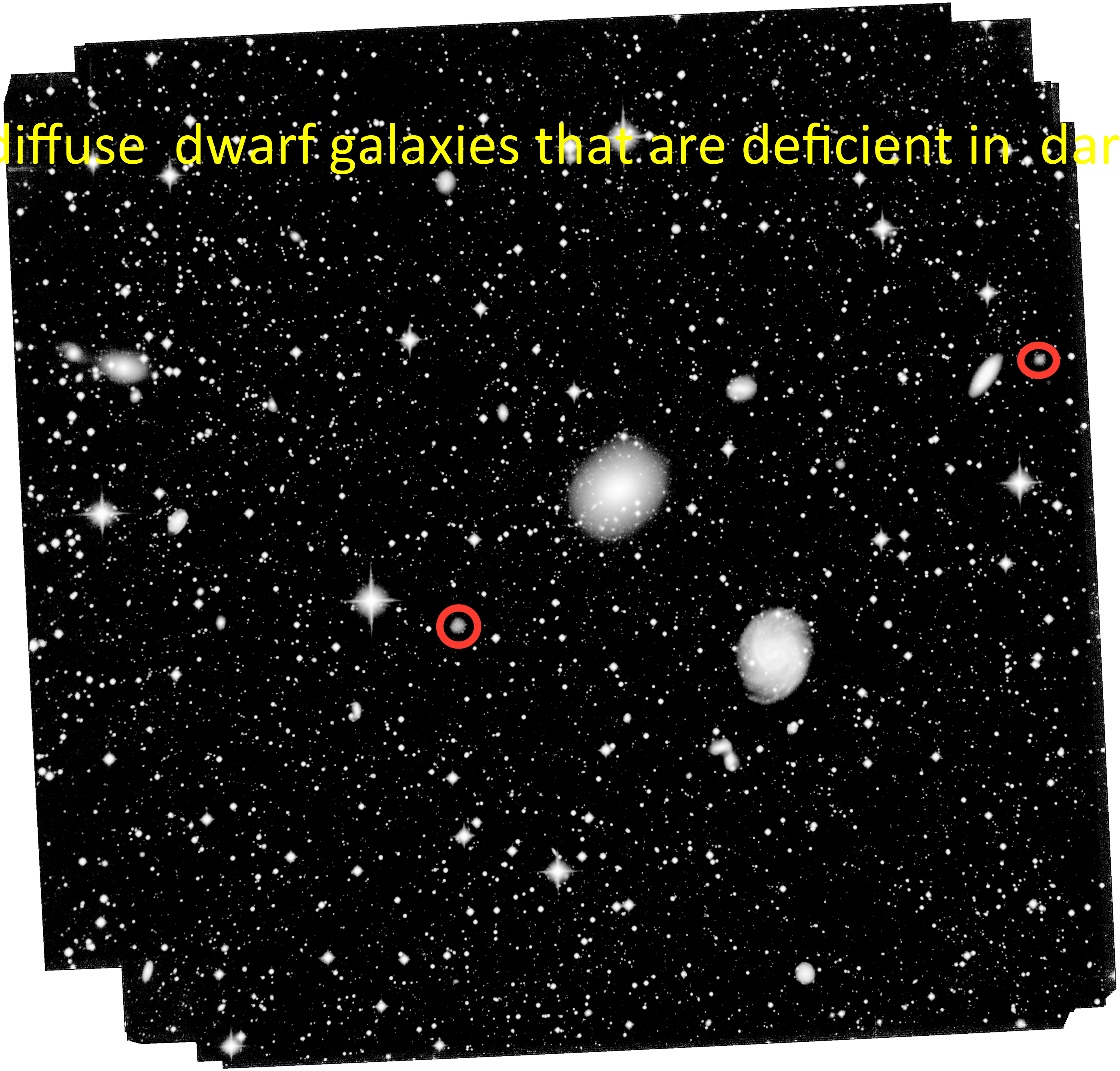
Parameter	Value	Referen
[majorMergerMassRatio]	0.1	§4.9.1
[mergerRemnantSizeOrbitalEnergy]	1	§4.9.2
[mergerTreeBuildCole2000AccretionLimit]	0.1	§4.16
[mergerTreeBuildCole2000MassResolution]	$5 \times 10^9 M_\odot$	§4.16
[mergerTreeBuildCole2000MergeProbability]	0.1	§4.16
[mergerTreeConstructMethod]	build	§4.14
[minorMergerGasMovesTo]	spheroid	§4.9.1
[modifiedPressSchechterFirstOrderAccuracy]	0.1	§4.15
[modifiedPressSchechterG0]	0.57	§4.15
[modifiedPressSchechterGamma1]	0.38	§4.15
[modifiedPressSchechterGamma2]	-0.01	§4.15
[powerSpectrumIndex]	0.961	§4.4.1;
[powerSpectrumReferenceWavenumber]	1 Mpc^{-1}	§4.4.1;
[powerSpectrumRunning]	0	§4.4.1;
[randomSpinResetMassFactor]	2	§3.7.2
[reionizationSuppressionRedshift]	9	§4.1
[reionizationSuppressionVelocity]	30 km/s	§4.1
[satelliteMergingMethod]	Jiang2008	§4.22.1
[sigma_8]	0.807	§4.4.1
[spheroidEnergeticOutflowMassRate]	1	§3.4.2
[spheroidOutflowExponent]	2	§4.23
[spheroidOutflowVelocity]	50 km/s	§4.23
[spinDistributionBett2007Alpha]	2.509	§4.6.3
[spinDistributionBett2007Lambda0]	0.04326	§4.6.3
[stabilityThresholdGaseous]	0.9	§4.7
[stabilityThresholdStellar]	1.1	§4.7
[starFormationDiskEfficiency]	0.01	§4.17
[starFormationDiskMinimumTimescale]	0.001 Gyr	§4.17
[starFormationDiskVelocityExponent]	-1.5	§4.17
[starFormationSpheroidEfficiency]	0.1	§4.17
[starFormationSpheroidMinimumTimescale]	0.001 Gyr	§4.17
[starveSatellites]	true	§3.2.2
[stellarPopulationPropertiesMethod]	instantaneous	§4.18
[summedNeutrinoMasses]	0	§4.4.2
[transferFunctionMethod]	Eisenstein + Hu	§4.4.2
[virialDensityContrastMethod]	spherical top hat	§4.4.5

SHARK semi-analytical model

Lagos et al. 2018

Parameter	suggested value range	variable/equation
halo properties and angular momentum		
halo_profile	nfw	equation (1)
lambda_random	0 (equation 2) or 1 (random distribution) (1)	
size_model	Mo98	Size calculation
gas cooling		
lambdamodel	cloudy or sutherland (cloudy)	Λ in equation (4)
model	Croton06 or Benson10 (Croton06)	Described in Section 4.4.1
gas accretion		
pre_enrich_z	$>0-10^{-5}$ (10^{-7})	$Z_{\rm min}$ in Section 4.3
chemical enrichment		
recycle	0.4588 for a Chabrier IMF	R in equation (31)
yield	0.02908 for a Chabrier IMF	p in equation (32)
zsun	0.018	adopted solar metallicity
stellar feedback		
model	Muratov15, Lagos13, Lagos13Trunc, Lacey16, Lacey16RedDep or Guo11 (Lagos13)	Section 4.4.4
v_sn	$50-500\,{\rm km\,s^{-1}}$ ($110\,{\rm km\,s^{-1}}$)	$v_{\rm hot}$ in equations (25)–(28)
beta_disc	$0.5-5$ (4.5)	β in equations (25)–(28)
redshift_power	-0.5 to 1.5 (0.12)	$z_{\rm P}$ in equations (27) and (29)
eps_halo	$0.1-10$ (2)	$\epsilon_{\rm halo}$ in equation (23)
eps_disc	$1-10$ (1)	$\epsilon_{\rm disc}$ in equation (26)
star formation		
model	BR06, GD14, KMT09 or K13 (BR06)	in Section 4.4.2
nu_sf	$0.25-1.25\,{\rm Gyr^{-1}}$ ($1\,{\rm Gyr^{-1}}$)	$\nu_{\rm SF}$ in equation (7)
boost_starburst	$1-10$ (10)	η_{burst} in Section 4.4.3
sigma_hi_crit	$0.01-0.1\,{\rm M_\odot\,pc^{-2}}$ ($0.1\,{\rm M_\odot\,pc^{-2}}$)	$\Sigma_{\rm thresh}$ in Section 4.4.2
po	$10,000-45,000\,{\rm K\,cm^{-3}}$ ($34,673,\,{\rm K\,cm^{-3}}$)	P_0 in equation (8); only relevant for BR06
beta_press	$0.7-1$ (0.92)	$\alpha_{\rm P}$ in equation (8); only relevant for BR06
gas_velocity_dispersion	$7-10\,{\rm km\,s^{-1}}$ ($10\,{\rm km\,s^{-1}}$)	$\sigma_{\rm gas}$ in equation (9); only relevant for BR06 an[d] K13
clump_factor_kmt09	$1-10$ (5)	only relevant for KMT09 and K13
reincorporation		
tau_reinc	$1-30\,{\rm Gyr}$ (25 Gyr)	$\tau_{\rm reinc}$ in equation (30)
mhalo_norm	$10^9-10^{11}\,{\rm M_\odot}$ ($10^{10}\,{\rm M_\odot}$)	$M_{\rm norm}$ in equation (30)
halo_mass_power	-2 to 0 (-1)	γ in equation (30)
reionization		
model	Lacey16 or Sobacchi13 (Sobacchi13)	in Section 4.4.9
zcut	$7-11$ (10)	in Section 4.4.9
vcut	$20-50\,{\rm km\,s^{-1}}$ ($35\,{\rm km\,s^{-1}}$)	in Section 4.4.9
alpha_v	-1 to 0 (-0.2)	only relevant for Sobacchi13 model, equation (36)
AGN feedback & BH growth		
model	Bower06 or Croton16 (Croton16)	AGN feedback model Section 4.4.10
mseed	$0-10^5\,{\rm M_\odot/h}$ ($10^4\,{\rm M_\odot/h}$)	$m_{\rm seed}$ in Section 4.4.10
mhalo_seed	$0-10^{11}\,{\rm M_\odot/h}$ ($10^{10}\,{\rm M_\odot/h}$)	$m_{\rm halo,seed}$ in Section 4.4.10
f_smbh	$10^{-5}-10^{-2}$ (8×10^{-3})	$f_{\rm smbh}$ in equation (37)
v_smbh	$100-1000\,{\rm km\,s^{-1}}$ ($400\,{\rm km\,s^{-1}}$)	$v_{\rm smbh}$ in equation (37)
tau_fold	$0.5-10$ (1)	$e_{\rm sb}$ in Section 4.4.10
alpha_cool	$0.3-3$ (0.5)	used in both Bower06 and Croton16; Section 4.4.10
accretion_eff_cooling	$0.07-0.4$ (0.1)	η in Section 4.4.10; only relevant for Croton16
kappa_agn	$10^{-5}-10$ (3×10^{-3})	$\kappa_{\rm r}$ in equation (40); only relevant for Croton16
f_edd	$0.0001-0.1$ (0.01)	Section 4.4.10; only relevant for Bower06

Ultradiffuse dwarf galaxies that are deficient in dark matter



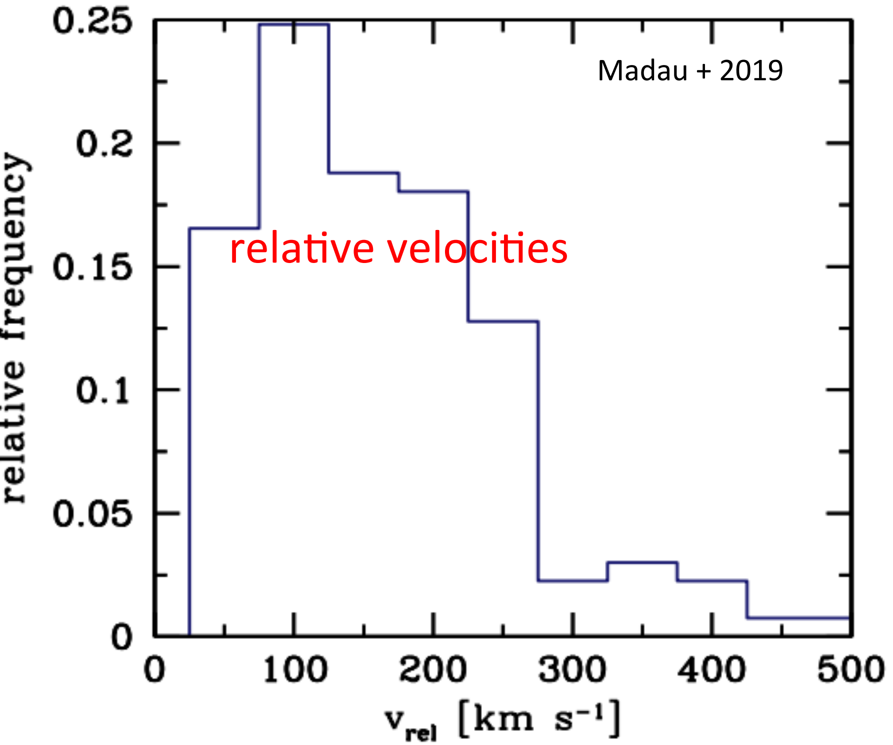
New physics?

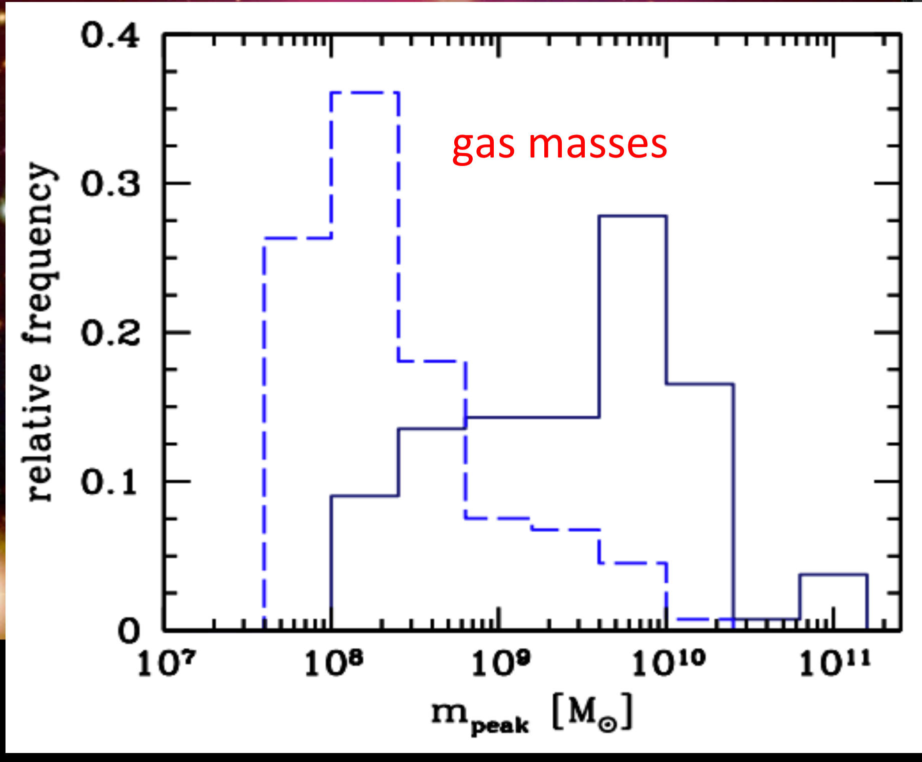
Perhaps just a minibullet cluster?

Gas atoms collide, DM particles do not

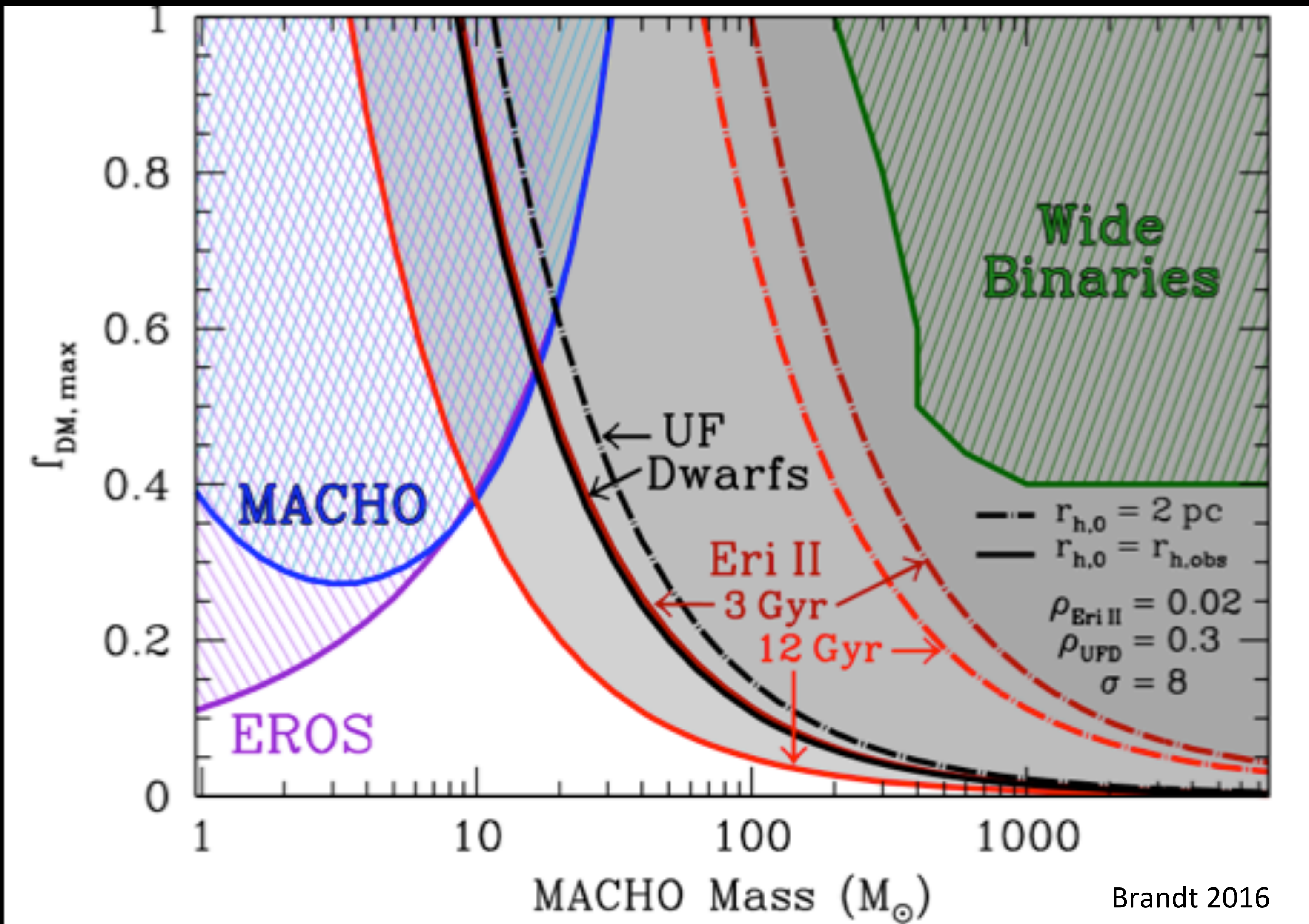
Star formation is at low efficiency

High density massive clumps form in cloud collisions: bright globular star clusters





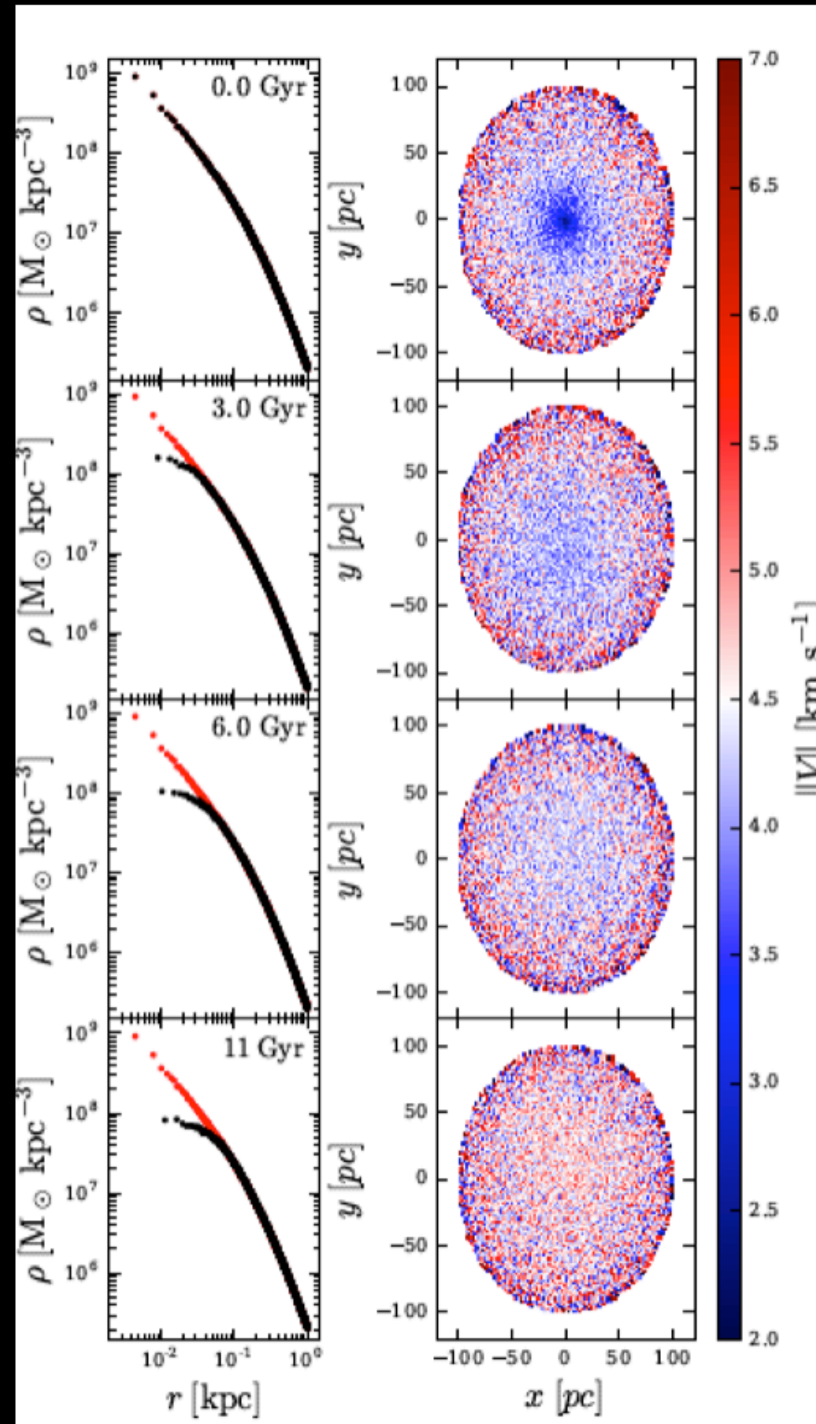
critical density of >10 M_{sun} PBHs destroys ultradiffuse dwarf galaxies
but can they survive with fewer PBHs?



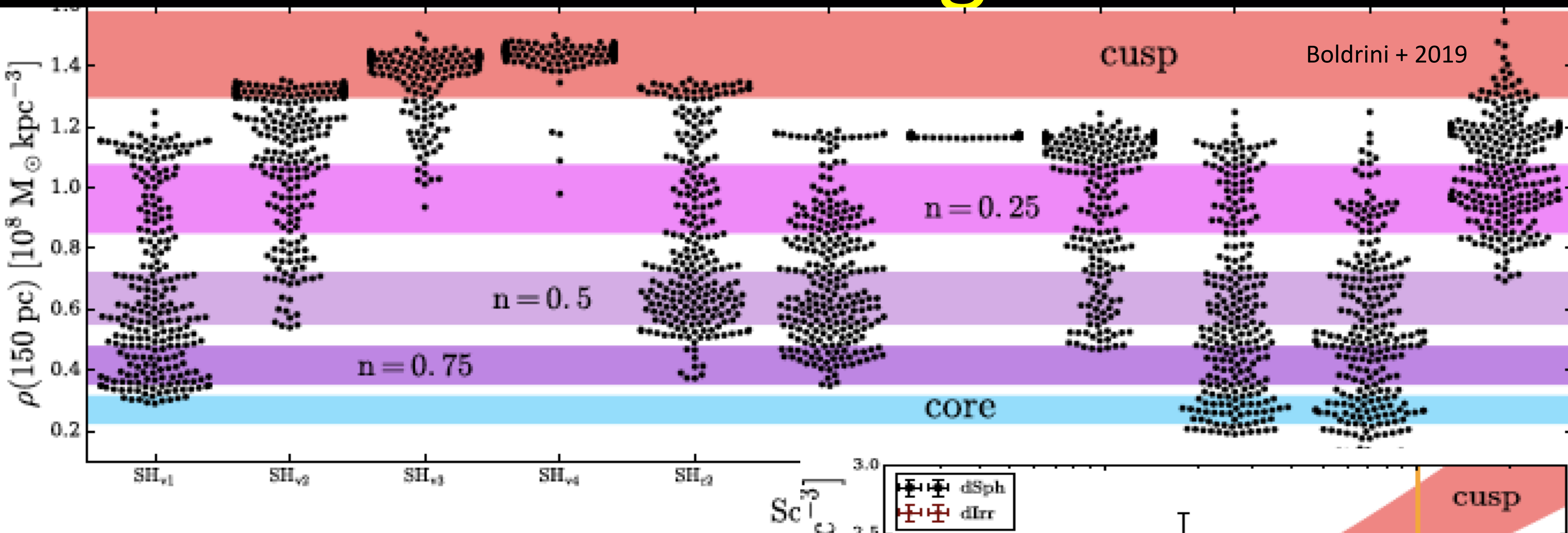
Baryonic solutions involving 1% PBH

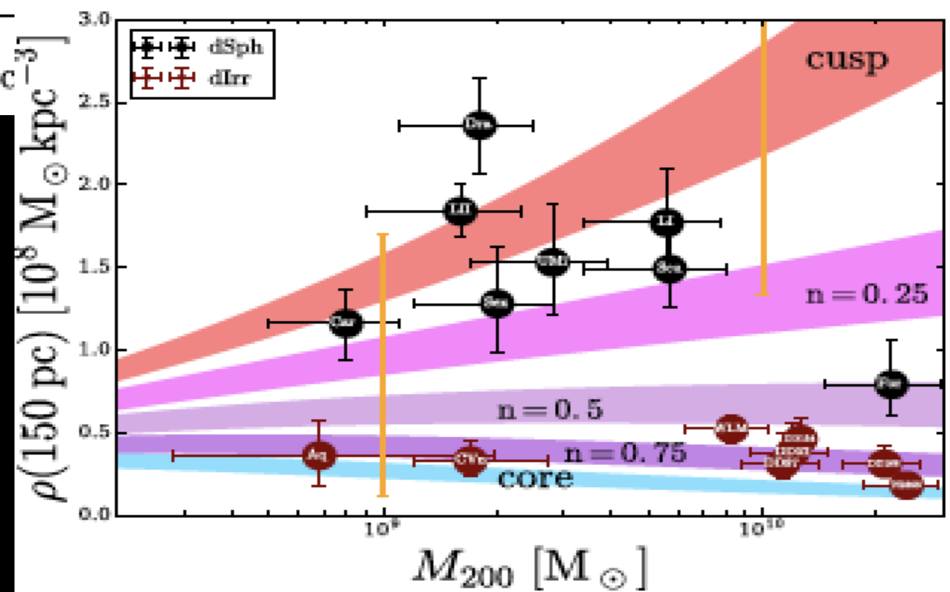
LIGO –compatible PBH fraction

Boldrini + 2019



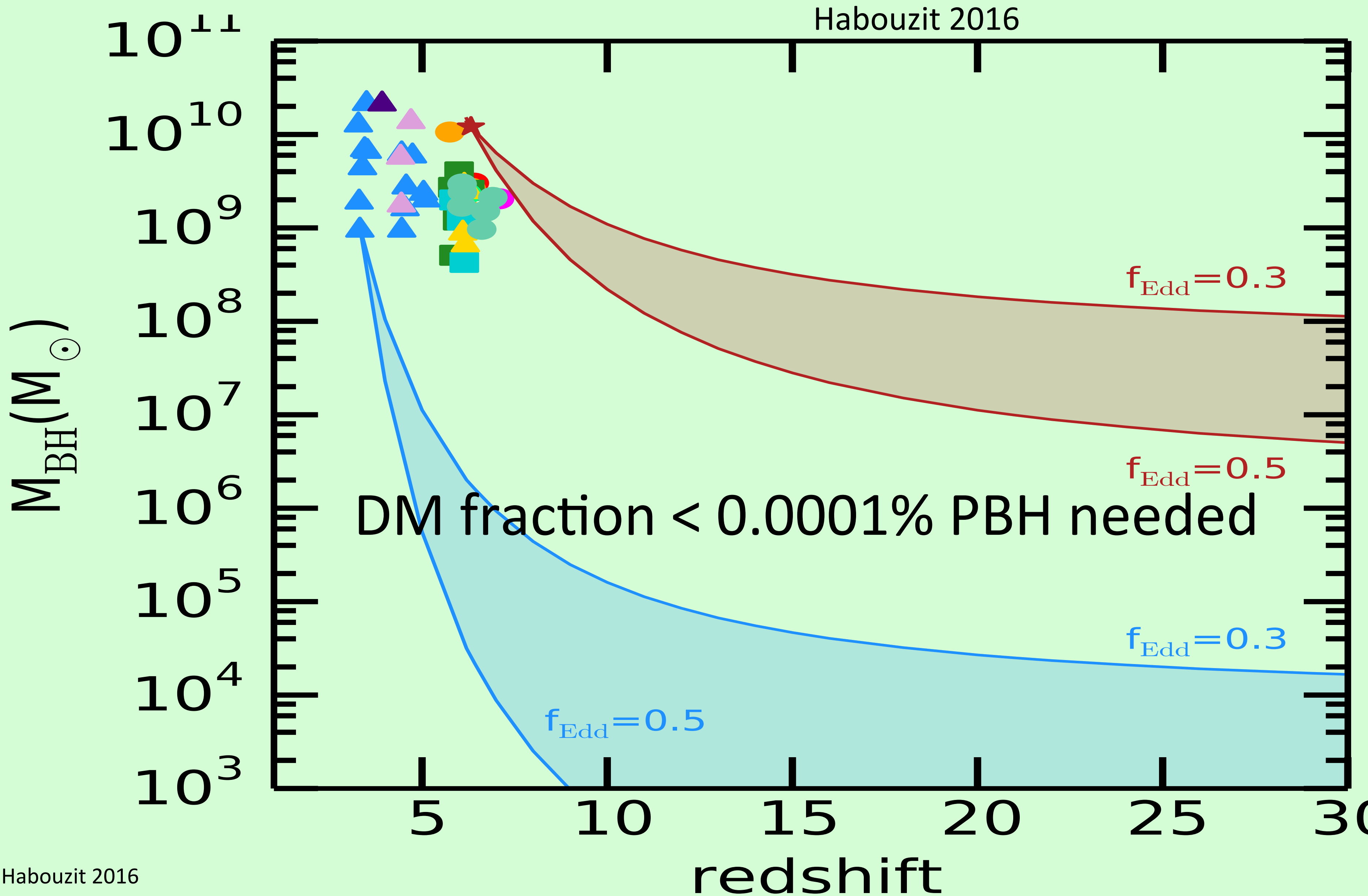
Baryonic solutions involving DM substructure mergers





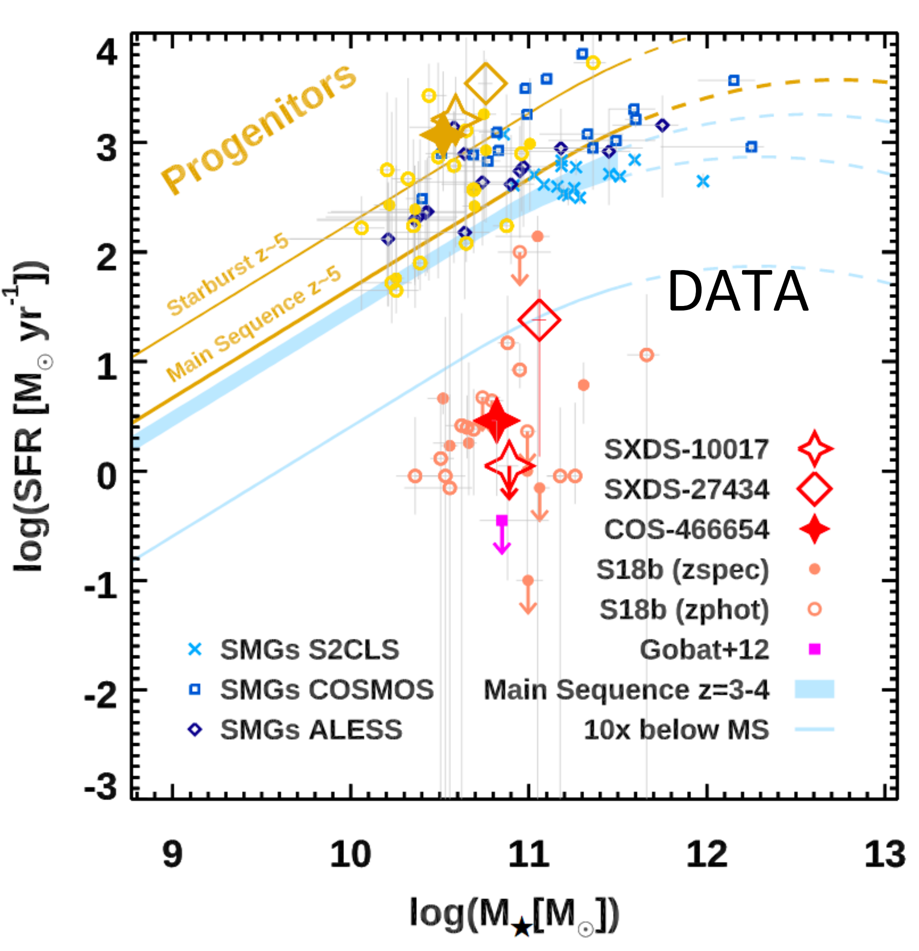
Diversity reconciled

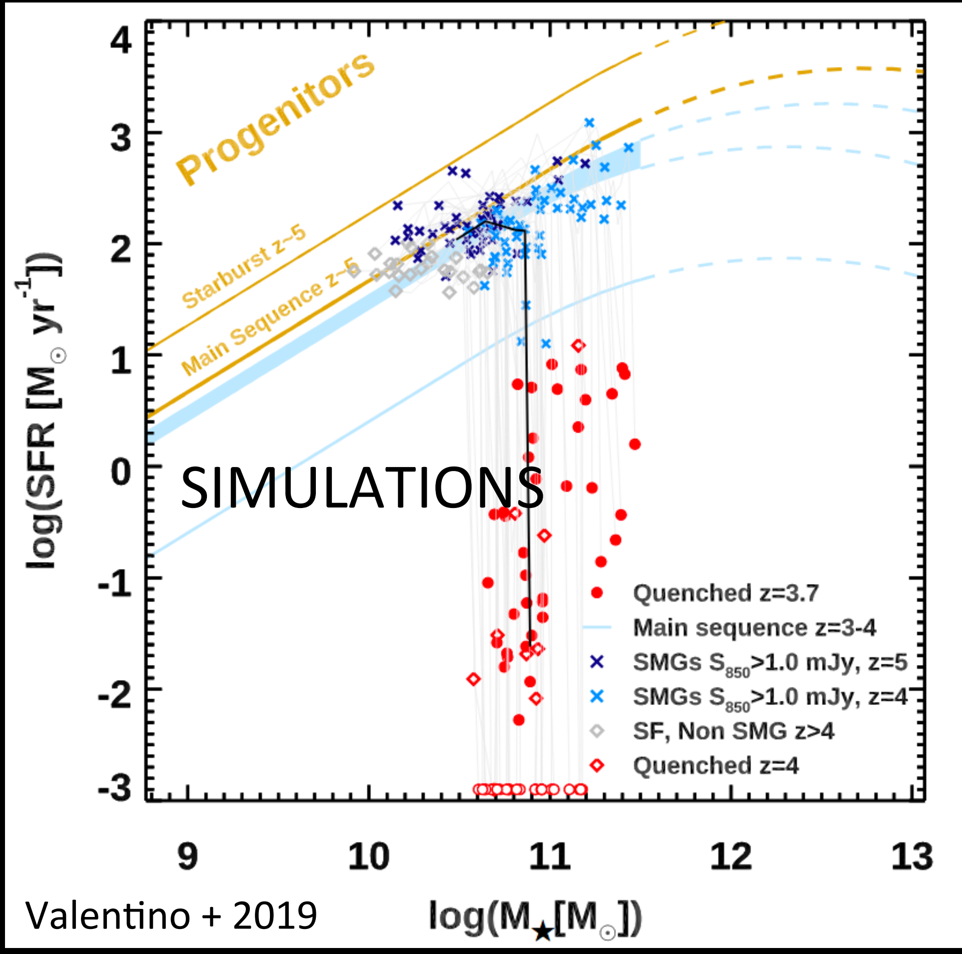
Black hole seeds are needed: eg massive PBH



Habouzit 2016

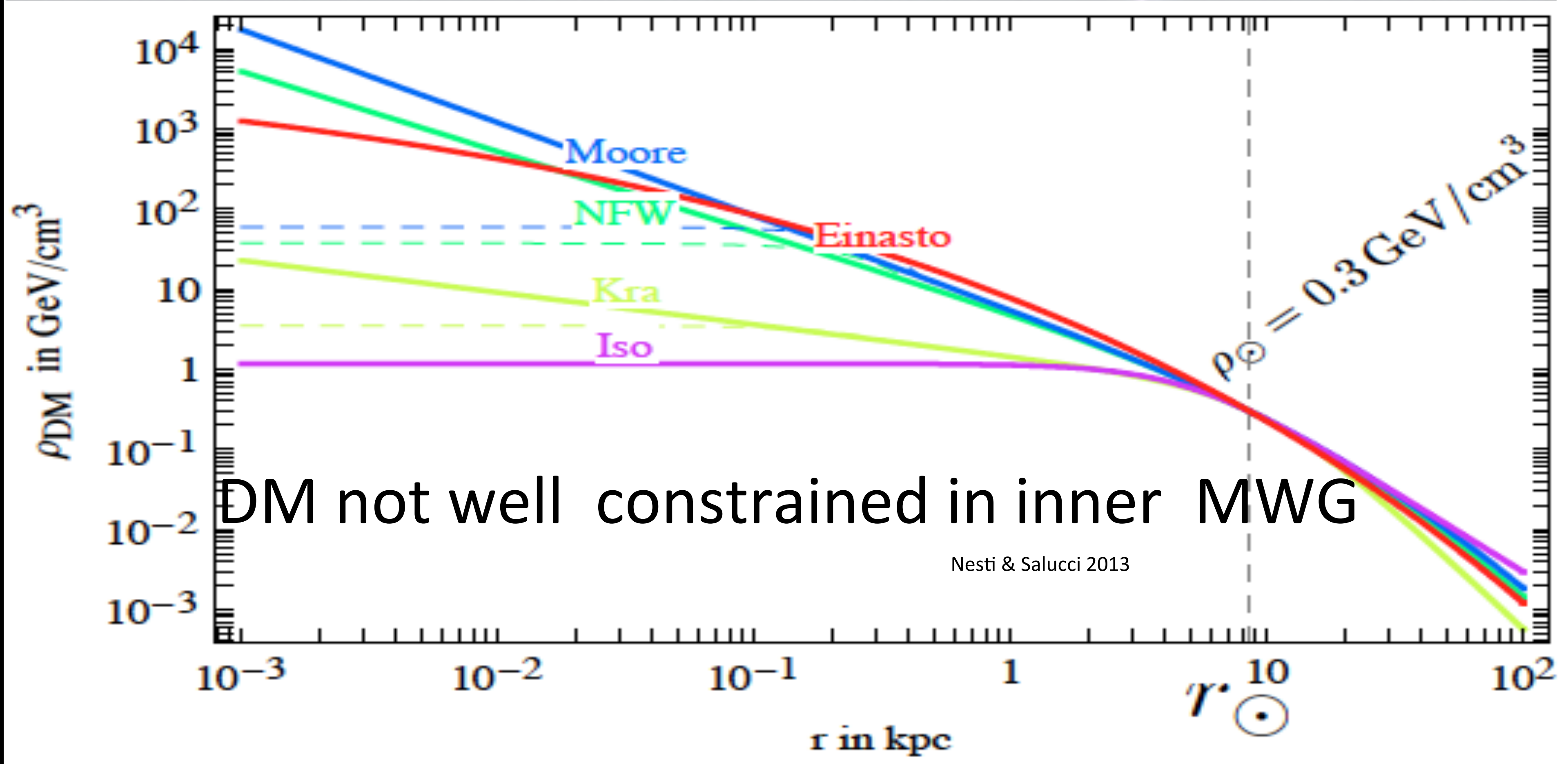
Is there a high z crisis?
galaxy seeds may be needed





Back to our galaxy

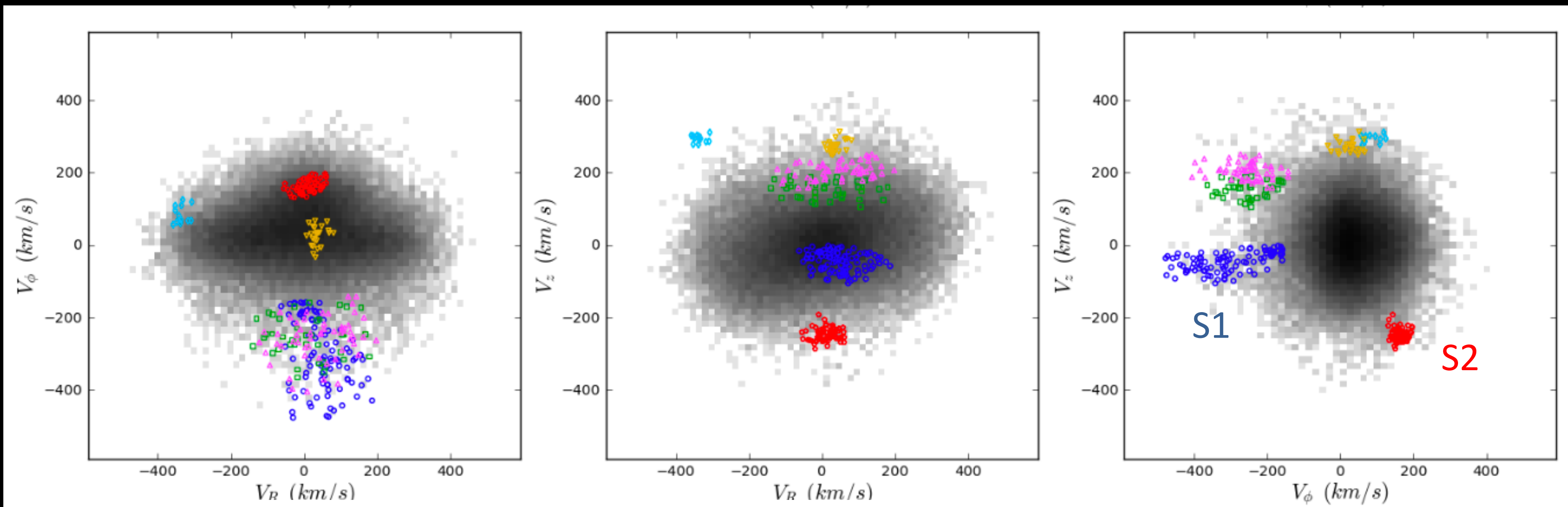
GAIA 2018: precise distances to a billion stars

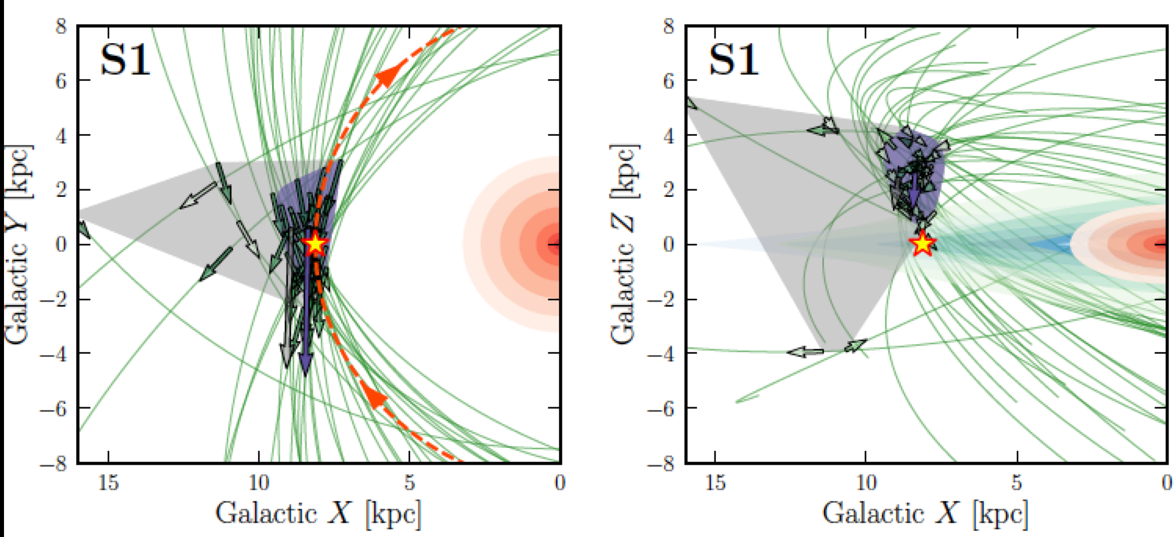


DM not well constrained in inner MWG

Nesti & Salucci 2013

Dark shards





10^{10} M^{DM}_{sun} and 10^{6} M^{*}_{sun}
some 9 Gyr ago

multiple tidal stream
wraps in halo

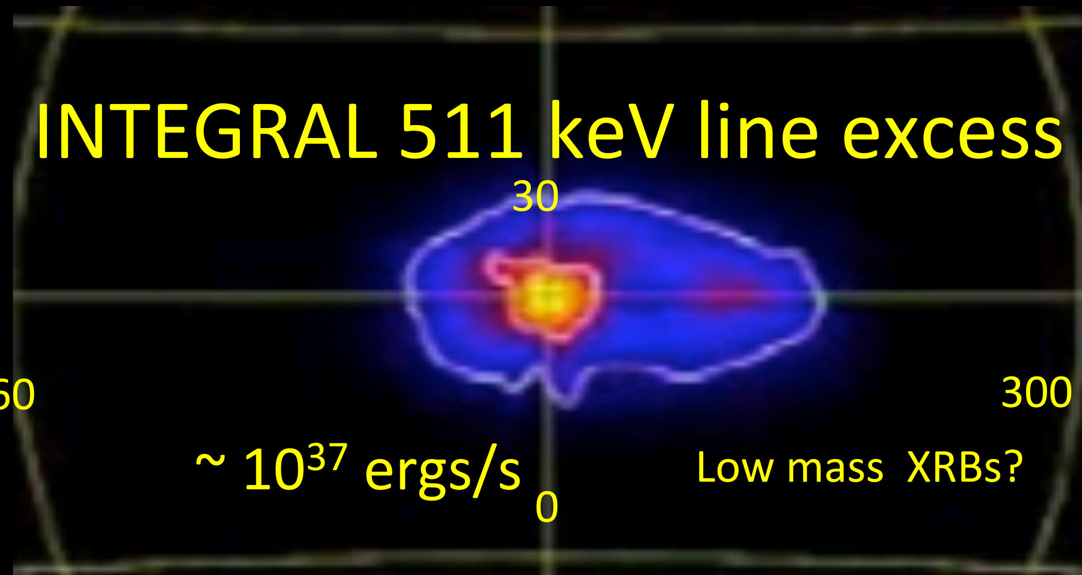
Myeong + 2017 O'Hare + 2019

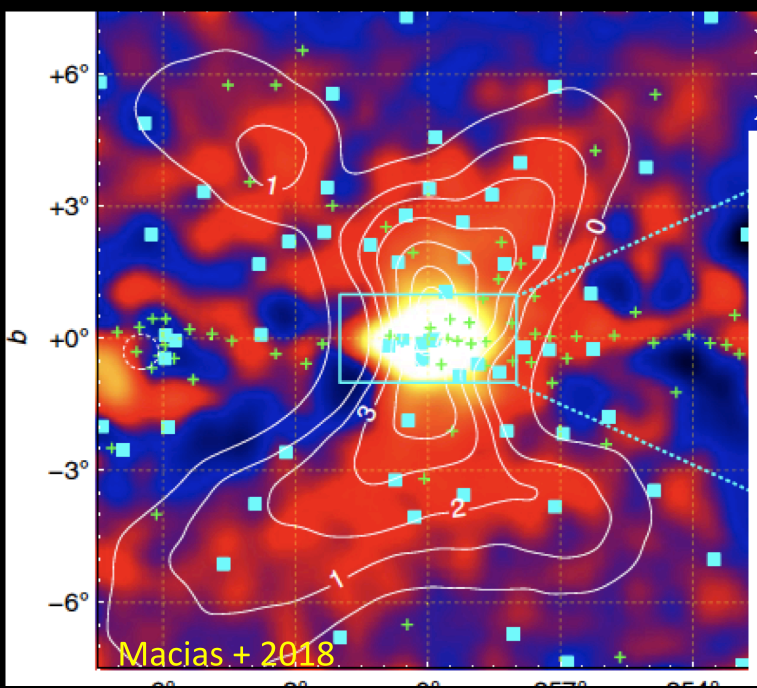
FERMI galactic center γ excess

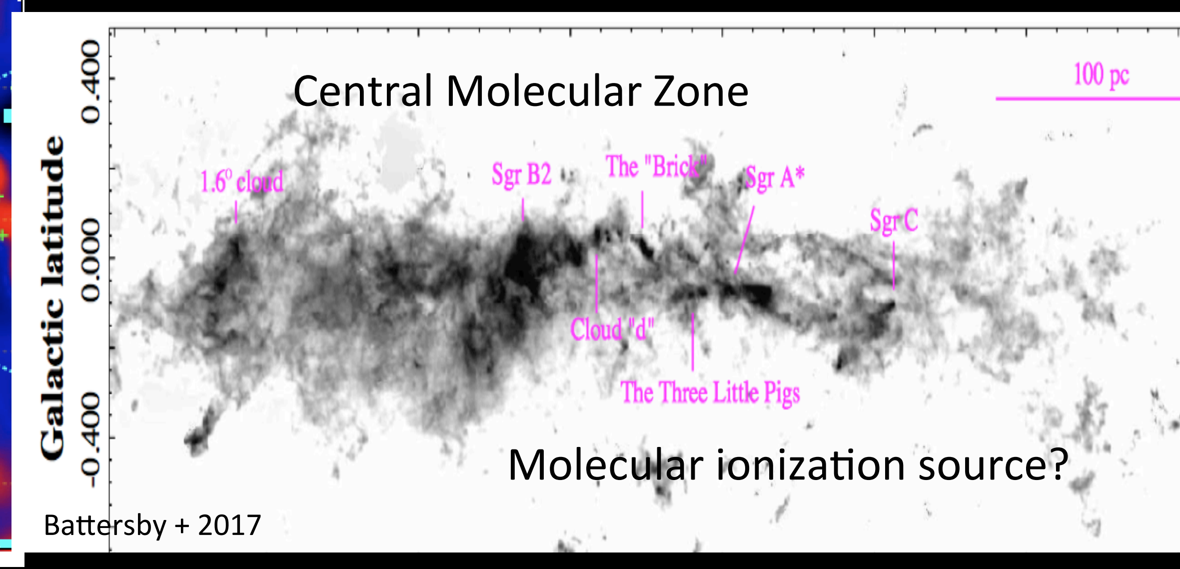
~ 10^{37} ergs/s

Macias + 2018

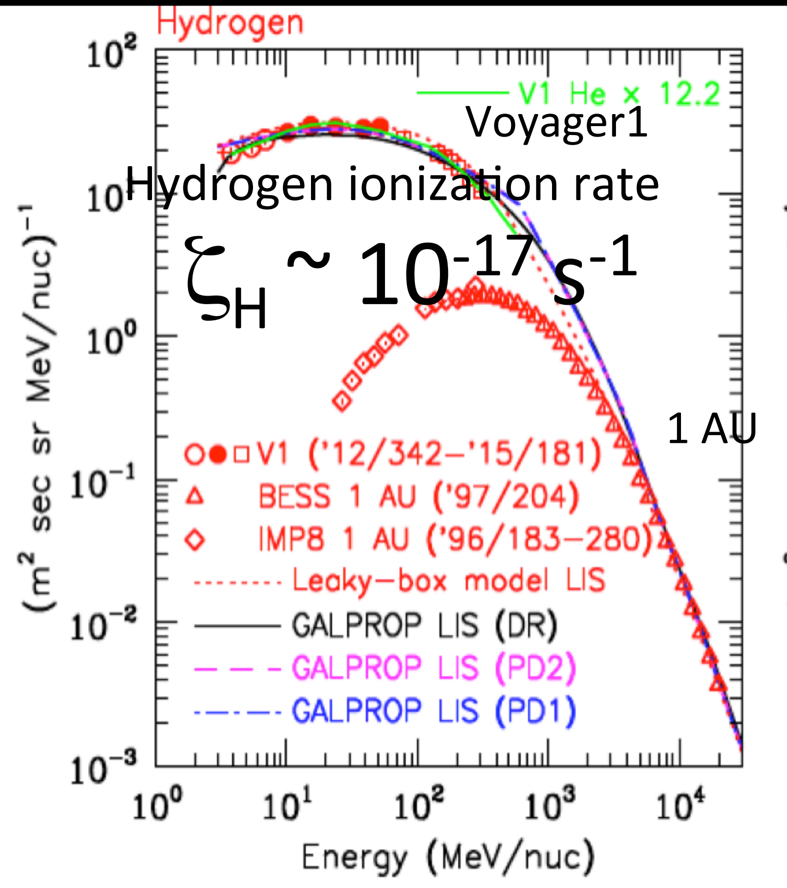
~ 10^4 faint MSPs?
Or ~ 100 GeV WIMP annihilations?







There is an unknown source of low energy cosmic rays



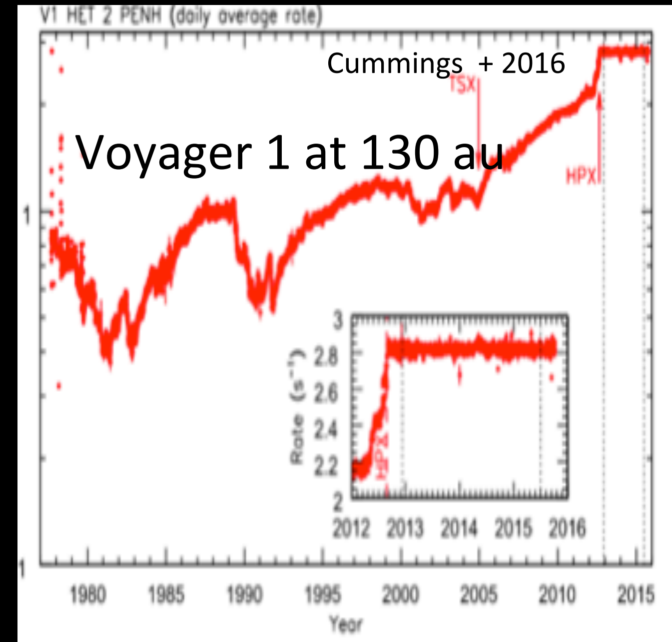
Voyager1

Hydrogen ionization rate

$\zeta_H \sim 10^{-17} s^{-1}$

1 AU

Too low!



Cummings + 2016

Voyager 1 at 130 au

caveats:

local bubble?

local reacceleration?

exotic origin?

From H_3^+ OH^+, H_2O^+ and ArH^+

$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16} s^{-1}$

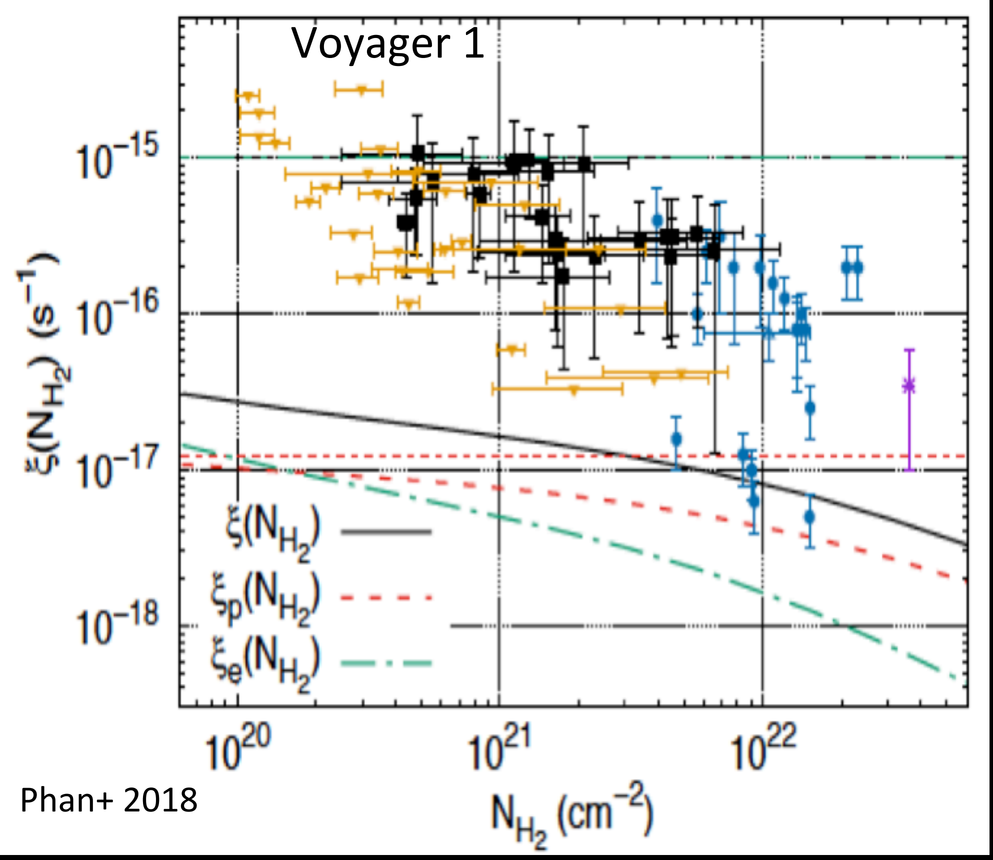
$\zeta_t(H_2) = 2.3\ \zeta_p(H)$

near solar circle

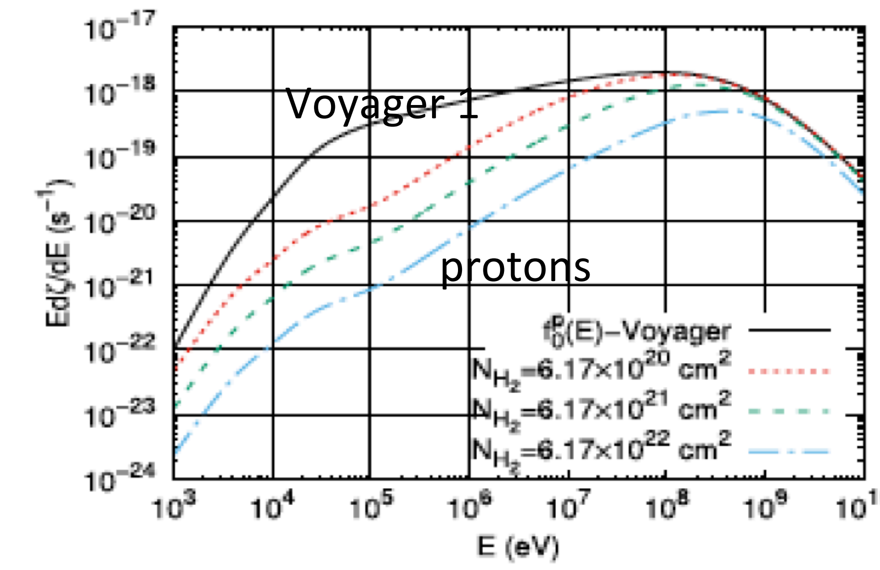
Collaborators:
M. Boudaud
D. Neufeld
M. Stref

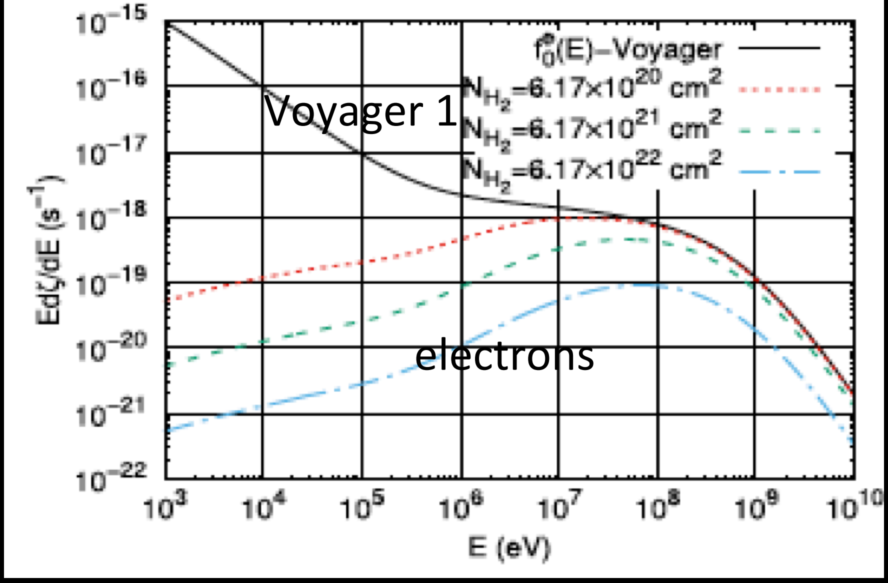
it gets worse!

Low energy cosmic rays do not penetrate dense molecular clouds



Phan+ 2018





Three alternatives

dense molecular gas ~10^{49} ionizations s^{-1} → ~10^{38} erg s^{-1} vs 10^{37} erg s^{-1} for FERMI GCE/ 511 keV

Need 10% GeV hadrons and MeV leptons + 90% soft hadrons or leptons

A: weakly annihilating dark matter clumps

motivated by GC concentration + ultracompact DM minihalos

Need ~10^5 sources in inner 300 pc for few M_{sun} UCMHs per GMC

B: hadronic jets from LMXRBs (WDs→MSP)

motivated by lepton jet interpretation of 511 keV line

and MSP interpretation of FERMI GCE (Bartels + 2018)

C: Local acceleration eg via turbulence in GMCs

dark matter or astrophysical sources!

ISSUES, to be continued

- No direct or indirect detection of DM
- Beyond SUSY, CDM: sub-GeV, axions…
- Primordial black holes: known physics
- Dwarf galaxy "anomalies" as dark matter probes
- Customized dark matter options: SIDM, scalar DM…
- Distant luminous quasars and massive galaxies
- The Milky Way galaxy as a DM probe: GCE γs, 511keV, ζ_{H2}