

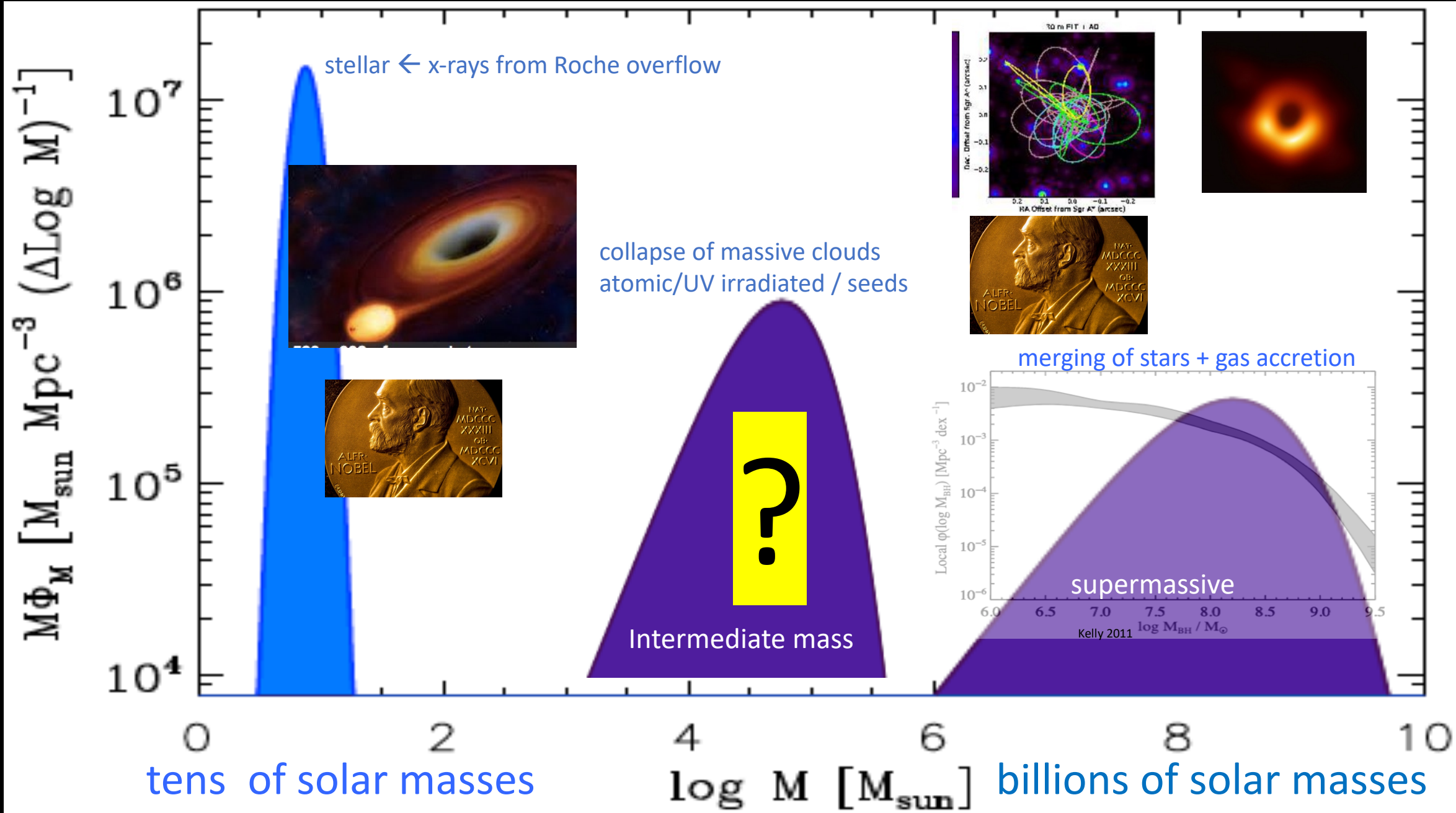
# new frontiers in cosmology

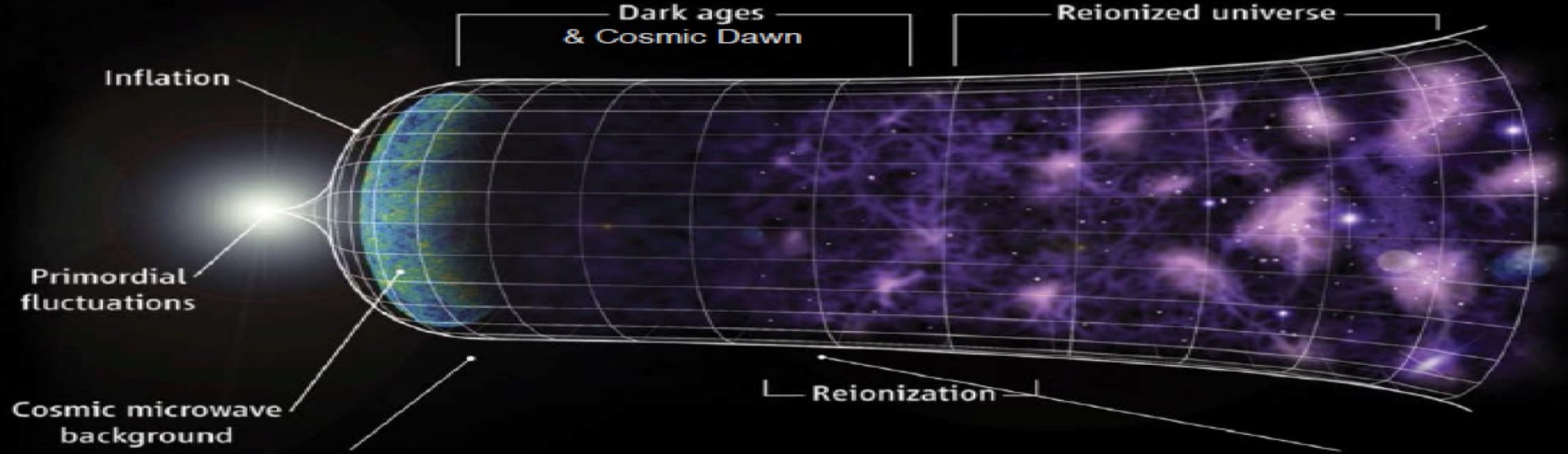
Joe Silk (IAP, JHU, BIPAC)

November 2022

In honour of Georg Raffelt

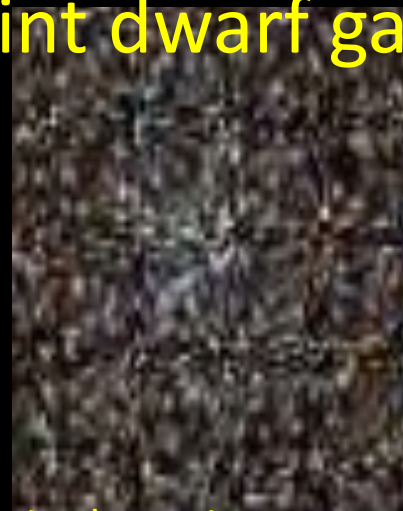
# three types of astrophysical black holes





- Dark matter
- Dark energy
- Dark ages
- Inflation
- Cosmic pevatrons
- fossils

## Ultra-faint dwarf galaxies



Most common galaxies in the Universe

Dark matter –dominated, usually

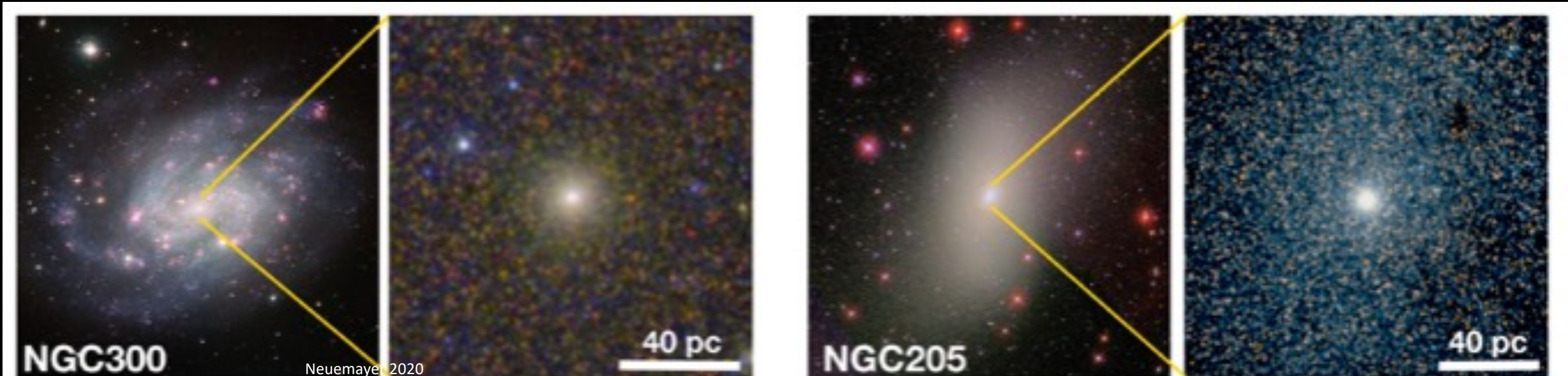
Are dark matter particles “exotic”? Or does feedback suffice?





# Nuclear star clusters

- The densest clusters in the Universe
- Ubiquitous in centres of galaxies
- Coexist with intermediate mass black holes..... $10^3$ - $10^5 M_{\text{sun}}$



# Feedback from outflows powered by accretion onto massive black holes

- Black hole feedback gives variety of dwarfs
- IMBH ubiquitous in dwarfs
- nuclear star clusters are common
- ideal environments for forming IMBH
- Merging at low  $z$ , in situ star formation at high  $z$
- IMBHs are numerous and can seed SMBH
- Expect many wandering IMBH
- Momentum boosting accounts for feedback

# Feedback by SMBH: basics

$$M_{\text{BH}} = f_{\text{gas}} \sigma^4 (\sigma_T / m_p) / (\pi G^2)$$

+ inverse Compton cooling, fails by  $\sim 10$  to eject

Need  $\delta p \sim 10 L_{\text{Edd}} / c$  momentum feedback

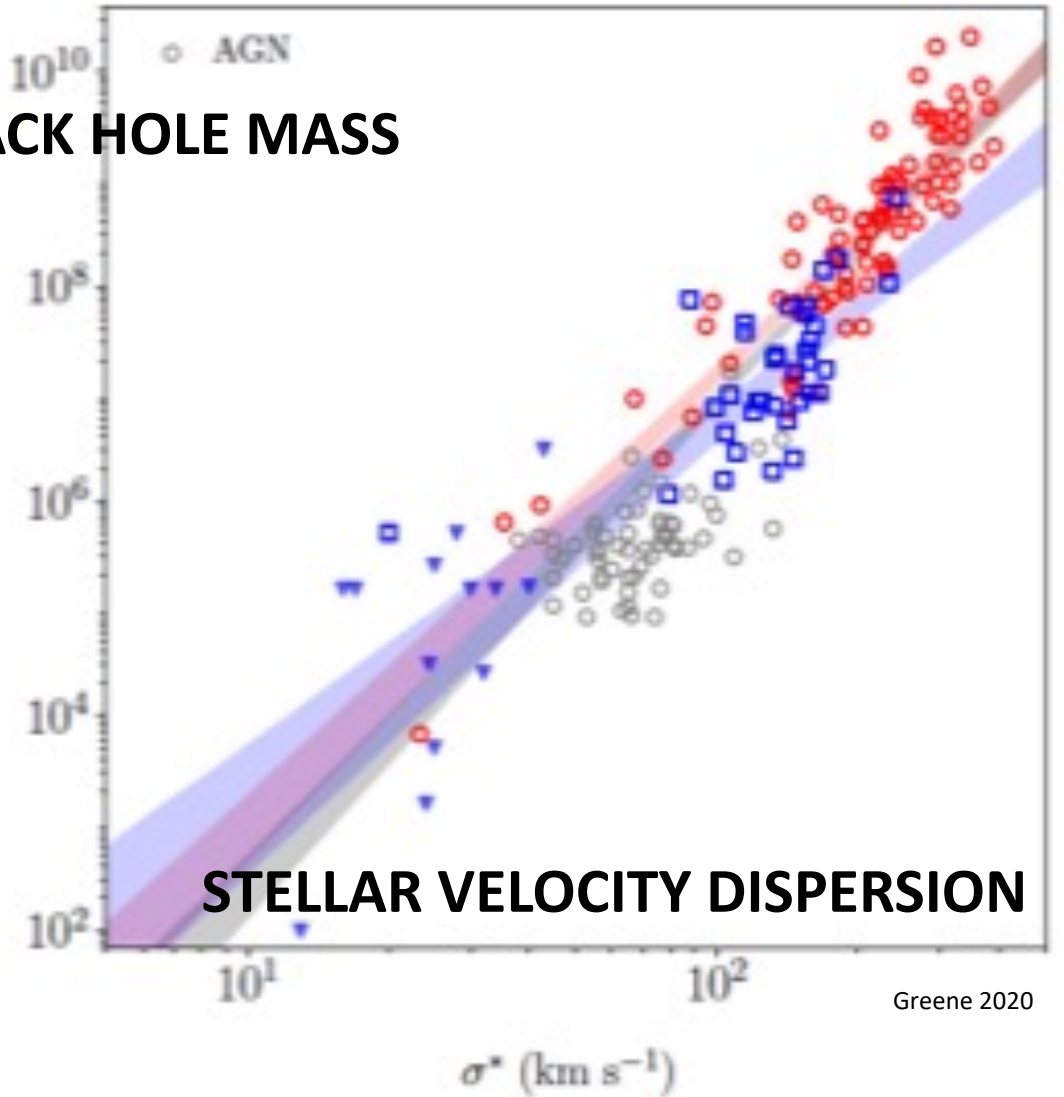
$$M_{\text{BH}} = 11 f_{\text{gas}} \sigma^5 (\sigma_T / m_p) / (\pi c G^2)$$

energy balance, shocked gas is too hot to cool.

Gives momentum boost since  $\delta p \sim \delta E / v$ .

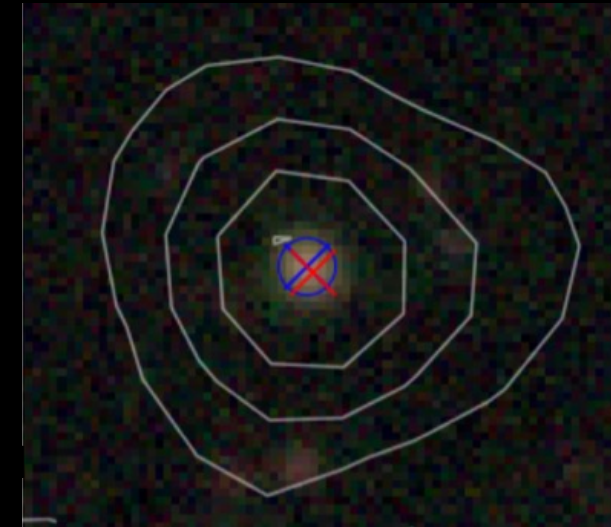
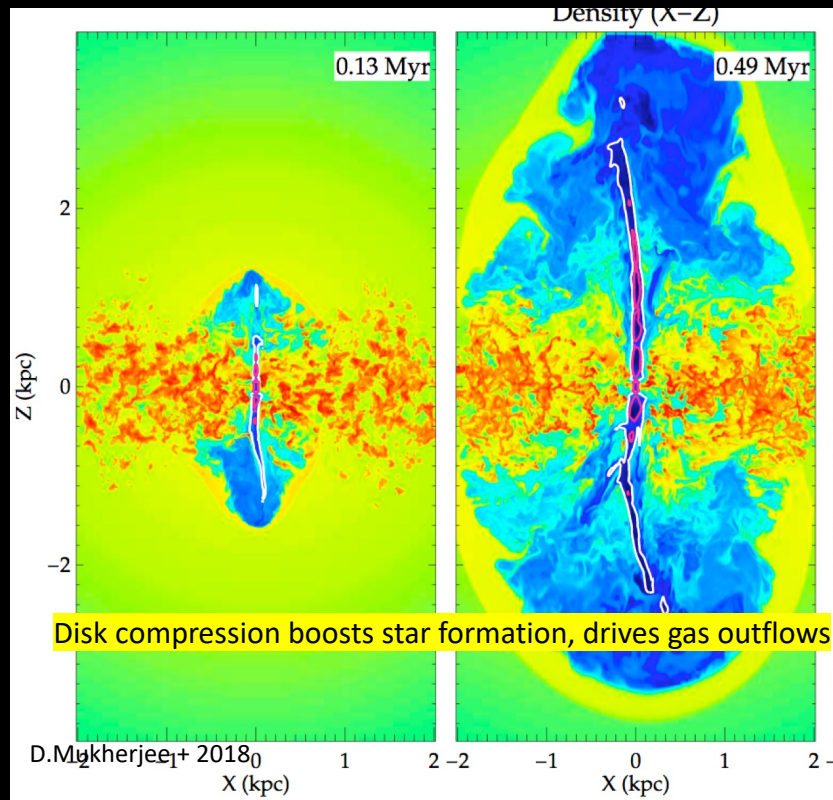
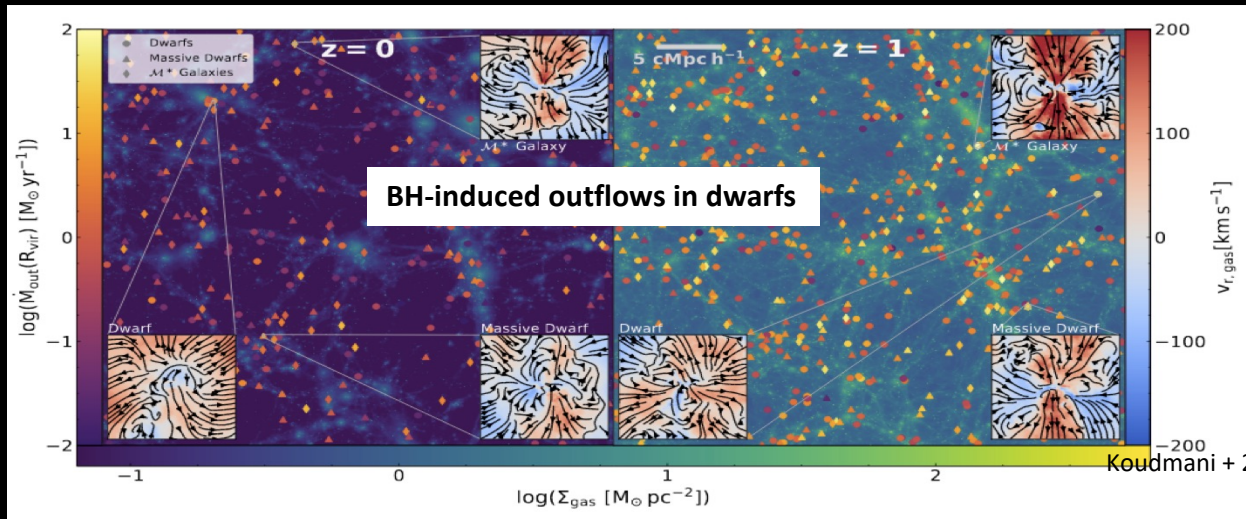
PREFERRED!

**BLACK HOLE MASS**

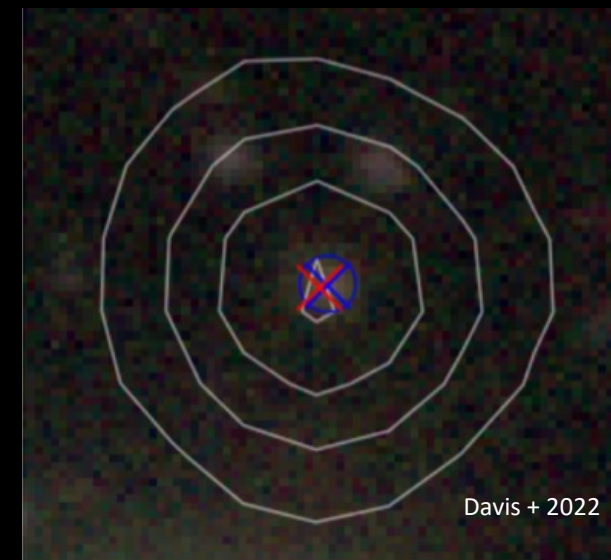




# Feedback by supermassive black holes



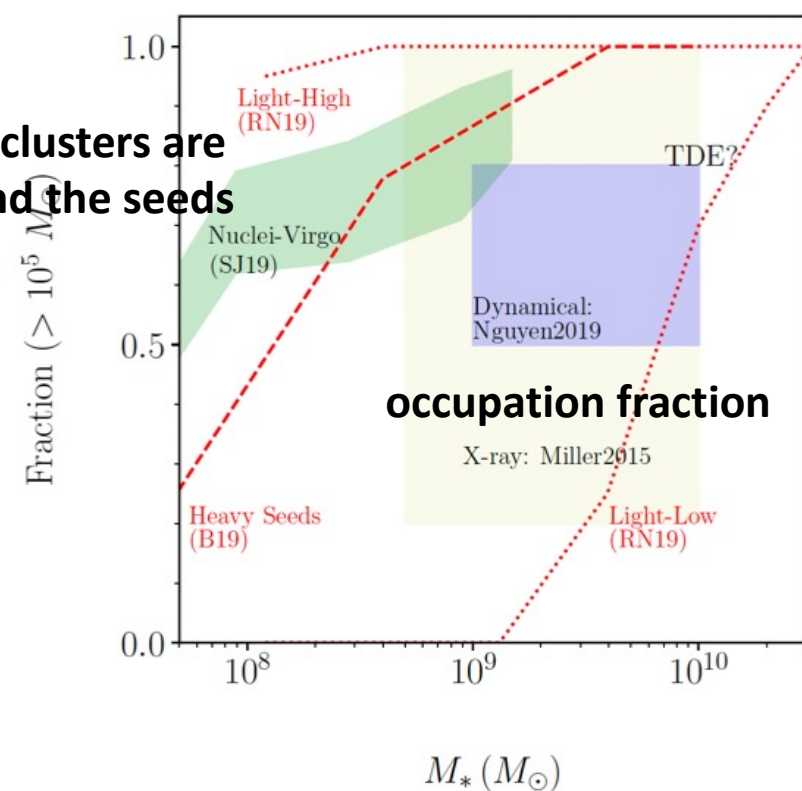
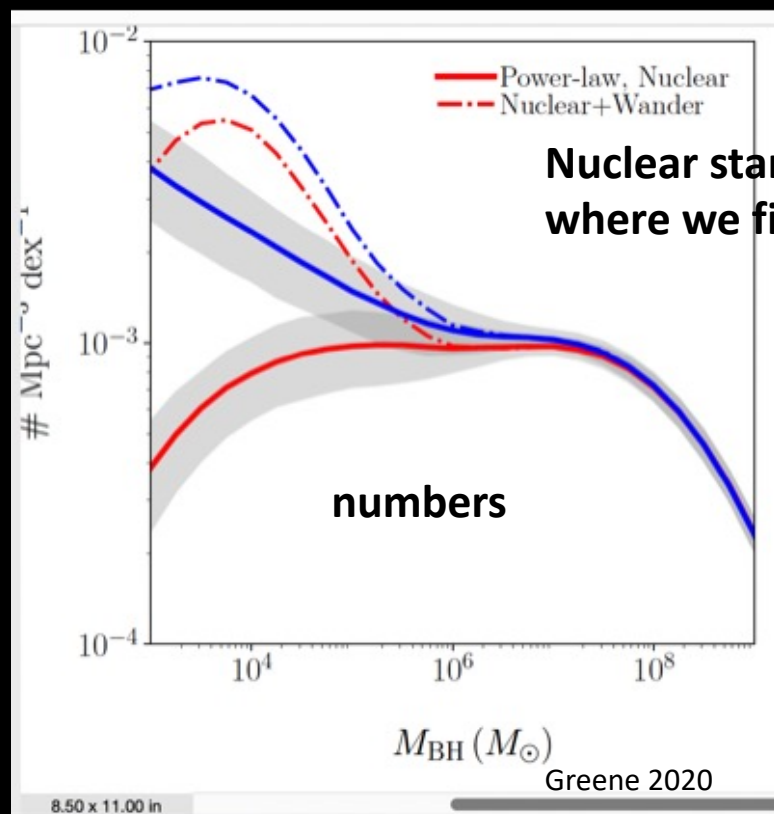
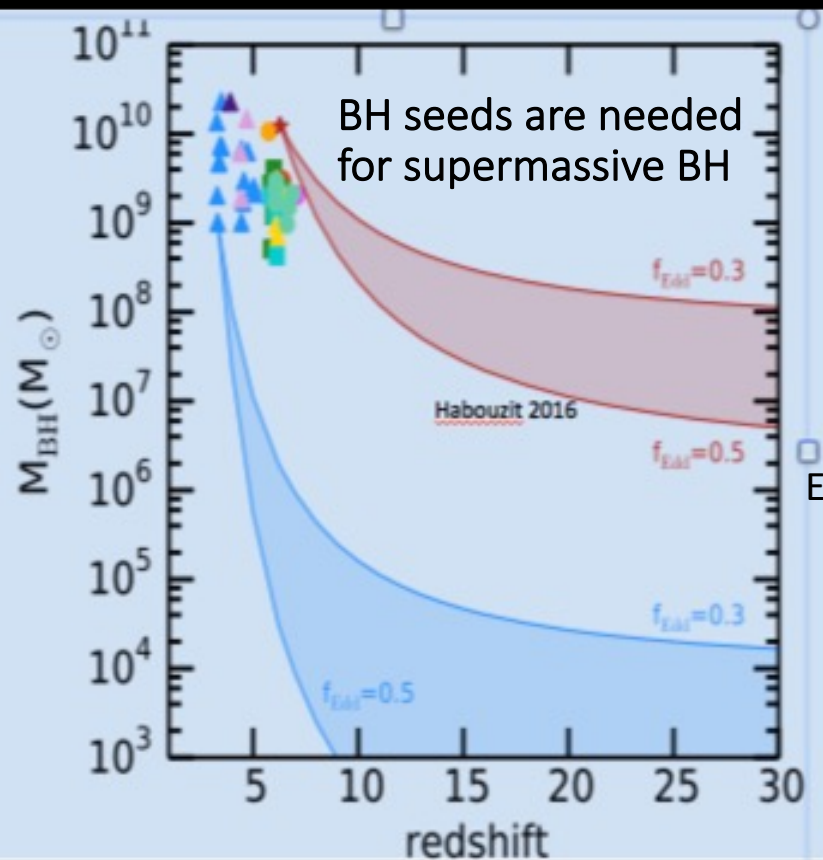
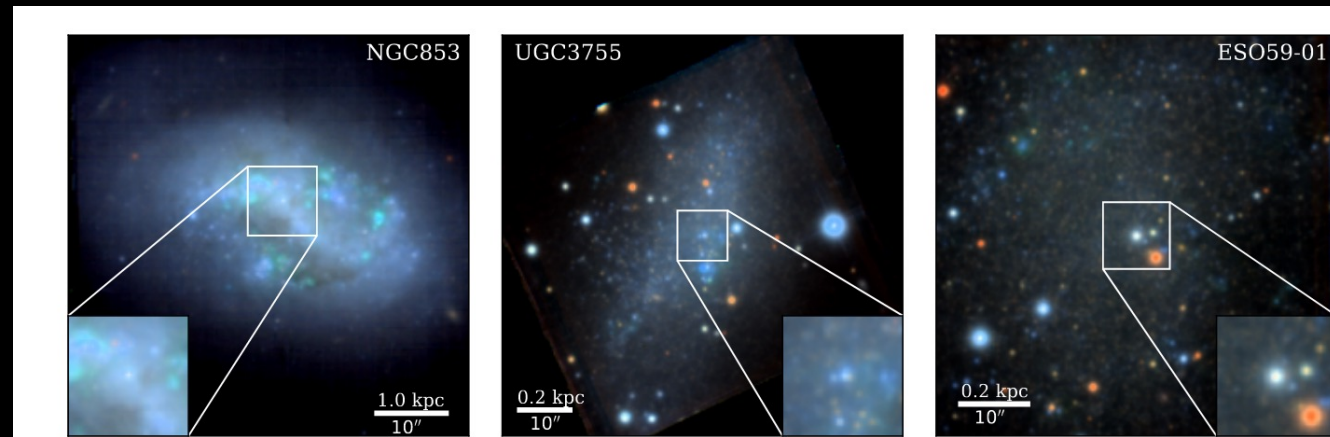
Radio AGN in dwarfs



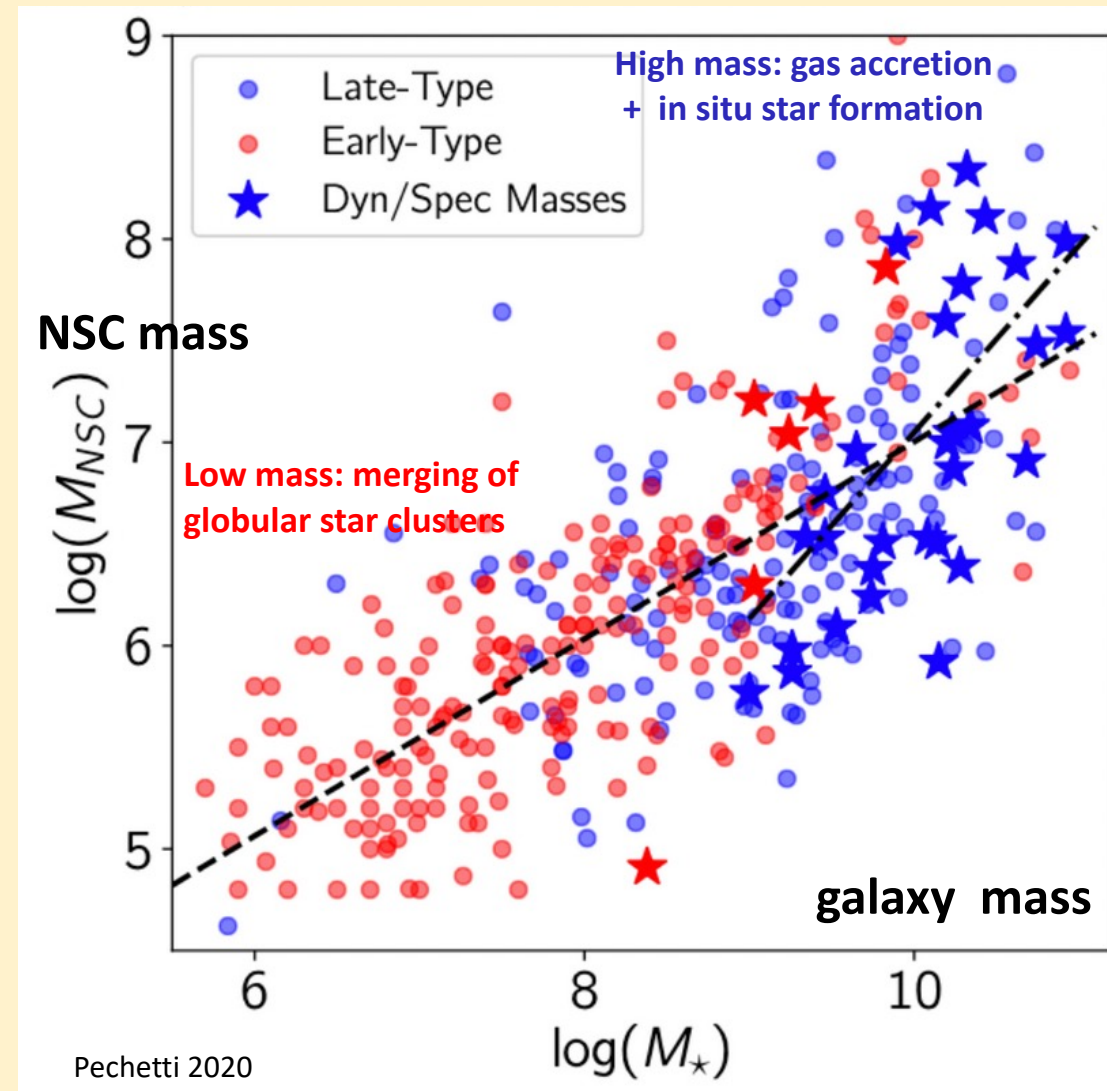
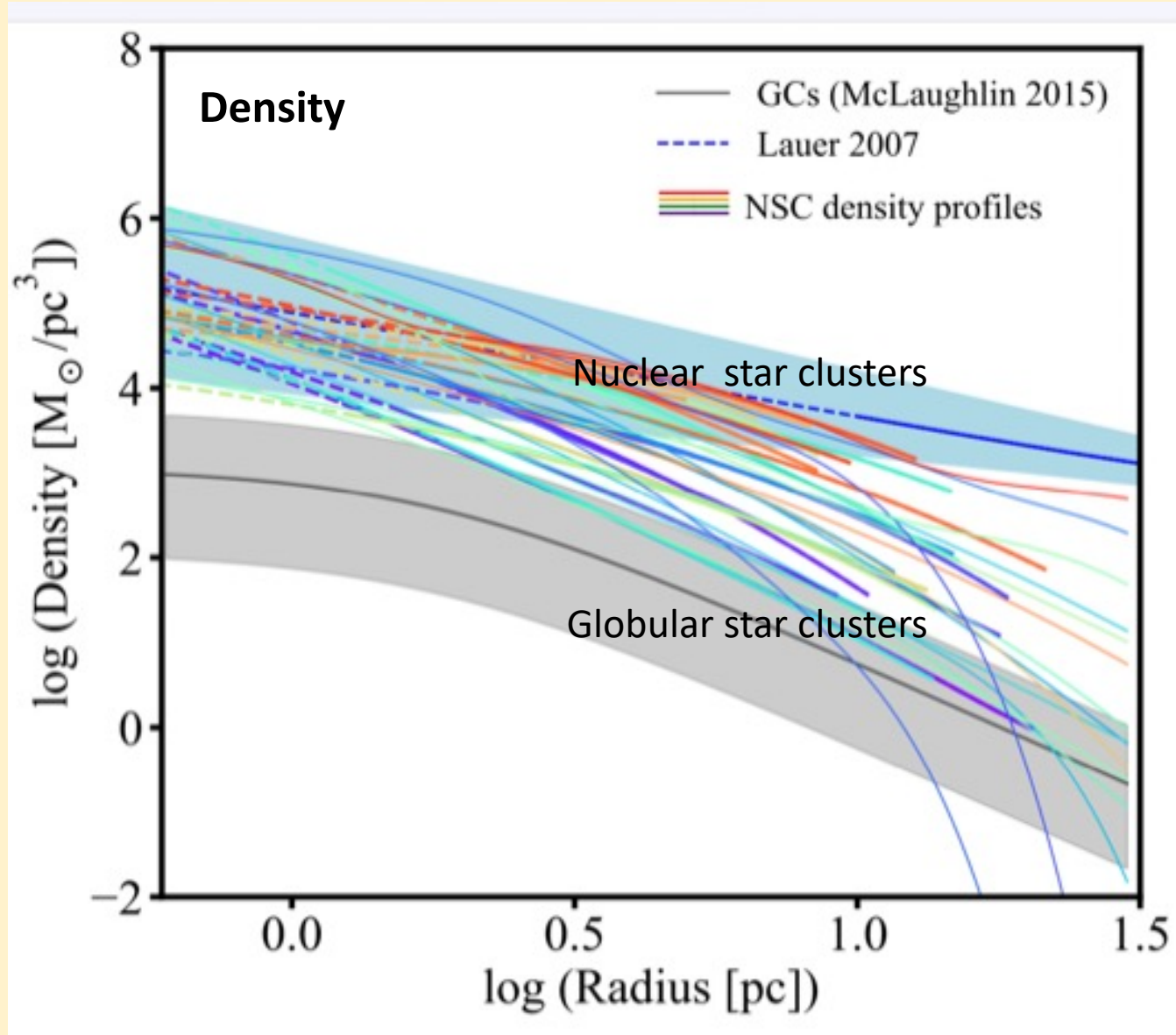
Davis + 2022



# The seeding problem

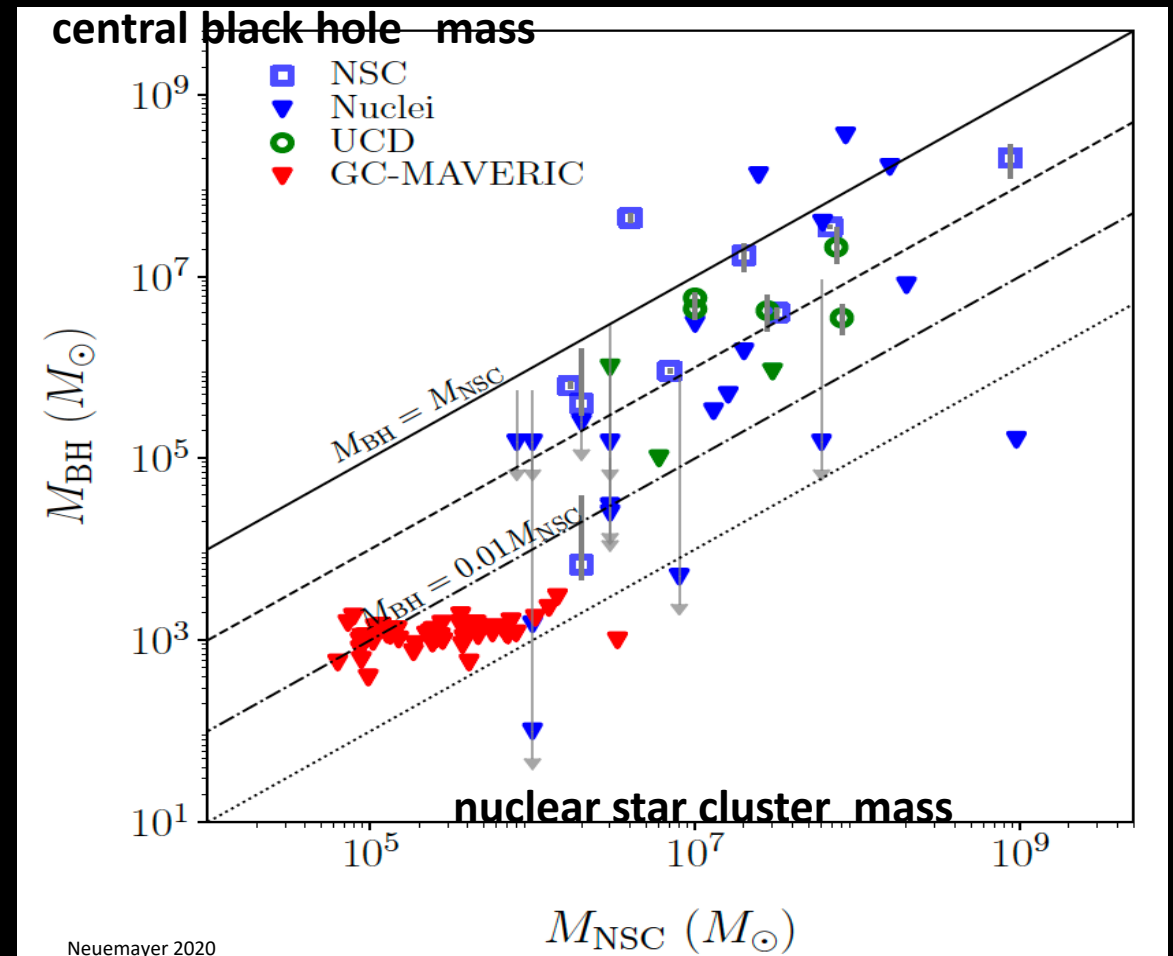
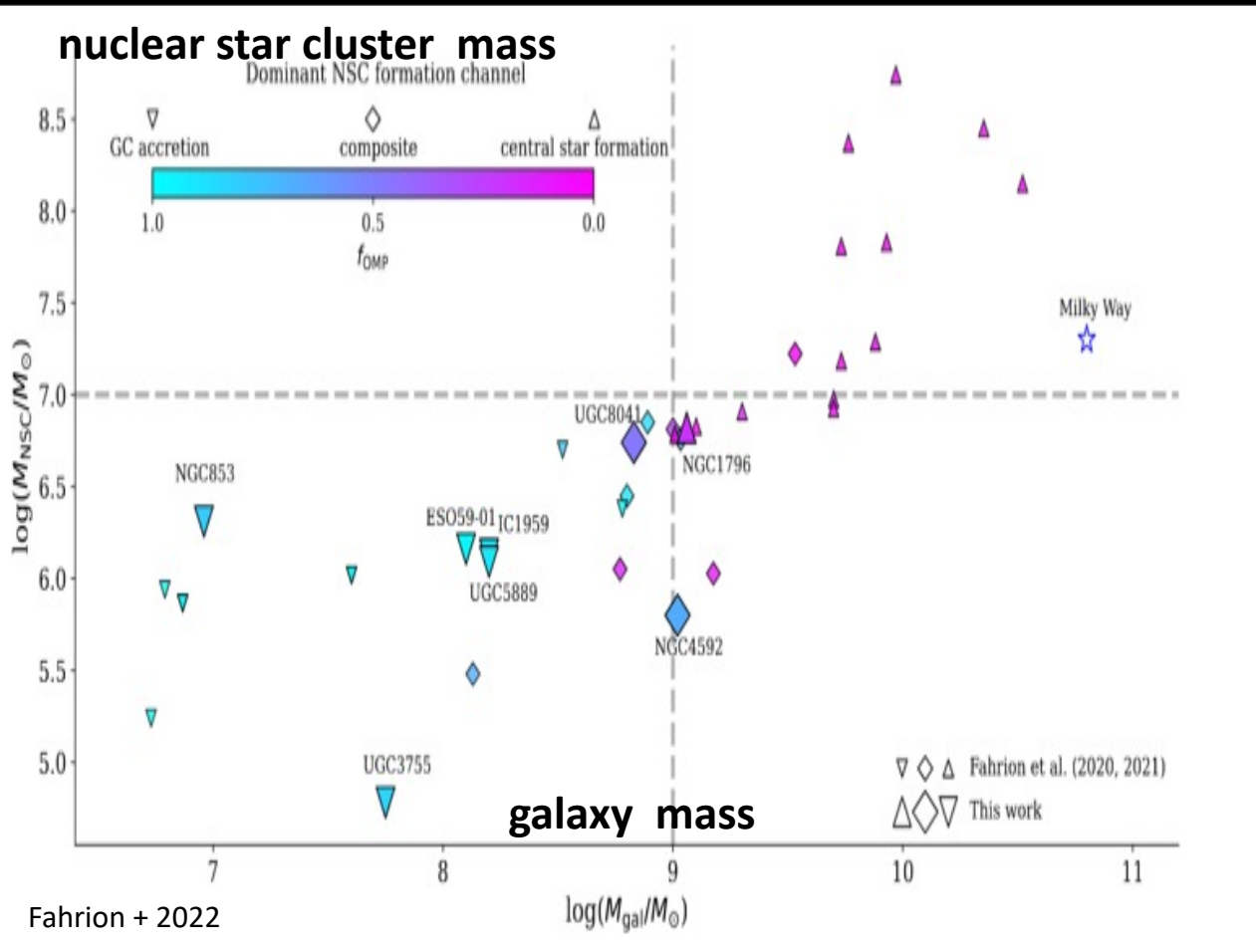


# Nuclear star clusters are the densest star clusters in the Universe



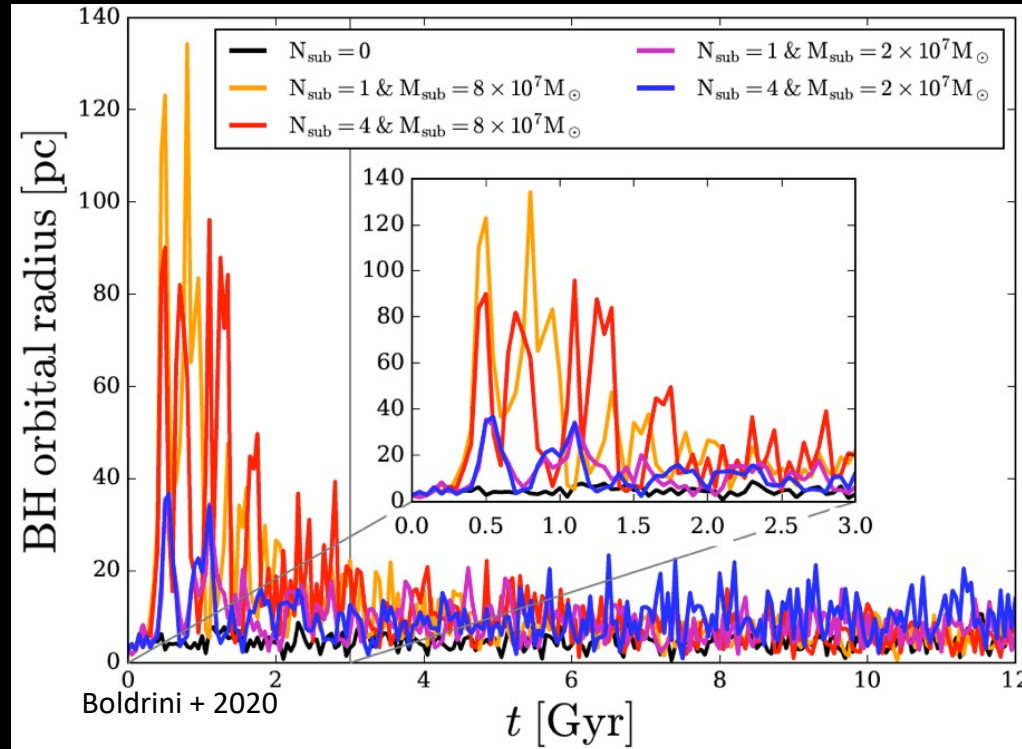
And it gets better....

...and better

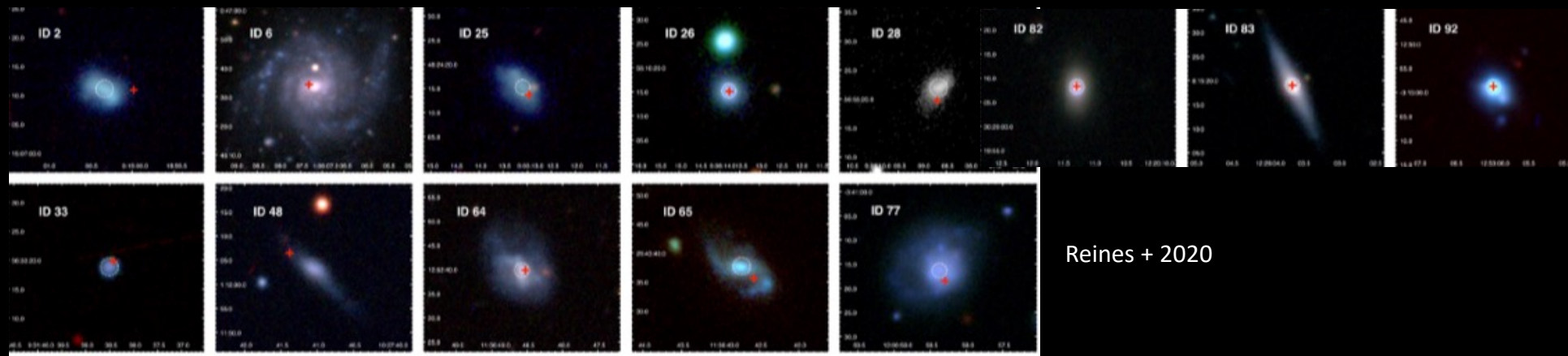




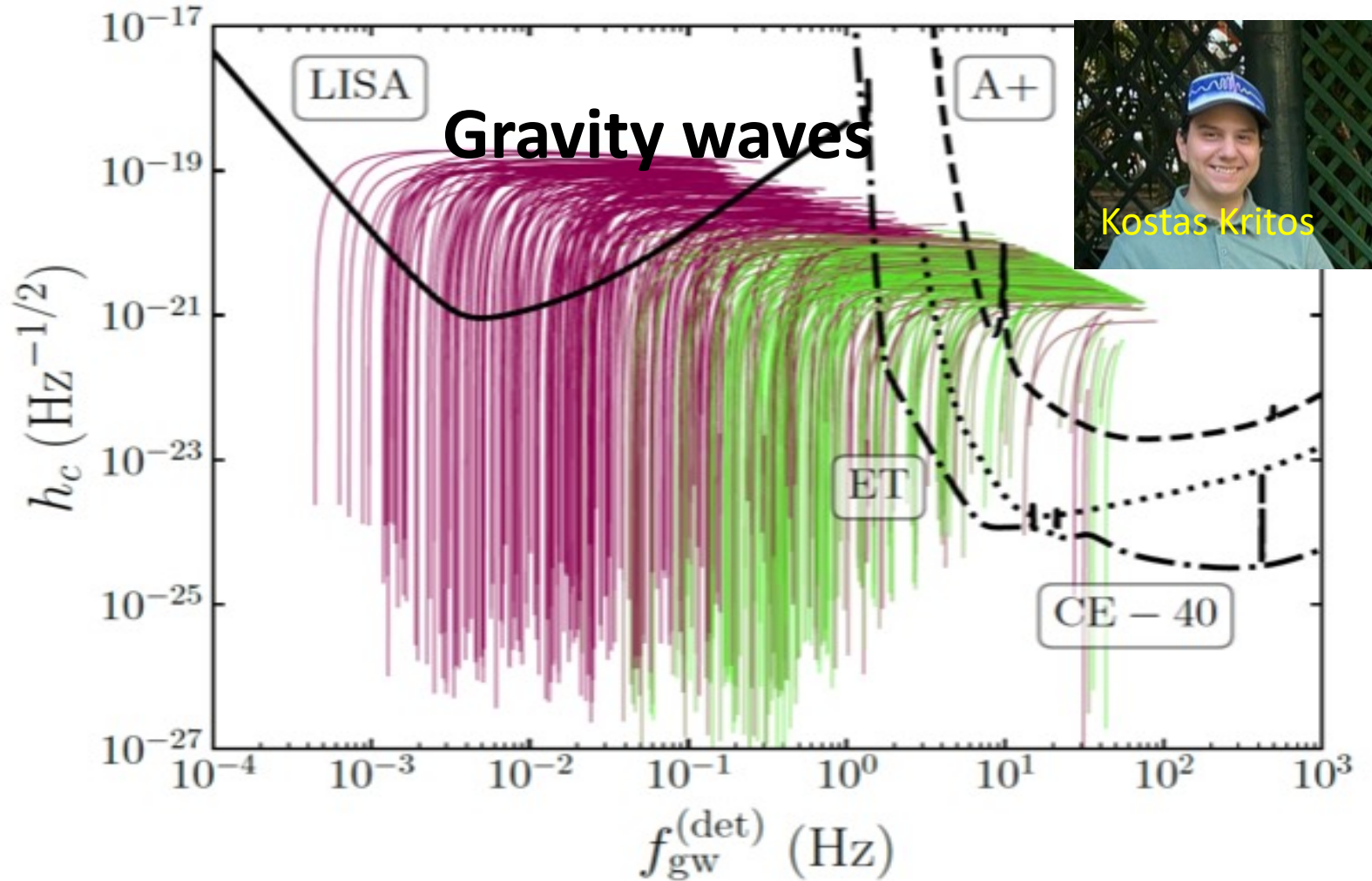
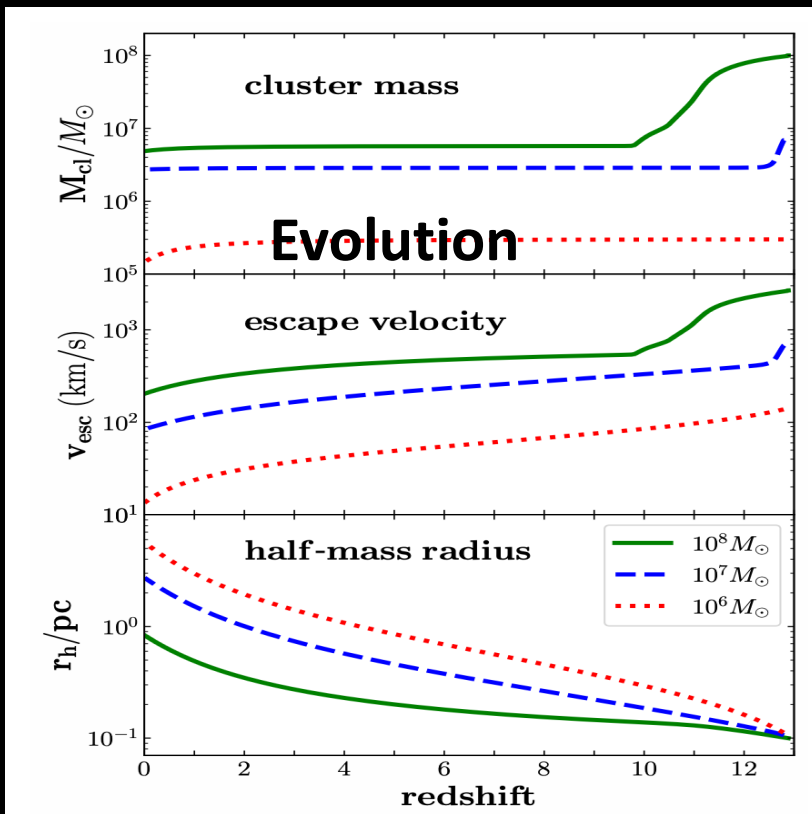
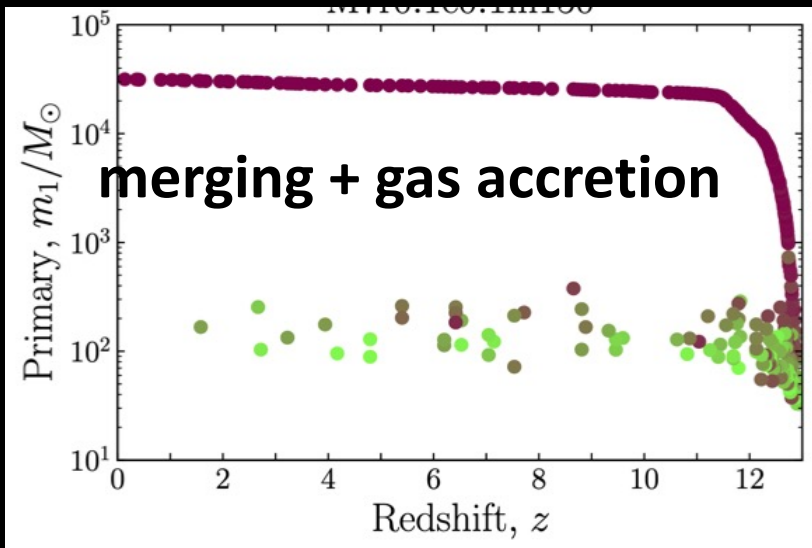
# one more CDM prediction: wandering IMBHs in dwarfs



Dark subhalo kicks or merger aftermath



# Form IMBH in massive NSC



Rapster: a fast code for dynamical formation of black-hole binaries in dense star clusters

Konstantinos Kritos,<sup>1,\*</sup> Vladimir Stokov,<sup>1,†</sup> Vishal Baibhav,<sup>2,‡</sup> and Emanuele Berti<sup>1,§</sup>

Dwarf galaxy “anomalies” don’t require particle “exotica”

Its all astrophysical feedback from IMBH with a little help from SNe

Intermediate mass black holes form early in nuclear star clusters  
via black hole merging and gas accretion

These are the likely seeds of supermassive black holes

LISA and 3G will probe their existence to  $z \sim 20$  via gravitational waves



# Thank you georg for great collaborations!

## CAN A MASS INVERSION SAVE SOLAR NEUTRINO OSCILLATIONS FROM THE LOS ALAMOS NEUTRINO?

Georg Raffelt (Max Planck Inst) Joseph Silk (UC, Berkeley)

***Phys.Lett.B 366 (1996) 429***

## PARTICLE DARK MATTER AND THE AGE OF GLOBULAR CLUSTERS

David Dearborn (LLNL) Georg Raffelt (UCBerkeley) Pierre Salati (LBL) Joseph Silk (UC Berkeley) Alain Bouquet (LAPP)

***Nature 343 (1990) 347***

## DARK MATTER AND THERMAL PULSES IN HORIZONTAL BRANCH STARS

David Dearborn. (LLNL) Georg Raffelt (UCBerkeley) Pierre Salati (UC Berkeley) Joseph Silk (UC,Berkeley) Alain Bouquet (LAPP)

***Astrophys.J. 354 (1990) 568***

## HORIZONTAL BRANCH STARS AS A PROBE OF NONBARYONIC DARK MATTER

Pierre Salati(UC,Berkeley) Alain Bouquet (LAPP) Georg Raffelt(UC,Berkeley) Joseph Silk (UC Berkeley) Astrophysics Workshop: Forefront Experimental Issues, 0026

## A STELLAR EVOLUTION BOUND ON RADIATIVE PARTICLE DECAYS AND THE COSMIC MICROWAVE BACKGROUND DISTORTION

Georg Raffelt (UC, Berkeley) Joseph Silk (UC, Berkeley).

***Astrophys.J. 336 (1989) 61***

## DARK MATTER AND STELLAR EVOLUTION

Georg Raffelt (UC, Berkeley) and LLNL, Joseph Silk (UC, Berkeley)

20th Yamada Conference: Big Bang, Active Galactic Nuclei and Supernovae

## MAGNETICALLY INDUCED NEUTRINO OSCILLATIONS AND NEUTRINO REFRACTIVE EFFECTS IN THE EARLY UNIVERSE

Masataka Fukugita (Kyoto U.) Dirk Notzold (MPI) Georg Raffelt (UC Berkeley and LLNL) Joseph Silk (UC, Berkeley)

***Phys.Rev.Lett. 60 (1988) 879***

## LIGHT NEUTRINOS AS COLD DARK MATTER Georg Raffelt (UC Berkeley and LLNL) Joseph Silk (UC Berkeley),

***Phys.Lett.B 192 (1987) 65-70***