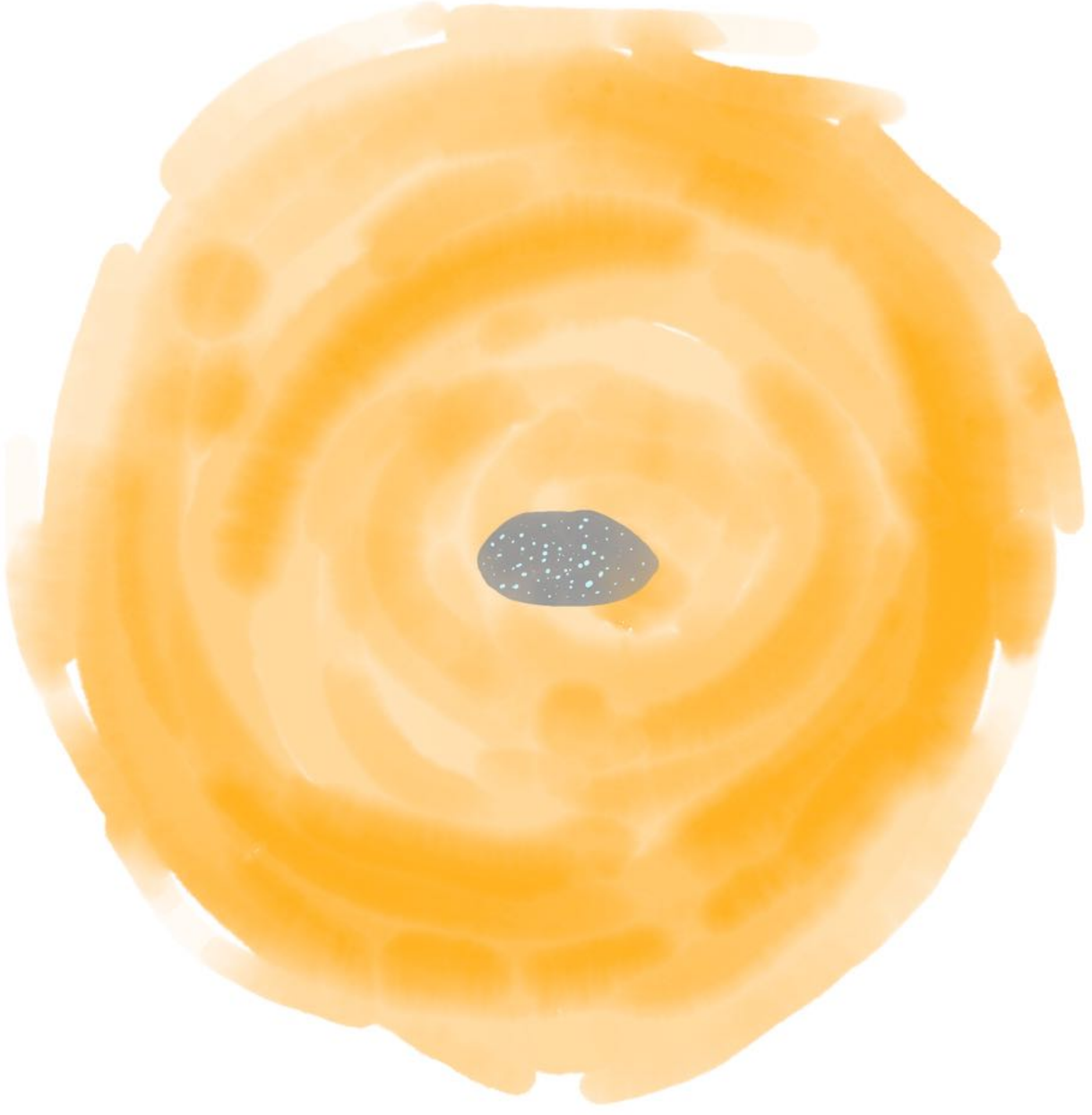
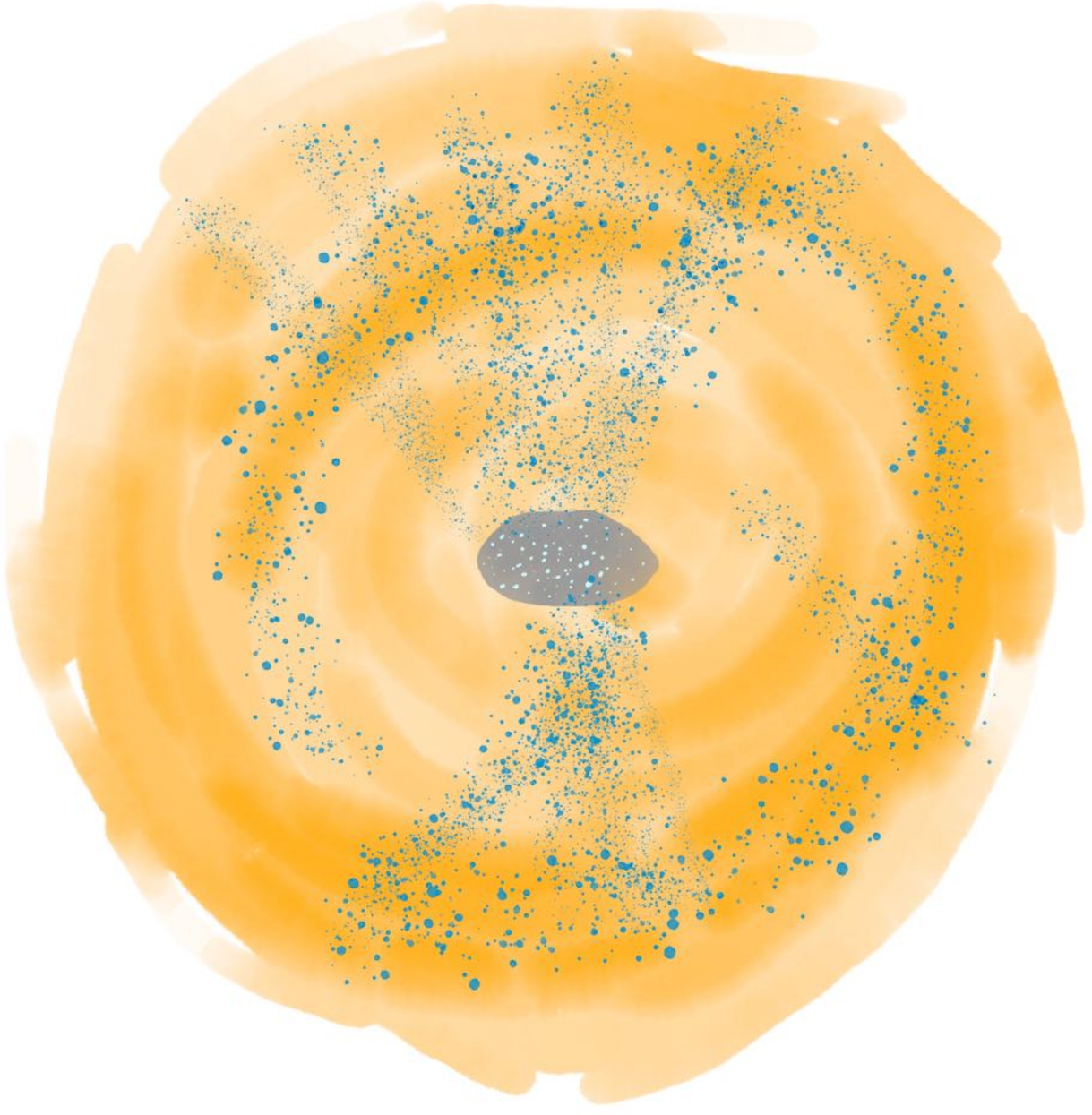
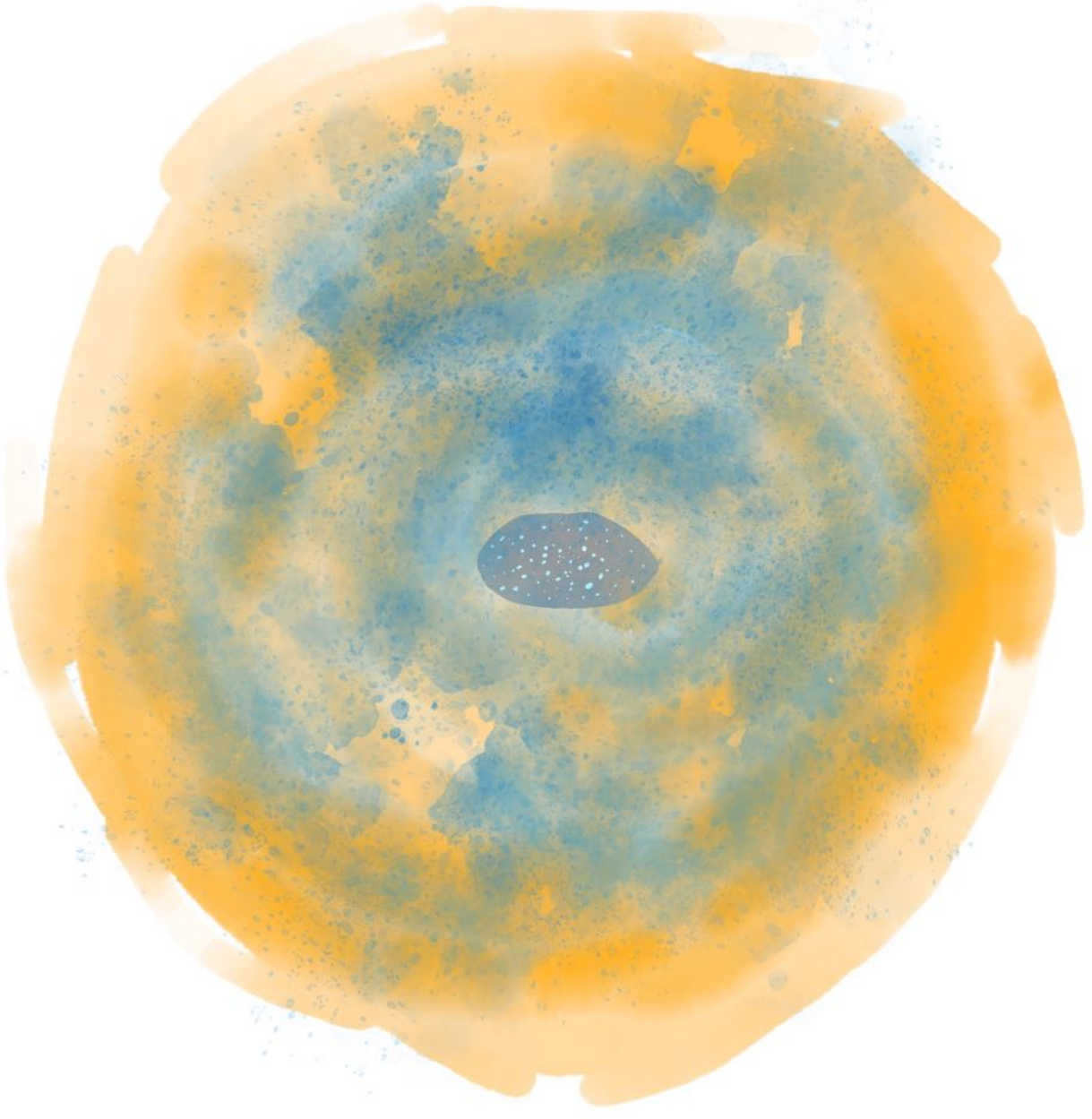
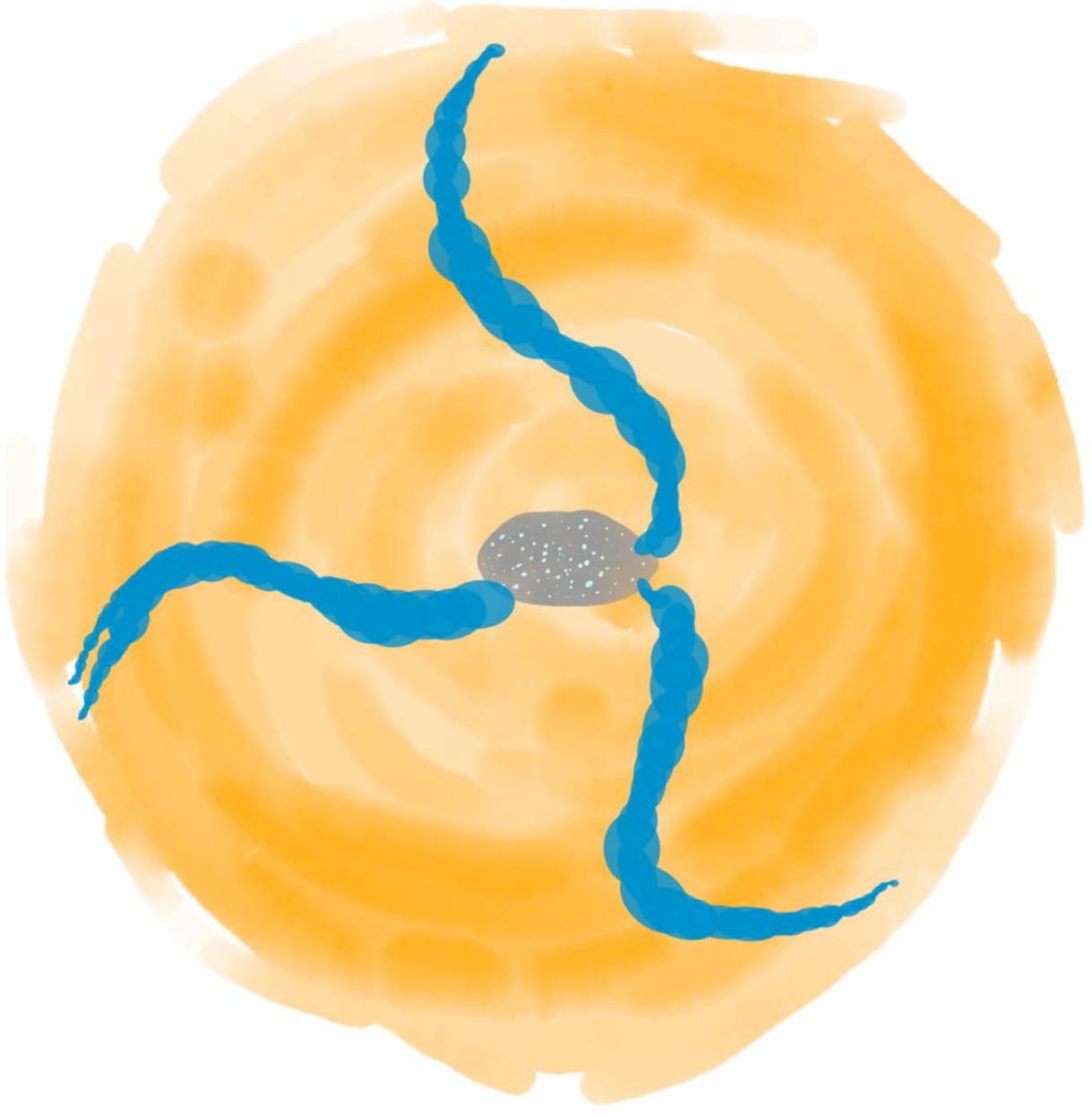
Why are gaseous halos often multiphase?

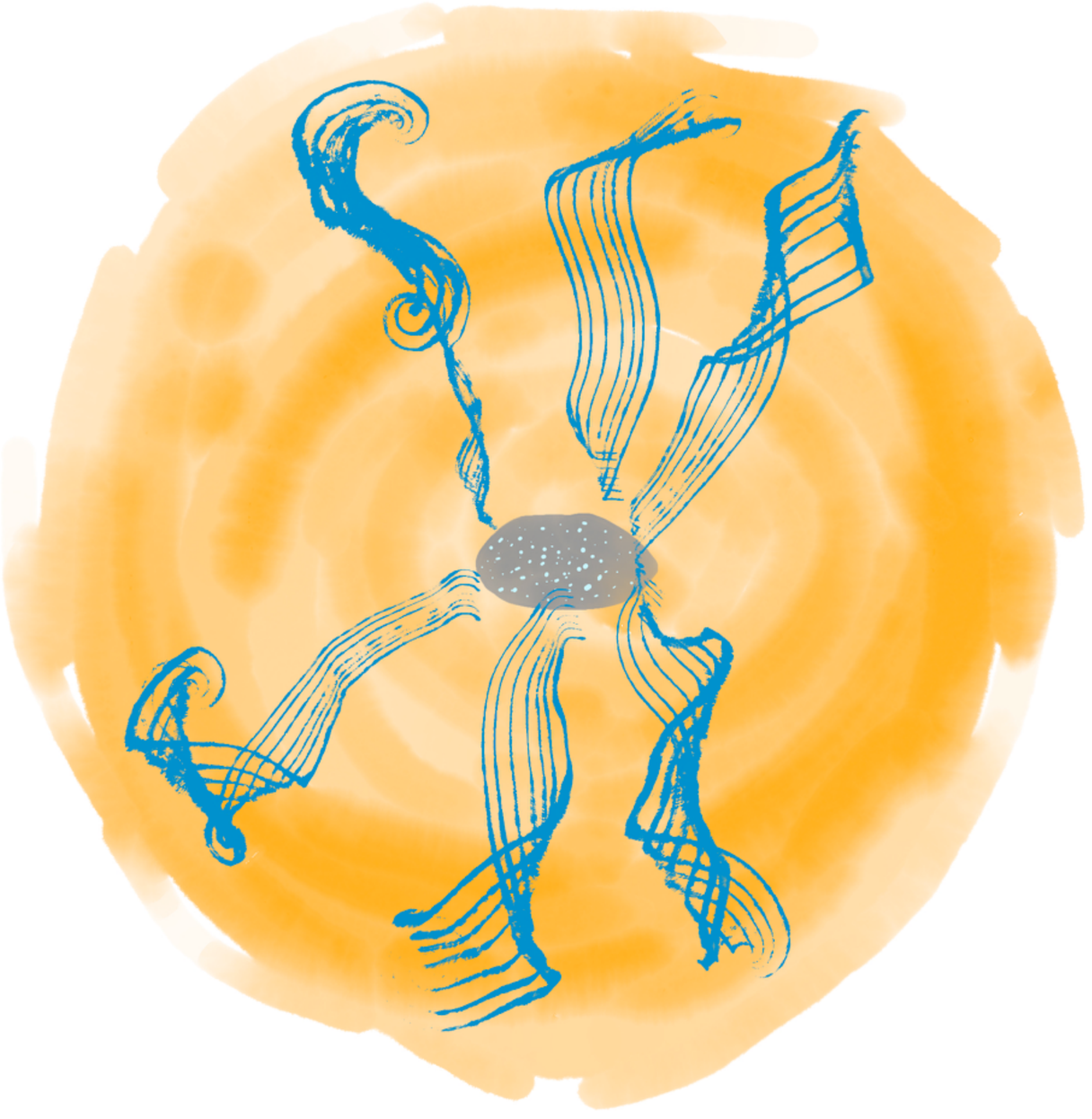
Drummond Fielding









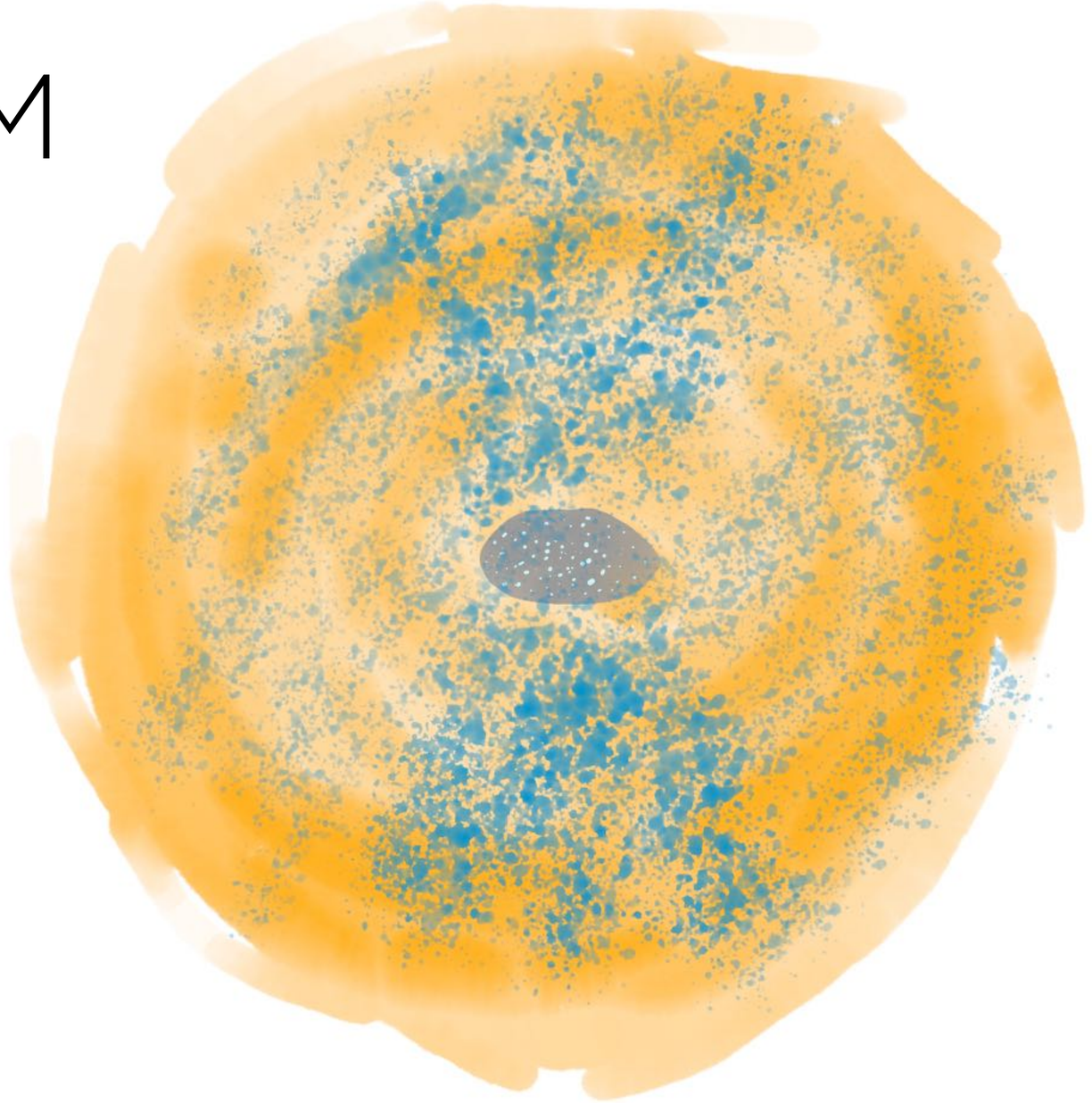


Multiphase CGM

volume-filling phase
hot T ~ T_{vir} ~ 10^6 K

intermediate phase
warm T ~ 10^5 K

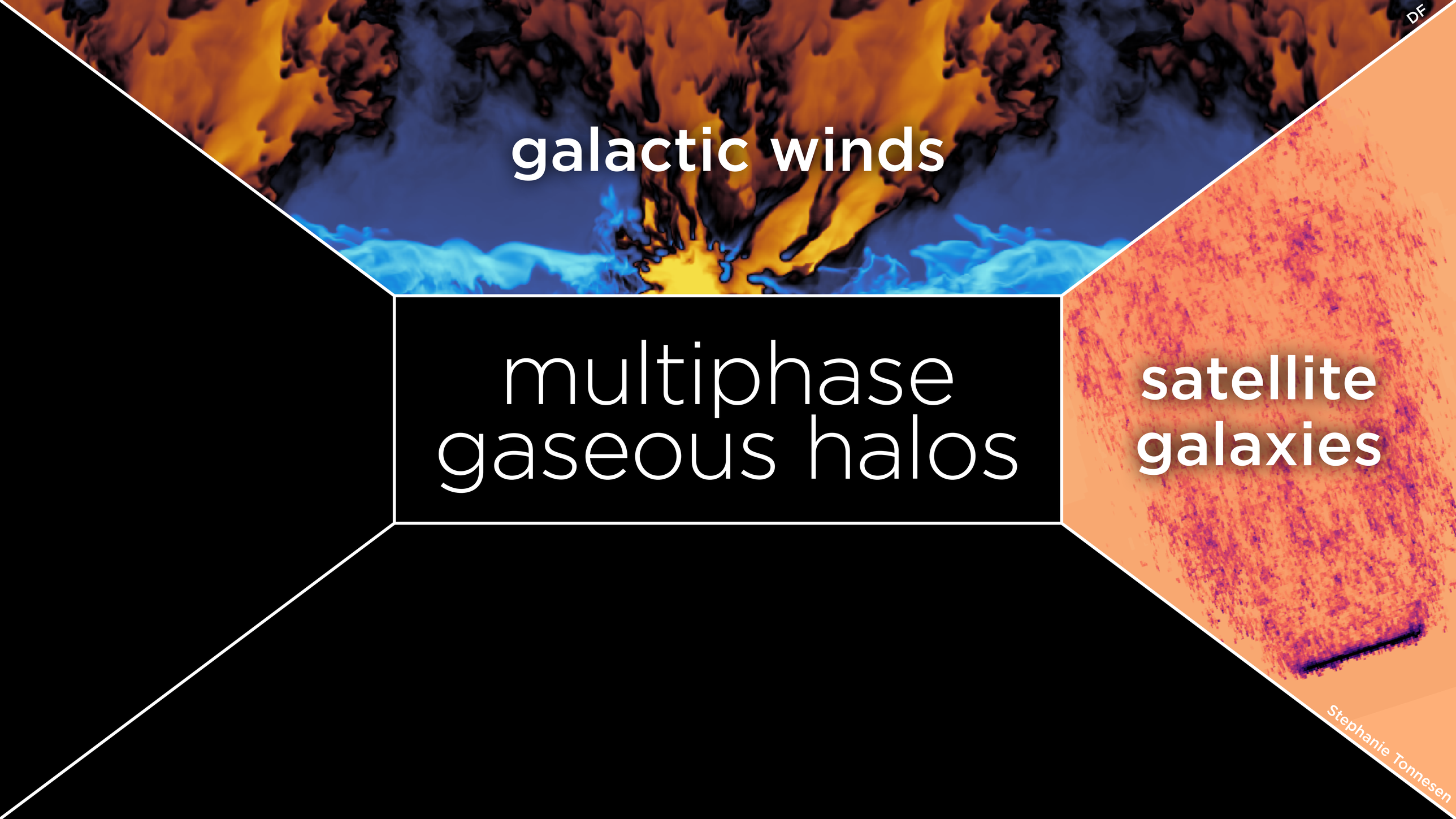
dense phase
cold T ~ T_{UVB} ~ 10^4 K

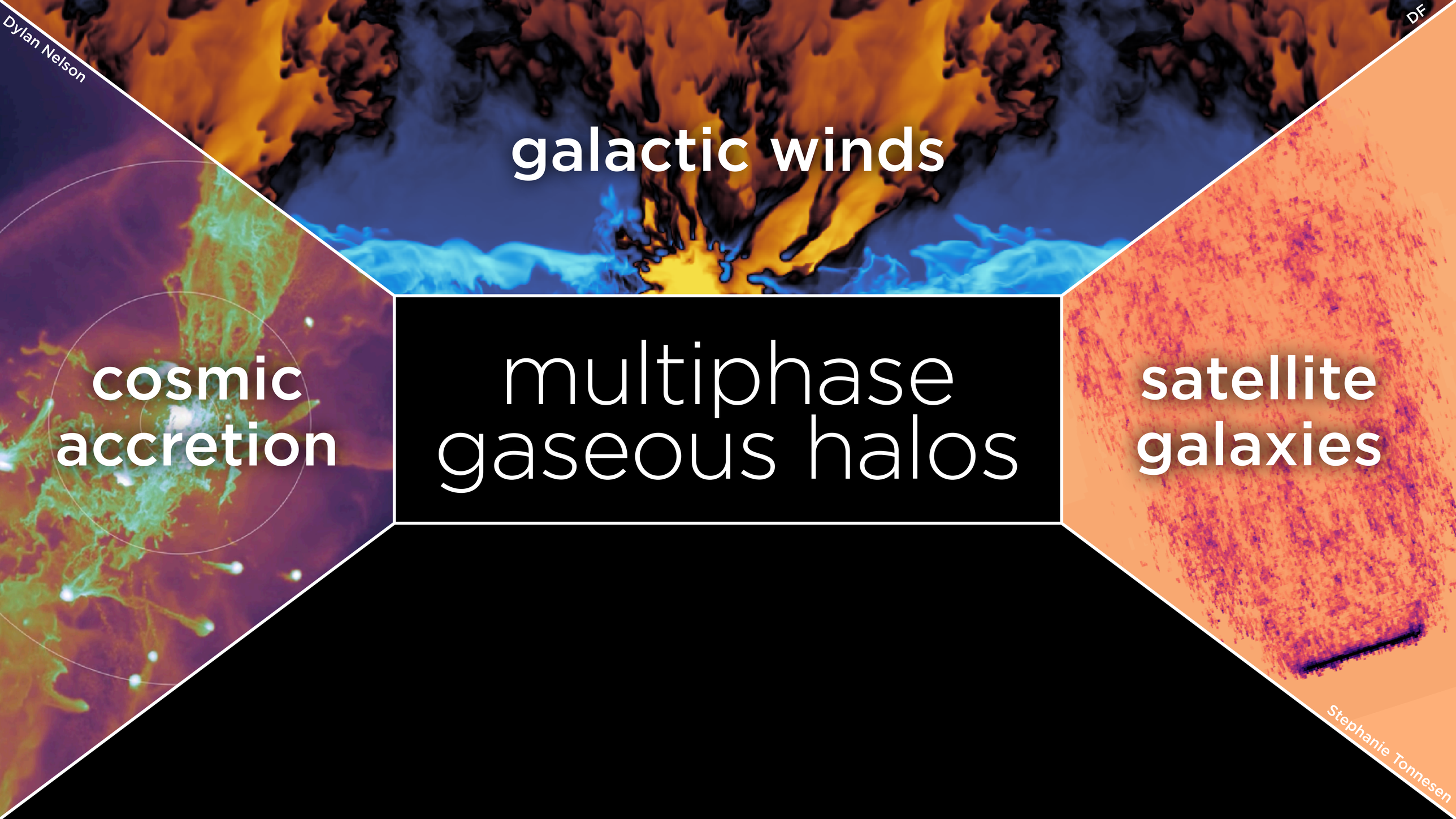


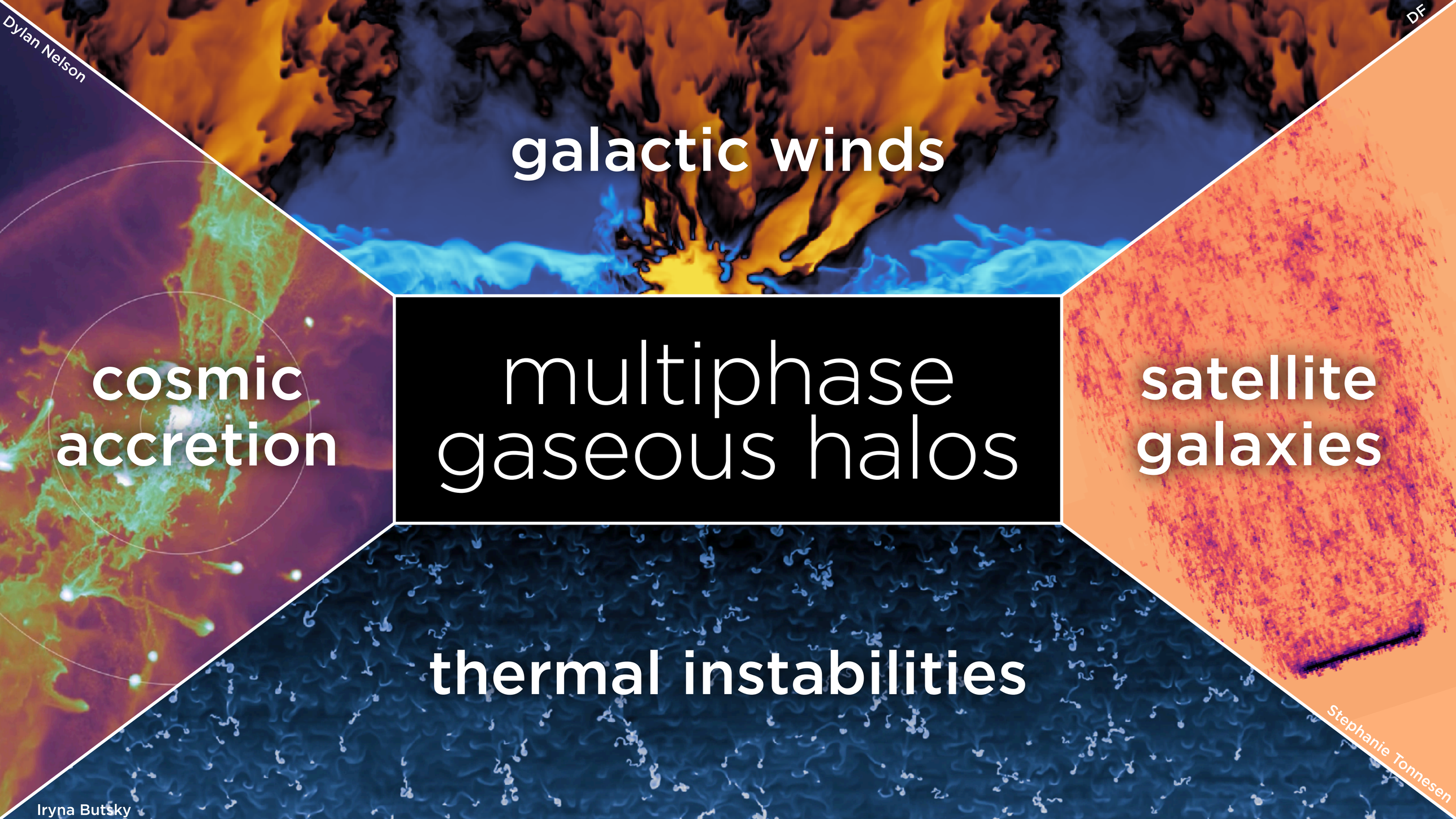
multiphase gaseous halos

galactic winds

multiphase gaseous halos


galactic winds
multiphase
gaseous halos
satellite
galaxies
DF
Stephanie Tonnesen


Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
Stephanie Tonnesen

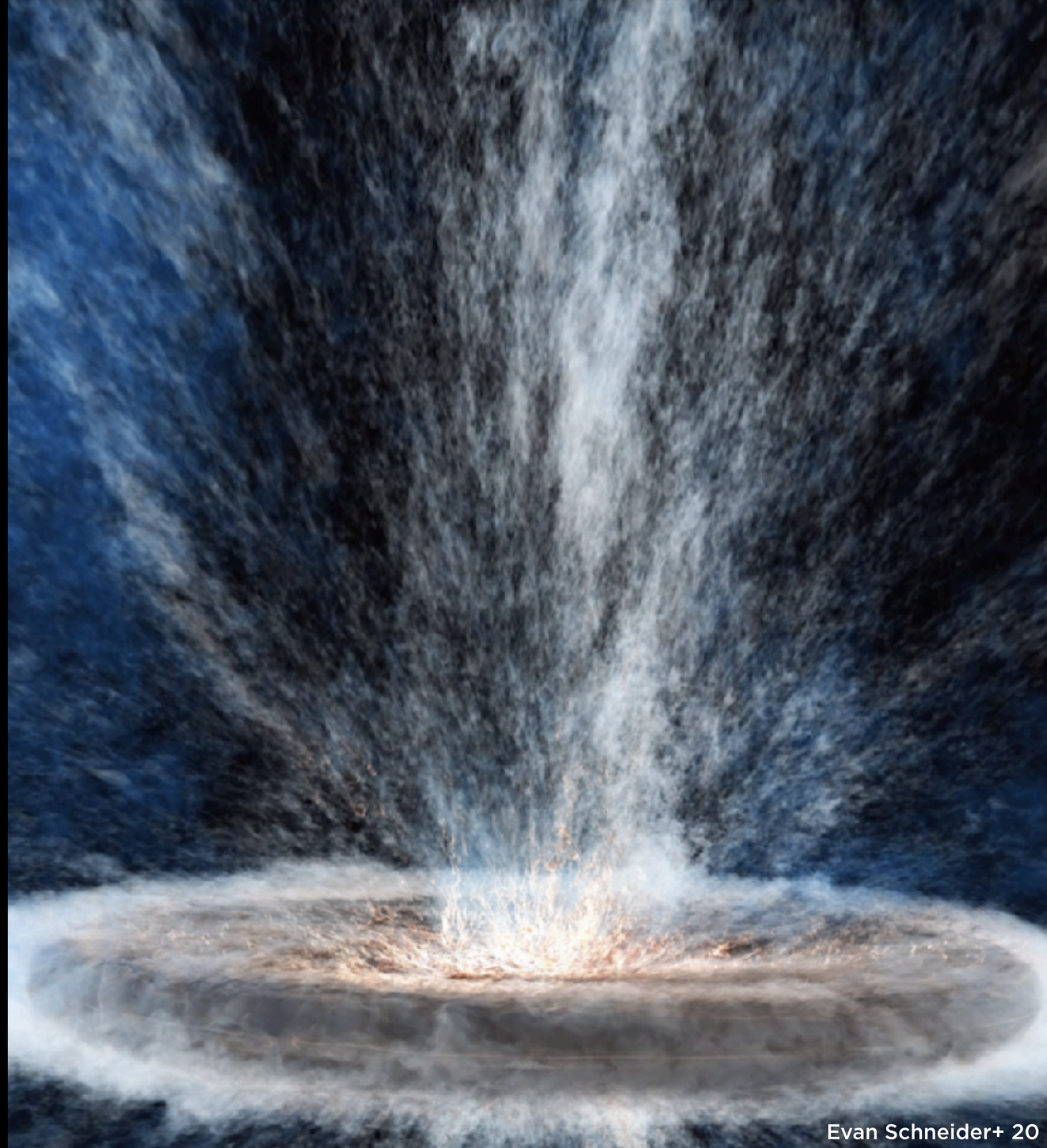

Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
thermal instabilities
Stephanie Tonnesen
Iryna Butsky

galactic winds

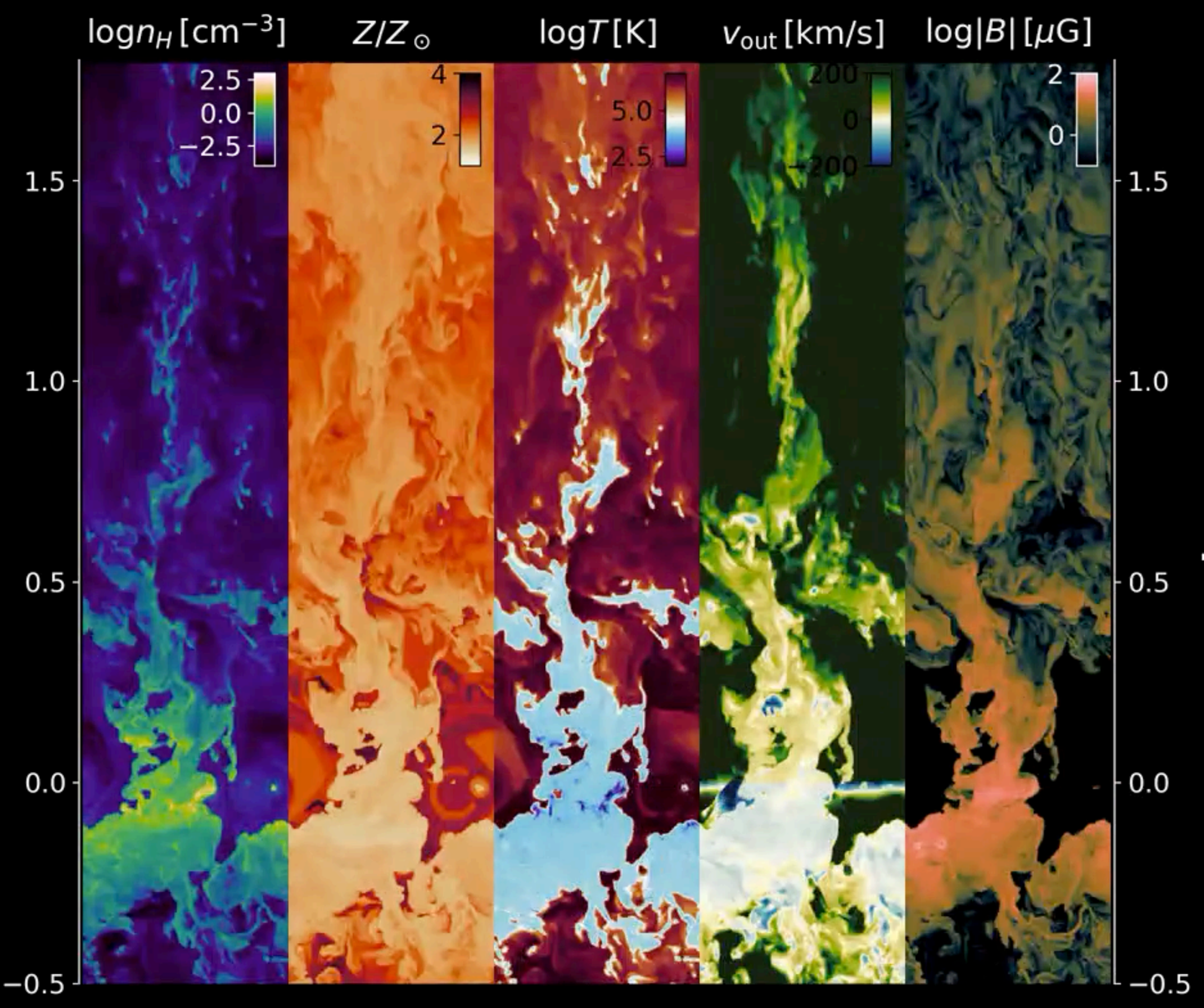
direct launching

How much cold gas is carried by winds?

What is the fate of cold gas in winds?



Evan Schneider+ 20



galactic winds

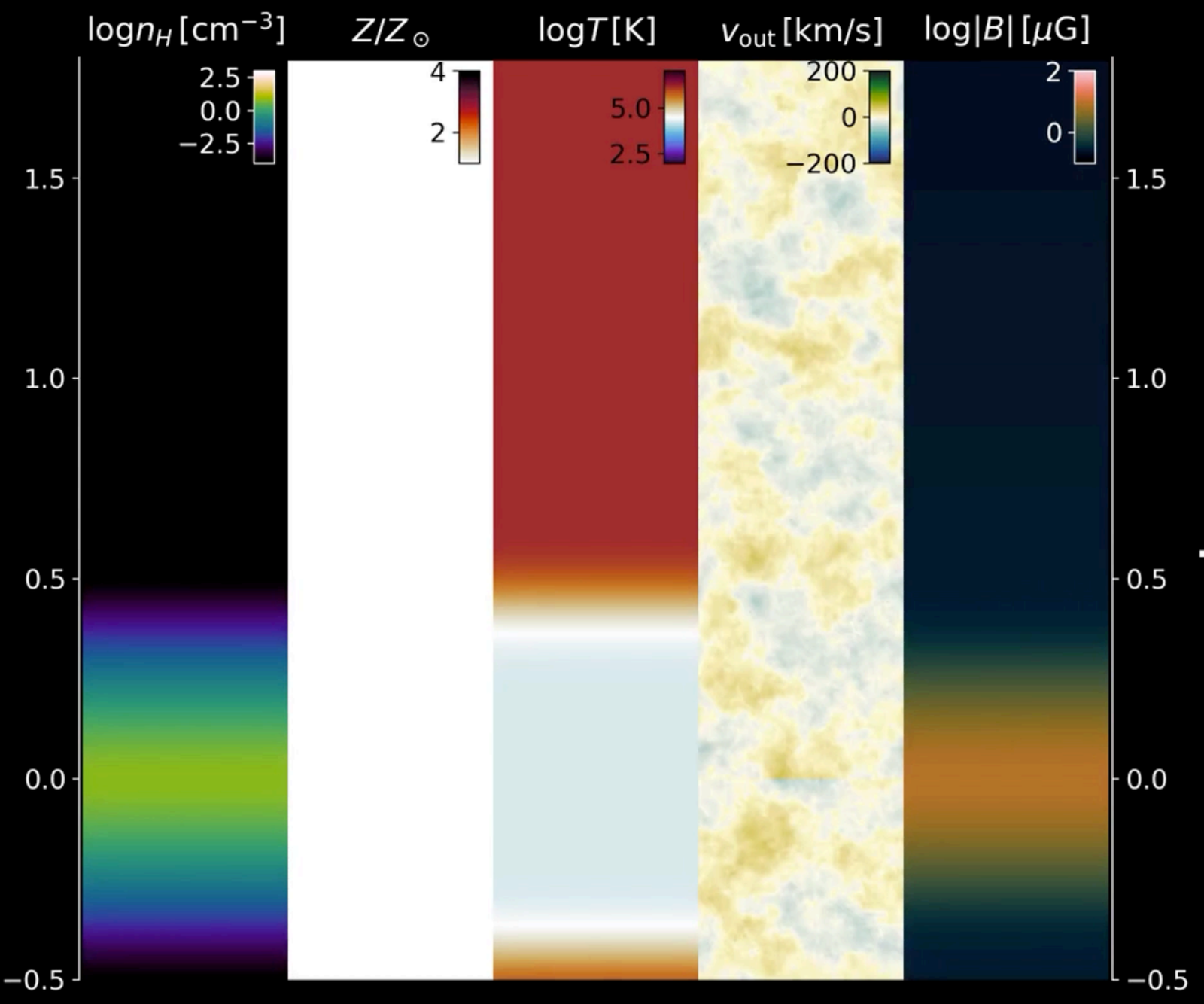
what leaves the ISM

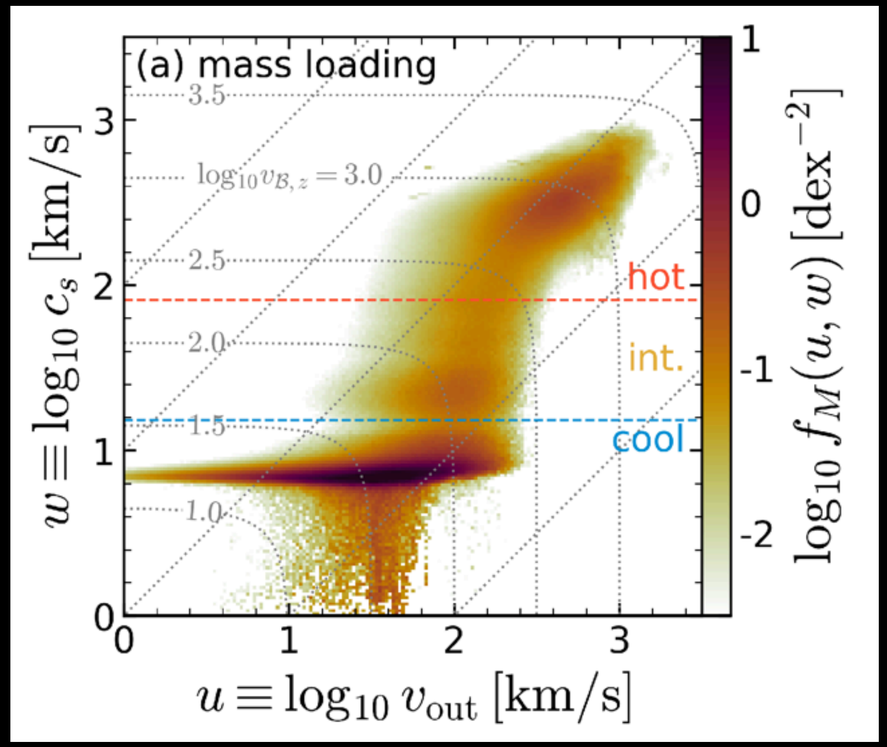
Resolving the wind launching process informs expected phase structure

Chang-Goo Kim+ 20

galactic winds

what leaves the ISM



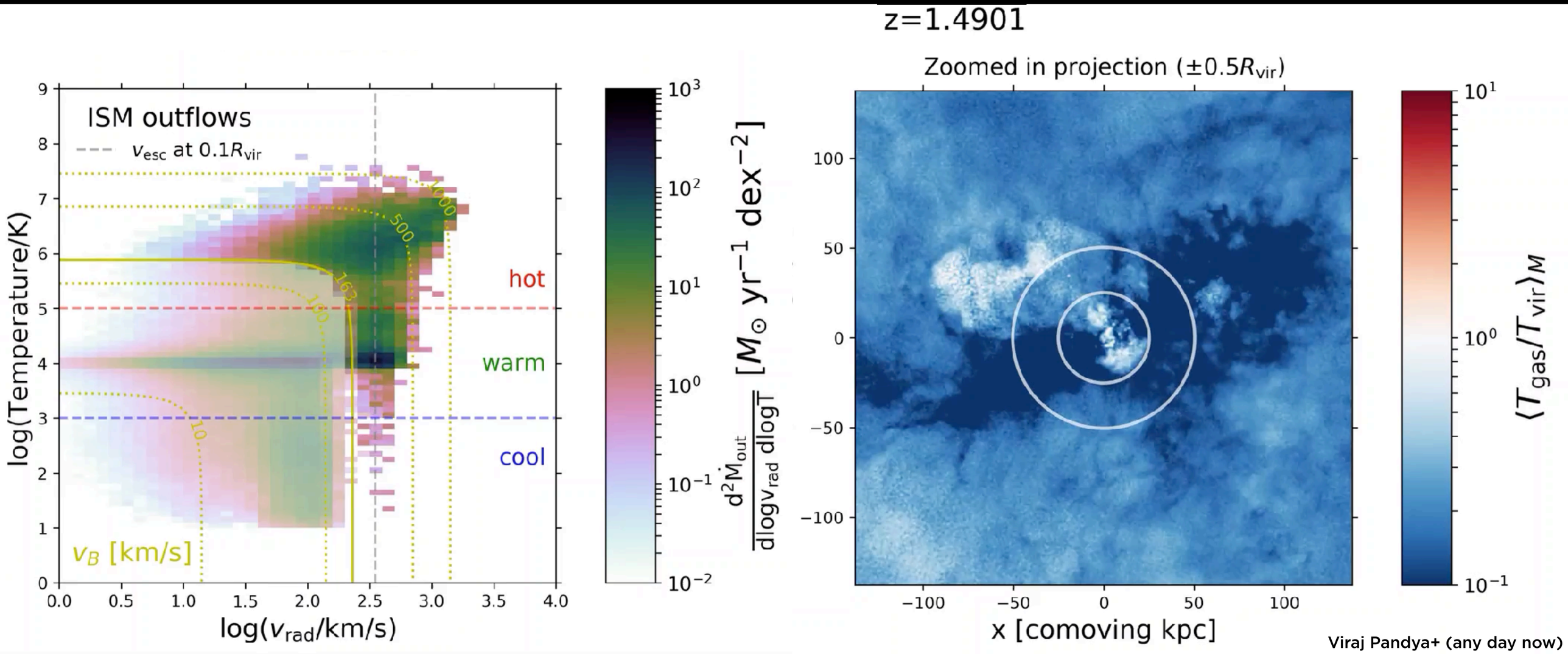


Chang-Goo Kim+ 20

galactic winds

cosmological zoom-in

Similar behavior in
FIRE-2 cosmo. zoom



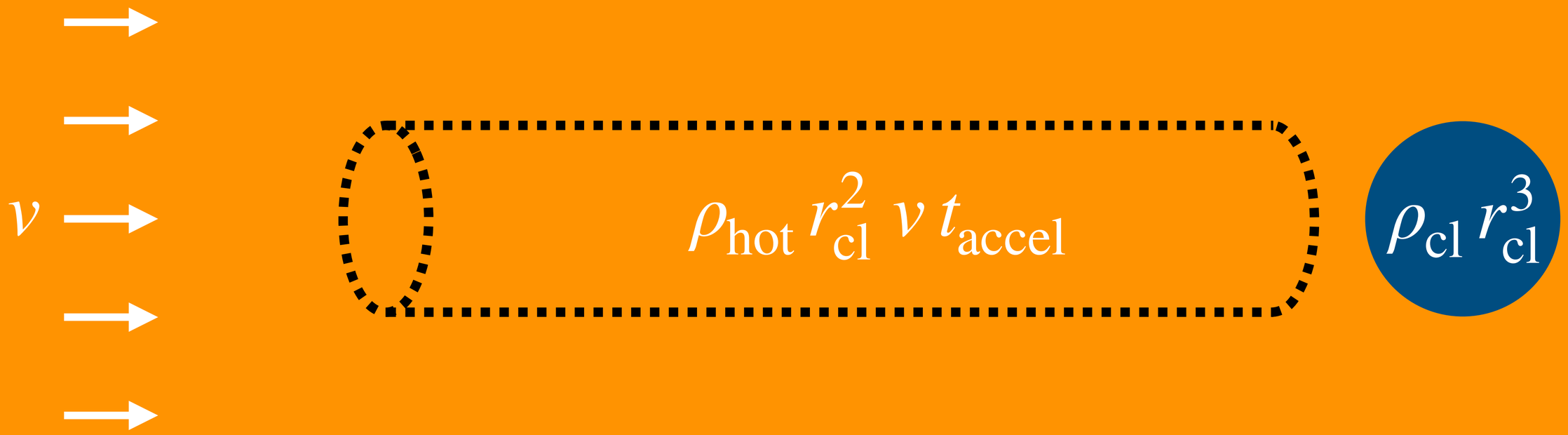
Viraj Pandya+ (any day now)

galactic winds

entrainment in trouble

Dong Zhang+ 2017

$$t_{\rm accel} = \frac{\rho_{\rm cl}}{\rho_{\rm hot}} \frac{r_{\rm cl}}{v} = \chi \frac{r_{\rm cl}}{v}$$



galactic winds

entrainment in trouble

$$t_{\rm destroy} \approx t_{\rm cc} = \chi^{1/2} \frac{r_{\rm cl}}{v}$$

Matthew Abruzzo+ 21

galactic winds

entrainment in trouble

$$\frac{t_{\rm destroy}}{t_{\rm accel}} = \chi^{-1/2} \ll 1 \quad ?!!?!?!$$

galactic winds

entrainment in trouble

If the mixed gas
radiatively cools rapidly
then clouds can survive!

$$t_{\rm cool,mixed} < t_{\rm destroy}$$

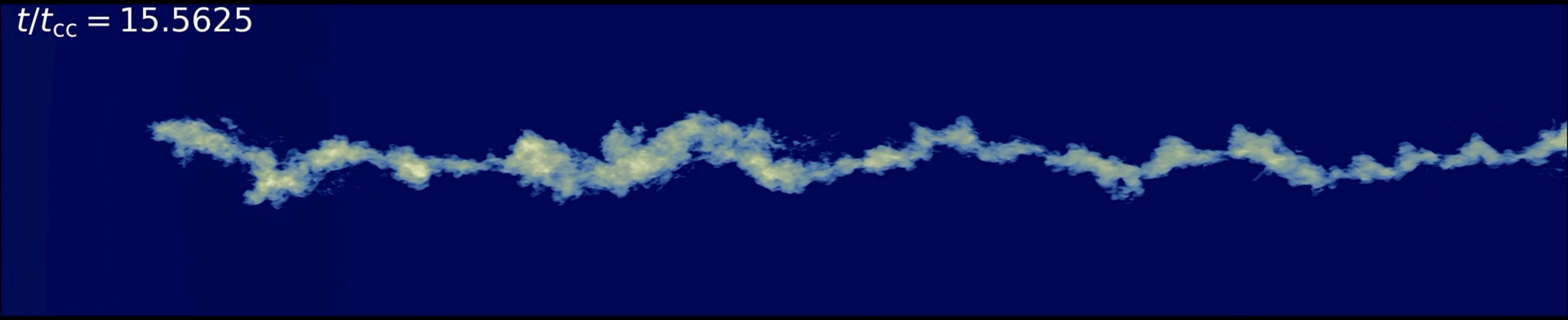
$$r_{\rm cl} > \frac{v\, t_{\rm cool,mixed}}{\chi^{1/2}}$$

Max Gronke and Peng Oh (2018)

galactic winds

entrainment in trouble

$$t_{\rm cool,mixed} < t_{\rm destroy}$$

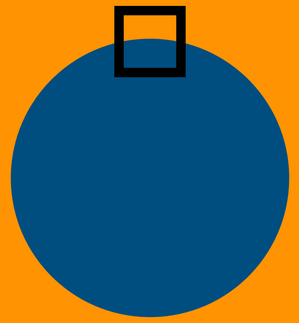


Matthew Abruzzo+ 21

See also: Max Gronke & Peng Oh 18,20; Zhihui Li+ 20; Martin Sparre + 19,20; Vijit Kanjilal+ 20; Wladimir Banda-Barragán+ 20a,b; and many more

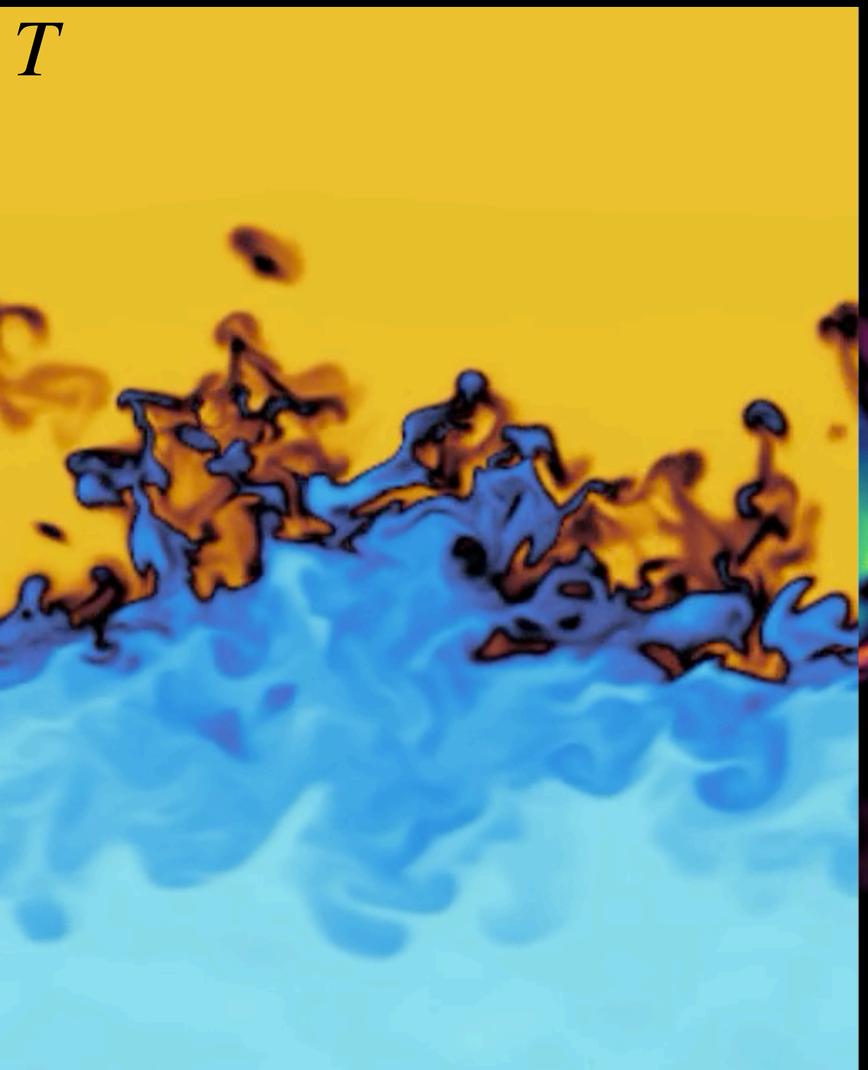
Turbulent Radiative Mixing Layers

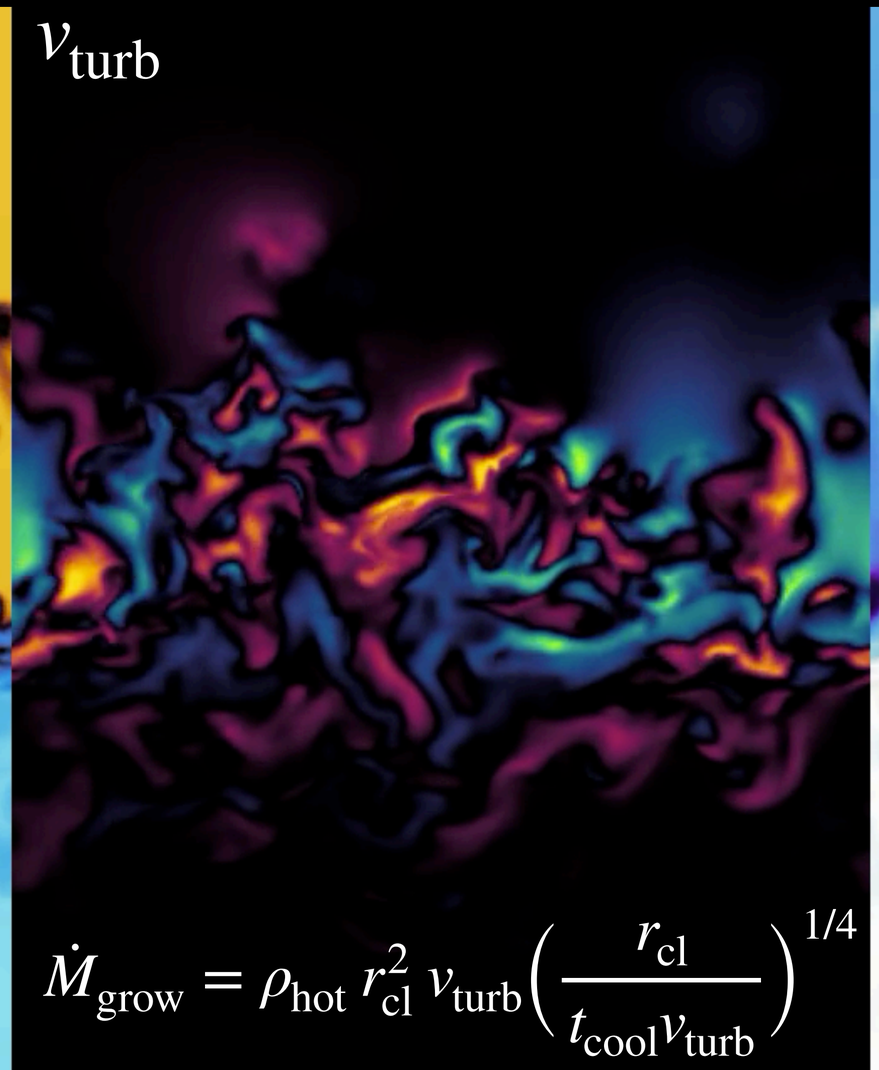
Taming the Turmoil

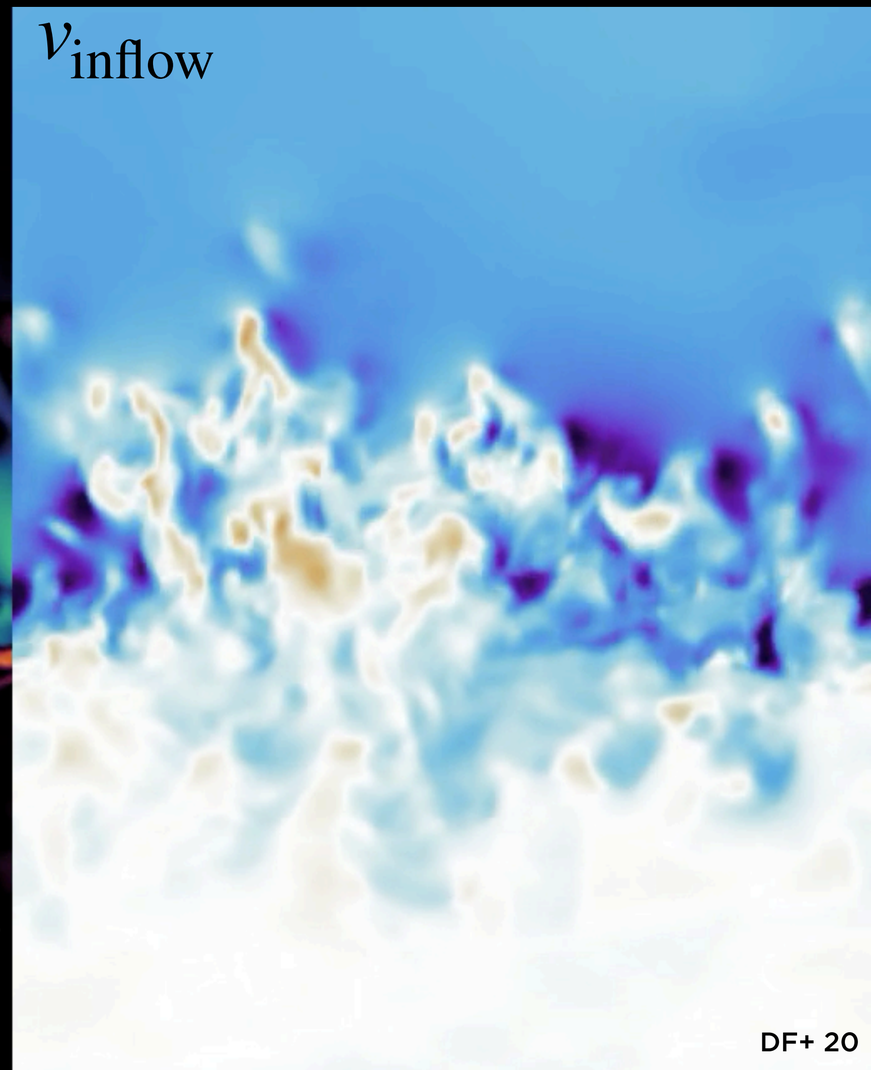


Turbulent Radiative Mixing Layers

Taming the Turmoil

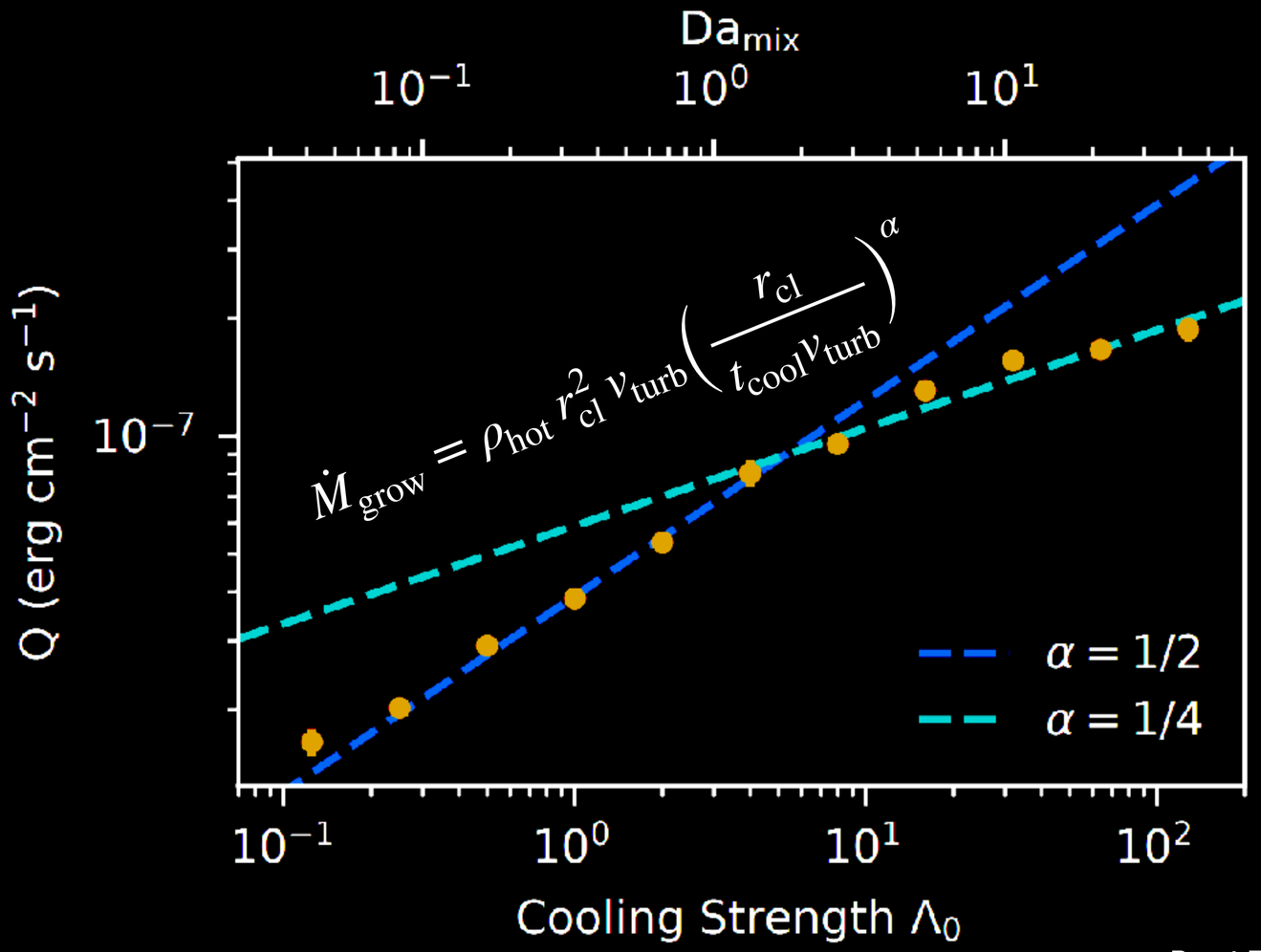




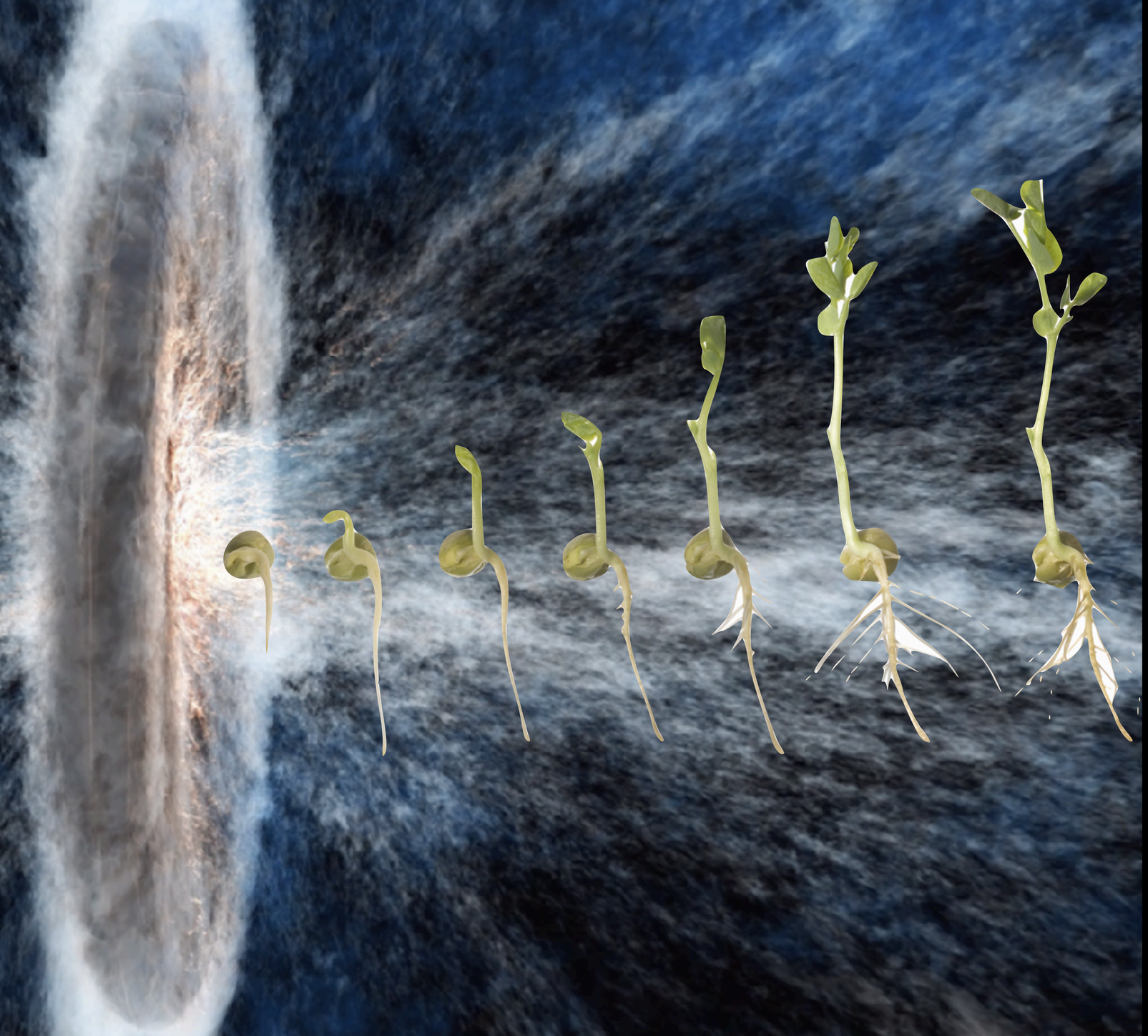


Turbulent Radiative Mixing Layers

the answer is in Da_{mix}



Brent Tan+ 20



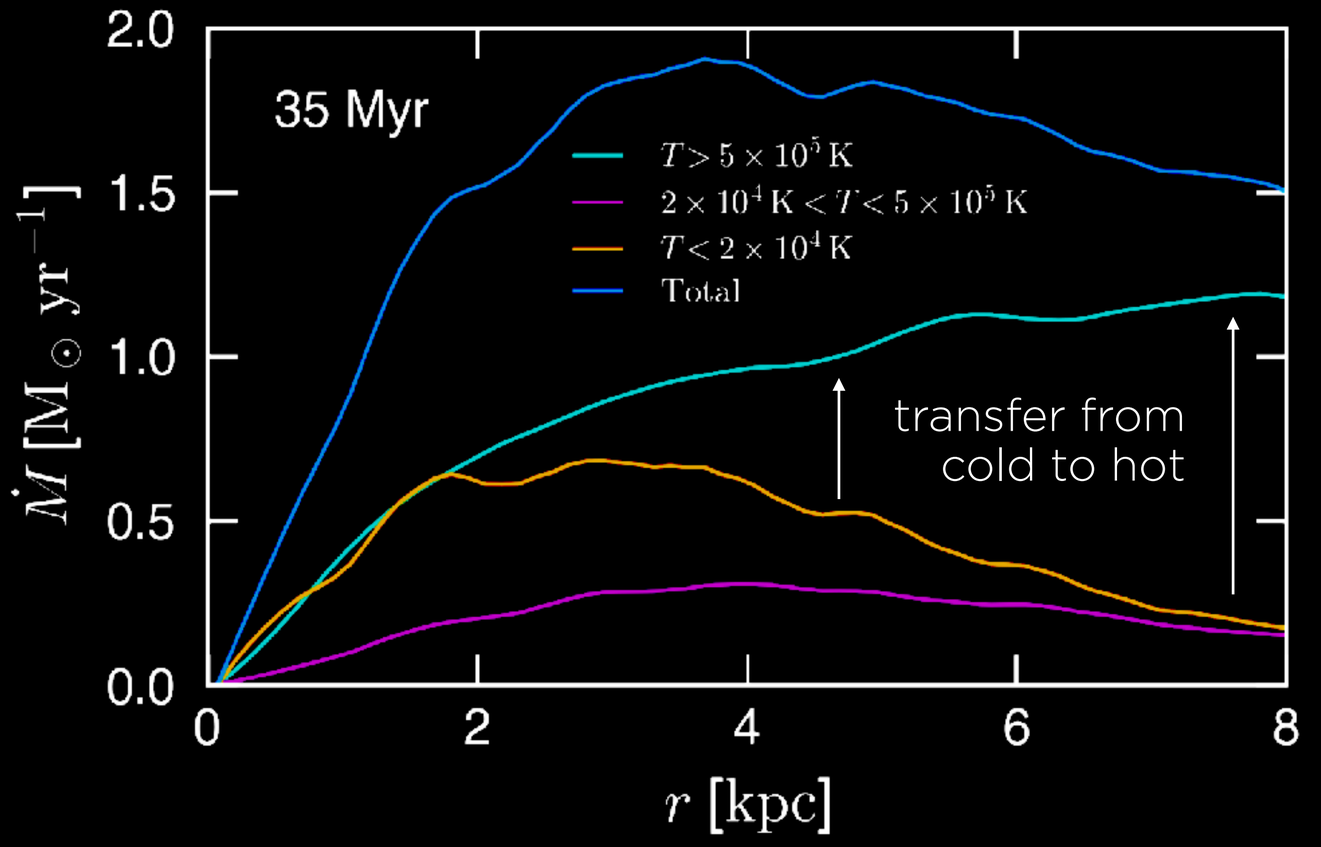
Grow as ya go

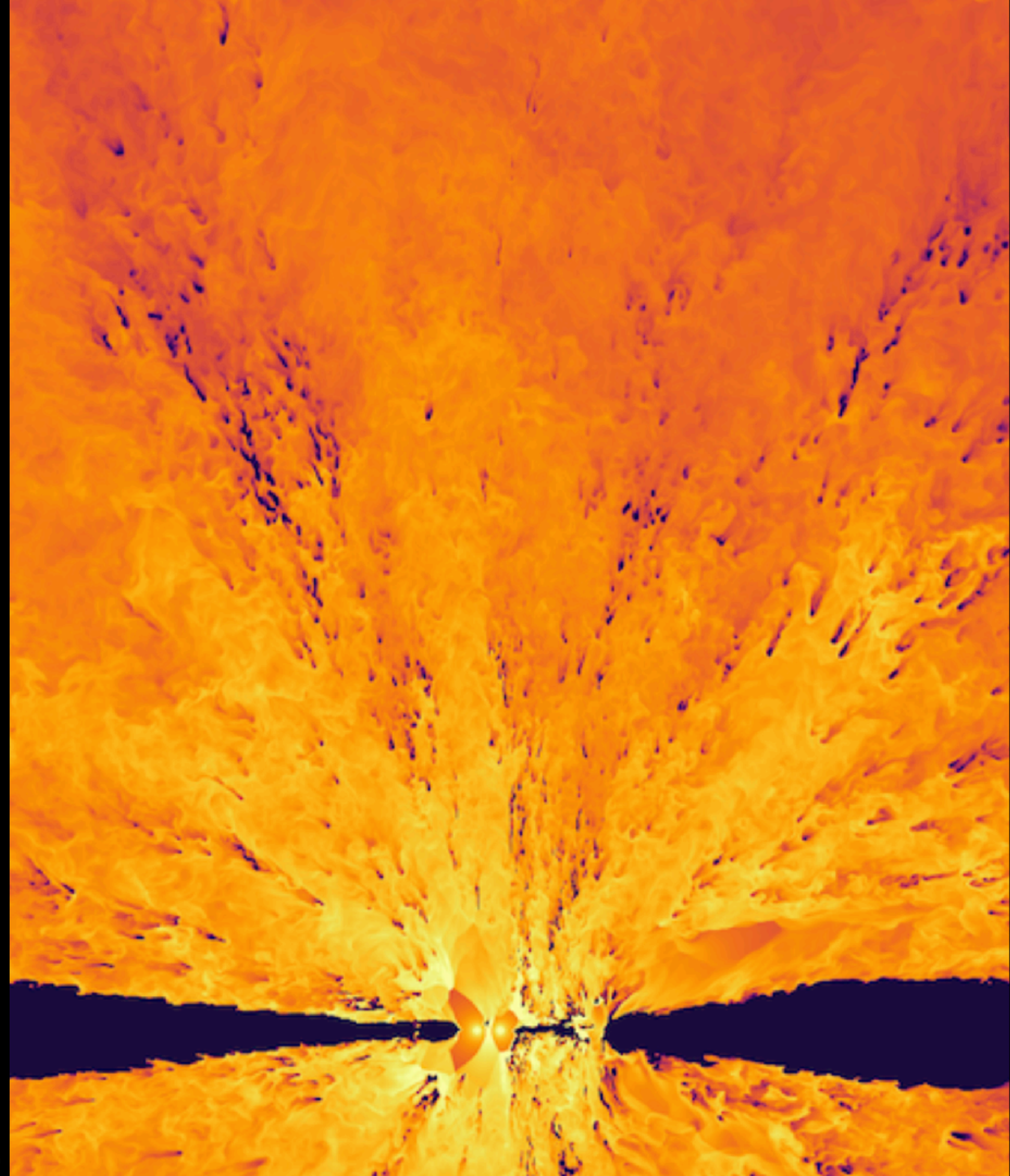
Seeds in the wind

Cold clouds may *grow* instead of being *destroyed* while *accelerated*

not quite so easy...

extrinsic turbulence can destroy clouds

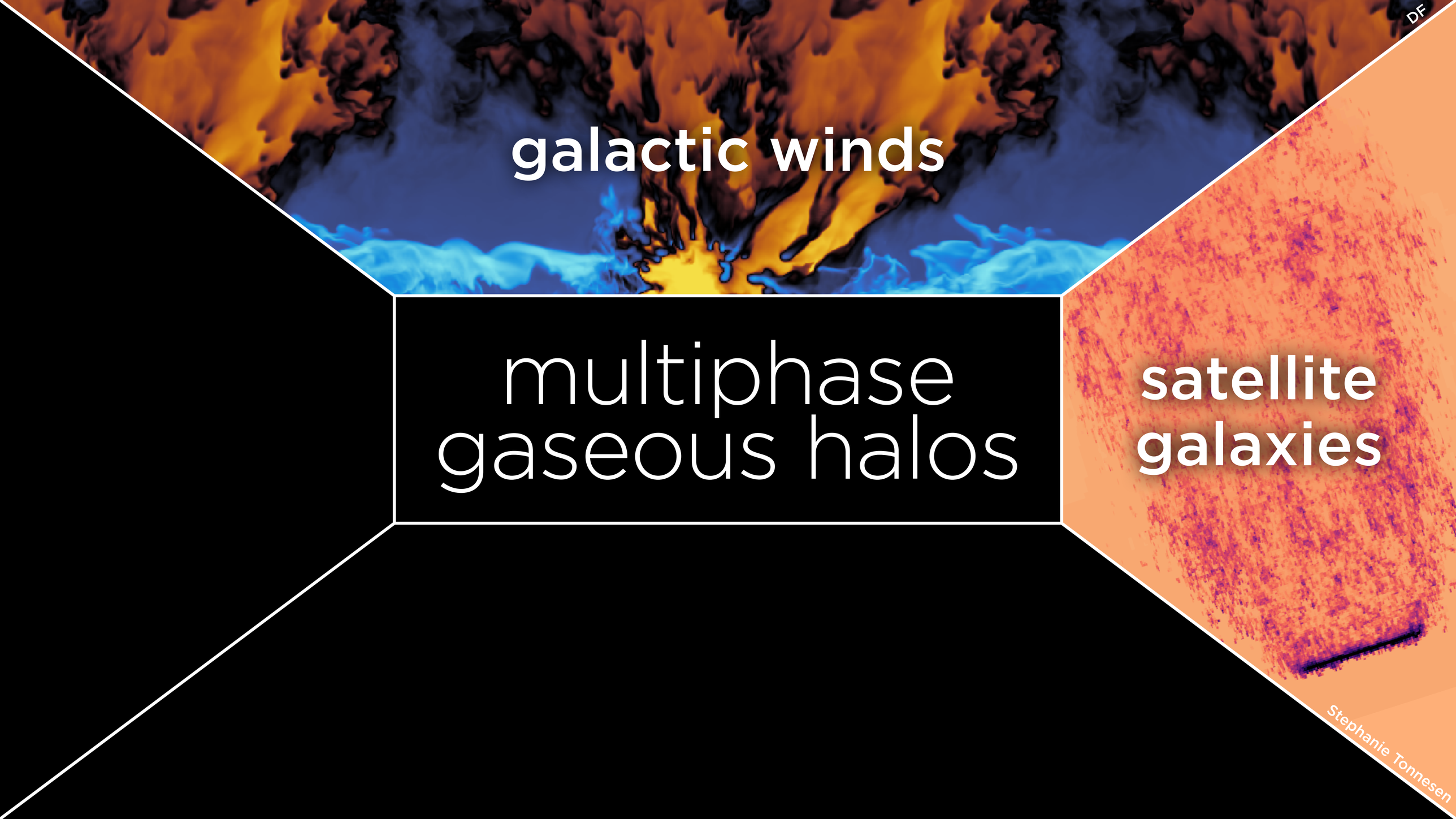


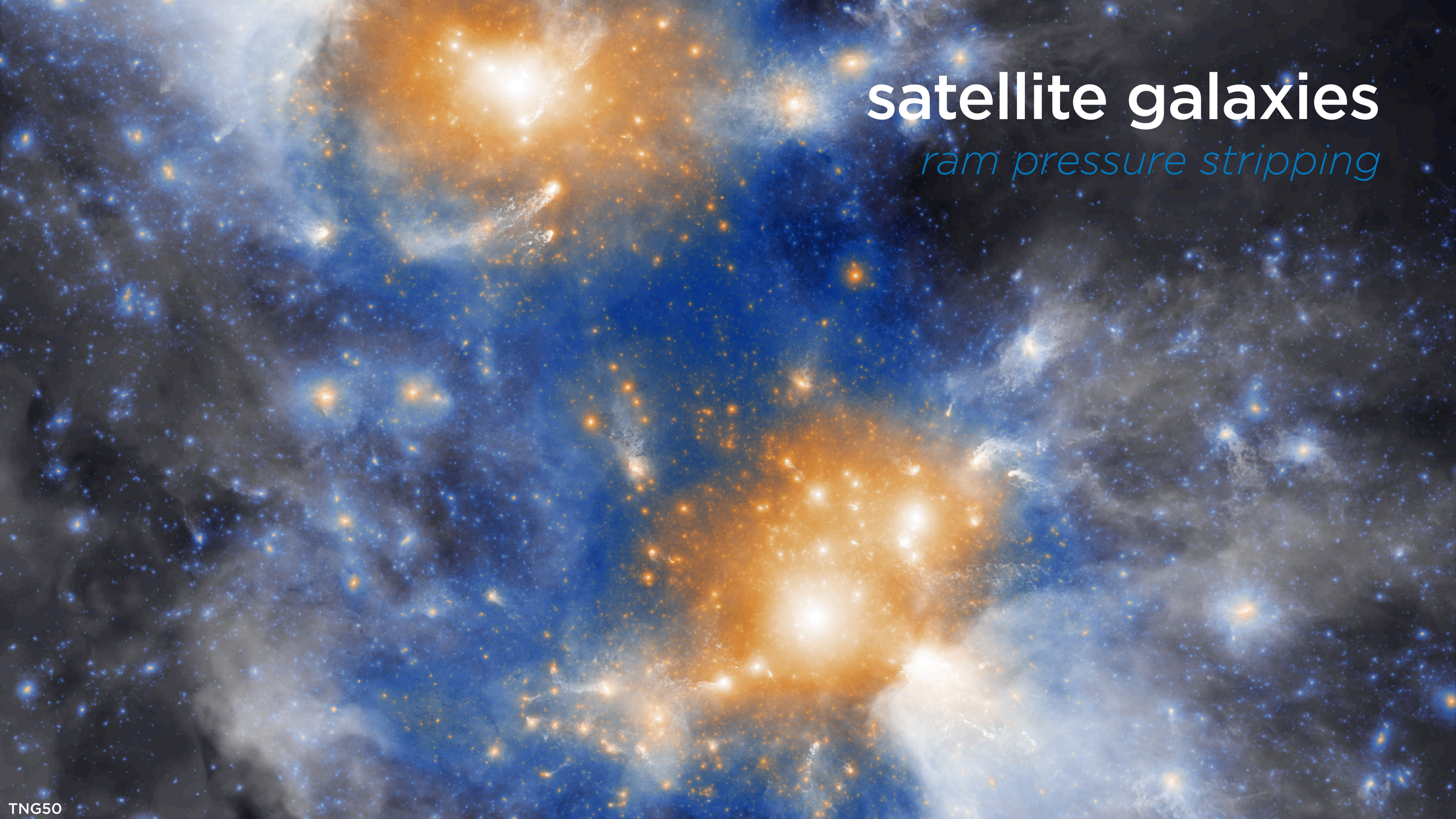


Evan Schneider+ 20

galactic winds

multiphase gaseous halos


galactic winds
multiphase
gaseous halos
satellite
galaxies
DF
Stephanie Tonnesen

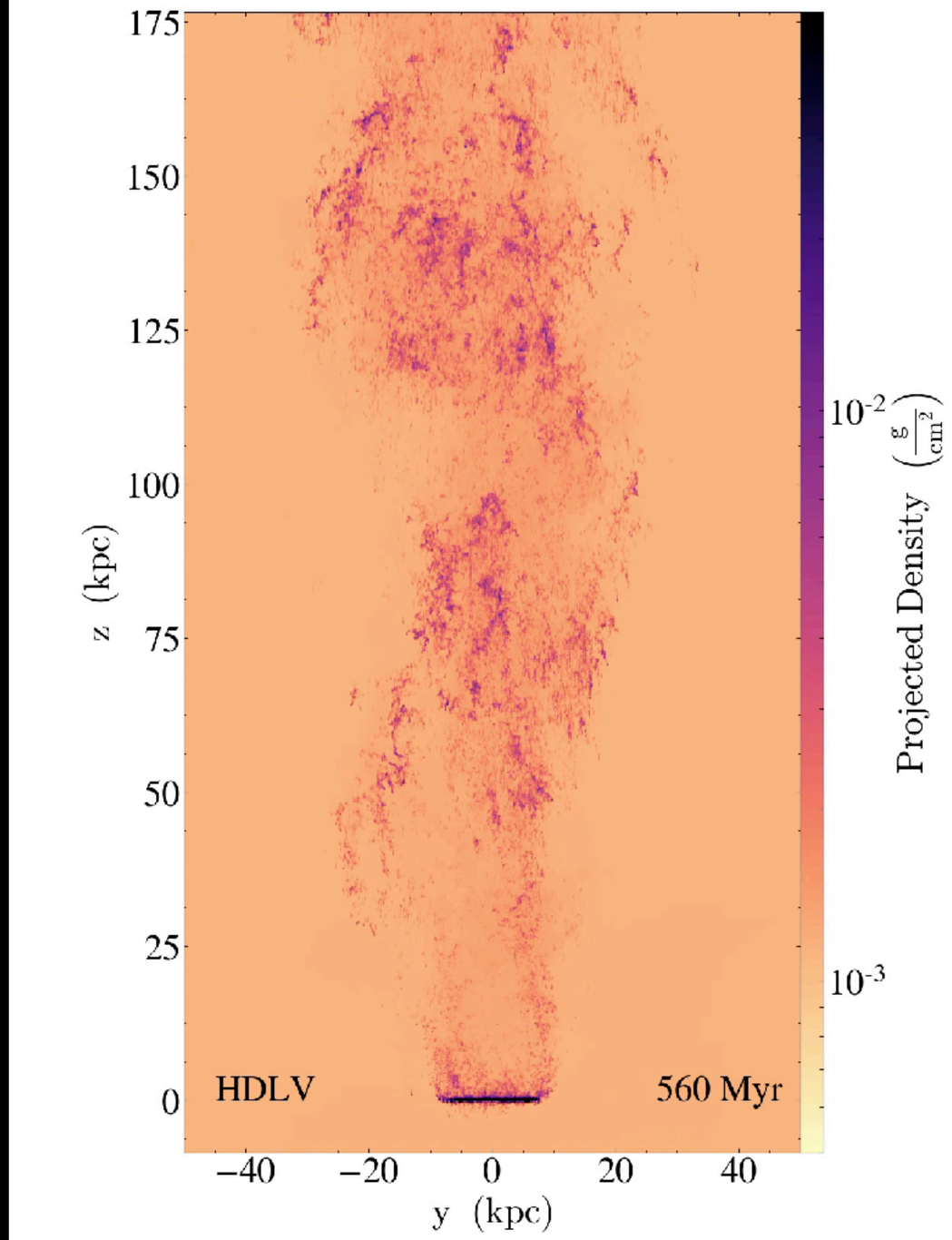

satellite galaxies
ram pressure stripping
TNG50

satellite galaxies

ram pressure stripping

ram pressure stripped
tails can cool and grow
like clouds in a wind

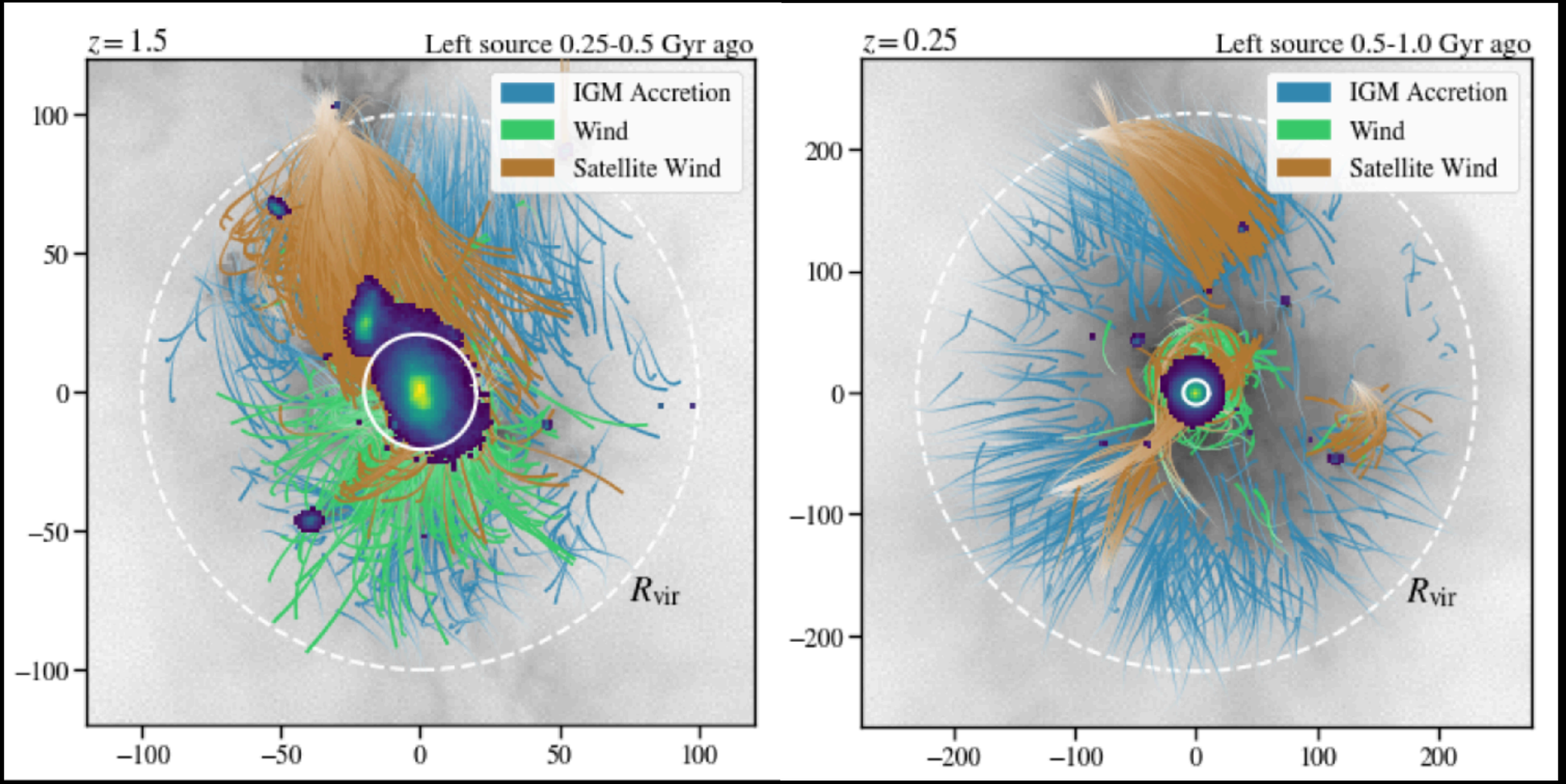
now with self gravity
and star formation!



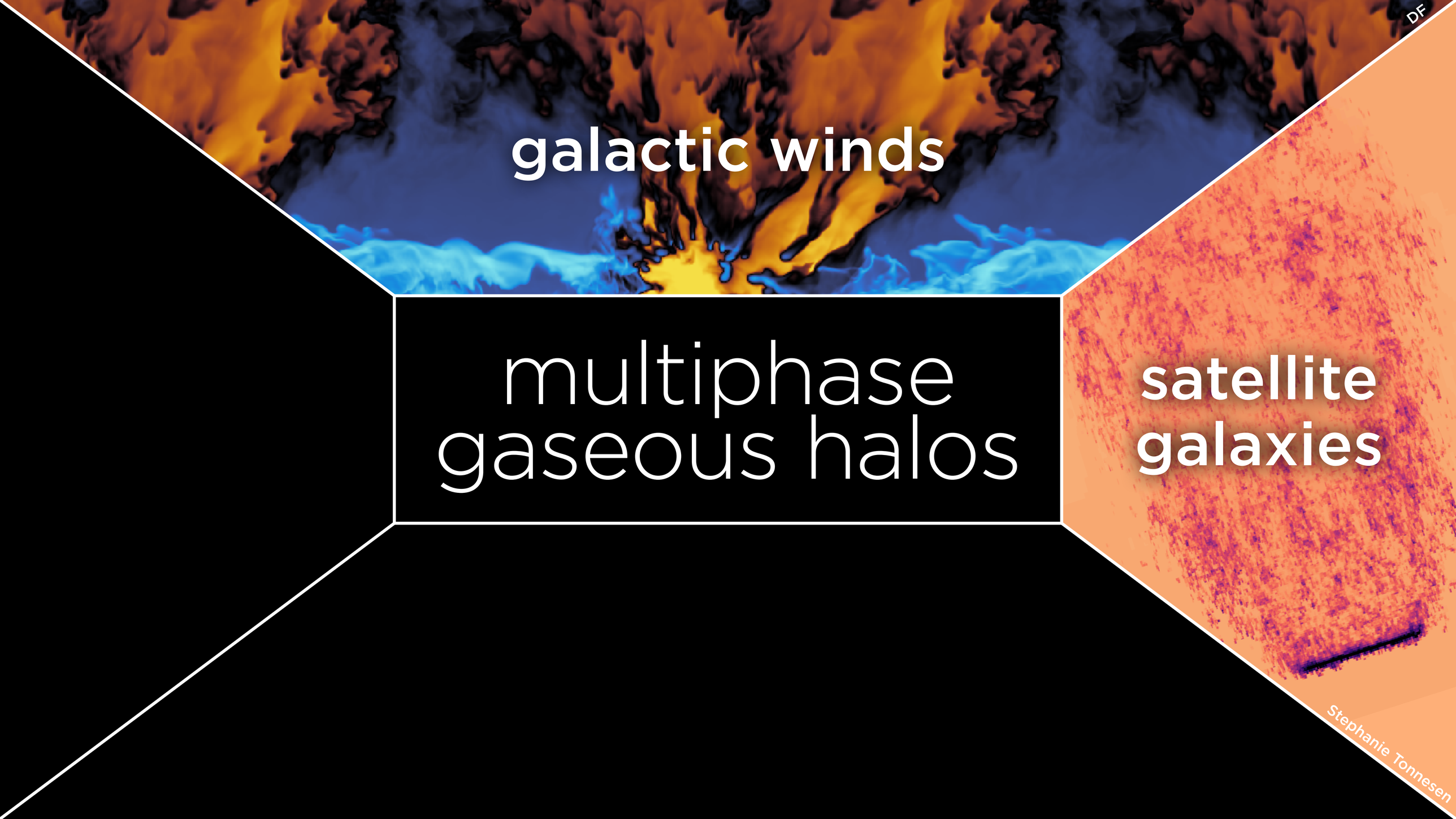
Stephanie Tonnesen+ 21

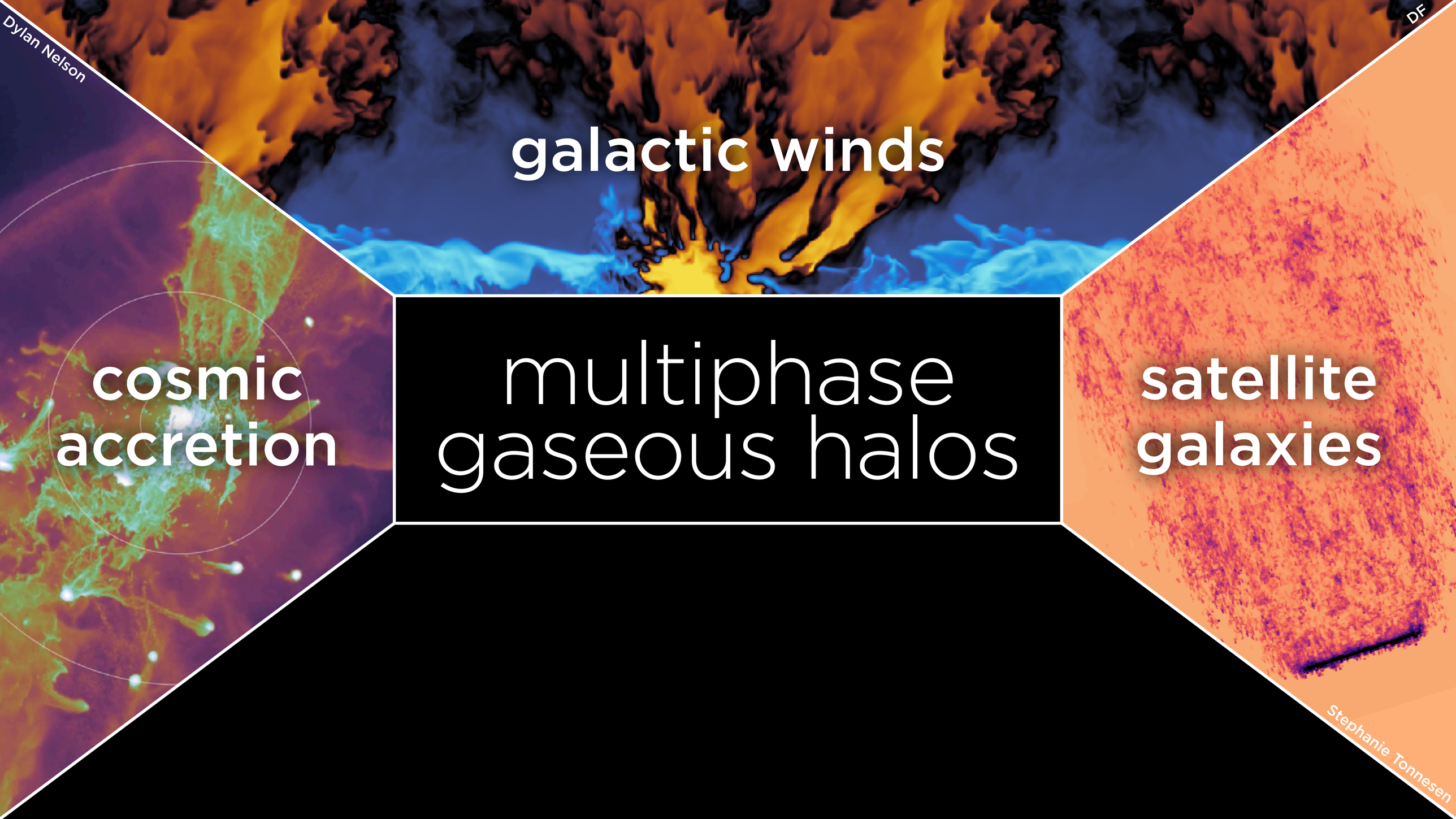
satellite winds

contribute to host CGM



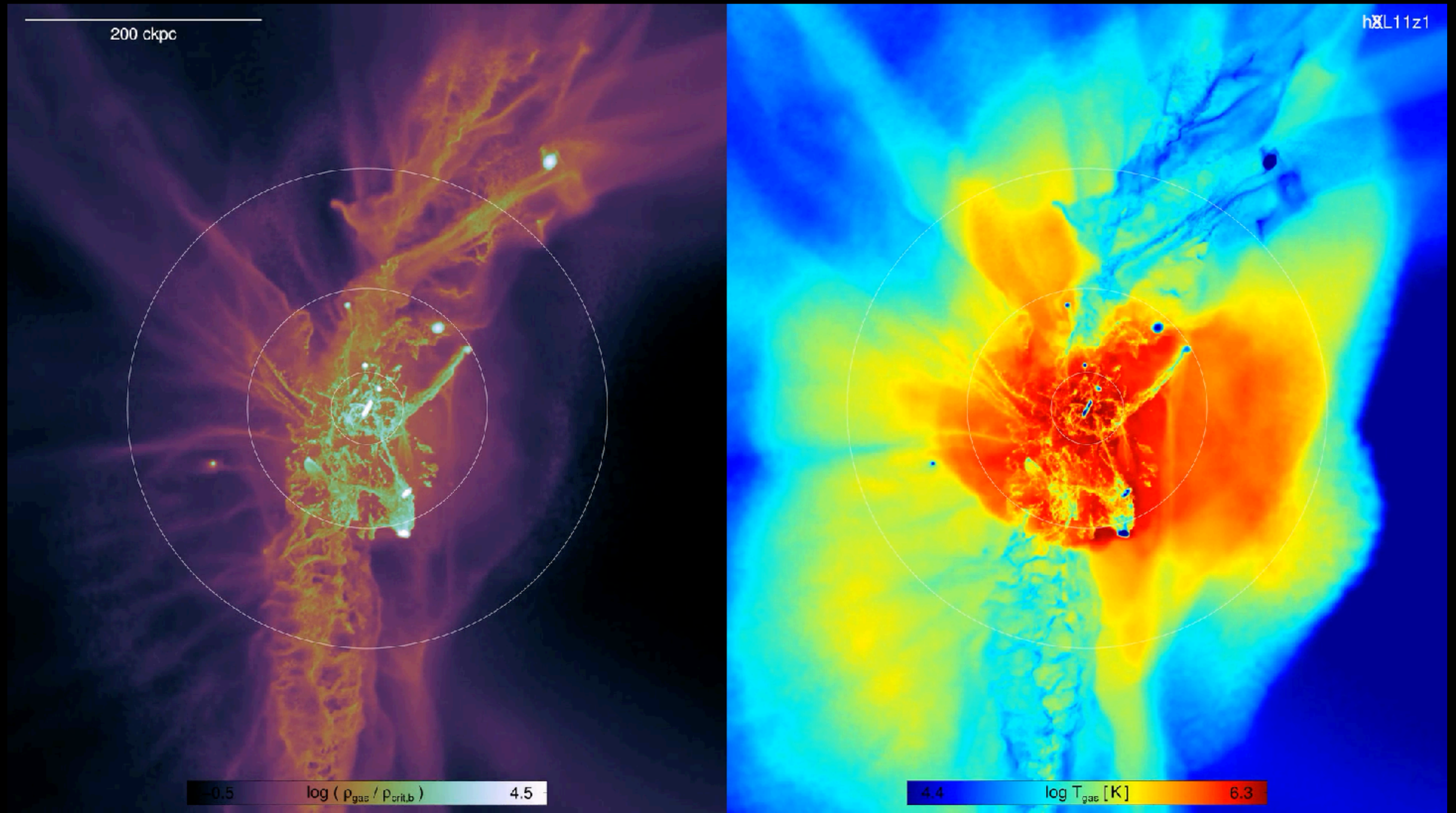
Zachary Hafen+ 19


galactic winds
multiphase
gaseous halos
satellite
galaxies
DF
Stephanie Tonnesen


Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
Stephanie Tonnesen

IGM accretion

cosmological view

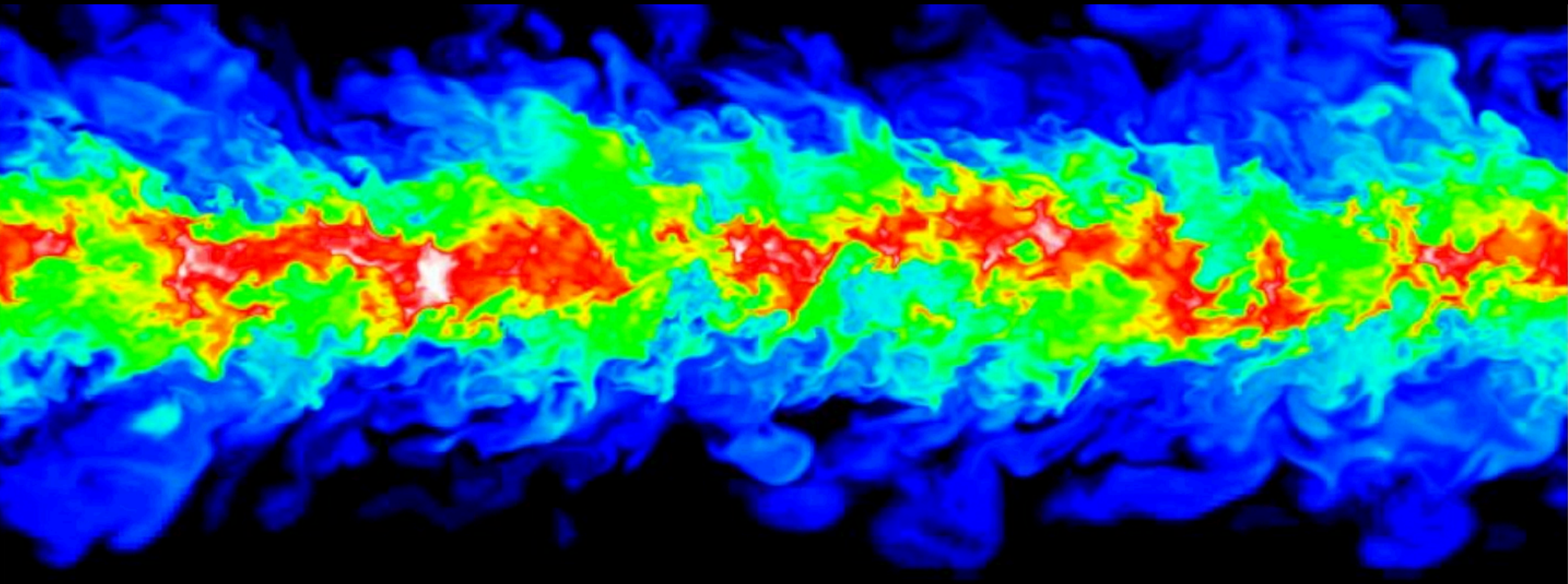


Dylan Nelson+ 16

IGM accretion

cold streams

streams are shredded while moving through the CGM

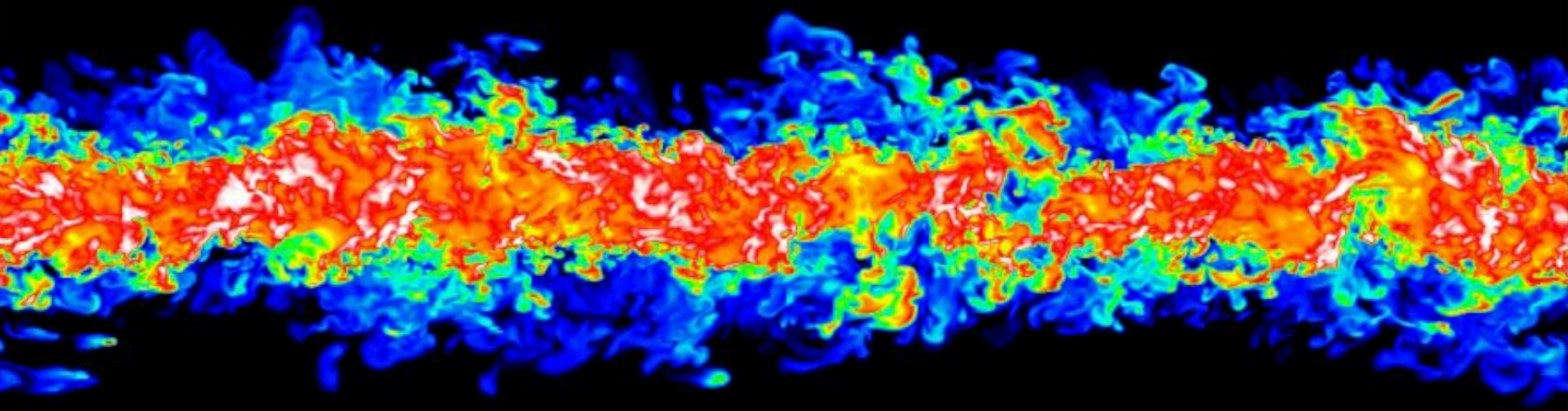


Nir Mandelker+ 20

IGM accretion

cold streams

cooling stabilizes the stream if $r_{\rm stream} \gtrsim v_{\rm turb} t_{\rm cool}$



Nir Mandelker+ 20

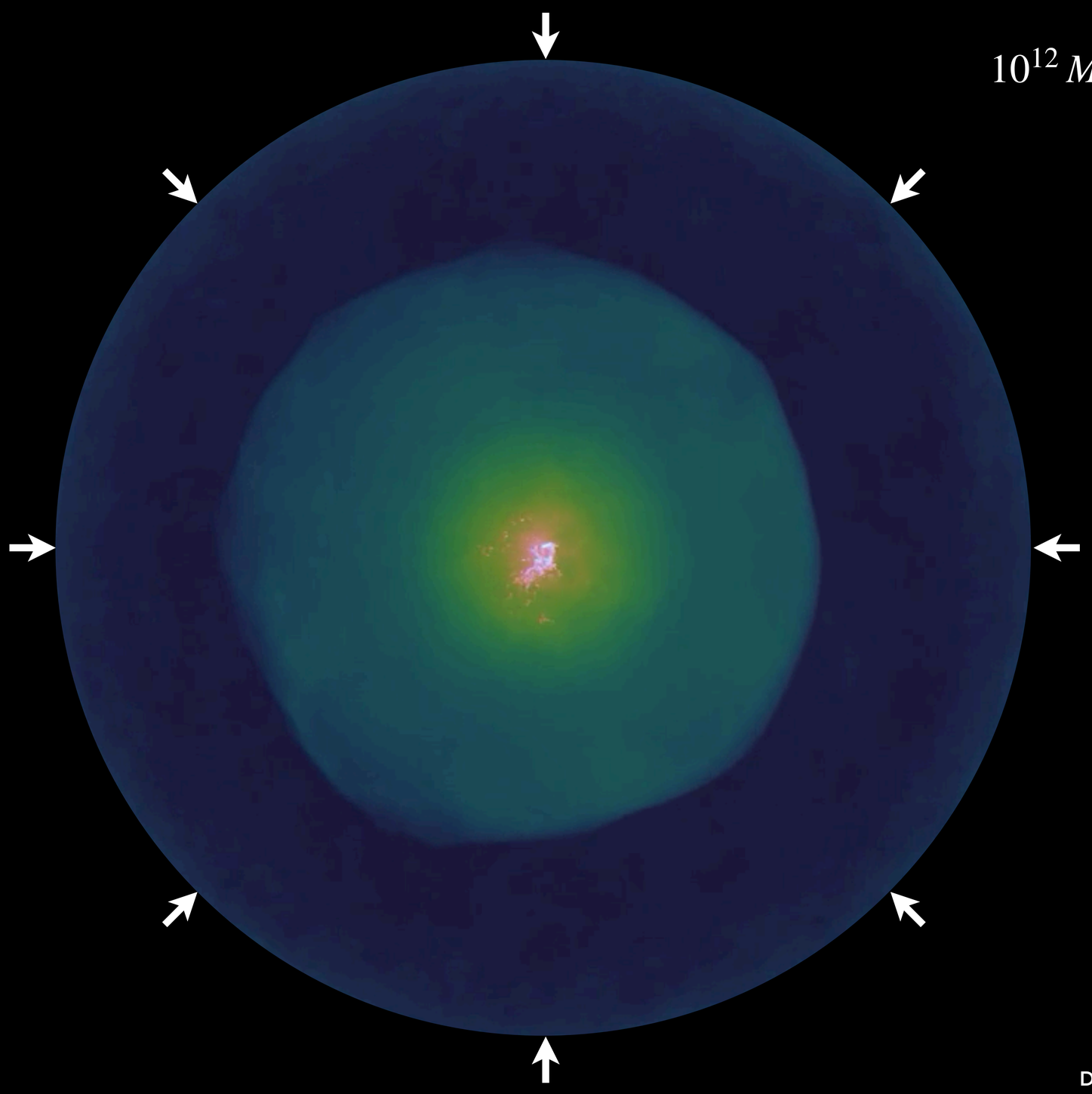
IGM accretion

building the hot halo

If accretion shock heated gas cools slowly

$$\left.\frac{t_{\rm cool}}{t_{\rm ff}}\right|_{\rm shock} > 1$$

hot outer CGM grows



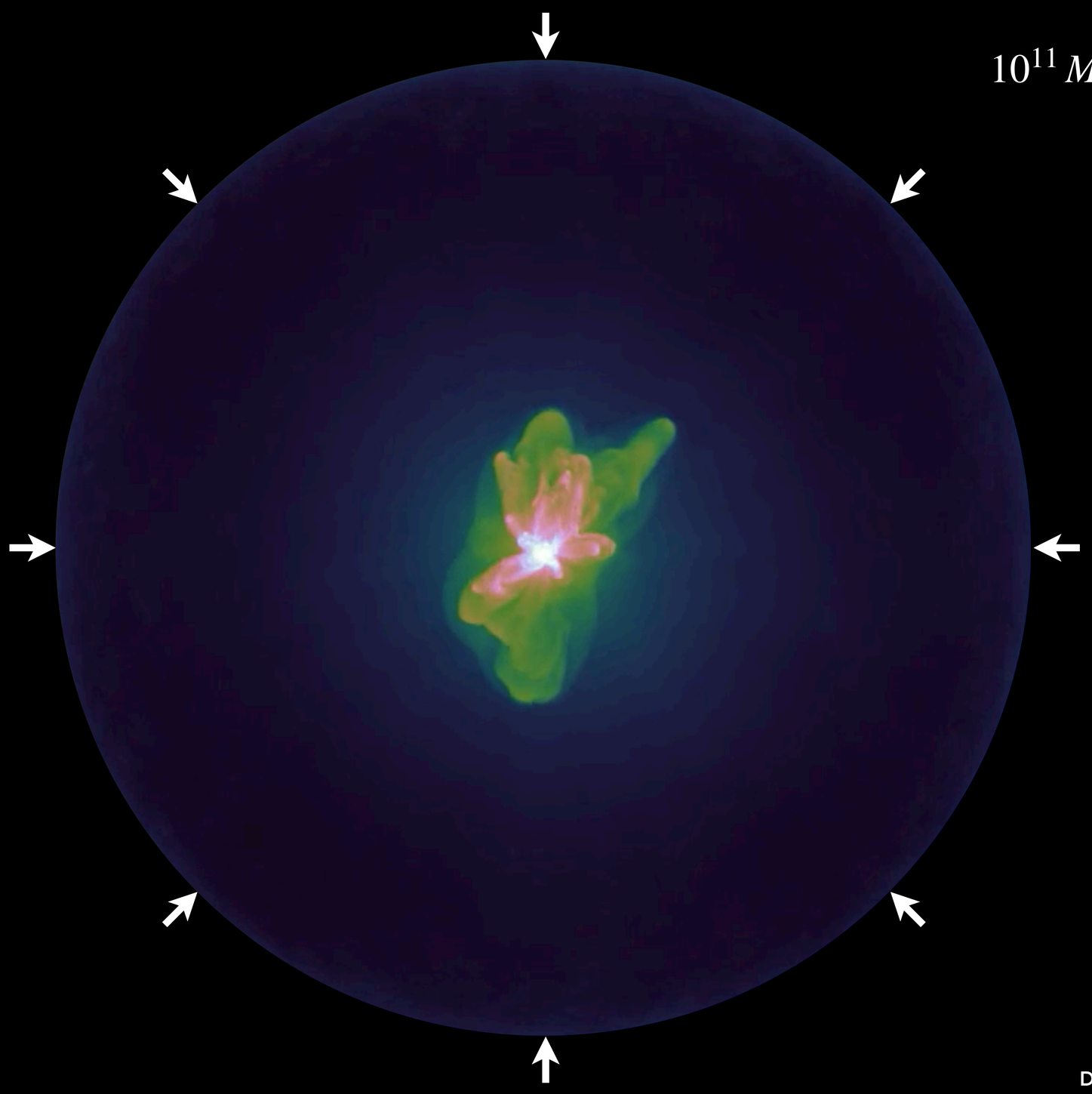
IGM accretion

building the hot halo

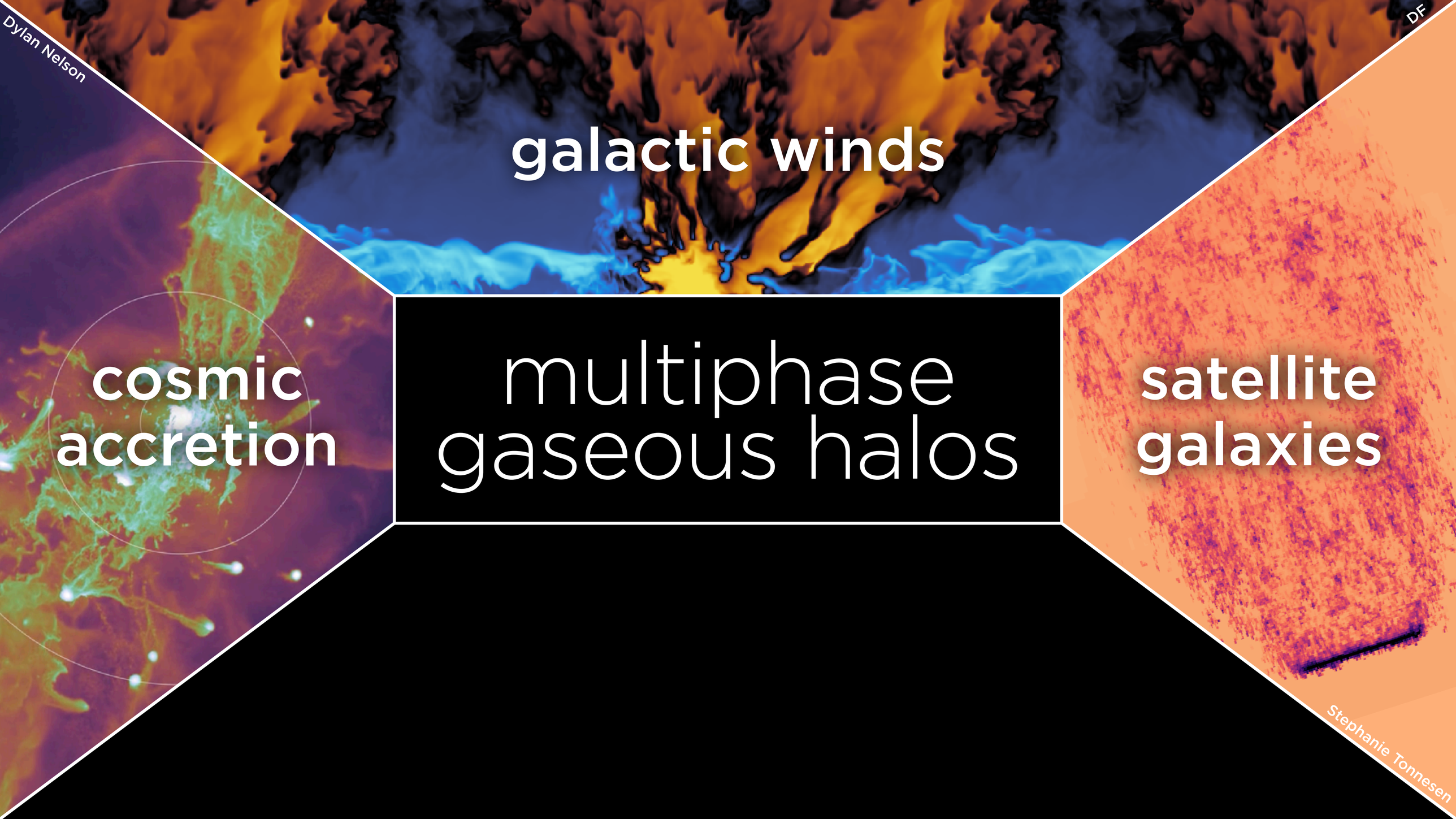
If accretion shock heated gas cools rapidly

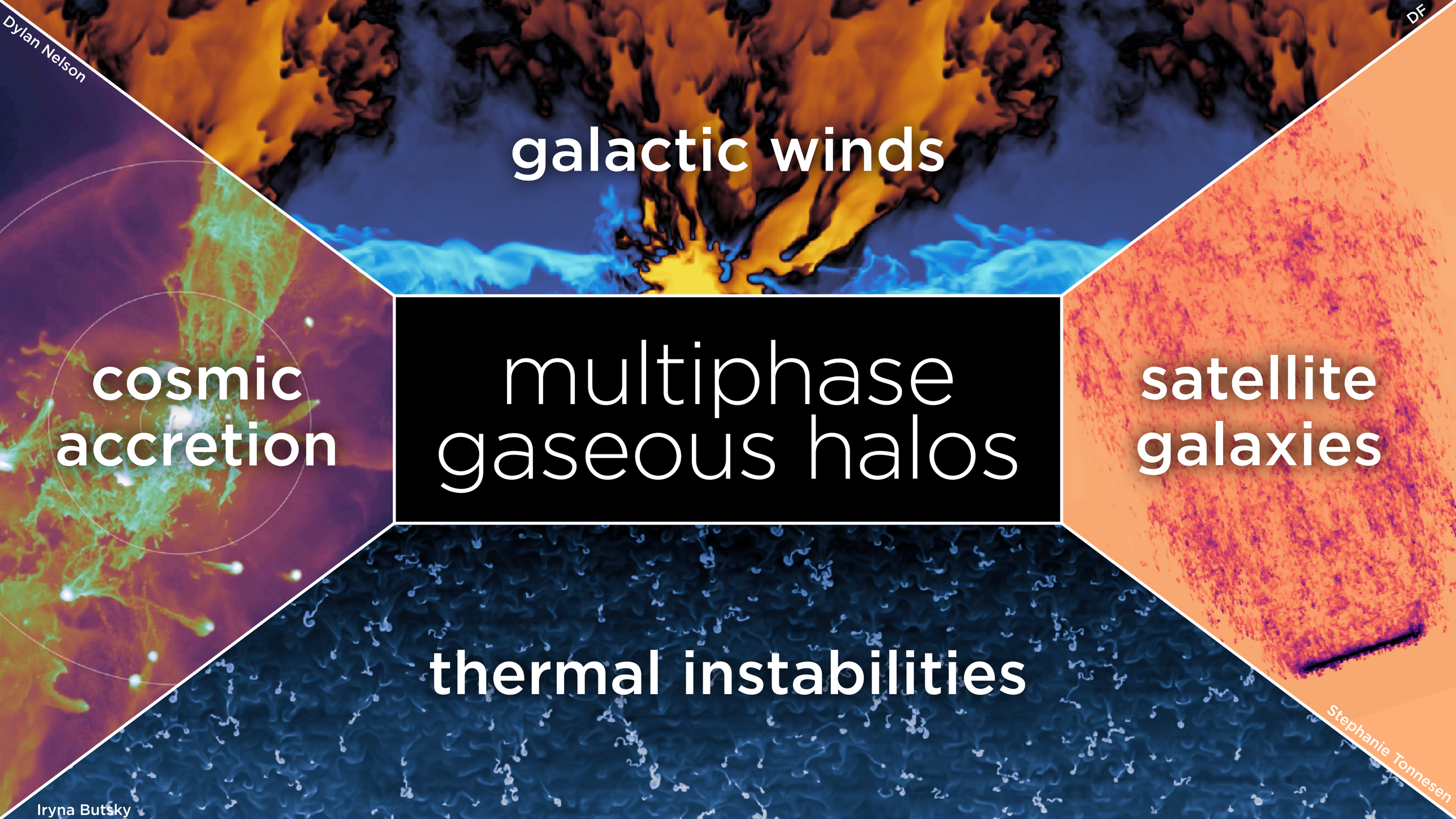
$$\left.\frac{t_{\rm cool}}{t_{\rm ff}}\right|_{\rm shock} < 1$$

feedback and turbulence dominate



DF+ 17

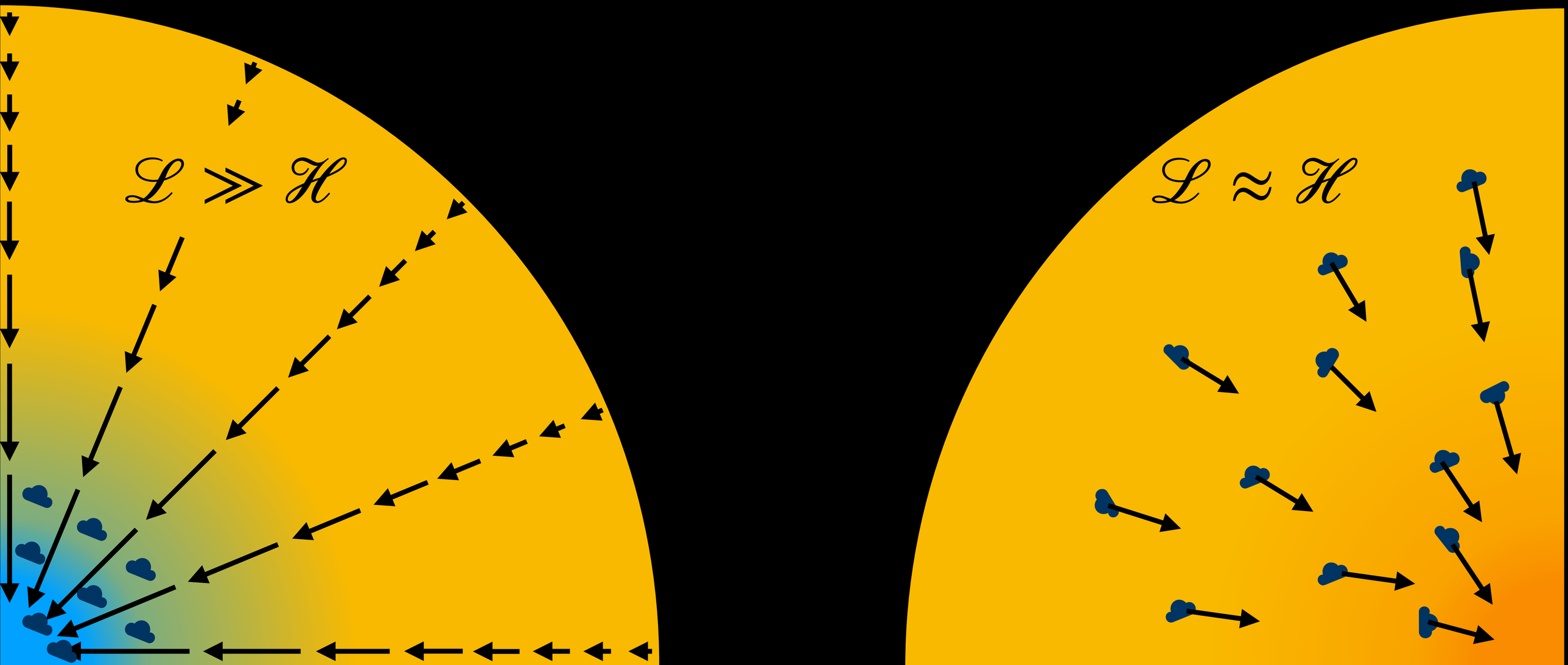

Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
Stephanie Tonnesen


Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
thermal instabilities
Stephanie Tonnesen
Iryna Butsky

thermal instability

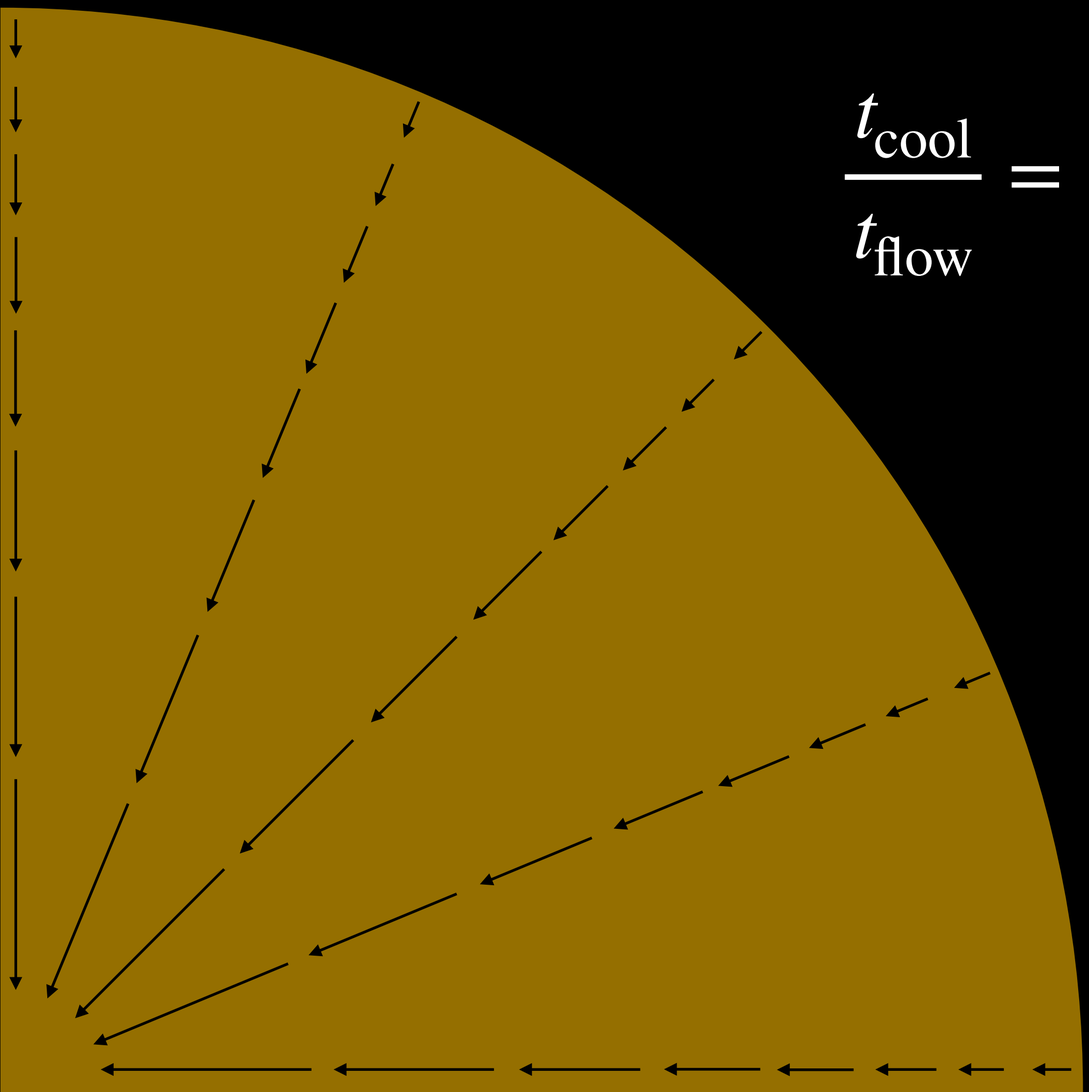
cooling flow

thermal balance



thermally instability

cooling flow

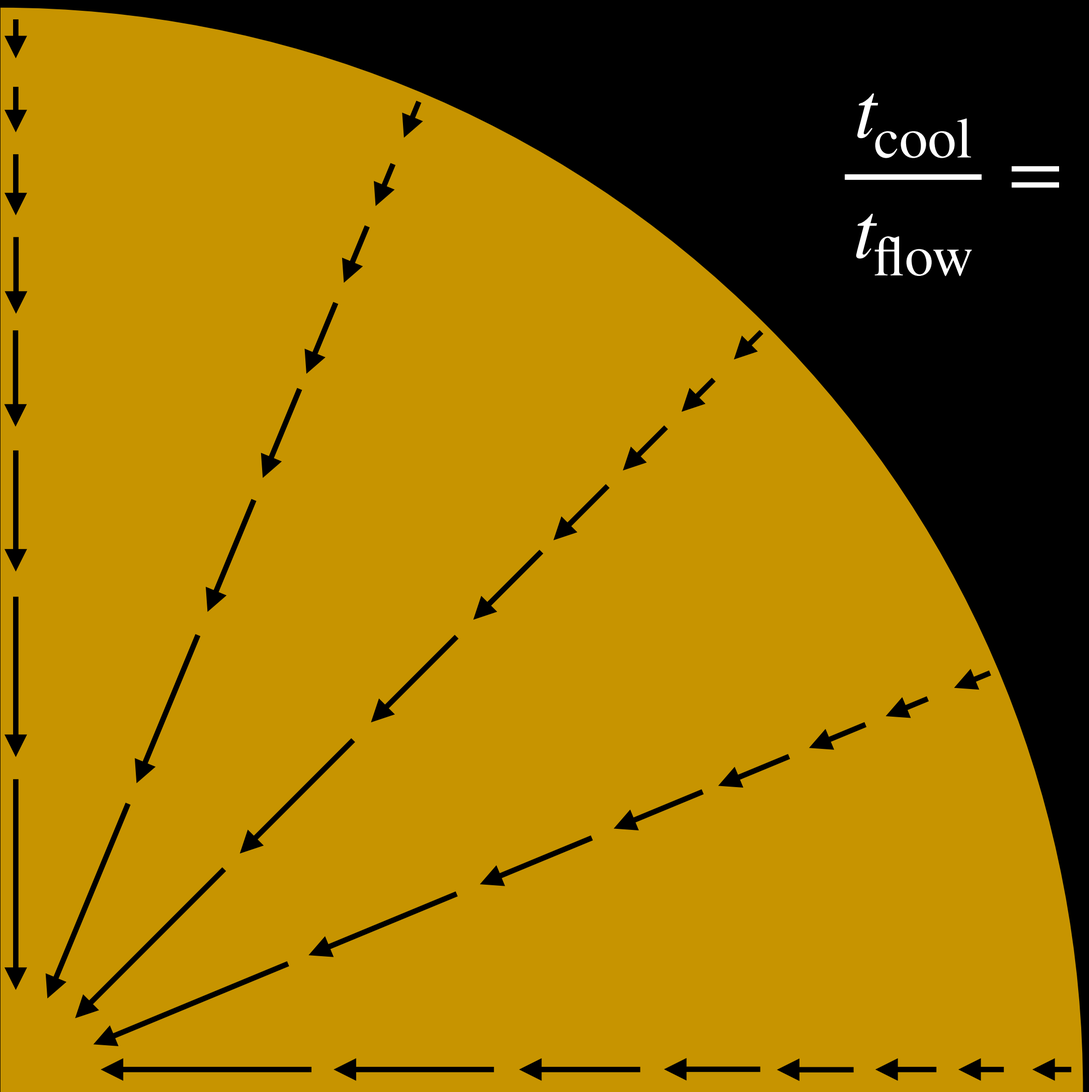


$$\frac{t_{\text{cool}}}{t_{\text{flow}}} = 1$$

compression
compensates
for cooling

thermally instability

cooling flow

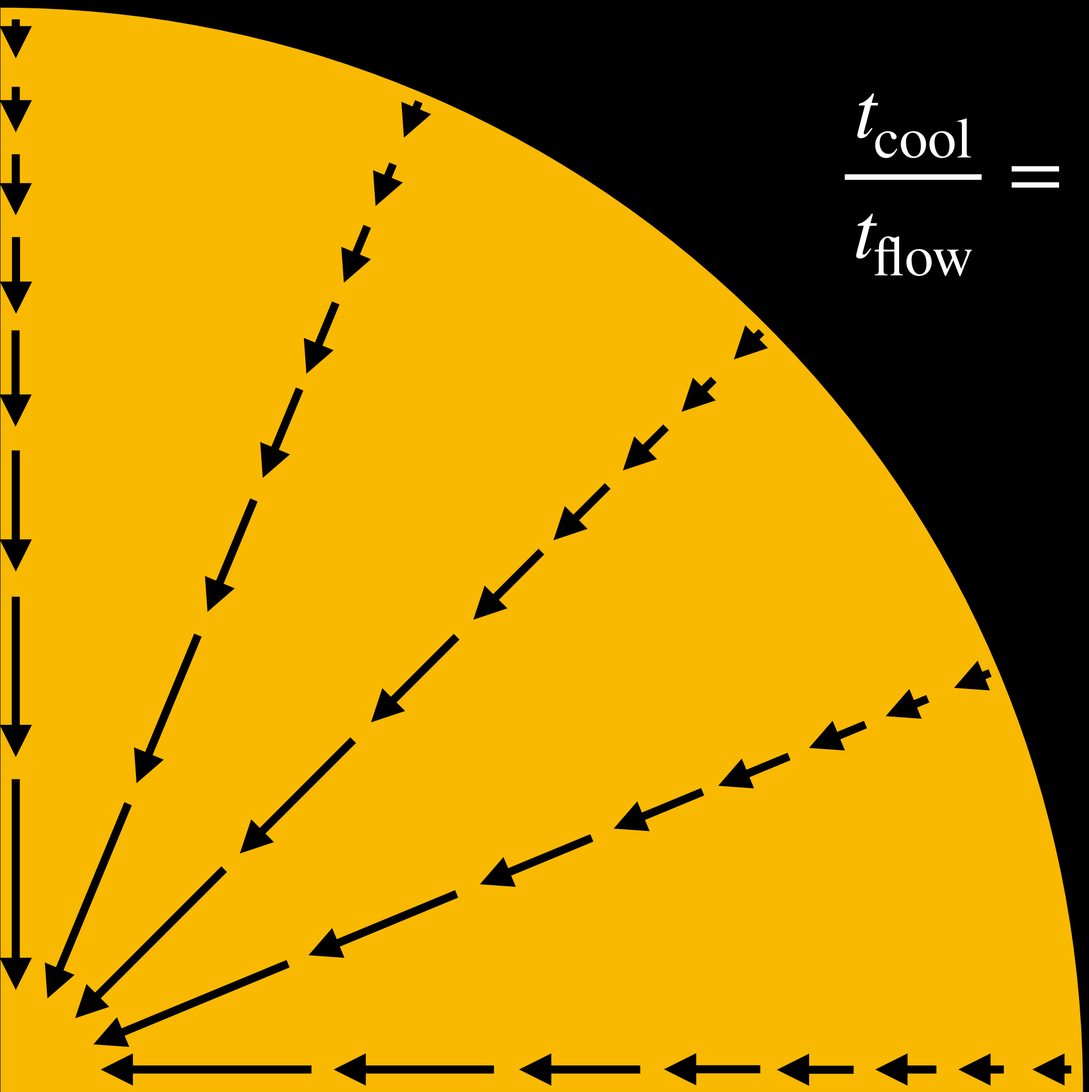


$$\frac{t_{\rm cool}}{t_{\rm flow}} = 1$$

faster cooling
leads to more
rapid inflows

thermally instability

cooling flow



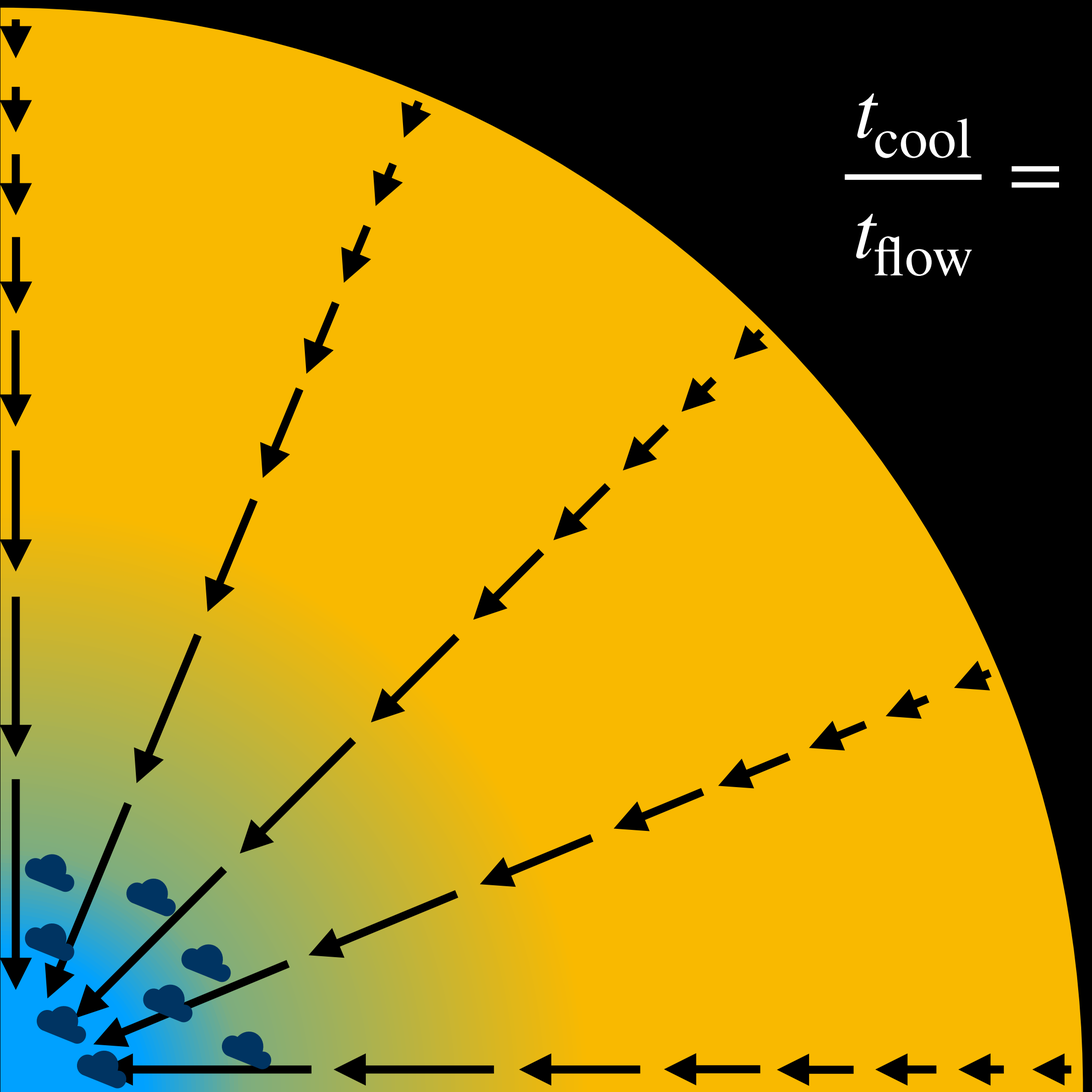
$$\frac{t_{\rm cool}}{t_{\rm flow}} = 1$$

faster cooling
leads to more
rapid inflows

until ...

thermally instability

cooling flow



$$\frac{t_{\rm cool}}{t_{\rm flow}} = 1$$

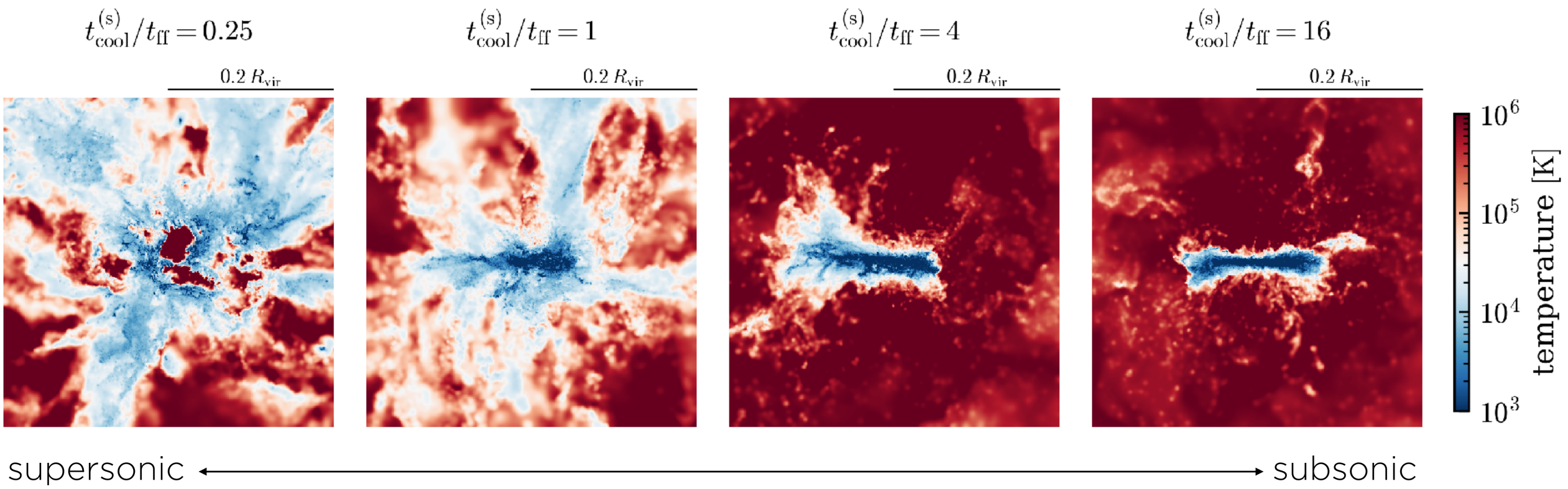
faster cooling leads to more rapid inflows

until $\mathscr{M} > 1$

and $\dfrac{t_{\rm cool}}{t_{\rm ff}} < 1$

thermally unstable cooling flows

in FIRE

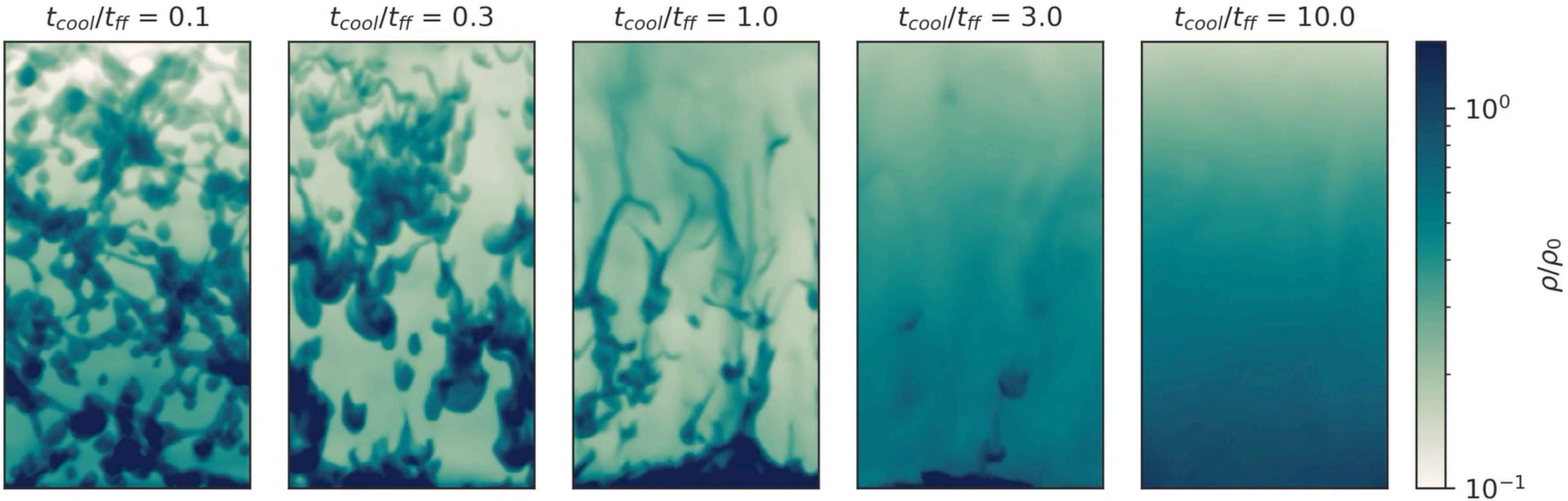


Jonathan Stern+ 20b

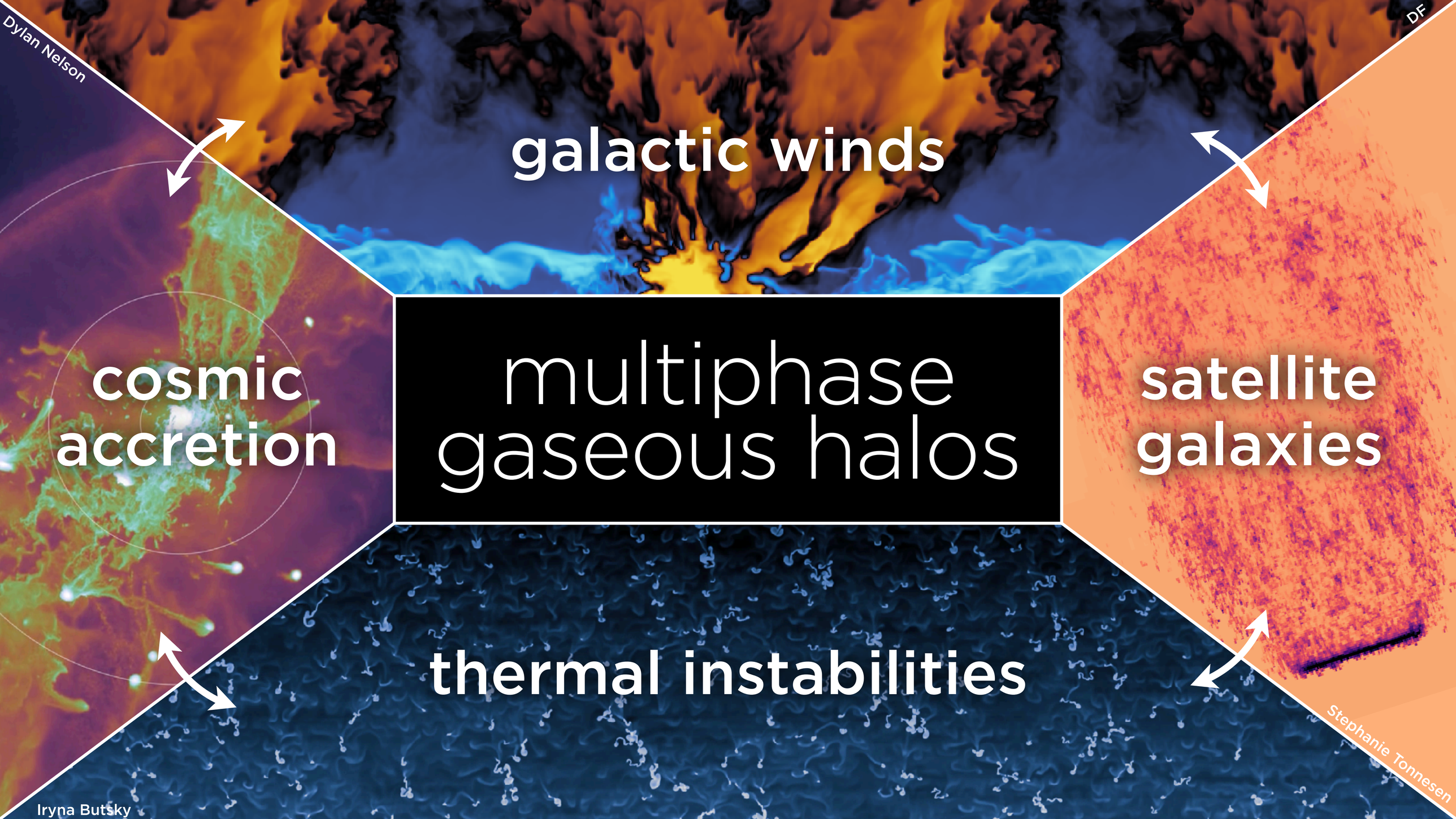
see also: Balbus & Soker 89; DF+17; Jonathan Stern+ 19, 20a; and many more

thermally instability

precipitation



Iryna Butsky+ 20 (with cosmic rays)
see also: McCourt+ 12 (hydro), Prateek Sharma+ 12 (spherical), Yuan Li+ 14 (jet heating), Suoqing Ji+ 18 (MHD), and many more


Dylan Nelson
DF
galactic winds
cosmic accretion
multiphase gaseous halos
satellite galaxies
thermal instabilities
Stephanie Tonnesen
Iryna Butsky

Why are gaseous halos often multiphase?

Why are gaseous halos often multiphase?

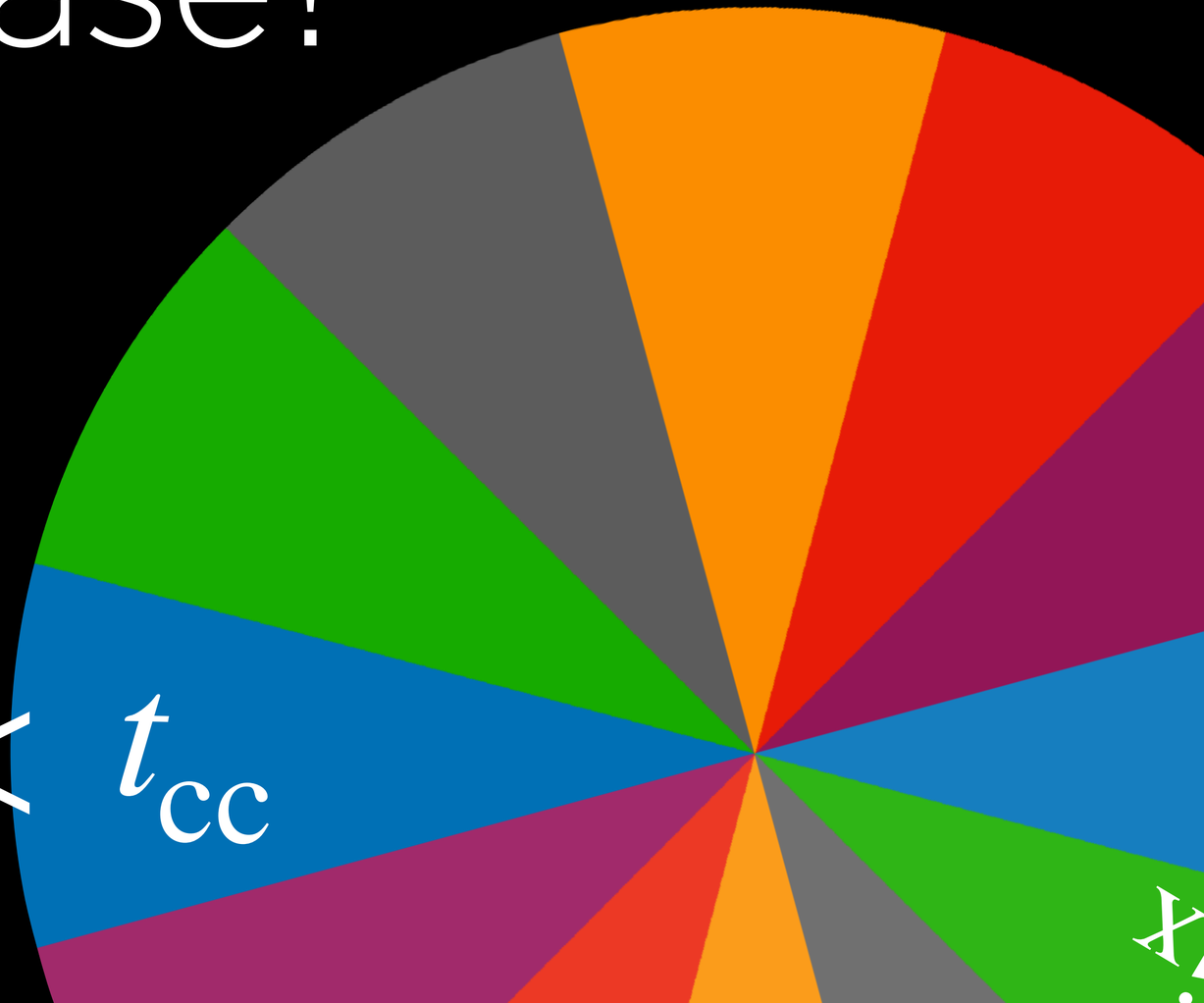
because

$t_{\rm cool} <$

Why are gaseous halos often multiphase?

because

$$t_{\rm cool} < t_{\rm cc}$$



Why are gaseous halos often multiphase?

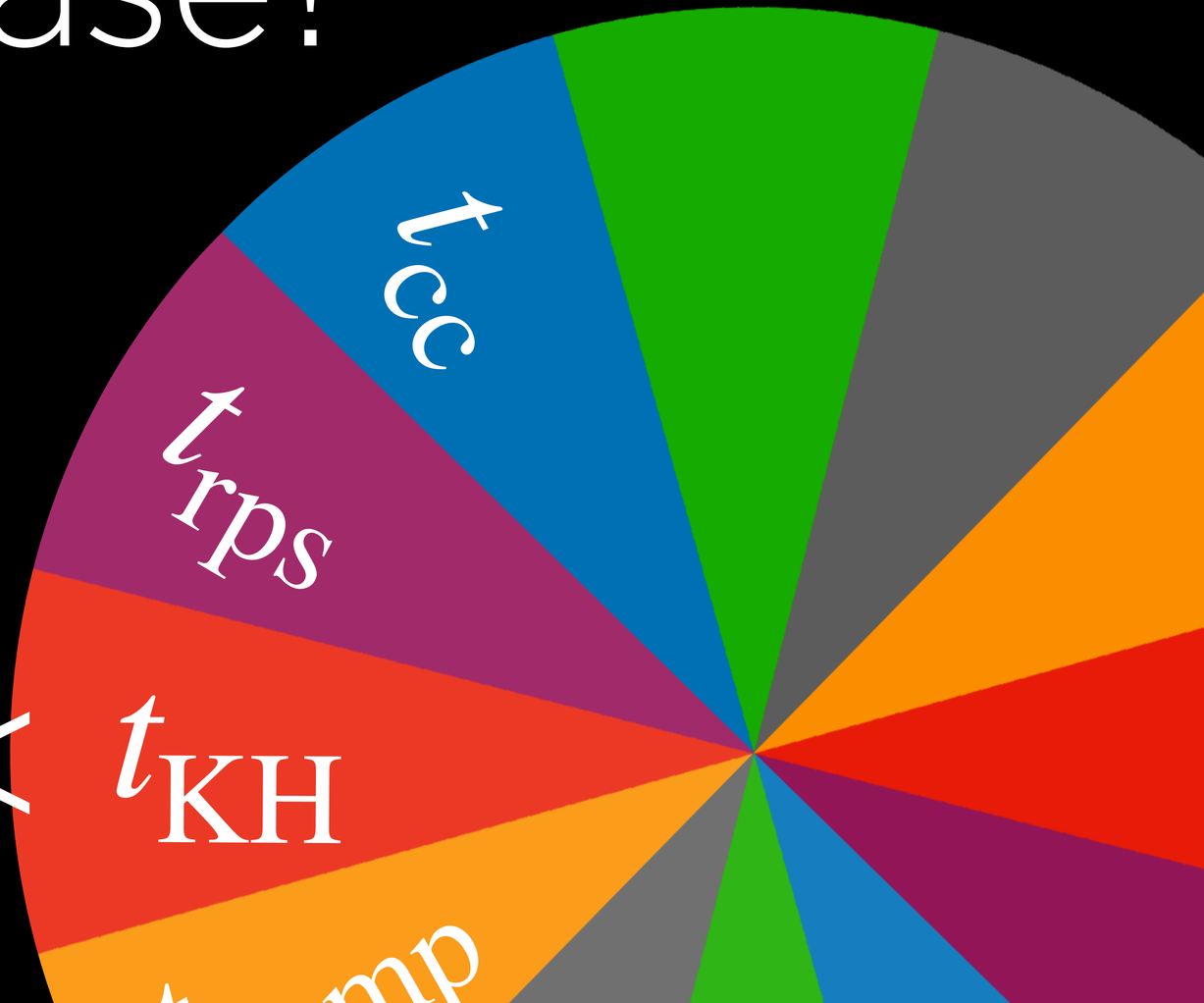
because

$$t_{\rm cool} < t_{\rm rps}$$

Why are gaseous halos often multiphase?

because

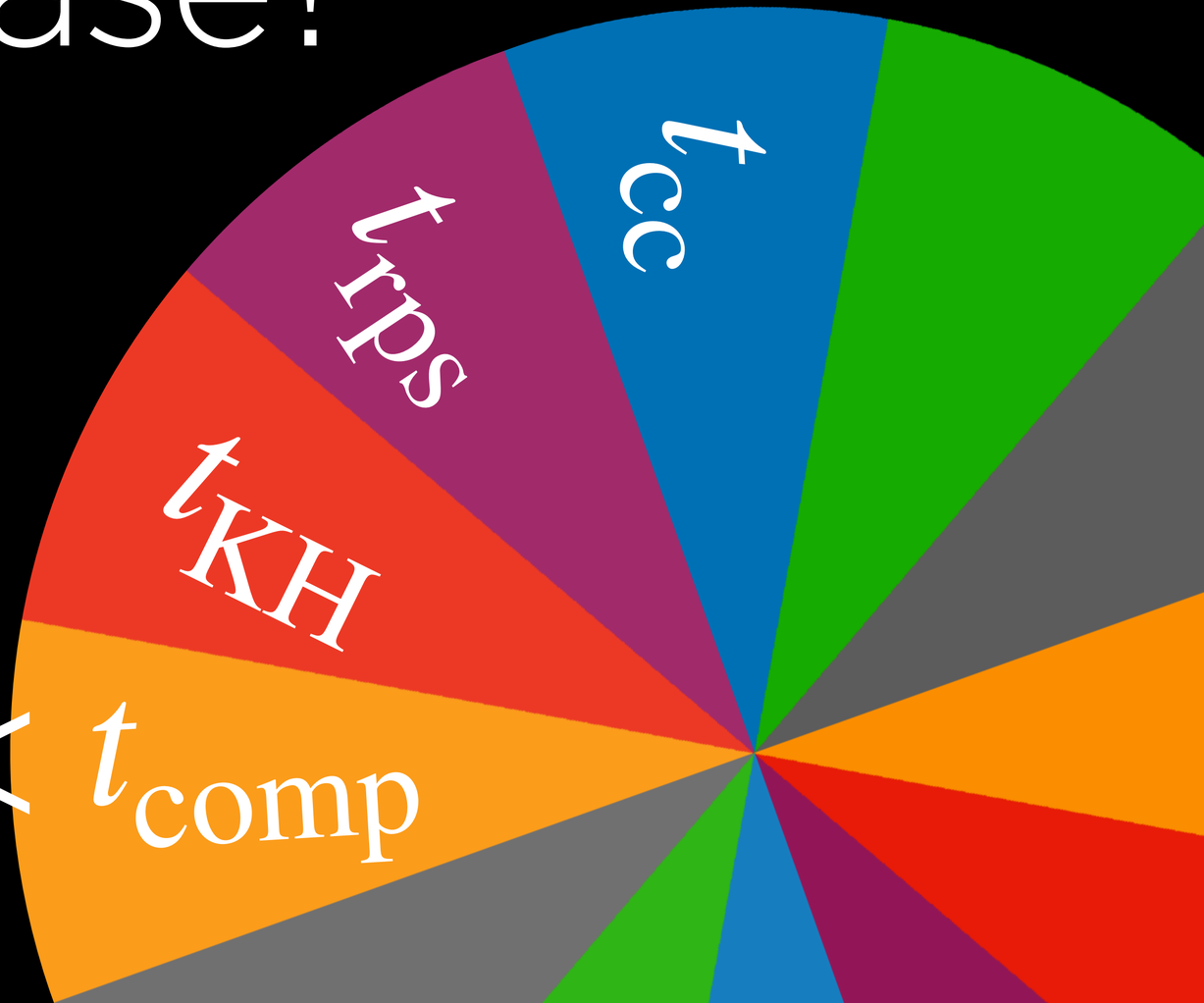
$$t_{\rm cool} < t_{\rm KH}$$



Why are gaseous halos often multiphase?

because

$$t_{\rm cool} < t_{\rm comp}$$



Why are gaseous halos often multiphase?

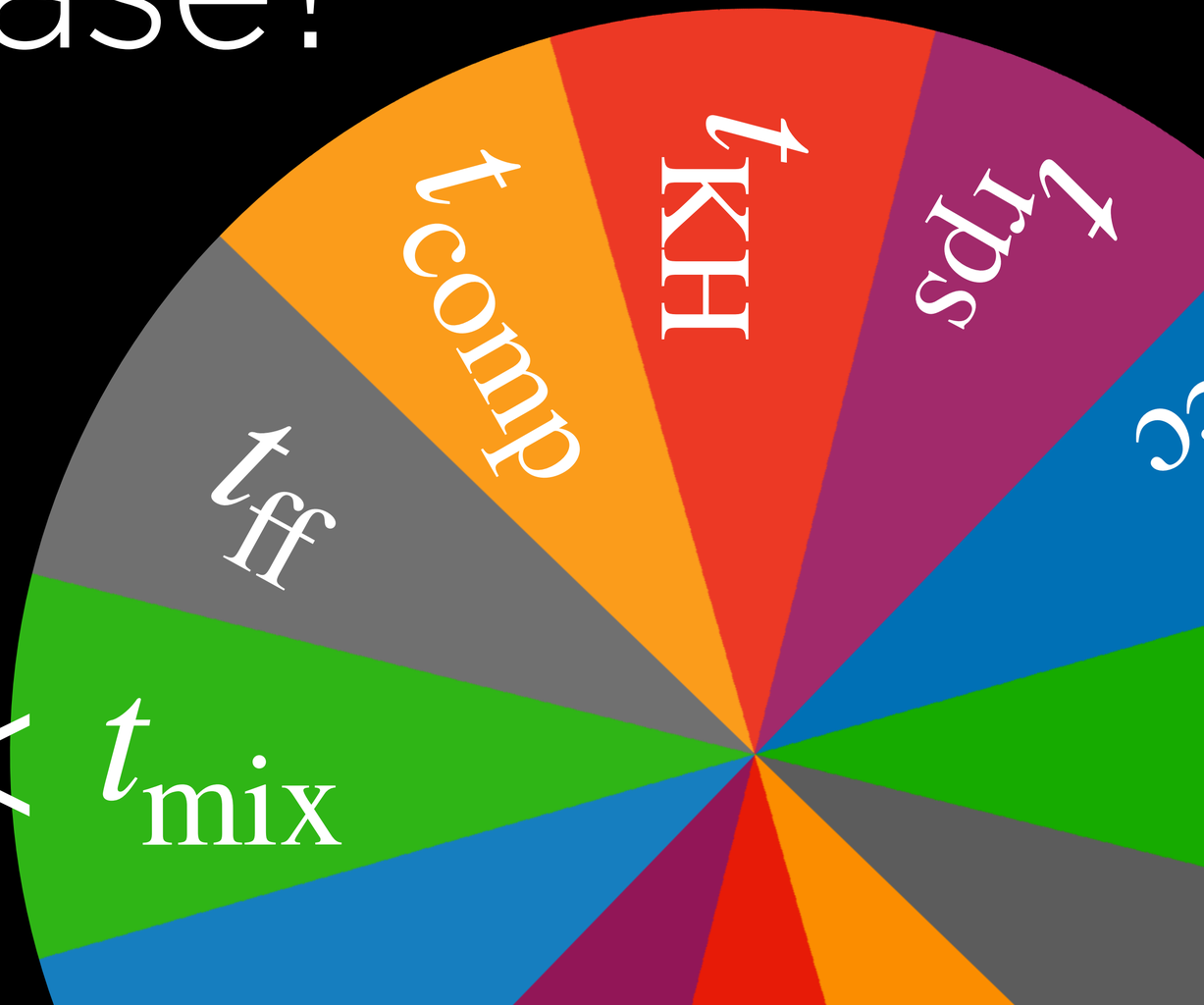
because

$$t_{\rm cool} < t_{\rm ff}$$

Why are gaseous halos often multiphase?

because

$$t_{\rm cool} < t_{\rm mix}$$



Are the phases in pressure equilibrium?

Yes, unless they are:

-moving too fast $t_{\rm flow} < r/c_s$

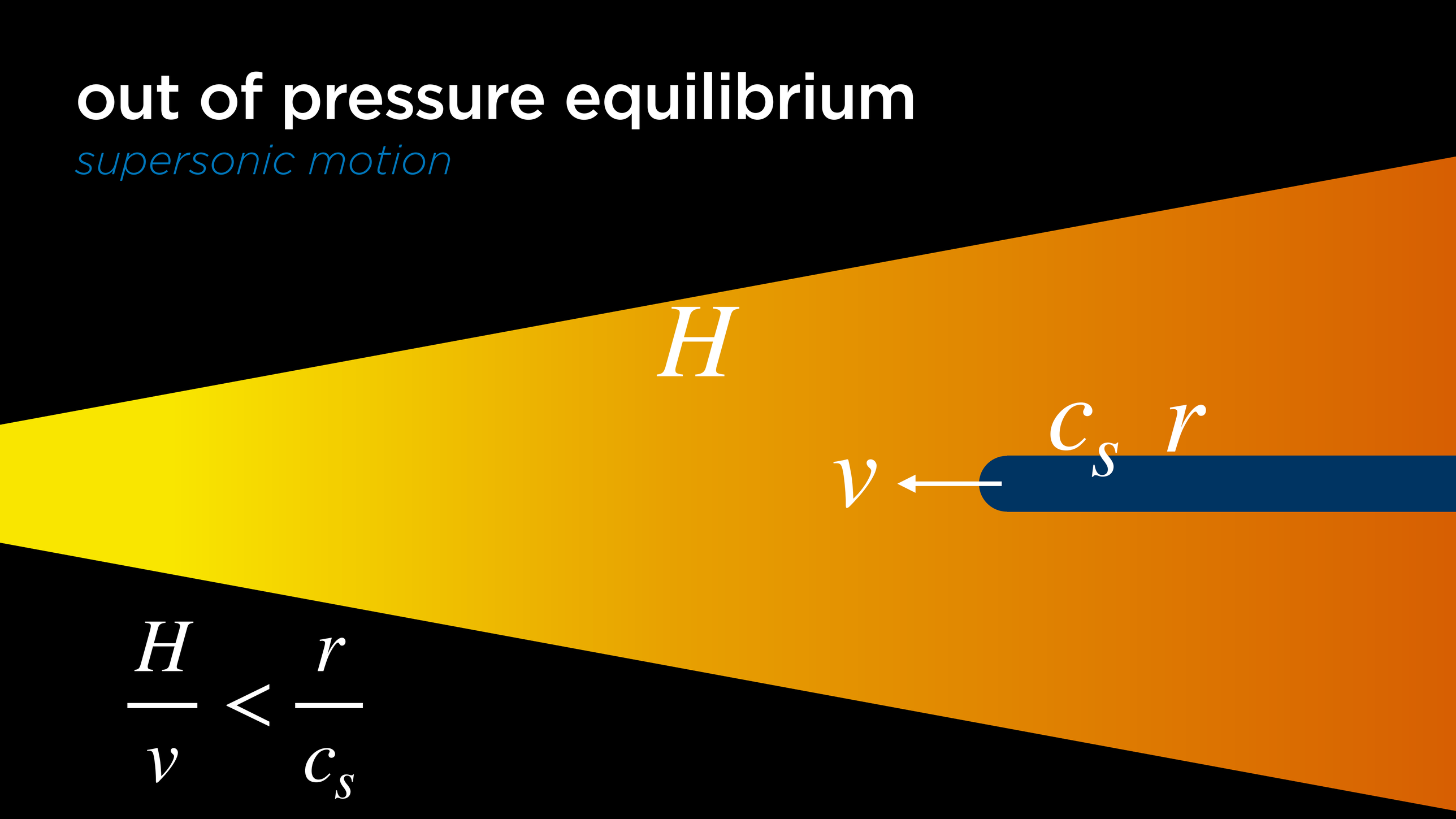
-cooling too fast $t_{\rm cool} < r/c_s$

-too low resolution $t_{\rm cool} < \Delta x/c_s$

-large non-thermal pressure (week 3)

out of pressure equilibrium

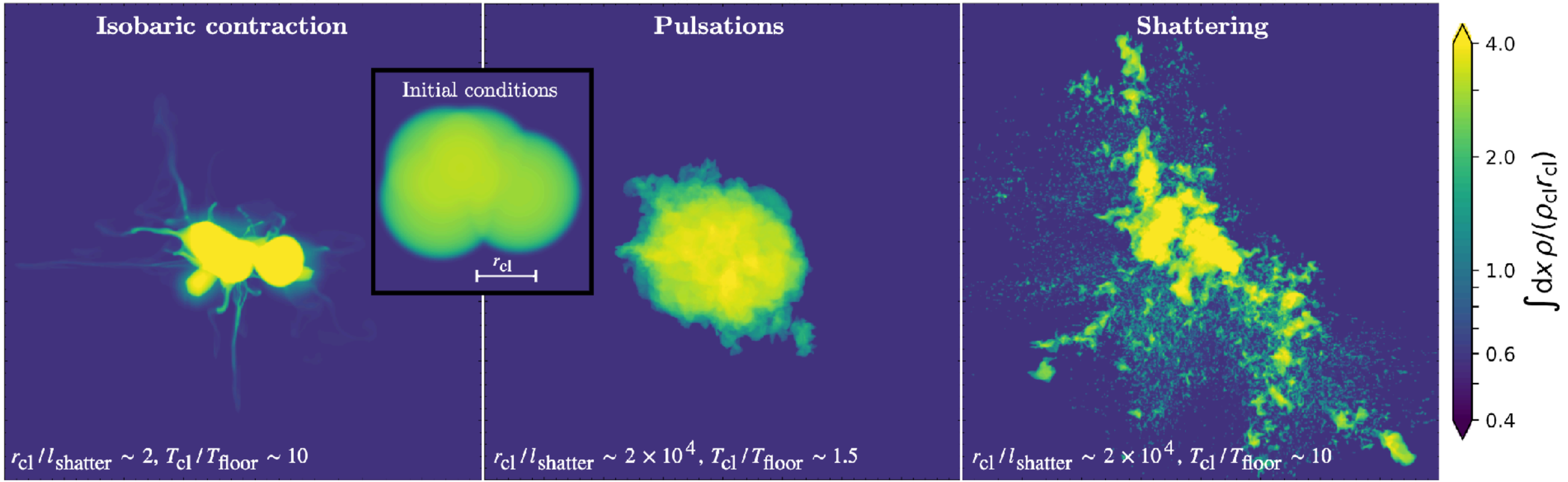
supersonic motion



$$\frac{H}{v} < \frac{r}{c_s}$$

out of pressure equilibrium

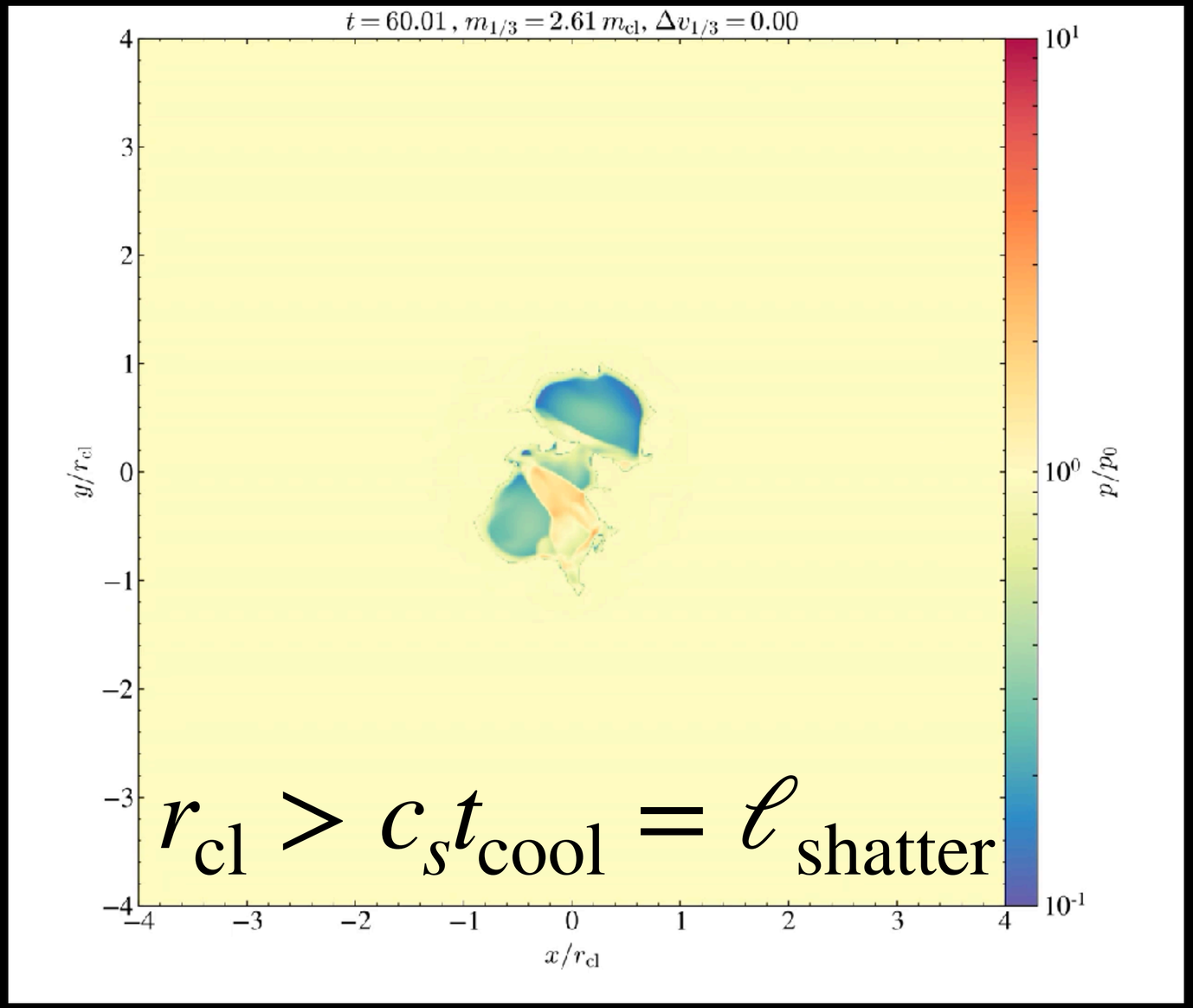
supersonic cooling

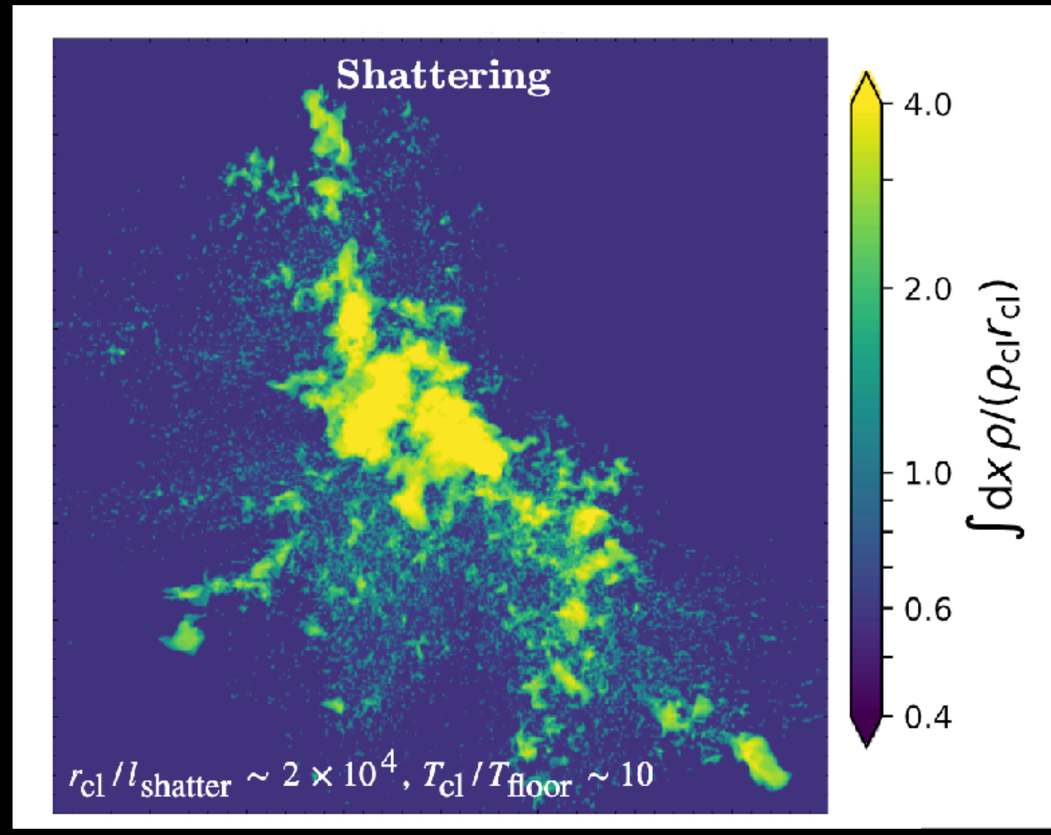


Max Gronke+ 20b

out of pressure equilibrium

supersonic cooling

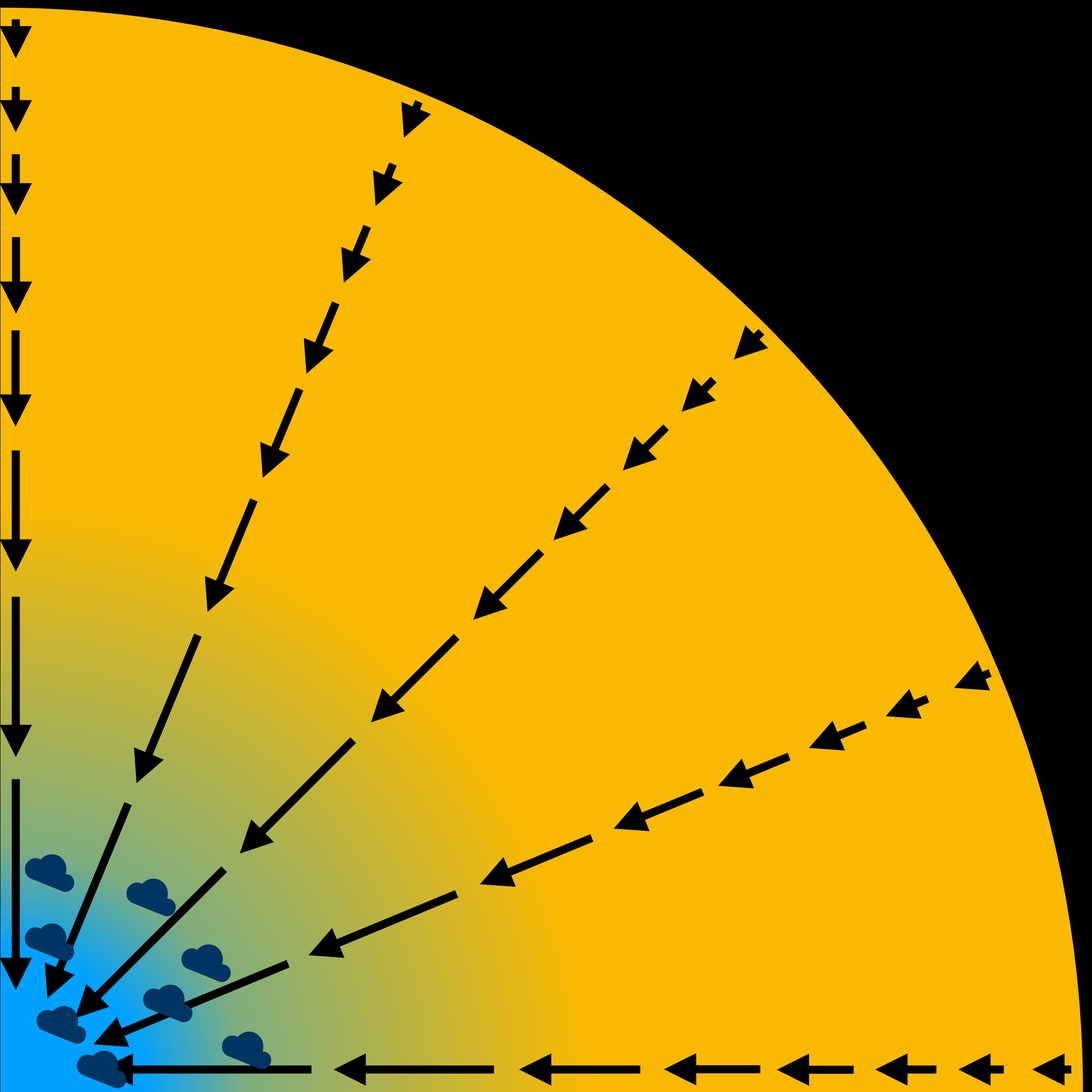




Max Gronke+ 20b

out of pressure equilibrium

supersonic cooling flow



moving too fast

+

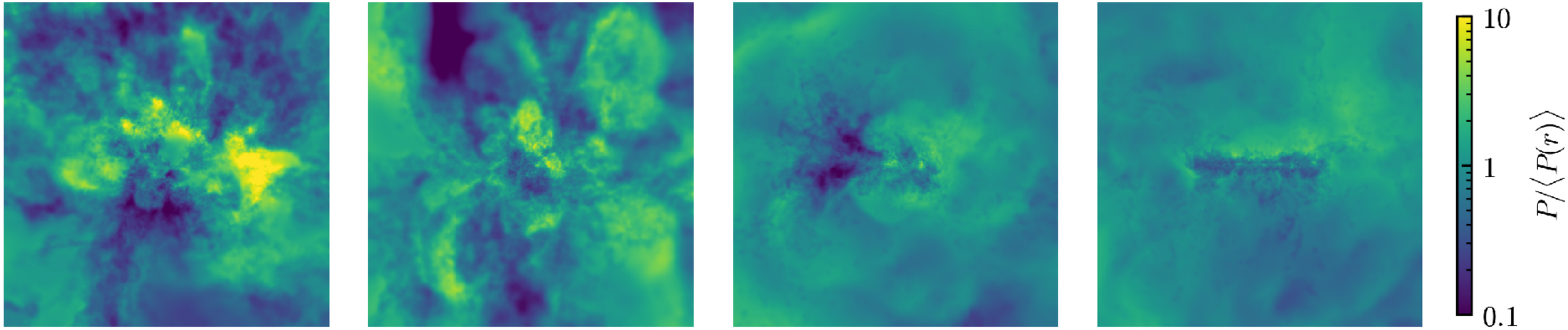
cooling too fast

since $\frac{t_{\rm cool}}{t_{\rm flow}} = 1$

and $\mathscr{M} > 1$

out of pressure equilibrium

supersonic cooling flow



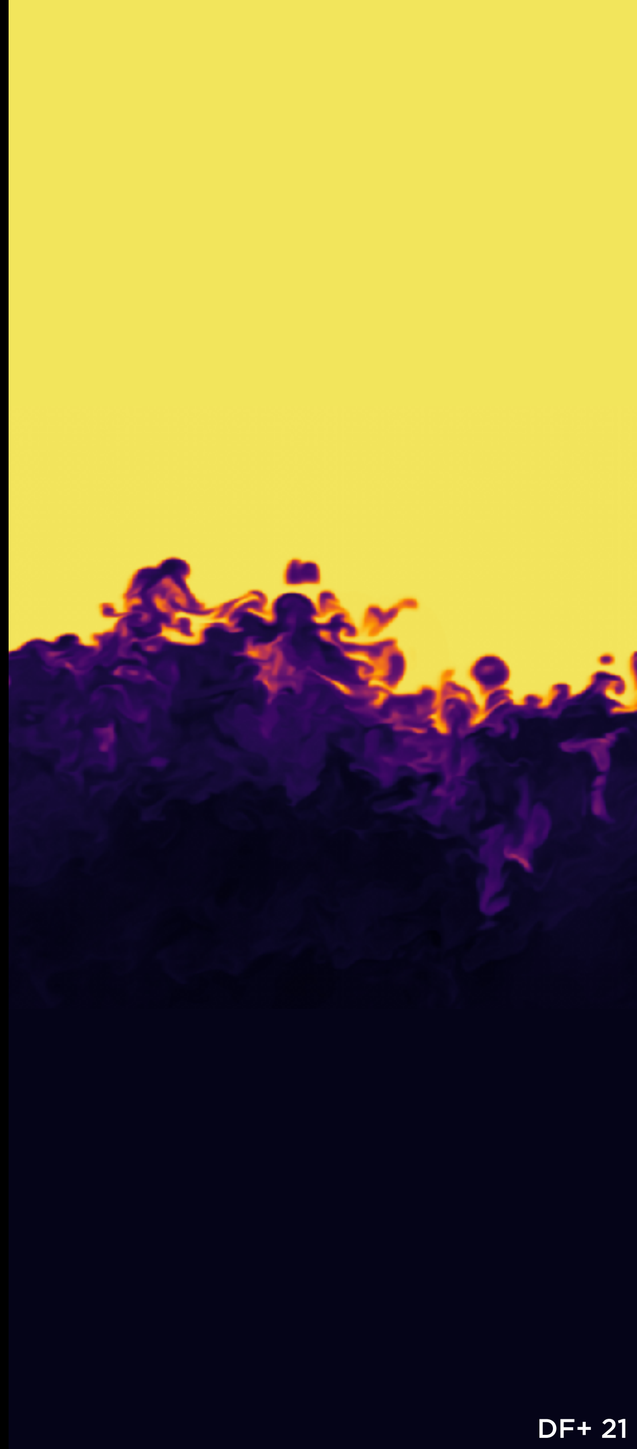
supersonic ⟵ ⟶ subsonic

Jonathan Stern+ 20b

see also: Balbus & Soker 89; DF+17; Jonathan Stern+ 19, 20a; and many more

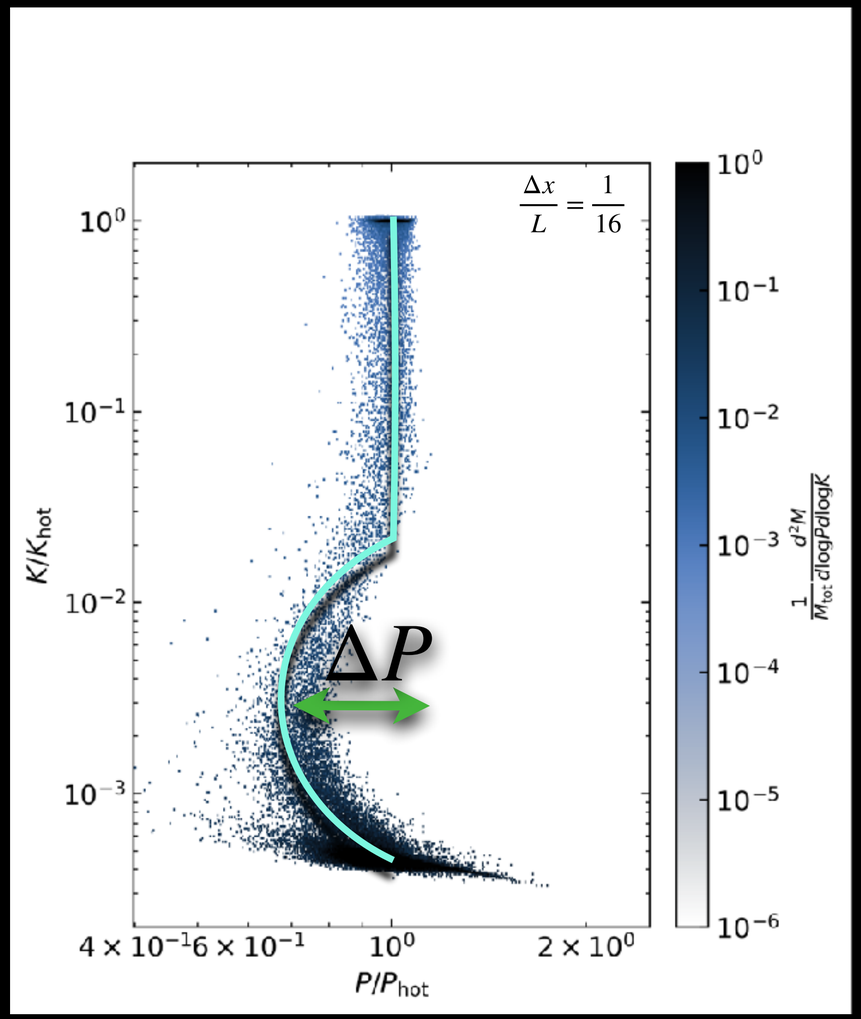
out of pressure equilibrium

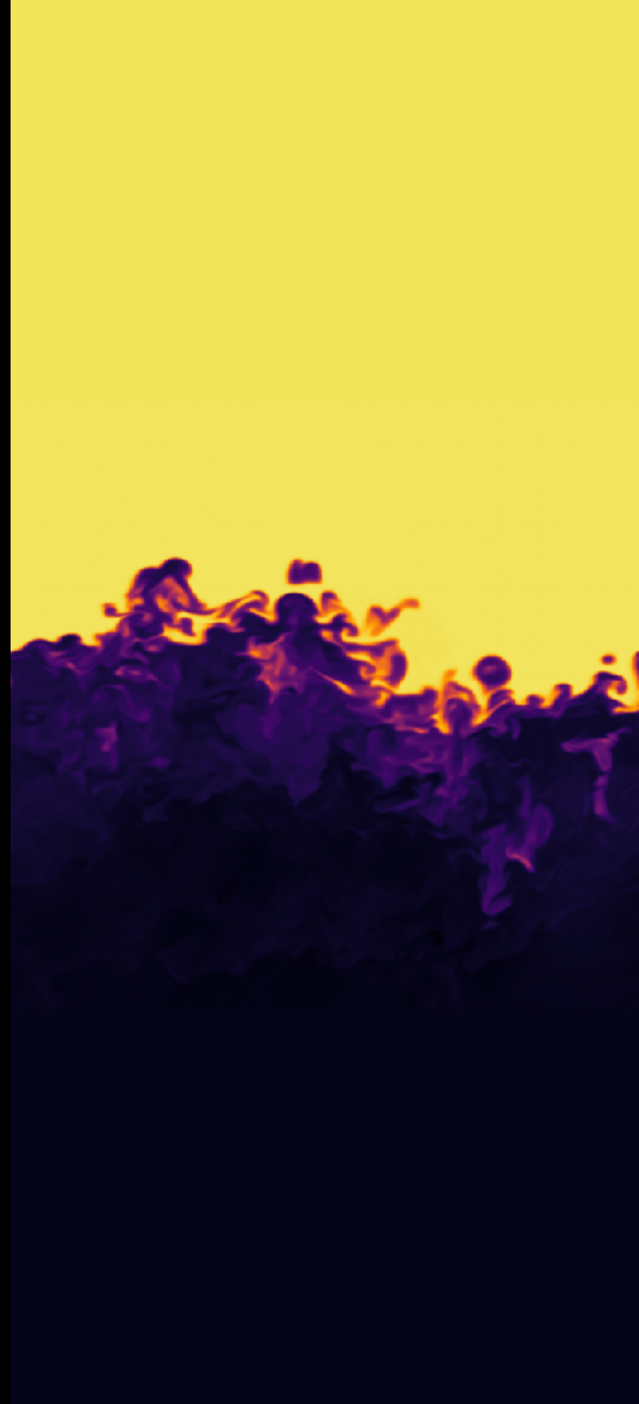
numerically under-resolved



out of pressure equilibrium

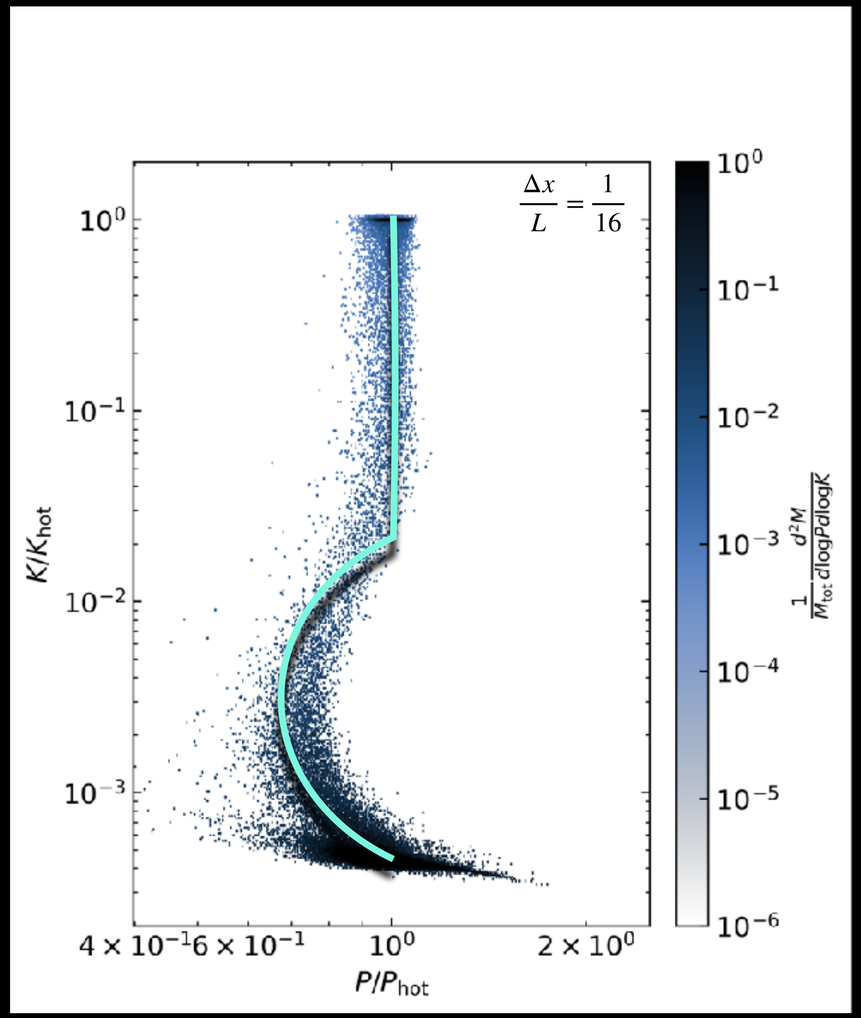
numerically under-resolved

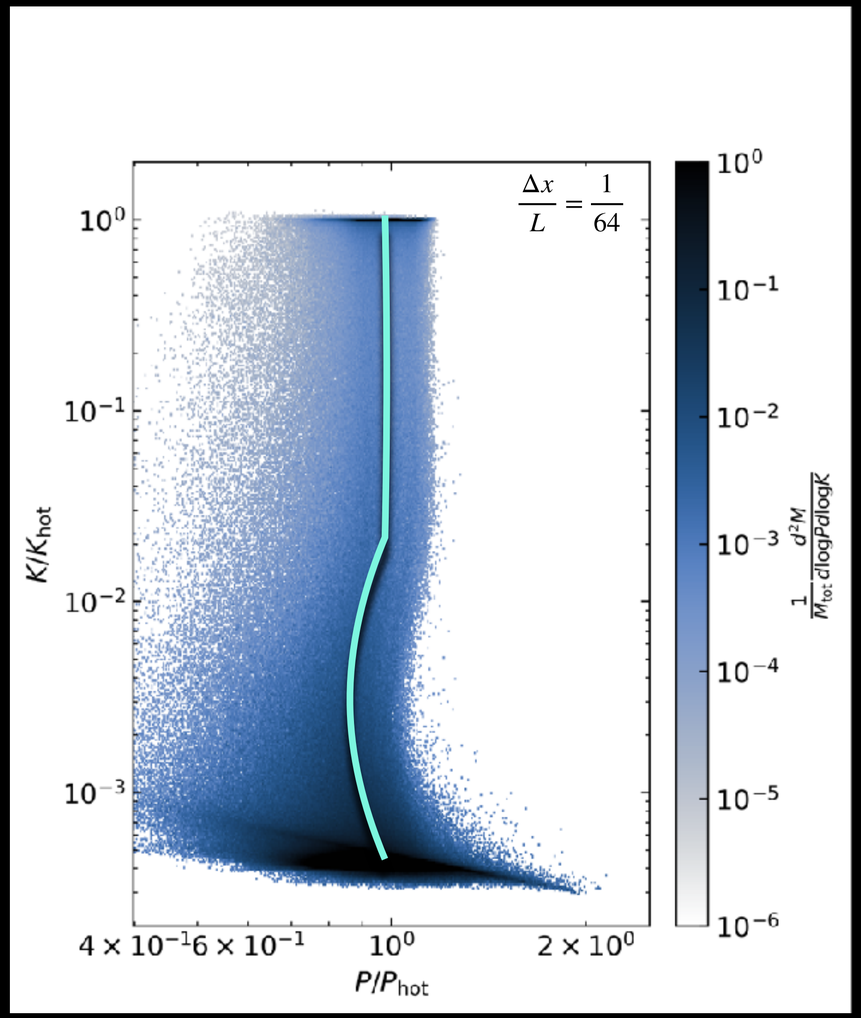


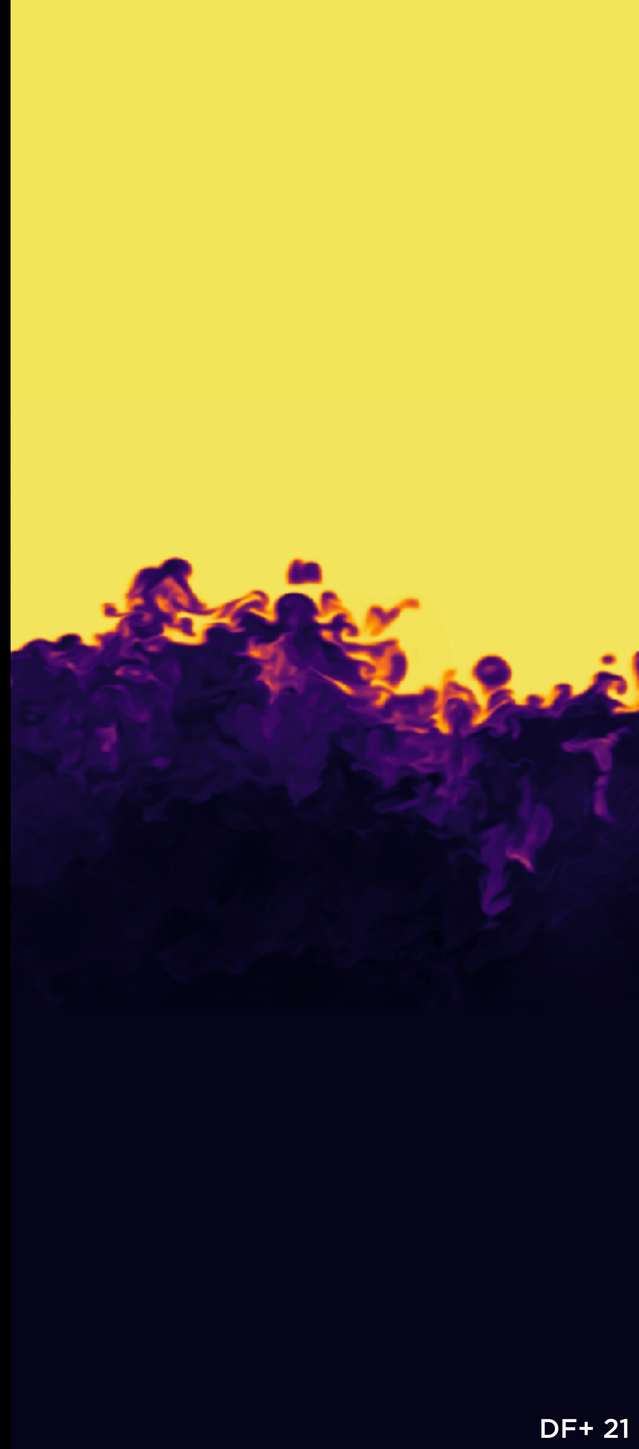


out of pressure equilibrium

numerically under-resolved

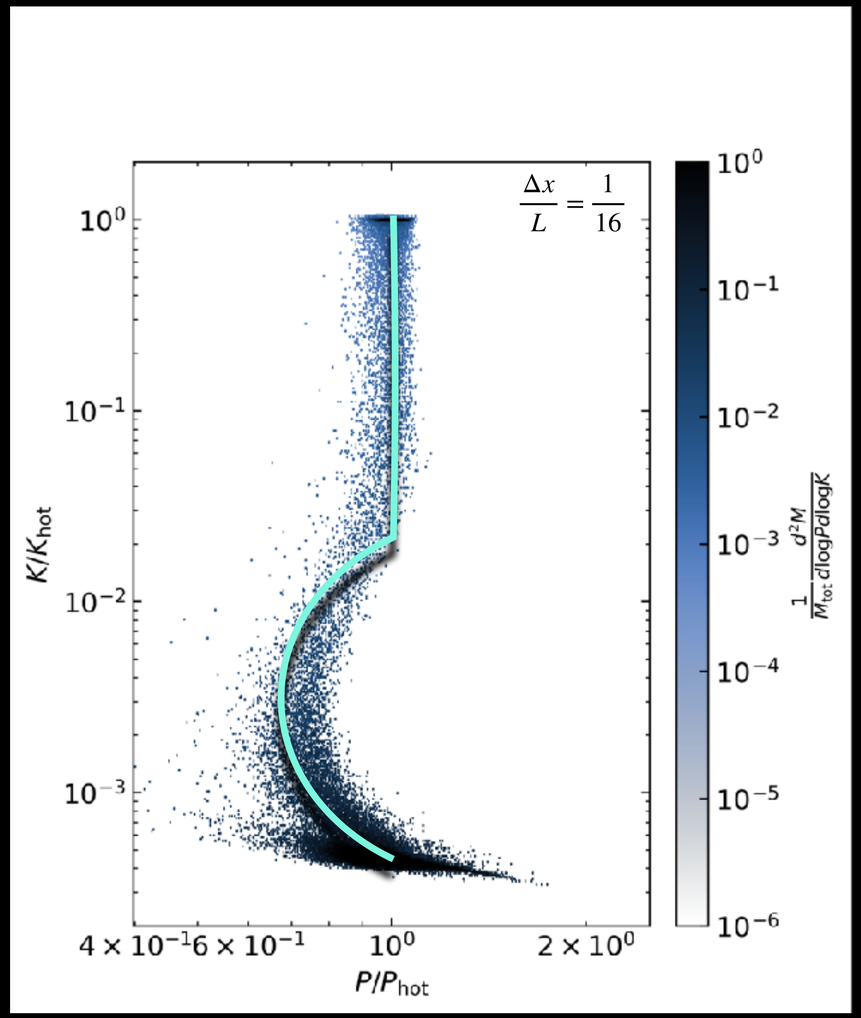


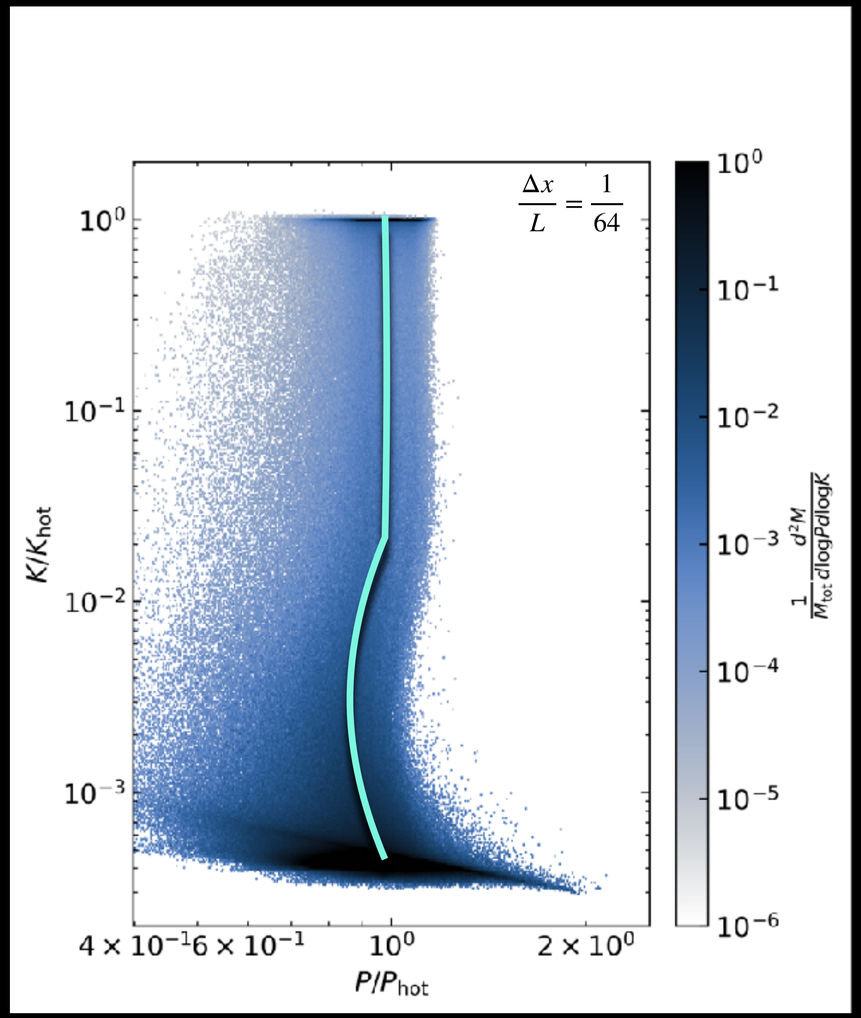


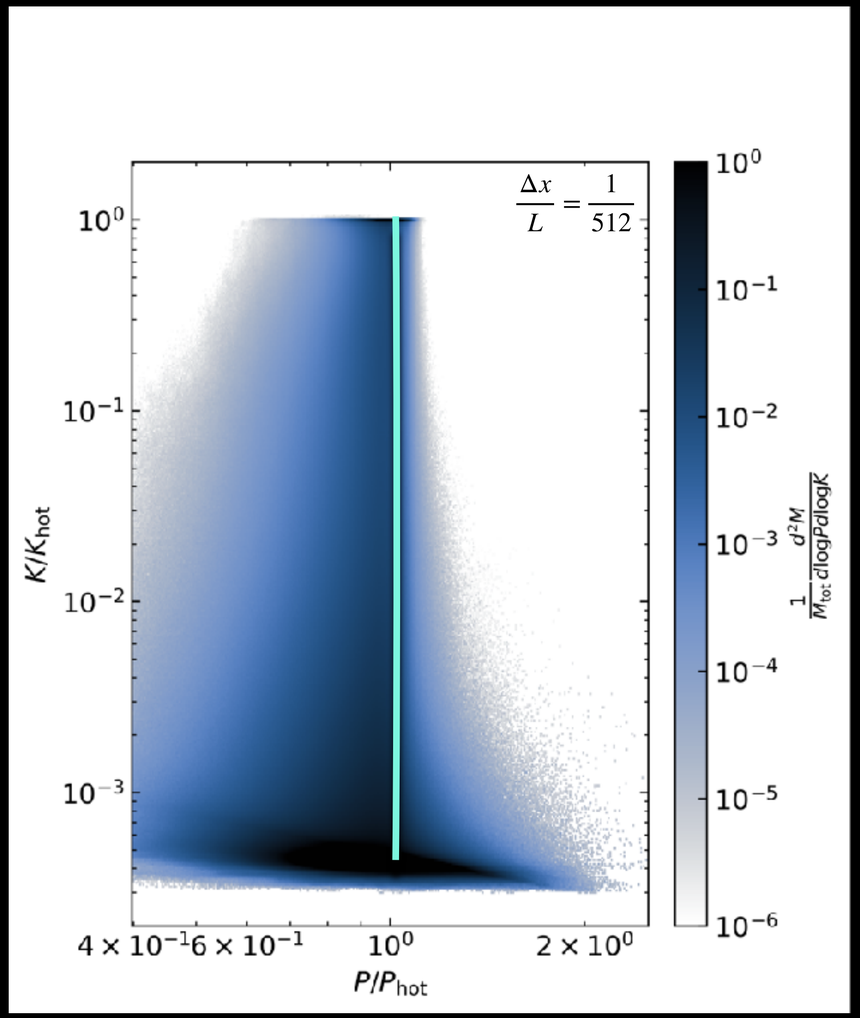


out of pressure equilibrium

numerically under-resolved

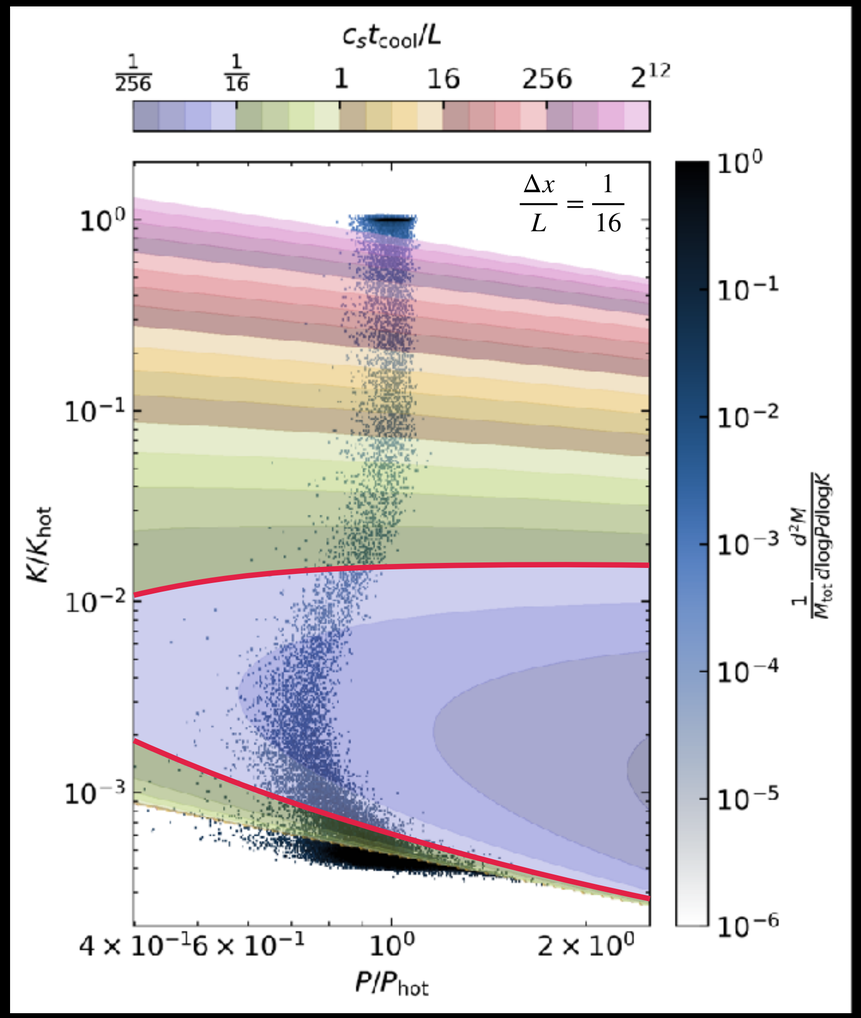


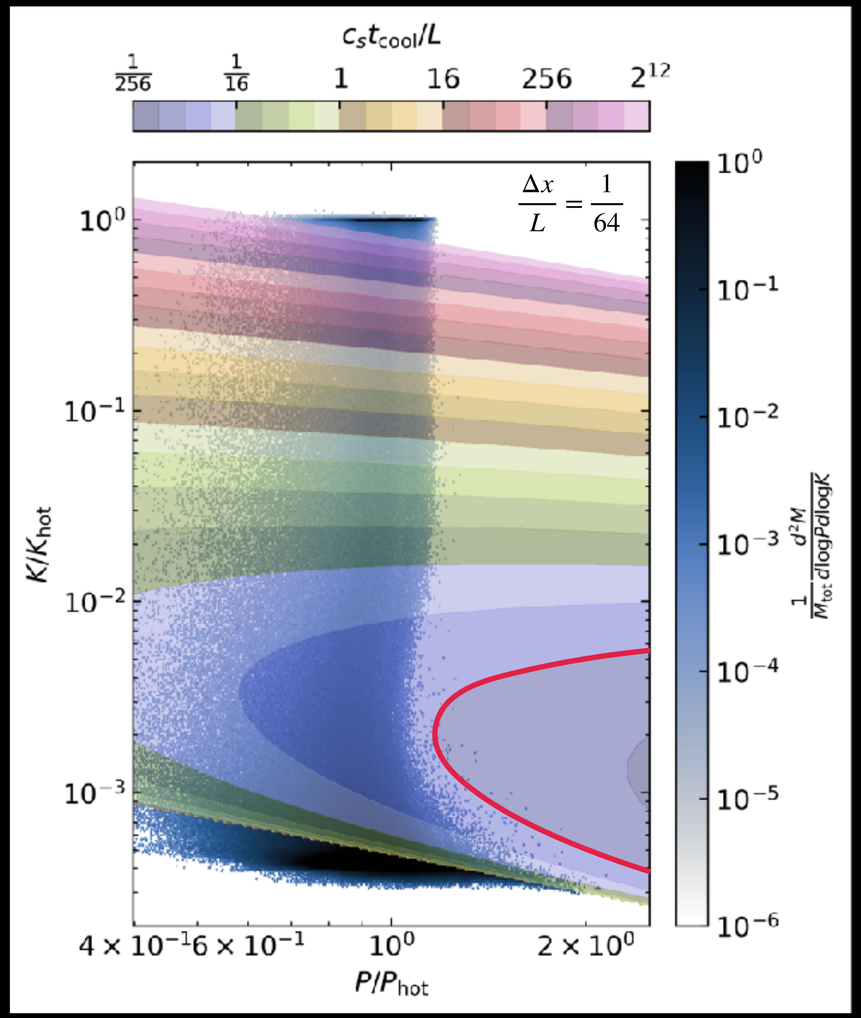


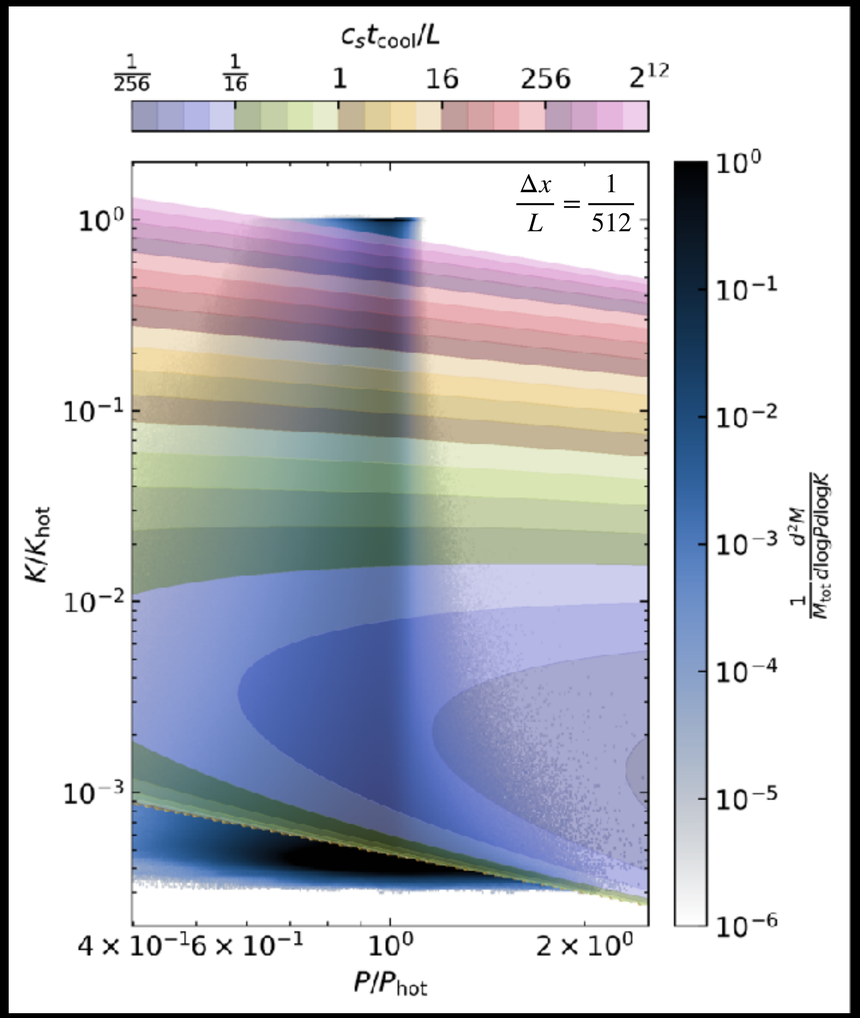


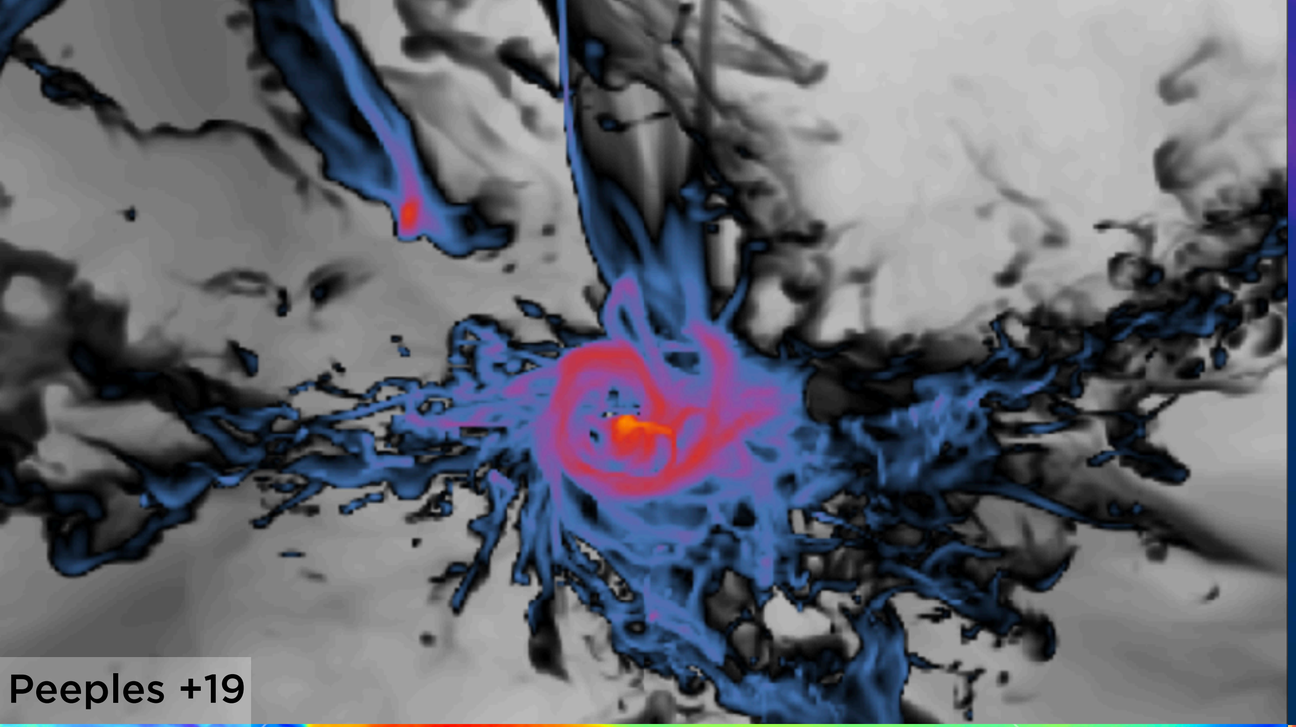
out of pressure equilibrium

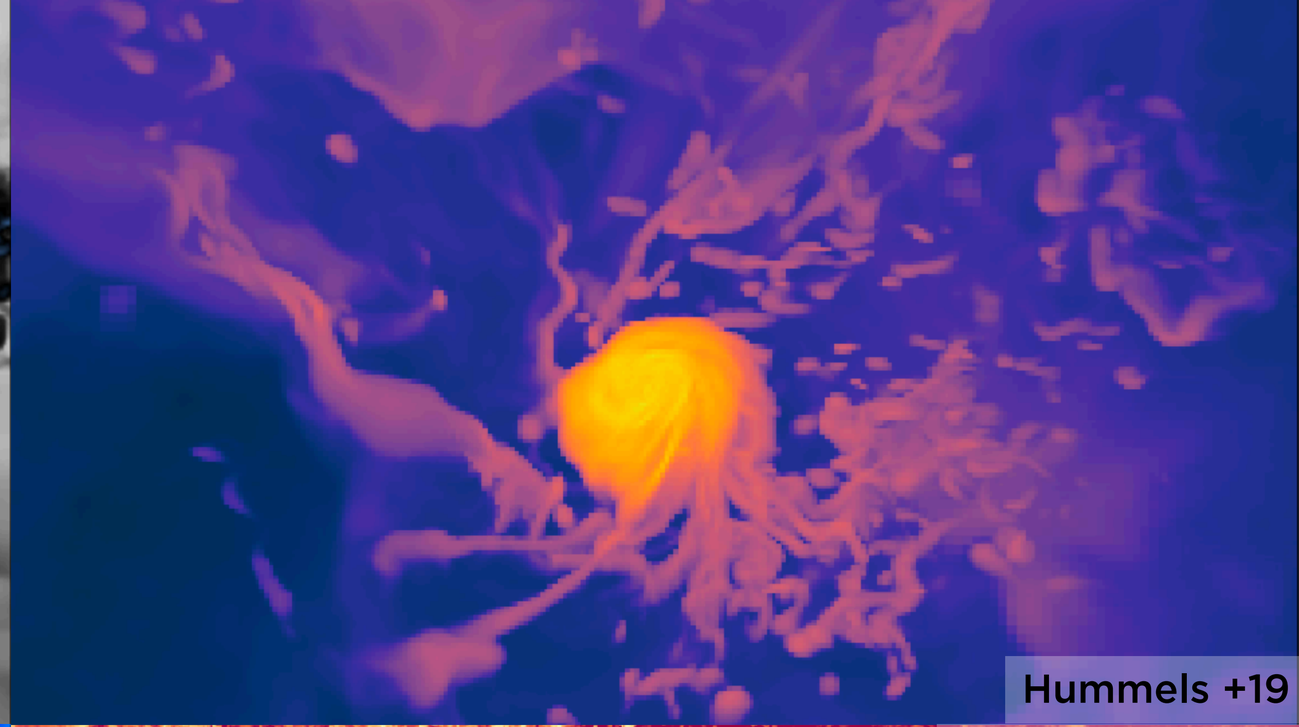
numerically under-resolved

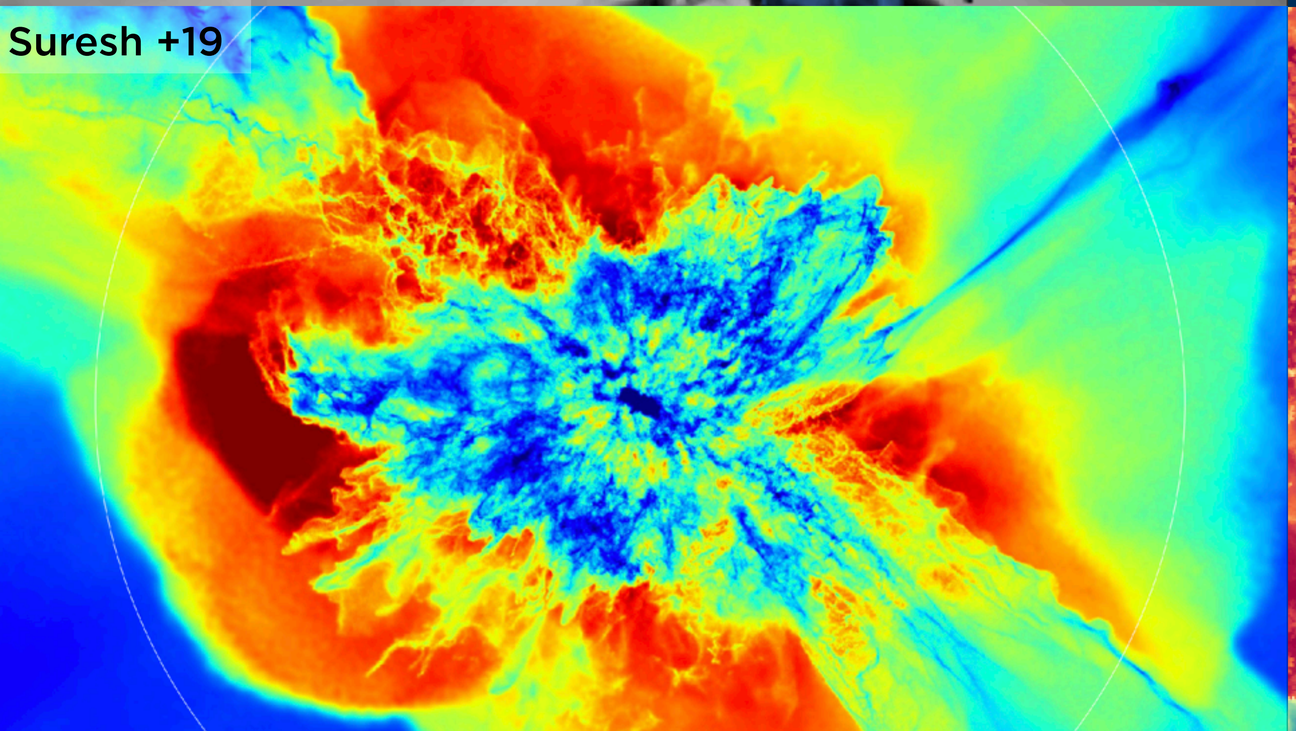


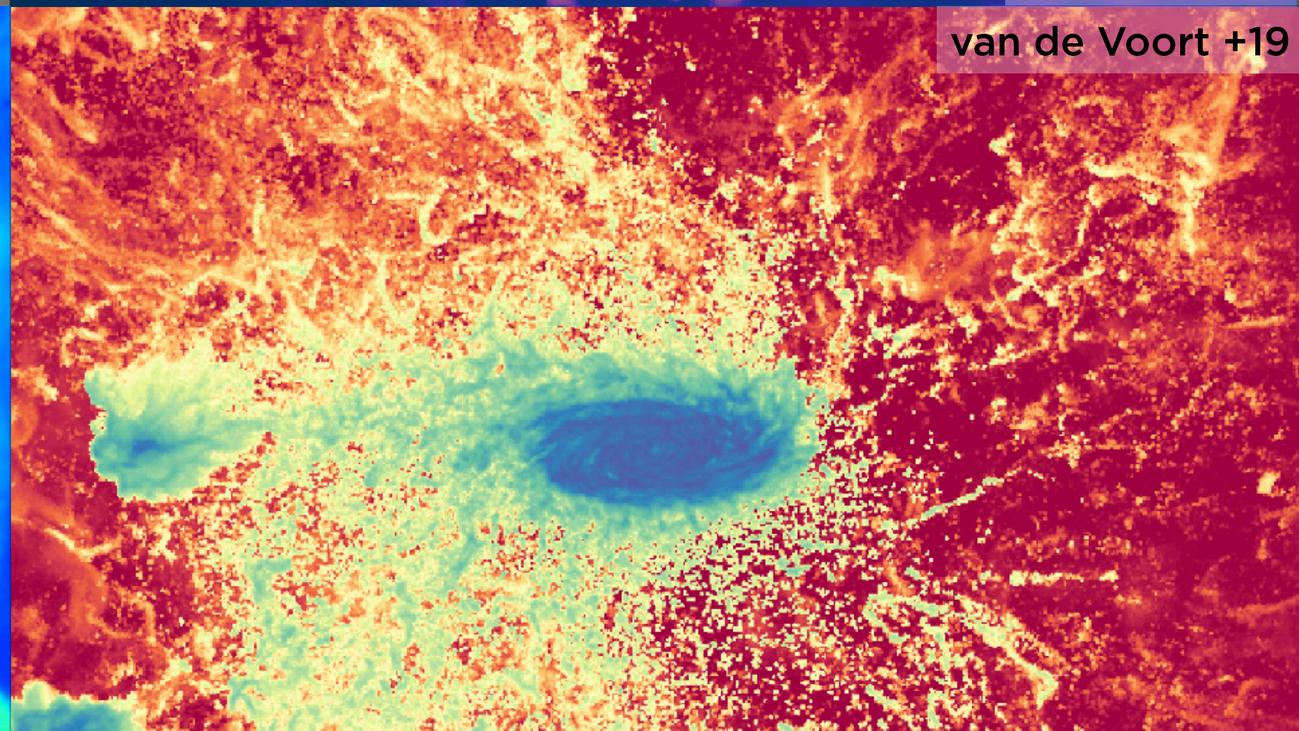





Peeples +19

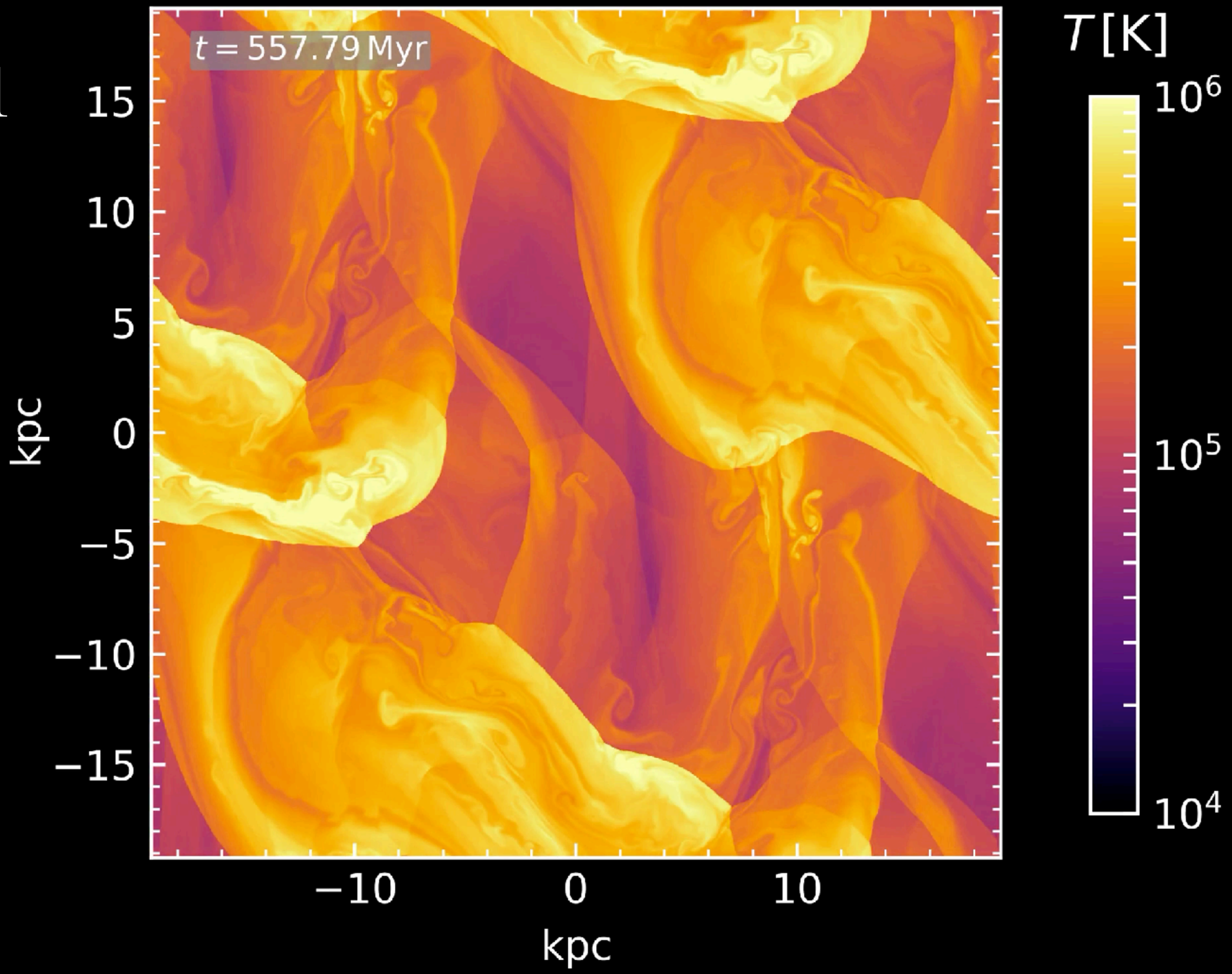

Hummels +19

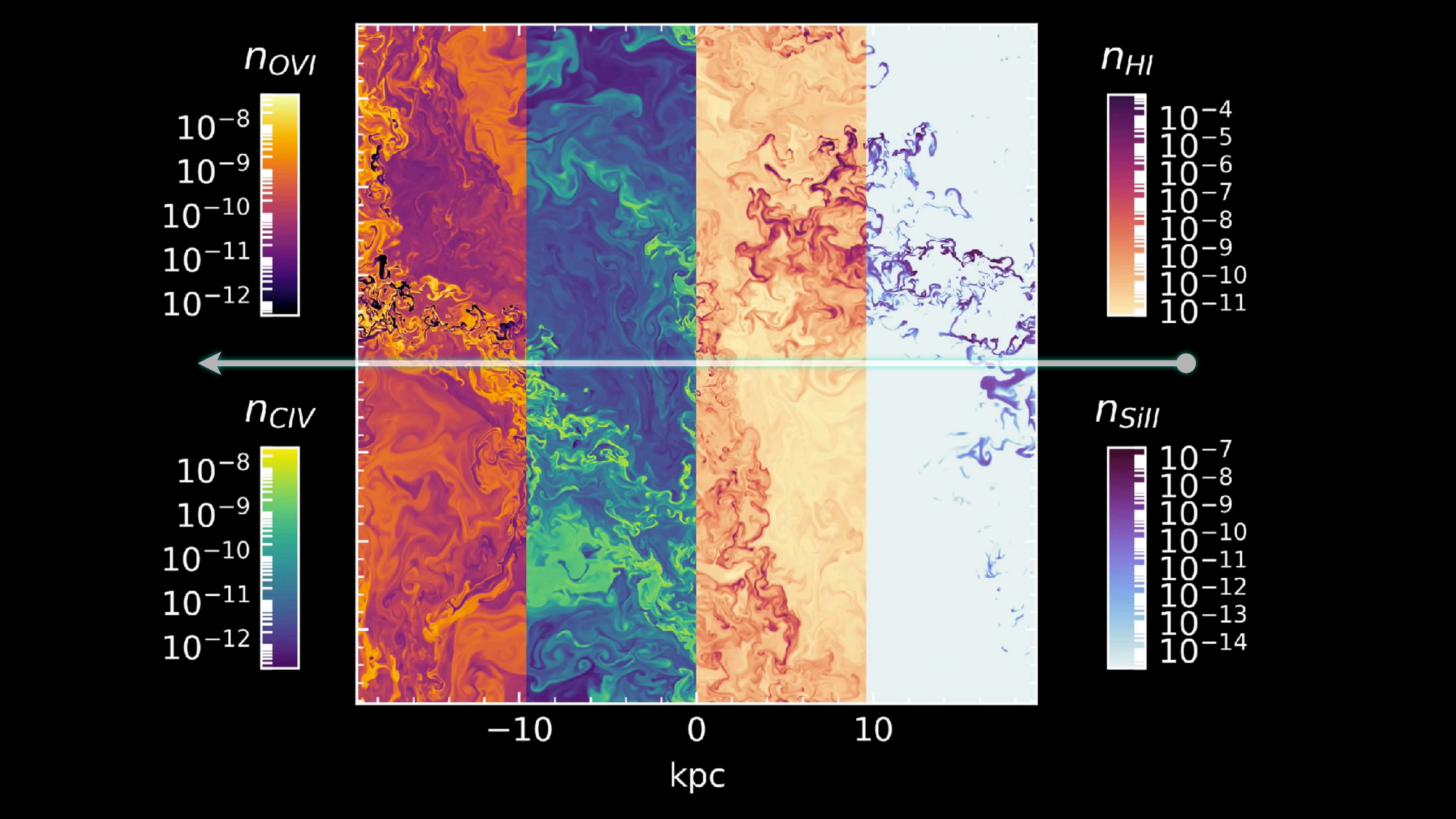

Suresh +19


van de Voort +19

A theorists perspective on the observational tracers of the multiphase CGM

$$\frac{t_{\rm cool}}{t_{\rm mix}} < 1$$




n_{OVI}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
n_{HI}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
n_{CIV}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
n_{SiII}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
−10
0
10
kpc

Multiphase CGM

a result of the
rich interplay of

galactic winds

satellite galaxies

IGM accretion

thermal instabilities