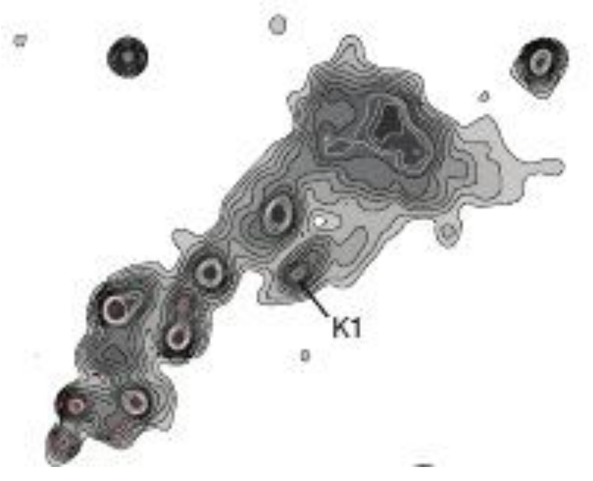
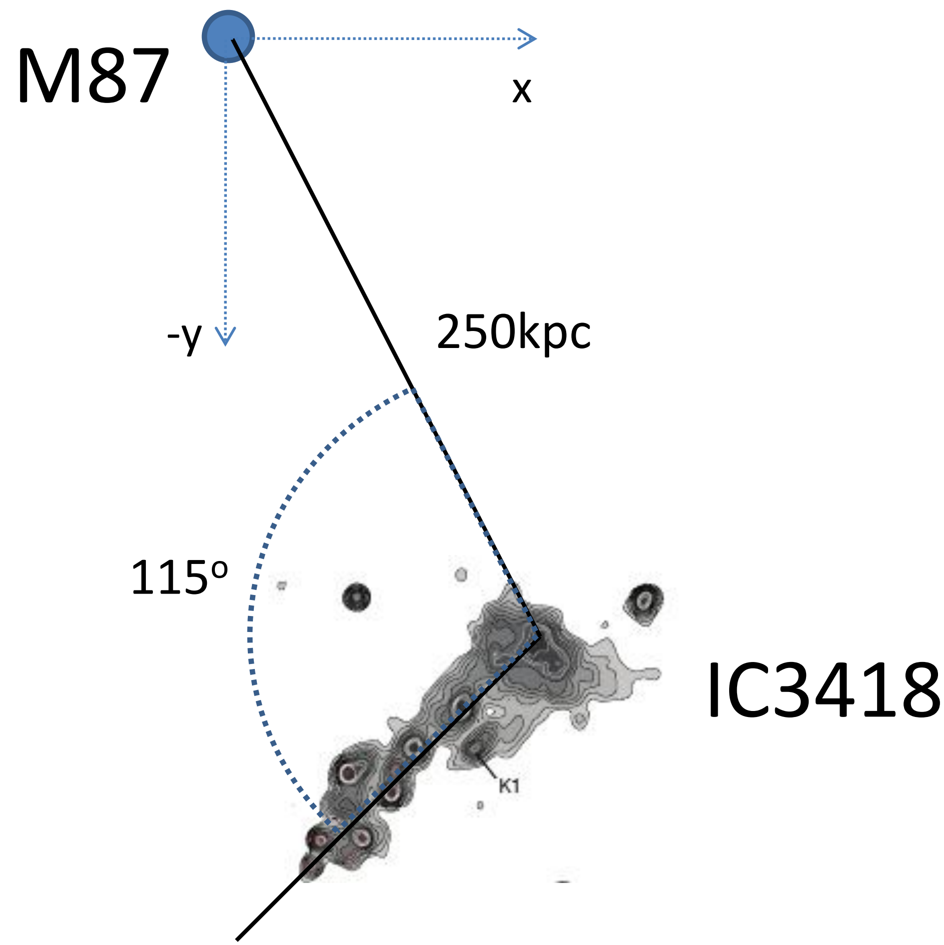
IC3418 – orbital models

- dIrr galaxy with a tail with H_α and UV knots (Hester et al. 2010)
- From observation we know:
  1. los-velocity: -1000km/s w.r.t. M87
  2. pos-position: 250kpc from M87
  3. pos-velocity direction: NW, tail angle of 115^o



- Free parameters:
  1. los-position
  2. tangential velocity
- Model:
  - spherically symmetric β-profile mass distribution truncated at 2Mpc
  - IC3418 represented as a point mass
  - xy = p-o-s; z = l-o-s


M87
x
-y
250kpc
115°
IC3418
K1

IC3418 – orbital models

- In a set of simulations we vary the current
  1. z-position in (-500, 500) kpc
  2. v_x , v_y -velocities in (500, 1000) km/s
- these values yield radial distances of (250-560) kpc and total velocities of (1200-1700) km/s
- Why we think IC3418 is close to M87:
  1. the projected distance from M87 is small
  2. moderately high velocity w.r.t. mean cluster velocity
  3. presence of stripping tail
  4. other rps-galaxies in Virgo occur within 500kpc from M87
- Limits on the tangential velocity:
  1. < 500km/s … too compact orbits
  2. >1000km/s … too prolonged/close-to-unbound orbits

Consistent orbits

-500kpc

-300kpc

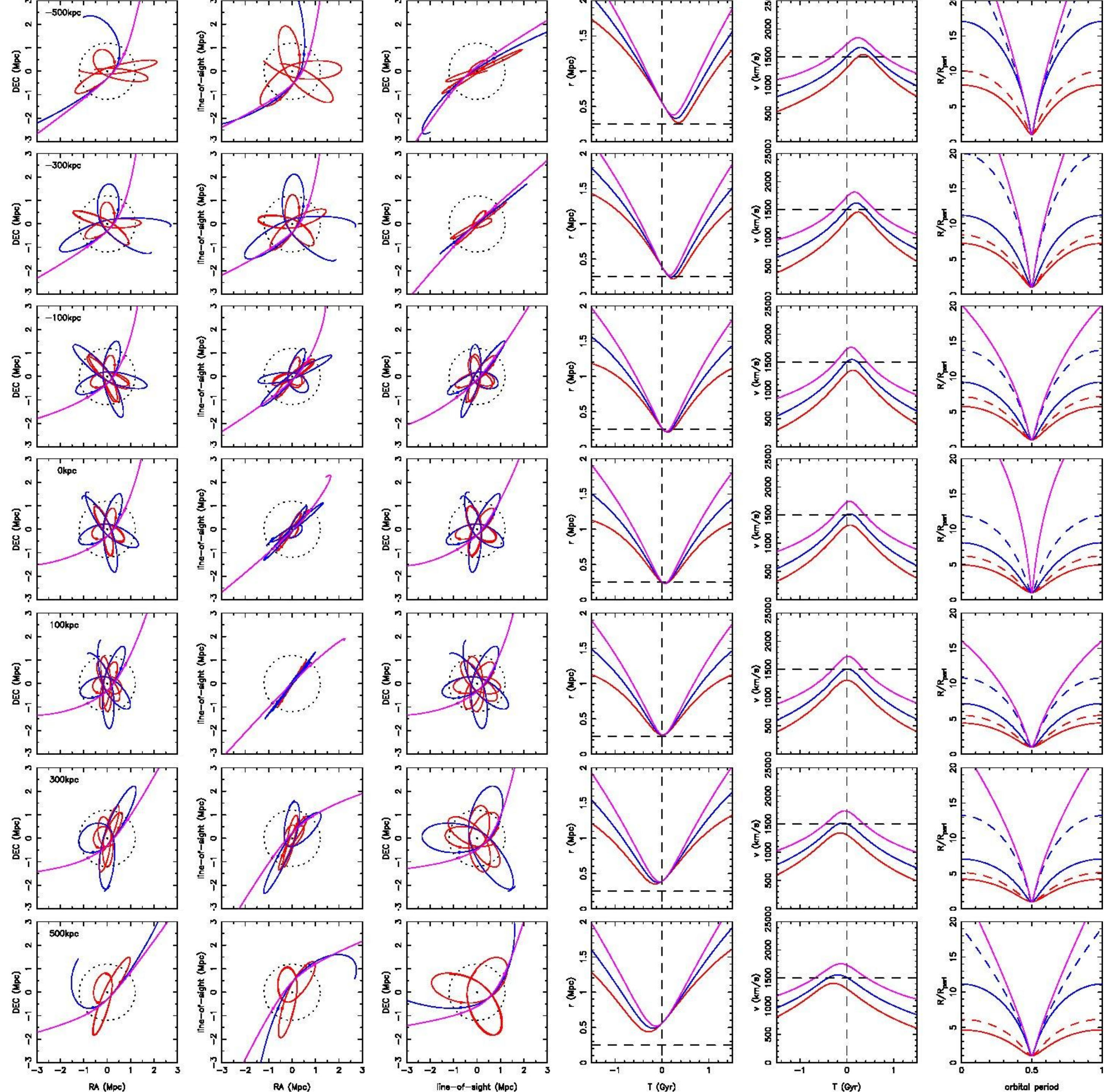
-100kpc

0kpc

100kpc

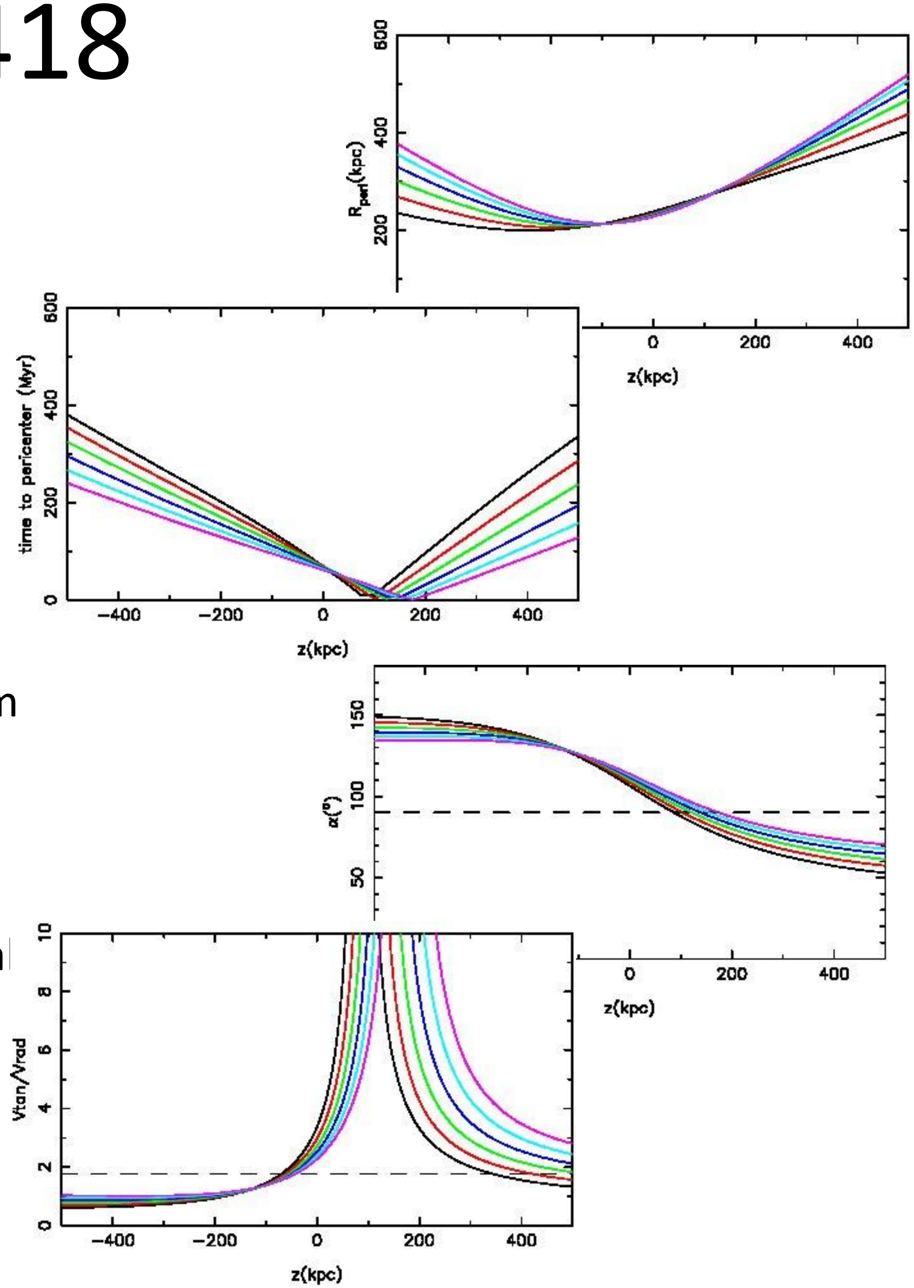
300kpc

500kpc



IC3418

- peri-to-apocenter distance ratios 1:5 – 1:20
  - rps galaxies in Virgo typically on 1:10 orbits
- almost all orbits within 350Myr from pericenter
- minimum pericenter distance ~200kpc
- Upper limit of the total velocity ~1700km/s
- Lower limit of the 3D distance ~250kpc
- => upper limit estimate of the current ram pressure ~1400cm^{-3}(km/s)^2
- We cannot determine whether IC3418 is now before or after closest approach to M87
- Tail angle – about 2-times more tangential than radial component of orbital motion in p-o-s



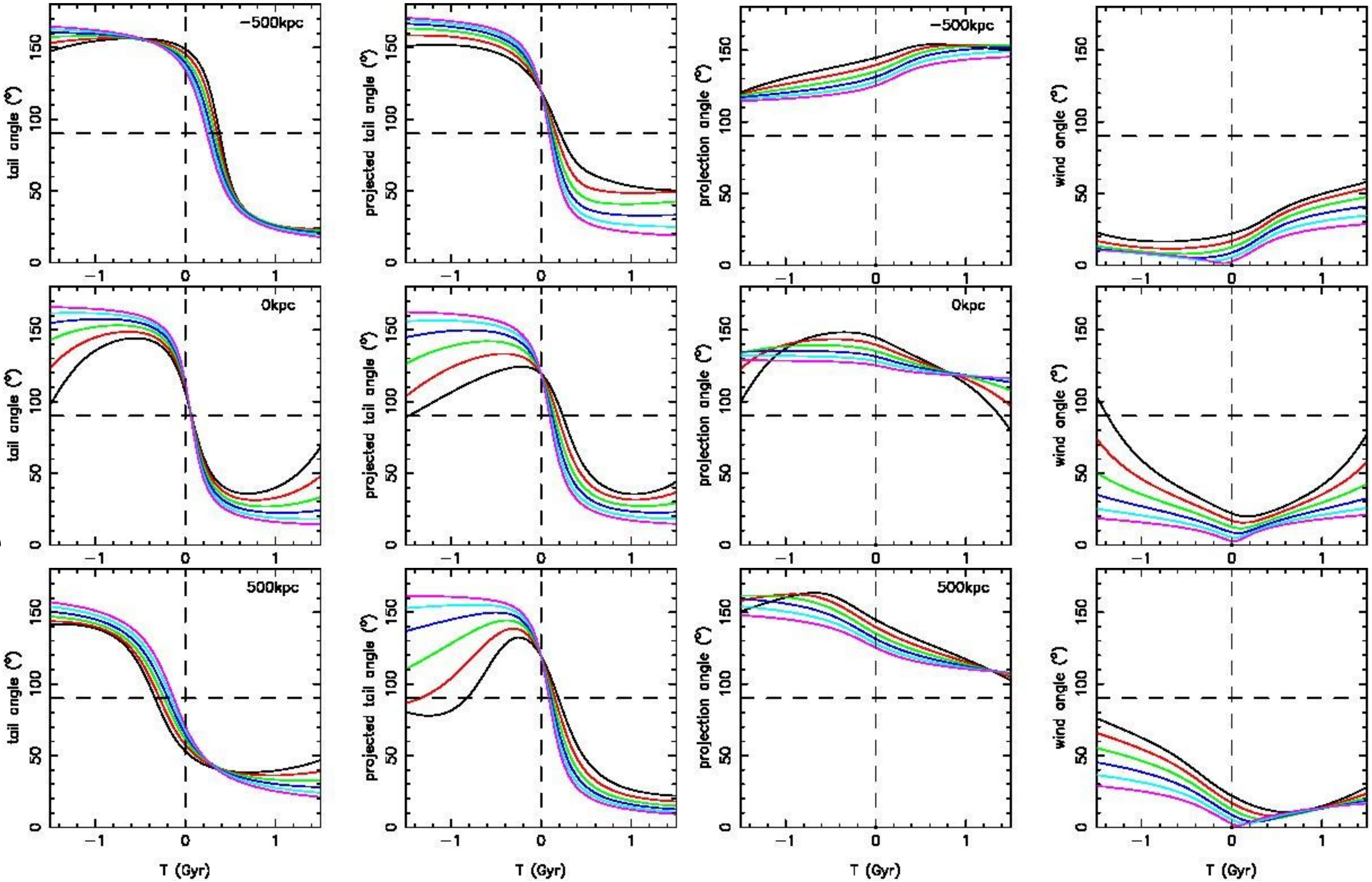
IC3418 – characteristic angles

- Evolution of 3D tail angle, projected tail angle, projection angle, & wind angle

PA ~ 45°
i ~ 50°

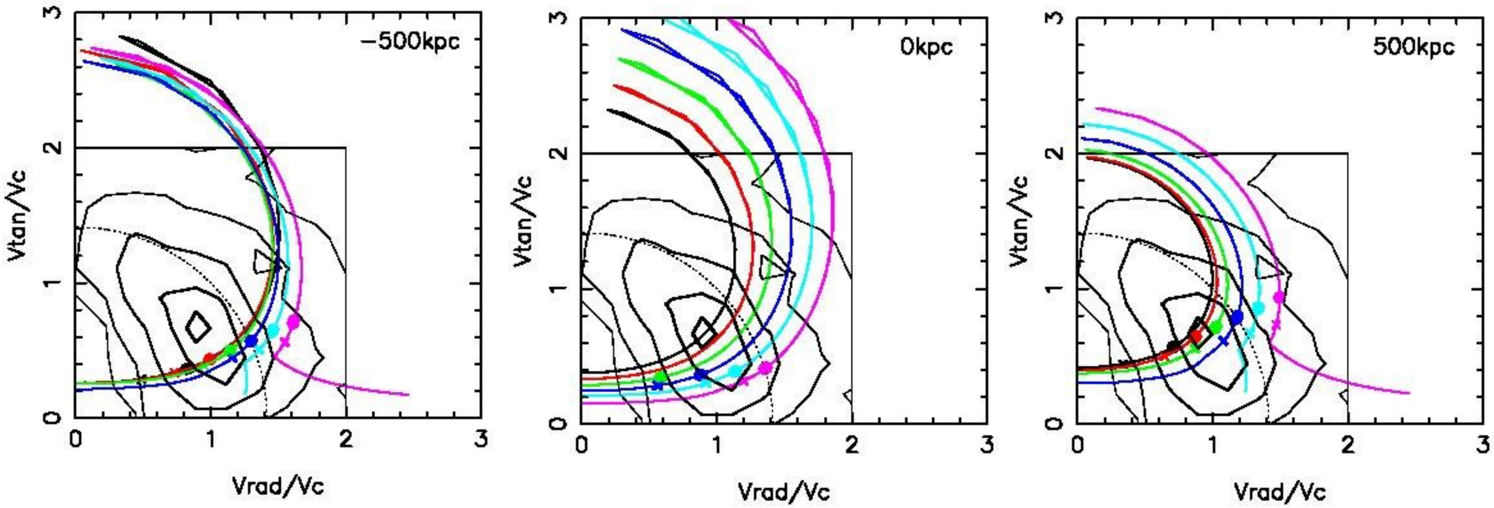
Tail length by a factor of 1.2-1.7 larger

wind angle currently within 20° of face-on



Cluster orbits

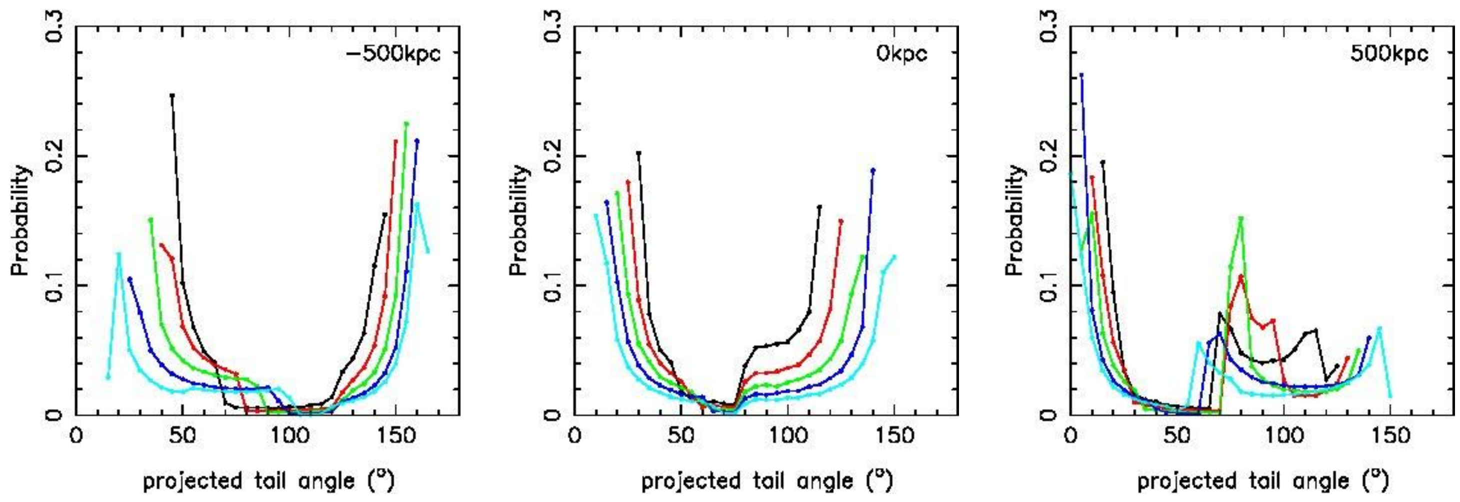
- Distribution of orbits in cosmological simulations (Benson 2005)
  – DM halos followed at the time of merging into their host haloes at distances of about one virial radius
  – Significant correlation between tangential and radial velocity components, with a peak of the distribution at vr=0.9vc, vt=0.7vc



- Most of our model orbits are consistent with the distribution
- less likely: rapid orbits with large |z|'s; slow orbits with small |z|'s

IC3418 – orbital statistics

- All modeled orbits consistent with the current state of IC3418. They however differ in the shape and orientation w.r.t. observer
- Evolution of observable parameters along individual orbits
  - Which orbits are more probable to bring the galaxy into its current observed state than the others?
  - Projected tail angle – evolution during one orbital period around T=0Gyr



- The minimum of the distribution shifts towards smaller angles for increasing current z's
- => We are likely observing IC3418 near but just AFTER its closest approach to M87

IC3418: pre- or post-peak?

- probability of the projected tail angle along different orbits
  - ⇒ probably post-peak
- RPS simulace – tails get narrower with time
  - ⇒ post-peak
- Randall et al. (2008) – possible orbits of M86
  - Based on the orbital energy analyses they were able to constrain significantly the range of possible orbits
  - Doesn’t work for IC3418 mainly due to lower los velocity
- Main results of our calculations:
  - obtuse projected tail angle does not mean that IC3418 is before the closest approach to M87
  - orbits with IC3418 on the far-side of the cluster are pre-peak
  - orbits with z~100kpc are at pericenter
  - IC3418 occurs within ~350Myr of pericenter
  - Minimum pericenter distance ~200kpc, upper-limit total velocity ~1700km/s
  - Maximum estimated current ram pressure ~1400$cm^{-3}(km/s)^2$
  - IC3418 is being stripped close to face-on
  - Actual length of the tail is by factor >1.2 larger

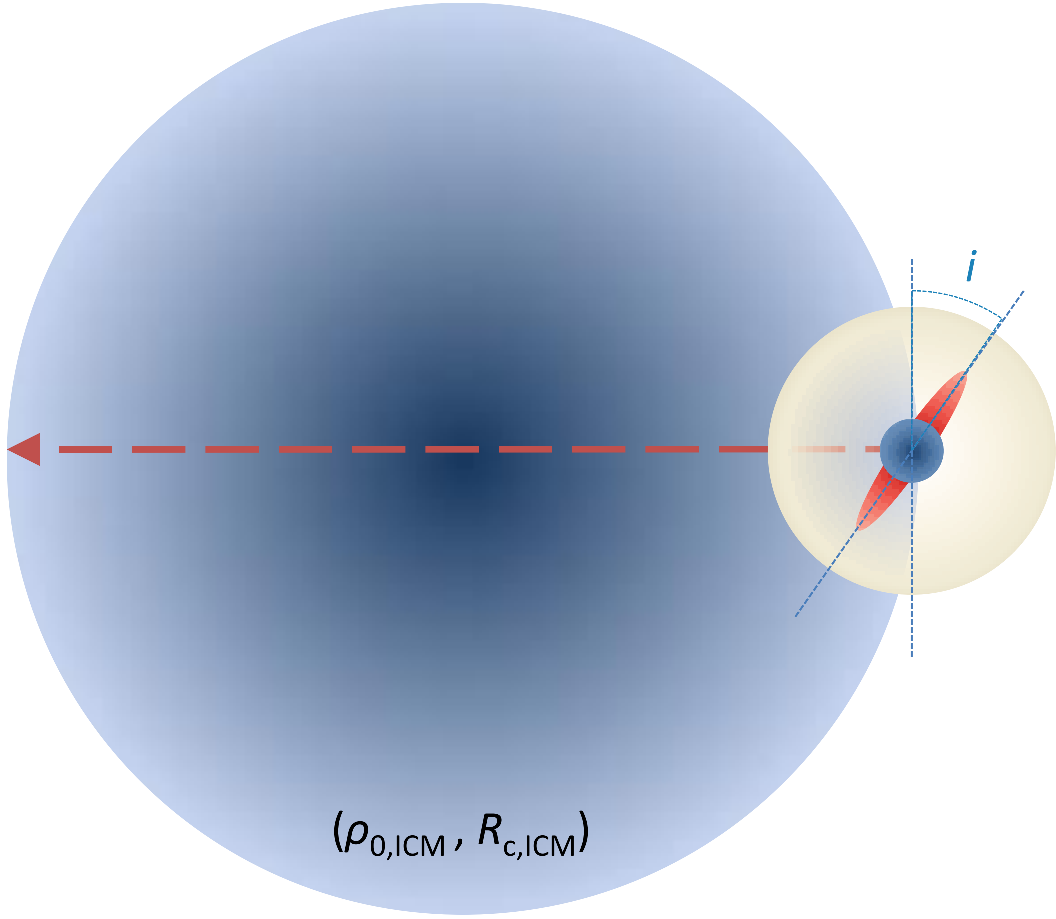
Suggestions

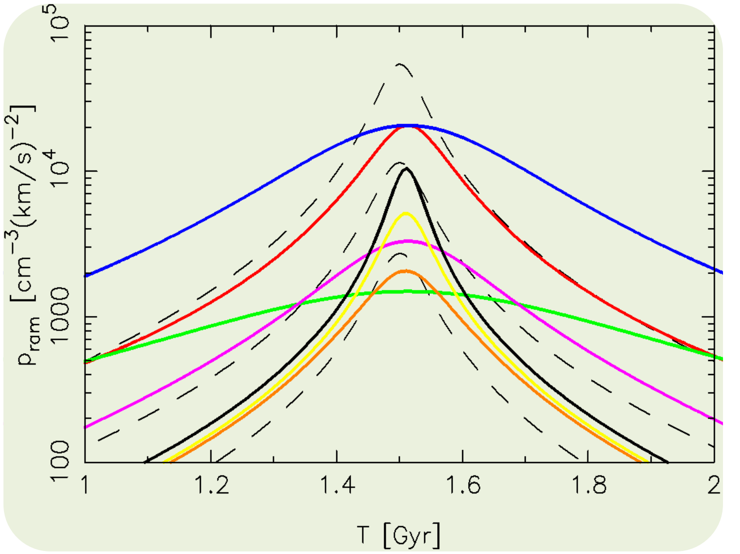
- dwarf galaxy => ram pressure at large distances from M87 should be enough to strip it
- at larger distances from M87 pressure from the surrounding ICM might be small to cause compression of the tail and induce SF

Modeling – what?

initial conditions

- free-fall orbit through different ICM distributions ⇒ corresponding ram pressure profiles

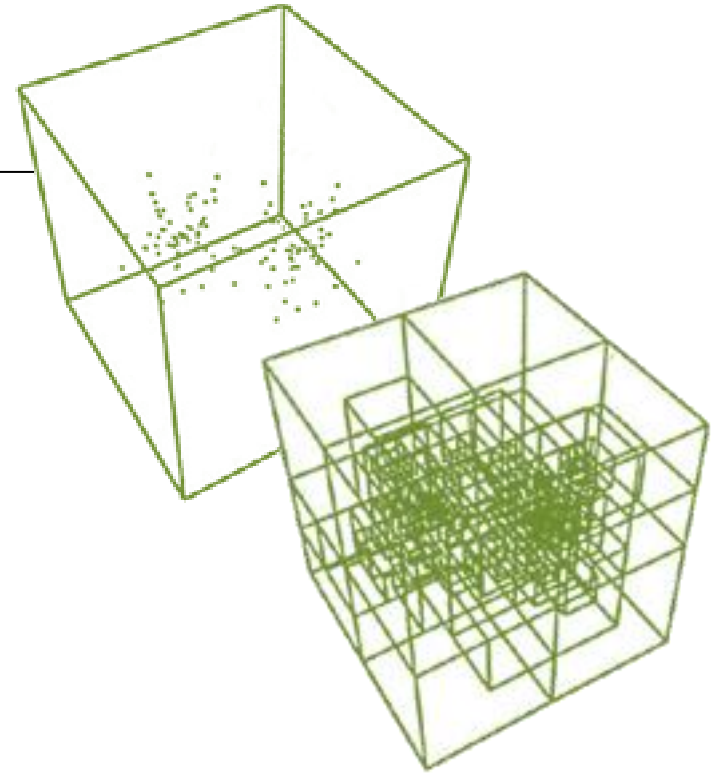




"strictly-radial" orbits may model slightly elliptical orbits with non-zero pericenter distances in higher but narrower ICM distributions

Modeling – how?

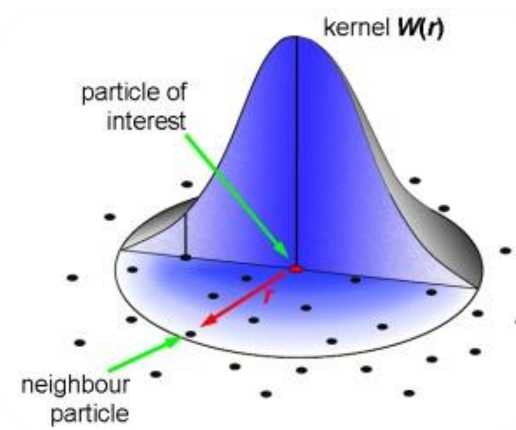
tree/SPH code



- 3D tree/SPH code GADGET (Springel et al.) adapted for calculations with ISM-ICM interaction

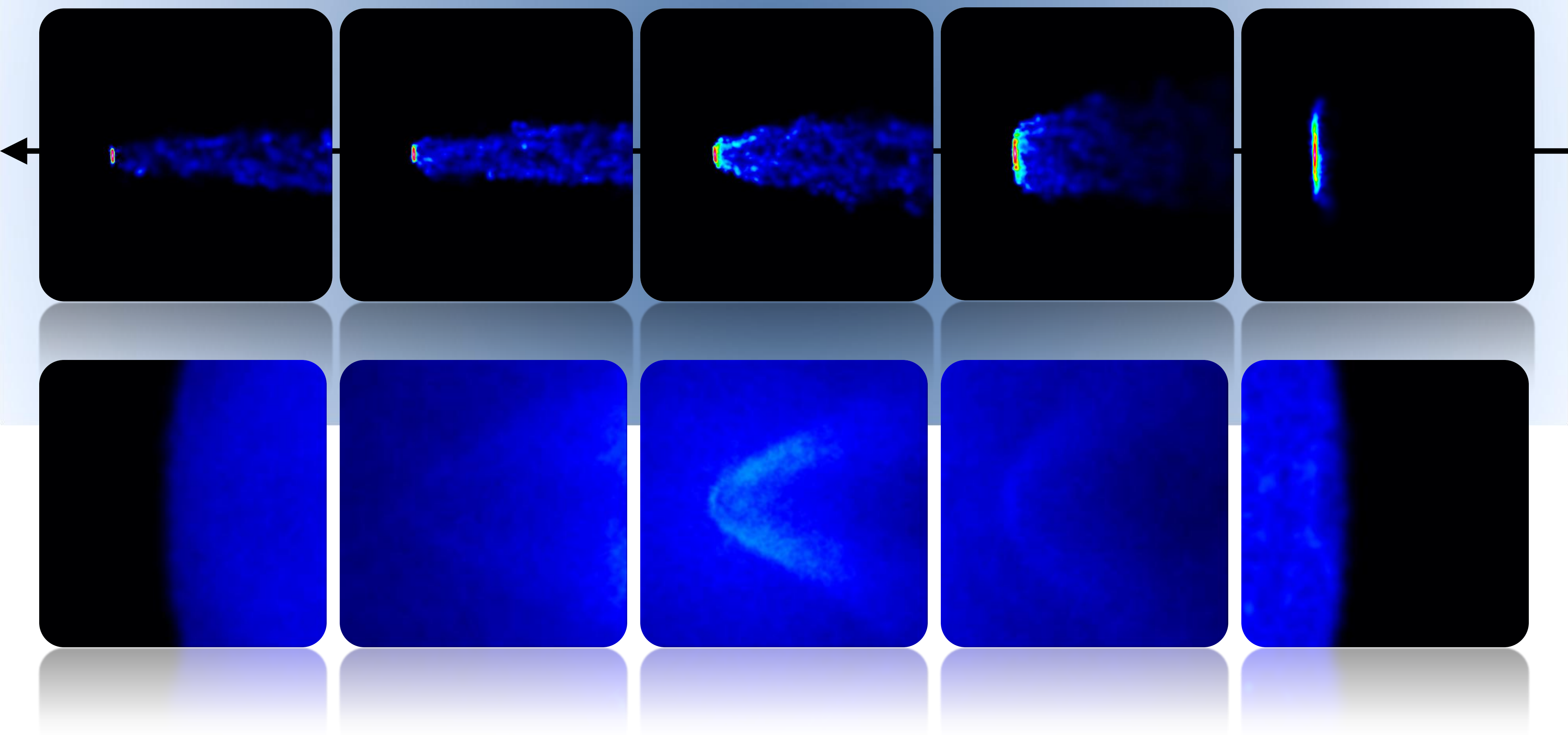
- SPH has significant problems with contact discontinuities where the density jump is very large

- basic idea: to estimate smoothing length of either ICM or ISM particles separately from neighbors of the corresponding phase
  - pros: reasonable number of particles, full coverage of the disk, ICM particles not shrinking to ISM sizes, ...
  - cons: ISM particles lack pressure gradients, low spatial resolution in ICM, possible slight overestimation of the stripping effect



Process of stripping

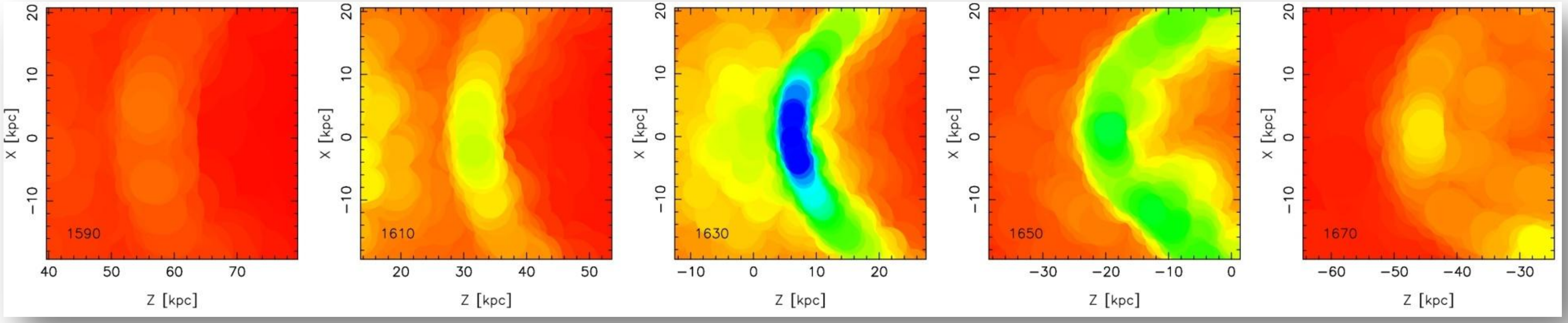
effects on ISM & ICM



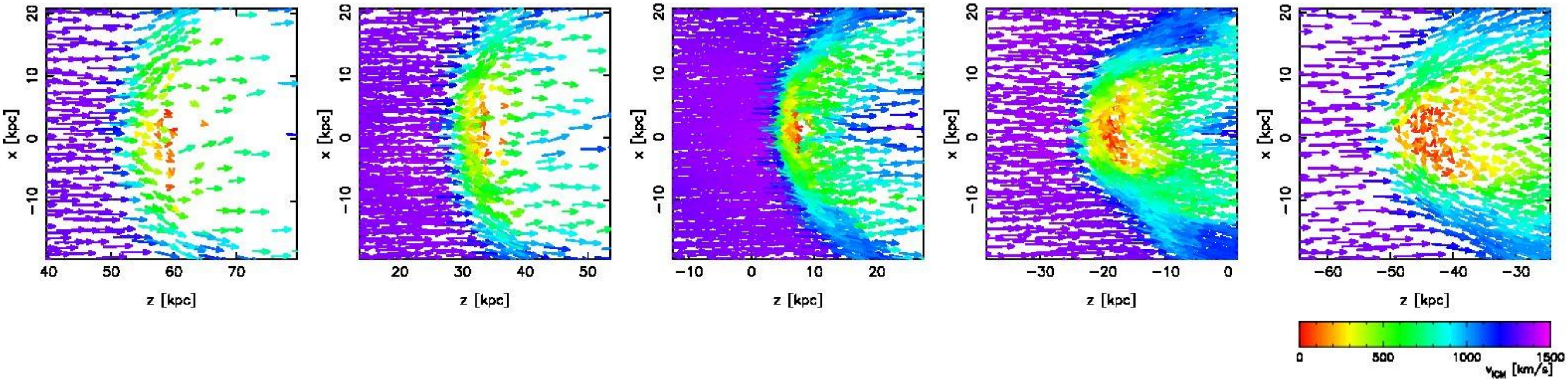
Process of stripping

effects on ICM

- Bow-shocks form in the ICM (face-on)



- Velocity vectors of the ICM particles

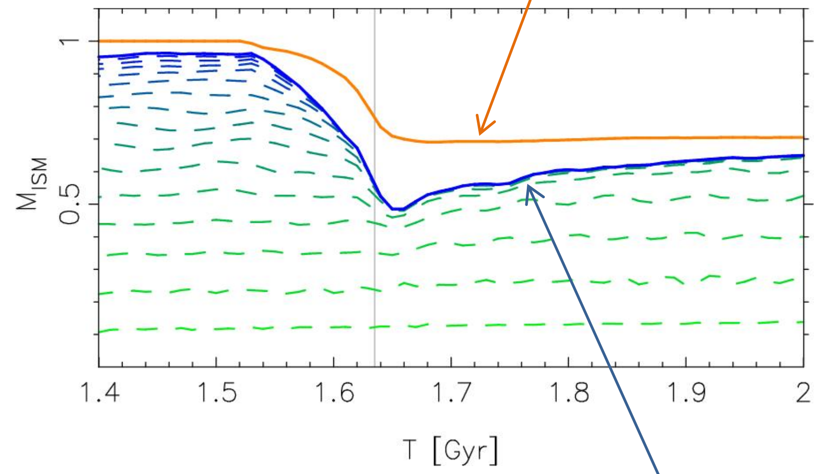


Consequences of stripping

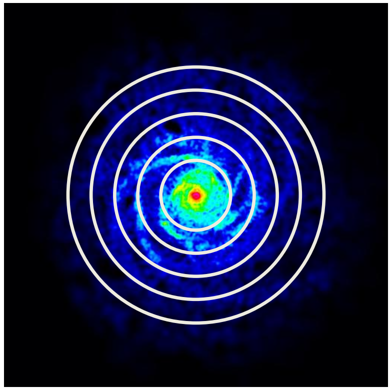
effects on ISM

- A large fraction of galaxy's ISM can be removed on time scales of 100 Myr
  - In our standard cluster model, about 30 % of the ISM is stripped from face-on galaxy
  - ICM enrichment
- a tail of stripped material is formed
- Compression of the windward edge of the disk
- Re-accretion of the stripped material
  - In the standard cluster model about 20 % of the ISM is re-accreted
- In the edge-on case the disk gets an asymmetric shape
- The tail winds up around the edge-on disk
- Clumps form in the tail

Bound mass fraction



Mass fraction within $r < R_i$, $|z| < 1$kpc



Grid of simulations

stripped amount & stripping radius

- Parameter study:
  - simulations with varying $R_{c,ICM}$ and $\rho_{0,ICM}$ parameters – from large to small ICM distributions
  - and varying inclination angle *i*
  - narrow ICM distributions or with low values of density may represent ICM overdensities or debris structures left over in the cluster from recent stripping events

Table 2. List of performed simulations – results. From left to right … simulations with decreasing inclination, stripped mass fraction estimate of GG72 criterio… …stimate of GG72.

GG72 not correct,

$p_{ram,max}$ is not *the* parameter

run	$M_{strip}^{90°}$ (%)	$M_{strip}^{70°}$ (%)	$M_{strip}^{45°}$ (%)	$M_{strip}^{20°}$ (%)	$M_{strip}^{0°}$ (%)	M_{strip}^{GG72} (%)	$r_{strip}^{90°}$ (kpc)	$r_{strip}^{70°}$ (kpc)	$r_{strip}^{45°}$ (kpc)	$r_{strip}^{20°}$ (kpc)	$r_{strip}^{0°}$ (kpc)	r_{strip}^{GG72} (kpc)
$R4\rho8$	93	91	89	86	70	93	1.5	0.9	1.4	0.8	1.2	1.5
$R4\rho4$	85	85	80	72	52	83	1.6	1.8	1.6	1.6	2.0	2.4
$R4\rho1$	59	56	48	34	24	57	2.5	2.6	2.6	3.7	5.1	4.5
$R4\rho0$	26	25	18	10	6	36	6.0	6.2	6.5	6.5	7.1	6.8
$R1\rho8$	79	77	70	54	36	92	1.5	1.6	1.6	2.2	2.7	1.6
$R1\rho4$	63	61	50	30	19	81	2.1	2.5	3.1	3.2	4.0	2.5
$R1\rho1$	30	27	20	10	5	57	5.5	6.3	6.5	7.2	8.0	4.5
$R1\rho0$	9	8	6	2	1	36	8.6	9.0	9.3	9.9	10.3	6.8
$R0\rho8$	37	35	27	13	7	92	5.5	4.6	6.1	6.5	7.2	1.6
$R0\rho4$	22	21	14	6	3	81	6.8	7.7	8.0	9.2	9.2	2.5
$R0\rho1$	5	5	3	1	1	57	9.8	9.9	10.2	10.6	10.7	4.5
$R0\rho0$	1	1	0	0	0	36	11.1	11.1	11.2	11.4	11.5	6.8

Role of inclination

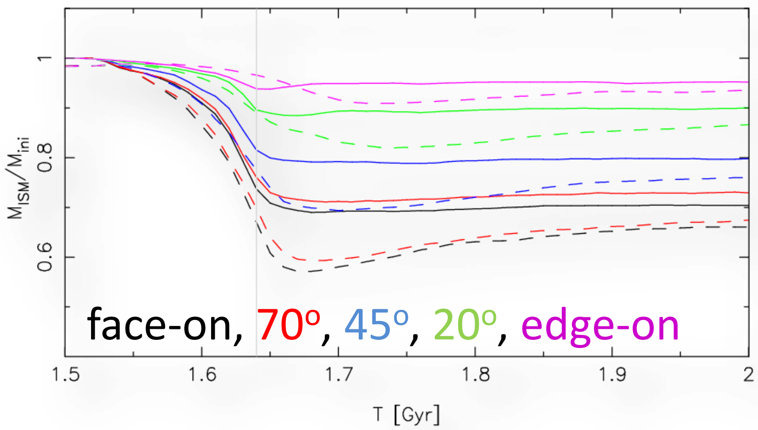
in our standard cluster

- galaxy rotation plays a role:
  - hydrodynamical shielding is more important in edge-on
  - asymmetry of the disk
  - paradox of inclined stripping (co-rotating disk side is more easily stripped although experiencing a lower ram pressure)
  - wound tail
- ISM column density seen by the wind is higher

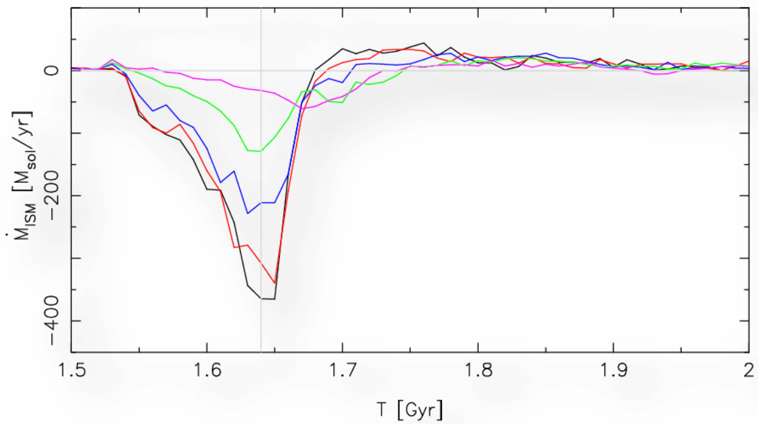
⇒ stripping declines for inclinations decreasing towards edge-on

- ”stripping rate”, i.e. the flow of the ISM through the boundary of the evaluation zone, exceeds from face-on galaxy almost 400 $M_\odot yr^{-1}$, and its peak value decreases towards ~ 50 $M_\odot yr^{-1}$ in the edge-on case

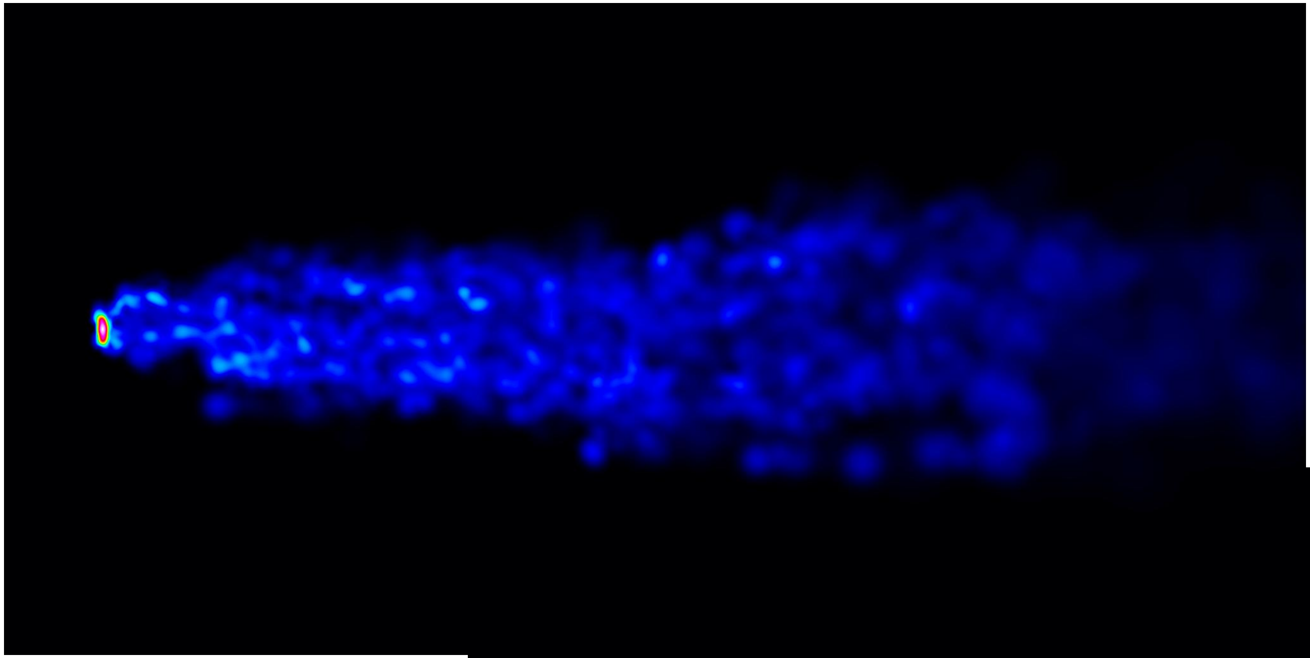
Stripped mass fraction:

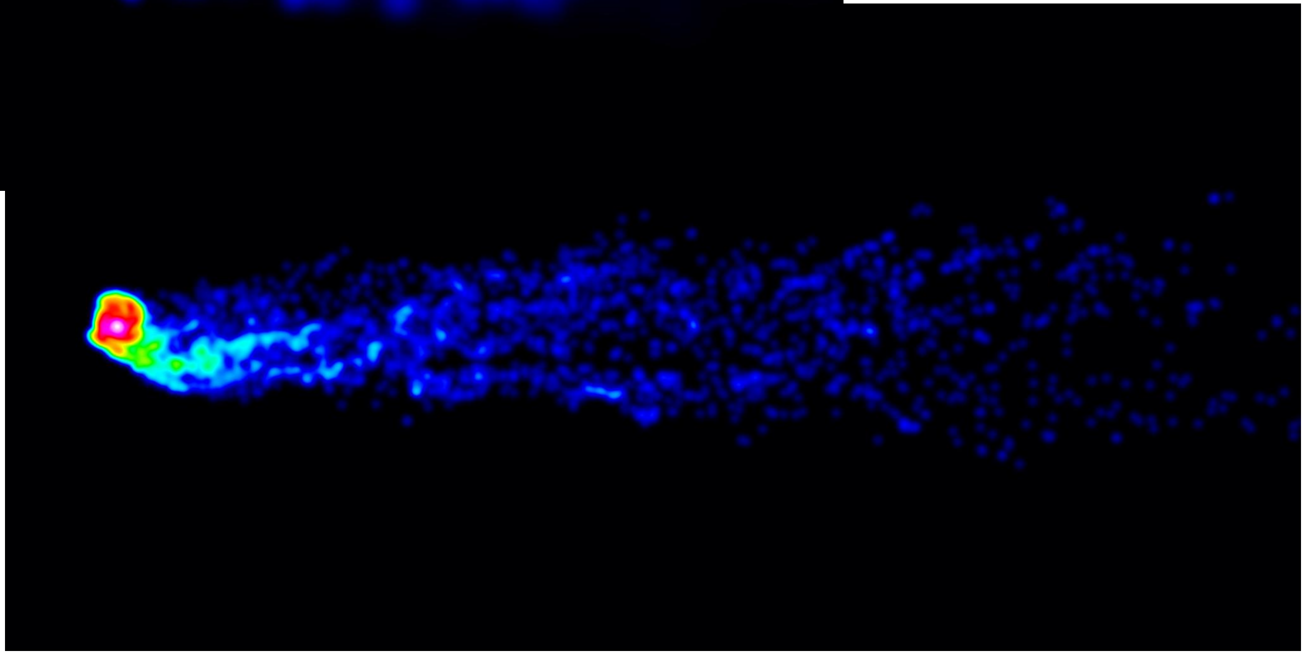


Striping/re-accretion rate:



Face-on vs. edge-on

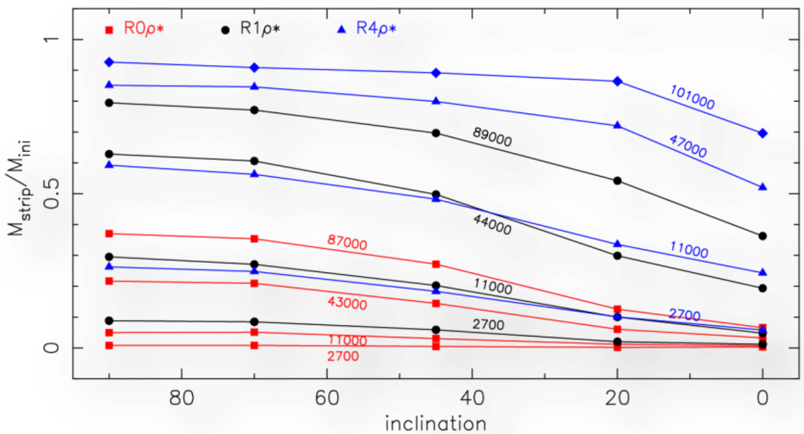


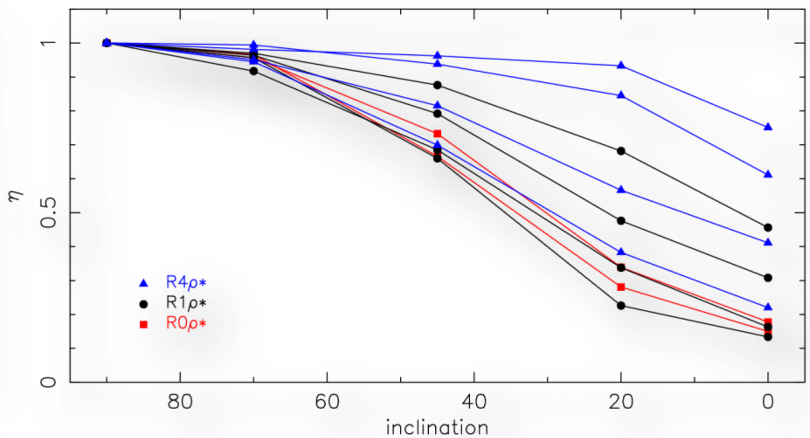


Stripped amount

& stripping efficiency

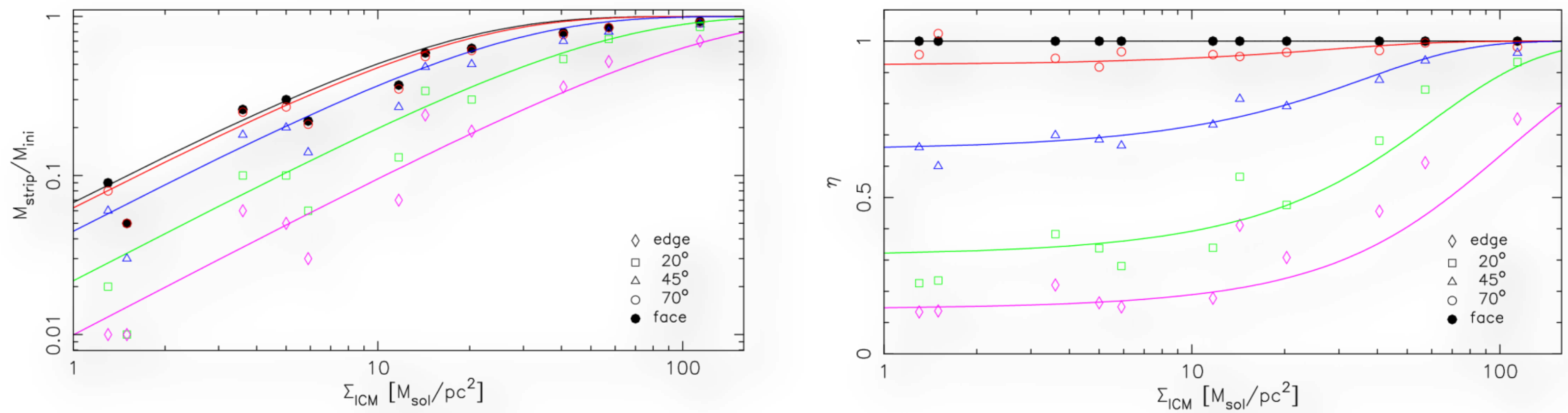
- Stripped amount: $M_{strip} = M_{fin} - M_{ini}$
  - almost no difference between face-on and 70°
  - for large pressure peaks, stripping amount is almost independent of inclination
  - dependence on inclination is more pronounced for smaller ram pressure peaks
  - runs with the same value of $R_{c,ICM} \cdot \rho_{0,ICM}$ quantity show close profiles of the $M_{strip}(i)$ curves
- Stripping efficiency: $\eta(i) = M_{strip,i} / M_{strip,face\text{-}on}$
  - η characterizes the relative strength of a given ram pressure profile to strip ISM from an inclined galaxy with respect to face-on case
  - stripping efficiency always declines for inclinations decreasing towards edge-on
  - both wider and higher ram pressure peaks yield higher efficiencies





The parameter is Σ_{ICM}

Amount of encountered ICM along orbit



- with increasing <u>amount of encountered ICM</u> (Σ_{ICM}) the stripped mass fraction and the efficiency increase
- for high Σ_{ICM}, these relations saturate towards complete stripping
- for lower Σ_{ICM}, edge-on stripping is reduced with respect to face-on by a constant factor

⇒ Σ_{ICM} is the key parameter determining the stripping outcome

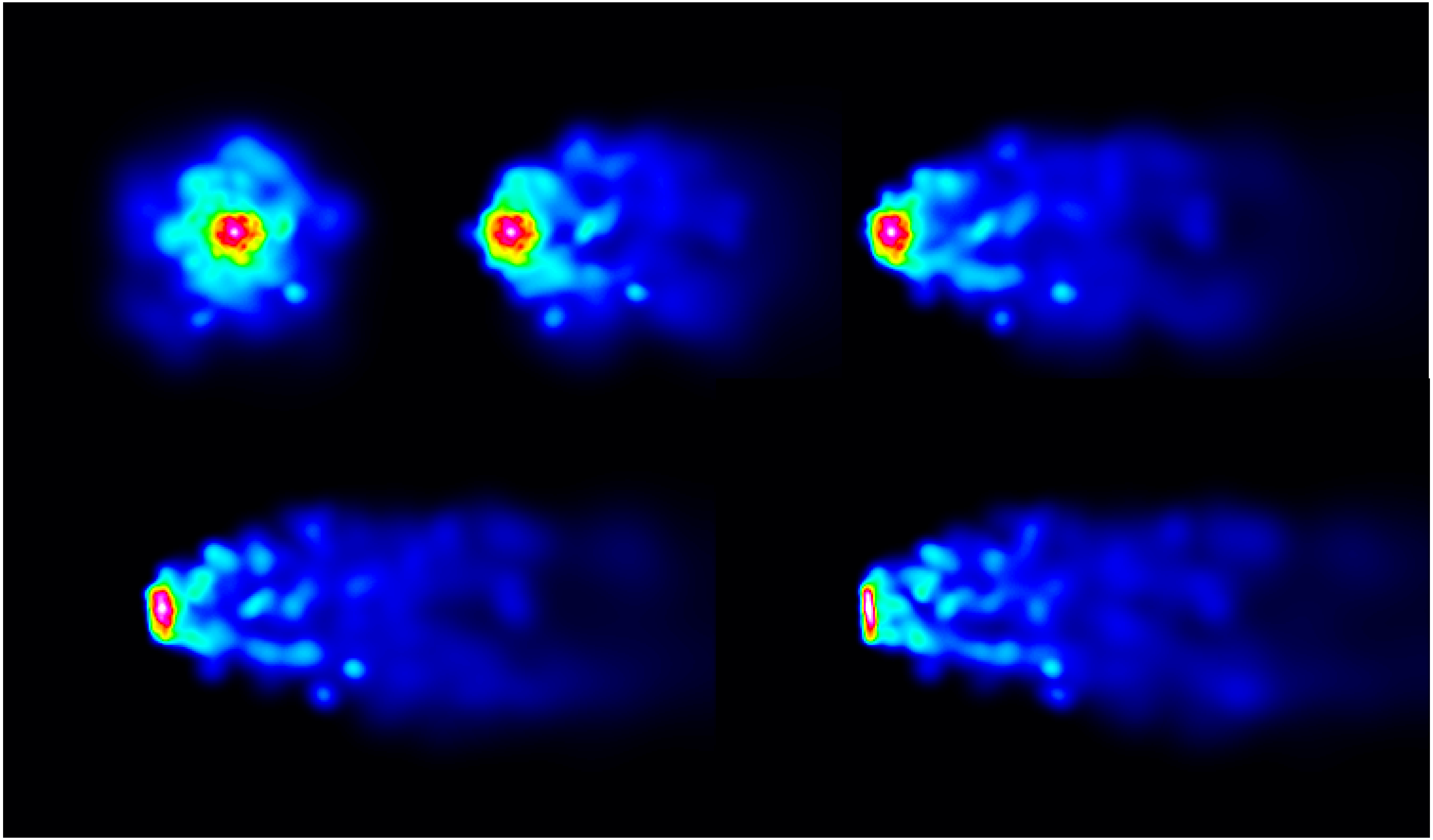
⇒ it is much more important than the maximum value of the ram pressure experienced along the orbit (Gunn & Gott 1972 criterion)

$$\frac{M_{\rm strip}}{M_{\rm ini}} = 1 - \exp\left[-0.01\,\Sigma_{\rm ICM}(1 + 6\sin^{1.5} i)\right]$$

$$\upsilon_{\rm after} = \langle \upsilon \rangle_{\rho_{\rm ICM}} \frac{\Sigma_{\rm ICM}}{\Sigma_{\rm ISM}}; \quad \upsilon_{\rm after} \geq \upsilon_{\rm esc}$$

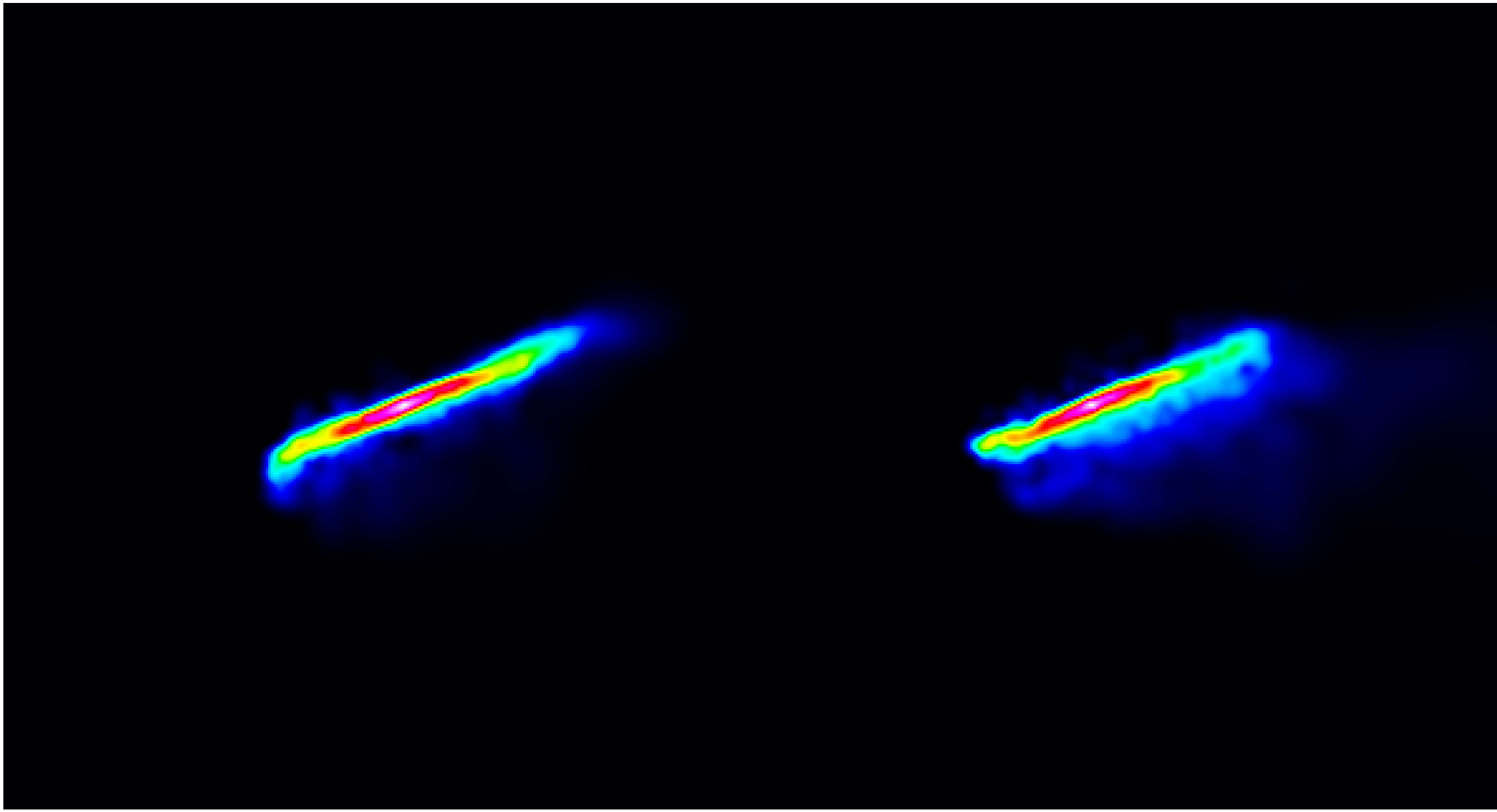
Stripping

projection effect



Up-turn

features



Atlas of model galaxies

- Our approach treats well the stripped/shifted gas in close-to-disk distances

- For our grid of simulations with different inclinations and ICM profiles,

  in combination with different l-o-s views,

  and different stages of stripping

  => create a model “VIVA” atlas – spectra and PVDs
- Look at observed galaxies in Virgo
  - Fraction of pre-peak, post-peak, peak
  - Decide on corresponding time-step in simulations

Spectra of galaxies

from our simulation grid

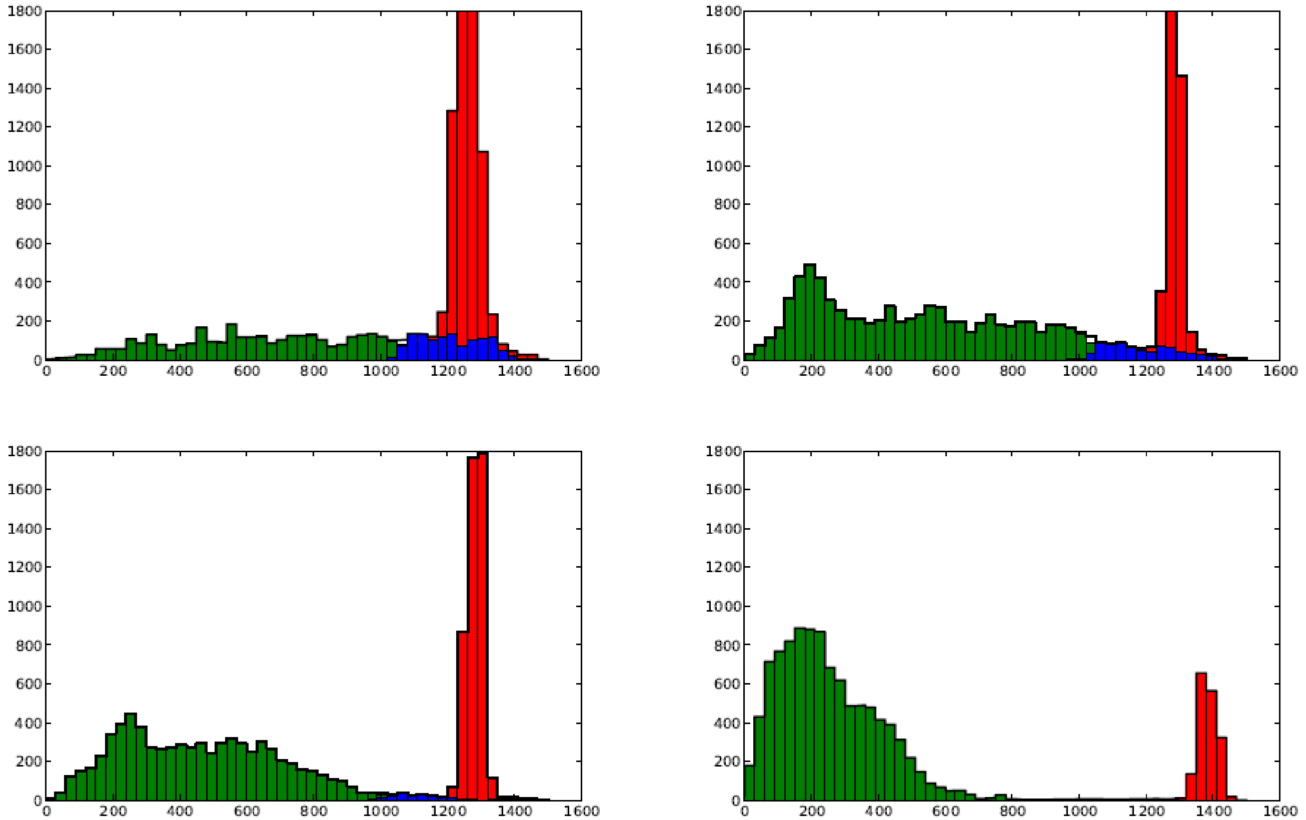
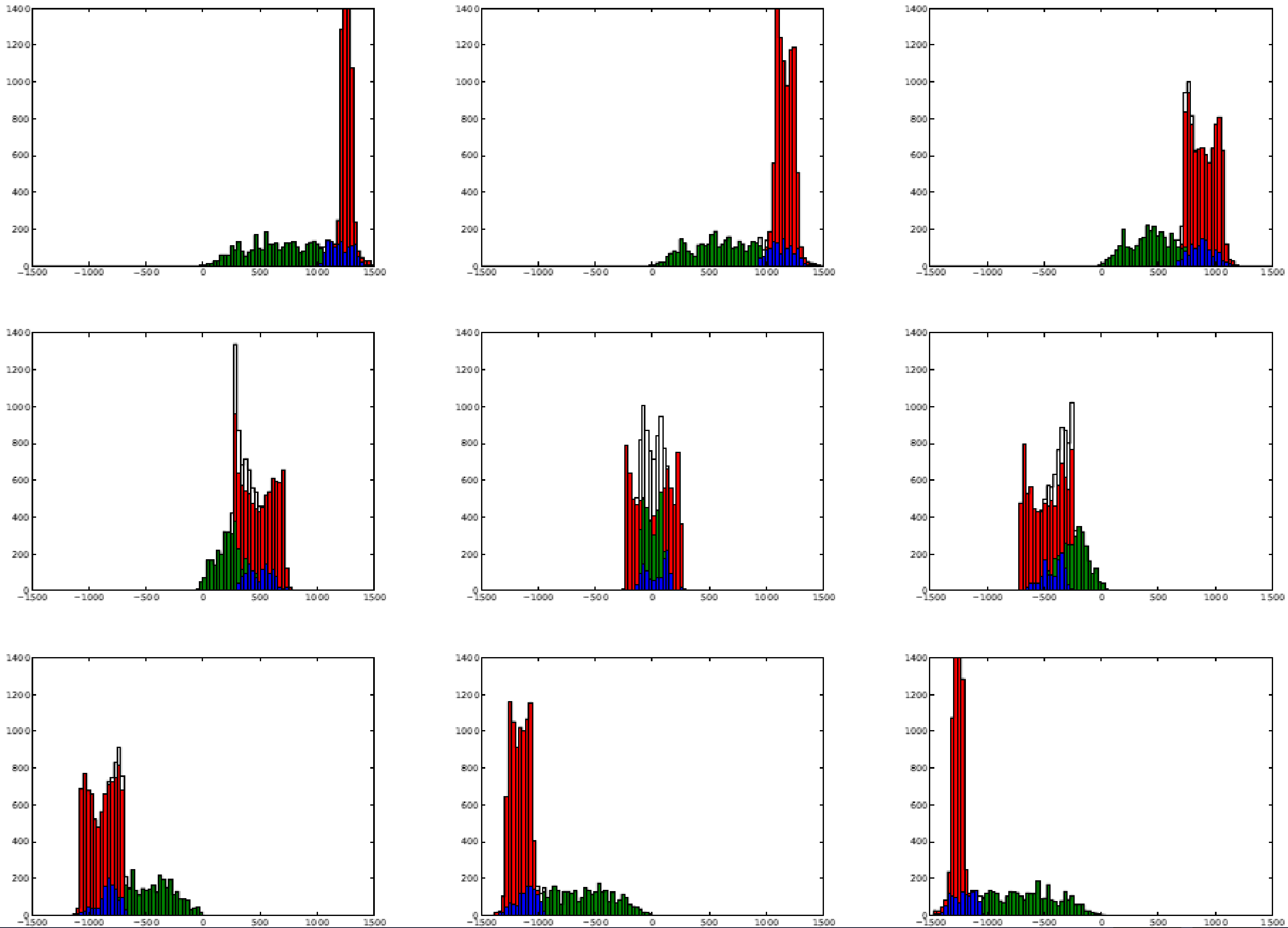


Figure 1: Velocity spectra (in km/s) of the ISM in galaxies stripped face-on in $R1\rho1$, $R1\rho4$, $R4\rho1$, and $R4\rho4$ simulations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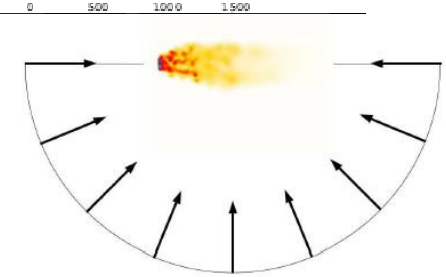

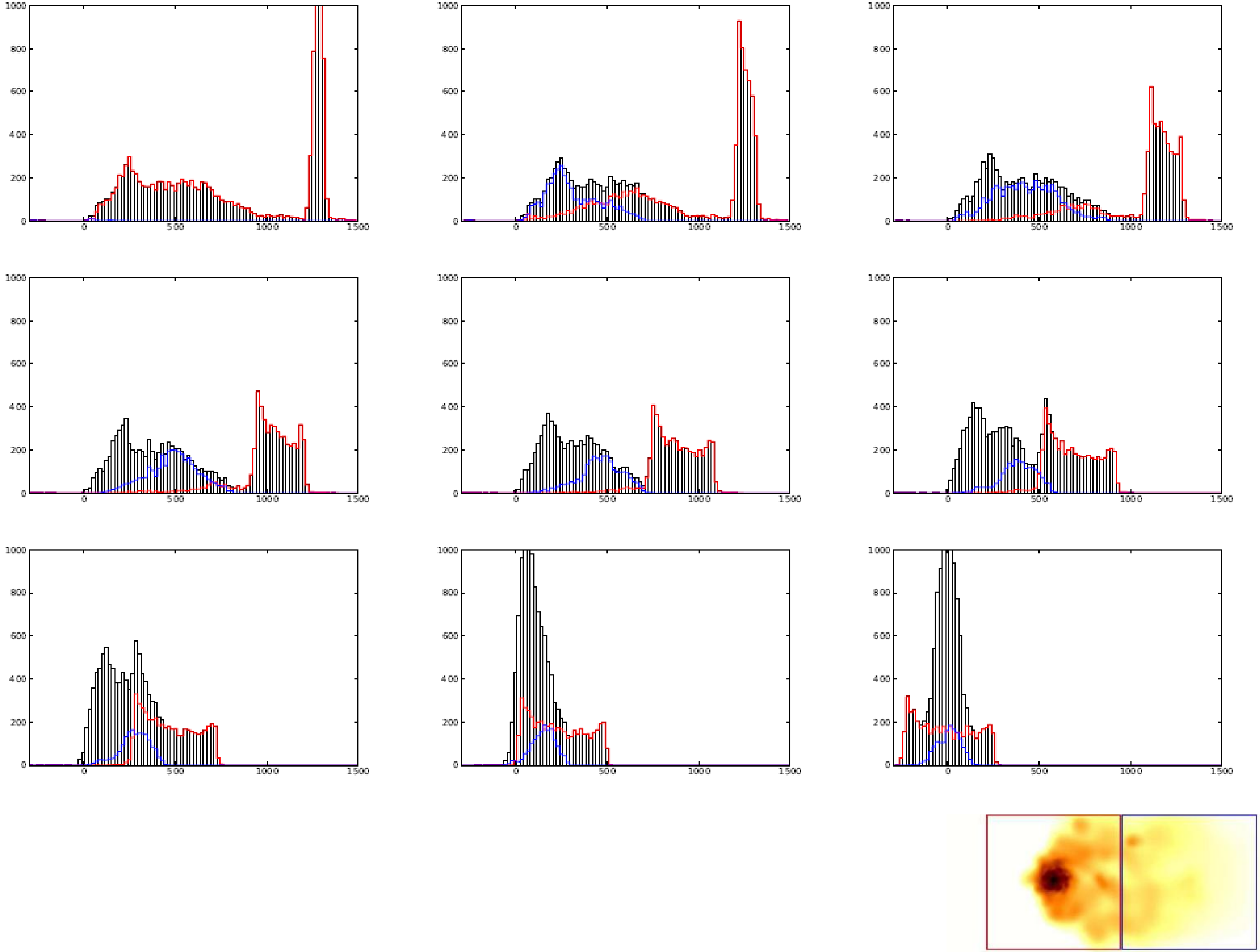

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