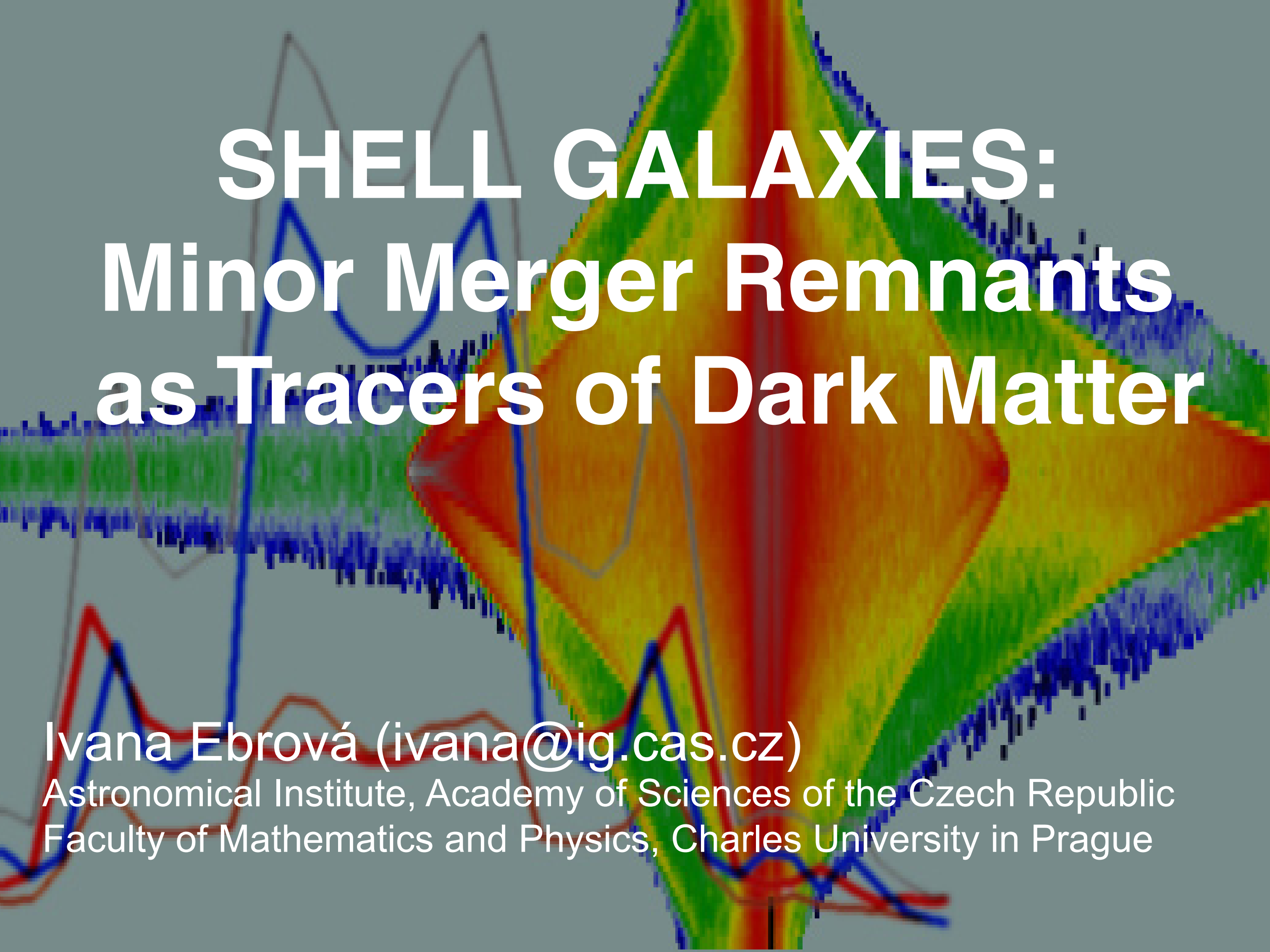

SHELL GALAXIES: Minor Merger Remnants as Tracers of Dark Matter

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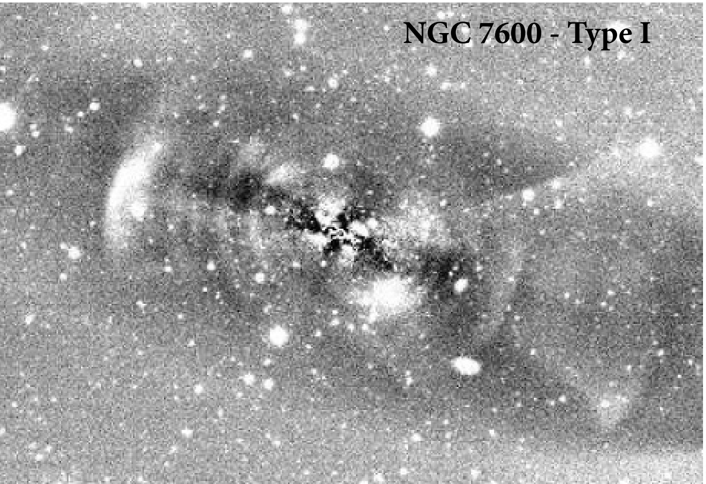
Shell Galaxies

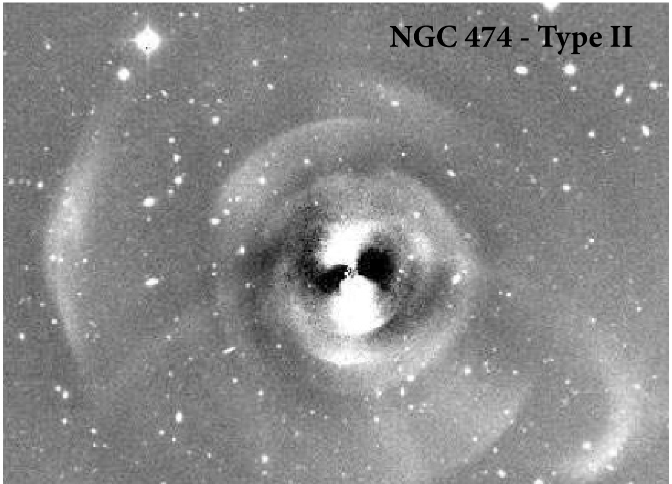
- shells – fine stellar structures which form (almost) concentric arcs which usually do not cross each other
- ~10% of E and S0 (up to 50% in regions of low density of galaxies; Malin & Carter, 1983; Schweizer, 1983; Schweizer & Ford, 1985; Colbert et al., 2001)
- from 1 to ~30 shells in a single galaxy (often less than 4; Malin & Carter, 1983)
- low contrast (0.1–0.2 mag)

Morphological Categories

Prieur (1990), Wilkinson et al. (1987)

- **Type I** (Cone) – interleaved in radius, well-aligned with the major axis, their separation increases with radius
- Type II (Randomly distributed arcs) – randomly distributed all around a rather circular galaxy
- Type III (Irregular) – system has more complex structure or has too few shells to be classified

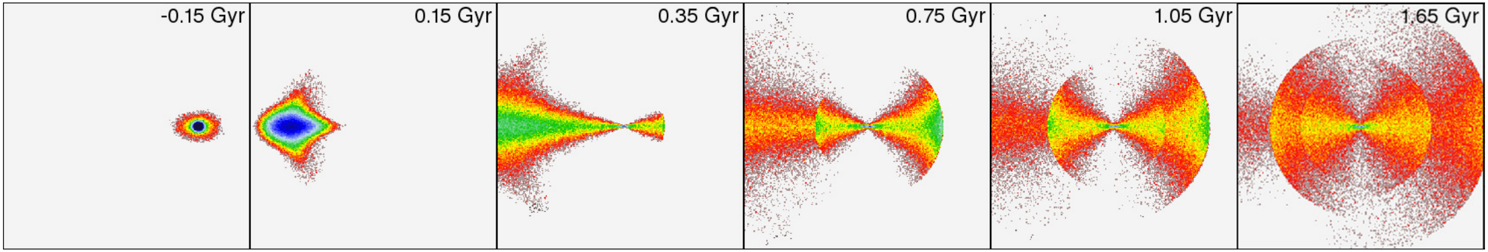




Turnbull et al. (1999)

Minor Merger Origin

- (nearly) **radial merger** of a massive (host) and a significantly less massive (satellite) galaxy developed by Quinn (1984)
- the satellite galaxy is disrupted and its stars oscillate in the potential of the host galaxy
- the stars cumulate at their turning points and form shells
- the most tightly bound stars reach their turning points first and **density waves propagate outwards**

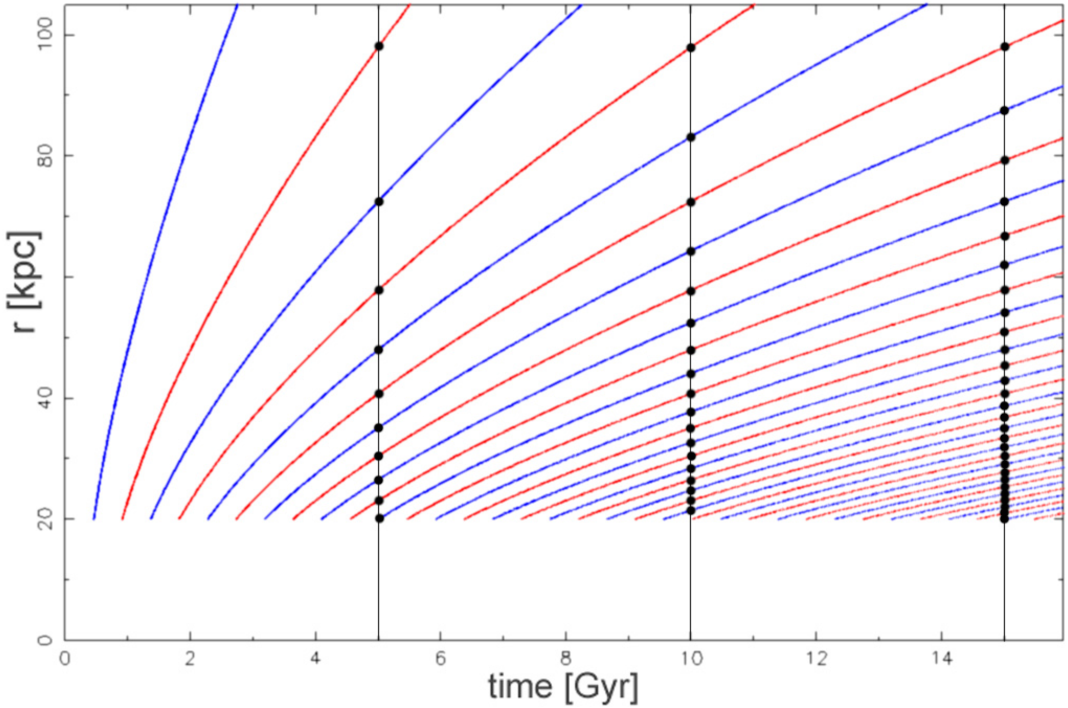


density maps, panels 300×300 kpc (only the matter of satellite displayed)

Spacing of Shells

- (in a simple case) positions of shells are determined by the potential of the host galaxy and the age of the merger

Each line shows the galactocentric distance of a shell as a function of time, blue at one side of the host galaxy, red at the other.



This could be useful...

- inferring the **age of the collision**: Canalizo et al. (2007) (quasar-merger connection?)
- reproducing the observed shape of the shell distribution with an extensive **dark matter halo**: Dupraz & Combes (1986), Hernquist & Quinn (1987)

But:

- similar radial distribution synthesised by using only dynamical friction: Dupraz & Combes (1987)
- problems with inner shells (for both DM and friction)
- shell formation is a more complicated process...

Key Ingredients

Dynamical friction

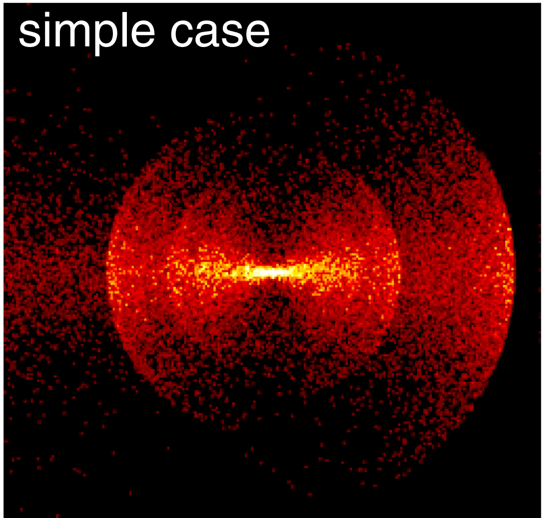
and

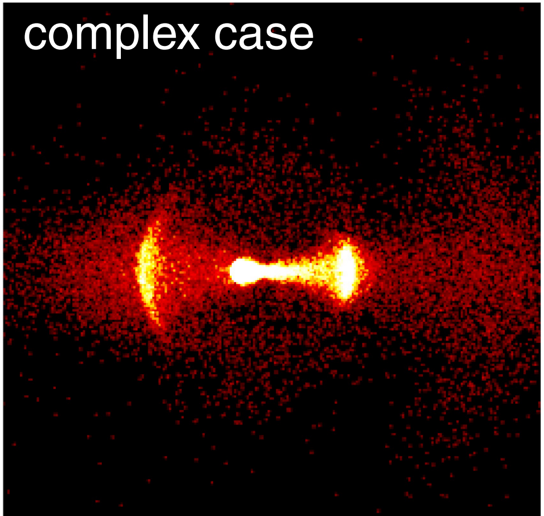
Gradual disruption

of the satellite galaxy during the merger.

Coupling of Both Effects

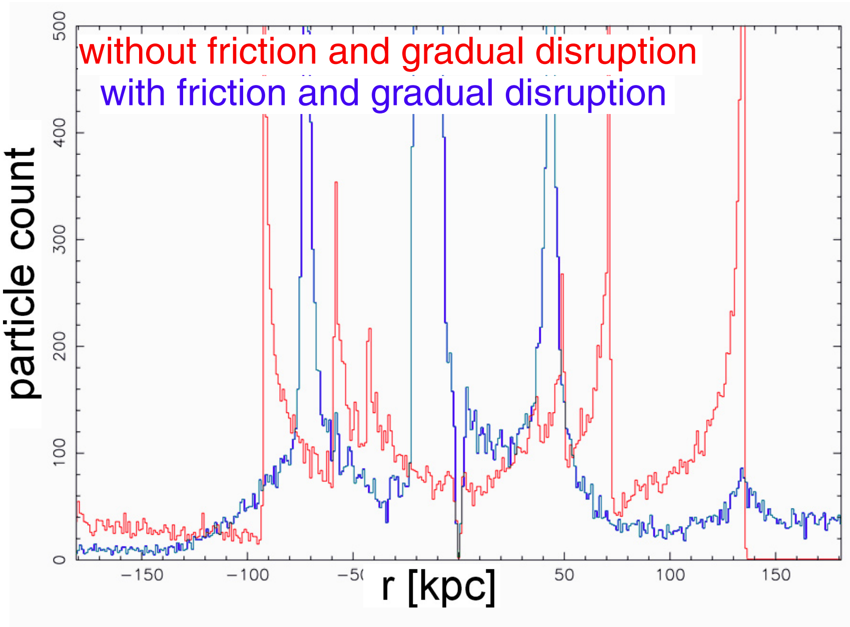
- stars are redistributed due to gradual disruption and their energy is progressively lowered due to dynamical friction
- it changes the resulting structure (results from test particles simulation)





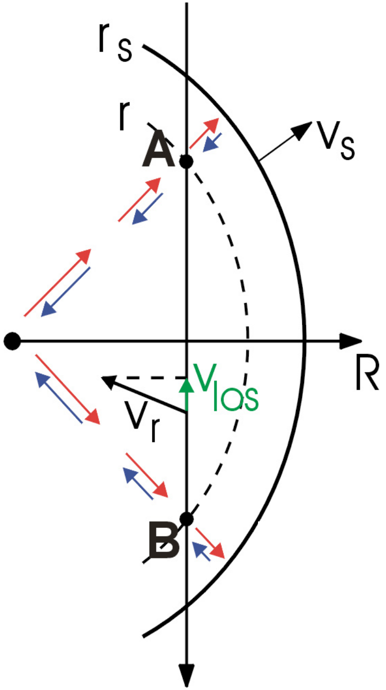
Coupling of Both Effects

- position of the outermost shell is not much affected, its brightness is drastically lowered (confirmed by self-consistent simulations, Ebrová et al., 2011a)
- following shells are shifted and new generations of shells are released during each passage of the satellite (Bartošková et al., 2011)



Conclusions I

- shells' space distribution is **not suitable for studying the host galaxy's potential** (already concluded by Dupraz & Combes, 1987)
- it is **tricky** even to try to **infer the age of the collision** using just the outermost shell (that could be observationally easily missed) ⟹ estimation of the age of merger wrong by factor of 2 or worse (Ebrová et. al., 2010)
- need of careful modeling of shell creation (host galaxy potential, dynamical friction, satellite disruption)
- or use shell kinematics, Merrifield & Kuijken (1998)

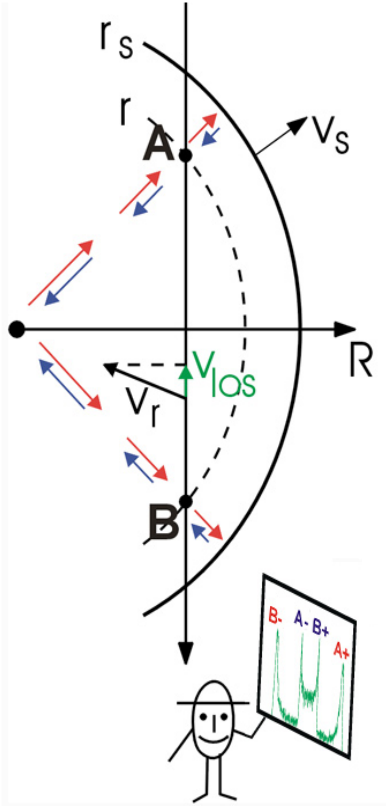


Kinematics of a Shell

- we look perpendicular to the collision axis
- the stars oscillate with velocity $v_r(r)$, but we observe only its line-of-sight (LOS) component
- combined contributions of all stars along the line-of-sight produce the observed spectrum
- stars that move inwards are returning from a point where the shell's edge was at some earlier time (lower energy)
- stars that move outwards will reach the shell's edge in the future (have higher energy/velocity at the same radius)

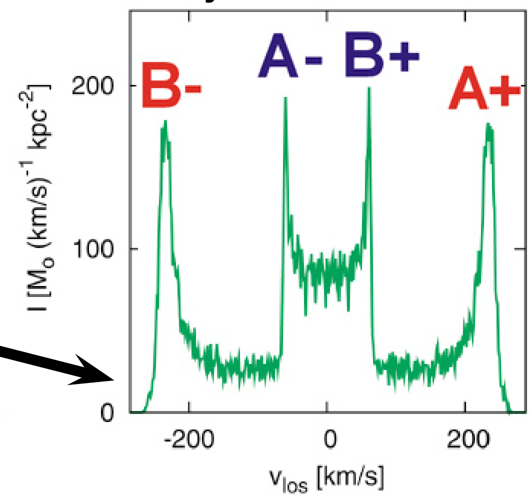
Quadruple Shape

Jílková et al. (2010), Ebrová et al. (2011b)



- max. contribution to the LOS velocity distribution (LOSVD) comes from two points A & B (Merrifield & Kuijken, 1998)
- inward-moving stars move towards Mr. Eggy in the more distant point A, away from him in the closer point B
- stars moving outwards conversely

⟹ symmetric quadruple shape of LOSVD (of a single spectral line)



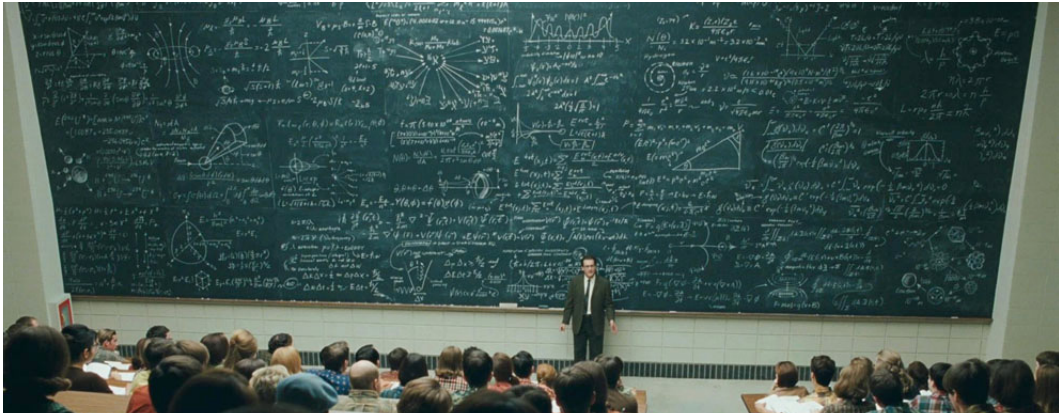
From Shells to Potential

- Merrifield & Kuijken (1998, hereafter MK98):
  - assumed a **static shell** ⟹ double-peaked LOSVD
  - positions of peaks at two projected radii ⟹ circular frequency at shell's radius
- but LOSVD is quadruple-peaked (Jílková et al., 2010; Ebrová et al., 2011b), so MK98 method is **not applicable**
- for a **moving shell** the situation is much more complicated
- we managed to connect the positions of peaks and the potential of the host galaxy

From Shells to Potential

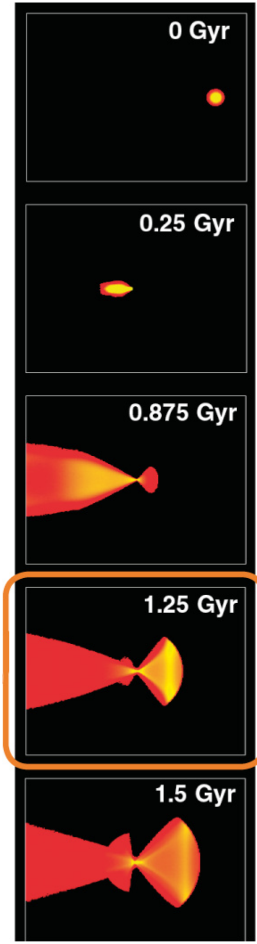
cumulative mass at the shell’s radius & phase velocity of the shell

our approximative equations...



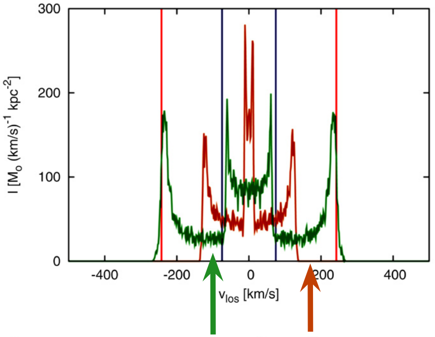
the positions of the peaks in the LOSVD

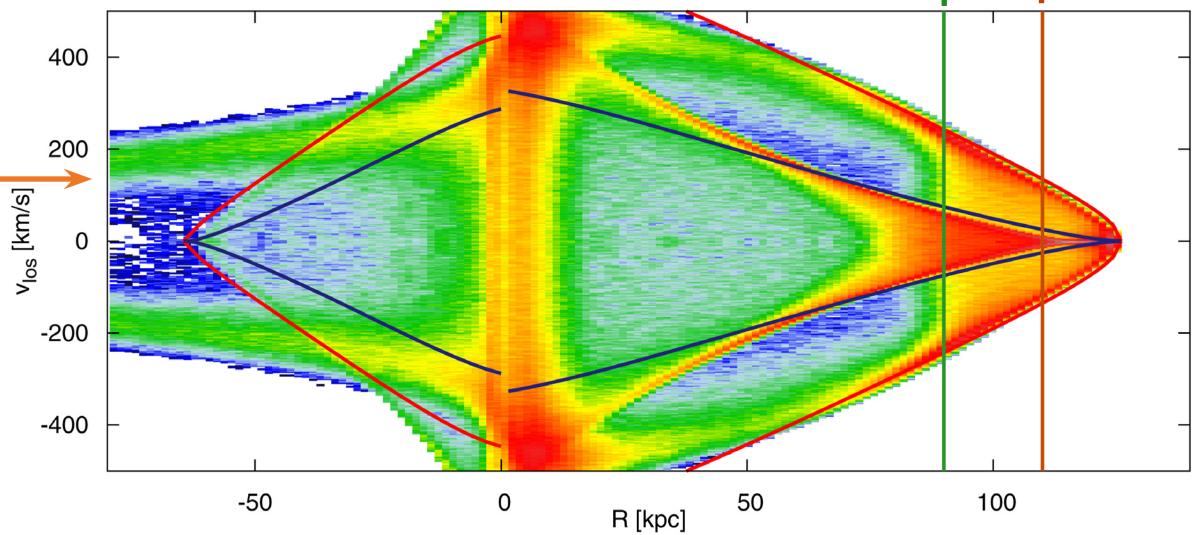
Test-Particle Simulation



LOSVD density map of a simulated shell galaxy

(Only stars of the satellite are taken into account. The host galaxy: luminous matter - de Vaucouleurs' + NFW dark halo.)



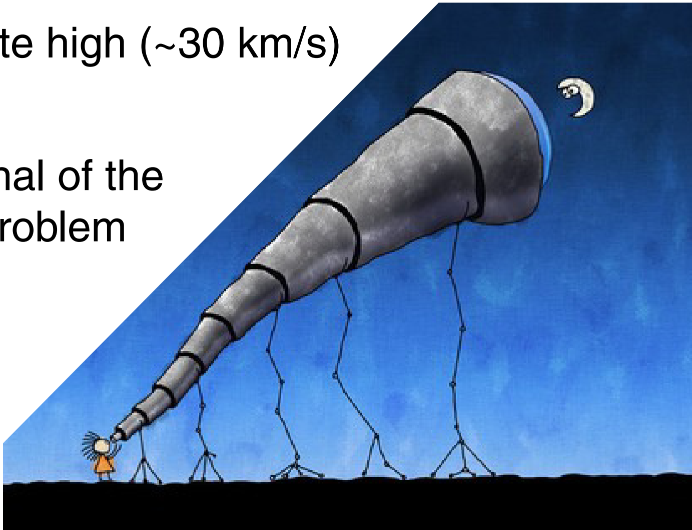


Conclusions II

- profile of a spectral line near the shell‘s edge is **quadruple-peaked** (for the radial merger model)
- potentially useful and independent method to measure the gravitational potential of elliptical galaxies on 10–100 kpc scales. But:

- the required spectral resolution is quite high (~30 km/s)
- the contrast of shells is low
- the signal is contaminated by the signal of the underlying host galaxy (not such a problem at higher galactocentric distances)

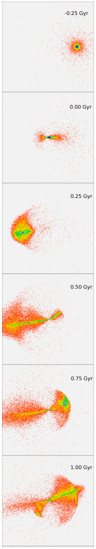
- **we need a bigger telescope**

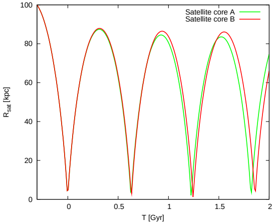


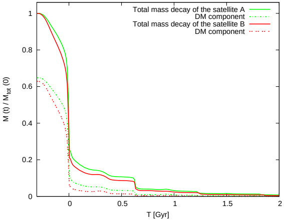
poster SPS5-1:

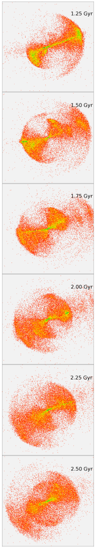
N-body simulations of shell galaxies: cannibalized dwarfs with dark matter halos

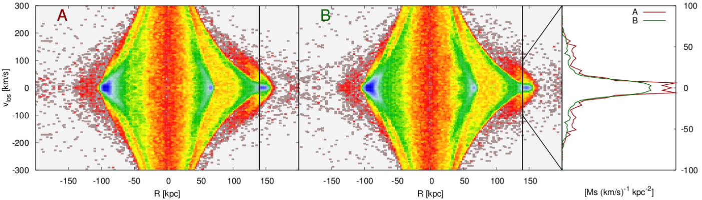
K. Bartošková et al.











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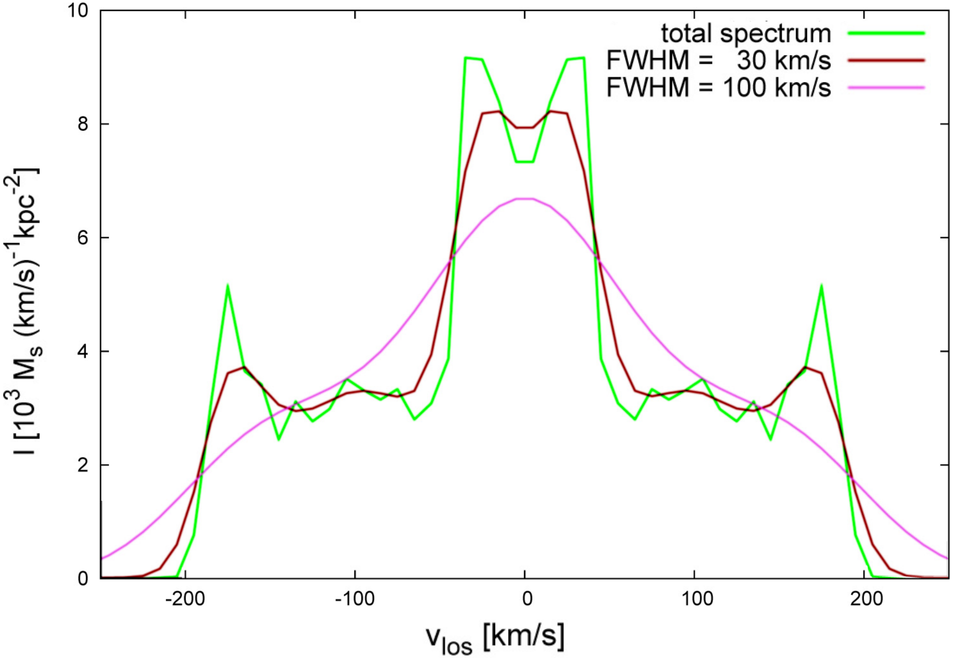
Extra Slide I

convolution of the simulated profile with Gaussians of different FWHM representing the instrumental dispersions



Extra Slide II

phase velocity of the shell in a potential w/ and w/o dark halo

de Vauccouleurs:

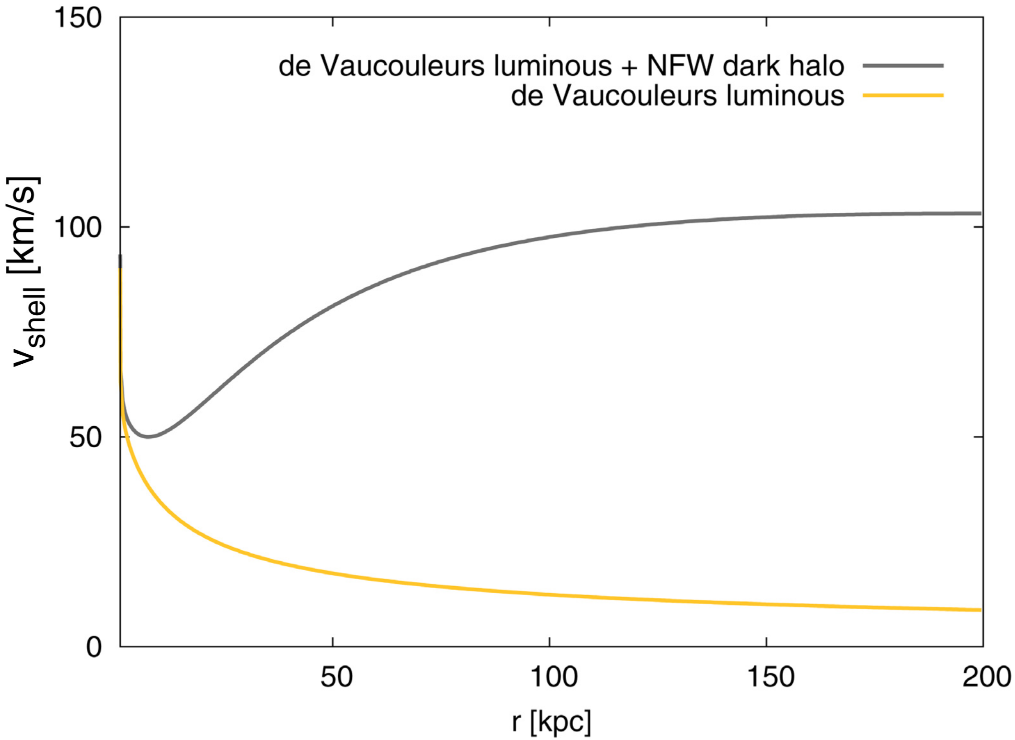
$b = 5.0$ kpc

$m = 2.e+11\ M_{sun}$

NFW halo:

$r_{NFW} = 210.0$ kpc

$\rho_0 = 140.0$



Extra Slide III

LOSVD density map from the slide 16 with scale bar