Proper Motions at Gpc Distances via the Moving Cluster Effect

Monthly Notices of the Royal Astronomical Society
450, 3, 3155–3168 (2015)

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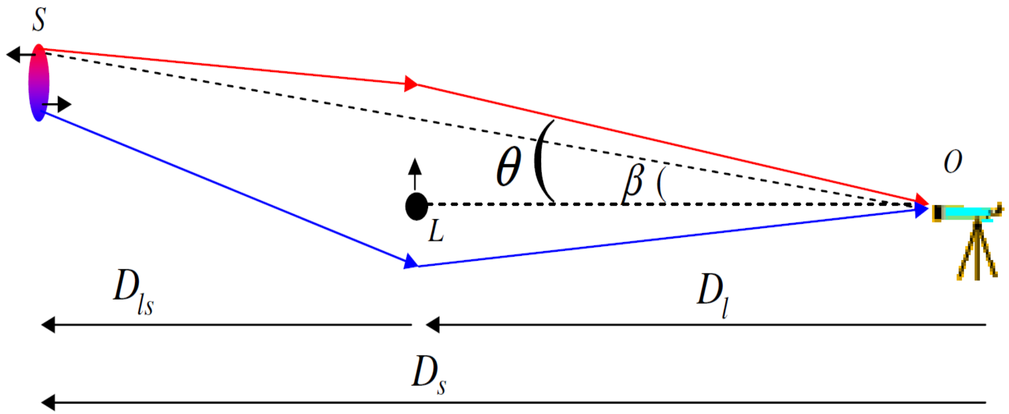
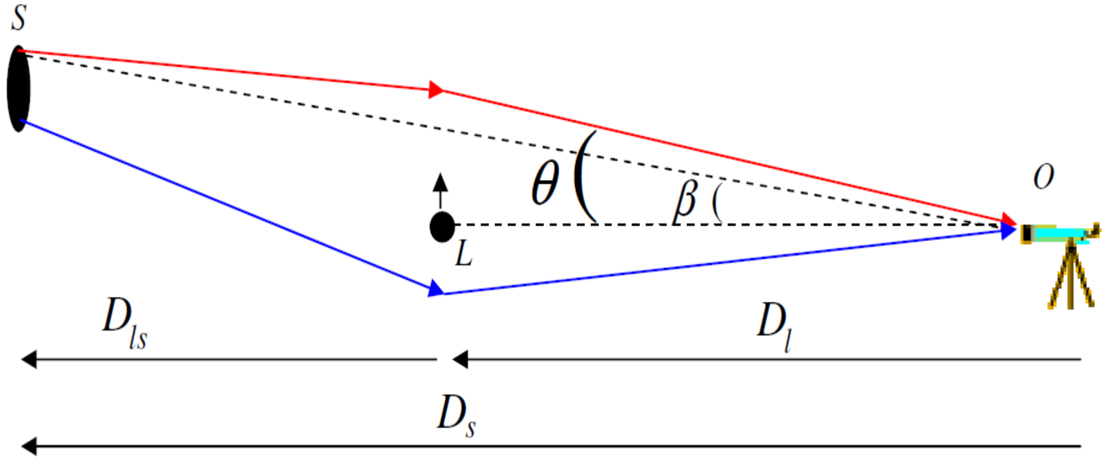
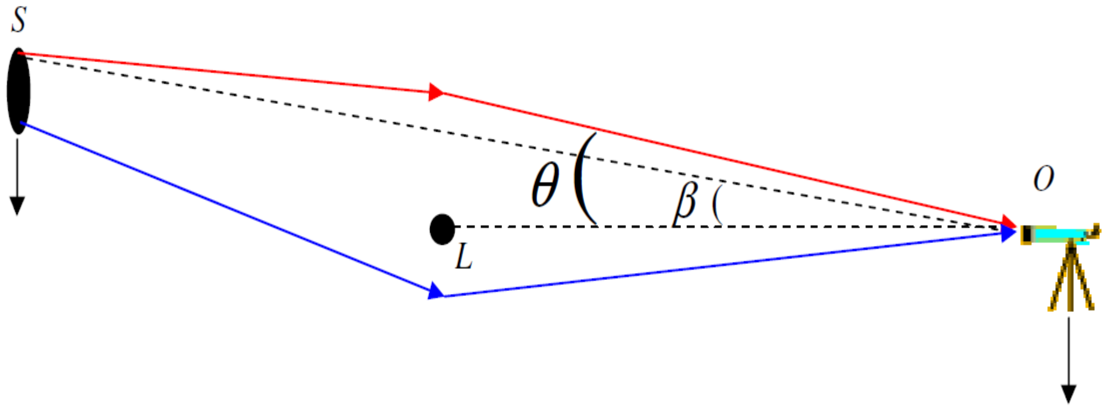
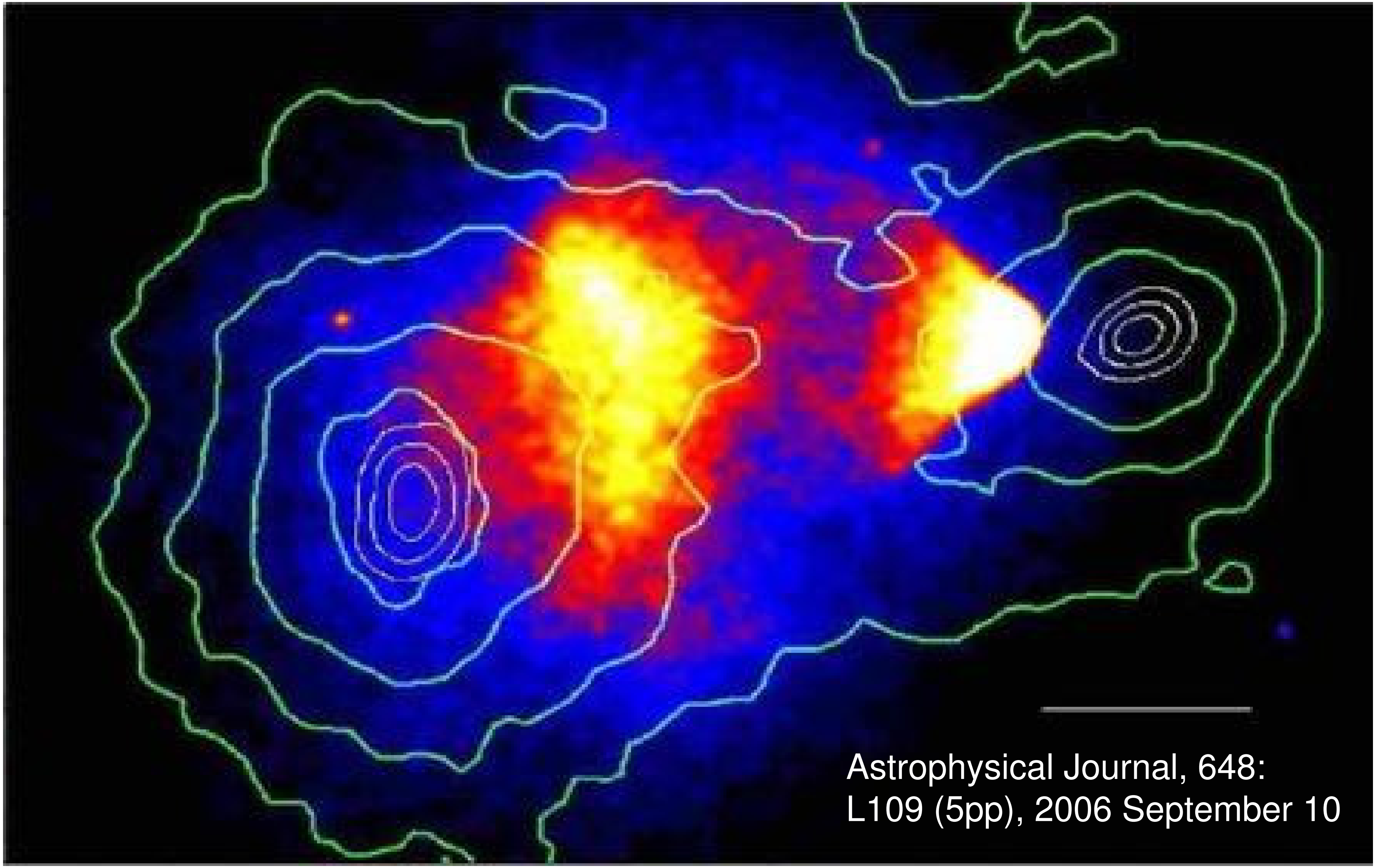






Motivation: The Bullet Cluster



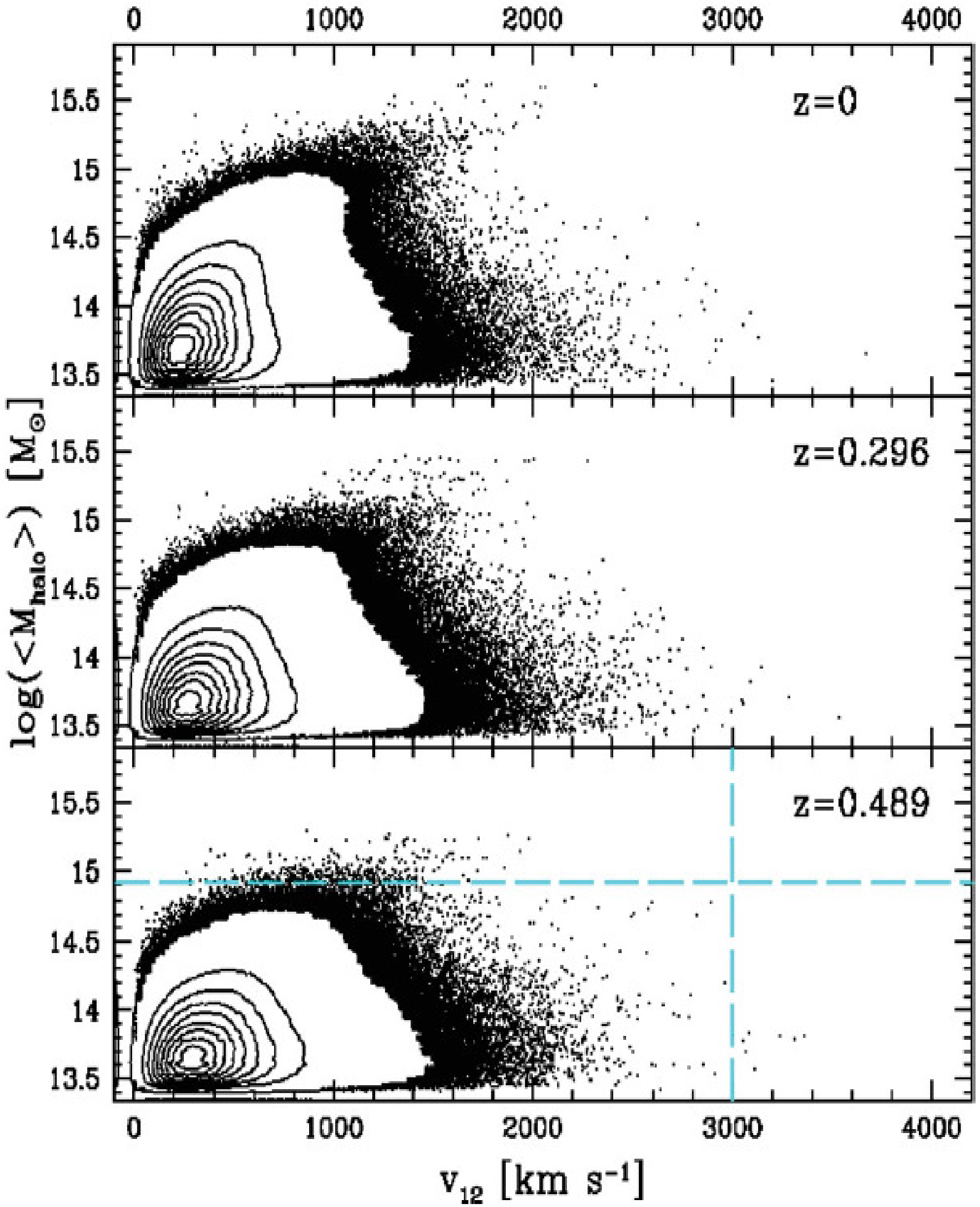
Collision Speed Too High For ΛCDM?

- Simulations of interaction can give an idea of collision speed
- This much exceeds the radial velocity difference

➢ Collision mostly in plane of sky

- Assuming hydrodynamic simulations correct, collision speed ~3000 km/s (Mastropietro & Burkert, MNRAS, 389, 967)
- This is very unlikely in ΛCDM, with $P \approx 10^{-9}$ (Lee & Komatsu, ApJ, 718 60). Similar conclusion reached by Thompson & Nagamine (MNRAS, 419, 3560).

Collision Speed Distribution



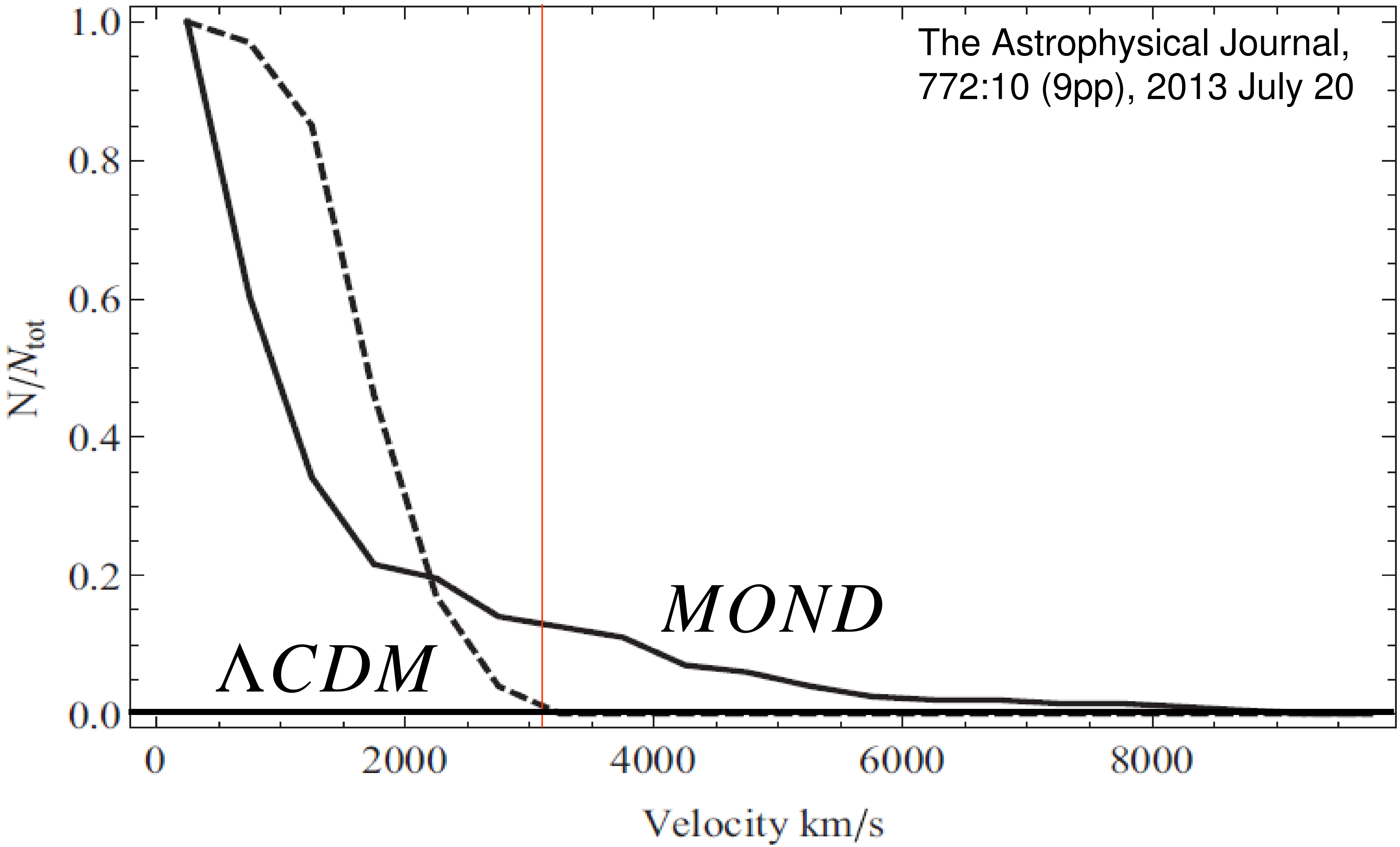
Thompson & Nagamine (MNRAS, 419, 3560)

- Bullet Cluster observed at z = 0.296, but components needed to have existed earlier.

➢ Nothing with higher mass and faster collision speed, so some tension with ΛCDM

- This could be a sign of modified gravity…

Model Comparison



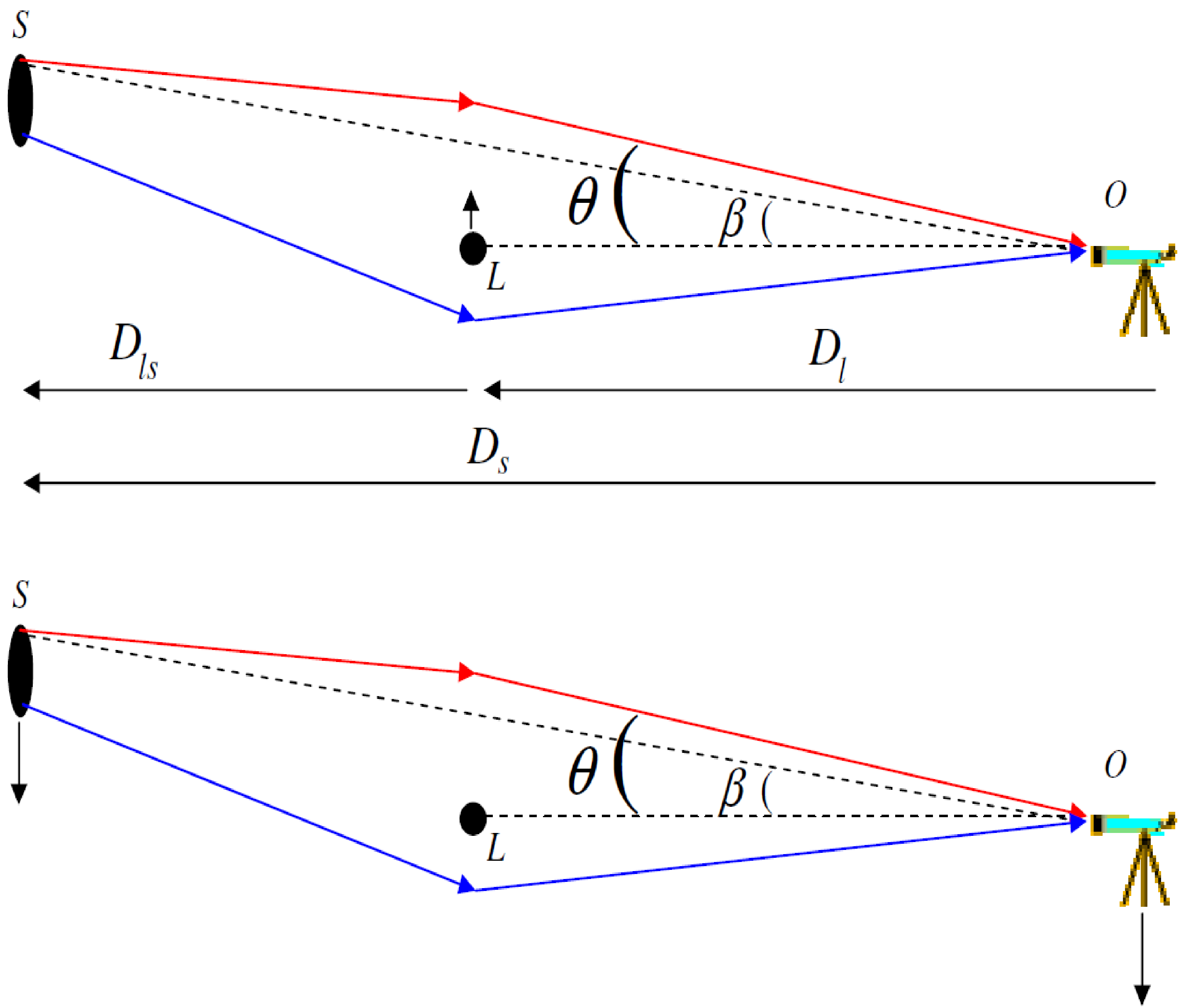
How reliable is the speed?

- Collision speed not directly measured (no proper motions), naturally!
- Hydrodynamic simulations are complicated and hampered by imperfect information about the actual system

➢ Is there a way to measure velocities of objects orthogonal to the line of sight at cosmological distances?

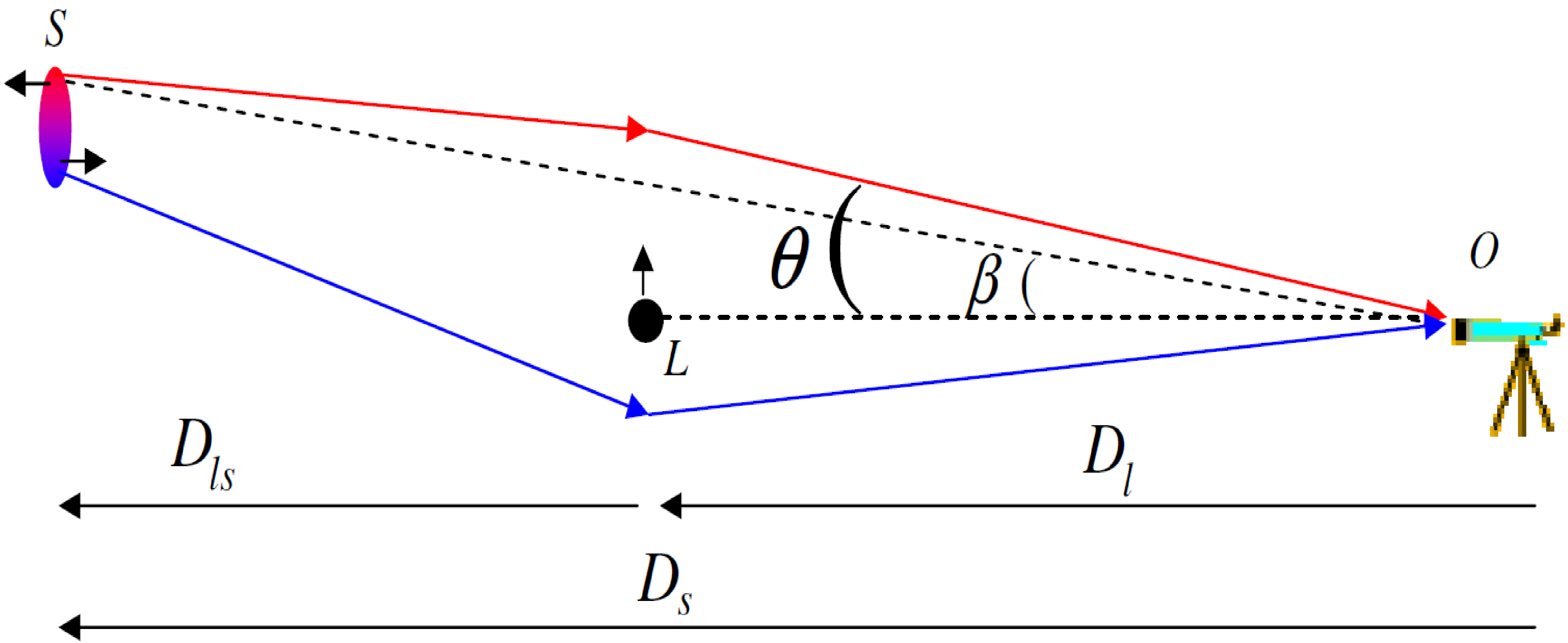
- Could be applied to other colliding clusters such as El Gordo at z = 0.87 (Molnar & Broadhurst, ApJ, v.800, #1 , 37)

The Moving Cluster Effect (MCE)



- Suggested in 1983 by Birkinshaw & Gull (Nature, 302, 315) and also Molnar et. al. (ApJ, 774, 70)
- Relies on time-dependence of the gravitational field to alter photon energies
- Effect different for photons on different sides of the lens
- $\delta V_r \equiv V_1 - V_2 = -\vec{v}_t \cdot (\vec{\alpha}_1 - \vec{\alpha}_2)$
- Magnitude ~1 km/s

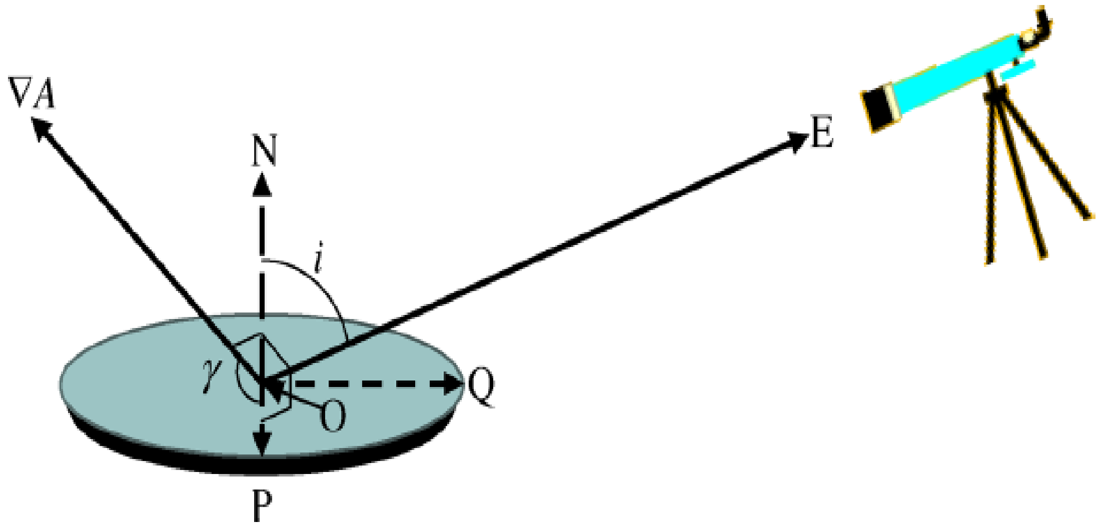
The Differential Magnification Effect (DME)



- Suppose the source is a rotating disk galaxy, with a redshift gradient
- Image will be unresolved (all photons probably need to be stacked to gain required accuracy)

➢ Images will have different redshifts due to magnification gradients

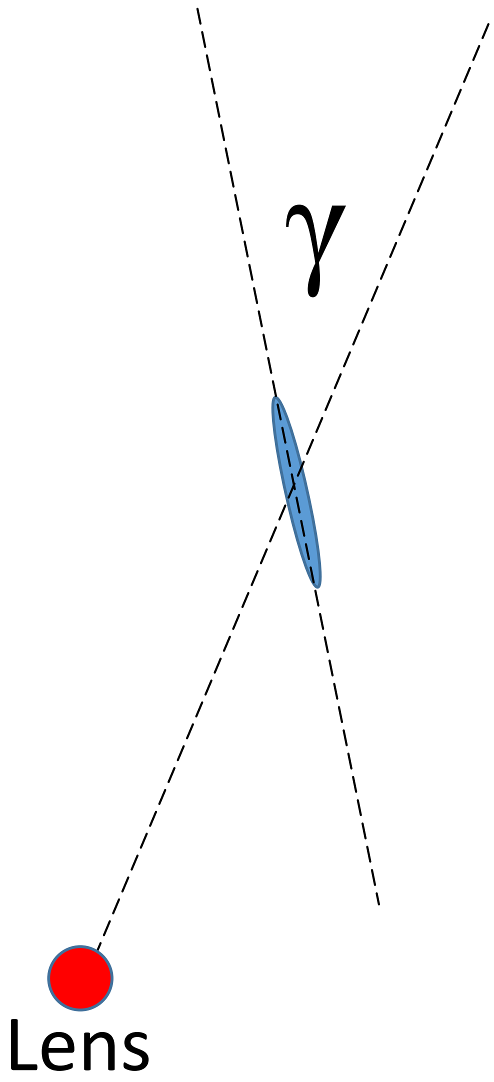
Governing Equation For The DME



- Suppose side of P is going towards Earth
- If it's nearer the lens, this side gets magnified more
- Effect slightly different in the two images
- Key thing is the magnification gradient ∇A

$$\overline{v_r} \equiv \frac{\int_{\text{Image}} A\Sigma v_r \, dS}{\int_{\text{Image}} A\Sigma \, dS} \propto \Delta\left(\frac{1}{A}\frac{\partial A}{\partial u}\right)$$

Summary of relevant parameters



$$\Delta\overline{v_r}\Big|_{MCE} = \frac{2v_t\sqrt{GM\left(u^2+4\right)}}{c}\sqrt{\frac{D_s}{D_{ls}D_l}}$$

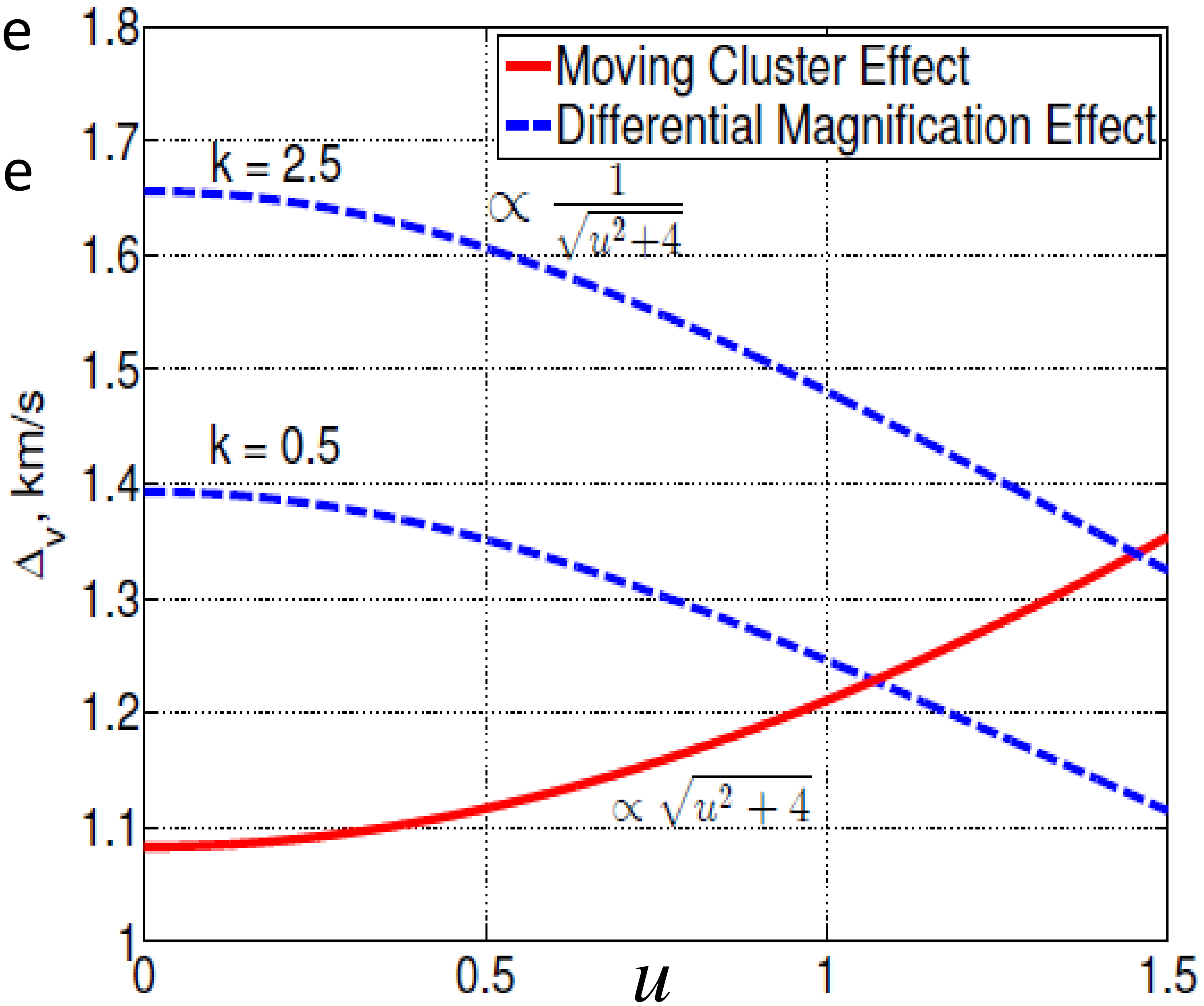
$$\Delta\overline{v_r}\Big|_{DME} = \frac{v_f\ r_d\ \sin i\ \cos\gamma\, I\, c\sqrt{D_l}}{\sqrt{u^2+4}\sqrt{GMD_{ls}D_s}}$$ where

$$I \equiv \int_0^\infty e^{-\tilde{r}}\,\widetilde{v_c}(\tilde{r})\,\tilde{r}^2\,d\tilde{r}$$

- It might be hard to tell which side of the source is approaching, let alone the precise value of γ or the disk scale length r_d, rotation curve shape I etc.
- But, we will (hopefully) have more than just the mean redshift of each image…

Comparing Magnitudes of the Effects

- Rotation curve shape parameterised by k (high for high surface brightness galaxies)
- Flatline level of rotation curve was fixed. If maximum value used instead, then results hardly depend on k
- But, how do we estimate other parameters?

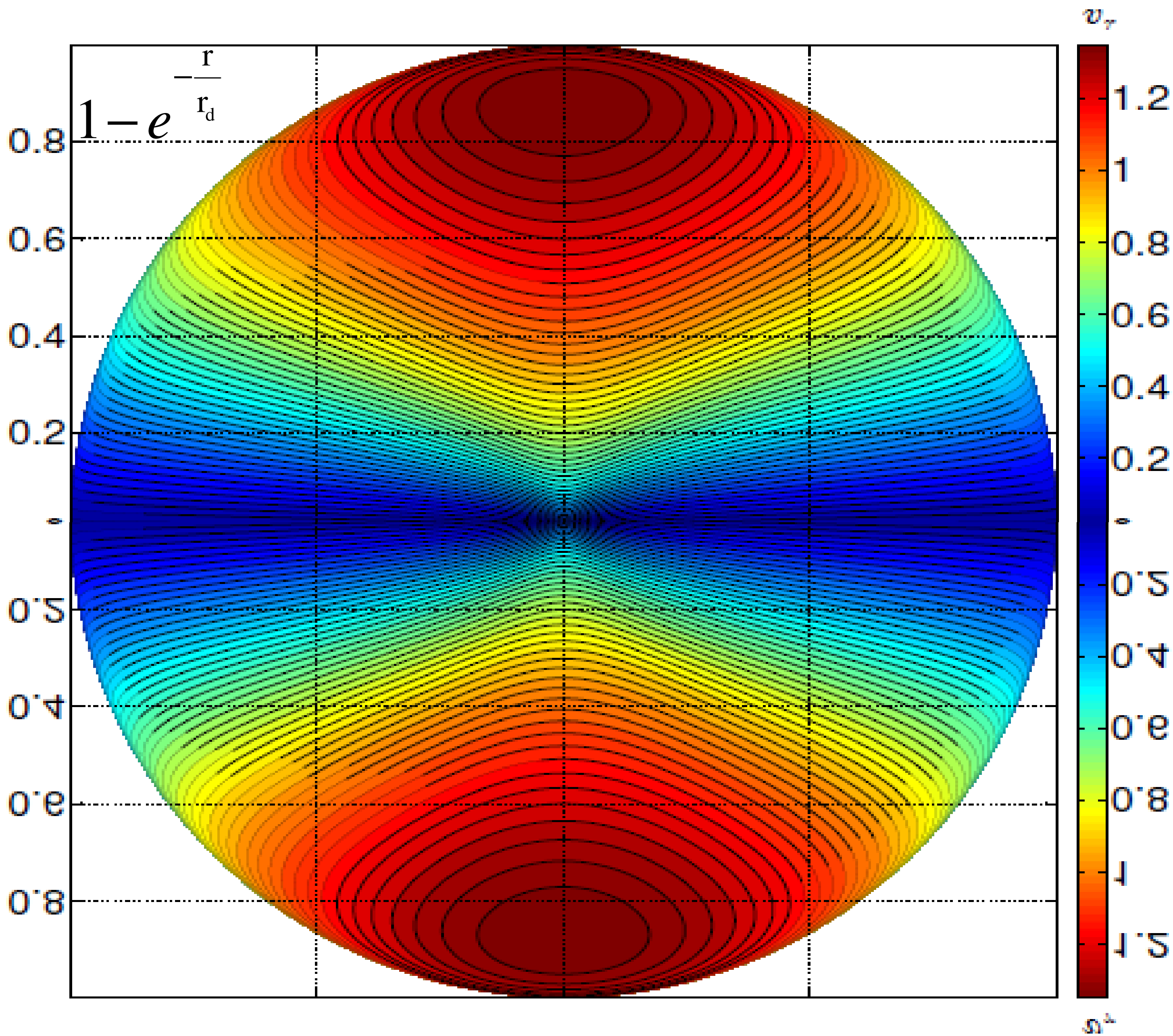


Detailed Spectral Line Profiles

- For a nearly edge-on galaxy, the radial velocity looks like this:
- Radial co-ordinate rescaled so equal areas have equal intensities in an exponential disk

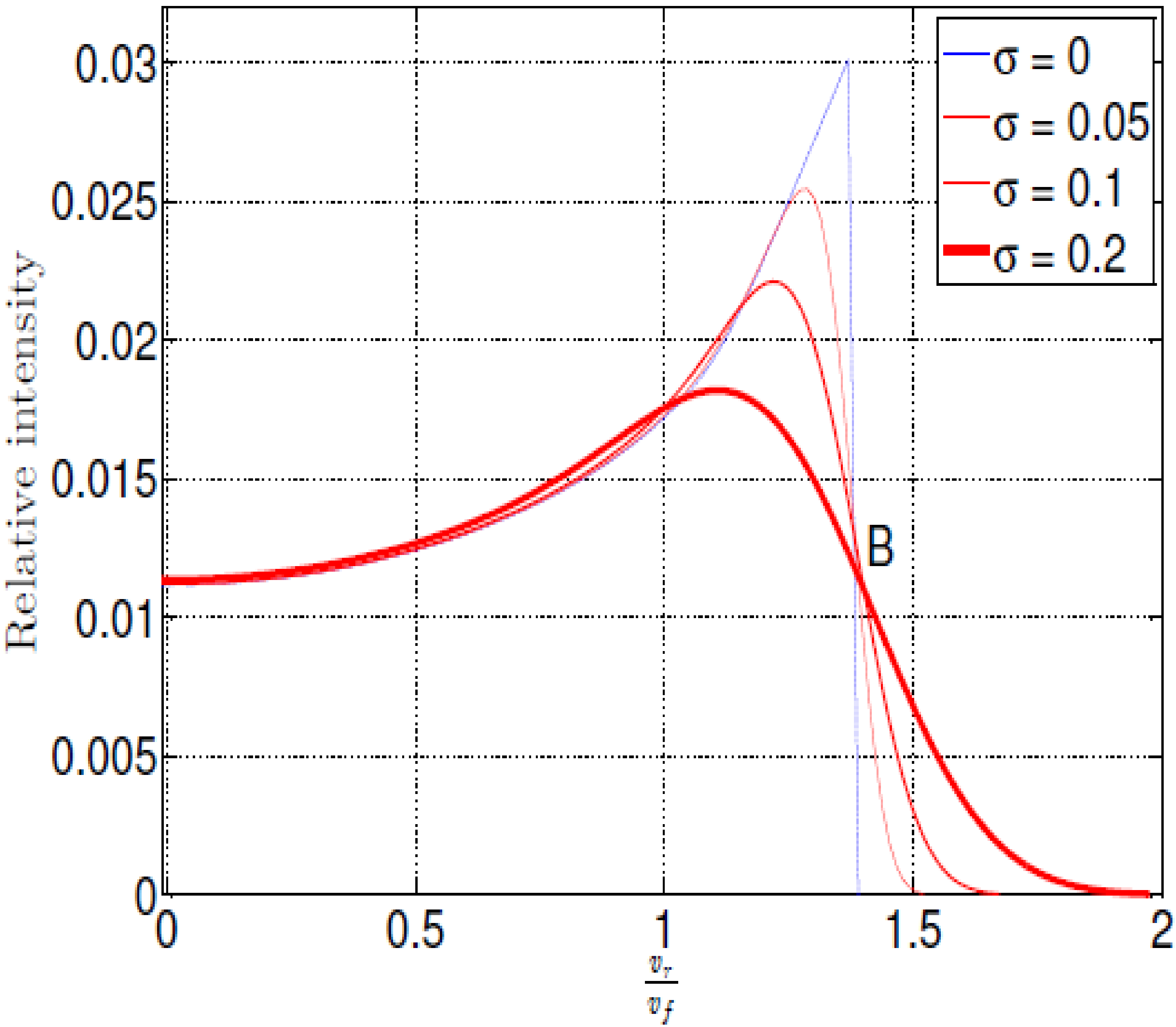
➢ Lots of light at

$v_r = \pm v_{max}$



Synthetic Line Profiles

- Convolve with Gaussians to allow for velocity dispersion/ measurement errors
- Might be good to find where intensity is e.g. 90% of level at $v_r = 0$ (point marked B) as this accurately tells you v_{max} over a wide range of σ

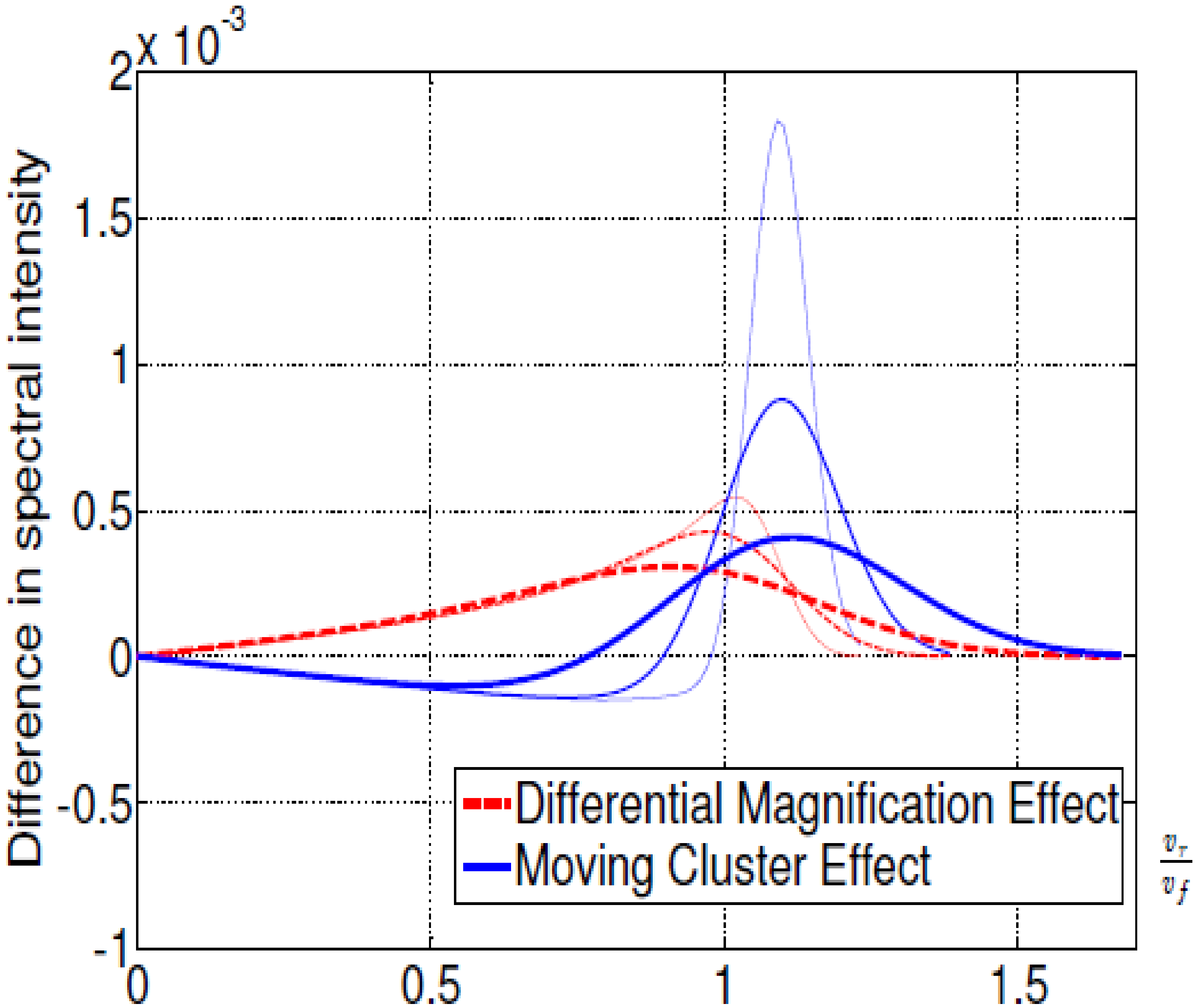


The Pattern Of Residuals

- MCE shifts spectrum horizontally

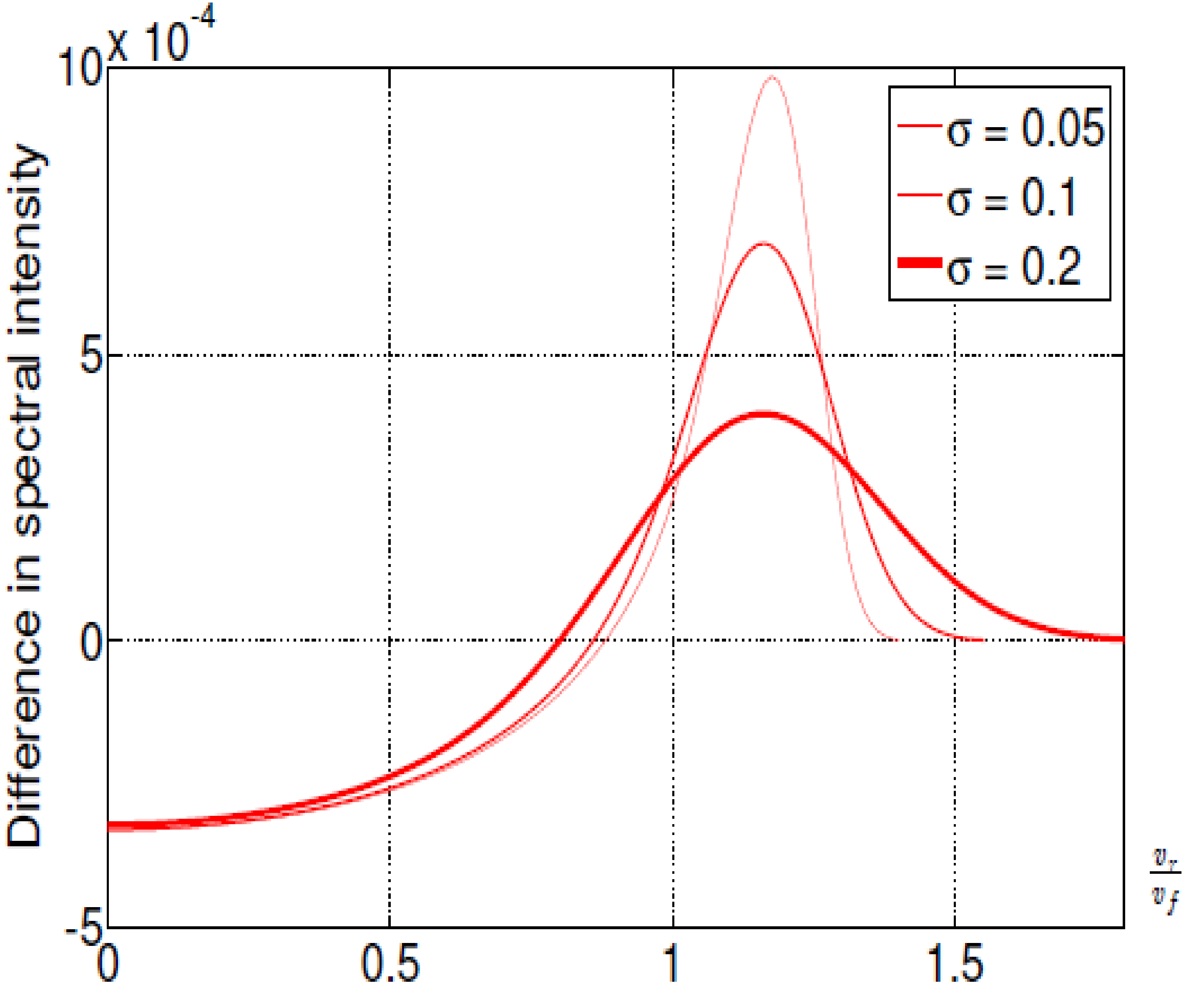
➢ Residuals ∝ derivative of the line profile

- DME magnifies one side more than other
- Both effects **antisymmetric** in v_r but slightly different:



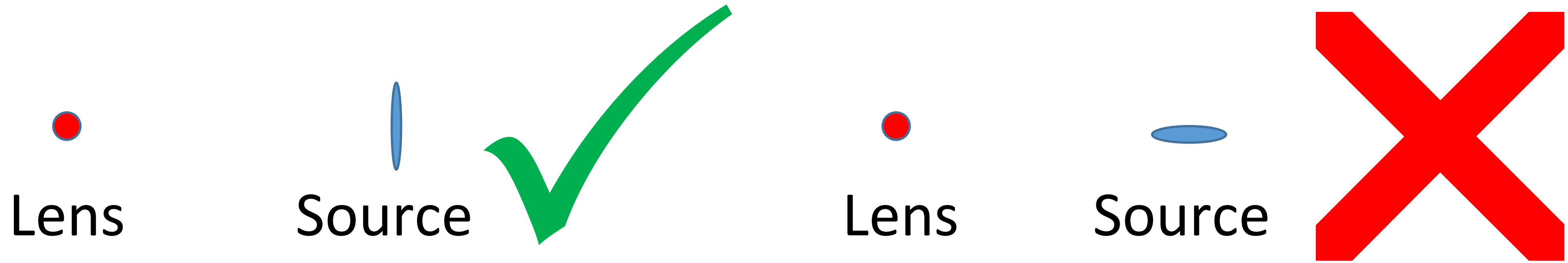
The Quadratic Differential Magnification Effect

- Pattern of residuals looks similar to MCE, but key difference: it is **symmetric** in v_r
- In this example, both horns magnified more than centre of galaxy & effect smaller in the image which was subtracted



Observing Strategies

- Use ellipticals/face-on spirals
- Smaller galaxies likely rotate slower (but harder to observe accurately)
- Edge-on disks OK if oriented suitably



•Only weak dependence on image position (may be different with more detailed model): perhaps there are some ‘sweet spots’ where (logarithmic) magnification gradients are small, i.e. low $\frac{1}{A}\nabla A$

Observing With ALMA

- Use the online exposure time calculator:

https://almascience.eso.org/proposing/sensitivity-calculator

- 100 m/s in observed $v_r \leftrightarrow$ 250 km/s in collision speed
- Actual collision speed ~3000 km/s and flux ~100 mJy for multiple image found by (ApJ, 691, 525), target dusty: good for ALMA

Parameter	Value
Declination	-56°
Frequency	150 GHz
Bandwidth per polarisation	100 m/s
Water vapour column density	Default: 5^{th} octile (1.796 mm)
Number of antennas	50×12 metre
RMS sensitivity	1.5 mJy

➢Suggests exposure time of 6 hours 10 minutes. Try it!