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How can dark energy be measured

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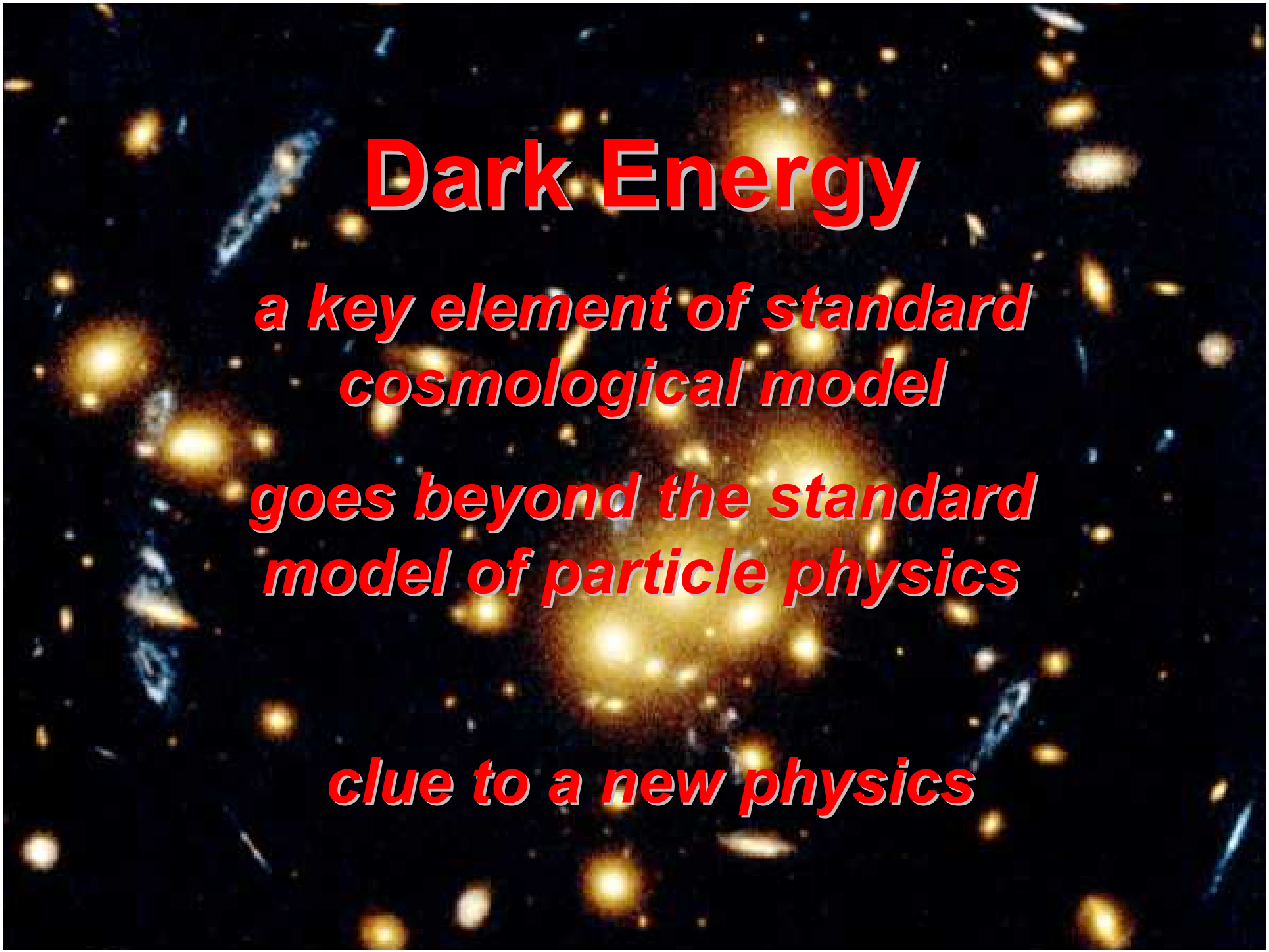

Dark Energy
a key element of standard cosmological model
goes beyond the standard model of particle physics
clue to a new physics

Dark energy – **weakly interacting physical essence permeating space of the visible Universe**

Three hypothesis of* DE:** ***vacuum, superweak field , modification of gravity

$E_{DE} \sim 10^{-3}$ eV (for $\rho_{DE} = E^4$)

New energy scale ?

Coincidence problem: $\rho_{DM} \approx \rho_b \approx \rho_{DE}$

Scales of fundamental interactions

1 GeV	strong
100 GeV	electroweak
10^{19} GeV	gravitational

Existence of LSS is a key point for

the coincidence problem

$$\Omega_{rad} << \Omega_m \,, \qquad \Omega_{DE} \leq \Omega_m$$

-window of gravitational instability
(+ initial amplitude of perturbations)

$$\Omega_{rad} << \Omega_b \leq \Omega_{DE}$$

- condition for formation of starts

DE ceases structure formation and restores Hubble outflows

lesson: DE *is a superweak field*

* for 14 Gyr – two inflationary stages
* there could be more than two, same reasons
* simple cause of inflation -- weak massive field
* inflation creates and restores Hubble outflows

History of the Universe is the history of origin and decay of massive fields

$$w(a) \equiv \frac{p_{DE}}{\rho_{DE}} = -1 + c_0 + c_1\alpha + \frac{1}{2}c_2\alpha^2 + \ldots$$

$$\alpha \equiv a - 1 = -\frac{z}{1+z}, \; w_0 = -1 + c_0, \; w_0' = c_1$$

c_n ($n = 0,1,2,\ldots$) – dark energy physics

Today all $|c_n| < 0.1$

Clue of DE physical nature

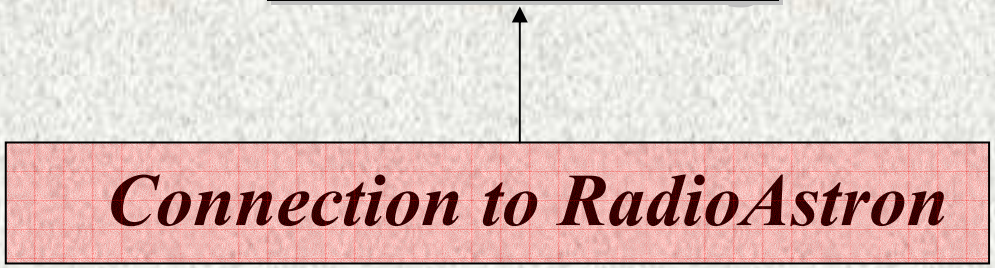
is a precise statistical measurement of z-dependant cosmic parameters

Three arguments for **DE** *evidence*

Structure

Dynamics

Geometry



Structure argument *(LSS + CMB)*

$\Omega_m = \rho_m / \rho_c < 0.3 \rightarrow$ open model? no

CMB anisotropy - flat *3-geometry*

More than 70% of energy of the Universe stays unclustered $\rightarrow p \approx -\rho$ *(dark energy)*

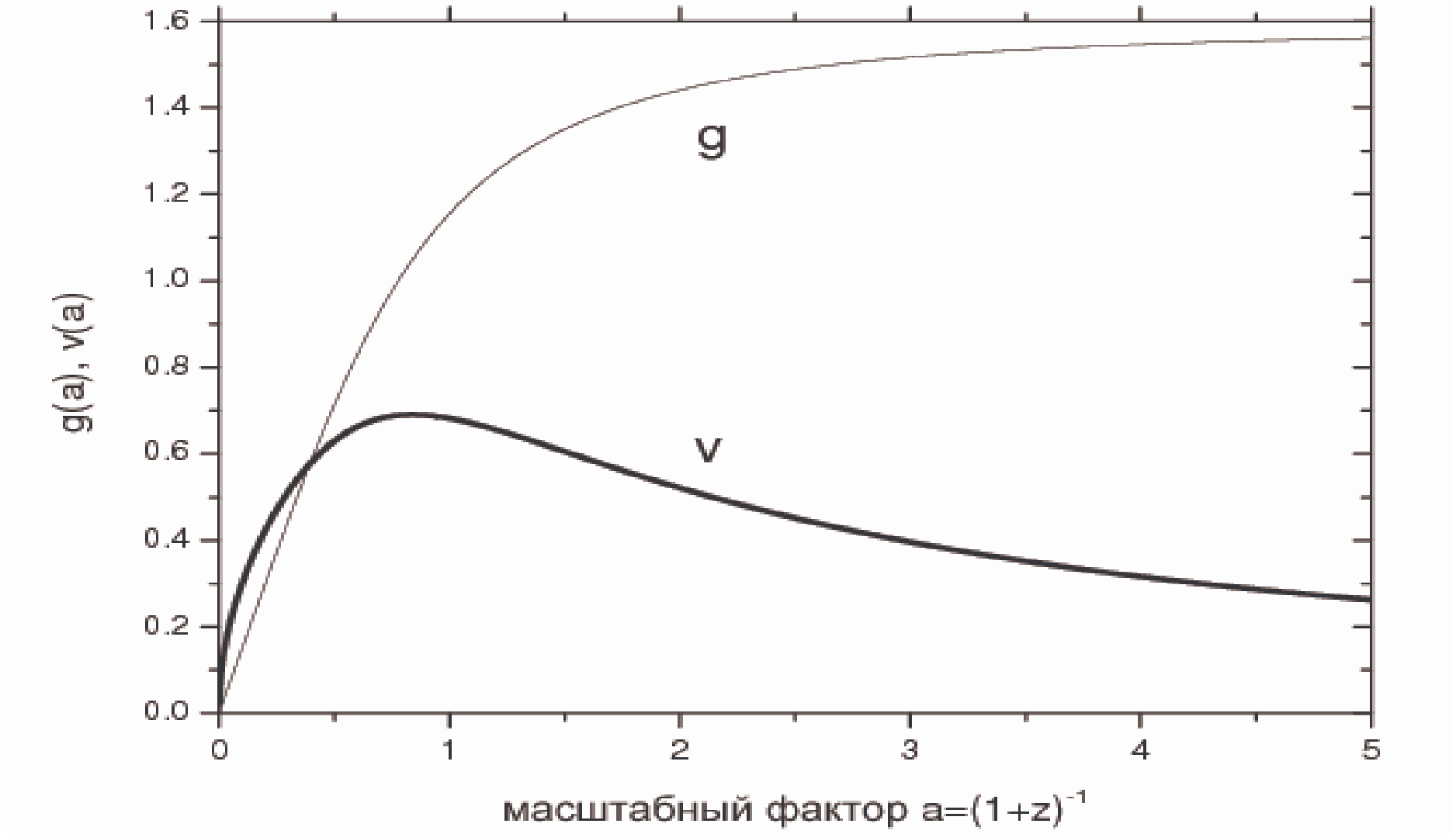
Consistency – peculiar velocities, lensing, X-ray gas in clusters, rotational velocities

Creation of the Universe is creation of the Hubble flows

Destruction of the Hubble flows is formation of the structure

DE prevents the structure formation and restores the Hubble flows

Growth factors of density and velocity perturbations



We are at the maximum of structure generation

It will take 20 Gyr more to halve velocity

peculiar velocities are at the maximum today

We live at the period of maximum LSS formation in the Universe

DE ***affects crucially dynamics of the structure generation***

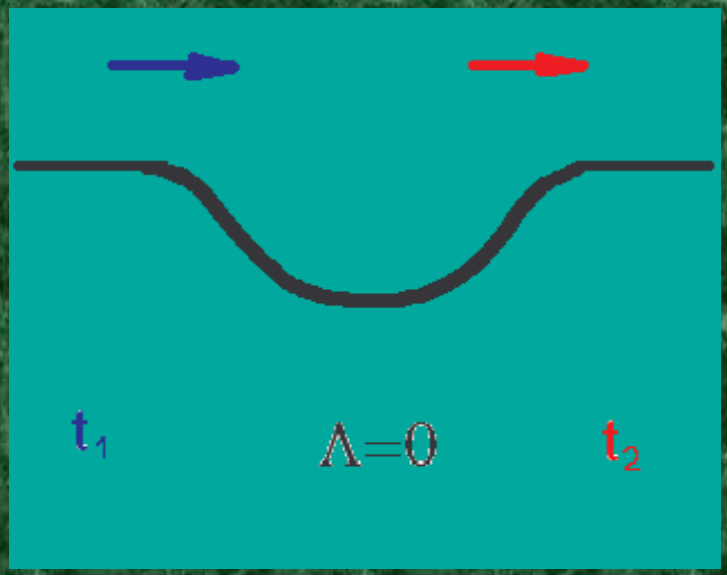
Use this chance:

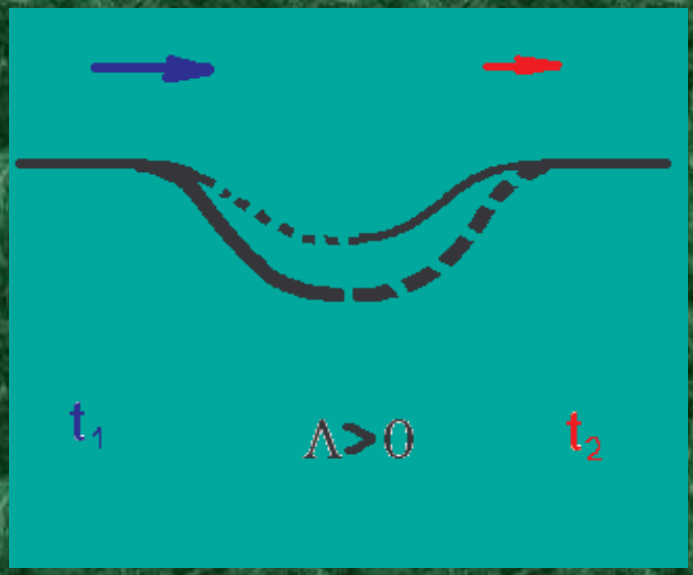
measure DE by weighting the structure with redshift

Dynamical argument

sky maps' cross-correlation: CMB *vs* LSS

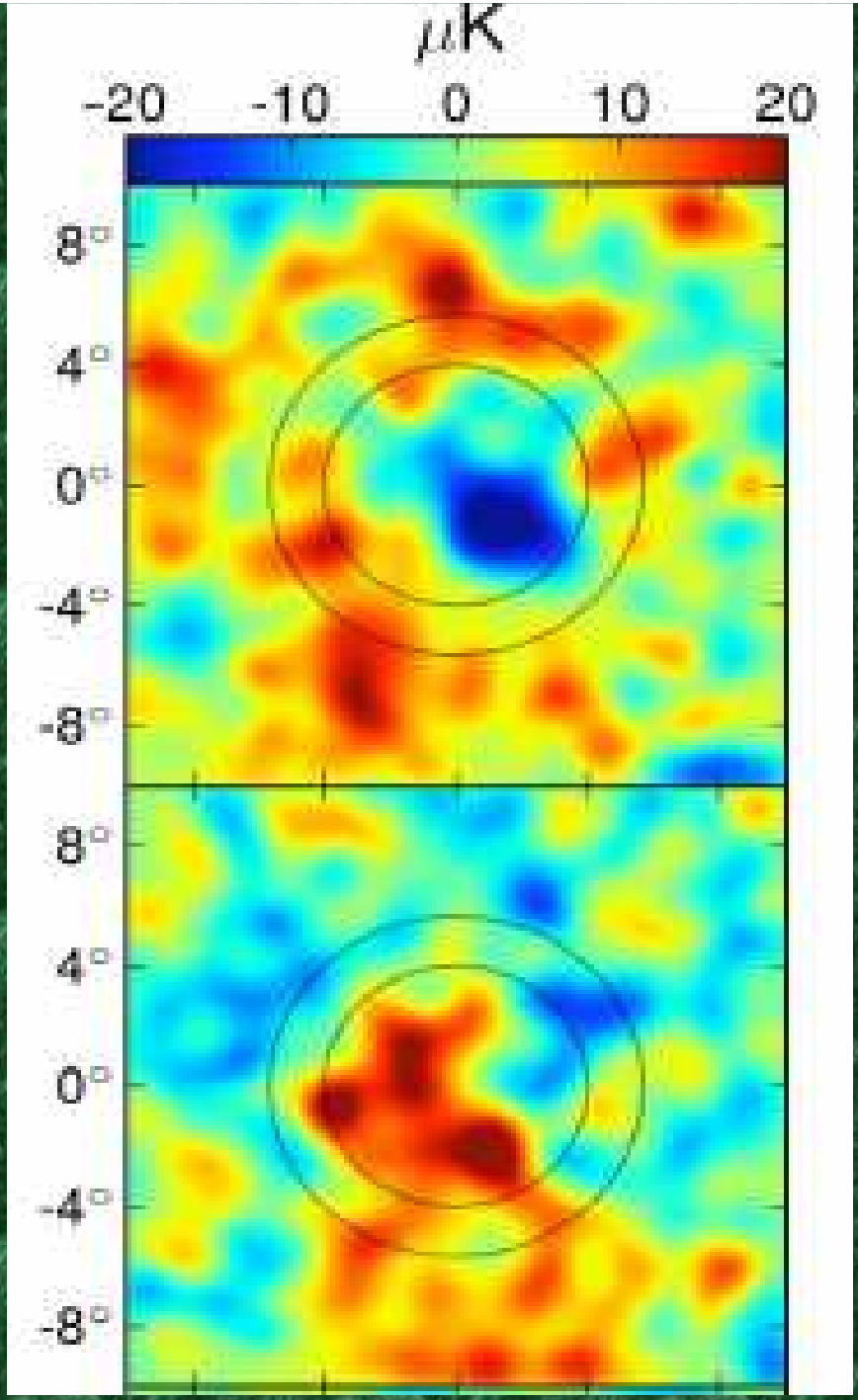
$$\Delta\Phi = 4\pi G\rho_m a^2\delta \sim \frac{\delta}{a} \sim \begin{cases} \text{const}, & \rho_m > \rho_\Lambda \\ a^{-1}, & \rho_m < \rho_\Lambda \end{cases}$$





50 voids

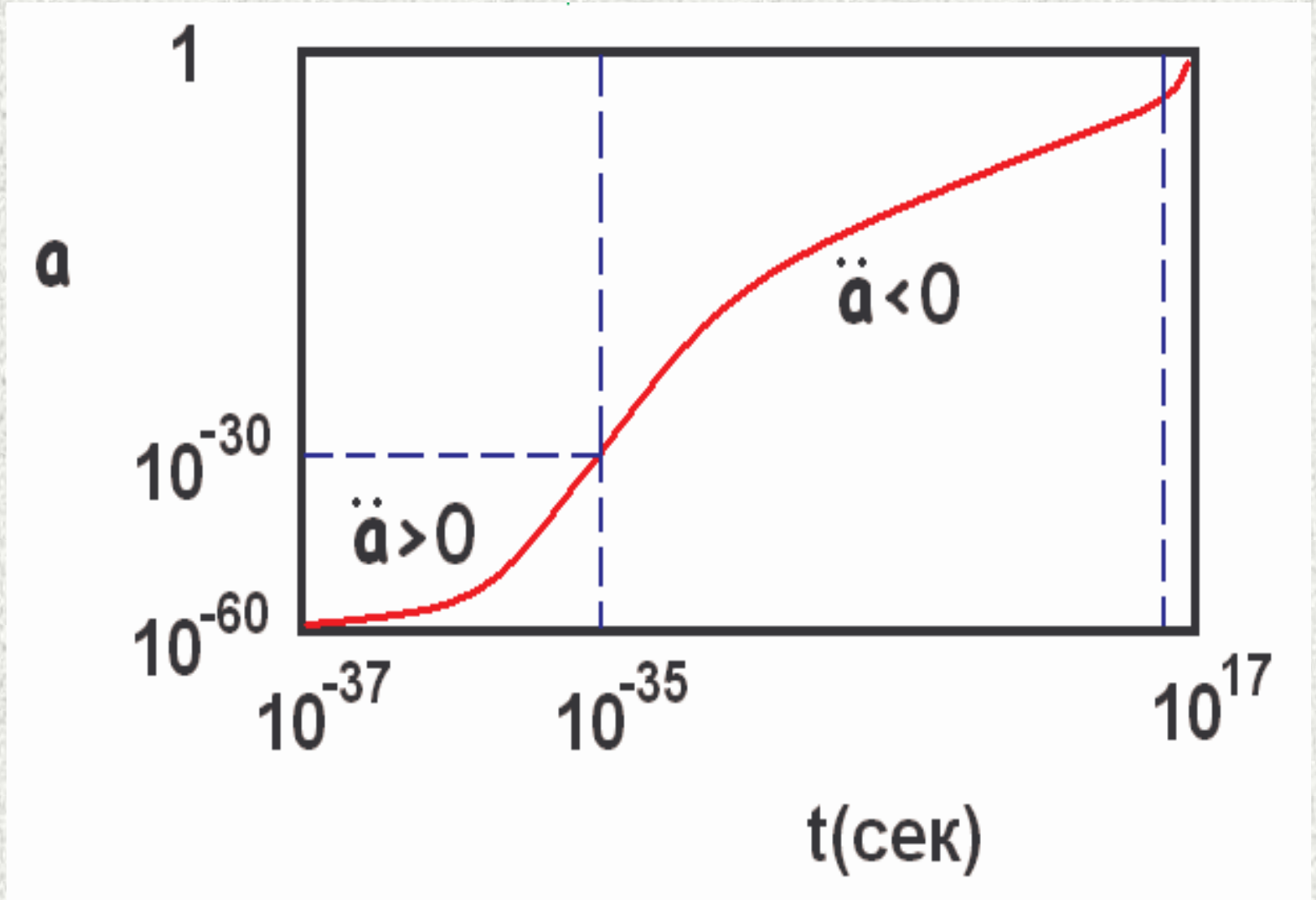
superclusters



Granett et al 2008

Geometrical argument

evolution of the scale factor



Magnitude/redshift relation $m(z)$

(SNIa, a standard candle)

Angular-size/redshift relation $\theta(z)$

(UCRSmas, a standard rod)

Comparison:

Angular-diameter distance $D = \dfrac{d}{\theta}$

Luminosity distance $R = D(1+z)^2 = r(1+z)$

Apparent/absolute magnitudes

$$m = M + 5(\log R[\mathrm{pc}] - 1)$$

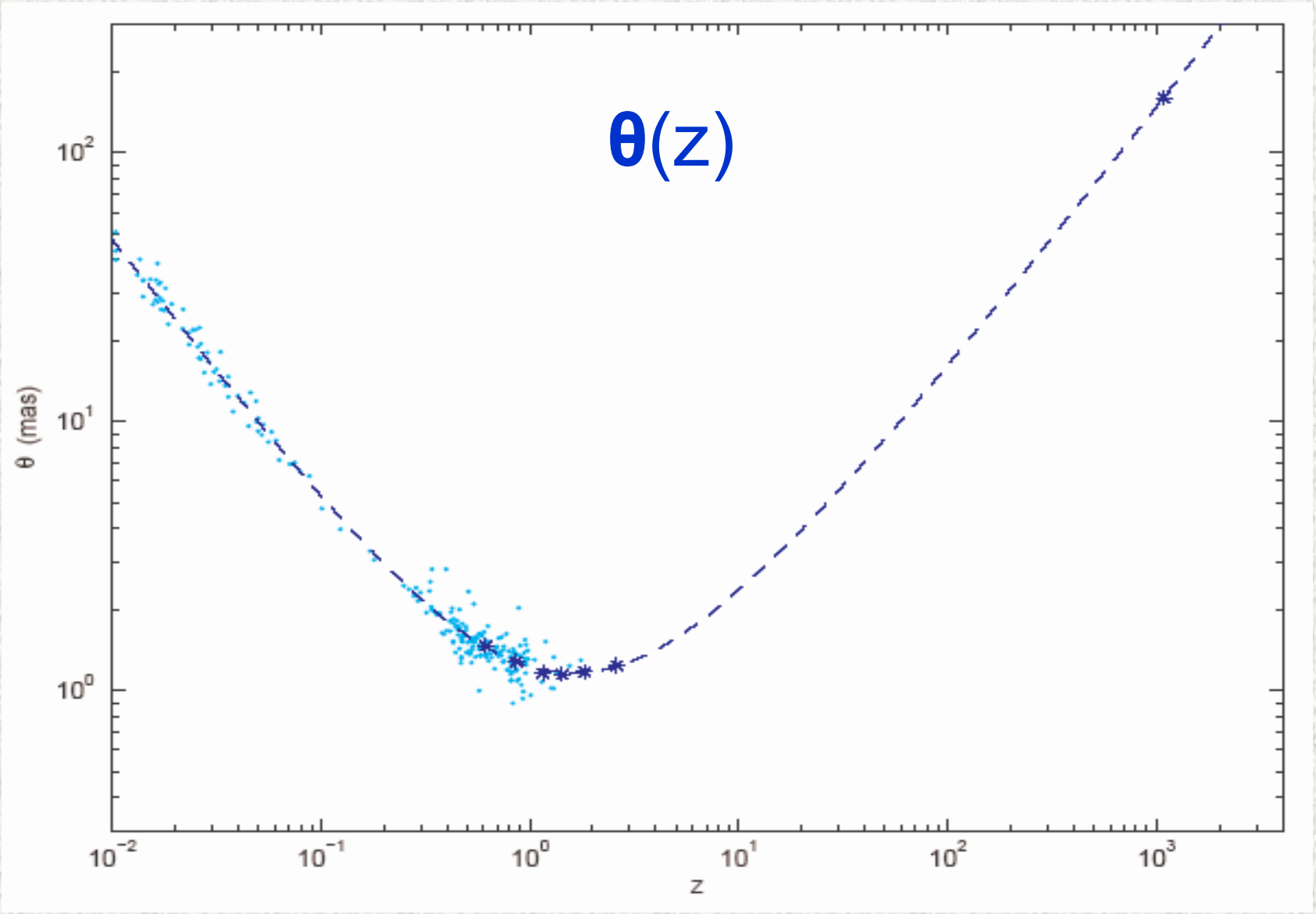
$$\theta(z) \Leftrightarrow m(z)$$

If d is a standard rod and M is a standard candle

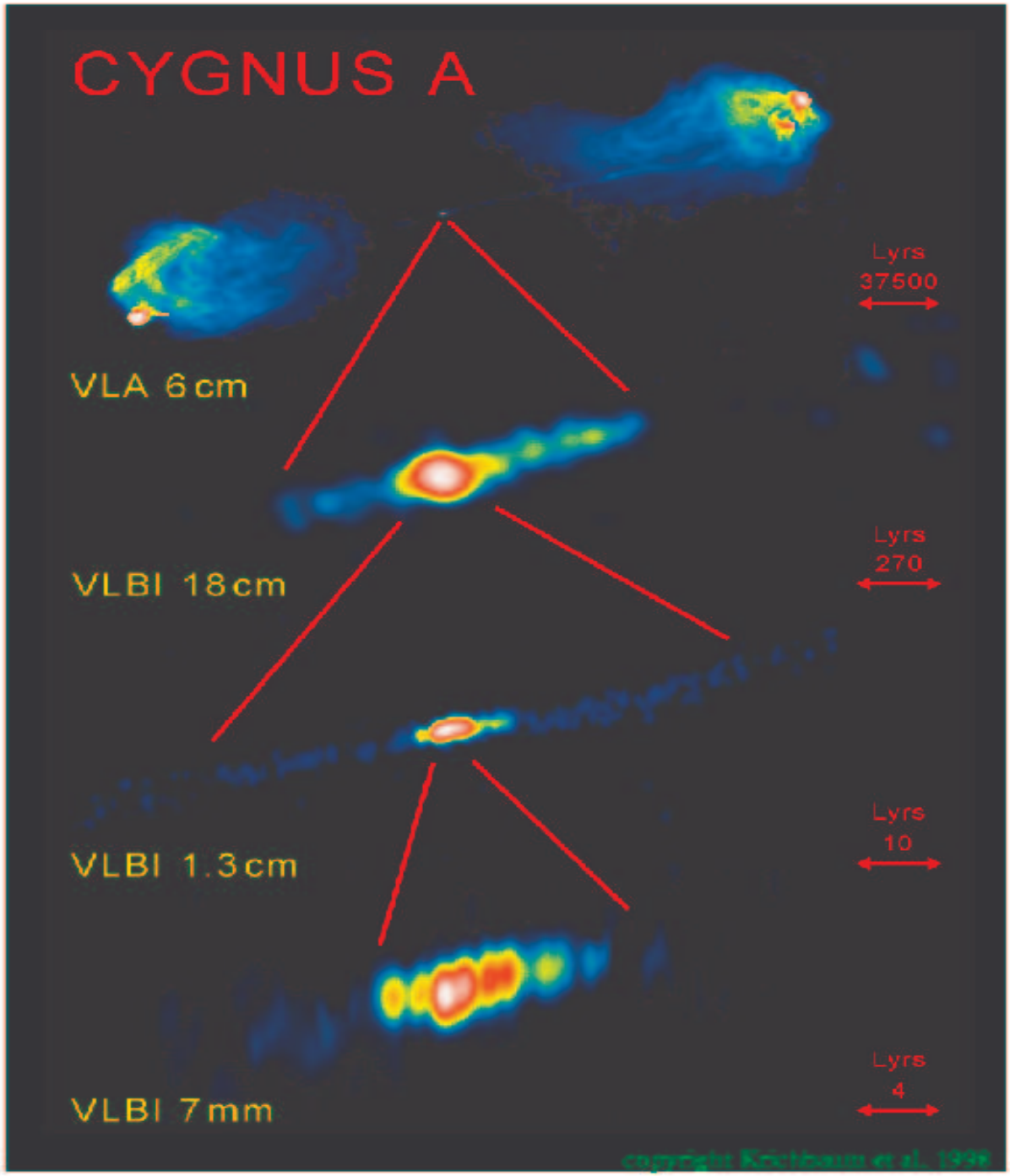
Measure geometry with $\boldsymbol{\theta}(z)$ and $\dot{\boldsymbol{\theta}}(z)$

If you know a physical size you know a distance

Ultra Compact Radio Sources



Jackson & Jannetta 2006


CYGNUS A
VLA 6cm
VLBI 18cm
VLBI 1.3cm
VLBI 7mm
Lyrs
37500
Lyrs
270
Lyrs
10
Lyrs
4

Four AGN properties

Size – not more than the Solar system

Brightness variability without a definite period

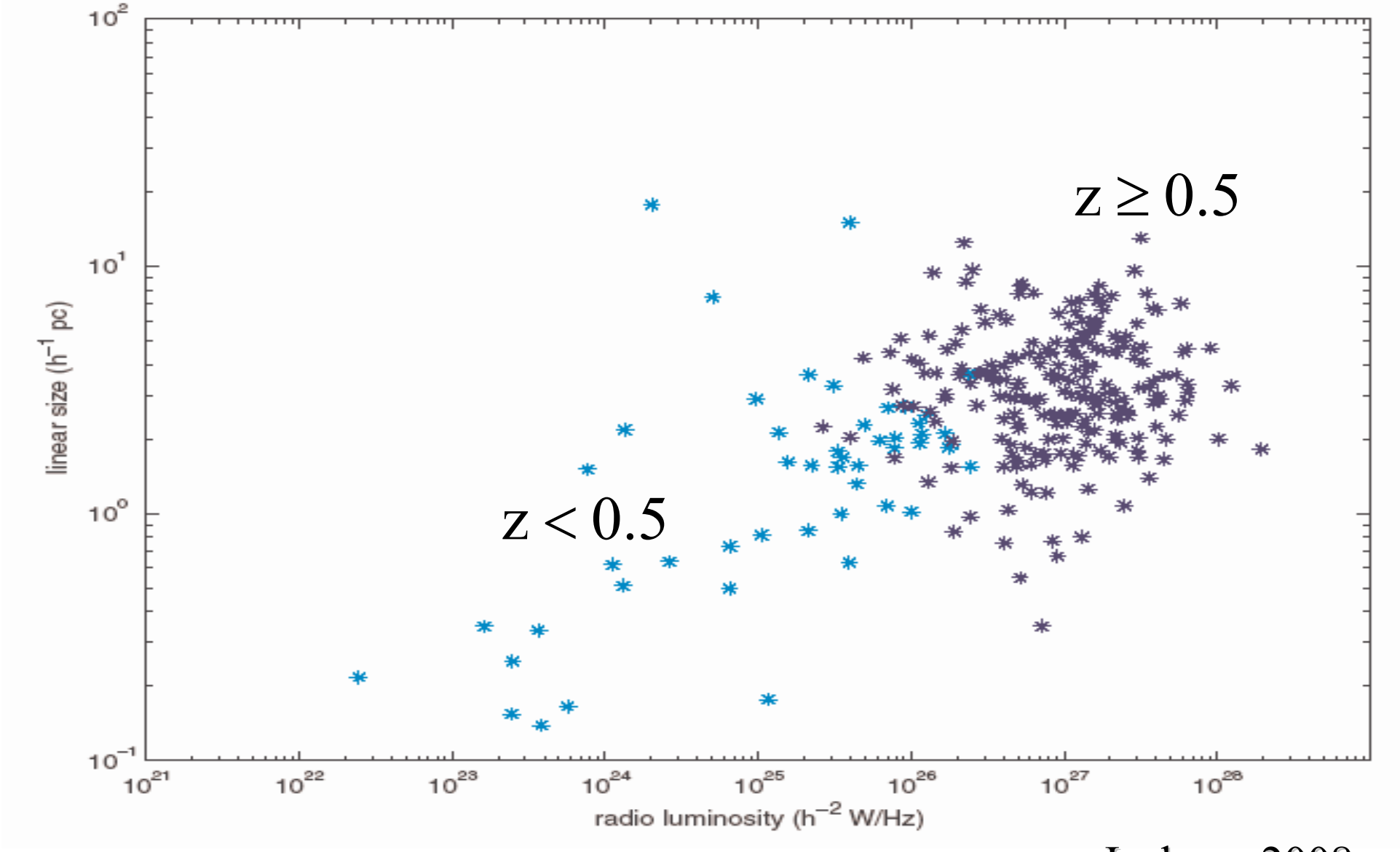
Fast **motion** of gas and/or relativistic particle flows

Huge energy release in the radio

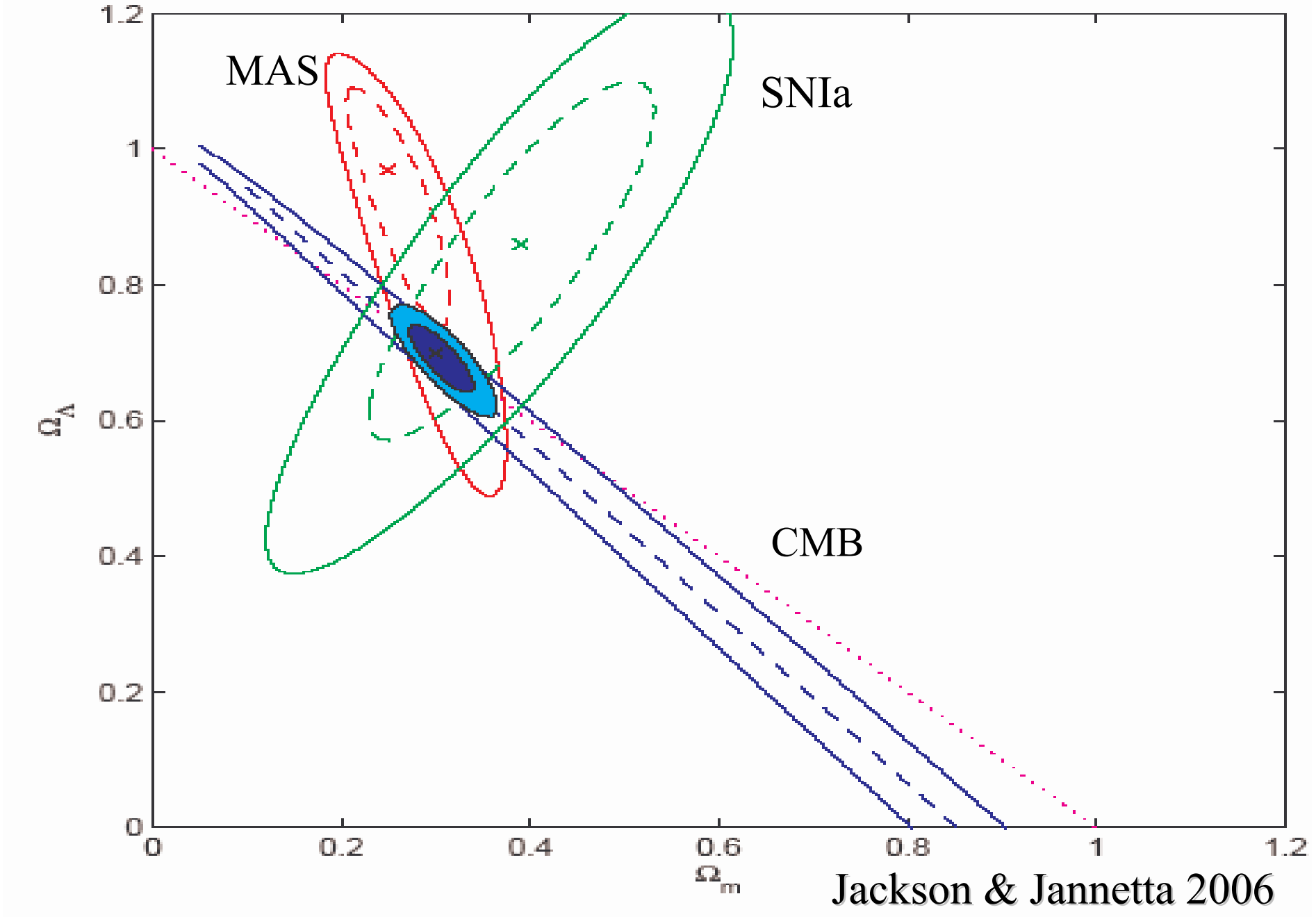
and/or optics and/or infrared and/or X-ray

(emission power is equivalent to 10^8 – 10^{12} Suns)

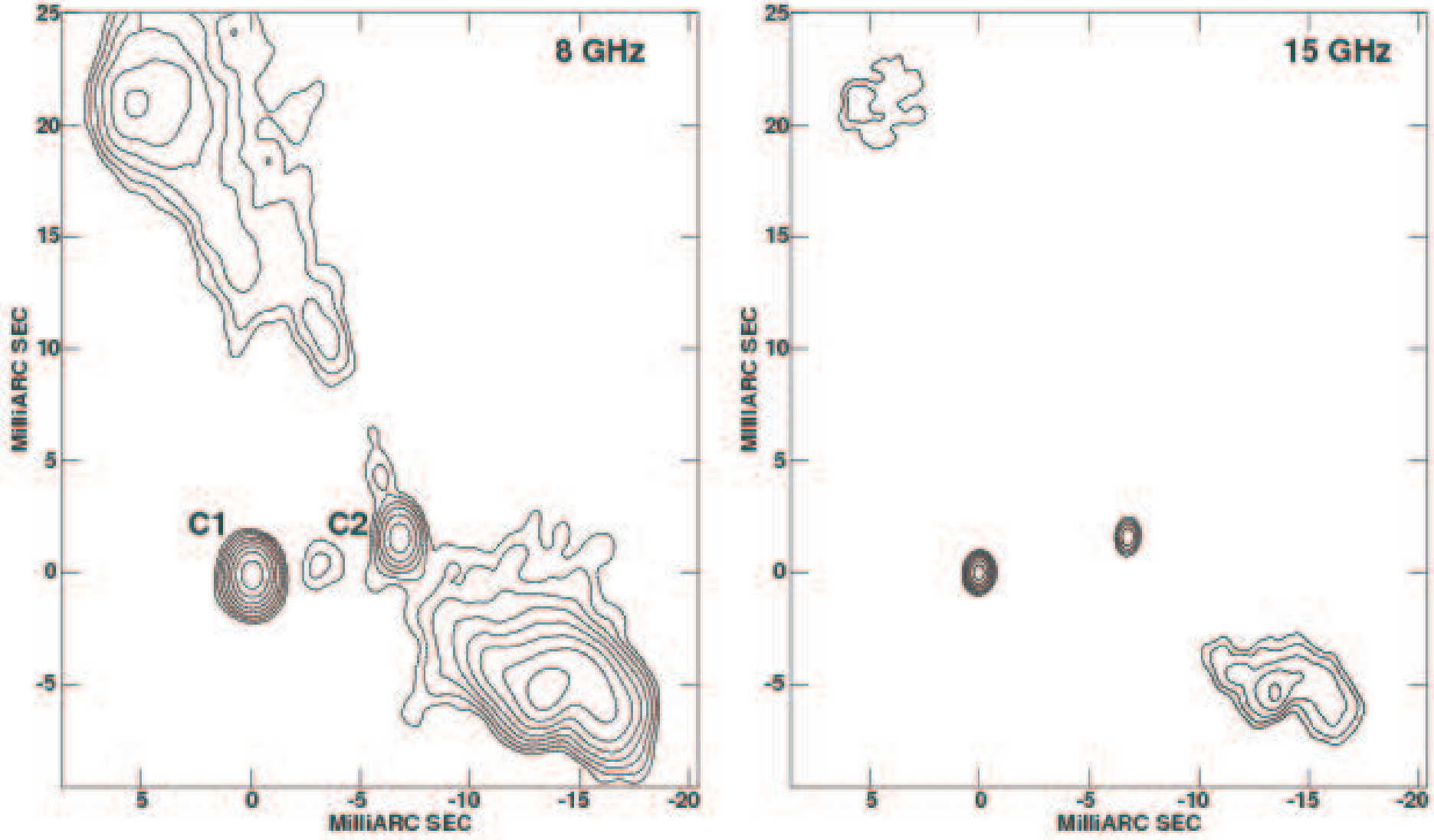
Indication of a stable linear size for UCRSmas at z > 0.5



Jackson 2008


MAS
SNIa
CMB
Ω_Λ
Ω_m
0
0.2
0.4
0.6
0.8
1
1.2
Jackson & Jannetta 2006

Double UCRS



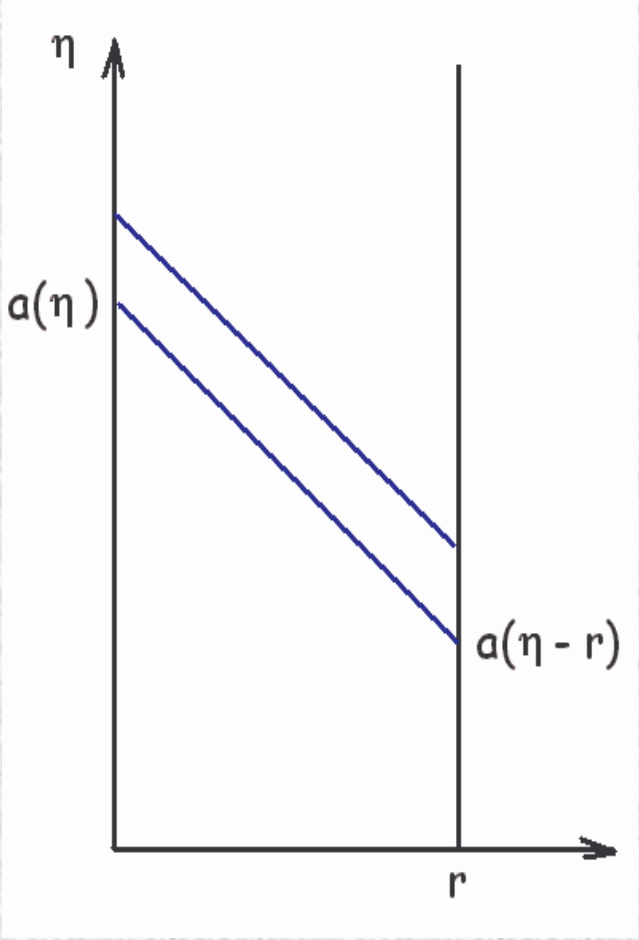
Rodriguez et al. 2006

$$\dot{\theta}(z)$$

Ultimate determination of H_0 and H(z)

a close future of the cosmic interferometry

θ/t and z/t relations

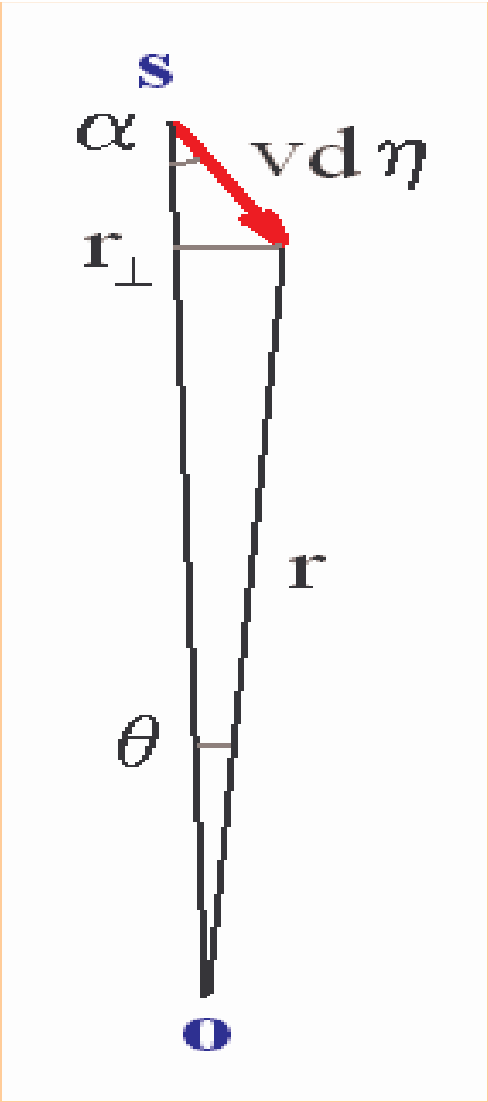


$$\frac{\dot{\theta}}{\theta} = -\frac{H(z)}{1+z}, \quad \frac{\dot{z}}{H_0} = 1+z-h(z)$$

$$h(z) = \frac{H(z)}{H_0} = \sqrt{0.7+0.3(1+z)^3}$$

$$\Delta\theta \cong -\left(\frac{\Delta t}{10\ \mathrm{yr}}\right)\left(\frac{\theta}{10'}\right)\ \mu\mathrm{as}$$

Ultraluminal motions



geodesic distance

$$r = \frac{x(z)}{H_0}, \quad x(z) = \int_0^z \frac{dz}{\sqrt{0.7 + 0.3(1+z)^3}}$$

proper time

$$dt = d\eta - dr = (1 - v\cos\alpha)\, d\eta$$

apparent motion max: $v = \cos\alpha$

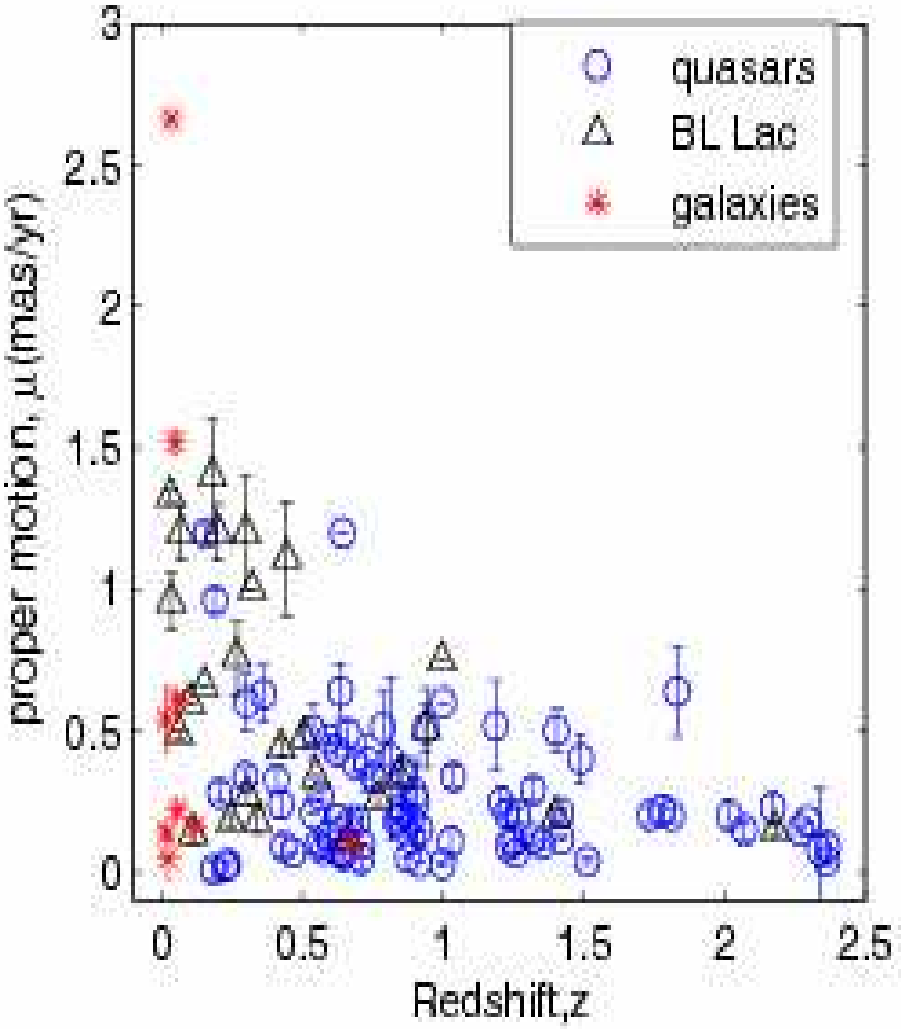
$$v_{app} = \dot{r}_\perp = \frac{v\sin\alpha}{1 - v\cos\alpha} \le \frac{v}{1 - v^2} \equiv v\gamma$$

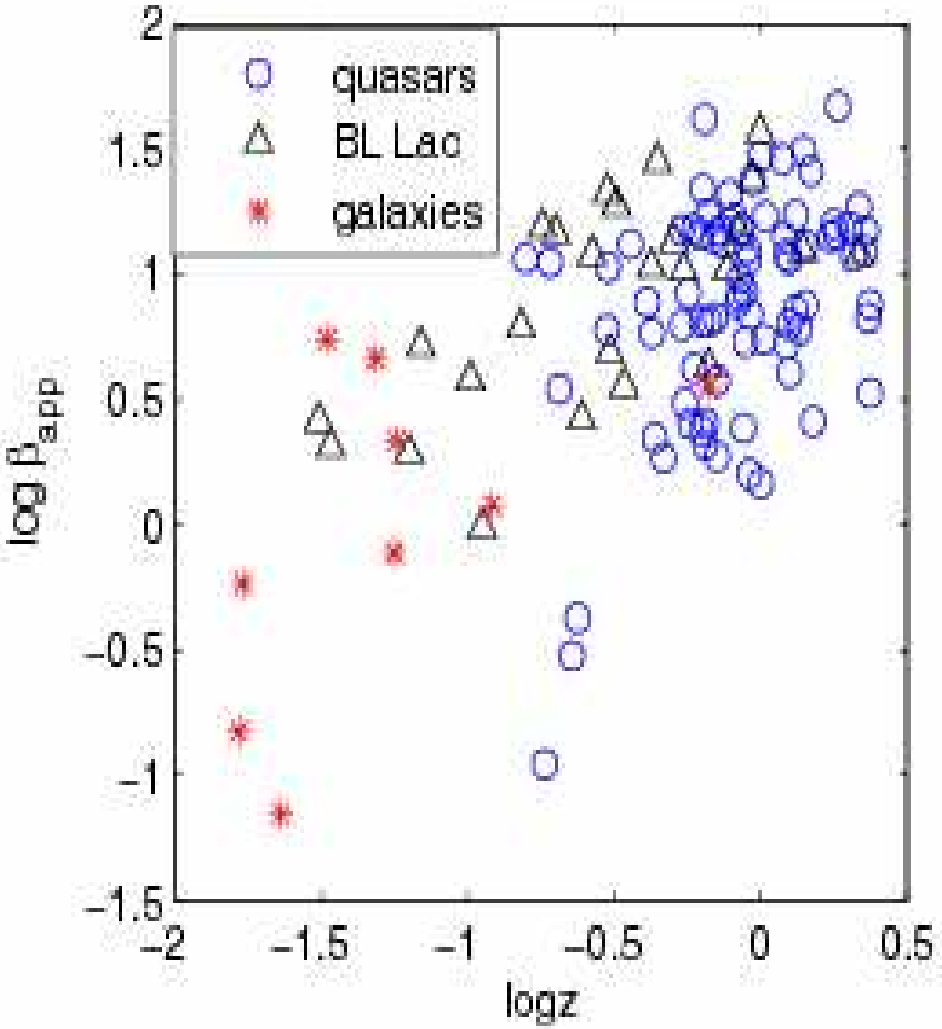
proper motion

$$\dot{\theta} = \frac{v_{app}}{r} \le \frac{15}{x(z)}\left(\frac{v\gamma}{yr}\right)\mu as \approx mas \;\; for\; \gamma \approx 25$$

$\dot{\theta}(z)$

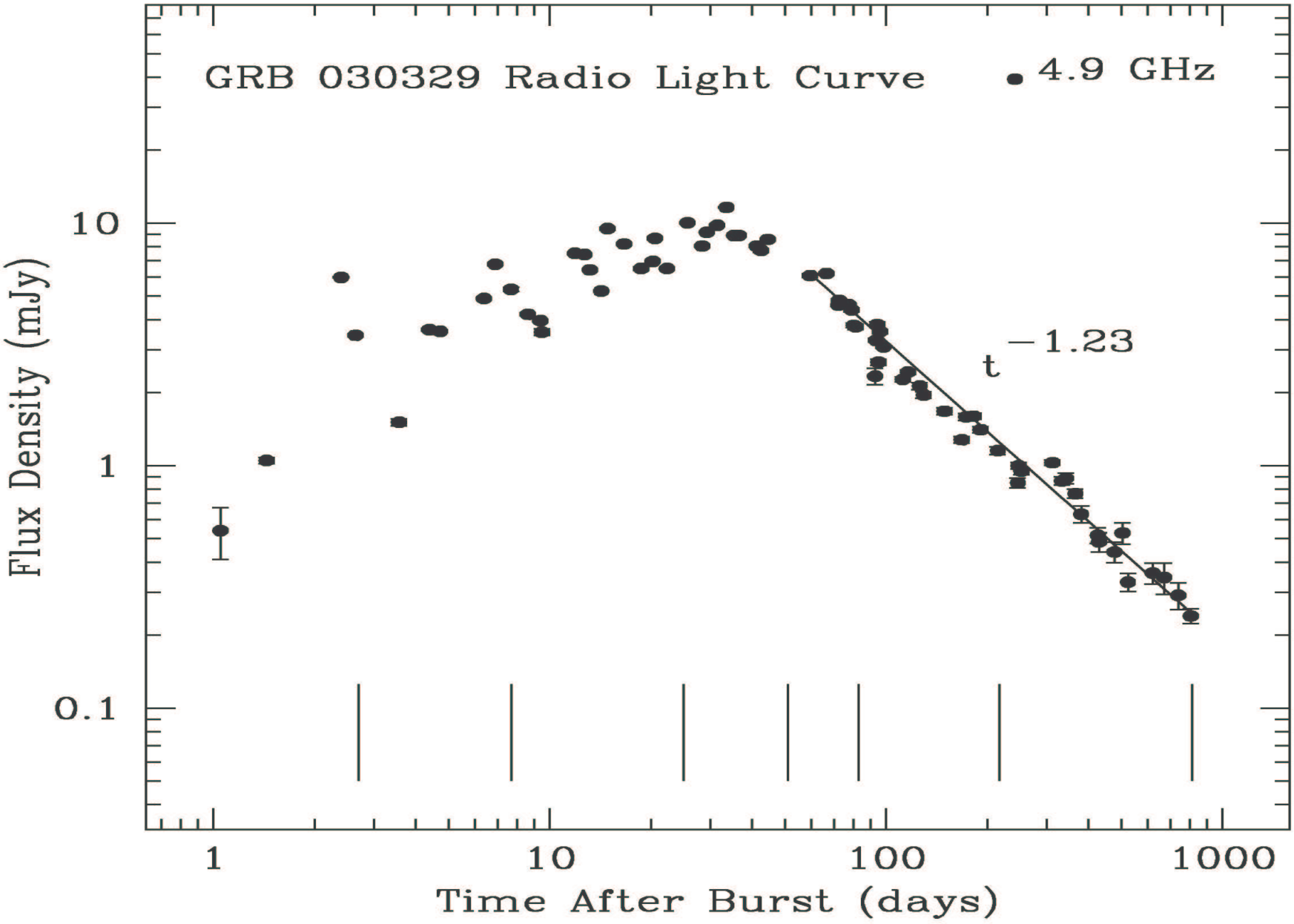
$V_{app}(z)$



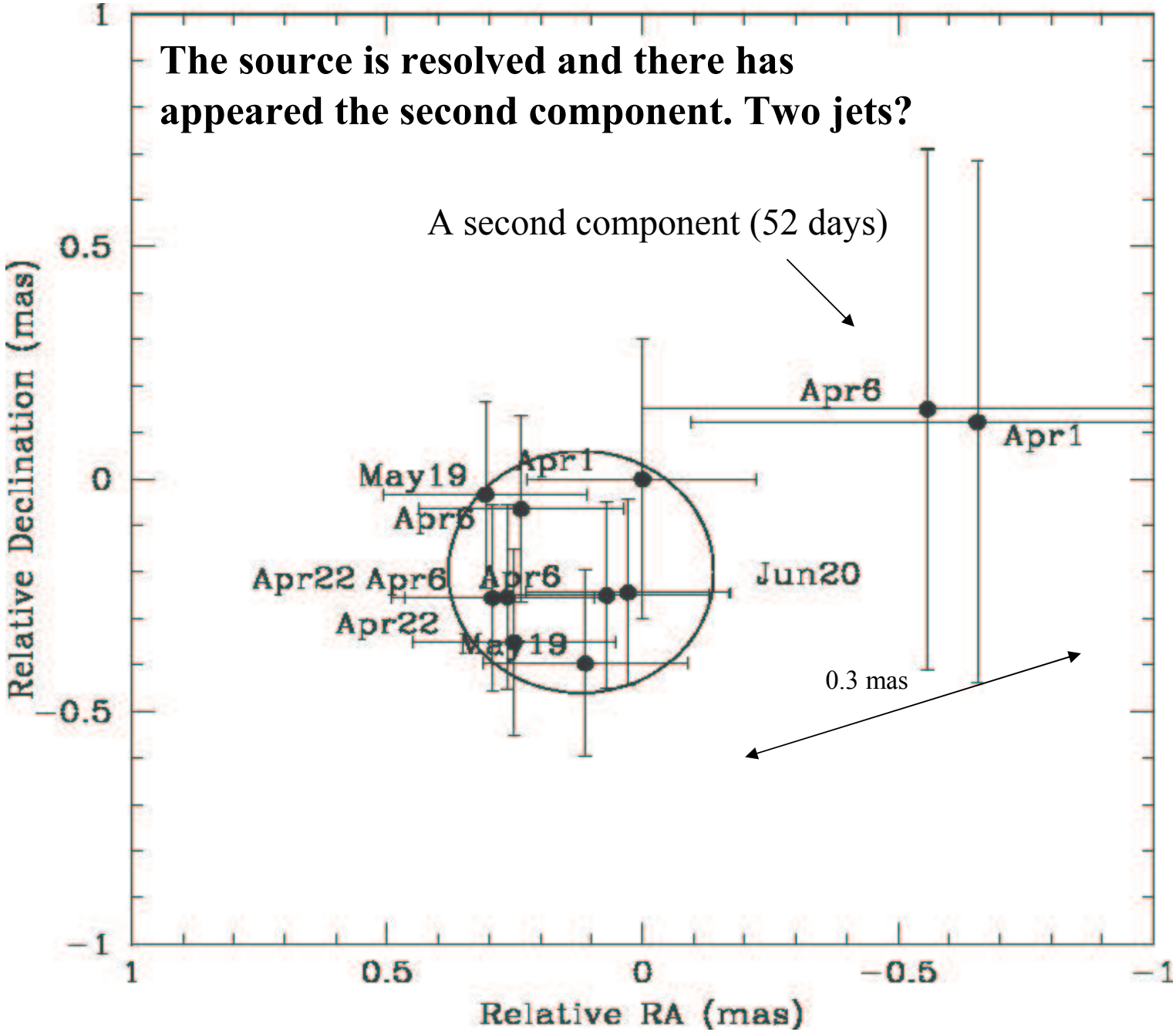


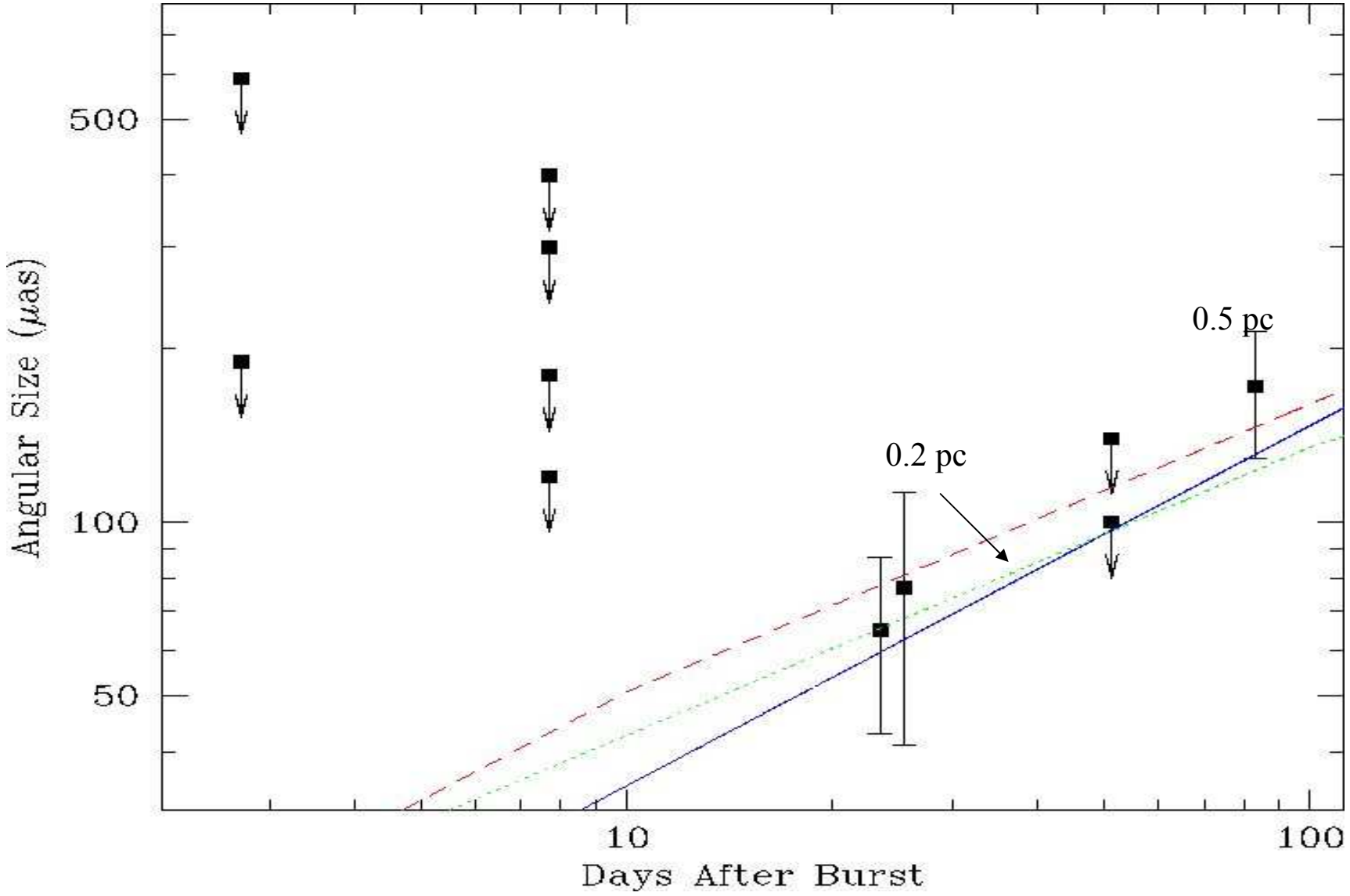
Zhang and Fan 2008

GRB afterglows



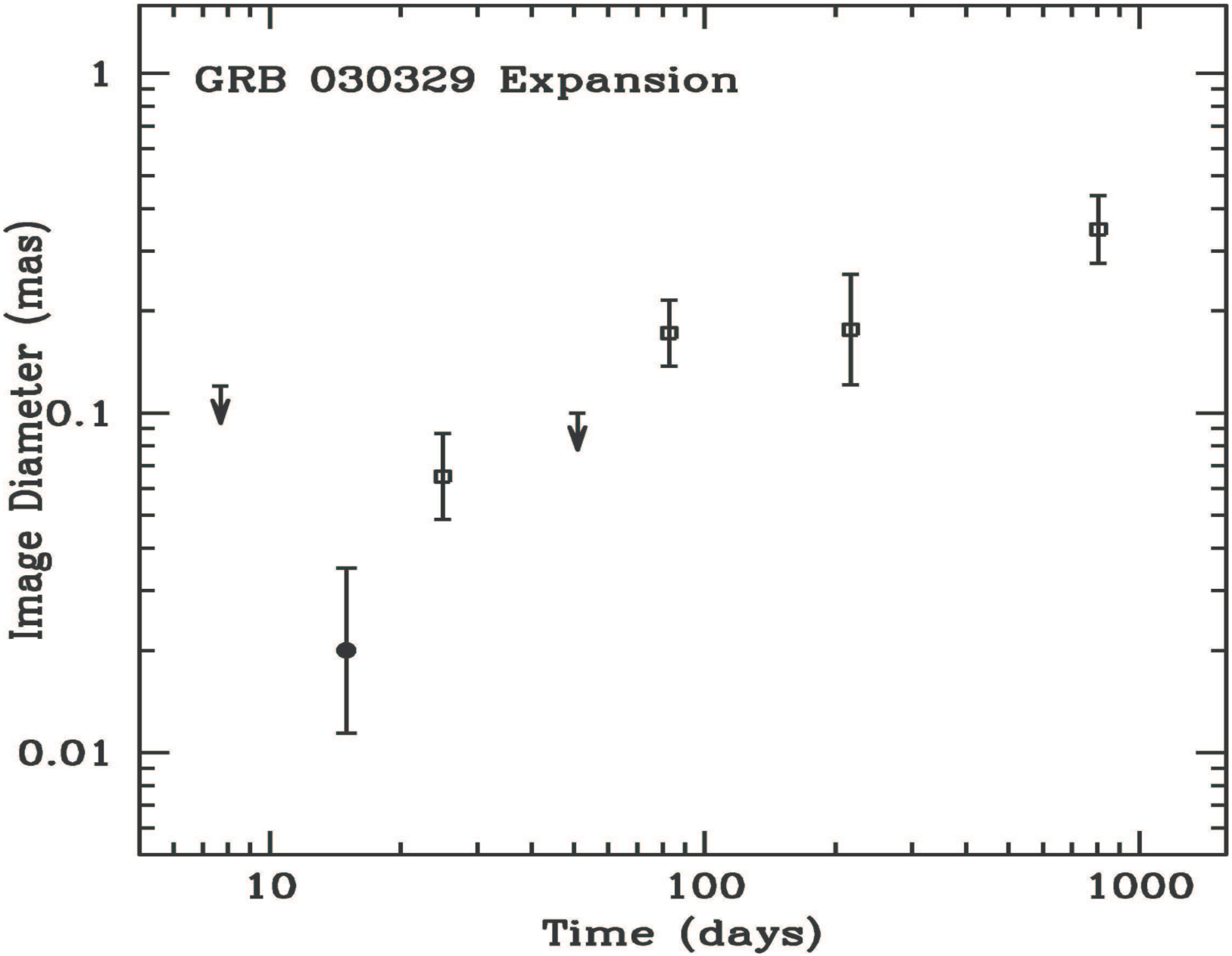
Pihlstrom et al. 2007


The source is resolved and there has appeared the second component. Two jets?
A second component (52 days)
Apr6
Apr1
May19
Apr1
Apr6
Apr22
Apr6
Apr6
Jun20
Apr22
May19
0.3 mas
Relative Declination (mas)
Relative RA (mas)
1
0.5
0
−0.5
−1
1
0.5
0
−0.5
−1



Jet expansion (main component) 3 -5 c

Taylor 2004, VLBI observations



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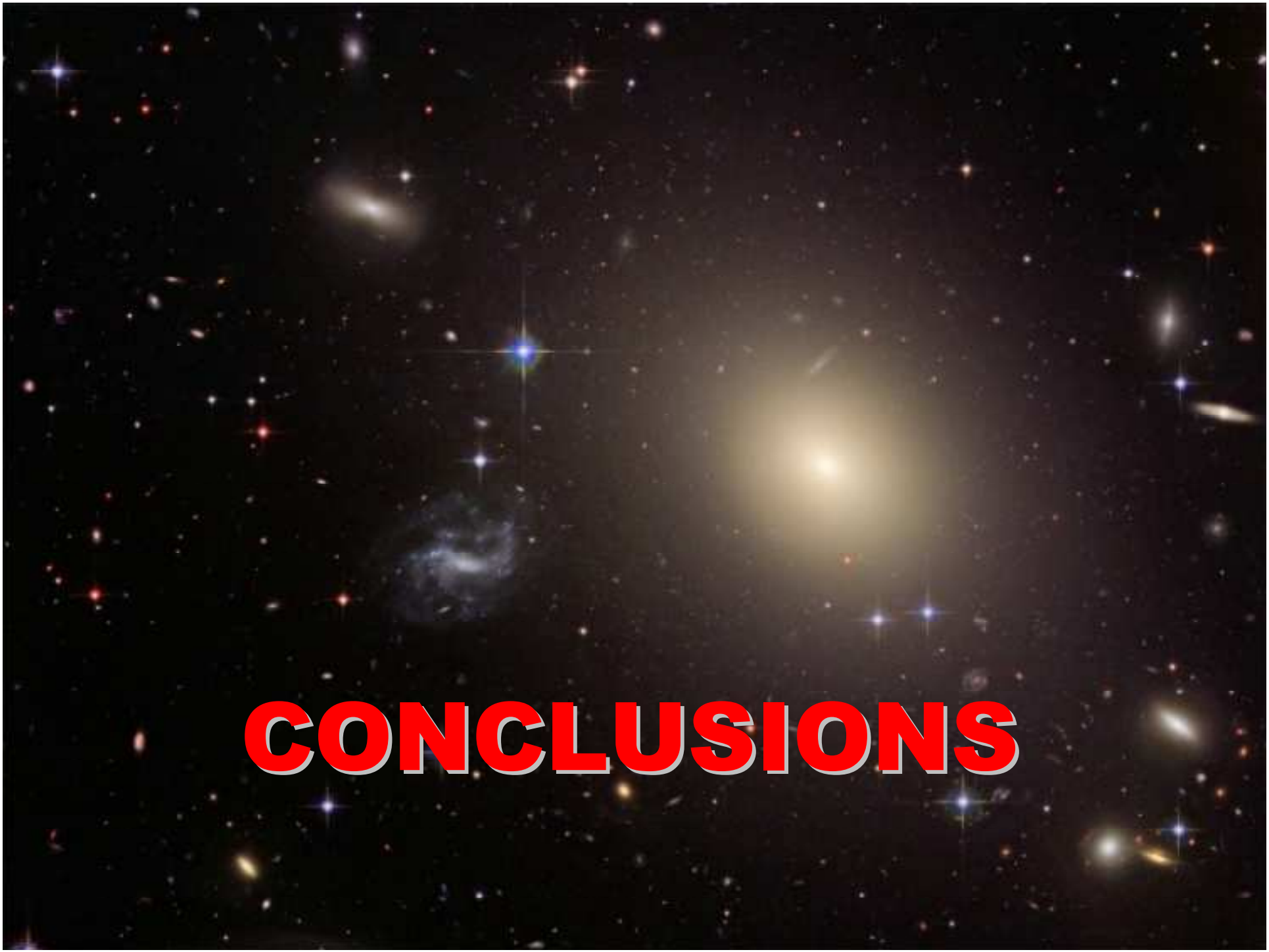
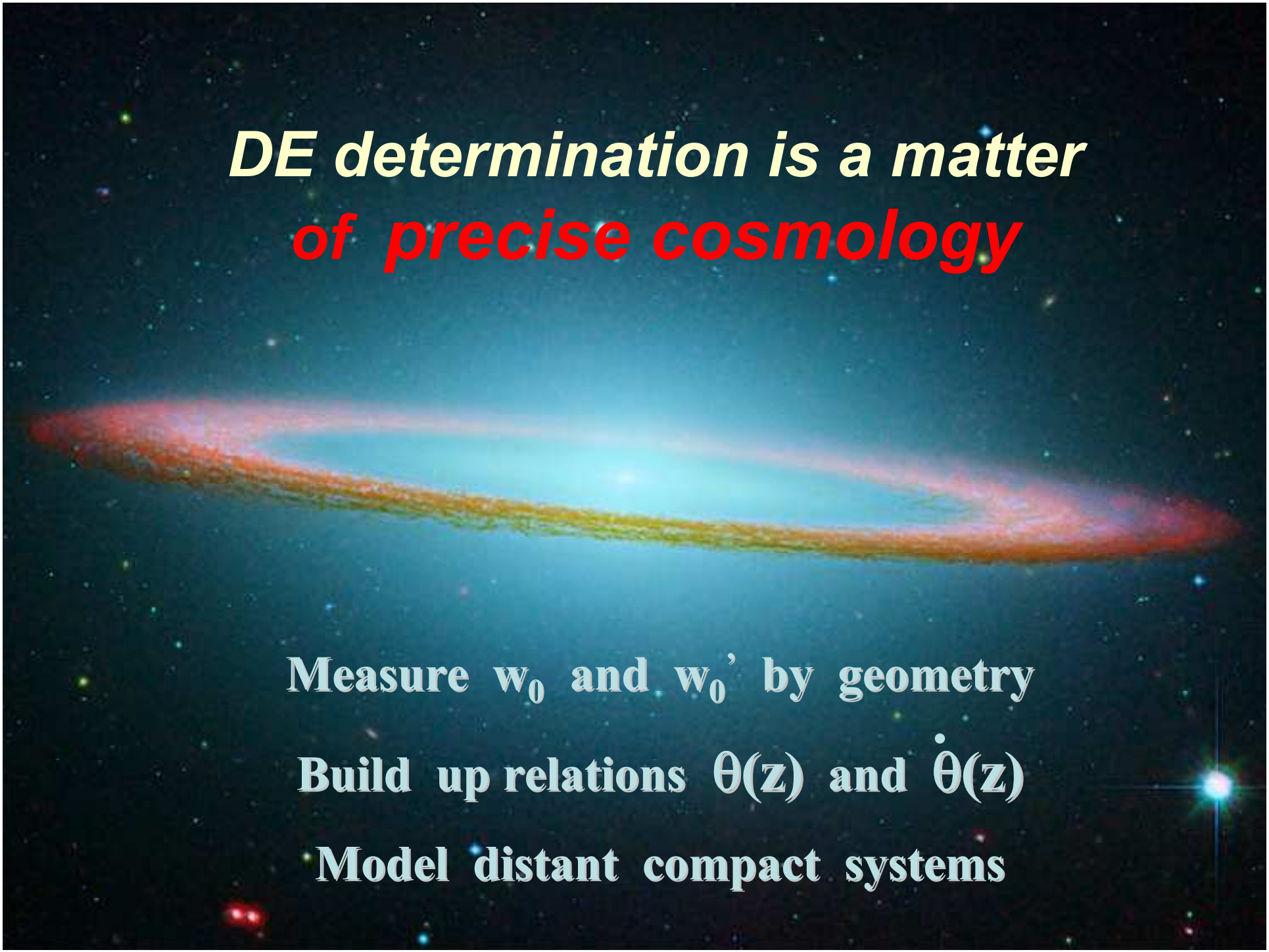

CONCLUSIONS


DE determination is a matter
of precise cosmology
Measure w_0 and w_0' by geometry
Build up relations $\theta(z)$ and $\dot{\theta}(z)$
Model distant compact systems