Cosmology and black holes: an invitation

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Cosmology and black holes: an invitation

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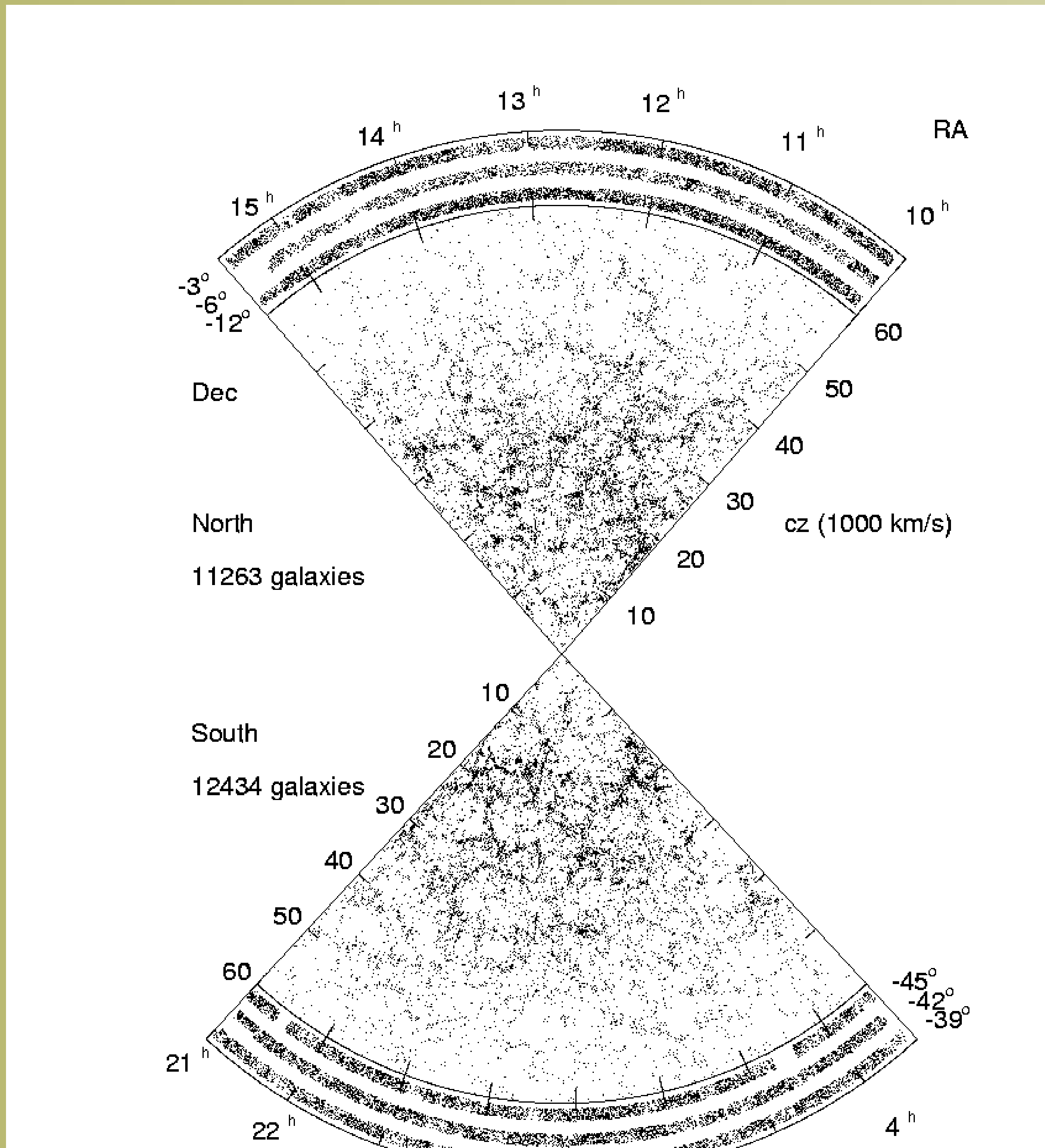
- Cosmology – expanding Universe
- Cosmic Microwave Background Radiation
- Black holes,gravitational lensing, gravitational waves

Pre-TechFest, January 2003

Cosmology

The expanding universe

- Homogeneity, isotropy
- Hubble law


13 h
12 h
14 h
RA
11 h
15 h
10 h
-3°
-6°
-12°
60
Dec
50
40
30
North
cz (1000 km/s)
11263 galaxies
20
10
10
South
20
12434 galaxies
30
40
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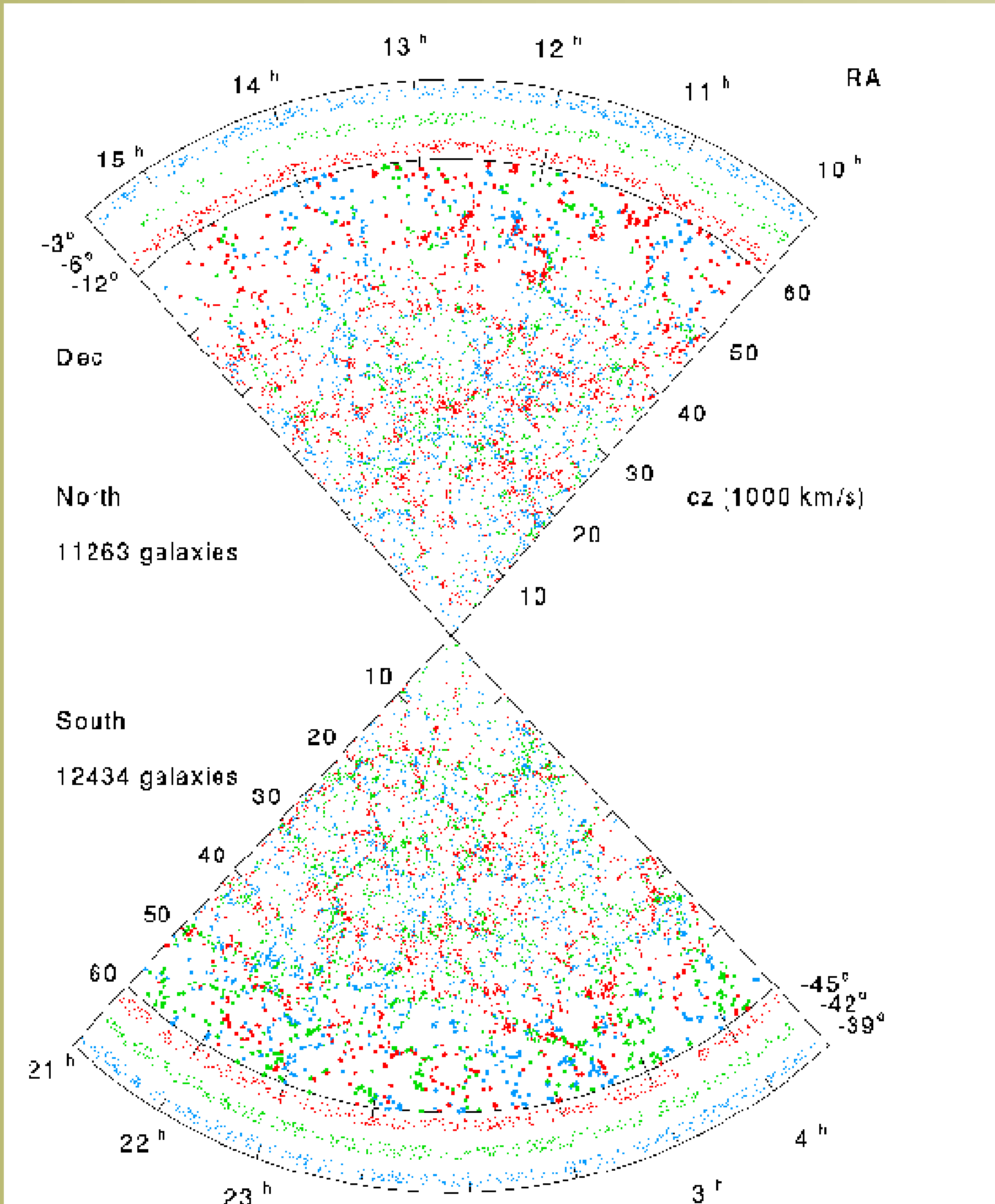
60
-45°
-42°
-39°
21 h
22 h
4 h



13 h
12 h
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11 h
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15 h
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-3°
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60
Dec
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30
North
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21 h
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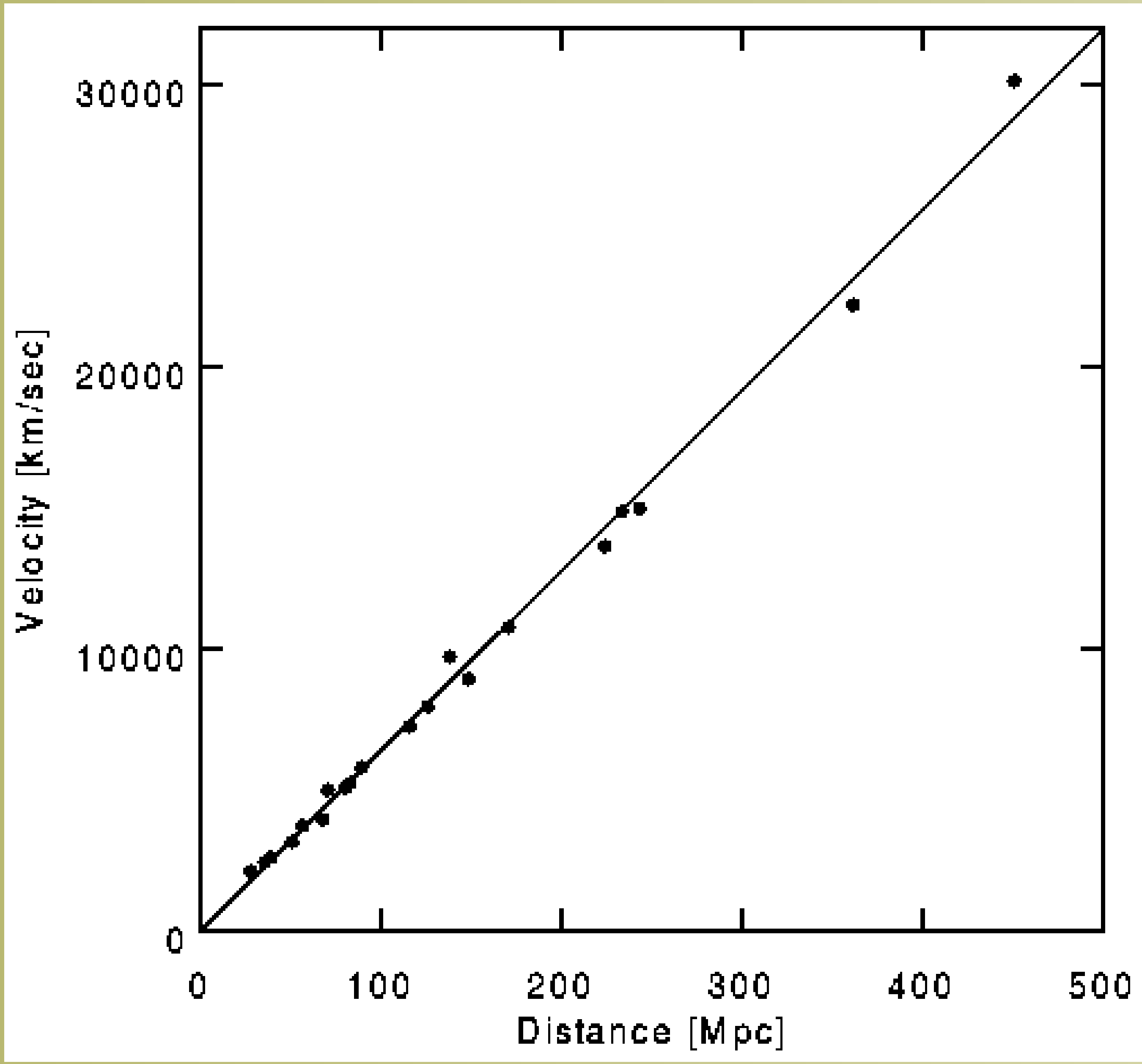
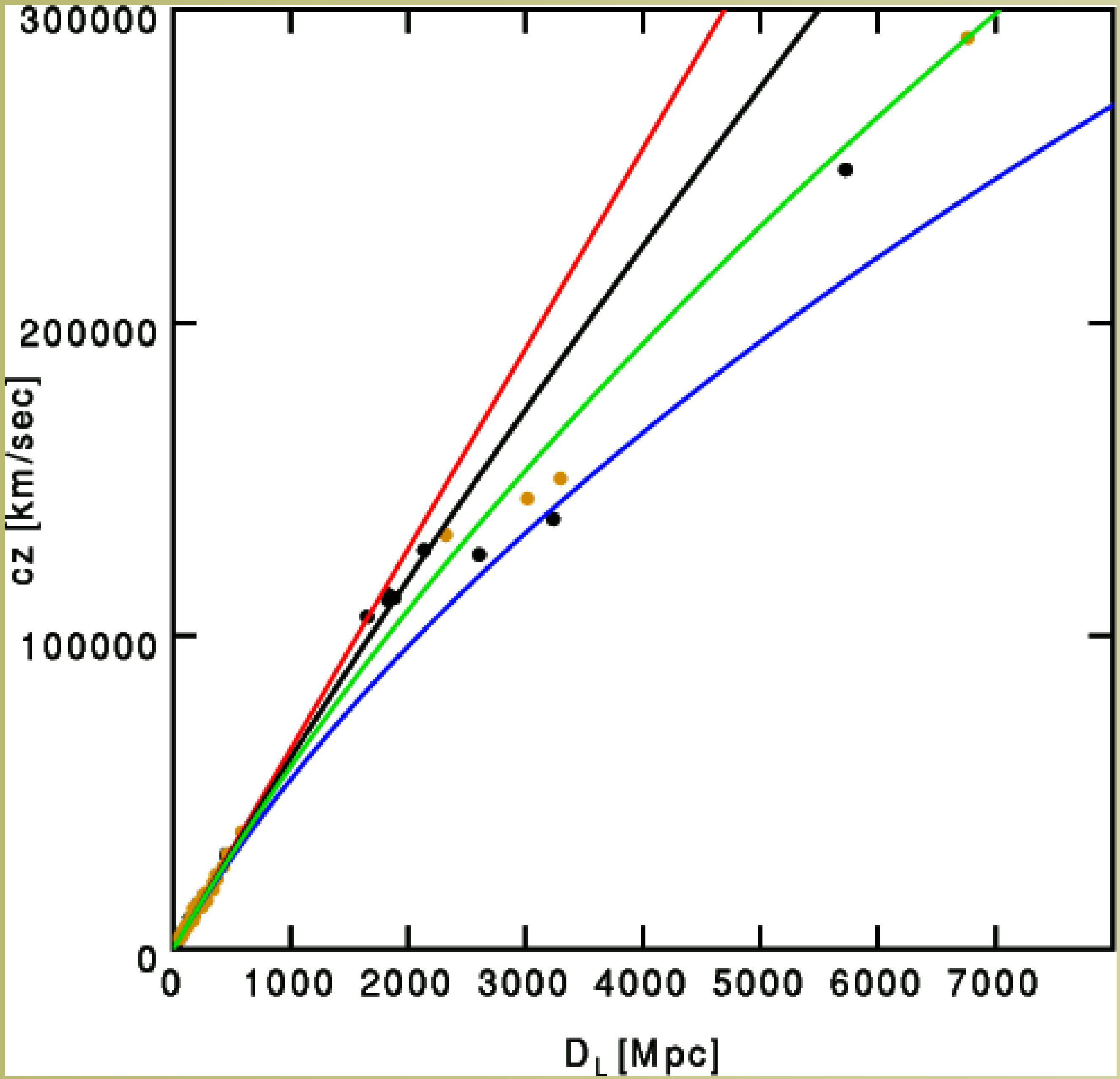
23 h
3 h


Velocity [km/sec]
30000
20000
10000
0
0
100
200
300
400
500
Distance [Mpc]


300000
200000
100000
0
cz [km/sec]
0
1000
2000
3000
4000
5000
6000
7000
D_L [Mpc]

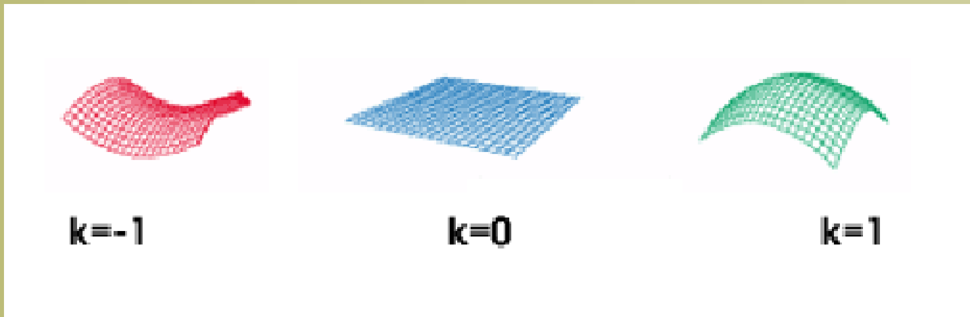
Gravity = curved space-time

General Relativity the theory of the space-time metric

$$\begin{aligned} ds^2 &= \sum_{\mu\nu} g_{\mu\nu} dx^\mu dx^\nu = dx^T g_{matrix} dx \\ &= dt^2 - R(t)^2 \{ \tfrac{dr^2}{1+kr^2} + r^2 d\theta^2 + r^2 \sin^2 d\phi^2 \} \end{aligned}$$

$R(t)$ the Scale factor ... A. A. Friedmann

$k = 0, \pm 1$ curvature constant : flat, spherical or hyperbolic geometries



Equation for R

$$\left(\frac{1}{R}\frac{dR}{dt}\right)^2 + \frac{k}{R^2} = \frac{8\pi}{3}G\rho$$

Equation of state $p = p(\rho)$ required

Radiation dominated Universe :

$p = \frac{1}{3}\rho \Rightarrow R(t) \propto t^{1/2}$

Matter dominated Universe :

$p = 0 \Rightarrow R(t) \propto t^{2/3}$

In the beginning – the Big Bang

Nuclear reactions in the Big Bang

- Matter and anti-matter not in equal quantities!

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- What kind of nuclei form as the Universe cools?
  - ⋆ 24% $^{4}\mathrm{He}$, 76% unprocessed H
  - ⋆ The rest minuscule but calculable

(pic)

... thermal history

e and p combine to form neutral Hydrogen ("recombination")

Left over photon gas at $T \approx 1eV \approx 12000K$

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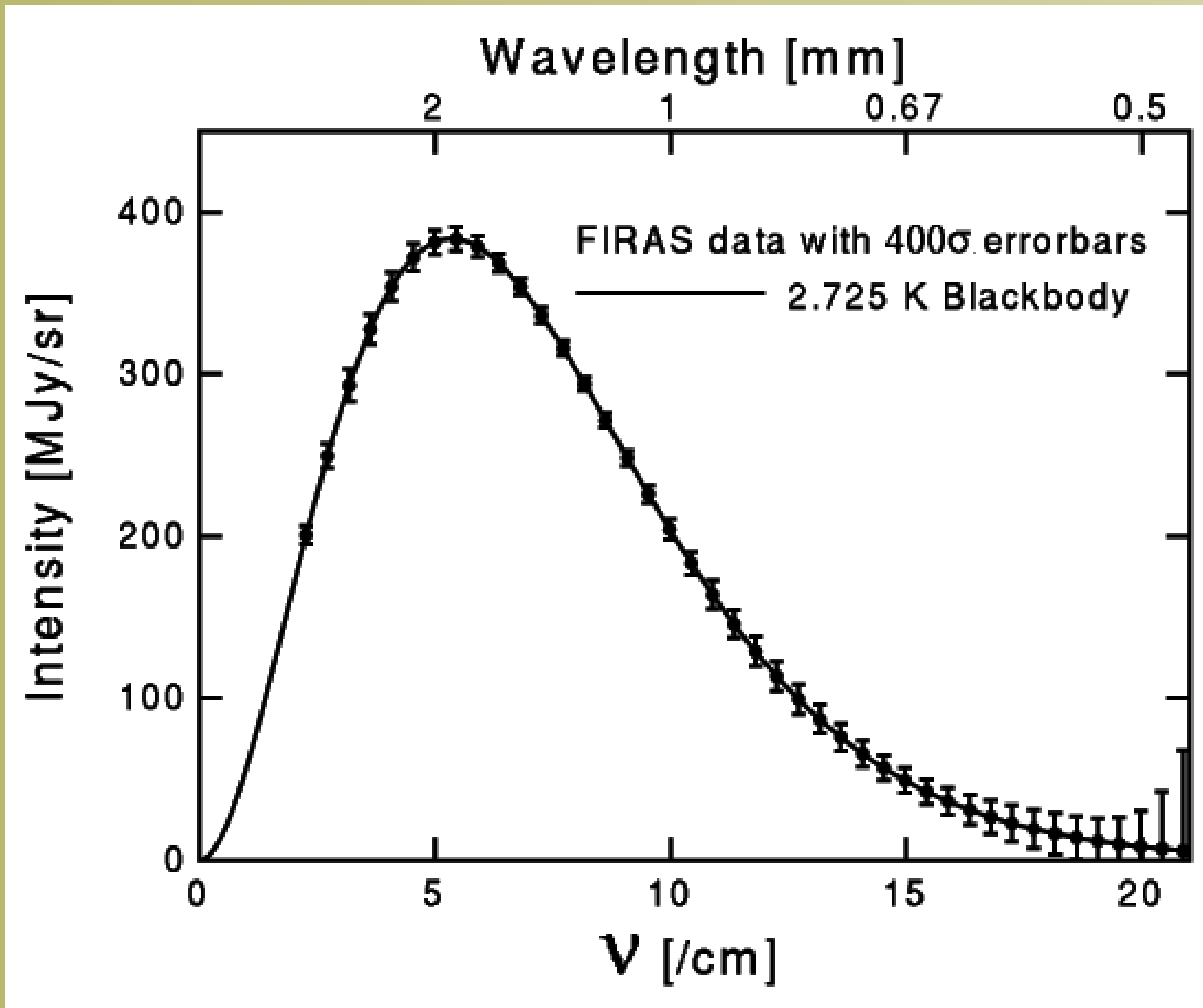

Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
0
5
10
15
20
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
ν [/cm]

More signals from cosmic frontier

Cosmic book keeping of contents

$$H^2 + \frac{k}{R^2} - \Lambda = \frac{8\pi G}{3}\rho \qquad \text{where } \rho = \text{Total energy}$$

another way of writing ...

$$1 + \frac{k}{H^2 R^2} = \Omega_\Lambda + \Omega_\rho$$

- ✔ Today LHS seems to be 1
  - ✔ So in the curvature term, $k = 0$

Signals ...

- ✔ Λ term seems to dominate, $\Omega_\Lambda = 0.7$
- ✔ But most of ρ is not baryons! Let $\Omega_\rho = \Omega_{DM} + \Omega_B$
  - ✔ Baryons contribute only $\Omega_B = 0.03$
  - ✔ $\Omega_{DM} = 0.27$ So much is the "Dark Matter"

Dark Matter and Dark Energy

Evidence for Dark Energy – acceleration in expansion rate

show movie

What can Dark Matter be?

It could have been neutrinos, but that would be too light ...

All other particles thoroughly searched at High Energy acceperators

Signature of new physics? Supersymmetry?

Inhomogeneity of photon gas

There are fluctuations $\frac{\Delta T}{T} \approx 10^{-6}$ as we scan different directions in sky

These are exactly as predicted by the theory of galaxy formation!

Before there was anything, there was nothing, right?

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Before there was anything, there was nothing, right?

So where did everything come from?

-BC cartoon

Black Holes

The theory ...

Schwarzschild solution to Einstein's equations

$$ds^2 = dt^2(1 - \frac{2GM}{rc^2}) - \frac{dr^2}{(1 - \frac{2GM}{rc^2})} + ...$$

Disaster at $R_s = \frac{2GM}{c^2}$?

The theory ...

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Disaster at $R_s = \frac{2GM}{c^2}$?

No, but the value is special.

If a given mass is concentrated to R less than its Schwarzschild radius it cannot be stopped from collapsing

R_s for the sun is

R_s for a 100kg person is

Total time of falling to $r = 0$ is finite

At $r = 0$ there is a ferocious singularity of space-time curvature.

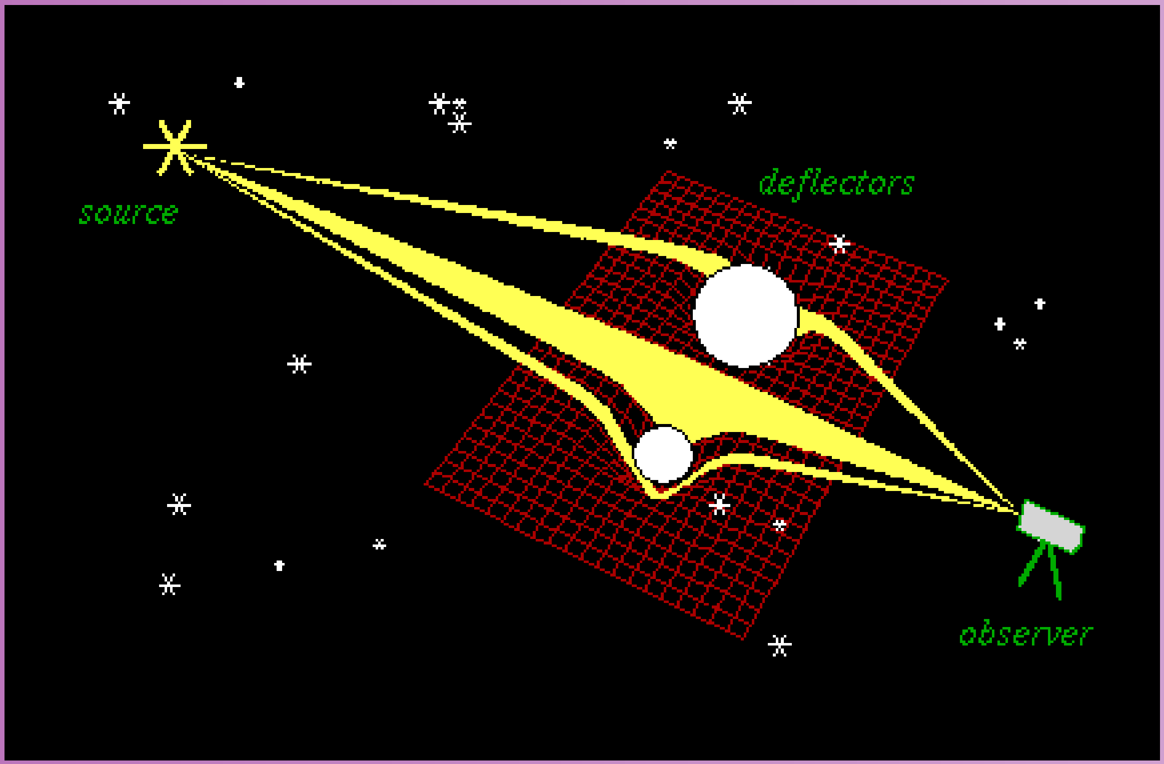
show 2 movies

Gravitational lensing

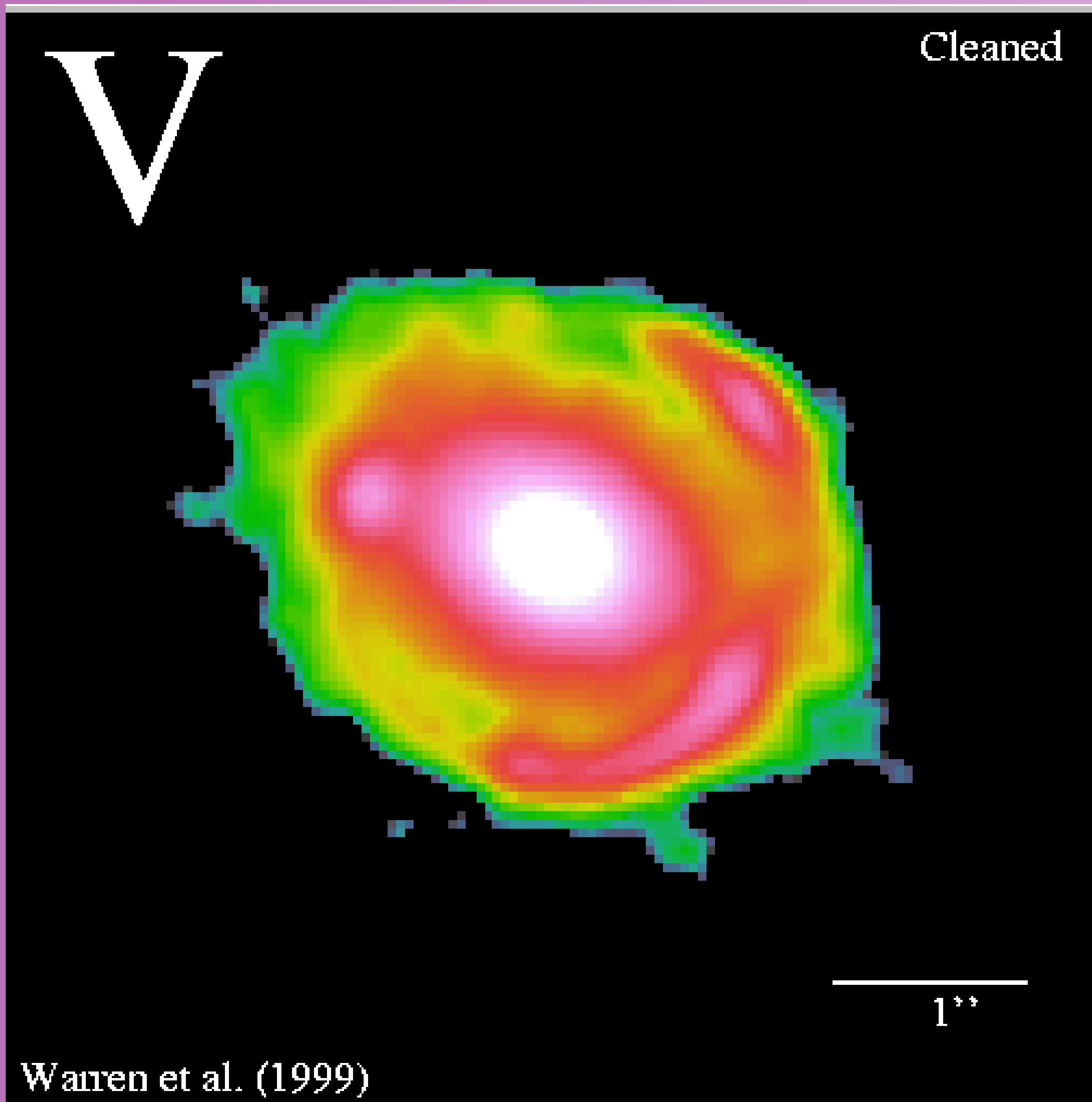
Huh ... ?

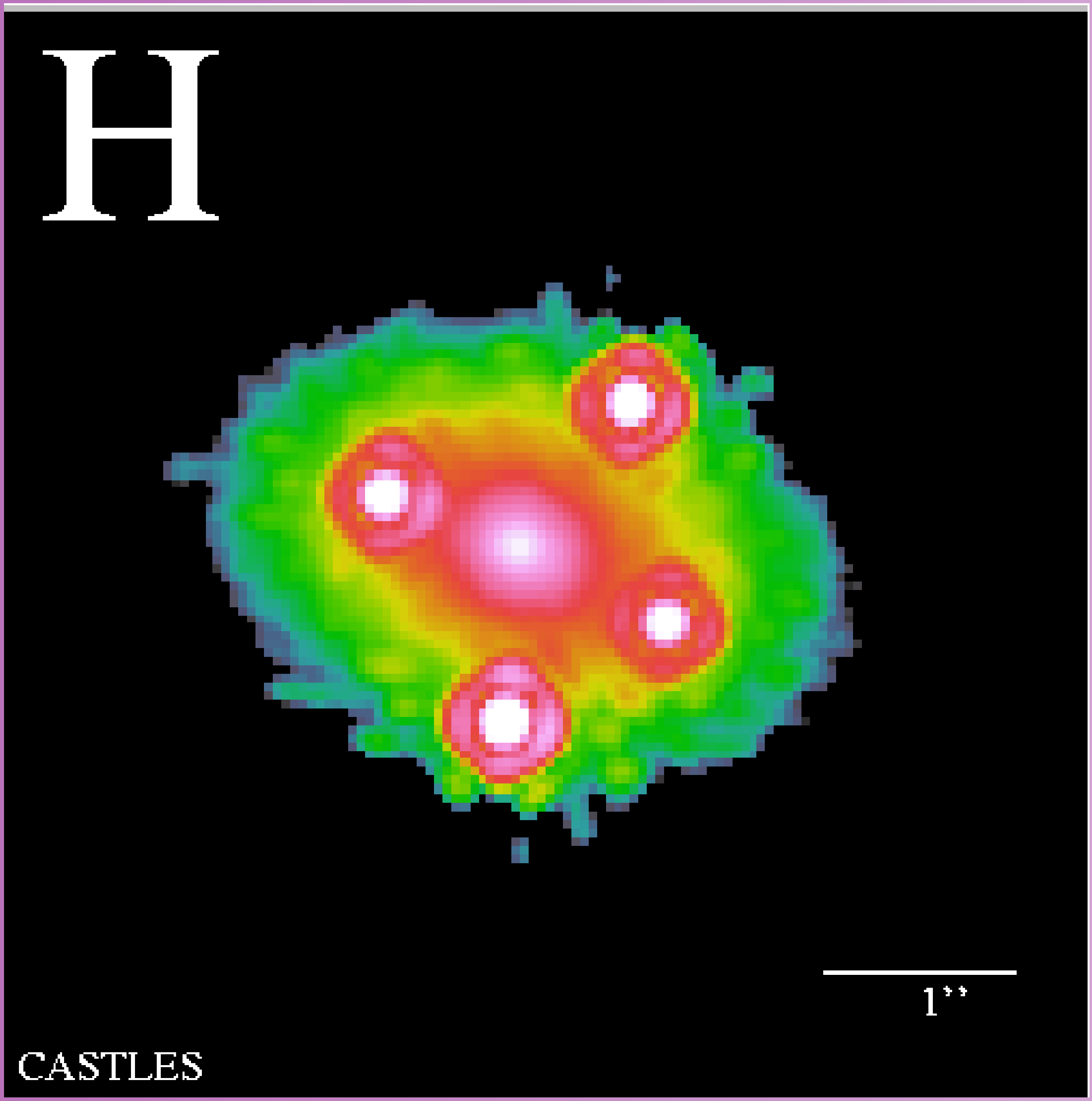
… *Ahh*

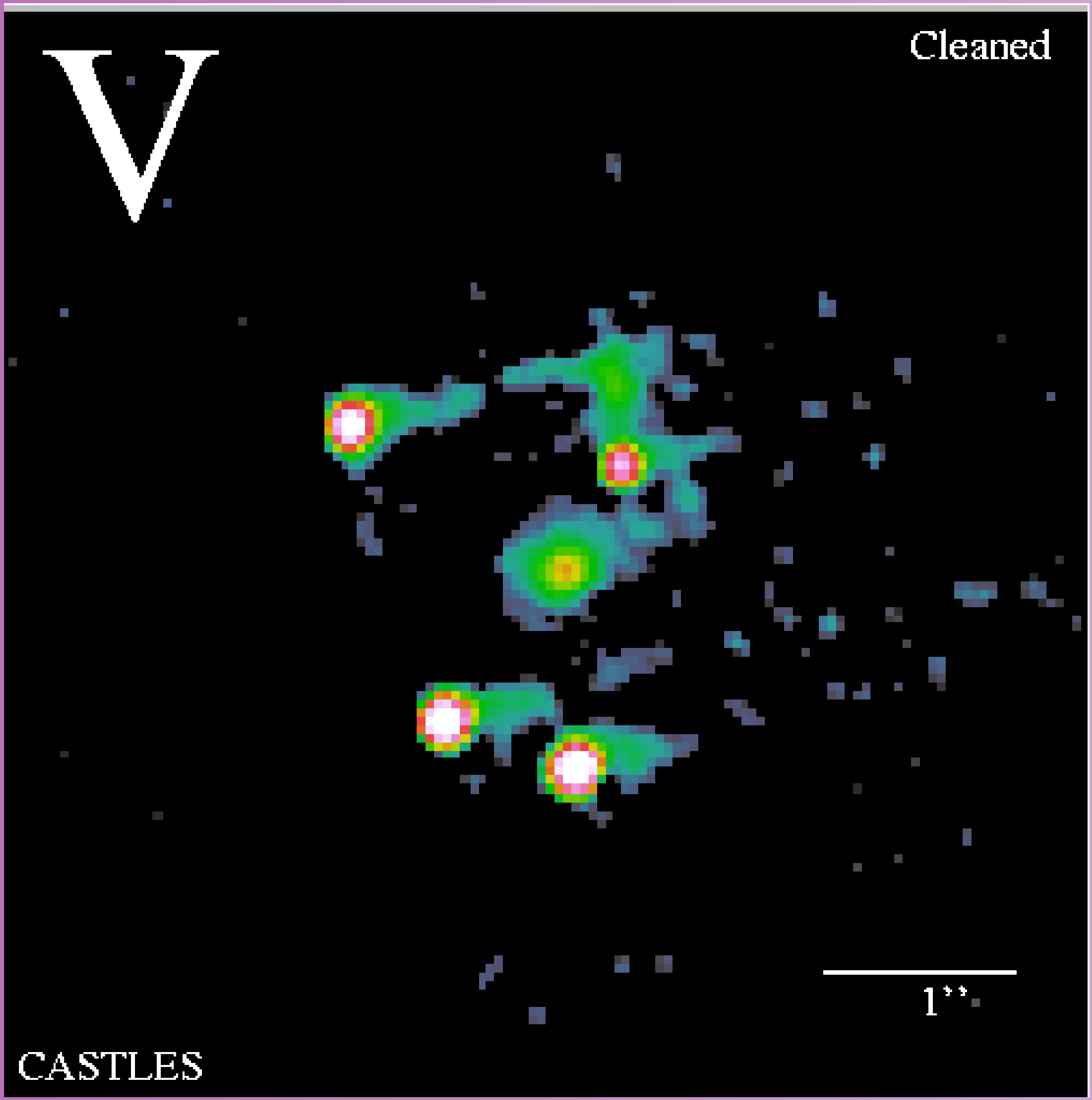
Physics argument



Show 2 movies


V
Cleaned
1''
Warren et al. (1999)


H
1''
CASTLES


V
Cleaned
1''
CASTLES

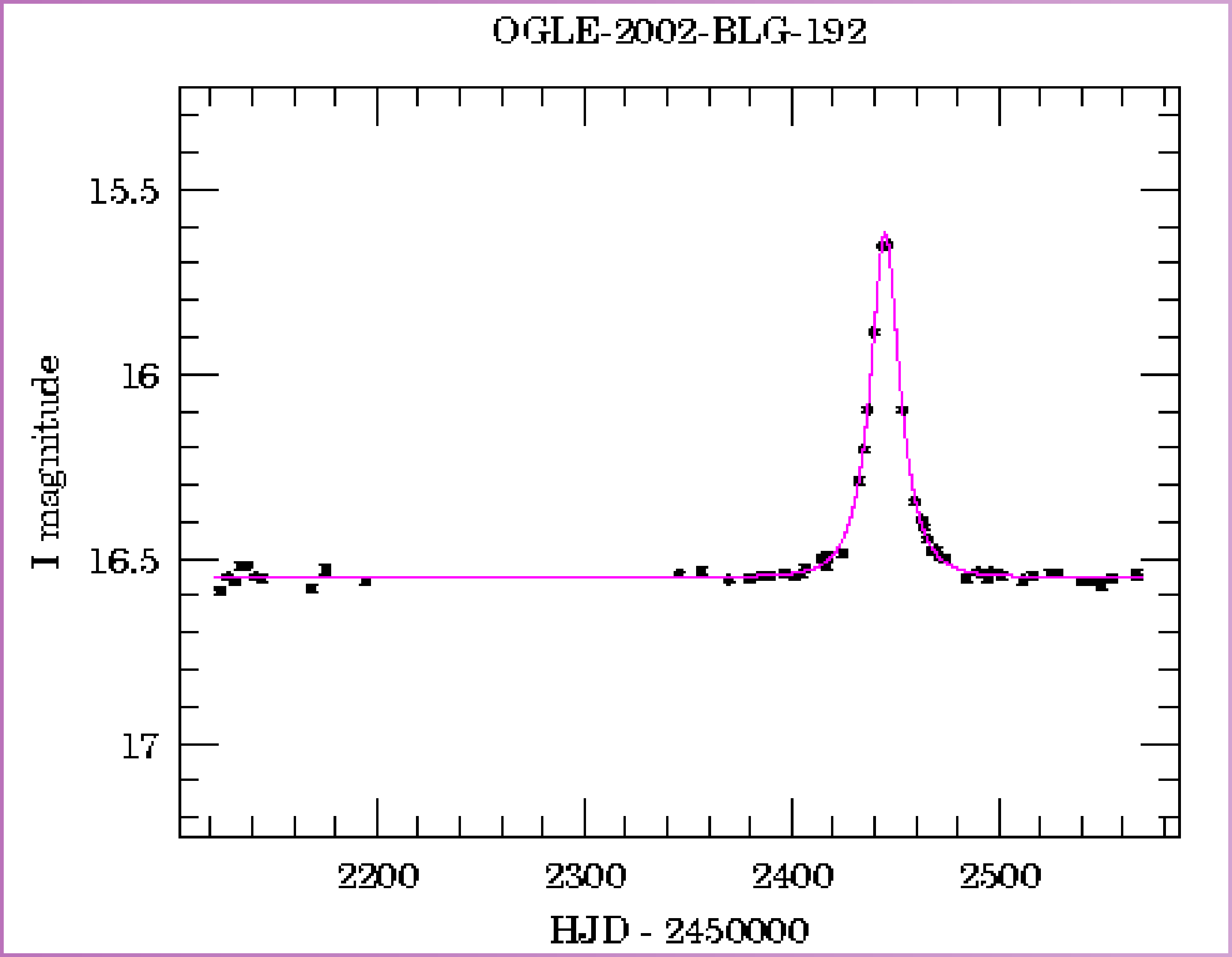
Microlensing

Lens much closer, but of small mass

Gives information about small optically invisible objects :

- *within our galaxy by lensing objects far away*
- *Planet occluding its larger partner star, both within our galaxy*

From OGLE project Poland, Chile, US ...


OGLE-2002-BLG-192
15.5
16
16.5
17
I magnitude
2200
2300
2400
2500
HJD - 2450000

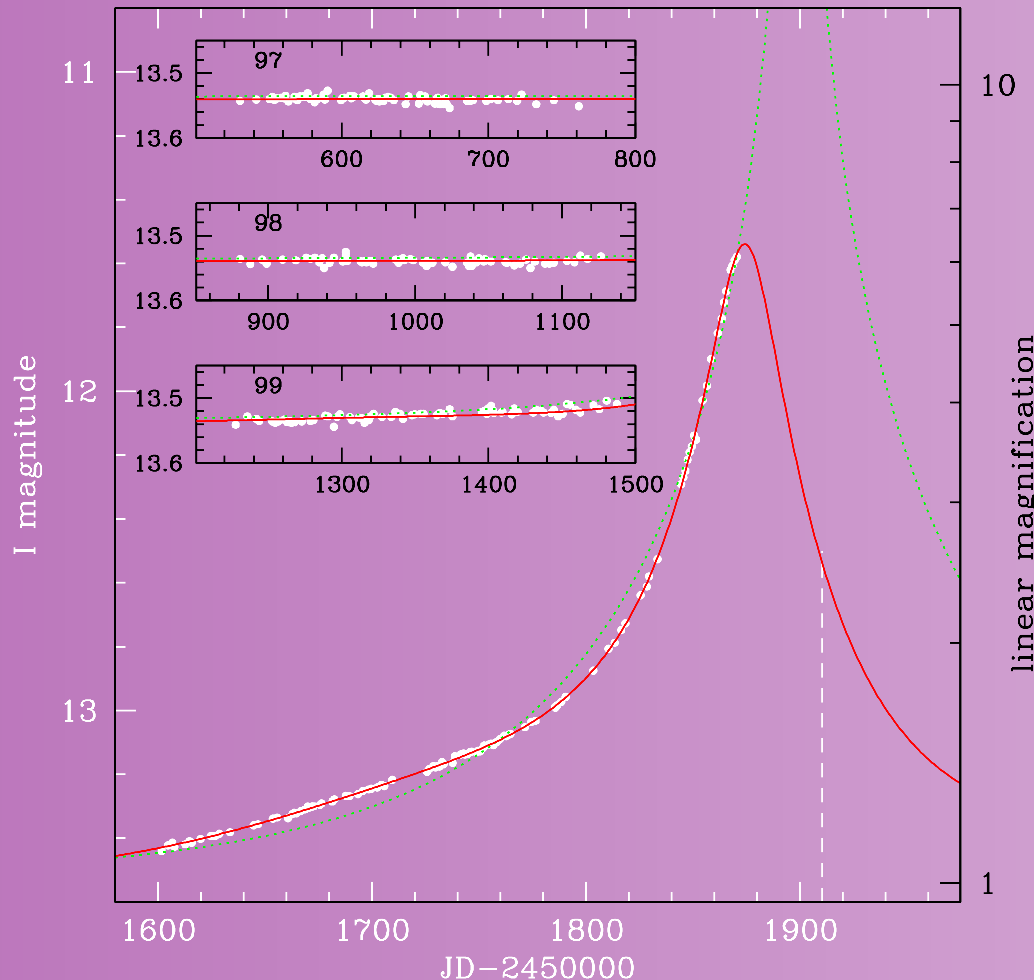


FIG. 2.— *I*-band light curve for the microlensing event OGLE-2000-BUL-43. The magnitude scale is shown on the left y-axis, while linear magnification is shown on the right y-axis. The dotted line is the standard model while the solid line is the best-fit model that takes into account the parallax effect and blending (second row in Table 1). The vertical dashed line marks January 1, 2001, 0UT. The three insets

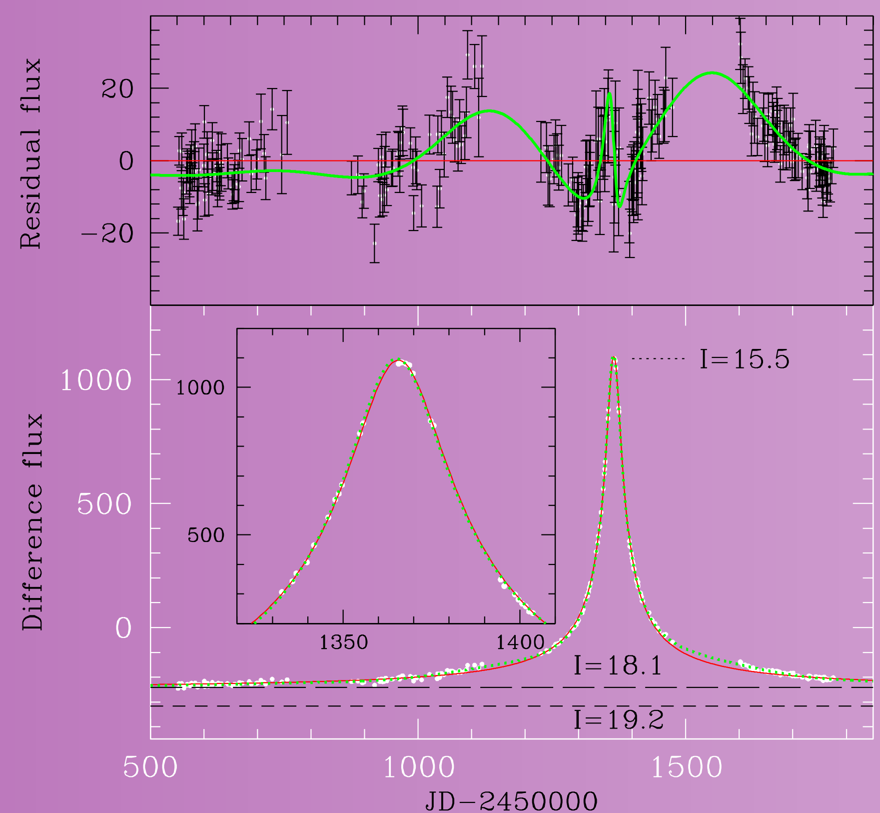
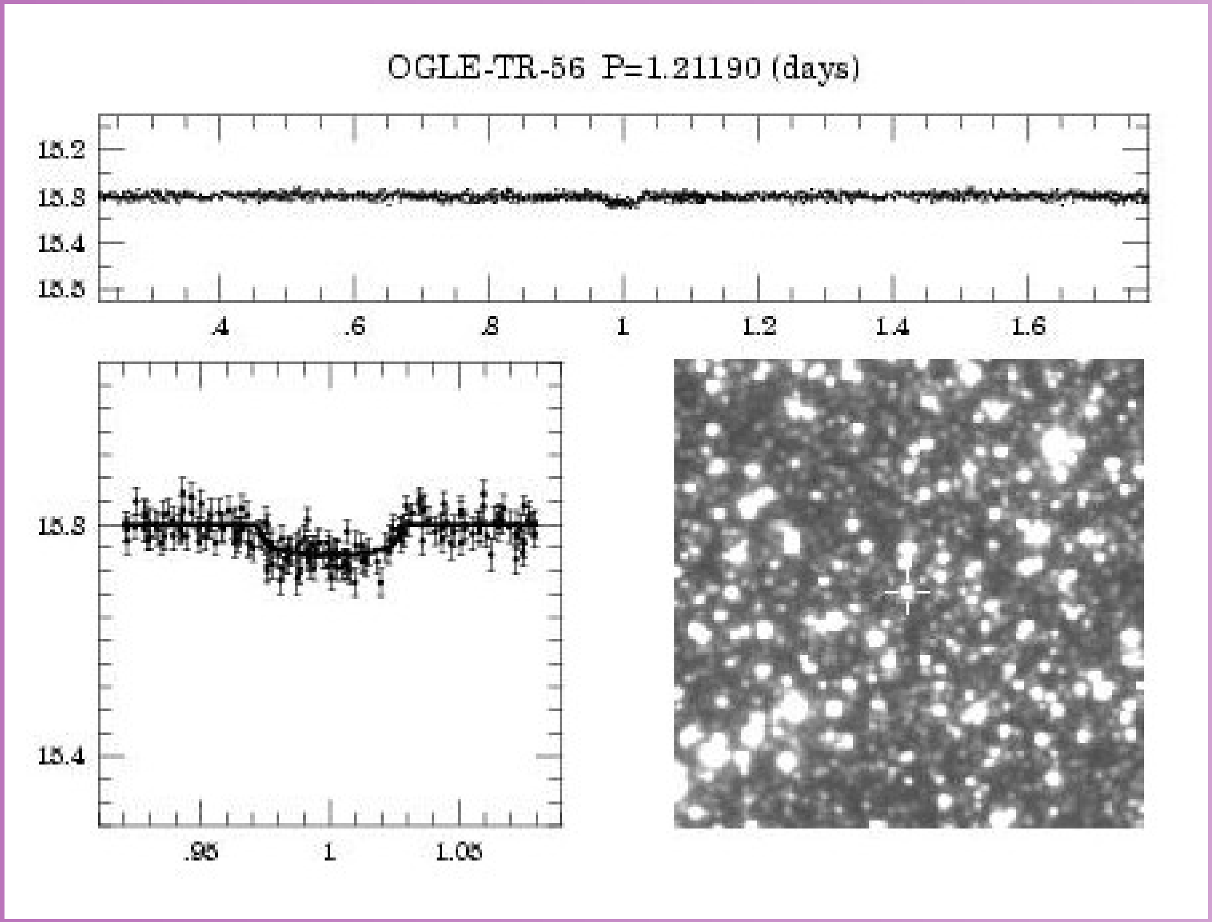


Figure 2. The *I*-band light curve for OGLE-1999-BUL-32 from difference image analysis. The solid and dotted lines are for the standard and parallax fits, respectively. The short-dashed line shows the baseline flux of the lensed star while the long-dashed line shows the total baseline flux of the lensed star and nearby blend(s). The approximate *I*-band magnitudes are indicated for these two baselines, together with the peak *I*-band magnitude. The inset shows the the light curve close to the peak. The top panel shows the residual flux (the observed data points subtracted by the standard model). Clearly the standard model shows systematic discrepancies. The curved solid line shows the prediction of the parallax model.


OGLE-TR-56 P=1.21190 (days)
15.2
15.3
15.4
15.5
.4
.6
.8
1
1.2
1.4
1.6
15.3
15.4
.95
1
1.05

Gravitational waves

Einstein's equations give a wave equation for perturbations in the metric tensor

Electromagnetic waves polarised – direction determined by plan of the electric field vector

Gravitational waves are simultaneous oscillations in two perpendicular directions

Upper Limits

E7 Data Analysis Working Groups

- **Compact binary inspiral:** ***"chirps"***
- **Supernovae / GRBs:** ***"bursts"***
- **Pulsars in our galaxy:** ***"periodic"***
- **Cosmological Signal** ***"stochastic background"***

Reports scheduled at the LIGO I Meeting this Thursday