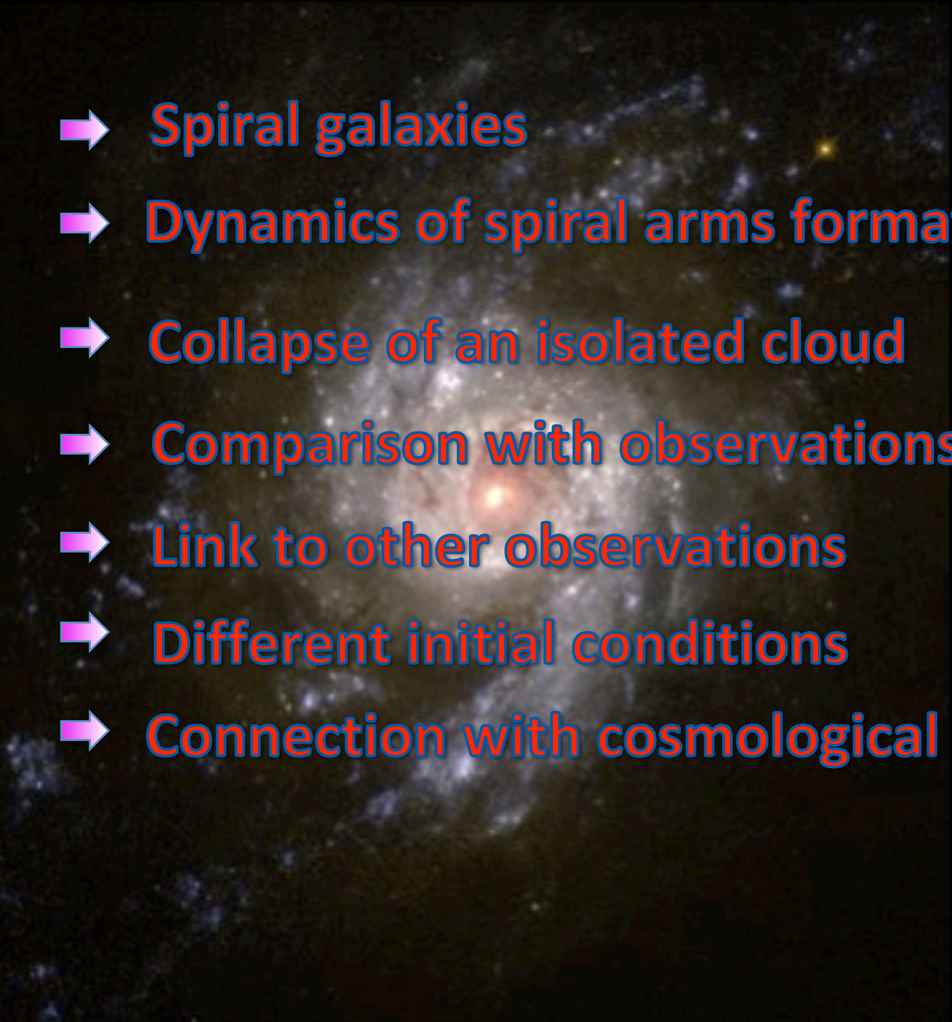
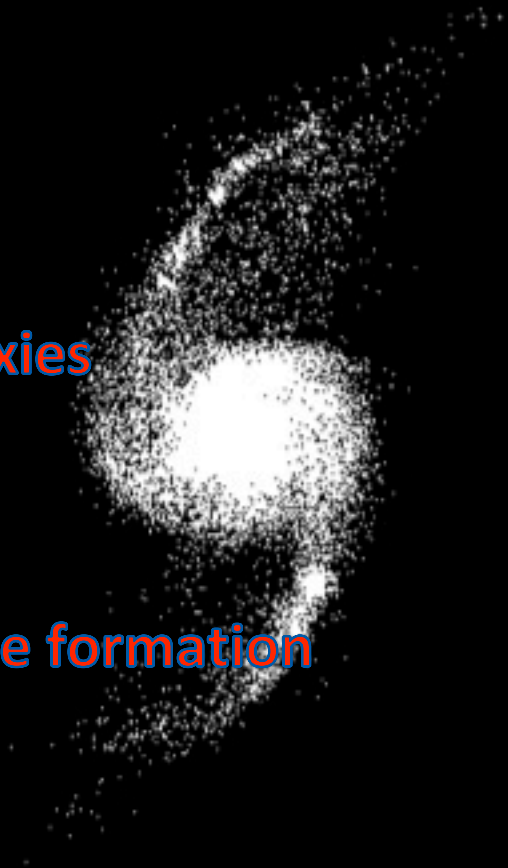
Transient spiral arms and galaxy rotation curves

Francesco Sylos Labini

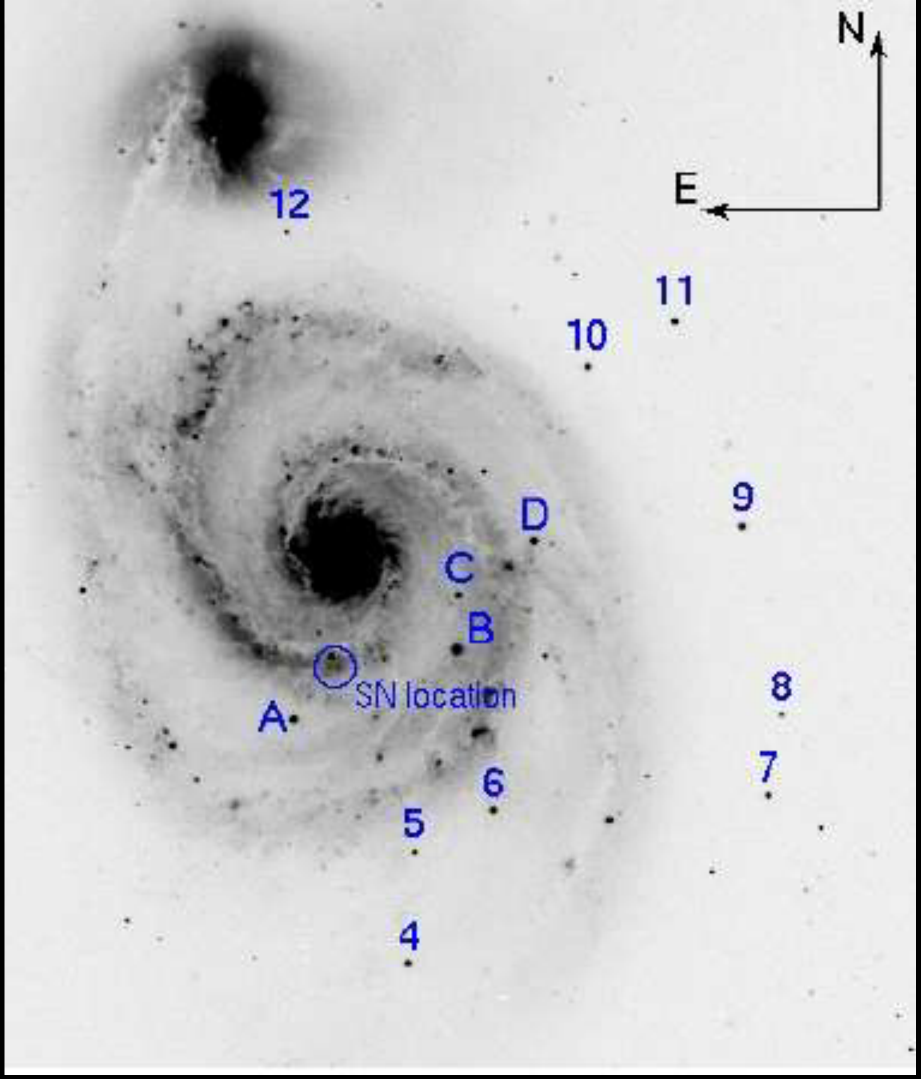
- Institute for Complex Systems, CNR (Rome, Italy)
- Enrico Fermi Center (Rome, Italy)



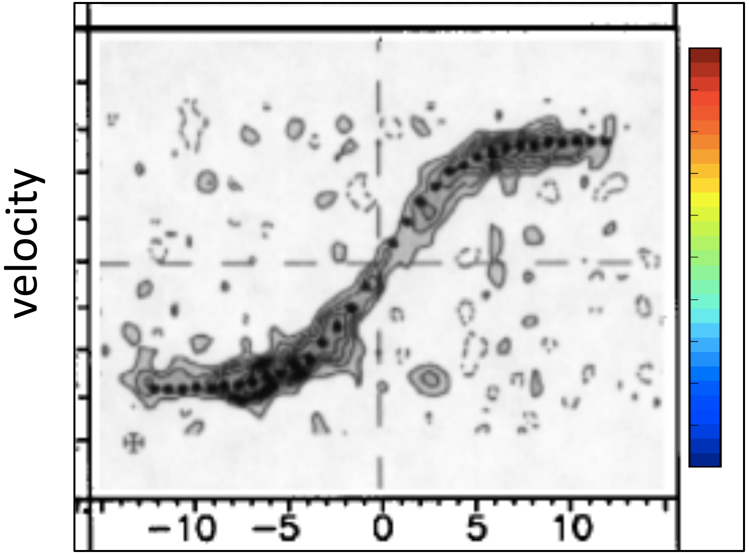


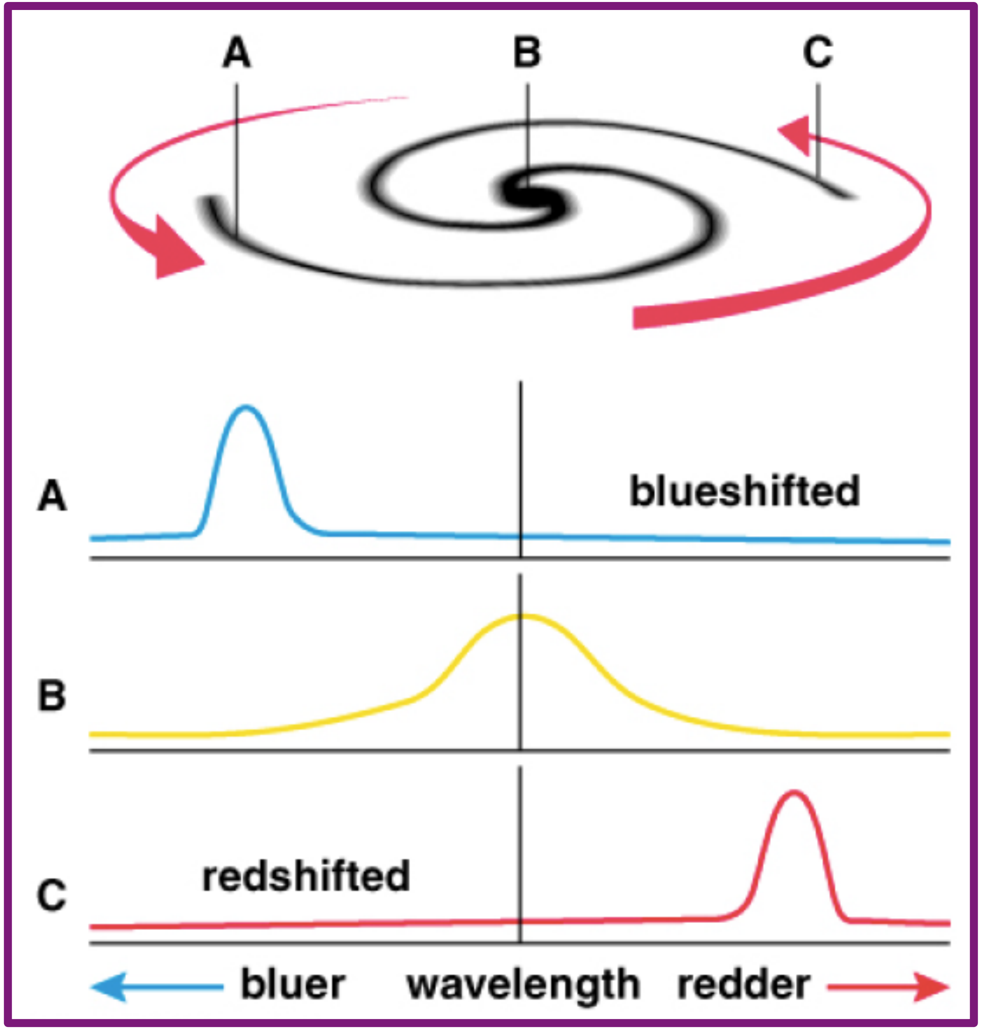
- Spiral galaxies
- Dynamics of spiral arms formation
- Collapse of an isolated cloud
- Comparison with observations of galaxies
- Link to other observations
- Different initial conditions
- Connection with cosmological structure formation

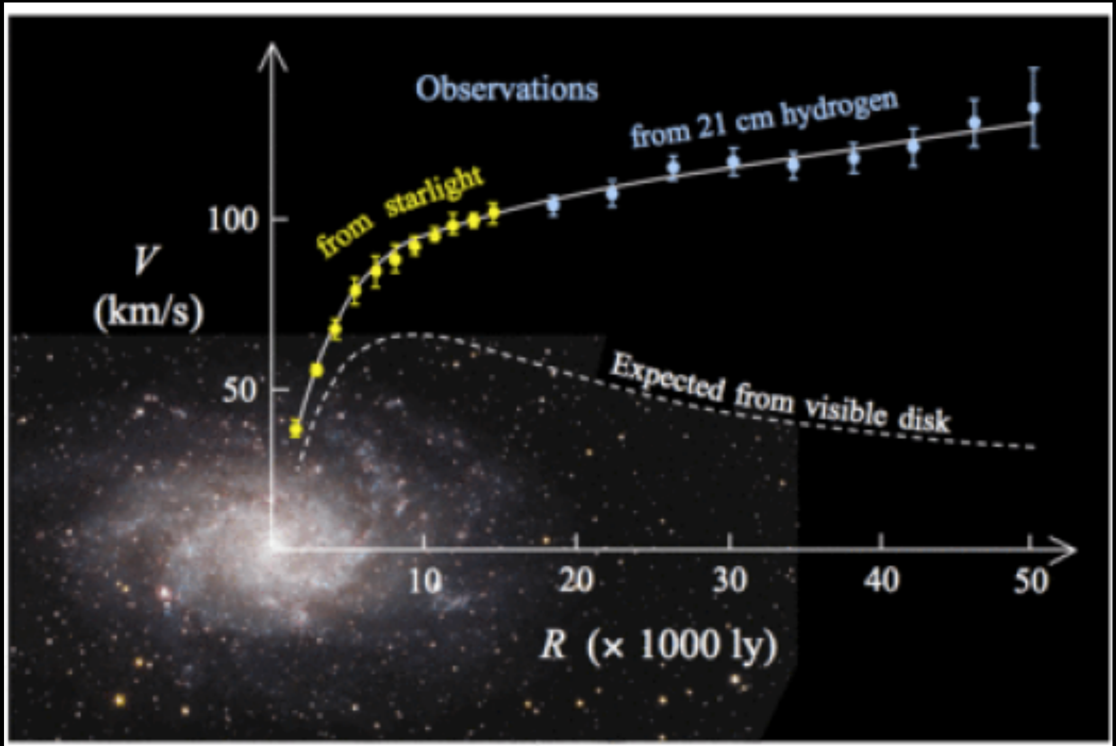


N
E
12
11
10
9
D
C
B
SN location
A
8
7
6
5
4


velocity
−10
−5
0
5
10


A
B
C
A
blueshifted
B
C
redshifted
bluer
wavelength
redder

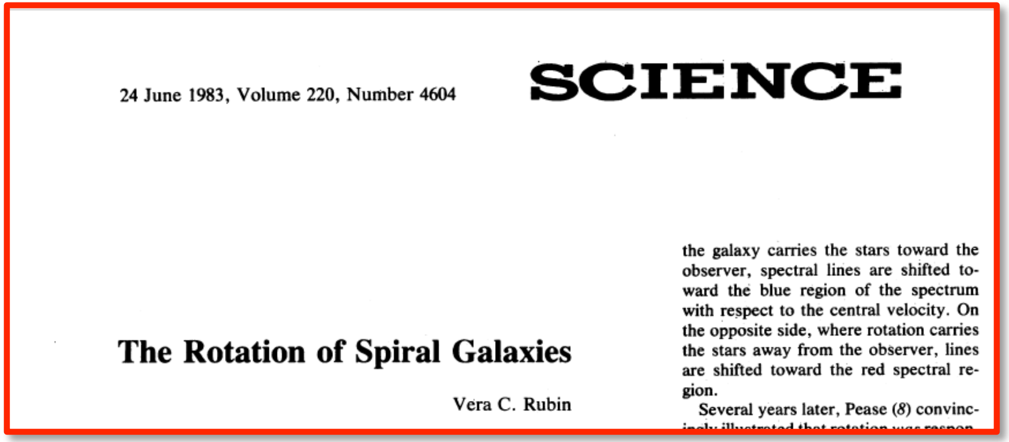


Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

$$F_N = ma$$

$$ma = m\frac{v_c^2(r)}{r} = \frac{GmM(r)}{r^2}$$ **Spheroidal mass distribution**

$$M(r) \propto v_c^2(r) \cdot r \sim r^{1+\alpha} \quad \alpha \geq 0 \;\; (\text{but also} \;\; \alpha < 0)$$



24 June 1983, Volume 220, Number 4604

SCIENCE

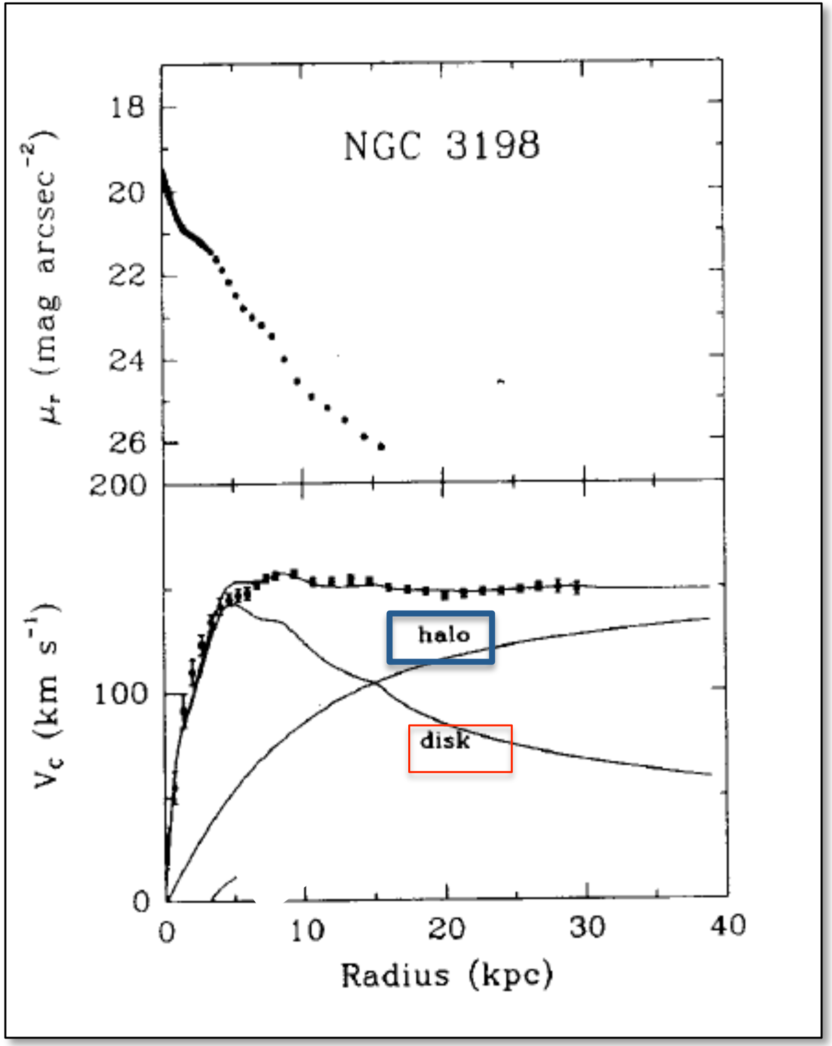
The Rotation of Spiral Galaxies

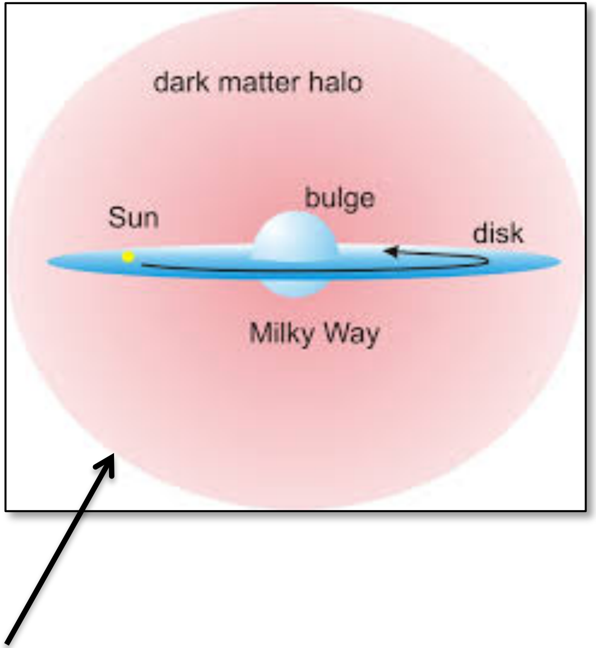
Vera C. Rubin

the galaxy carries the stars toward the observer, spectral lines are shifted toward the blue region of the spectrum with respect to the central velocity. On the opposite side, where rotation carries the stars away from the observer, lines are shifted toward the red spectral region.

Several years later, Pease (8) convinc-

- Newton's dynamics
- Newton's gravity
- *Equilibrium*





$$P(v) \approx \quad \text{isotropic}$$

$$F_N = m\mu\left(\frac{a}{a_0}\right)a$$

$$\mu(x) \to 1 \quad for \quad x \gg 1$$

$$\mu(x) \to x \quad for \quad x \ll 1$$

$$F_N = m\frac{a^2}{a_0} \quad for \quad a < a_0$$

$$m\frac{a^2}{a_0} = m\frac{(v^2/r)^2}{a_0} = \frac{GMm}{r^2} \to \boxed{v^4 = GMa_0}$$

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

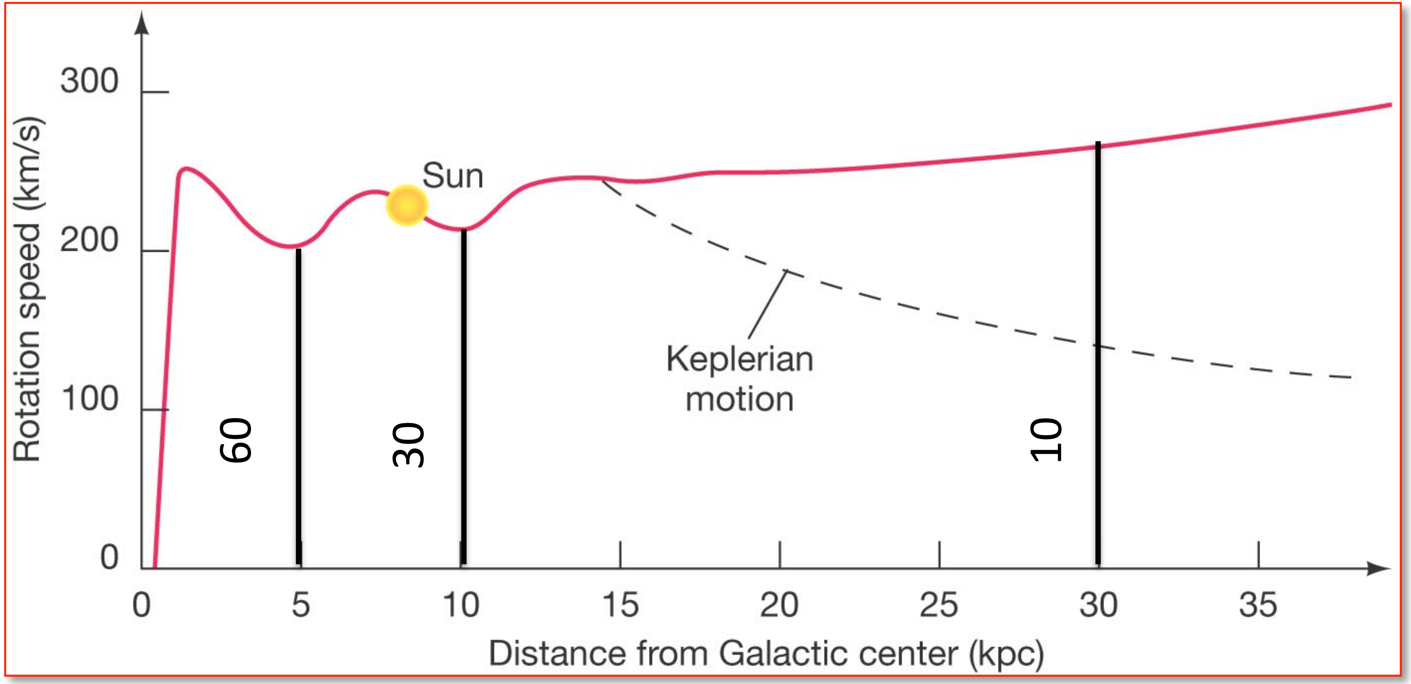
M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

- ➢Modified Newton dynamics
- ➢Newton gravity
- ➢*Equilibrium*

$$v_G = 200\beta \text{ km sec}^{-1}$$

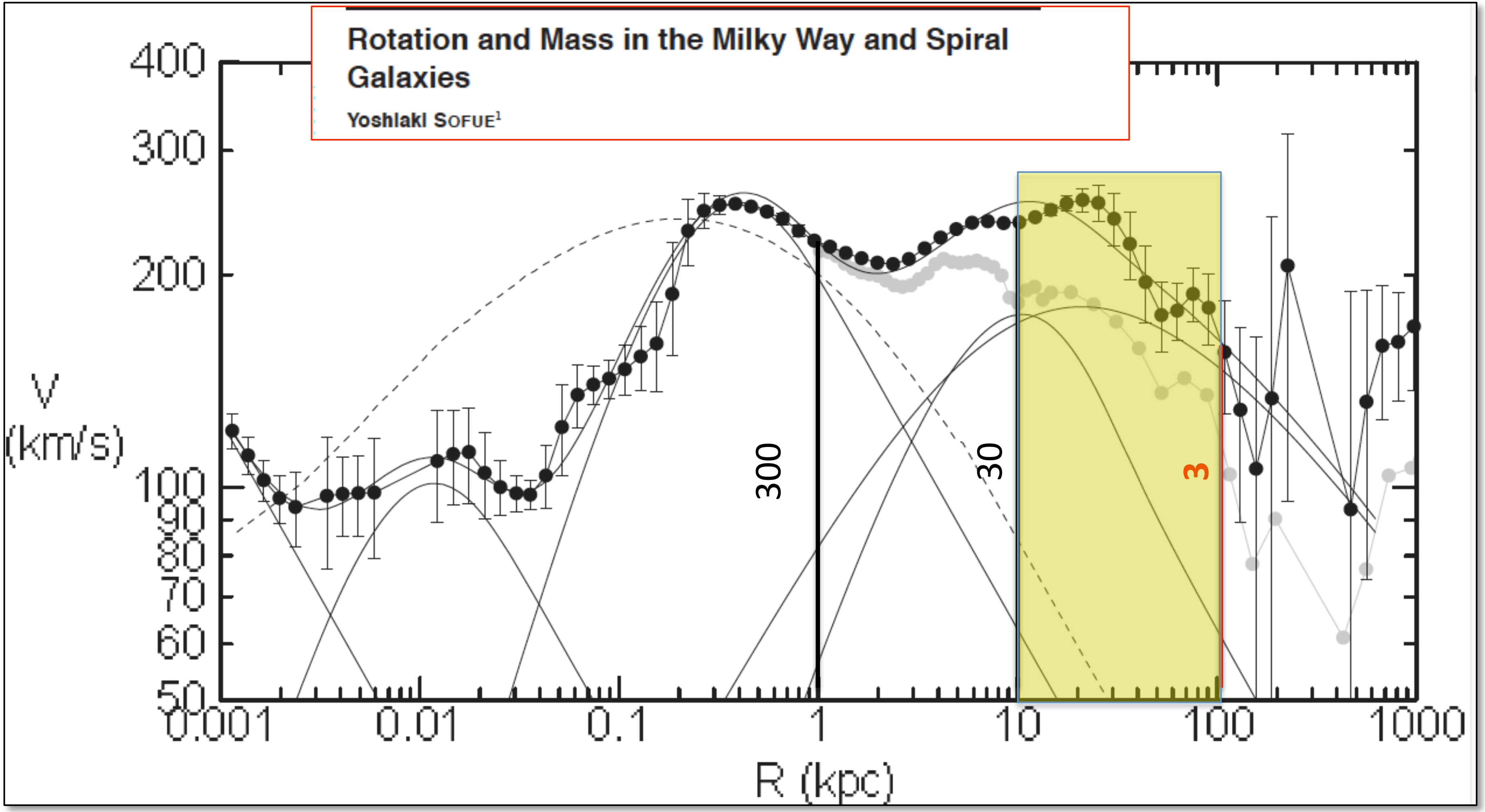
$$T_G = 10 \cdot \Delta \text{ Gyr}$$

$$n_{Rev}(R) = \frac{T_{age}}{\tau_{Rev}(R)} = \frac{T_{age} v_c(R)}{2\pi R} \approx \frac{30\Delta\beta}{R/10\text{Kpc}}$$



Rotation and Mass in the Milky Way and Spiral Galaxies

Yoshiaki SOFUE[1]



$$a = a_c = \frac{v^2}{r}$$ ⟺ Stationary equilibrium

- Not a trivial assumption!
- But used both by DM and MOND
- How long to relax ? Transients? Which QSS?

Gravity is long-range !

- **Dynamics of spiral galaxy formation**

Dynamics of spiral arms formation

Publications of the Astronomical Society of Australia (PASA)

doi: 10.1017/pas.2014.xxx.

Dawes Review 4: Spiral Structures in Disc Galaxies

Clare Dobbs[1], and Junichi Baba[2]
[1]School of Physics and Astronomy, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK
[2]Earth-Life Science Institute, Tokyo Institute of Technology 2-12-1-I2-44 Ookayama, Meguro, Tokyo 152–8551, Japan

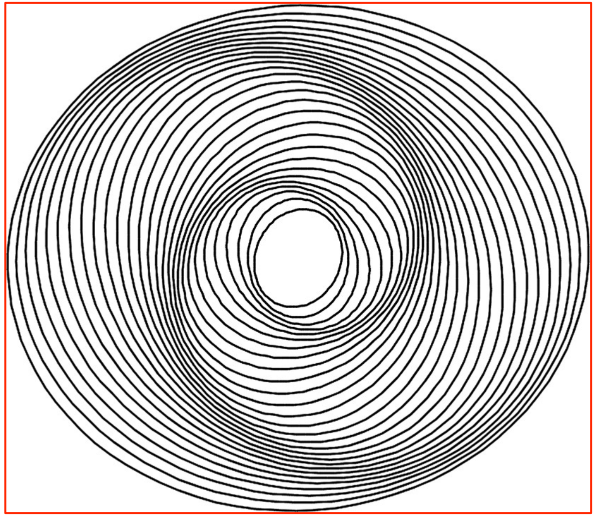
Abstract
The majority of astrophysics involves the study of spiral galaxies, and stars and planets within them, but how spiral arms in galaxies form and evolve is still a fundamental problem. Major progress in this field was made primarily in the 1960s, and early 1970s, but since then there has been no comprehensive update on the

Three **main mechanisms** hypothesised to produce spiral arms

- Quasi-stationary density wave theory
- Local instabilities, perturbations, or noise which are swing amplified into spiral arms
- Tidal interactions

ON THE SPIRAL STRUCTURE OF DISK GALAXIES

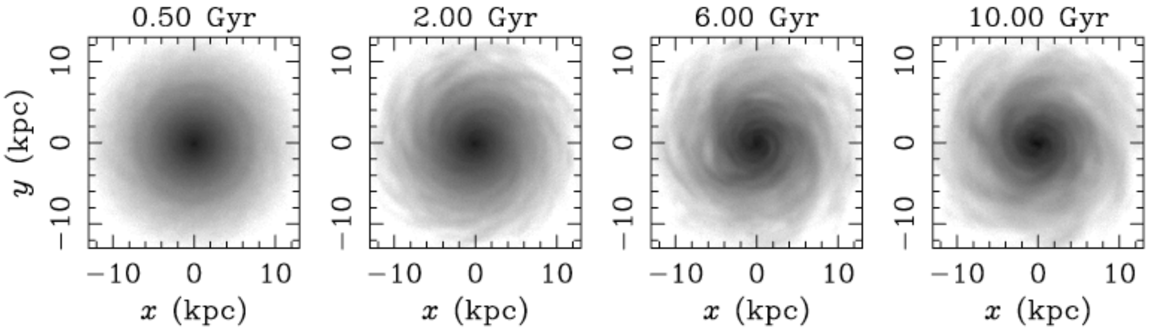
C. C. LIN AND FRANK H. SHU
Department of Mathematics, Massachusetts Institute of Technology
Received March 20, 1964



II. SPIRAL ARMS AS SHEARED GRAVITATIONAL INSTABILITIES

P. Goldreich and D. Lynden-Bell*

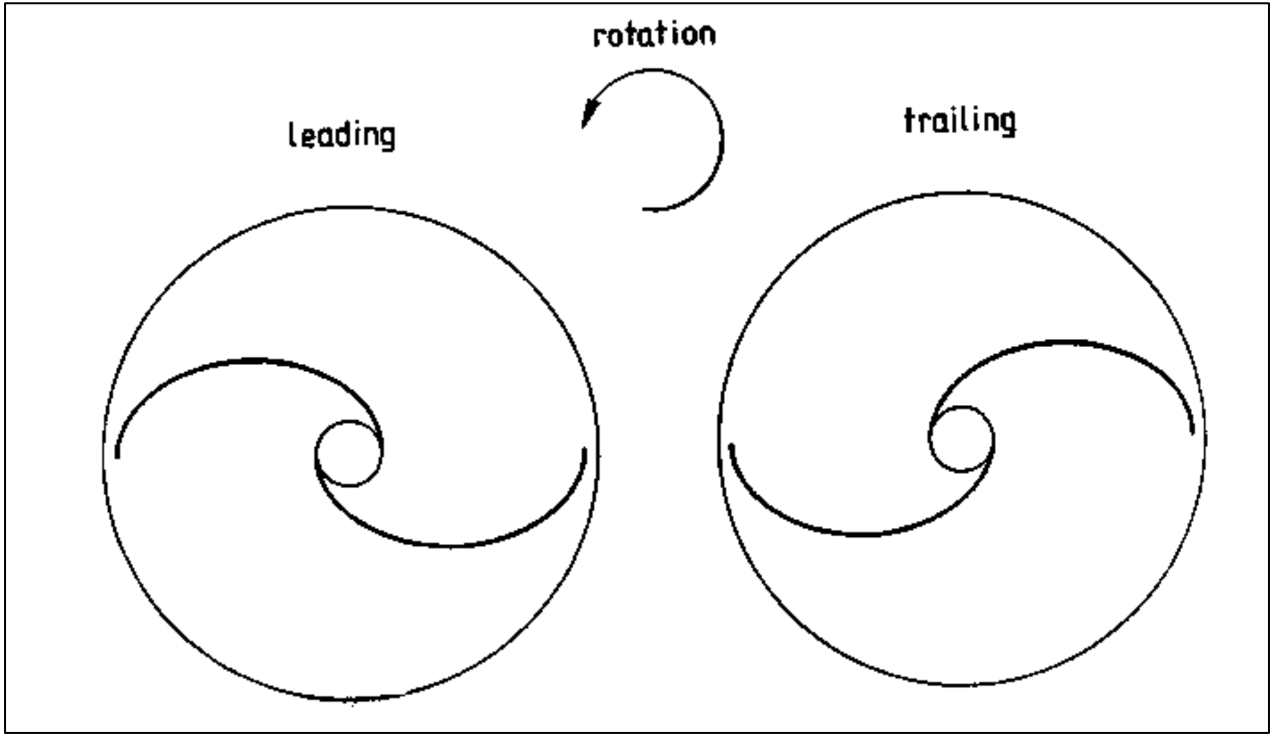
(Received 1964 June 25)



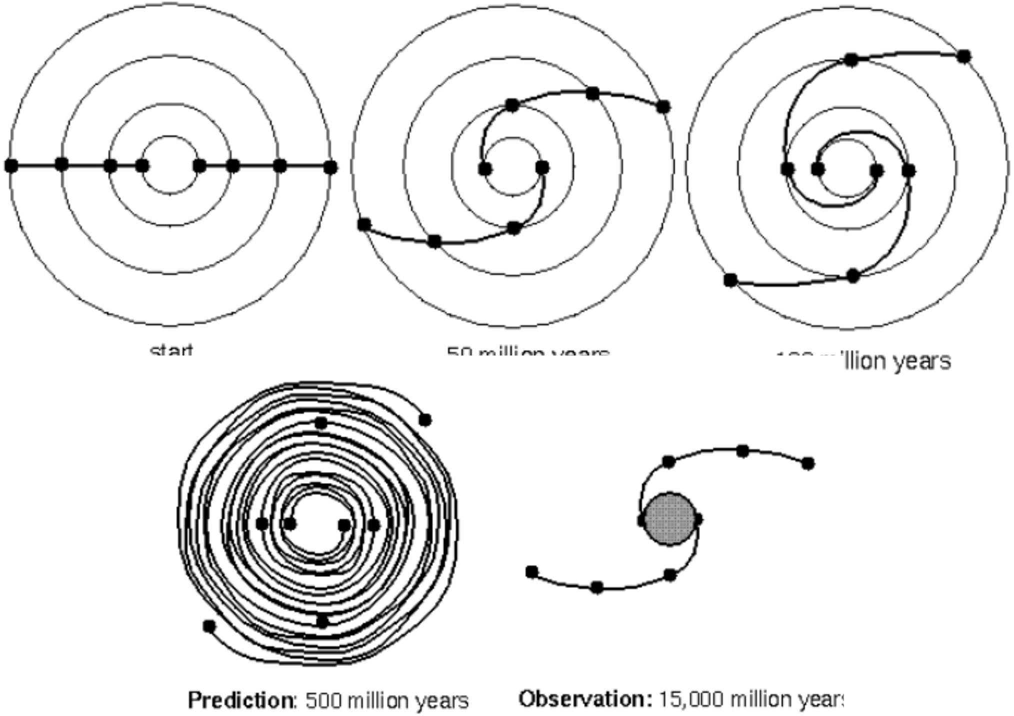
- **The strength and number of arms**: The dominance of two-armed patterns in grand-design spirals is a striking observational fact that **demands explanation** in a successful theory of spiral structure.

Trailing nature of arms

In all cases in which the answer is unambiguous, the spiral arms trail.



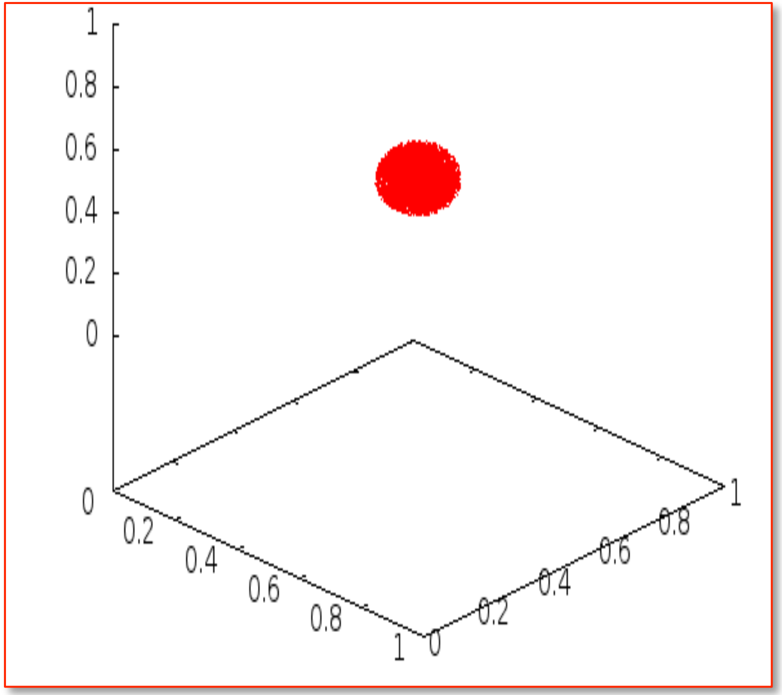
Winding Problem



Differential rotation rotation creates a spiral pattern in a short time

Collapse of an isolated cloud

Dynamics of a **spherical** isolated cold cloud

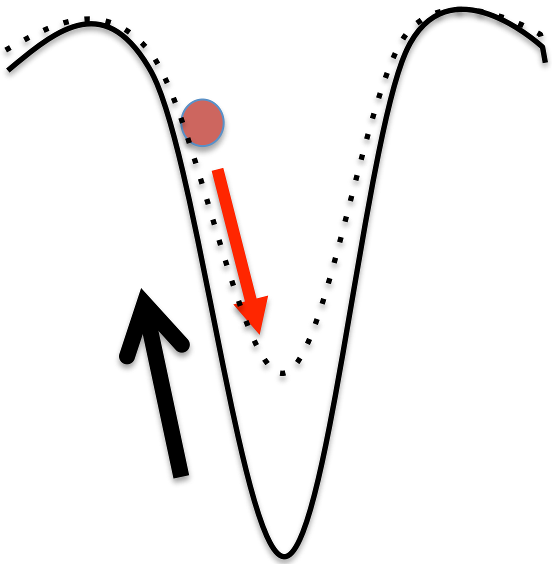


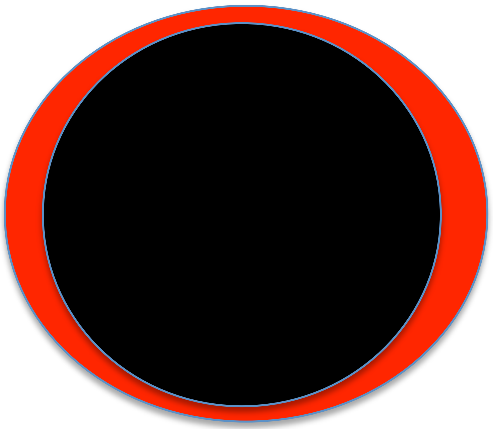
$$\begin{cases} E_{tot} = const \\ \vec{L}_{tot} = const \\ \vec{P}_{tot} = const \end{cases}$$

$$\frac{d^2\vec{r}_i}{dt^2} = -Gm \sum_{j \neq i}^{j=1,N} \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|^3}$$

Joyce M., Marcos B., Sylos Labini F., MNRAS, **397**, 2, 775-792 (2009) Sylos Labini, F. 2013, Astron.Astrophys, **552A**, 36

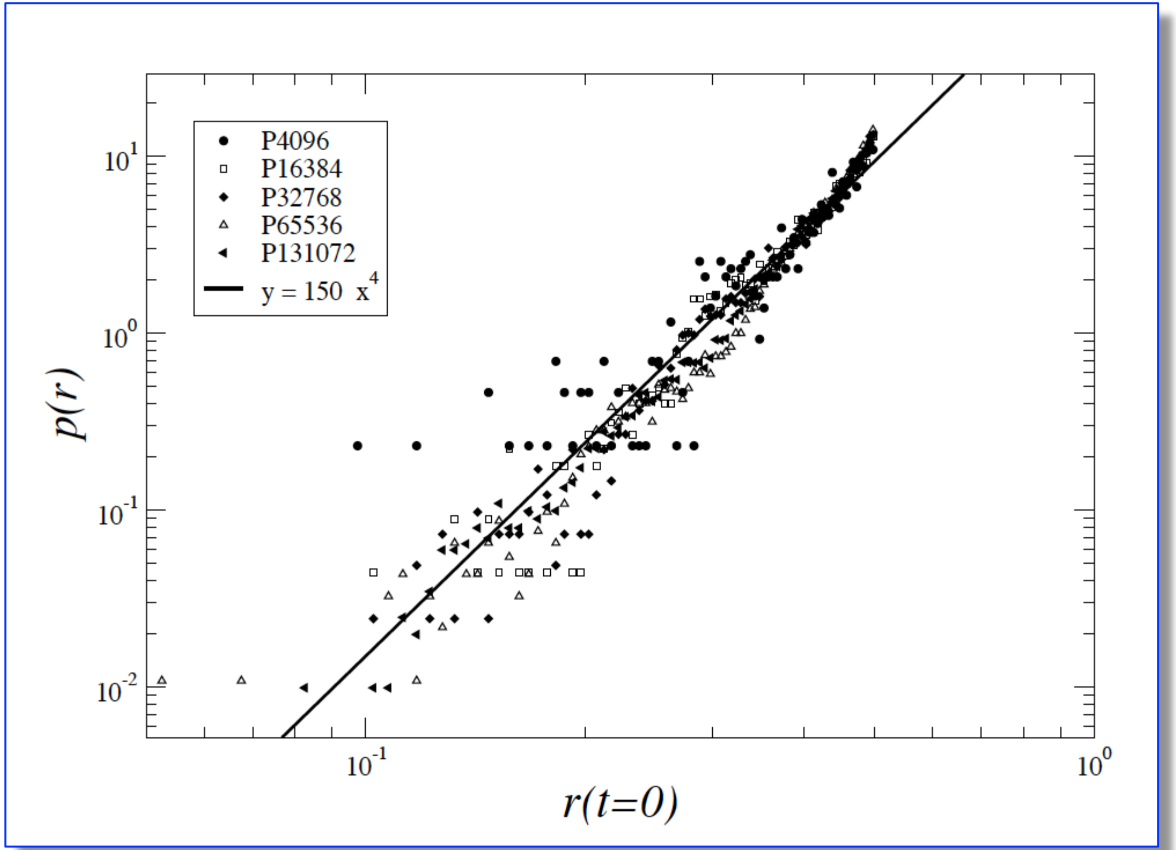
Particles motion in a **rapidly varying** gravitational field



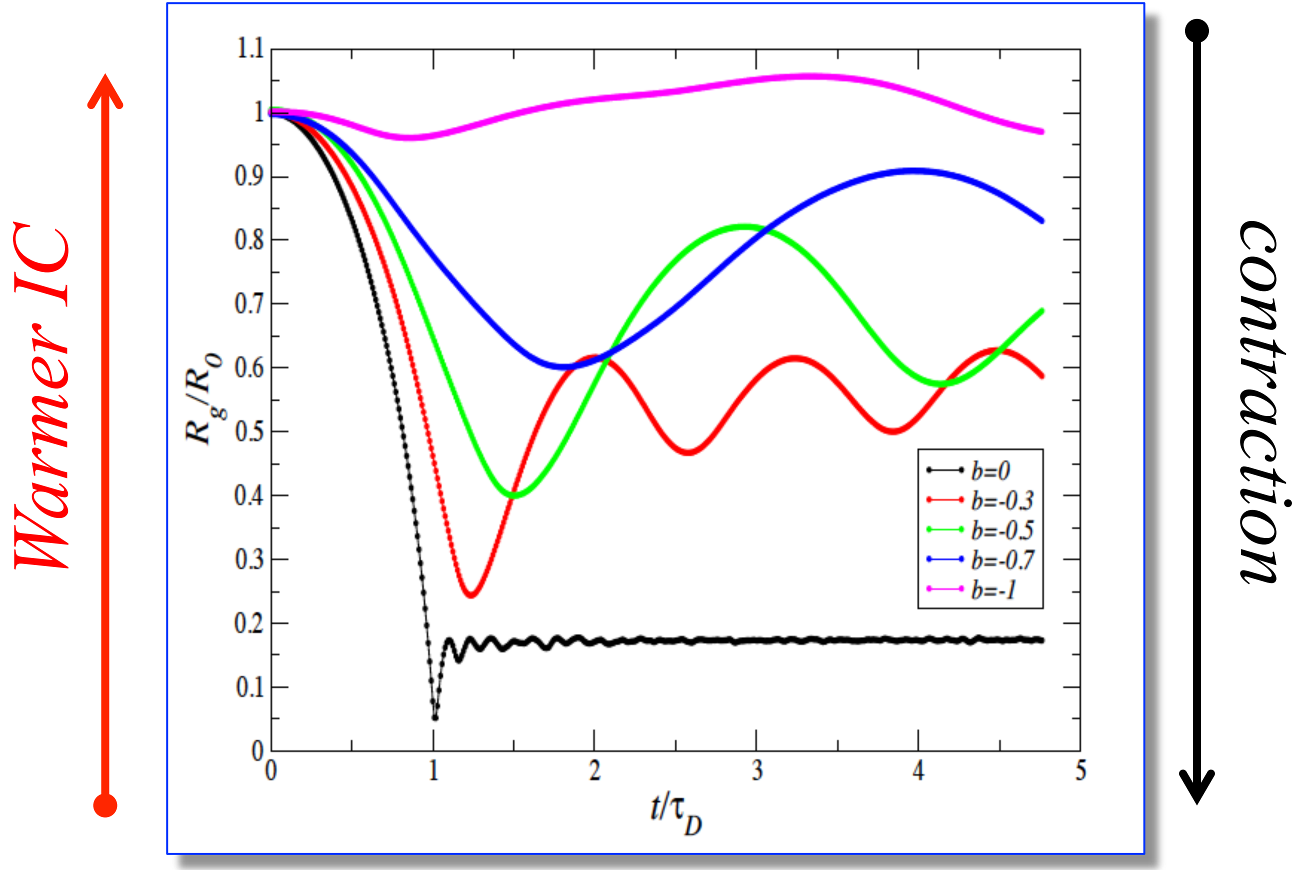


$$\epsilon(t) \neq const$$

Probability of being ejected



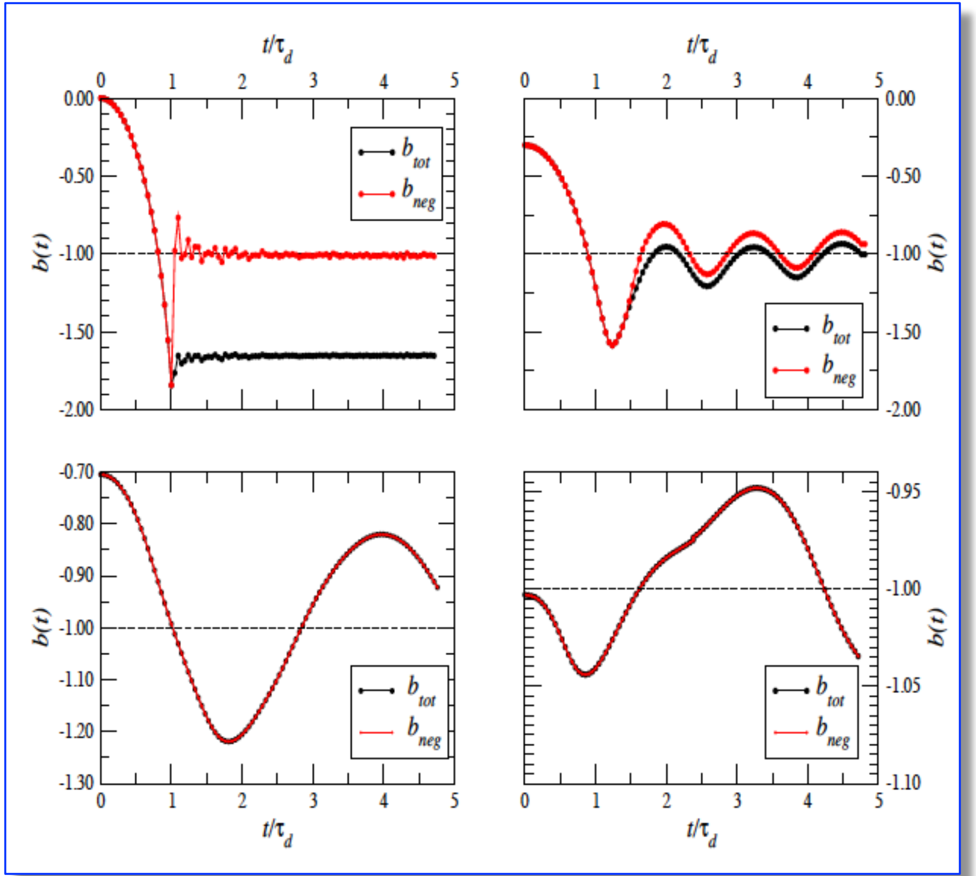
From cold to warm clouds



Sylos Labini, F, Mon.Not.R.Acad.Soc, **429**, 679, 2013

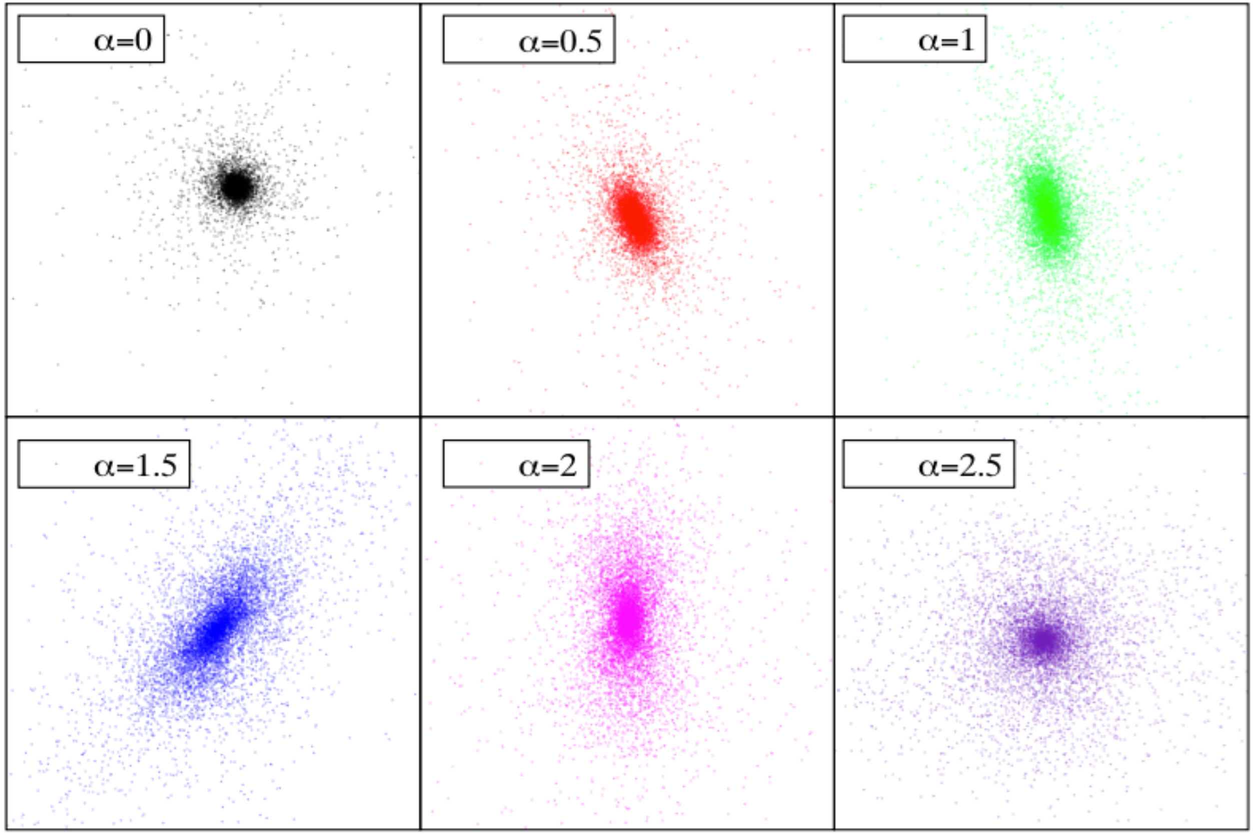
From cold to warm clouds

$$b = \frac{2K}{W}$$



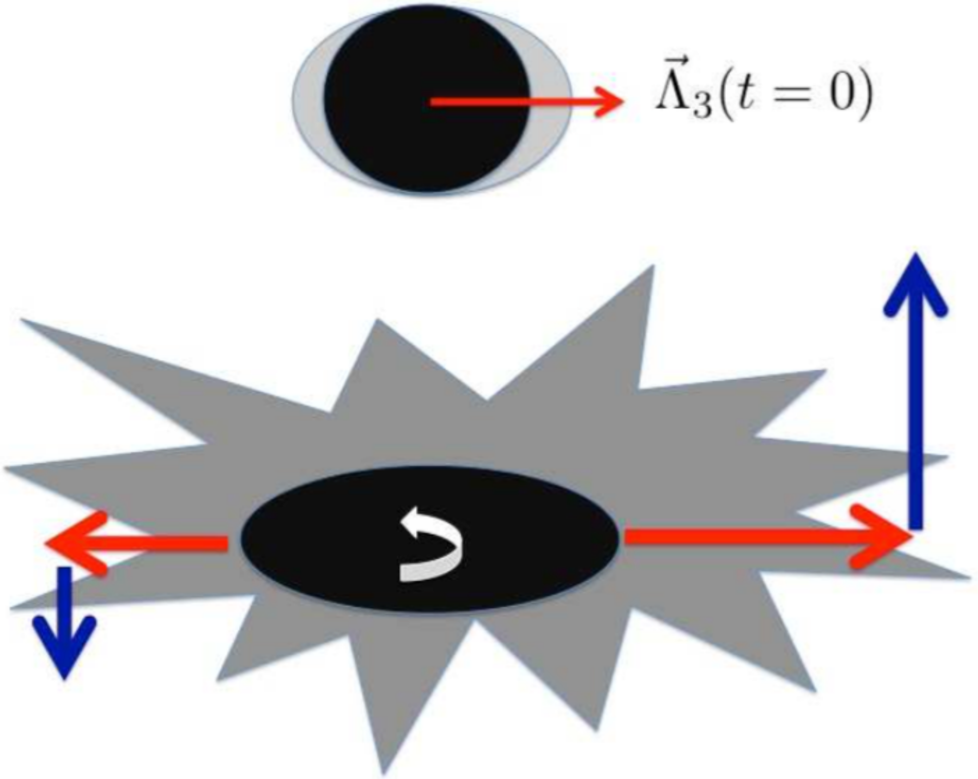
Sylos Labini, F, 2012, Mon.Not.R.Acad.Soc., **423**, 1610S

Breaking of spherical symmetry



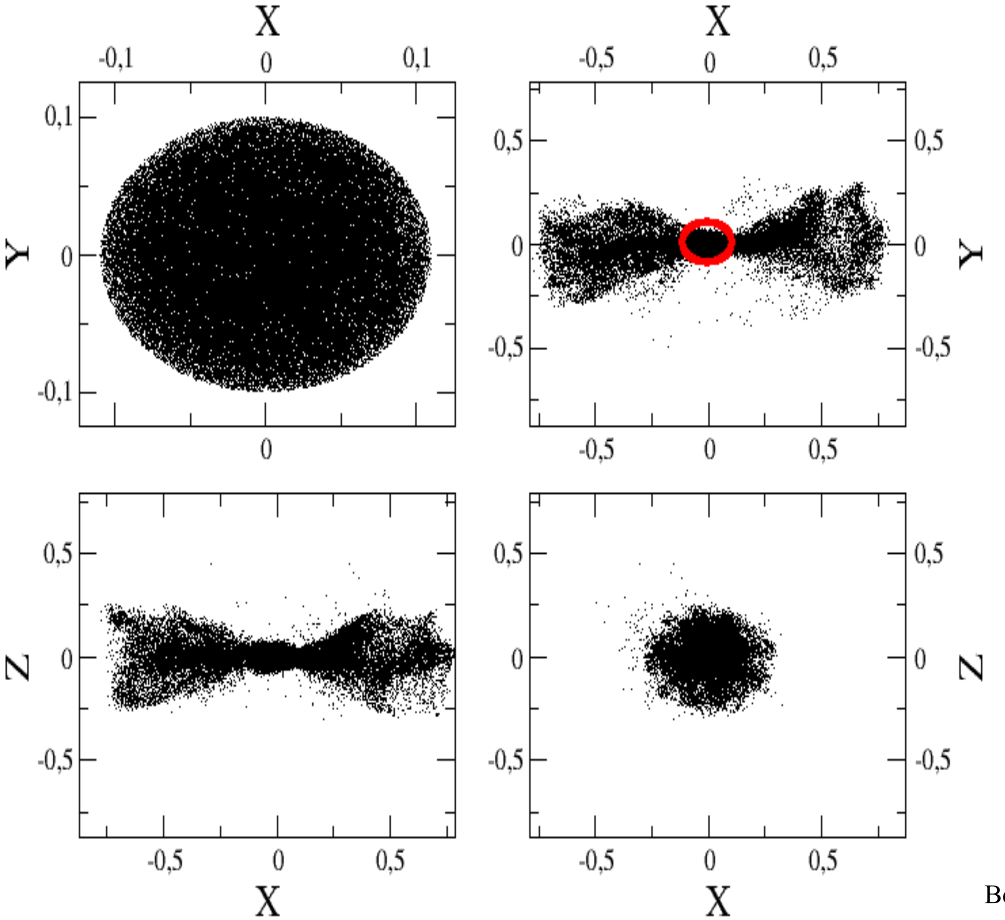
Benhaiem D. Joyce M., Sylos Labini F., Worrakiponpon, T. A&A, **585**, A139, 2016

Generation of Angular Momentum



Benhaiem D. Joyce M., Sylos Labini F., Worrakiponpon, T. A&A, **585**, A139, 2016

Collapse of an **ellipsoidal** isolated cloud

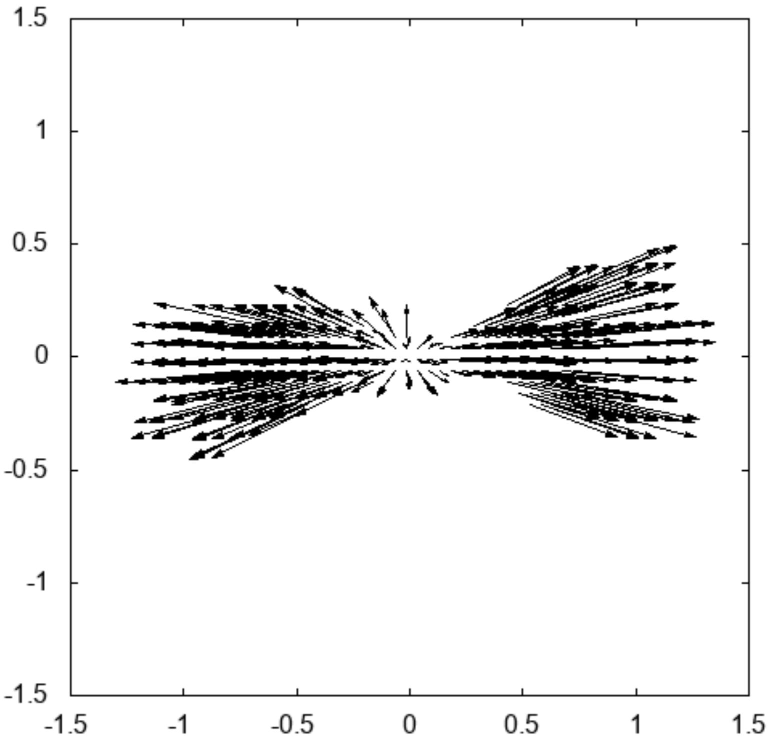


$$a_x \geq a_y \geq a_z$$

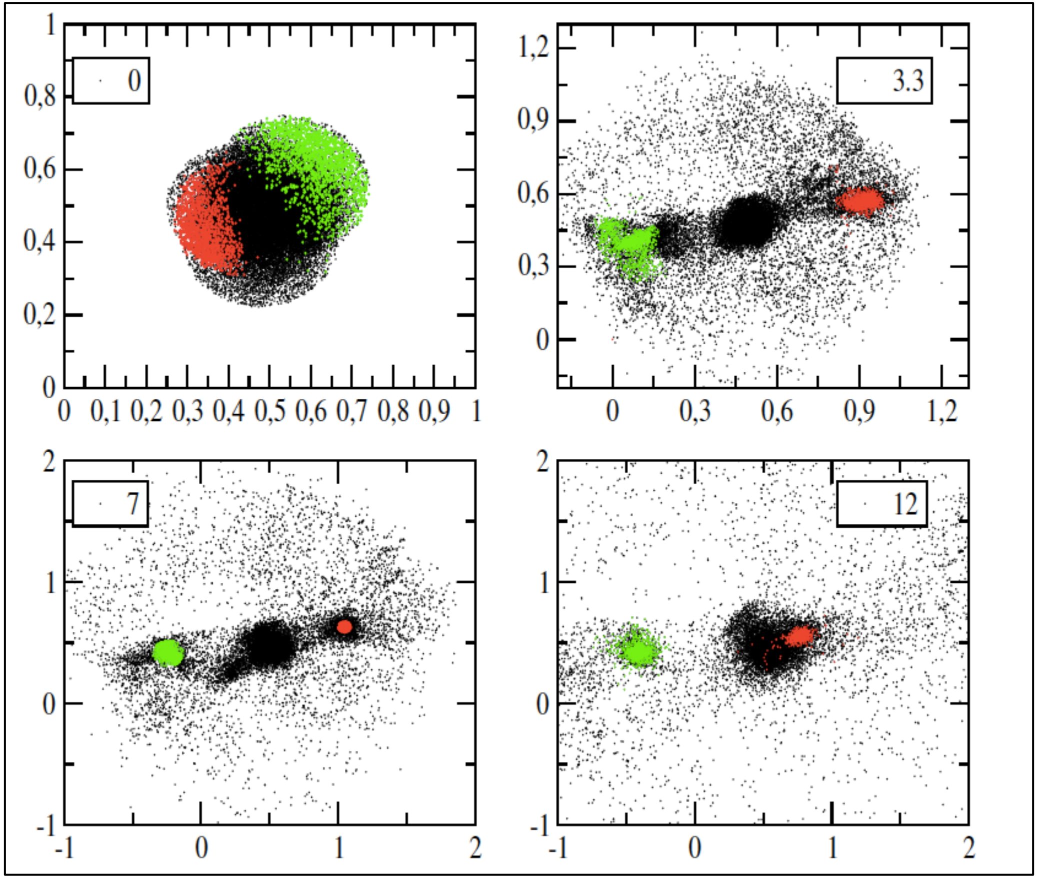
$$\begin{cases} \iota_x = \dfrac{a_x}{a_z} - 1 \\ \iota_y = \dfrac{a_y}{a_z} - 1 \end{cases}$$

Benhaiem & Sylos Labini Mon.Not.R. Astron. Soc 448, 2634-2643 (2015)

Collapse of an **ellipsoidal** isolated cloud

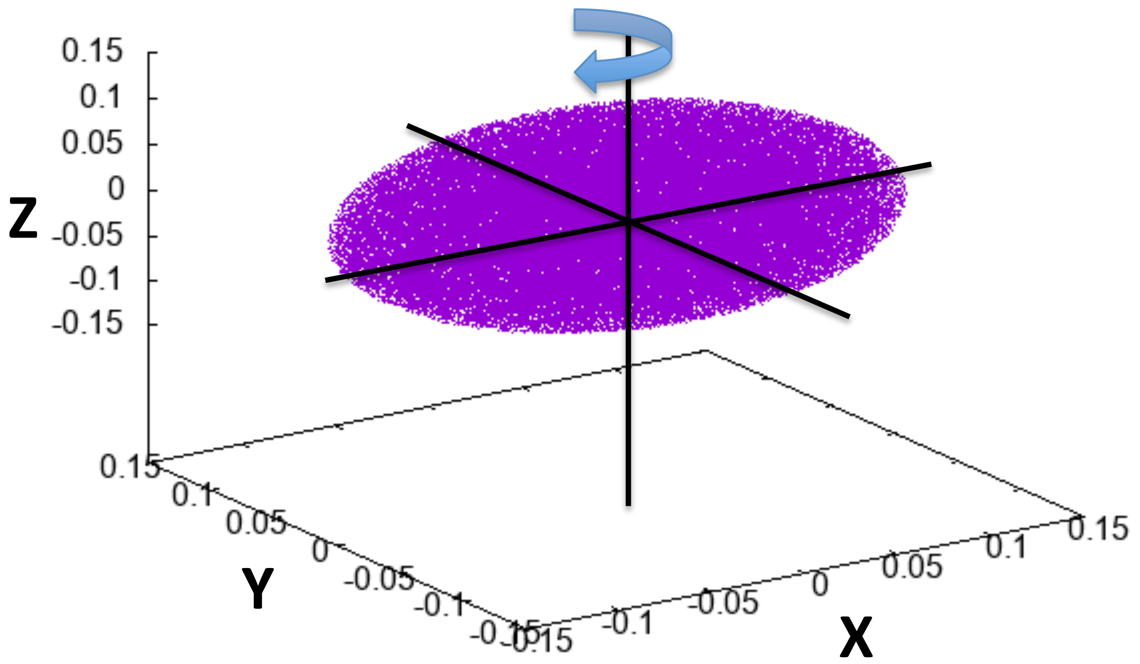


Collapse of irregular inhomogeneous clouds



Benhaiem & Sylos Labini, Astron.Astrophys. 598, A95 (2017)

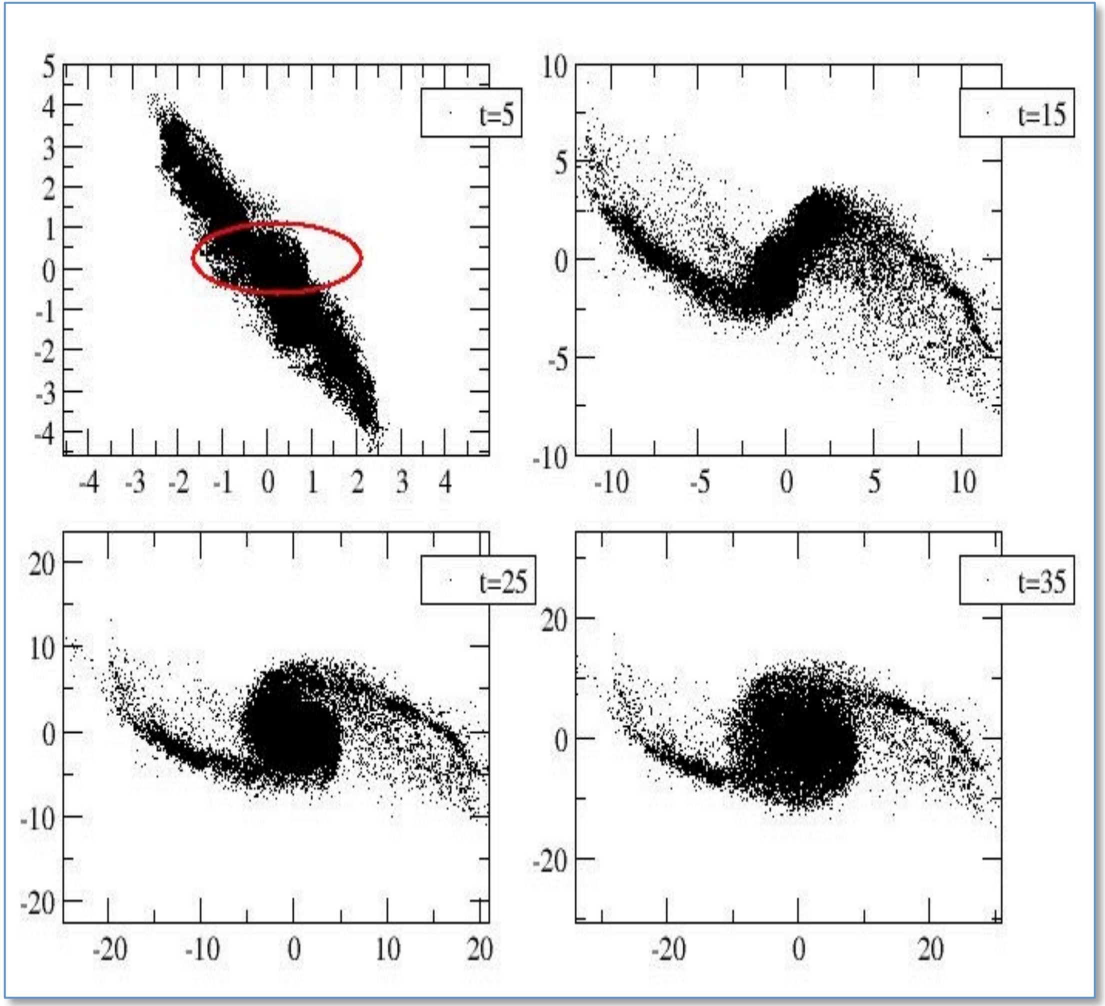
Collapse of **rotating ellipsoidal** clouds

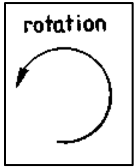


$$\begin{cases} \vec{v} = \vec{\Omega} \times \vec{r} \\ \vec{\Omega} = [0, 0, \Omega] \end{cases}$$

$$\tau_d = \sqrt{\frac{\pi^2 a_3^3}{8GM}}$$

D. Benhaiem, M. Joyce, F. Sylos Labini, Astrophys.J in the press (2017)


t=5
t=15
t=25
t=35


rotation

$\epsilon \leq 0$ → Long return times

$\Phi(r) \sim \frac{GM_c}{r}$ → Spherically symmetric potential

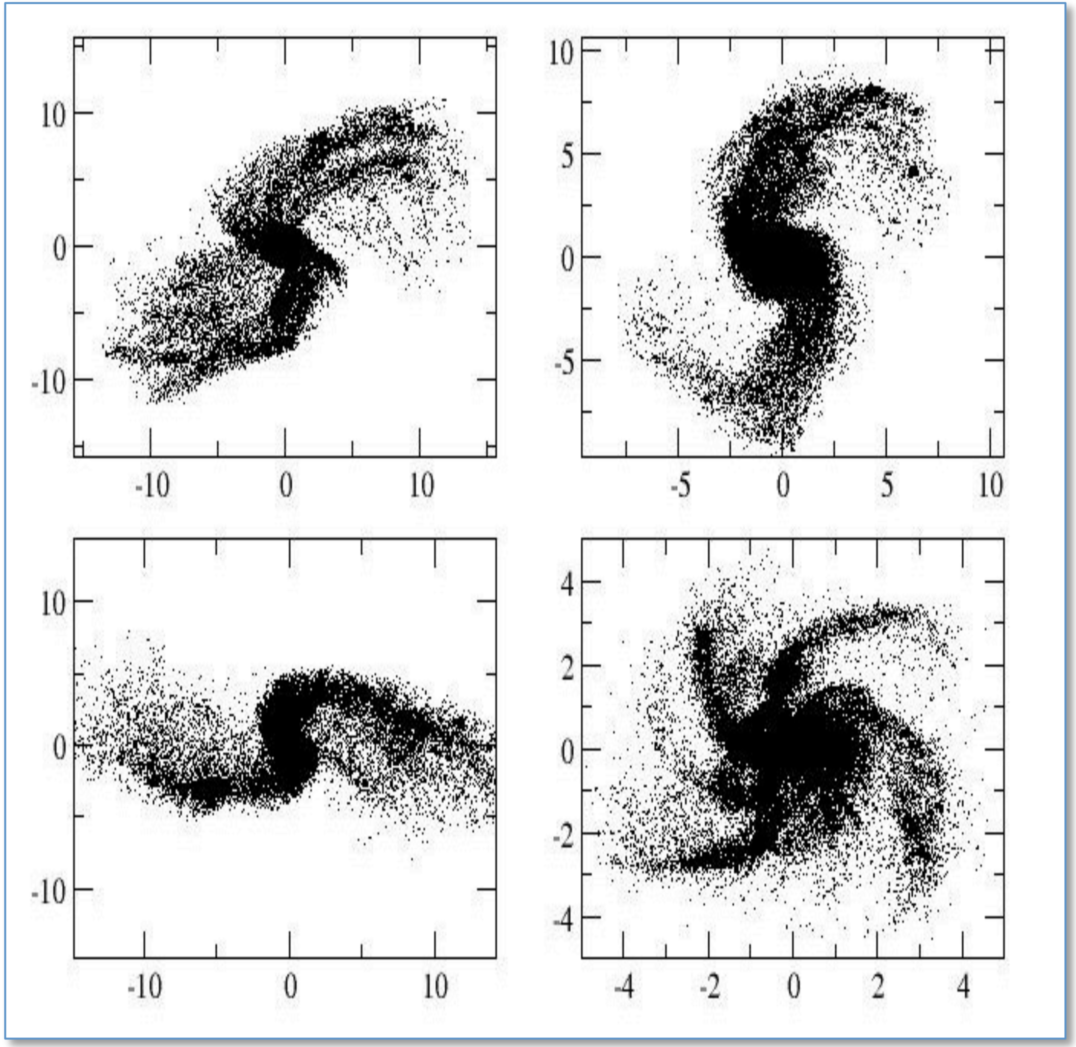
$\epsilon(t) \approx const.$ → Energy conservation

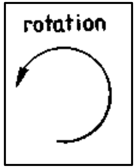
$\vec{\ell}(t) \approx const.$ → Angular momentum conservation

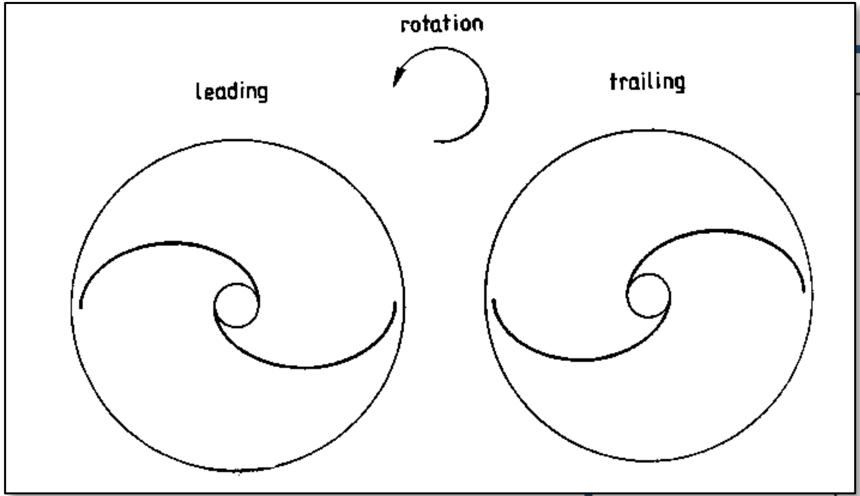
Angular momentum conservation

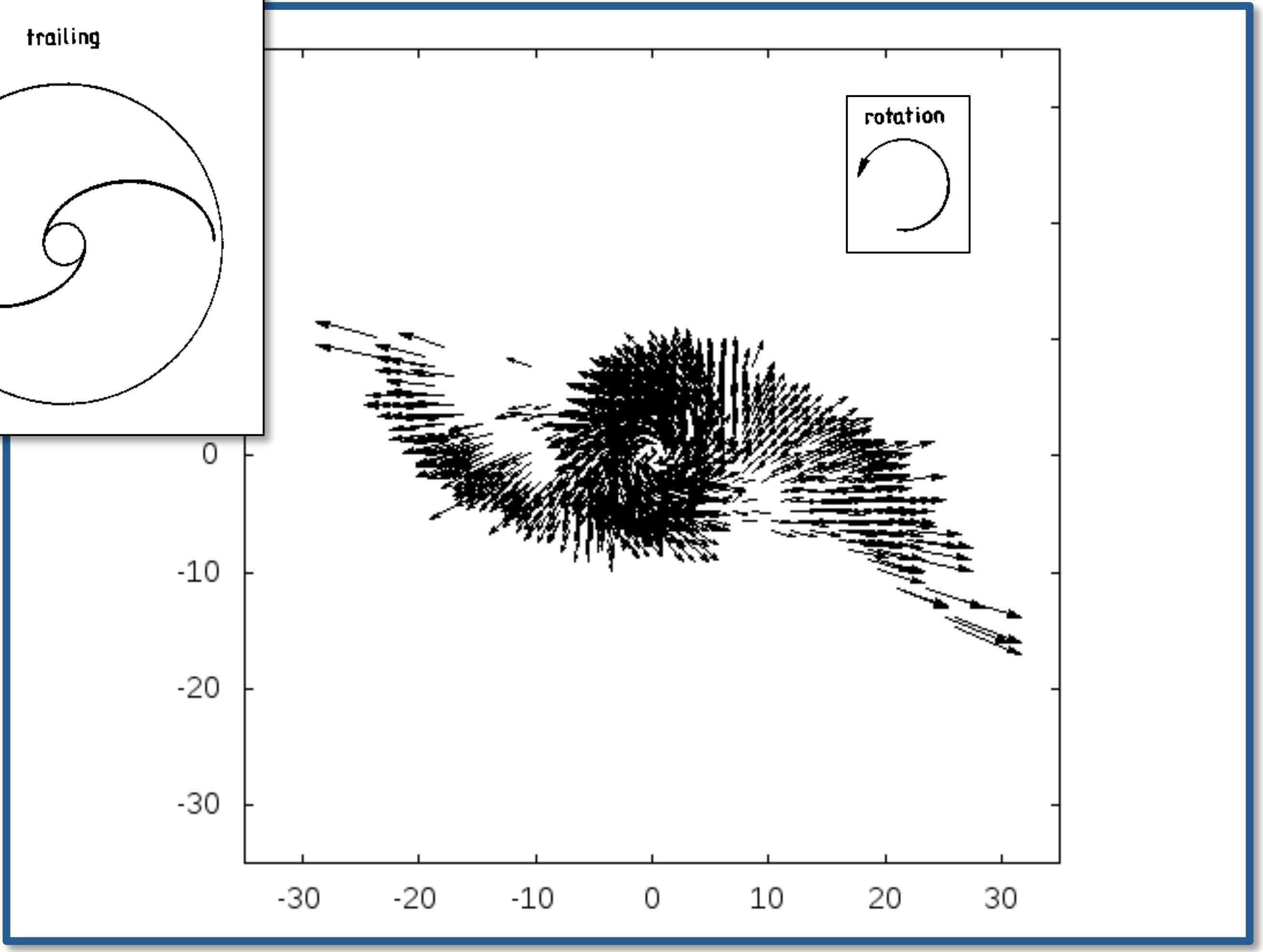
$$\vec{\ell} = \vec{r} \times m\vec{v} = (r^2 m)\vec{\omega} \approx const.$$

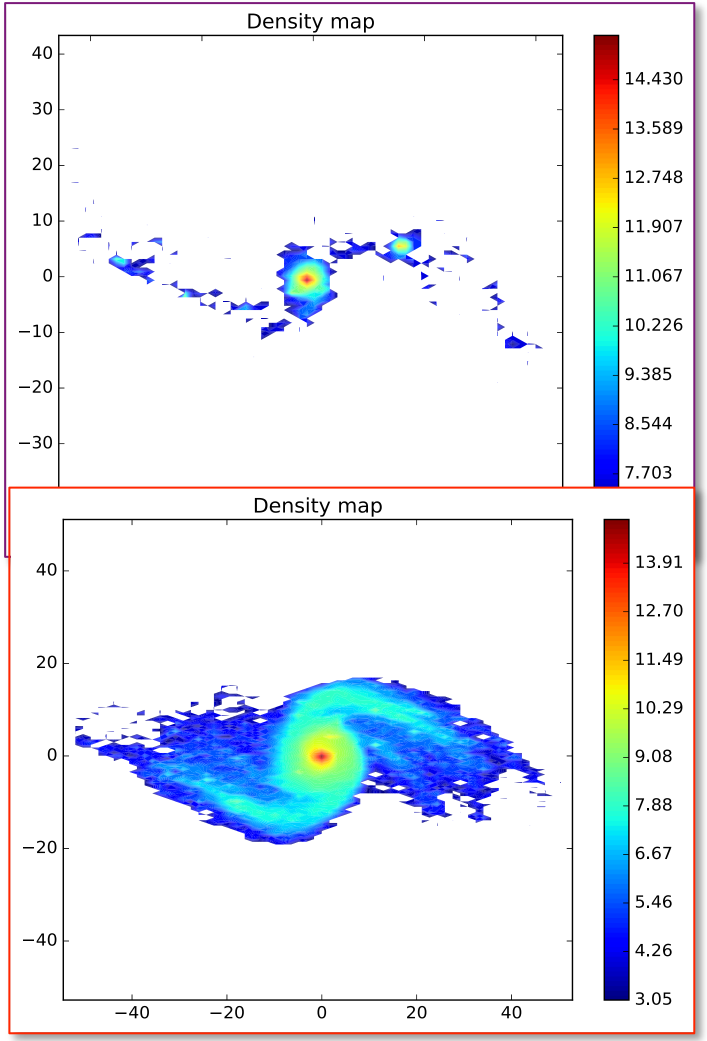
$$|\vec{\omega}| = \frac{|\vec{v}_\perp|}{r}$$

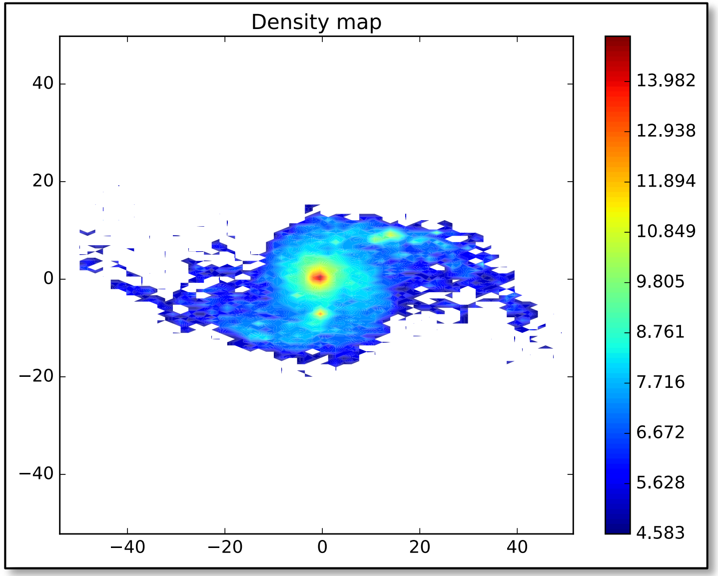

10
0
-10
-10
0
10
10
5
0
-5
-5
0
5
10
10
0
-10
-10
0
10
4
2
0
-2
-4
-4
-2
0
2
4


rotation

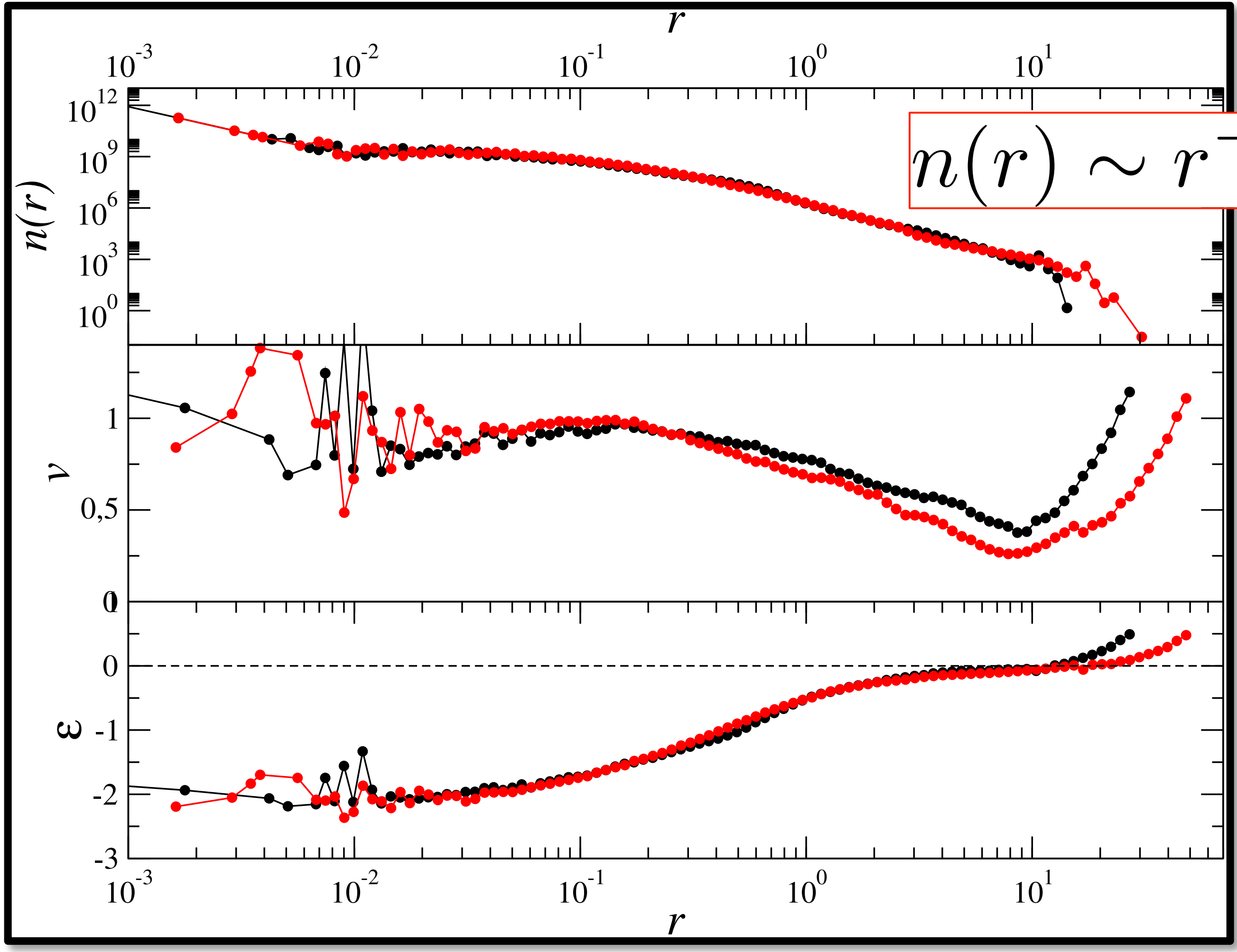

rotation
leading
trailing


rotation
0
-10
-20
-30
-30
-20
-10
0
10
20
30

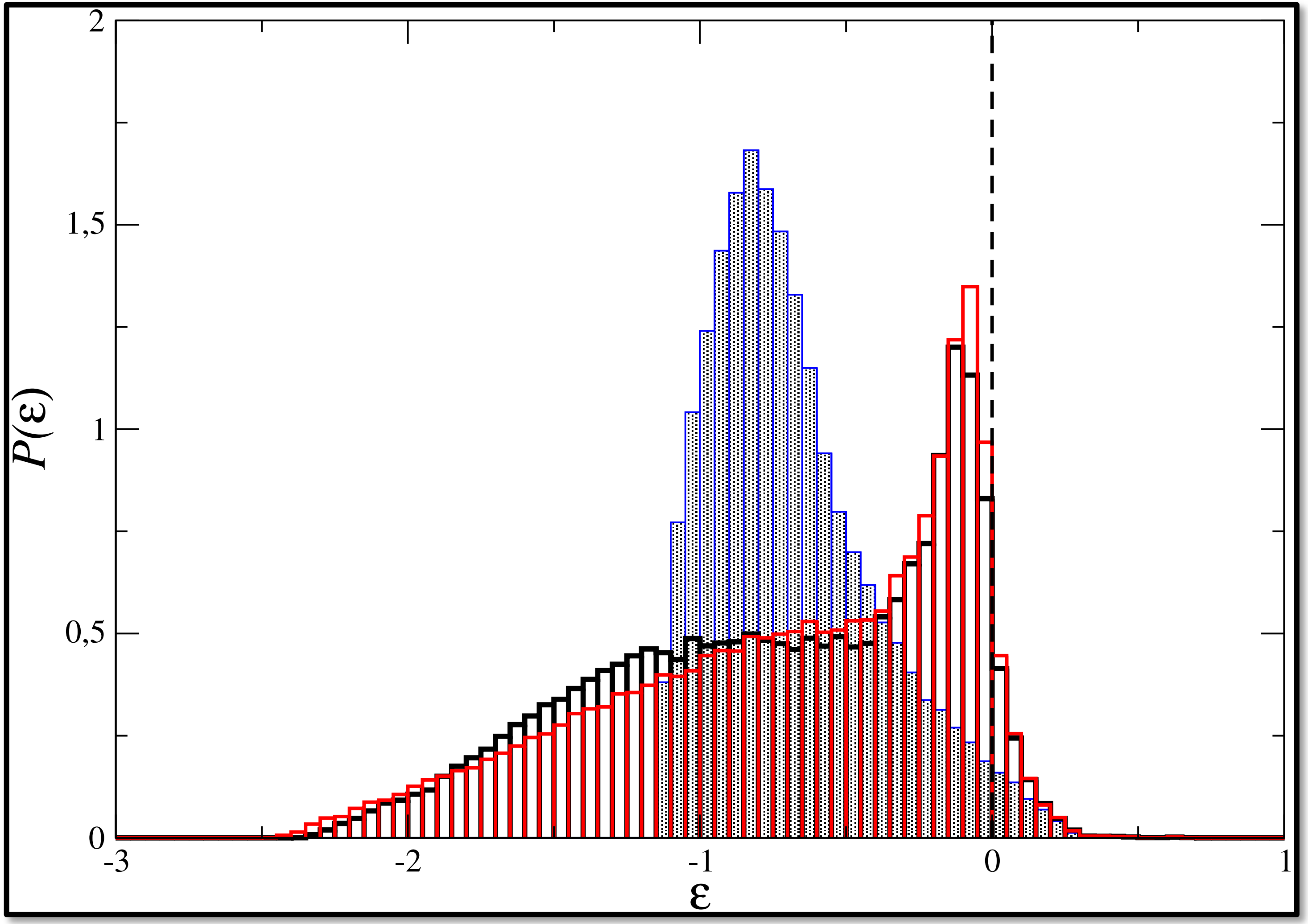

Density map
40
30
20
10
0
−10
−20
−30
14.430
13.589
12.748
11.907
11.067
10.226
9.385
8.544
7.703
Density map
40
20
0
−20
−40
−40
−20
0
20
40
13.91
12.70
11.49
10.29
9.08
7.88
6.67
5.46
4.26
3.05


Density map
40
20
0
−20
−40
−40
−20
0
20
40
13.982
12.938
11.894
10.849
9.805
8.761
7.716
6.672
5.628
4.583

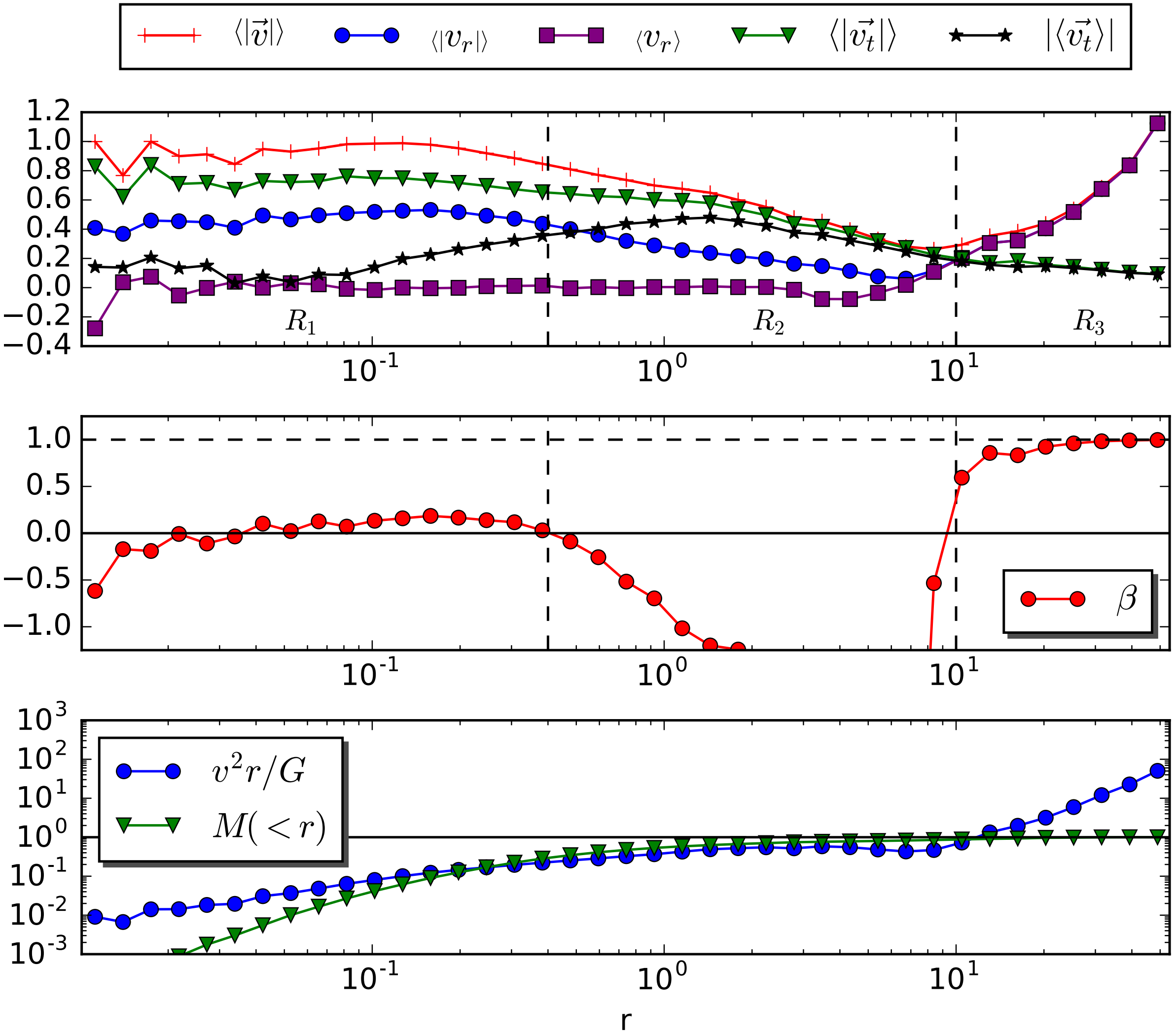
- Two arms (mainly)
- Trailing arms
- No winding problem
- Pitch angle some tens degrees



r
n(r)
v
ε
$n(r) \sim r^{-4}$



2
1,5
1
0,5
0
P(ε)
-3
-2
-1
0
1
ε

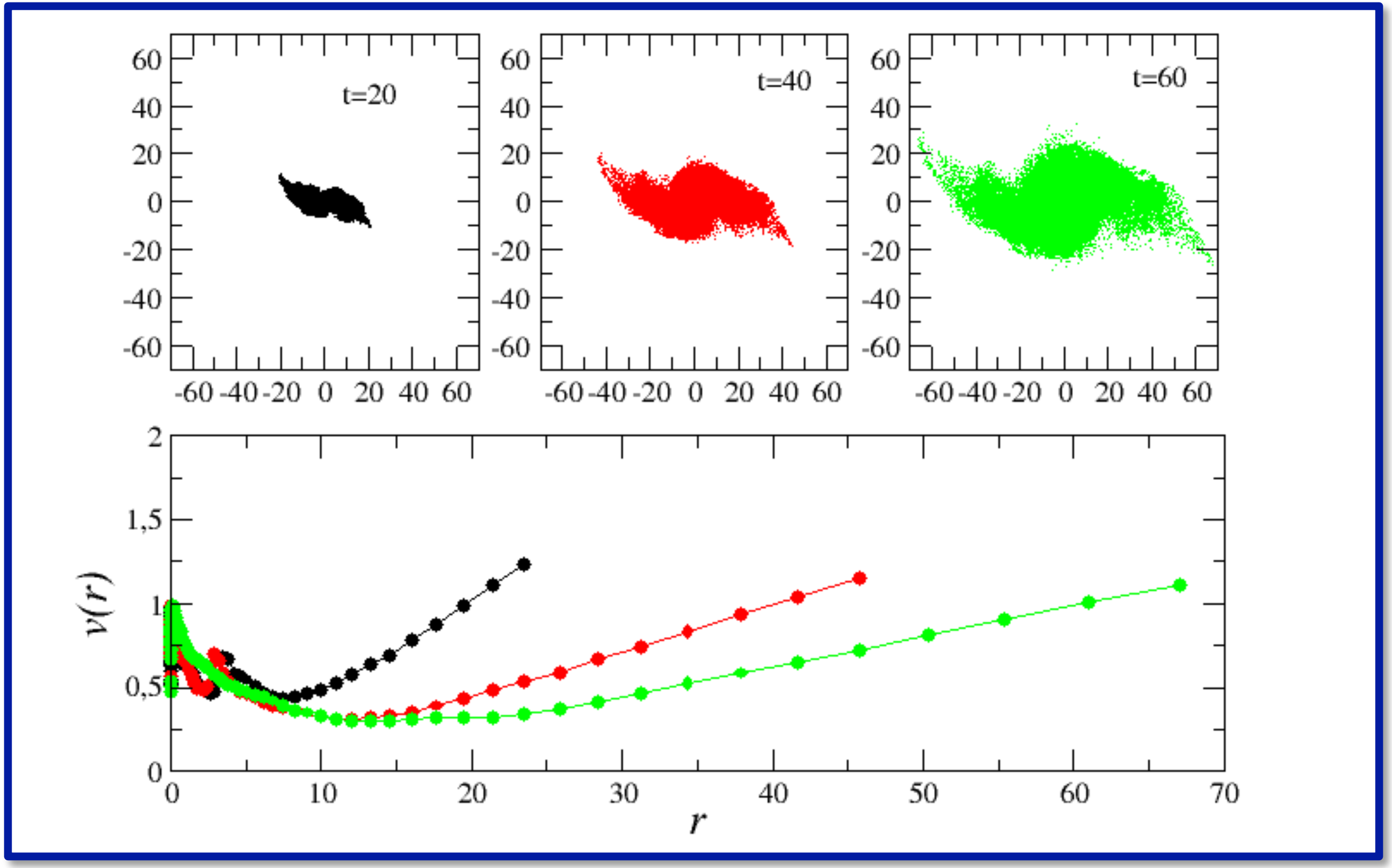


$$v_r = \frac{\vec{r}\cdot\vec{v}}{r}$$

$$\vec{v}_t = \frac{\vec{r}\times\vec{v}}{r}$$

$$\beta(r) = 1 - \frac{\langle v_t^2\rangle}{2\langle v_r^2\rangle}$$

$$M_c = \frac{v^2\cdot r}{G}$$



t=20
t=40
t=60
v(r)
r

$$\tau_d = \sqrt{\frac{\pi^2 a_3^3}{8GM}}$$

$$v_{200} = \frac{a_3/\tau_d}{200} \text{ km/sec}$$

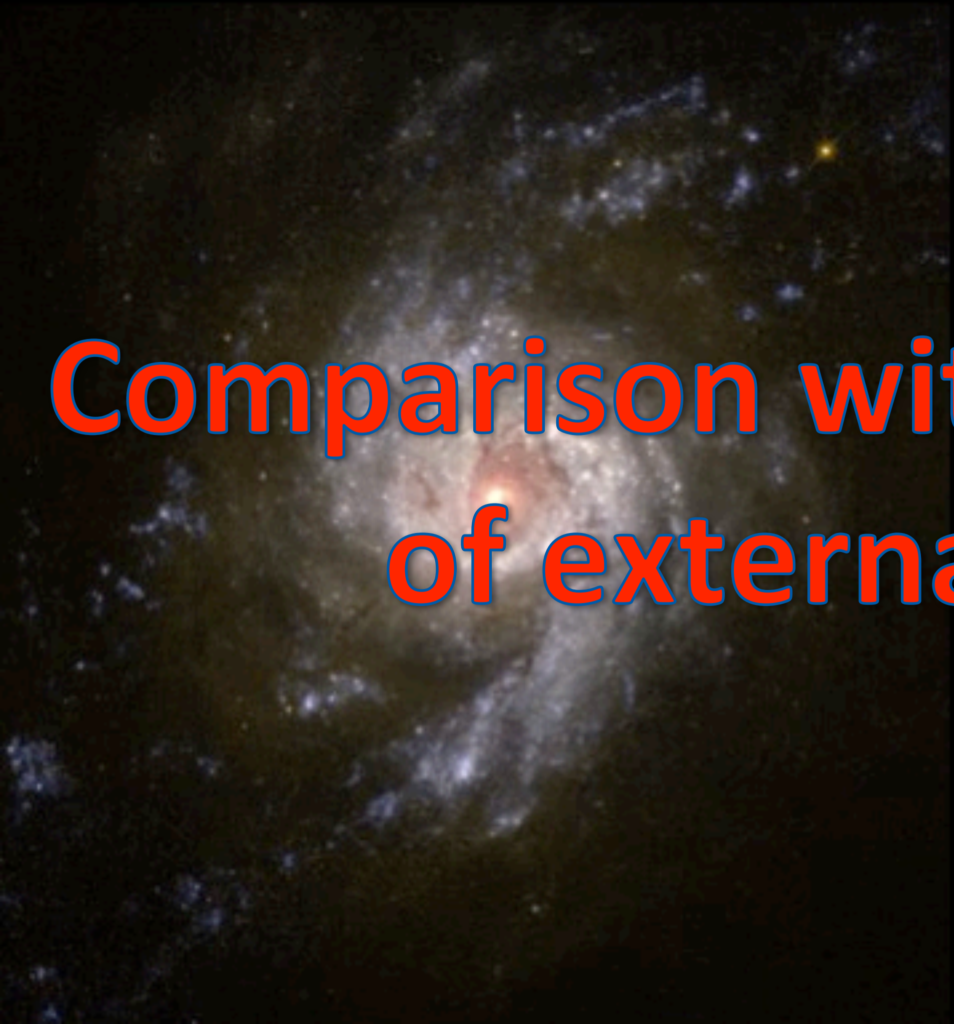
$$\begin{cases} a_3 \approx \left(\frac{200\, v_{200}}{n} \times t_{\mathrm{Gyr}} \right) \text{ kpc} \\ t_{\mathrm{Gyr}} \sim 1 \\ n \approx 50 \end{cases}$$

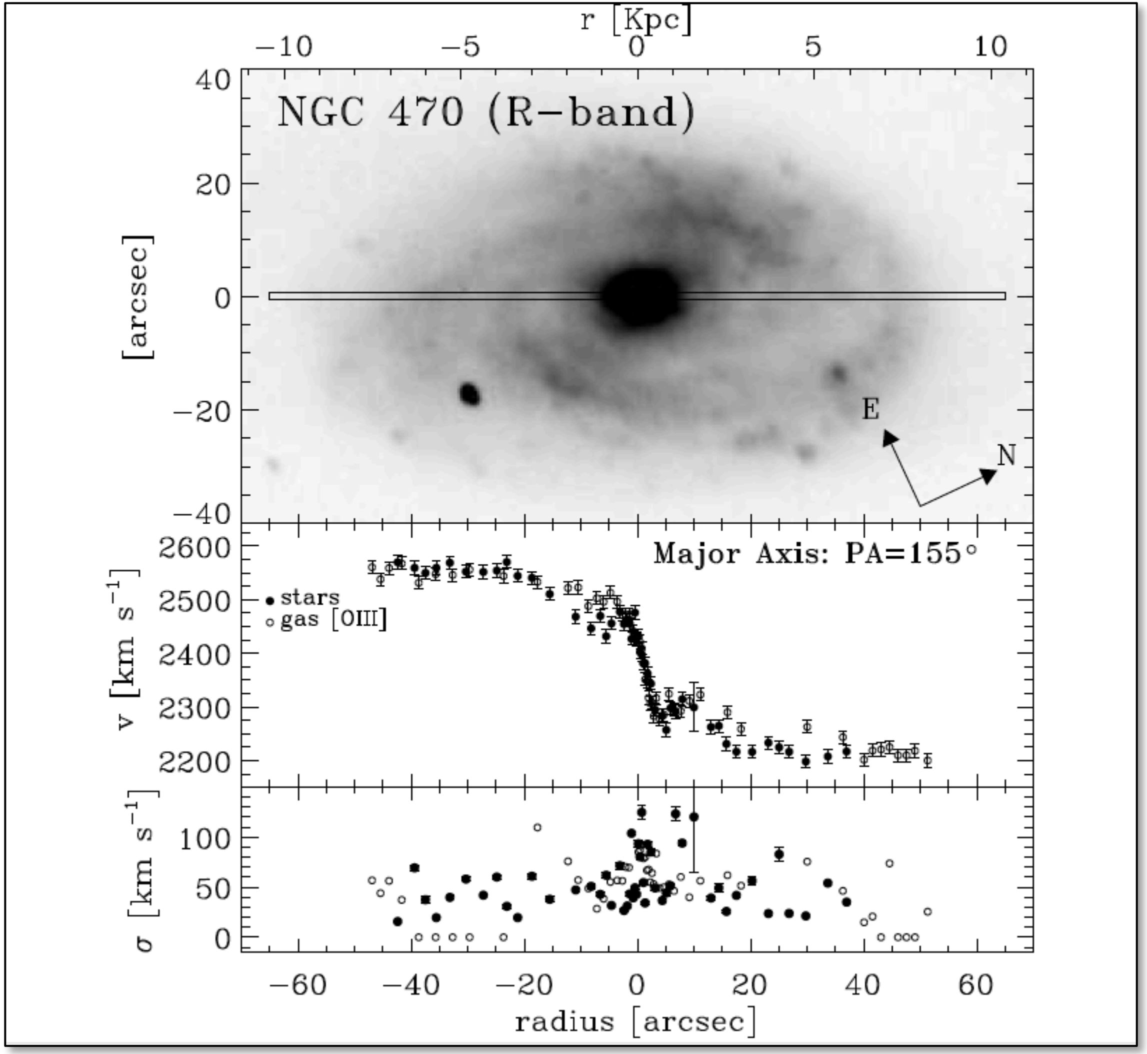
$$M = \frac{\pi^2 a_3^3}{8G\tau_d} \approx 10^{11} M_\odot$$

$$R_2 \approx 50 \ \text{ kpc}$$

$$R_1 \approx 2 \ \text{ kpc}$$

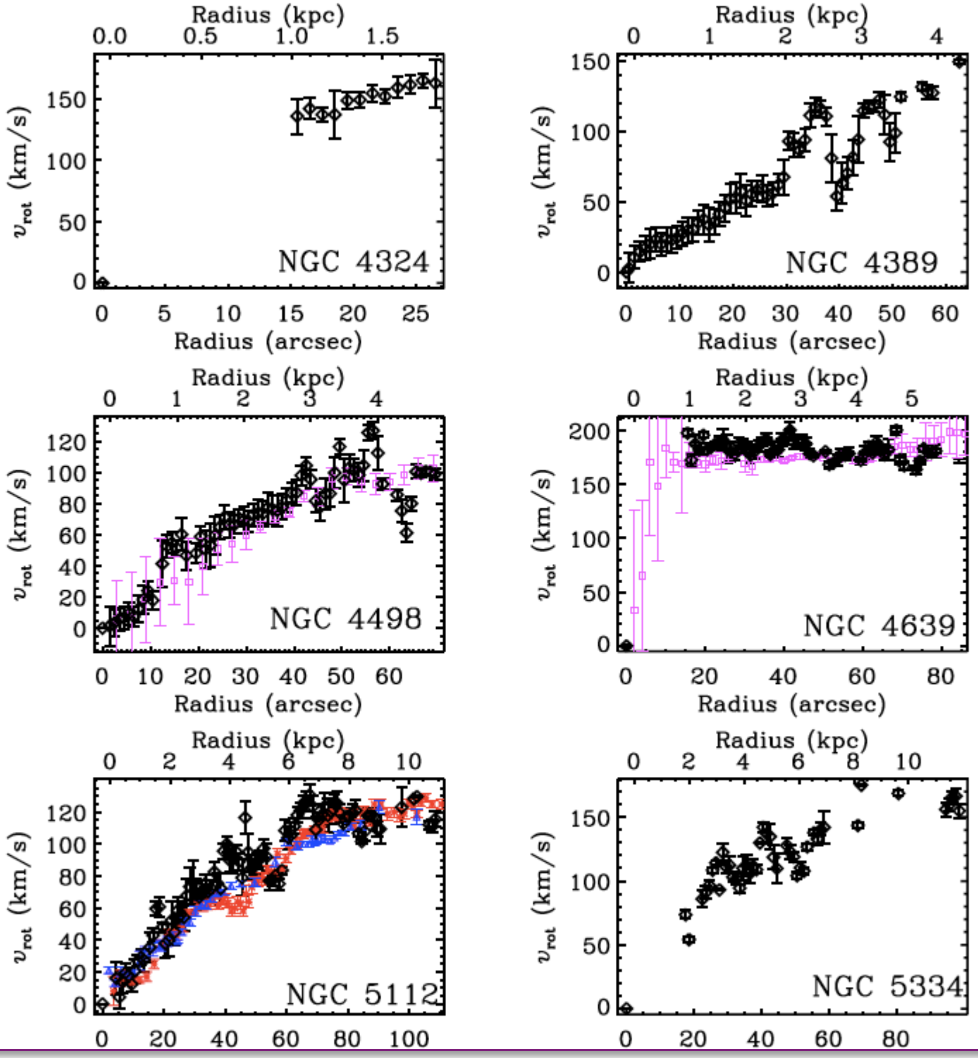
Comparison with observations of external Galaxies

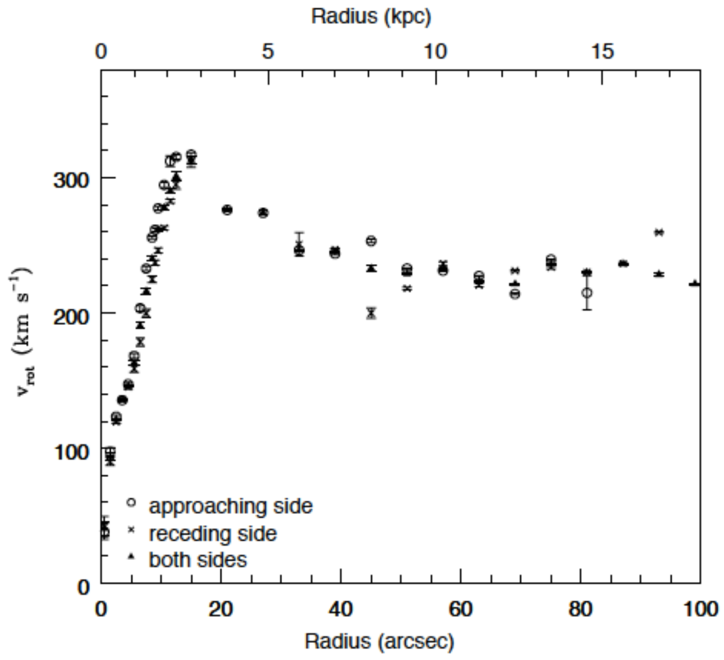


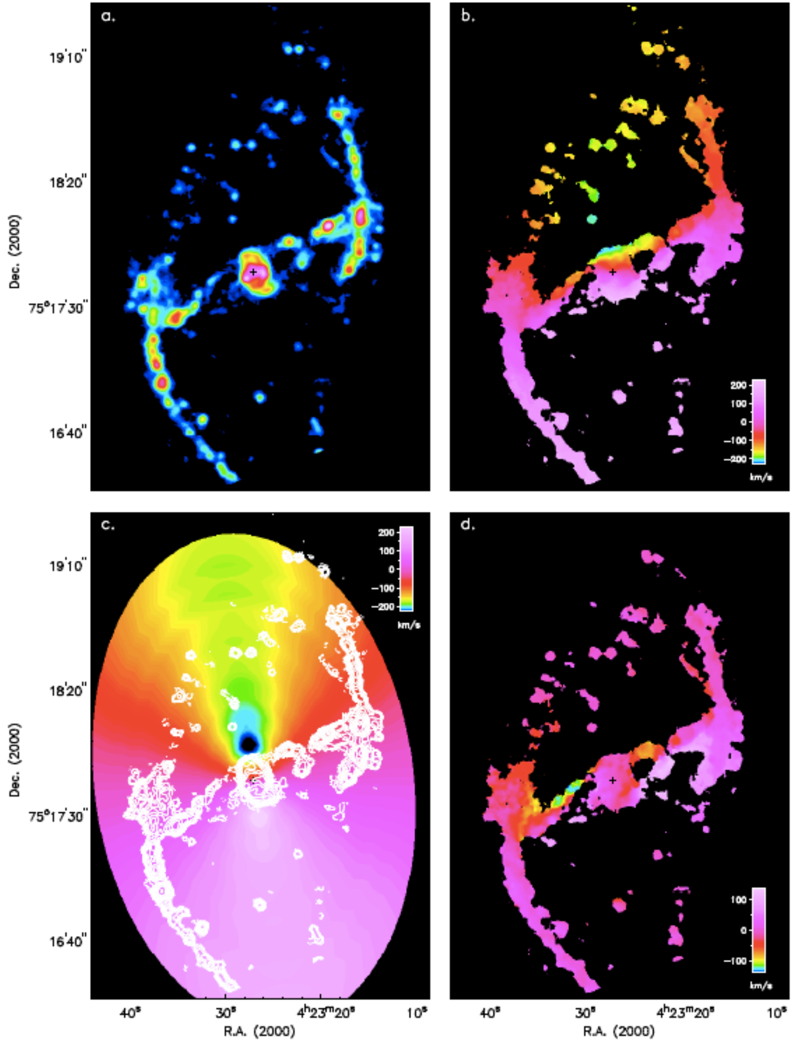


r [Kpc]
−10
−5
0
5
10
40
20
0
−20
−40
[arcsec]
NGC 470 (R−band)
E
N
Major Axis: PA=155°
stars
gas [OIII]
2600
2500
2400
2300
2200
v [km s−1]
100
50
0
σ [km s−1]
−60
−40
−20
0
20
40
60
radius [arcsec]

Erroz-Ferrier et al., MNRAS 451, 1004–1024 (2015)




Radius (kpc)
0
5
10
15
300
200
100
0
v_{rot} (km s^{-1})
approaching side
receding side
both sides
0
20
40
60
80
100
Radius (arcsec)


a.
b.
c.
d.
19'10"
18'20"
75°17'30"
16'40"
Dec. (2000)
km/s
40s
30s
4h23m20s
10s
R.A. (2000)

NGC 2748

Erroz-Ferrier et al., MNRAS 451, 1004–1024 (2015)

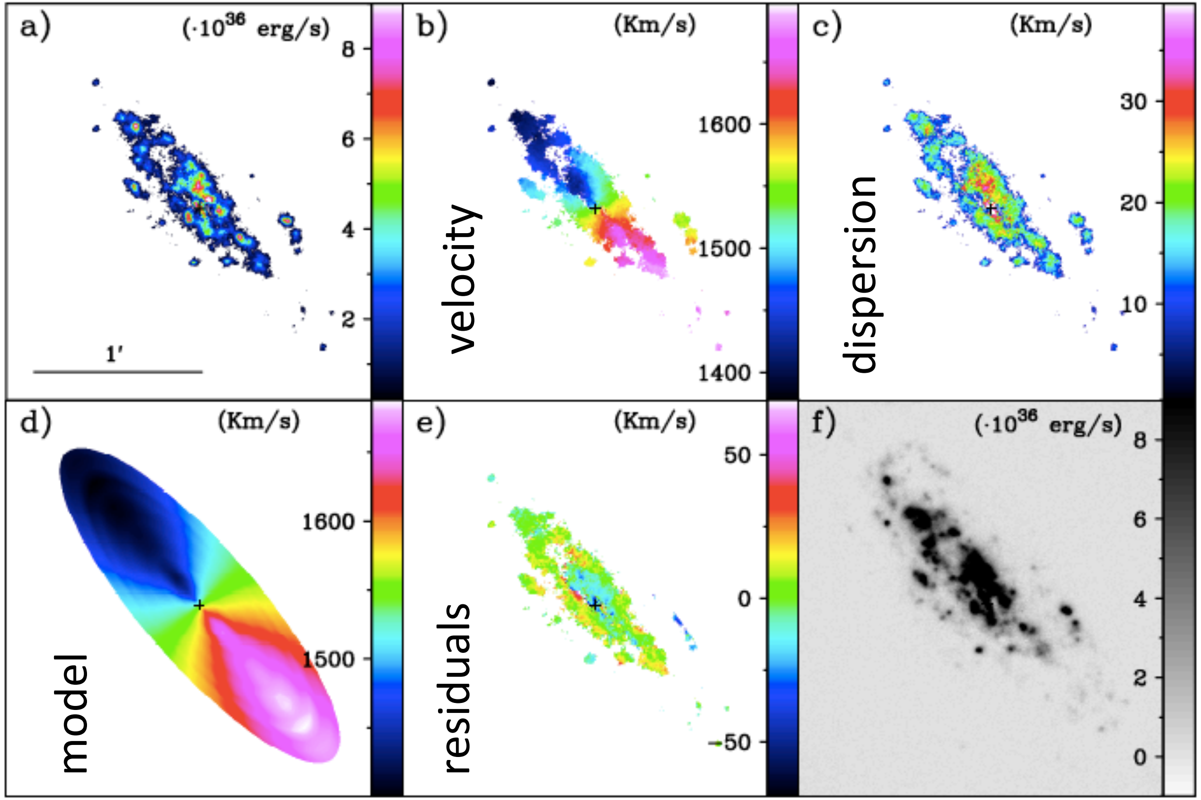
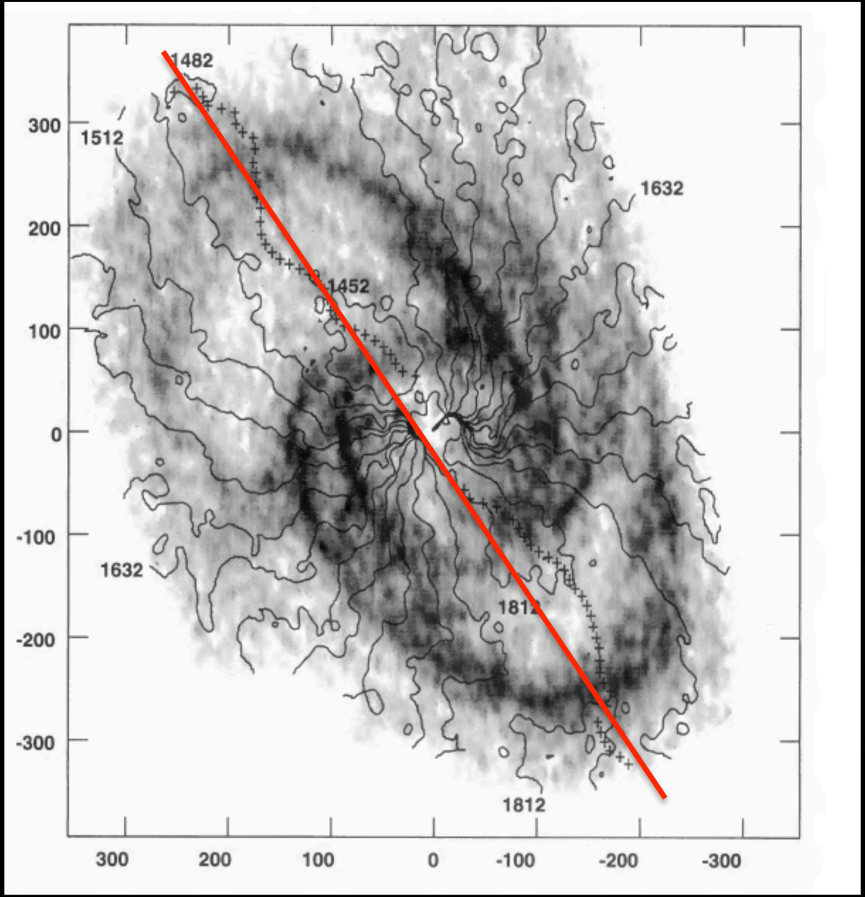
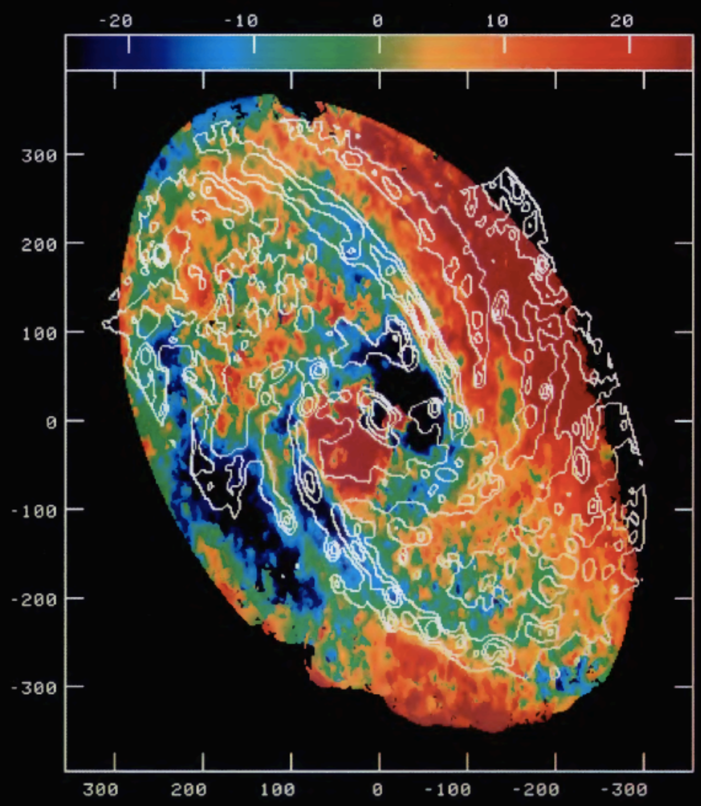


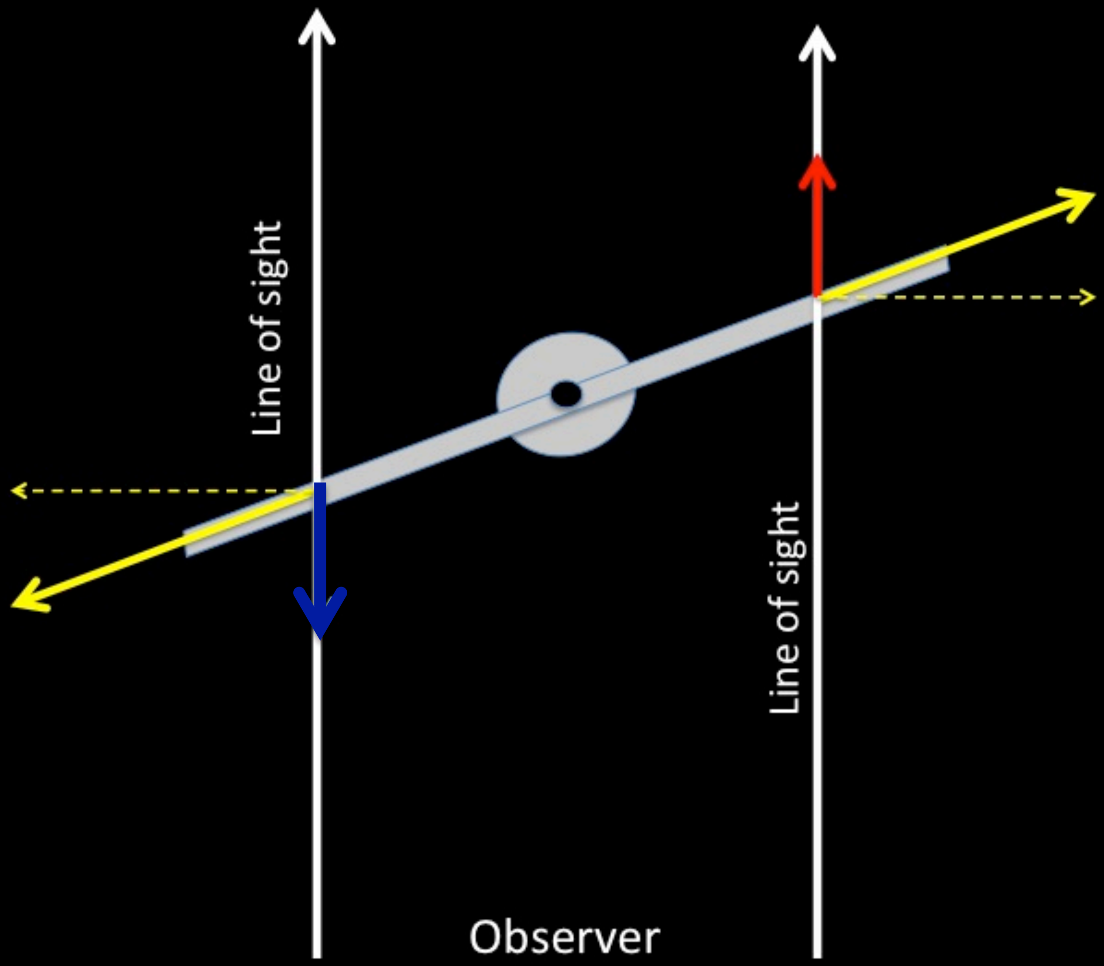
Figure A5. Same as Fig. A1 but for NGC 2712 (top) and NGC 2748 (bottom).

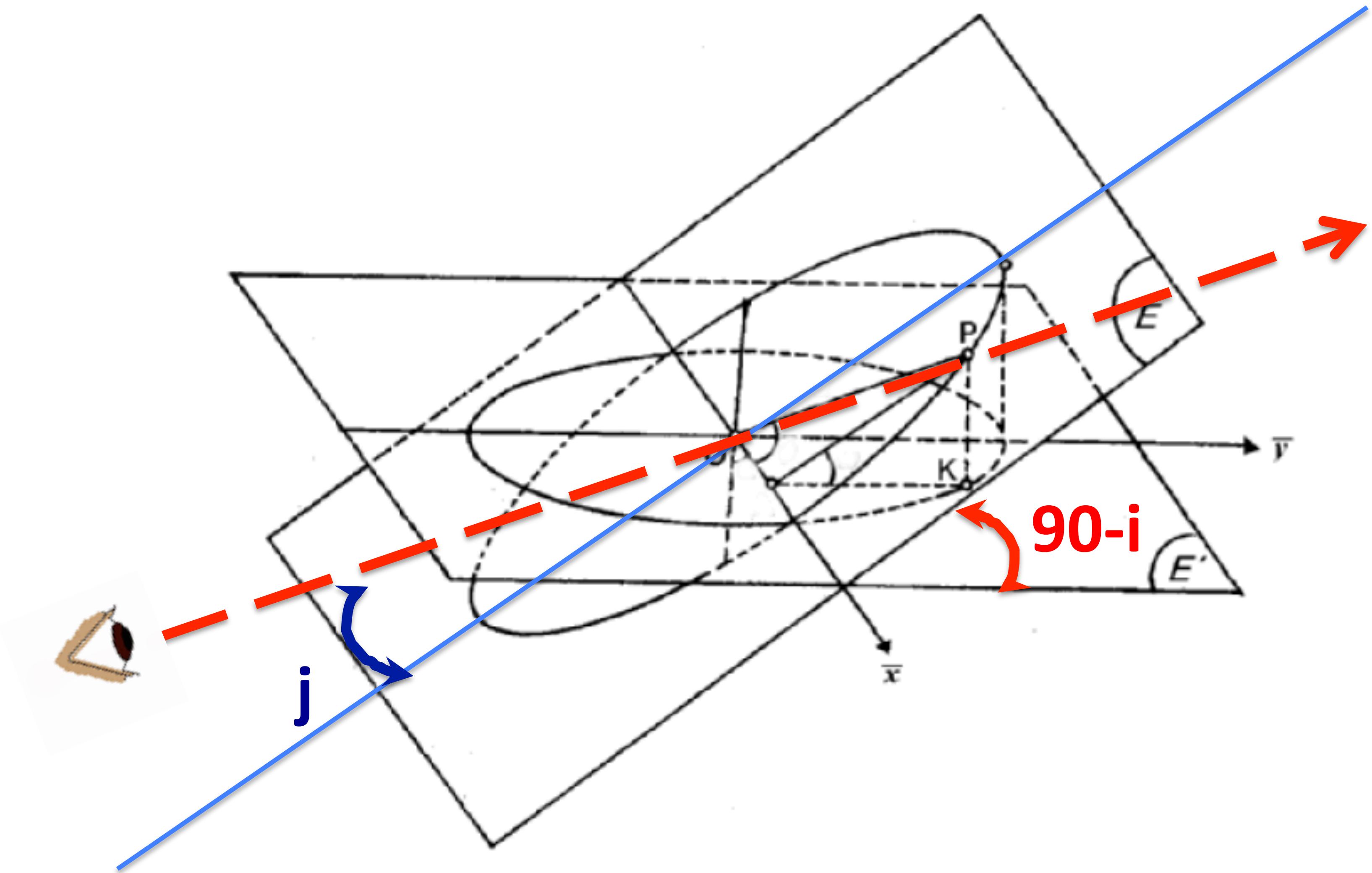


1482
1512
1632
1452
1632
1812
1812
300
200
100
0
-100
-200
-300

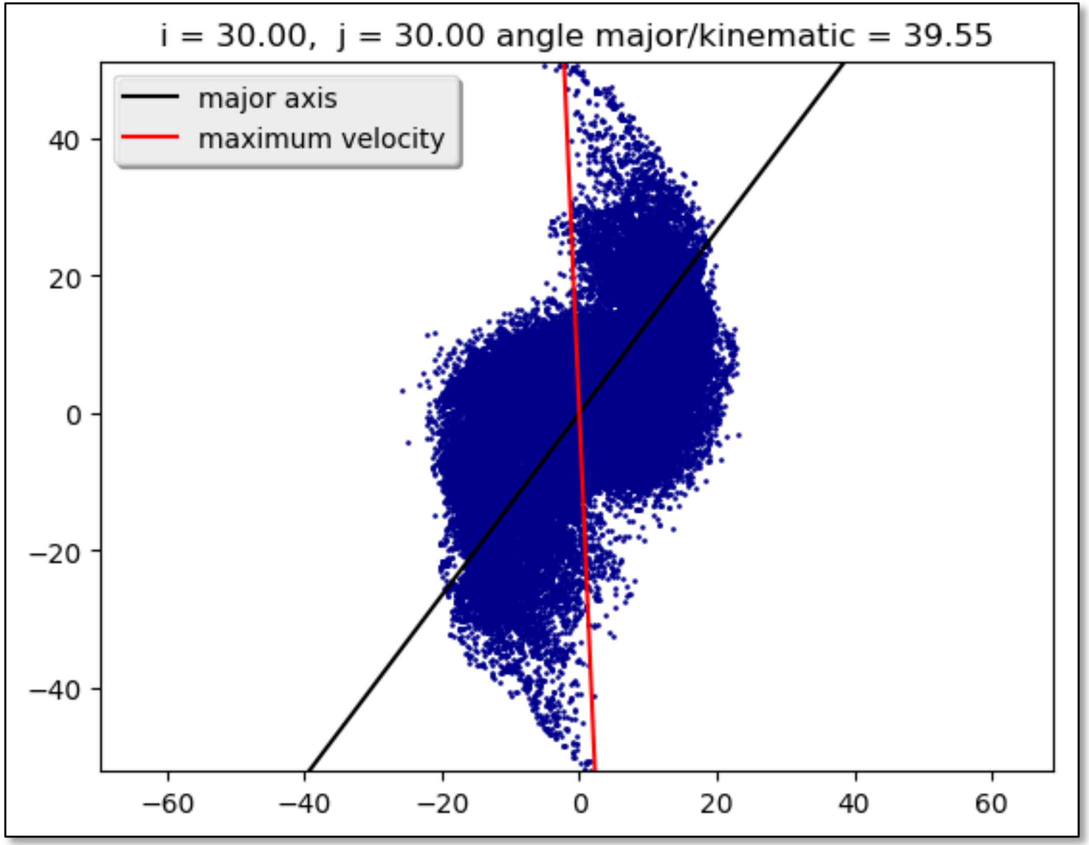


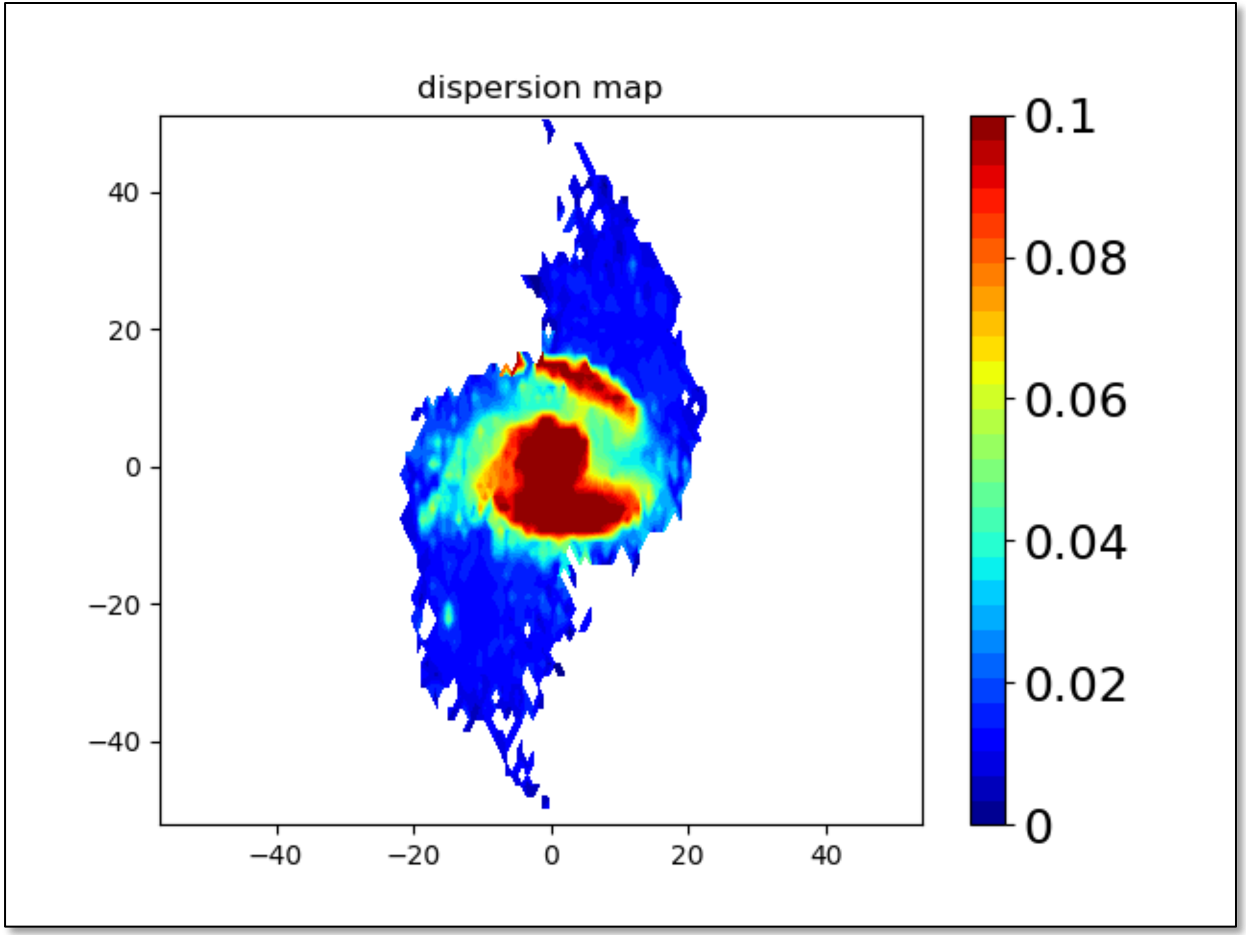
-20
-10
0
10
20
300
200
100
0
-100
-200
-300
300
200
100
0
-100
-200
-300


Line of sight
Line of sight
Observer

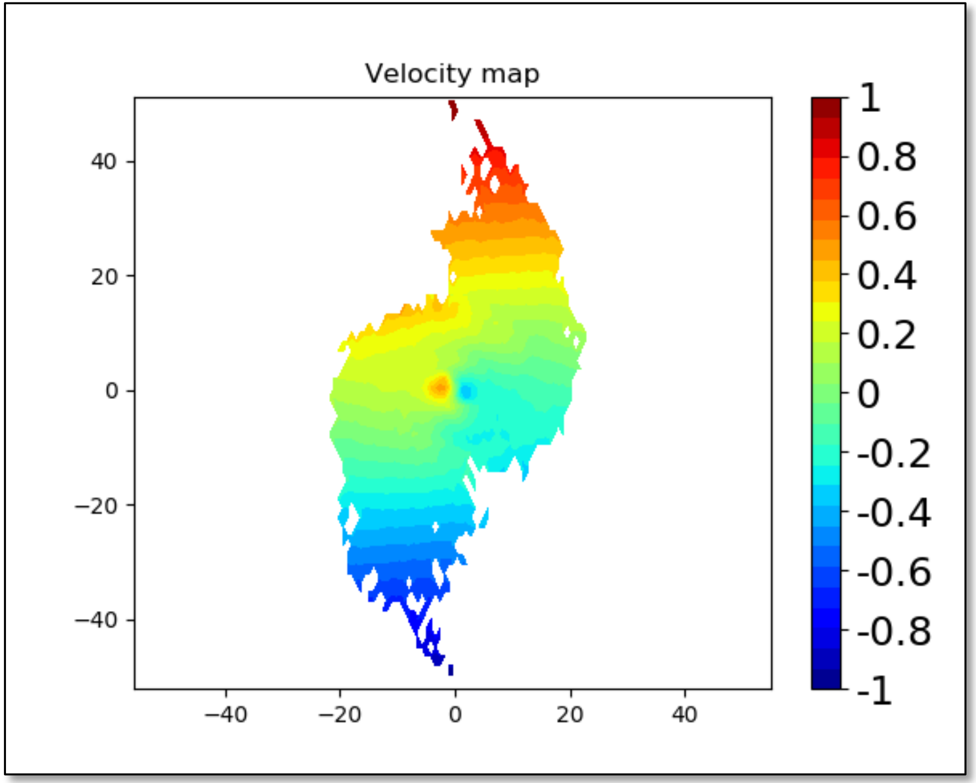


E
P
O
K
y
x
90-i
E'
j

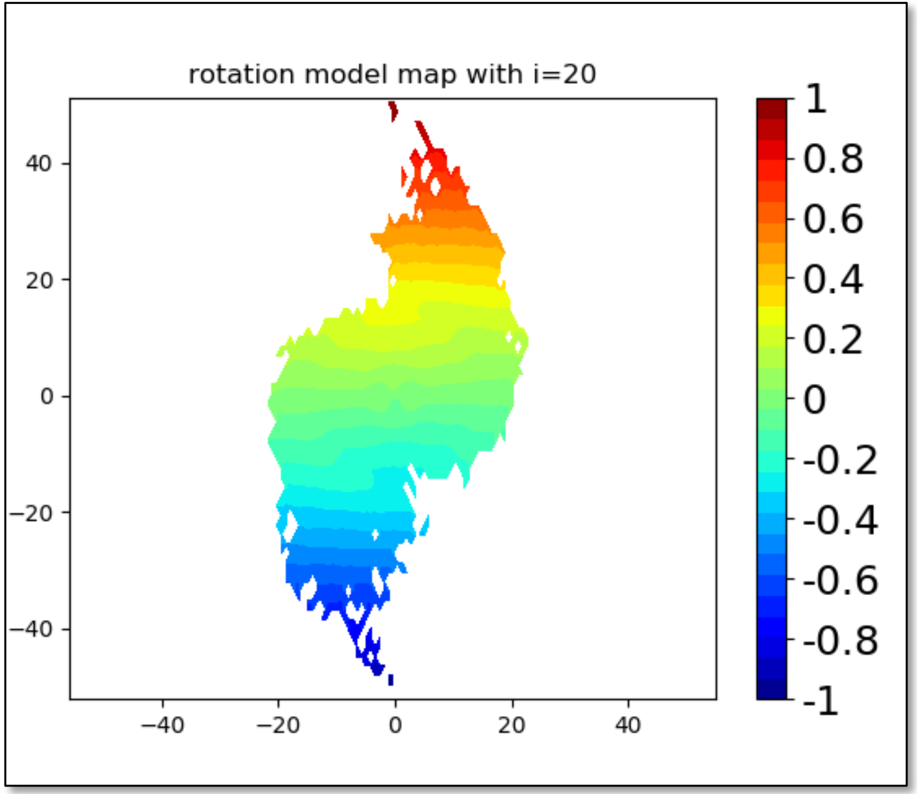

i = 30.00, j = 30.00 angle major/kinematic = 39.55
major axis
maximum velocity
40
20
0
−20
−40
−60
−40
−20
0
20
40
60



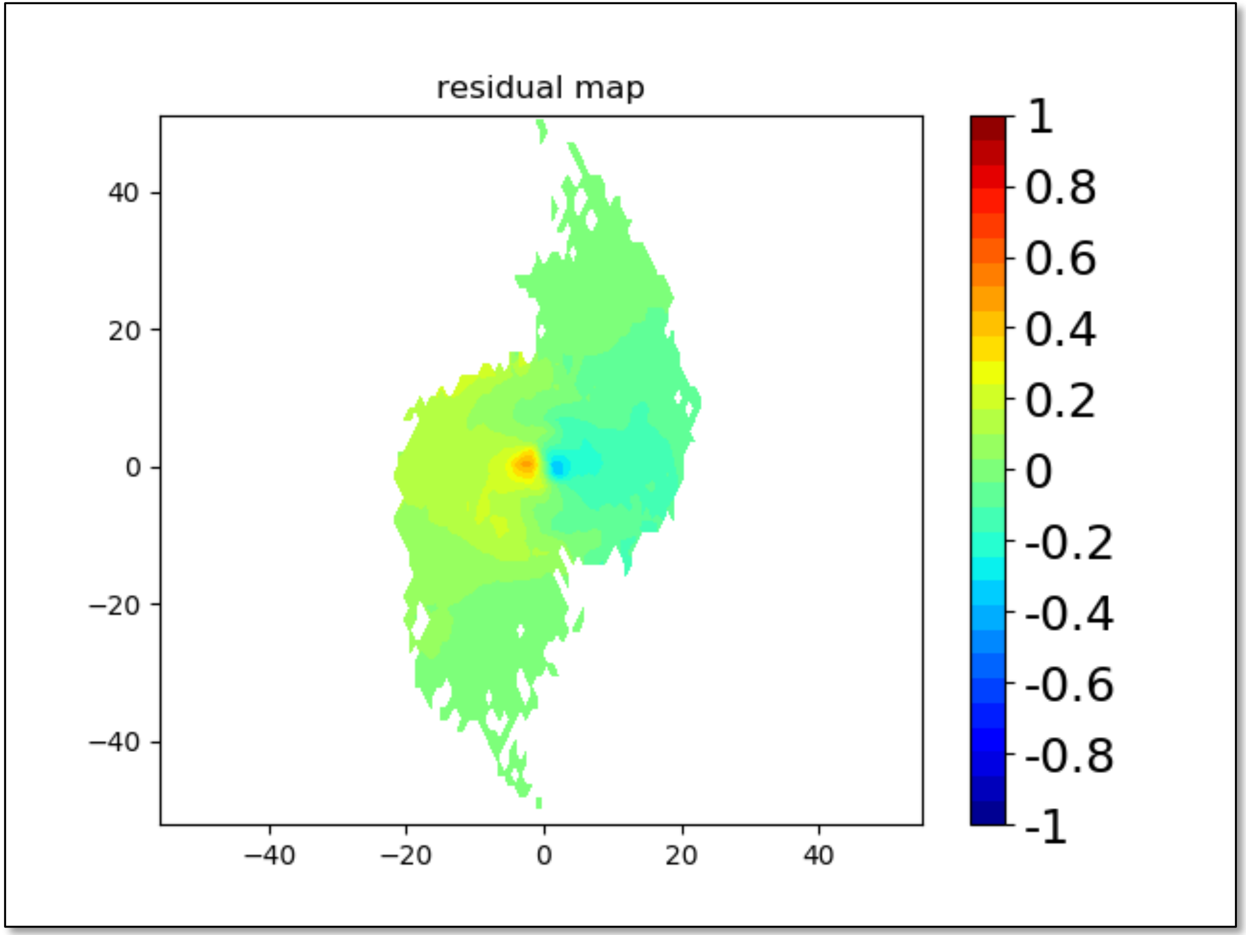
dispersion map
40
20
0
−20
−40
−40
−20
0
20
40
0.1
0.08
0.06
0.04
0.02
0



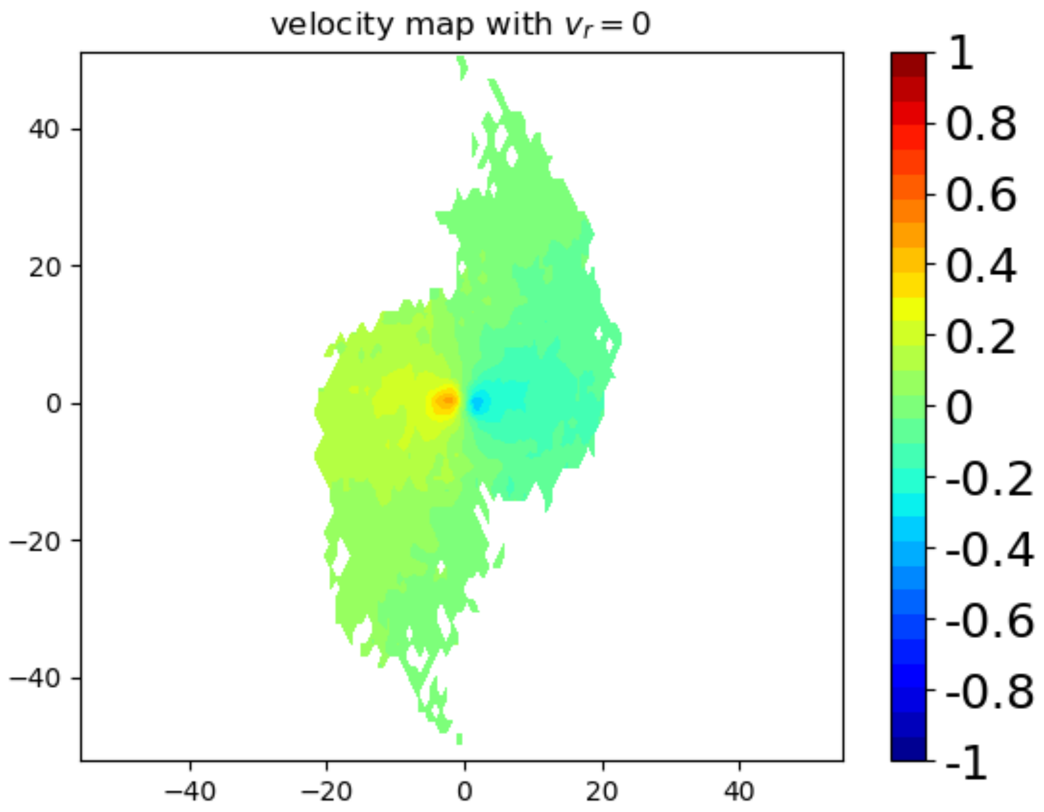
Velocity map
40
20
0
−20
−40
−40
−20
0
20
40
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1



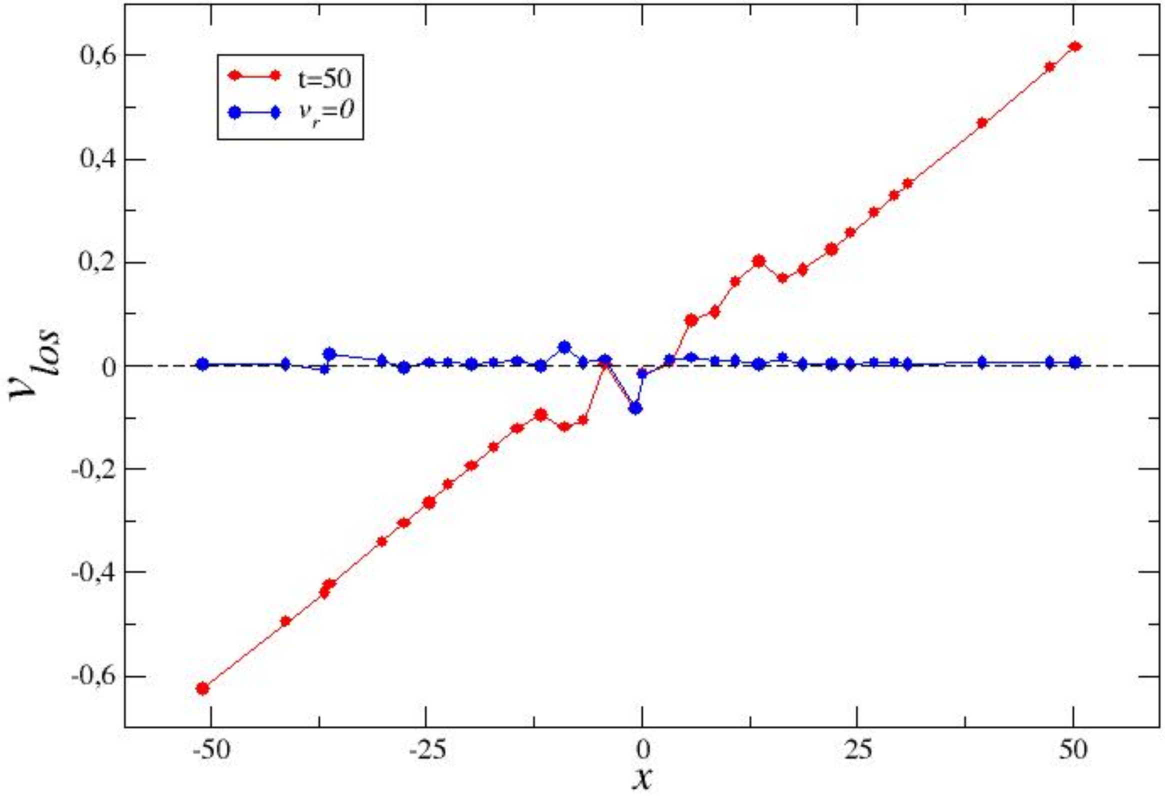
rotation model map with i=20
40
20
0
−20
−40
−40
−20
0
20
40
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

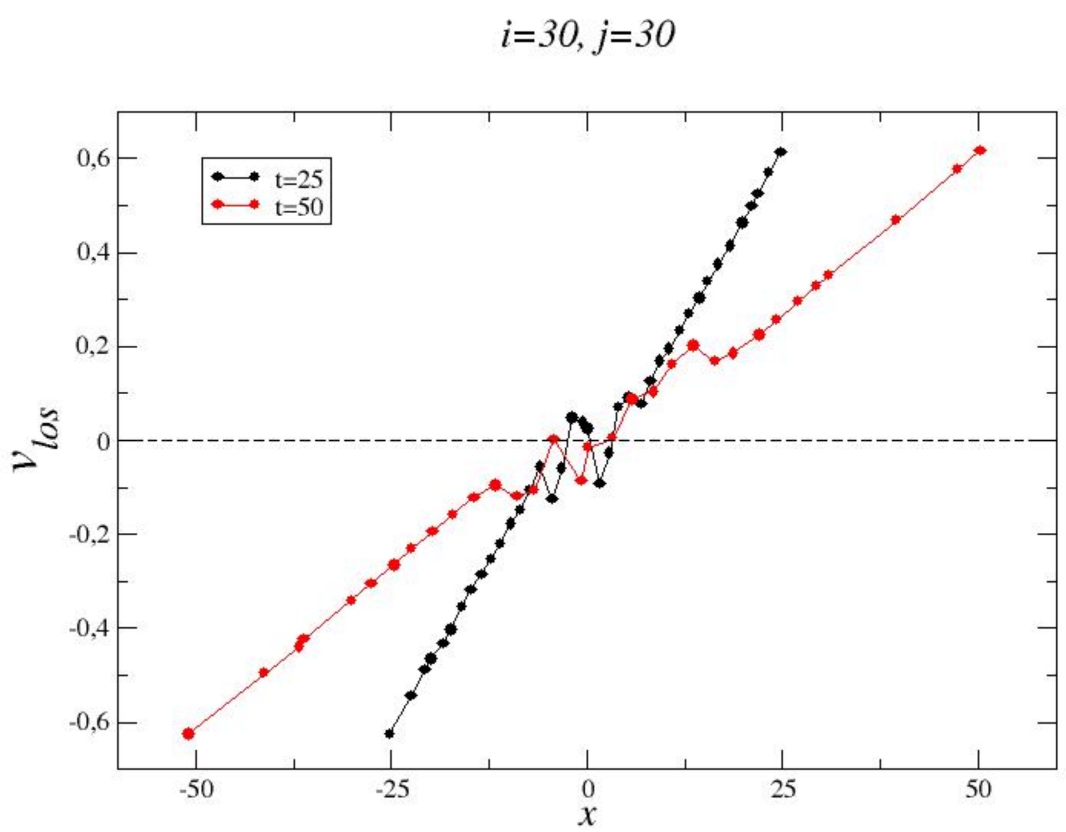


residual map
40
20
0
−20
−40
−40
−20
0
20
40
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

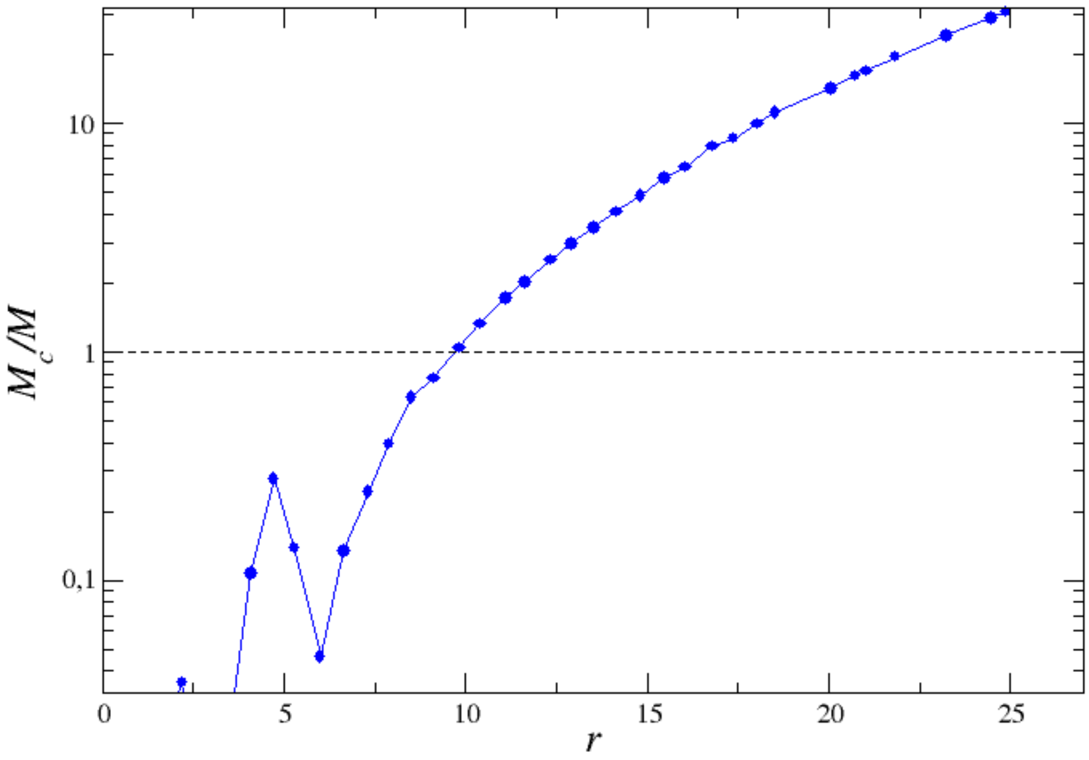

velocity map with $v_r = 0$
40
20
0
−20
−40
−40
−20
0
20
40
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

i=30, j=30

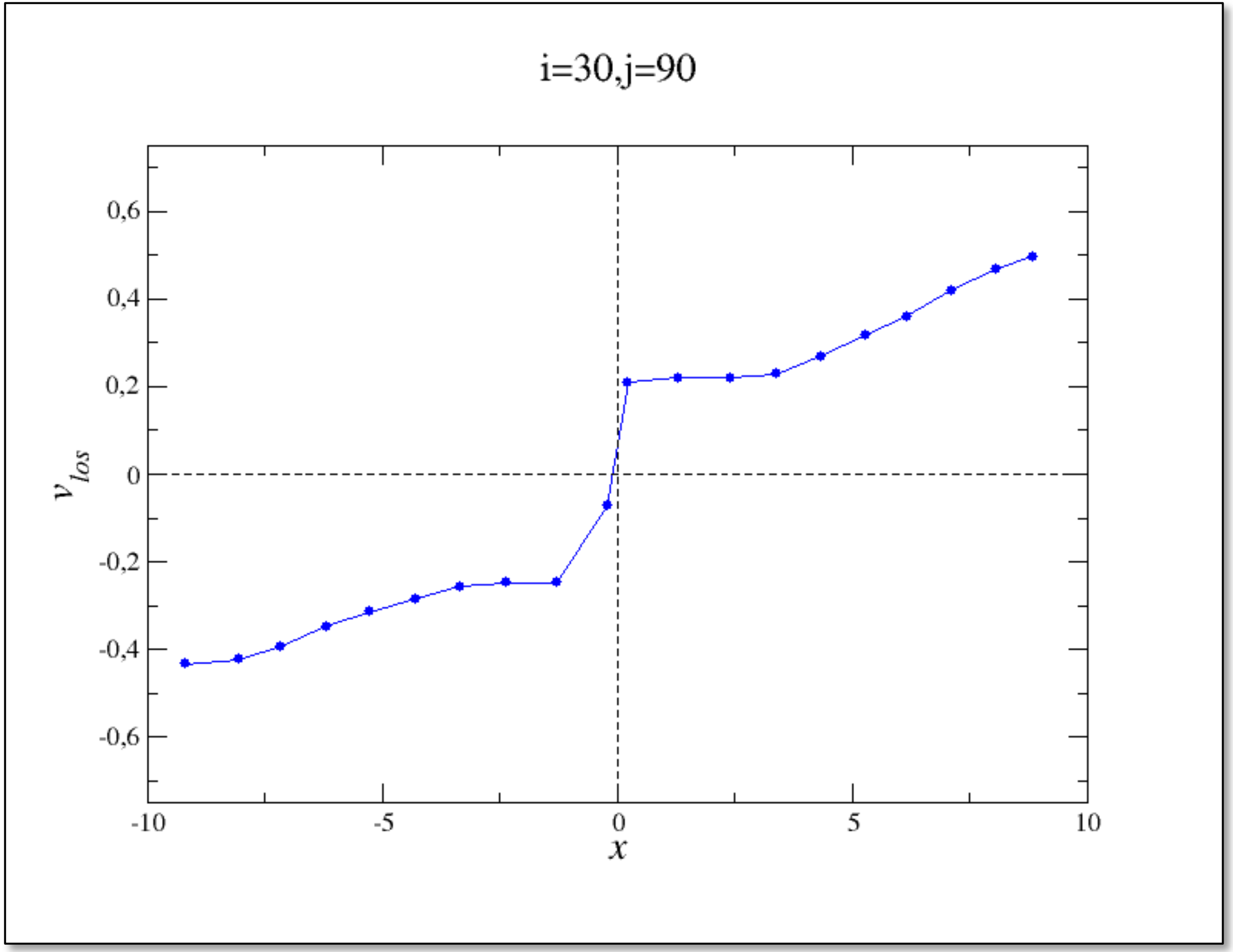




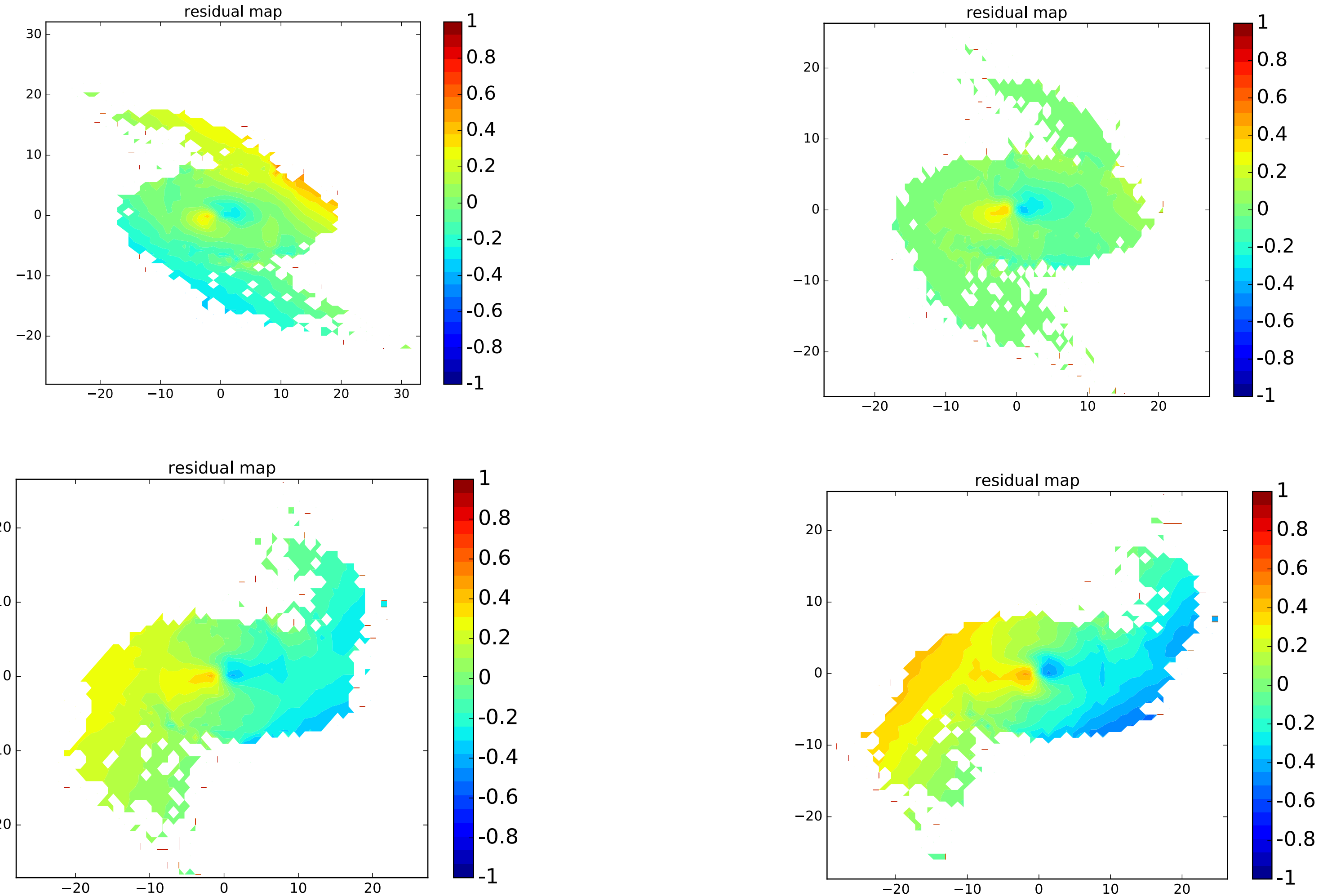
i=30, j=30
t=25
t=50
0,6
0,4
0,2
0
-0,2
-0,4
-0,6
v_{los}
-50
-25
0
25
50
x



10
1
0,1
0
5
10
15
20
25
r
M_c /M



(no core-cusp problem …)


residual map
30
20
10
0
−10
−20
−20
−10
0
10
20
30
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
residual map
20
10
0
−10
−20
−20
−10
0
10
20
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
residual map
20
10
0
−10
−20
−20
−10
0
10
20
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
residual map
20
10
0
−10
−20
−20
−10
0
10
20
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

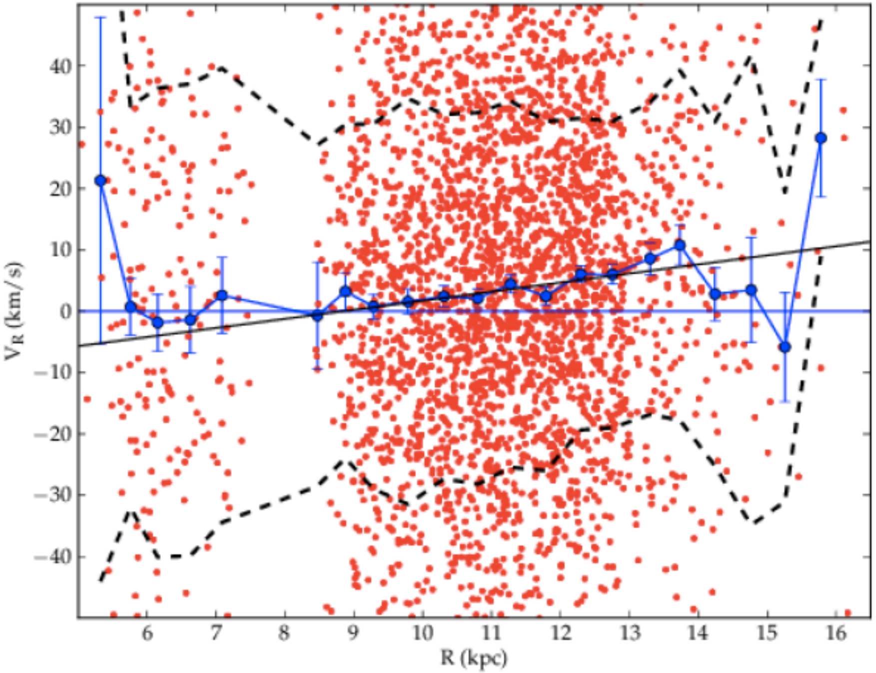
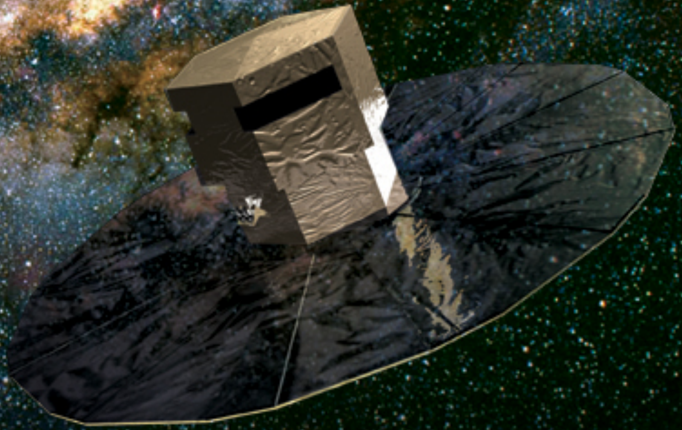


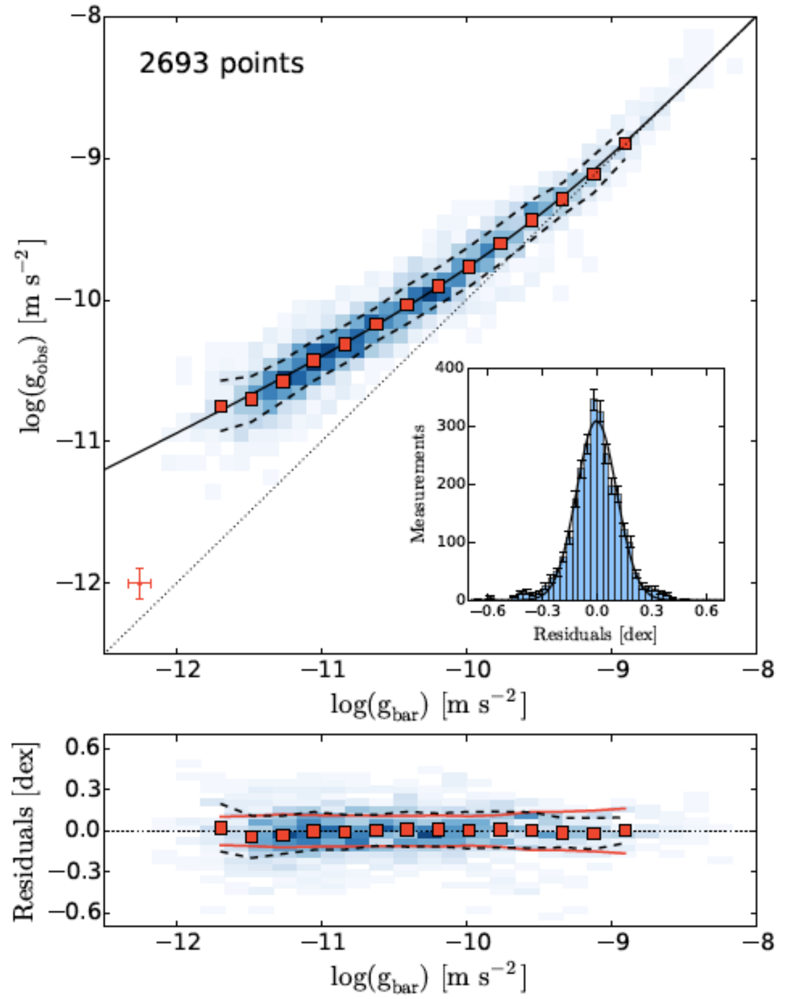
Figure 2. Radial galactocentric velocity derived from Eq. (4) with radial heliocentric velocities from APOGEE for RCG sources within a region close to the Galactic center-Sun line. The blue line and its error bars represent the average within bins of $\Delta R = 0.5$ kpc. The region between both dashed lines is the zone within one rms of dispersion of the points.

GAIA

determines the position, parallax, and annual proper motion of 1 billion stars with an accuracy of about 20 microarcseconds at 15 mag, and 200 μas at 20 mag.



Link to other observations



The Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA

James M. Schombert
Department of Physics, University of Oregon, Eugene, OR 97403, USA

(Dated: September 21, 2016)

$$a_c \propto \sqrt{g(r)}$$

$$a_c \approx \frac{v_{max}^2}{r}$$

$$g(r) \approx \frac{GM_c}{r^2}$$

$$a_c \approx \frac{v_{max}^2}{r} \approx \sqrt{a_0\, g(r)}$$

$$a_0 = \frac{v_{max}^4}{GM_c}$$

$$L \propto v^4$$

A New Method of Determining Distances to Galaxies

R. Brent Tully[1*] and J. Richard Fisher[2]

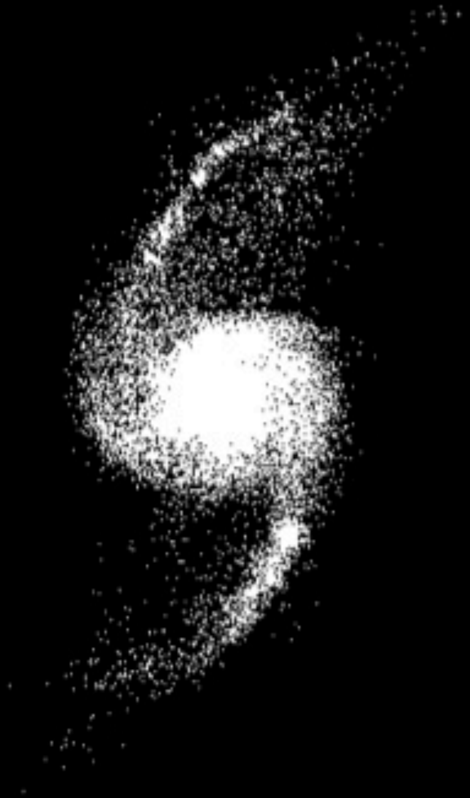
$$\langle I \rangle \approx \text{const}$$

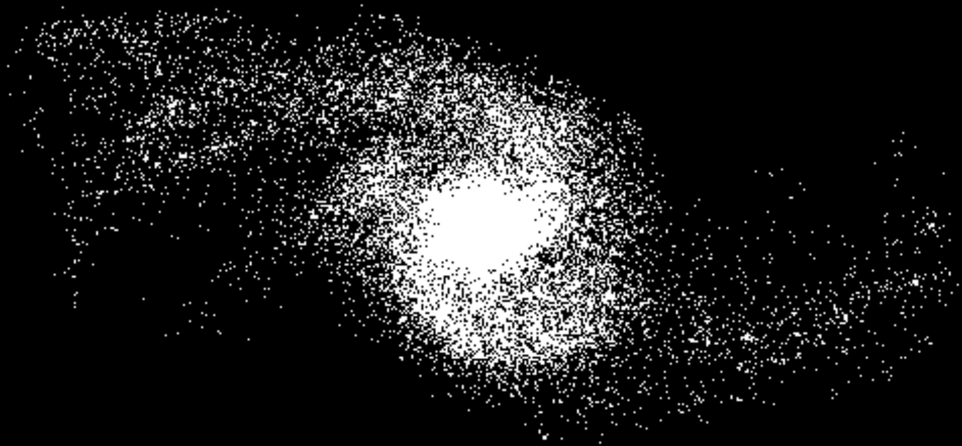
$$\frac{M}{L} \approx \text{const}$$

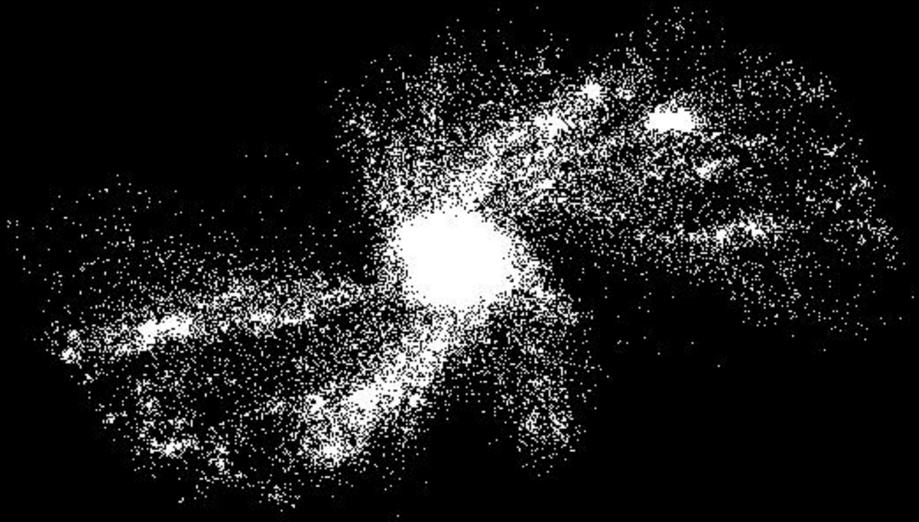
$$M \sim r \quad \text{(DM....)}$$

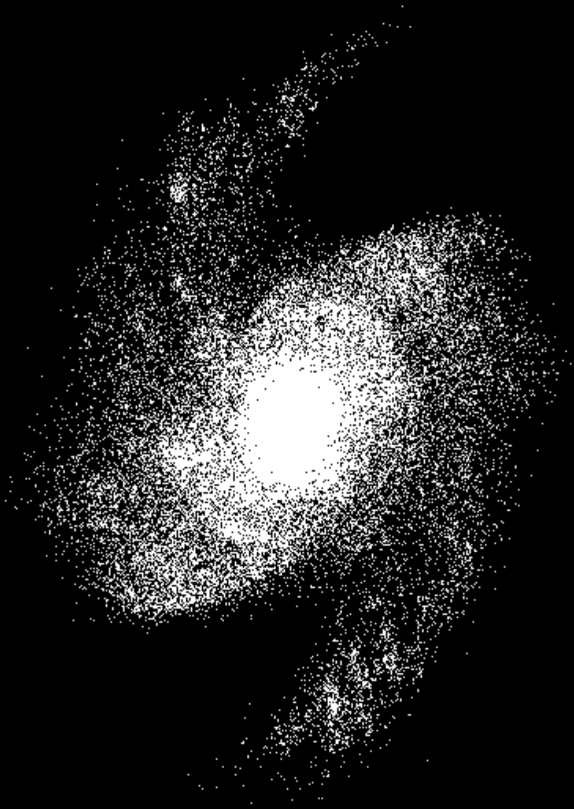
TF → correlation DM and VM

Different initial conditions

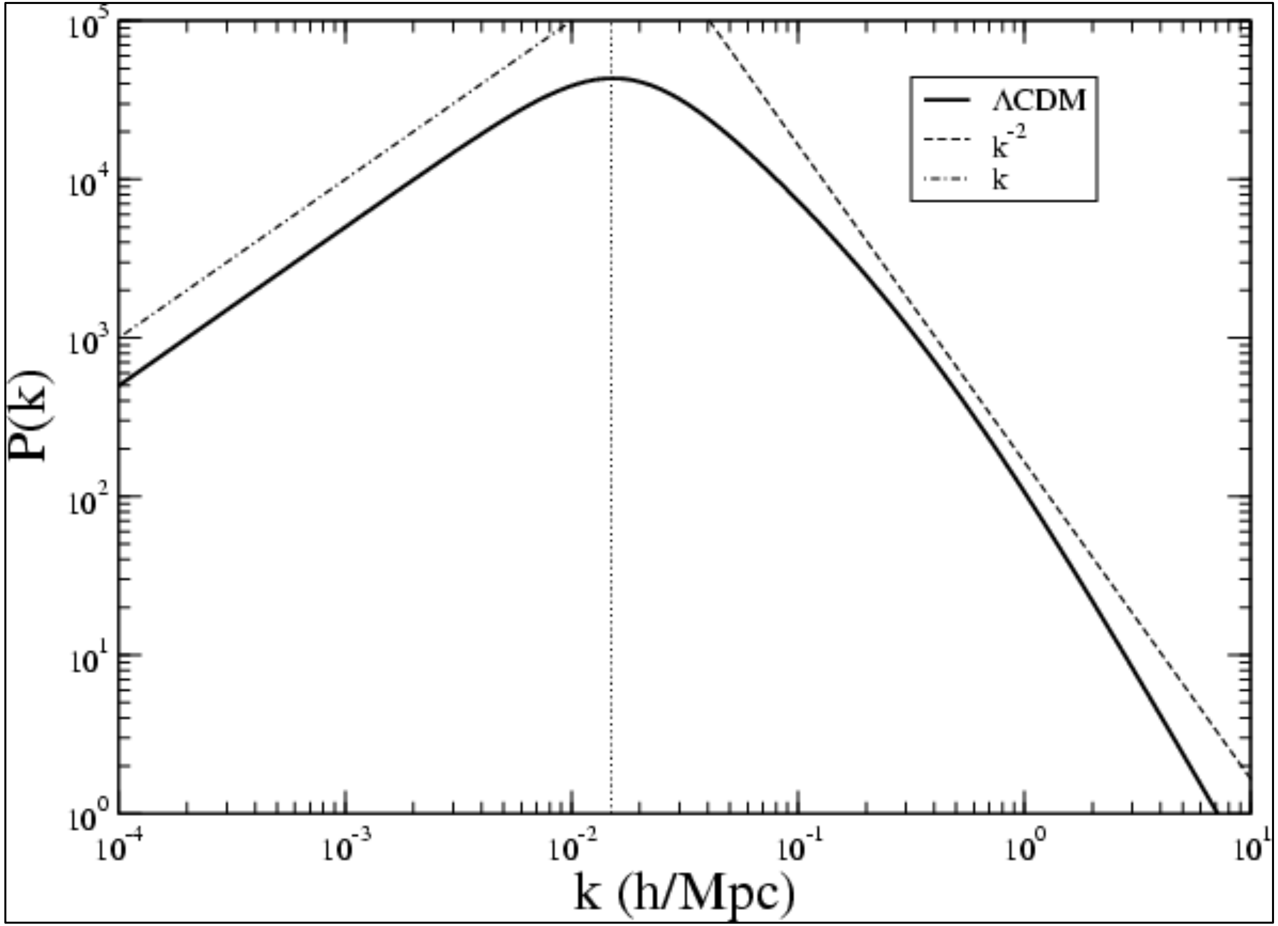




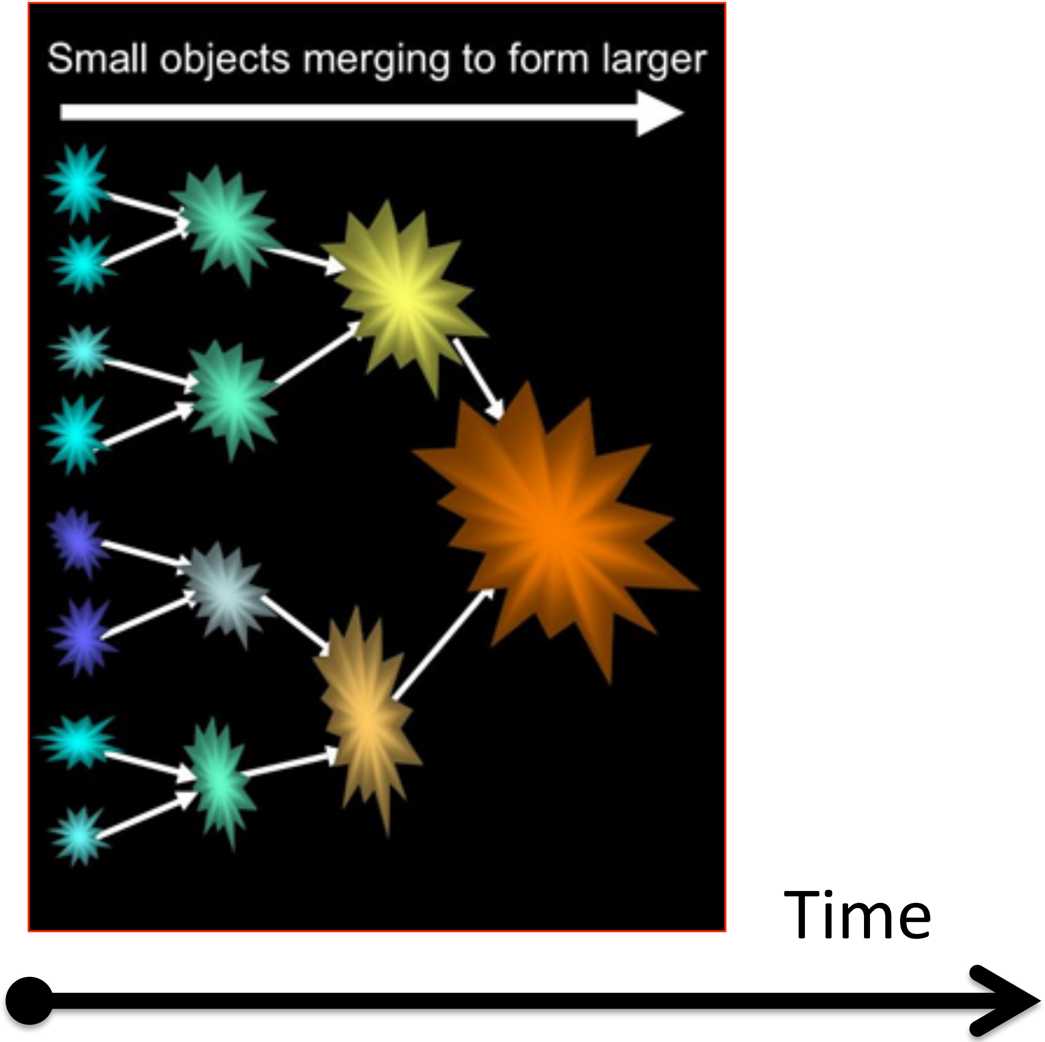



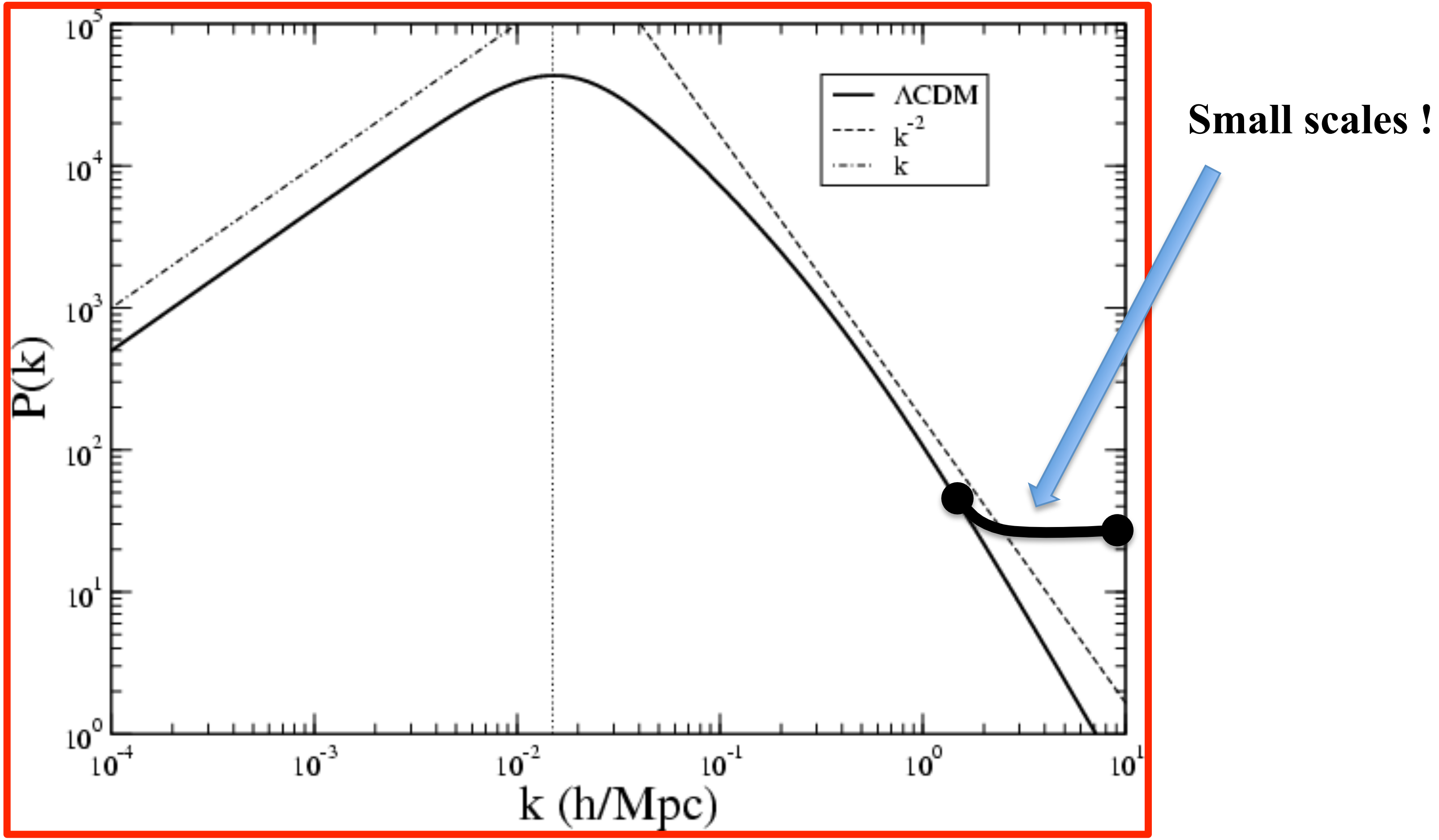



Connection with cosmological structure formation

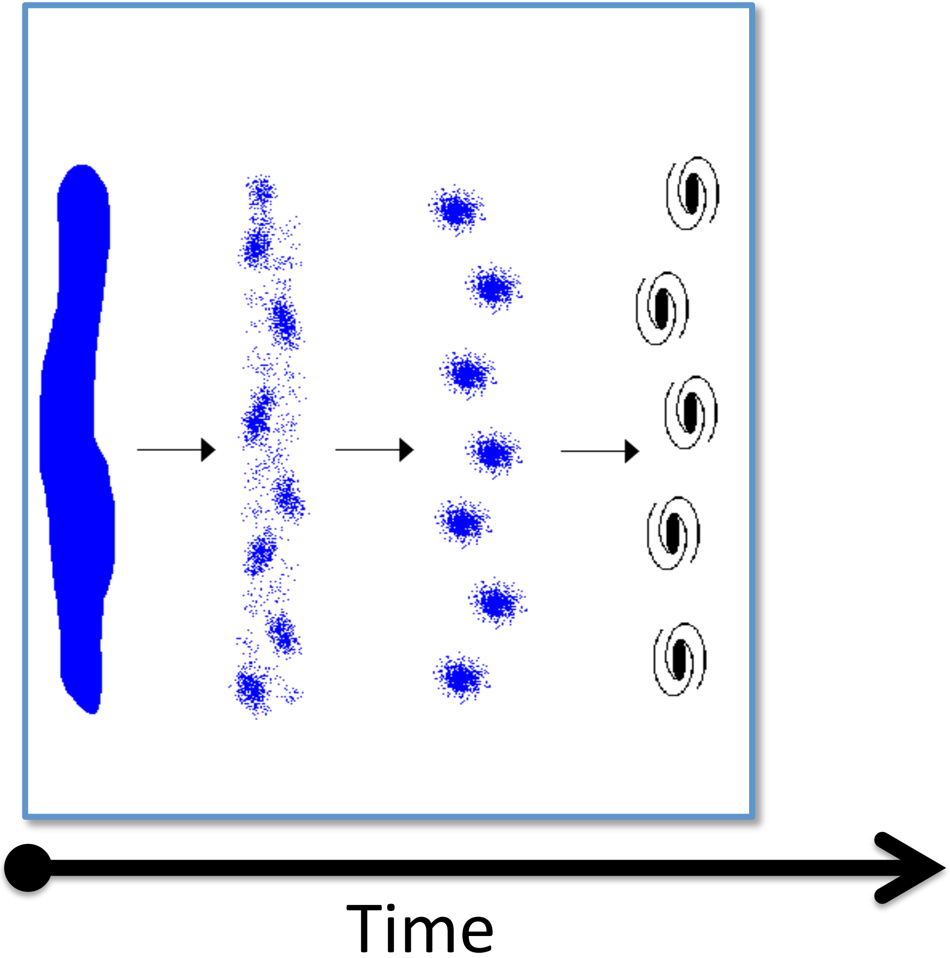


P(k)
k (h/Mpc)
ΛCDM
k^-2
k
10^0
10^1
10^2
10^3
10^4
10^5
10^-4
10^-3
10^-2
10^-1
10^0
10^1


Small objects merging to form larger
Time

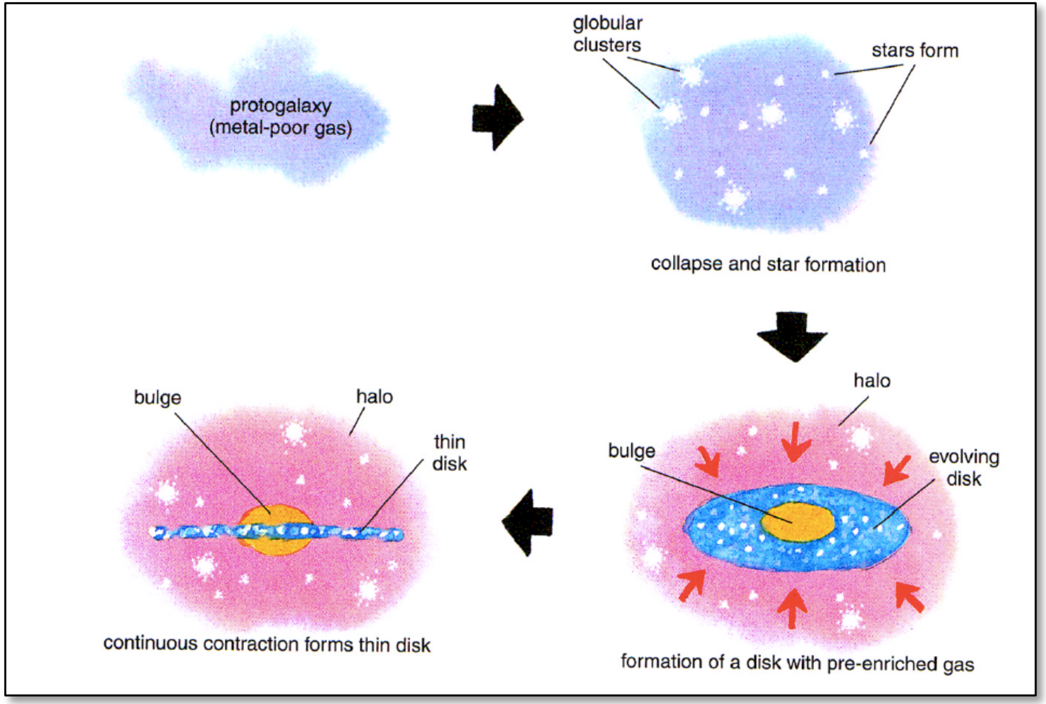


ΛCDM
k^-2
k
P(k)
k (h/Mpc)
Small scales !


Time

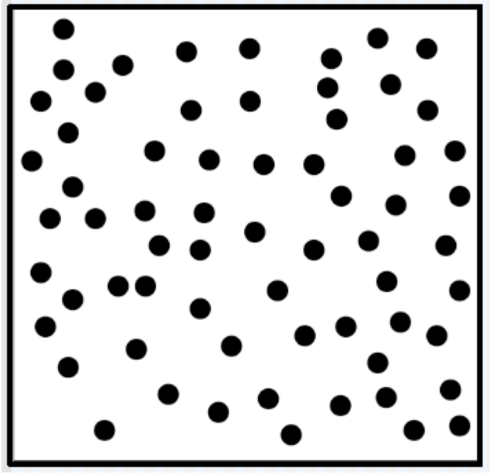
EVIDENCE FROM THE MOTIONS OF OLD STARS THAT THE GALAXY COLLAPSED

O. J. EGGEN, D. LYNDEN-BELL,* AND A. R. SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 17, 1962



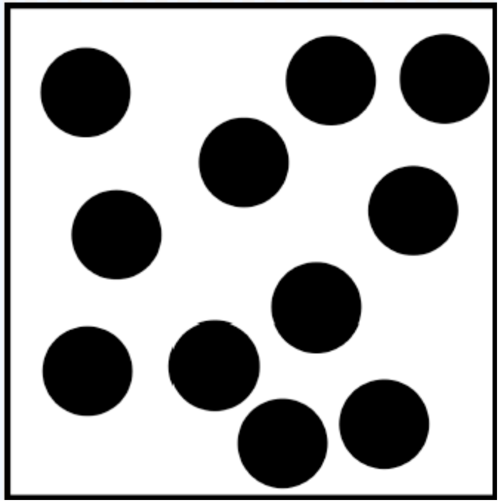
Real physical CDM particles (…)

$$\frac{10^{30} - 10^{80}}{Mpc^3}$$



Cosmological Simulations

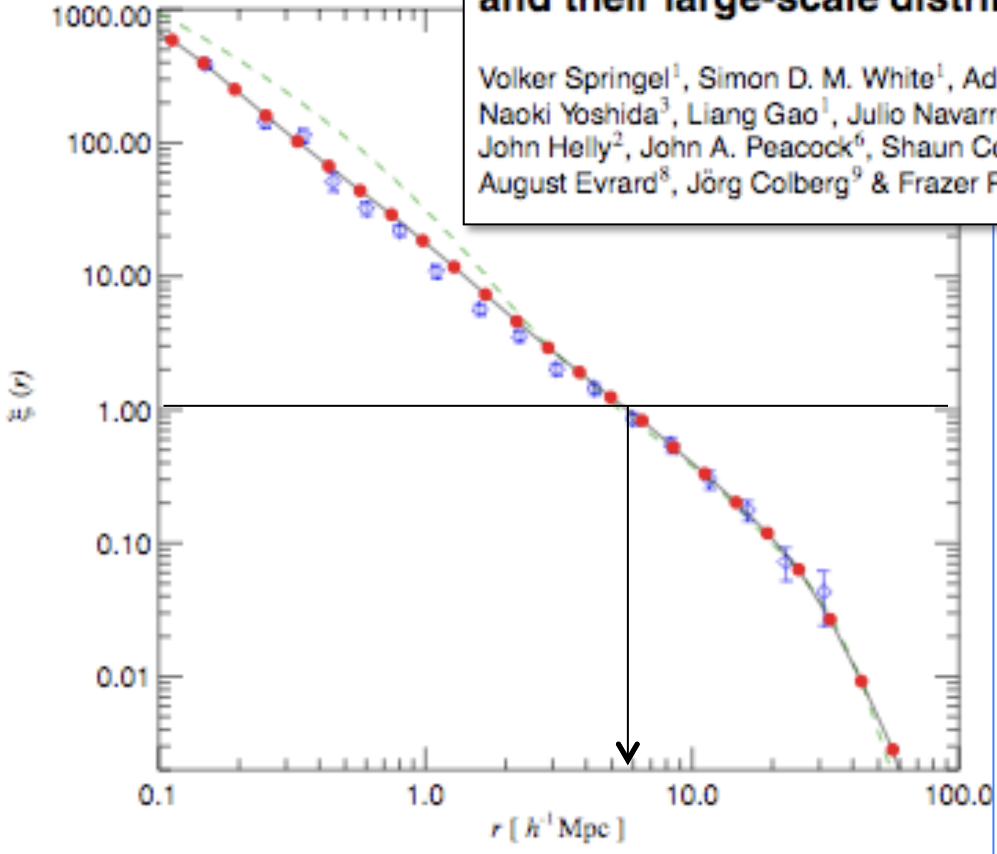
$$\frac{10 - 100}{Mpc^3}$$



Problem: $\Lambda > r_{min}$

Simulating the joint evolution of quasars, galaxies and their large-scale distribution

Volker Springel[1], Simon D. M. White[1], Adrian Jenkins[2], Carlos S. Frenk[2], Naoki Yoshida[3], Liang Gao[1], Julio Navarro[4], Robert Thacker[5], Darren Croton[1], John Helly[2], John A. Peacock[6], Shaun Cole[2], Peter Thomas[7], Hugh Couchman[5], August Evrard[8], Jörg Colberg[9] & Frazer Pearce[10]



Non linear clustering in

$$\epsilon \approx \frac{\Lambda}{10} < r < 10\Lambda$$

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **470**, 4099–4111 (2017) doi:10.1093/mnras/stx1356
Advance Access publication 2017 June 5

Stable clustering and the resolution of dissipationless cosmological *N*-body simulations

David Benhaiem,[1,2★] Michael Joyce[2,3★] and Francesco Sylos Labini[4,1,5★]
[1]*Istituto dei Sistemi Complessi Consiglio Nazionale delle Ricerche, Via dei Taurini 19, 00185 Rome, Italy*
[2]*UPMC Univ Paris 06, UMR 7585, LPNHE, F-75005 Paris, France*
[3]*CNRS IN2P3, UMR 7585, LPNHE, F-75005 Paris, France*
[4]*Museo Storico della Fisica e Centro Studi e Ricerche 'Enrico Fermi', Via Panisperna 89 A, 00184 Rome, Italy*
[5]*INFN Unit Rome 1, Dipartimento di Fisica, Universitá di Roma Sapienza, Piazzale Aldo Moro 2, 00185 Roma, Italy*

A&A 552, A36 (2013)
DOI: 10.1051/0004-6361/201321037

Astronomy & Astrophysics

A toy model to test the accuracy of cosmological *N*-body simulations

F. Sylos Labini[1,2]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Particle number dependence in the non-linear evolution of *N*-body self-gravitating systems

D. Benhaiem[1,2], M. Joyce[2], F. Sylos Labini[3,1,4] and T. Worrakitpoonpon[5]
[1]*Istituto dei Sistemi Complessi Consiglio Nazionale delle Ricerche, Via dei Taurini 19, 00185 Rome, Italy*
[2]*Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC IN2P3 CNRS UMR 7585, Sorbonne Universités, 4, place Jussieu, 75252 Paris Cedex 05, France*
[3]*Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi", 00186 Rome, Italy*
[4]*INFN Unit Rome 1, Dipartimento di Fisica, Universitá di Roma Sapienza, Piazzale Aldo Moro 2, 00185 Roma, Italy*
[5]*Faculty of Science and Technology, Rajamangala University of Technology Suvarnabhumi, Nonthaburi Campus, Nonthaburi 11000, Thailand*

21 September 2017

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **429**, 1088–1101 (2013) doi:10.1093/mnras/sts390

Evolution of isolated overdensities as a control on cosmological *N*-body simulations

Michael Joyce[1★] and Francesco Sylos Labini[2,3]
[1]*Laboratoire de Physique Nucléaire et de Hautes Energies, UMR 7585, Université Pierre et Marie Curie – Paris 6, F-75252 Paris Cedex 05, France*
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[3]*Insitute of Complex Systems (ISC), Consiglio Nazionale delle Ricerche, Via dei Taurini 19, I-00185 Rome, Italy*

Thanks to ….

David Benhaiem

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Michael Joyce

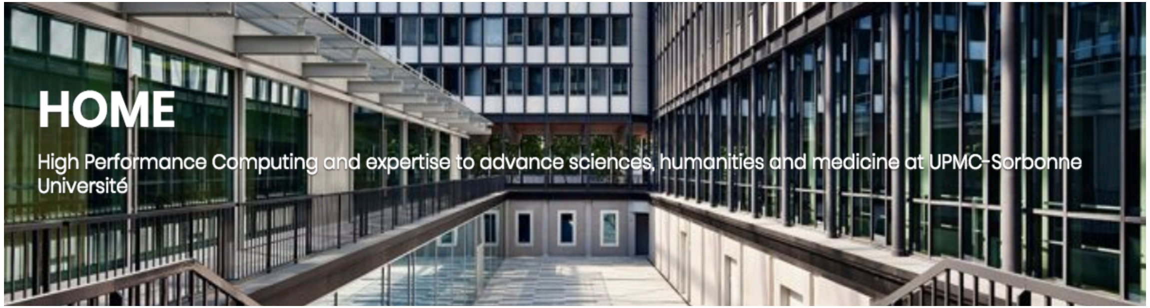
Professor of Physics at the Université Pierre et Marie Curie – Paris VI (France)

Tirawut Worrakitpoonpon

Staff member at the Rajamangala University of Technology Suvarnabhumi (Bangkok, Thailand)

Istituto Nazionale di Fisica Nucleare

DYNSYSMATH
DYNamical systems and non equilibrium states of complex SYStems: MATHematical methods and physical concepts



HPC resources of The Institute for scientific Computing and Simulation financed by Region Ile de France and the project Equip@Meso