DARK MATTER

and

COSMIC RAYS

Paolo Lipari
4th school on Cosmic Rays and Astrophysics
UAFBC Sao Paulo, 30th august 2010

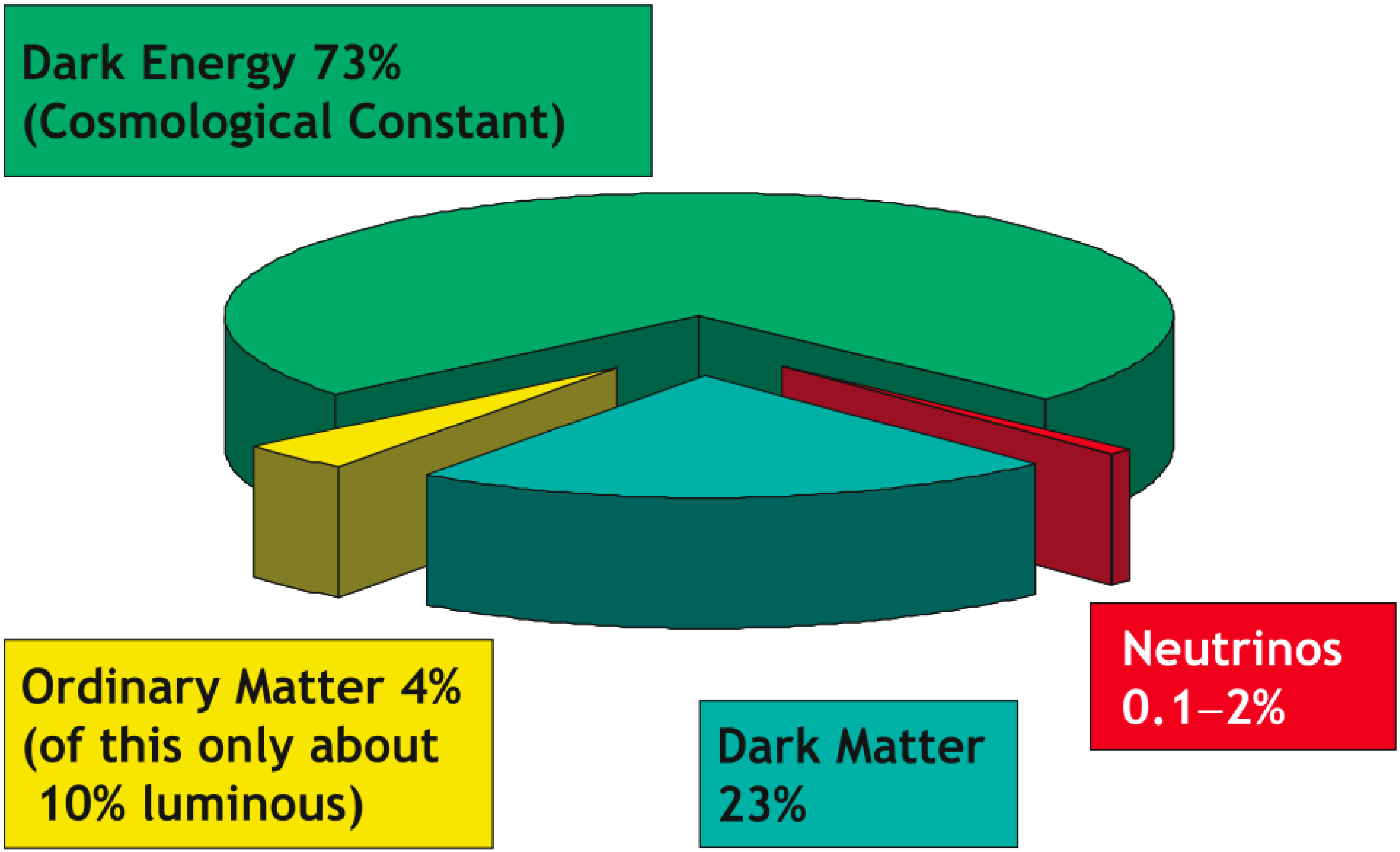
Mysteries of the DARK UNIVERSE

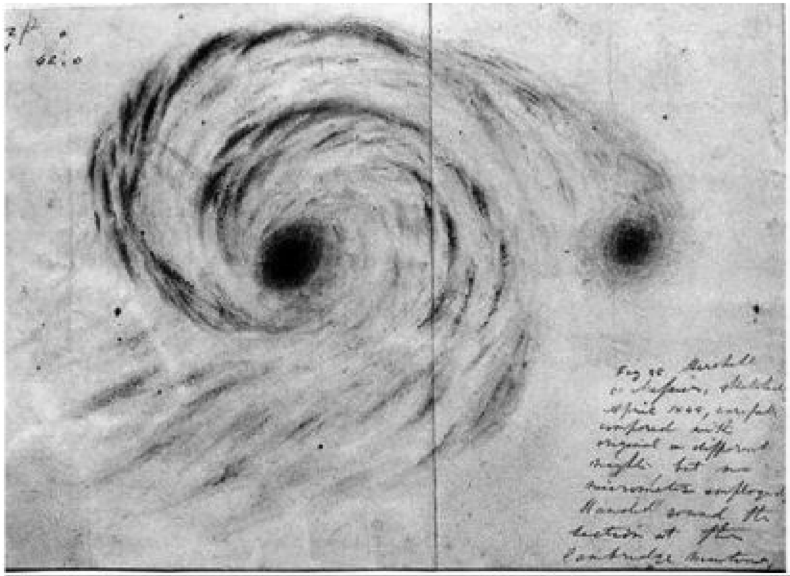
DARK MATTER:

Holds together galaxies
and other large scale structures
[A new elementary particle ?]

DARK ENERGY :

Drives apart galaxies
And other large scale structures
[The energy of vacuum itself ?]


Dark Energy 73%
(Cosmological Constant)
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1–2%



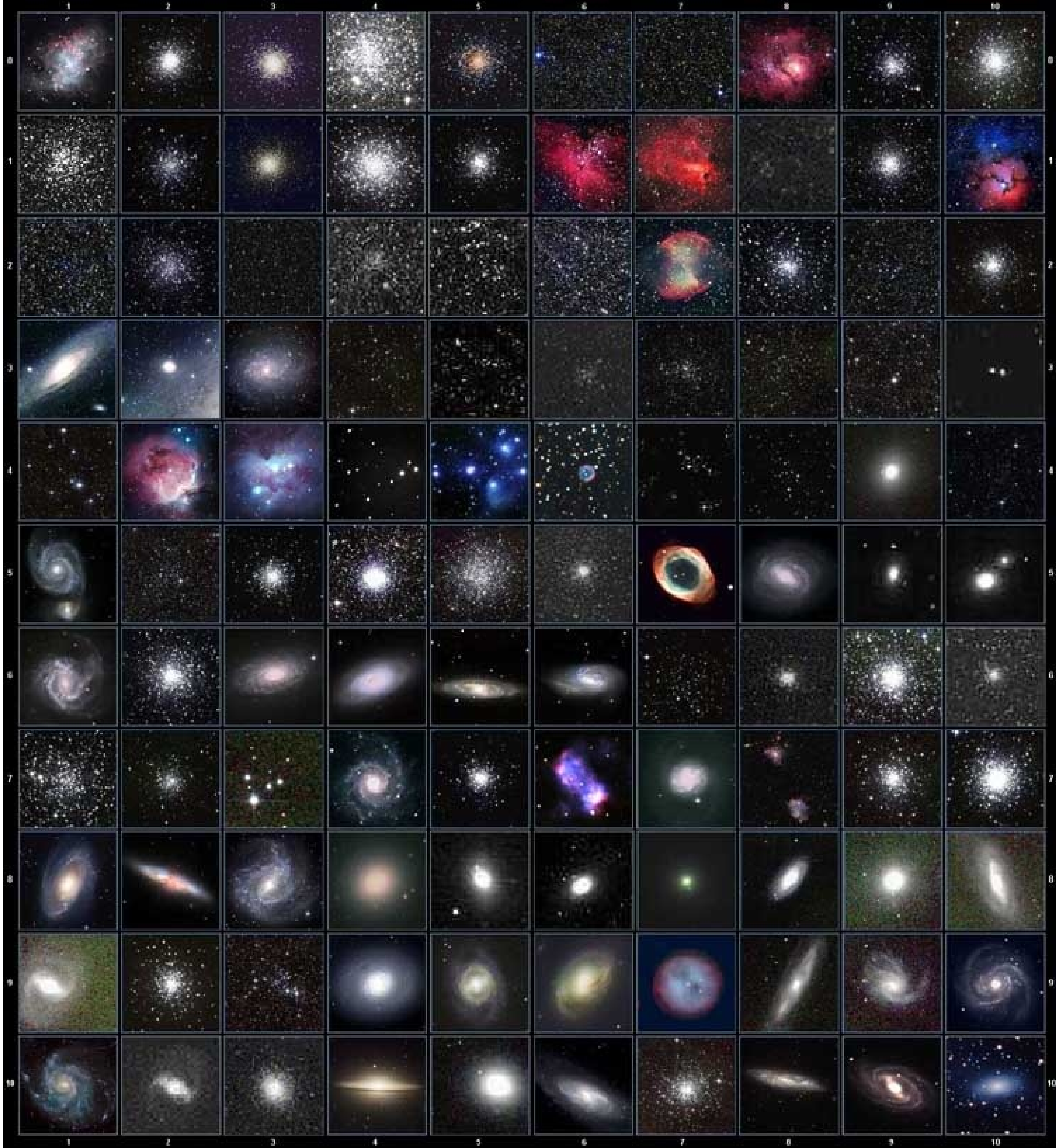


1920
“Great debate”
Shapley-Curtis
Nature of the Nebulae

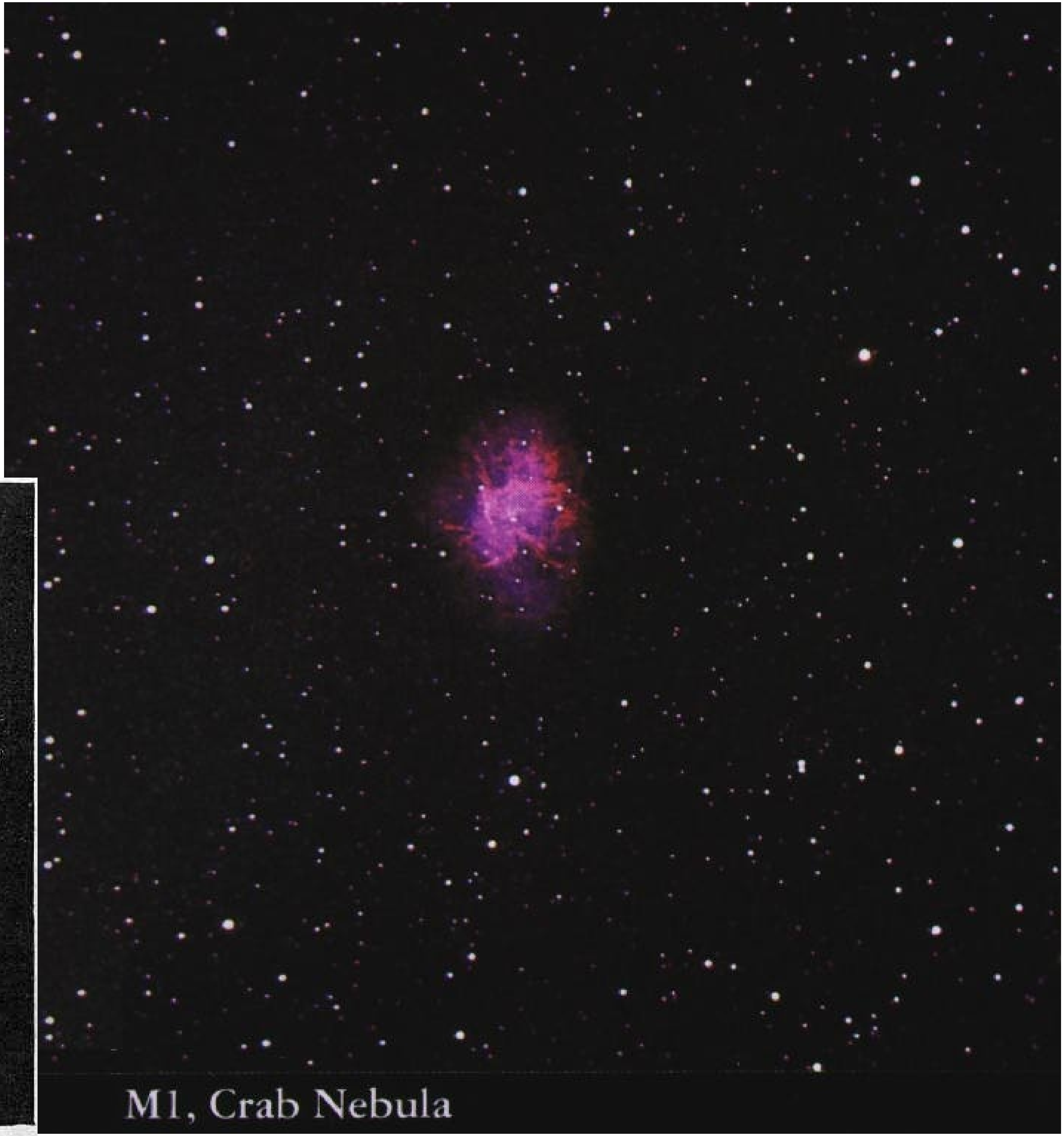
Island Universes ?
(Immanuel Kant)

The mistery
Of the Nebulae

The Messier
Catalogue
(1774)



M1: The CRAB Nebula



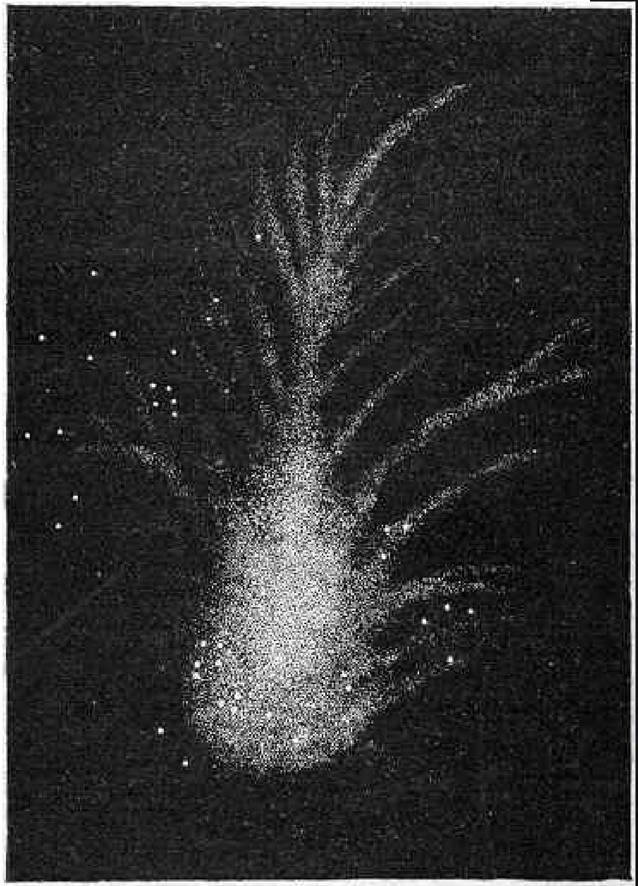
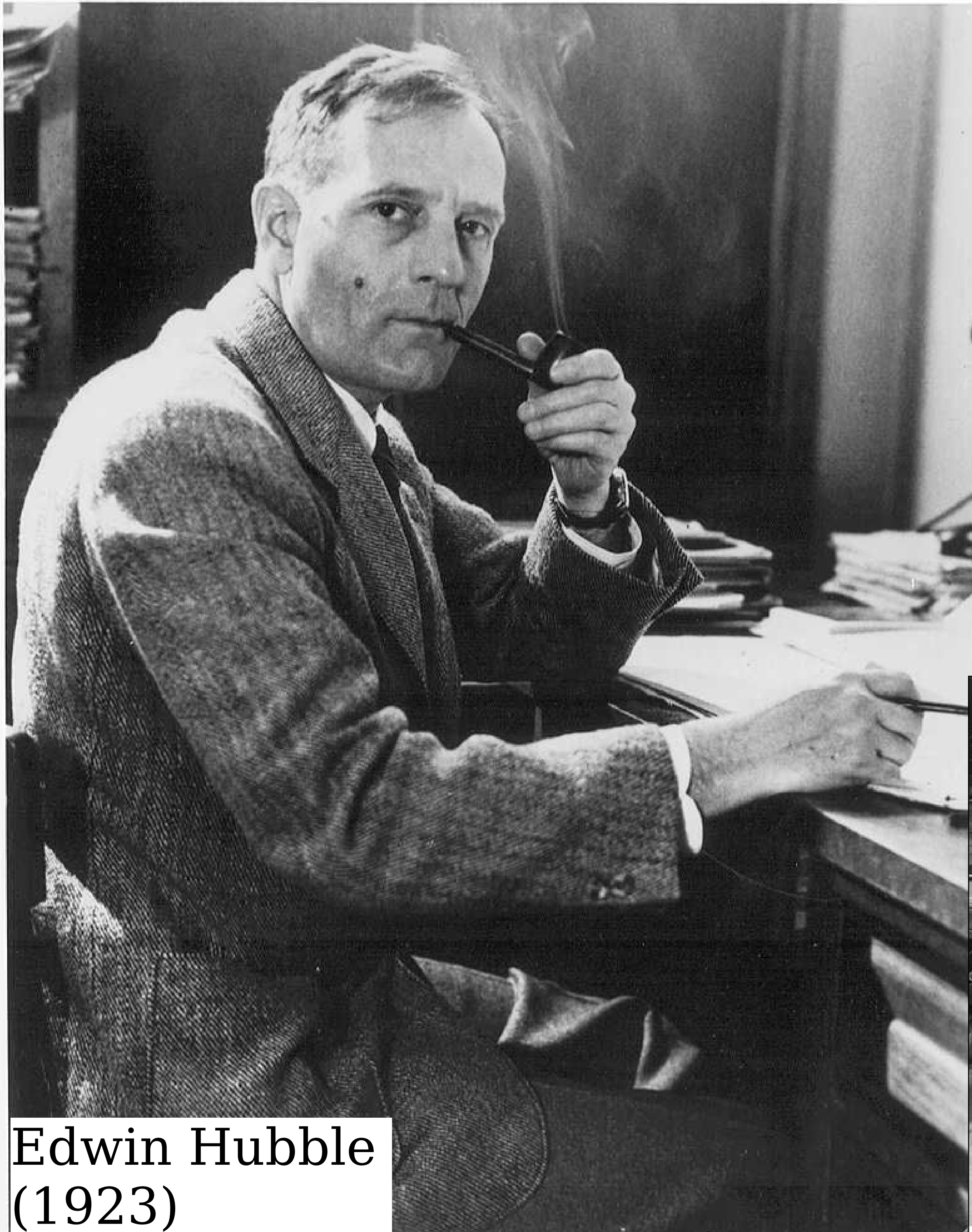


Fig. 438.

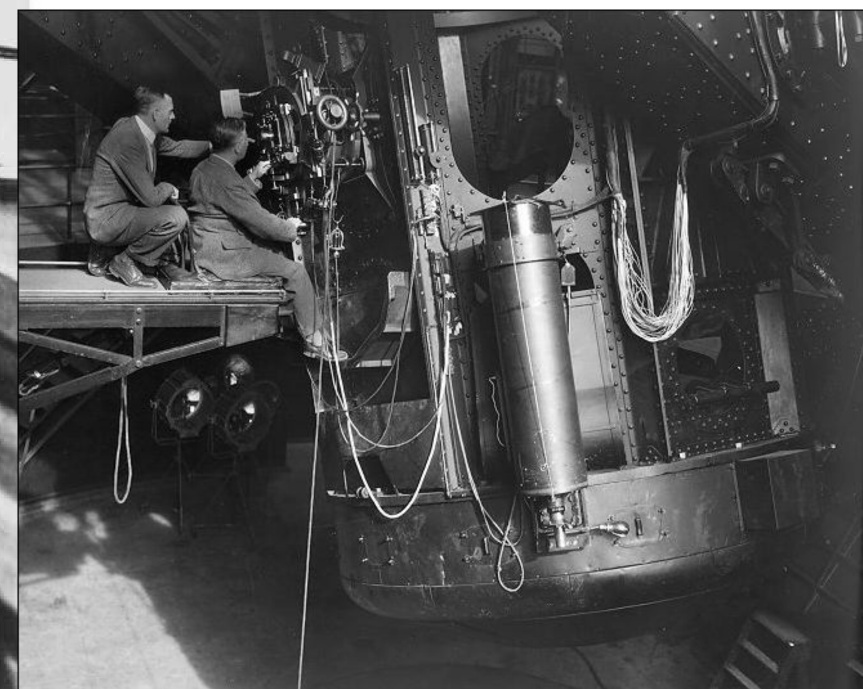
M31:
ANDROMEDA

Discovery of the Expansion of the Universe.

Velocity of Galaxies.



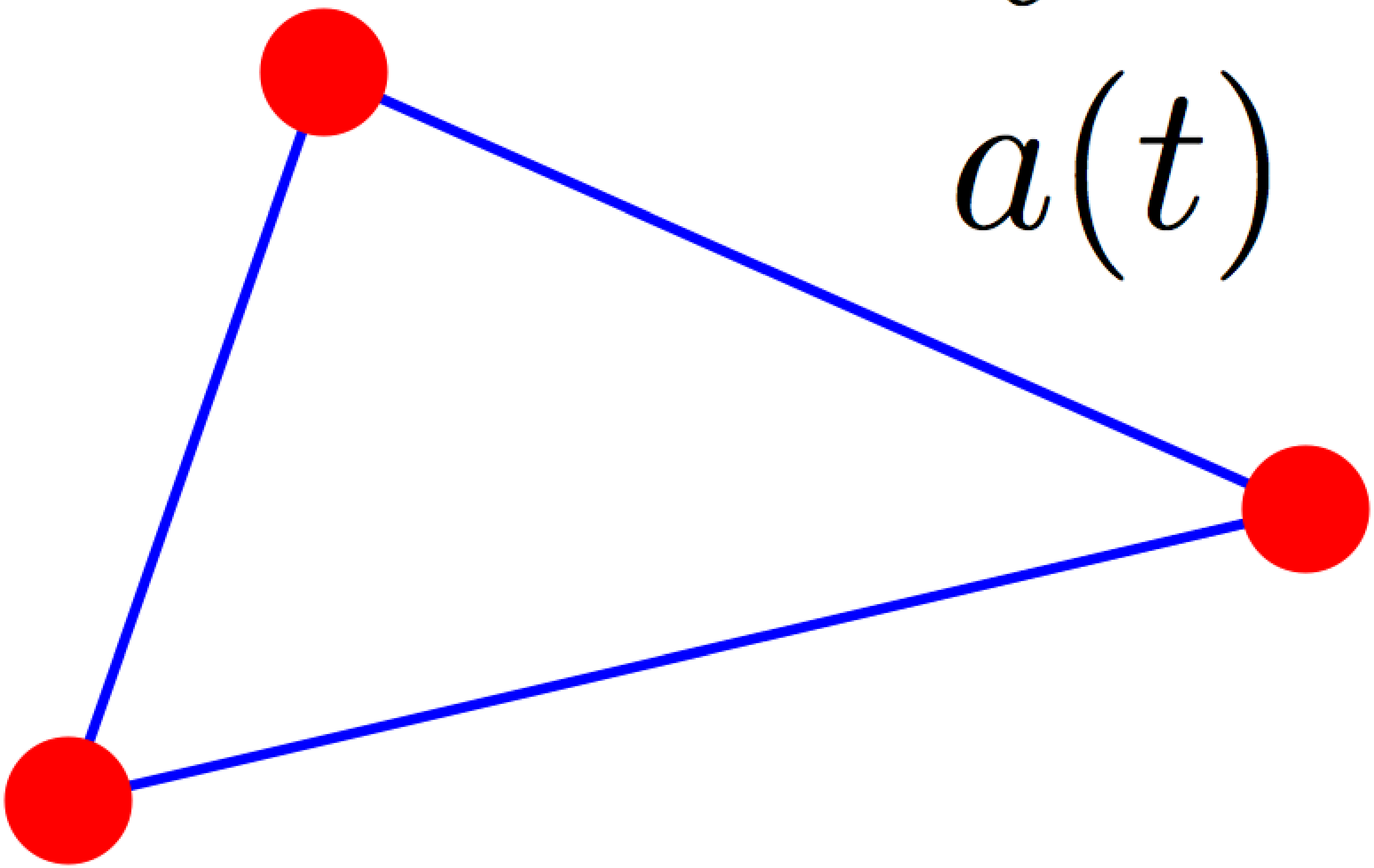
Edwin Hubble (1923)



Rescaling of all distances.

t : Universal time

$a(t)$: Scale function

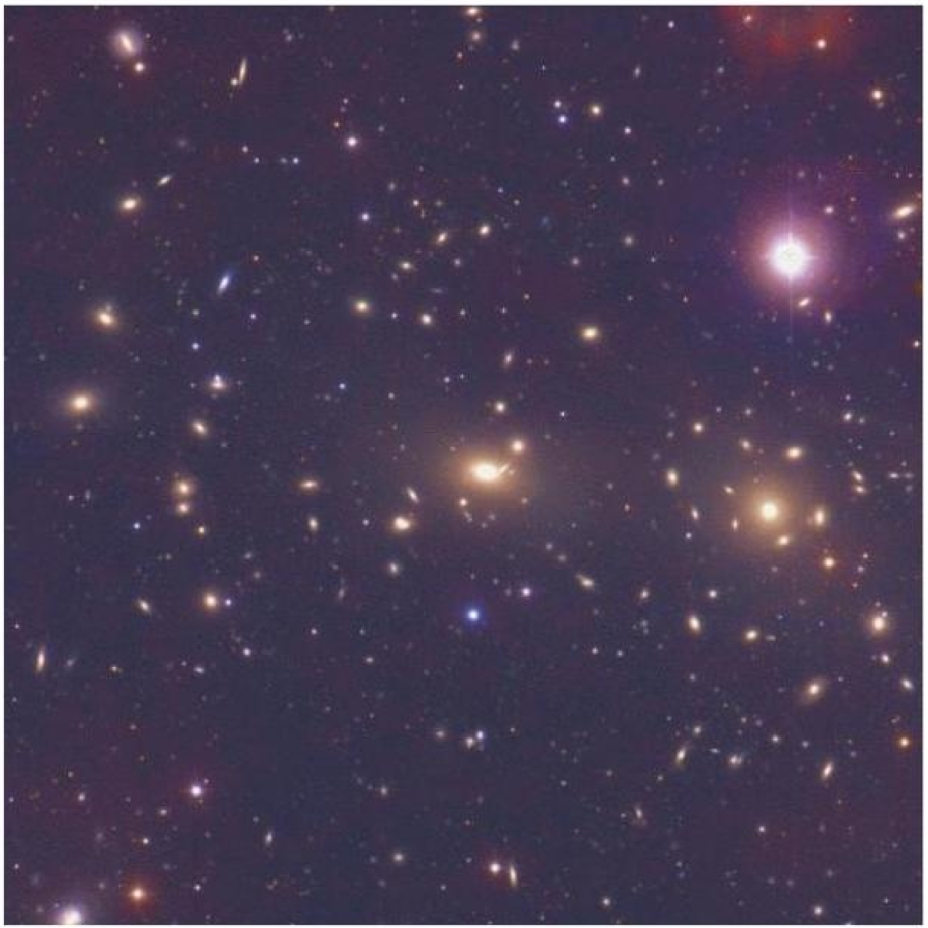


t_0 : present

$a(t_0) = 1$

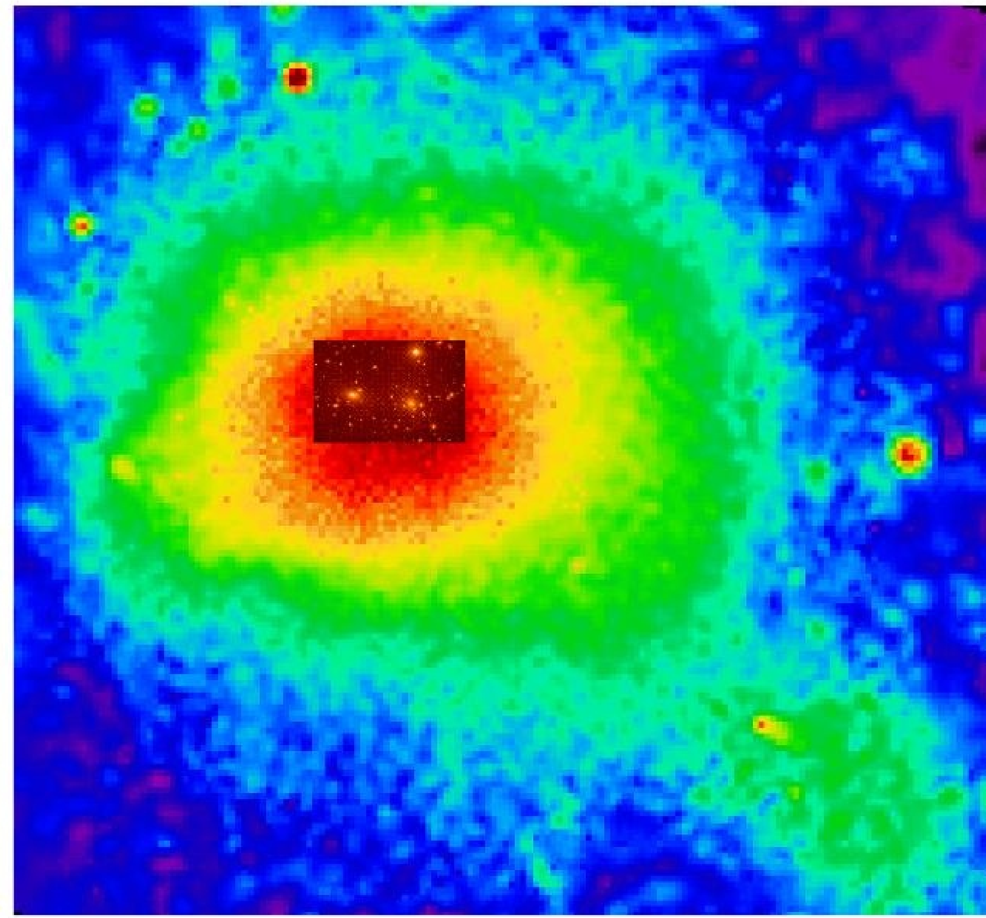
$$\boxed{\vec{R}_{ij}(t) = a(t)\ \vec{r}_{jk}}$$

COMA Galaxy Cluster



Optical

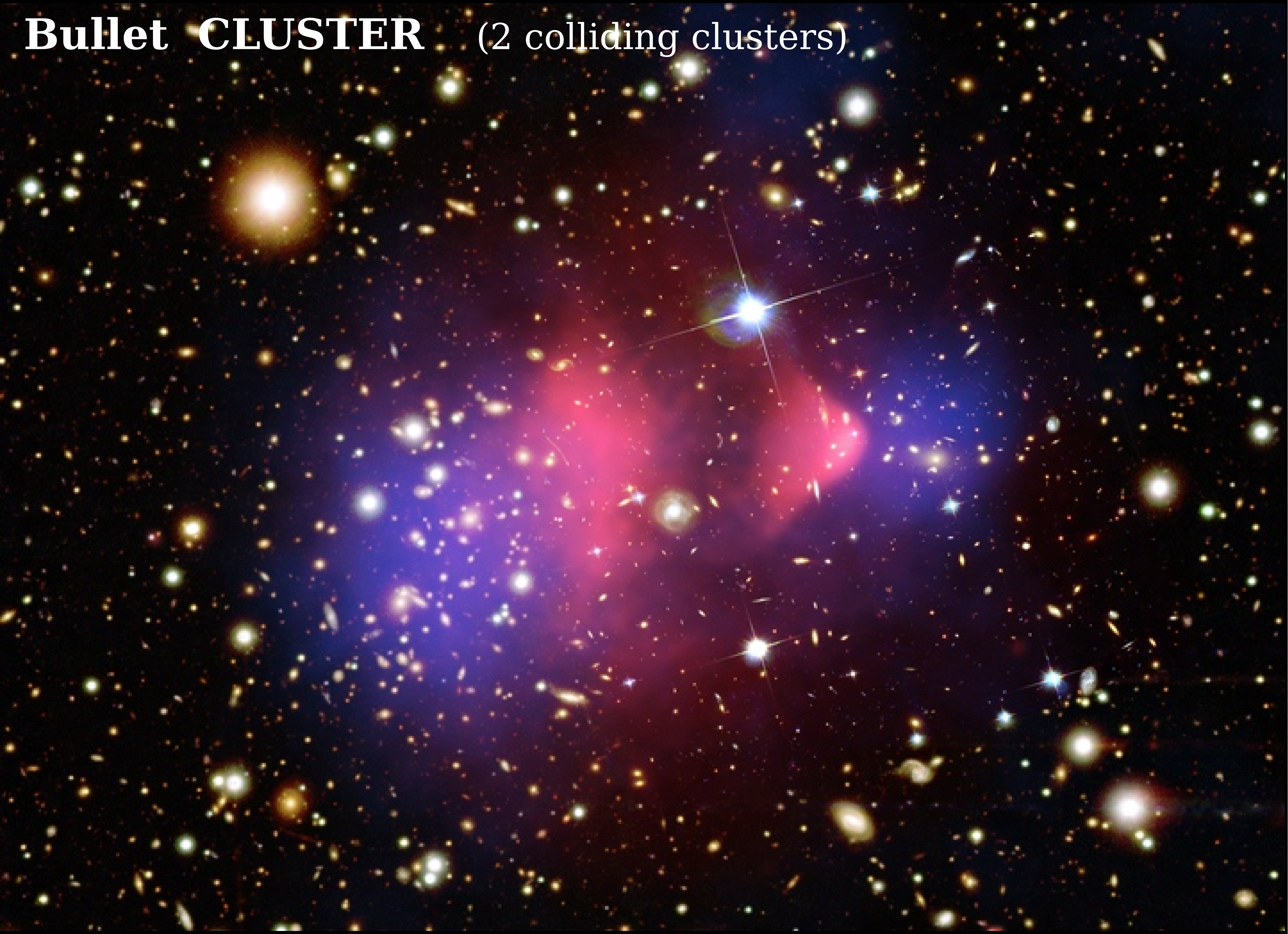
Fritz Zwicky 1933
First argument for Dark Matter



X-ray
[hot gas confined by
deep gravitational well]

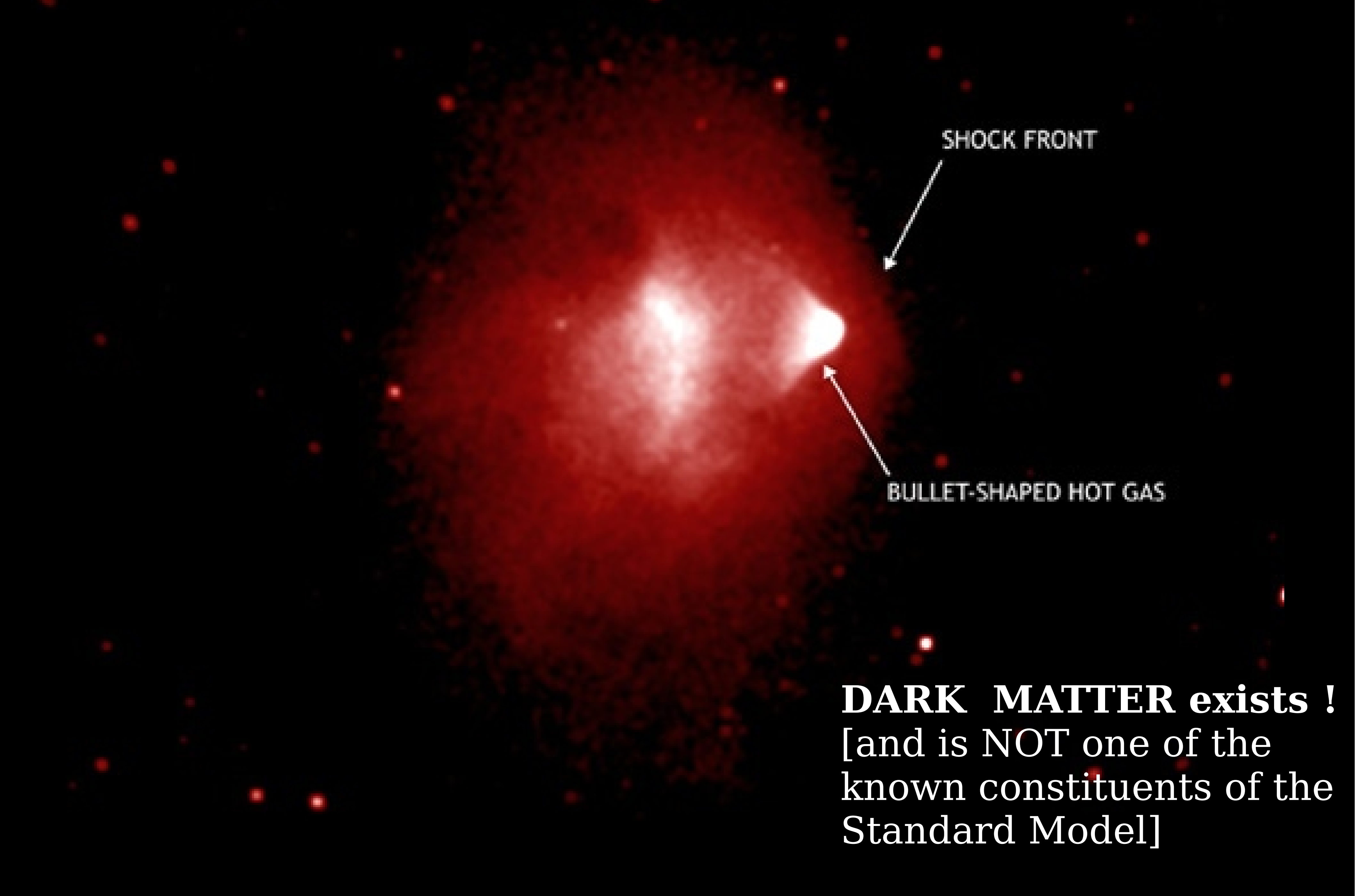

VIRGO
CLUSTER
Virgo Cluster
Intes Mk69@900mm
St10XME L265min 300sec sub RGB 60/57/62min 200sec bin2x2
Gahberg 20080427/0507/0508
www.kerschhuber.astronomie.at

Bullet CLUSTER (2 colliding clusters)

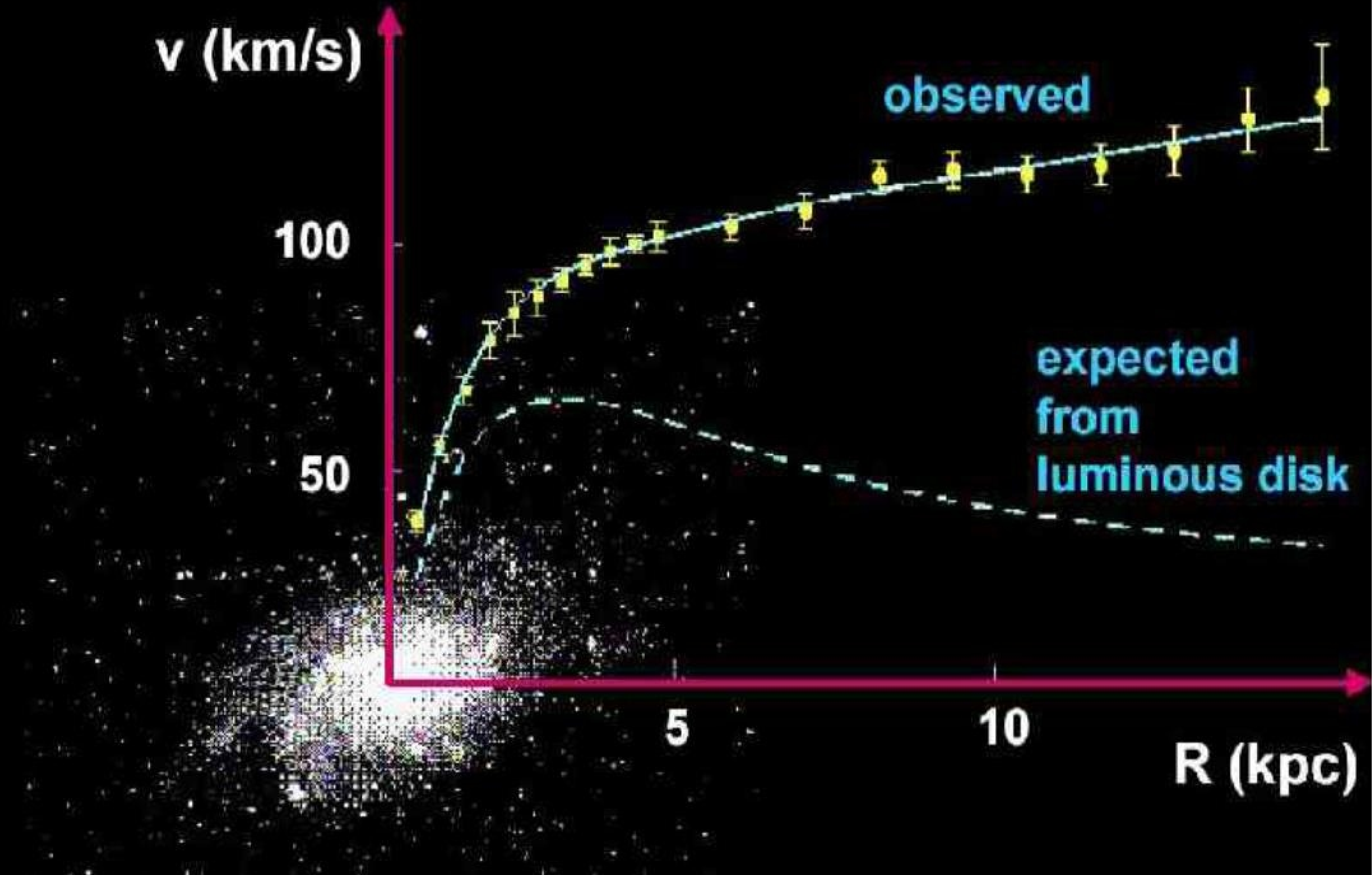


MASS DISTRIBUTION
(from gravitational lensing)

X-RAY Emission
(gas of ordinary matter)

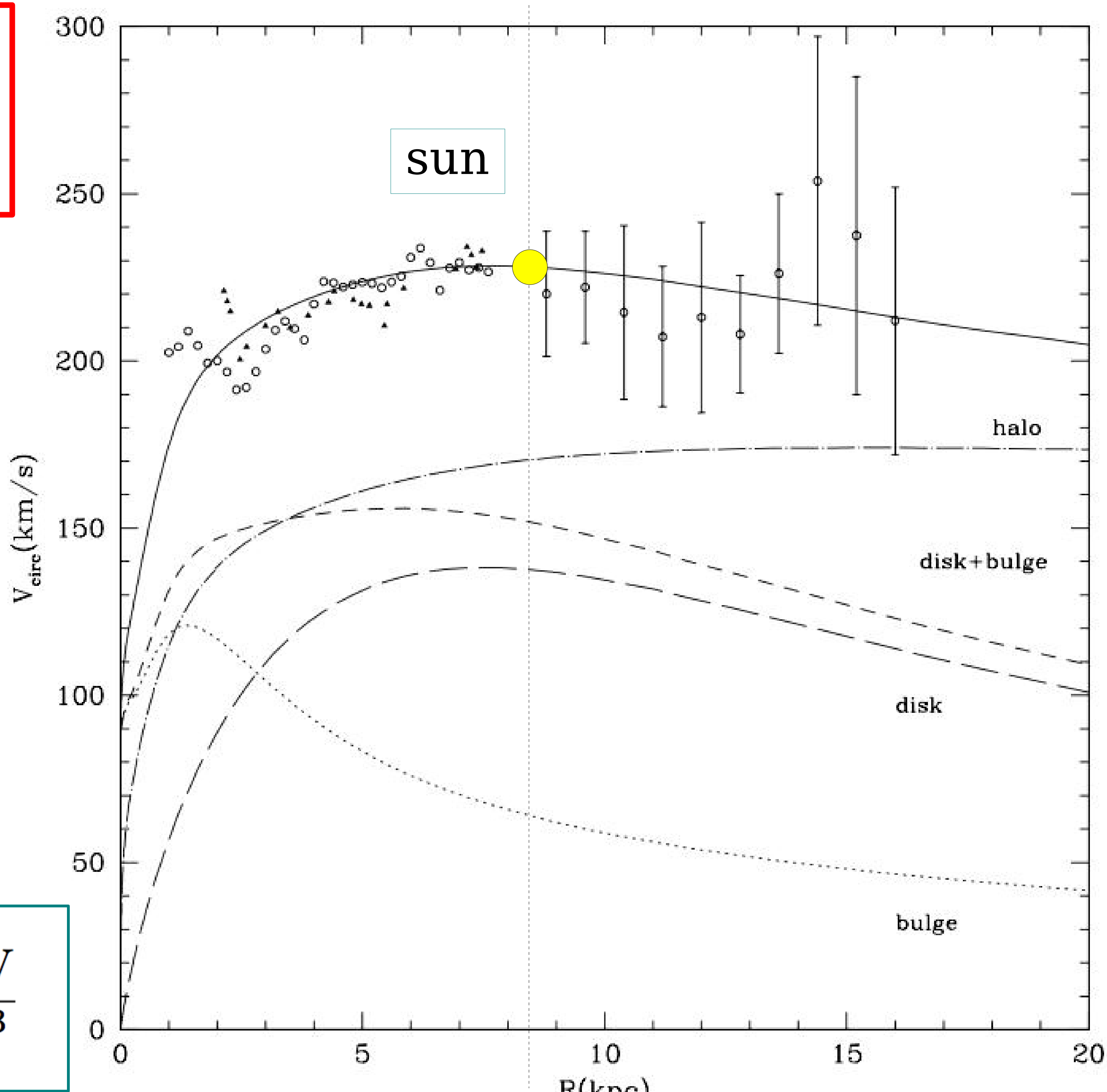


DARK MATTER exists !
[and is NOT one of the known constituents of the Standard Model]



Galactic Dark Halos

MILKY WAY

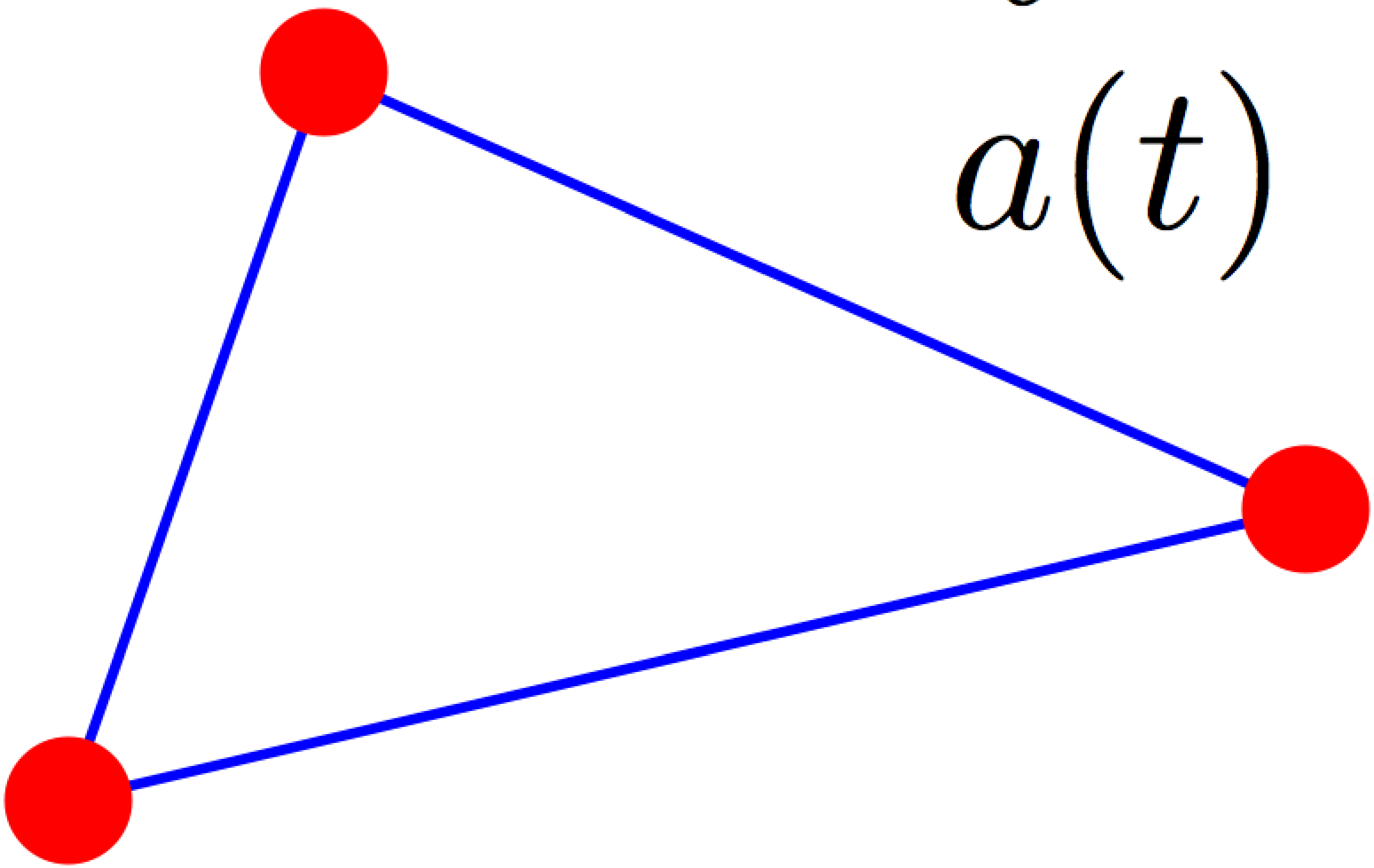


$$\rho_{\oplus} \simeq 0.3 \ \frac{\text{GeV}}{\text{cm}^3}$$

Rescaling of all distances.

t : Universal time

$a(t)$: Scale function



t_0 : present

$a(t_0) = 1$

$$\boxed{\vec{R}_{ij}(t) = a(t)\ \vec{r}_{jk}}$$

Expansion and Redshift

$$\lambda_{\text{emission}} \qquad t$$

Photon emitted
At time t

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{a(t_0)}{a(t)}$$

Wavelength
"stretched"
by the expansion

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} \frac{1}{a(t)}$$

$$\lambda_{\text{observed}} = \lambda_{\text{emission}} (1+z)$$

Definition of redshift z

$$\boxed{z(t) = \frac{1}{a(t)} - 1}$$

Relation between
Redshift z and scale a(t)

ENERGY evolution

$$p \simeq \frac{1}{\lambda}$$

Momentum associated
to wavelength like in Quantum Mechanics/

$$E_{\mathrm{now}} = \frac{E_{\mathrm{emission}}}{1 + z_{\mathrm{emission}}}$$

For relativistic
Particles (E = p)

$$\boxed{E(t) = E_{\mathrm{emission}} \, \frac{1 + z(t)}{1 + z(t_{\mathrm{emission}})}}$$

Energy evolution with time.

Dynamics of the expansion:

$$\boxed{\left[\frac{da(t)}{dt}\right]^2 = \frac{8\,\pi\,G\,\rho(t)}{3}\;a^2(t) - K}$$

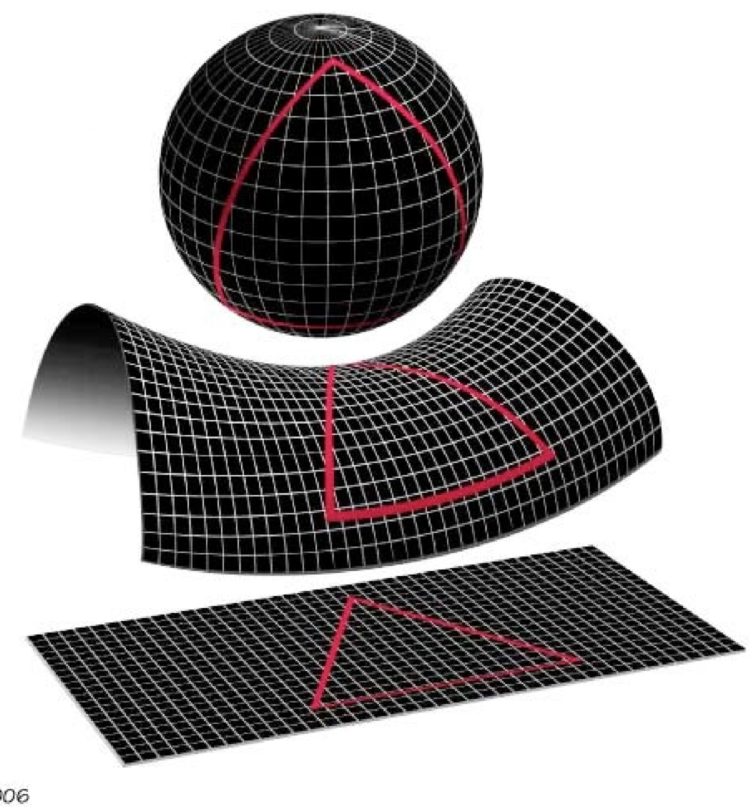
Friedmann's equation.

[obtained from Einstein equations Of General Relativity]

$K > 0$

$K < 0$

$K = 0$

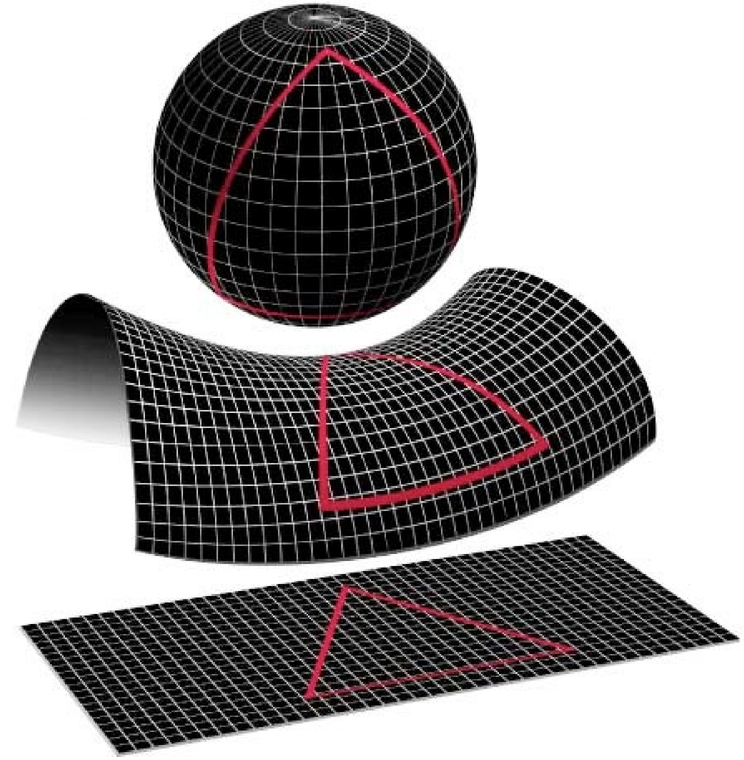


Constant K
Geometry of Space

$$K > 0$$

$$K < 0$$

$$K = 0$$



MAP990006

$$[K] = [t^{-2}]$$

$$K = \frac{c^2}{R_0^2}$$

R_0 : Curvature radius of space

Derivation from elementary Newtonian dynamics
[wrong motivation, but right answer]:

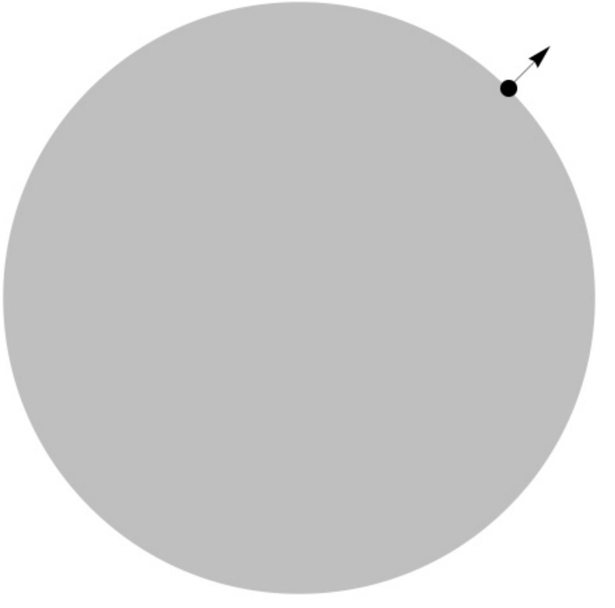
Spherical symmetry:
Choose an arbitrary center point.
Definition of energy = Kinetic + Potential

$$\frac{1}{2}\, m \left(\frac{dr}{dt}\right)^2 - \frac{G\, M(r)\, m}{r} = E$$

$$M(r) = \frac{4\,\pi}{3}\, \rho(t)\, r^3$$

$$r = R_0\, a(t)$$

$$K = \frac{2\,E}{m\, R_0^2}$$



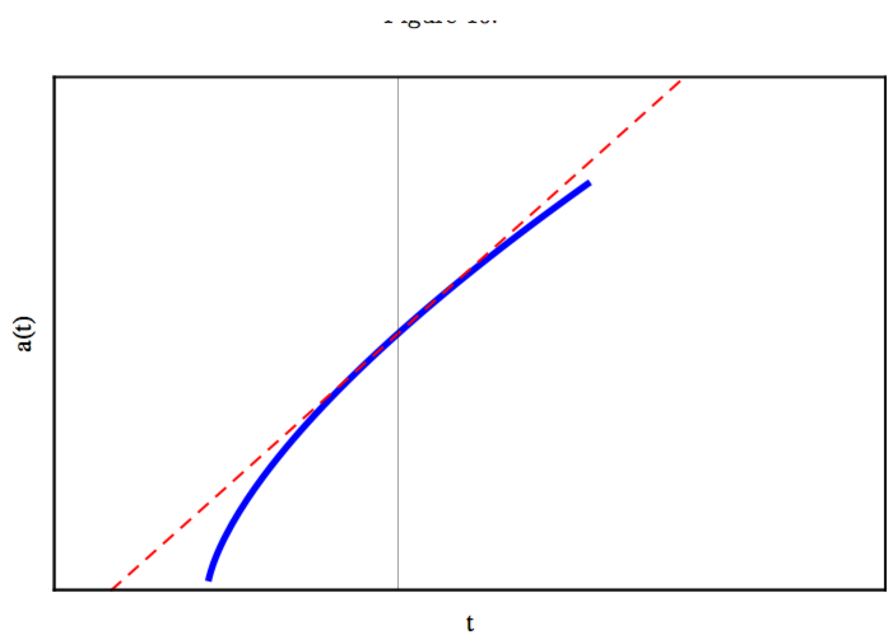
The Hubble “constant” [constant in space not in time]

$$\boxed{H(t) = \frac{\dot{a}(t)}{a(t)}}$$

$$H_0 \equiv H(t_0) = \dot{a}(t_0)$$

$$H_0 \simeq 70 \ \frac{\text{Km/s}}{\text{Mpc}}$$

$$\boxed{H_0 \simeq [14.0 \ \text{Gyr}]^{-1}}$$



$$\left[\frac{da(t)}{dt}\right]^2 = \frac{8\,\pi\,G\;\rho(t)}{3}\;a^2(t) - K$$

Substitute: $t = t_0$

$$H_0^2 = \frac{8\,\pi\,G\;\rho_0}{3} - K$$

$K = 0$

Flat space

$$\Longrightarrow \quad \rho_0 = \rho_{\text{critical}} = \frac{3\,H_0^2}{8\,\pi\,G}$$

$$1 = \frac{8\,\pi\,G\,\rho_0}{3\,H_0^2} - \frac{c^2}{R_0^2\,H_0^2}$$

$$1 = \frac{\rho_0}{\rho_c} - \frac{c^2}{R_0^2\,H_0^2}$$

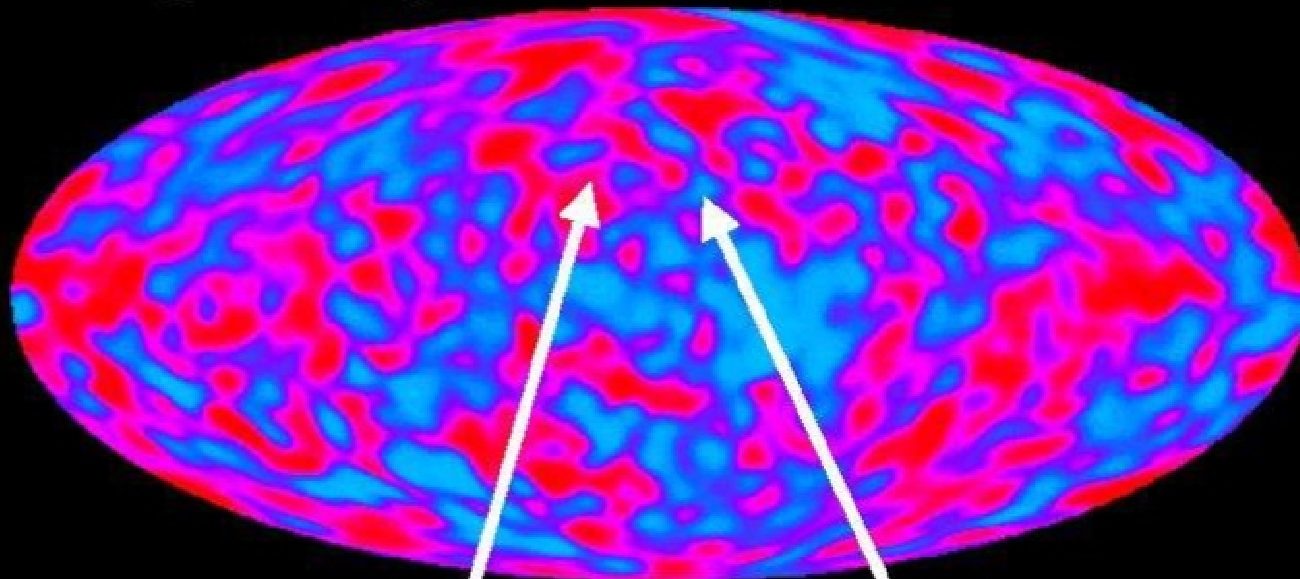
$$\Omega_k = -\frac{c^2}{R_0^2\,H_0^2}$$

Curvature term

$$\boxed{1 = \Omega_0 + \Omega_k}$$

Geometry defined by Ω_0

Angular power spectrum, C_l



$$T_1(\theta_1,\phi_1) \quad T_2(\theta_2,\phi_2)$$

$$\left\langle T_1 T_2 \right\rangle = \sum a_{lm} Y_{lm}(\theta,\phi)$$

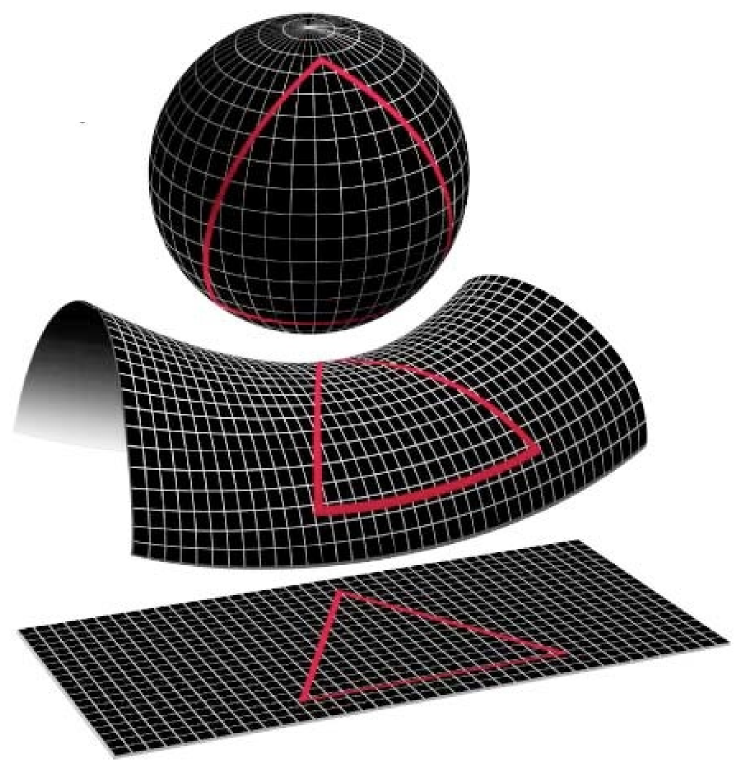
$$\left\langle \left| a_{lm} \right|^2 \right\rangle^{1/2} \equiv C_l$$

$$\boxed{\Omega_0 = \frac{\rho_0}{\rho_c}}$$

$$\Omega_0 > 1$$

$$\Omega_0 < 1$$

$$\Omega_0 = 1$$



Solutions of Friedmann's equation

$$\left[\frac{da(t)}{dt}\right]^2 = \frac{8\,\pi\,G\,\rho(t)}{3}\,a^2(t) - K$$

$\rho(t)$ Average Energy Density of the Universe

Need one additional equation “equation of state”
For the evolution of rho(t).

Average energy density of the universe at present:

$$E = \sqrt{p^2 + m^2}$$

$$\rho_0 = \rho_{\mathrm{matter}} + \rho_{\mathrm{radiation}} + \rho_{\mathrm{vacuum}}$$

$$E \simeq m \qquad\qquad E \simeq p$$

Average energy density of the universe at present:

$$E = \sqrt{p^2 + m^2}$$

$$\rho_0 = \rho_{\text{matter}} + \rho_{\text{radiation}} + \boxed{\rho_{\text{vacuum}}}$$

$E \simeq m$

$E \simeq p$

Energy associated to the vacuum.

Equivalent to the introduction of a "cosmological constant"

$$\Lambda = 8\pi \, G \, \rho_{\text{vacuum}}$$

$$\rho_0 = \rho_{\mathrm{matter}} + \rho_{\mathrm{radiation}} + \rho_{\mathrm{vacuum}}$$

$$\boxed{\rho(t) = \frac{\rho_{\mathrm{matter}}}{a^3(t)} + \frac{\rho_{\mathrm{radiation}}}{a^4(t)} + \rho_{\mathrm{vacuum}}}$$

Particle conservation

Particle conservation + momentum redshift

.... the vacuum is the vacuum...

$$\rho_0 = \rho_{\text{matter}} + \rho_{\text{radiation}} + \rho_{\text{vacuum}}$$

$$\boxed{\rho(t) = \frac{\rho_{\text{matter}}}{a^3(t)} + \frac{\rho_{\text{radiation}}}{a^4(t)} + \rho_{\text{vacuum}}}$$

Particle conservation

Particle Conservation + momentum redshift

.... the vacuum Is the vacuum...

$$\rho(z) = \rho_{\text{matter}}\,(1+z)^3 + \rho_{\text{radiation}}\,(1+z)^4 + \rho_{\text{vacuum}}$$

$$\rho(t) = \frac{\rho_0}{a^4(t)}$$ Radiation Dominated

$$\rho(t) = \frac{\rho_0}{a^3(t)}$$ Matter Dominated

$$\rho(t) = \rho_0$$ Vacuum Dominated

$$\frac{da(t)}{dt} = \sqrt{\frac{8\pi\, G\, \rho_0}{3}}\, \frac{1}{a(t)} \qquad a(t) \propto t^{1/2}$$

$$\frac{da(t)}{dt} = \sqrt{\frac{8\pi\, G\, \rho_0}{3}}\, \frac{1}{\sqrt{a(t)}} \qquad a(t) \propto t^{2/3}$$

$$\frac{da(t)}{dt} = \sqrt{\frac{8\pi\, G\, \rho_0}{3}}\, a(t) \qquad a(t) = e^{H\, t}$$

ACCELERATED EXPANSION !!
Vacuum positive energy = Repulsion

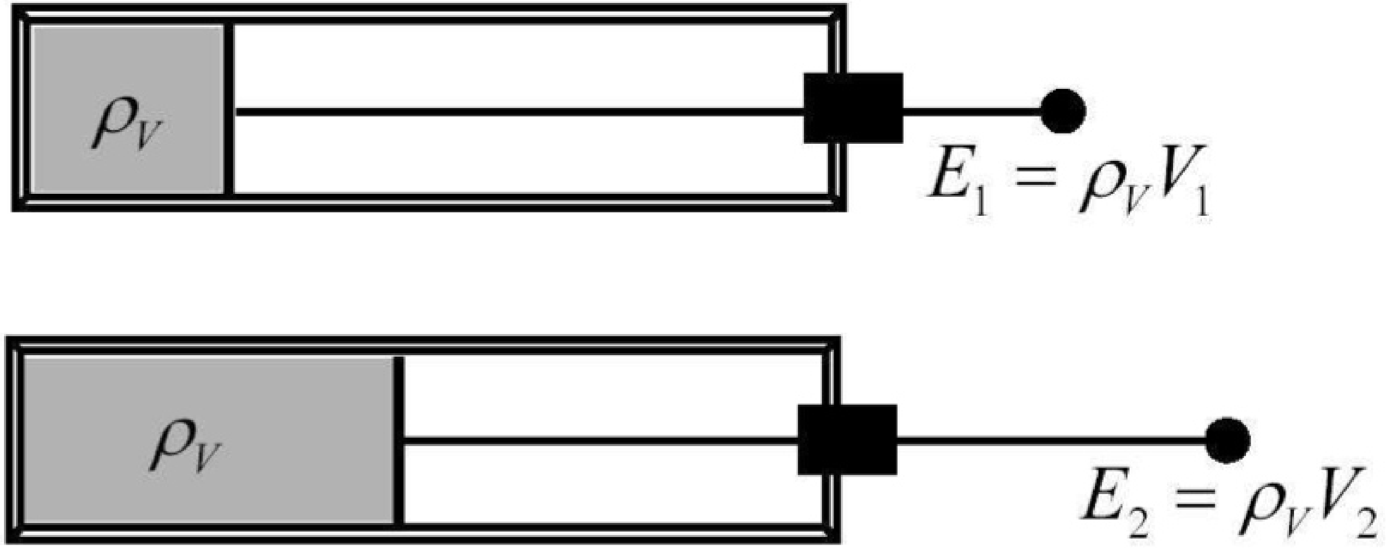
$$\boxed{\frac{da(t)}{dt} = \sqrt{\frac{8\pi\, G\, \rho_0}{3}}\; a(t) \qquad a(t) = e^{H\, t}}$$

Acceleration of the scale a(t)
from Einstein equations

$$\boxed{\ddot{a}(t) = -\frac{4\pi G}{3}\,[\rho(t) + 3\,p(t)]\,a(t)}$$

Acceleration involves
Density + pressure of the content of the universe.

Vacuum Pressure



$$\Delta E = \rho_{\text{vacuum}} \, \Delta V$$

$$W = -p_{\text{vacuum}} \, \Delta V$$

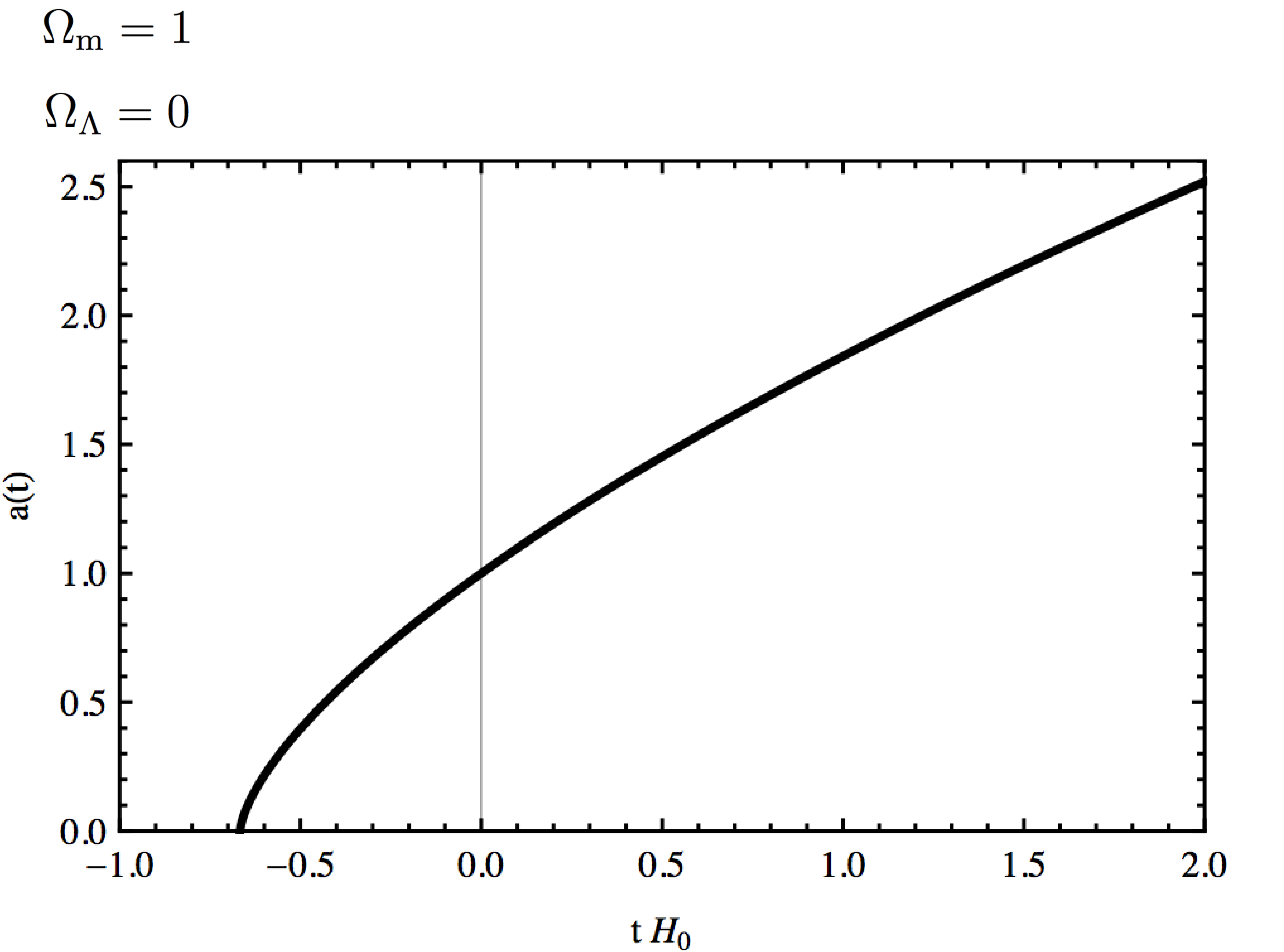
Need to “pull” the piston

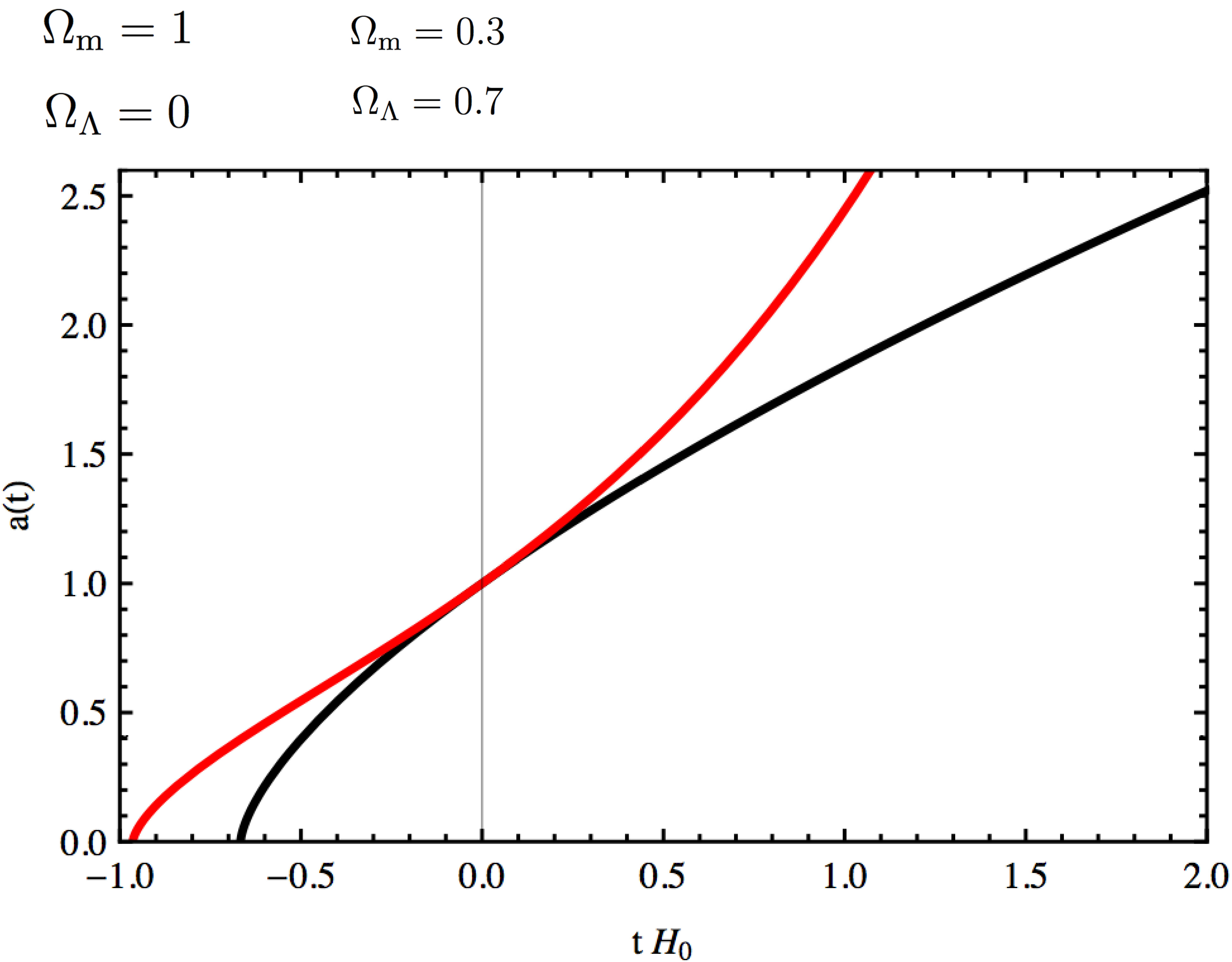
$$\boxed{\rho_{\text{vacuum}} = -p_{\text{vacuum}}}$$

$$\frac{1}{H_0^2}\left[\frac{da(t)}{dt}\right]^2 = a^2(t)\left[\frac{\Omega_{\mathrm{m}}}{a^3(t)} + \frac{\Omega_{\mathrm{r}}}{a^4(t)} + \Omega_\Lambda + \frac{\Omega_k}{a^2(t)}\right]$$

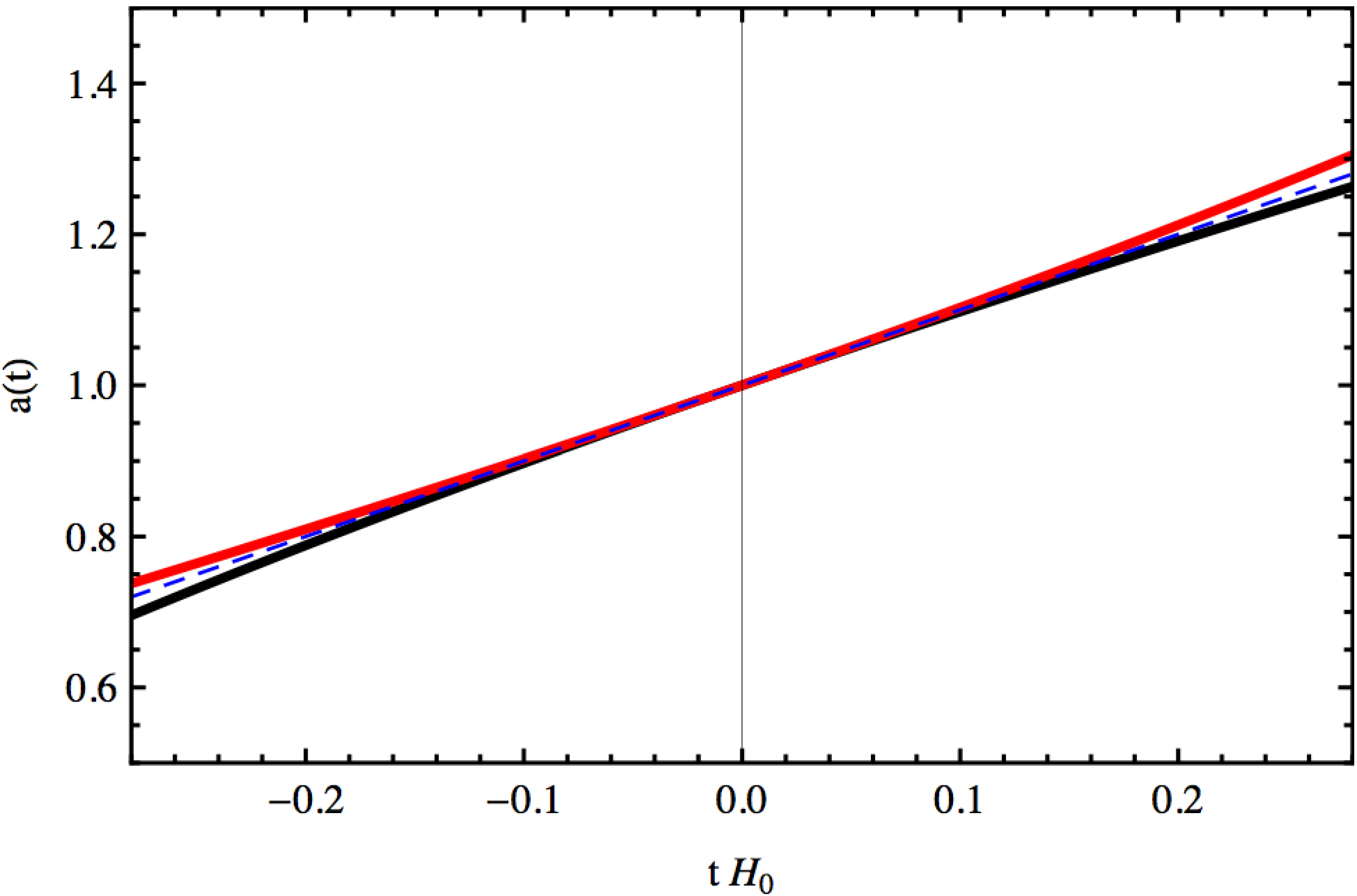
$$1 = \Omega_{\mathrm{mat}} + \Omega_{\mathrm{rad}} + \Omega_\Lambda + \Omega_k$$

Friedmann's equation


$\Omega_m = 1$
$\Omega_\Lambda = 0$
a(t)
t H_0
2.5
2.0
1.5
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0

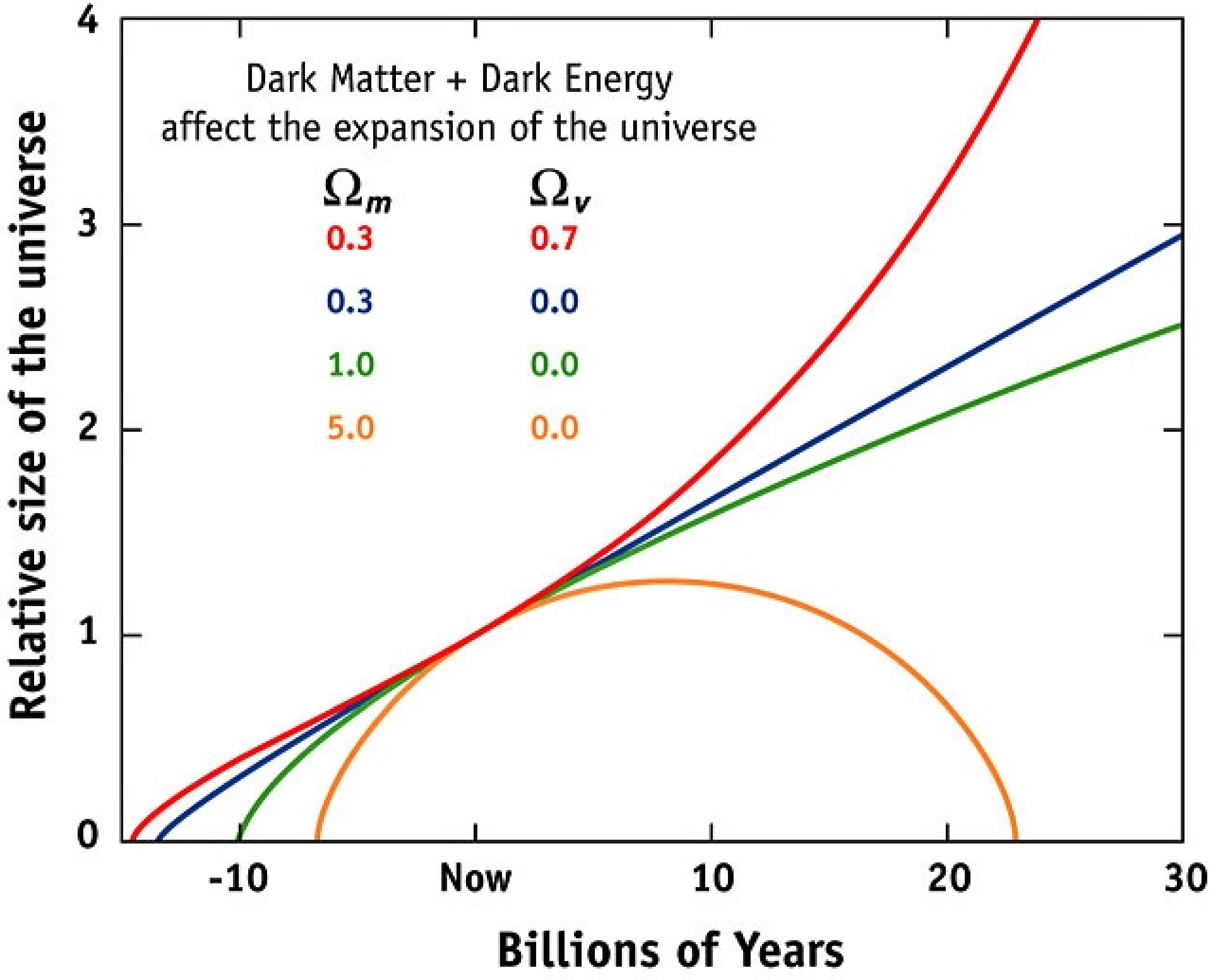


$\Omega_{\mathrm{m}} = 1$
$\Omega_\Lambda = 0$
$\Omega_{\mathrm{m}} = 0.3$
$\Omega_\Lambda = 0.7$
a(t)
2.5
2.0
1.5
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
t H_0



1.4
1.2
1.0
0.8
0.6
a(t)
−0.2
−0.1
0.0
0.1
0.2
t H_0

Expansion of the Universe

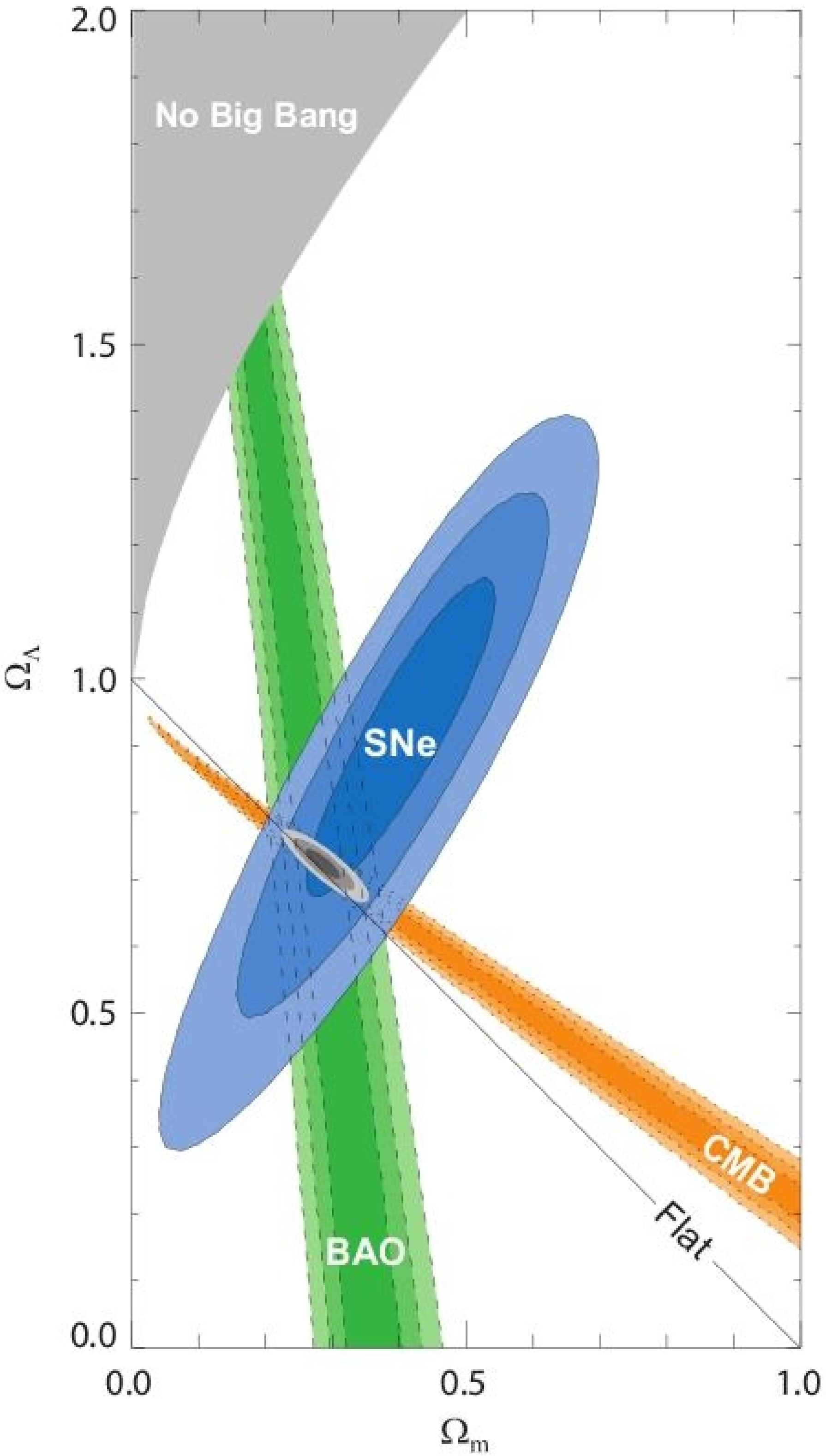


Determination of the density and “equation of state” of the Universe.

1. SN1a luminosity – reshift relation

2. Cosmic Microwave Backround Radiation Anisotropies

3. Galaxy Distributions

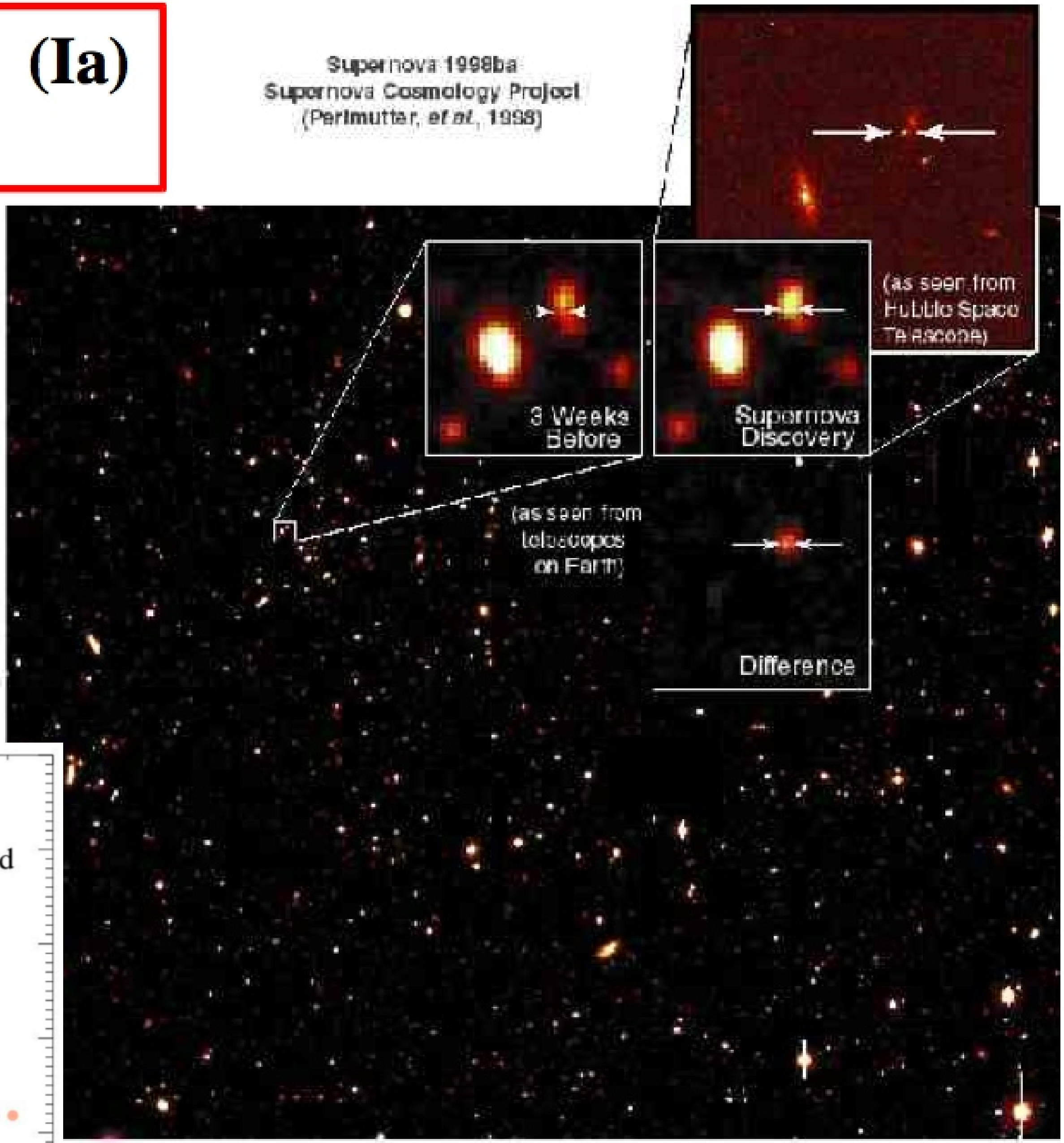


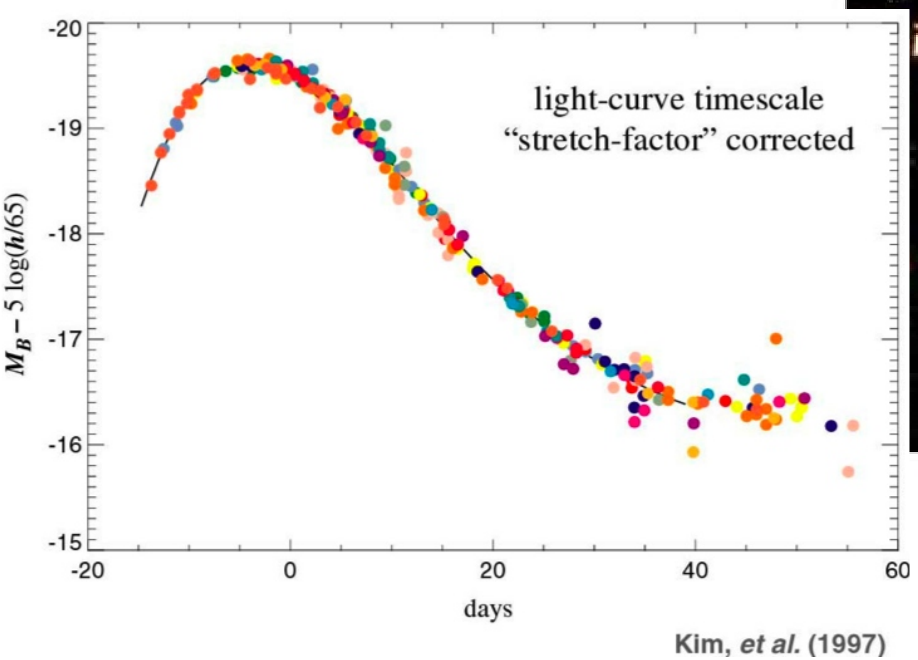
No Big Bang
SNe
CMB
Flat
BAO
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
Ω_Λ
Ω_m

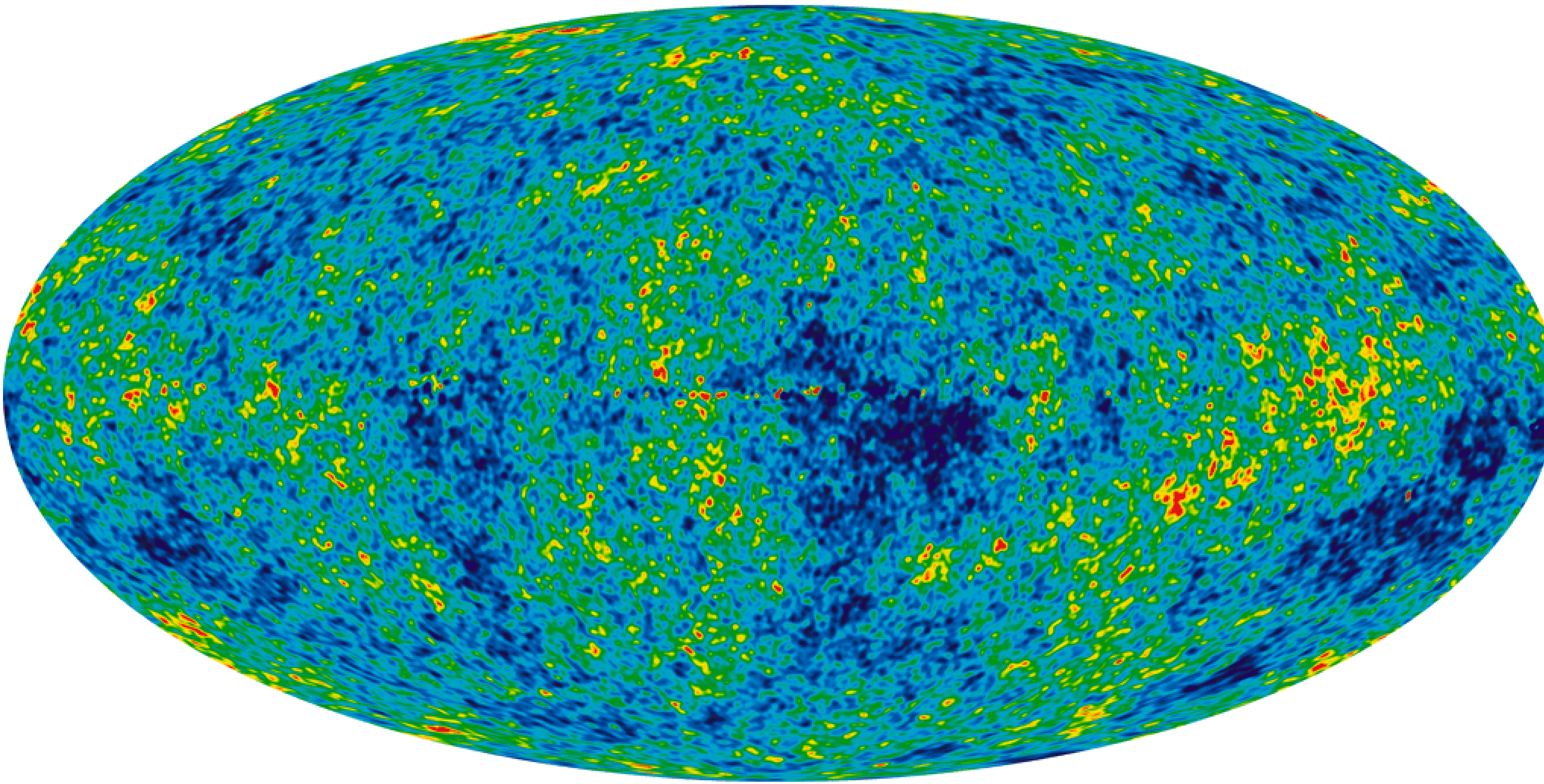
SUPERNOVAE (Ia) STUDIES

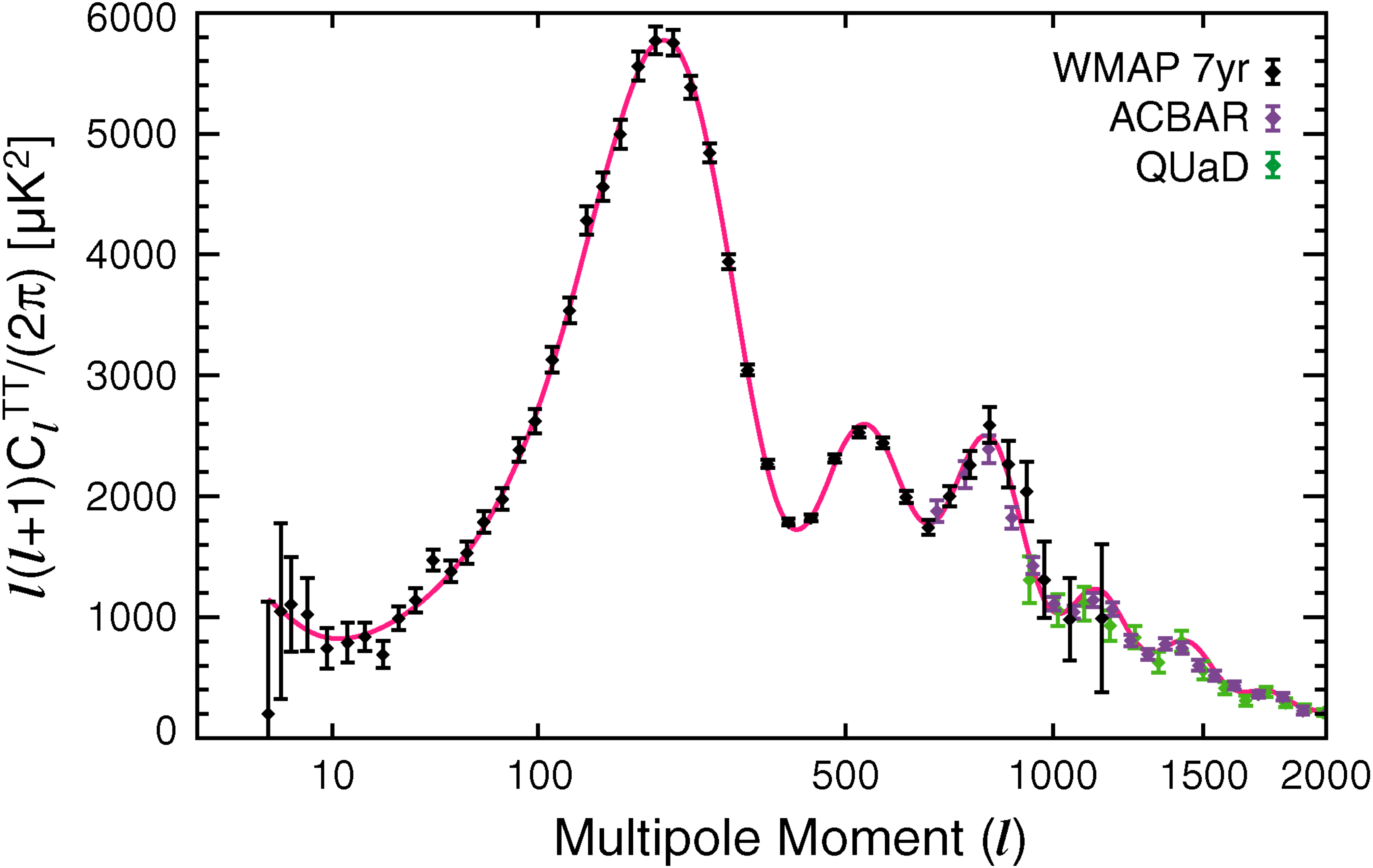
$$a(t) \leftrightarrow \ell(z)$$

SN1a as
standard candles





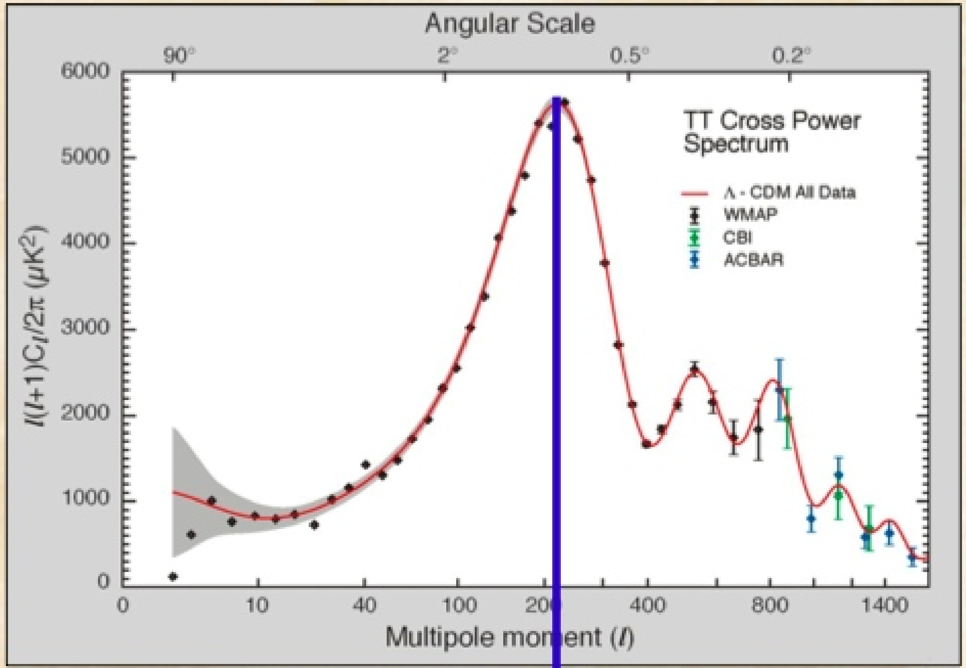




6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
WMAP 7yr
ACBAR
QUaD
$l(l+1)C_l^{TT}/(2\pi)$ [μK^2]
Multipole Moment (l)

Flat Universe from CMBR Angular Fluctuations

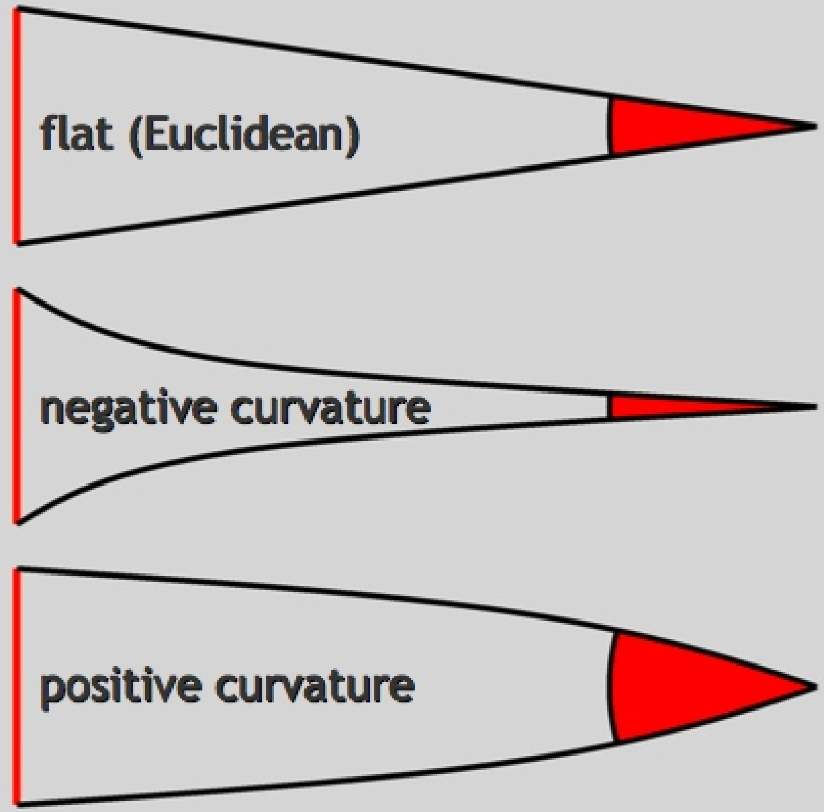
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



$$\ell_{max} \approx 200/\sqrt{\Omega_{tot}}$$

$$\Omega_{tot} = 1.02 \pm 0.02$$

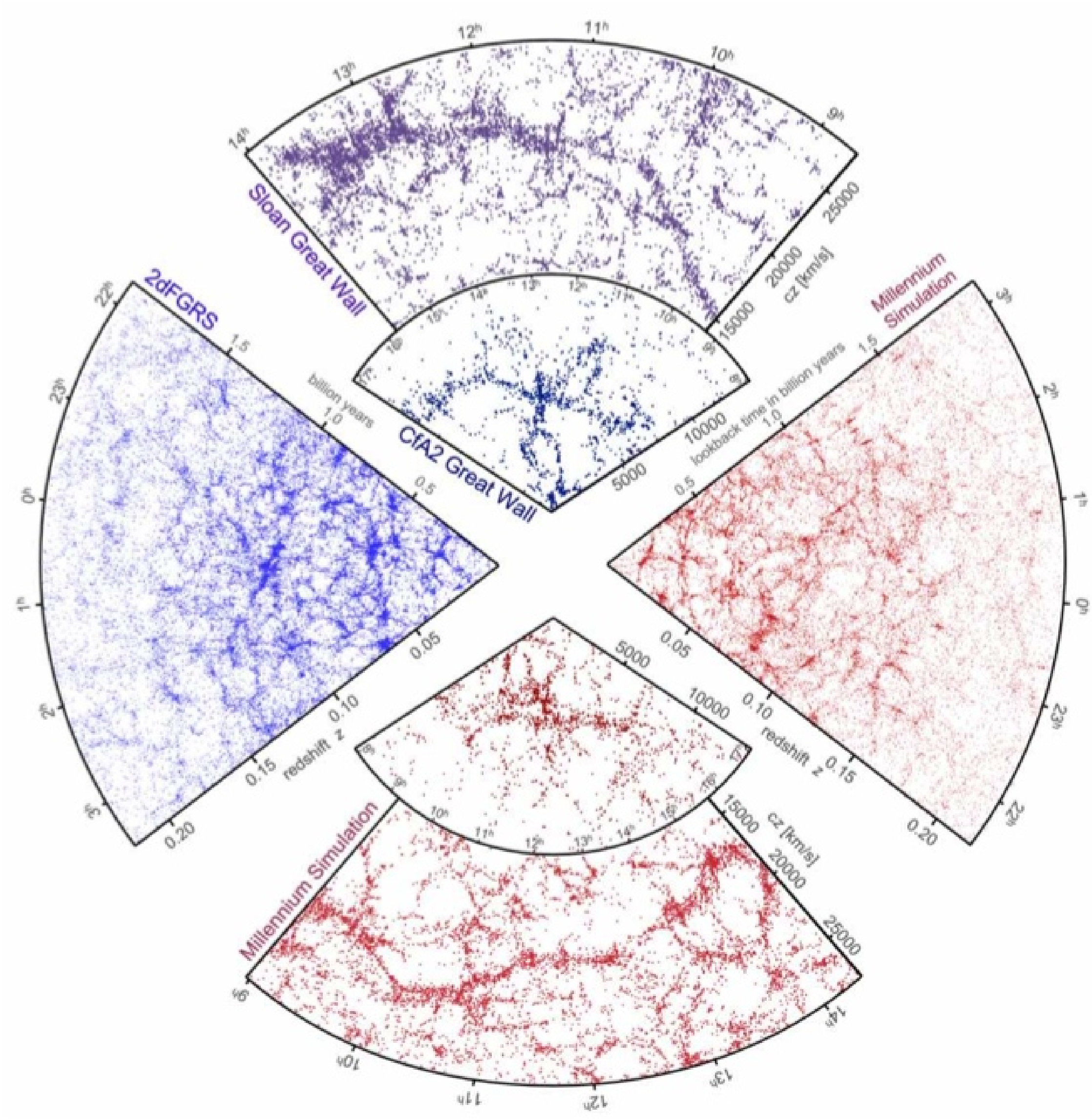
Triangulation with acoustic peak



Known physical size of acoustic peak at decoupling ($z \approx 1100$)

Measured angular size today ($z = 0$)

Large Scale Galaxy distributions



DARK MATTER: we know a lot :

...but we
do NOT know
much more...

It exists (no modified gravity for the bullet cluster!)

Good estimate of the cosmological average (22%)

Most of it is non baryonic

Most of it is “cold”

It cannot be explained by the Standard Model
in Particle Physics !!

What is the Dark Matter ?

Artists And Dark Matter

Cold Dark Matter
(Tate Gallery. London)

Cornelia Parker




What is the Dark Matter ?

Possible theoretical ideas

Thermal Relic

Axion

Super-massive particles

What is the Dark Matter ?

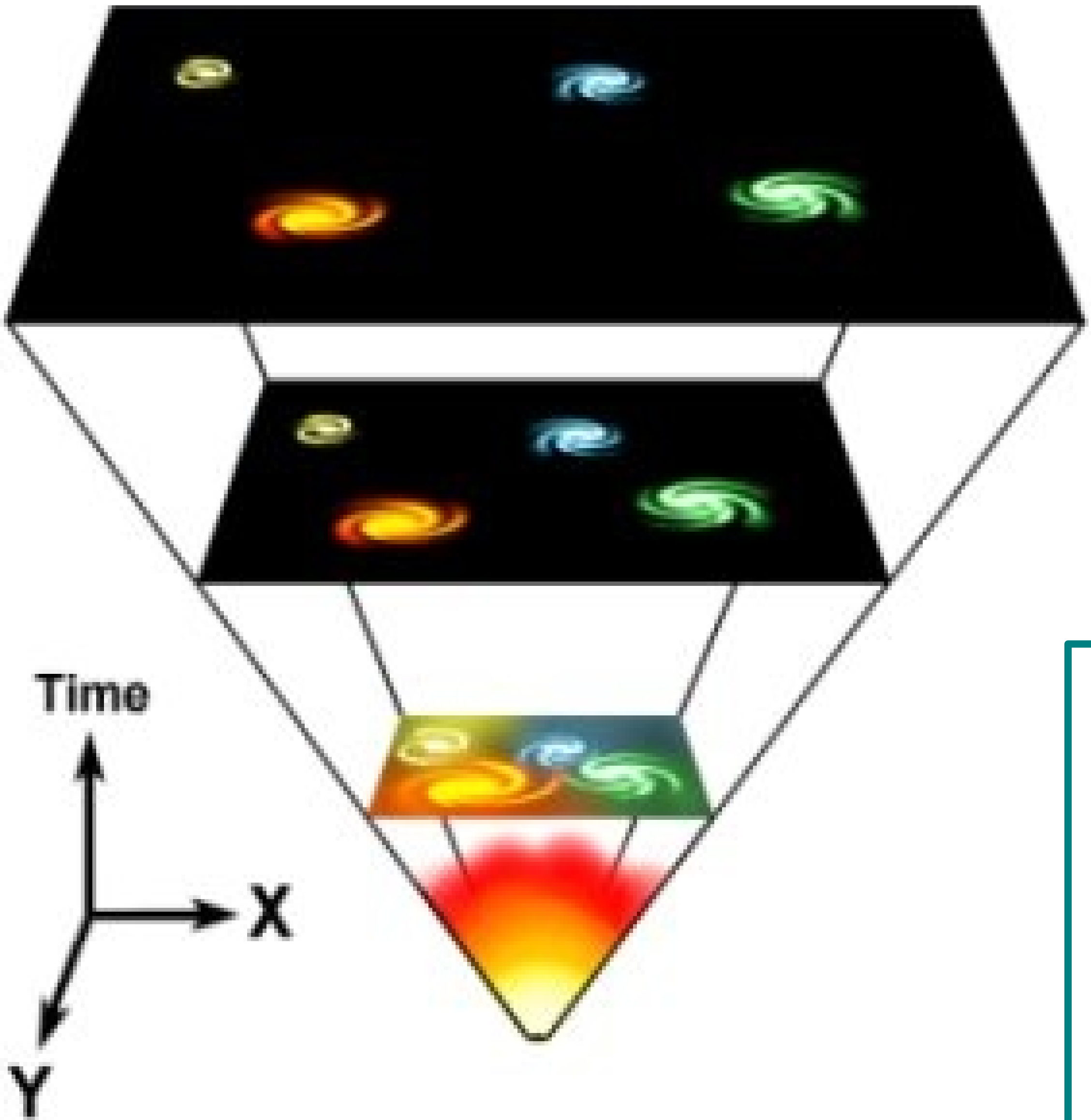
Possible theoretical ideas

Thermal Relic

Axion

Super-massive particles

Discuss only this idea
[perhaps the best motivated]
[Offers the best chances of discovery]



Early Universe
was HOT

[Adiabatic
Compression
Of a fluid]

"COSMIC SOUP"

$$\boxed{a + b \leftrightarrow c + d}$$

Frequent reactions
Between all particles
Present in the "soup"

$$\gamma + \gamma \leftrightarrow e^{+} + e^{-}$$

$$e^{+} + e^{-} \leftrightarrow q_j + \overline{q}_j$$

$$\boxed{a + b \leftrightarrow c + d}$$

$$\gamma + \gamma \leftrightarrow e^+ + e^-$$

$$e^+ + e^- \leftrightarrow q_j + \overline{q}_j$$

THERMAL
EQUILIBRIUM

New particle χ

$$e^+ + e^- \leftrightarrow \chi + \overline{\chi}$$

$$\gamma + \gamma \leftrightarrow \chi + \overline{\chi}$$

$(\overline{\chi} \equiv \chi)$

$$n_j = n_{\bar{j}}$$

Thermal equilibrium
Distribution

$$\frac{dN_j}{d^3x\, d^3p} = \frac{g_j}{(2\,\pi\,\hbar\,c)^3}\,\frac{1}{e^{E/T} \mp 1}$$

Boson
fermion

$$n_j \neq n_{\bar{j}}$$

$$\frac{dN_j}{d^3x\, d^3p} = \frac{g_j}{(2\,\pi\,\hbar\,c)^3}\,\frac{1}{e^{(E-\mu_j)/T} \mp 1}$$

$$n(T) = \int d^3p \, \frac{dN}{d^3x \; d^3p}$$

$$\rho(T) = \int d^3p \; E(p) \, \frac{dN}{d^3x \; d^3p}$$

High Temperature

$$T \gg m_\chi$$

$$n_{\rm boson}(T) = g \, \frac{\zeta(3)}{\pi^2} T^3$$

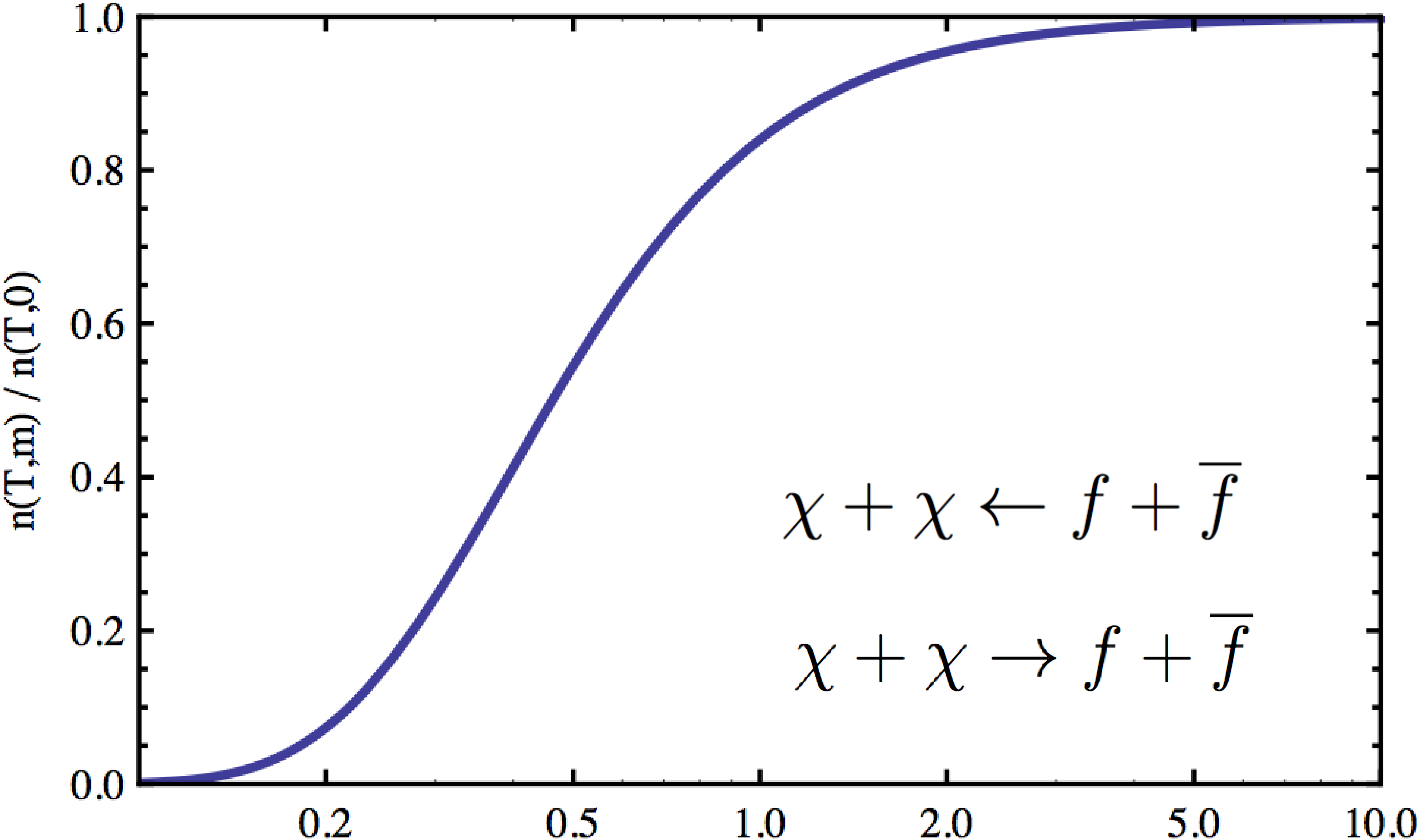
$$n_{\rm fermion}(T) = g \, \frac{\zeta(3)}{\pi^2} T^3 \times \frac{3}{4}$$

$$\rho_{\rm boson}(T) = g \, \frac{\pi^2}{30} T^4$$

$$\rho_{\rm fermion}(T) = g \, \frac{\pi^2}{30} T^4 \times \frac{7}{8}$$

$$T \sim m_\chi$$

Particle density
starts to decrease
With respect to the case of small mass



Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]
"box" of constant volume.
Equal distributions for particle and anti-particle

$$dP_{\rm distruction} = n_\chi \; \langle \sigma_{\chi\chi \to {\rm anything}} \; v \rangle \; dt$$

Probability of disappearance per unit time

$$\langle \sigma \; v \rangle = \int d^3 v_1 \int d^3 v_2 \; f_\chi(\vec{v}_1) \; f_\chi(\vec{v}_2) \; \sigma(|\vec{v}_1 - \vec{v}_2|) \; |\vec{v}_1 - \vec{v}_2|$$

Velocity averaged cross section
[in many cases $\sigma(v) \; v = {\rm constant}$]

Particle anti-particle annihilation and the "Relic Density"

[Pedagogical discussion]
"box" of constant volume.
Equal distributions for particle and anti-particle

$$dP_{\rm distruction} = n_\chi \; \langle \sigma_{\chi\chi\to{\rm anything}} \; v \rangle \; dt$$

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Velocity averaged cross section
[in many cases $\sigma(v) \; v = \text{constant}$]

$$dn_\chi = -n_\chi \; dP_{\rm dist} = -n_\chi^2 \; \langle \sigma v \rangle \; dt$$

Evolution of the Particle density

$$\frac{dn(t)}{dt} = -n^2(t)\,\langle \sigma\, v \rangle$$

Time evolution
Of the density

$$n(t_i) = n_i$$

Initial condition

$$\frac{dn}{n^2} = -\langle \sigma\, v \rangle\, dt$$

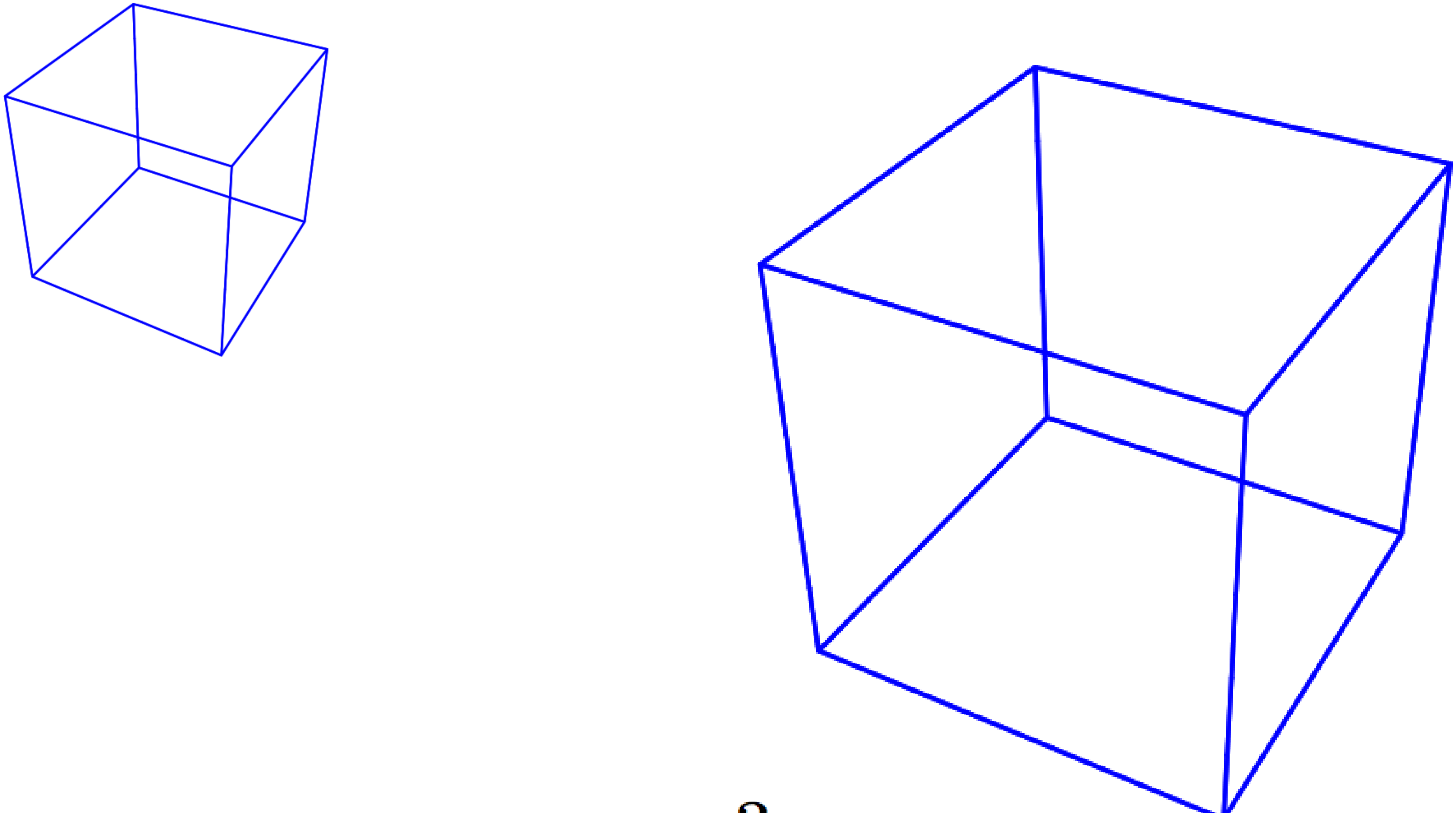
$$n(t) = \frac{n_i}{1 + n_i \langle \sigma\, v \rangle (t - t_i)}$$

Solution

$$\boxed{\lim_{t \to \infty} n(t) = 0}$$

All particles annihilate.

Annihilation in an Expanding Universe



$$n_{\text{comoving}} = n(t)\, a^3(t)$$

$$\frac{d[n(t)\,a^3(t)]}{dt} = -n^2(t)\,a^3(t)\,\langle\sigma\,v\rangle$$

Evolution equation
For the comoving
density

$$n(t)\,a^3(t) = \frac{n_i\,a_i^3}{1 + n_i\,a_i^3\,\langle\sigma\,v\rangle\;\int_{t_i}^{t} dt\;[a(t)]^{-3}}$$

Solution

$$\boxed{(t - t_i) \to a^3(t_i)\;\int_{t_i}^{t}\frac{dt}{a(t)^3}}$$

Difference with
Respect to the case
Of constant volume

$$\frac{d[n(t)\,a^3(t)]}{dt} = -n^2(t)\,a^3(t)\,\langle \sigma\, v \rangle$$

Evolution equation
For the comoving
density

$$n(t)\,a^3(t) = \frac{n_i\,a_i^3}{1 + n_i\,a_i^3\,\langle \sigma\, v \rangle\;\int_{t_i}^{t} dt\;[a(t)]^{-3}}$$

Solution

$$\boxed{(t - t_i) \rightarrow a^3(t_i) \int_{t_i}^{t} \frac{dt}{a(t)^3}}$$

Difference with
Respect to the case
Of constant volume

Possible convergent integral
For $t \rightarrow \infty$ Finite relic density

$$T(t) \propto \frac{1}{a(t)}$$

$$a(t) \propto t^{1/2}$$

$$T(t) \propto t^{-1/2}$$

$$dt \propto \frac{dT}{T^3}$$

$$\int_{t_i(m)}^{\infty} \frac{dt}{a(t)}^{3} \propto \int_{m}^{0} \frac{dT}{T^3}\, T^3 = \int_{0}^{m} dT = m$$

$$n(t)\,a^3(t) = \frac{n_i\,a_i^3}{1 + n_i\,a_i^3\,\langle \sigma\,v \rangle\ \int_{t_i}^{t} dt\ [a(t)]^{-3}}$$

$$\lim_{t\to\infty}[n(t)\,a^3(t)] \simeq n(t_0)a(t_0)^3 = n(t_0) \propto \frac{1}{m\,\langle \sigma\,v \rangle}$$

$$n_j(t_0) \propto \frac{1}{\langle \sigma\, v \rangle\; m_j}$$

$$\rho_j(t_0) = m_j\, n_j(t_0) \propto \frac{1}{\langle \sigma\, v \rangle}$$

$$\Omega_j^0 \propto \frac{1}{\langle \sigma\, v \rangle}$$

$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle}\right]$$

The "relic density" of a particle
Is determined by its annihilation cross section
M

(several complications are possible)

$$\sigma(\chi\chi \to \mathrm{anything}) \simeq 10^{-36}\ \mathrm{cm}^2$$

$$\sigma \simeq \frac{\alpha^2}{M^2}\,(\hbar\, c)^2$$

$$\boxed{\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v\rangle}\right]}$$

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(several complications are possible)

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$$\sigma \simeq \frac{\alpha^2}{M^2}\,(\hbar\, c)^2$$

Weak interaction mass scale

$$\boxed{M \simeq 200\ \mathrm{GeV}}$$

Dark Matter in the form of WIMP's

Weakly Interacting Massive Particles

WIMP's “miracle”

PHYSICS beyond the STANDARD MODEL is **REQUIRED** to explain Dark Matter !!

Extension of the Standard Model are EXPECTED at the electroweak mass scale

These extensions can "naturally" result in the existence of Dark Matter !

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is **REQUIRED** to explain Dark Matter !!

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existence of Dark Matter !

LHC/Dark Matter connection !!

Problems with a different status:
DM problem : direct observational puzzle.
New physics at EW scale : theoretically motivated prediction

Are LHC/ILC and DARK Matter searches studying the same Physics ?

Are LHC/ILC and DARK Matter searches studying the same Physics ?

This is certainly possibles !
[... but not necessary ...]

The physics may or may not be related

Lines of investigations that are independent and complementary

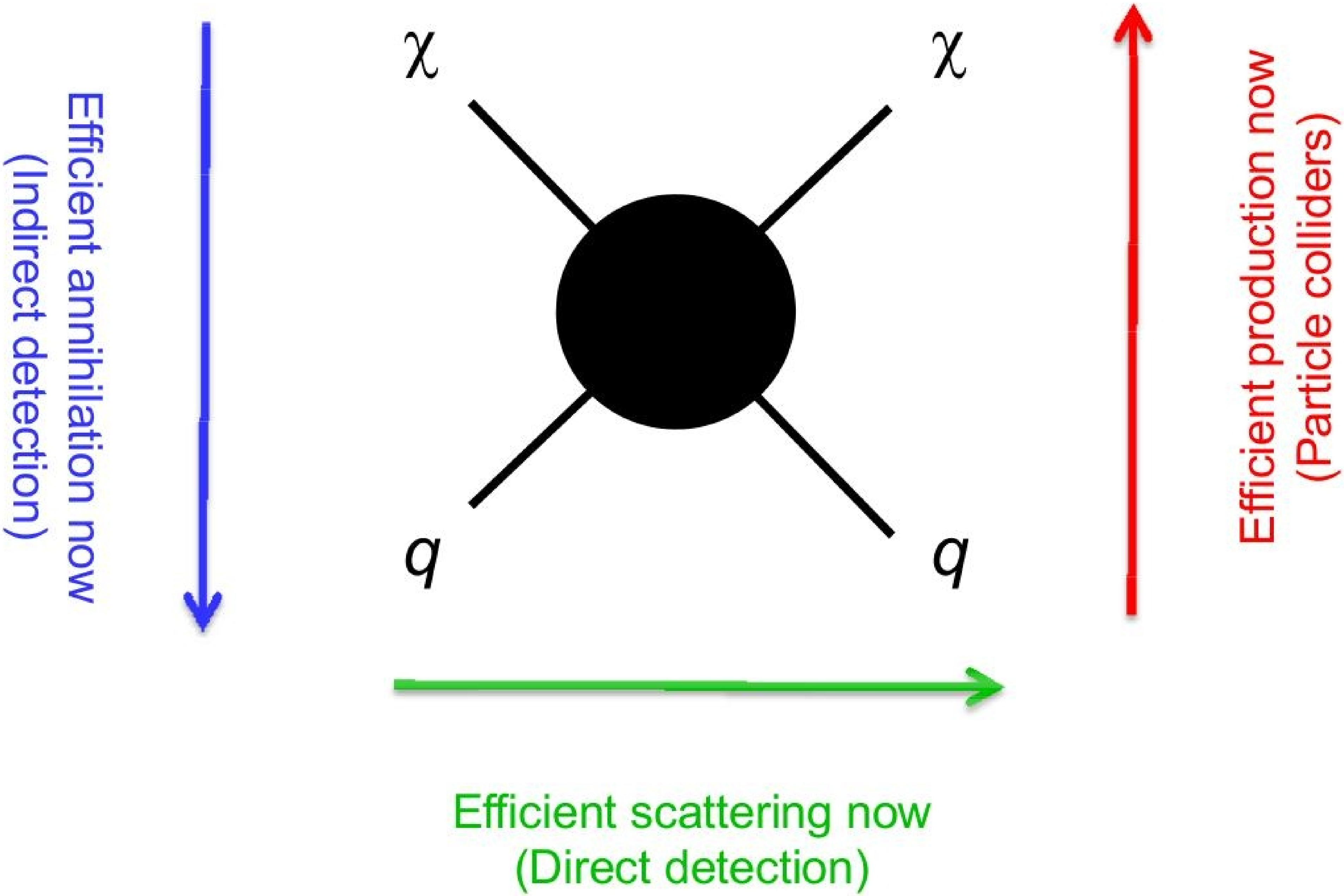
Problems with a different status:
DM problem : direct observational puzzle.
New physics at EW scale : theoretically motivated prediction

Three roads to the study of the "WIMP" hypothesis:

1. Direct Detection

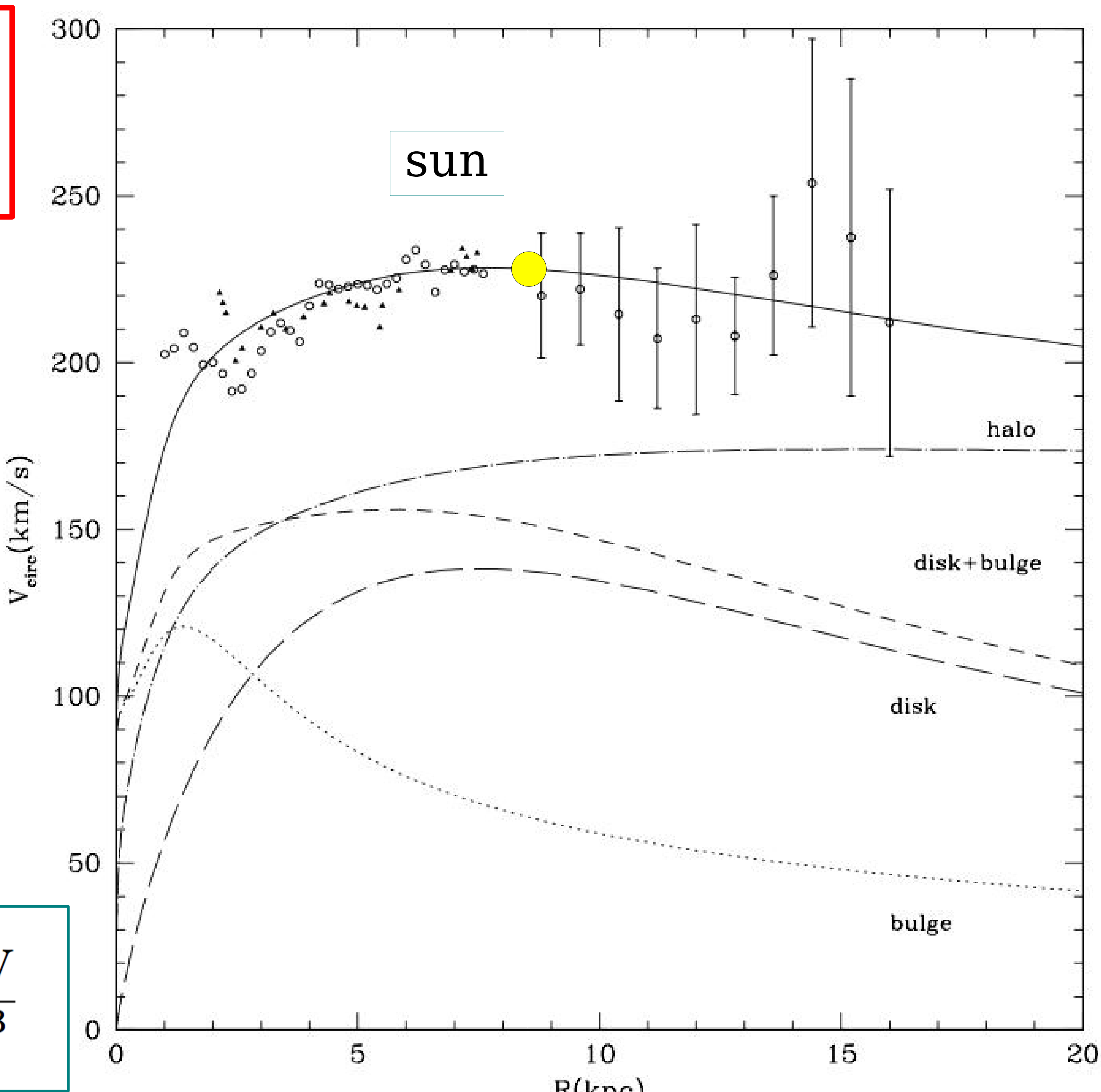
2. Indirect Detection
   [Observation of annihilation products
   In our own Galaxy]

3. Discovery of a new stable particle
   In an accelerator [LHC]



Efficient annihilation now
(Indirect detection)
χ
χ
q
q
Efficient production now
(Particle colliders)
Efficient scattering now
(Direct detection)

MILKY WAY



$$\rho_{\oplus} \simeq 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Astrophysical information

Dark Matter in the Milky Way

$$\rho_{\rm dm}(\vec{x})$$

Dark Matter
density distribution

$$f_{\rm dm}(\vec{v}, \vec{x})$$

Velocity distribution

[consistency requirement]

Astrophysical information

Dark Matter in the Milky Way

$$\rho_{\rm dm}(\vec{x})$$

Dark Matter
density distribution

$$f_{\rm dm}(\vec{v}, \vec{x})$$

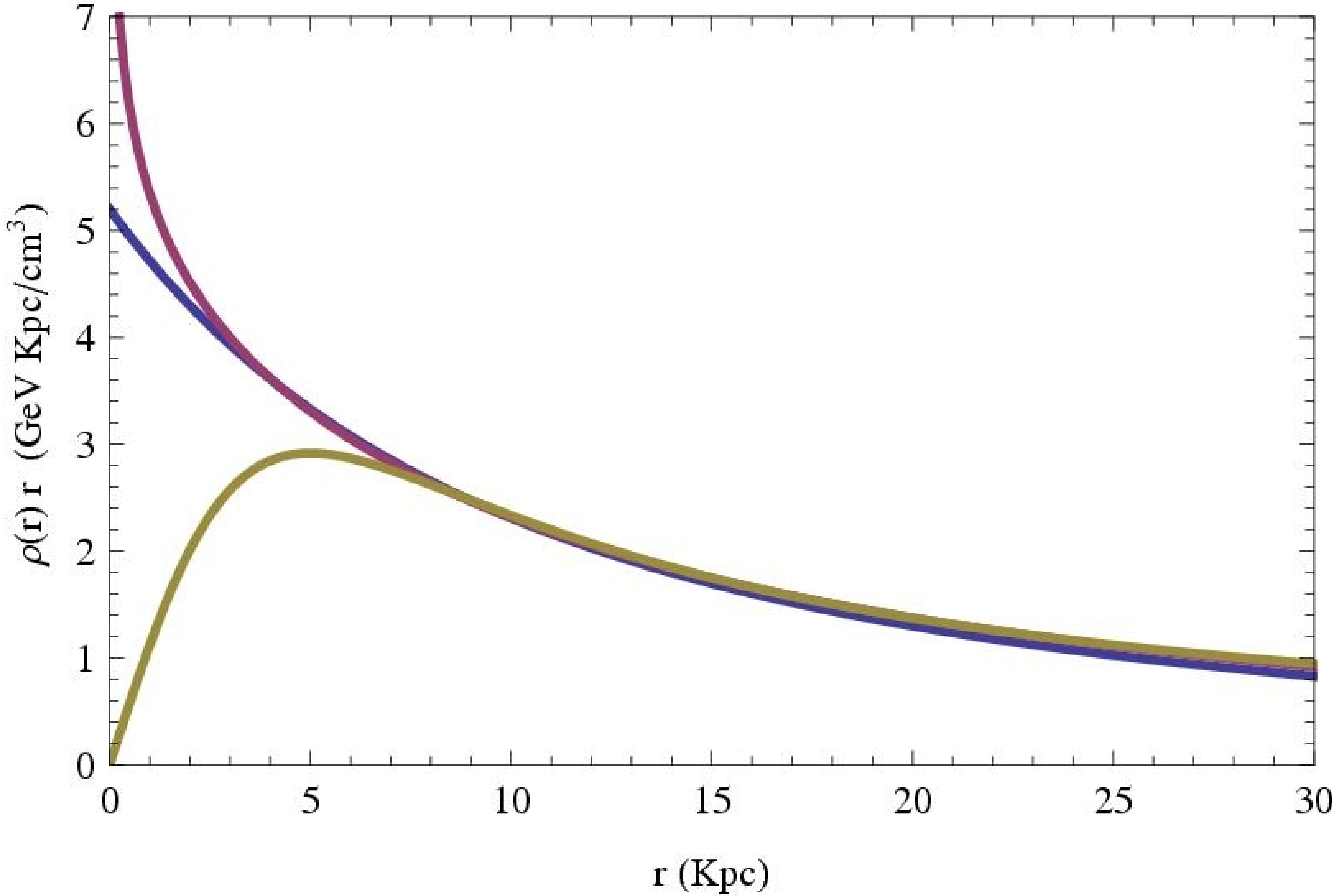
Velocity distribution

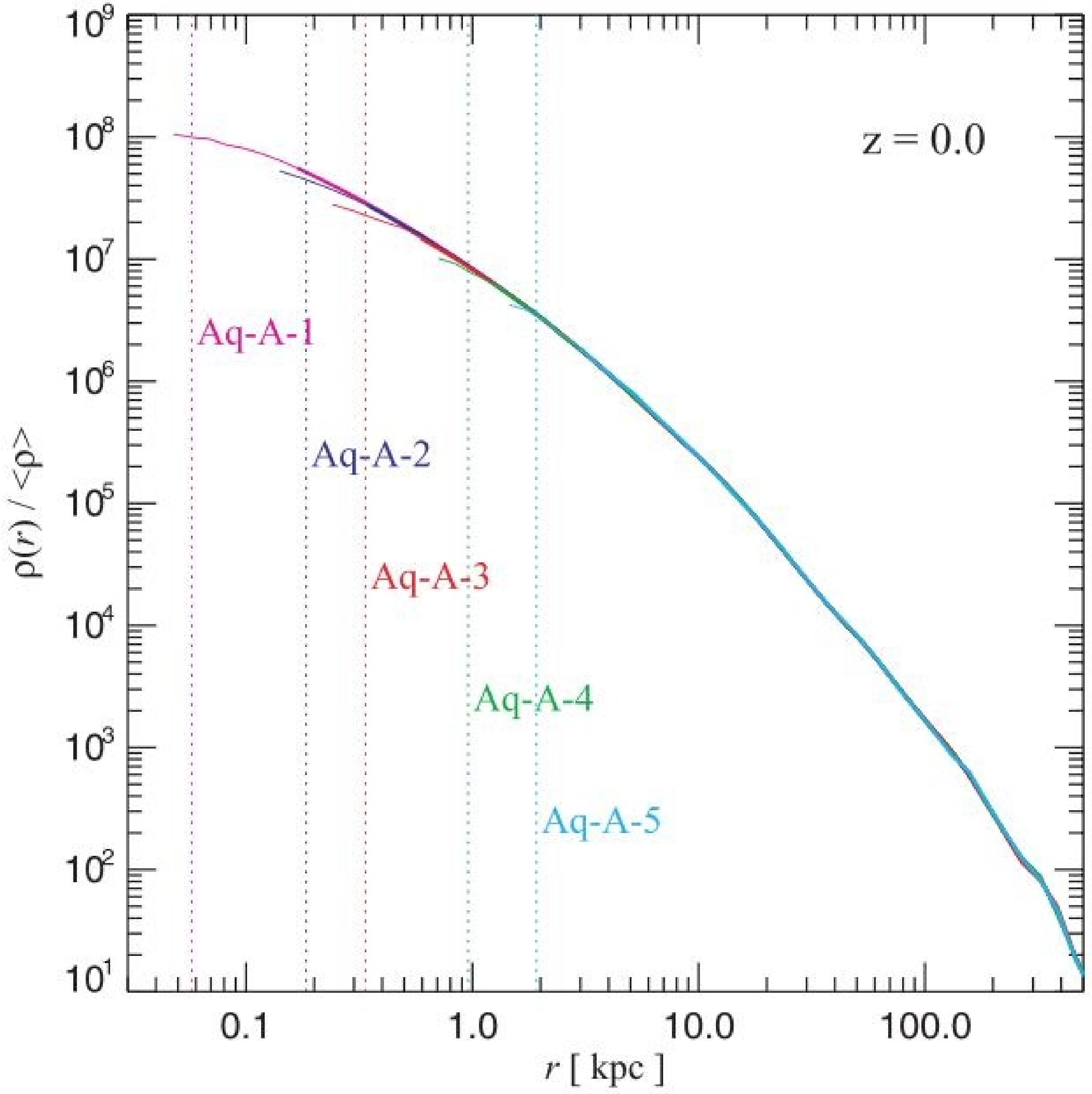
[consistency requirement]

Problems:

- “The CUSP”
- “Granularity” [“the BOOST factor”]

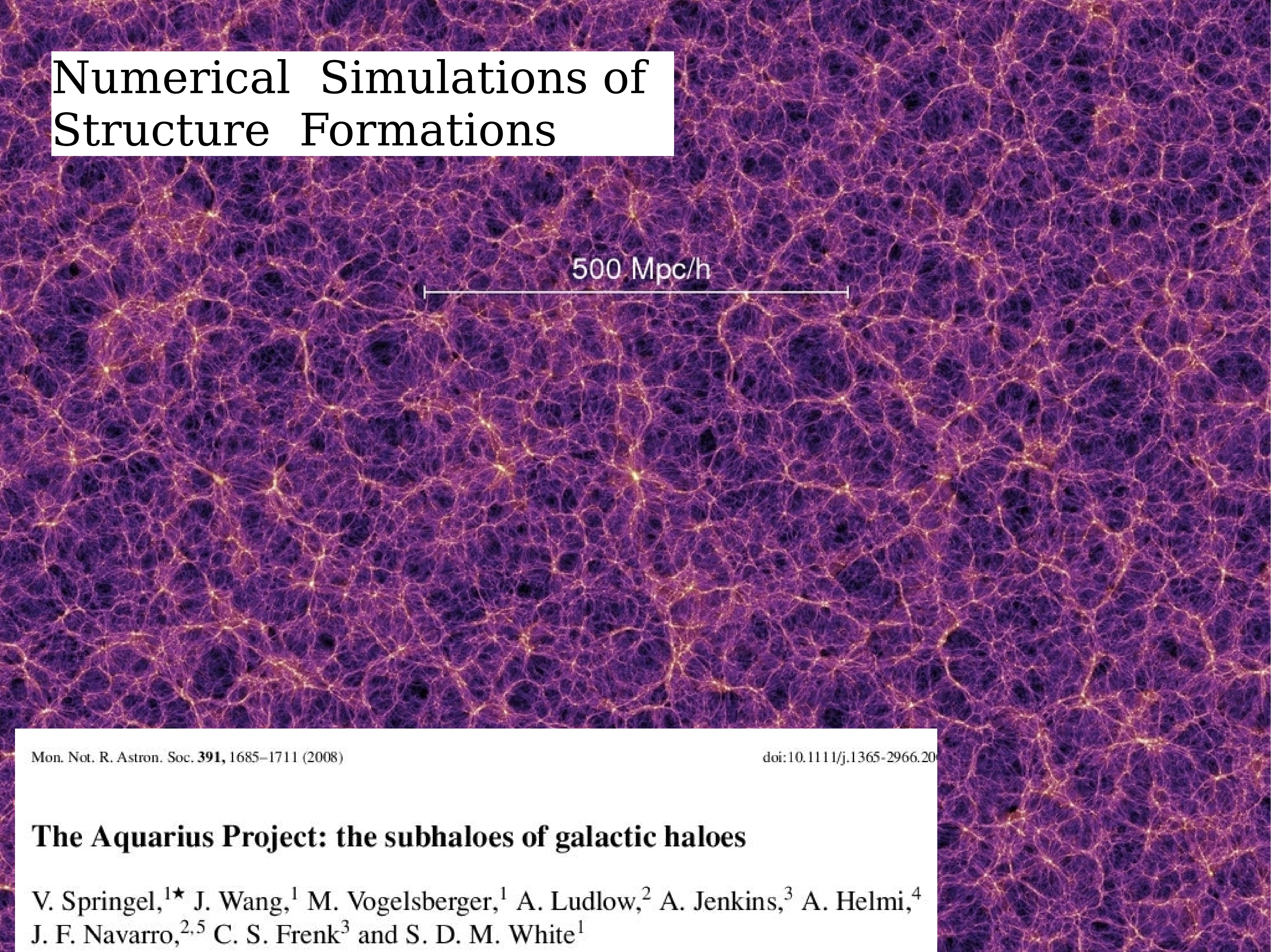
Isothermal (constant)
"NFW" (Navarro-Frenk-Wolf) (1/r divergence)
"Moore" (stronger divergence)





Shape of the “CUSP”

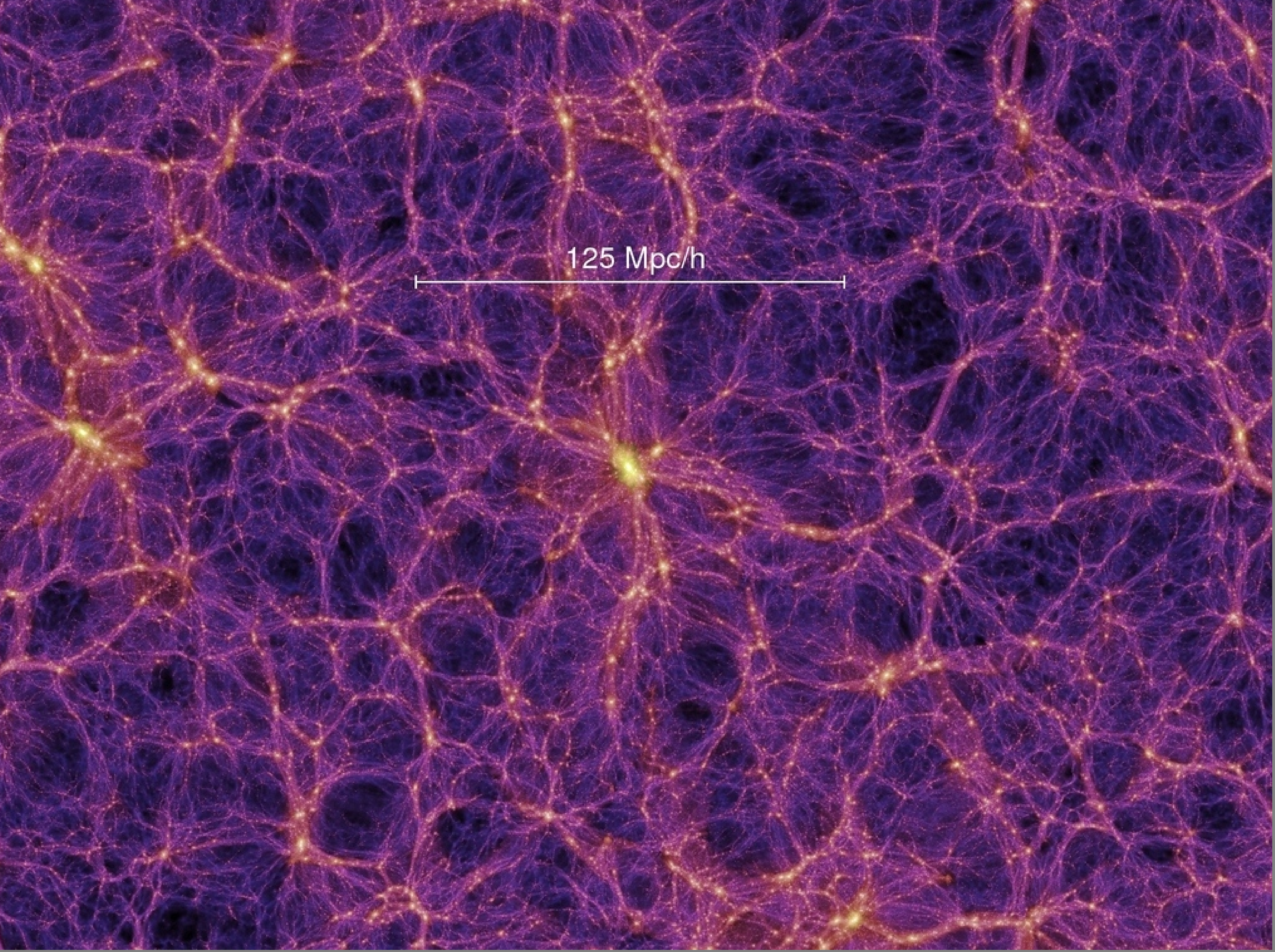
Numerical Simulations of Structure Formations

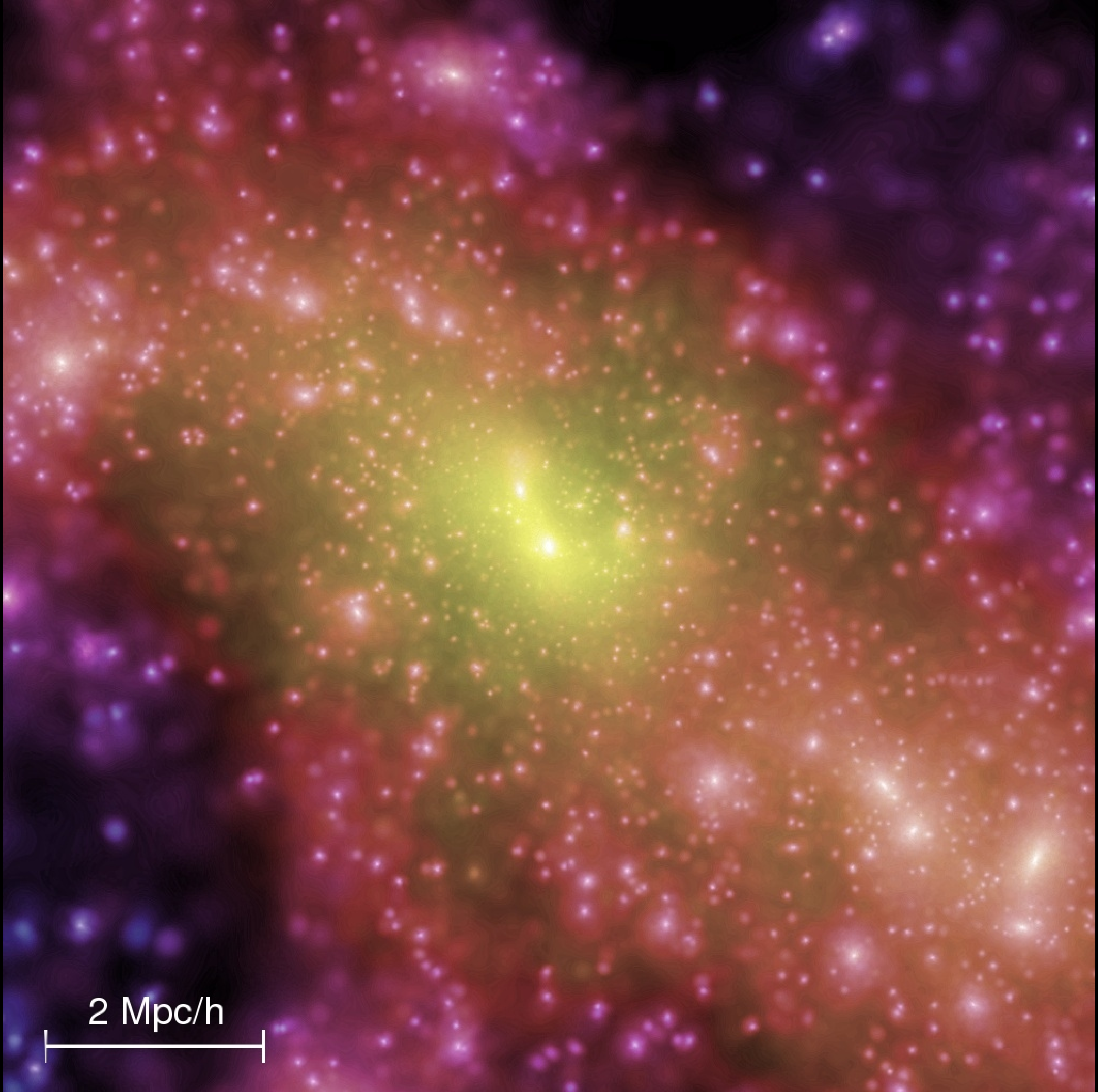


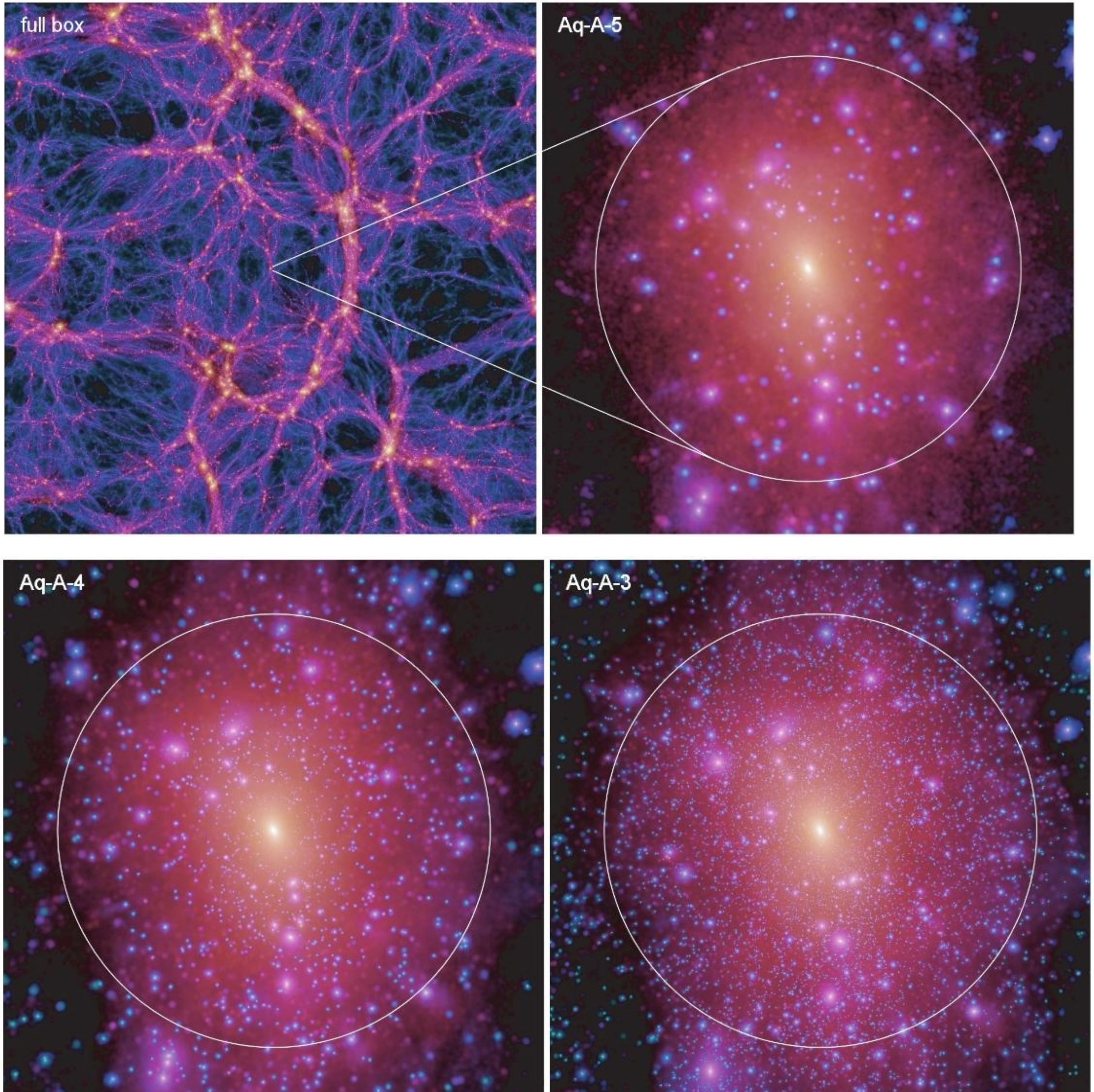
Mon. Not. R. Astron. Soc. **391,** 1685–1711 (2008) doi:10.1111/j.1365-2966.20

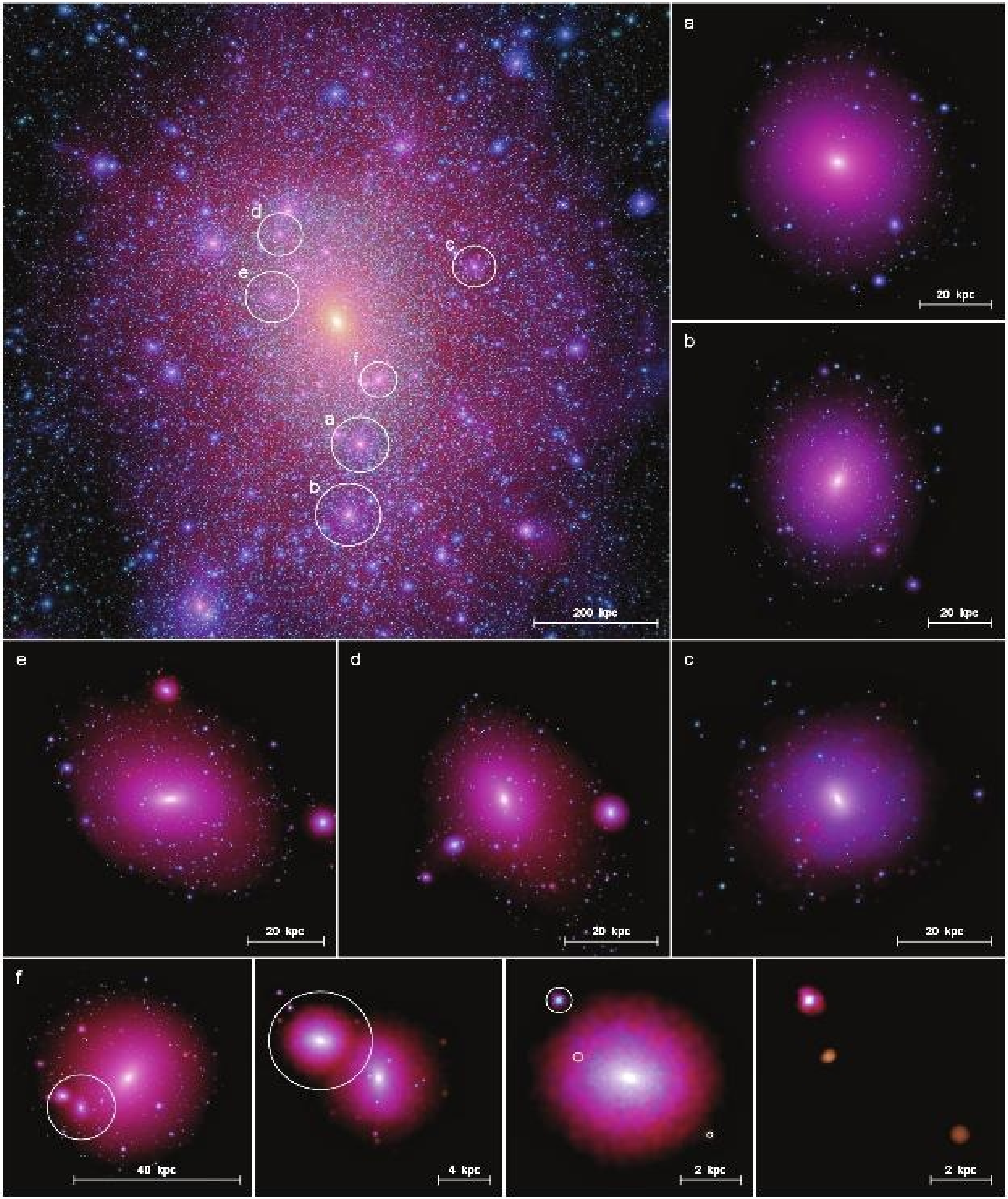
The Aquarius Project: the subhaloes of galactic haloes

V. Springel,[1★] J. Wang,[1] M. Vogelsberger,[1] A. Ludlow,[2] A. Jenkins,[3] A. Helmi,[4]
J. F. Navarro,[2,5] C. S. Frenk[3] and S. D. M. White[1]


125 Mpc/h


2 Mpc/h


full box
Aq-A-5
Aq-A-4
Aq-A-3



Significant Structure in DM

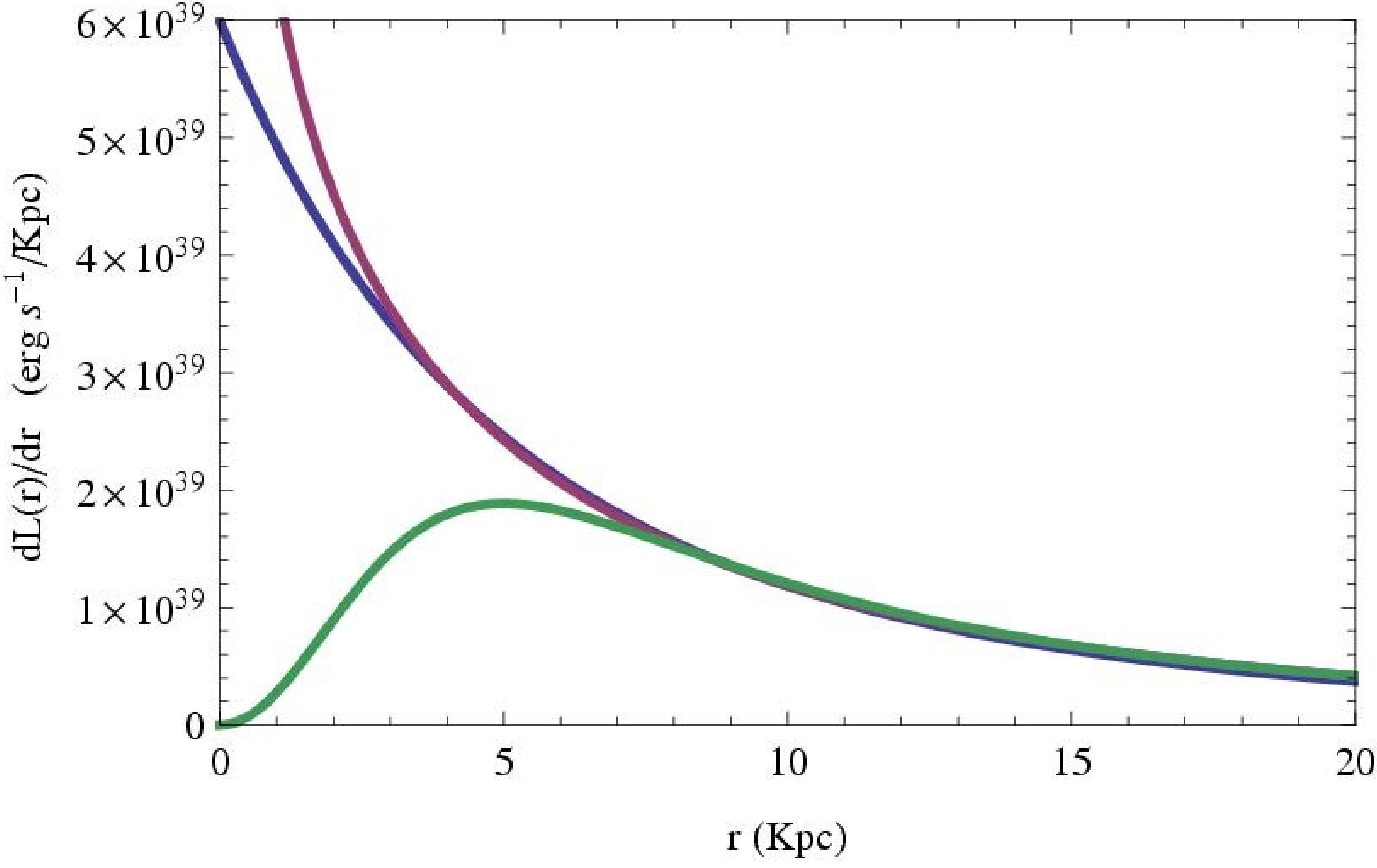
"Boost factor"

Power injection for Dark Matter annihilation

$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{{M_\chi}^2} \langle \sigma \; v \rangle \; M_\chi$$

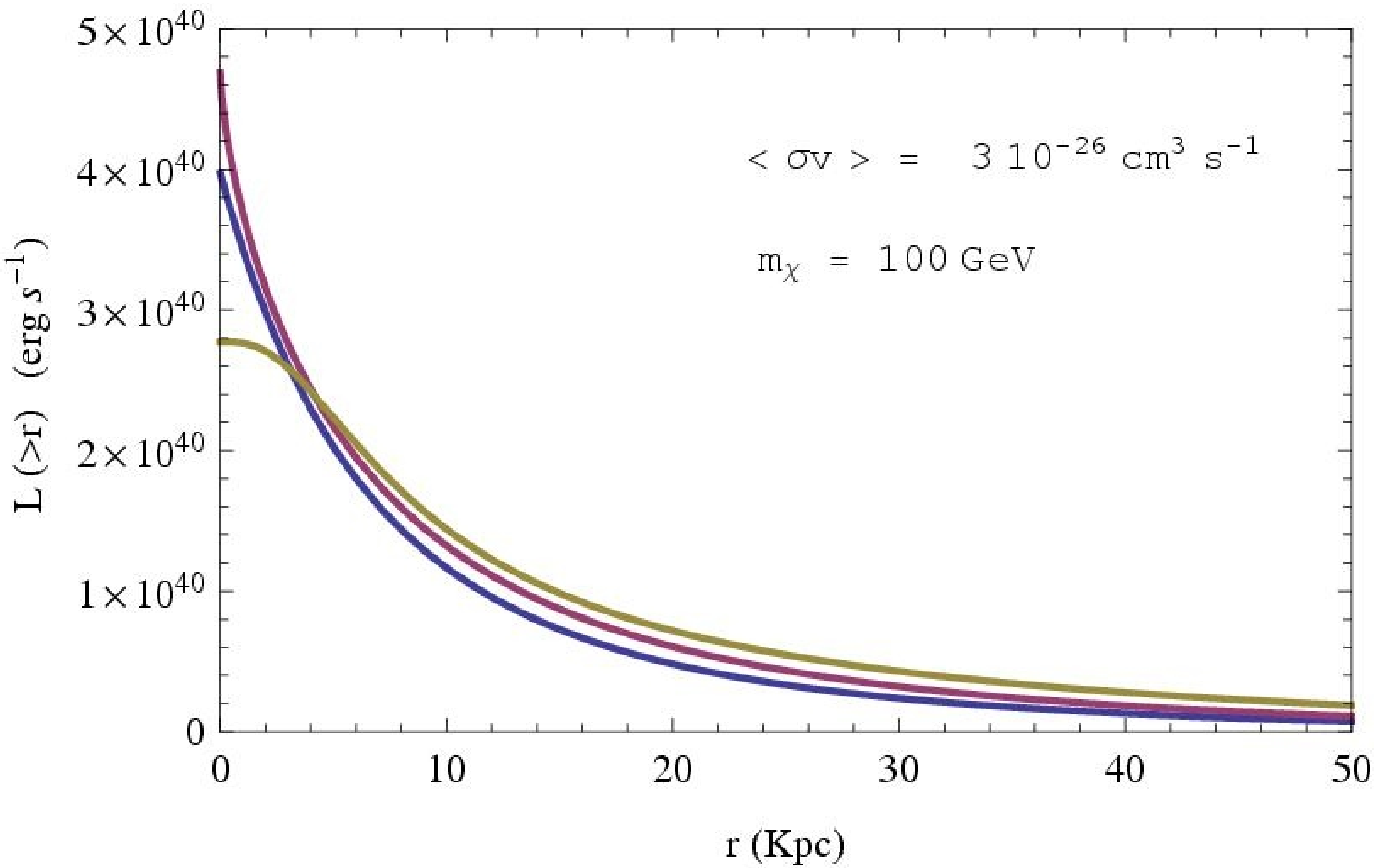
$$\chi + \chi \rightarrow \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha$$

Power injection from DM annihilation



Power injection from DM annihilation

$$L_{\rm Galaxy}^{\rm DM} \simeq 4\times 10^{40}\ \frac{\rm erg}{\rm s}\ \left[\frac{\langle \sigma v\rangle}{3\times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}}\right]\ \left[\frac{100\ {\rm GeV}}{M_\chi}\right]\times {\rm Boost}$$



$$L(\vec{x}) = \frac{\rho(\vec{x})^2}{{M_\chi}^2} \langle \sigma \ v \rangle \ M_\chi$$

- $$L_{\rm DM} \propto \frac{1}{M_\chi}$$

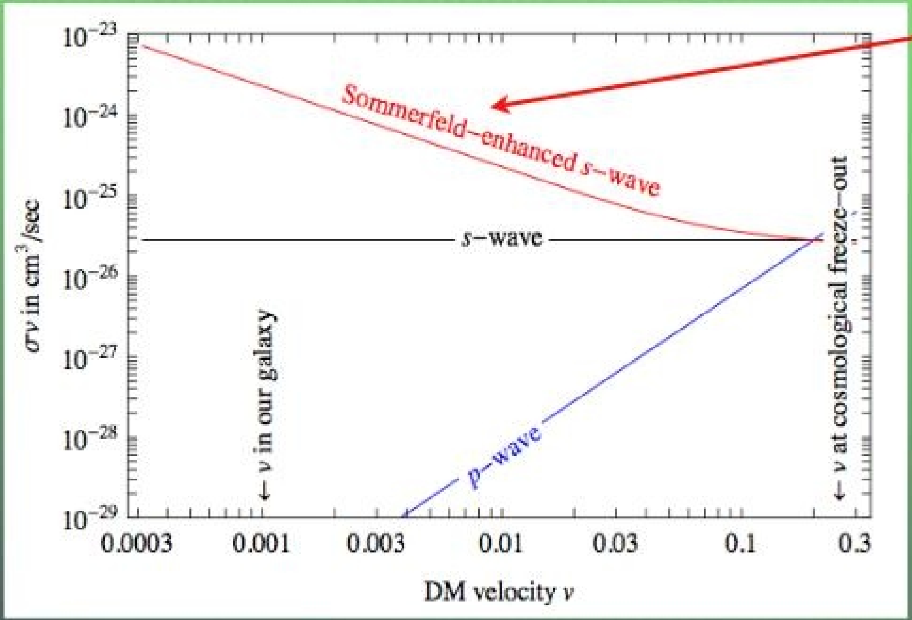
- $$\langle \rho(\vec{x})^2 \rangle \geq \langle \rho(\vec{x}) \rangle^2$$ "Granularity" boosts the power output.

- The "WIMP miracle" $v_{\rm freeze\ out} \simeq 0.2 \div 0.3$

$$\langle \sigma \ v \rangle \simeq 3 \times 10^{-26} \ {\rm cm}^3 \, {\rm s}^{-1}$$ $v_{\rm Galaxy} \simeq 10^{-3}$

First possibility: Sommerfeld effect

Different possibilities for extrapolating the cross section from the early Universe:



a non-perturbative enhancement in the cross section at low velocities

Hisano, Matsumoto & Nojiri,(2003); e.g.: Cirelli et al., arXiv:0809.2409

DM is charged under a (new) gauge force, mediated by a "light" boson: this sets a non-perturbative long-range interaction, analogously to Coulomb interaction for positronium:

$$V(r) = -\frac{\alpha}{r}$$

gives the enhancement in the cross section:

$$S = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2 = \frac{\pi\,\alpha/v}{1-e^{-\pi\,\alpha/v}} \xrightarrow{v \ll \alpha} \frac{\pi\,\alpha}{v}$$

The same 1/v enhancement is obtained for a Yukawa potential. In a DM context, first studied in the MSSM for pure very massive Winos or Higgsinos and weak interaction as gauge force (light W boson l

Piero Ullio

Annihilation cross section

$$\sigma(\chi + \overline{\chi} \to \text{anything}, v_{\text{rel}})$$

$$\left.\frac{dn}{dE}\right|_{(\chi+\chi\to\gamma)}$$

$$\left.\frac{dn}{dE}\right|_{(\chi+\chi\to\gamma, e^+, \overline{p}, \nu_\alpha)}$$

Inclusive spectra

In most models DM particle = Majorana particle

$$B(\chi + \overline{\chi} \to F)$$

Branching Ratios in different final states F

DM – Nuclei Elastic Scattering

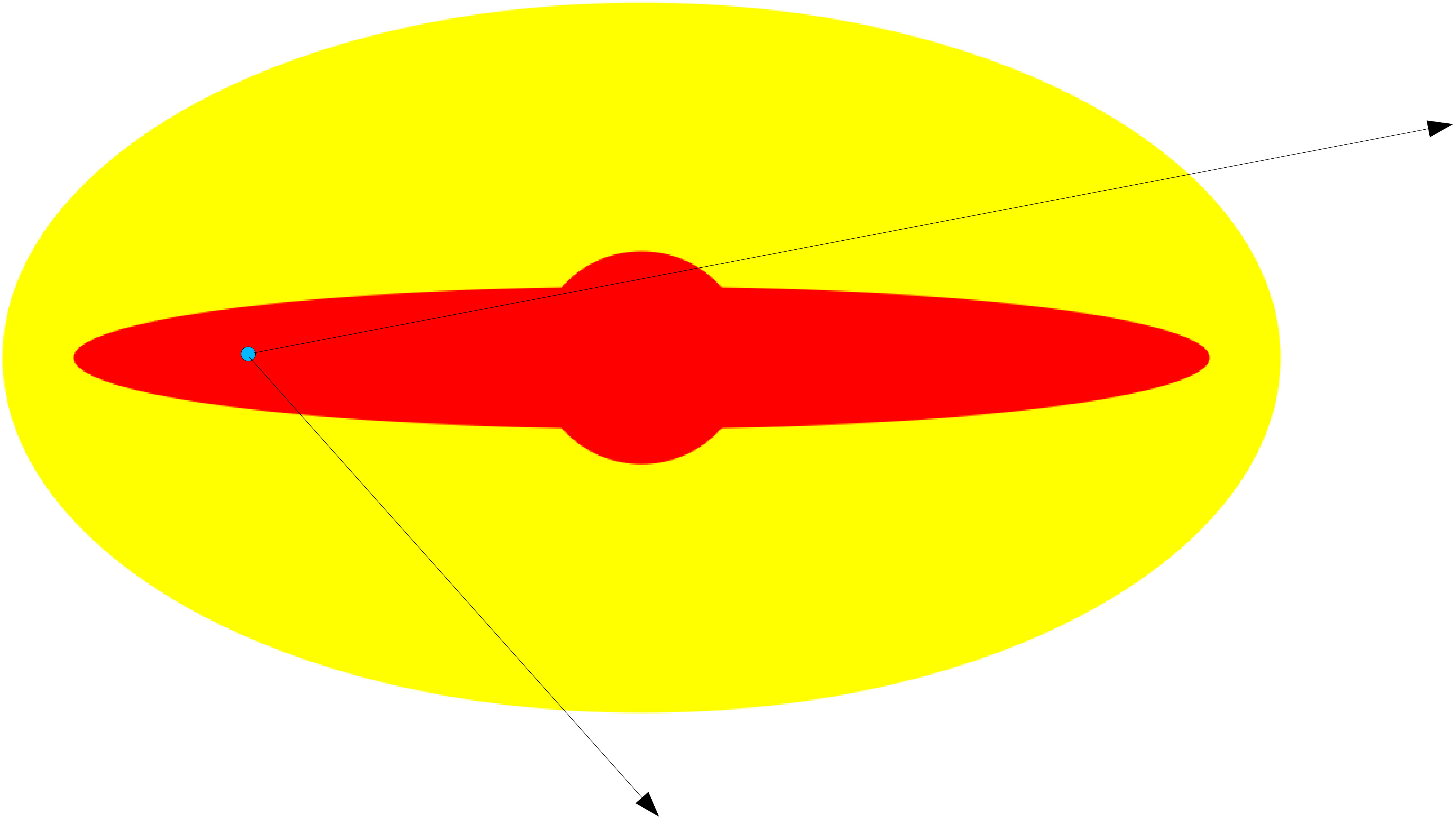
$$\sigma(\chi + A \to \chi + A)$$

$$\left.\frac{d\sigma}{d\cos\theta^*}\right|_{(\chi+A\to\chi+A)}$$

Direct detection
Accretion in Sun, Stars....

[effect on Star formation
near the galactic center]

Photon emission from DM annihilation



$$J(\Omega) = \frac{1}{R_\odot} \int_0^\infty d\ell \; \rho(\ell;\Omega)$$

Photons from Dark Matter

$$\phi_\gamma(\Omega) = K_\gamma \; J(\Omega) \; \boxed{\frac{dn}{dE}(E)\Big|_{\chi\chi\to\gamma}}$$

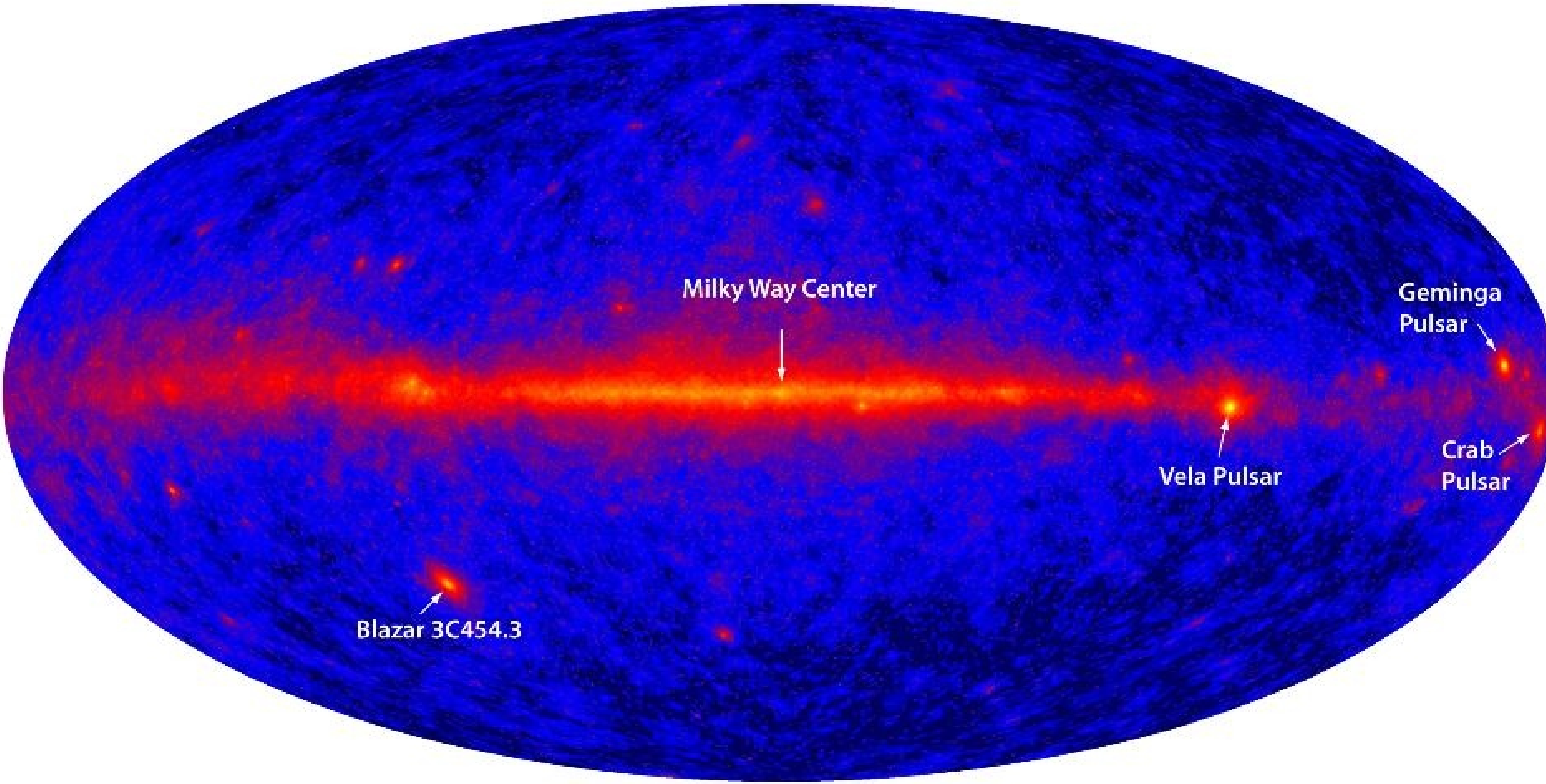
Spectrum

$$K_\gamma = \frac{1}{4\pi} \frac{\langle \sigma \, v \rangle}{2} \frac{\langle \rho_\odot \rangle^2}{{M_\chi}^2} R_\oplus$$

$$K_\gamma \simeq 3.7 \times 10^{-10} \; \left[\frac{\langle \sigma \, v \rangle}{3 \times 10^{-6} \, \mathrm{cm}^3 \, \mathrm{s}^{-1}}\right] \; \left[\frac{100 \; \mathrm{GeV}}{M_\chi}\right]^2$$

$$J(\Omega) = \frac{1}{R_\odot} \int d\ell \; \frac{\rho^2(\ell, \Omega)}{\rho_\odot^2}$$

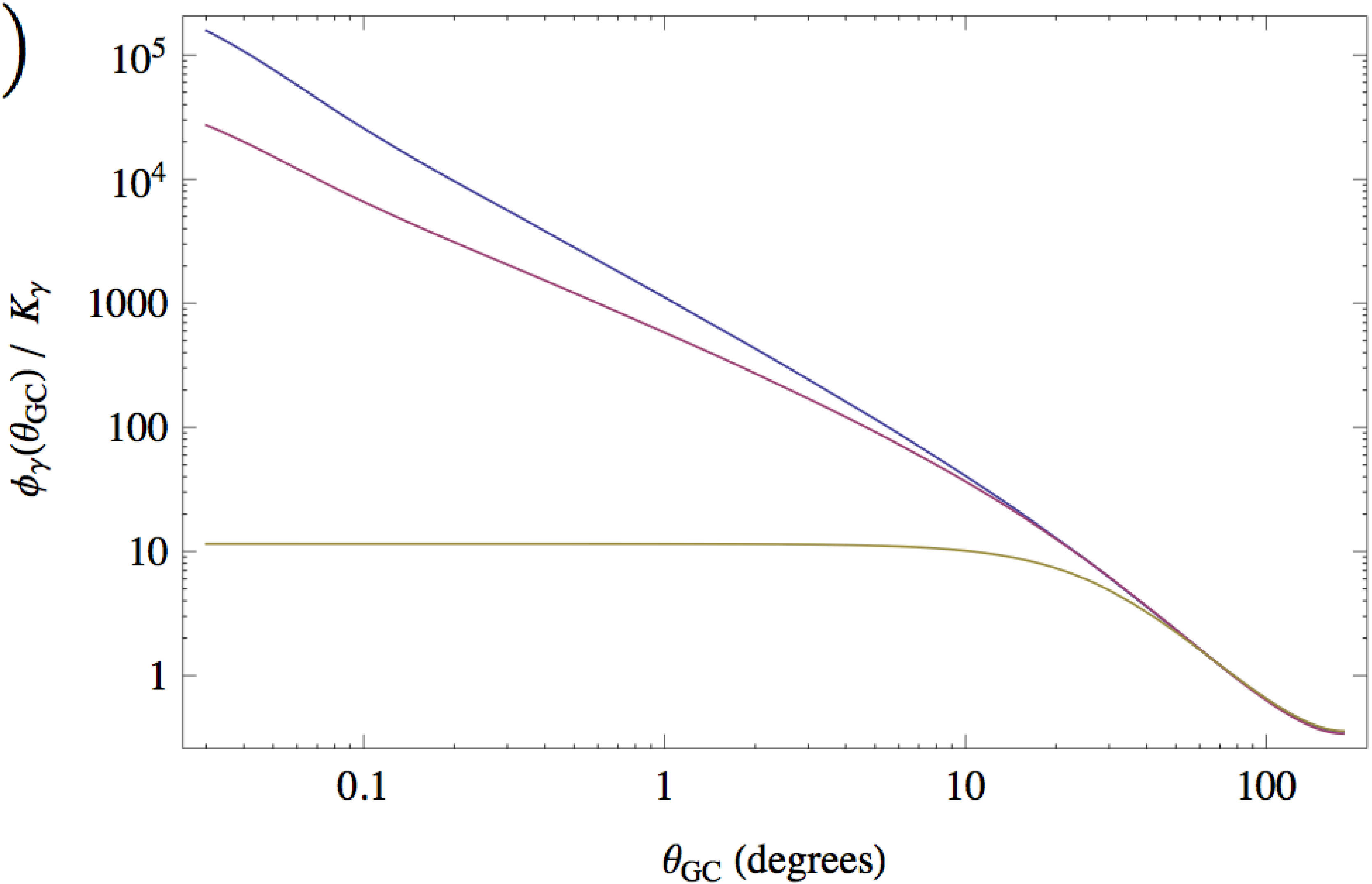
Adimensional
Angular factor



$E_\gamma > 100$ MeV

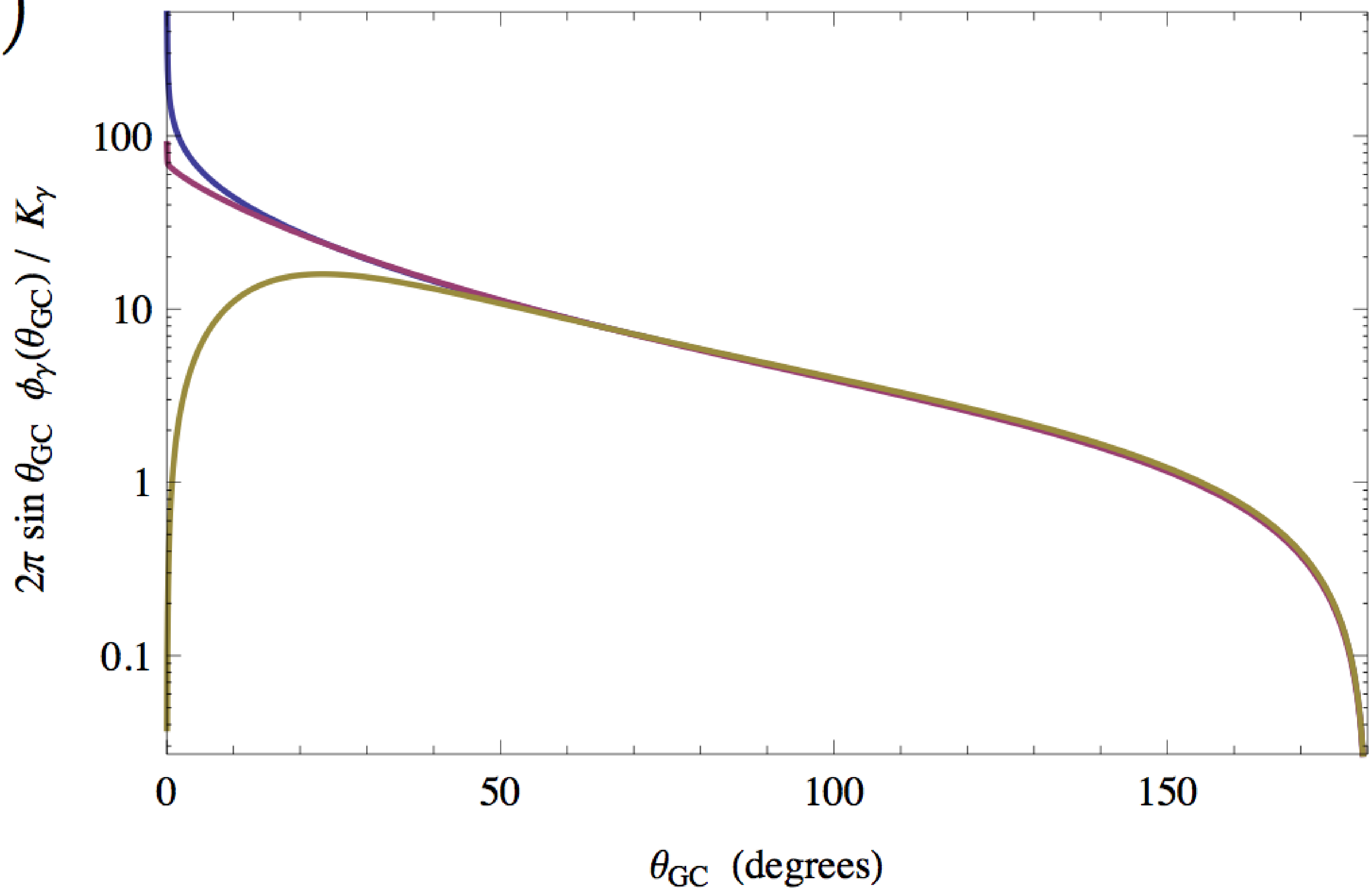
Angular dependence of the Photon flux

$J(\Omega)$

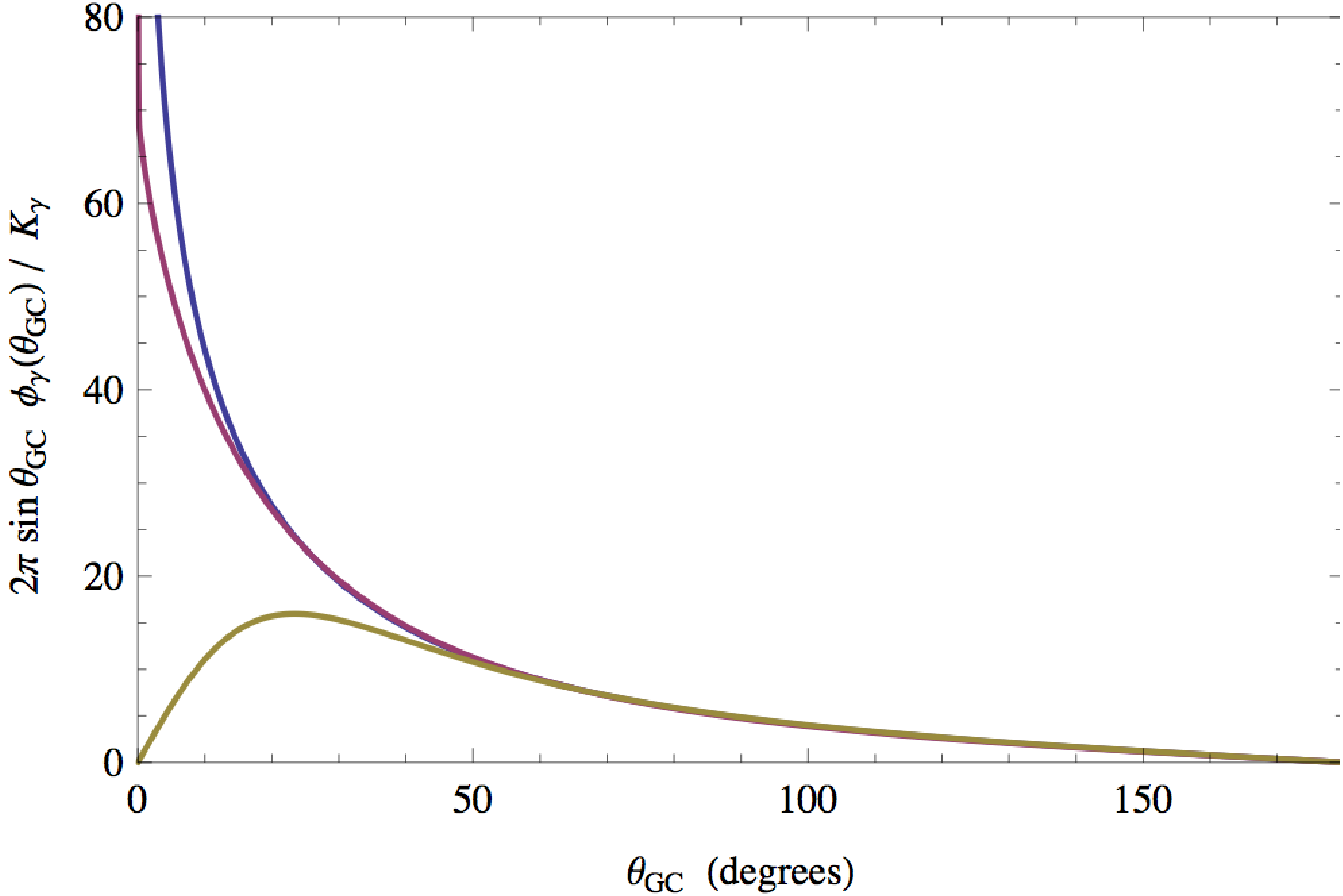


Angular dependence of the Photon flux

$J(\Omega)$



Photon rate



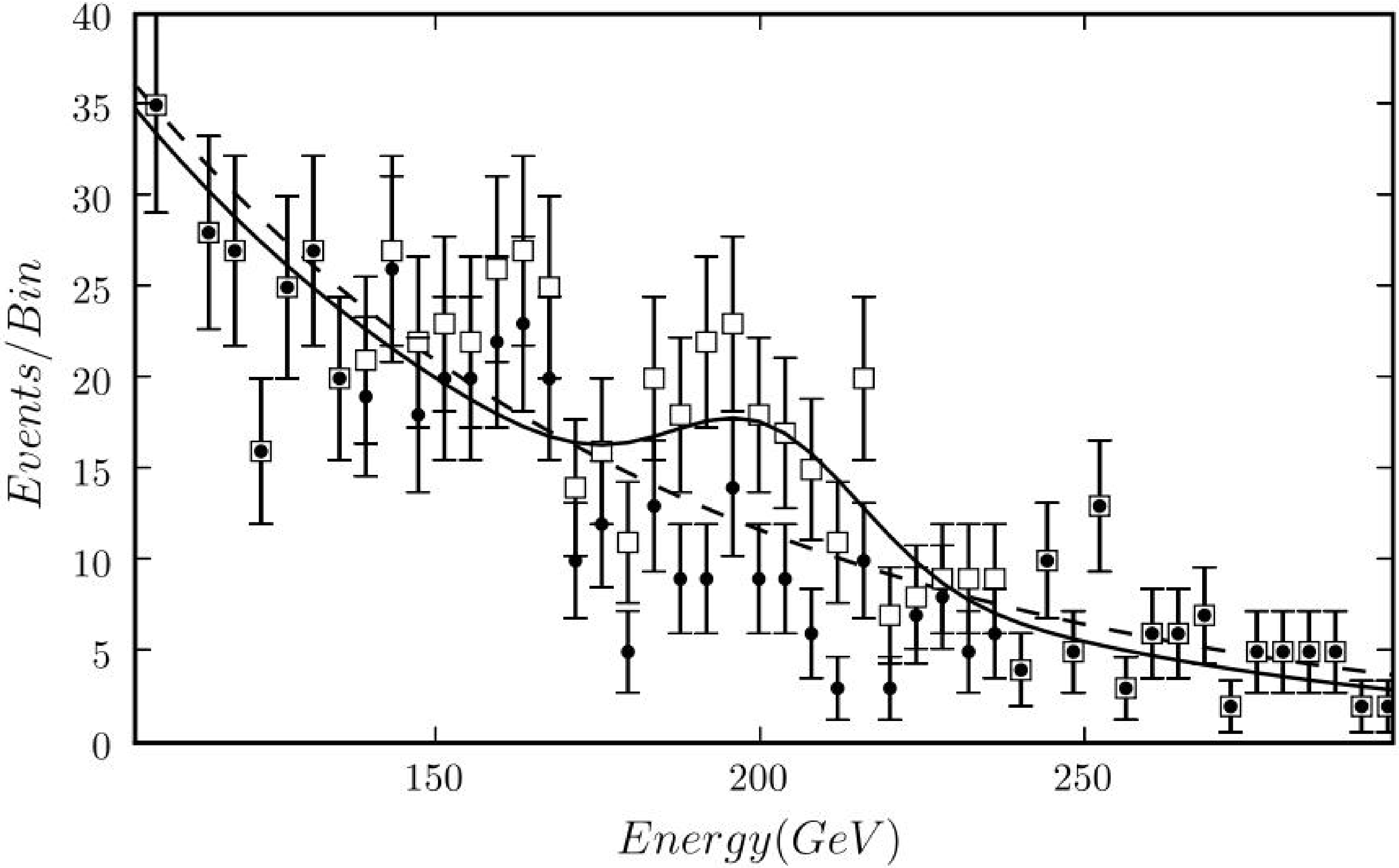
$$\frac{1}{4\pi}\int d\Omega\ J(\Omega) \simeq 3.0 \qquad (3.5, \quad 1.8)$$

$$\frac{1}{4\ \pi} \int d\Omega\ J(\Omega) \simeq 3.0 \qquad (3.5, \quad 1.8)$$

Fermi sensitivity: A = 9500 cm2

$$AT \simeq 0.45 \times 10^{11}\ \mathrm{cm}^2\ \mathrm{s}\ N_{\mathrm{years}}$$

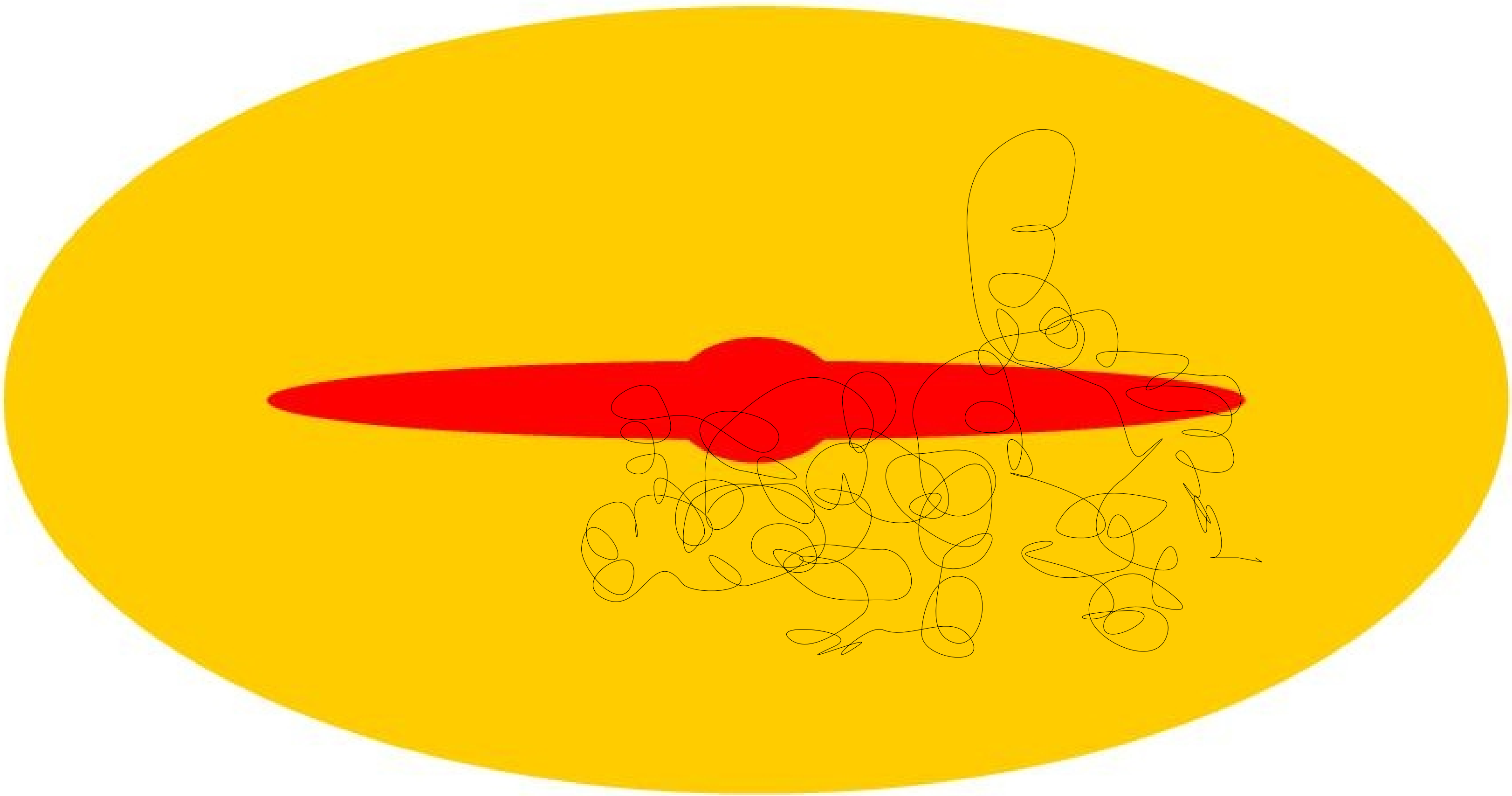
$$\boxed{N_{\gamma}^{\mathrm{NFW}} \simeq 430 \left[\frac{\langle \sigma\, v \rangle}{3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{s}^{-1}}\right] \left[\frac{100\ \mathrm{GeV}}{M_{\chi}}\right]^2 N_{\mathrm{years}}}$$

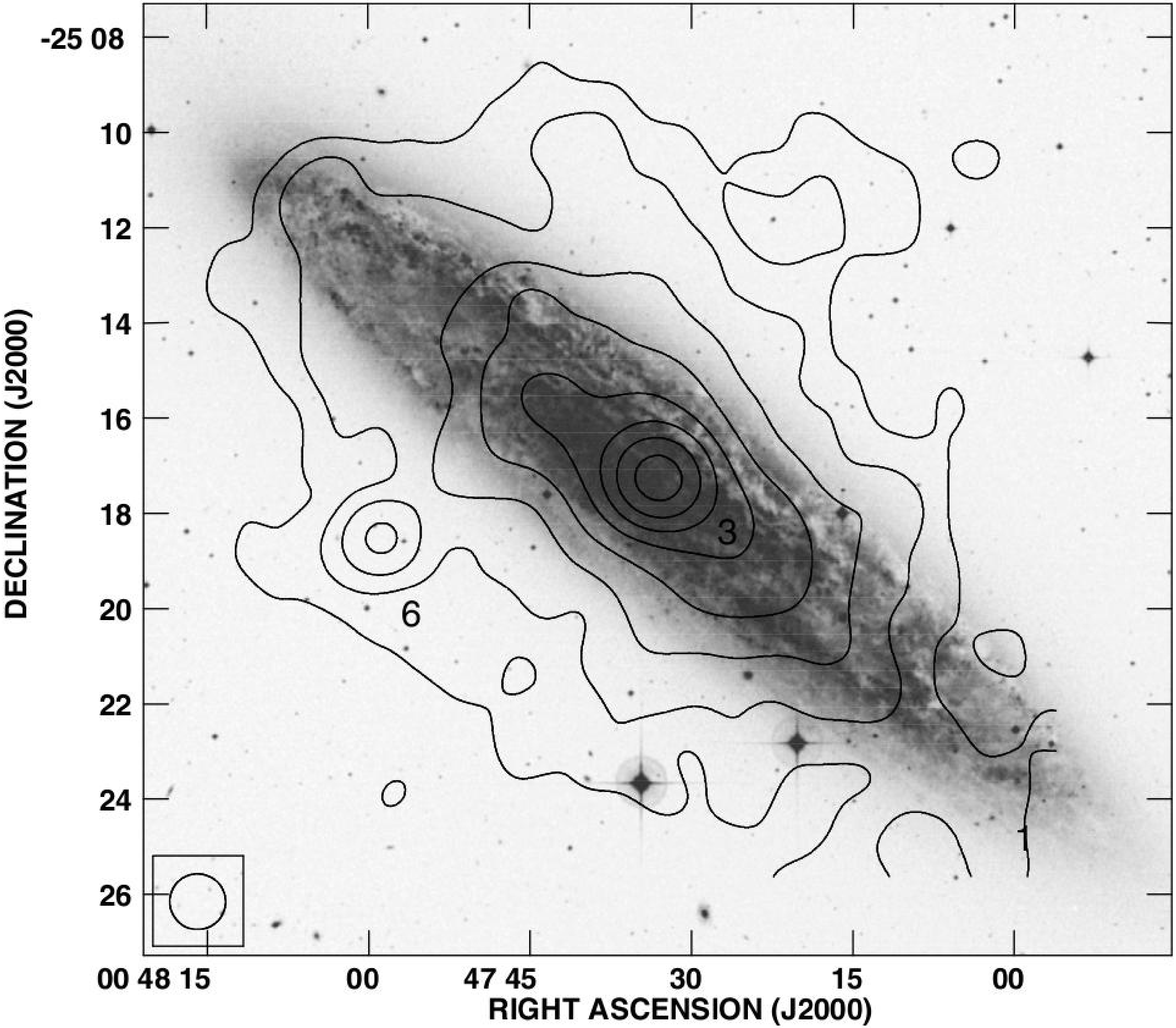


40
35
30
25
20
15
10
5
0
150
200
250
Events/Bin
Energy(GeV)

Charged Particles:

Magnetic confinement
Energy Loss





Total power radio continuum at $\lambda 90$ cm obtained from VLA observations with $70''$ resolution. Contours are at 3, 6, 12, 24, 48, 96, 192, 384, 768, 1536, and 3077×8 mJy/beam.

Propagation
as diffusion