DARK MATTER

and

COSMIC RAYS

2nd part

Paolo Lipari
4th school on Cosmic Rays and Astrophysics
UAFBC Sao Paulo, 31th august 2010

- Our universe contains a large amount of “Dark Matter” that does not appear to emit or absorb light.

- The dark-matter is present at different scales
  - the entire universe
  - Cluster of galaxies
  - Spiral galaxies halos.

- The dark matter is “non baryonic” that is different from ordinary matter (!) [made of protons, neutrons (baryons) and electrons].

- The dark-matter is “cold”: moving non relativistically [energy density dominated by rest mass]

- The dark-matter is visible via gravitational effects. Other type of interactions (with ordinary matter, and with itself) are very weak [or perhaps absent]

Possible explanation for the dark-matter:

“THERMAL RELIC” or **“WIMP”**

stable [or very long lived] elementary particle
that was in thermal equilibrium in the Early Universe
for $T >> m$.

When T falls below m,
the particle is not created anymore, but it starts to
self-annihilate.

The energy density of the particles that survive to the
Present Epoch is determined by its
annihilation cross section
[and is independent from its mass]

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

“Weak interaction
scale cross section”

WIMP's

Some people are so “excited” by the fact that the self-annihilation cross section needed to find the cosmological density is a weak scale cross section that they have called it:

the WIMP's “miracle”

Some people are so “excited” by the fact that the self-annihilation cross section needed to find the Cosmological density is a weak scale cross section that they have called it:

the WIMP's “miracle”

But why are people excited ?

Because it is like

“Killing two birds with a single stone”

A particle with properties similar to the ones required had been proposed for completely independent reasons in Particle Physics [Super-symmetry]

Supersymmetry

Fermionic degrees
of freedom

Bosonic degrees
Of freedom

All “internal quantum numbers”
(charge, color,…) must be identical

Standard Model fields

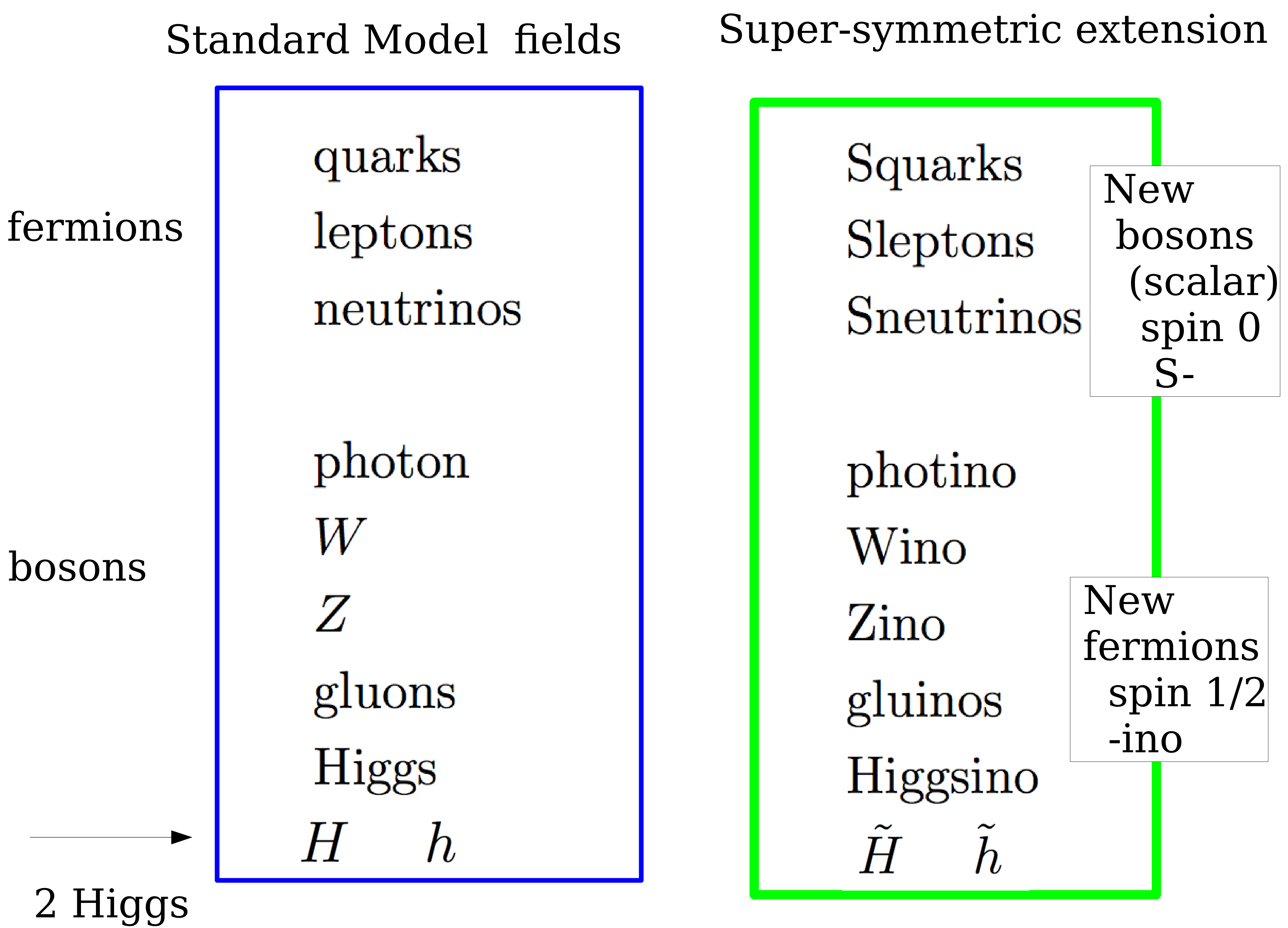
fermions

- quarks
- leptons
- neutrinos

bosons

- photon
- W
- Z
- gluons
- Higgs

	Standard Model fields	Super-symmetric extension	
fermions	quarks leptons neutrinos	Squarks Sleptons Sneutrinos	New bosons (scalar) spin 0 S-
bosons	photon W Z gluons Higgs	photino Wino Zino gluinos Higgsino	New fermions spin 1/2 -ino


Standard Model fields
Super-symmetric extension
fermions
bosons
2 Higgs
quarks
leptons
neutrinos
photon
W
Z
gluons
Higgs
H h
Squarks
Sleptons
Sneutrinos
photino
Wino
Zino
gluinos
Higgsino
$\tilde{H}$ $\tilde{h}$
New bosons (scalar) spin 0 S-
New fermions spin 1/2 -ino

“Minimum Supersymmetric Model”

Minimal extension of the Standard Model with
the required (super)-symmetry.

Note:
The (super)-symmetry exists also with interactions
All interaction properties of the old and new
particles are then determined.

Particles related by super-symmetry
have equal-masses

.... but all the new supersymmetric particles have not
been observed... So they must have higher mass.
Therefore the (super) symmetry must be broken.
[How exactly to break the symmetry is a problem]

Motivations for Super-symmetry:

Motivations for Super-symmetry:

“Beauty”

Motivations for Super-symmetry:

“Beauty” [?!]

Solving the “Hierarchy problem”

Radiative corrections to the Higgs mass become naturally very large.

Boson and Fermion loops in Feynman diagrams have opposite sign, and their contributions cancel.

For the cancellation to be exact the masses of the pair boson- fermion must be equal.
For the cancellation to operate, the masses of the Super-symmetric particles cannot be too large.

At least ONE of the new super-symmetric particles must be absolutely stable. [R-parity conservation.]

Key point that connects super-symmetry To the Dark-Matter problem.

Which one of the new particles is stable?
Depends on the details of how the supersymmetry is Broken.

In most cases it is a Linear combination
Of the 4 – neutral spin ½ fermions
The NEUTRALINO.

$$|\chi\rangle = c_1 \; |\tilde{\gamma}\rangle + c_2 \; |\tilde{z}\rangle + c_3 \; |\tilde{H}\rangle + c_4 \; |\tilde{h}\rangle$$

Here something remarkable happens.

In some part of the parameter space
of the minimal super-symmetric model
the neutralino has such properties
that its relic density is equal
to the one observed for Dark-Matter

Neutralino is stable
It is in thermal equilibrium in the early universe
It has the right cosmological density

Neutralino = Dark-Matter particle

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What mass ? Infinite solutions. (m ~ 100 GeV) typical

Argument can be made more general.

Special “mass scale” : electro-weak mass scale

$$M_W \simeq 80 \text{ GeV}$$

Weak Bosons

$$M_Z \simeq 91 \text{ GeV}$$

$$M_H \sim 120 \text{ GeV}$$

Higgs particle [??]

May be many other particles exist and have masses
Of this order. Strong motivations for LHC

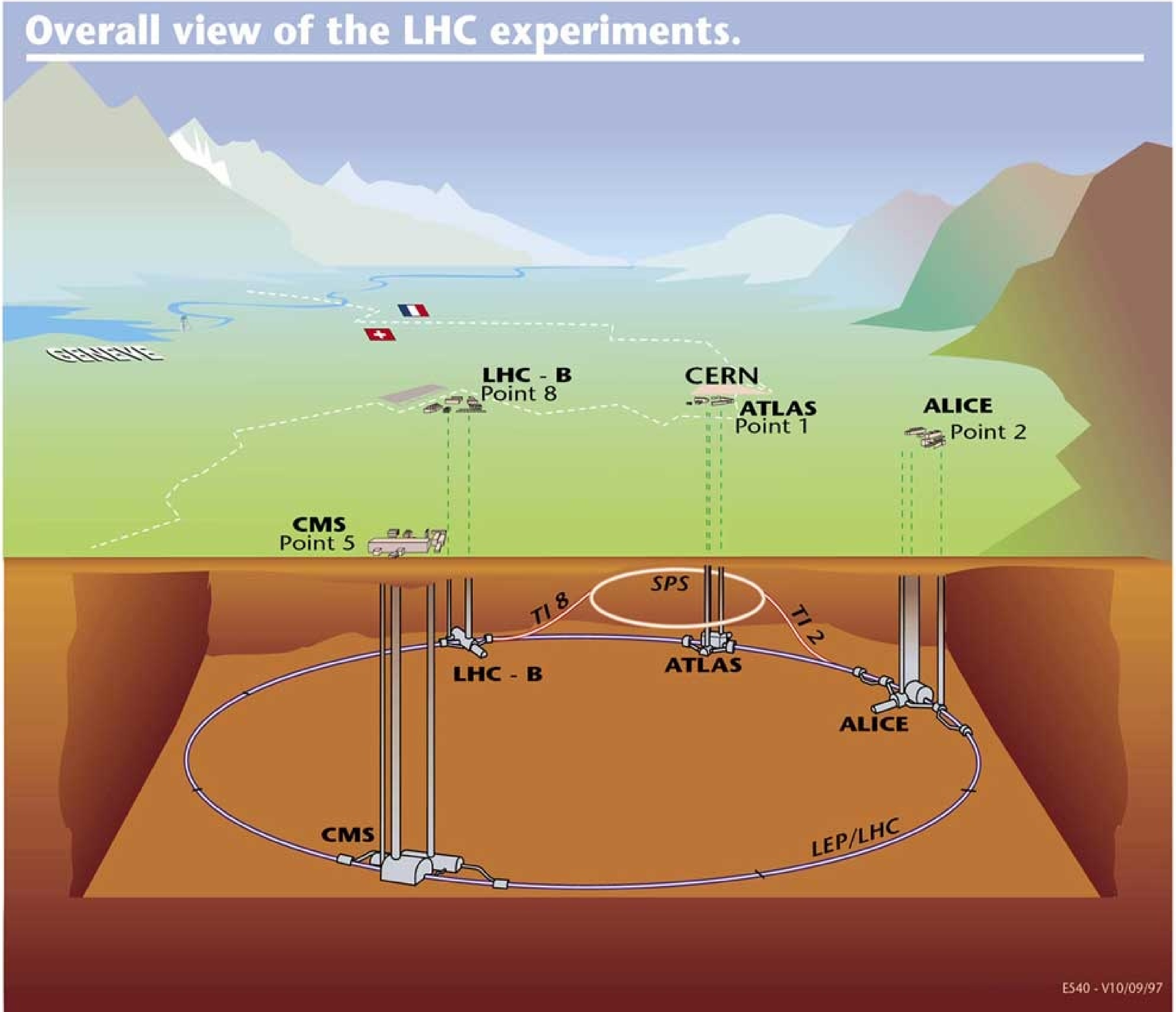
A NEW particle seems to be required
To explain the observed Dark Matter

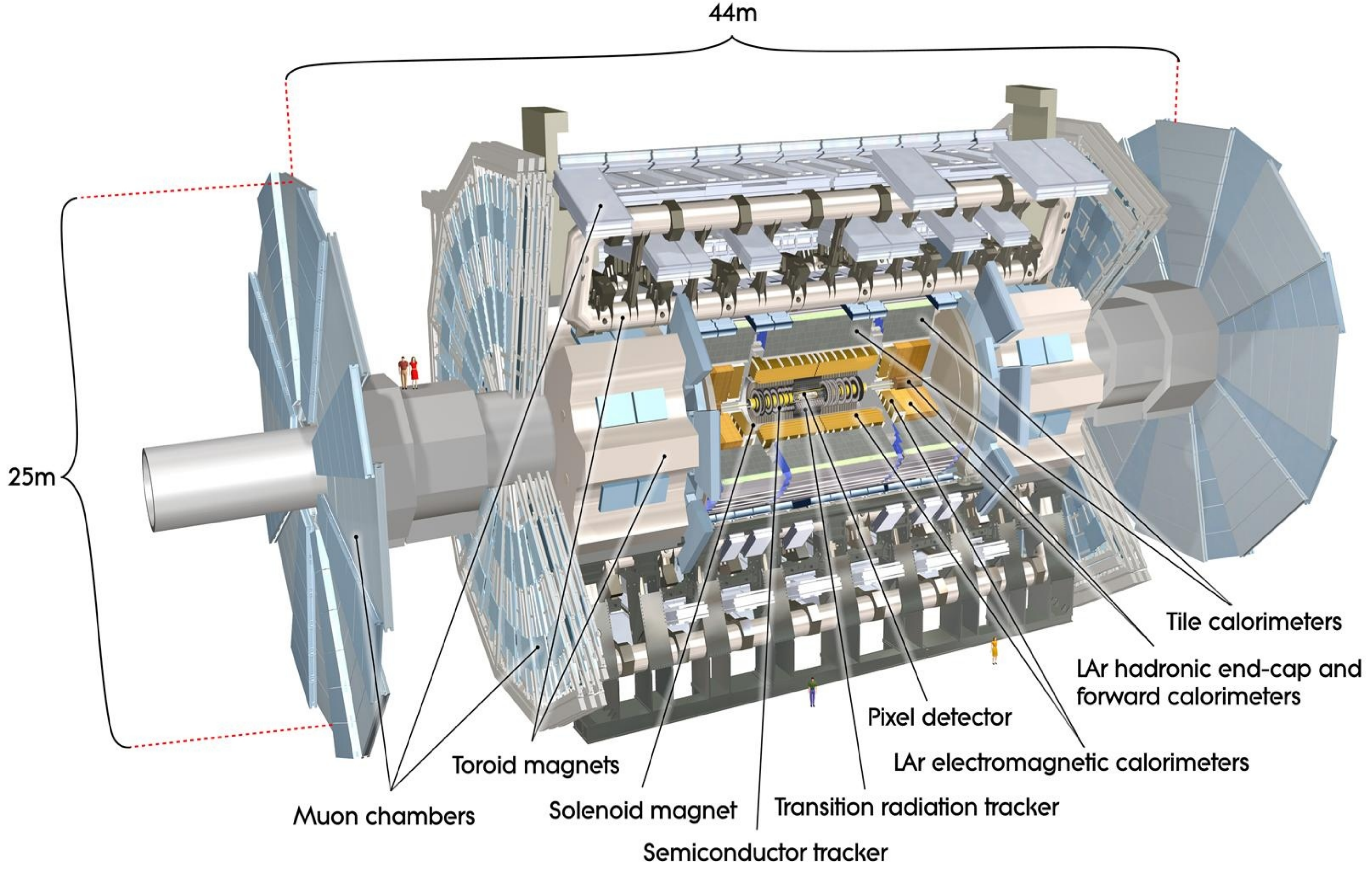
Extension of the Standard Model
are EXPECTED at the electro-weak
mass scale

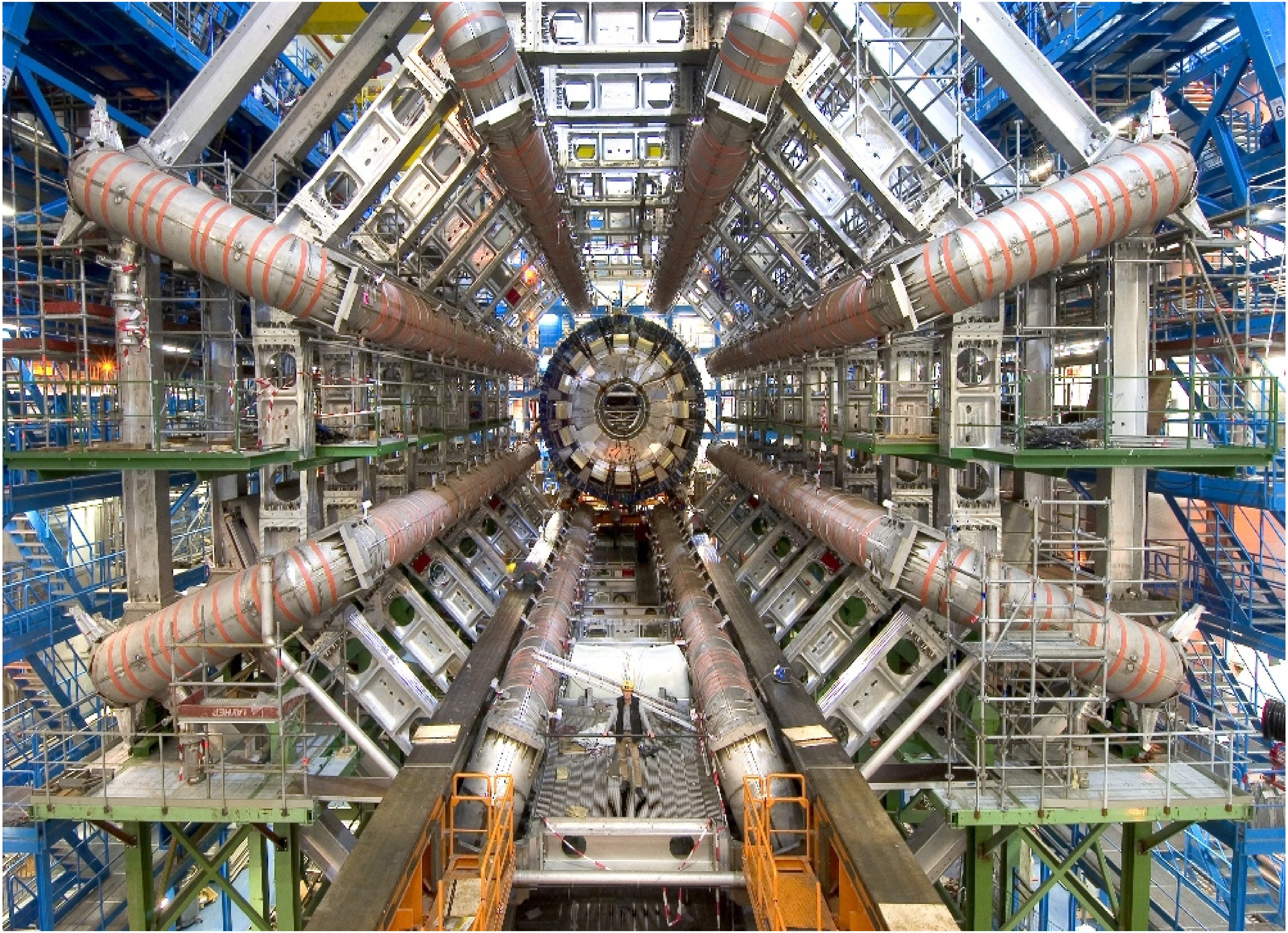
These extensions can “naturally” result in the
existence of Dark Matter !

LHC/Dark Matter connection !!

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


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

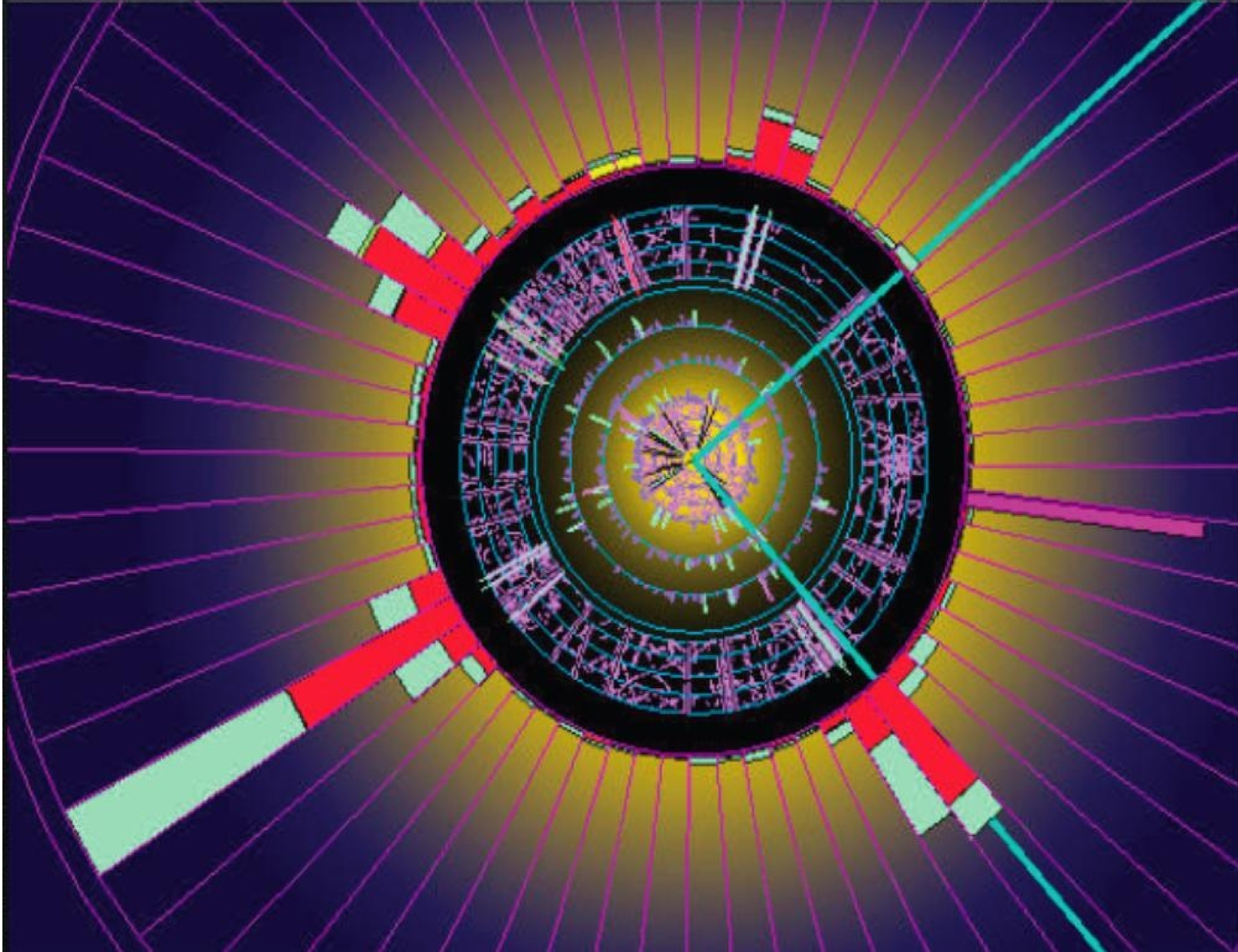

44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



How would you “see” the Dark-Matter particle
if it is produced at LHC ?

This particle interacts WEAKLY
Therefore (in practice always) it will fly the
Through the detector without leaving any signal
[like a neutrino]

But the new particle can be detected
Via 4-momentum conservation
[“Missing energy and (transverse) momentum”]

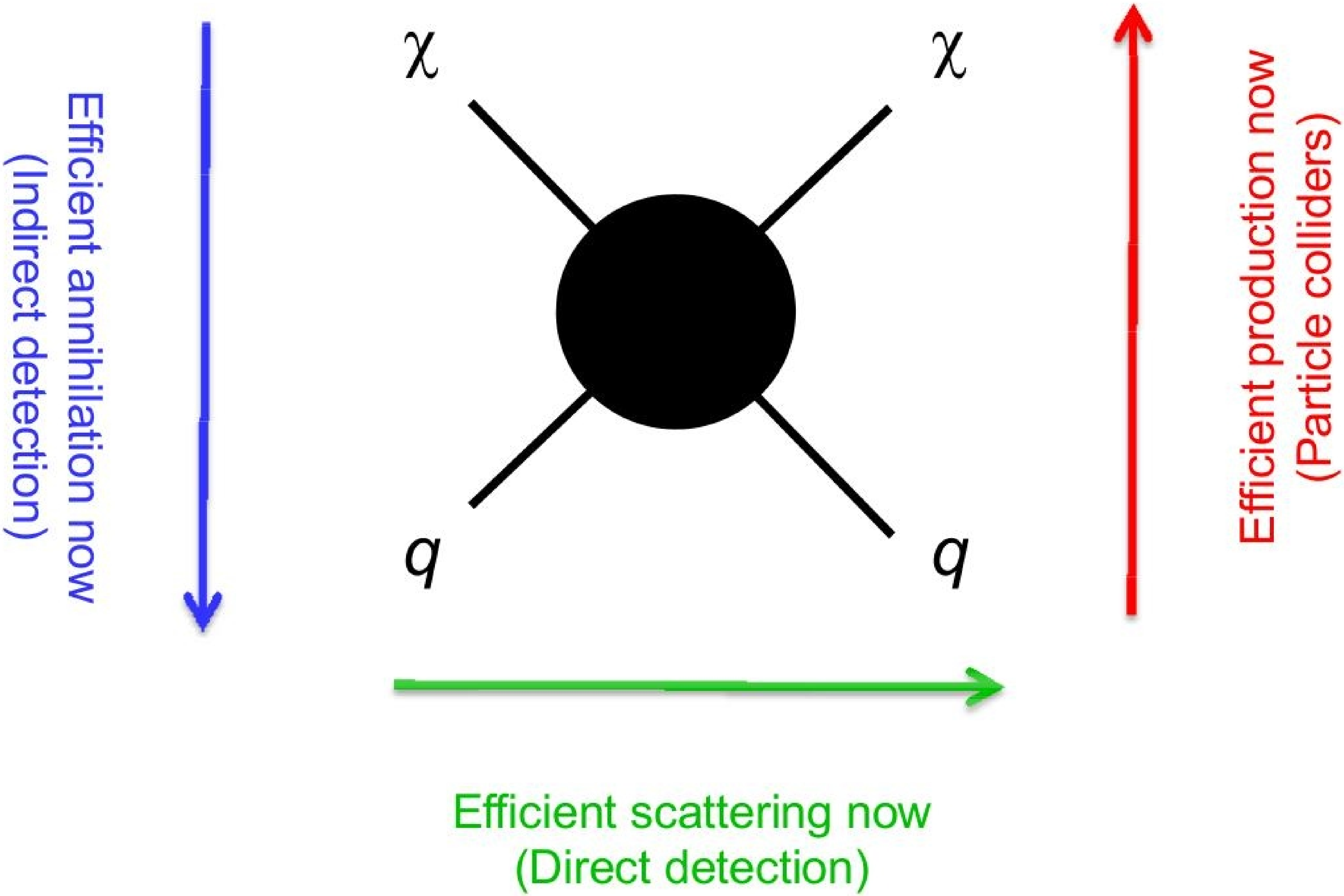


Three roads to the study of the "WIMP" hypothesis:

1. Direct Detection

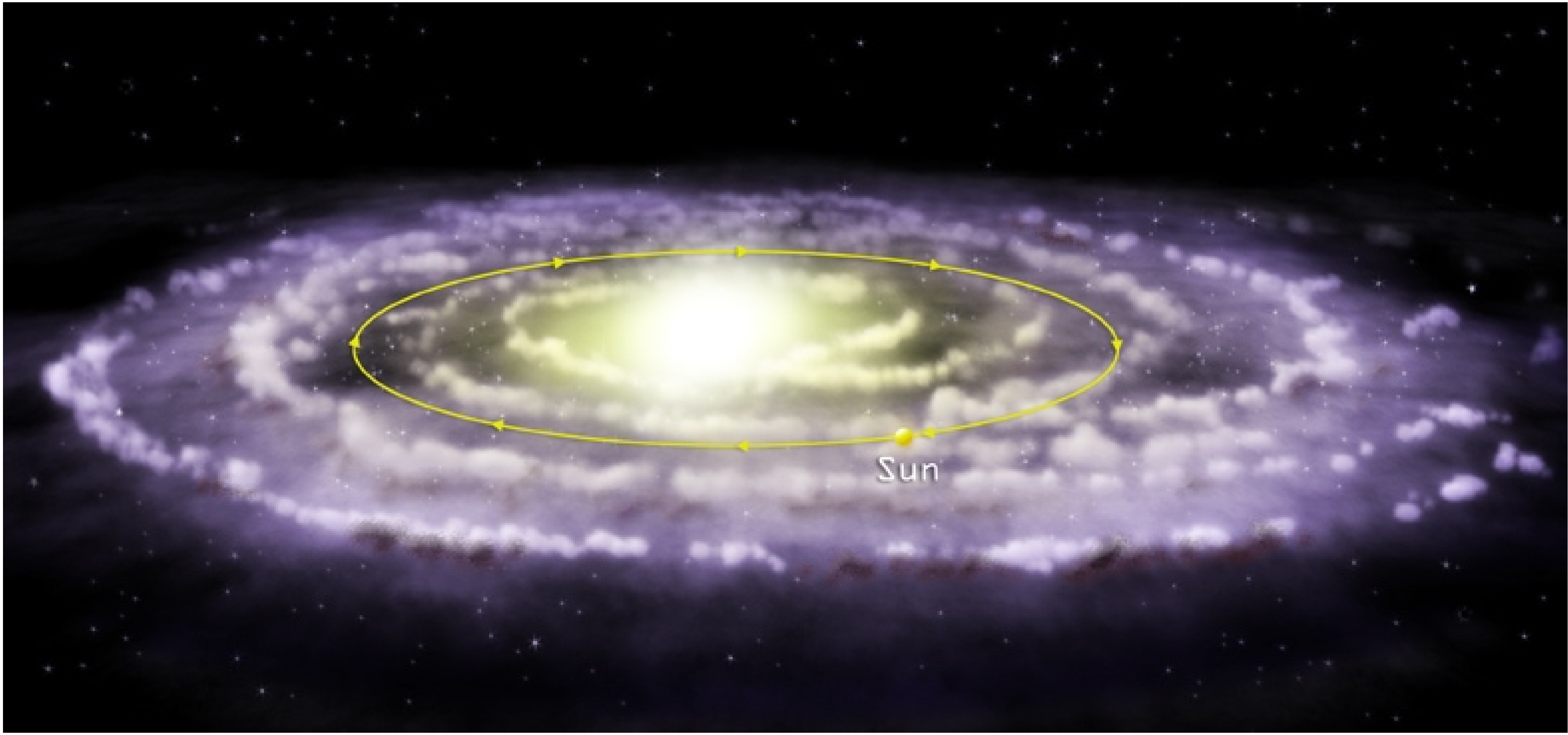
2. Indirect Detection
   [Observation of annihilation products
   In our own Galaxy]

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

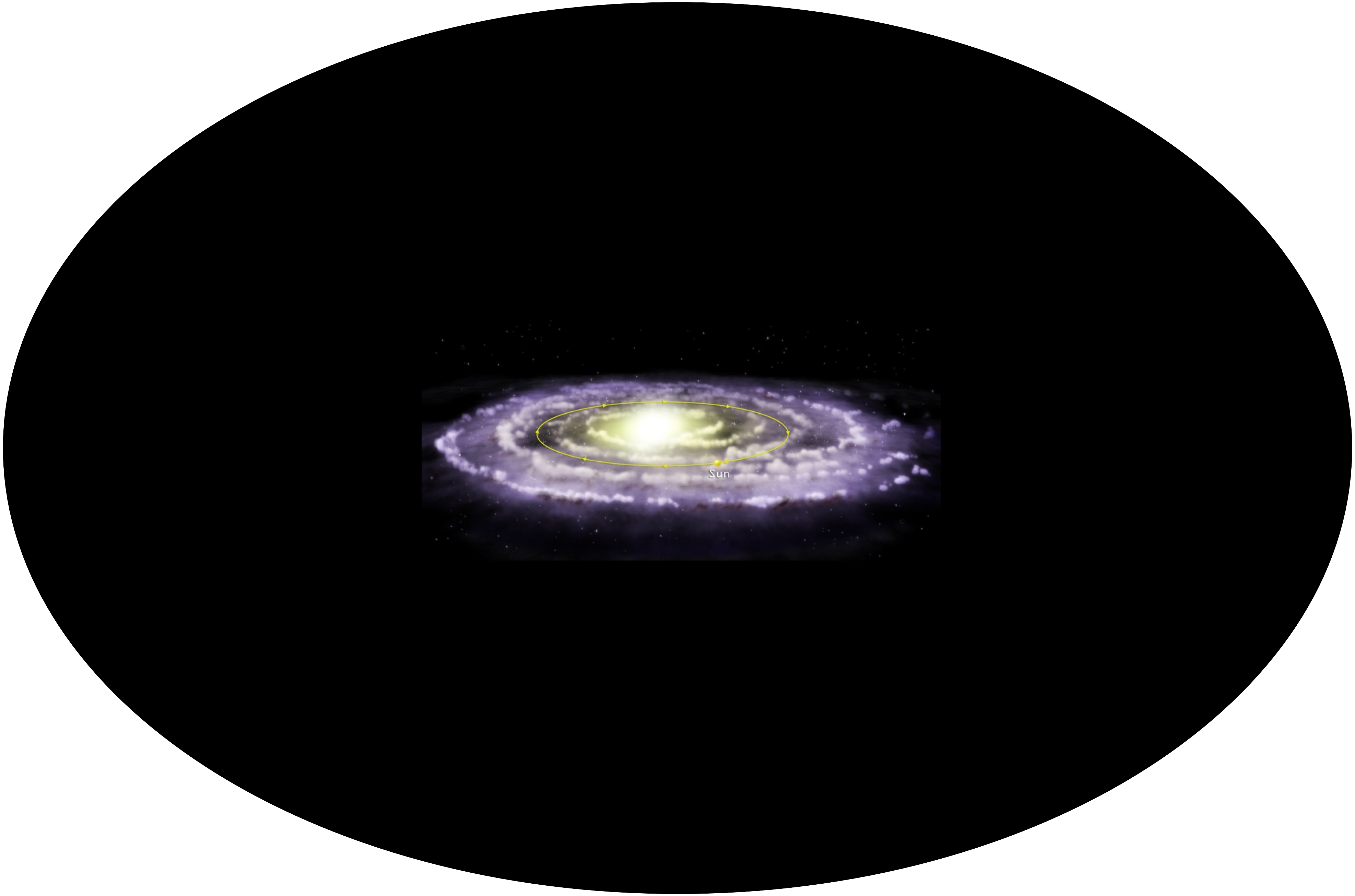


χ
χ
q
q
Efficient annihilation now
(Indirect detection)
Efficient production now
(Particle colliders)
Efficient scattering now
(Direct detection)

Indirect searches for DARK MATTER



Indirect searches for DARK MATTER



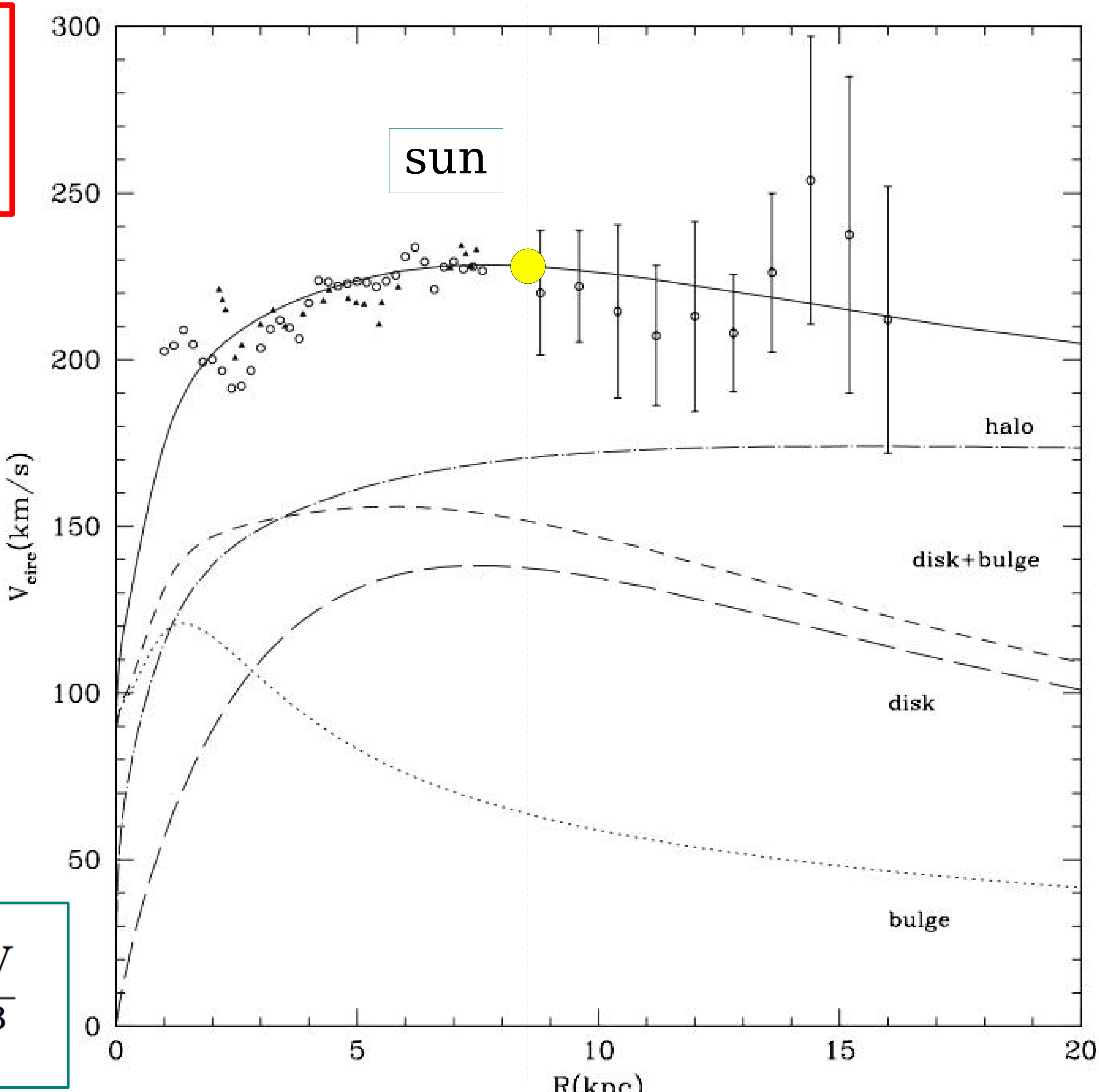
Power injection for Dark Matter annihilation

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

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

Injection of energy because of DM annihilation in
Our own galaxy.

MILKY WAY



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

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

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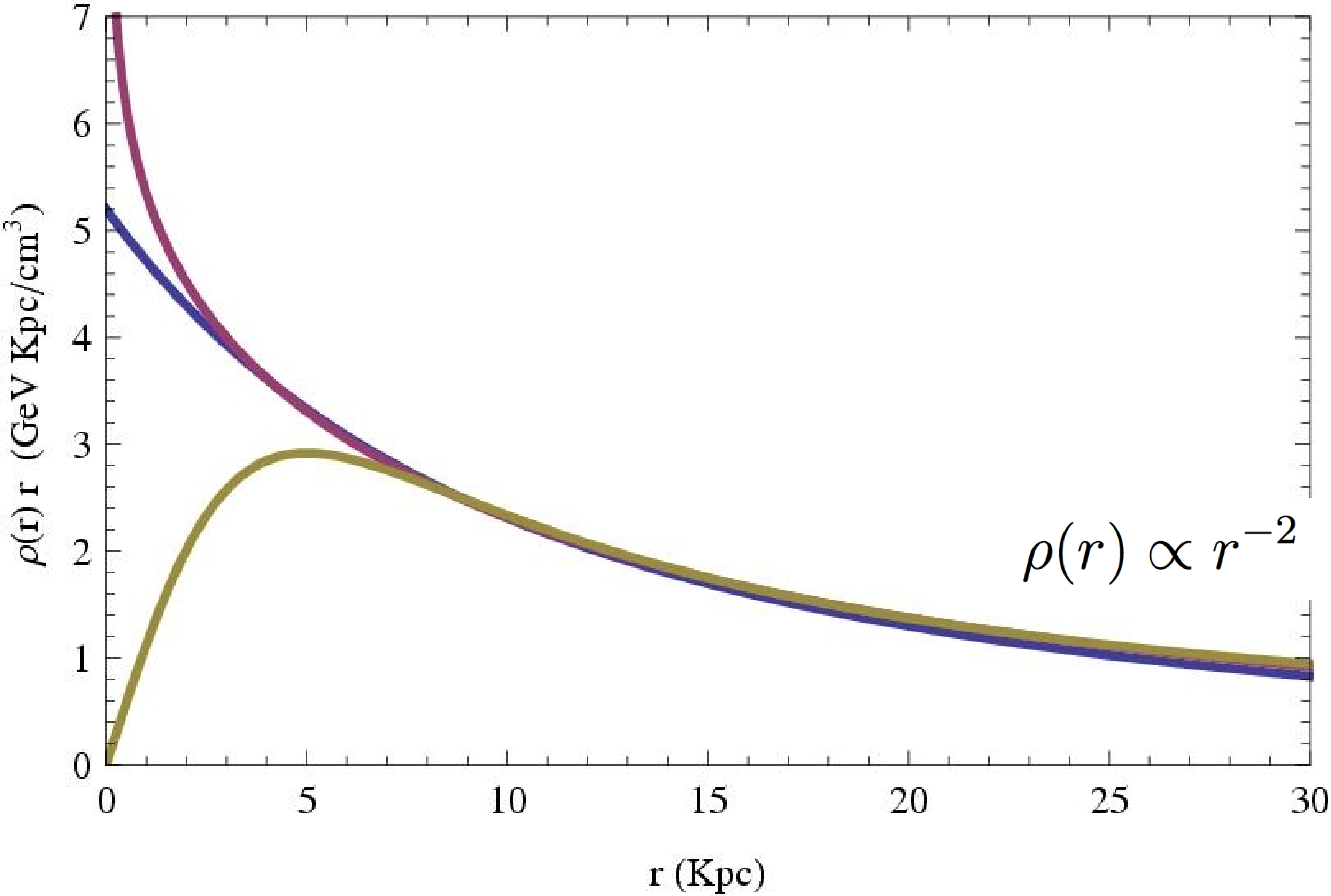
Velocity distribution

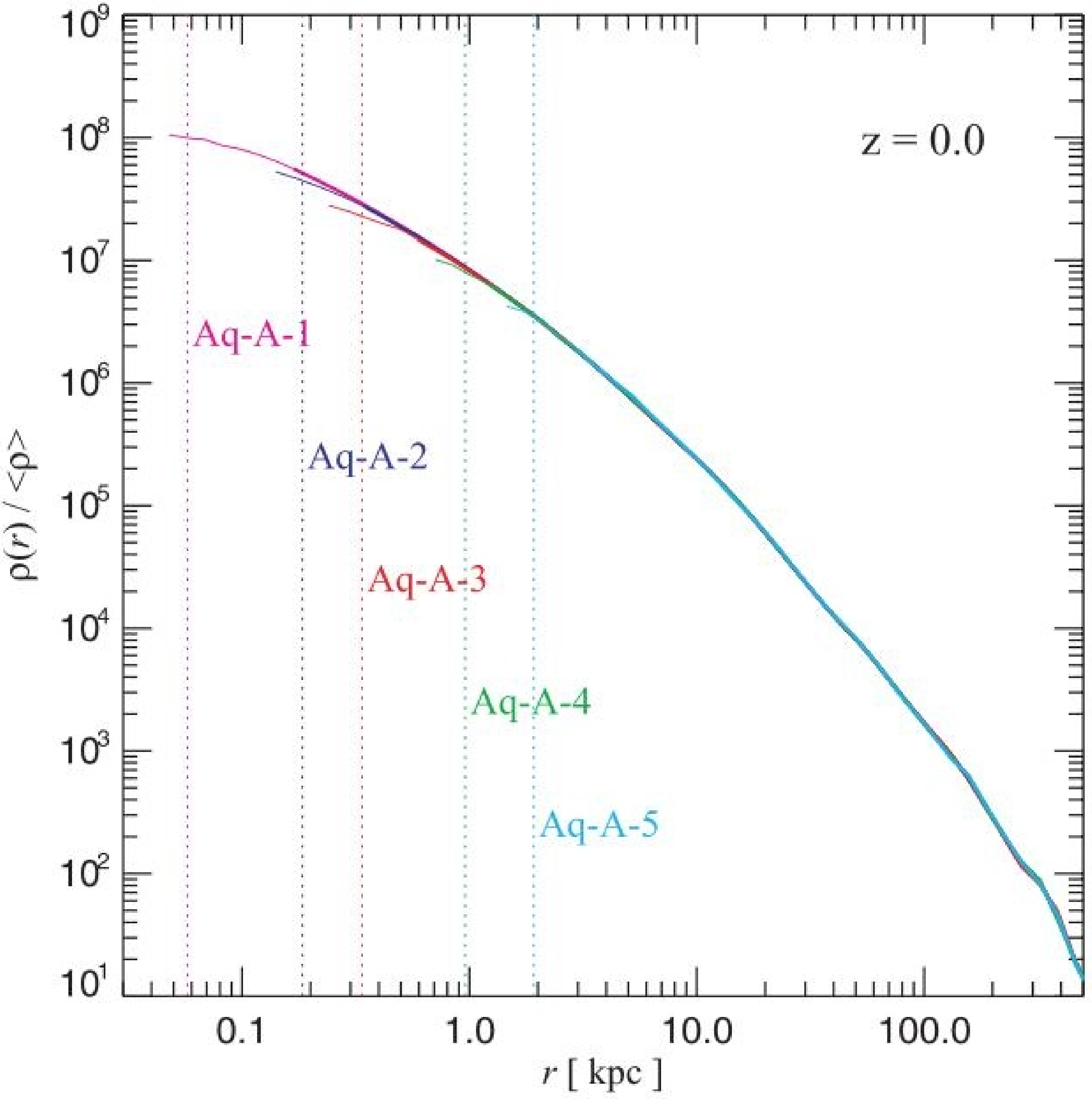
[consistency requirement]

Problems:

- "The CUSP"
- "Granularity" ["the BOOST factor"]

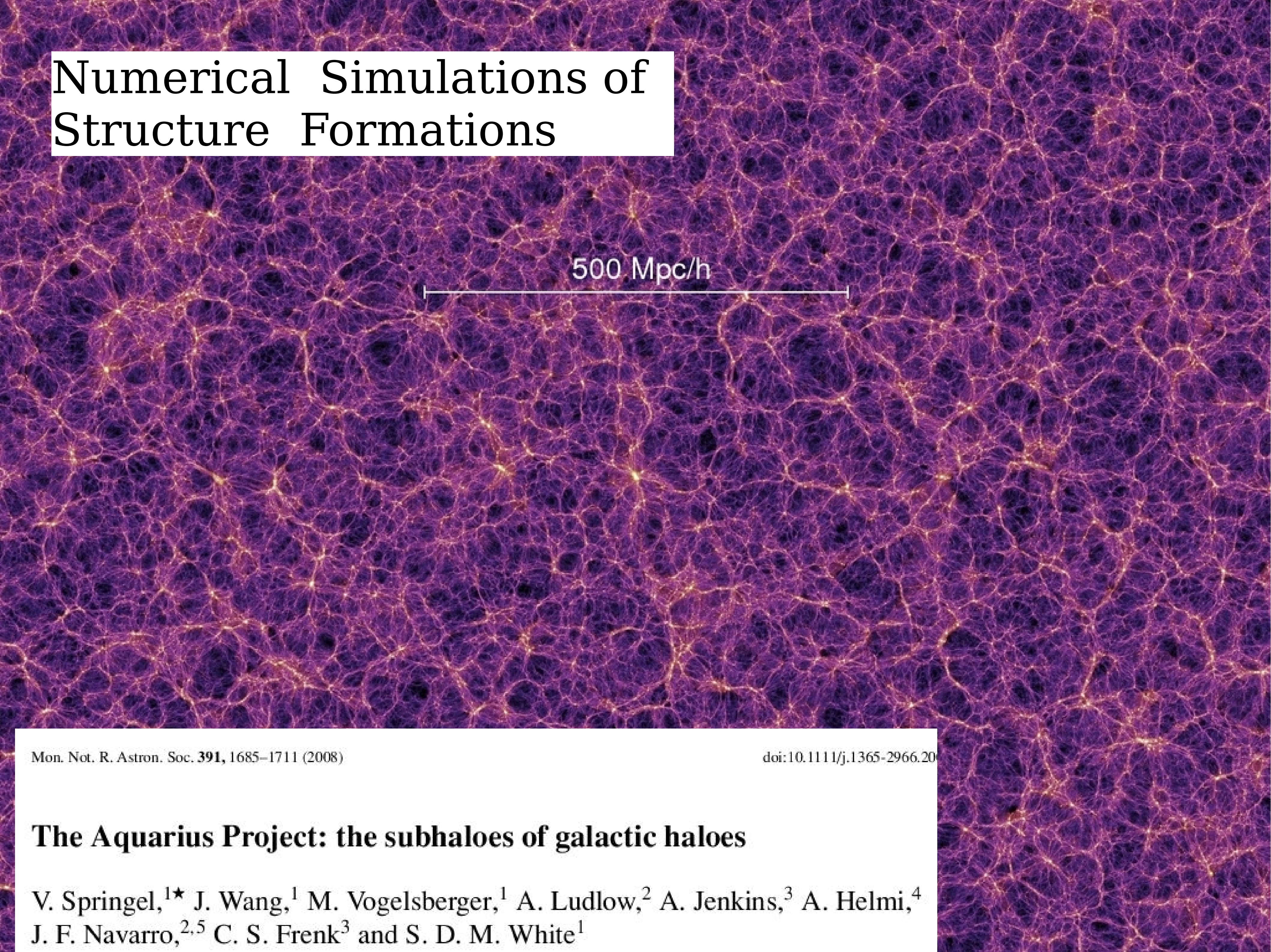
Isothermal (constant)
"NFW" (Navarro-Frenk-White) (1/r divergence)
"Moore" (stronger divergence)





Shape of the
“CUSP”

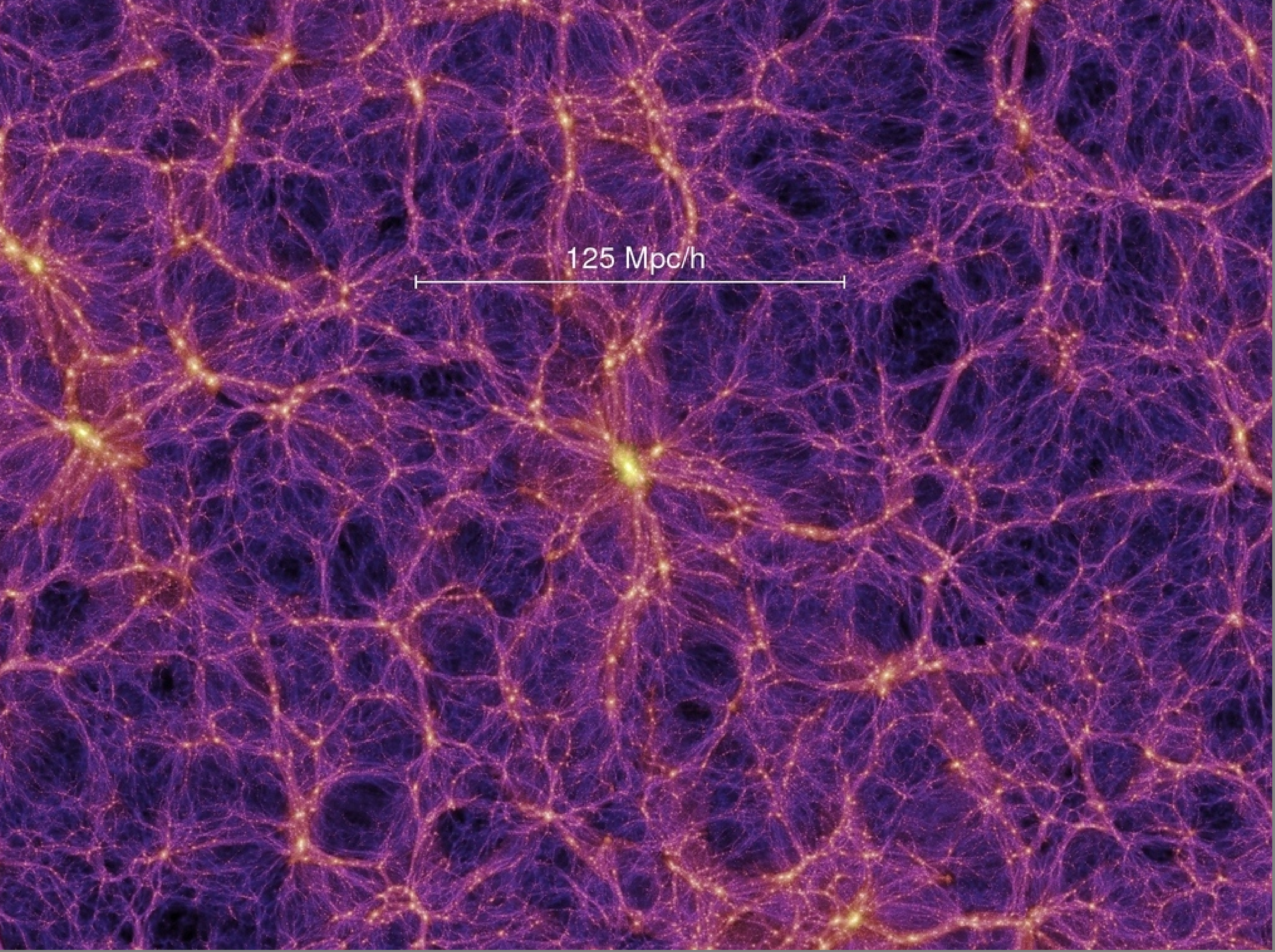
Numerical Simulations of Structure Formations

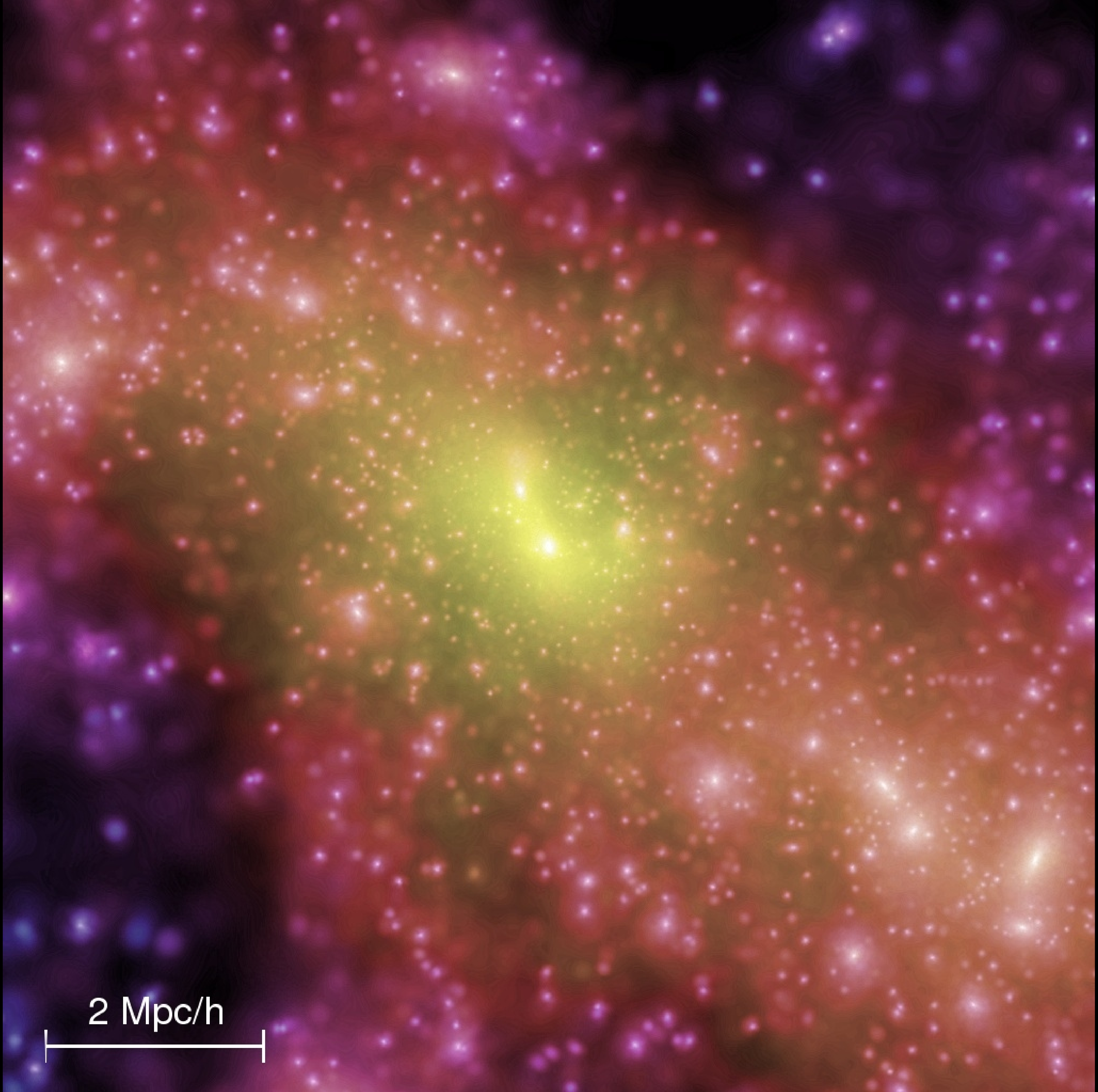


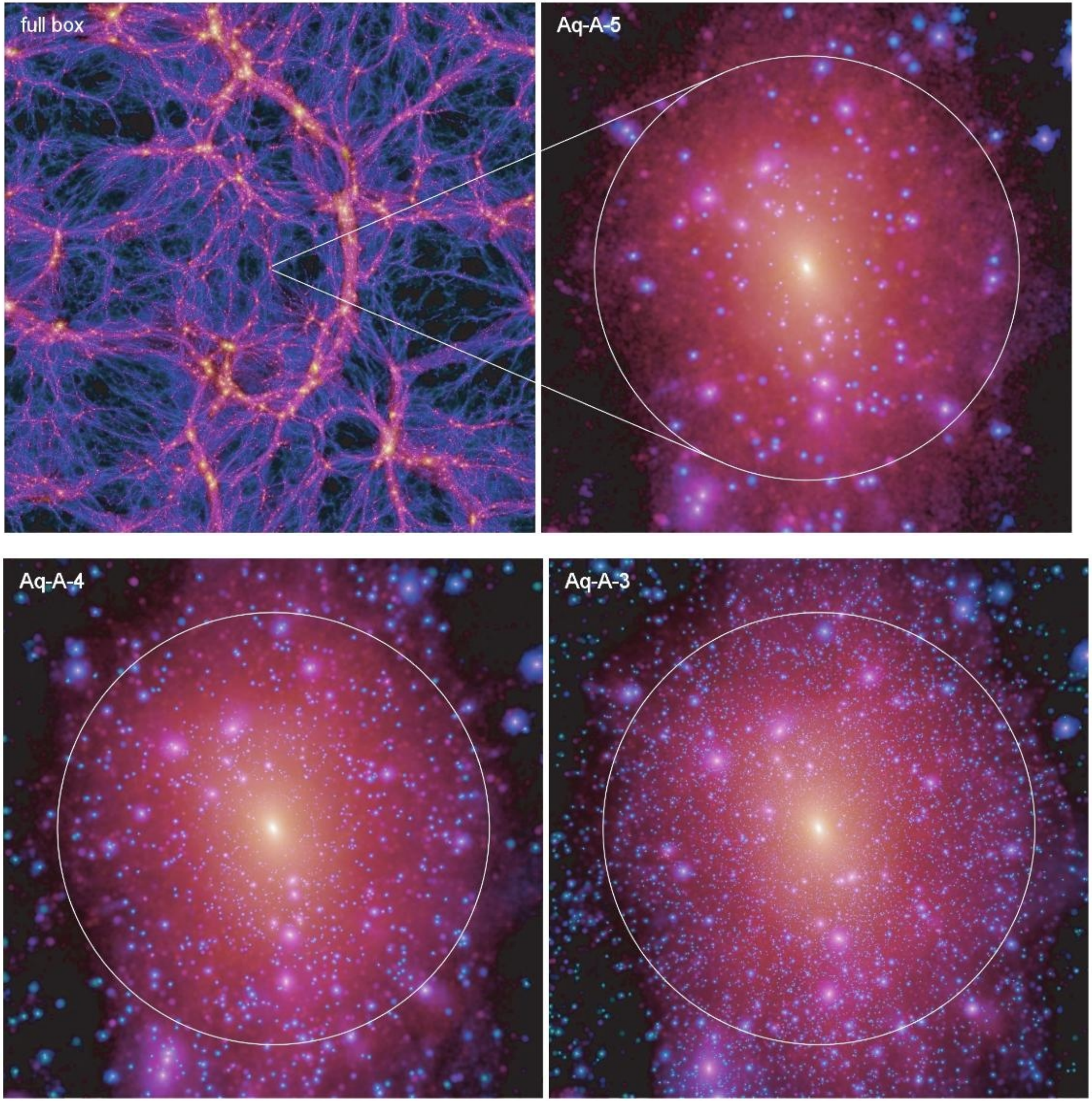
Mon. Not. R. Astron. Soc. **391,** 1685–1711 (2008) doi:10.1111/j.1365-2966.20

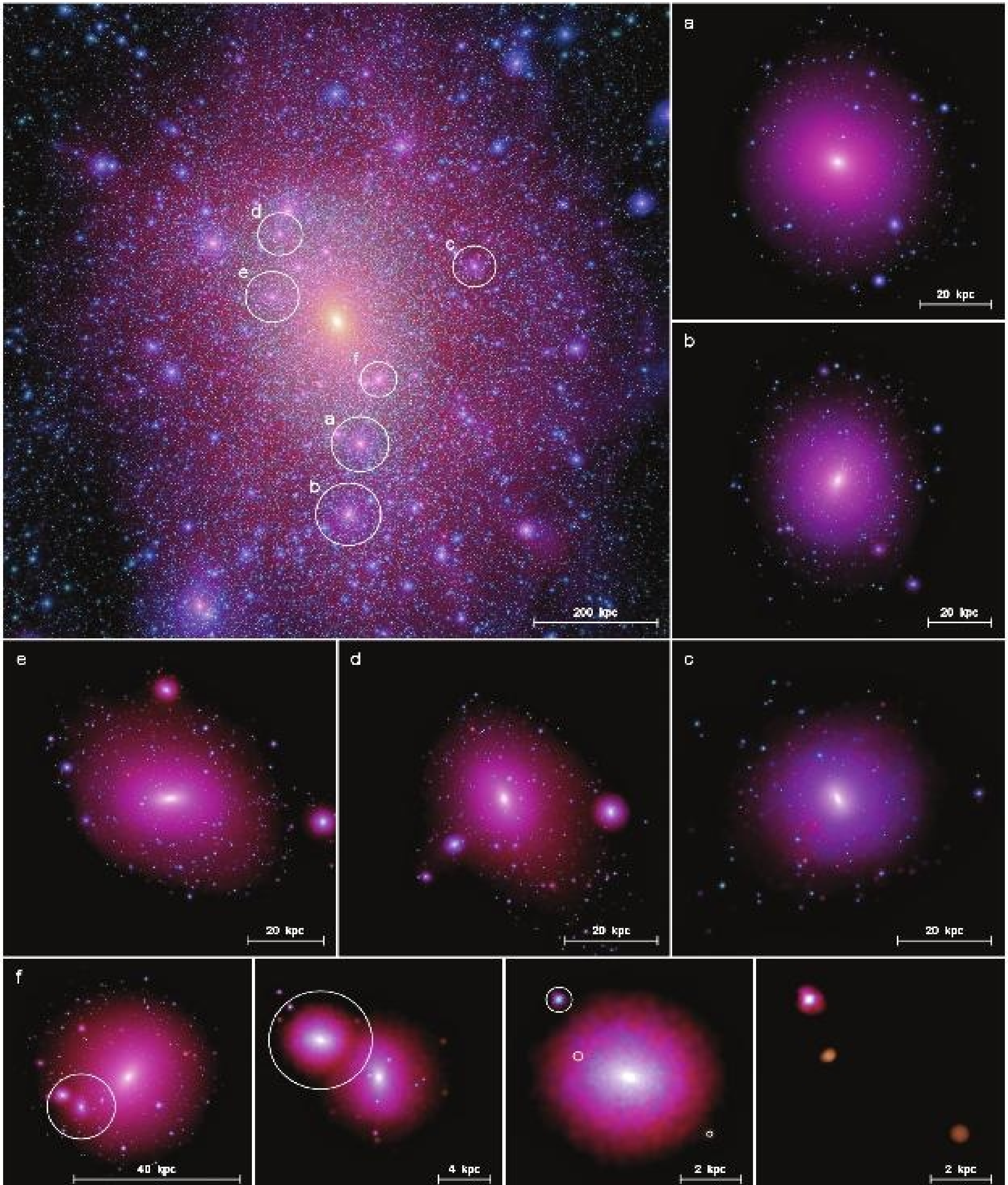
The Aquarius Project: the subhaloes of galactic haloes

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”

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

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

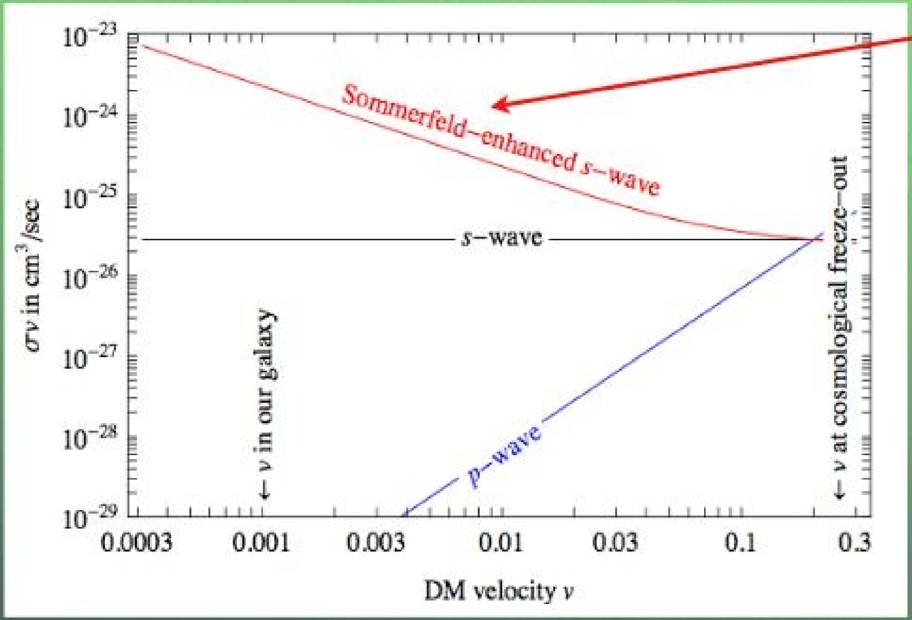
- $$\langle \rho(\vec{x})^2 \rangle \geq \langle \rho(\vec{x}) \rangle^2$$ "Granularity" boosts the power output.

- 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

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

Branching Ratios in different final states F

In most models DM particle = Majorana particle

DM – Nuclei Elastic Scattering

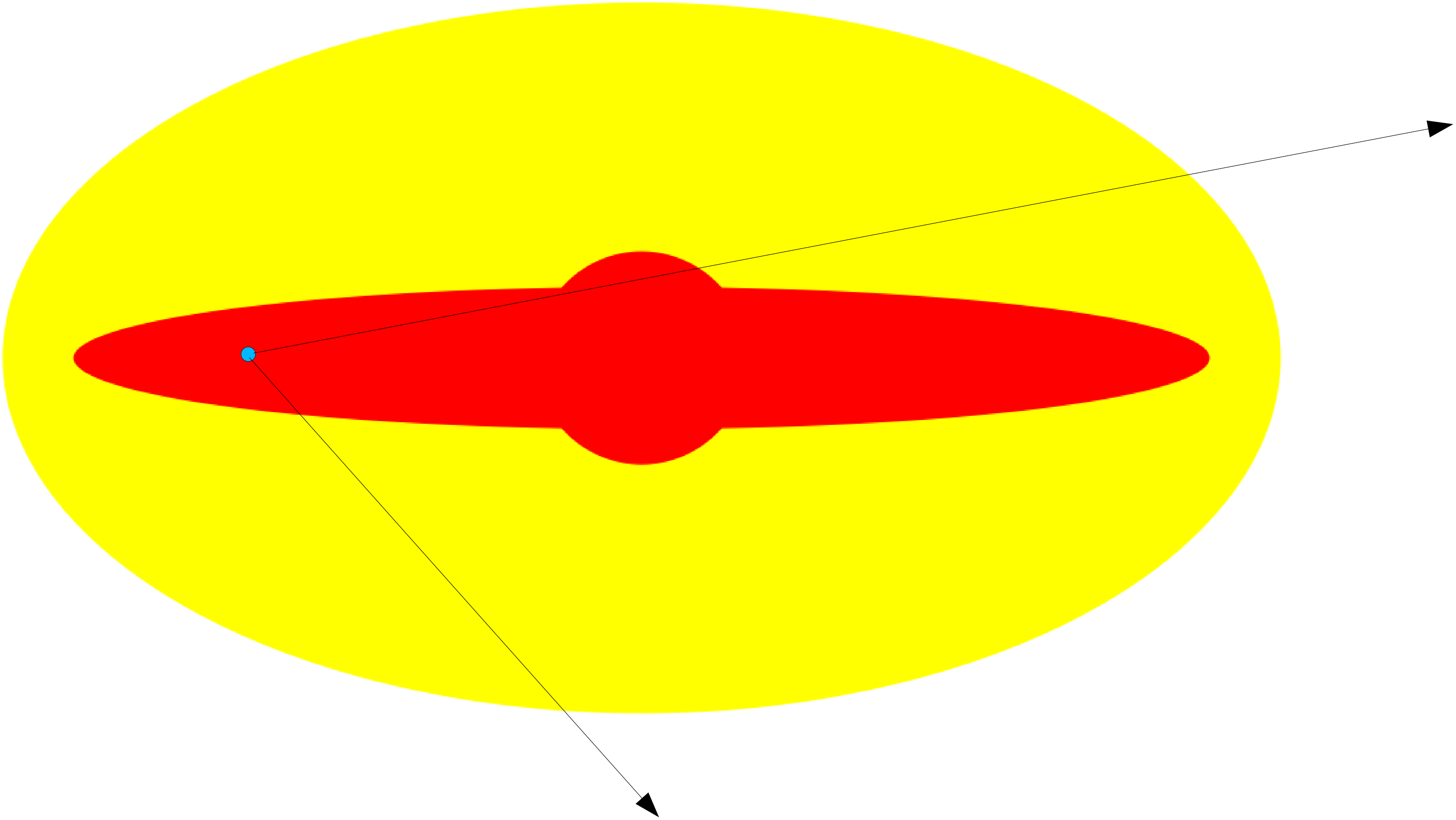
$$\sigma(\chi + A \to \chi + A)$$

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

Direct detection
Accretion in Sun, Stars....

[effect on Star formation
near the galactic center]

Photon emission from DM annihilation



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

Photons from Dark Matter

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

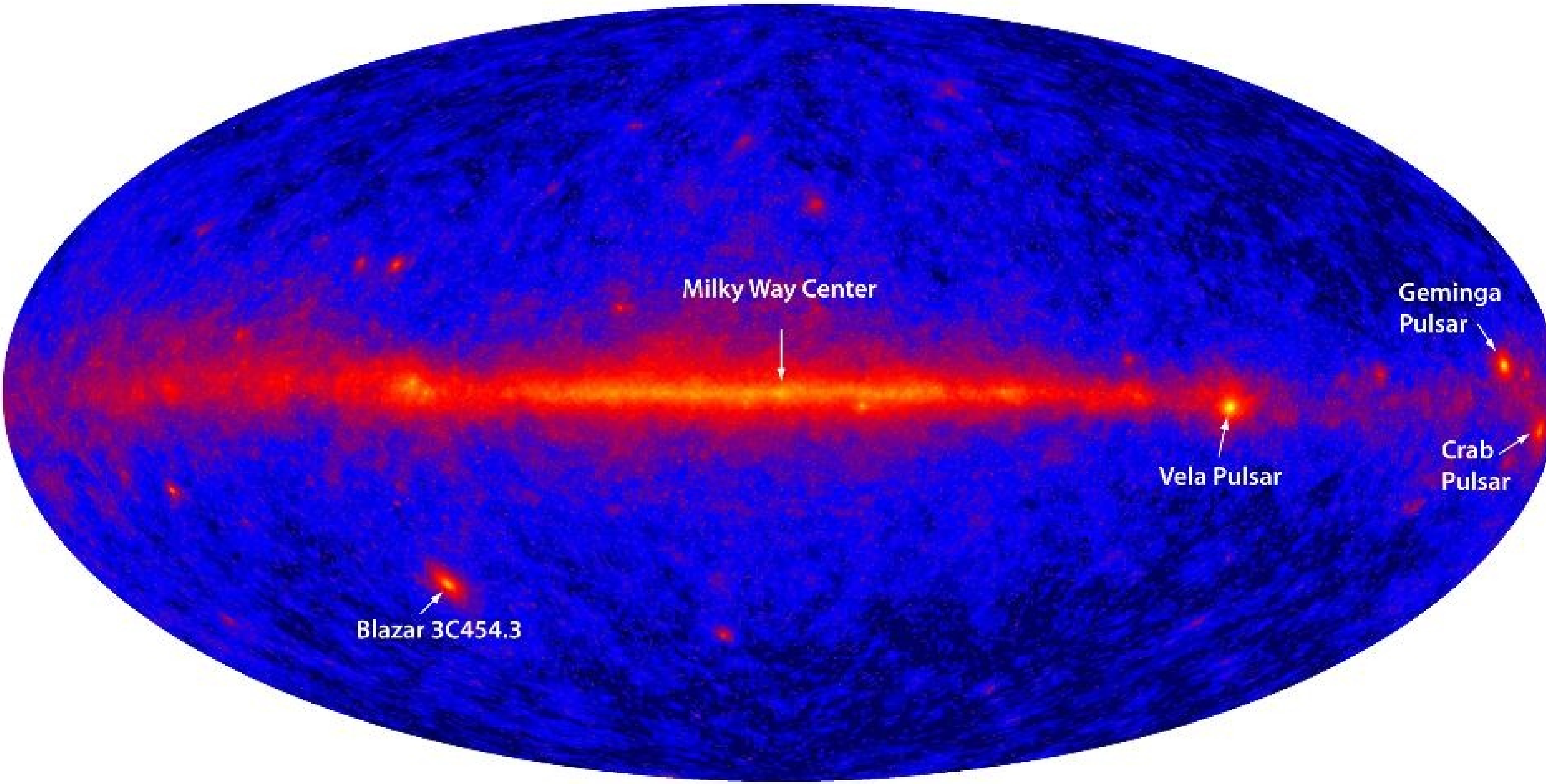
→ Spectrum

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

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

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

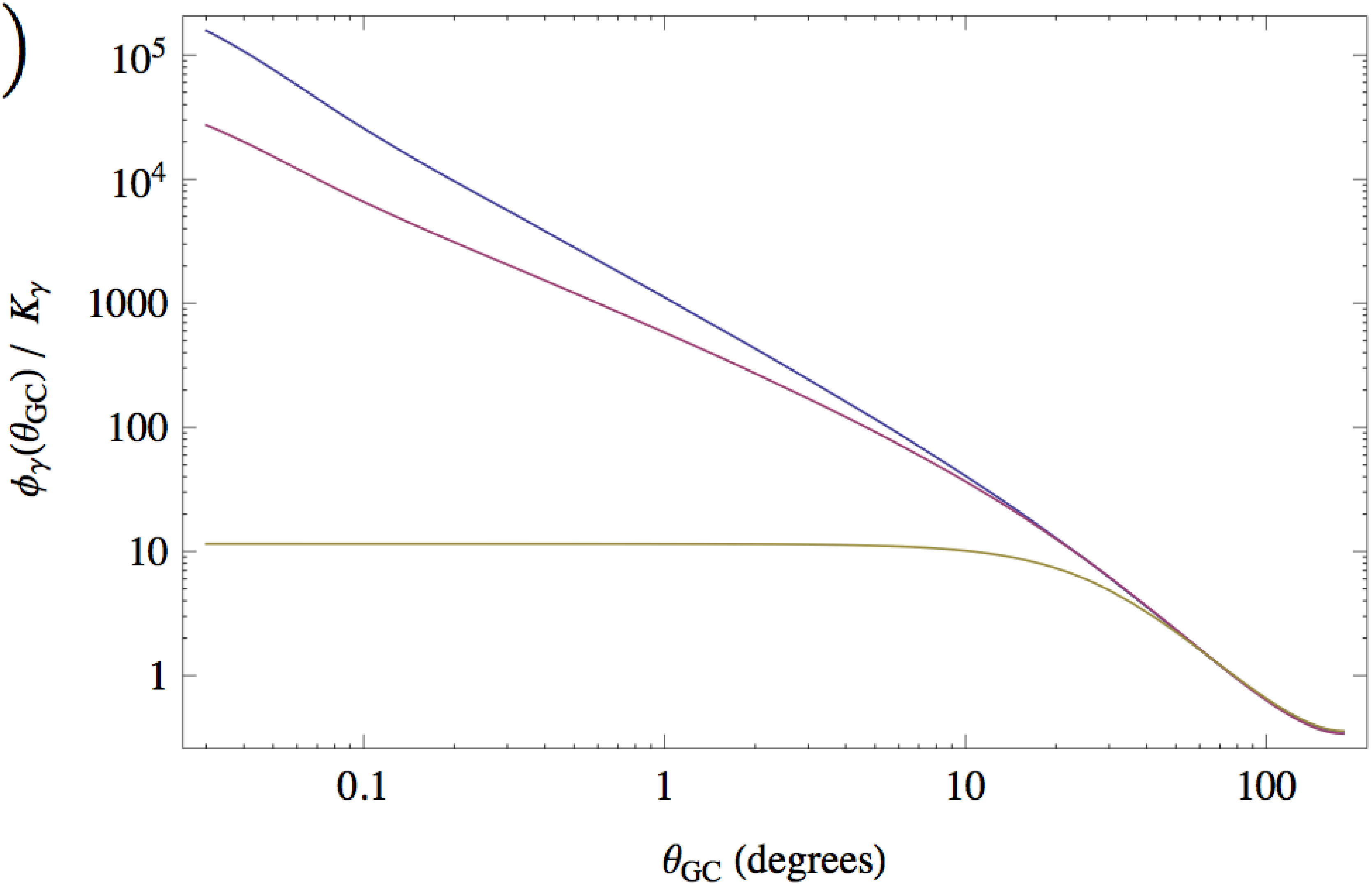
Adimensional
Angular factor



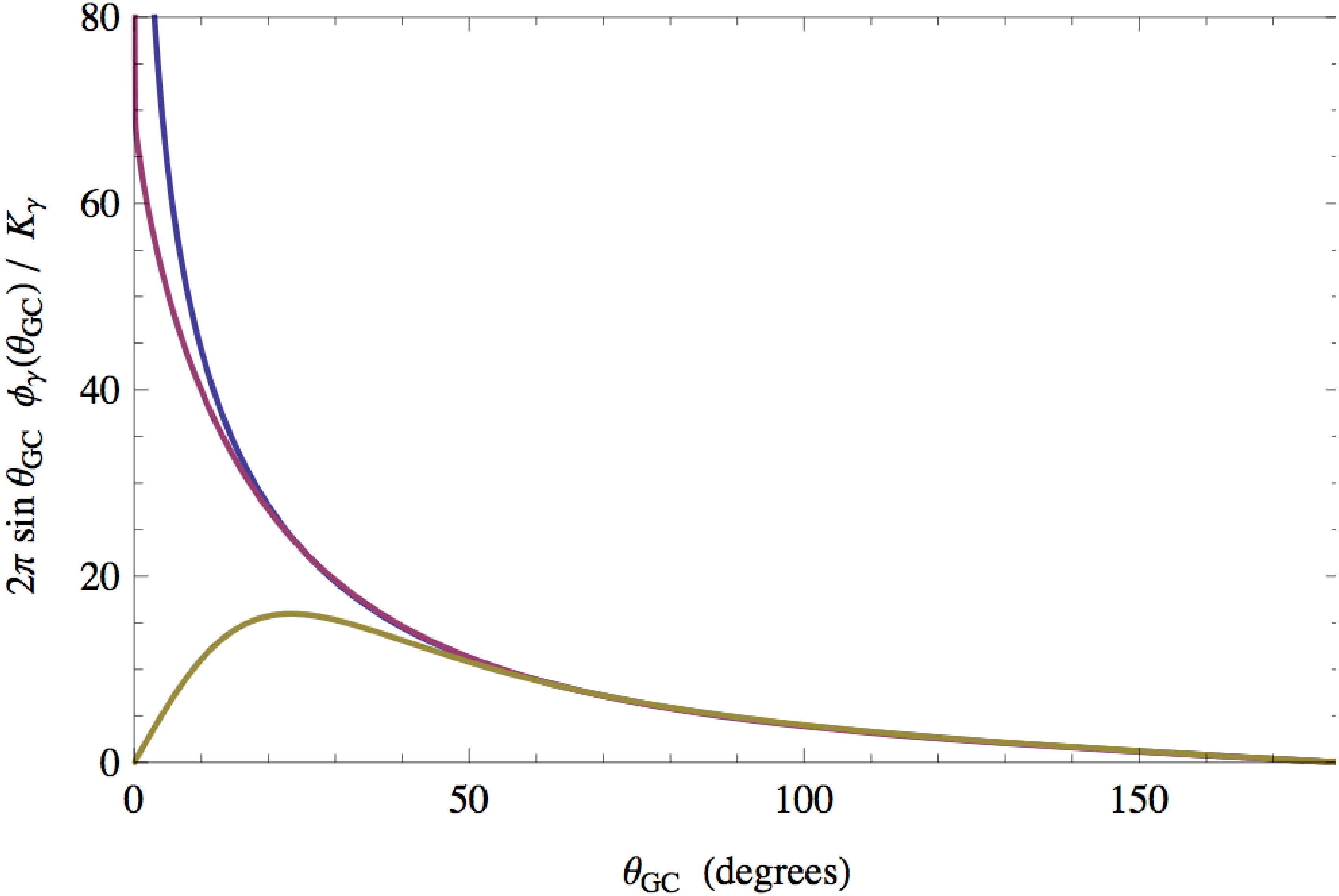
$E_\gamma > 100$ MeV

Angular dependence of the Photon flux

$J(\Omega)$



Photon rate



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

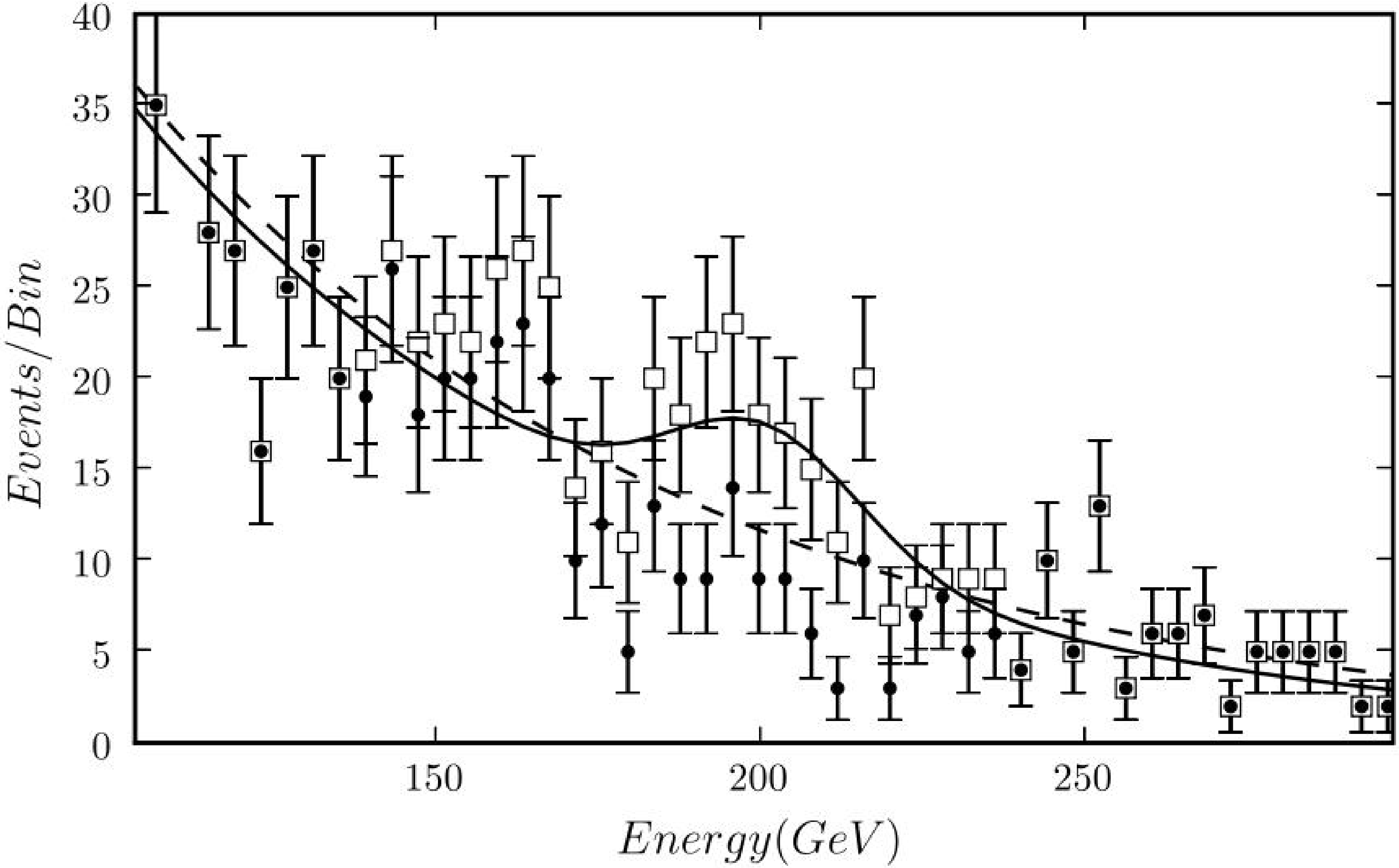
Spectral features.

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

Fermi sensitivity: A = 9500 cm2

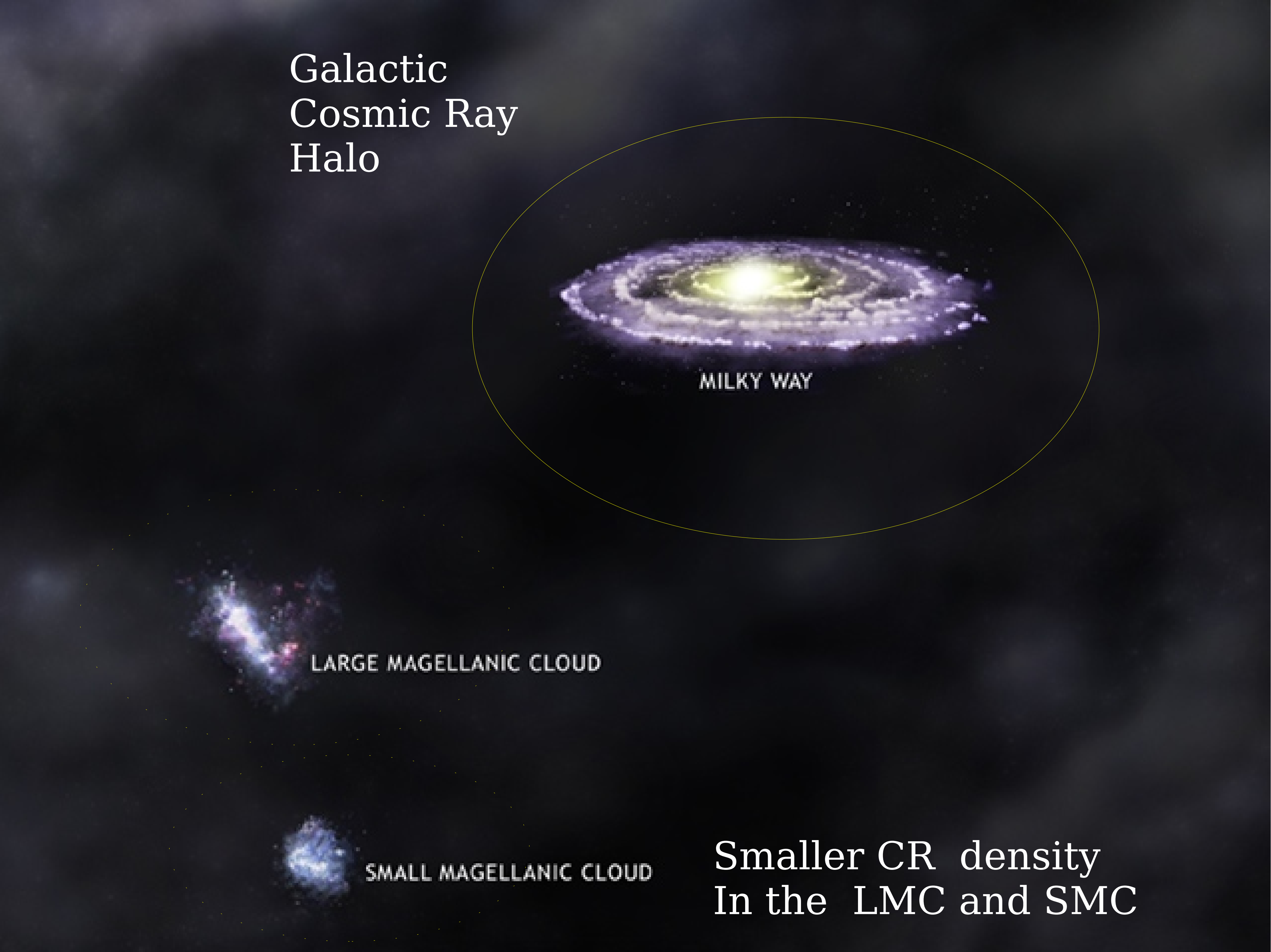
$$AT \simeq 0.45 \times 10^{11}\ \mathrm{cm}^2\ \mathrm{s}\ N_{\mathrm{years}}$$

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



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

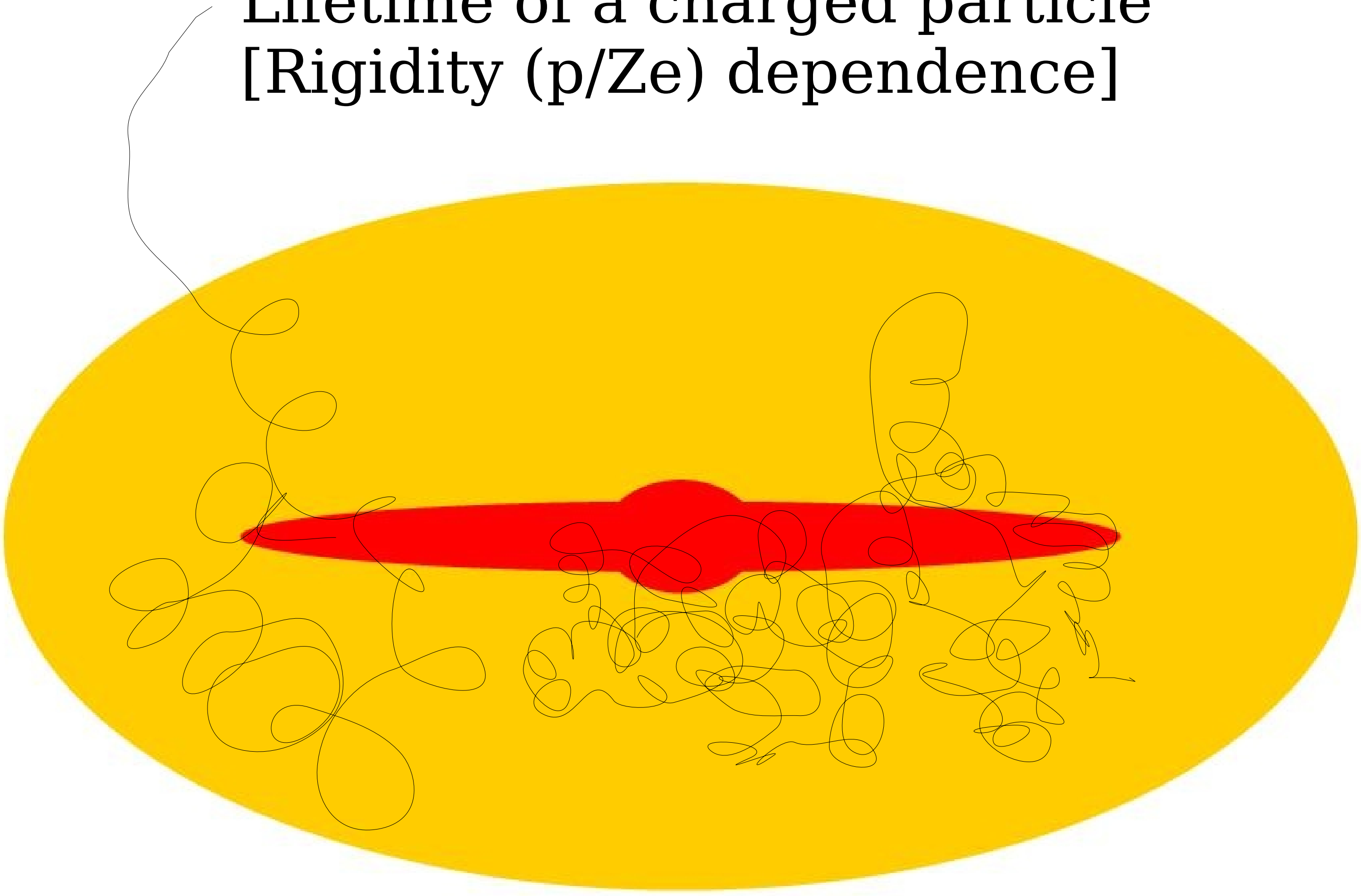
Propagation of Charged Particles in the Milky Way


Galactic
Cosmic Ray
Halo
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
Smaller CR density
In the LMC and SMC

Charged Particles: magnetic confinement

Escape

Lifetime of a charged particle
[Rigidity (p/Ze) dependence]



Charged Particles: magnetic confinement

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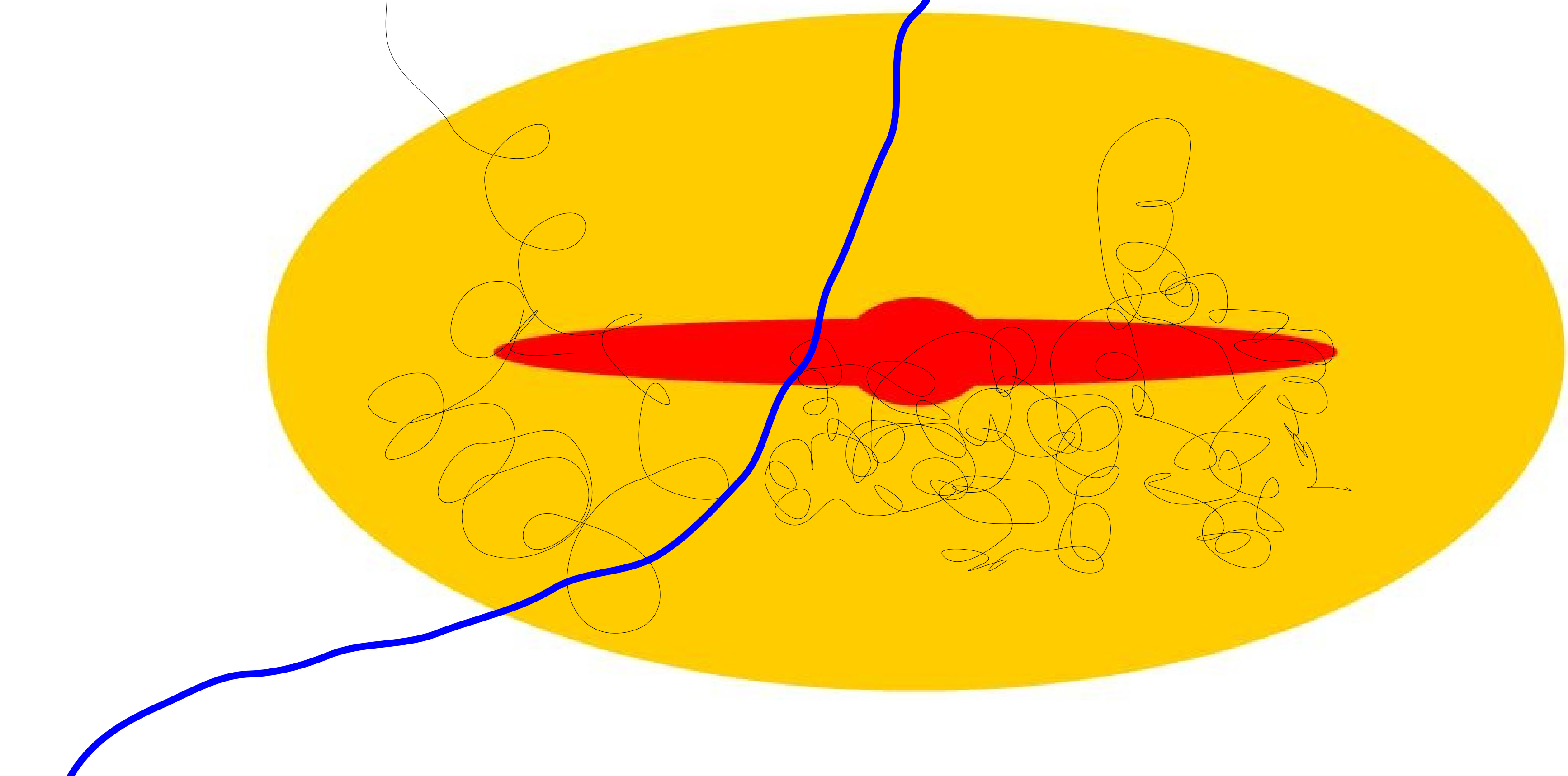
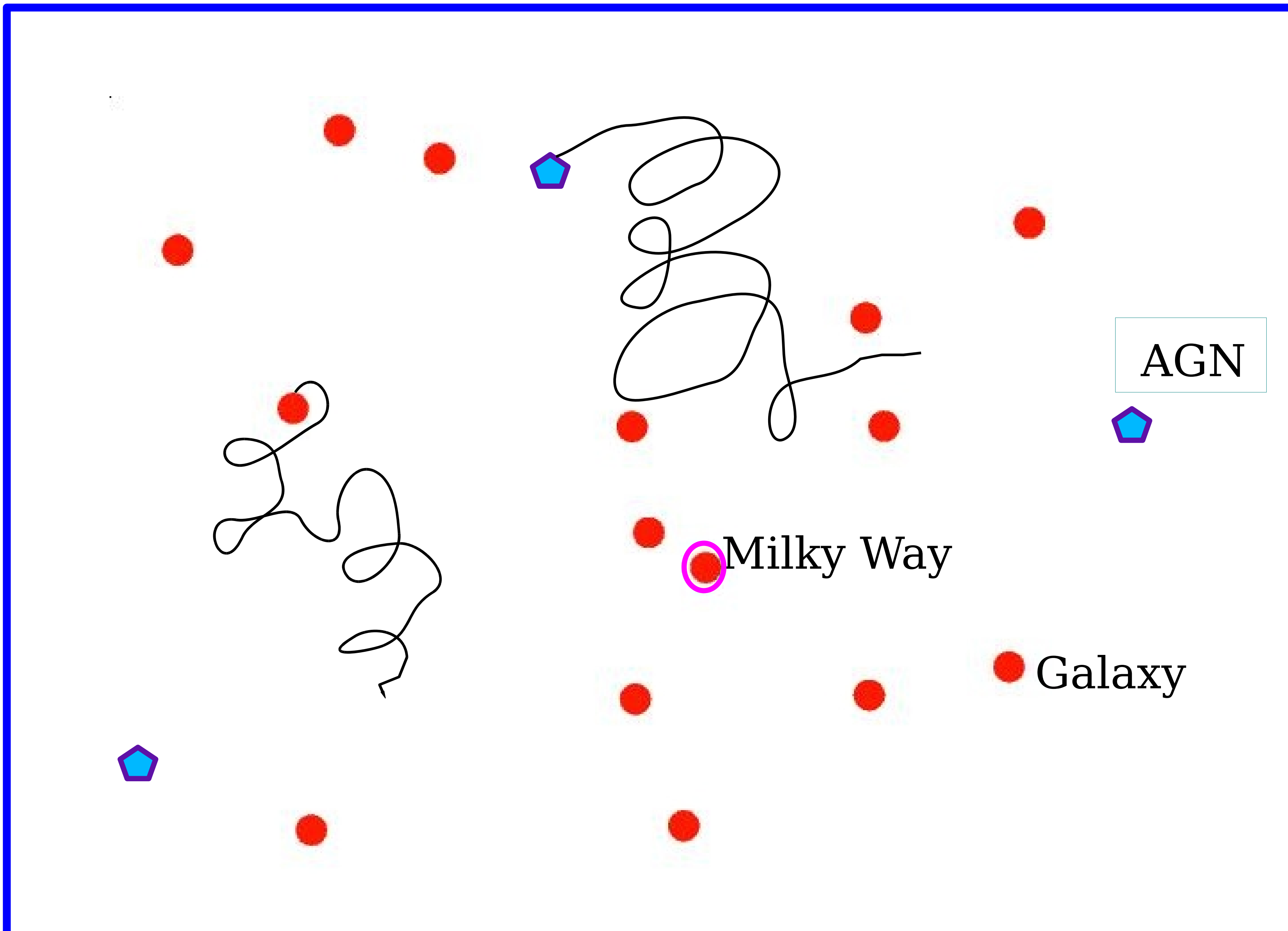
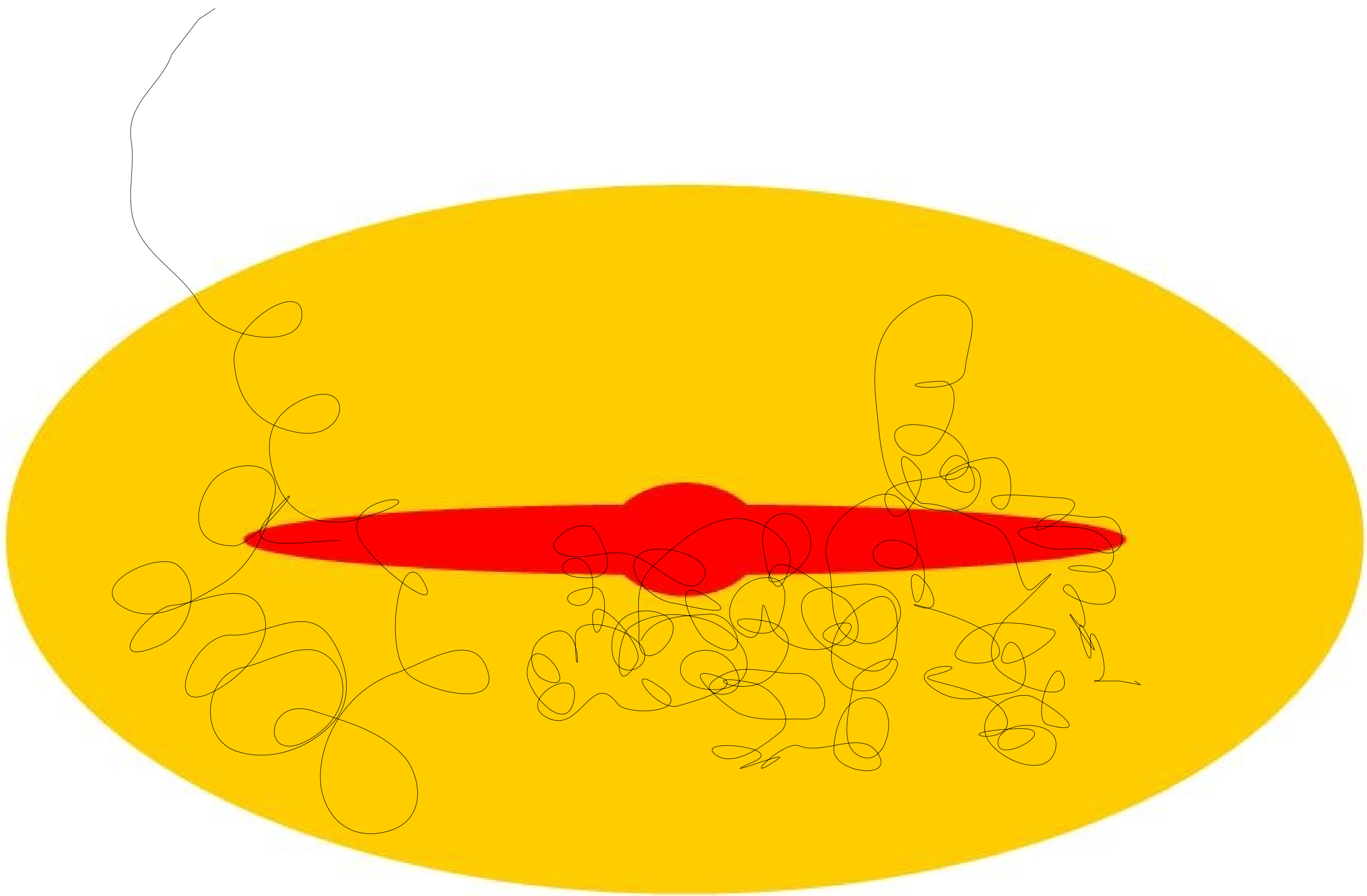


(high energy) Extra-galactic CR crossing the Galaxy.

Piece of extragalactic space: Non MilkyWay-like sources

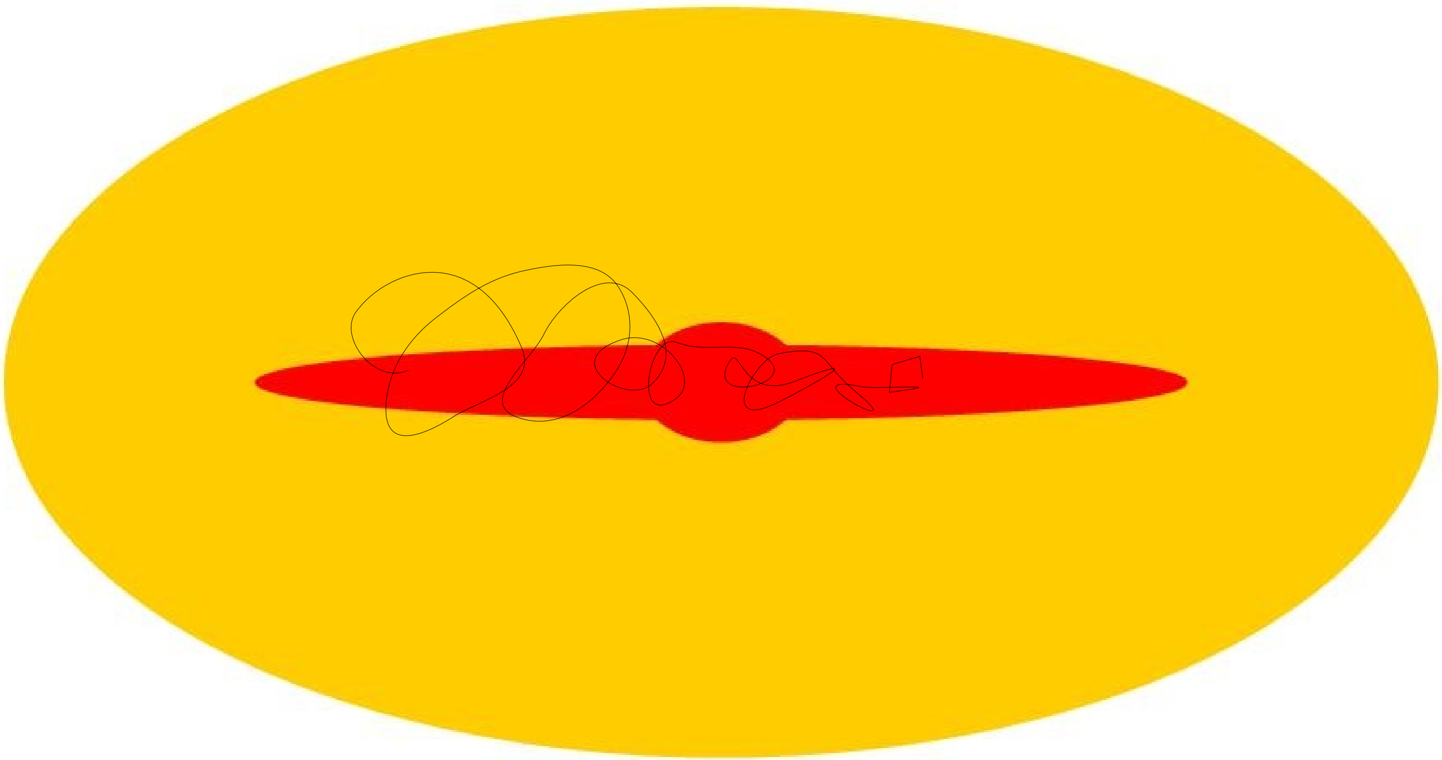


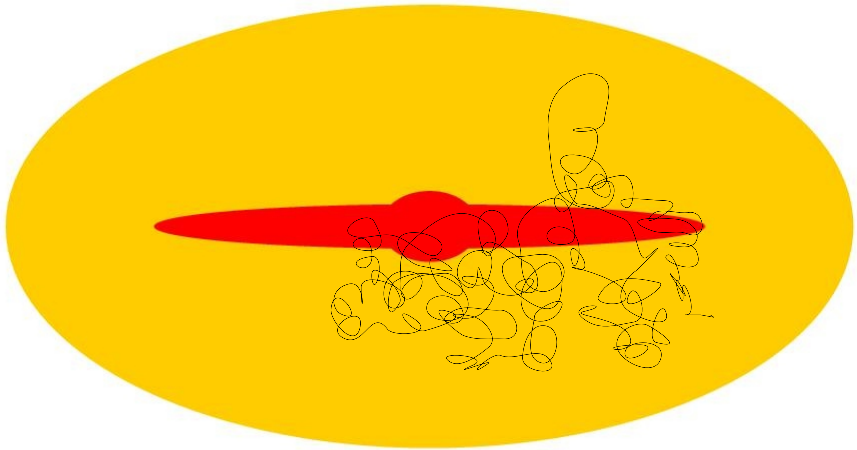
Do relativistic particles really escape from the galaxy ?



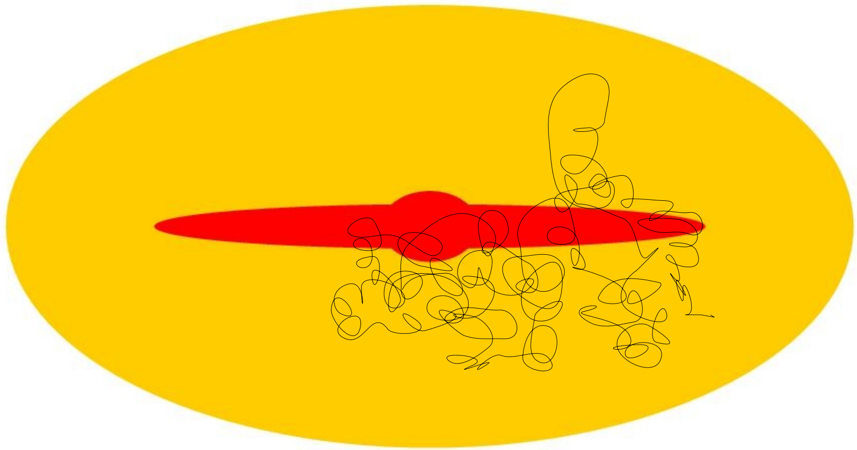
Do relativistic particles really escape from the galaxy ?

Electrons (and positrons) lose most of
Their energy before escape.
Their time of residence is determined by energy loss.



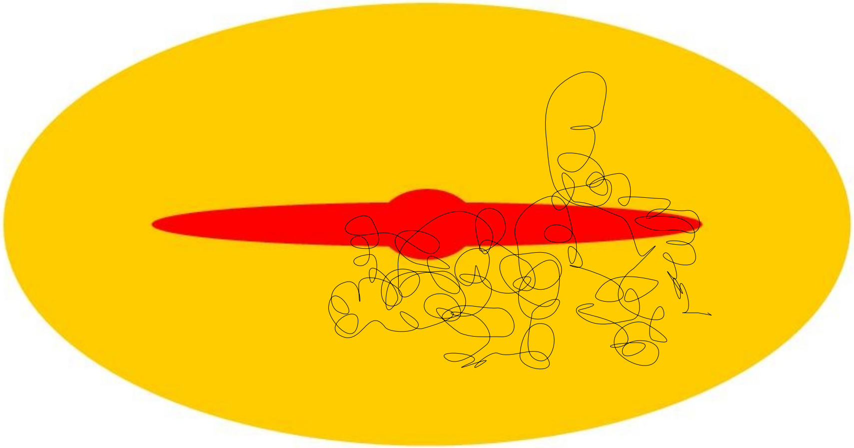


SOURCE(s) + Propagation → Observable Cosmic Rays



SOURCE(s) + Propagation $\rightarrow$ Observable Cosmic Rays

$$\chi + \chi \rightarrow e^{+} + \ldots$$



SOURCE(s) + Propagation → Observable Cosmic Rays

$$\chi + \chi \to e^{+} + \ldots$$

$$p + p_{\mathrm{ISM}} \to e^{+} \ldots$$

$$p + p_{\mathrm{ISM}} \to \pi^{+} \ldots$$

$$\pi^{+} \to \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \to e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

Possible
positron accelerators

One general [formal] way to solve the problem of the calculation cosmic ray fluxes:

For each particle type: p, e-, e+, He, Li, Be, B, ... , Fe, ...

Compute the integral:

$$n(E, \vec{r}_{\rm obs}) = \int_0^\infty dt \int d^3 r_0 \int dE_0 \; q(E_0, \vec{r}_0, t) \; f(E, \vec{r}_{\rm obs}; \; E_0, \vec{r}_0, t)$$

$$\phi = \frac{c\,\beta}{4\,\pi}\, n$$

Source of CR particles
with energy E_0
at time t_0 (in the past)
at position r_0

$$n(E, \vec{r}_{\rm obs}) = \int_0^\infty dt \int d^3 r_0 \int dE_0 \, q(E_0, \vec{r}_0, t) \, f(E, \vec{r}_{\rm obs};\ E_0, \vec{r}_0, t)$$

(Measurable) Density of
CR particles
With energy E,
at the present time
"here" (r_{obs})

"Propagation
Probability"

"Secondary Particles:"

$$p + p_{\mathrm{ISM}} \longrightarrow \overline{p} + \ldots$$

$$p + p_{\mathrm{ISM}} \longrightarrow e^+ \ldots$$

Continuous
(time, space)
Injection
In the volume
Of the Galaxy

$$p + p_{\mathrm{ISM}} \rightarrow \pi^+ \ldots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$q_{e^+}(E, \vec{r}) \simeq c\, \sigma_{pp}\; n_{\mathrm{ISM}}(\vec{r})\; n_p(E, \vec{r})\; Z_{pp \rightarrow e^+}$$

$$q_{e^+}(E, \vec{r}) \simeq c\, \sigma_{pp}\; n_{\rm ISM}(\vec{r})\; n_p(E, \vec{r})\; Z_{pp\to e^+}$$

Source spectrum of secondary
has a shape determined by the primary spectrum.
(and known physics).

$$q_{e^+}(E, \vec{r}) = \int dE_0\; n_p(E_0, \vec{r})\; c\, \sigma_{pp}(E_0)\; n_{\rm ISM}(\vec{r}) \times \frac{dN_{pp\to e^+}}{dE}(E; E_0)$$

$$\frac{dN_{pp\to e^+}}{dE}(E; E_0) \simeq \frac{1}{E_0}\; F\left(\frac{E}{E_0}\right)$$

Source of Relativistic particles
From Dark Matter annihilation:

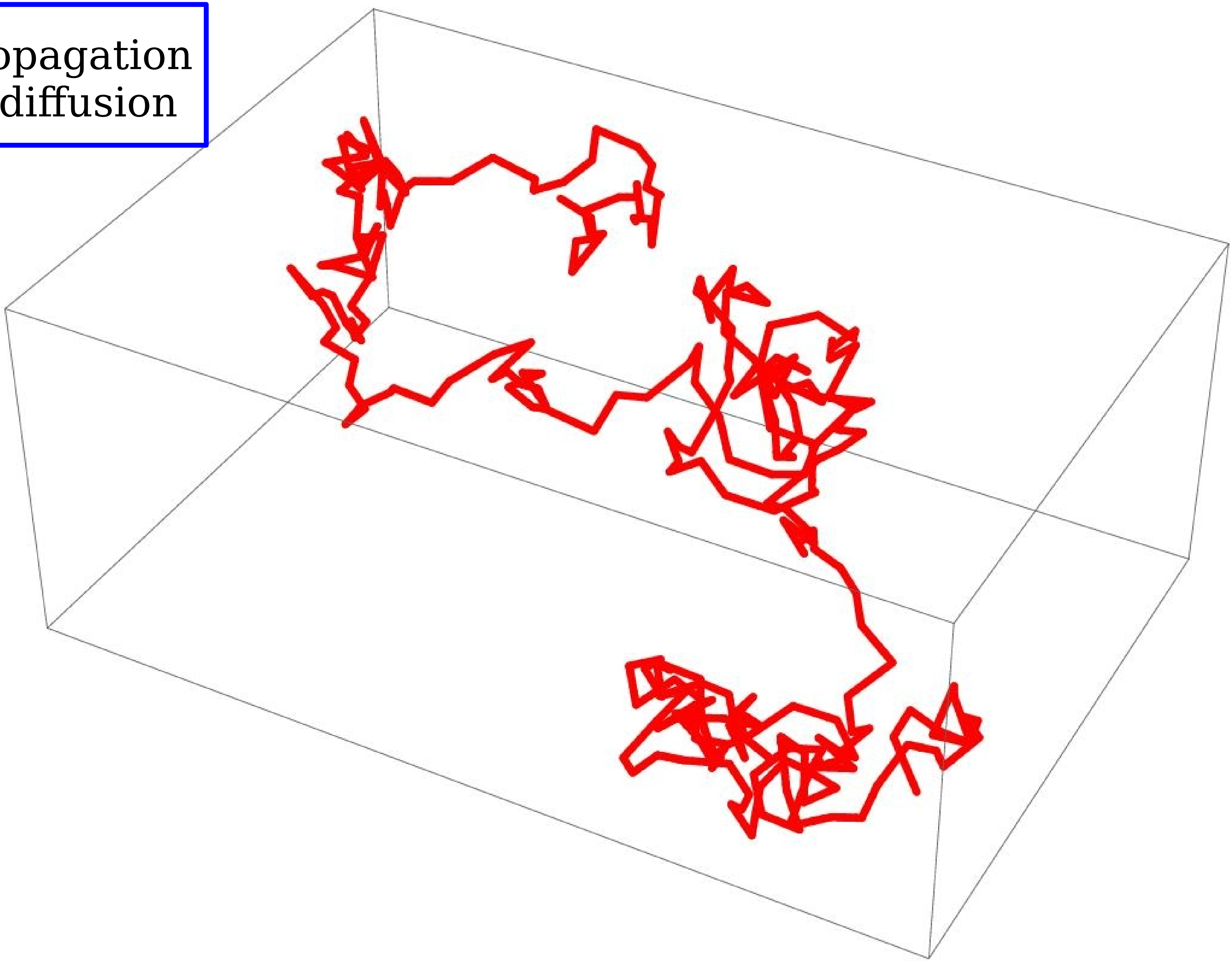
$$q_{e^+}(E,\vec{r}) = \left(\frac{\rho_\chi(\vec{r})}{m_\chi}\right)^2 \langle\sigma_{\chi\chi}\, v(\vec{r})\rangle \frac{dN_{\chi\chi\rightarrow e^+}}{dE}(E)$$

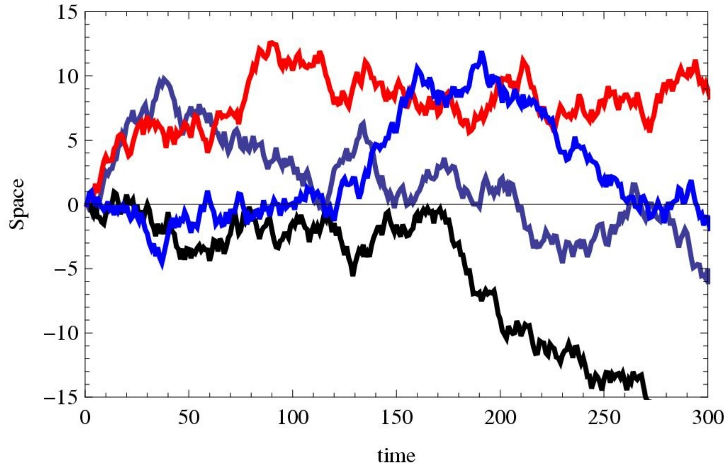
DM density

Annihilation
Cross section

“Branching
Ratios” in
Different
Annihilation
channels

Propagation as diffusion

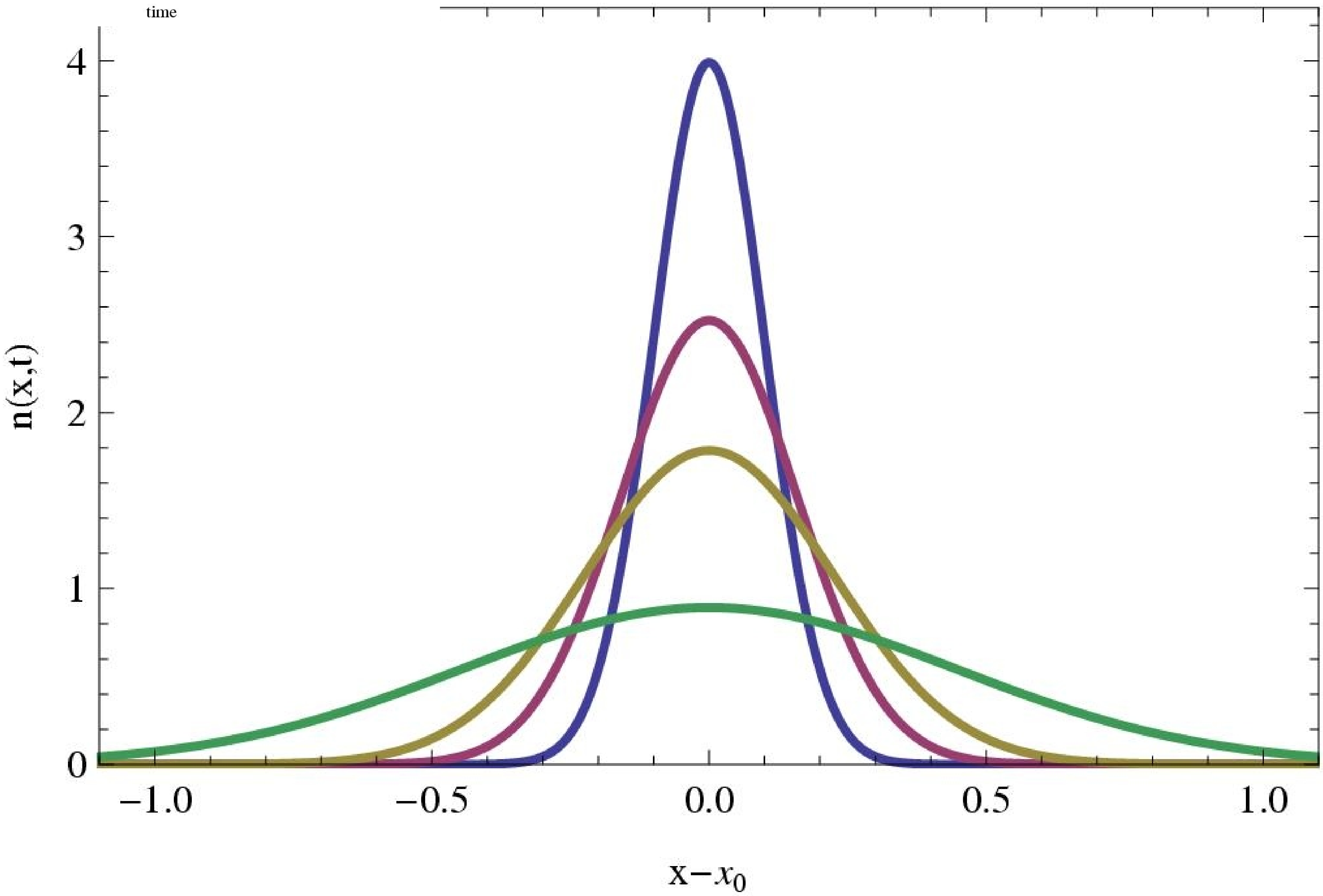




One dimensional diffusion

$$\sigma_x^2 = 2\,D\,t \qquad \frac{|\vec{r} - \vec{r}_s|^2}{4\,D\,t}$$

Diffusion coefficient D



Effect of energy Losses on the spectrum

$$\frac{dE}{dt} = \beta(E)$$

Energy Loss (variation)

$$n(E, t + dt)\ dE = n(E', t)\ dE'$$

$$E' = E - \beta(E)\ dt$$

$$\frac{\partial n(E,t)}{\partial t} = -\frac{\partial [n(E,t)\ \beta(E)]}{\partial E}$$

Fundamental propagation equation:

$$\frac{\partial n(E,\vec{r},t)}{\partial t} = q(E,\vec{r},t) + \vec{\nabla}\cdot D(E,\vec{r})\,\vec{\nabla} n(E,\vec{r},t) - \frac{\partial}{\partial E}\left[\beta(E,\vec{r})\, n(E,\vec{r},t)\right]$$

Source Diffusion Energy Loss

- Source $q(E,\vec{r},t)$
- Diffusion coefficient $D(p/Z,\vec{r})$
- Energy Loss $\beta(E,\vec{r})$

Fundamental propagation equation:

$$\frac{\partial n(E,\vec{r},t)}{\partial t} = q(E,\vec{r},t) + \vec{\nabla}\cdot D(E,\vec{r})\,\vec{\nabla} n(E,\vec{r},t) - \frac{\partial}{\partial E}\left[\beta(E,\vec{r})\; n(E,\vec{r},t)\right]$$

Source Diffusion Energy Loss

$$-\frac{n(E,\vec{r},t)}{\tau_{\mathrm{int}}(E)} - \frac{n(E,\vec{r},t)}{\tau_{\mathrm{dec}}(E)} \cdots$$

additional terms:

interaction
decay
convection
reacceleration

Fundamental propagation equation:

$$0 = q(E,\vec{r},t) + \vec{\nabla}\cdot D(E,\vec{r})\,\vec{\nabla}n(E,\vec{r},t) - \frac{\partial}{\partial E}\left[\beta(E,\vec{r})\,n(E,\vec{r},t)\right]$$

Source Diffusion Energy Loss

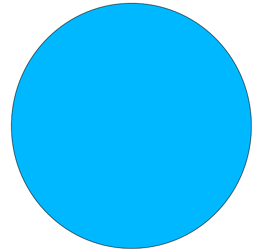
Stationary Solution

PROTON SPECTRUM

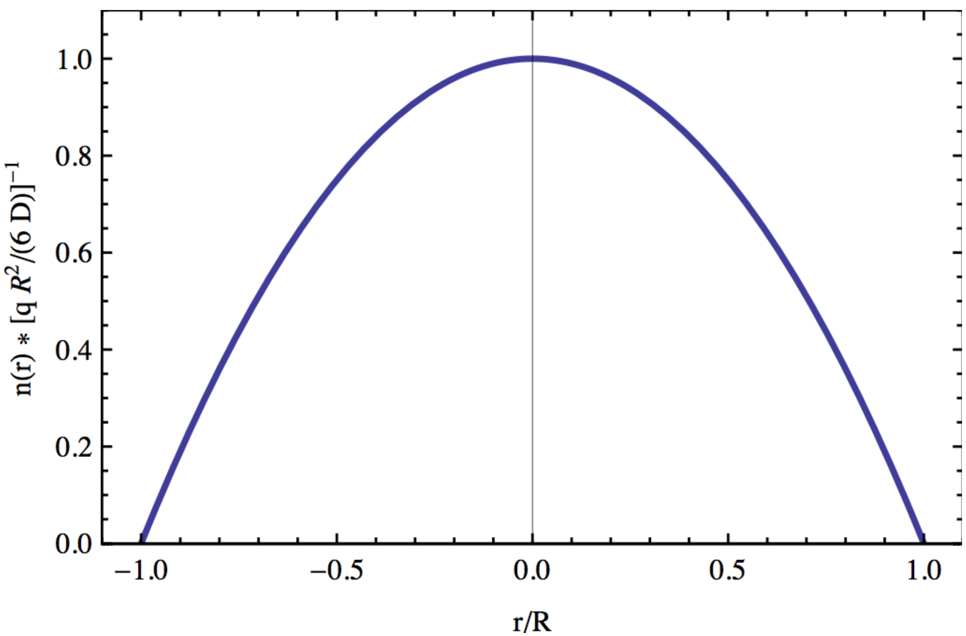
Injection Spectrum

Escape	[diffusion description]
Interaction	[small effect]
Energy Loss	[negligible]

Toy Model:
“Spherical Galaxy” :



$$q(E,\vec{r}) = \begin{cases} q(E) & \text{for } r < R \\ 0 & \text{for } r \geq R \end{cases}$$



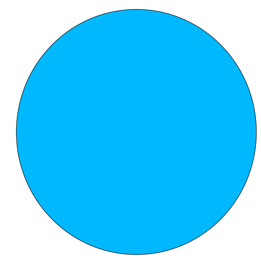
$$D(E,\vec{r}) = \begin{cases} D(E) & \text{for } r < R \\ \infty & \text{for } r \geq R \end{cases}$$

Exact solution :

$$n(E,r) = \frac{q(E)\,R^2}{D(E)} \left[1 - \frac{r^2}{R^2}\right]$$

$$n(E,r) = \frac{q(E)\, R^2}{D(E)} \left[1 - \frac{r^2}{R^2}\right]$$

$$\frac{R^2}{D(E)} \sim \tau_{\mathrm{escape}}(E)$$

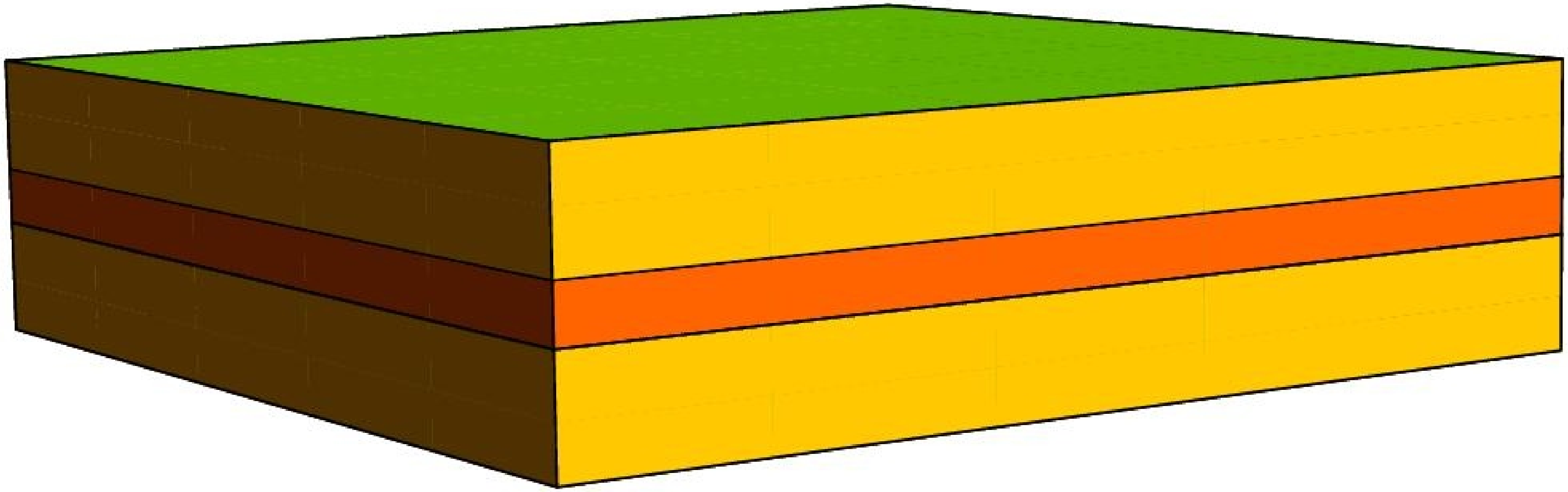


$$n(E) \simeq q(E)\ \tau_{\mathrm{escape}}(E)$$

"Slab Galaxy"

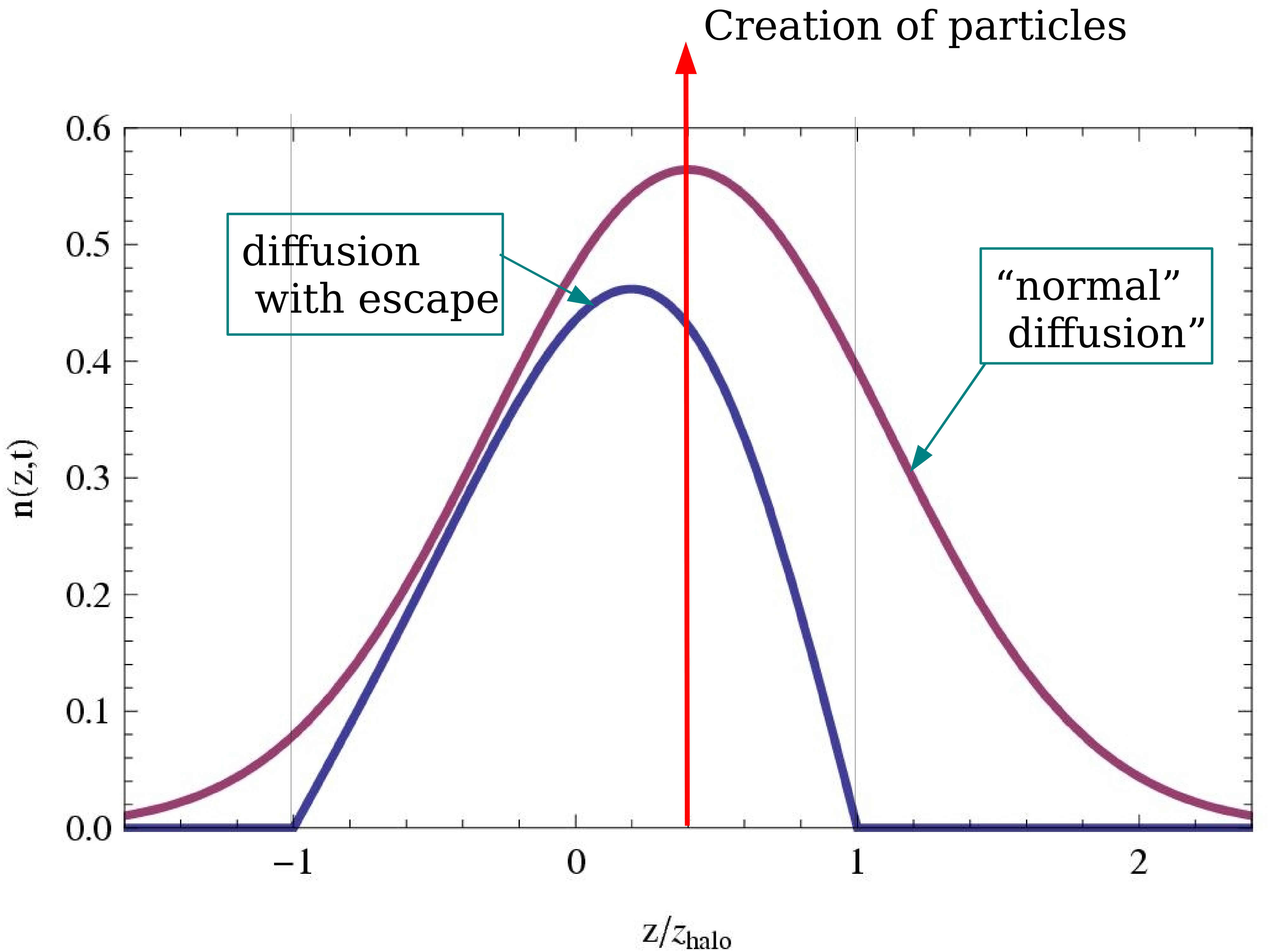
Galaxy modeled as an infinite "slab"

1-D problem



$$q(E,\vec{r}) = \begin{cases} q(E) & \text{for } |z| \leq z_{\text{disk}} \\ 0 & \text{for } |z| > z_{\text{disk}} \end{cases}$$

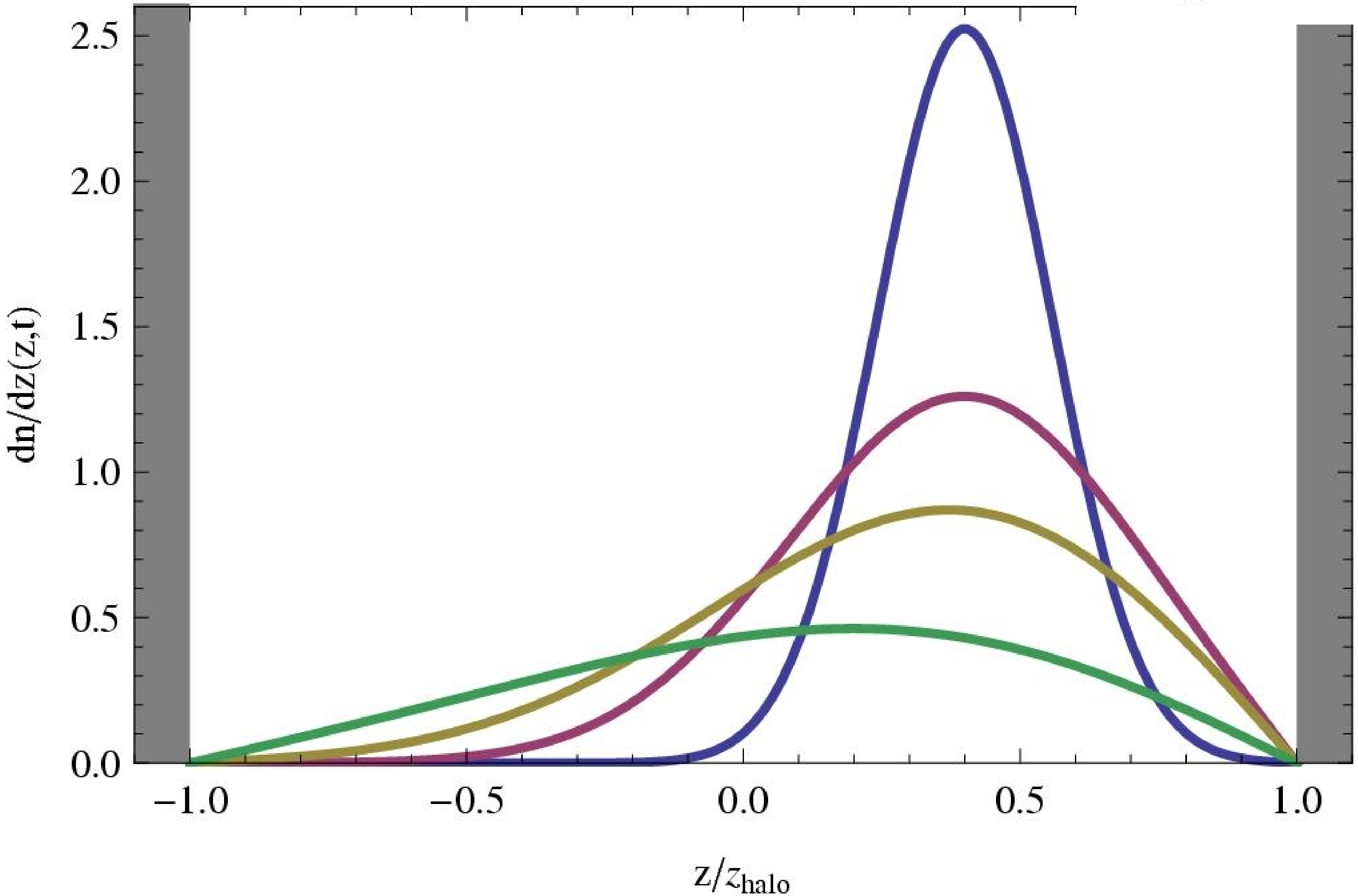
$$D(E,\vec{r}) = \begin{cases} D(E) & \text{for } |z| \leq z_{\text{halo}} \\ 0 & \text{for } |z| > z_{\text{halo}} \end{cases}$$


Creation of particles
diffusion with escape
"normal" diffusion
n(z,t)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−1
0
1
2
z/z_halo

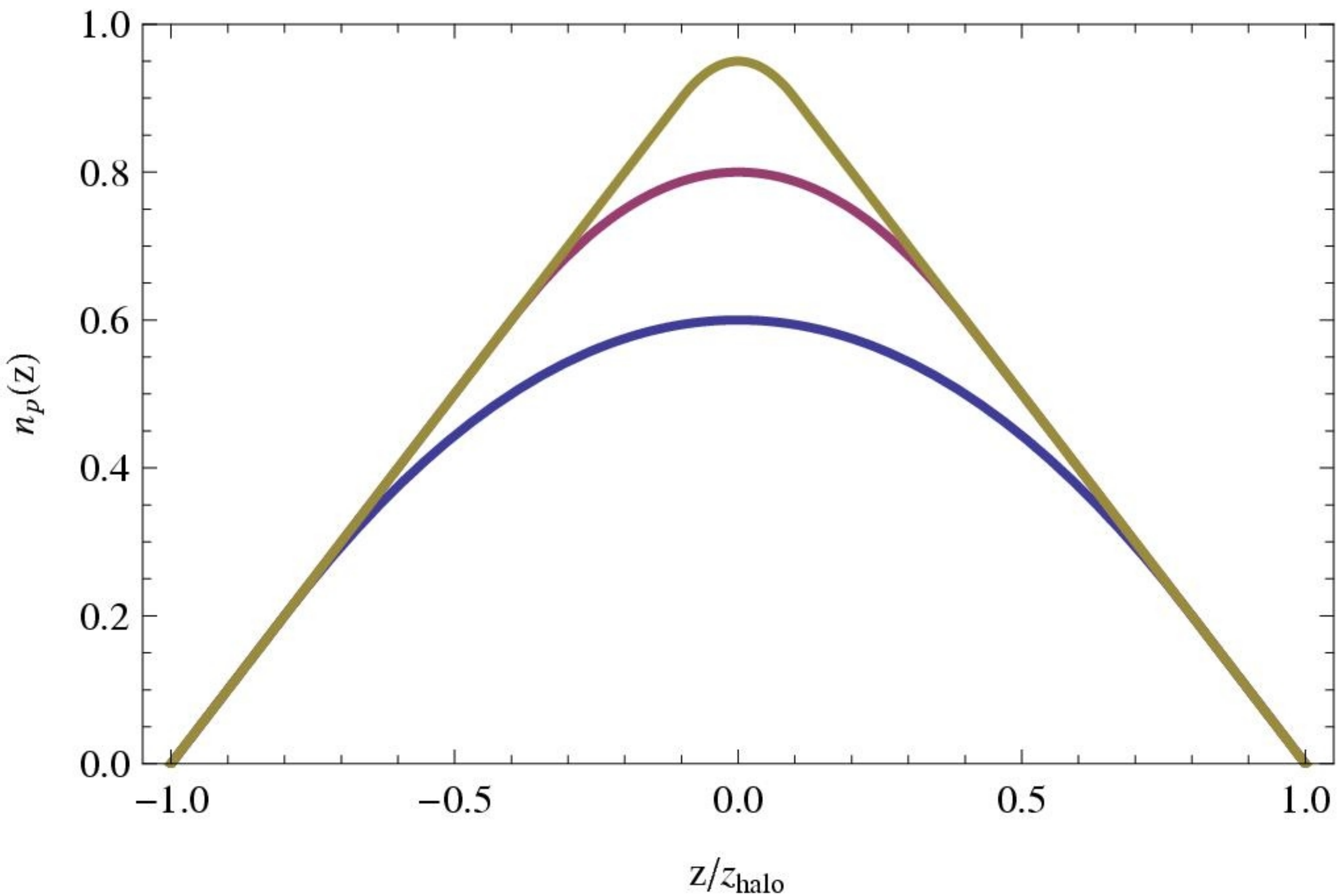
$$f(z,t;-b,a) = \frac{1}{(4\,\pi\,D\,t)^{1/2}} \sum_{n=-\infty}^{+\infty} \left\{ \exp\left[-\frac{(z-z_n)^2}{4\,D\,t}\right] - \exp\left[-\frac{(z-z'_n)^2}{4\,D\,t}\right] \right\}$$

$$z_n = 2\,n\,(a+b)$$

$$z'_n = 2a - 2\,n\,(a+b)$$



$$n(E,\vec{r}) = \frac{q(E)}{2\,D(E)}\; z_{\rm disk}\; z_{\rm halo} \quad \times \begin{cases} 1 - \frac{1}{2}\frac{z_{\rm disk}}{z_{\rm halo}} - \frac{1}{2}\frac{z^2}{z_{\rm disk}\; z_{\rm halo}} & \text{for} \quad |z| \leq z_{\rm disk} \\ 1 - \frac{1}{2}\frac{|z|}{z_{\rm halo}} & \text{for} \quad |z| > z_{\rm disk} \end{cases}$$



Stationary sources
(no time dependence)

Isotropic Diffusion description
Good approximation:

Factorization
of the energy dependence:
- For the source.
- For the diffusion coefficient

$$q(E, \vec{r}) = q(E)\; q_{\rm space}(\vec{r})$$

$$D(E, \vec{r}) = D(E)\; D_{\rm space}(\vec{r})$$

$$n(E, \vec{r}) = n(E)\; n_{\rm space}(\vec{r}) = \frac{q(E)}{D(E)}\; n_{\rm space}(\vec{r})$$

$$q(E) \propto E^{-\alpha}$$

$$D(E) \propto E^{\delta}$$

$$n(E) \propto \frac{q(E)}{D(E)} \propto E^{-(\alpha+\delta)}$$

Anisotropies

$$\phi(E,\Omega) \simeq \phi(\Omega)$$

“Dipole moment” of the angular distribution

$$\phi(E,\Omega) \simeq \phi_0(E) + \phi_1(E) \times cos\theta_{\hat{n}}$$

$$\Delta = \frac{\phi_{\max} - \phi_{\min}}{\phi_{\max} + \phi_{\min}} \simeq \frac{\phi_1}{\phi_0}$$

Cosmic Ray Nuclear Composition

Overabundance of Li, Be, B

Sub-iron elements

Spallation effect:

Column density
Confinement time

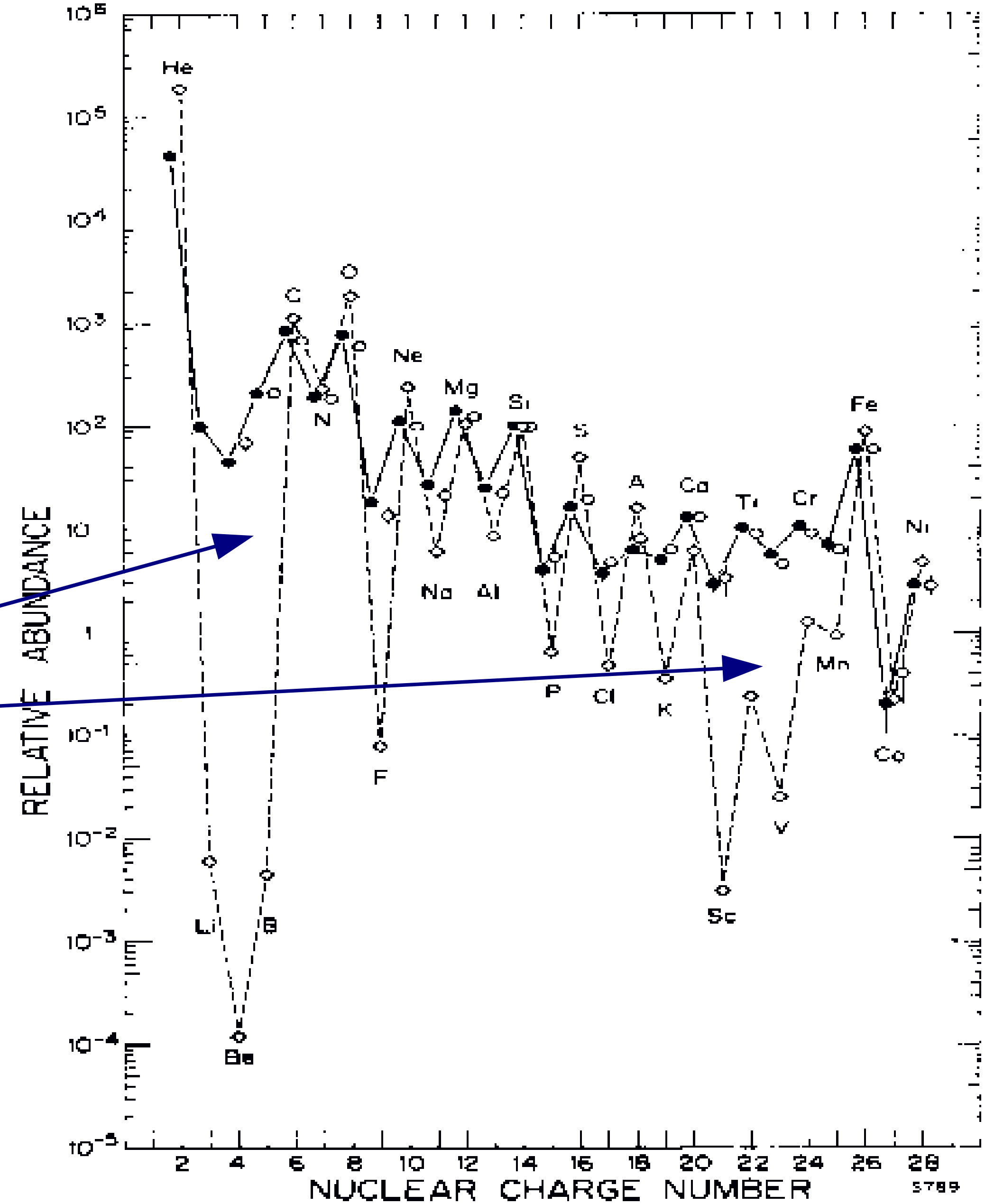


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with permission from J. A. Simpson (1983). Ann. Rev. Nucl. Part. Sci.* ***33*** *by Annual Reviews, Inc.*].

Injection of Secondary Nuclei:

A = Primary Nucleus (C, N, O)
A' = "Secondary Nucleus" (Li, Be, B)

$$q_{A'}(E, \vec{r}) = \sum_A n_A(E, \vec{r}) \; c \; n_{\rm ISM}(\vec{r}) \; \sigma_{pA} \; B_{pA \to A'}$$

E = Energy per nucleon:

$$q_{A'}(E) \propto n_A(E) \propto \frac{q_A(E)}{D(E)}$$

Different Spectrum!

$$n_{A'}(E) \propto \frac{q_{A'}(E)}{D(E)} \propto \frac{q_A(E)}{[D(E)]^2}$$

$$\frac{n_{A'}(E)}{n_A(E)} \propto \frac{\langle n_{\rm ISM} \rangle}{D(E)}$$

$$n_A(E) \propto \; E^{-(\alpha+\delta)}$$

Primary Nucleus

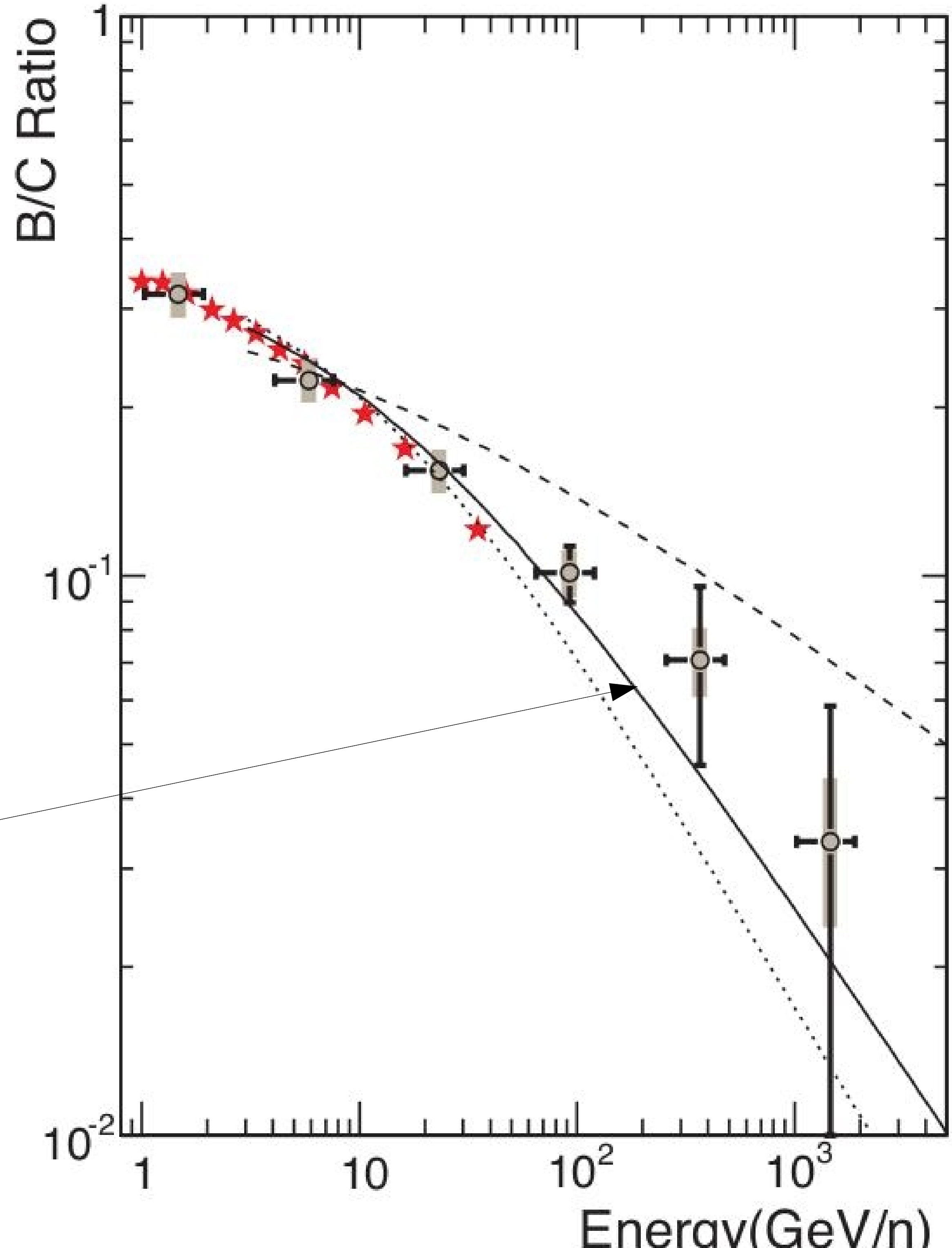
$$n_{A'}(E) \propto \langle n_{\rm ISM} \rangle \; E^{-(\alpha+2\,\delta)}$$

Secondary Nucleus

$$\frac{n_{A'}(E)}{n_A(E)} \propto \langle n_{\rm ISM} \rangle \; E^{-\delta}$$

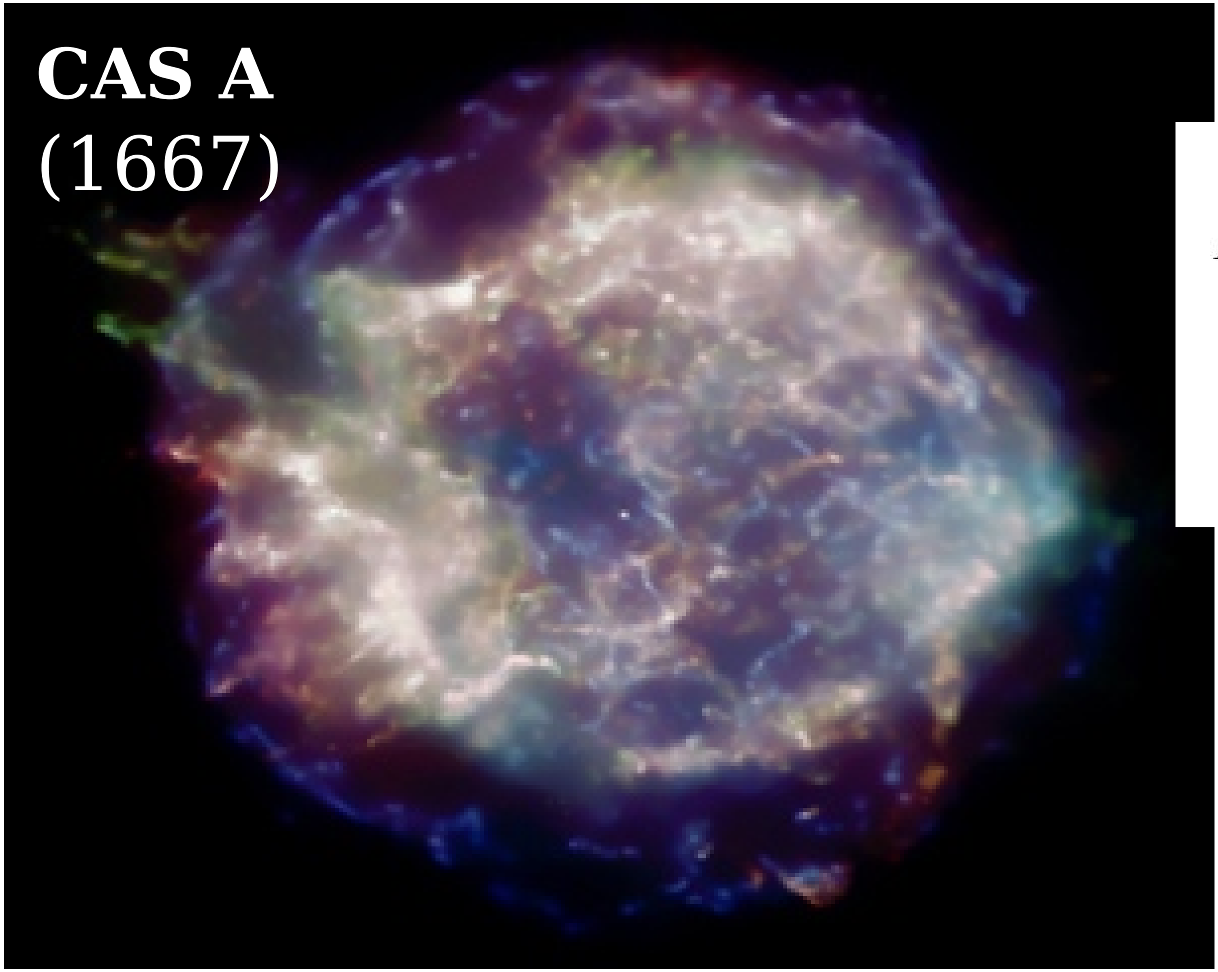
Primary/Secondary

From CREAM



tau(E) ~ $E^{-0.6}$

The SuperNova "Paradigm" for CR acceleration



Powering the galactic Cosmic Rays

$$L_{\rm cr}(\text{Milky Way}) \simeq \frac{\rho_{\rm cr}\, V_{\rm conf}}{T_{\rm conf}}$$

$$\simeq 2 \times 10^{41} \left(\frac{\rm erg}{\rm s}\right)$$

$$\simeq 5 \times 10^{7}\, L_{\odot}$$

- ENERGETICS
- DYNAMICS [Diffusive Shock acceleration]

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq E_{\rm SN}^{\rm Kinetic}\ f_{\rm SN}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq \left[1.6 \times 10^{51}\ {\rm erg}\right]\ \left[\frac{3}{\rm century}\right]$$

$$M = 5\ M_\odot$$

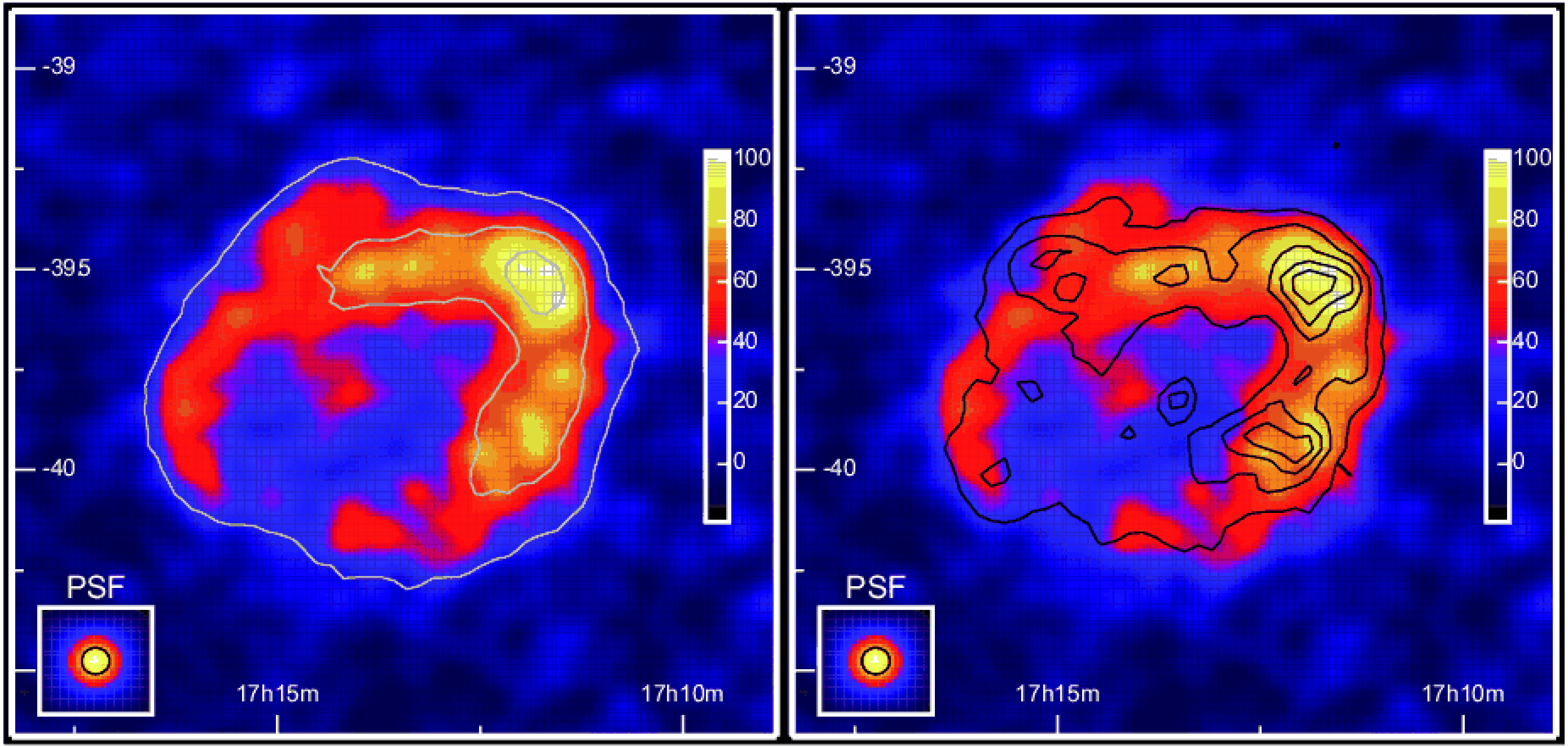
$$v \simeq 5000\ {\rm Km/s}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq 1.5 \times 10^{42}\ \frac{\rm erg}{\rm s}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

HESS Telescope

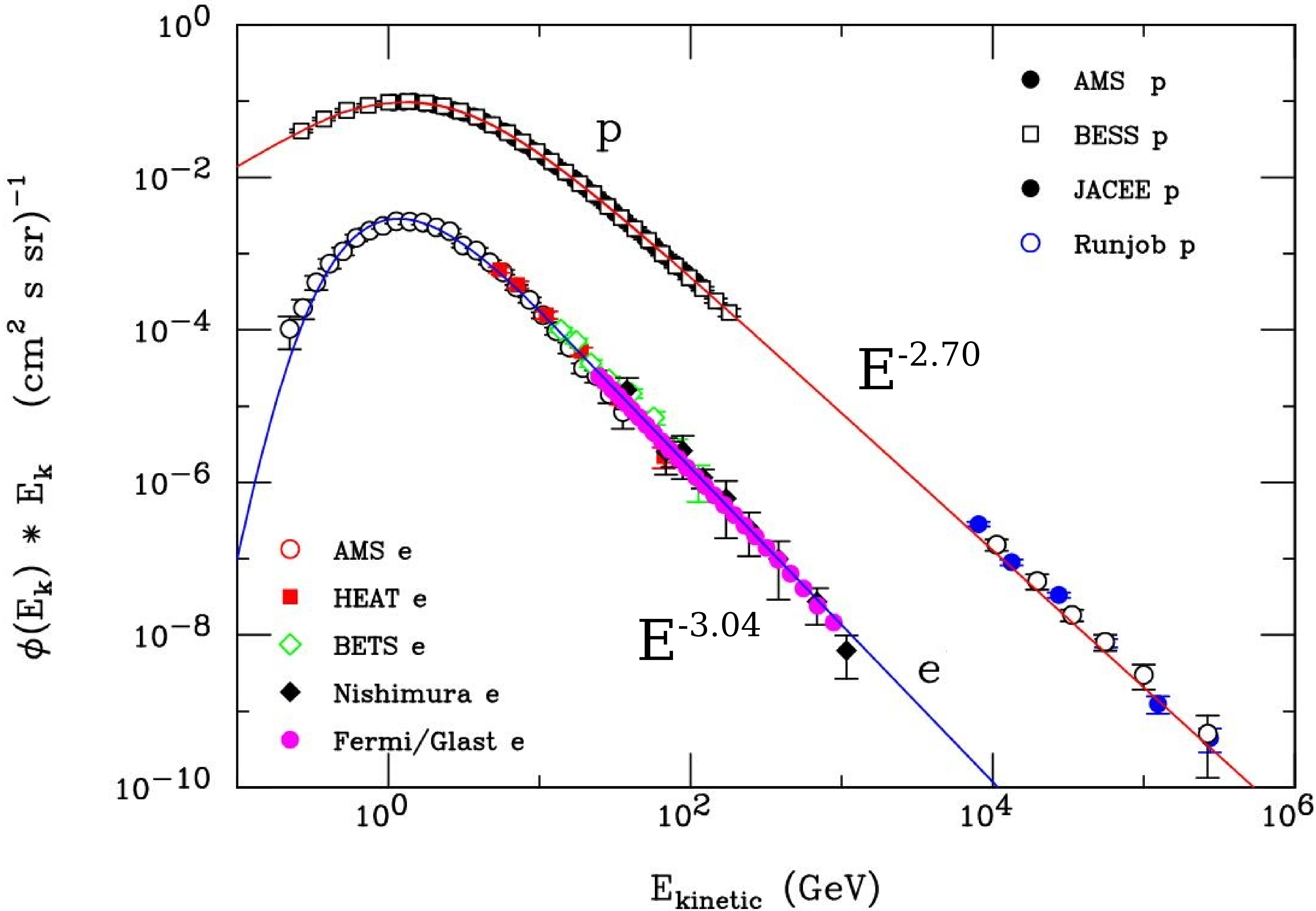
Observations with TeV photons



Comparison with ROSAT observation

COSMIC RAY ELECTRONS

Proton and electron energy spectra



Which are the SOURCES of the CR electrons ?
Are they the same as the proton sources?

Is the Shape of electron Source Spectrum
the same as for protons ?

Relative Normalization ?

Which are the SOURCES of the CR electrons ?
Are they the same as the proton sources?

Probably yes !

Is the Shape of electron Source Spectrum
the same as for protons ?

Probably yes !

Relative Normalization ?

Only partially understood

Which are the SOURCES of the CR electrons ?
Are they the same as the proton sources?

Probably yes !

Is the Shape of electron Source Spectrum
the same as for protons ?

Probably yes !

Relative Normalization ?

Only partially understood

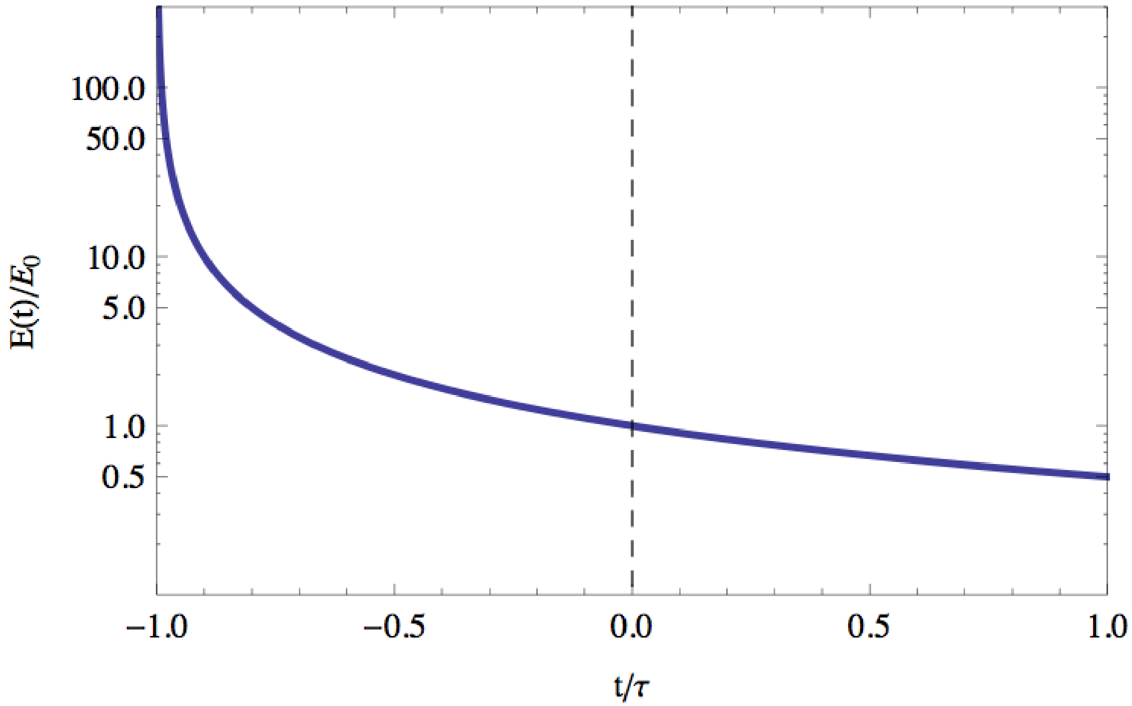
CO-ACCELERATION (electrons, p, nuclei) problem

Electron/Positron propagation

$$-\frac{dE}{dt} \equiv \beta(E) \simeq b\ E^2$$

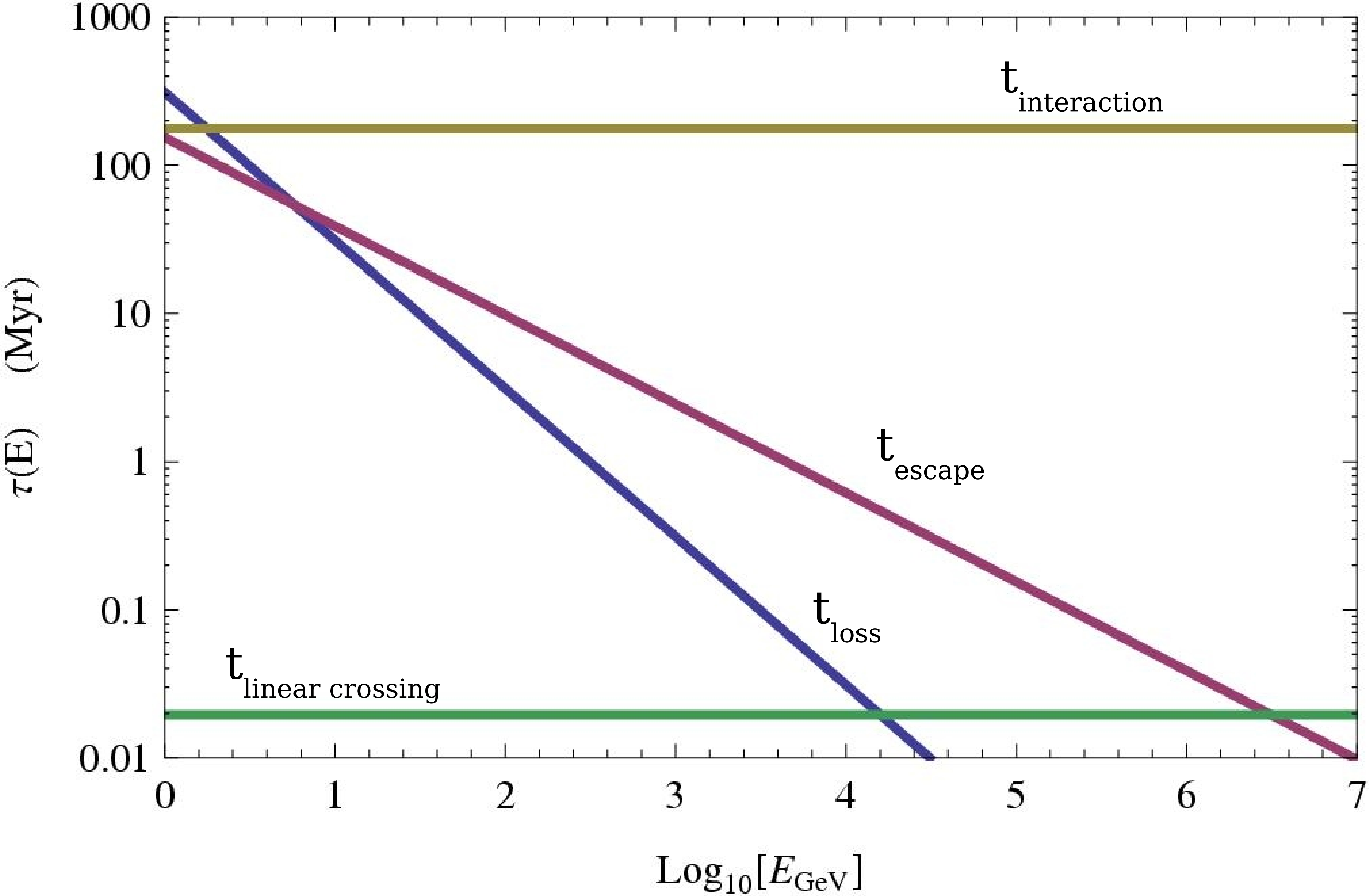
$$b = \frac{4}{3}\,\sigma_{\rm Thomson}\,c\ \left[\frac{B^2}{8\,\pi} + \rho_\gamma\right]\ \frac{1}{m^2}$$

$$E(E_0,t) = \frac{E_0}{1 + b\,E_0\,t}$$



$$\tau_{\rm loss}(E) = \frac{1}{b\,E}$$

$$\tau_{\rm loss}(E) = 350 \times \left[\frac{6\ \mu{\rm Gauss}}{\langle B\rangle}\right]^2\ E_{\rm GeV}^{-1}\ {\rm Myr}$$



1000
100
10
1
0.1
0.01
τ(E) (Myr)
t interaction
t escape
t loss
t linear crossing
0
1
2
3
4
5
6
7
Log10[E GeV]

The electron/positron CR density:

$$n_e(E, \vec{r}, t) = \int dt \int d^3 r_0 \int dE_0 \; q(E_0, \vec{r_0}, t_0) \; G_e(E, \vec{r}, t; E_0, \vec{r_0}, t_0)$$

Homogeneous injection

$$n_e(E) = \frac{1}{\beta(E)} \int_E^\infty dE_0 \; q(E_0)$$

$$q(E) = q_0 \; E^{-\alpha}$$

Power law source spectrum

$$n_e(E) = \frac{q_0}{b\,(\alpha - 1)} \; E^{-(\alpha+1)}$$

Observable spectrum

$$n_e(E) = q_e(E) \; \tau_{\rm loss}(E) \; \frac{1}{\alpha - 1}$$

$$\alpha_e = \alpha_0 + 1$$

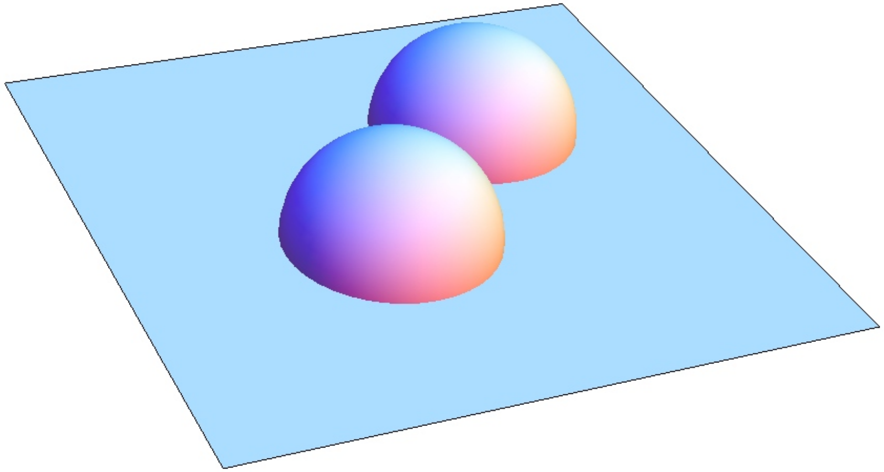
Injection from a thin plane:

$$n_e(E,0) = \frac{1}{4\sqrt{\pi}}\,\frac{q_0}{\sqrt{D_0\,b}}\,C(\alpha,\delta)\;E^{-(\alpha+1/2+\delta/2)}$$

$$C(\alpha,\delta) = \sqrt{1-\delta}\int_1^\infty dx\,\frac{x^{-\alpha}}{\sqrt{1-x^{\delta-1}}}$$

$$n_e(E) \sim q_e(E)\,\frac{\tau_{\rm loss}(E)}{R_{\rm diff}(E)}$$

$$\alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2}$$



$$q_e(p) = K_e \, p^{-\alpha}$$

$$q_p(p) = K_p \, p^{-\alpha}$$

Injection is
a power law in
MOMENTUM

Normalization Condition for the same source:

$$\int_{p(T_{\min}, m_e)}^{\infty} dp \;\, q_e(p) = \int_{p(T_{\min}, m_p)}^{\infty} dp \;\, q_p(p) = N$$

$$K_{e,p} = N \; (\alpha - 1) \;\; [T_{\min} \, (2 \, m_{e,p} + T_{\min})]^{\alpha - 1/2}$$

$$\frac{K_e}{K_p} \simeq \left(\frac{m_e}{m_p} \right)^{\frac{(\alpha-1)}{2}} \simeq 0.016$$

Protons
and Electrons
from SAME
dominant source

Injection from a plane

$$\alpha_p = \alpha_0 + \delta \simeq 2.70$$

$$\alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2} \simeq 3.04$$

Injection from a plane

$$\alpha_p = \alpha_0 + \delta \simeq 2.70$$

$$\alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2} \simeq 3.04$$

$$\alpha_0 \simeq 2.38$$

$$\delta \simeq 0.32$$

Homogeneous injection

$$\alpha_p = \alpha_0 + \delta \simeq 2.70$$

$$\alpha_e = \alpha_0 + 1 \simeq 3.04$$

$$\alpha_0 \simeq 2.04$$

$$\delta \simeq 0.66$$

$$\phi_j(E) \propto q_j(E)\ \tau_j(E)$$

$$\tau_p(E) \propto E^{-\delta}$$

Hadronic escape
[escape]

$$\tau_e(E) \propto E^{-\delta_e}$$

Energy loss
+ diffusion

$$\phi_p(E) \propto q_p(E)\ E^{-\delta}$$

$$\phi_{A_{\mathrm{secondary}}}(E) \propto [q_p(E)\ E^{-\delta}]\ E^{-\delta}$$

$$\propto q_p(E)\ E^{-2\,\delta}$$

$$\phi_p(E) \propto q_p(E)\ E^{-\delta}$$

$$\phi_{e^-}(E) \propto q_e(E)\ E^{-\delta_e}$$

$$\phi_{e^+}(E) \propto \left[q_p(E)\ E^{-\delta}\right]\ E^{-\delta_e}$$

Positron flux is expected to be
Softer than electrons, and softer than protons.