Cosmic Rays & Galactic Winds

Lecutre given at the Summer School: “Magnetic Fields: From Star-forming Regions to Galaxy Clusters and Beyond”

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ZAA

Lecture Overview

- Introduction
- Cosmic Rays
- Galactic Winds
- Theory & Models
- Self-consistent modeling of galactic outflows & ionization structure
- Electron transport in NGC 891 and NGC 253
- Diffuse radial γ-ray gradient in the Milky Way
- Cosmic Ray Acceleration Beyond the "Knee"
- Summary

Cosmic Rays

Cosmic Radiation

Includes -

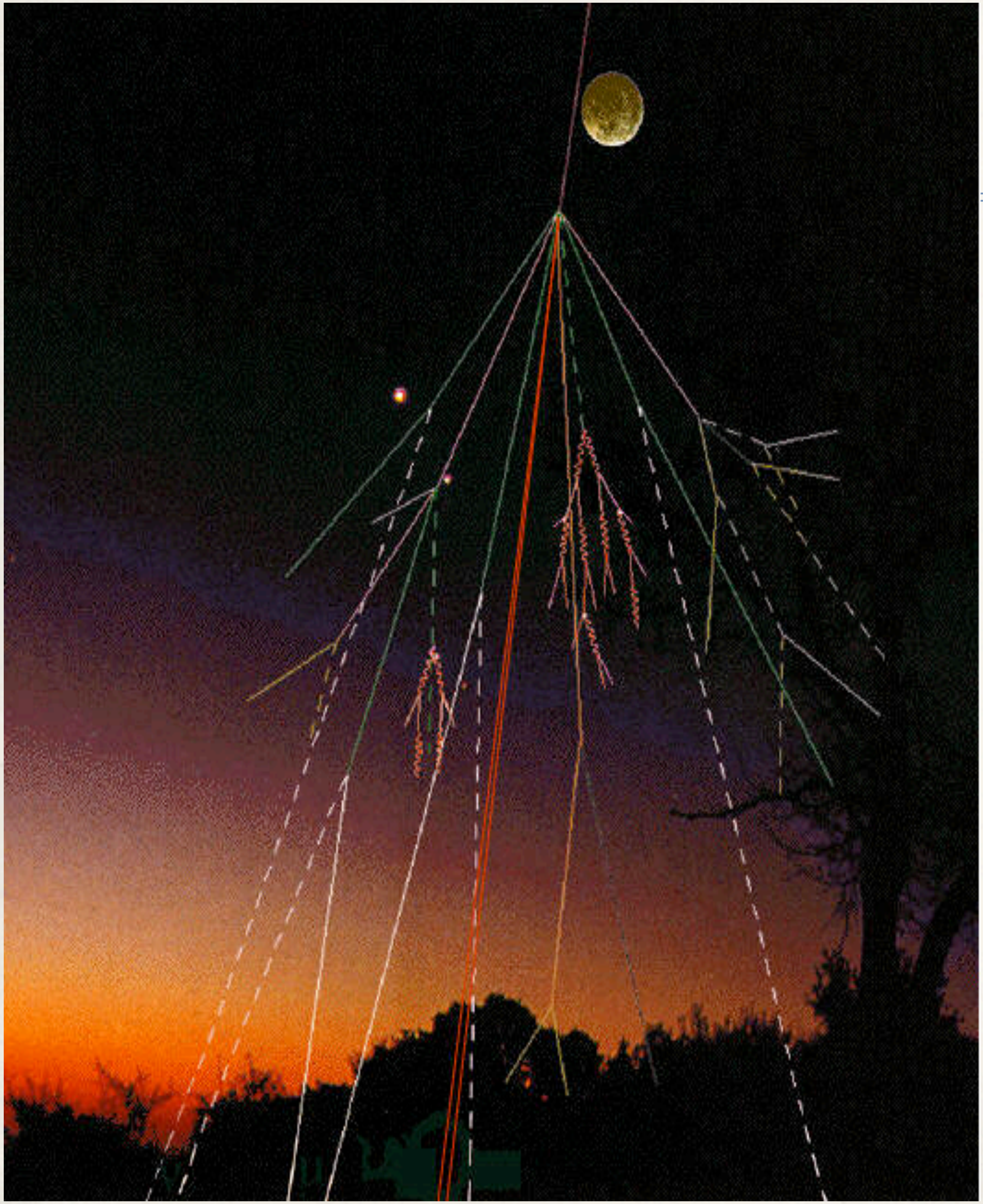
- **Particles** (2% electrons, 98% protons and atomic nuclei)
- **Photons**

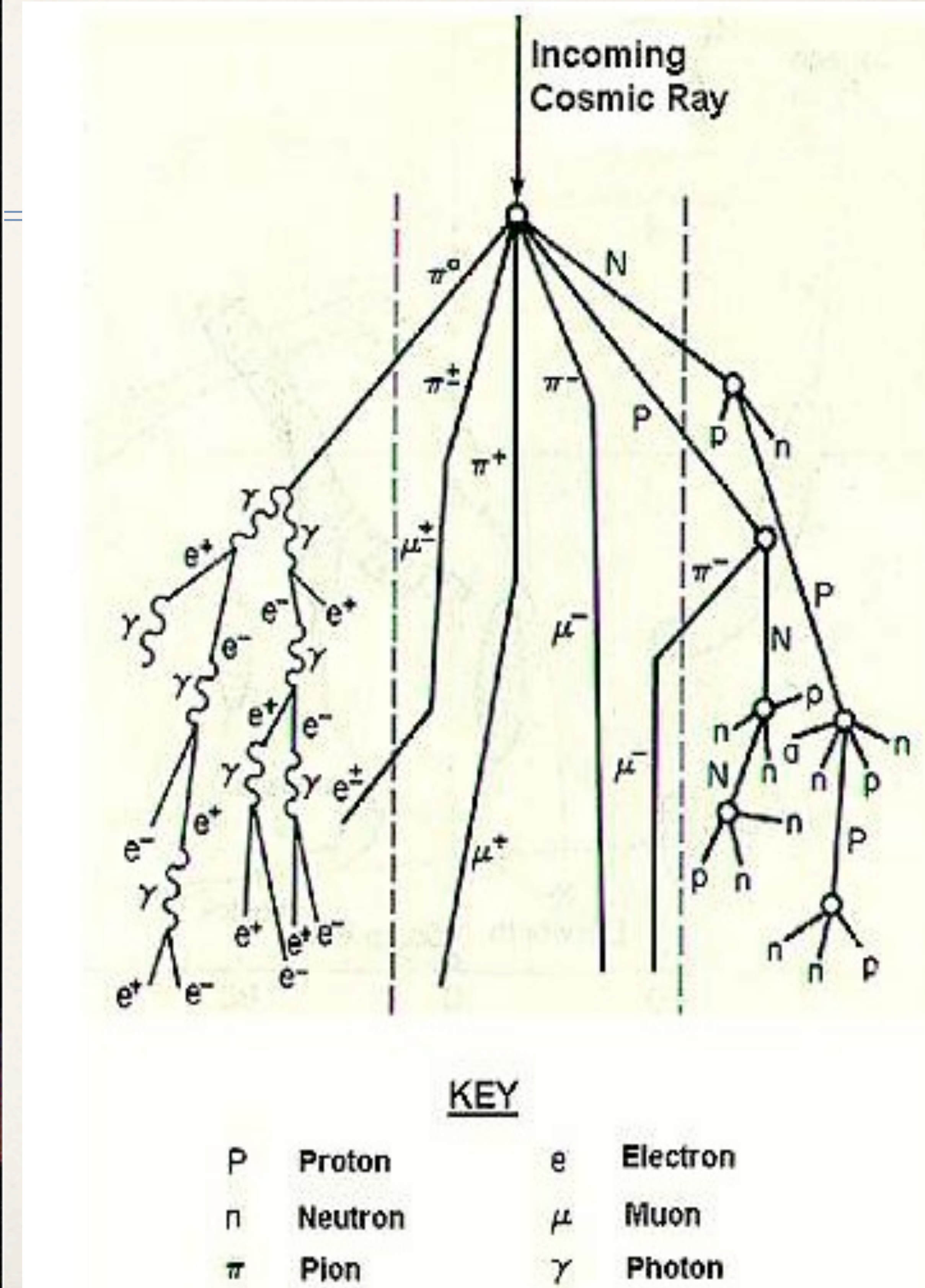
- Large energies ($10^9 eV \leq E \leq 10^{20} eV$)
  γ-ray photons produced in collisions of high energy particles

Extraterrestrial Origin

- Increase of ionizing radiation with altitude
- 1912 Victor Hess‘ balloon flight up to 17500 ft. (without oxygen mask!)
- Used gold leaf electroscope

Cosmic Showers



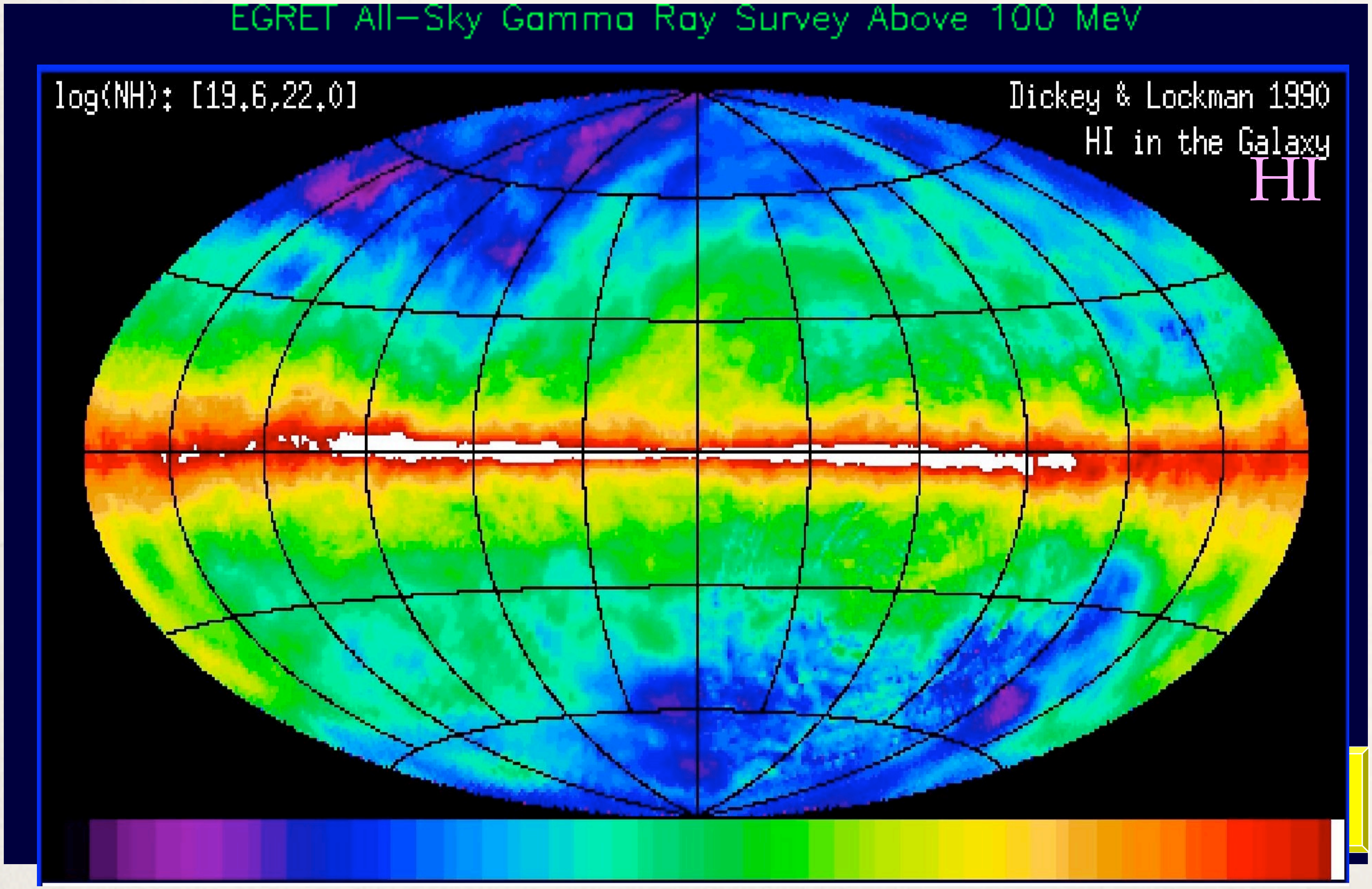


Dieter Breitschwerdt - Ringberg Summer School "Magnetic Fields" - 18.7.2011

Inelastic collision of CRs with ISM

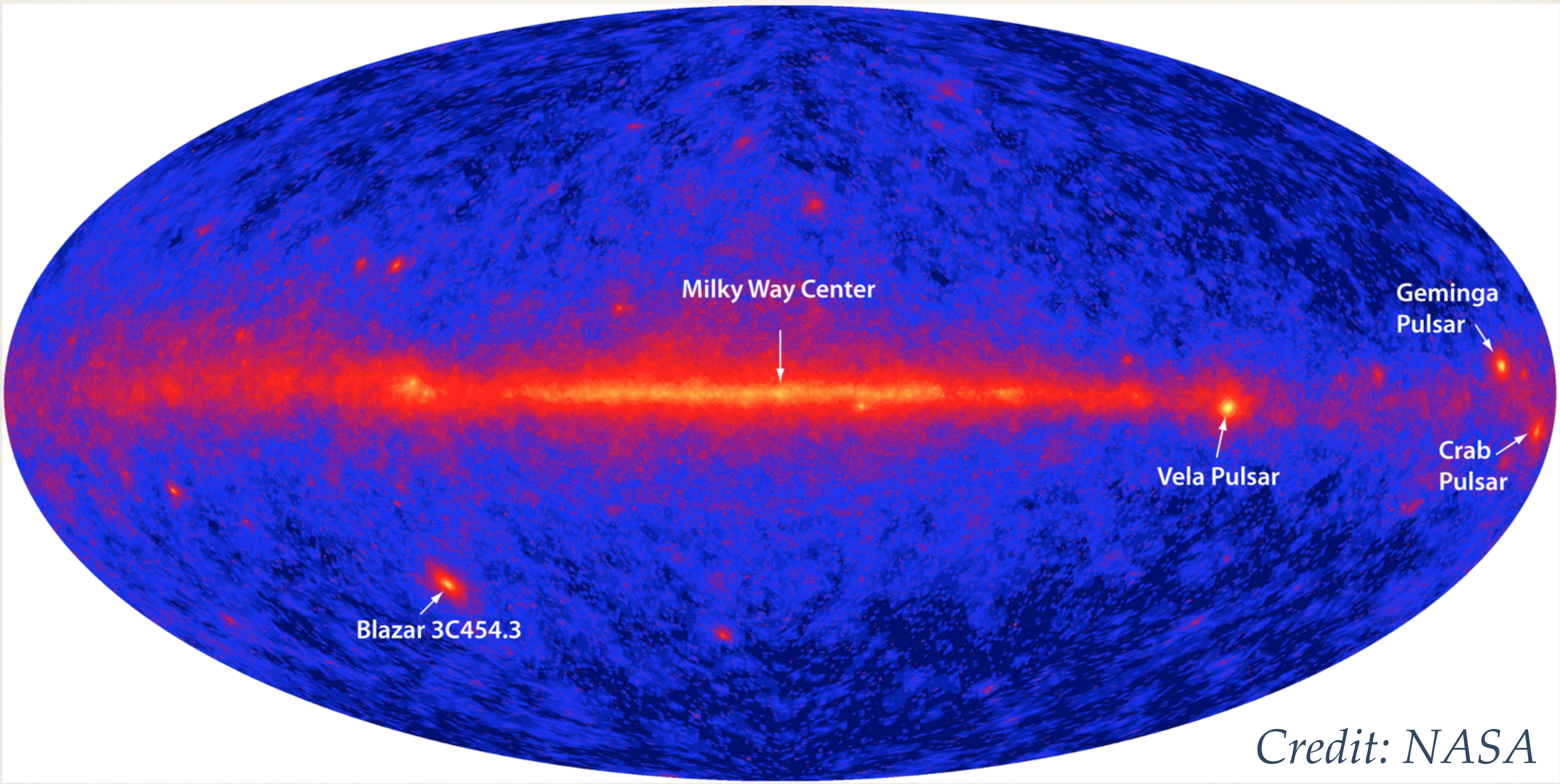
$$p + p \rightarrow p + p + \pi^0$$
$$\pi^0 \rightarrow 2\gamma$$

For E > 100 MeV dominant process



- Diffuse γ-emission maps the Galactic HI distribution
- Discrete sources at high lat.: AGN (e.g. 3C279)

FERMI LAT All-Sky Map



Gamma-ray All-Sky Map (1 year; launch: 11.6.08): 20 MeV - 300 GeV (LAT)

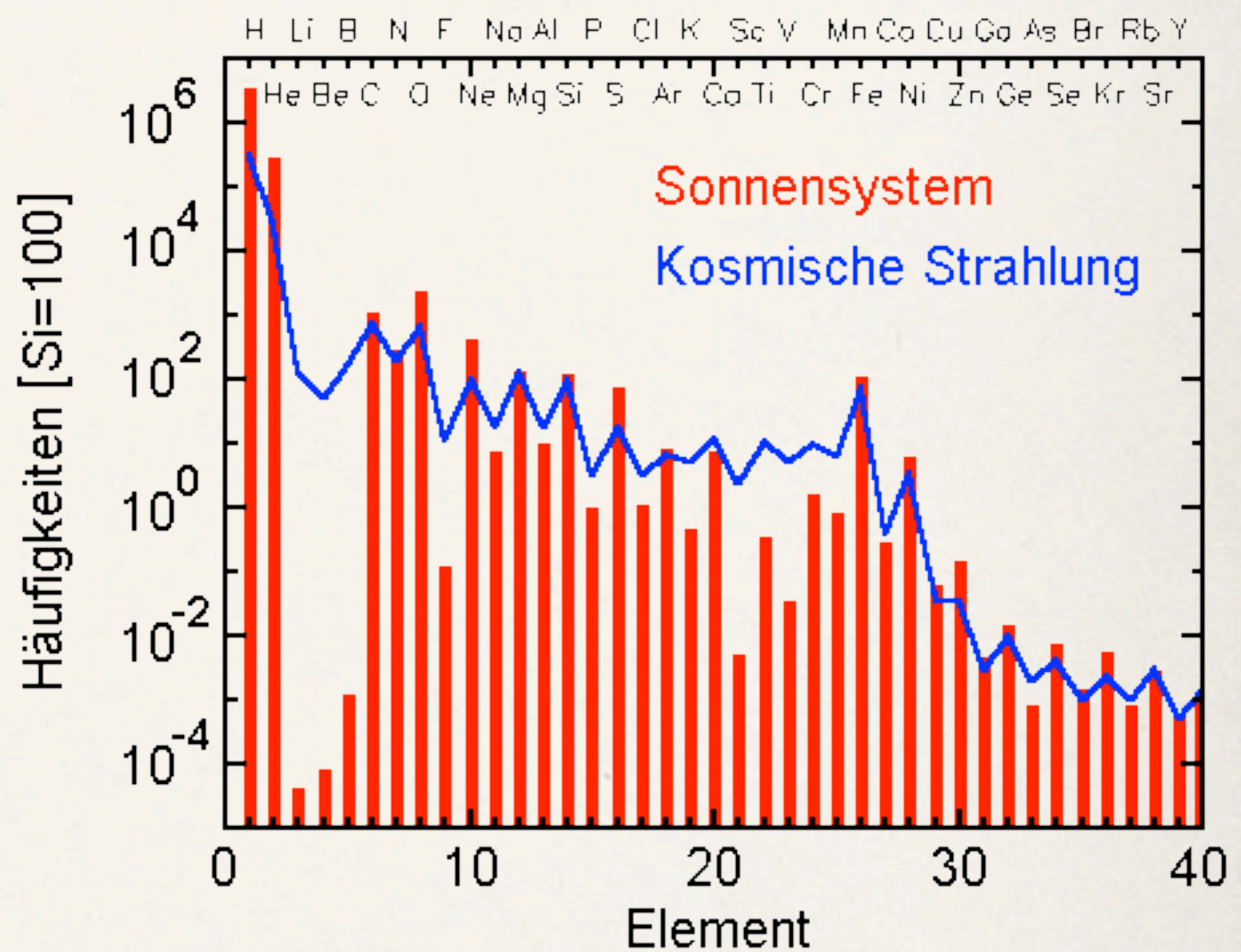
Chemical composition

Groups of nuclei	Z	CR	Universe
Protons (H)	1	700	3000
α (He)	2	50	300
Light (Li, Be, B)	3-5	1	0.00001*
Medium (C,N,O,F)	6-9	3	3
Heavy (Ne->Ca)	10-19	0.7	1
V. Heavy	>20	0.3	0.06

Note: Overabundance of light elements → spallation!

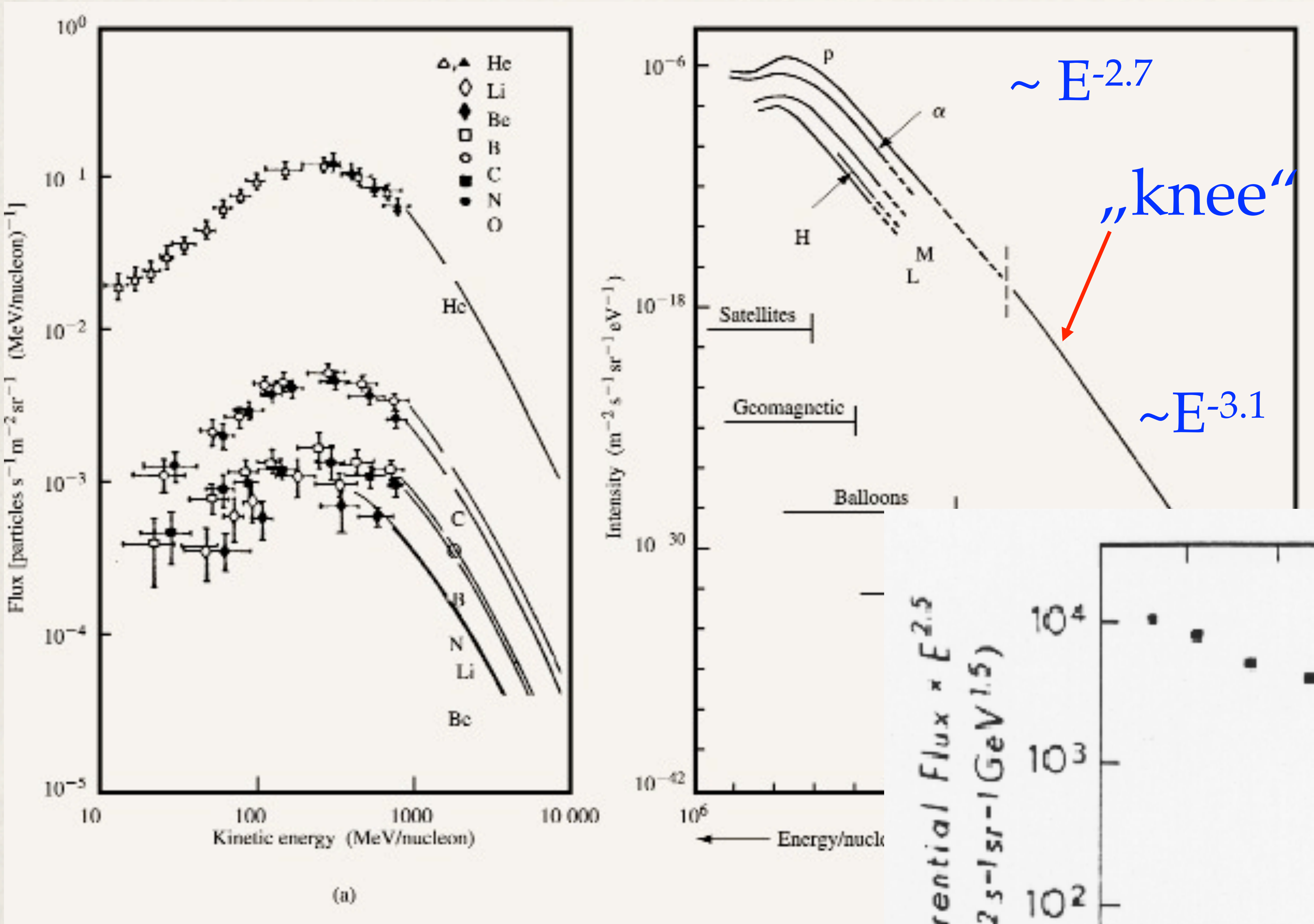
Chemical Composition: Origin of light elements

- Chemical Composition similar to ISM ➔ acceleration of interstellar matter
- Over-abundance of light elements caused by fragmentation of ISM particles in inelastic collision with CR primaries ➔ CR secondaries, e.g. Li, Be, B
- Sc, V, Ti, Cr as spallation products of iron nuclei
- Use fragmentation probabilities and calculate transfer equations by taking into account all possible channels

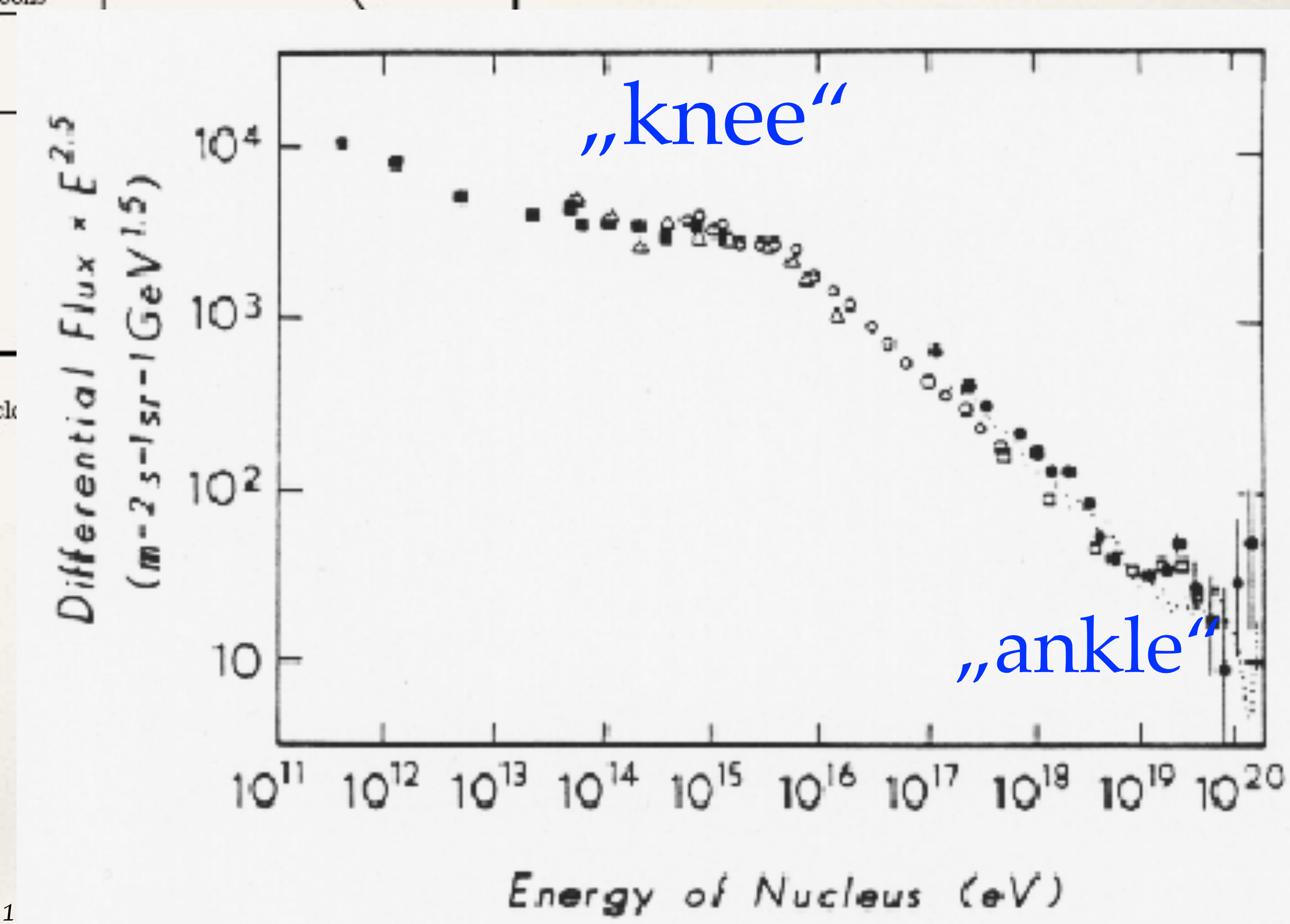


GSFC/NASA: Chemical composition of galactic Cosmic Rays http://imagine.gsfc.nasa.gov/docs/science/know_l2/cosmic_rays.html

Differential Energy Spectrum



- differential energy spectrum power law
- $10^9 < E < 10^{15}$ eV: -2.7
- $10^{16} < E < 10^{19}$ eV: -3.1



- for E > 10^{19} eV CRs are extragalactic (r_g ~ 3 kpc for 1019 eV protons at B ~ 1 μG)

Primary CR energy spectrum

- Power law spectrum for 10^9 eV < E < 10^{15} eV:

$$I_N(E) \propto E^{-\gamma} \quad \text{with } \gamma \approx 2.70 \ \text{ or } N(E)dE = KE^{-\gamma}\,dE$$

- $[I_N]$ = cm^{-2} s^{-1} sr^{-1} (GeV/nucleon)$^{-1}$
- Steepening for E > 10^{15} eV with $\gamma = 3.08$ („knee“)
- becoming shallower for E > 10^{18} eV („ankle“)
- Below E ~ 10^9 eV CR intensity drops due to solar modulation (magnetic field inhibits particle streaming)
- gyroradius:

$$r_g = \frac{\gamma_L m_0 v \sin\vartheta}{ZeB} = \left(\frac{pc}{Ze}\right)\frac{\sin\vartheta}{Bc} = R\,\frac{\sin\vartheta}{Bc}$$

- R ... rigidity, θ ... pitch angle

Example: CR with E=1 GeV has r_g ~ 10^{12} cm! For B ~ 1μG @ 10^{15} eV, r_g ~ 0.3 pc

Important CR facts:

- **CR Isotropy**:
  - Energies 10^{11} eV < E < 10^{15} eV: $\delta I / I \approx 6\times10^{-4}$ (anisotropy) consistent with CRs streaming away from Galaxy
  - Energies 10^{15} eV < E < 10^{19} eV: anisotropy increases -> particles escape more easily (energy dependent escape) Note: @ 10^{19} eV, r_g ~ 3 kpc
  - Energies E > 10^{19} eV: CRs from Local Supercluster? particles cannot be confined to Galactic disk
- **CR clocks**:
  - CR secondaries produced in spallation (from O and C) such as ^{10}Be have half life time τ_H~ 1.6 Myr -> β-decay into ^{10}B

– From amount of ^{10}Be relative to other Be isotopes and ^{10}B and τ_H the mean CR residence time can be estimated to be

$\tau_{esc} \sim 2\ 10^7$ yr for a 1 GeV nucleon

→ **CRs have to be constantly replenished!**

What are the sources?

– Detailed quantitative analysis of amount of primaries and secondary spallation products yields a mean Galactic mass traversed („***grammage***“ x) as a function of rigidity *R*:

$$x(R) = 6.9 \left(R / 20\ \mathrm{GV} \right)^{-\xi}\ \mathrm{g/cm^2},\ \xi = 0.6$$

for 1 GeV particle, x ~ 9 g/cm^2

– Mean measured CR energy density:

$$\varepsilon_{CR} \sim \varepsilon_{mag} \sim \varepsilon_{th} \sim \varepsilon_{turb} \cong 1\ \mathrm{eV/cm^3}$$

- If *all* CRs were extragalactic, an extremely high energy production rate would be necessary (more than AGN and radio galaxies could produce) to sustain high CR back-ground radiation
- assuming energy equipartion between B-field and CRs radio continuum observations of starburst galaxy M82 give $\varepsilon_{CR}(M82) \sim 100\varepsilon_{CR}(Galaxy)$
- CR production rate proportional to star formation rate

→ *no constant high background level!*

→ *CR interact strongly with B-field and thermal gas*

CR propagation

- High energy nucleons are ultrarelativistic -> light travel time from sources

$$\tau_{lc} \sim L/c \approx 3\times10^4 \text{ yr} << \tau_{esc}$$

- CRs as charged particles *strongly coupled to B-field*
- *B-field:* $\vec{B} = \langle \vec{B}_{\rm reg} \rangle + \delta\vec{B}$ *with strong fluctuation component* $\delta\vec{B}$ ➔ *MHD (Alfvén) waves*

➡ Cross field *propagation by pitch angle scattering*

➡ random walk of particles!

- CRs **DIFFUSE** through Galaxy with mean speed

$$\langle v_{diff} \rangle \sim L/\tau_r \approx 10\text{ kpc}/2\times10^7\text{ yr} = 490\text{ km/s} \sim 10^{-3} c$$

- Mean gas density traversed by particles

$$\langle \rho_h \rangle \approx x/c\tau_{esc} \sim 5\times10^{-25}\text{ g/cm}^3 \sim \frac{1}{4}\langle \rho_{ISM} \rangle$$

- particles spend most time outside the Galactic disk in the Galactic *halo!* → *„confinement“ volume*
  - CR „height“ ~ 4 times h_g (=250 pc) ~ 1 kpc
  - CR diffusion coefficient:

$$\kappa \sim h_{CR} \times L/\tau_{esc} \approx 5\times10^{28}\,\mathrm{cm}^2/\mathrm{s}$$

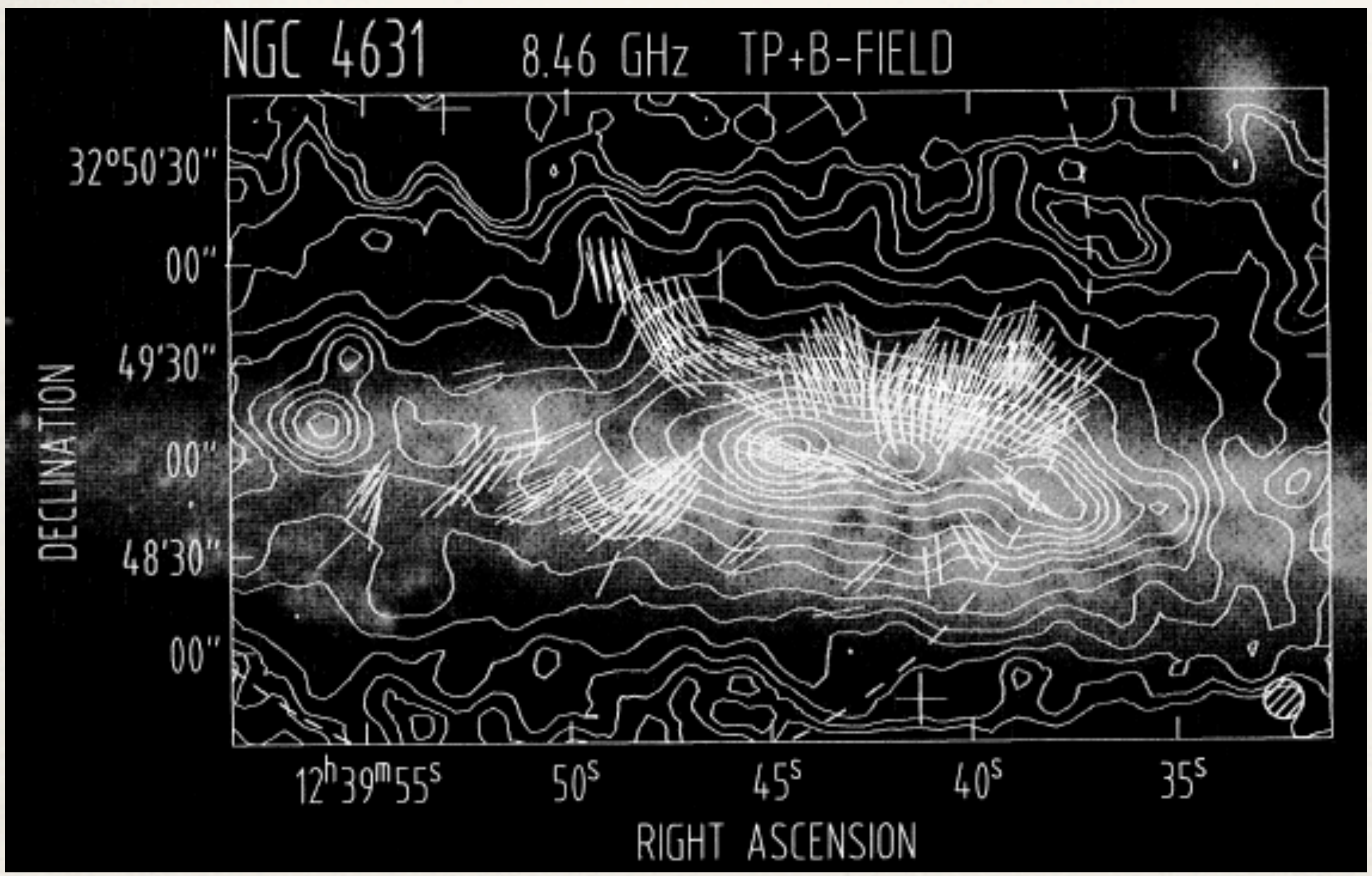
  - Mean free path for CR propagation: $\lambda_{CR} \sim 3\kappa / c \sim 1\,\mathrm{pc}$

→ strong scattering off magnetic irregularities!

- Analysis of radioactive isotopes in meteorites: CR flux roughly constant over last 10^9 years

CR origin

- CR electrons (~ 1% of CR particle density) must be of Galactic origin due to strong synchrotron losses in Galactic magnetic field and inverse Compton losses



- Note: radio continuum observations of edge-on galaxies show halo field component

Golla, G. et al.

- Estimate of total Galactic CR energy flux:

$$F_{CR} \sim \varepsilon_{CR} \, V_{conf} / \tau_{esc} \approx 10^{41} \text{ erg/s}$$

Note: only ~ 1% radiated away in γ-rays!

- Enormous energy requirements leave as most realistic Galactic CR source supernova remnants (SNRs)
  - Available hydrodynamic energy:

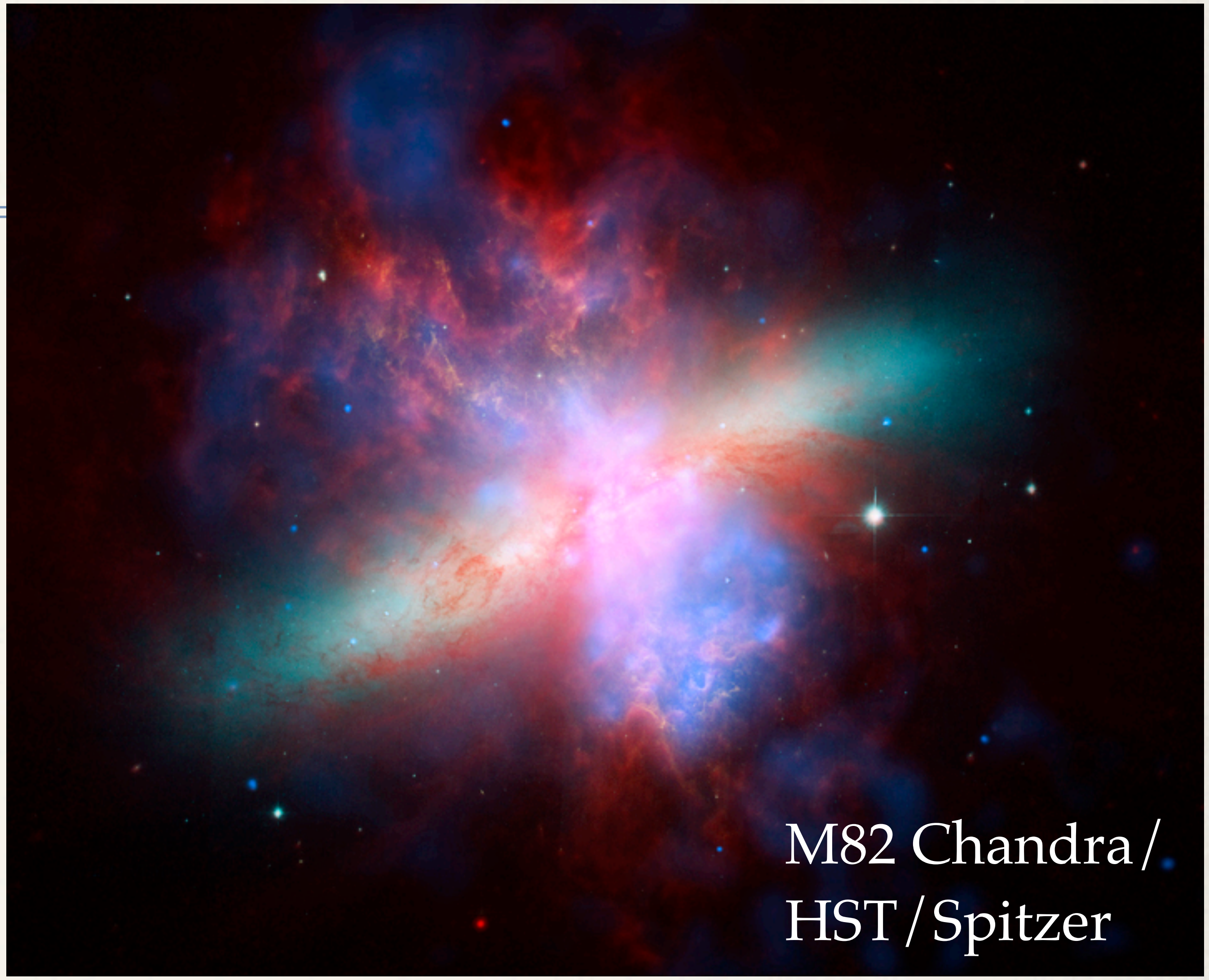
$$F_{SNR} \sim \nu_{SN} E_{SNR} \approx 3/100 \text{ yr} \times 10^{51} \text{erg} \approx 10^{42} \text{ erg/s}$$

→ about 10% of total SNR energy has to be converted to CRs

  - Promising mechanism: *diffusive shock acceleration*
- *Ultrahigh energy CRs must be extragalactic*

$$r_g \geq 100 \text{ kpc} > R_{gal} \quad (\text{for } E \sim 10^{20} \text{eV})$$

Galactic Winds



- **Galaxies** are essential building blocks of the Universe
- **feedback processes** in the disk and halo become ever more important for their appearance and evolution ➔ **Galactic Cosmic Matter Cycle**
- **star formation** generates hot plasma, "metals", CRs, B-fields in disk & halo
- no hydrostatic halo ➔ **superbubbles**, **outflows** (fountain & winds)

Parker's Wind Theory

Assumption:

- steady state flow
- polytropic gas: $P \sim \rho^\gamma$
- spherical geometry
- no sources and sinks, i.e. $q=Q=0$

$$\frac{1}{r^2}\frac{d}{dr}\left(\rho\, u\, r^2\right)=q$$

Mass

$$\rho\, u\frac{du}{dr}=-\frac{dP}{dr}-qu-g$$

Momentum

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho\, u\, r^2\left(\frac{1}{2}u^2+\frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right]=Q$$

Energy

$$c_g^2=\gamma\frac{P}{\rho},\quad P=A(S)\rho^\gamma,\quad M=\frac{u}{c}$$

Wind Equation & Solution

Für $q = Q = 0$ und $g = \frac{GM}{r^2}$ derivation of „wind equation“

$$\frac{1}{u}\frac{du}{dr} = \frac{\frac{2c_g^2}{r} - \frac{GM}{r^2}}{u^2 - c^2}$$

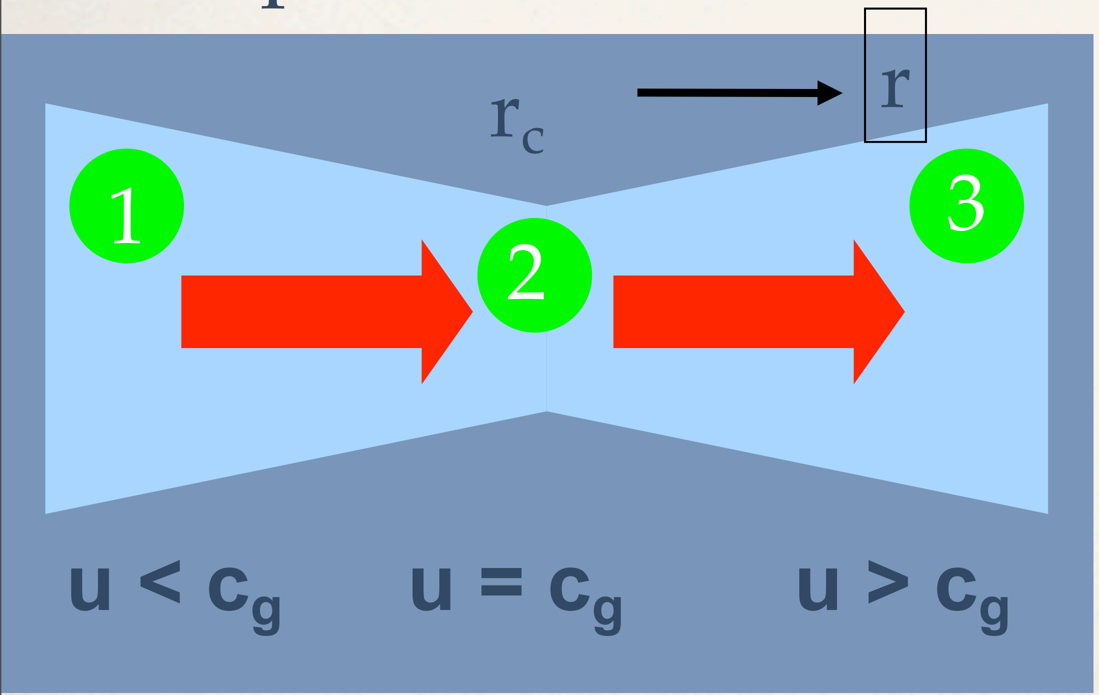
Inner Boundary Condition:

$$r \to 0 : u \to 0$$

Outer Boundary Condition:

$$r \to \infty : \quad P \to 0$$

Principle: de Laval Nozzle



smooth transsonic solution

For accelerating flow: $\frac{du}{dr} > 0$

2 $r = r_c = \frac{GM}{2c_g^2} : \quad u = c_g$

Cricitcal Point

Numerator: c^2 (1/A) dA/dr

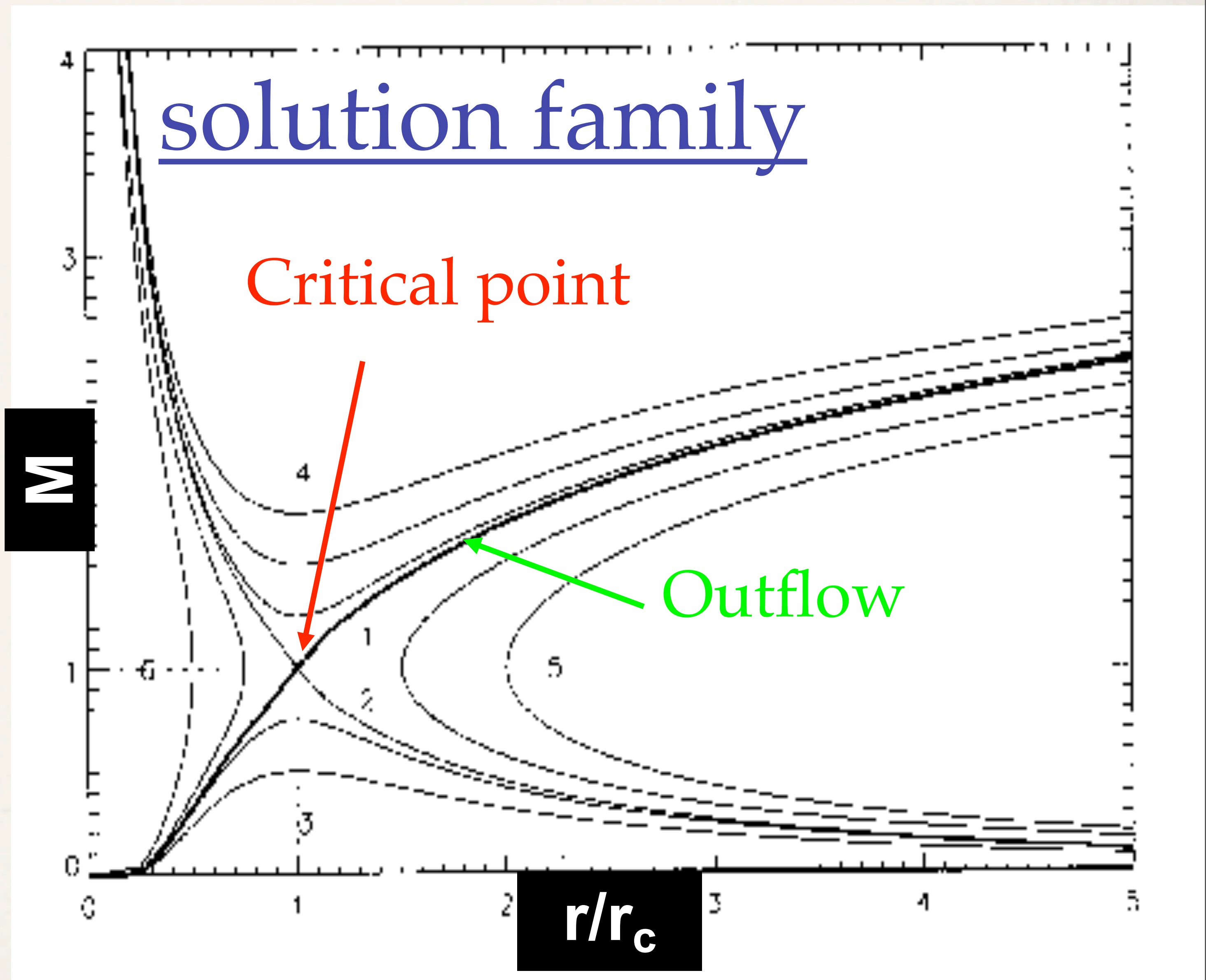
- Equations are integrated inwards and outwards from critical point (Parker's solar wind solution)
- Mass loss rate and terminal velocity are derived from Bernoulli's equation:

$$\frac{1}{2}u^2 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} - \frac{GM}{r} = const.$$

equating at r=r_c and r→∞:

$$\frac{1}{2}c_g^2 + \frac{c_g^2}{\gamma - 1} - \frac{GM}{r_c} \approx \frac{1}{2}u_\infty^2$$

$$\Rightarrow u_\infty = \sqrt{\frac{5 - 3\gamma}{\gamma - 1}}c_g, \quad \dot{m} = 4\pi\, r_c^2 \rho_c c_g$$

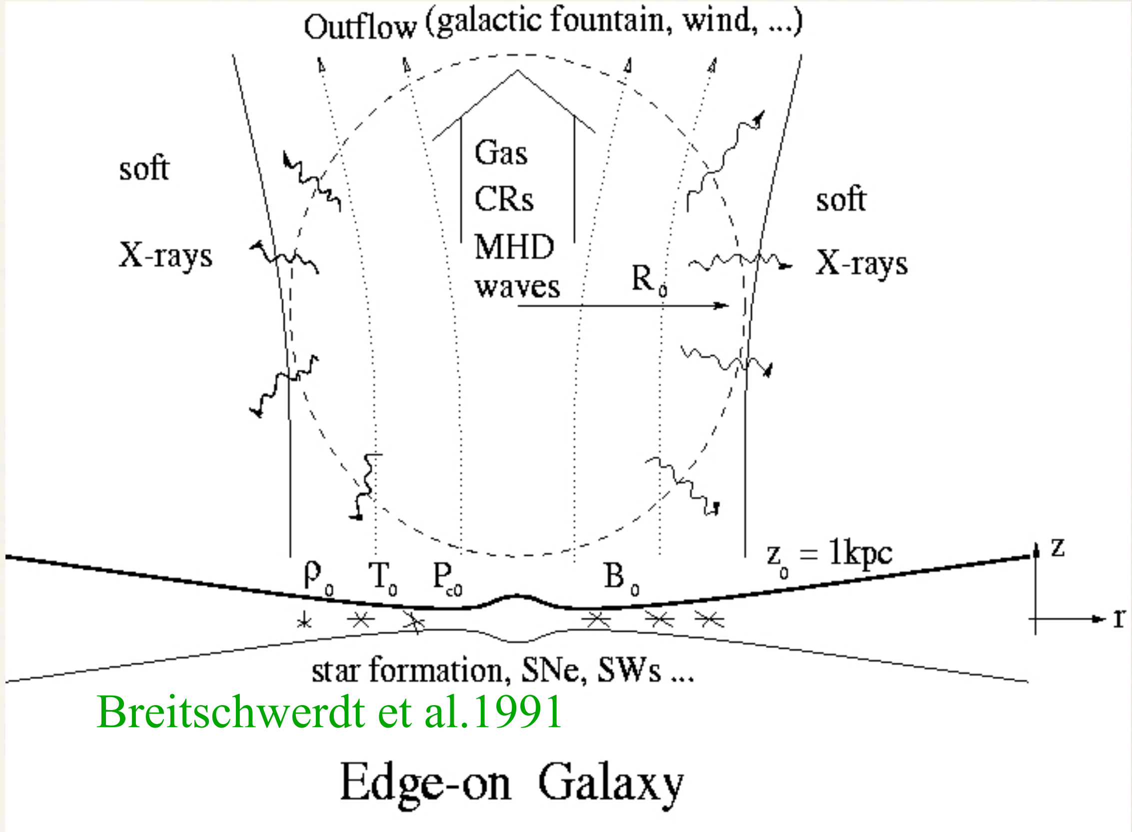


Modeling galactic winds (I)

- **model edge-on (starburst) galaxies:** e.g. NGC 253, NGC 3079
- underlying **galactic wind** model: **steady-state outflow** driven by **thermal gas, CR and wave pressures** (cf. Breitschwerdt et al. 1991)
- **dynamically and thermally self-consistent** modelling:
  - Outflow changes ϱ and T
  - this modifies ionization structure
  - which in turn modifies cooling function $\Lambda(\varrho, T)$
  - which changes outflow
- flow is described in a flux tube given by:

$$A(z) = A_0 \left[1 + \left(\frac{z}{H}\right)^2\right]$$

Mass-loaded wind flow!!!



***Top**: steady-state galactic wind model, in which gas, CRs and waves drive an outflow with a smooth subsonic-supersonic transition if there is strong coupling between CRs and gas*

Self-consistent Modeling of Outflows & Ionization Structure

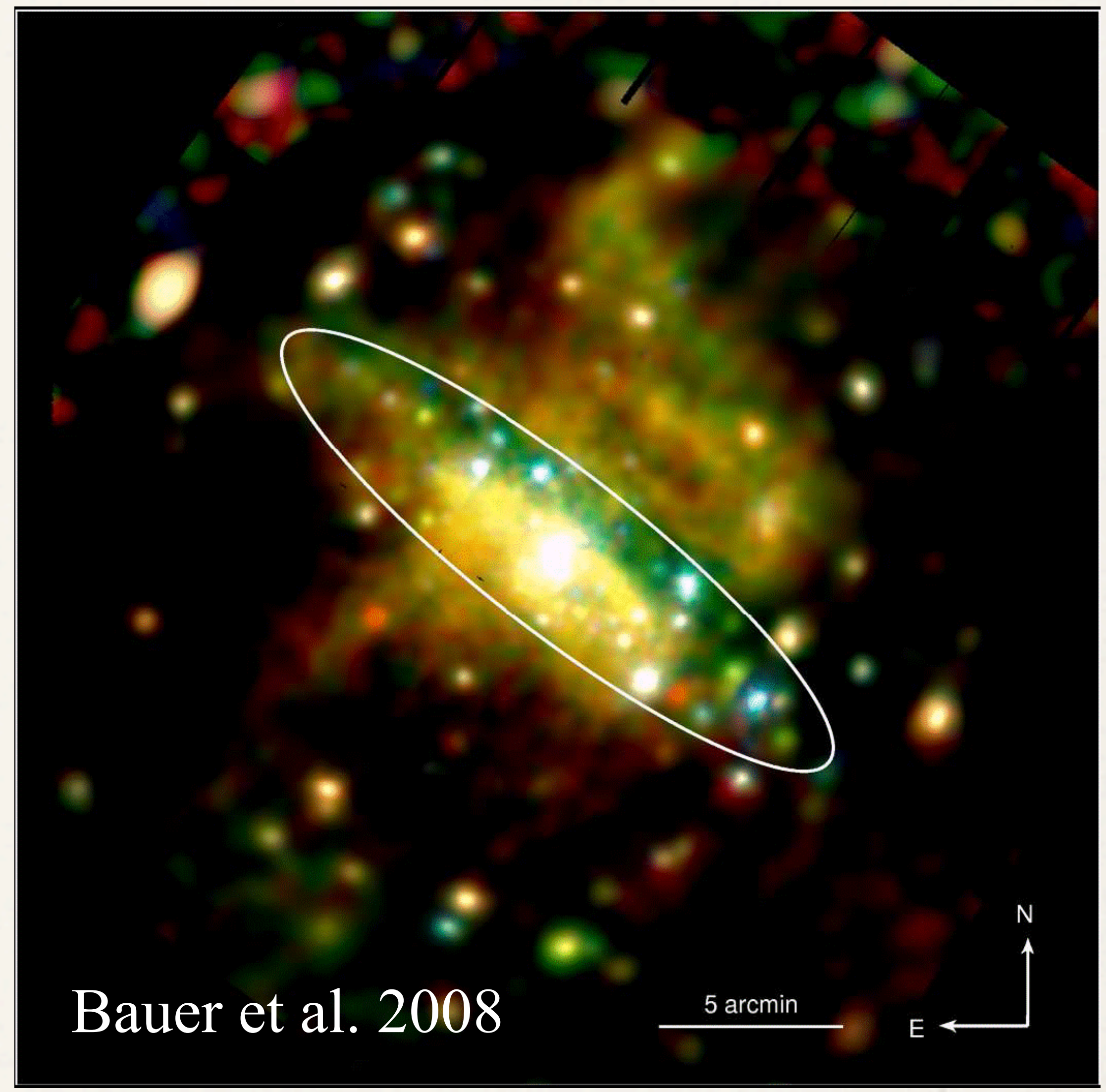
Procedure:

- **Generating** an outflow model and follow time-dependent evolution of ions (NEI)
- **Binning** of high-resolution unabsorbed synthetic (model) spectrum into e.g. EPIC pn channels (for XMM-Newton)
- **Folding** spectrum through detector response matrix

➡ Treating observed and synthetic spectrum equally!

- **Fitting** synthetic spectrum in XSPEC (X-ray spectral fitting routine) to observational data
- **Comparing** with observed spectrum and iterate outflow model if necessary until convergence

Modeling galactic halos with outflow (I): NCG 253

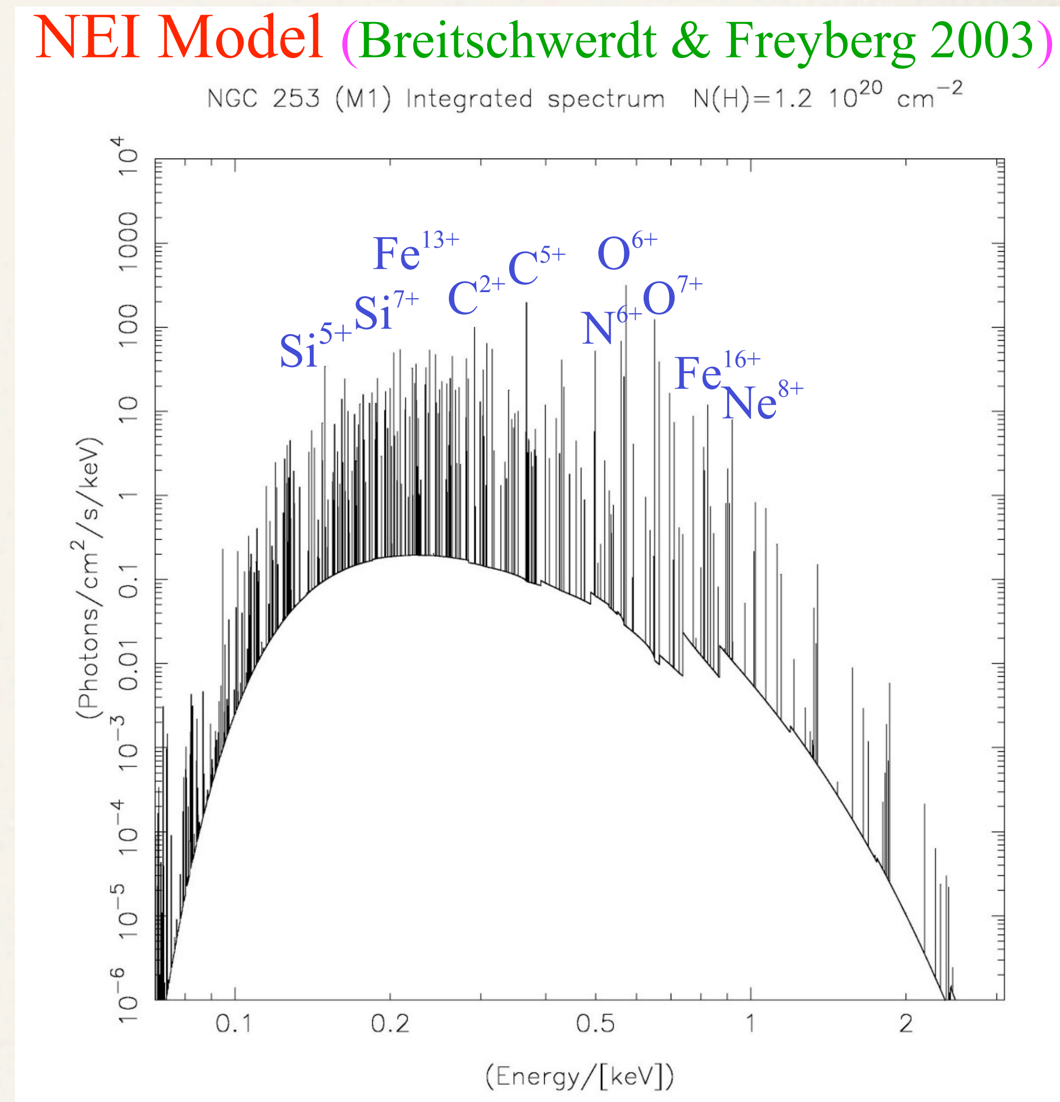


- 2MASS mosaic of NGC253
- Shows also extranuclear SB

- XMM EPIC pn: Soft X-ray halo of NGC253 (0.2 – 0.5 keV)

Modeling galactic halos with outflow (IV): NCG 253

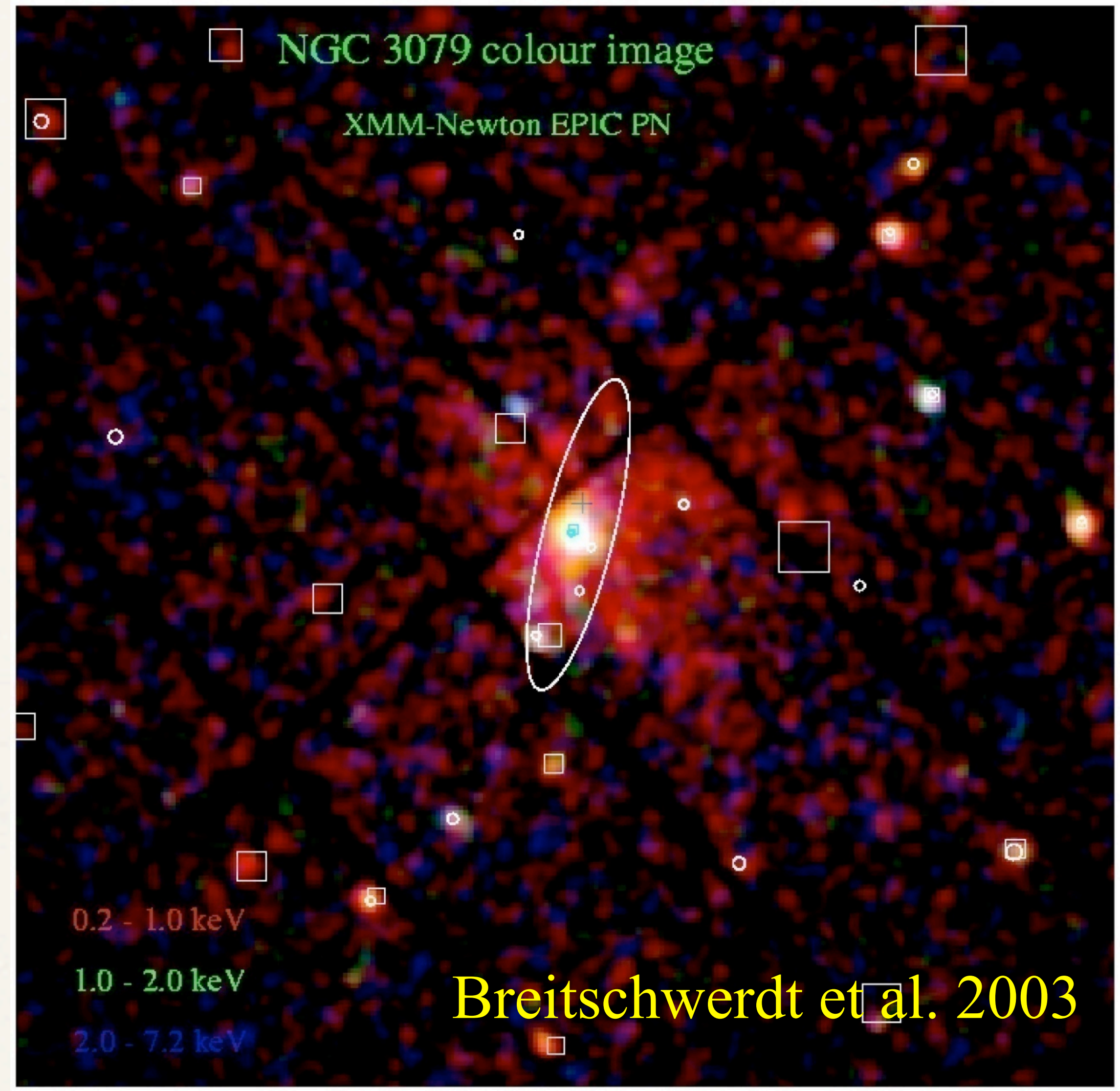
- **NEI spectrum** mimics a "multi-temperature" halo by its characteristic lines, but is physically radically different from it
- **Reason**: Sum of CIE spectra cannot represent the specific **thermodynamic** path of a true NEI spectrum



__Top__: Integrated spectrum of a dynamically and thermally self-consistent NEI simulation; the spectrum is a composite of continuum and lines, which are characteristic for the plasma history ➔ spectrum will be folded through detector response

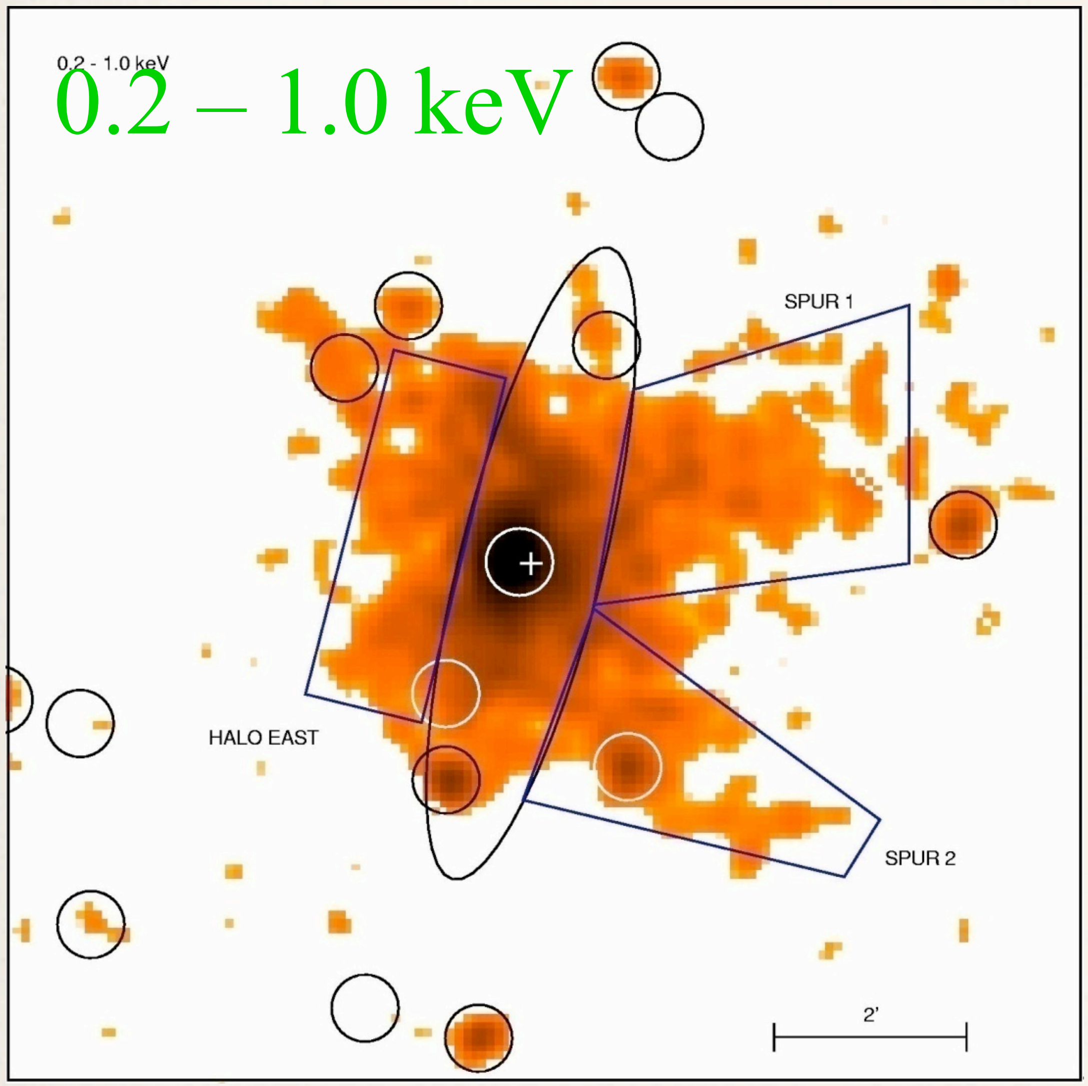
Modeling galactic halos with outflow (V): NCG 3079

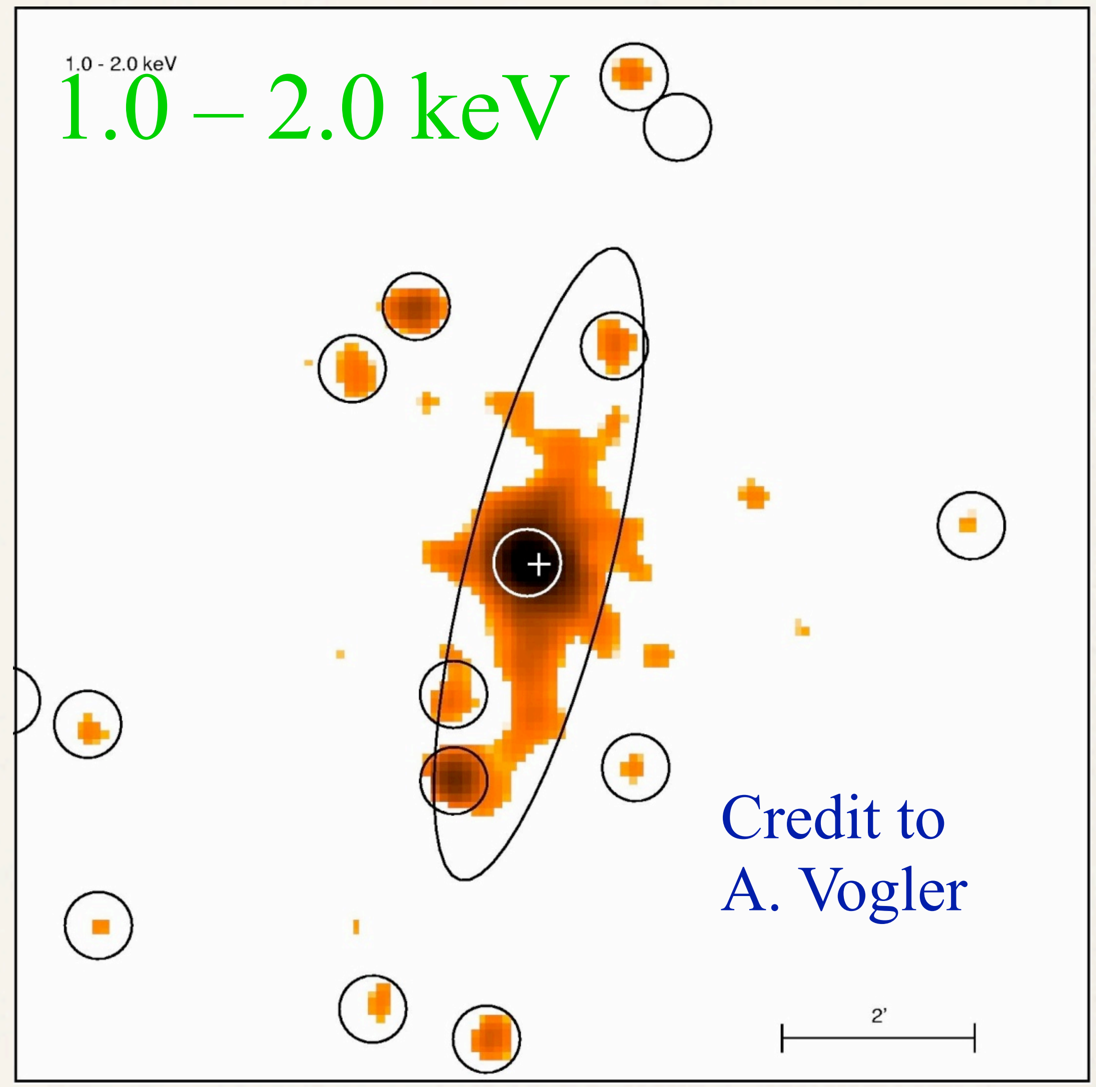
- **NGC 3079**: starbust LINER SBc galaxy
- Distance ~ 17 Mpc, Inclination ~ 85°
- **Low foreground absorption** Log(N(H))= 19.9 ➔ important for recording soft X-ray photons since photoelectric absorption ~ E^{-3}



Top: *NGC 3079, XMM-Newton image (EPIC pn camera); the optical disk is indicated by the D_{25} ellipse; the exposure was 25 ksec.*

Modeling galactic halos with outflow (VI): NCG 3079





- large extended soft halo emission
- $0.2 \leq E \leq 1.0$ keV

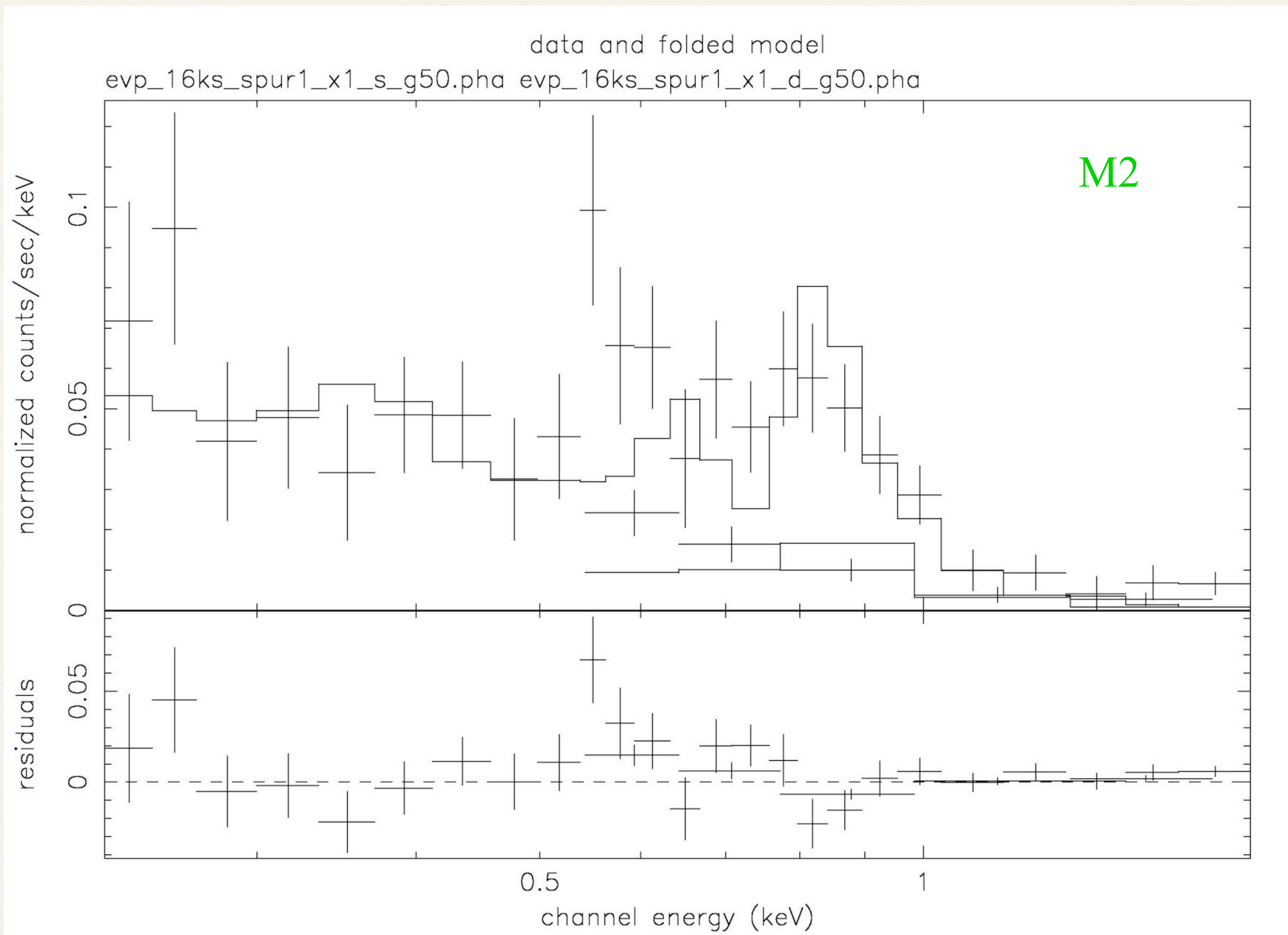
- morphology: soft X-ray spurs
- hard emission largely confined to disk

Modeling galactic halos with outflow (VII): NCG 3079

Model	n_0 [cm^{-3}]	T_0 [10^6 K]	B_0 [μG]	u_0 [km/s]
M1	$3\ 10^{-3}$	3.0	2.0	200.3
M2	$3\ 10^{-3}$	5.0	5.0	312.9
M3	$3\ 10^{-3}$	4.0	5.0	260.4
M4	$4.2\ 10^{-3}$	3.7	5.0	234.1
M5	$5\ 10^{-3}$	3.6	5.0	220.0

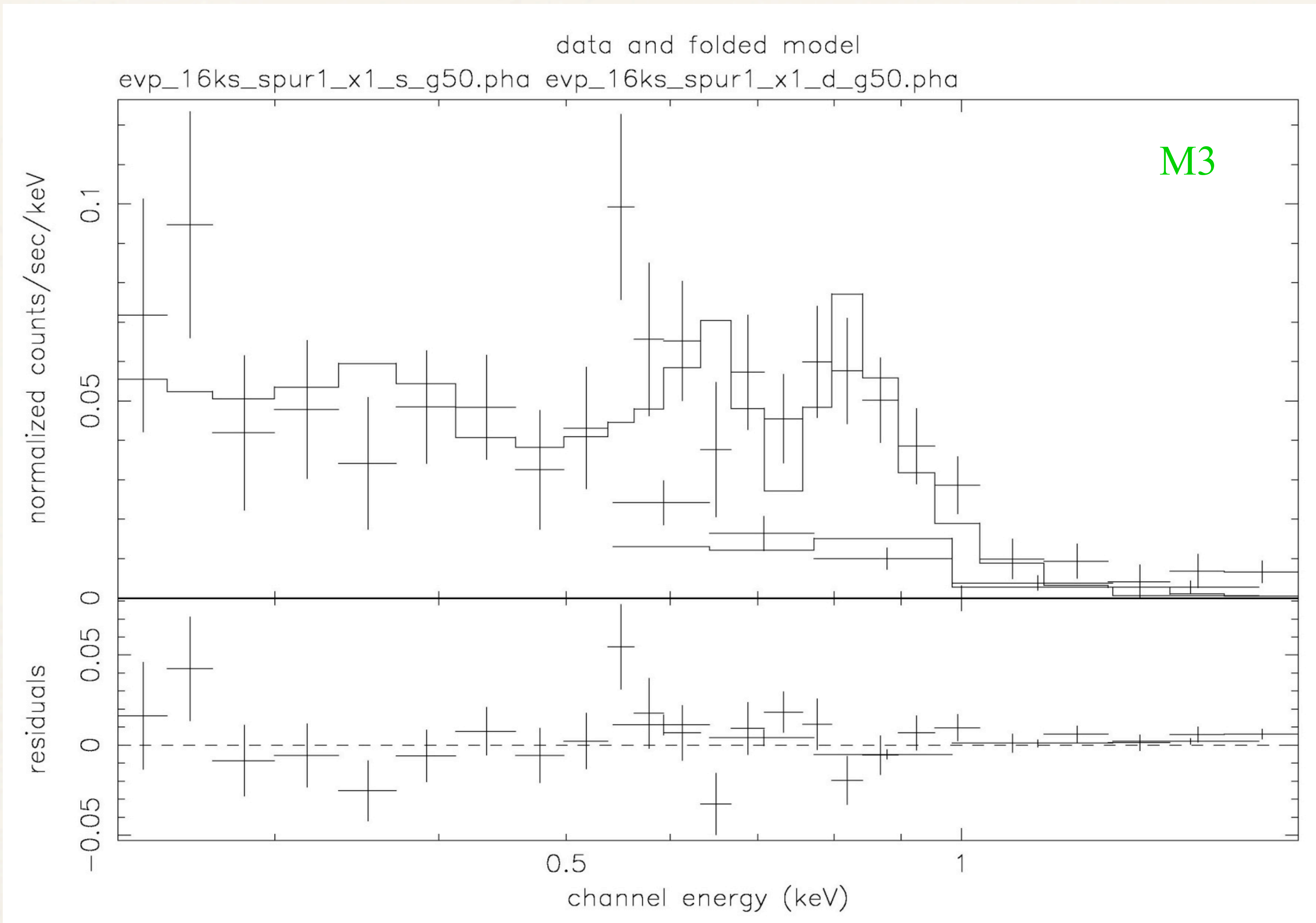
- changing inner boundary conditions, where wind is emanating

Modeling galactic halos with outflow (VII): NCG 3079

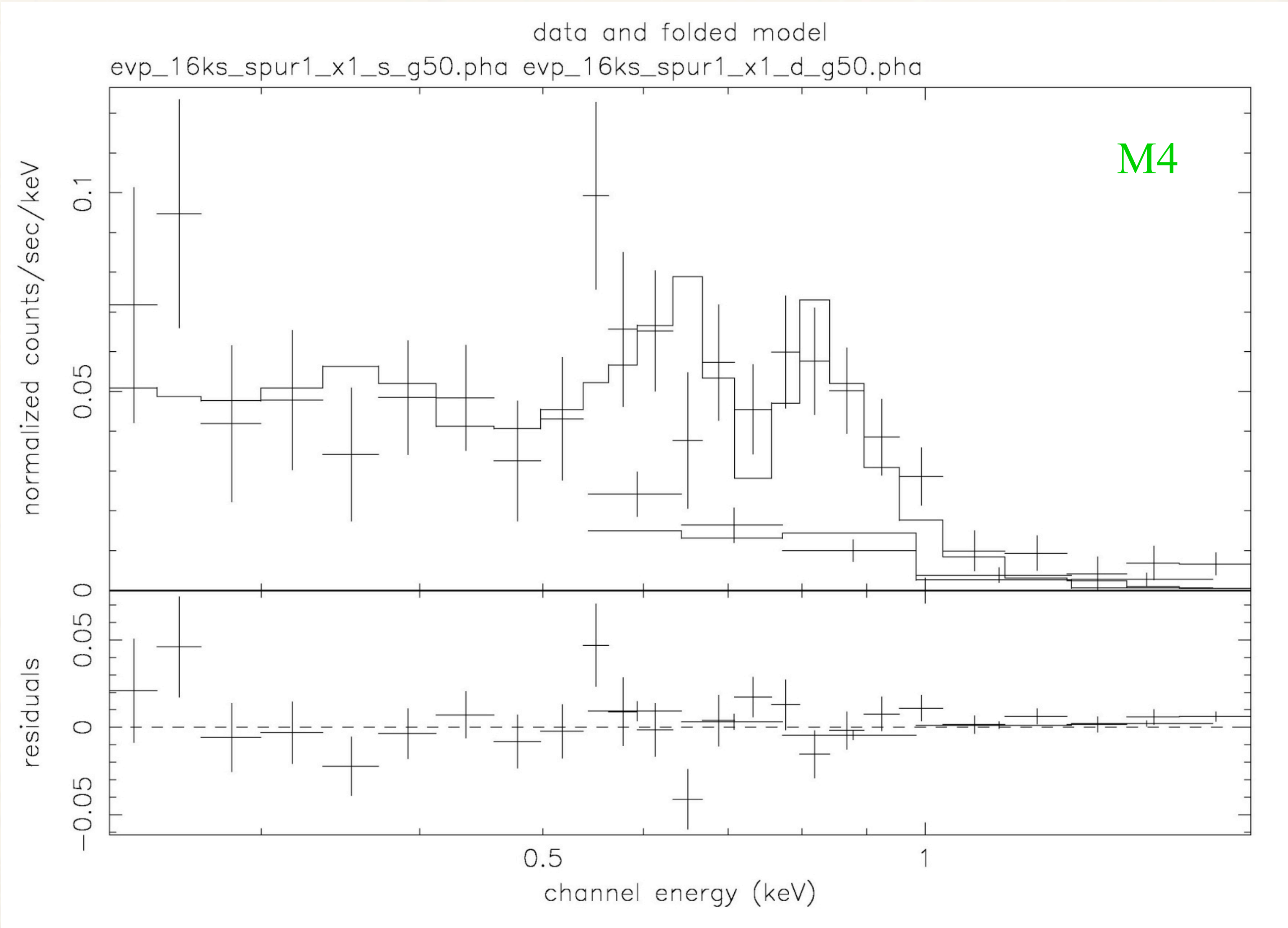


- bad fit in the 0.5 - 0.8 keV region
- too much emission in the 0.8 - 1 keV region ➔ T too high

Modeling galactic halos with outflow (VII): NCG 3079



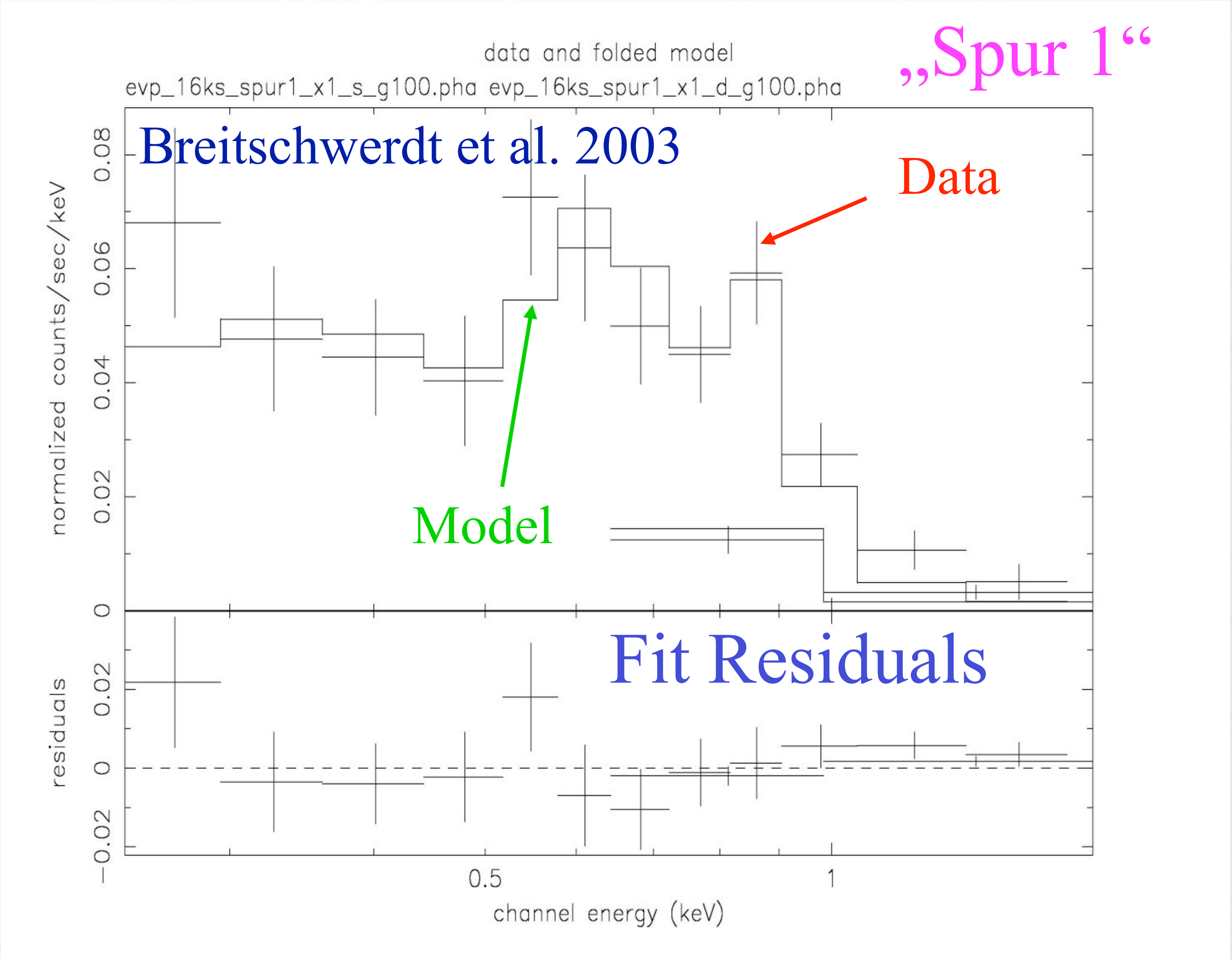
Modeling galactic halos with outflow (VII): NCG 3079



- better fit: T still slightly too high

Modeling galactic halos with outflow (VII): NCG 3079

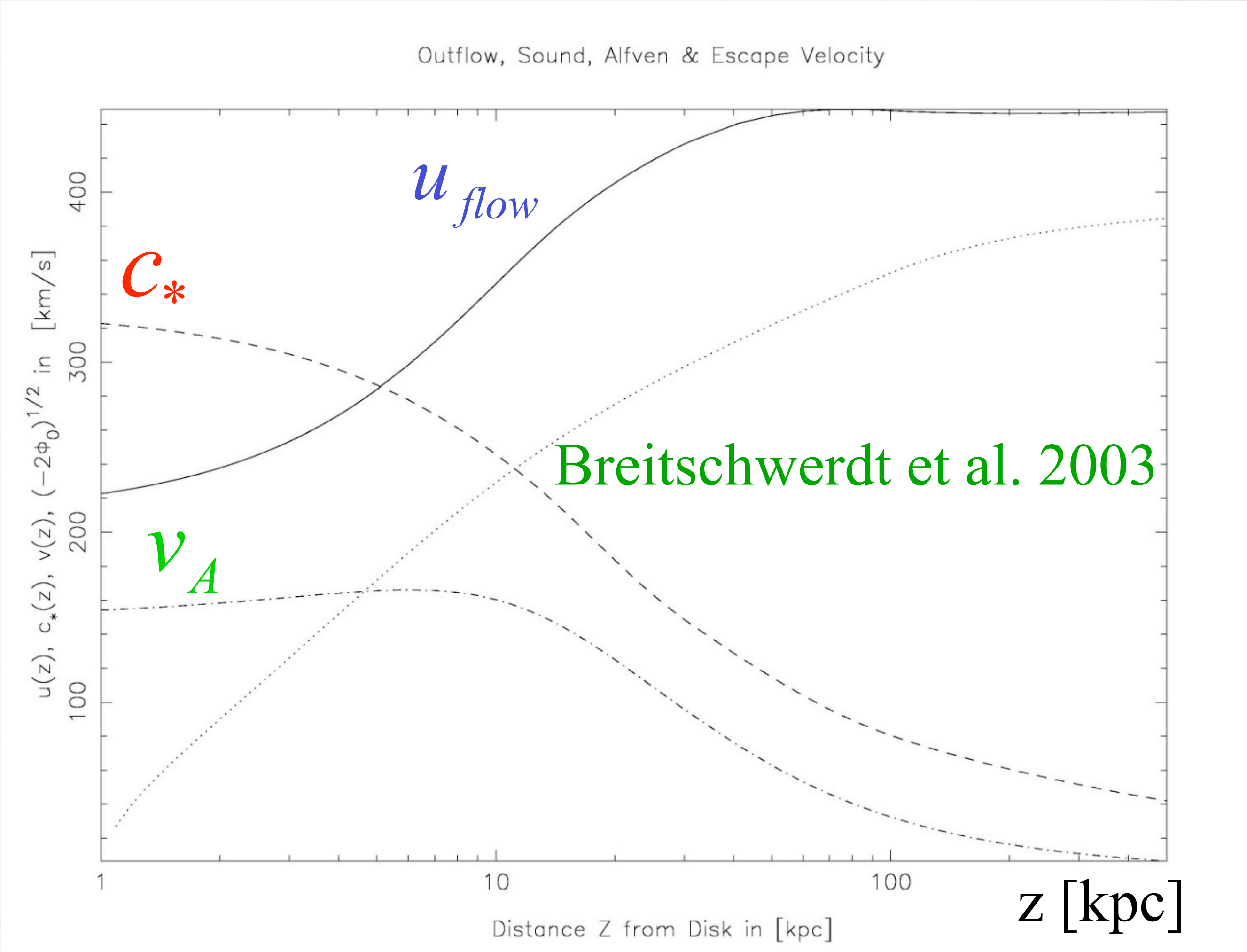
- **best fit model:**
- galactic wind with gravitational potential (including dark matter halo)
- **$n_0 = 5\ 10^{-3}\ cm^{-3}$, $T_0 = 3.6\ 10^6$ K, $B_0 = 5\mu G$, $u_0 = 220$ km/s**
- foreground absorption: N(H) = $3.9\ 10^{20}\ cm^{-2}$
- goodness of fit: $X^2_{red} = 1.2$
- derived mass loss rate: dm/dt = $\varrho_0\ u_0 = 0.055\ M_{sol}/yr/kpc^2$
- **mass loss rate in "spur" region** (R = 8kpc): dM/dt = $\pi/2\ R^2\ \varrho_0\ u_0$ = **$3.5\ M_{sol}/yr$**



Top: Comparison between data and dynamically and thermally self-consistent galactic wind model ➔ 5 iterations were necessary to achieve an acceptable fit

Modeling galactic halos with outflow (V): NCG 3079

- **NGC 3079: smooth subsonic-supersonic transition ➔** critical point (M=1) in the flow at z ~ 5 kpc from the disk
- superbubble gas injected at the inner boundary (z_0 = 1 kpc) with initial velocity u_0 = 220 km/s (subsonic, but super-alfvenic)
- terminal velocity ~ 450 km/s



Top: Derived outflow characteristics for the best fit model

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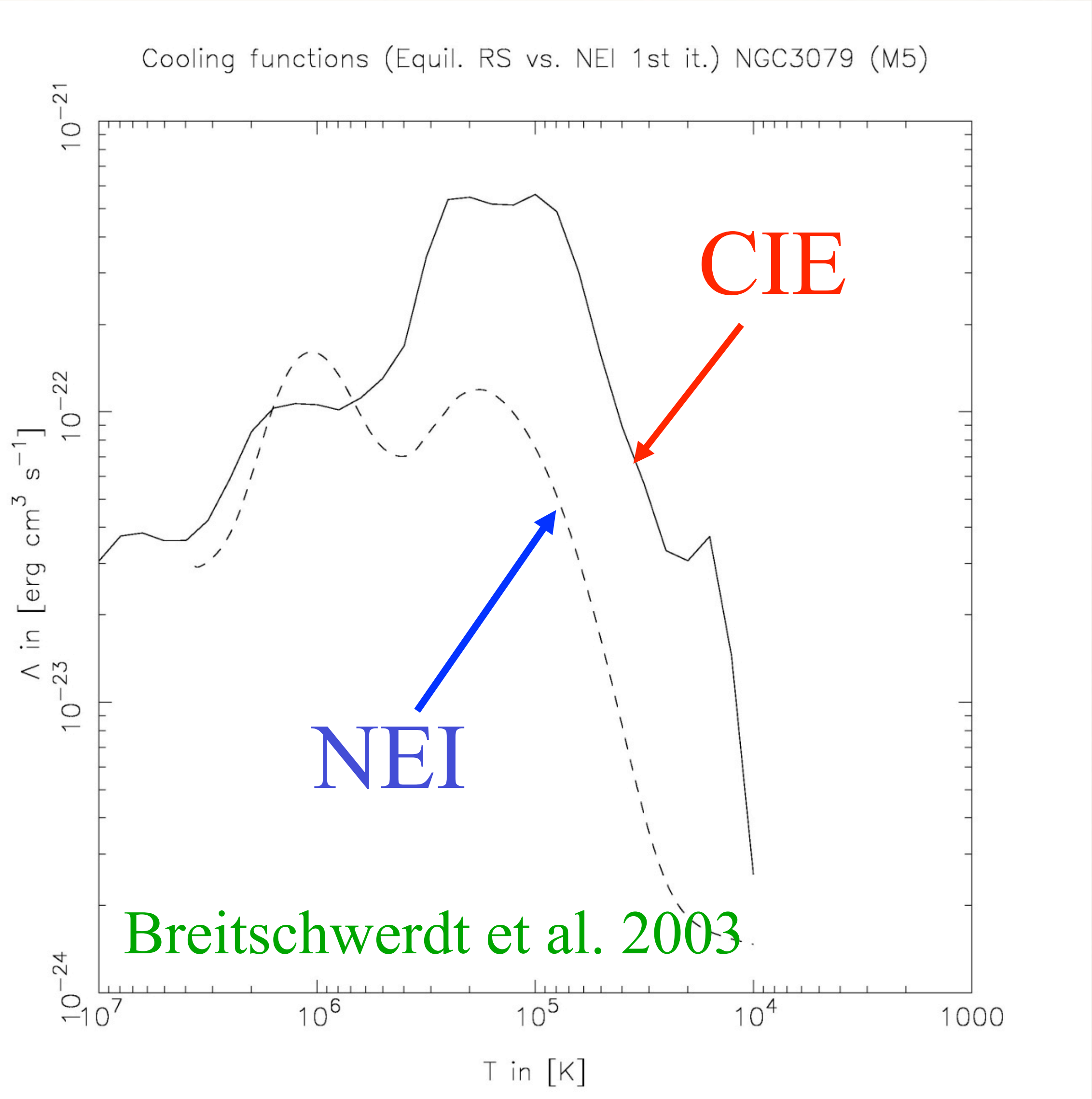
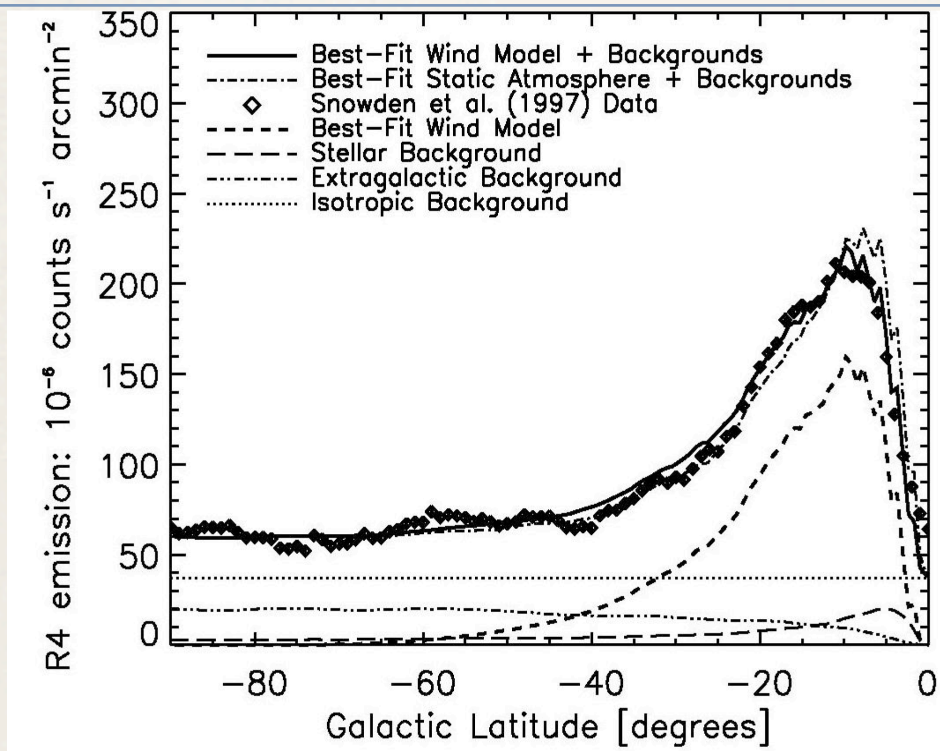
Modeling galactic halos with outflow (V): NCG 3079

- **Cooling Function**: Cooling curve depends on the ionization state of the plasma
- in case of a fast adiabatically expanding flow the difference between CIE and NEI cooling curves is striking
- whereas the CIE cooling curve peaks at ~ 10^5 K, the NEI curve in this particular model has a maximum ~ 10^6 K, where OVII, OVIII lines are abundant due to **delayed recombination**

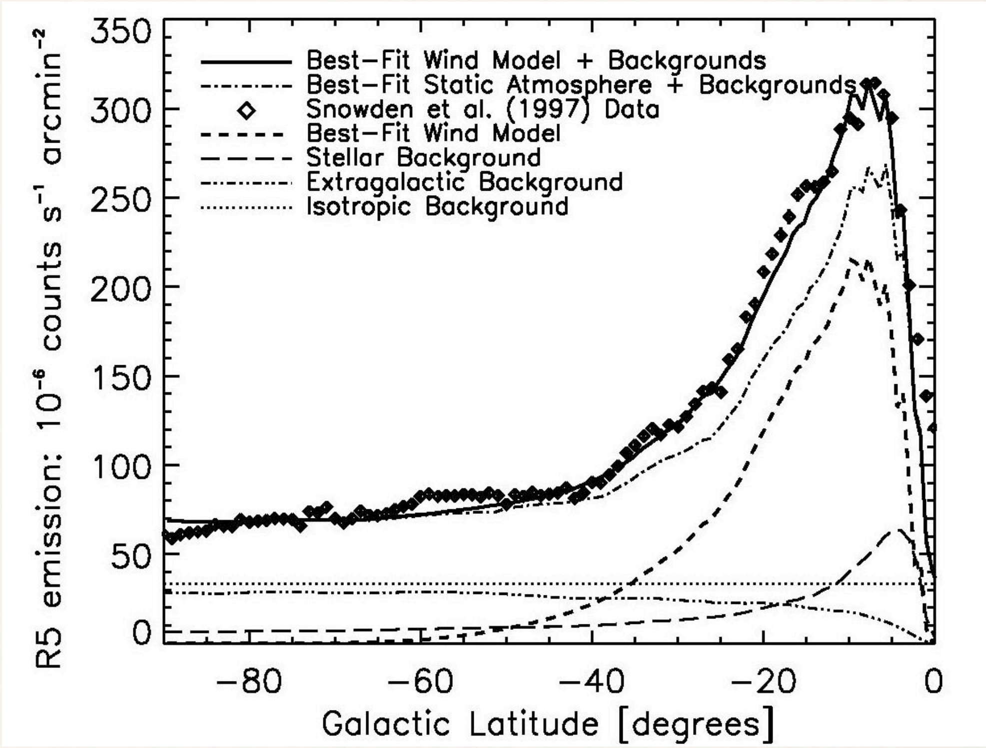


Top: *Comparison between cooling curve for CIE and for a dynamical NEI model for the starburst galaxy NGC 3079*

Cosmic Ray driven Wind in the Milky Way?



Top: *ROSAT PSPC observations (Snowden et al. 1997); shown is ROSAT R4 band (0.64 keV)*

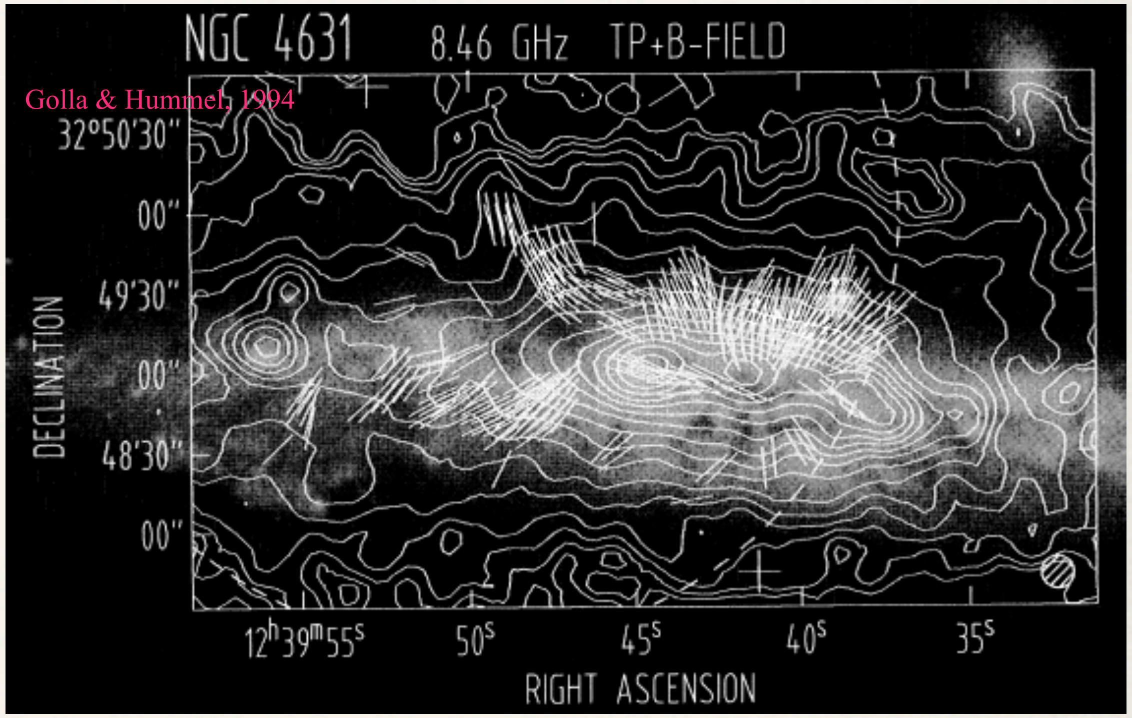


Top: *ROSAT PSPC observations (Snowden et al. 1997); shown is ROSAT R5 band (0.85 keV)*

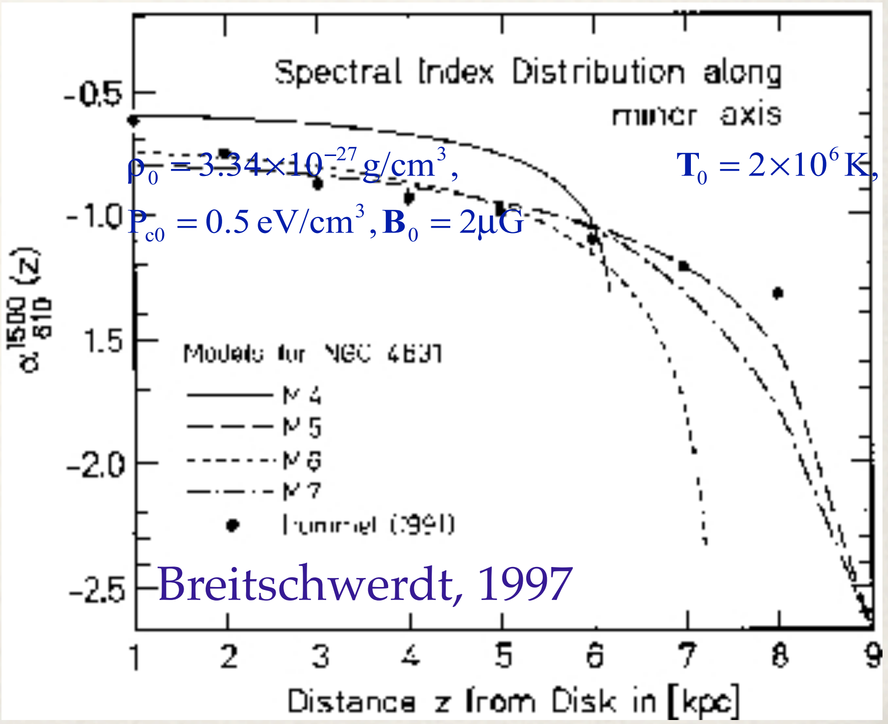
- To fit ROSAT PSPC data in a given region of the MW sky, Everett et al. (2008) show that a **CR driven wind** gives a statistically much better fit than a hydrostatic halo (especially for ROSAT R5 band)
- for lower halo here CIE is a good approximation, since deviation from NEI still small
- fiducial wind model for Milky Way: $\mathbf{n_0 = 6.9\ 10^{-3}\ cm^{-3}}$, $\mathbf{T_0 = 2.9\ 10^6\ K}$, $\mathbf{u_0 = 173\ km/s}$

CR electron transport in galactic halos (I): NCG 4631

- **Non-thermal radio emission of NGC 4631:** significant linear polarization for z ≤ 5 kpc
- noticeable B-field component perpendicular to galactic disk
- **Modelling**: solve **diffusion-advection transport equation for electrons** incl. **synchrotron** and **inverse Compton** losses
- **radio spectral index** variation is a measure of dominant transport process: flat curve is indicative of accelerating **advection** flow, compensating for increasing losses with time ➔ galactic wind



Top: radio map superimposed with polarization vectors on optical image
Right: self-consistent spectral index variation in galactic wind model

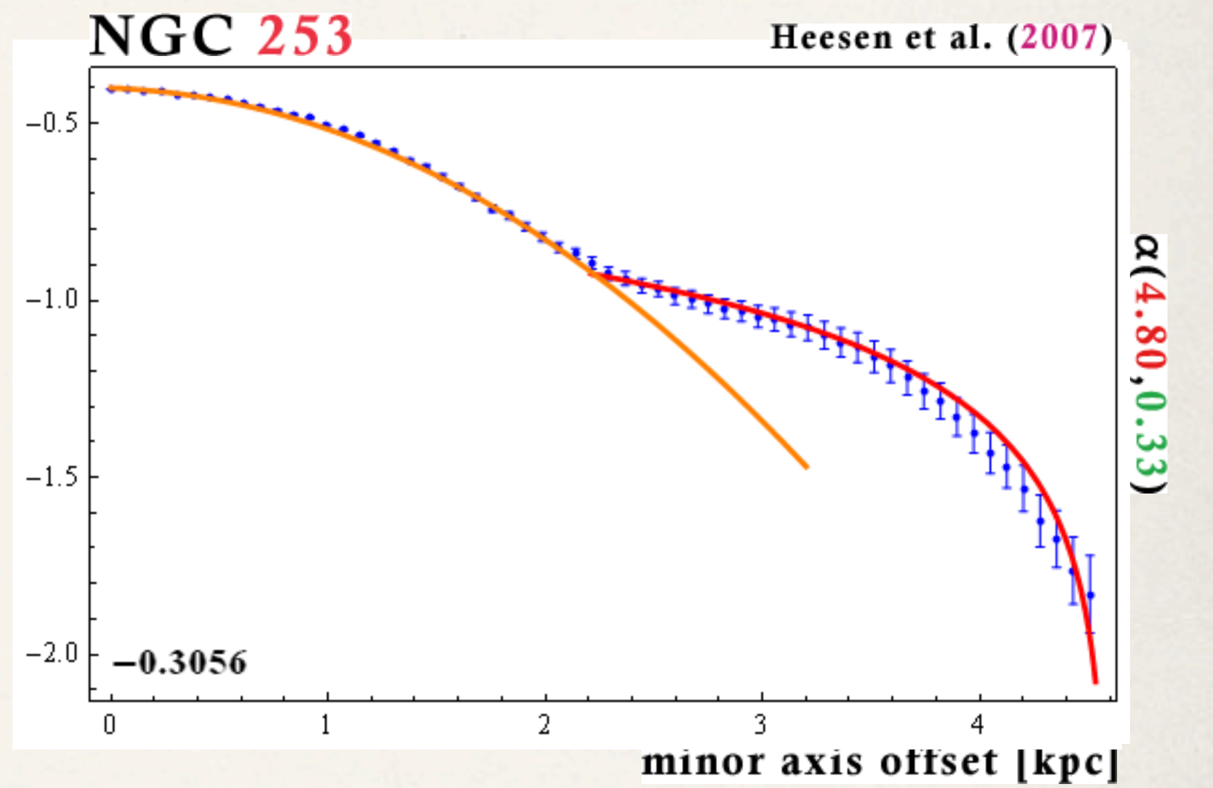


CR electron transport in galactic halos (II): NCG 253

- **Non-thermal radio emission of NGC 253:**
- CR electron transport equation

$$
\begin{aligned}
& - \frac{\partial}{\partial z}\left(D(E,z)\frac{\partial N(E,z)}{\partial z} - u(z)N(E,z)\right) \\
& - \frac{\partial}{\partial E}\left(\frac{1}{3}\frac{du}{dz}EN(E,z) - \frac{dE}{dt}N(E,z)\right) = Q(E,z) \\
Q(E,z) & = K_0 E^{-\gamma_0} h_g \delta(z)
\end{aligned}
$$

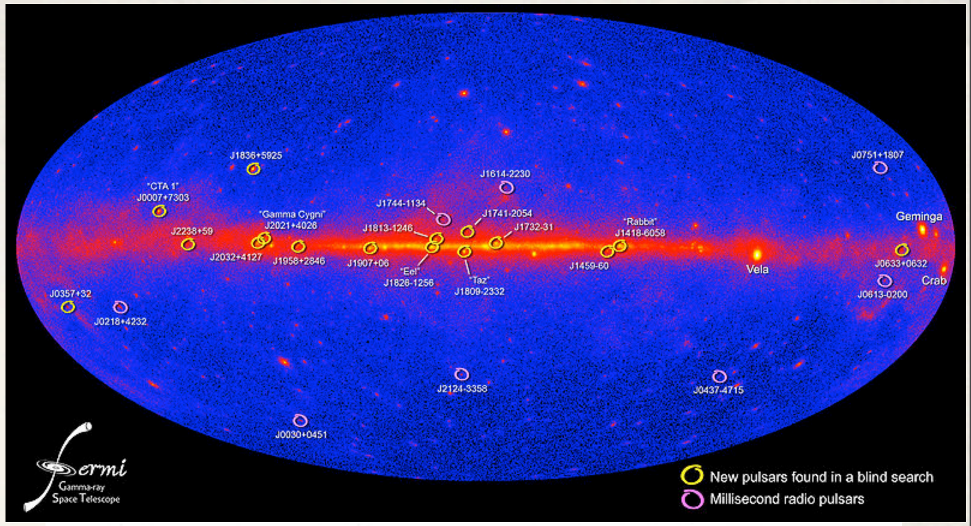
- spectral index close to sources up to vertical distances from disk of z ~ 1-2 kpc dominated by **diffusion**
- for z ≥ 1-2 kpc transport dominated by **advection**
- transport mechanism varies locally in agreement with local superbubble break-out from galactic disk



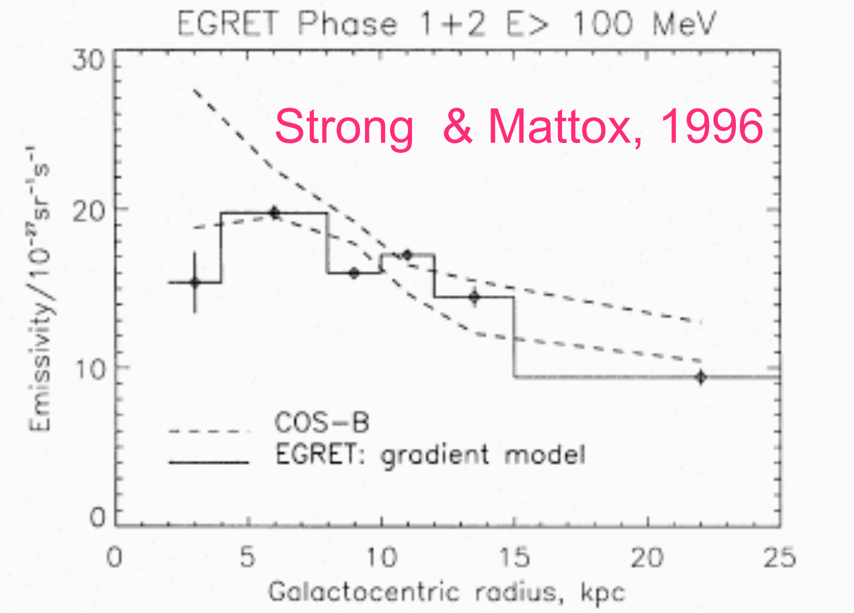
Advection Diffusion Diffusion-Advection

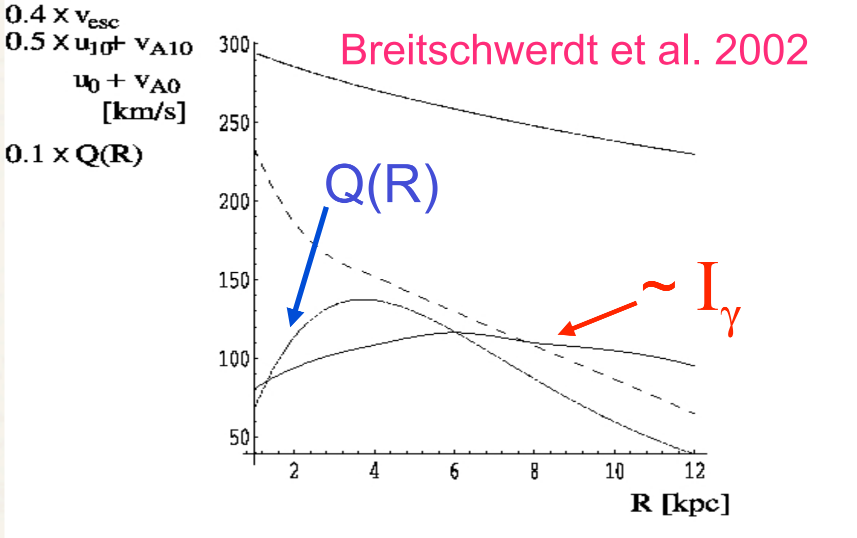
Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.

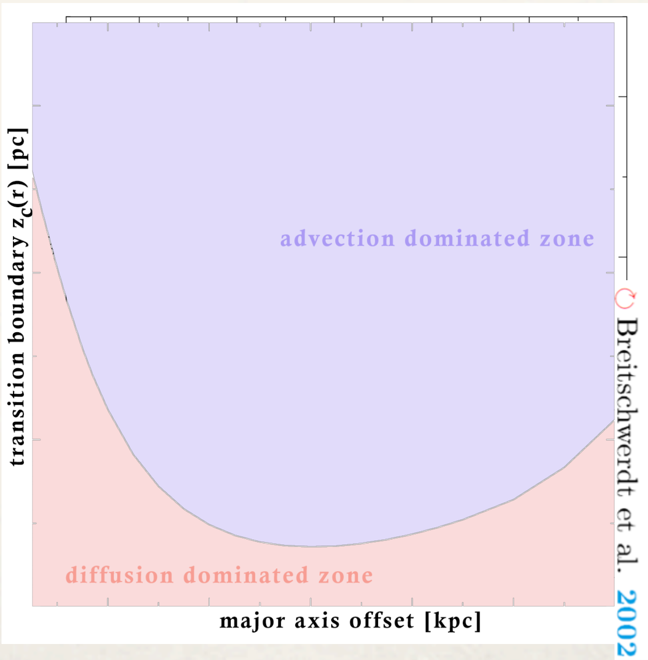
Radial Diffuse γ-ray Gradient in the Galaxy



- **Diffuse γ-ray gradient in the Milky Way:** Cos-B, EG-RET measured **shallow** gradient of diffuse γ-emission
- for E > 100 MeV γ-rays are mainly due to **π_0-decay**, which are due to interaction between CR protons and HI atoms ➔ γ-emission should follow **CR source** distribution (SNRs and pulsars), which peaks at R ~ 4 kpc
- diffusion model can only marginally reproduce γ-ray gradient for huge CR halo
- **simple model**: radially dependent **diffusion-advection** boundary due to local radial variations in **star formation**



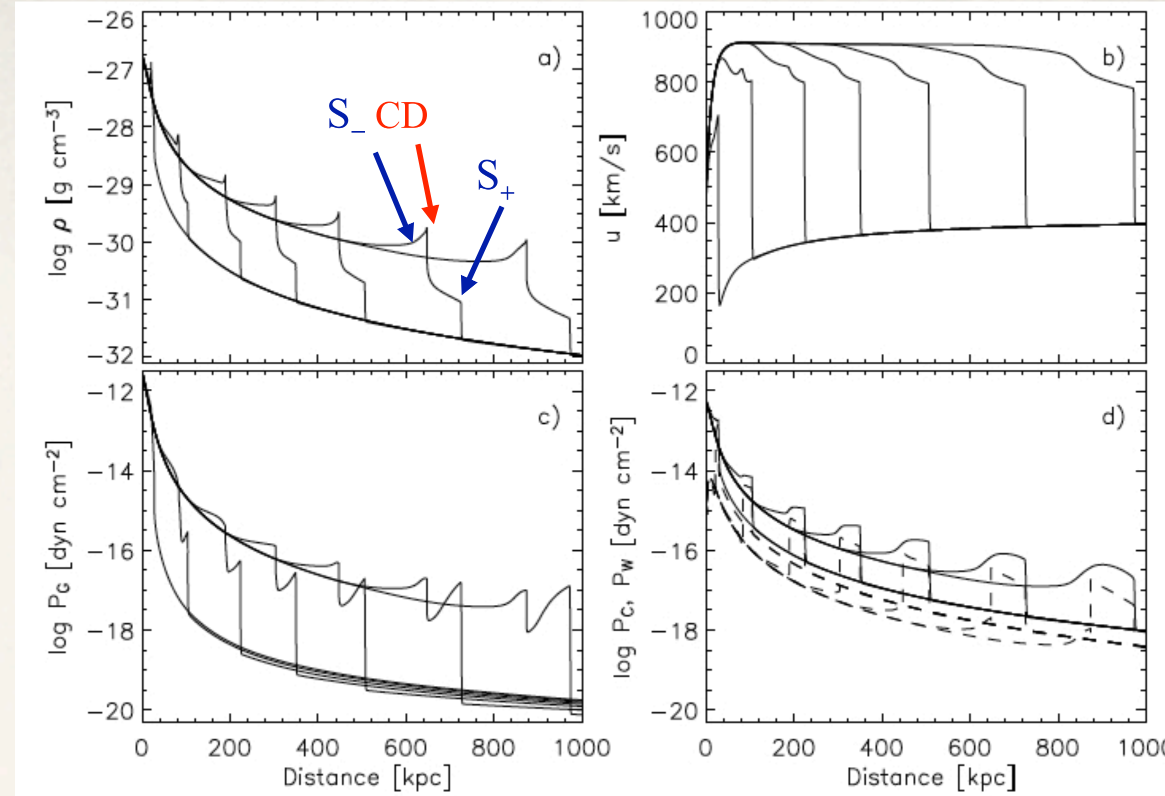




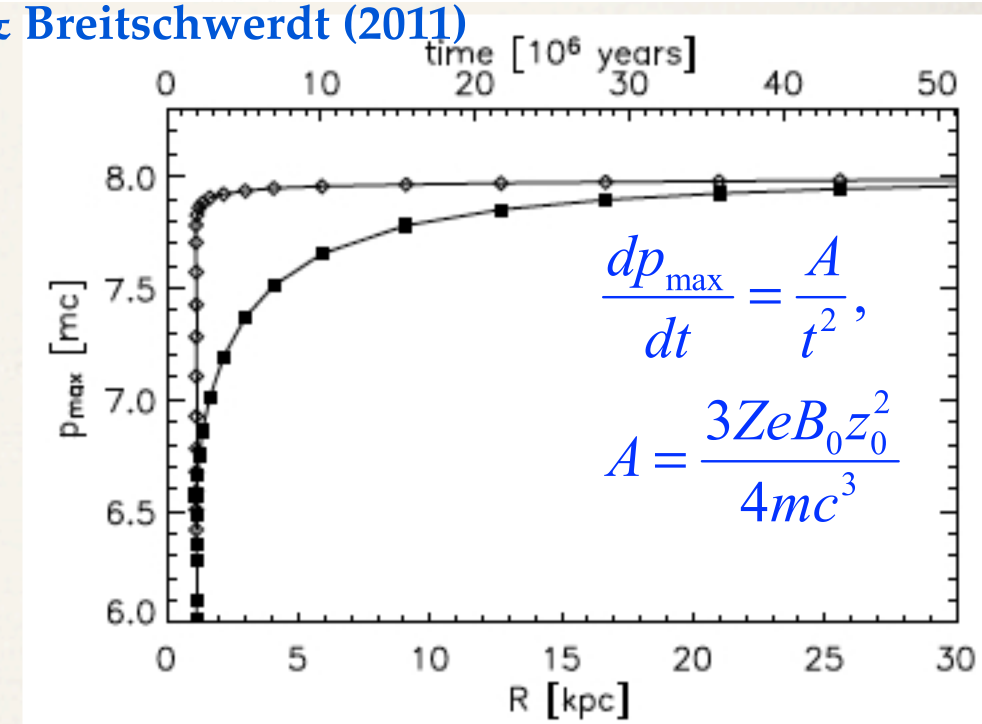
Top: Fermi γ-ray all-sky survey
Middle: diffuse γ-ray gradient according to COS-B and EGRET observations
Bottom: model (galactic wind) of diffuse γ-ray emission

CR acceleration beyond the “Knee” (I)

- **Time-dependent galactic wind** calculations (Dorfi & Breitschwerdt 2010) confirm **stationary** wind solutions as time-asymptotic flow
- for starburst galaxies we use **time-dependent boundary conditions**, reflecting the duration of a starburst ➔ increase of CR & gas pressures by a factor of 10 at $z=z_0$
- double shock structure in the galactic wind region ➔ **post-acceleration** of galactic CRs (**1st order Fermi**)
- particles are convected downstream of **forward shock**, i.e. towards the galactic disk
- particle acceleration modifies shock ➔ **subshock** ➔ shock strengthens as propagating down a density gradient
- within a few 10^6 - 10^7 yr, particles can reach energies up to **10^{17} - 10^{18} eV**



Dorfi & Breitschwerdt (2011)



Top: density (a), velocity (b), gas (c), CR and wave pressures (d) for shocks in a galactic wind of the Milky Way for $3\ 10^7 \leq t \leq 10^9$ yr
Bottom: maximum momentum of particles post-accelerated in galactic wind for forward (filled squares) and forward + reverse shock (diamonds)

Summary & Conclusions

- Cosmic Rays (CRs) are essential component of ISM
- CR energy density comparable to thermal plasma, magnetic field, turbulent motions
- CR composition similar to ISM but with light element enhancement (spallation)
- CR differential energy spectrum consists of power laws
- 10% of total SN energy is turned into CRs
- Diffusive shock acceleration as most probable mechanism
- CRs leave Galaxy ➔ replenishment in ~ 2 10^7 yr
- CRs couple to plasma via self-excited waves ➔ CR transfer momentum to gas
- CR driven outflows ➔ galactic winds
- enhanced star formation and **superbubbles** drive thermal **galactic winds**
- winds can explain **X-ray and radio halos ➔ thermally & dynamically self-consistent** models ➔ flattening of **radio spectral index** due to **advection flow**
- **CR acceleration** beyond the "**knee**" ➔ wind shocks can explain energies & spectrum!

Thank you for your attention!

CR acceleration beyond the "Knee" (I)

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- for starburst galaxies we use **time-dependent boundary conditions**, reflecting the duration of a starburst ➔ increase of CR & gas pressures by a factor of 10
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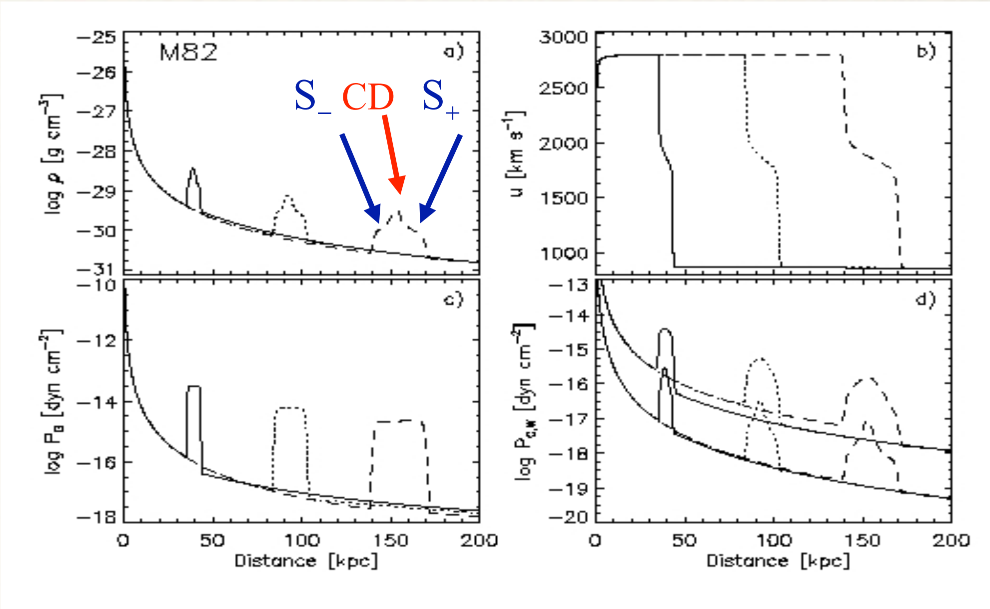

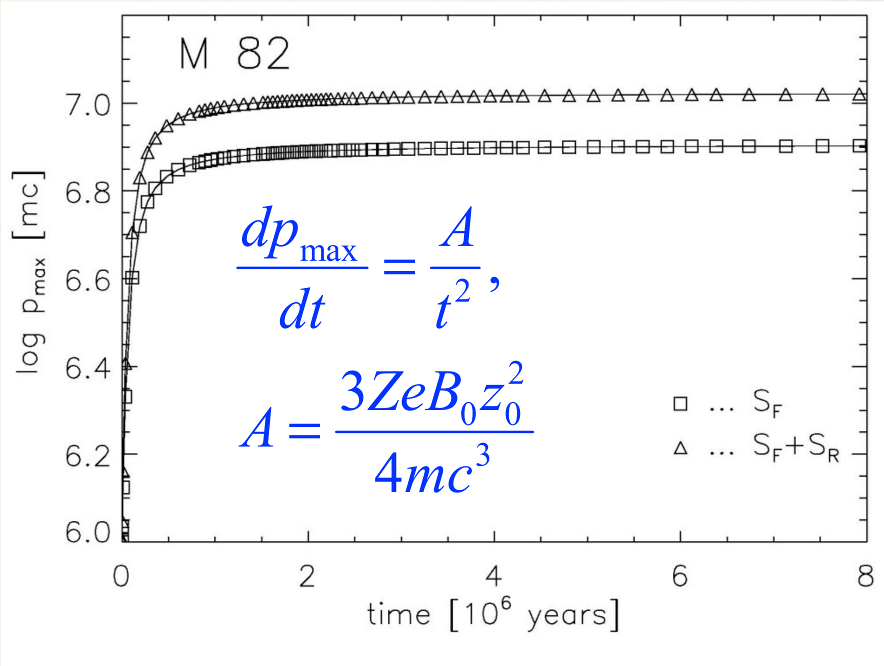

$$\frac{dp_{max}}{dt} = \frac{A}{t^2},$$

$$A = \frac{3ZeB_0 z_0^2}{4mc^3}$$

__Top__: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.