Max-Planck-Institut für
Astrophysik

MAX-PLANCK-GESELLSCHAFT

Galactic outflows and cosmic rays

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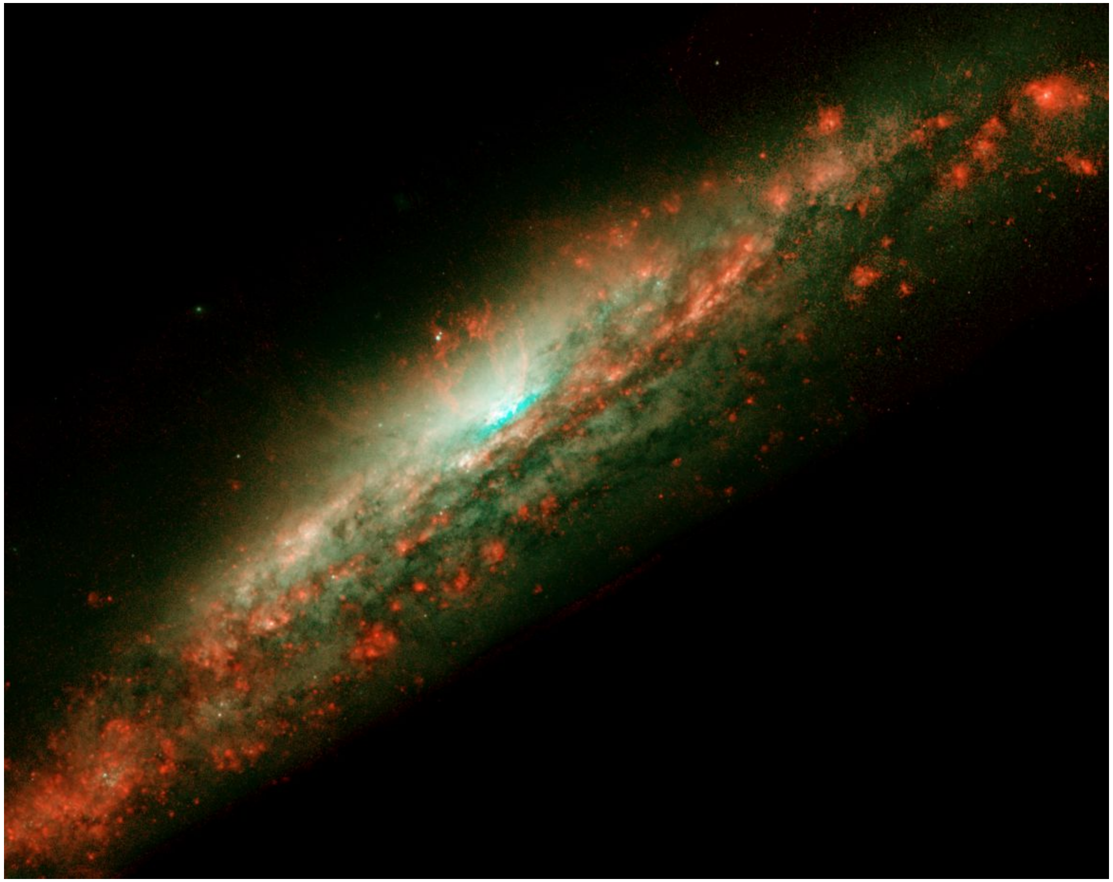
‘SN driven’ winds in other galaxies

- Strong bi-polar outflows (200 – 500 km/s) at rates similar to the star formation rate are detected in all star forming galaxies and mergers (up to z ≈ 2) starbursts (e.g. Heckmann et al. 1990, Martin 2005, Veilleux et al. 2005, Martin et al. 2012, Sturm et al. 2011, Rubin et al. 2014 etc.)

'SN driven' winds in other galaxies



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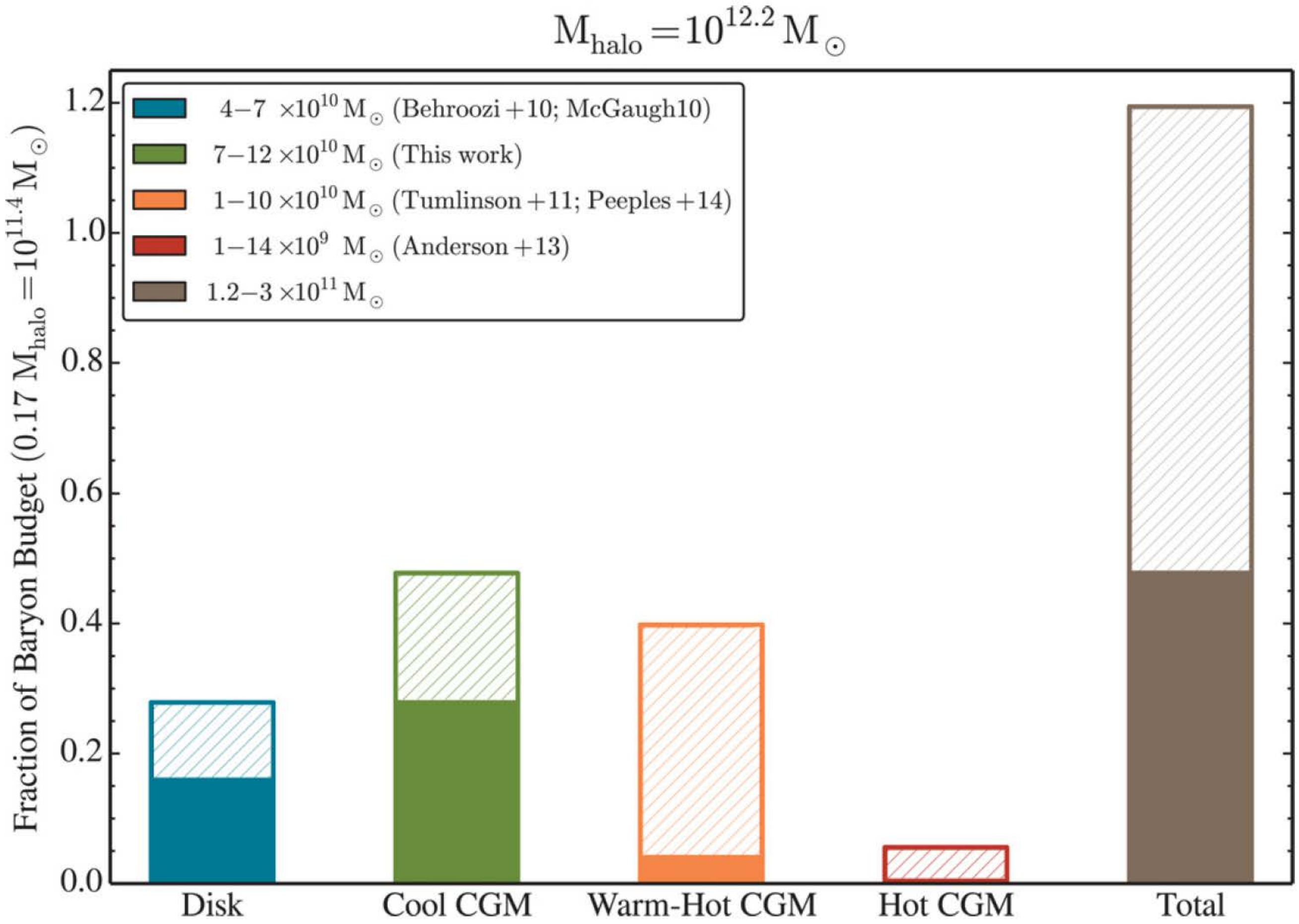
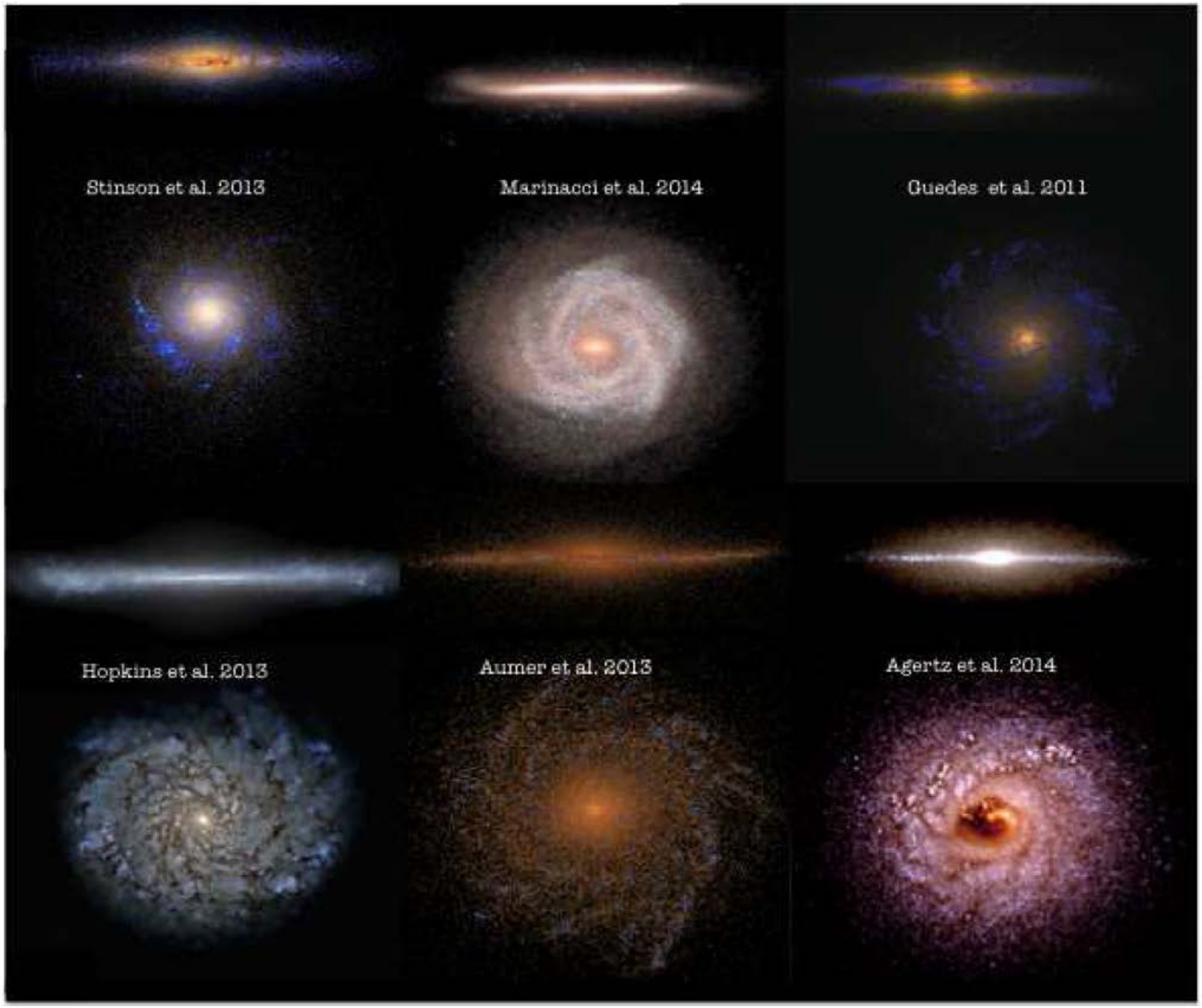
Most of the baryons are in the halos



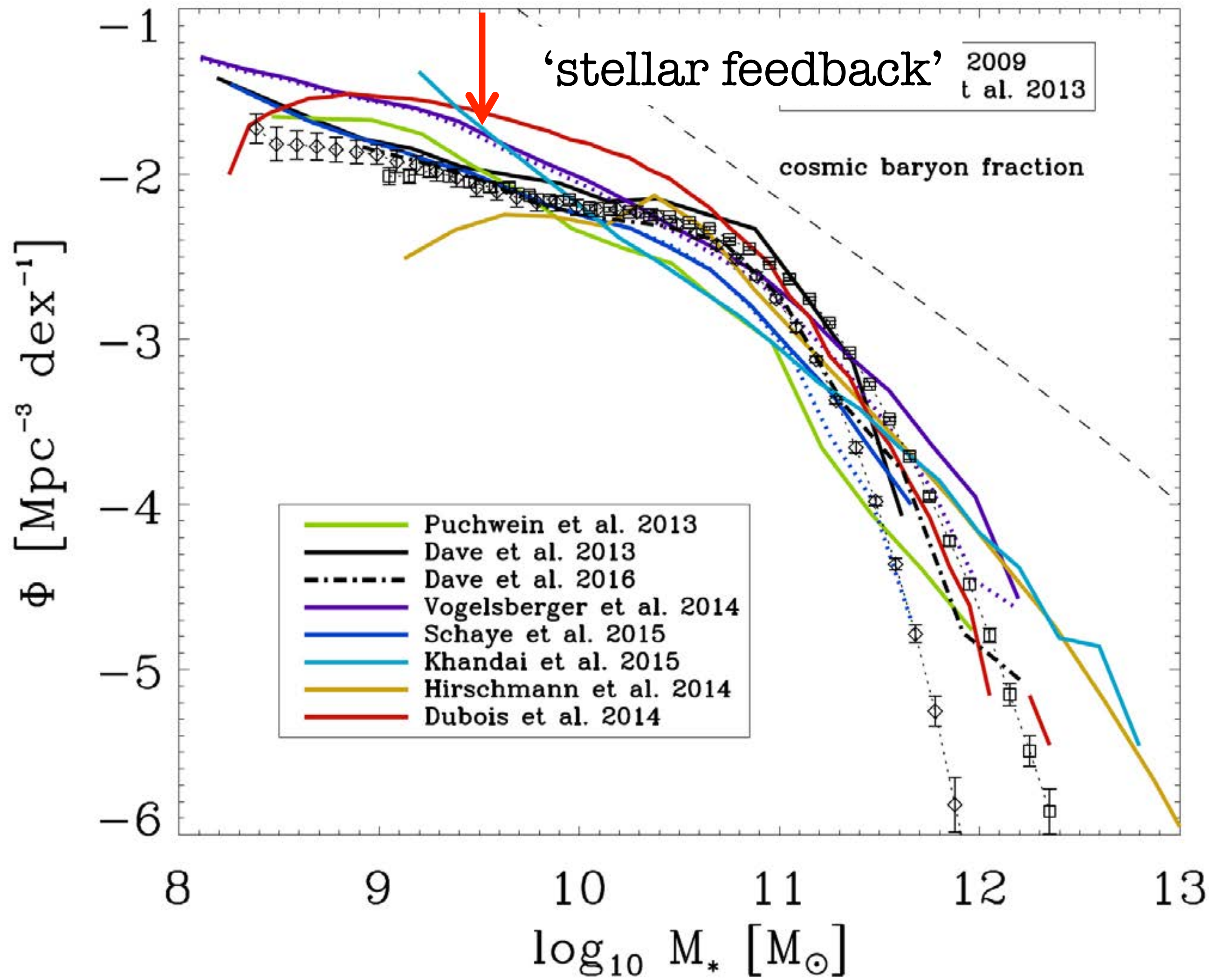
- Most of the baryons are in the galactic halos (e.g. Werk et al. 2014)
- All of this is might be regulated by massive stars

Disk galaxies in cosmological simulations



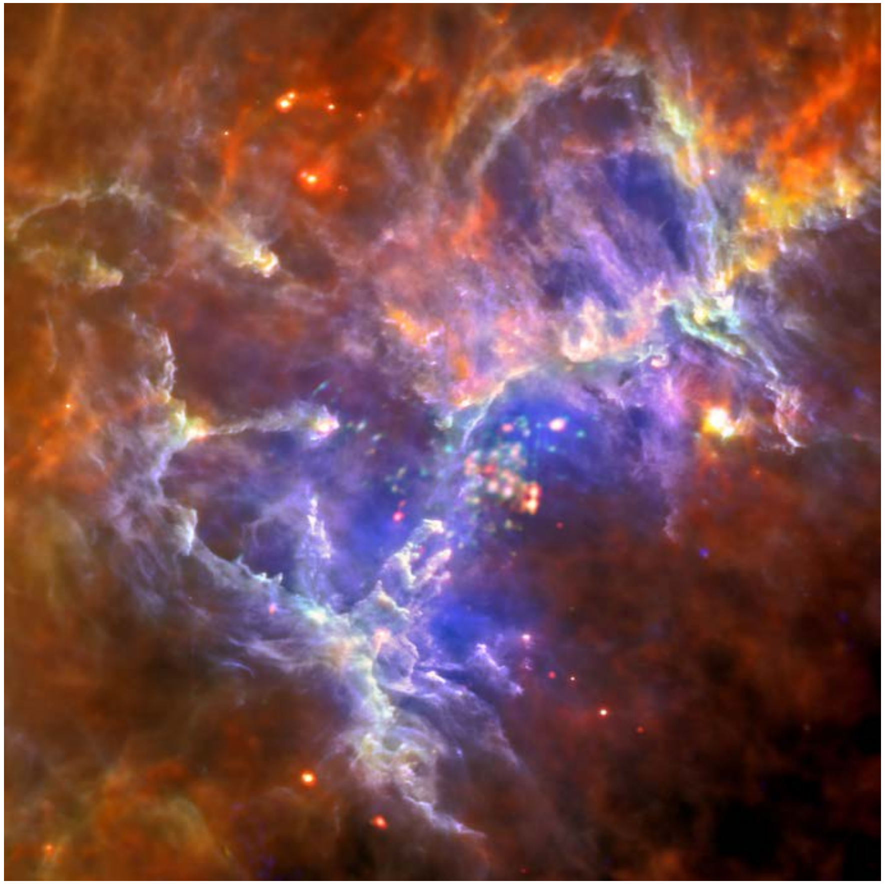
Naab & Ostriker, 2017, ARA&A

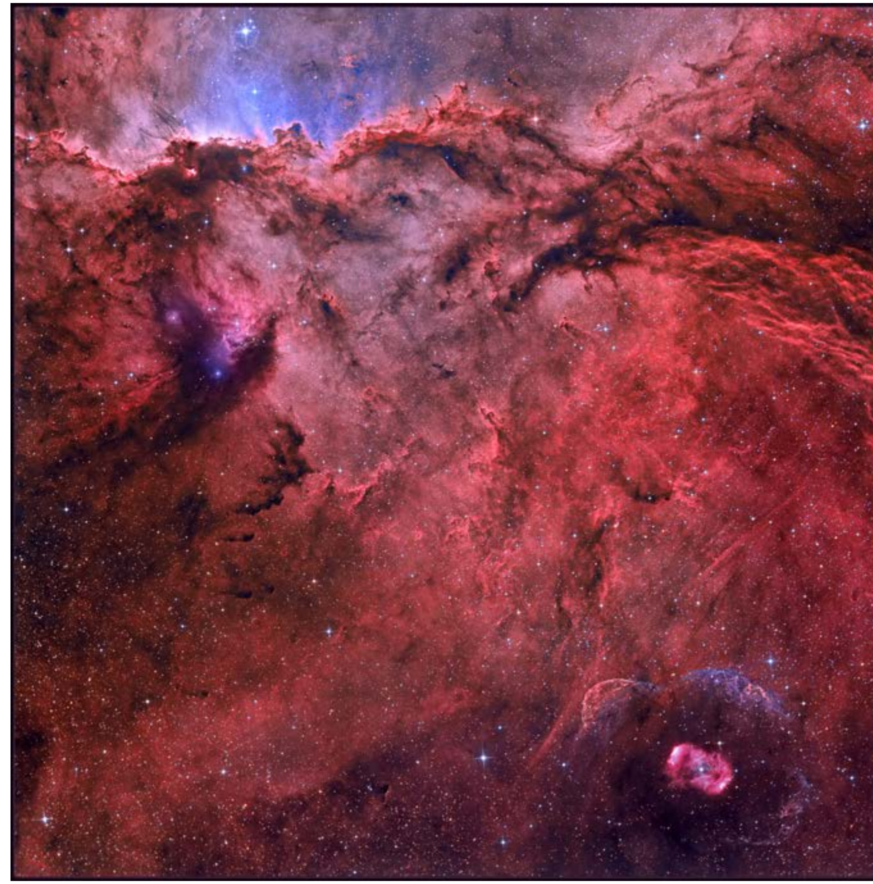
Galaxy populations in cosmological simulations



Naab & Ostriker, 2017, ARA&A

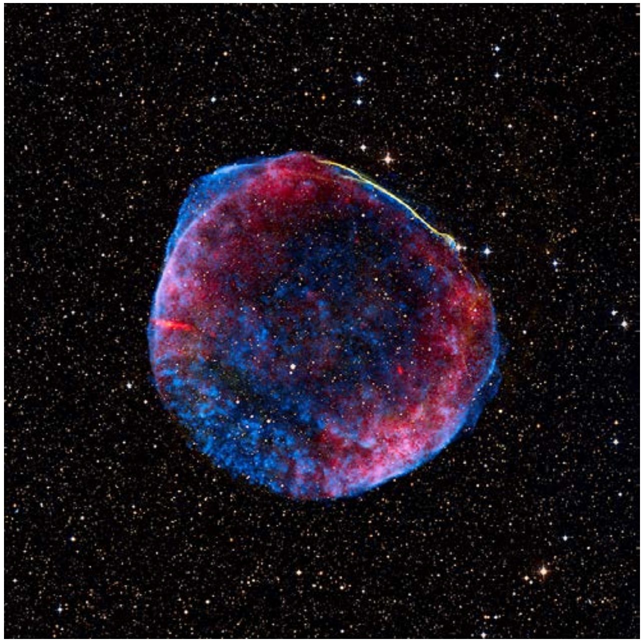
HII & wind regions in the Milky Way





- Ionization and winds from massive stars heat and shape the ISM – deposition of energy and momentum

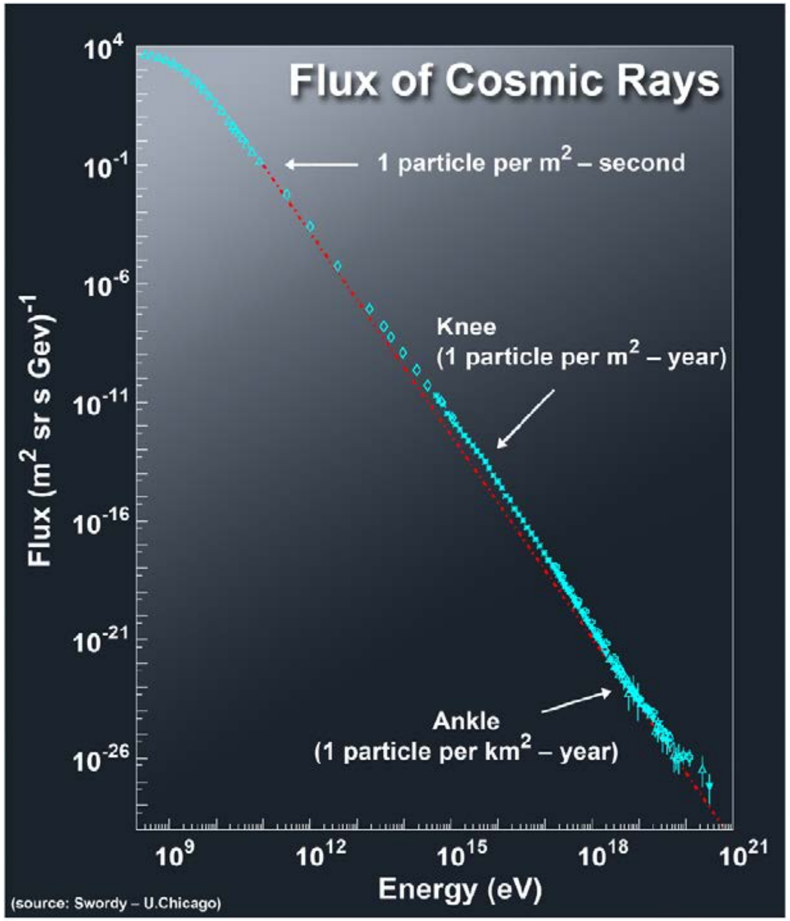
SN remnants in the Milky Way



- SN expel gas at 1000 – 6000 km/s and drive shocks into the ISM
- Particles are accelerated to relativistic energies (Krymsky 1977; Axford et al. 1977; Bell 1978a,b; Blandford & Ostriker 1978) – mostly protons

Ackermann et al. 2013, Nikolic et al. 2013

Cosmic rays in galaxies



- Simulation focus on relativistic protons with ≈1GeV and more
- Highest energy densities – possibly strongest impact on dynamics

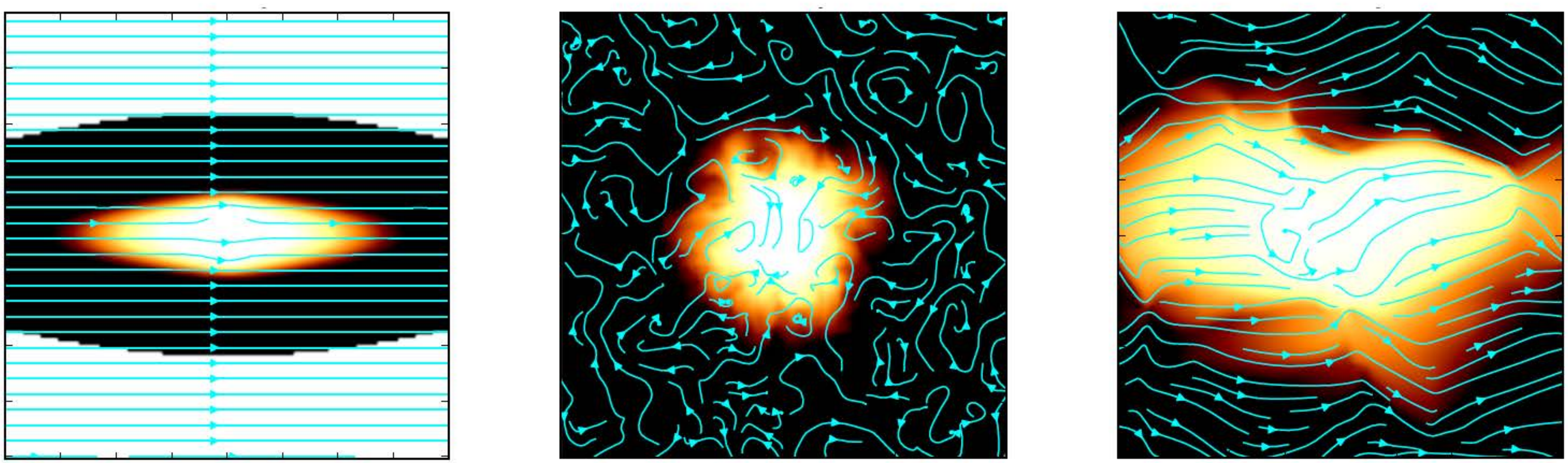
Magnetic fields and cosmic rays?

Cosmic rays are highly relativistic particles (protons) accelerated in supernova remnants – energy density in the ISM is comparable to magnetic and kinetic

Cosmic ray transport is described by a diffusion process

Diffusion mainly along magnetic fields with $K = 10^{28}$ cm^2/s
(see e.g. Strong et al. 2007)

Diffusion perpendicular to magnetic fields is reduced by a factor 10



Girichidis et al. 2016

Magnetic fields and cosmic rays?

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) + \nabla p_{\mathrm{tot}} = \rho \mathbf{g}$$

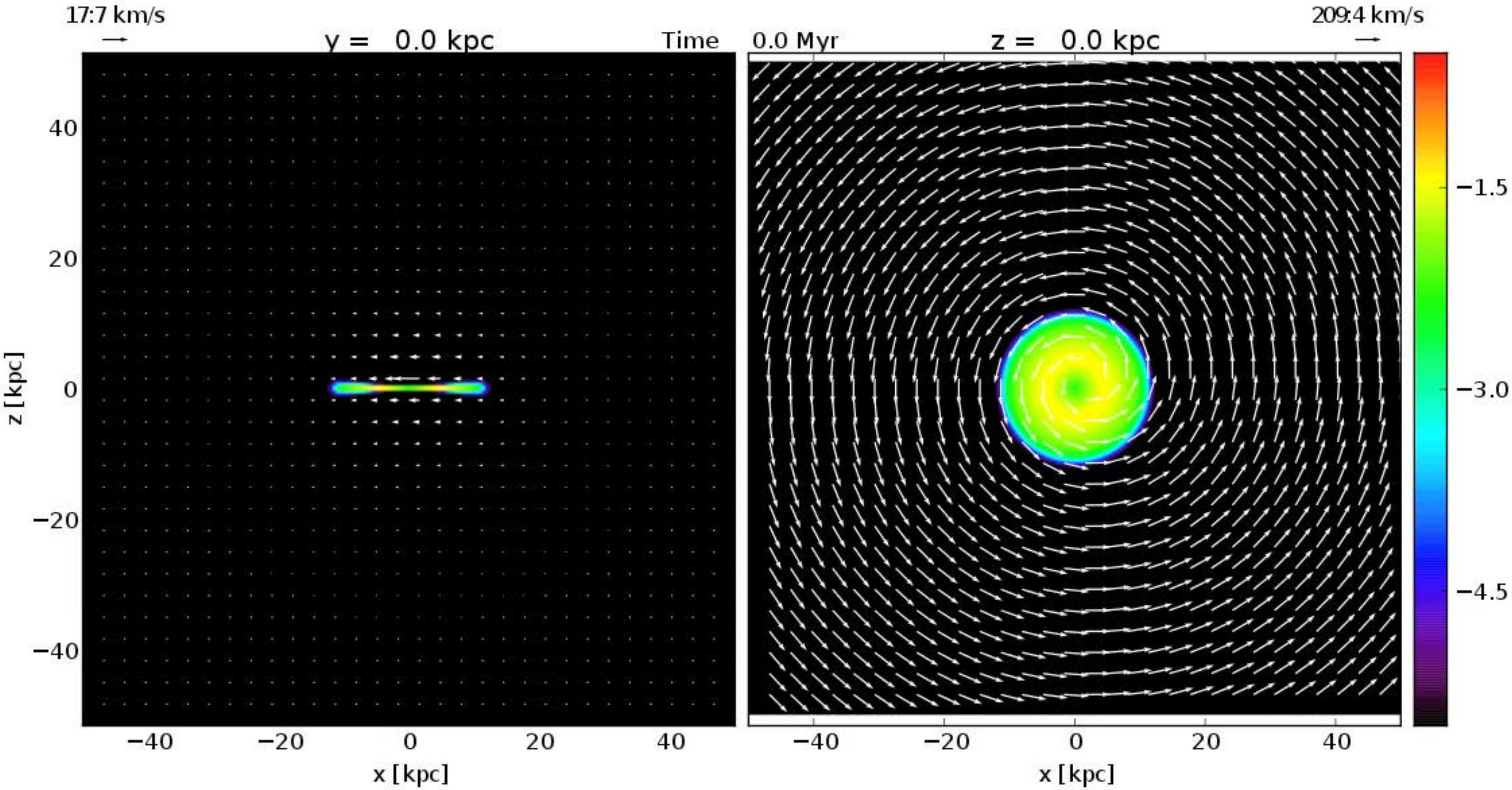
$$\frac{\partial e_{\mathrm{tot}}}{\partial t} + \nabla \cdot \left[(e_{\mathrm{tot}} + p_{\mathrm{tot}})\, \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} + \nabla (\mathsf{K} \nabla e_{\mathrm{cr}})$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

$$\frac{\partial e_{\mathrm{cr}}}{\partial t} + \nabla (e_{\mathrm{cr}} \mathbf{v}) = -p_{\mathrm{cr}} \nabla \cdot \mathbf{v} + \nabla (\mathsf{K} \nabla e_{\mathrm{cr}}) + Q_{\mathrm{cr}}$$

Girichidis et al. 2016

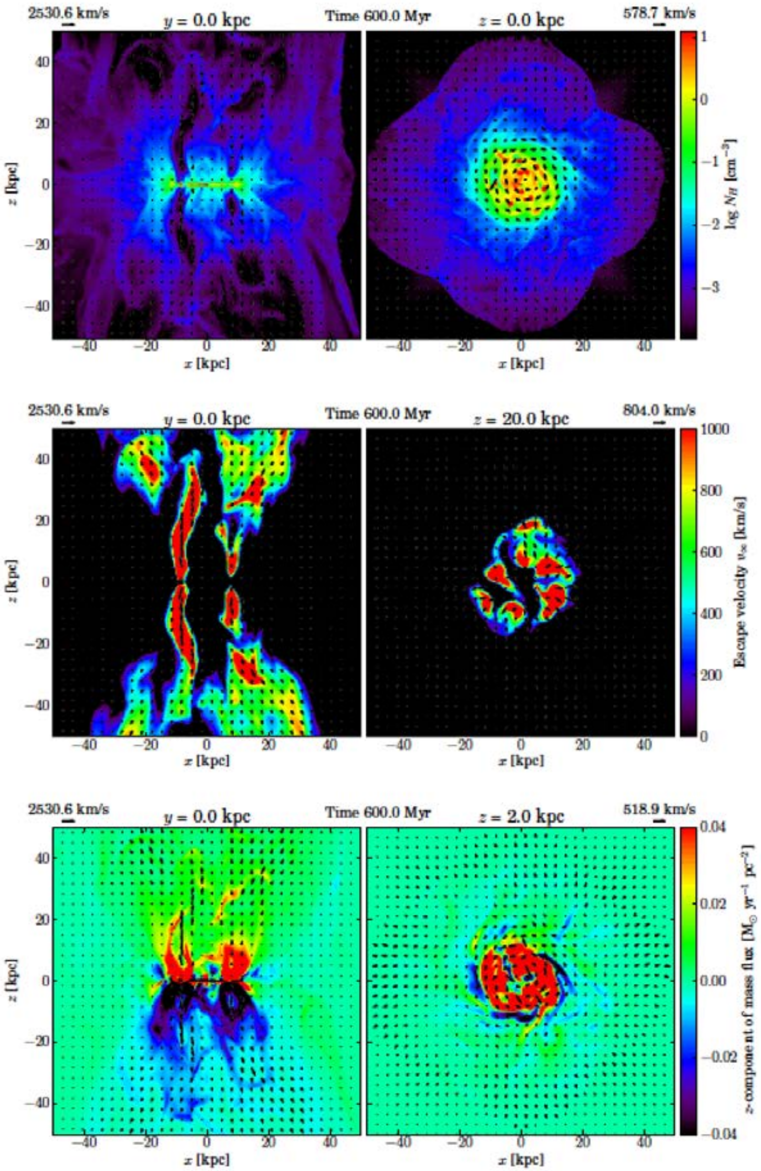
Cosmic ray driven winds

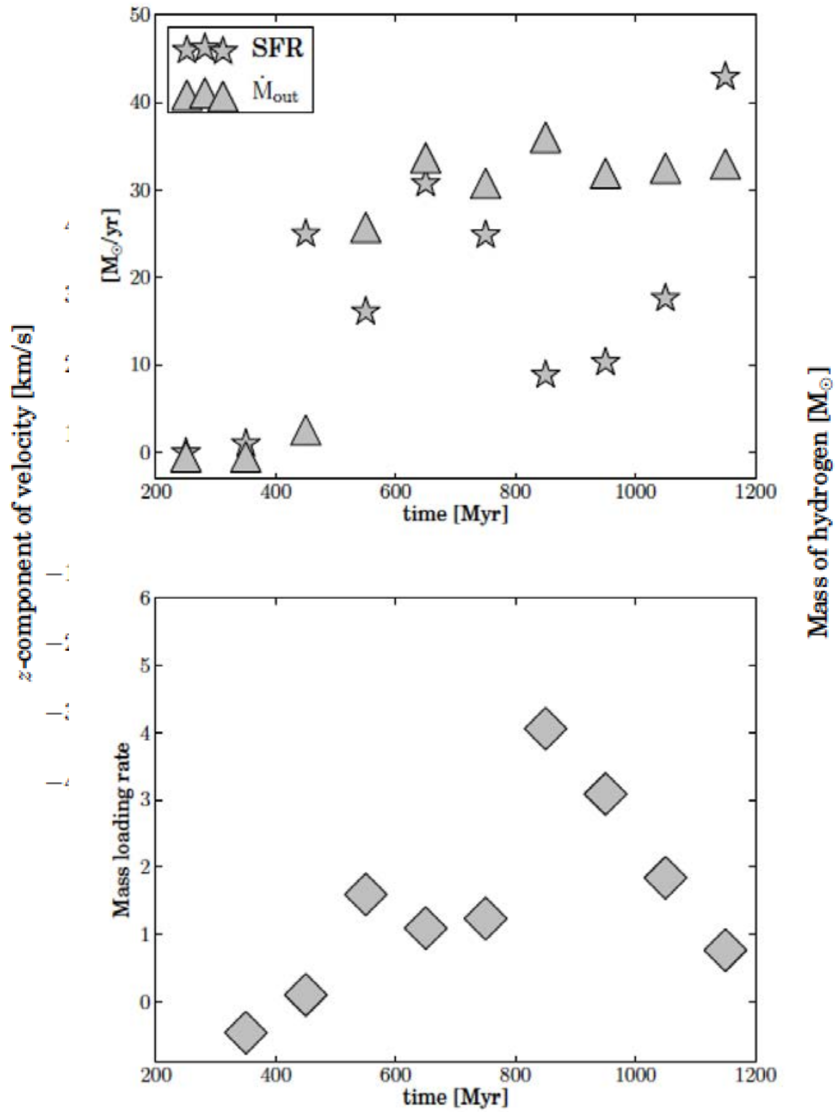


- Cosmic ray driven winds naturally drive bi-polar outflows with outflow rates similar to the star formation rate – even in the absence of thermal/kinetic input (e.g. Hanasz et al. 2009, Dorfi & Breitschwerdt 2012, Uhlig et al. 2012)

Hanasz, Lesch & Naab et al. 2013

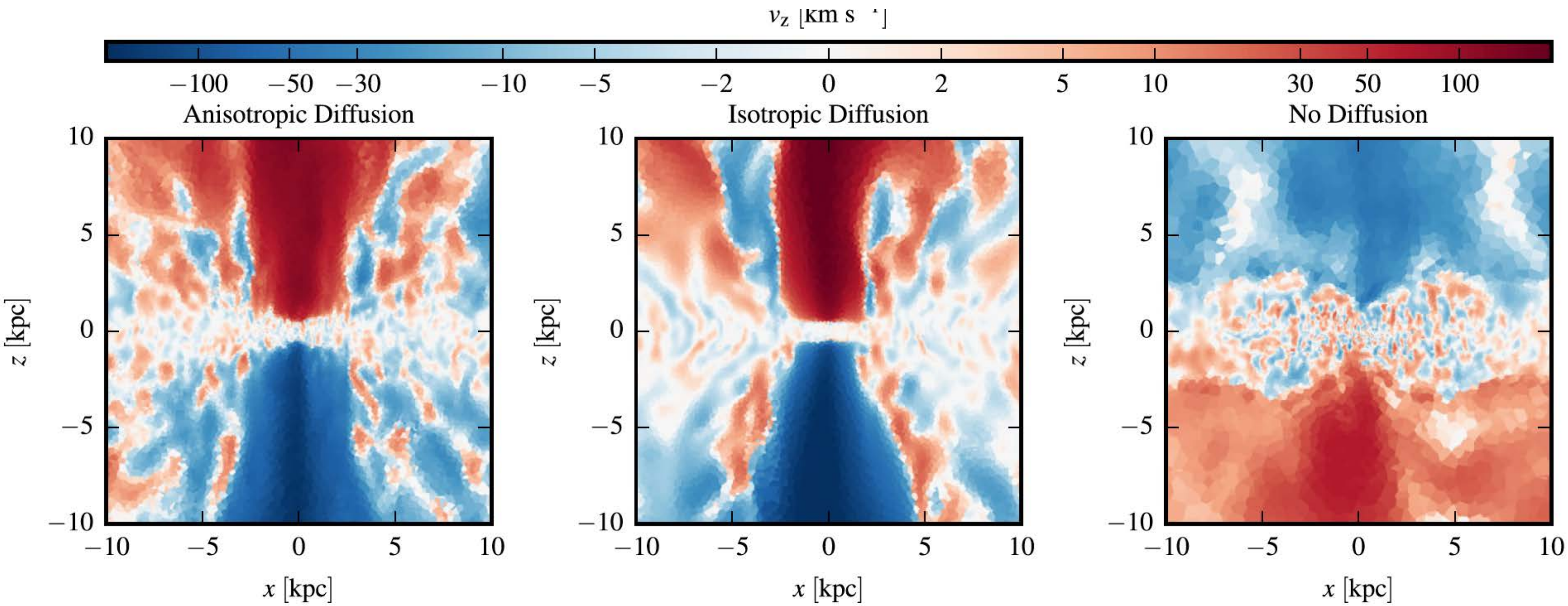
Cosmic ray driven winds





Hanasz, Lesch & Naab et al. 2013

Cosmic ray driven winds



Pakmor et al. 2016

- Anisotropic diffusion with a model for Coulomb and hadronic losses
- Isotropic diffusion suppresses the amplification of magnetic fields

galaxy scales see: Yang et al. 2012, Hanasz et al. 2013, Booth et al. 2013, Salem & Bryan et al. 2014, Ruszkowski et al. 2016

Stratified disk – random driving

SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

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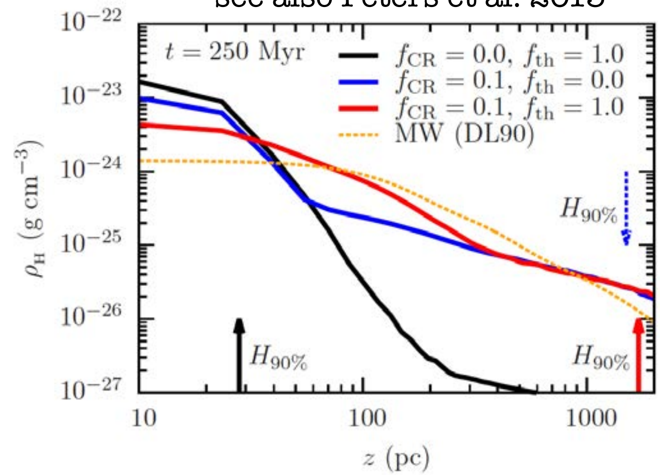
Walch et al., MNRAS 454, 238 (2015)
Girichidis et al., arXiv:1508.06646

KS SN rate, clustered driving, $B_0 = 3\,\mu\mathrm{G}$

Magnetic fields and cosmic rays?

see also Peters et al. 2015



implementation for cosmic rays (Girichidis et al. 2016)

- Diffusion coefficient κ = 10^{28} cm^2/s
- CR driven pressure gradient drives gas out of the disk in a slow (colder)wind (Girichidis et al. 2016, see Peters et al. 2016, Simpson et al. 2016)

galaxy scales see: Yang et al. 2012, Hanasz et al. 2013, Booth et al. 2013, Salem & Bryan et al. 2014, Ruszkowski et al. 2016

Gamma rays and cosmic rays?

- Relativistic proton interaction – pions (π_0) decay into gamma-rays
- Probability for nucleon collision: $p = \sigma_{pp}\, c\;\; n_{ISM}$, with $\sigma_{pp} \approx 2.5 \times 10^{-30}\ m^2$
- Number of collisions per second in Volume $V \approx V\, n_{CR}\, p$
- Gamma ray luminosity:

$L\gamma\; = 1/3\;\; \sigma_{pp}\, c\;\; n_{ISM}\;\; n_{CR}\, E_{CR}\, V$

Girichidis et al. 2017, in prep.

Summary on cosmic rays and outflows

- Cosmic rays, as a non-relativistic component of the interstellar medium, can now be modeled in galaxy formation and interstellar medium simulations
- Relativistic protons, generated in supernova remnants, might promote the formation of galactic outflows – little losses and additional pressure gradient
- Study the local chimney in magnetic fields and cosmic rays
- Penetration of CR into dense molecular clouds (including ionization streaming losses), changes heating ionization and chemistry of clouds, X_{CO}
- Future studies with energy dependent diffusion and losses (Girichidis et al. in prep)