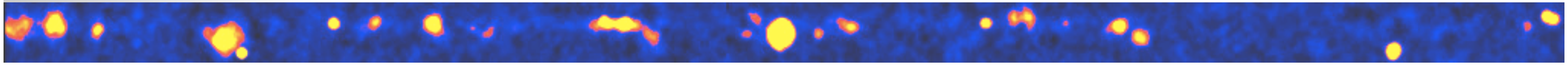
Topics



Preliminaries: Units, coordinates & other useful(?) stuff

Gamma ray production by protons

- Basics
- Gamma-ray visibility of supernova remnants
- Seeing molecular clouds in gamma rays

Radiation processes involving electrons

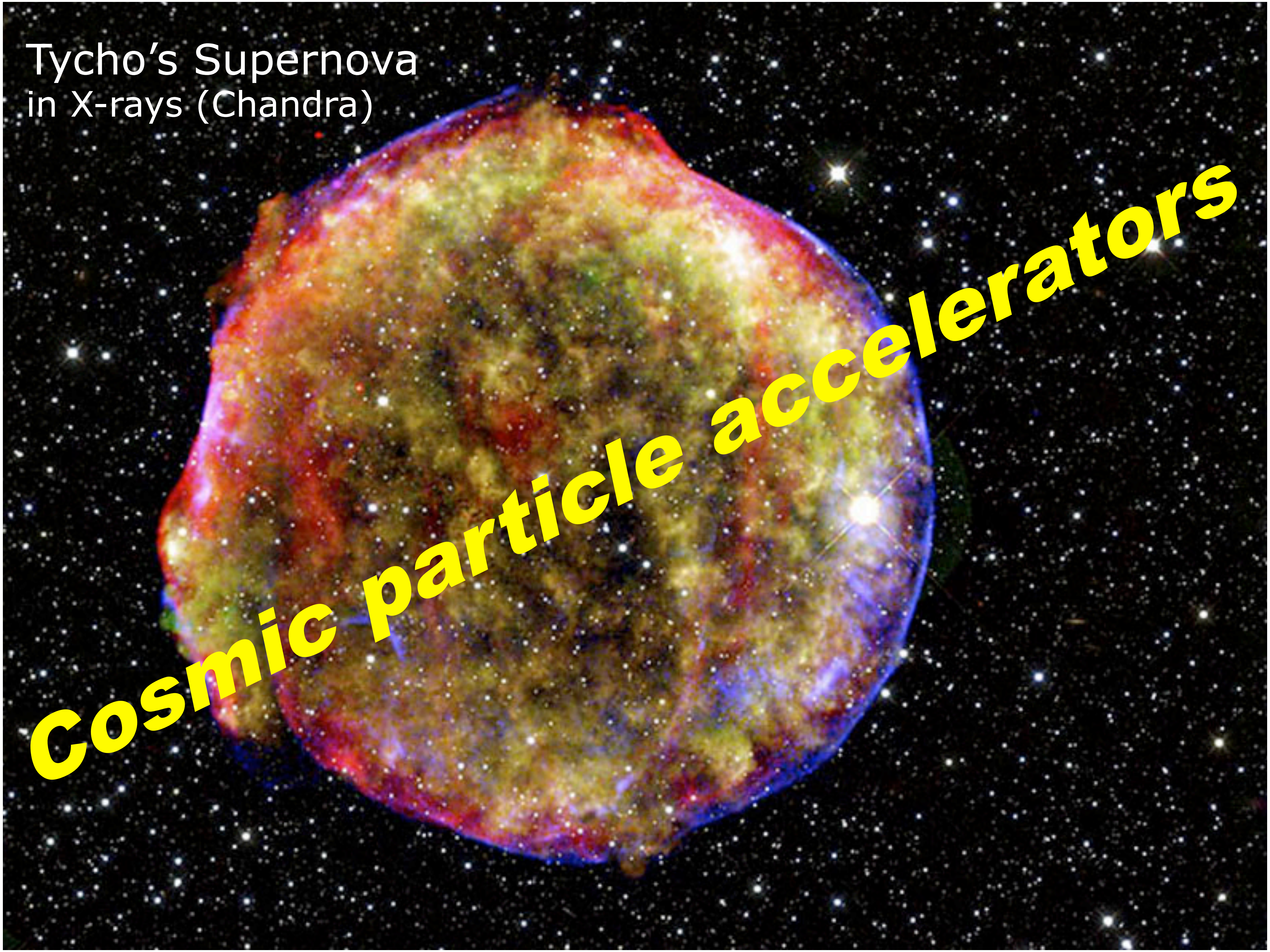
- Inverse Compton scattering
- Synchrotron radiation
- Radiation cooling
- Application to real objects

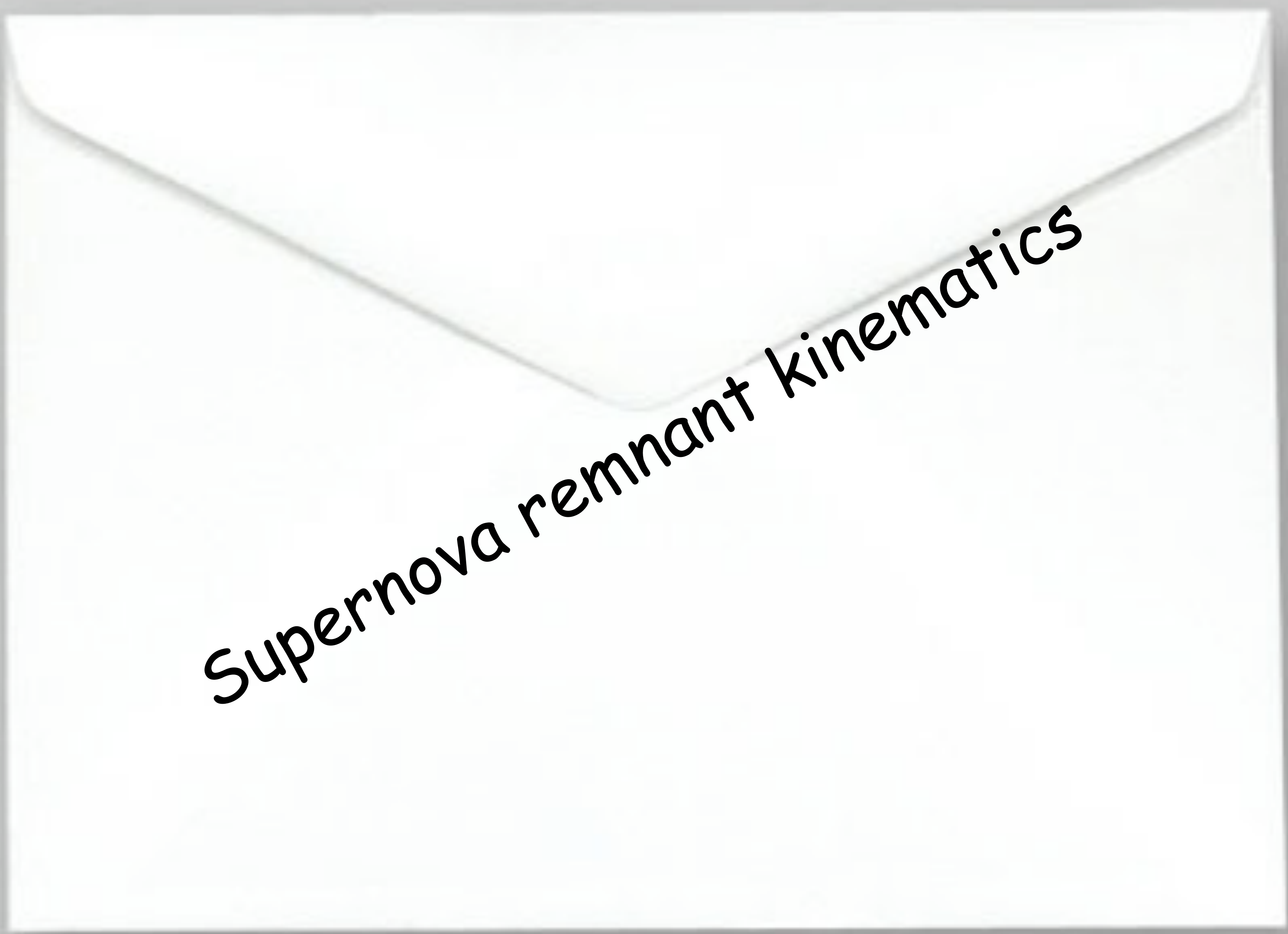
Gamma ray propagation - will they reach us?

Cosmic particle accelerators

- **Supernova remnant kinematics**
- **Supernova remnant shocks**
- **Particle propagation and particle acceleration**
- **Nonlinear effects, escape, …**

The receiving end: Detecting gamma rays


Tycho's Supernova
in X-rays (Chandra)
Cosmic particle accelerators


Supernova remnant kinematics

Supernova shocks

Supernova ejecta

Interstellar medium

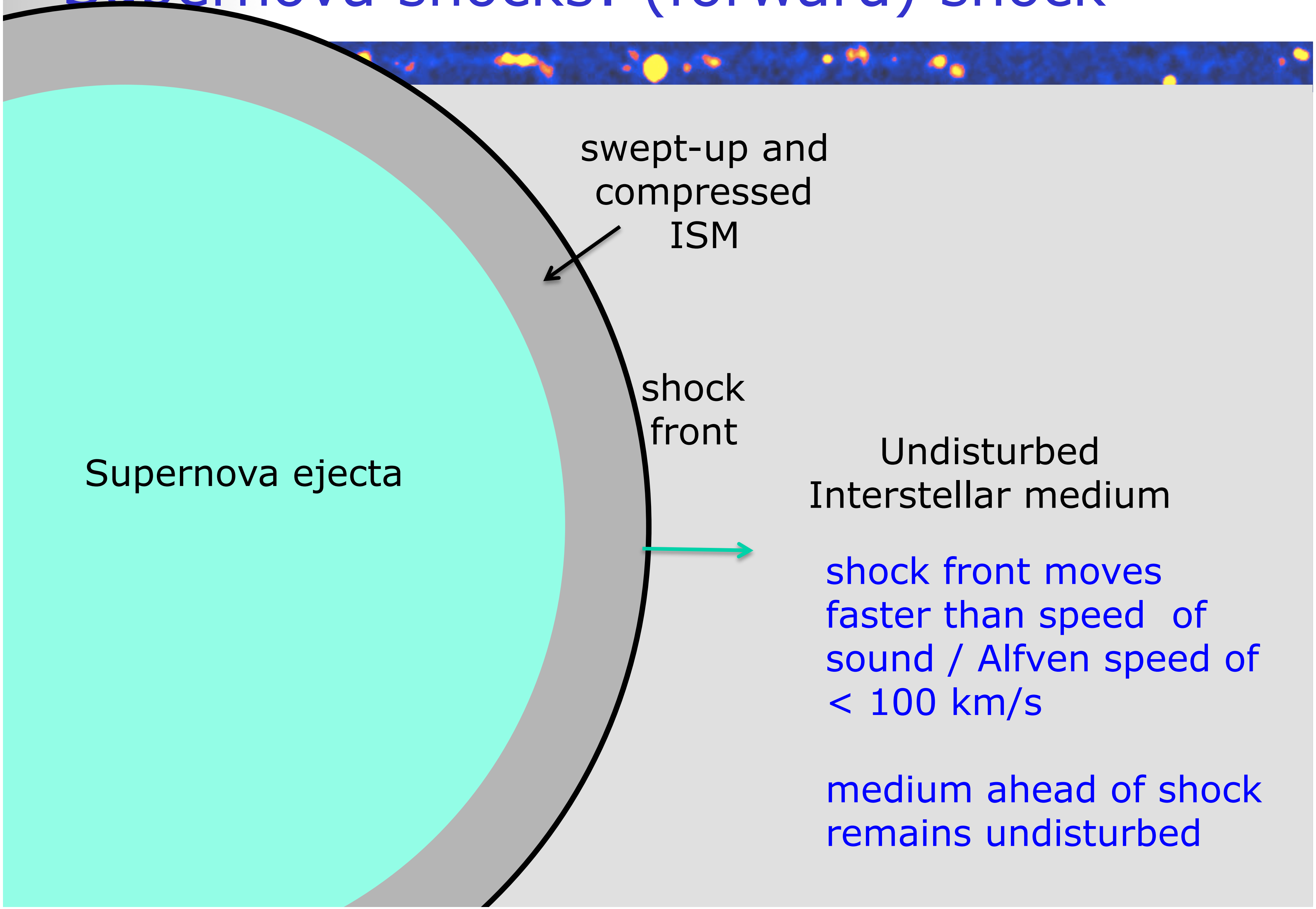
few 1000 km/s

Typical ejecta masses:
few solar masses ($2 \cdot 10^{30}$ kg)

Ejecta speeds: up to 10000 km/s (3% c)

Kinetic energy:
1 solar mass @ 10000 km/s = 10^{44} J = 10^{51} erg

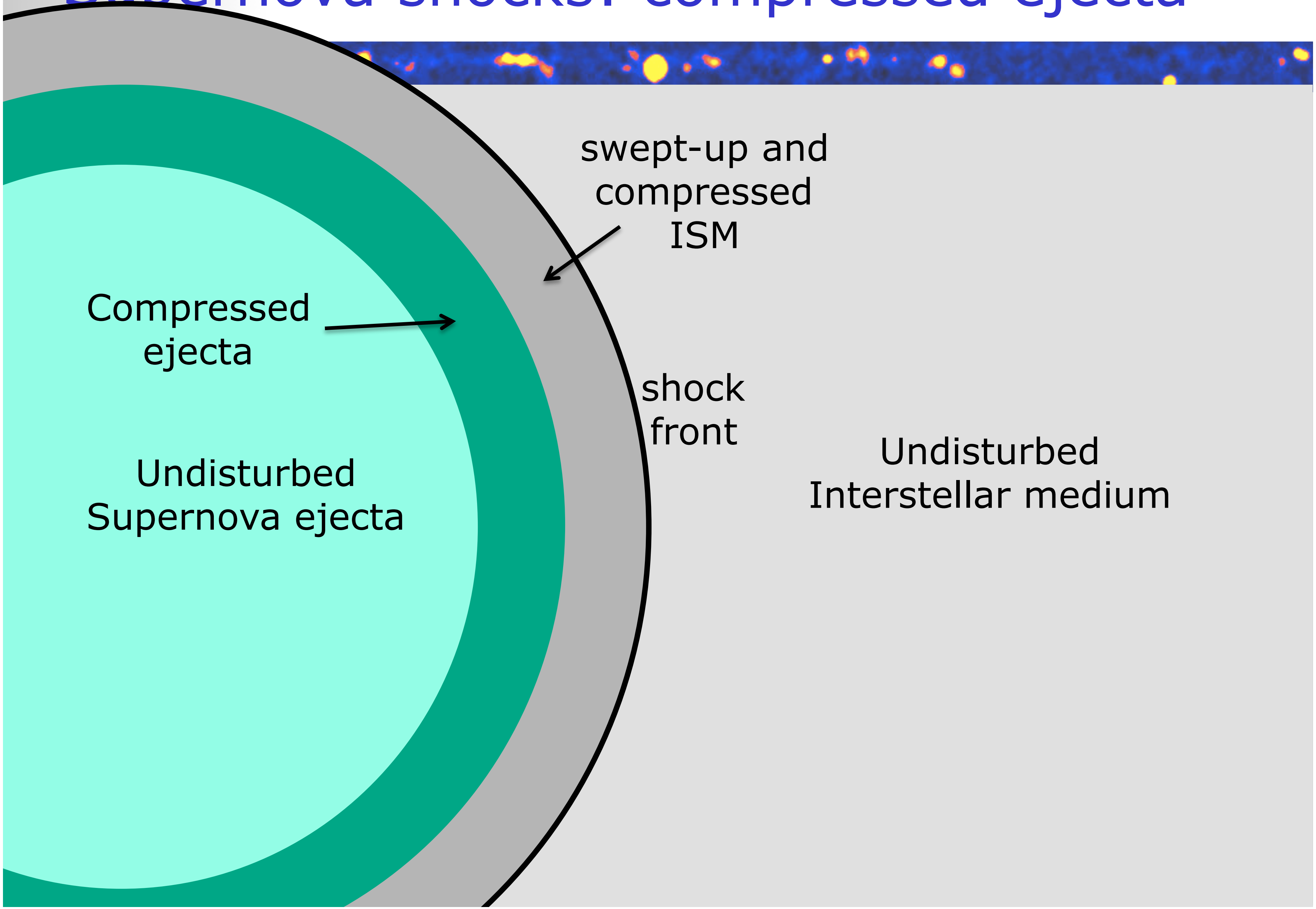
Supernova shocks: (forward) shock



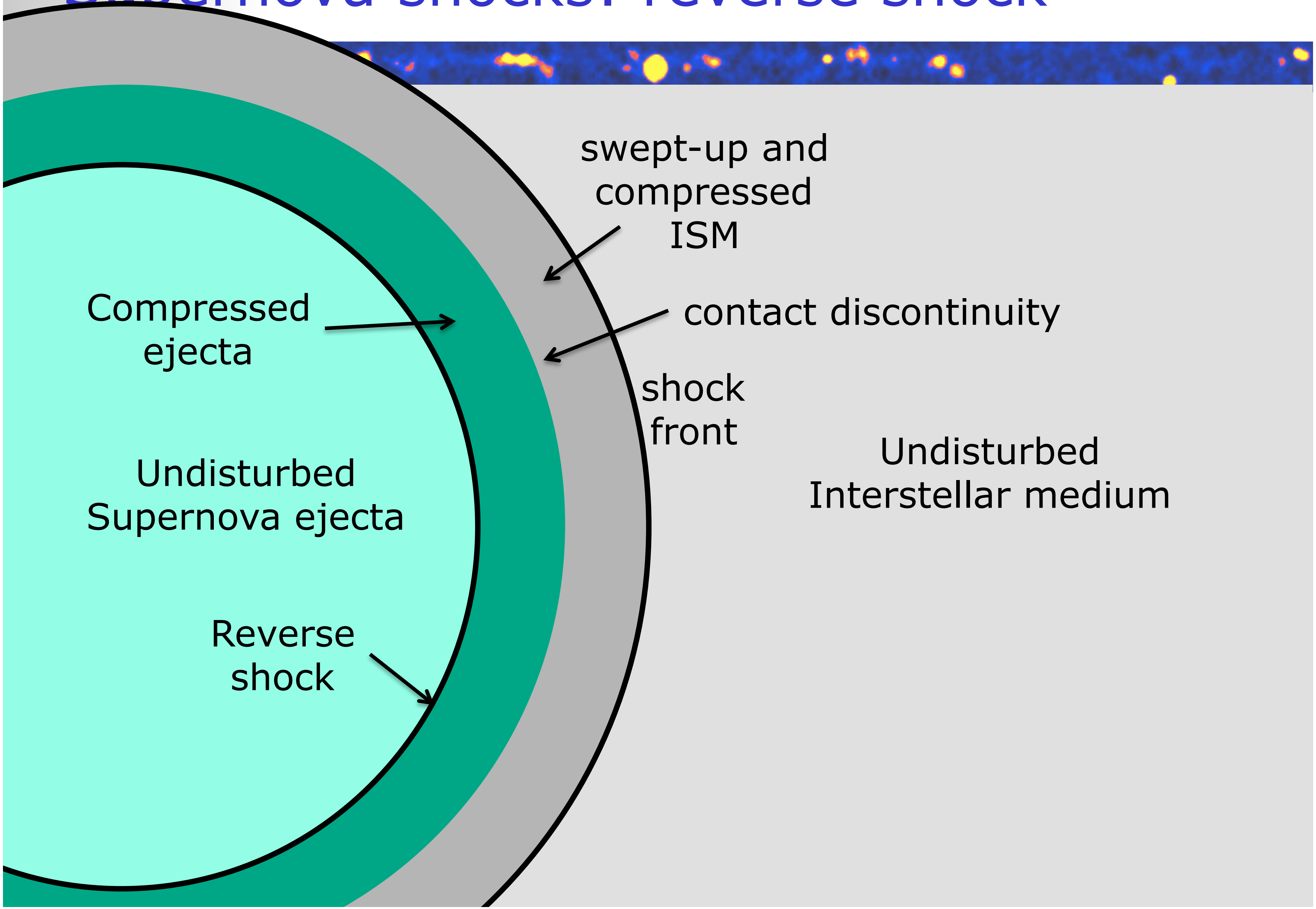
shock front moves faster than speed of sound / Alfven speed of < 100 km/s

medium ahead of shock remains undisturbed

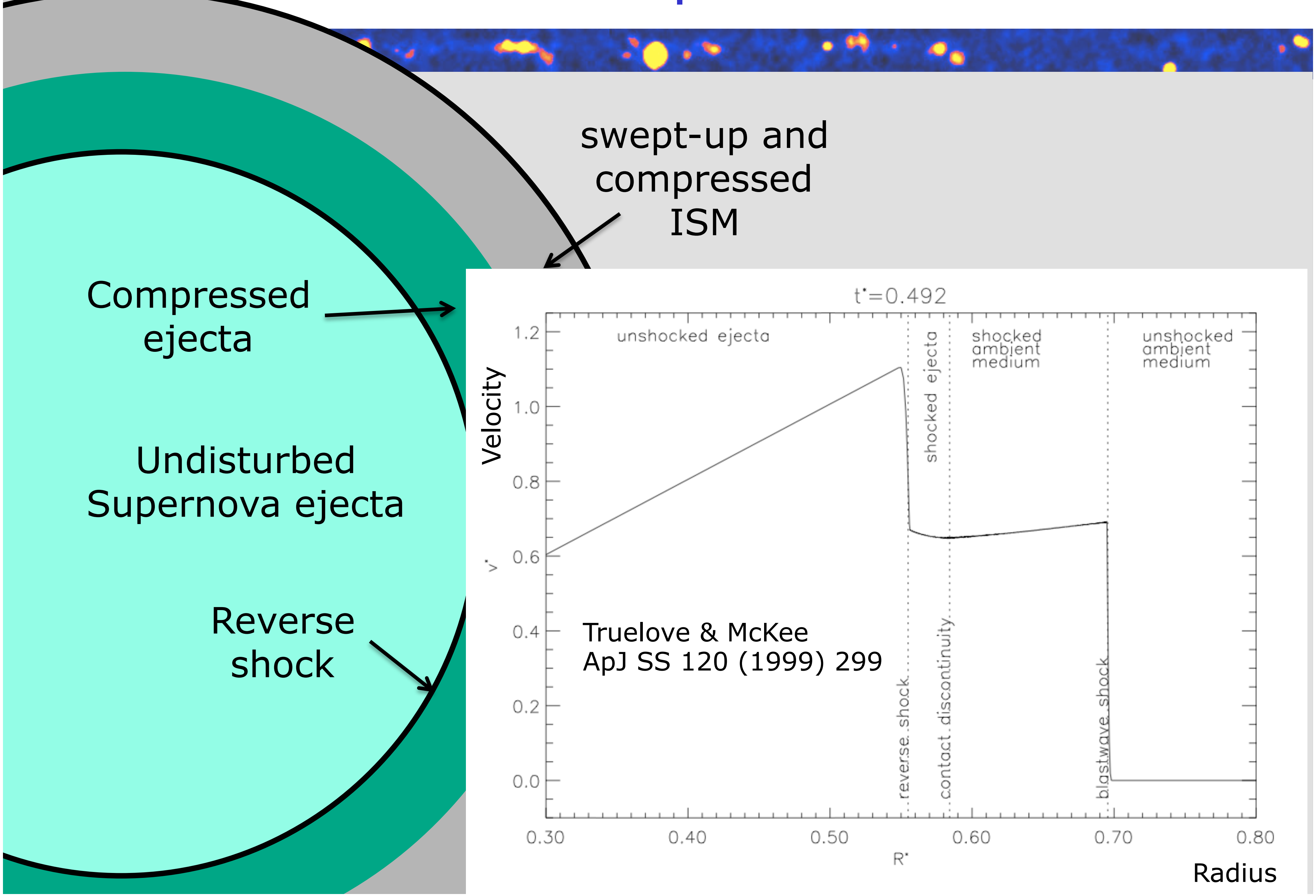
Supernova shocks: compressed ejecta



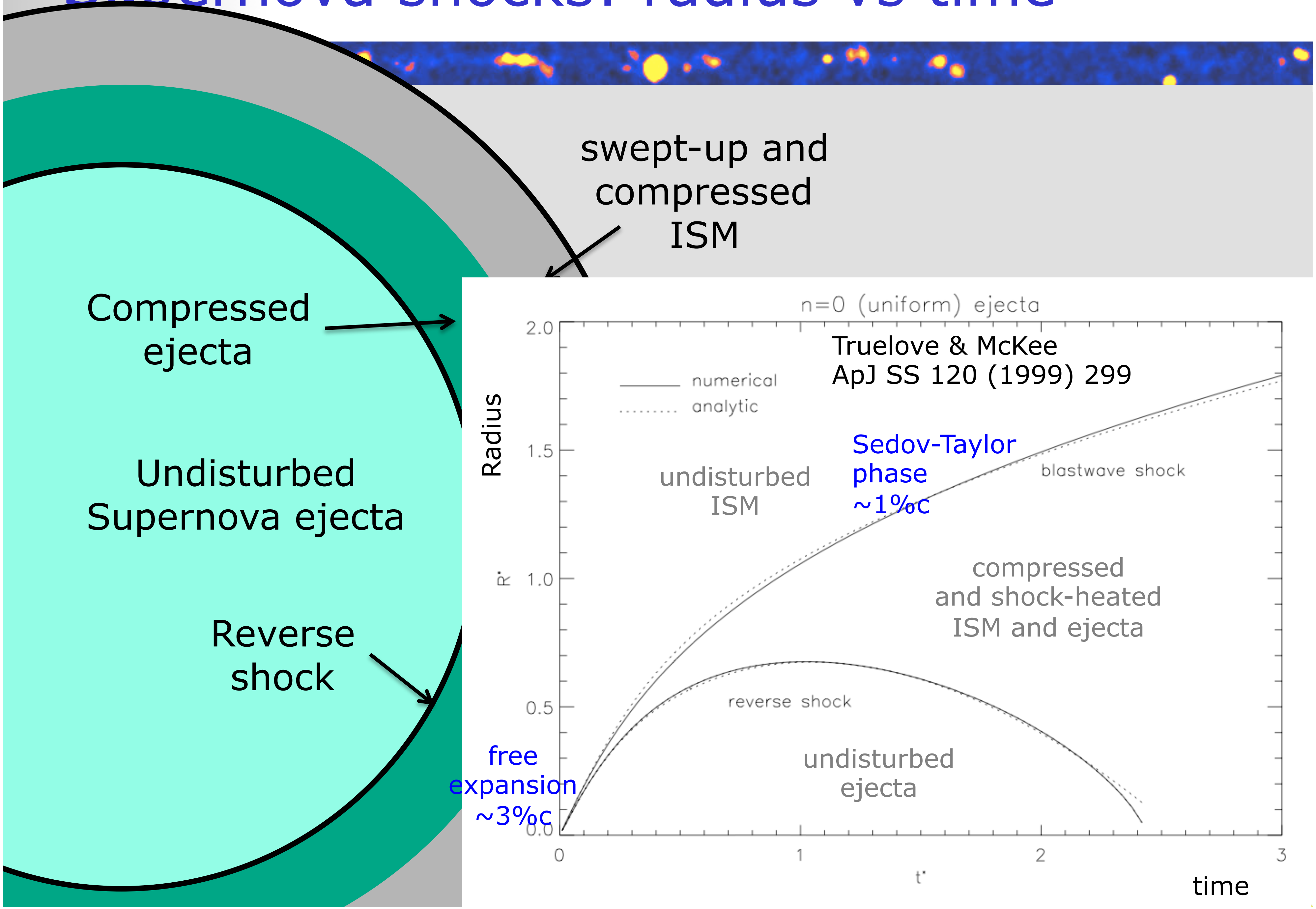
Supernova shocks: reverse shock



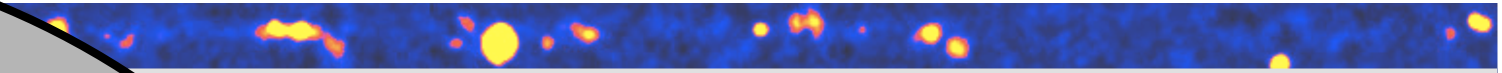
Supernova shocks: speed vs radius

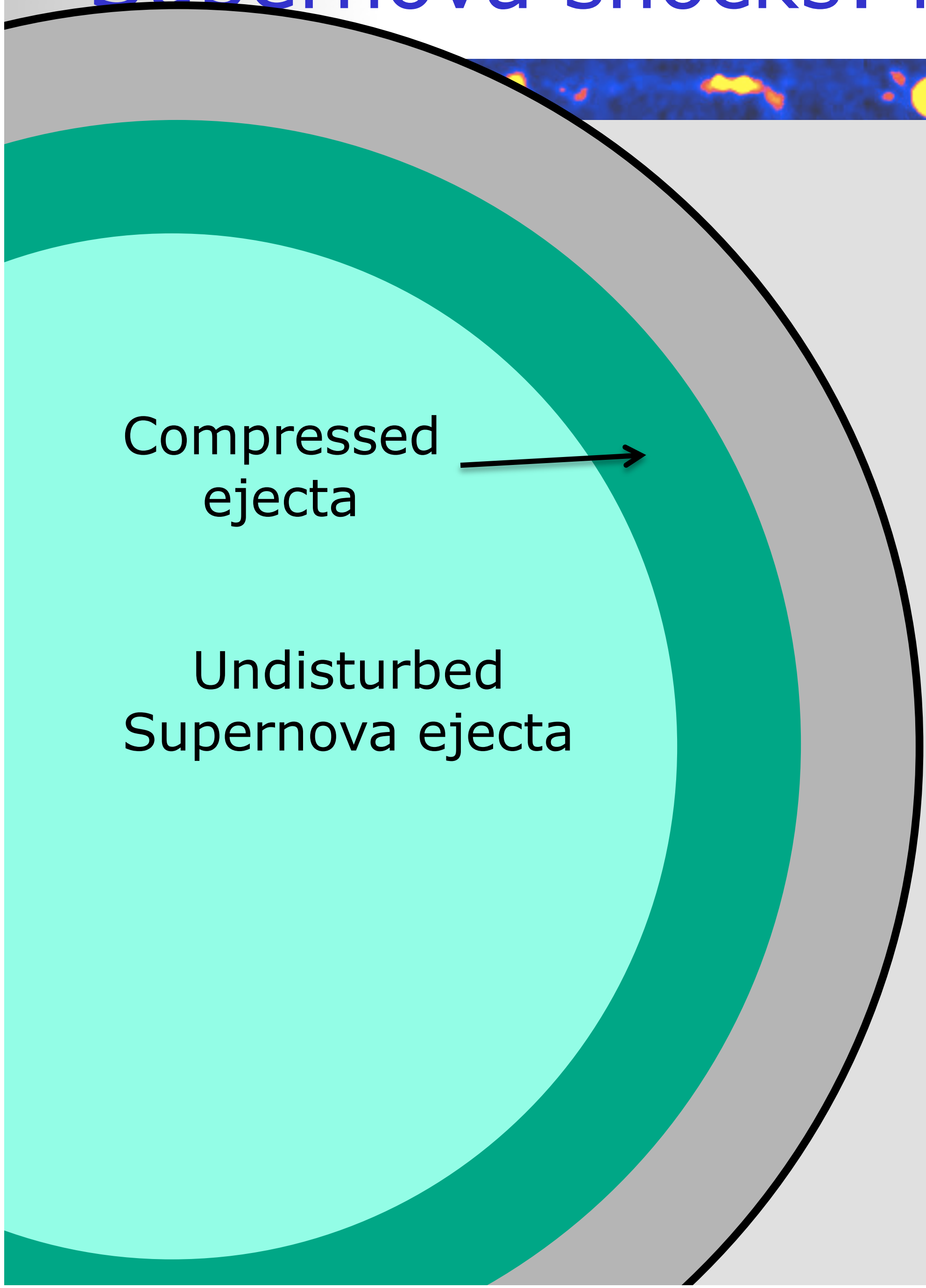


Supernova shocks: radius vs time



Supernova shocks: radius vs time





Case A)
swept-up ISM mass << M_{ej} :
"free expansion" at
constant (initial) speed

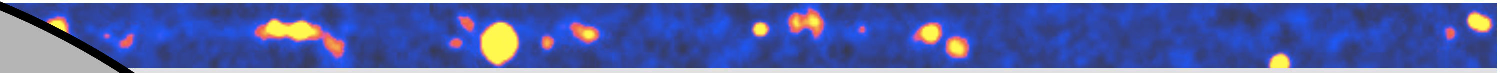
$$v_{1000\,km/s} \approx 10\,E_{51}^{1/2}\left(\frac{M_{sol}}{M_{ej}}\right)^{1/2}$$

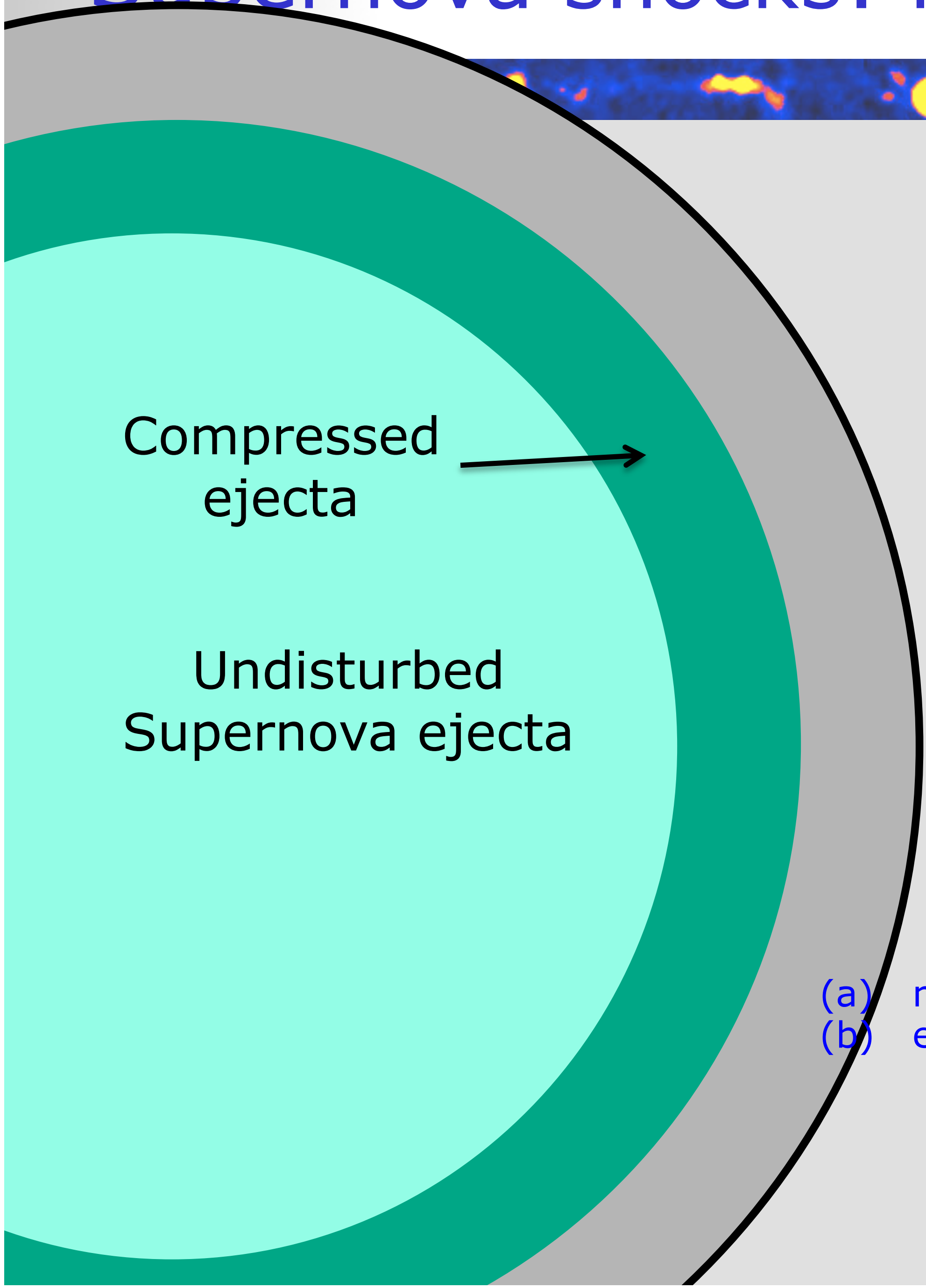
ends at

$$R_{pc} \approx 2\left(\frac{M_{ej}}{\rho_{H/cm^3} M_{sol}}\right)^{1/3}$$

$$t_{yr} \approx \frac{R}{v} \approx 200\left(\frac{M_{ej}}{\rho_{H/cm^3}^2 M_{sol}}\right)^{-1/6}$$

Supernova shocks: radius vs time





Case B)
swept-up ISM mass >> M_{ej} :
expansion slows down
"Sedov-Taylor" phase

$$R = f(E_{SN}, \rho, t)$$

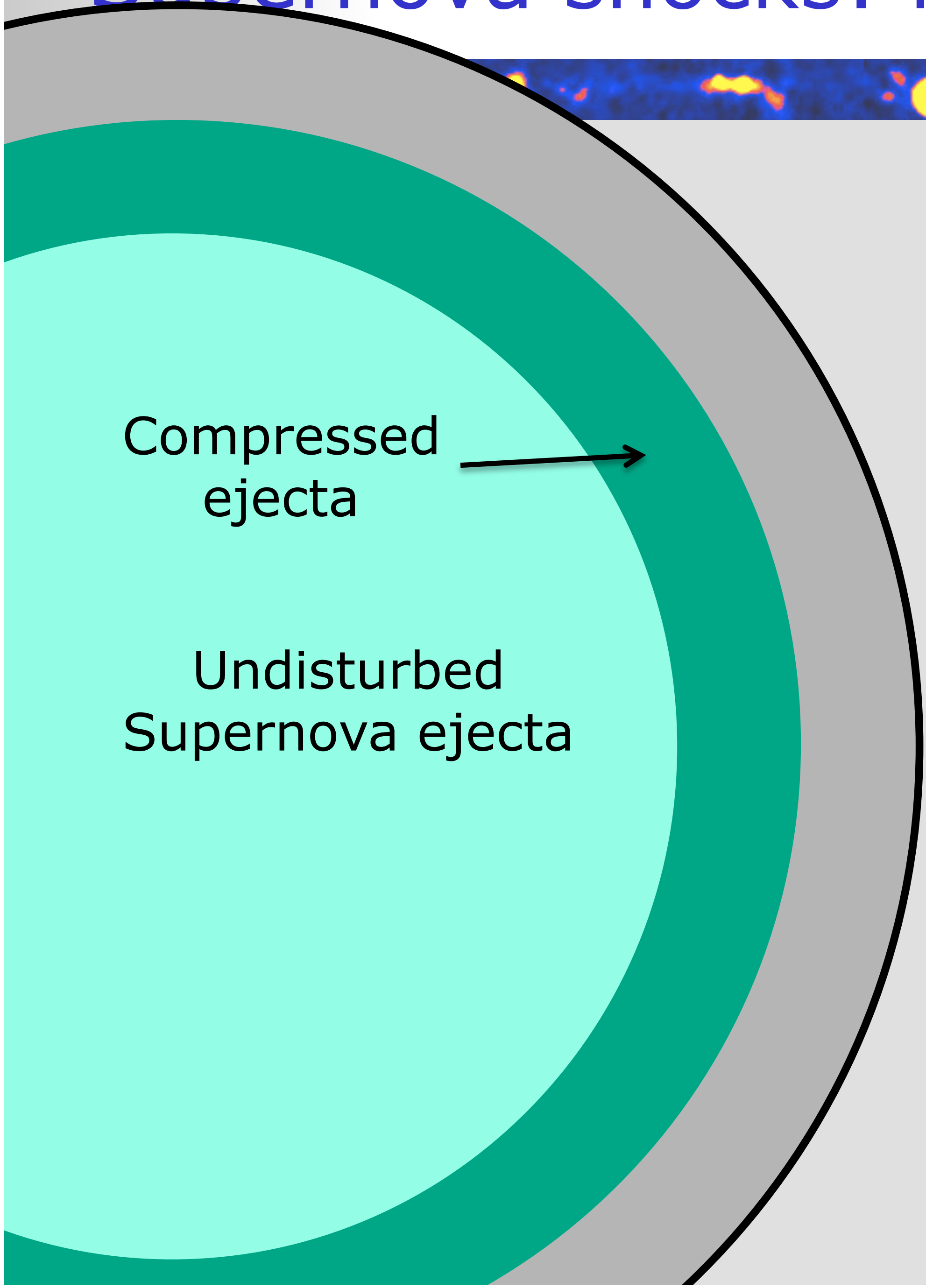
find combination which has right dimension:

$$R \approx \left(\frac{E_{SN}}{\rho} \right)^{1/5} t^{2/5}$$

(a) match to free exp.
(b) exact calculation

$$R_{pc} \approx 0.3 \left(\frac{E_{51}}{\rho_{H/cm^3}} \right)^{1/5} t_{yr}^{2/5}$$

Supernova shocks: radius vs time

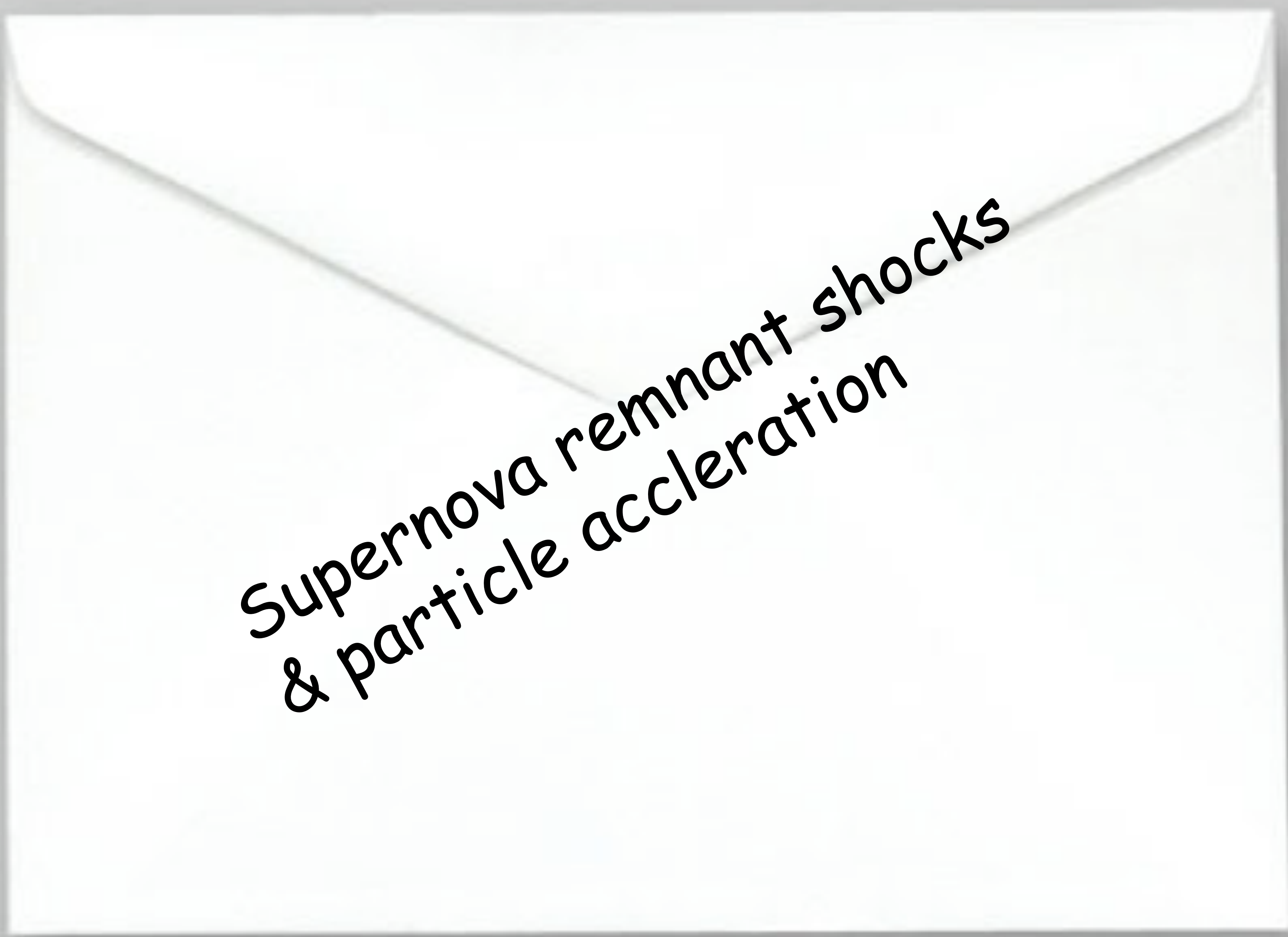


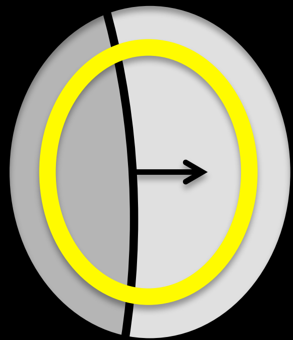
Case C)
"Radiative phase"
radiation losses of heated gas dominate – the end of the SNR as far as high-energy astrophysics is concerned

slightly lengthy estimate gives

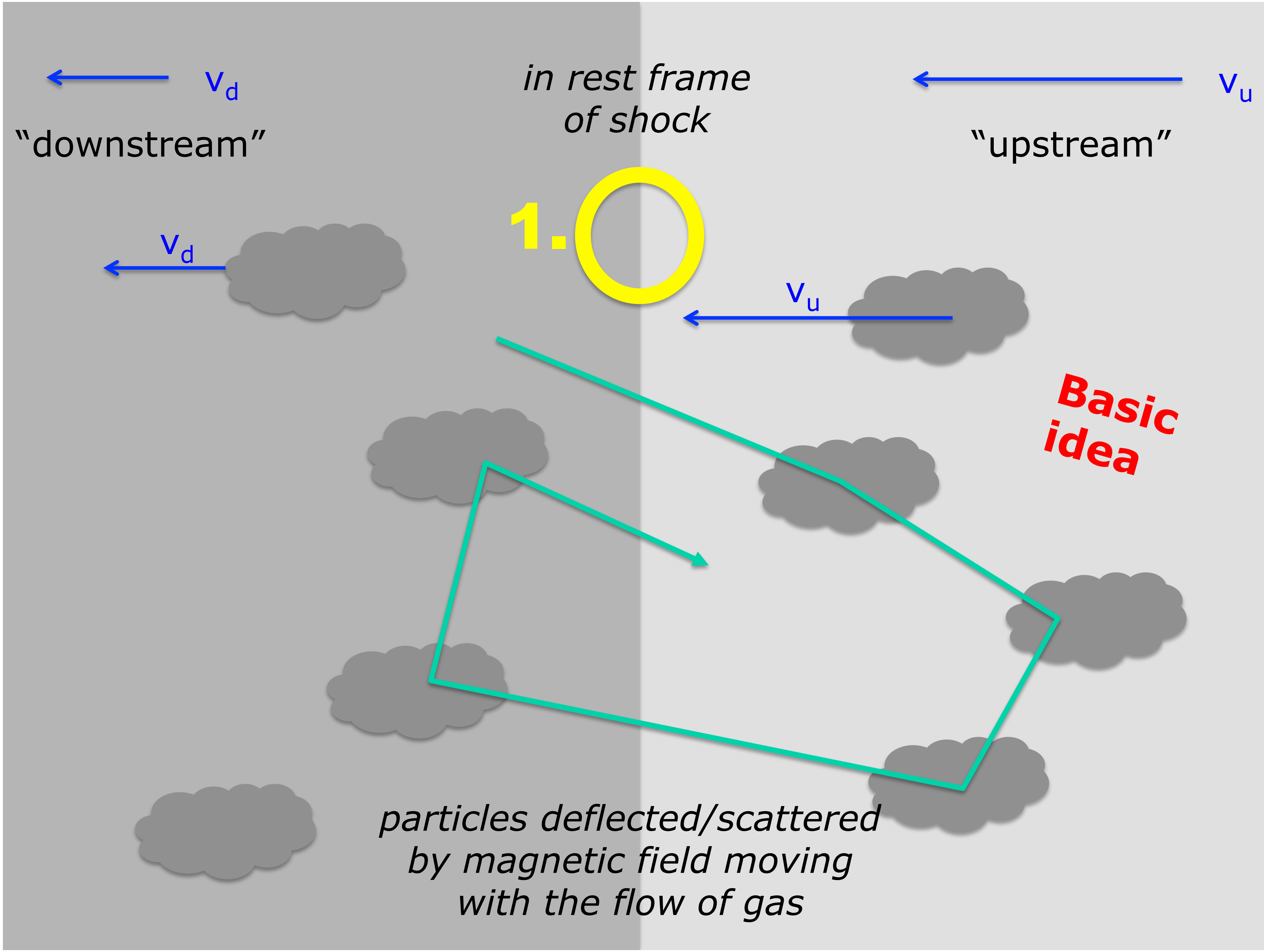
$$t_{yr} \approx 13000\, E_{51}^{3/14} \rho_{H/cm^3}^{-4/7}$$

$$R_{pc} \approx 14 E_{51}^{2/7} \rho_{H/cm^3}^{-3/7}$$


Supernova remnant shocks
& particle accleration

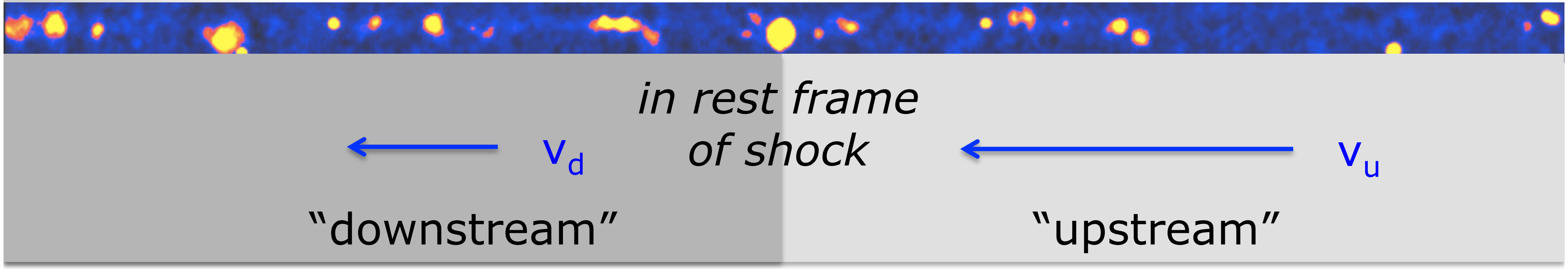


place observer in
rest frame of shock



v_d
"downstream"
in rest frame
of shock
v_u
"upstream"
1.
v_d
v_u
Basic
idea
particles deflected/scattered
by magnetic field moving
with the flow of gas

What happens at the shock



speed $v_d < v_u$
density $\rho_d > \rho_u$
pressure $p_d > p_u$
temperature $t_d > t_u$

$\longleftrightarrow$

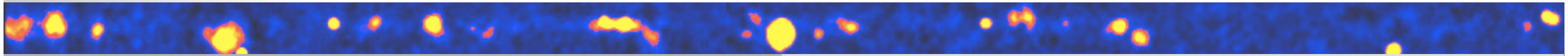
compression ratio
$r = \rho_d/\rho_u = v_u/v_d$

$\longleftrightarrow$

speed v_u
density ρ_u
pressure p_u
temperature t_u

Crucial number: compression ratio r

What happens at the shock



in rest frame of shock

v_d ← | ← v_u

"downstream" | "upstream"

speed $v_d < v_u$ density $\rho_d > \rho_u$ pressure $p_d > p_u$ temperature $t_d > t_u$	↔ compression ratio $r = \rho_d/\rho_u = v_u/v_d$ ↔	speed v_u density ρ_u pressure p_u temperature t_u

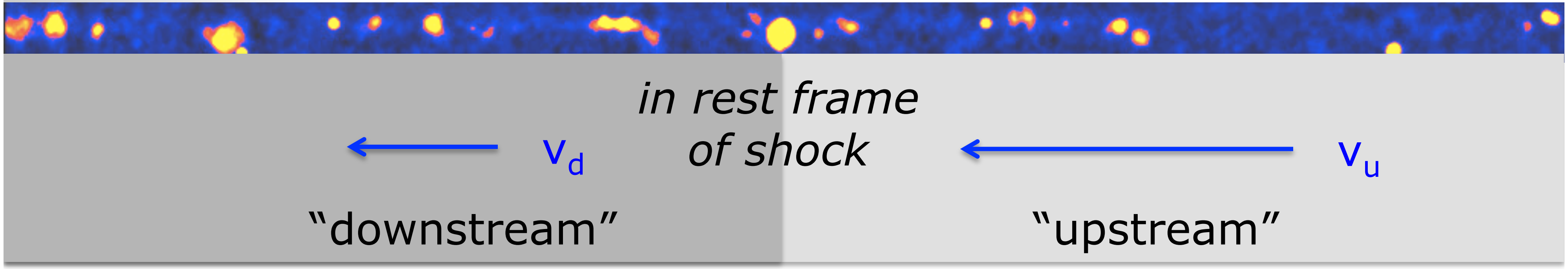
Continuity equations:

Mass $$v_u \rho_u = v_d \rho_d$$

Momentum $$p_u + v_u \left(v_u \rho_u \right) = p_d + v_d \left(v_d \rho_d \right)$$

Energy/mass $$h_u + \frac{1}{2} v_u^2 = h_d + \frac{1}{2} v_d^2$$

Shock compression ratio

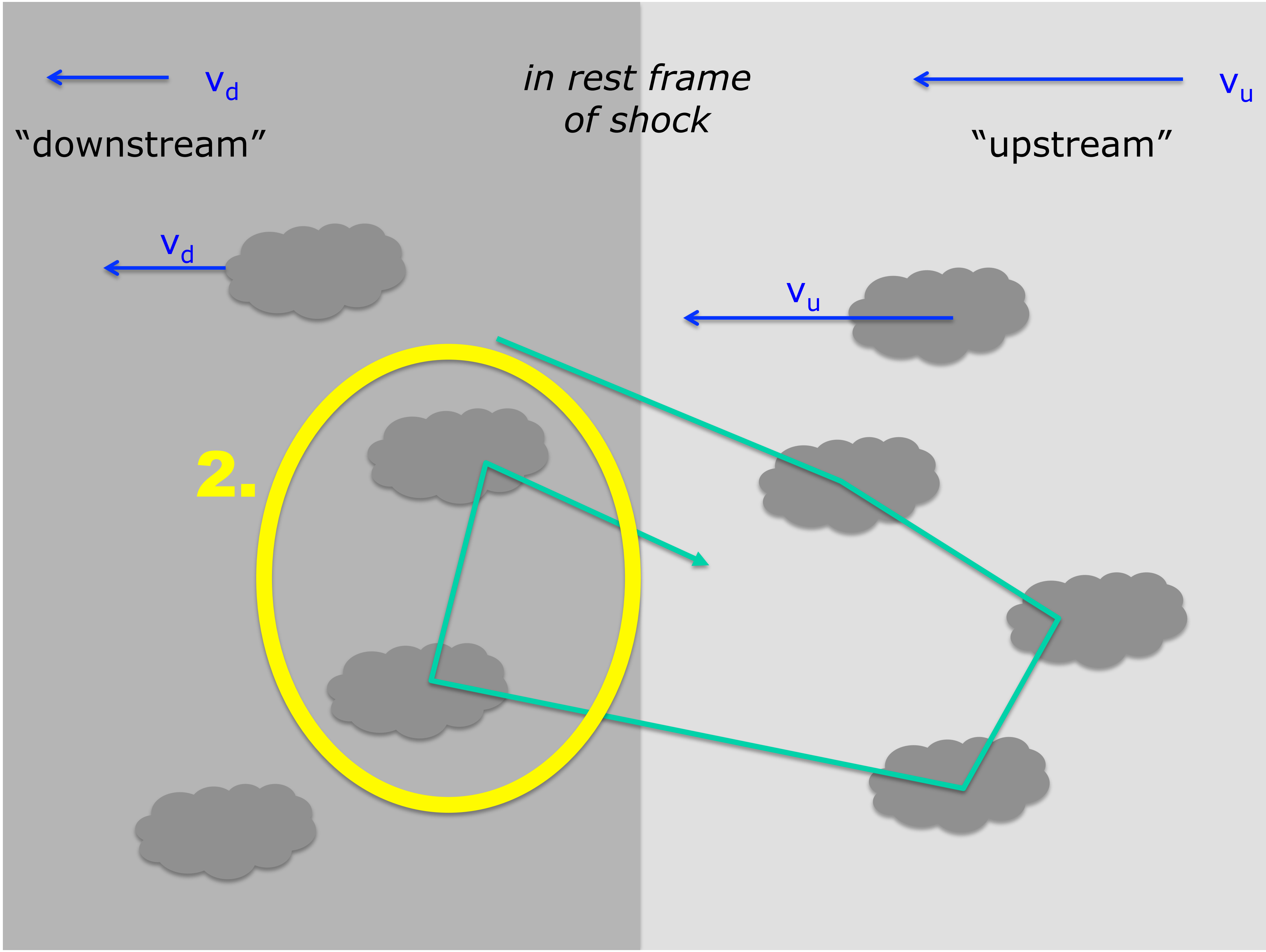


$$\text{Compression rate } r = \frac{\gamma + 1}{\gamma - 1} = 4$$

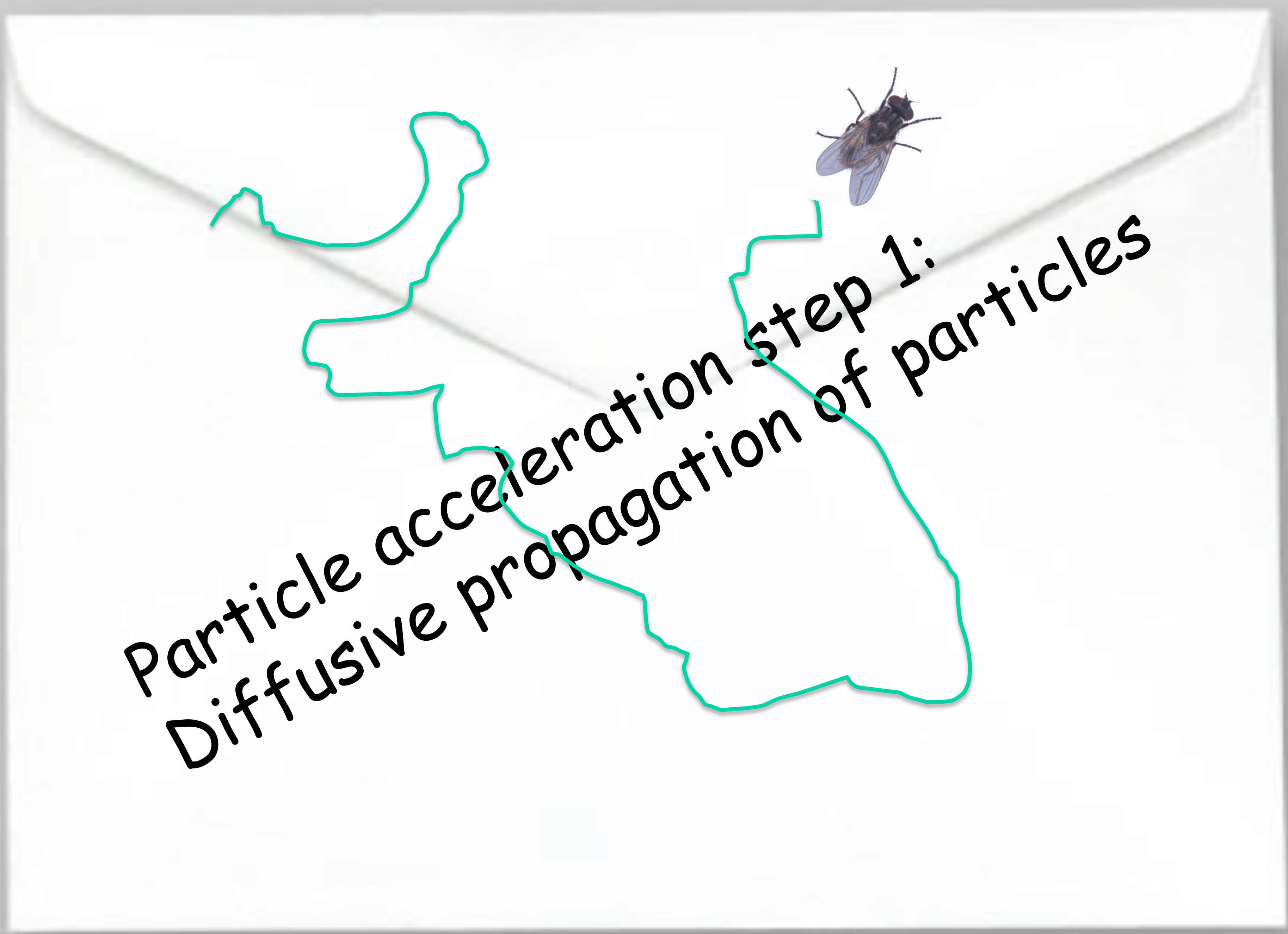
for strong shocks and monatomic gas

with adiabatic index γ=5/3

($pV^{\gamma} = const$ for adiabatic processes)

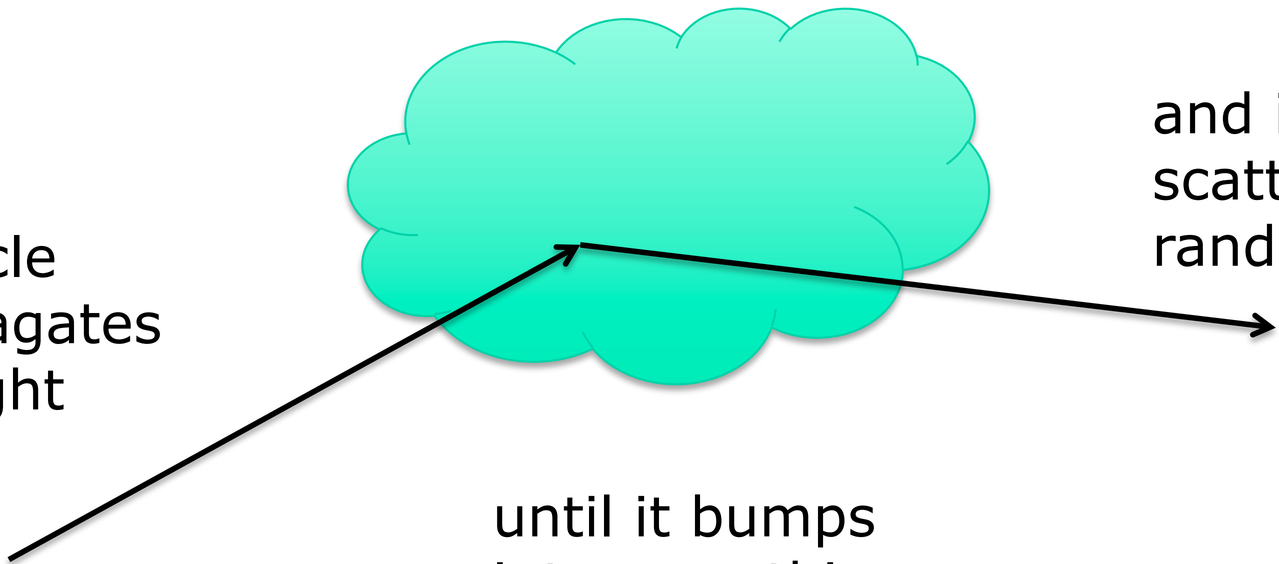


v_d
in rest frame of shock
v_u
"downstream"
"upstream"
v_d
v_u
2.


Particle acceleration step 1:
Diffusive propagation of particles

Basic diffusion picture

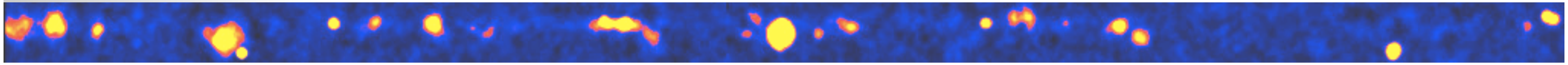
particle
propagates
straight



until it bumps
into something
with large inertia
(magnetic field)

and is elastically
scattered by a
random angle

Description 1: Diffusion equation



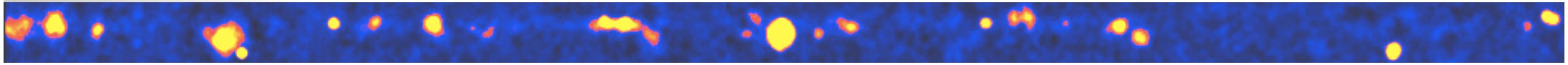
$$J = -D\nabla\rho \quad \text{and} \quad \frac{\partial\rho}{\partial t} = \nabla J \quad \text{hence} \quad \frac{\partial\rho}{\partial t} = -D\Delta\rho$$

with diffusion coefficient *D*
(or in worst case diffusion tensor)

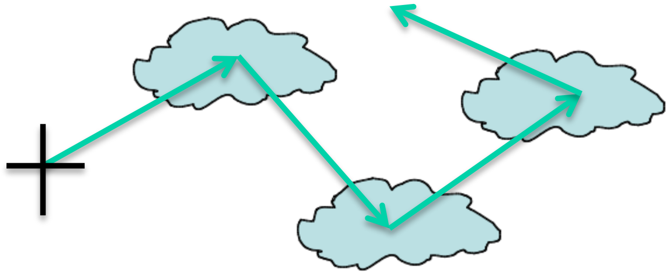
For a Gaussian distribution
easily solved by σ = *2Dt*

$$\rho = \frac{C}{(16\pi Dt)^{3/2}}\exp\left(-\frac{r^2}{4Dt}\right) \quad \text{with} \qquad \left\langle r^2 \right\rangle = 2Dt$$

Description 2: Random walk



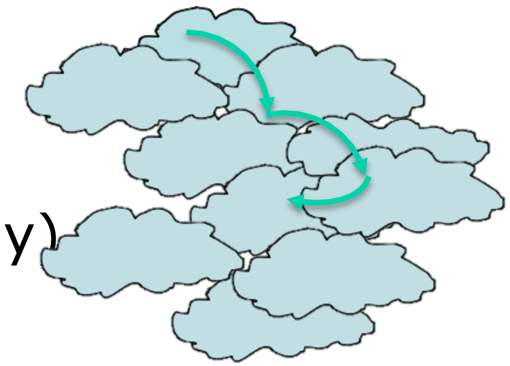
Simplest model:
$n = t/\tau$ random steps
of size L



$$<\mathbf{r}^2> = (\mathbf{r}_1 + \mathbf{r}_2 + \ldots + \mathbf{r}_n)^2 = nL^2 = (t/\tau)L^2 = Lct \equiv 2Dt$$

Diffusion
coefficient
$D=Lc/2$

Maximum turbulent magnetic field: $L \approx R_{Gyro}$
"Bohm diffusion"



$\rightarrow D = R_{Gyro}c/2$ (or $D = R_{Gyro}c/3$, if done properly)

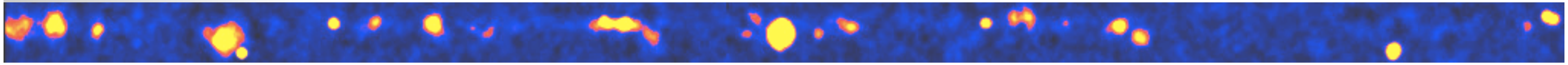
with $R_{pc} \approx E_{PeV}/B_{\mu G}$,

$<\mathbf{r}_{pc}{}^2>^{1/2} \approx 0.3\ (E_{PeV}\ t_{yr}/\ B_{\mu G})^{1/2}$

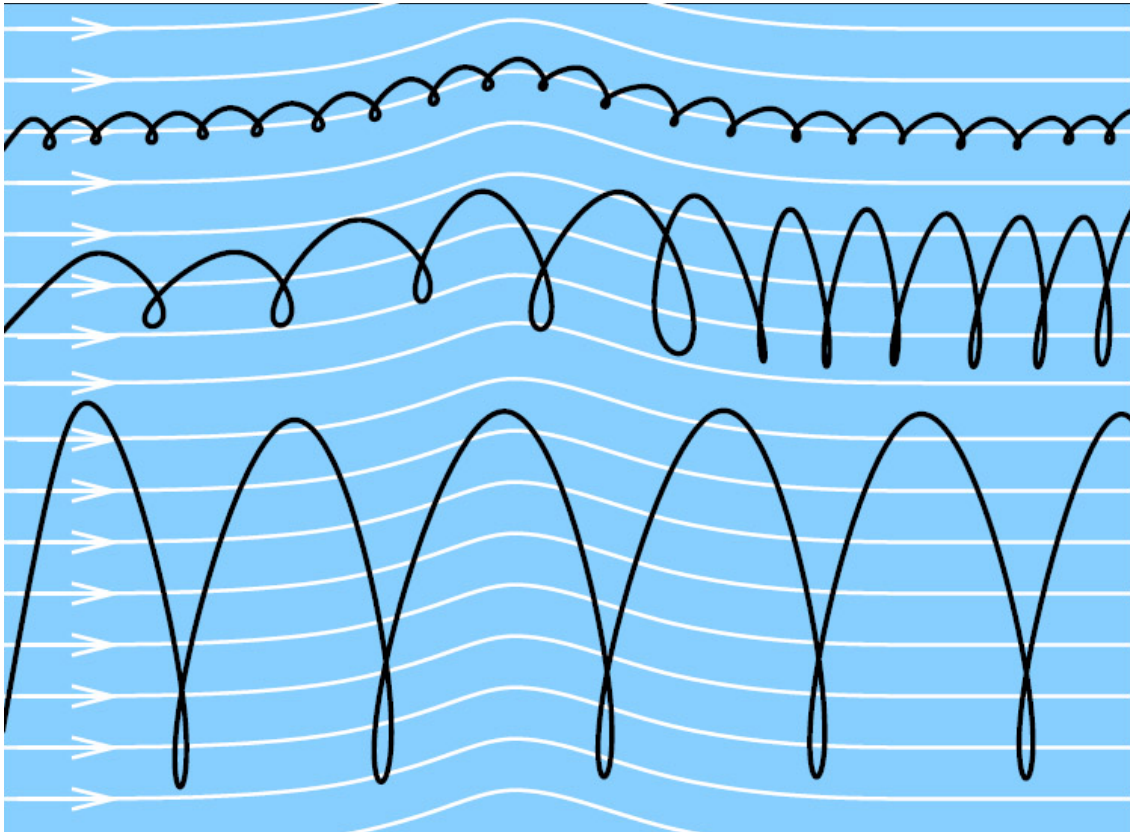
a few light years
in a century !

Diffusion & magnetic fields

particles do not "bounce off" fields!



Diffusion depends on scale of turbulence of field in relation to gyro radius



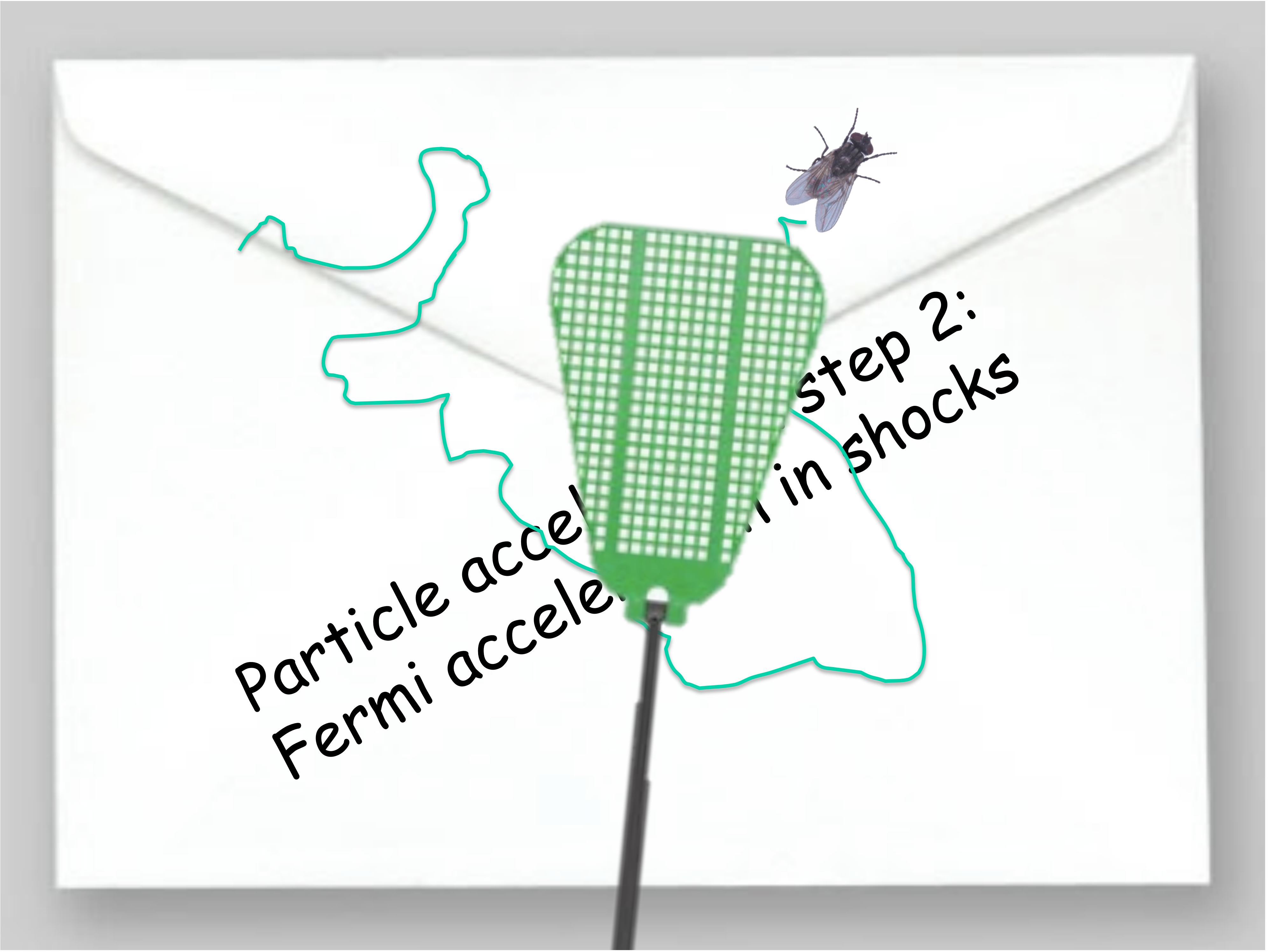
Particle follows field line

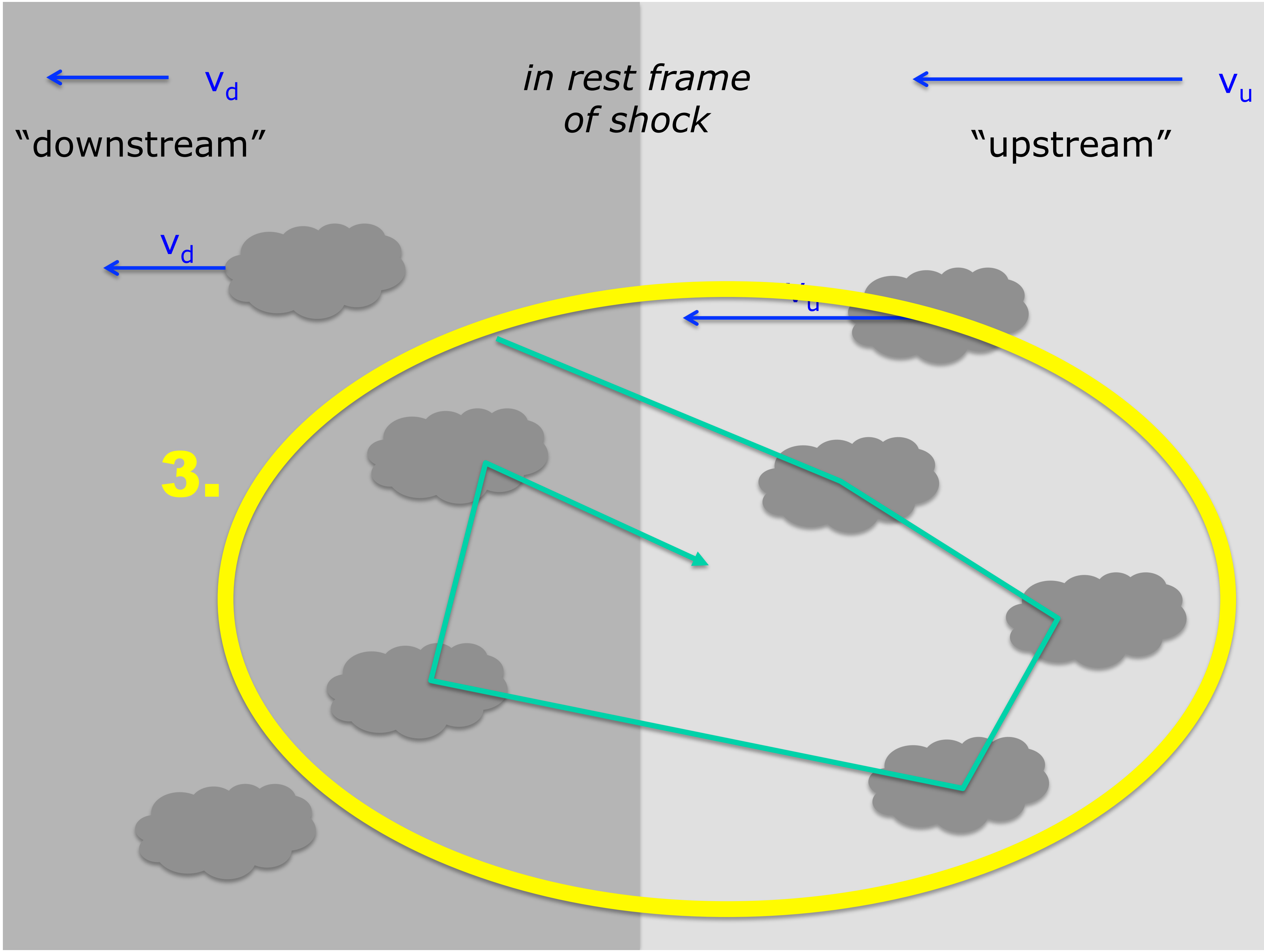
Pitch angle scattering

particle ignores turbulence

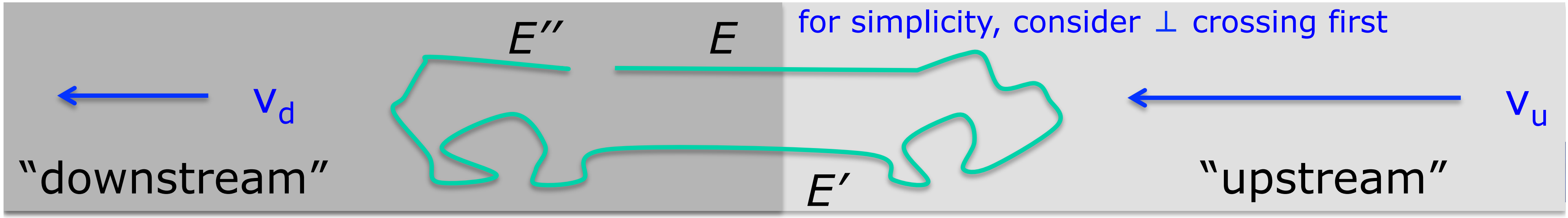
from R.J. Protheroe, Texas Symp. 2006

Effective diffusion coeff. often much larger than Bohm diffusion


Particle accel
step 2:
Fermi accele
in shocks



v_d
in rest frame
of shock
v_u
"downstream"
"upstream"
v_d
v_u
3.



Start with E in downstream rest frame. After crossing shock front:

Particle in medium with speed $v_u - v_d = \left(1-\frac{1}{r}\right)v_{sh} = \left(1-\frac{1}{r}\right)c\beta_{sh}$.

Energy in upstream restframe:

$$E' = \gamma\left(E + \left(1-\frac{1}{r}\right)\beta_{sh}p\right) \underset{\substack{\beta<<1 \\ E>>mc^2}}{\approx} \left(1+\left(1-\frac{1}{r}\right)\beta_{sh}\right)E$$

Energy gain per cycle

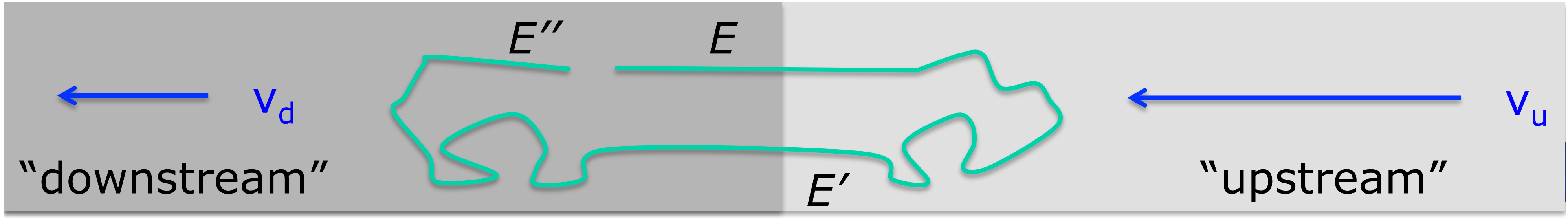
Scatters elastically in upstream restframe:

keeps E', direction isotropic

Returns with E' in downstream region

$$E'' \approx \left(1+\left(1-\frac{1}{r}\right)\beta_{sh}\right)\left(1+\left(1-\frac{1}{r}\right)\beta_{sh}\right)E \approx \left(1+2\left(1-\frac{1}{r}\right)\beta_{sh}\right)E$$

Start next cycle with E''. With proper angle averaging: $2 \rightarrow 4/3$



After n cycles:

$$\mathrm{E}_n \approx \left(1+\frac{4}{3}\left(1-\frac{1}{r}\right)\beta_{sh}\right)^n E_0 = (1+k)^n E_0$$

Resulting spectrum

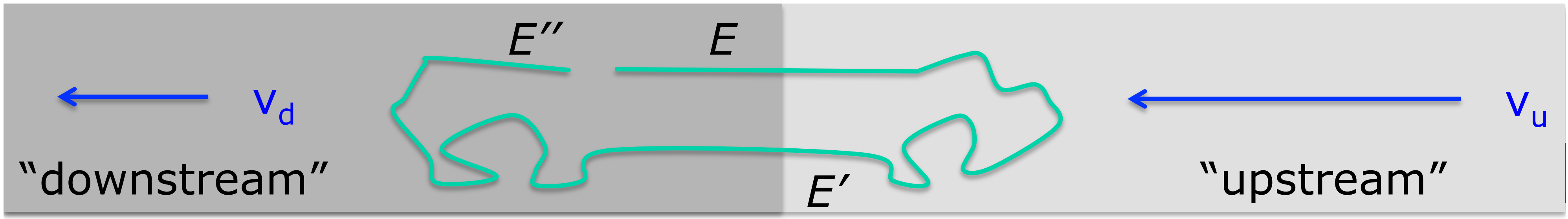
Probability to escape per cycle P

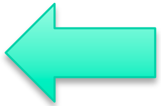
Probability to reach (at least) $E_n : P_n = (1-P)^n$

(Integral) spectrum:

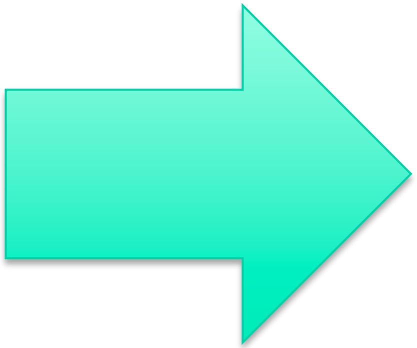
$$P(E > E_n) = (1-P)^{\frac{\log(E_n/E_0)}{\log(1+k)}} = e^{\log(1-P)\frac{\log(E_n/E_0)}{\log(1+k)}} = \left(\frac{E_n}{E_0}\right)^{\frac{\log(1-P)}{\log(1+k)}}$$

Index of (differential) spectrum: $\Gamma = -\dfrac{\log(1-P)}{\log(1+k)} + 1$





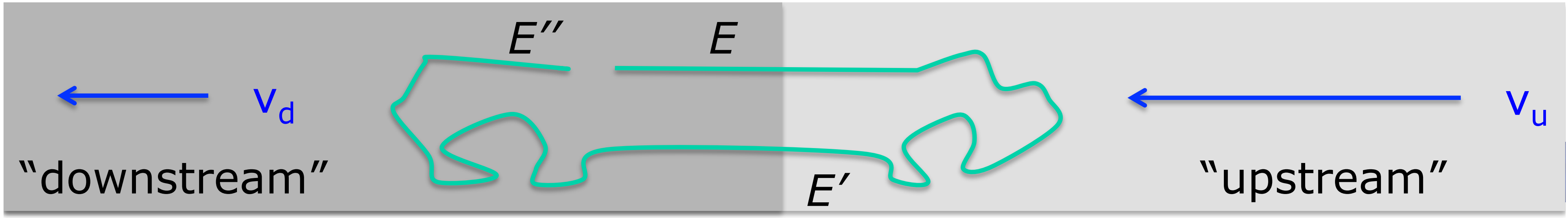
rate Φ_{escape} of particles flowing away downstream (i.e. lost)



rate Φ_{cross} of particles crossing shock towards upstream region (i.e. doing one more cycle)

Escape probability P: basic idea

$$P \approx \Phi_{escape}/\Phi_{cross}$$



Escape probability and spectral index

Flux of particles swept downstream:

$$\Phi_{escape} = \rho_{particle,d} v_d$$

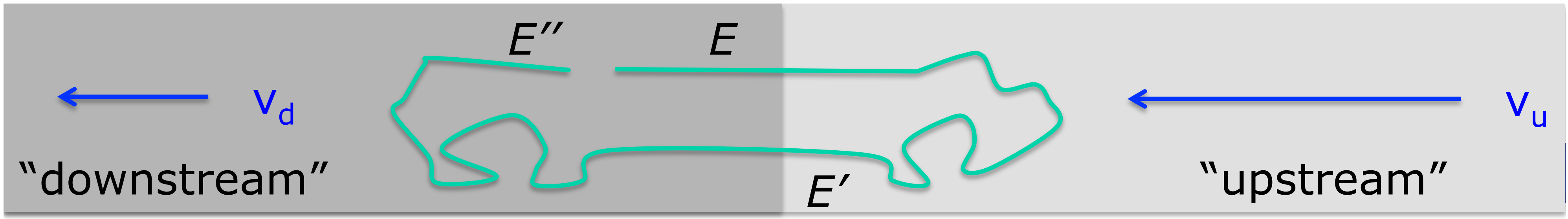
Flux of particles crossing shock towards upstream:

$$\Phi_{cross} = \frac{\rho_{particle,d} c}{4} >> \Phi_{escape}$$

Escape probability $P \approx \frac{\Phi_{escape}}{\Phi_{cross}} \approx \frac{4v_d}{c} = \frac{4\beta_{sh}}{r}$

Spectral index: $\Gamma = -\frac{\log(1-P)}{\log(1+k)} + 1 \approx \frac{P}{k} + 1 \approx \frac{\frac{4\beta_{sh}}{r}}{\frac{4}{3}\left(\frac{r-1}{r}\right)\beta_{sh}} + 1 = \frac{r+2}{r-1}$

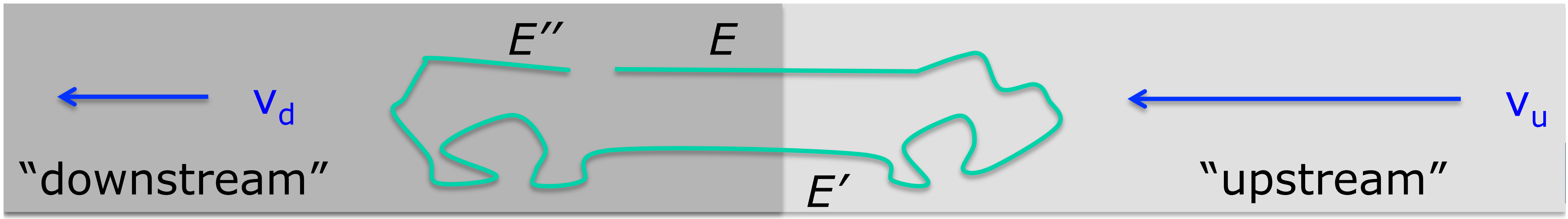
For strong shocks
r=4 ➜ Γ=2

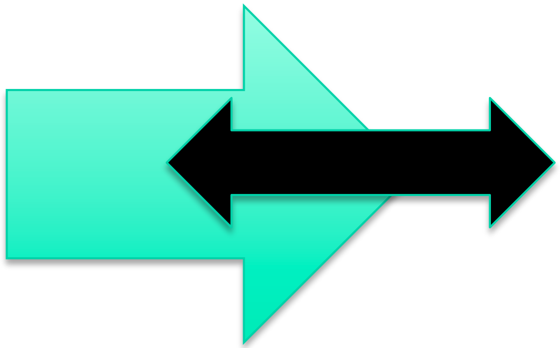


How fast is the acceleration?

i.e. how long does one cycle last?

What determines the maximum energy reached in the process?





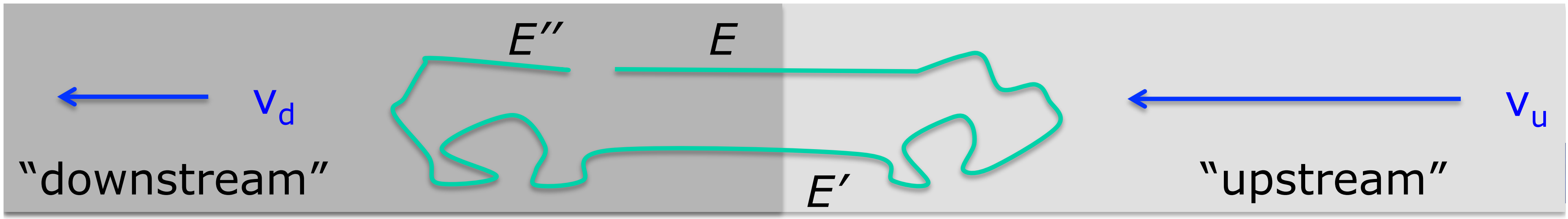
\# of particles
upstream
= density x
scale length
(per shock area)

rate Φ_{cross} of particles crossing
shock towards upstream region
(i.e. doing one more cycle)

How long does one cycle last: basic idea

\# upstream = crossing rate x residence time

help by Luke Drury is gratefully acknowledged!



Upstream
scale length λ

How far upstream
do particles move?

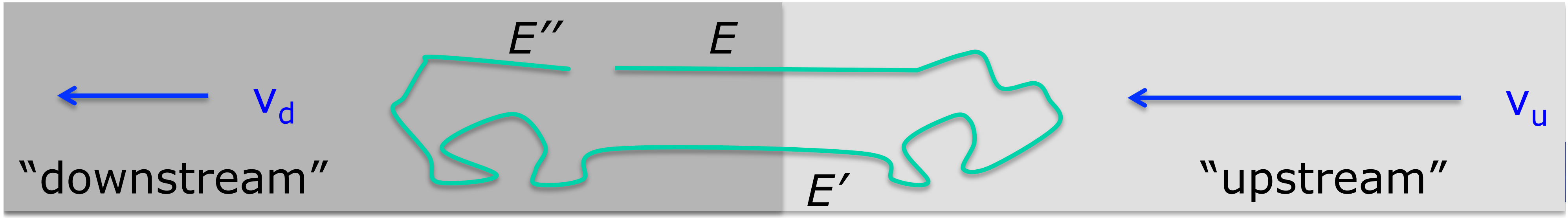
Diffusion flow $D\nabla\rho \approx D\rho/\lambda$

Streaming flow ρv_u

Steady state: $D\rho/\lambda = \rho v_u \Rightarrow \lambda = \dfrac{D}{v_u} \underset{\substack{Bohm\\ diff.}}{=} \dfrac{R_{gyro}c/3}{v_u}$

Number of upstream partices (per shock area)

$$N \approx \rho\lambda \approx \rho D / v_u$$



Cycle time

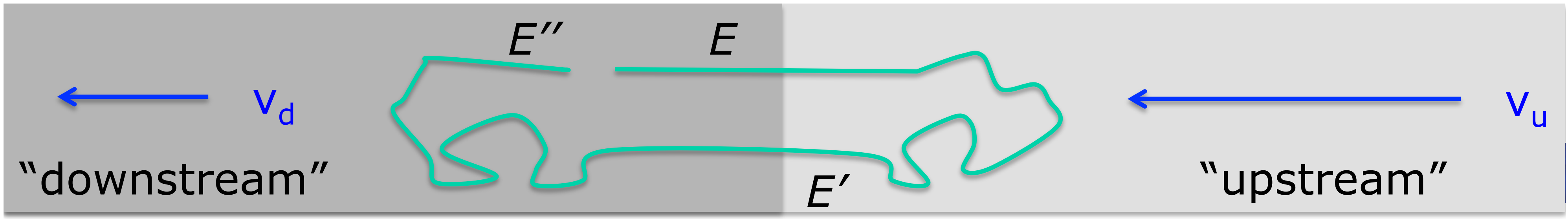
Number of upstream partices (per shock area)

$$N \approx \rho\lambda \approx \rho D / v_u$$

Flux through shock: $\Phi = \dfrac{\rho c}{4}$ particles per time

Since $\Phi\tau_u = N$, $\quad \tau_u = \dfrac{4D}{v_u c} \underset{\substack{Bohm\\ diff.}}{=} \dfrac{4(R_{gyro}c/3)}{v_u c} \approx \dfrac{R_{gyro}}{v_u}$

+ similar time scale spent downstream



$$\text{Cycle time } \tau \approx \text{ few } \frac{R_{gyro}}{v_u} \approx 5 \frac{E_{PeV}}{B_{\mu G}} \frac{1}{\beta_{sh}} \text{yr}$$

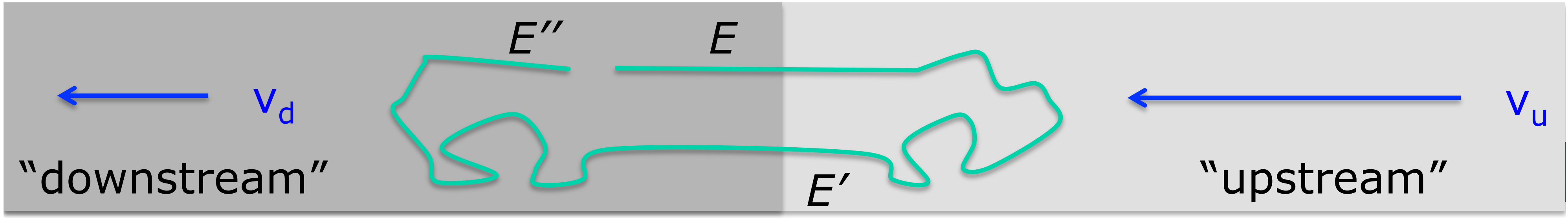
$$\frac{dE}{dt} \approx \frac{\beta_{sh} E}{\tau} \propto \beta_{sh}^2 B \approx 0.2 \beta_{sh}^2 B_{\mu G} \text{ PeV/yr}$$

few μG x 4?

few 10^{-4}

the larger the B field,
the faster the acceleration

Acceleration speed



Maximum energy

Maximum energy depends on

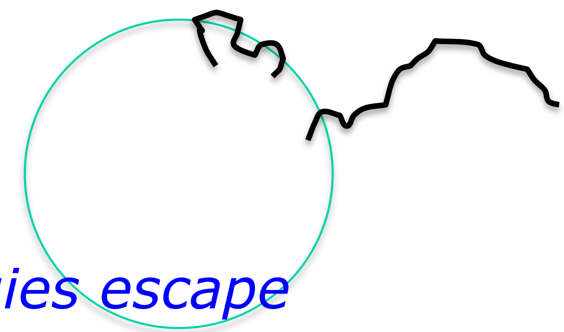
- Acc. rate x age of remnant
- Losses (electrons)
- Escape (up- or downstream)

$$\text{Upstream scale length } \lambda \approx \frac{D}{v_u} \approx \frac{R_{gyro} c/3}{v_u} = \frac{R_{gyro}}{3\beta_{sh}}$$

Once $\lambda \approx O(R_{SNR})$ particles will obviously escape

$$\text{Escape: } R_{gyro} \approx \frac{E_{PeV}}{B_{\mu G}} pc \approx 3\beta_{sh} R_{SNR}$$

O(1 pc)



the larger the B field,

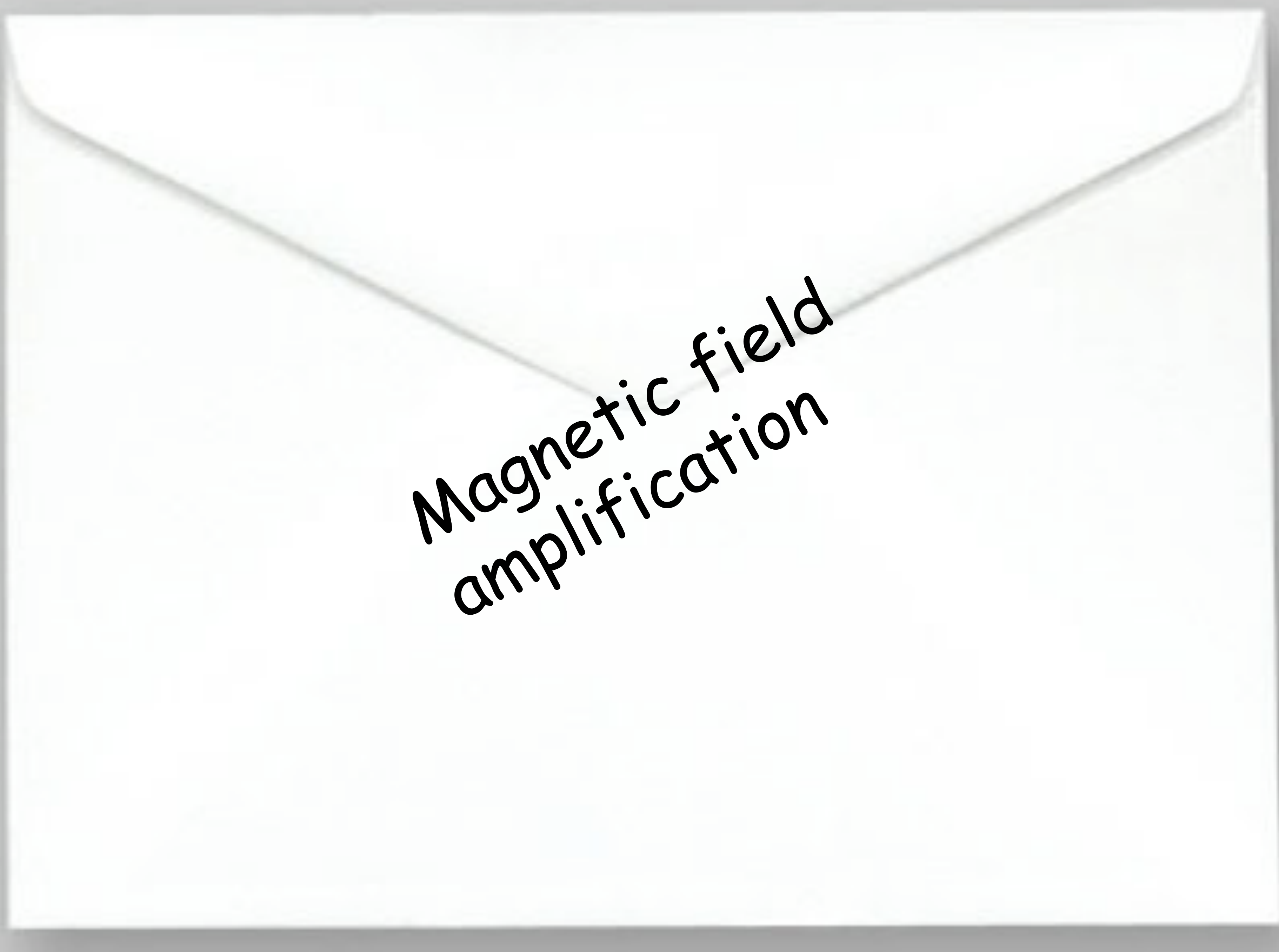
the higher the peak energy

as the shock slows down, lower energies escape

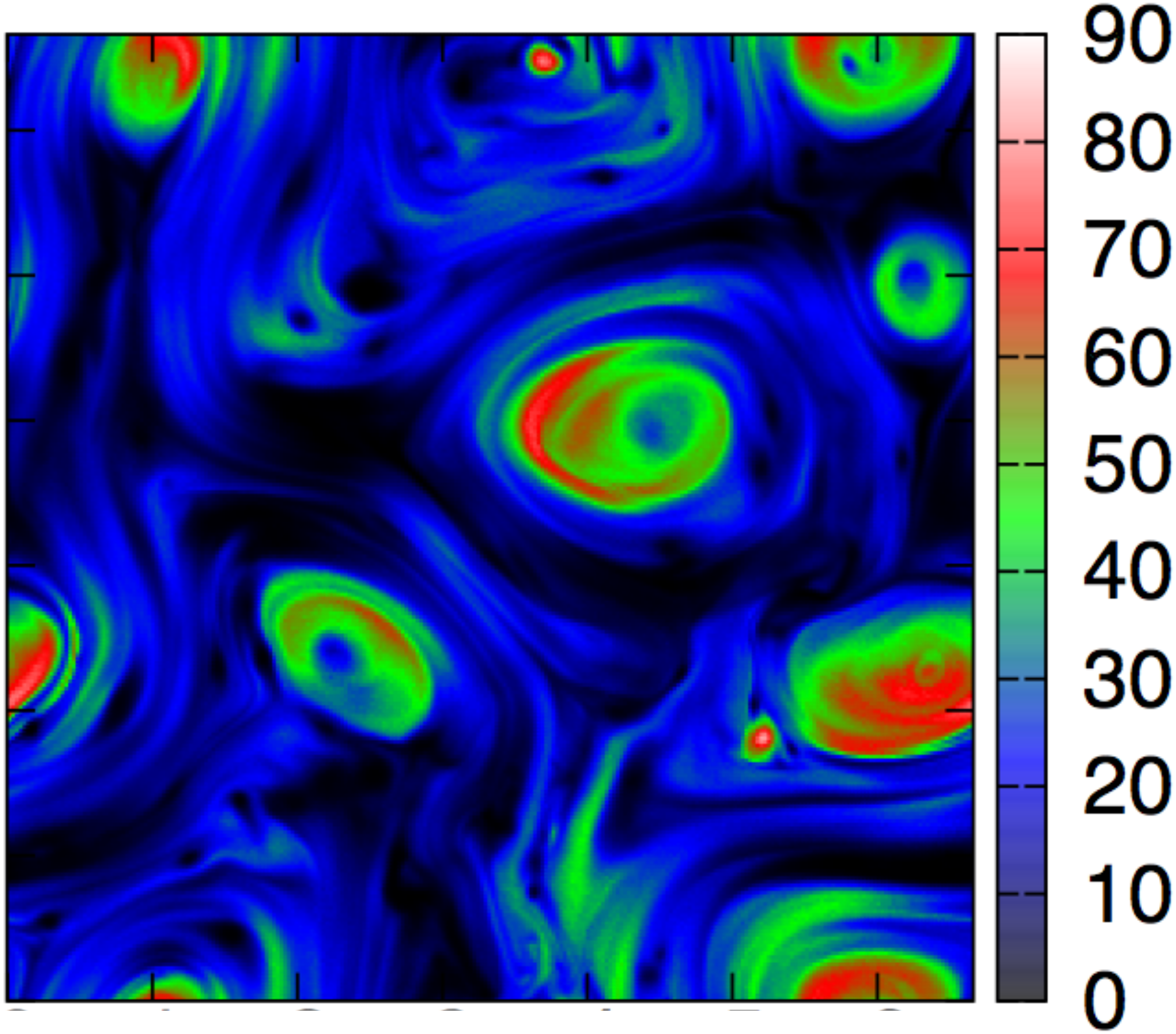
So far, “test particle” case

Accelerated particles do not react back onto their environment

but does this make sense for “efficient” acceleration which converts a fair fraction of supernova ejecta energy into cosmic rays ??


Magnetic field
amplification

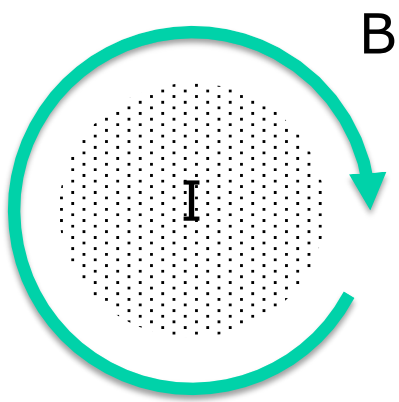
Field amplification by streaming CRs



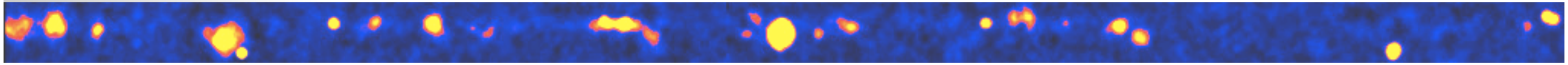
Front view:

Magnetic field in shock

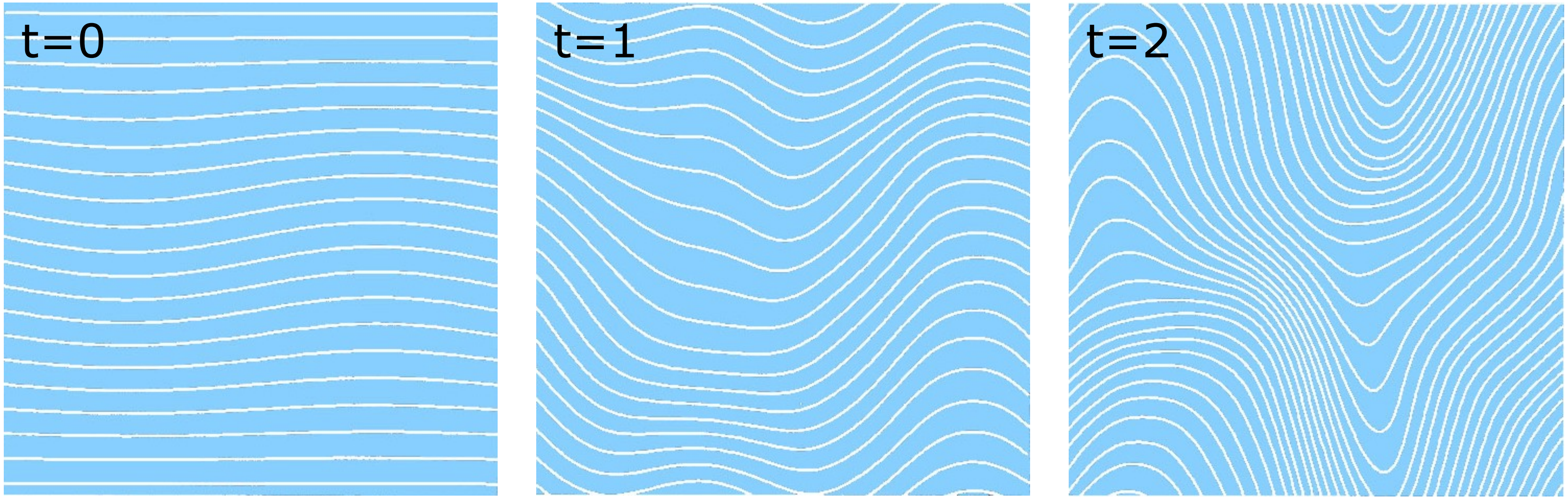
Ohira et al.
arXiv:0812.0901



Field amplification by streaming CRs



S.G. Lucek, A.R. Bell, MNRAS 314 (2000) 65

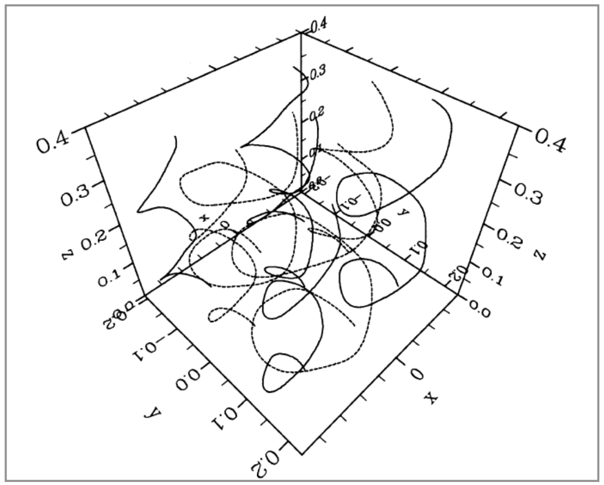


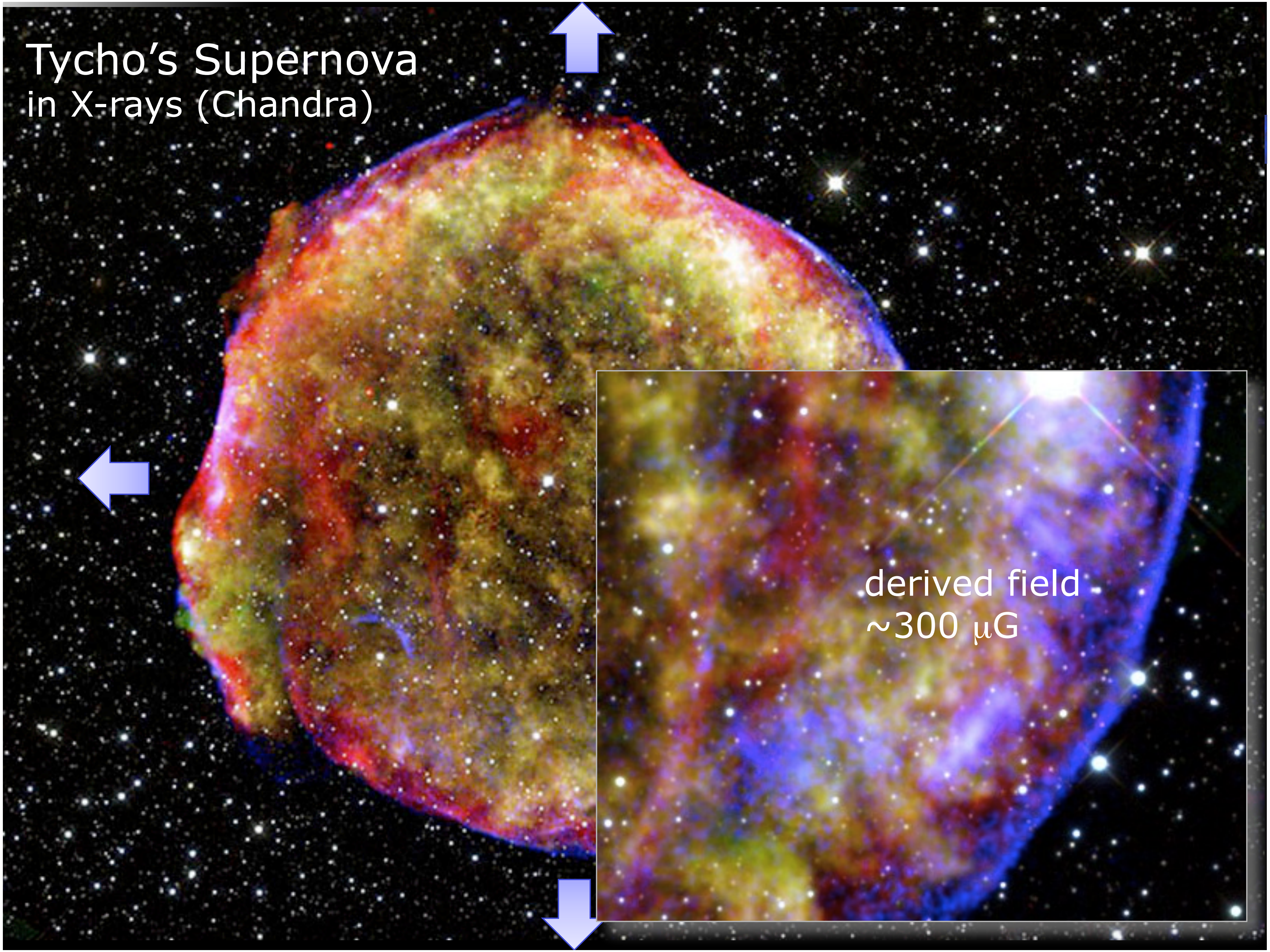
RMS B field amplified by factor up to 30

A.R. Bell, MNRAS 353 (2004) 550

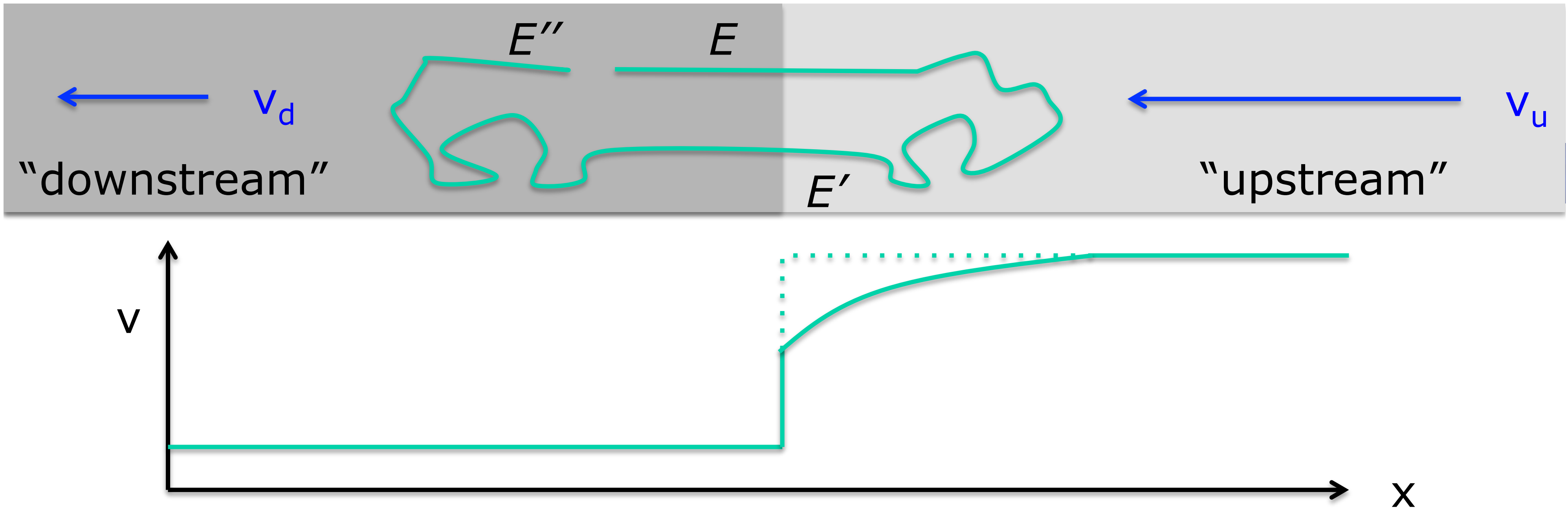
Accelerated particles create B turbulence!

➜ Provide upstream scattering centers




Tycho's Supernova
in X-rays (Chandra)
derived field
~300 μG


Non-linear shock
modification



For efficient acceleration is the energy density in upstream cosmic rays no longer negligible compared to kinetic energy of instreaming gas.

Two effects:

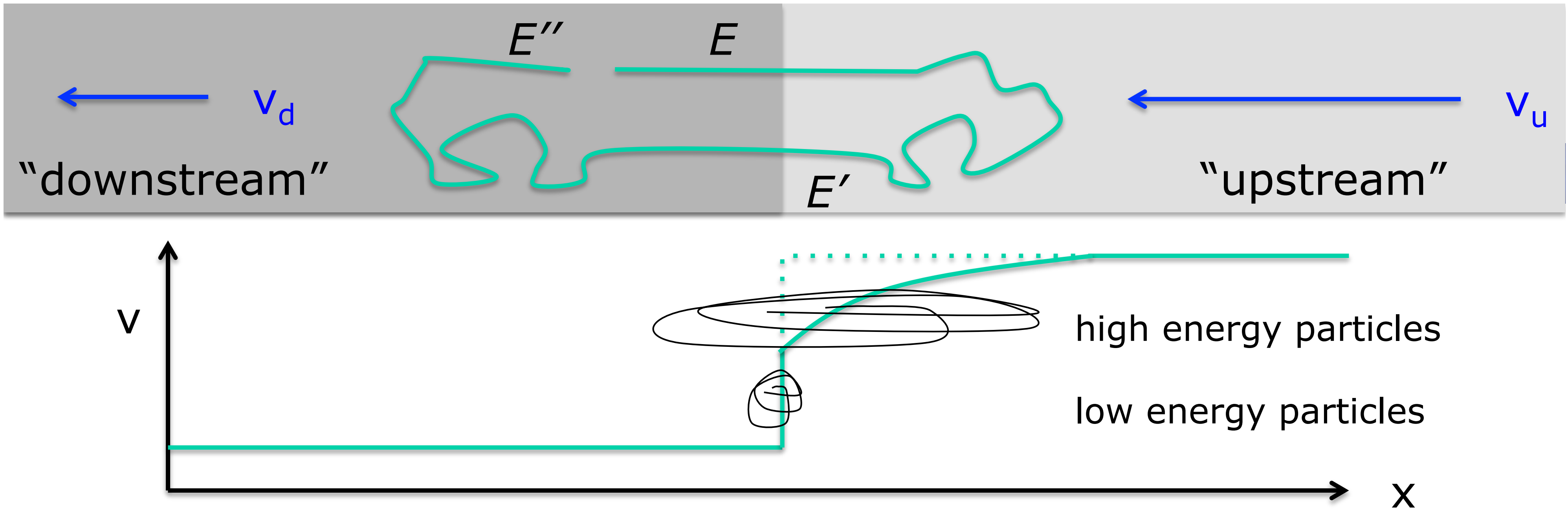
- Shock precursor
- Increased shock compression ratio

Effect of the "cosmic ray gas"

Shock compression ratio for large M:

- for ideal gas with $\gamma = 5/3$: $\quad r \approx \frac{\gamma+1}{\gamma-1} = 4$ and $\Gamma = \frac{r+2}{r-1} = 2$

- for relativistic gas $\gamma = 4/3$: $\; r = 7$ and $\Gamma = 1.5$

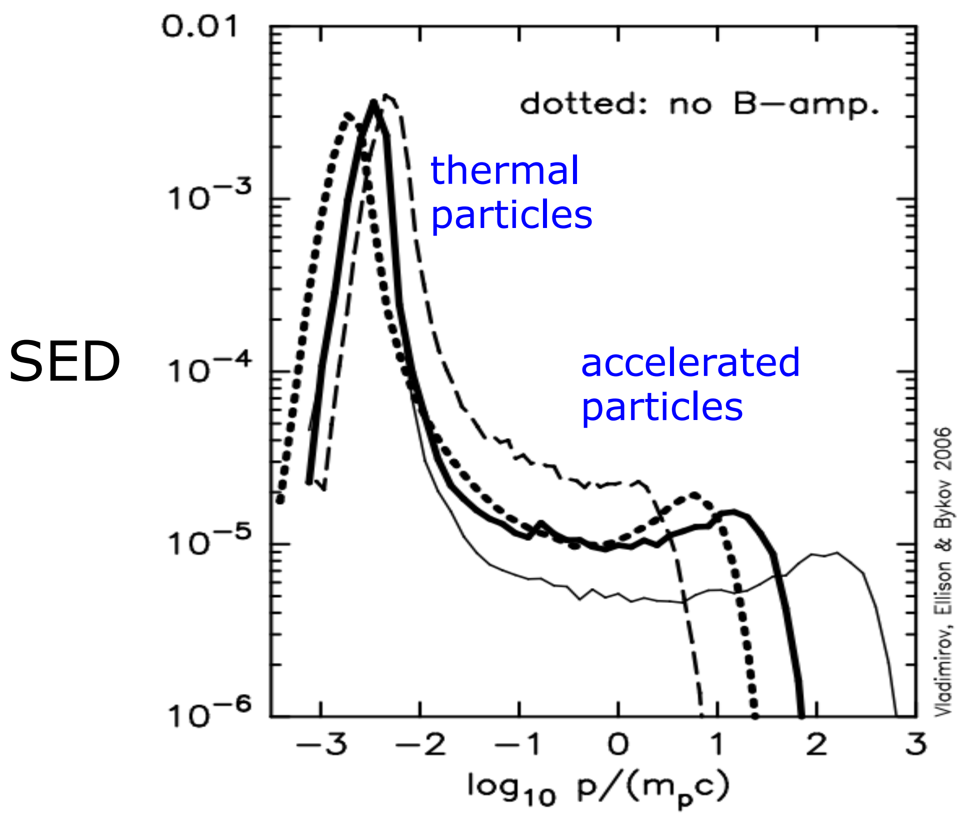


Low energy particles see reduced r:

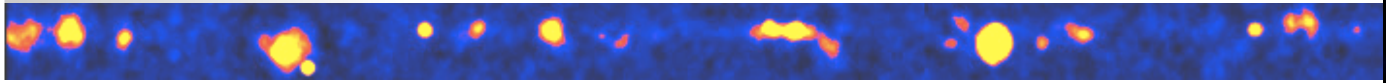
$\Gamma = (r+2)/(r-1) > 2$

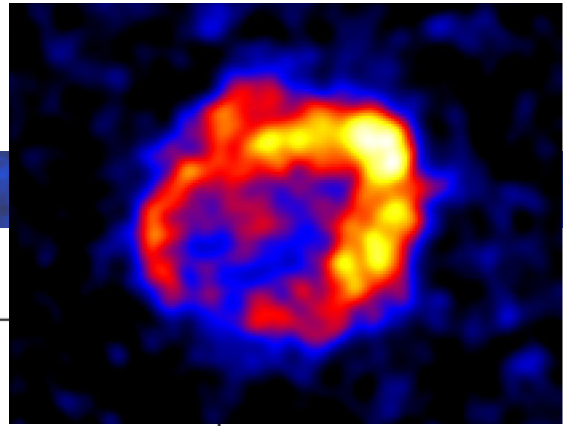
High energy particles see full & increased r:

$\Gamma = (r+2)/(r-1) < 2$

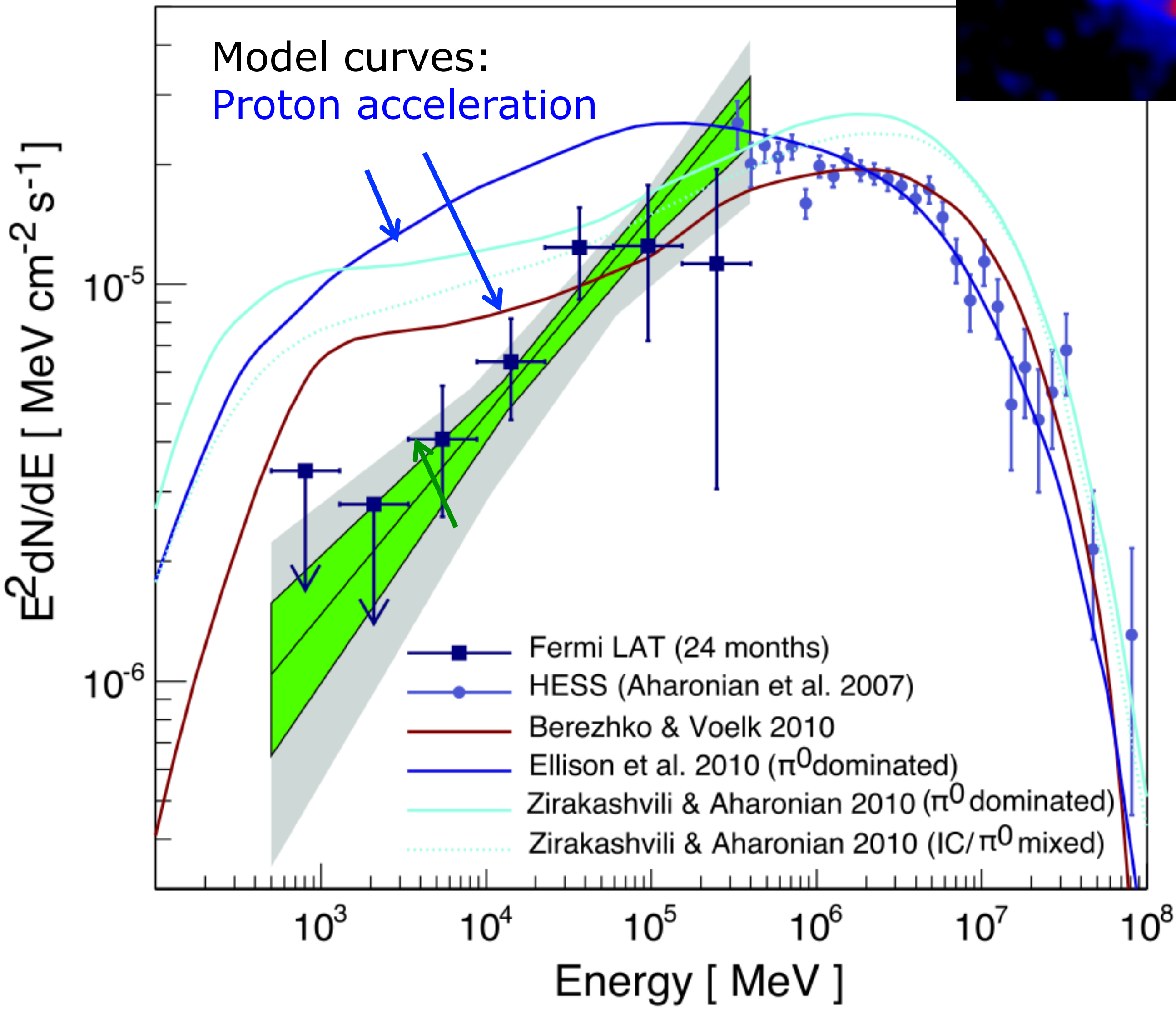


The remnant RX J1713.7-3946



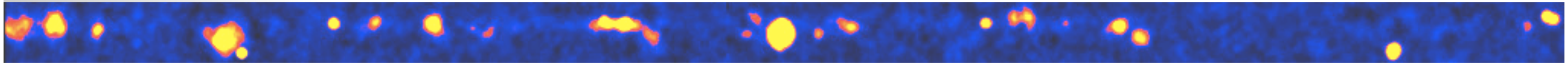


Fermi-LAT Collab.
arXiv:1103.5727

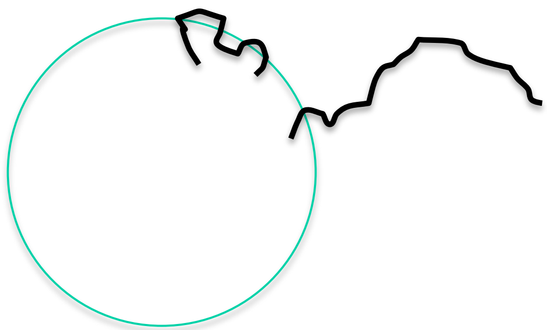


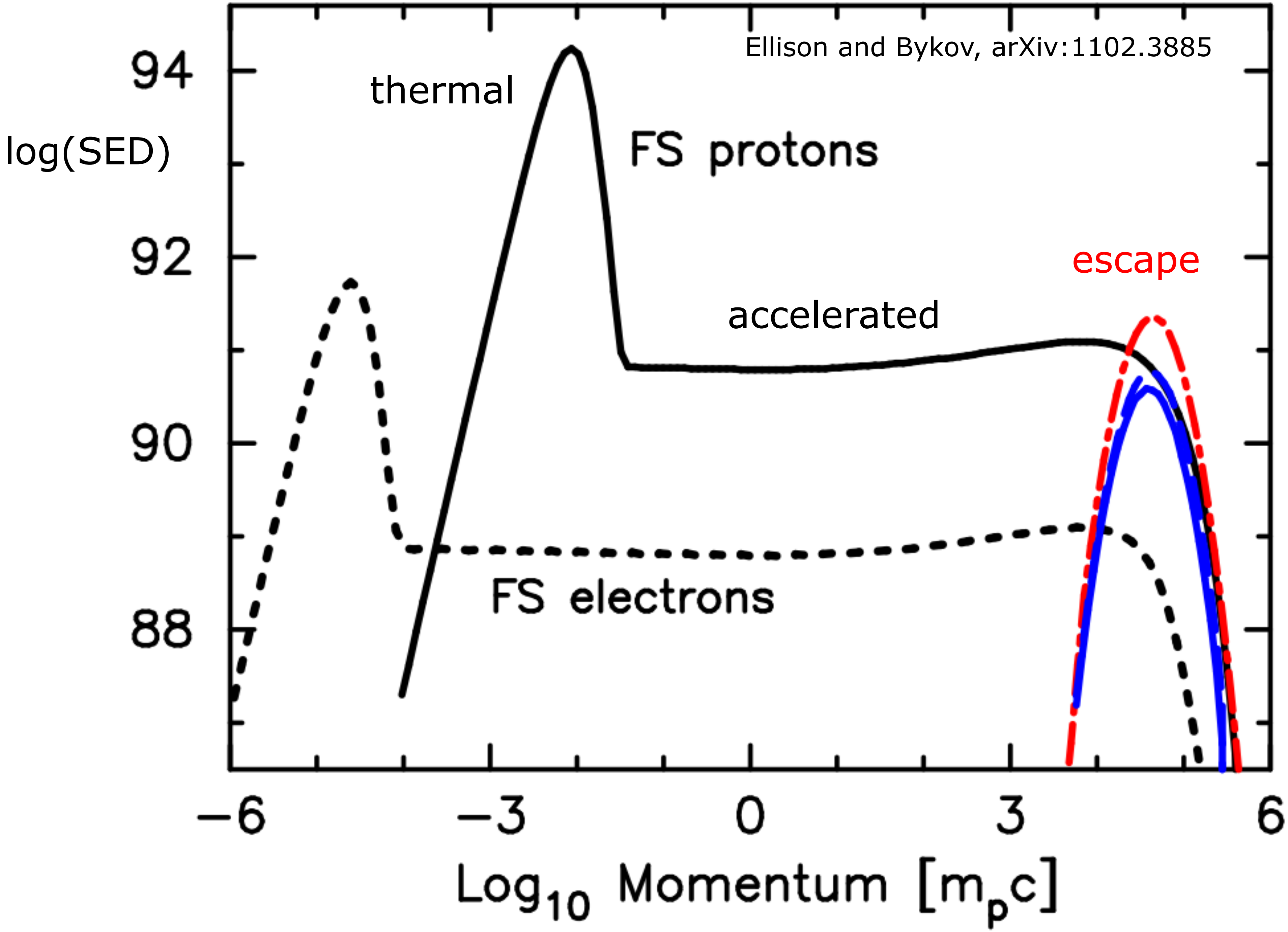
Cosmic rays escaping
from supernova remnants

Particles escaping from remnant



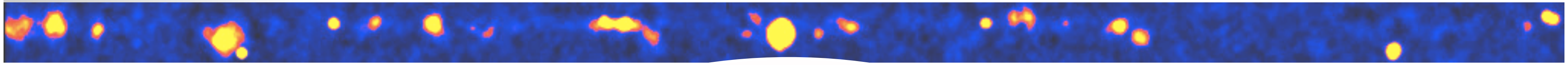
Particles where Gyroradius becomes a fraction of remnant radius will escape

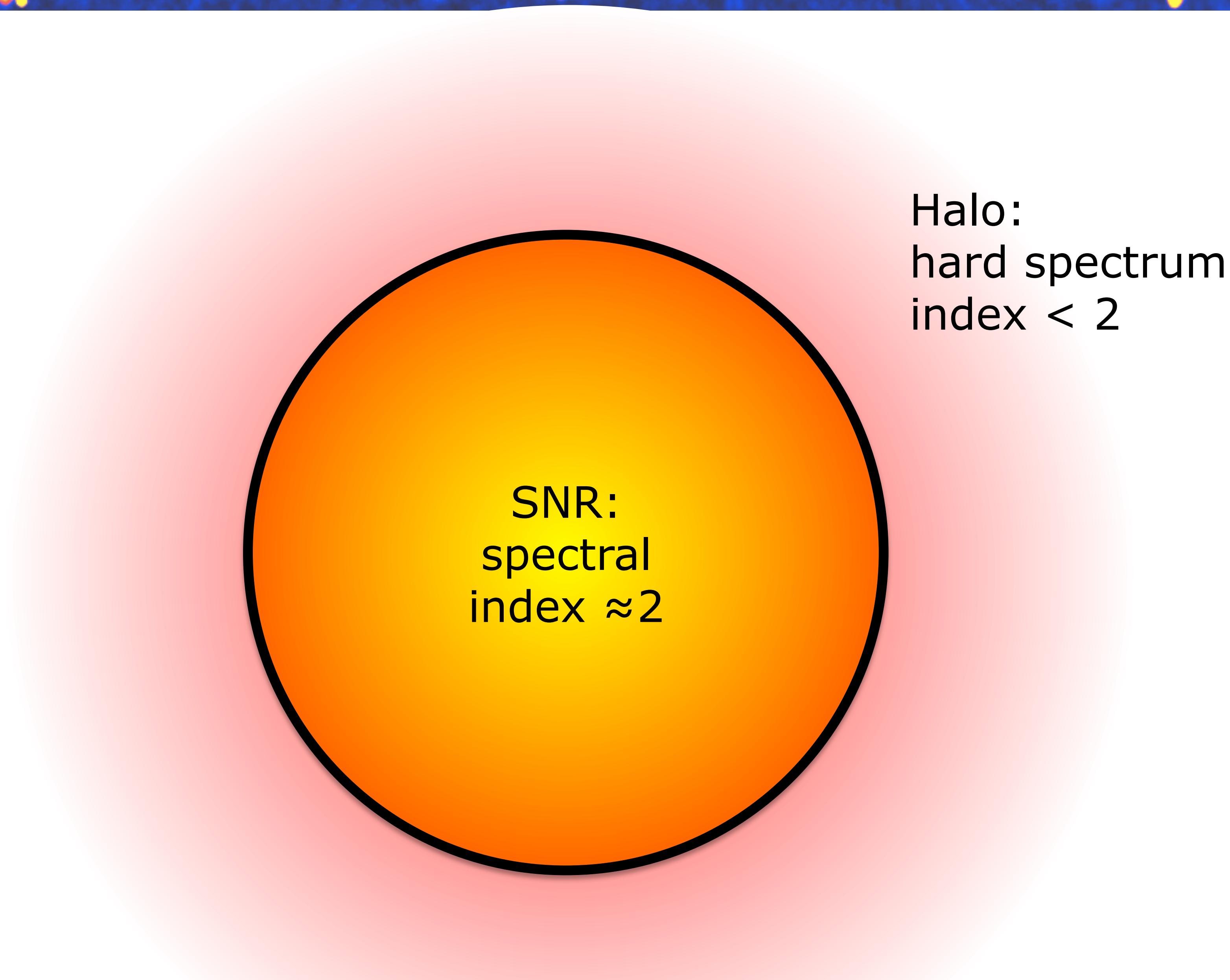




Ellison and Bykov, arXiv:1102.3885
log(SED)
94
92
90
88
thermal
FS protons
accelerated
escape
FS electrons
−6
−3
0
3
6
Log$_{10}$ Momentum [m_pc]

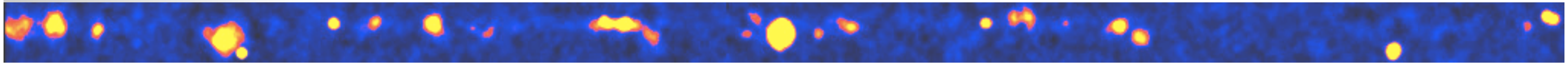
Gamma ray “glow” around remnants?

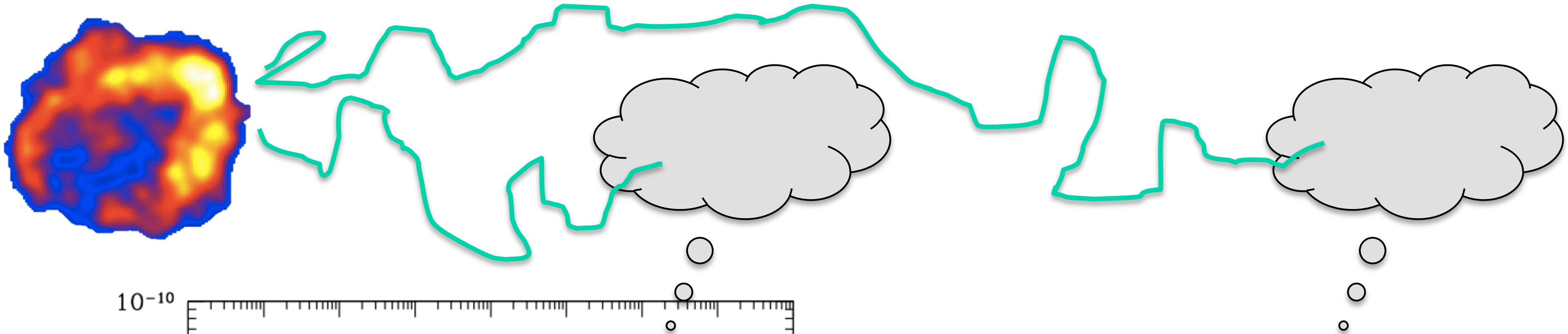


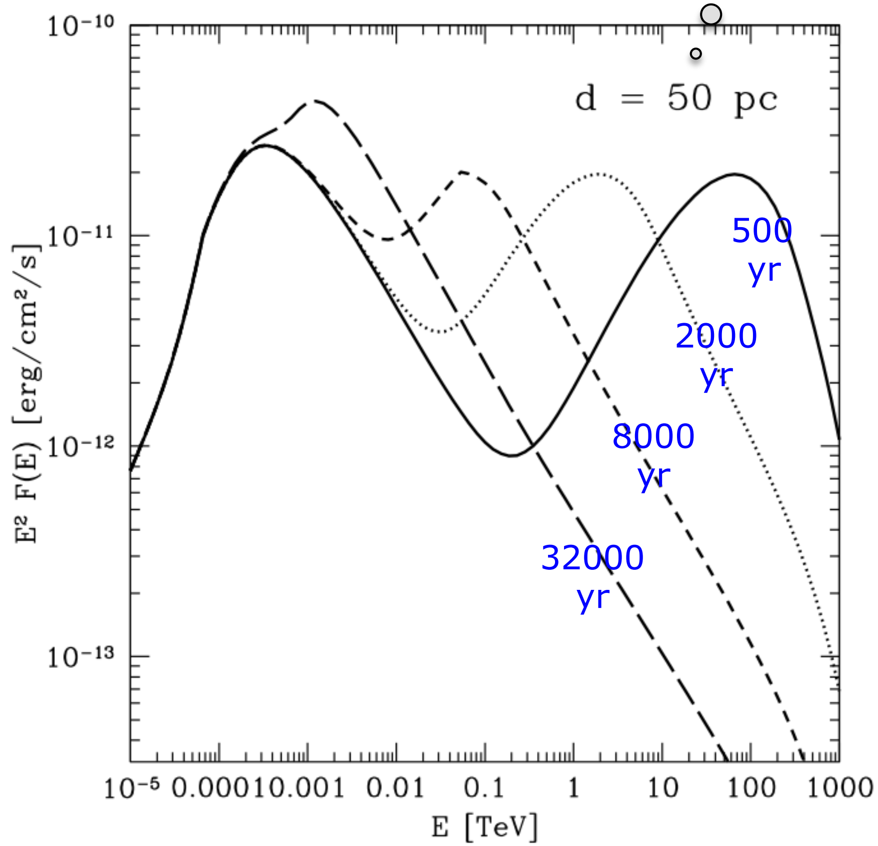


Probing CR escape

Gabici et al
arXiv:0901.4549





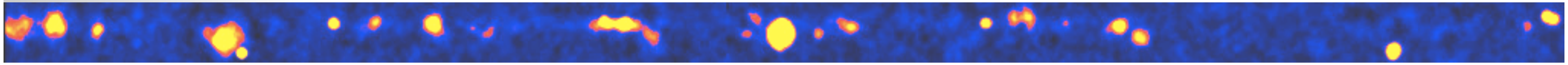


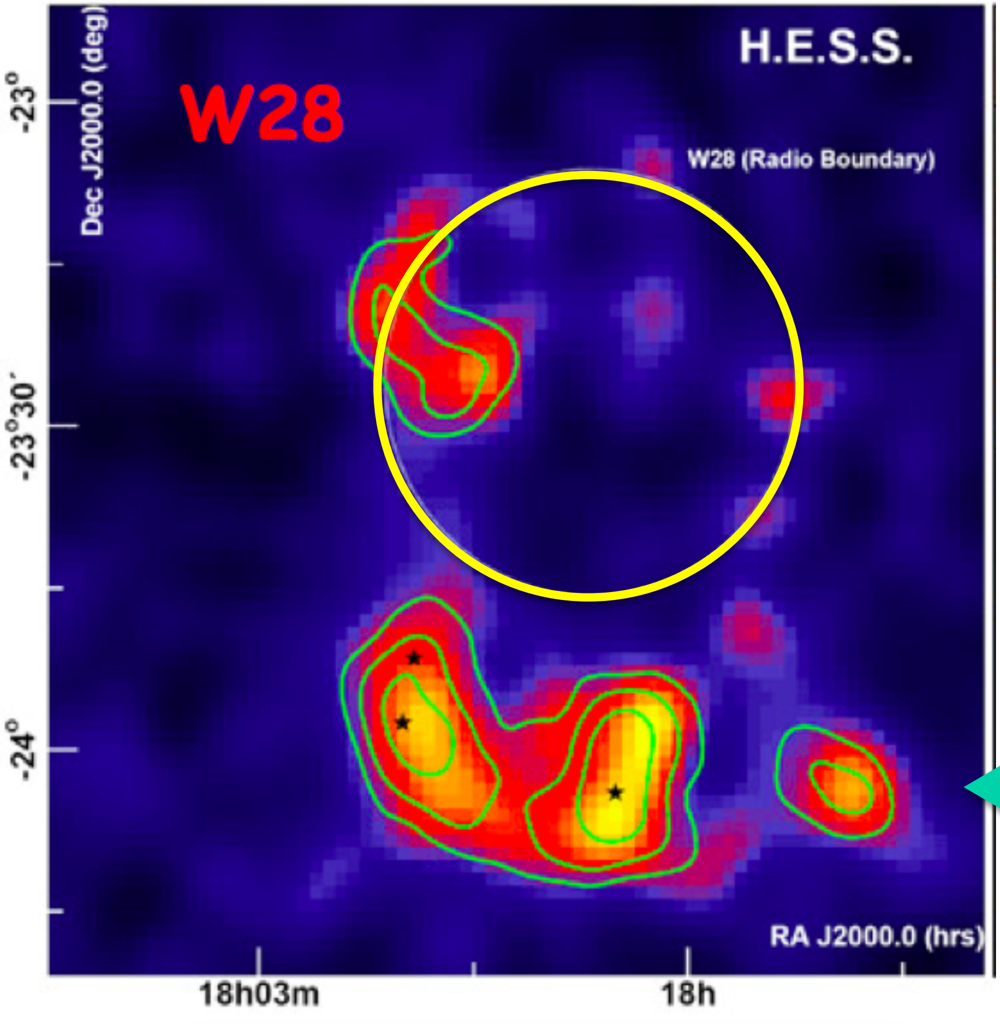
High-energy particles

(a) escape first
(b) diffuse faster

➜ Hard spectrum of gamma rays from clouds

The SNR W28





HESS:
Aharonian et al., arXiv:0801.3555

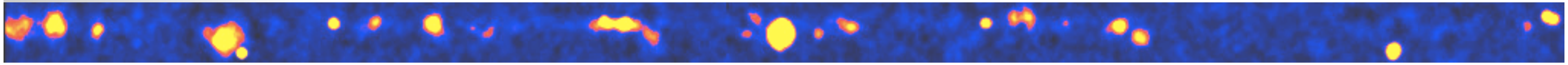
Fermi:
Abdo et al., ApJ 718 (2010) 348

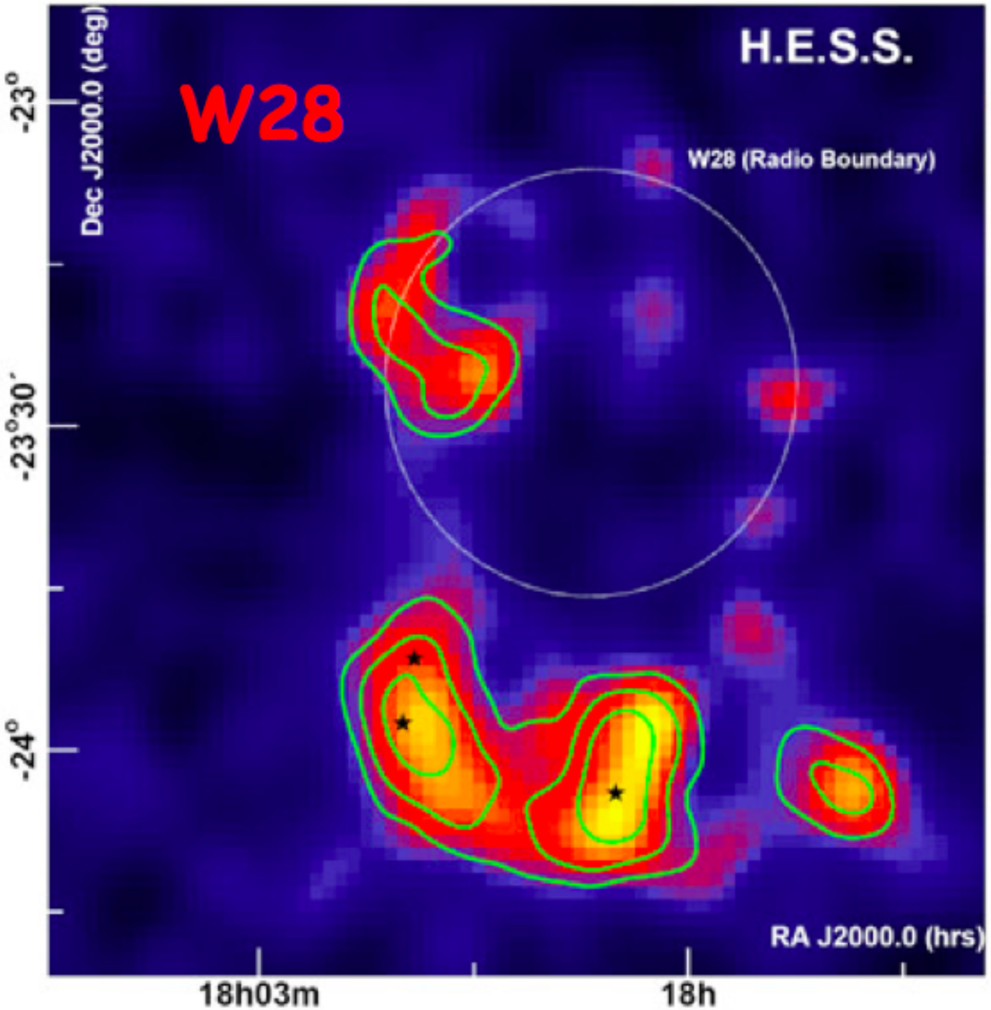
AGILE
Giuliani et al., arXiv:1005.0784

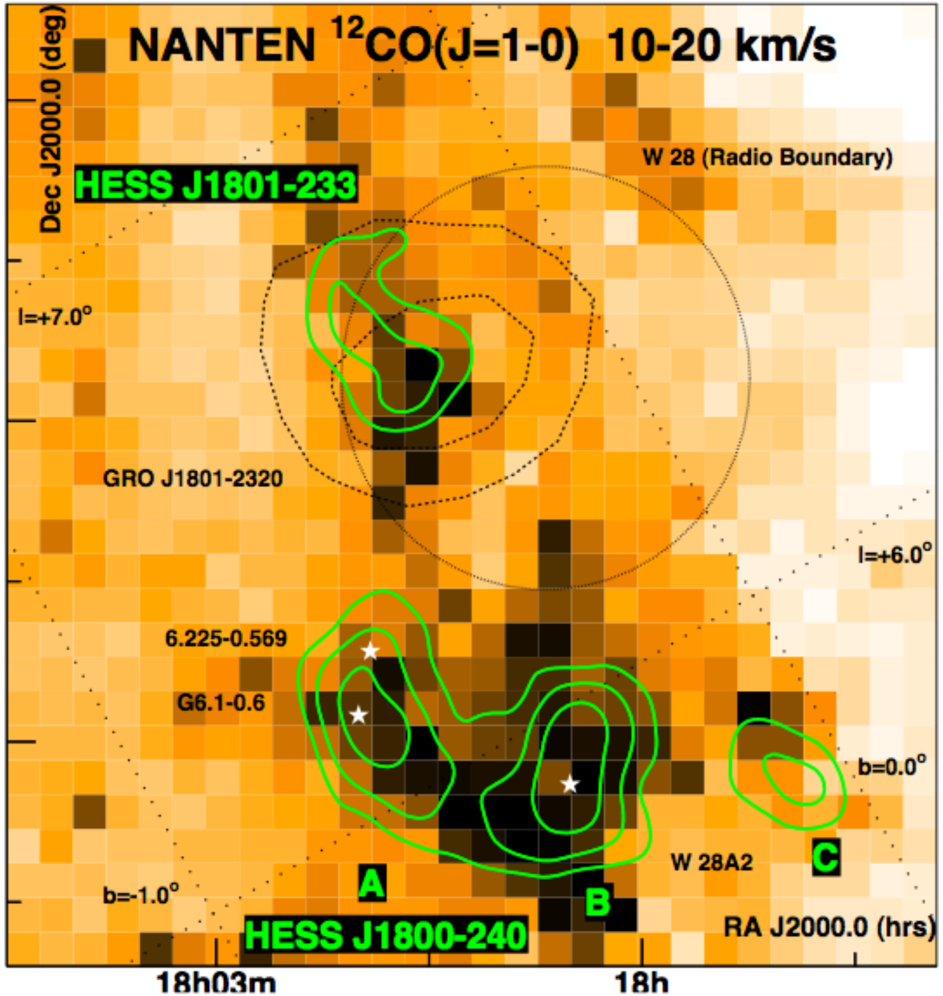
Models:
Gabici et al., arXiv:1009.5291
Li & Chen, arXiv:1009.0894
Ohira et al., arXiv:1007.4869

CRs escaping from 35-150 kyr old SNR interacting with clouds?

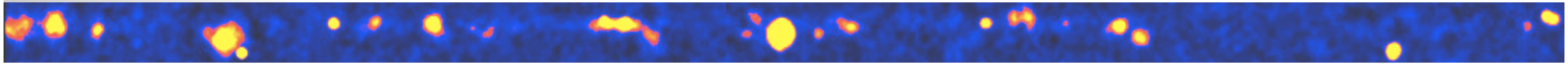
The SNR W28 & clouds seen in CO

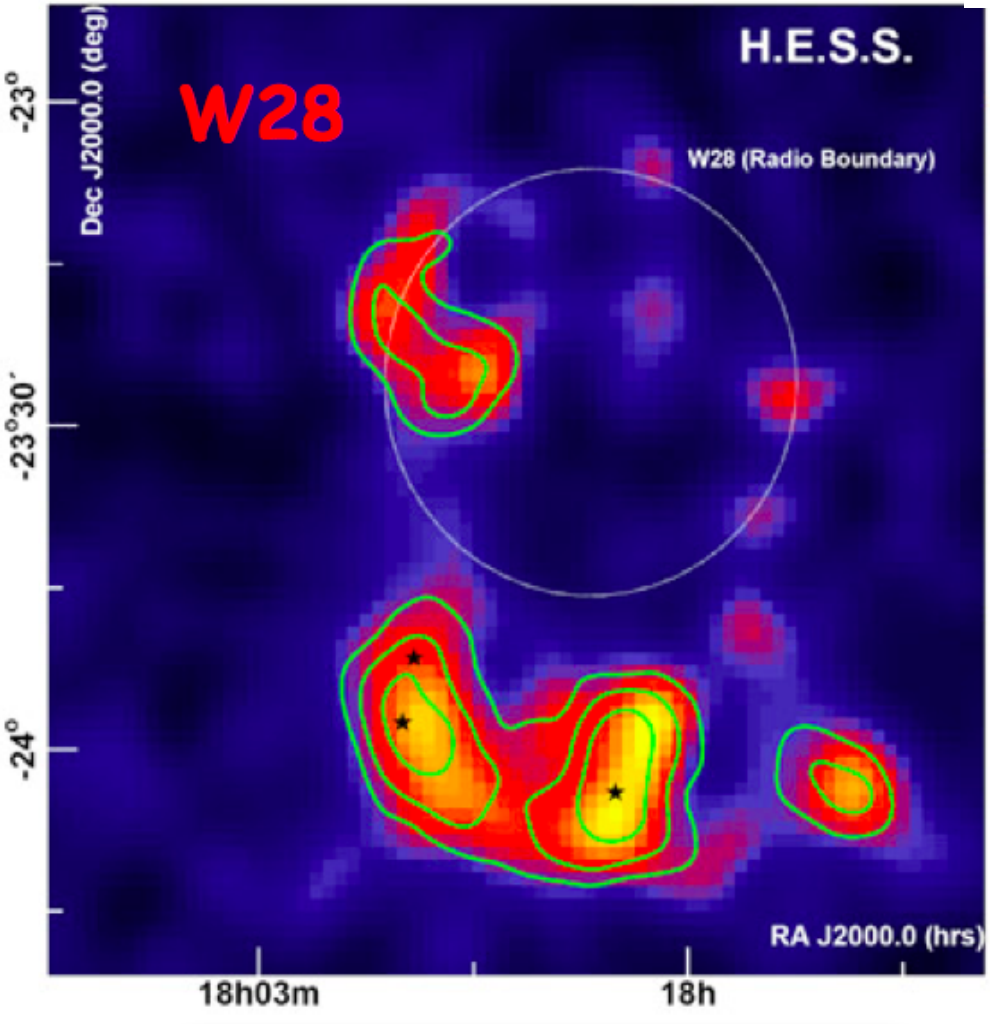


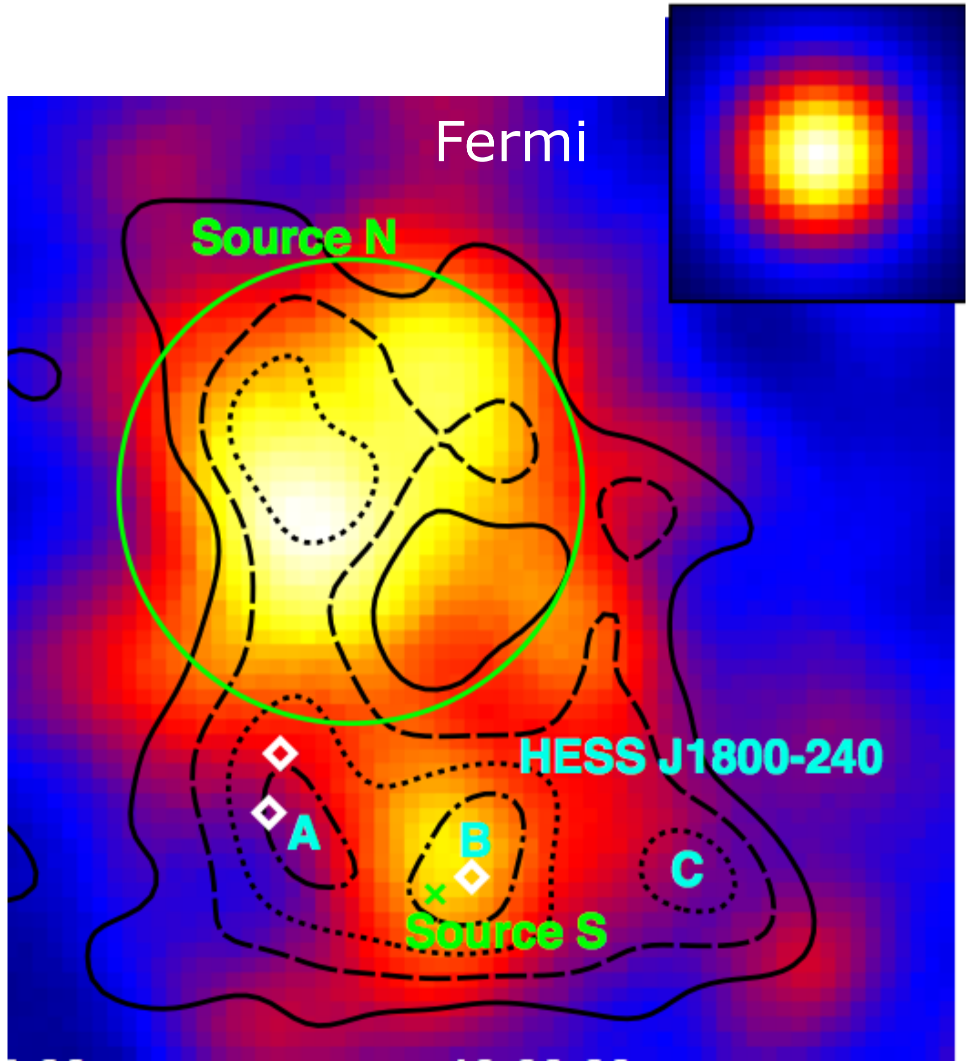


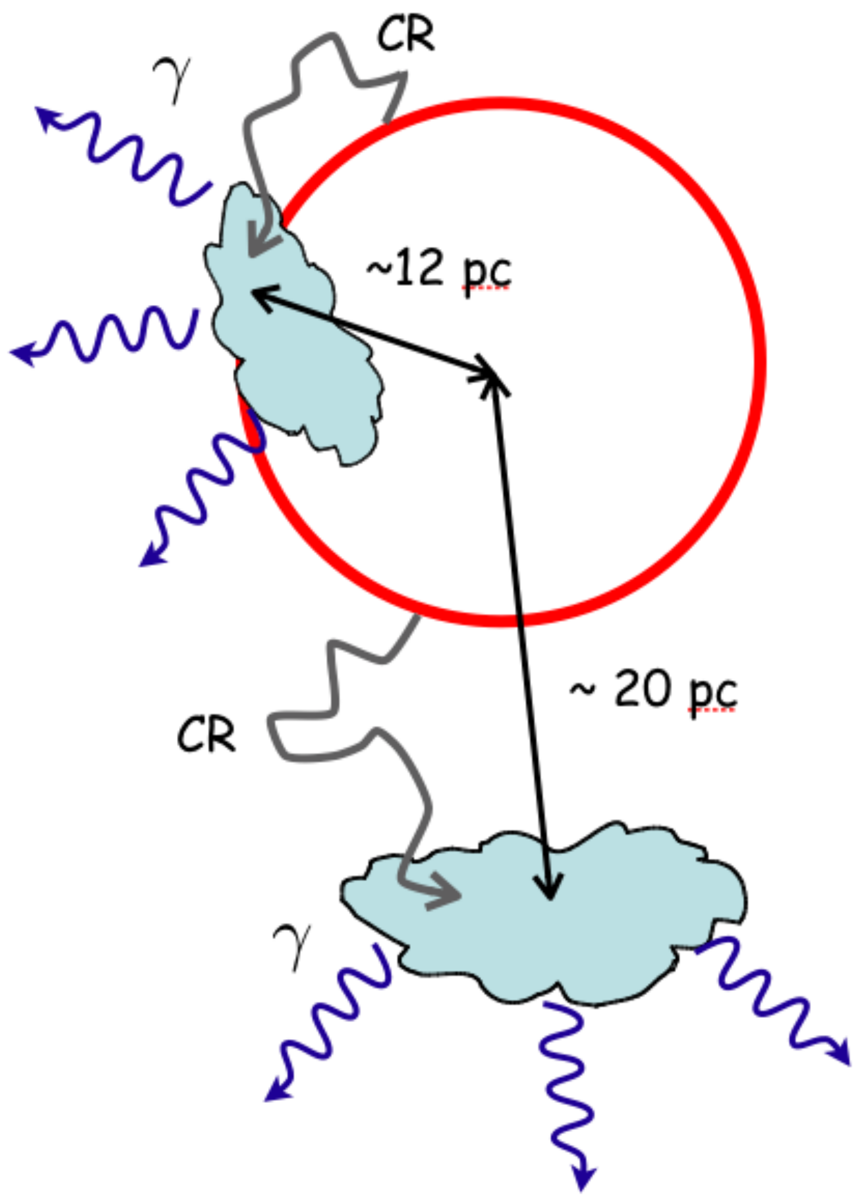


The SNR W28 @ TeV and GeV

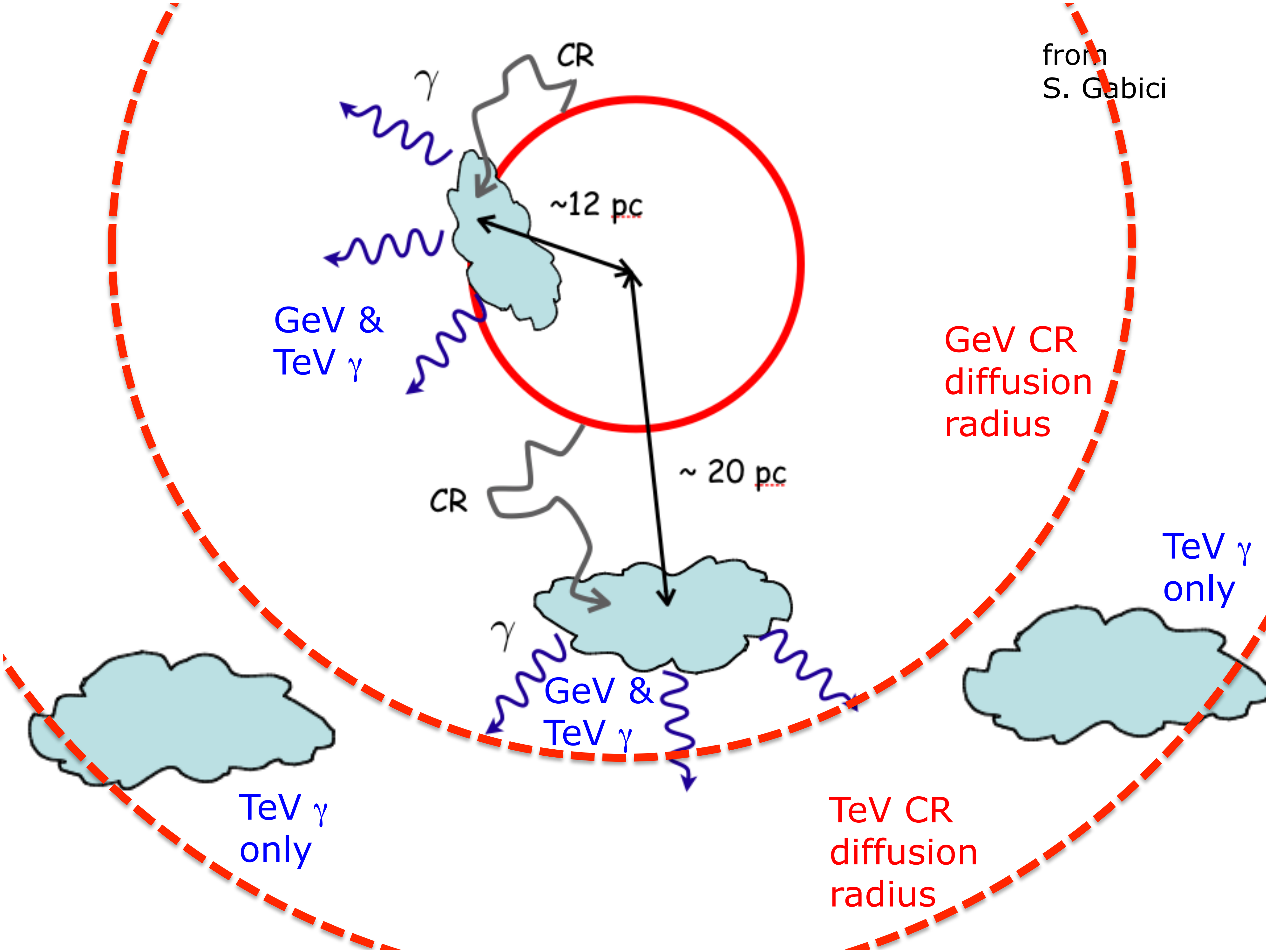






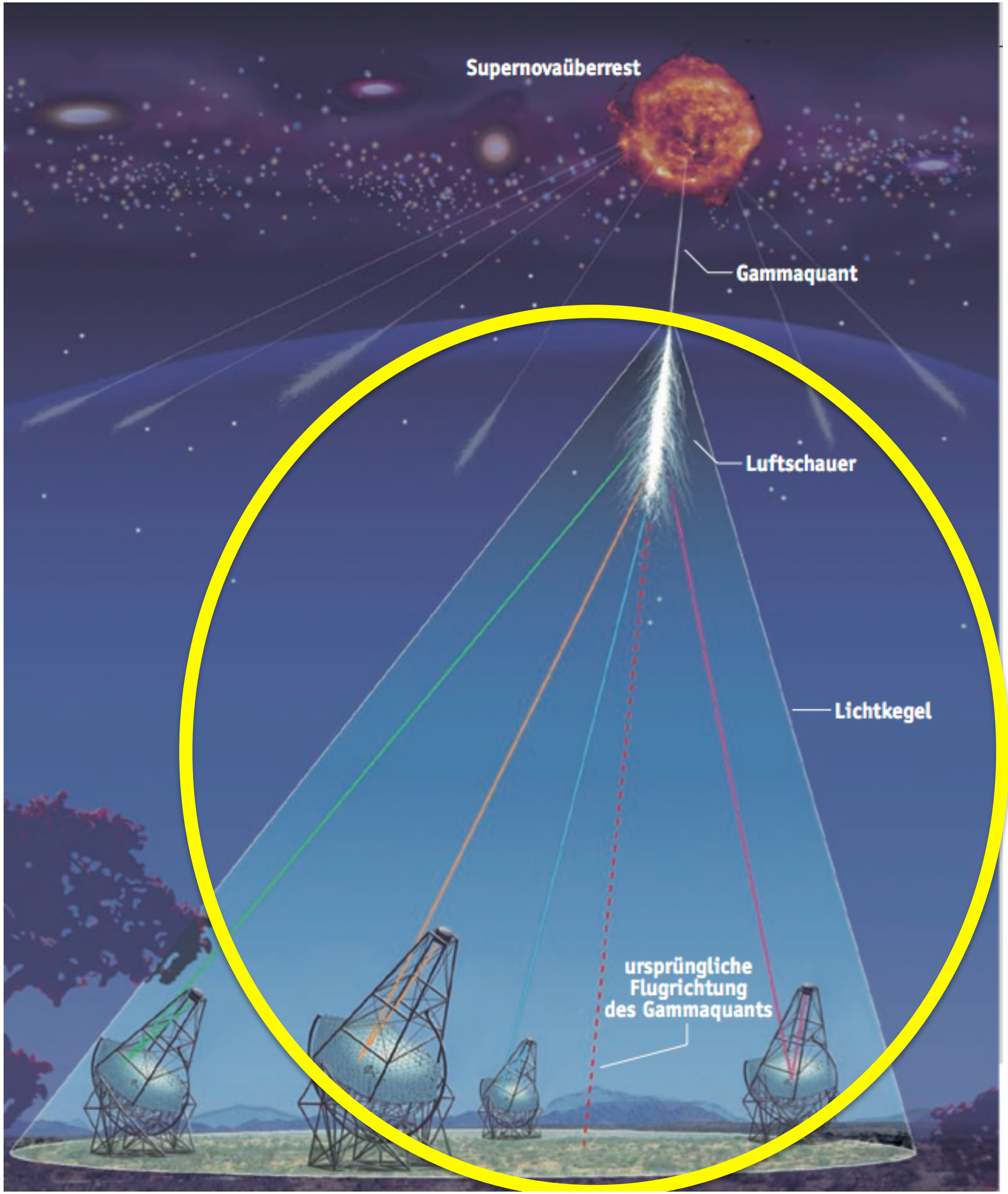


from
S. Gabici

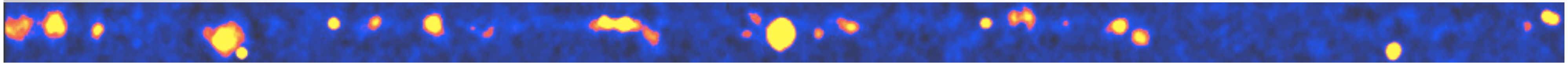


from
S. Gabici
CR
γ
~12 pc
GeV &
TeV γ
GeV CR
diffusion
radius
~ 20 pc
CR
γ
TeV γ
only
GeV &
TeV γ
TeV γ
only
TeV CR
diffusion
radius

The receiving end:
Detecting gamma rays


Supernovaüberrest
Gammaquant
Luftschauer
Lichtkegel
ursprüngliche
Flugrichtung
des Gammaquants

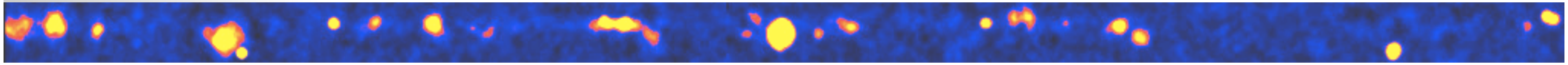
Characteristics

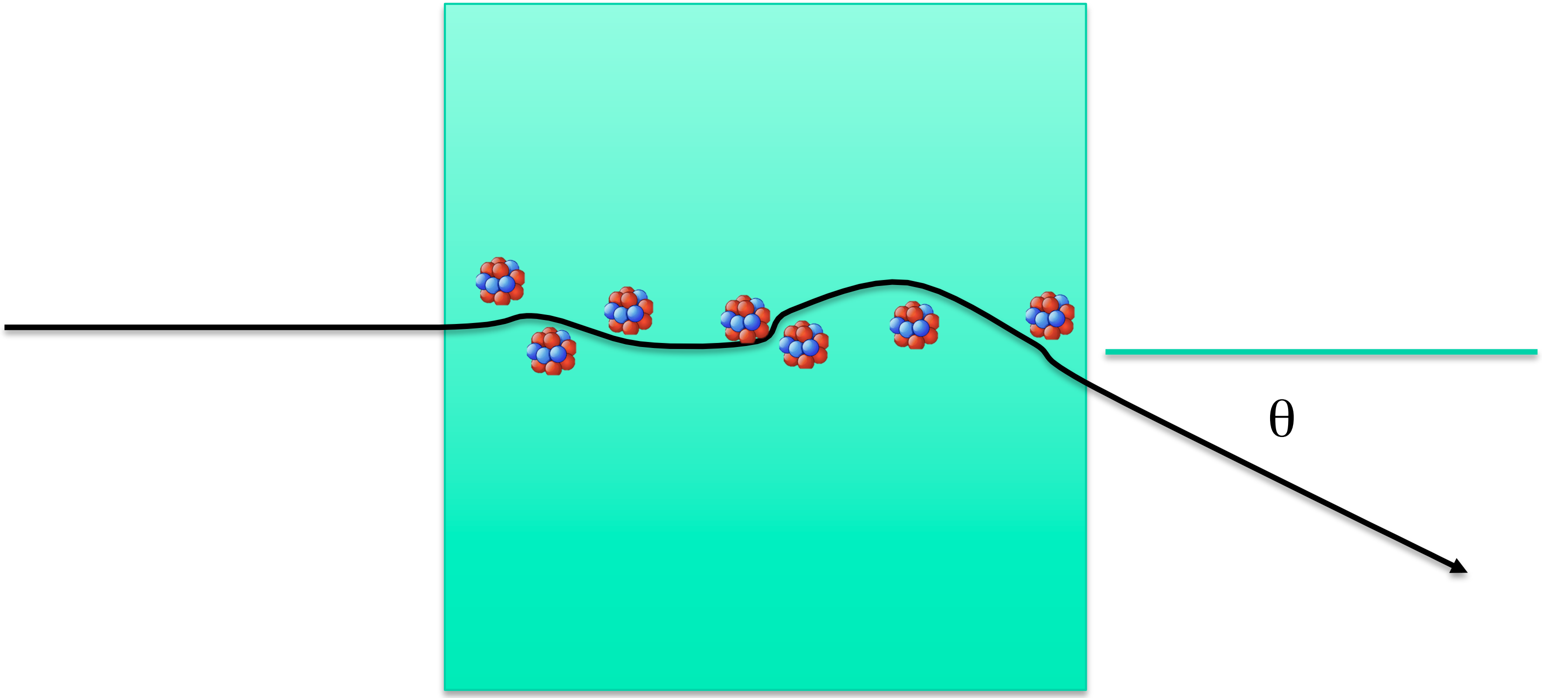


Energy threshold
Effective photon detection area
Angular resolution
Background rejection
Flux sensitivity

Fermi-LAT
Cherenkov telescopes

Need to know: Multiple Coulomb scattering



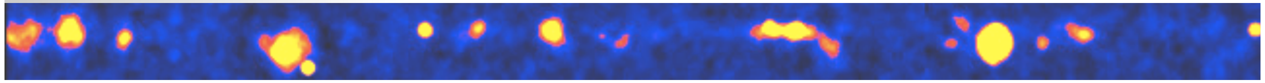


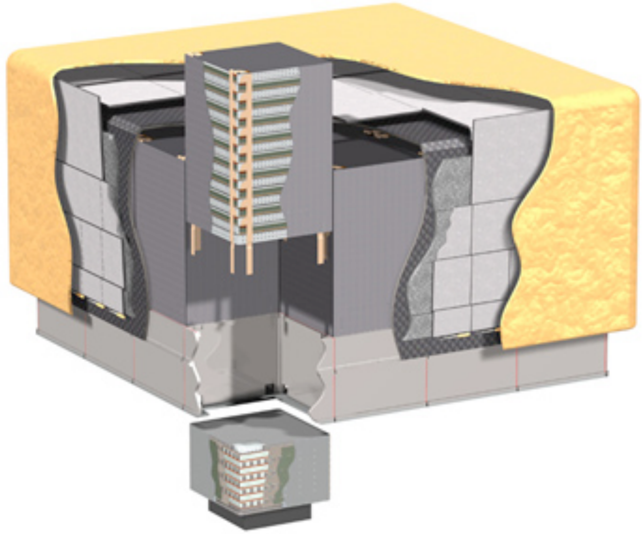
$$\theta_{rms} \approx \frac{14\ \text{MeV/c}}{p}\sqrt{\frac{x}{X_0}}$$

$\approx 1^0$ for 1 GeV particle over 1 RL

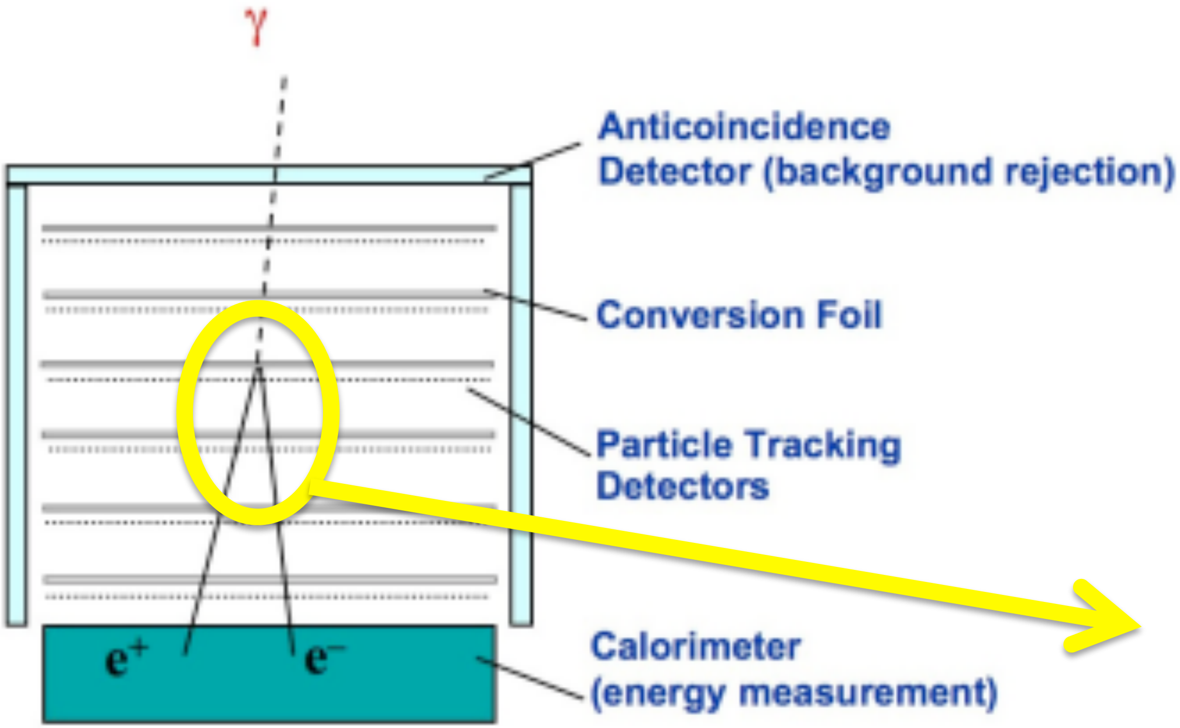
$\approx 10^0$ for 100 MeV particle over 1 RL

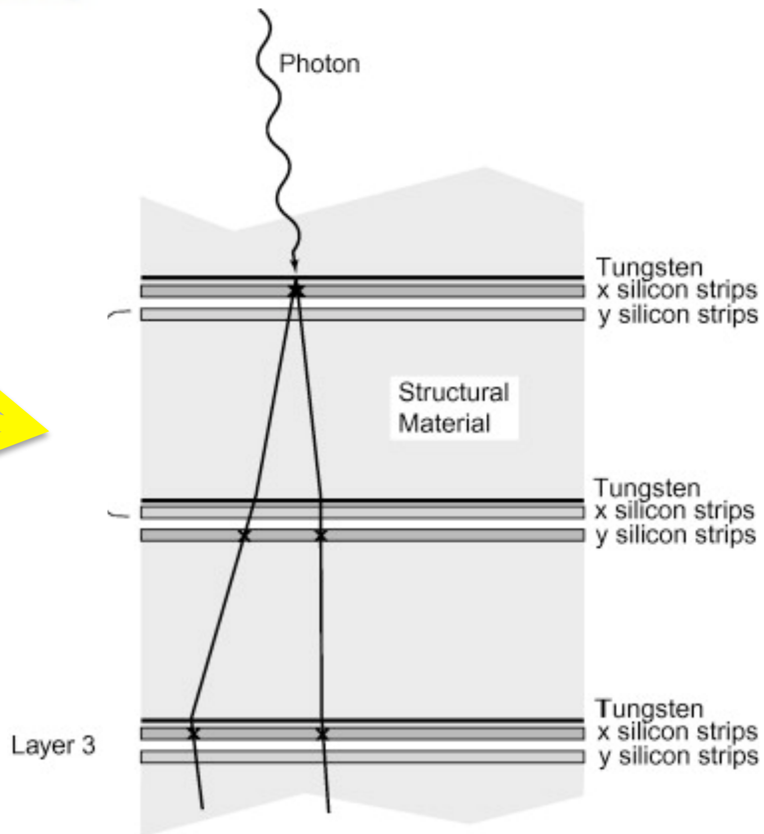
Fermi LAT





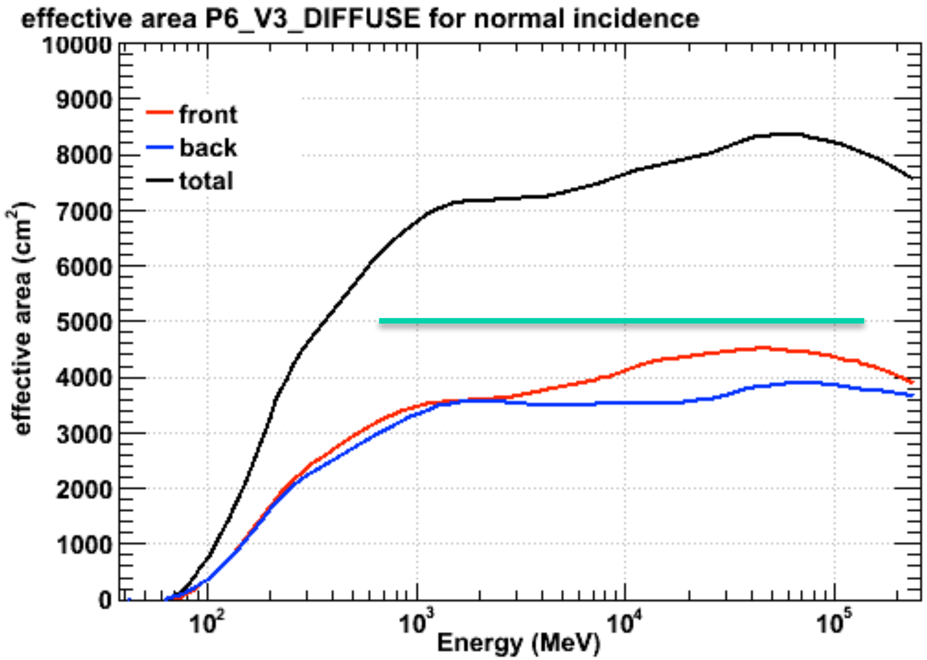
Pair conversion tracker and calorimeter





12 planes with 3% RL
4 last planes with 18% RL

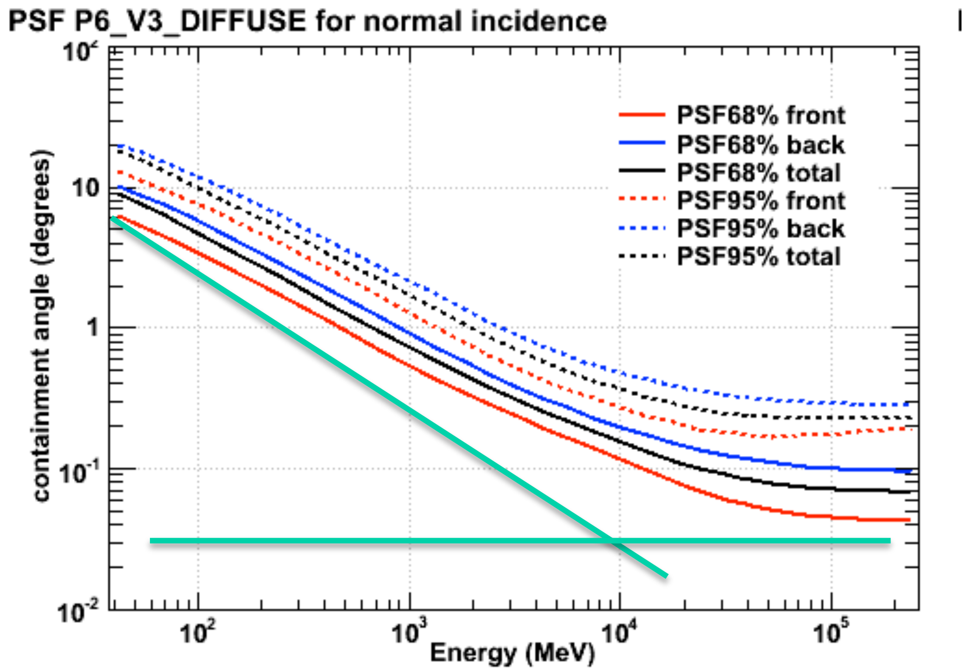
Conversion prob. after 10 layers
(30% RL): (7/9) x 30%
Effective detection area:
1.4 m x 1.4 m x 23% = 0.5 m²



Angular resolution:
track over 3 layers = 10% RL

$$\theta_{rms} \approx \frac{14\ \mathrm{MeV/c}}{p}\sqrt{\frac{x}{X_0}} \approx \frac{0.3^0}{E_{GeV}}$$

Strip resolution
50 μm/10 cm = 0.03°



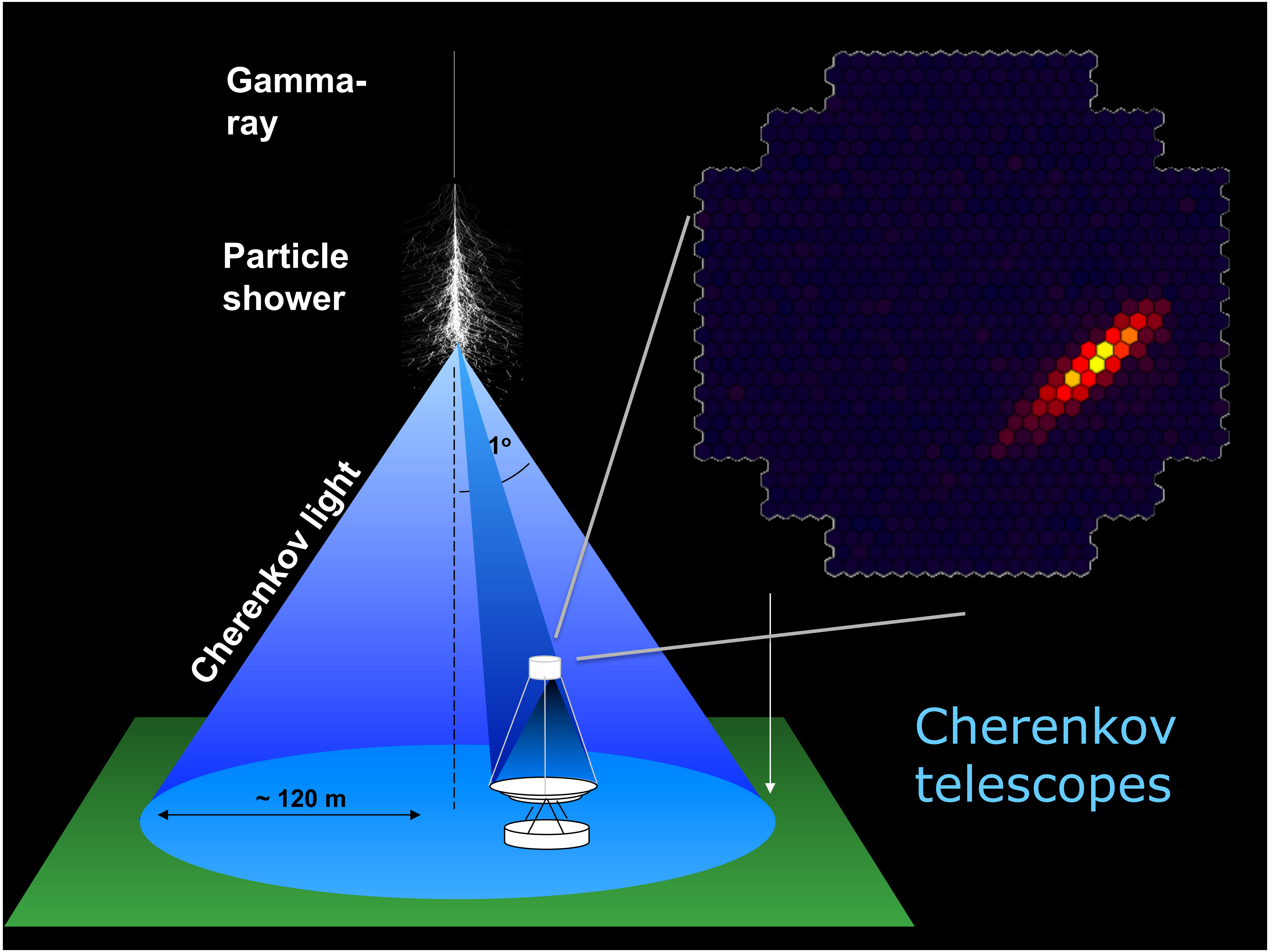
Flux sensitivity

Essentially (instrument-)background-free

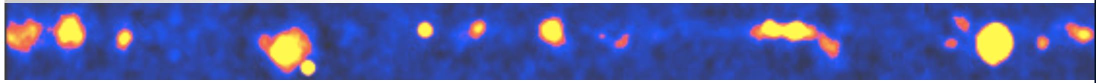
Fermi-LAT (few 100 MeV)

1 yr, 2 sr, eff. area 8000 cm^2

$2 \cdot 10^{-9}$ $ph/cm^2s \sim 10^{-12}$ erg/cm^2s


Gamma-
ray
Particle
shower
Cherenkov light
1°
~ 120 m
Cherenkov
telescopes

Shower development

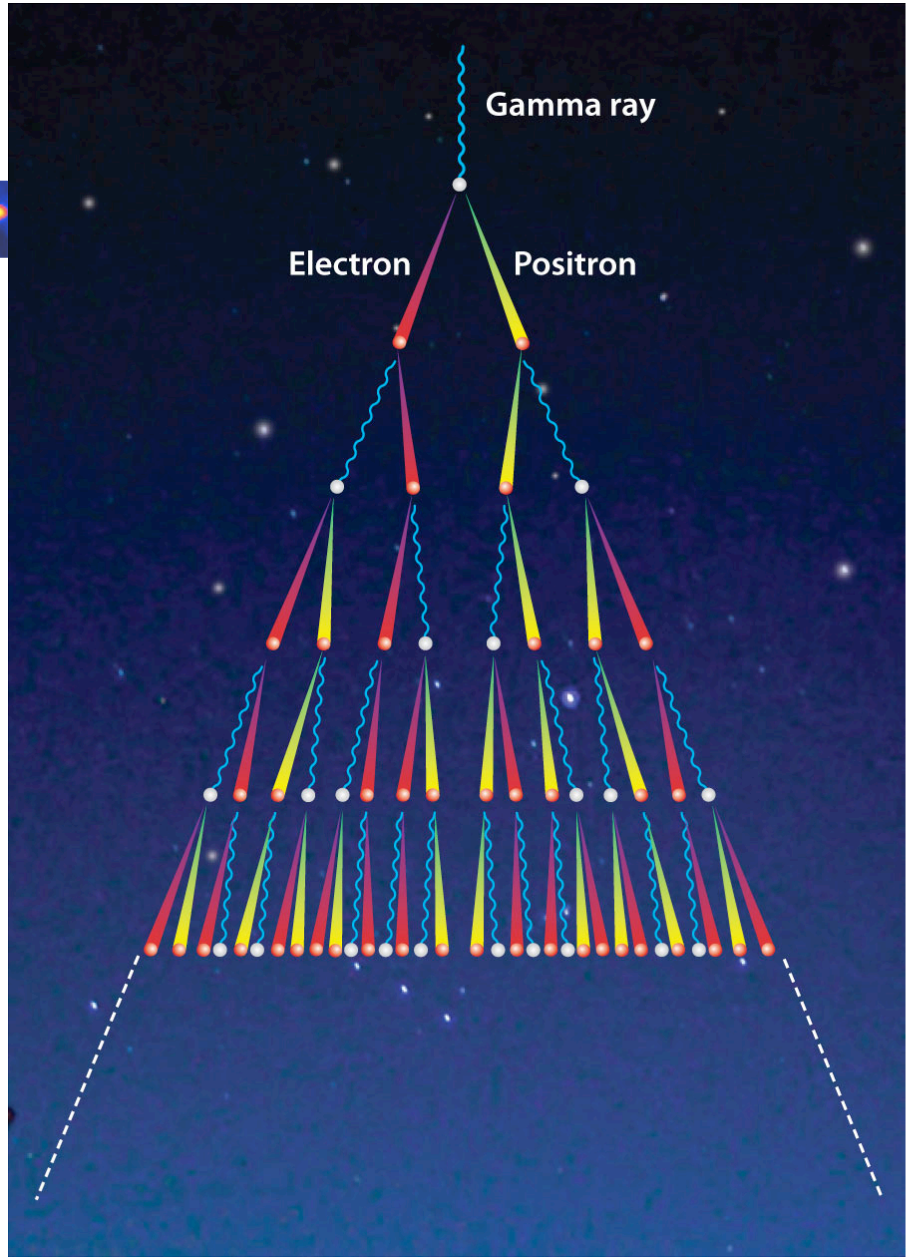


Particle number doubles after ~each radiation length until ionization losses dominate ("critical energy" ~85 MeV)

$$t_{\max} \approx \frac{\ln(E_0 / E_c)}{\ln 2} \approx 14 \text{ RL at 1 TeV}$$

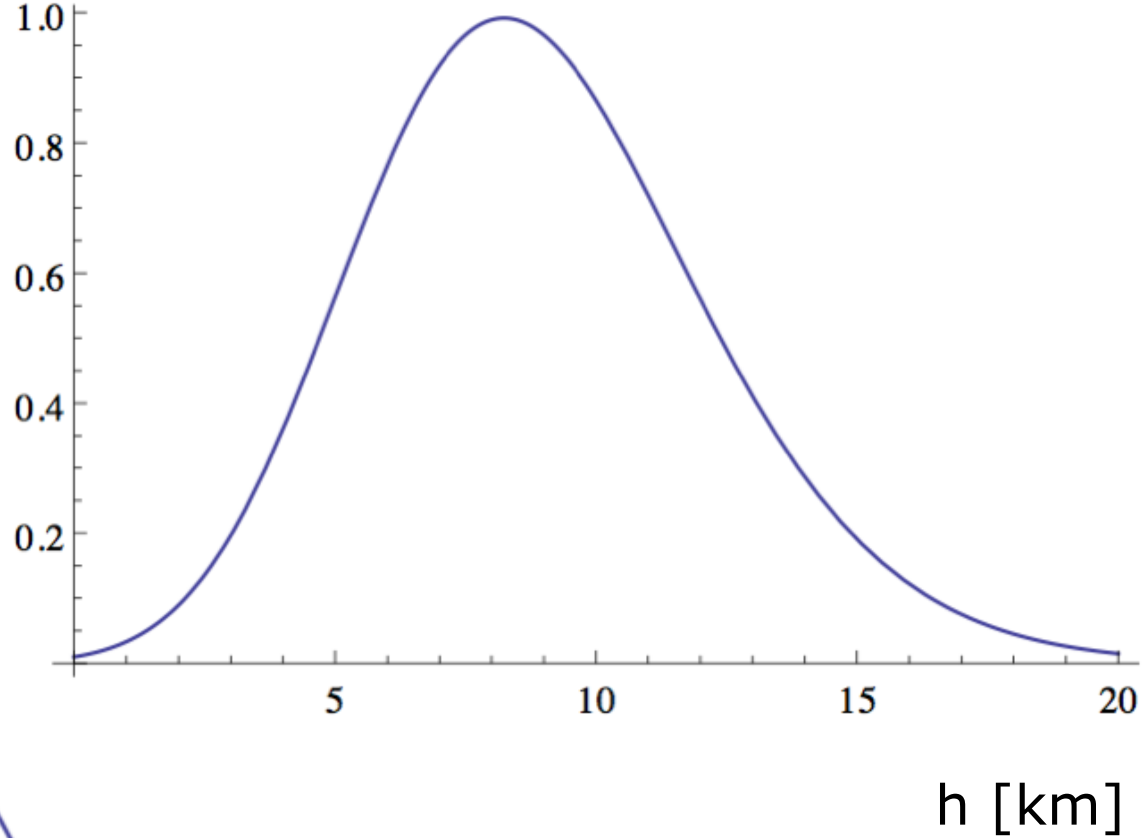
More exact (PDG):

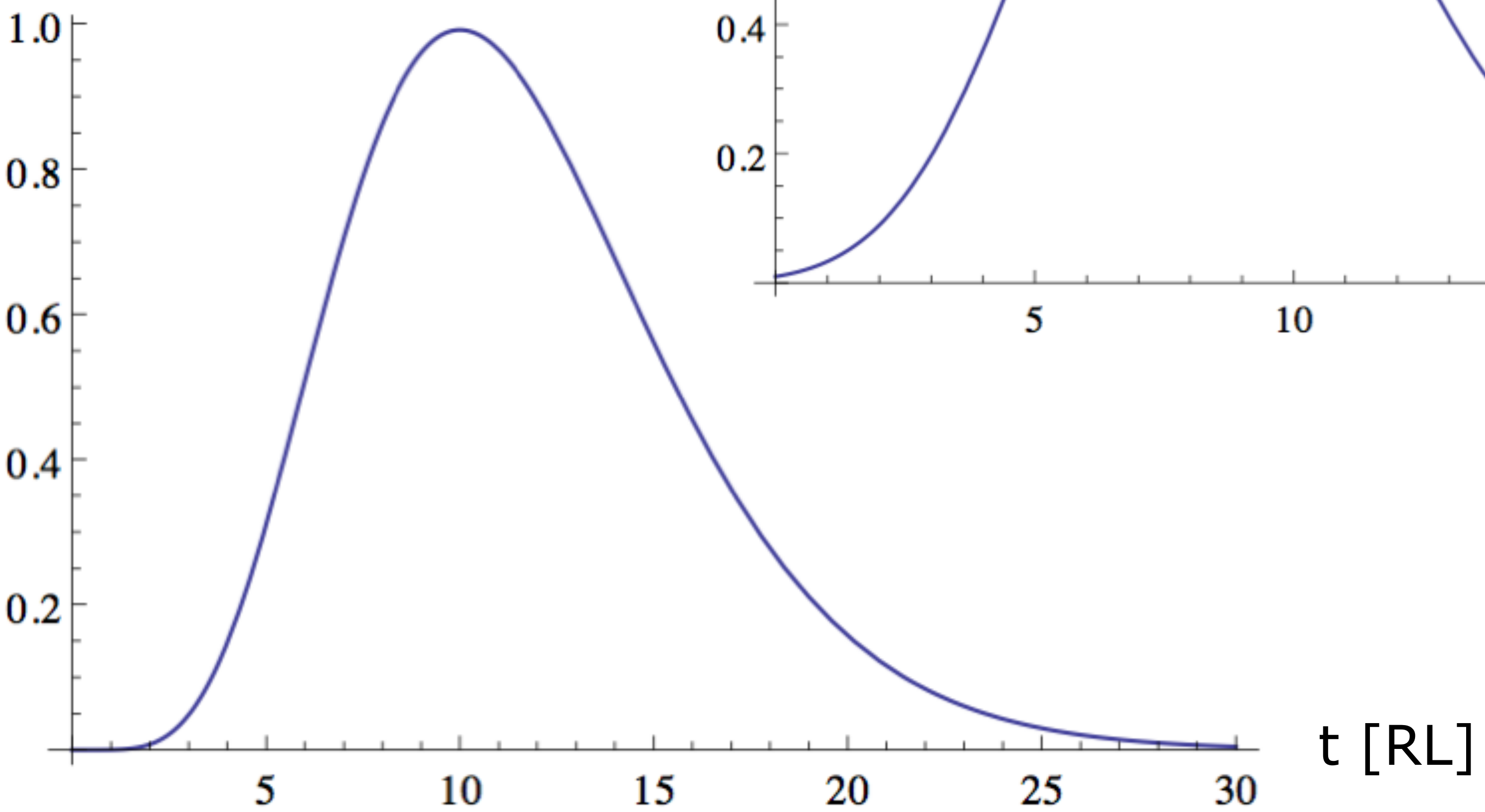
$$t_{\max} \approx \ln(E_0 / E_c) + 0.5$$
$$\approx 10 \text{ RL at 1 TeV}$$



see yesterday afternoon

TeV Gamma ray shower development





Cherenkov light pool size & intensity

Refractive index of air

$$n = 1 + \varepsilon \quad ; \quad \varepsilon \approx 3 \cdot 10^{-4} e^{-h/8km} \approx 10^{-4} \quad \text{at shower maximum}$$

Cherenkov threshold

$$\text{Cherenkov threshold} \;\; \beta > \frac{1}{n} \quad ; \quad \beta = \frac{\sqrt{E^2 - m^2}}{E} \approx 1 - \frac{m^2}{2E^2} > \frac{1}{n} \approx 1 - \varepsilon$$

$$\frac{m^2}{2E^2} < \varepsilon \quad \Rightarrow \quad E > \frac{m}{\sqrt{2\varepsilon}} = 35\ \text{MeV} \;\; \text{(at shower maximum);} \;\; < E_{crit}\,!$$

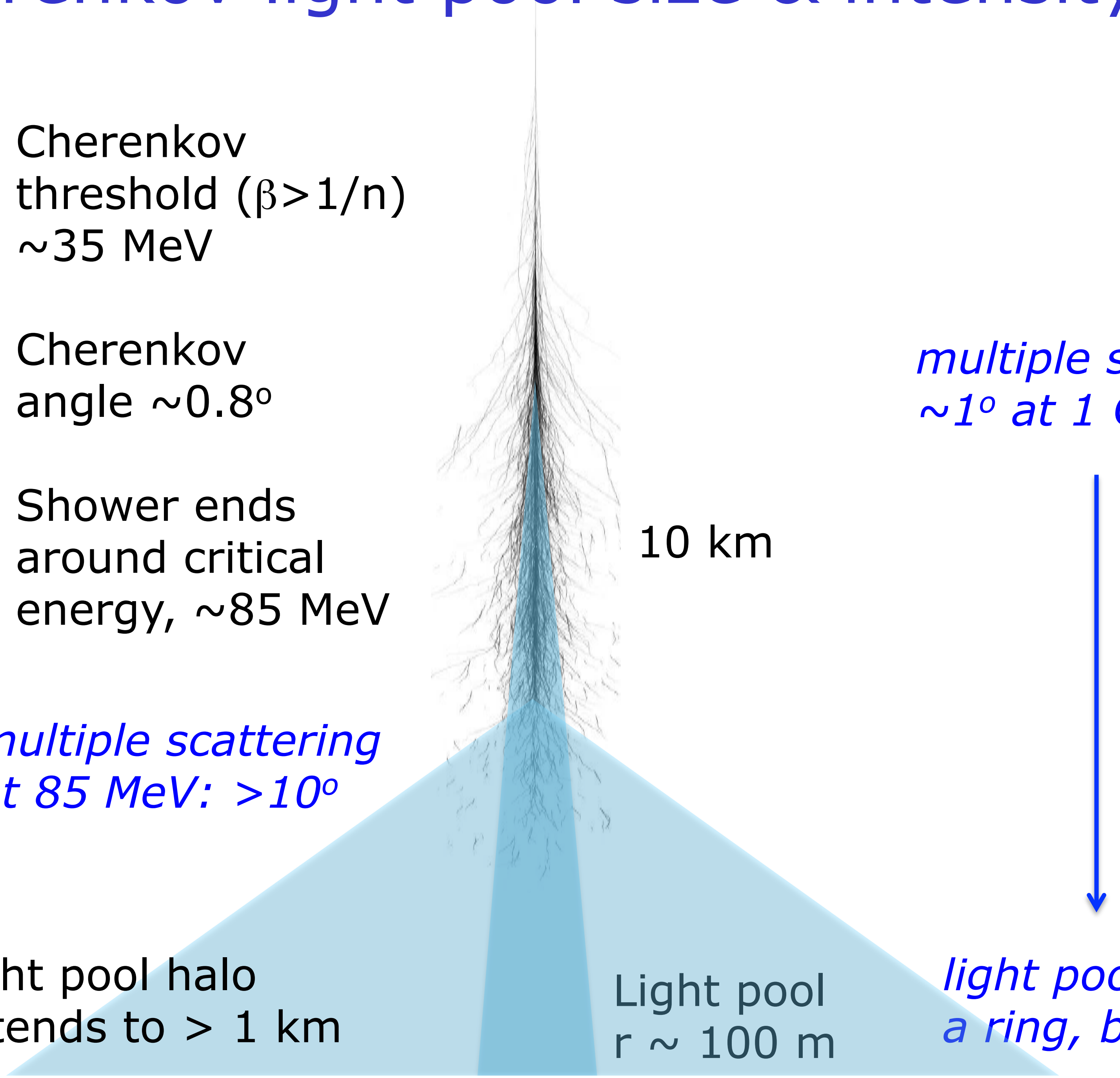
Cherenkov angle

$$\theta = \arccos(\beta n) \underset{\cos\theta \approx 1 - \frac{\theta^2}{2}}{\approx} \sqrt{2\left(1 - \frac{1}{\beta n}\right)} \underset{\beta=1}{\approx} \sqrt{2\varepsilon} \approx 0.8^0 \quad \text{at shower max.}$$

Light yield

$$\text{Yield} \sim 500 \sin^2\theta \frac{\text{ph.}}{\text{cm}} \approx 1000\varepsilon \frac{\text{ph.}}{\text{cm}} \approx 0.1 \frac{\text{ph.}}{\text{cm}} \approx 10^4\ /\,\text{RL}\ (\sim 1\ \text{km})$$

Cherenkov light pool size & intensity



Cherenkov light pool size & intensity

Cherenkov light from full shower

A TeV shower contains $E_0 / E_c \approx 10^4$ particles

Over 1 rad. lenght (1000 m @ shower max):

$\Rightarrow \quad 10^4$ part. $\times$ 1000 m $\times$ 0.1 ph./cm $\approx 10^8$ ph./TeV

With mult. scatt. angle at E_{crit} : $\sim 10^0$

$\Rightarrow$ Radius of light pool ~1-2 km; photon density ~few 10 ph./m^2

Considering only the higher-energy shower particles

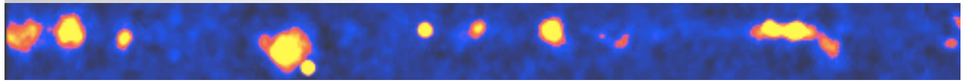
2RL higher up higher up:

For $\theta_{ms} \approx \theta_{Ch.}$: $E \approx 1$ GeV; shower contains ~1000 particles

$\Rightarrow$ 1000 part. $\times$ 1000 m $\times$ 0.1 ph./cm $\approx 10^7$ ph./TeV

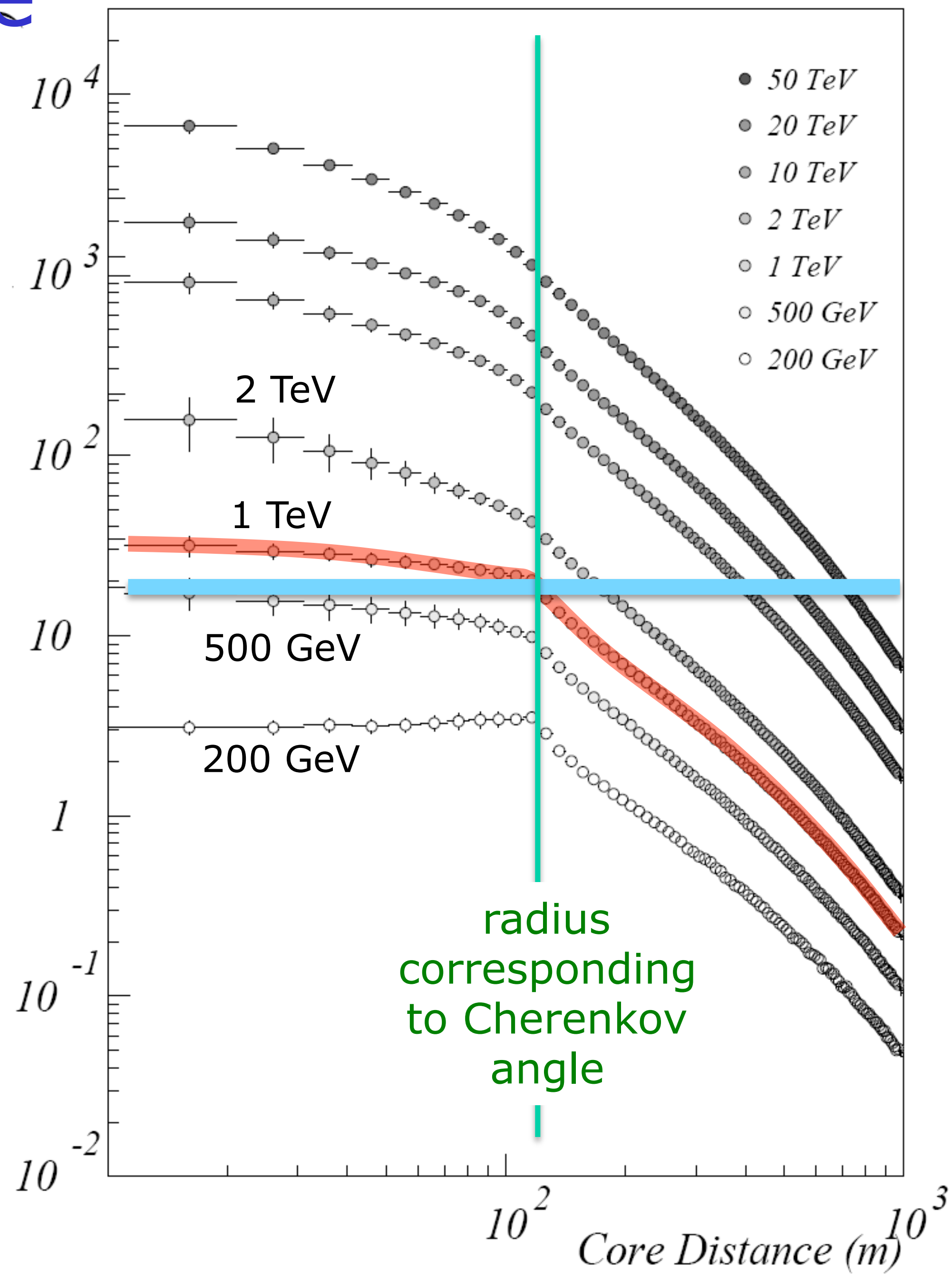
$\Rightarrow$ over 110 m radius light pool: ~300 ph./m^2

Intensity vs distance



detected photons per m²

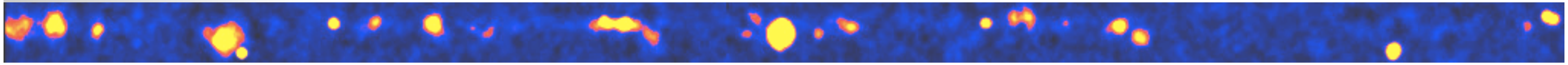
detection threshold

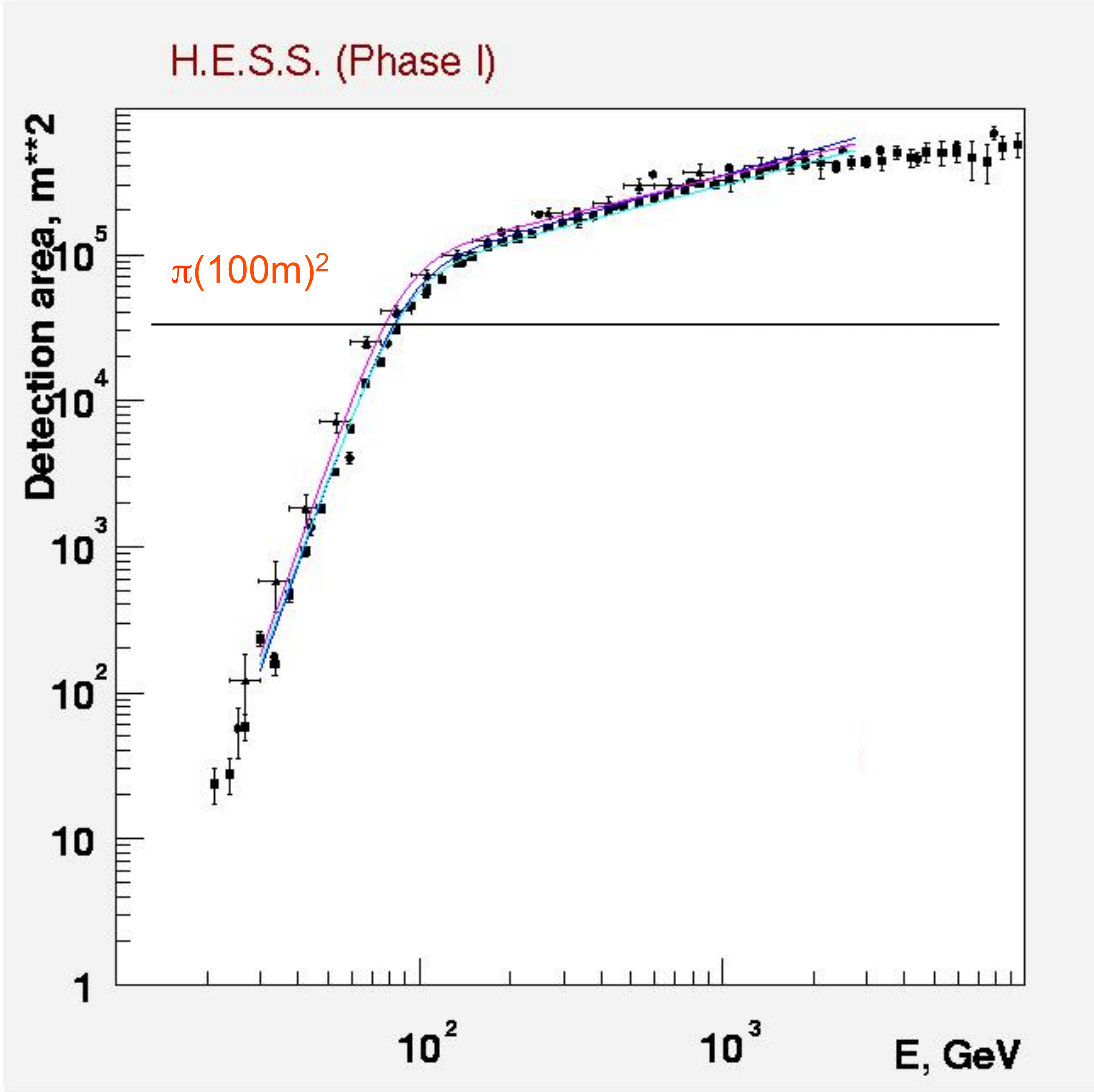


I. de la Calle Perez, S. D. Biller

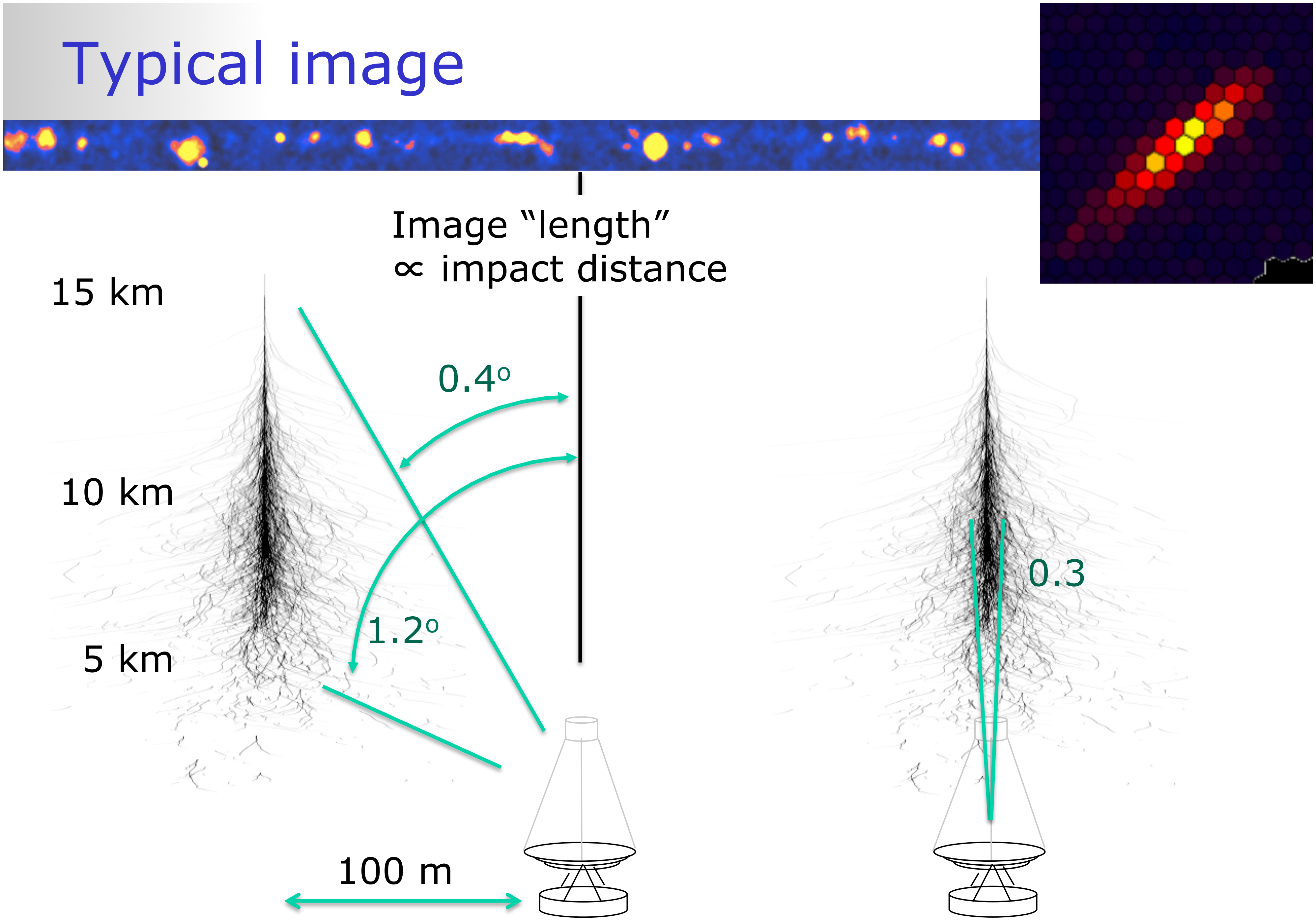
APP 26 (2006) 69

Energy threshold & detection area

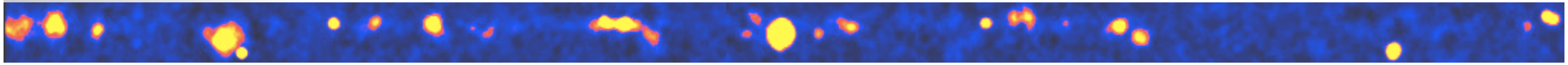




Typical image



Angular resolution



governed by

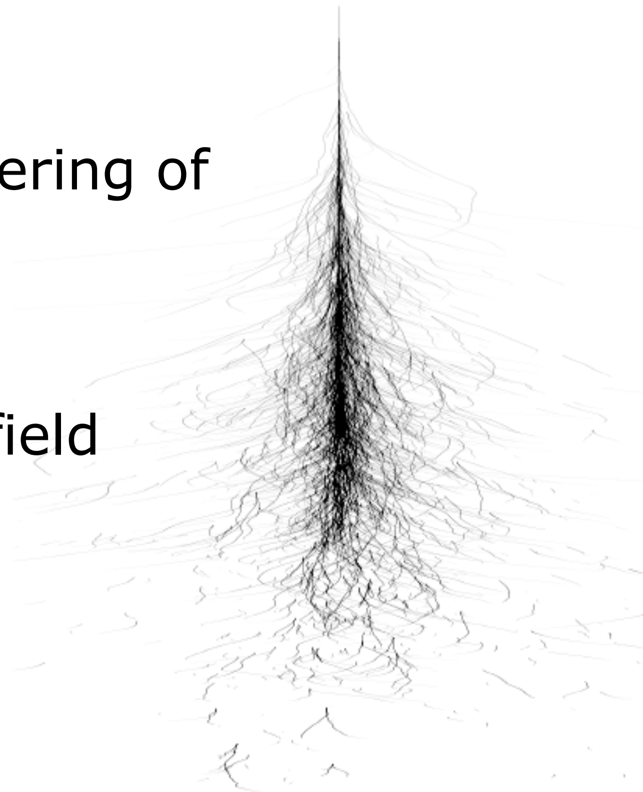
shower fluctuations and multiple scattering of shower particles
(typically 1000 particles @ 1 TeV)

deflection of particles in Earth magn. field

photon statistics in image
(typically 100 photons)

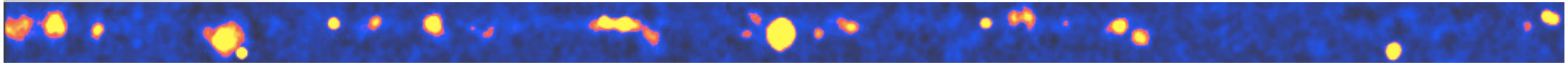
reconstruction algorithm

…



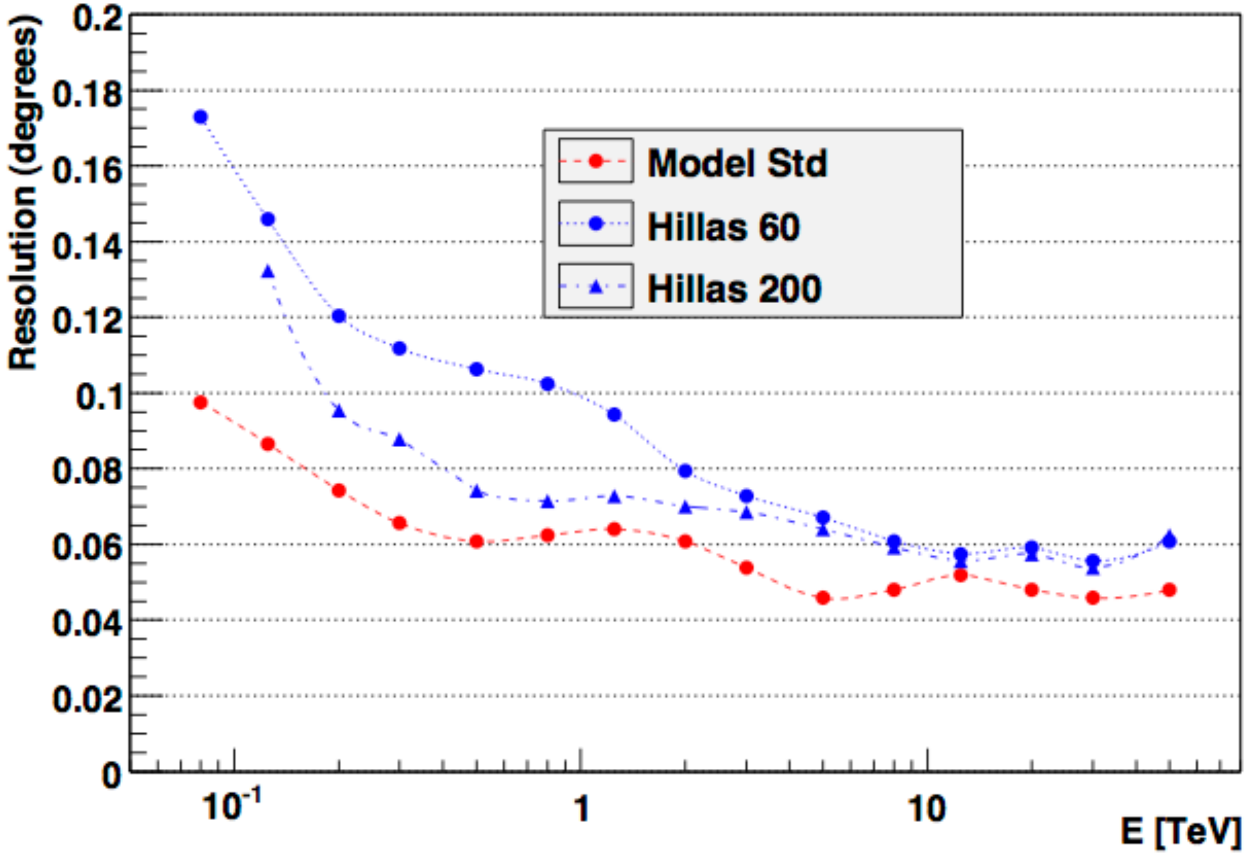
Angular resolution

…somewhat oversimplified…



Photons within the central 110 m pool scatter within $\sim 1^0$ from shower axis

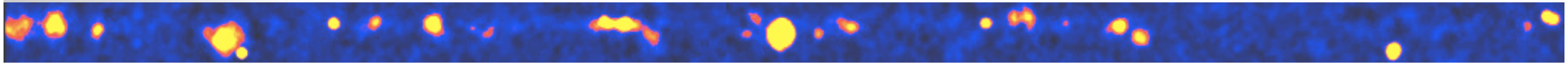
Measure shower direction with precision $\sim \dfrac{1^0}{\sqrt{n_{ph}}} \approx 0.1^0$



H.E.S.S.

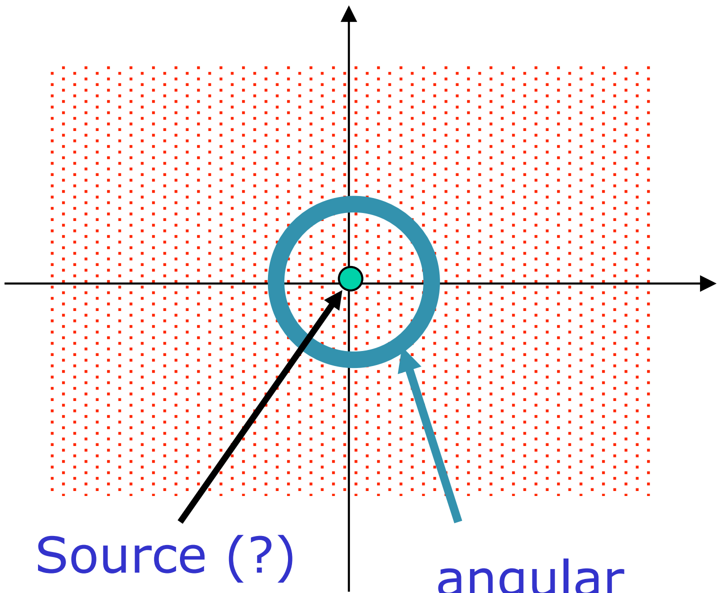
note:
no. of detected photons does not increase linearly with energy, since showers eff. area increases!

Sensitivity in a toy model



Ignore threshold; assume some (fixed) detection area A and observation time T

reconstructed shower directions



Source (?)

angular resolution θ

\# of background events:

$$(dN/d\Omega\ dA\ dT)_{BG}\ \eta_{BG}\ \pi\theta^2\ T\ A$$

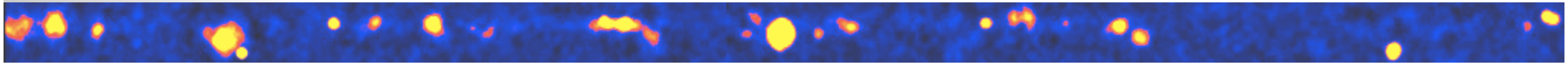
\# of signal events:

$$(dN/dA\ dT)_{Sig}\ \eta_{Sig}\ T\ A$$

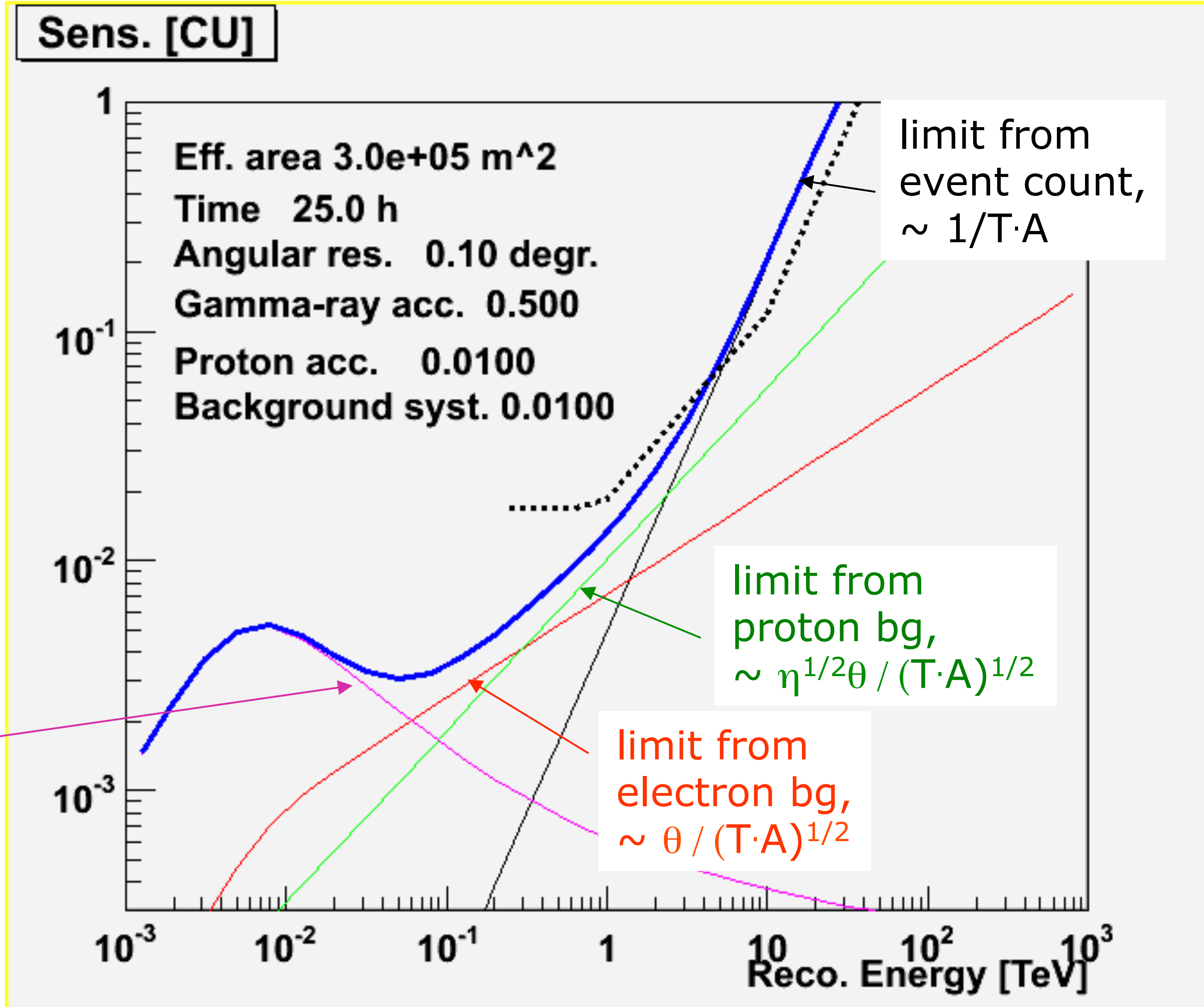
Significance $\cong$ #Signal/#Background$^{1/2}$:

$$\sim (T\ A)^{1/2}\ \eta_{BG}^{-1/2}\ \theta^{-1}$$

Sensitivity in a toy model



Minimal detectable flux per band $\Delta\log_{10}E=0.2$, relative to a power-law Crab spectrum



limit from syst. error on background, indep. of T,A; $\sim\theta^2$

Finally ….

(almost?) made it all the way from the gamma ray source to the detector …

thanks for your attention

& apologies for all the important things (including possibly "your" work) which I omitted