Interfacing High-Energy Astrophysics and Cosmological Structure Formation

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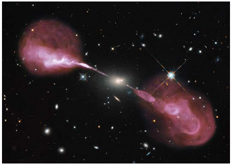
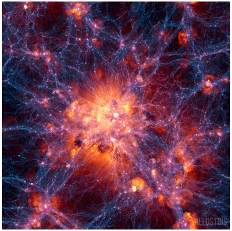
May 4, 2015 / Colloquium, Universität Erlangen Nürnberg

Astroparticle physics and cosmology

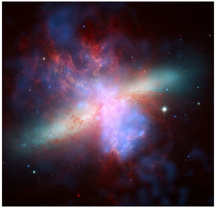
active galactic nuclei



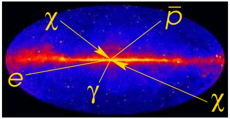
intergalactic medium



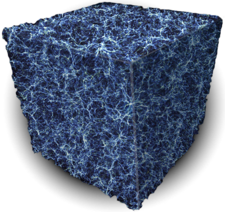
galaxy formation



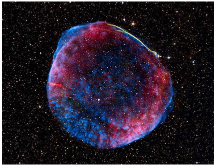
Astroparticle Physics and Cosmology



dark matter



large–scale structure



particle acceleration
magnetic amplification

The Questions

Interfacing high-energy astrophysics and cosmological structure formation

- **What is the impact of cosmic rays on galaxy formation?**
  understanding the sources and transport of cosmic rays and magnetic fields in cosmological settings
  $\rightarrow$ predictive theory of galaxy and cluster formation
  $\rightarrow$ realistic models for radio, X-ray, γ-ray and ν astronomy

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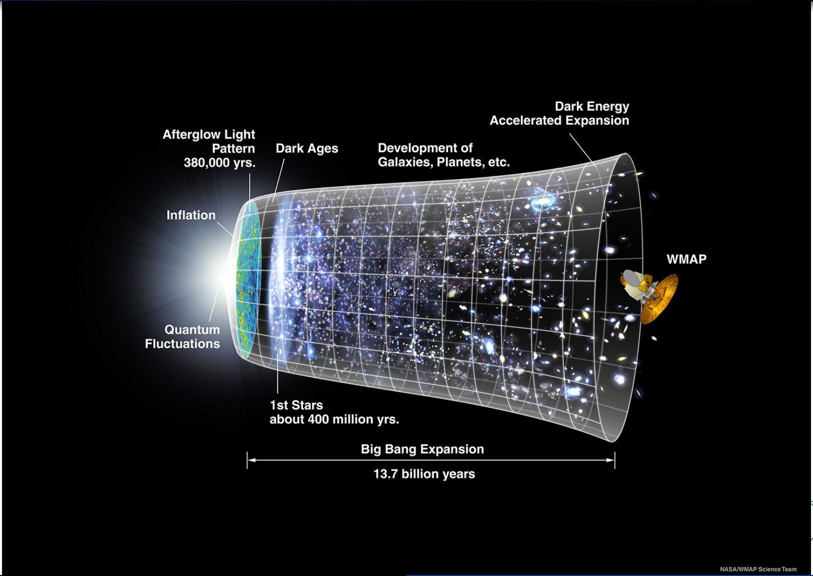
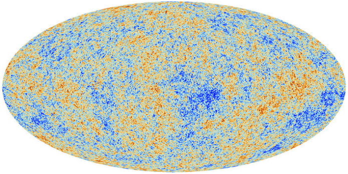
- **What is the nature of dark matter?**
  opening a complementary window to probe dark matter physics
  $\rightarrow$ structure formation, particle physics

Timeline of our Universe



Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves

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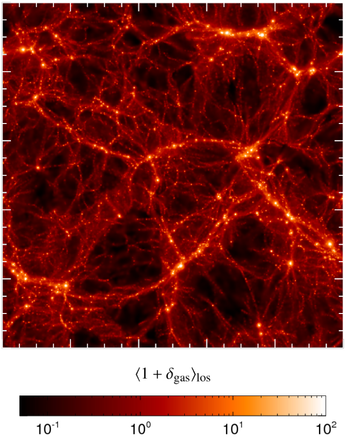
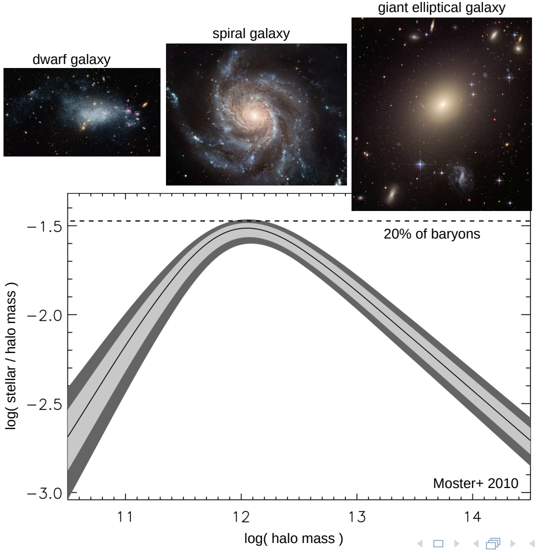


C.P.+ (2006)

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves
- cosmic matter assembles in the “cosmic web” through gravitational instability
- galaxies form as “beats on a string” along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

Puzzles in galaxy formation

Puzzles in galaxy formation



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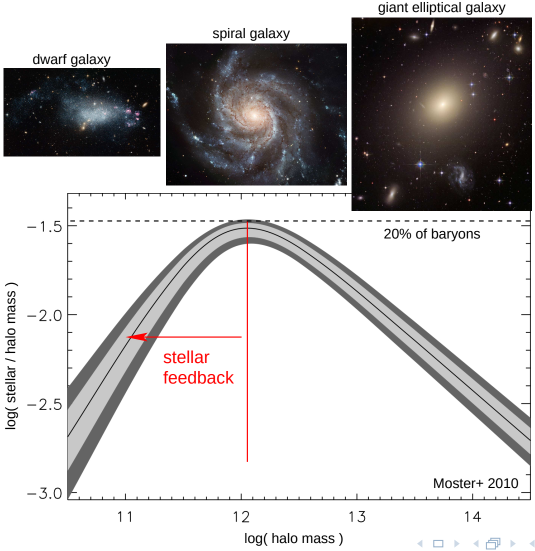

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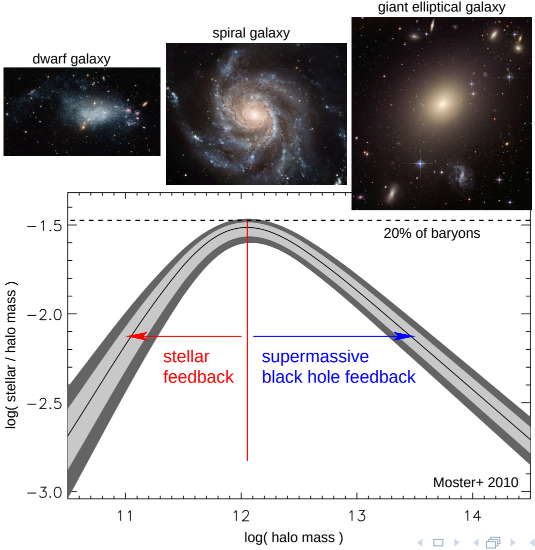
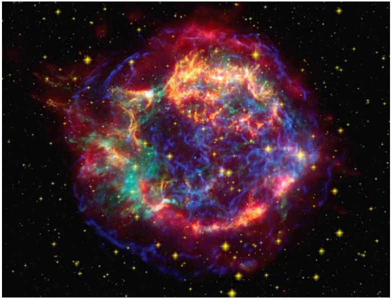


Galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

Galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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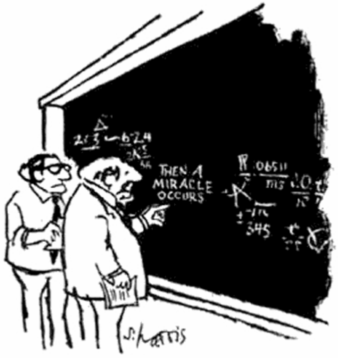
Galactic winds



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

© Sydney Harris

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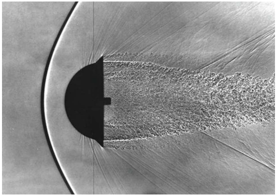
Shock waves

shock waves: sudden change in density, temperature, and pressure that decelerates supersonic flow.



thickness $\sim$ mean free path $\lambda_{\rm mfp}$

in air, $\lambda_{\rm mfp} \sim \mu$m,
on Earth, most shocks are mediated by collisions.

slide concept Spitkovsky

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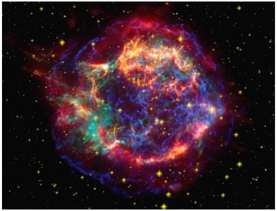

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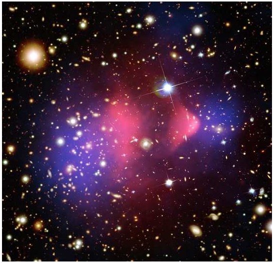


clusters/galaxies, Coulomb collisions set $\lambda_{\rm mfp}$:

$\lambda_{\rm mfp} \sim L_{\rm cluster}/10, \qquad \lambda_{\rm mfp} \sim L_{\rm SNR}$

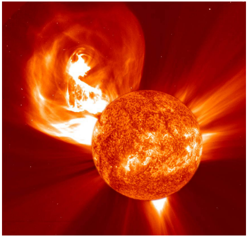
Mean free path $\gg$ observed shock width!

$\rightarrow$ shocks must be mediated without collisions, but through interactions with collective fields

$\rightarrow$ collisionless shocks

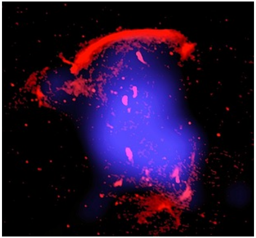
slide concept Spitkovsky

Astrophysical shocks



solar system shocks $\sim R_\odot$
coronal mass ejection (SOHO)

interstellar shocks $\sim$ 20 pc
supernova 1006 (CXC/Hughes)

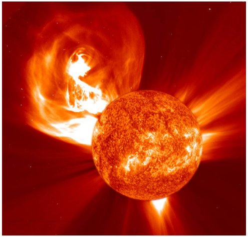


cluster shocks $\sim$ 2 Mpc
giant radio relic (van Weeren)

Astrophysical shocks

astrophysical collisionless shocks can:

- accelerate particles (electrons and ions) $\rightarrow$ cosmic rays (CRs)
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions



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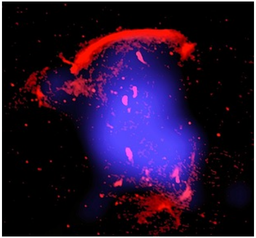

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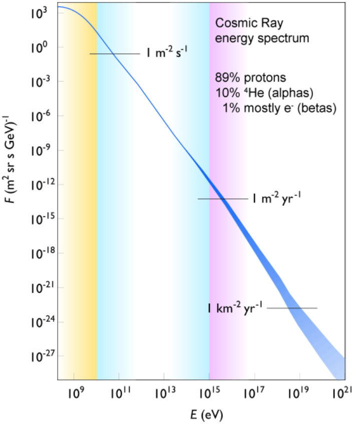
Galactic cosmic ray spectrum



data compiled by Swordy

- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

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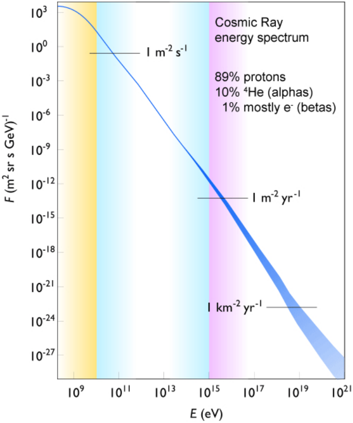

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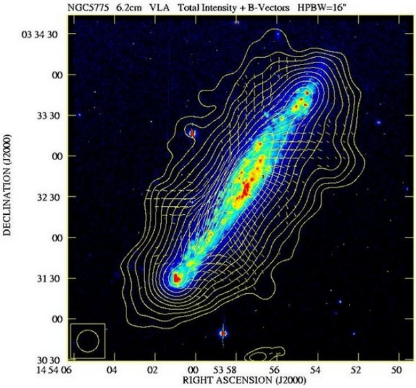
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and interstellar gas all similar:

  $\rightarrow$ CRs and magnetic fields appear to be necessary for understanding galaxy formation!

Why are CRs important for wind formation?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface

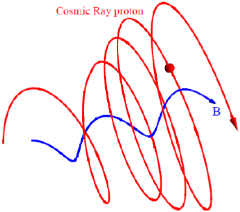


Tüllmann+ (2000)

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^{\gamma}$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind → "CR battery"
- poloidal ("open") field lines at wind launching site → CR-driven Parker instability

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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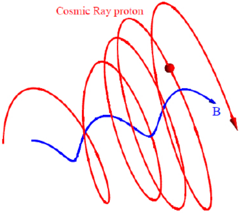

→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

CR transport

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = -v_{\rm A} \frac{\boldsymbol{\nabla} P_{\rm cr}}{|\boldsymbol{\nabla} P_{\rm cr}|} \text{ with } v_{\rm A} = \sqrt{\frac{\boldsymbol{B}^2}{4\pi\rho}}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \frac{\boldsymbol{\nabla} P_{\rm cr}}{P_{\rm cr}},$$

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- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$ (neglecting CR diffusion):

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}] = P_{\rm cr} \boldsymbol{\nabla} \cdot \boldsymbol{v} + |\boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm cr}|$$

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot (\varepsilon_{\rm cr} \boldsymbol{v}) + \boldsymbol{\nabla} \cdot [(\varepsilon_{\rm cr} + P_{\rm cr})\boldsymbol{v}_{\rm st}] = -P_{\rm cr} \boldsymbol{\nabla} \cdot \boldsymbol{v} - |\boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm cr}|$$

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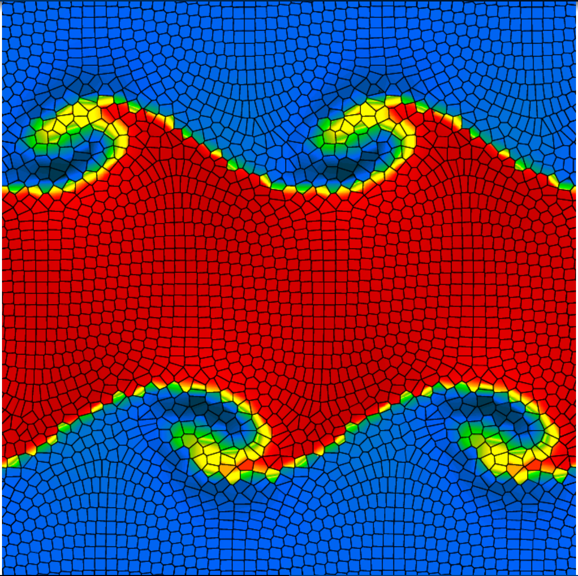
\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot[\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st})] &= -P_{\rm cr}\boldsymbol{\nabla}\cdot(\boldsymbol{v} + \boldsymbol{v}_{\rm st})
\end{aligned}$$

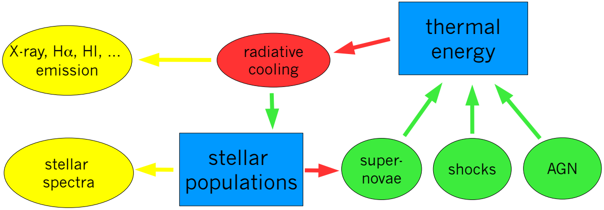
Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

ISM observables:

Physical processes in the ISM:



loss processes
gain processes
observables
populations

C.P., Enßlin, Springel (2008)

Simulations with cosmic ray physics

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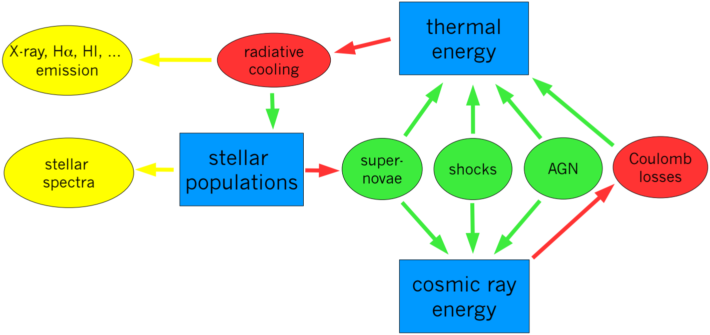

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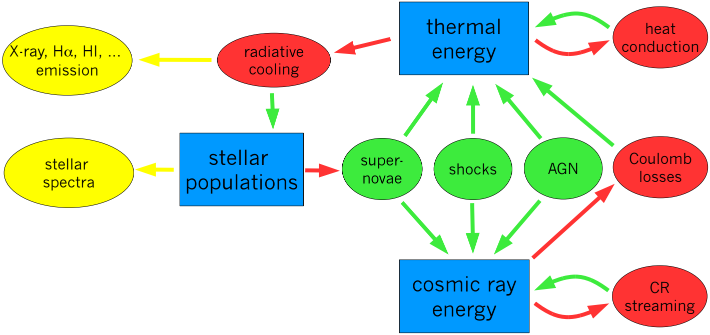

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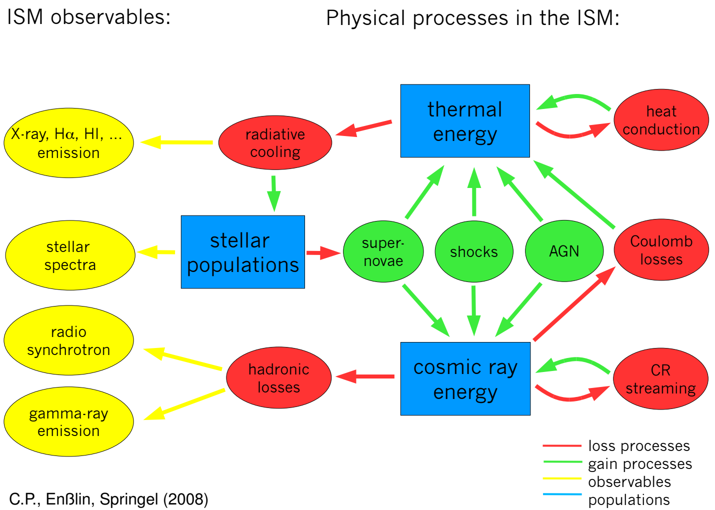
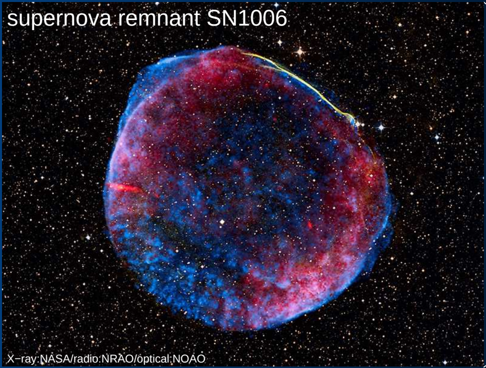


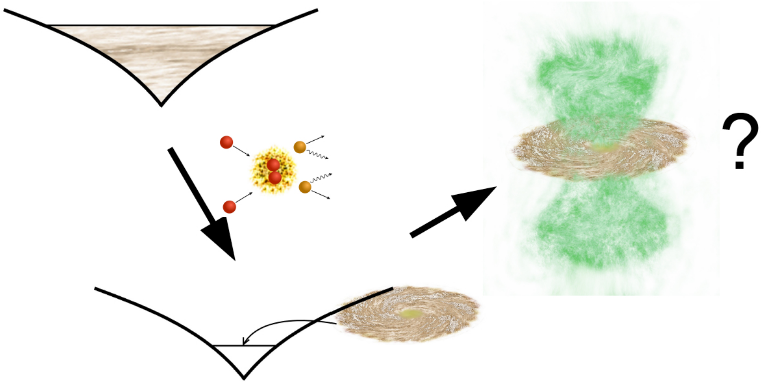
C.P., Enßlin, Springel (2008)

Star formation feedback drives galactic winds

How high-energy astrophysics informs cosmological structure formation



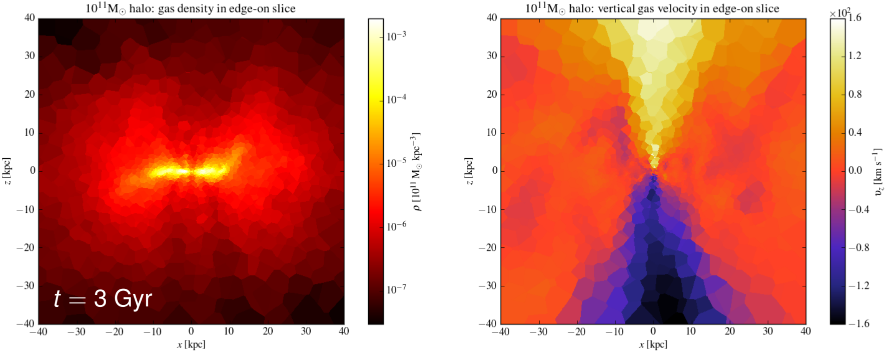
Simulation setup



Pfrommer, Pakmor, Springel, in prep.

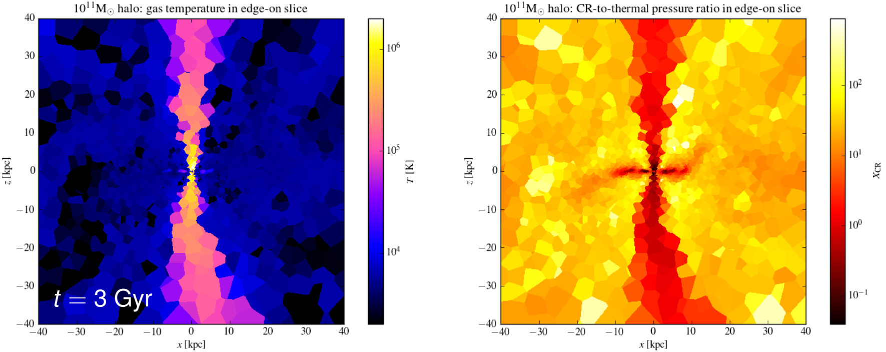
note: MHD + CR physics with isotropic CR diffusion

CR driven winds: density and vertical velocity



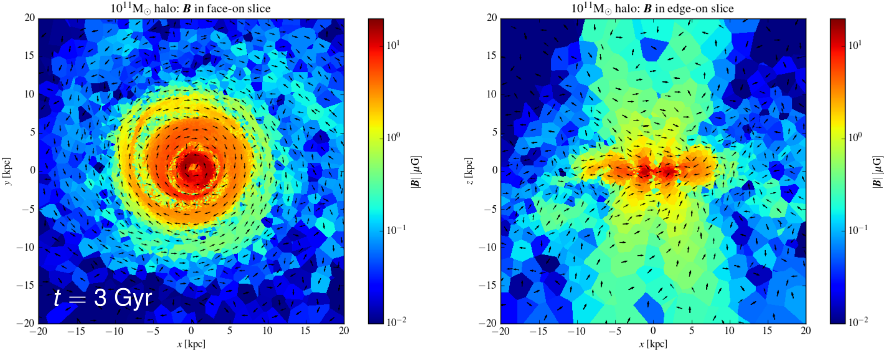
- CR pressure launches super wind that escapes from the halo
- forming disk collimates the wind into a biconical morphology with a time-varying opening angle

CR driven winds: temperature and $X_{\rm CR} = P_{\rm CR}/P_{\rm th}$



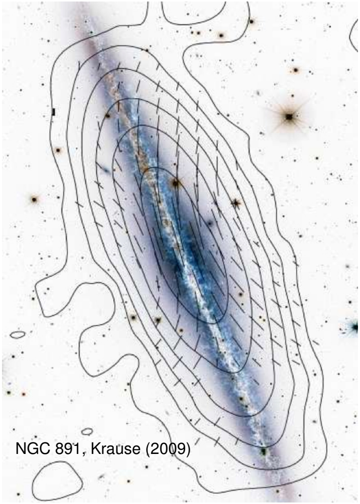
- CR pressure dominates over thermal one in halo ($\gamma = 4/3$ vs. $5/3$)
- CR-induced Alfvén waves heat and energize the wind
  $\rightarrow$ acceleration through additional energy deposition

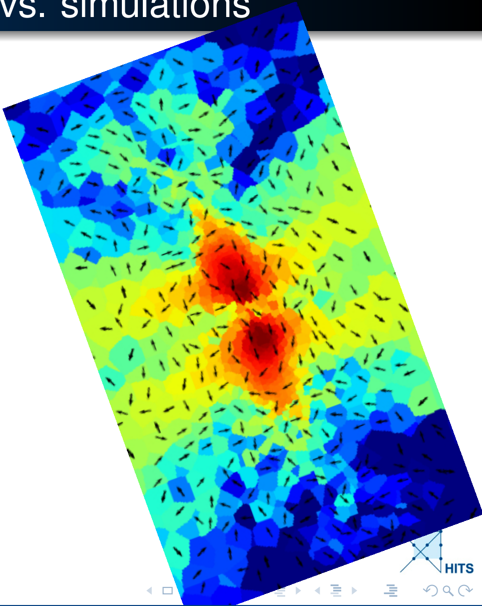
CR driven winds: *B* field, face and edge-on view



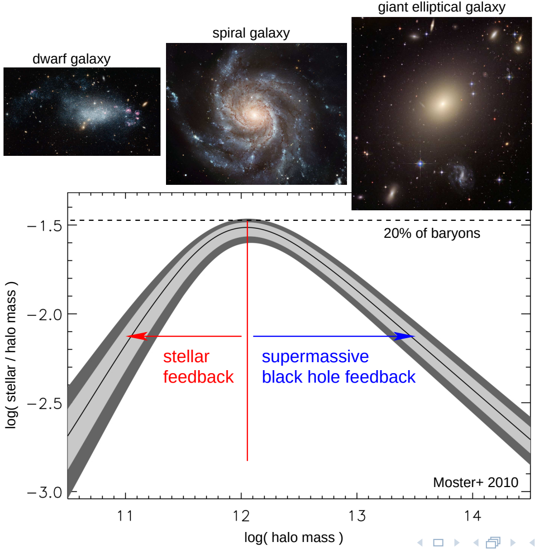
- disk: magnetic shear amplification aligns ***B*** with velocity field
- halo: X-shaped ***B*** morphology due to time varying collimation
- narrower wind $\rightarrow$ faster outflow $\rightarrow$ lower density channel

Halo *B* field: observations vs. simulations

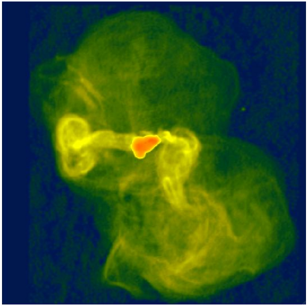




Puzzles in galaxy formation



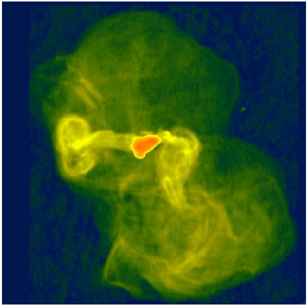
Feedback heating: M87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated AGN feedback!

Feedback heating: M87 at radio wavelengths



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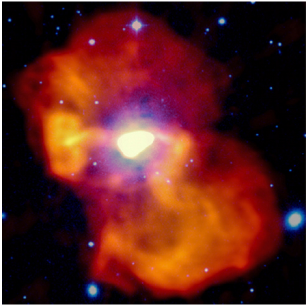
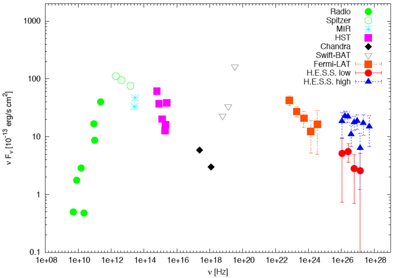


$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons → time-integrated AGN feedback!
- LOFAR: same picture → puzzle of "missing fossil electrons"
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

The gamma-ray picture of M87

- high state is time variable
  $\rightarrow$ jet emission
- low state:
  (1) steady flux
  (2) γ-ray spectral index (2.2)
  $=$ CRp index
  $=$ CRe injection index as probed by LOFAR
  (3) spatial extension is under investigation (?)



Rieger & Aharonian (2012)

$\rightarrow$ **confirming this triad would be smoking gun for first γ-ray signal from a galaxy cluster!**

AGN feedback = cosmic ray heating (?)

hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\rm CR} = -\boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm CR}$$

- calibrate $P_{\rm CR}$ to γ-ray emission and $\boldsymbol{v}_{\rm st} \propto \boldsymbol{v}_{\rm A}$ to radio and X-ray emission $\rightarrow$ spatial heating profile

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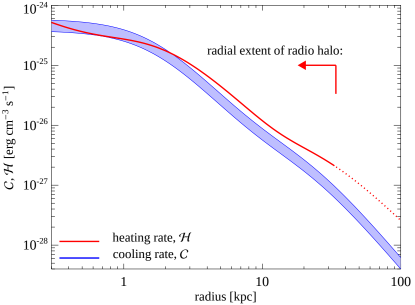
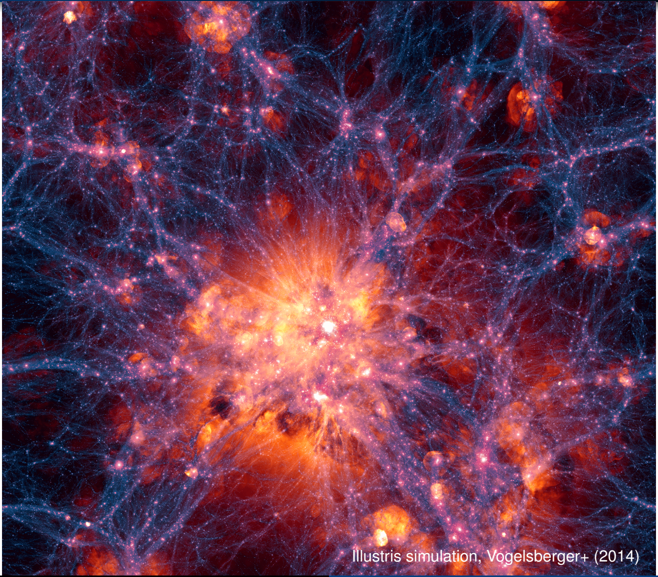


C.P. (2013)

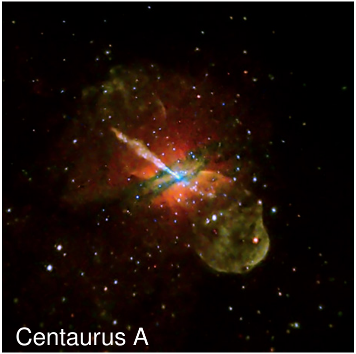
→ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!

Propagation of γ rays through intergalactic space



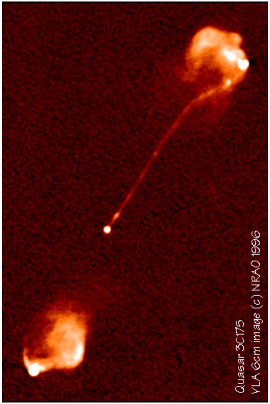
Illustris simulation, Vogelsberger+ (2014)

Active galactic nucleus (AGN)



- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets

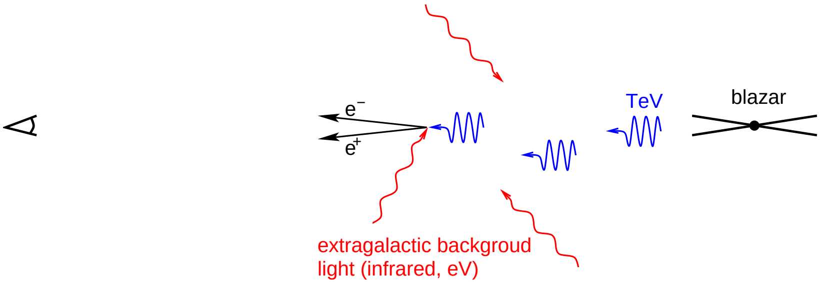
Active galactic nucleus at a cosmological distance



Quasar 3C175 at $z \simeq 0.8$:
jet extends 10^6 light years across

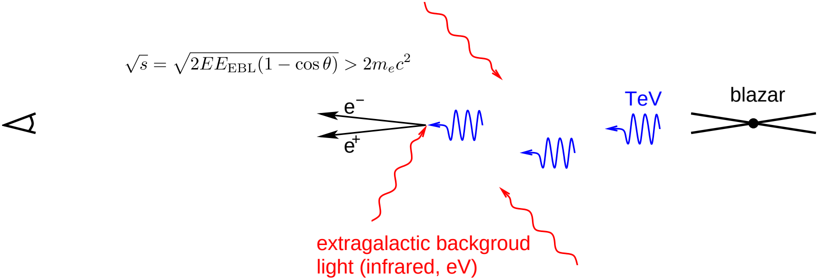
- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets
- AGNs are the most luminous sources in the universe $\rightarrow$ discovery of distant objects
- blazar: jet aligned with line-of-sight

Annihilation and pair production



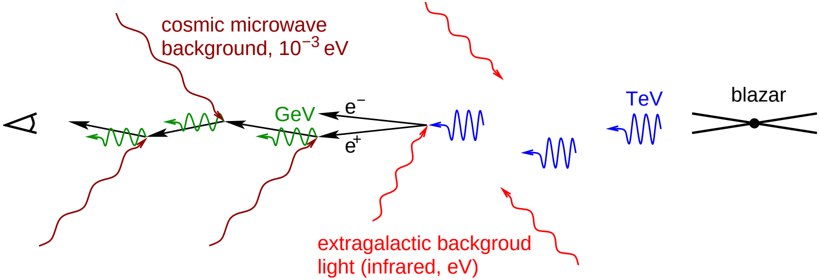
Annihilation and pair production

$$\sqrt{s} = \sqrt{2EE_{\mathrm{EBL}}(1-\cos\theta)} > 2m_e c^2$$



$$\lambda_{\gamma\gamma} \sim (35\ldots700)\ \mathrm{Mpc\ for}\ z = 1\ldots0$$

Inverse Compton cascades



$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

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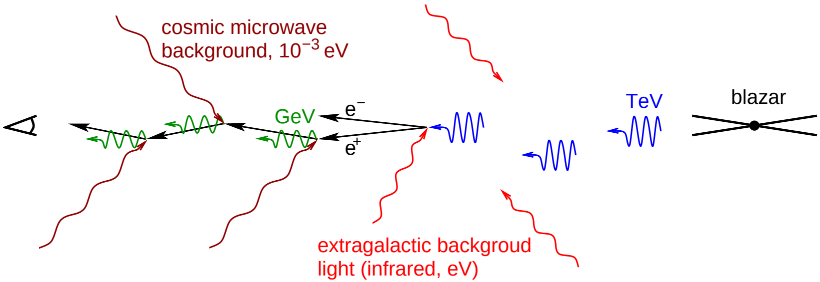
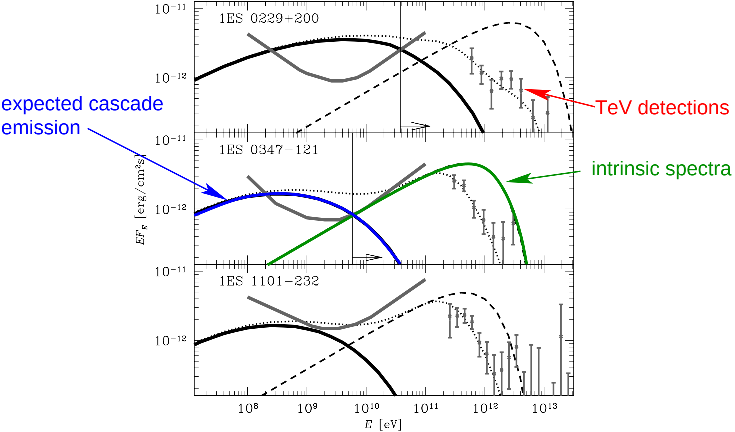


$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

$\longrightarrow$ each TeV point source should also be a GeV point source!

What about the cascade emission?

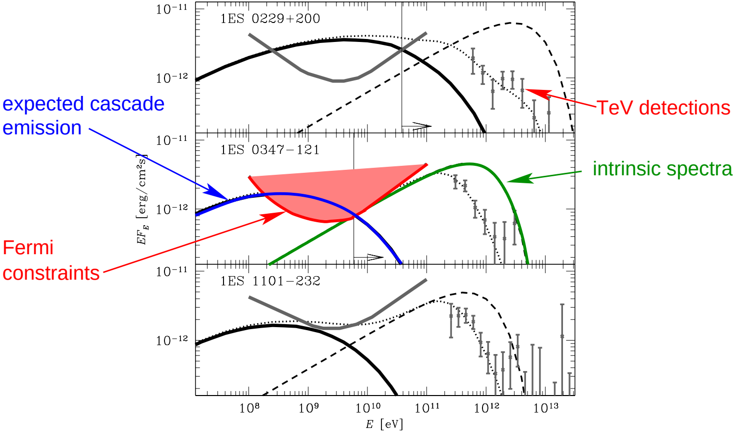
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

What about the cascade emission?

Every TeV source should be associated with a 1-100 GeV gamma-ray halo – **not seen!**



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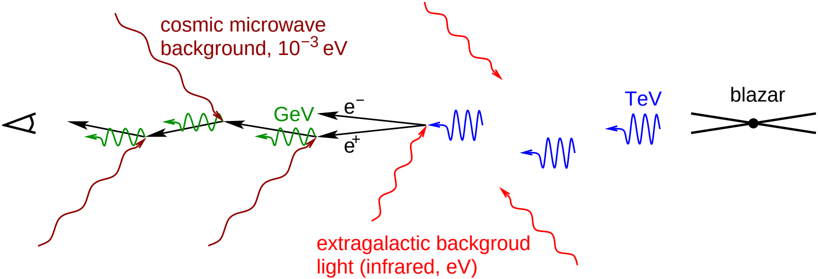

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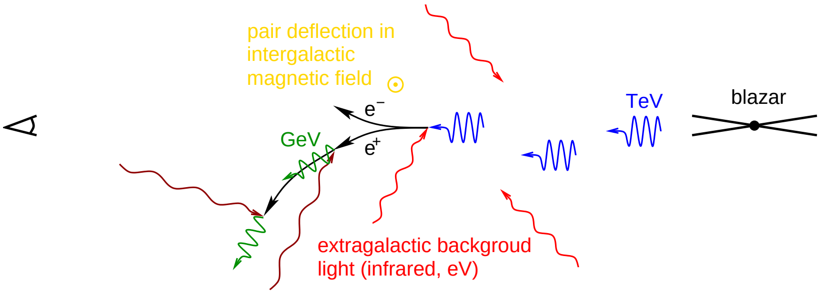
Magnetic field deflection



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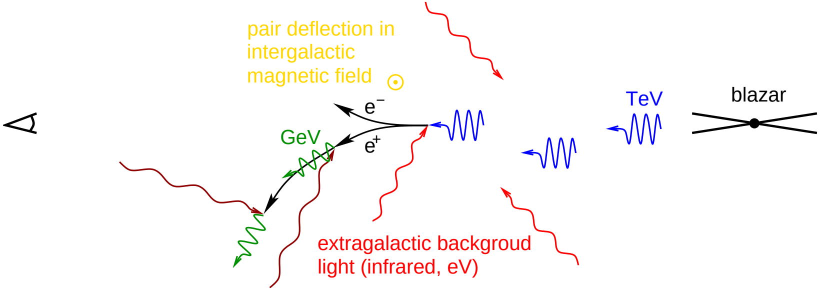
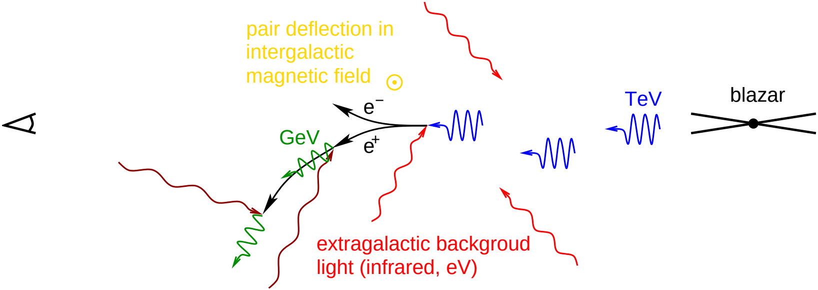


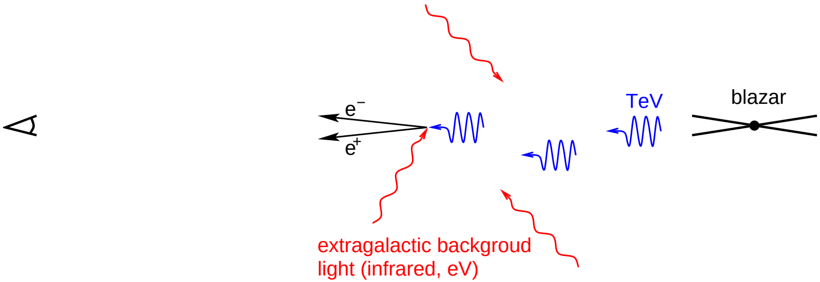
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution,
  gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mathrm{G}$ − primordial fields?

Magnetic field deflection

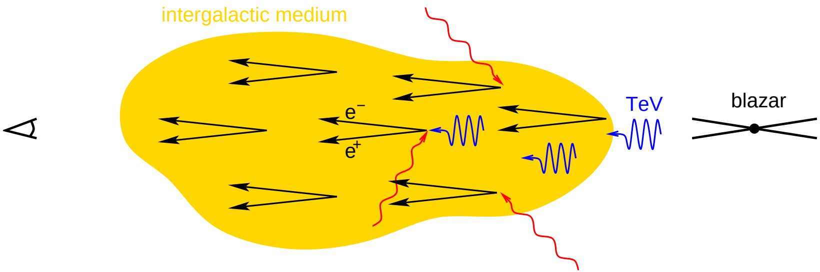


- problem for unified AGN model: no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since other−wise, extragalactic GeV background would be overproduced!

What else could happen?



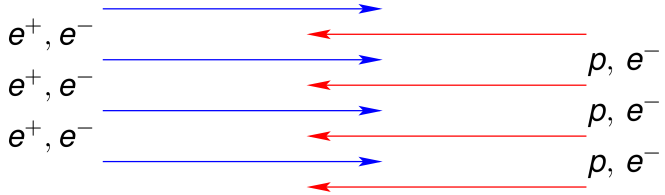
Plasma instabilities



pair plasma beam propagating through the intergalactic medium

Plasma instabilities

- pair beam   intergalactic medium (IGM)



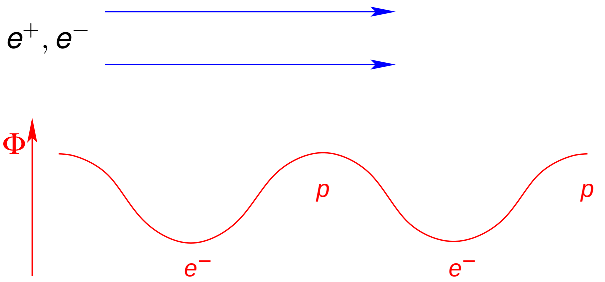
- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \qquad \lambda_p = \left.\frac{c}{\omega_p}\right|_{\bar{\rho}(z=0)} \sim 10^8\,\mathrm{cm}$$

Two-stream instability: mechanism

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

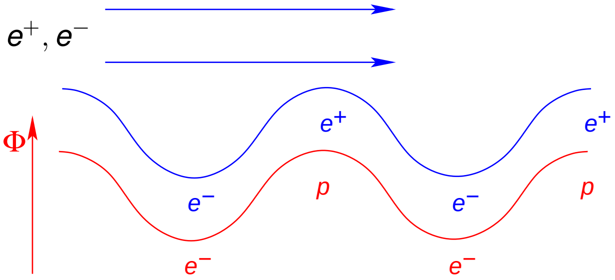
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



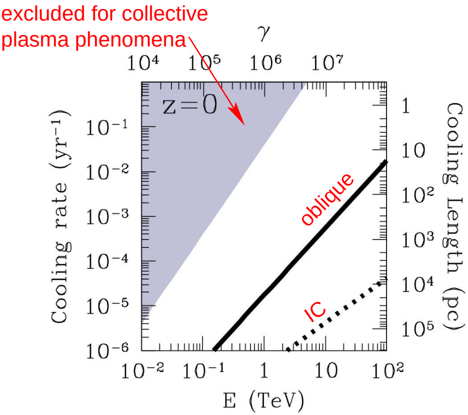
Two-stream instability: mechanism

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

- beam-e^+/e^- couple in phase with the background perturbation: enhances background potential
- stronger forces on beam-e^+/e^- $\rightarrow$ positive feedback
- exponential wave-growth $\rightarrow$ instability



Beam physics – growth rates



Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)

- consider a light beam penetrating into relatively dense plasma
- maximum growth rate

$$\Gamma \simeq 0.4\,\gamma\,\frac{n_{\text{beam}}}{n_{\text{IGM}}}\,\omega_p$$

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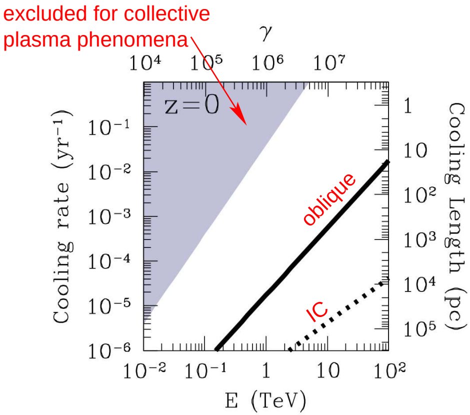

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$$\Gamma \simeq 0.4\,\gamma\,\frac{n_{\mathrm{beam}}}{n_{\mathrm{IGM}}}\,\omega_p$$

- oblique instability beats inverse Compton cooling by factor 10-100
- **assume** that instability grows at linear rate up to saturation

TeV emission from blazars – a new paradigm

$$\gamma_{\rm TeV} + \gamma_{\rm eV} \quad\rightarrow\quad e^{+} + e^{-} \quad\rightarrow\quad \begin{cases} \text{inv. Compton cascades} & \rightarrow \quad \gamma_{\rm GeV} \\ \text{plasma instabilities} & \rightarrow \quad \text{IGM heating} \end{cases}$$

Collaboration: Broderick, Chang, Lamberts, Pfrommer, Puchwein, Shalaby

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absence of $\gamma_{\rm GeV}$'s has significant implications for ...

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars:
  explains *Fermi's* γ-ray background and blazar number counts

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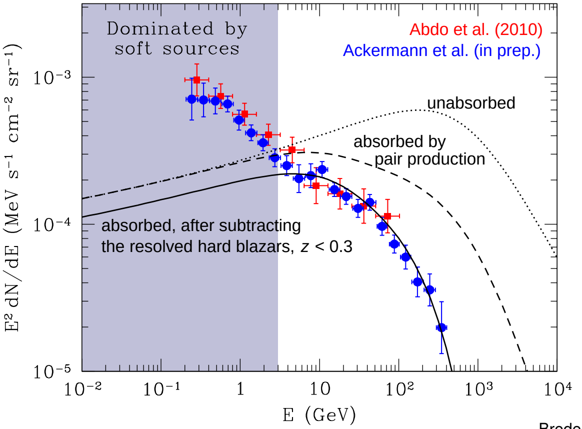
Extragalactic gamma-ray background



Broderick, C.P.+ (2014)

→ evolving population of hard blazars provides excellent match to latest extragalactic gamma-ray background by *Fermi* for $E \gtrsim 3$ GeV

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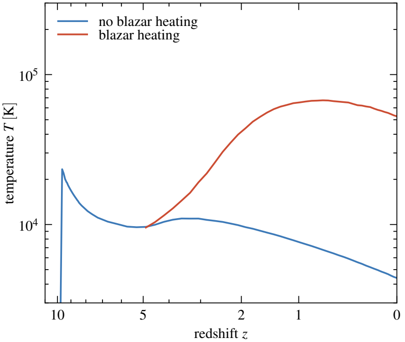
additional IGM heating has significant implications for ...

- thermal history of the IGM: Lyman-α forest
- late time structure formation: dwarf galaxies, galaxy clusters

Collaboration: Broderick, Chang, Lamberts, Pfrommer, Puchwein, Shalaby

TeV blazars heat the intergalactic medium

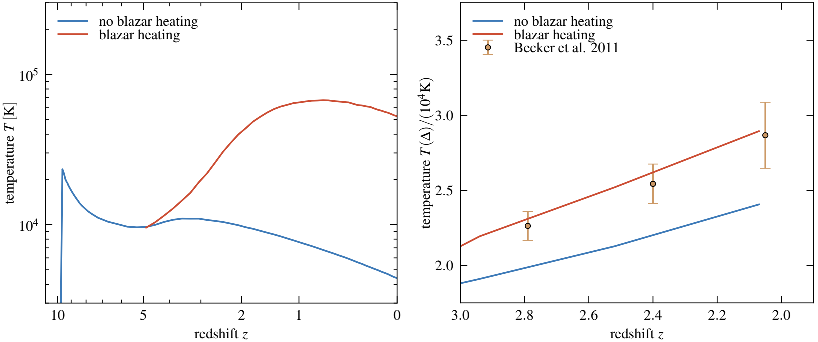
$T(z)$ at mean density ($\Delta = 0$)



- every region in the universe is heated by at least one blazar
- TeV blazars increase temperatures at mean density ($\Delta = 0$) by a factor 10 today

TeV blazars heat the intergalactic medium

$T(z)$ at mean density ($\Delta = 0$) — observed $T[z(\Delta)]$



Puchwein, C.P., Springel, Chang, Broderick (2012)

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Conclusions

- the non-thermal universe uncovered by high-energy radiation provides new probes of fundamental physics and cosmology
- radio and X-ray astronomy have provided impressive discoveries of new phenomena; now the age of γ-ray and cosmic-ray astronomy has begun and ν astronomy is about to open up
- theory and simulations are helpful for understanding the physics of the sources and for assessing the impact of non-thermal processes on structure formation and cosmology

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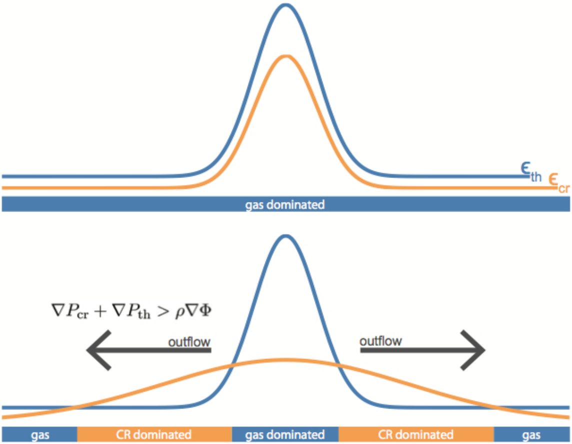
$\rightarrow$ non-thermal multi-messenger analyses:

"The only true voyage of discovery would be not to visit new landscapes but to possess other eyes and to behold the universe through the eyes of another, of a hundred others."

Marcel Proust

Additional slides

Cosmic ray driven wind: mechanism



CR streaming: Uhlig, C.P.+ (2012)

CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014)

Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
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→ blazar heating increases M_J by 30 over pure photoheating!

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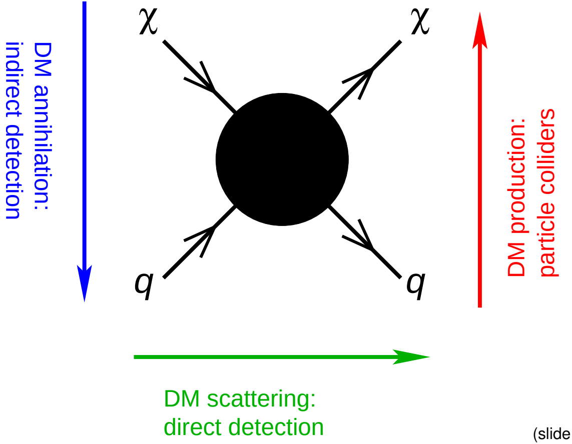
  → blazar heating increases M_J by 30 over pure photoheating!
- complications: non-linear collapse, delayed pressure response in expanding universe

  → expect slight reduction: $M_{J,\mathrm{blazar}}/M_{J,\mathrm{photo}} \approx 10$

C.P., Chang, Broderick (2012)

Searching for dark matter (DM)

correct relic density → DM annihilation in the Early Universe



(slide concept Feng)