Gamma-ray Astronomy

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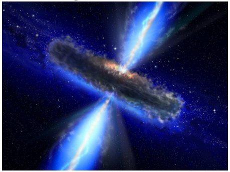
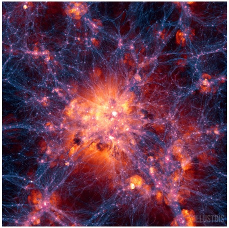
Sep 30, 2014 / Astroparticle Physics in Germany:
Status and Perspectives

Which physics can gamma-ray astronomy probe?

active galactic nuclei

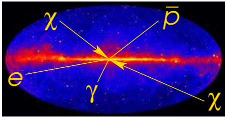


intergalactic space

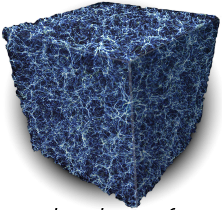


galaxy formation

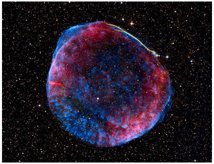
... and don't forget the UNEXPECTED!



dark matter



structure of space time



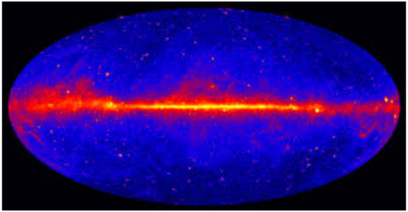
particle acceleration
magnetic amplification

The Questions
Probing physics and cosmology with gamma-ray astronomy

- **which objects can we see?**
  active galactic nuclei (blazars, radio galaxies), starburst galaxies, gamma-ray bursts, diffuse radiation
  $\longrightarrow$ astronomy: characterization, population studies
- **what underlying physics can we probe?**
  most extreme physics laboratories of the cosmos:
  plasma instabilities, particle acceleration, magnetic fields
  $\longrightarrow$ plasma physics, high-energy astrophysics
- **what (fundamental) physics can we hope to learn?**
  galaxy formation, dark matter, structure of space time
  $\longrightarrow$ structure formation, cosmology, particle physics

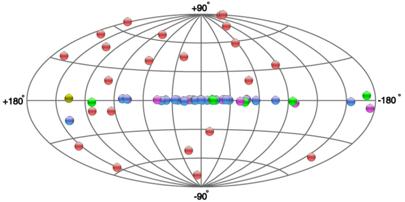
The gamma-ray sky at GeV-to-TeV energies

GeV: all-sky survey by *Fermi*



NASA/DOE/Fermi LAT Collaboration

TeV: Čerenkov telescope observations



H.E.S.S./MAGIC/VERITAS

- dramatic increase in number of sources and phenomena:
  - huge discovery potential for high-energy astrophysics
  - wonderful playground for creative theoreticians
- GeV and TeV observations provide complementary views with different strengths and weaknesses (homogeneous vs. biased selection functions, "average" vs. extreme energies)

Gamma-ray emission induced by cosmic rays

Complementary information to cosmic rays: gamma rays point back to origin

hadronic processes:

- pion decay:

$$\mathrm{p}+\mathrm{ion} \rightarrow \begin{cases} \pi^0 & \rightarrow \quad \gamma\gamma \\ \pi^\pm & \rightarrow \quad \mathrm{e}^\pm + 3\nu \end{cases}$$

- photo-meson production:

$$\mathrm{p}+\gamma \rightarrow \begin{cases} \pi^0 & \rightarrow \quad \gamma\gamma \\ \pi^\pm & \rightarrow \quad \mathrm{e}^\pm + 3\nu \end{cases}$$

- Bethe-Heitler pair production:

$$\mathrm{p}+\gamma \rightarrow \mathrm{p} + e^+ + e^-$$

leptonic processes:

- inverse Compton:

$$\mathrm{e}^* + \gamma \rightarrow \mathrm{e} + \gamma^*$$

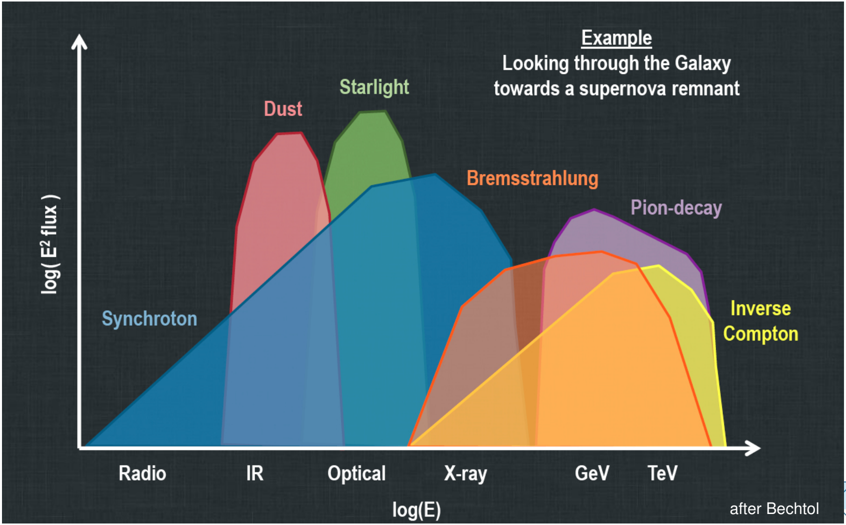
- synchrotron radiation:

$$\mathrm{e}^* + B \rightarrow \mathrm{e} + B + \gamma^*$$

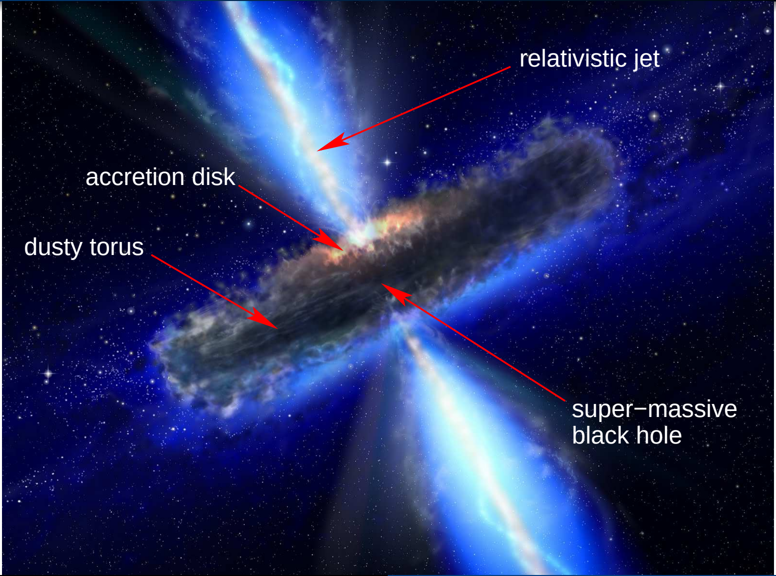
- bremsstrahlung:

$$\mathrm{e}^* + \mathrm{ion} \rightarrow \mathrm{e} + \mathrm{ion} + \gamma^*$$

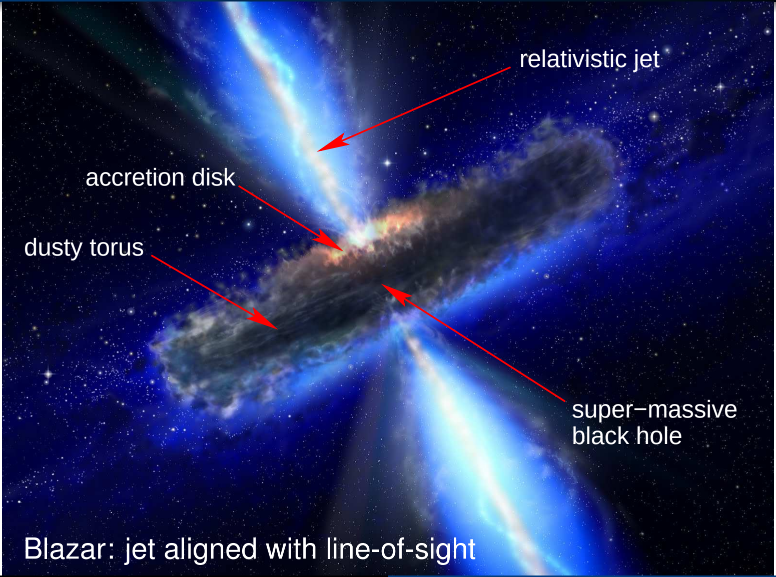
A sketch of the nonthermal emission



The physics and cosmology of active galactic nuclei

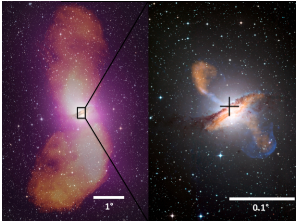


The physics and cosmology of active galactic nuclei

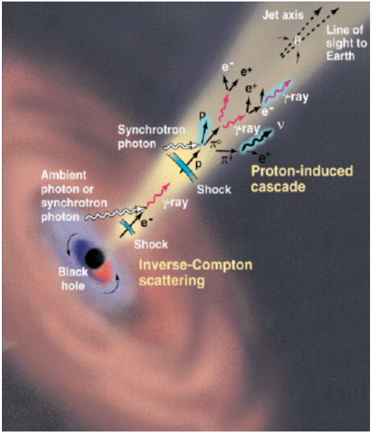


Active galactic nuclei

- active galactic nuclei (AGN)
  - compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
  - AGN emission is caused by mass accretion onto a supermassive black hole → launching of relativistic jets
  - particle acceleration in jets → radio and γ-ray emission
  - jet momentum pushes ambient plasma around → *AGN feedback* prevents cooling catastrophe in cores of galaxy clusters and mitigates star formation in ellipticals
- example: Cen A (3.7 Mpc) "AGN under the microscope"
  - GeV emission from giant radio lobes *(Fermi)*
  - TeV emission from nucleus/inner jet (H.E.S.S.)



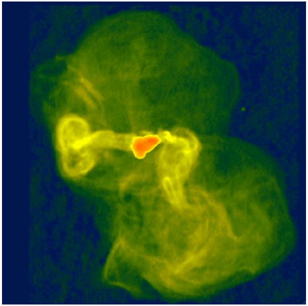
Active galactic nuclei: paradigm and open questions



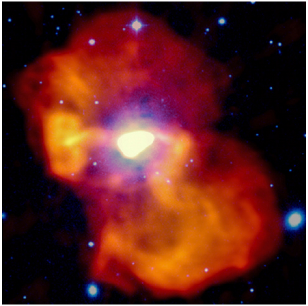
- current paradigm for emission:
  - synchrotron self Compton
  - external Compton
  - proton-induced cascades
  - proton synchrotron
- open questions:
  - energetics
  - mechanisms for jet formation and collimation
  - plasma composition (leptonic vs. hadronic, 1-zone vs. spine-layer)
  - acceleration mechanisms

- TeV "flares" may sign instabilities in the accretion of matter onto the central supermassive black hole

Feedback heating: M87 at radio wavelengths



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

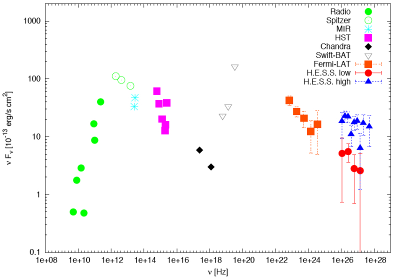


$\nu = $ 140 MHz (LOFAR/de Gasperin+ 2012)

- 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!**

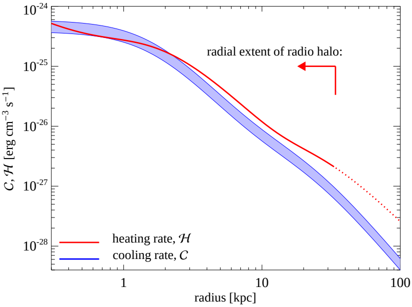
AGN feedback = cosmic ray heating (?)

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

- cosmic rays excite Alfvén waves that dissipate the energy → heating rate

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

- calibrate $P_{\rm CR}$ to γ-ray emission and $\boldsymbol{v}_A$ to radio and X-ray emission → spatial heating profile

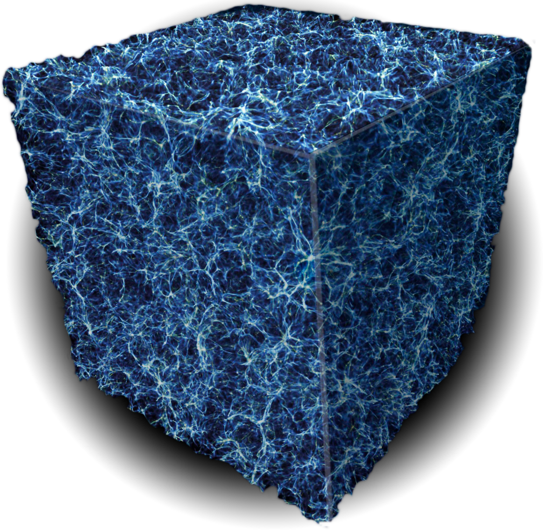


C.P. (2013)

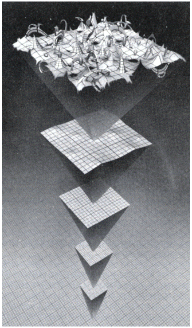
→ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!

HITS

Probing the structure of space-time with gamma rays



Probing the structure of space-time: idea



- does quantum gravity make space-time 'foamy' or discrete at the Planck scale?

$$l_{\mathrm{P}} = \hbar/(m_{\mathrm{P}}c), \quad t_{\mathrm{P}} = \hbar/(m_{\mathrm{P}}c^2), \quad m_{\mathrm{P}} = \sqrt{\hbar c/G}$$

- this does not happen in string theory, but in other approaches like *loop quantum gravity*
- preserving the $O(3)$ subgroup of $SO(3,1)$, we parametrize the new dispersion rel. for photons

$$c^2 \boldsymbol{p}^2 = E^2(1 + \xi E/E_{\mathrm{QG}} + \eta E^2/E_{\mathrm{QG}}^2 + \dots)$$

- assuming the Hamiltonian equ. of motions $\dot{x}_i = \partial H/\partial p_i$, we get

$$\upsilon \equiv \partial E/\partial p = c\,(1 - \xi E/E_{\mathrm{QG}} + \dots) \quad \Rightarrow \quad \Delta t = \xi E/E_{\mathrm{QG}}\, L/c$$

→ we can test this *energy-dependent time delay* by studying the propagation of high-energy gamma ray pulses (Amelino-Camelia+ 1998)

Quantum gravity constraints with gamma-ray bursts

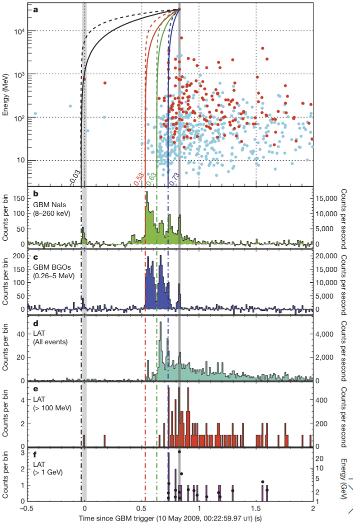
- expected time delay for $E_{\mathrm{QG}} \sim E_{\mathrm{P}} = 10^{19}$ GeV and GeV pulse structure

$$\Delta t \approx 10\,\mathrm{ms}\,\frac{E}{\mathrm{GeV}}\,\frac{L}{\mathrm{Gpc}}$$

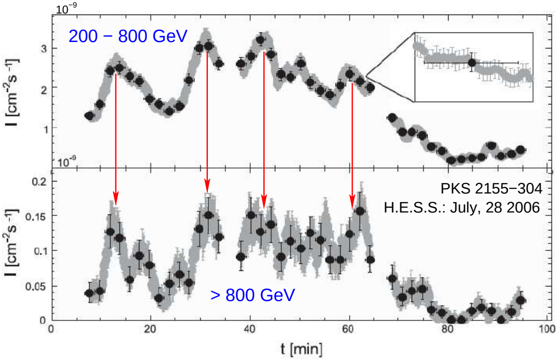
- idea: use pulses from gamma-ray bursts or blazar flares
- assuming anomalous photon dispersion dominated by the linear term yields the constraint (Abdo+ 2009)

$$E_{\mathrm{QG}} > 1.2 \times 10^{19}\,\mathrm{GeV}, \;\text{for}\; \xi = 1$$

...set mainly by the early arrival time of the 31 GeV photon!



Quantum gravity constraints with blazar flares

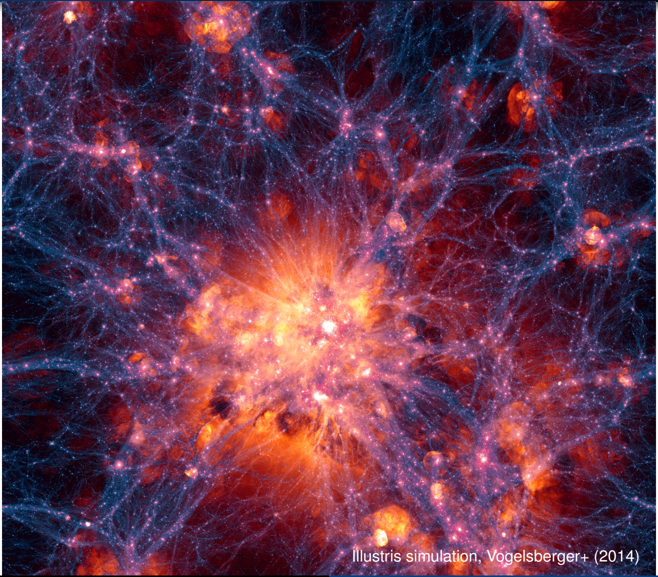


→ no observable time delay between low and high energy photons!

→ constraints on energy-dependent violation of Lorentz invariance:
$E_{QG} > 2.1 \times 10^{18}$ GeV (90% CL limit)

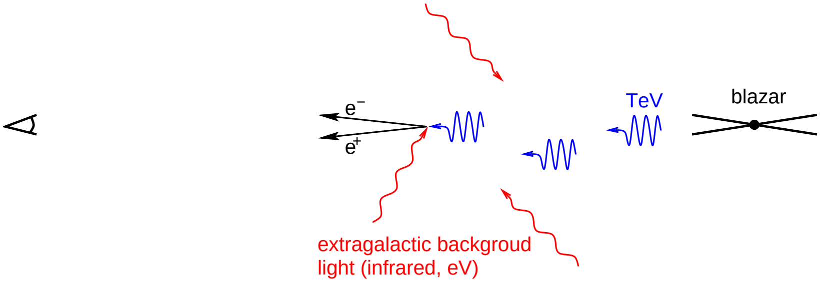
→ photons of all energies travel in vacuum at about the same speed!

Propagation of γ rays through intergalactic space



Observational gamma-ray cosmology

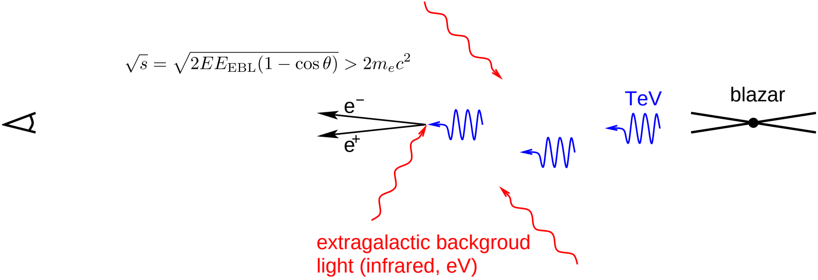
Annihilation and pair production



Observational gamma-ray cosmology

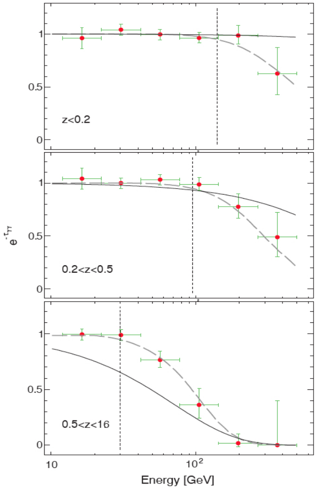
Annihilation and pair production

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



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

The *Fermi* gamma-ray horizon

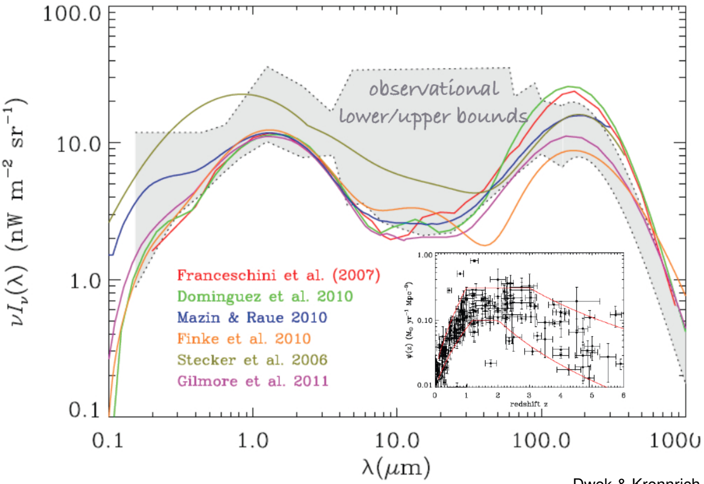


Ackermann+ (2012)

- staking of 150 significantly detected BL Lac blazars
- absorption feature moves to lower *E* for higher source redshifts (propagation distances) due to attenuation of gamma rays by EBL
- *UV*($>$ 5 eV) EBL intensity: $3(\pm1)\mathrm{nW\ m^{-2}sr^{-1}}$ at $z \sim 1$

Extragalactic background light

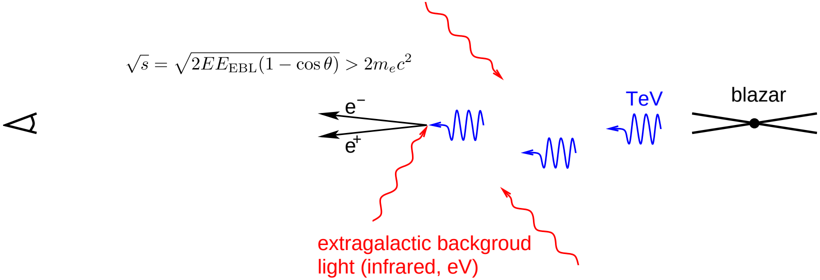
Unique probe of the integrated star formation rate



Dwek & Krennrich (2012)

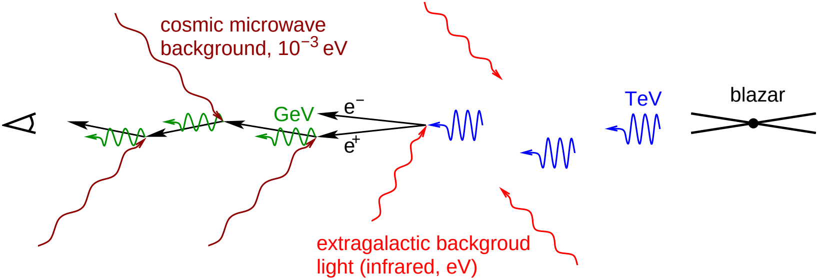
Annihilation and pair production

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



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

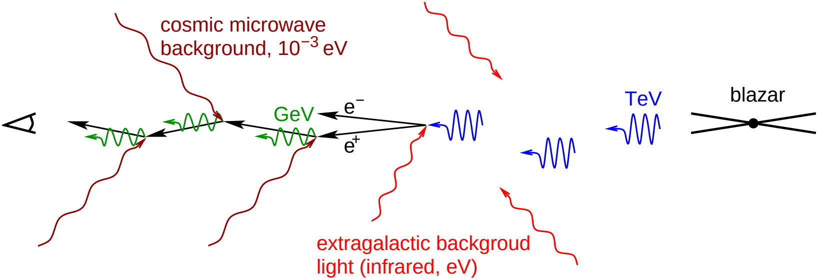
Inverse Compton cascades



$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$

$\lambda_{\gamma\gamma} \sim (35\dots700)$ Mpc for $z = 1\dots0$

Inverse Compton cascades

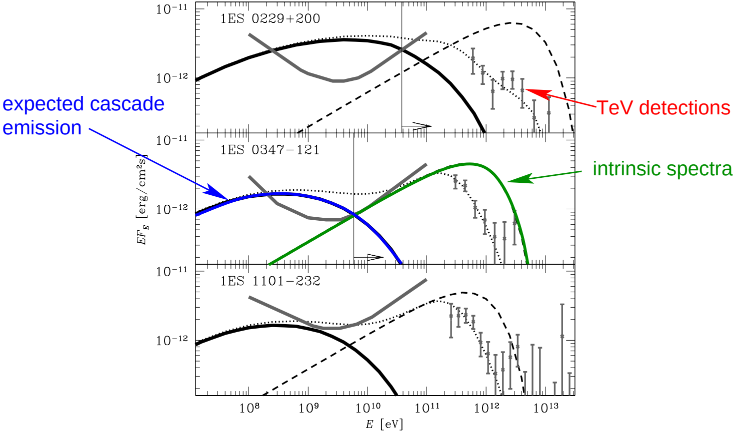


$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35\dots700)$ Mpc for $z = 1\dots0$

→ each TeV point source should also be a GeV point source!

What about the cascade emission?

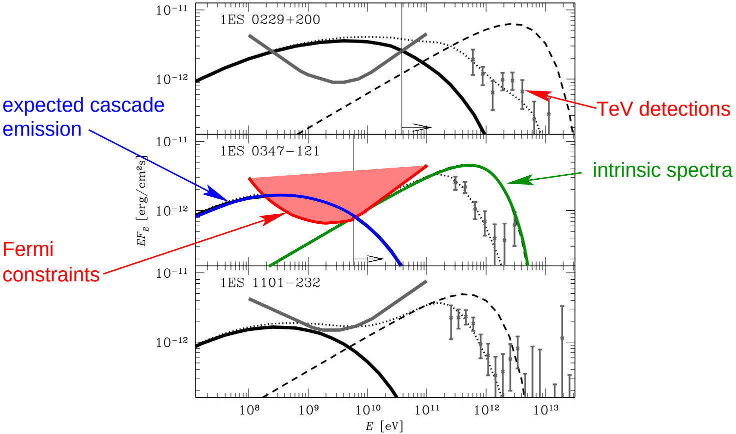
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

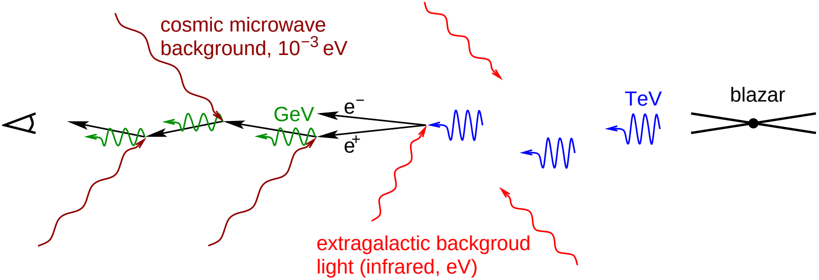
What about the cascade emission?

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



Neronov & Vovk (2010)

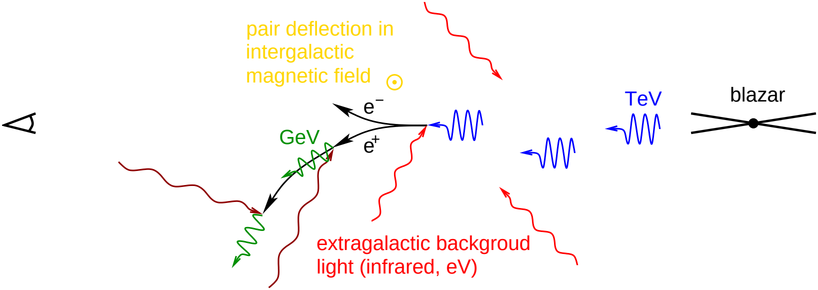
Inverse Compton cascades



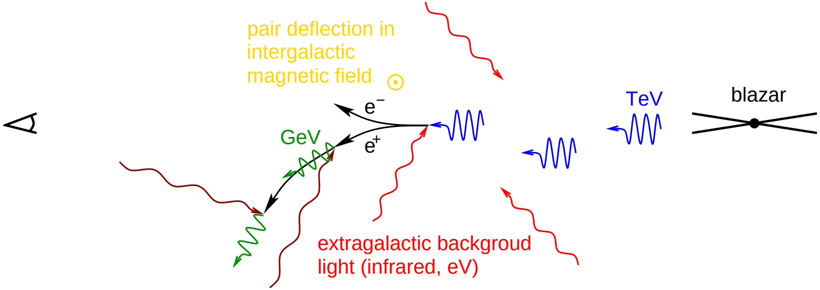
$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$

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

Magnetic field deflection

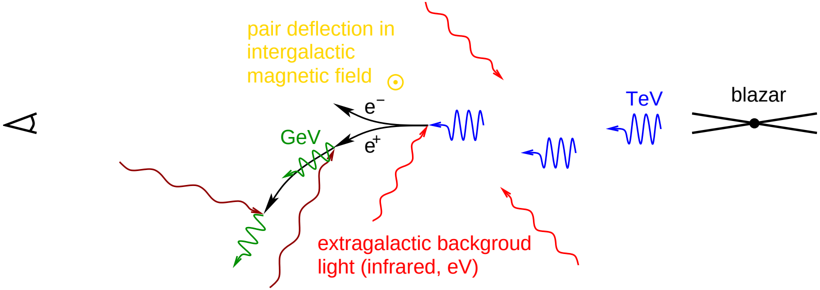


Magnetic field deflection



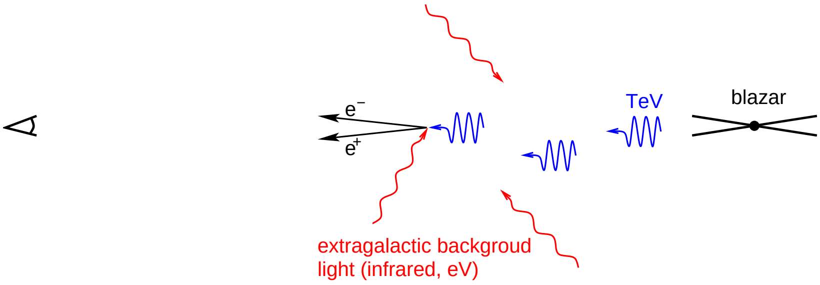
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution,
  gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mathrm{G}$ − primordial fields?

Magnetic field deflection

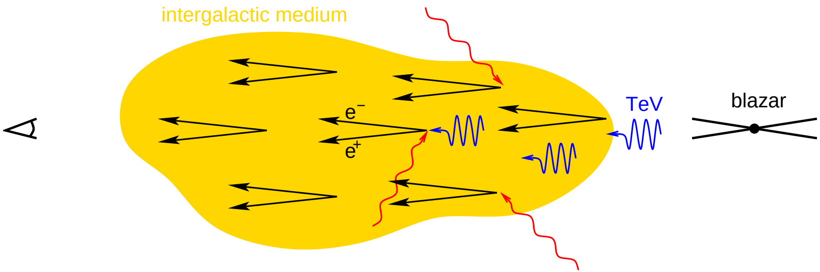


- problem for unified AGN model: no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since other−wise, extragalactic GeV background would be overproduced!

What else could happen?



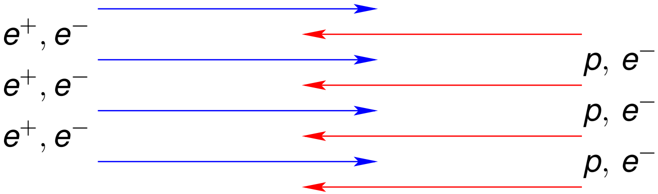
Plasma instabilities



→ pair plasma beam propagating through the intergalactic medium

Plasma instabilities

- pair beam — intergalactic medium (IGM)



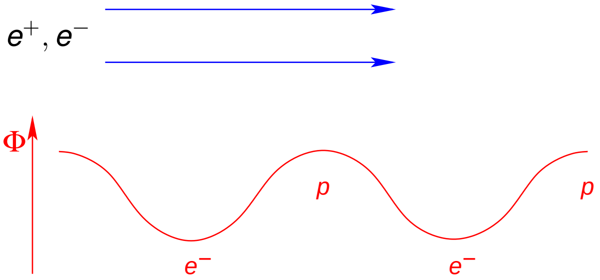
- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

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

Two-stream instability: mechanism

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

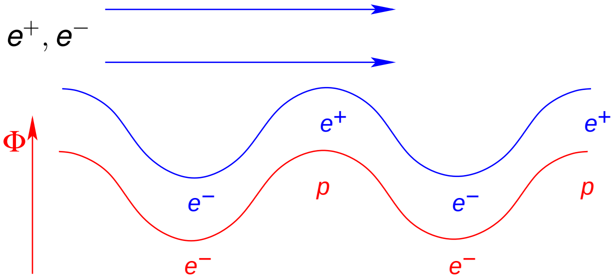
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



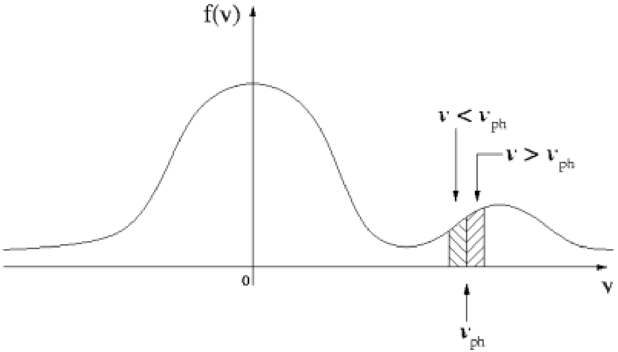
Two-stream instability: mechanism

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



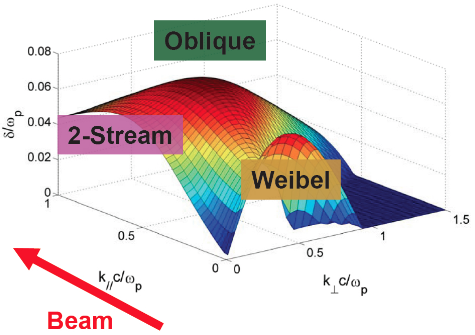
Two-stream instability: momentum transfer

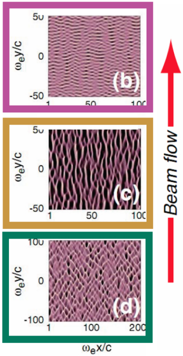


- particles with $v \gtrsim v_{\mathrm{phase}}$:
  pair momentum → plasma waves → growing modes: instability
- particles with $v \lesssim v_{\mathrm{phase}}$:
  plasma wave momentum → pairs → Landau damping

Oblique instability

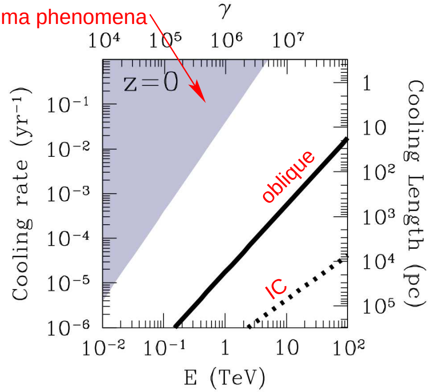
- ***k*** oblique to $\boldsymbol{v}_{\text{beam}}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- oblique grows faster than two-stream: *E*-fields can easier deflect ultra-relativistic particles than change their parallel velocities (Nakar, Bret & Milosavljevic 2011)





Bret (2009), Bret+ (2010)

Beam physics – growth rates



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

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

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

- 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

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

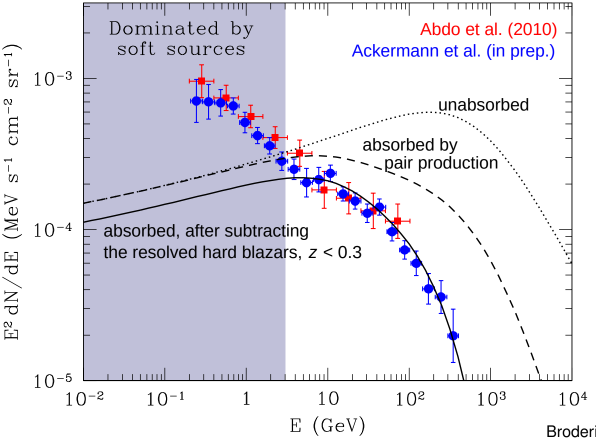
absence of γ_{GeV}'s has significant implications for . . .

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

additional IGM heating has significant implications for . . .

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

Extragalactic gamma-ray background

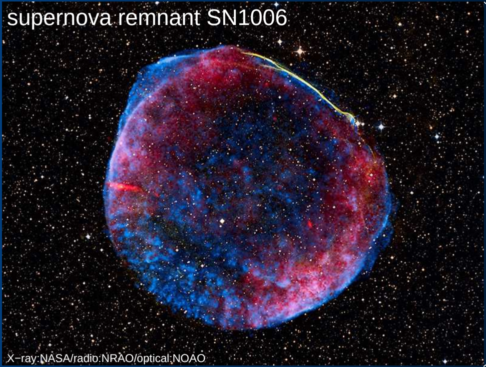


Broderick, C.P.+ (2014)

→ evolving population of hard blazars provides excellent match to latest EGRB by *Fermi* for $E \gtrsim 3$ GeV

Supernova remnants probe acceleration physics

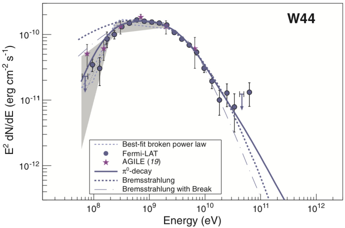
How galactic gamma-ray astronomy informs high-energy astrophysics and cosmological structure formation



Supernova remnants probe acceleration physics

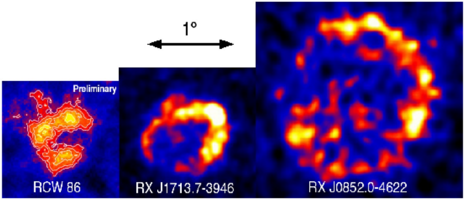
- high Mach number SNR shocks amplify magnetic fields and accelerate CR electrons up to $\sim$ 100 TeV (*Chandra* X-ray synchrotron observations)
- pion bump provides evidence for CR proton acceleration (*Fermi*/AGILE γ-ray spectra)
- shell-type SNRs show evidence for efficient shock acceleration beyond $\sim$ 100 TeV (HESS TeV γ-ray observations)

Fermi observations of W44:



Ackermann+ (2013)

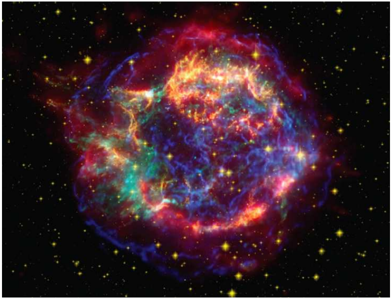
HESS observations of shell-type SNRs:



Hinton (2009)

HITS

Physics of galaxy formation



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, accelerate electrons, amplify magnetic fields

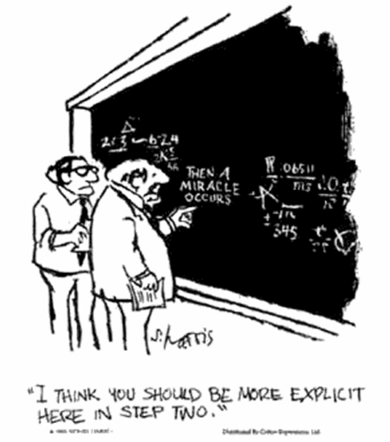
Physics of galaxy formation

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, accelerate electrons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ explains puzzle of low star formation efficiency in dwarf galaxies

Physics of galaxy formation



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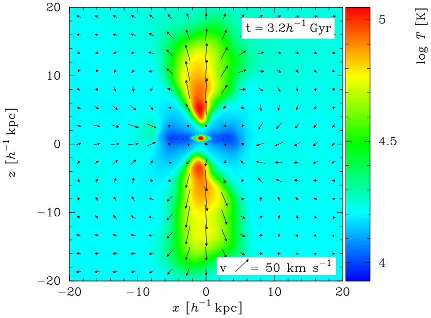
Cosmic ray-driven winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

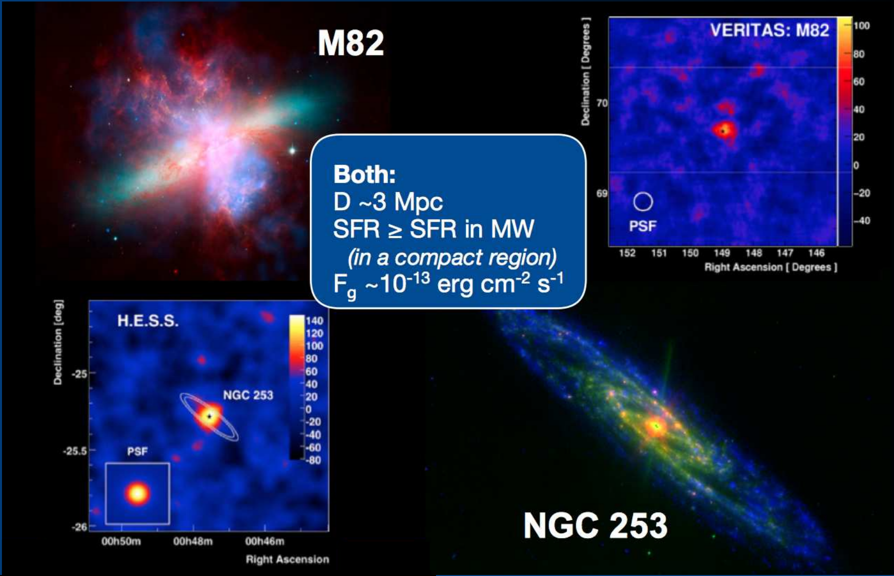


galaxy simulation, 10^{10} $M_\odot$

Uhlig, C.P.+ (2012)

- toy model: cosmic rays successfully launch and energize super winds that expel a large fraction of gas from the halo

Starburst galaxies

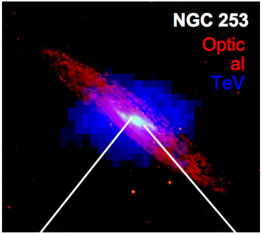


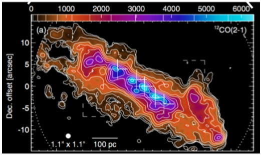
Both:
D ~3 Mpc
SFR ≥ SFR in MW
(in a compact region)
$F_g \sim 10^{-13}$ erg cm^{-2} s^{-1}

Cosmic rays and star formation

the picture: star formation → supernova remnants → proton acceleration → pion decay gamma rays induced by p-p interactions

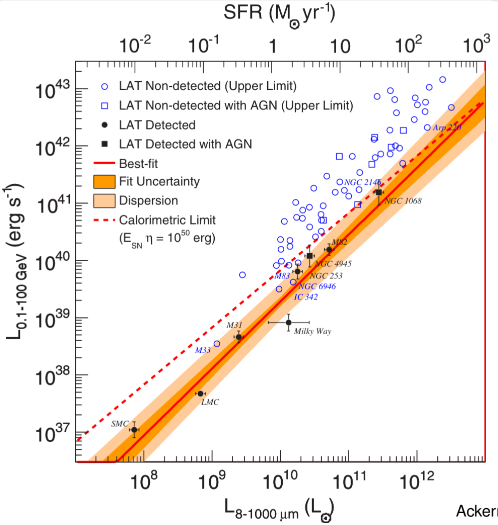
- **dense material in starburst region**
  - $\langle n \rangle \sim 250\ \mathrm{cm}^{-3}$
  - $t_{\mathrm{pp}} \sim t_{\mathrm{esc}}$
  - approaching the calorimetric limit
  - large NT bremsstrahlung and B: efficient electron emission
- **far-IR – radio correlation**
  - implies universal conversion: star form. → CR → synchrotron
  - now: far-IR – gamma-ray correlation





Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Ackermann+ (2012)

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 cosmic-ray astronomy has begun and neutrino (and gravitational wave?) astronomy is about to open up
- this is the right time to put γ-ray astronomy on the global observatory map $\rightarrow$ the Cherenkov Telescope Array

$\rightarrow$ 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