The Quest for Gamma-rays in Clusters of Galaxies

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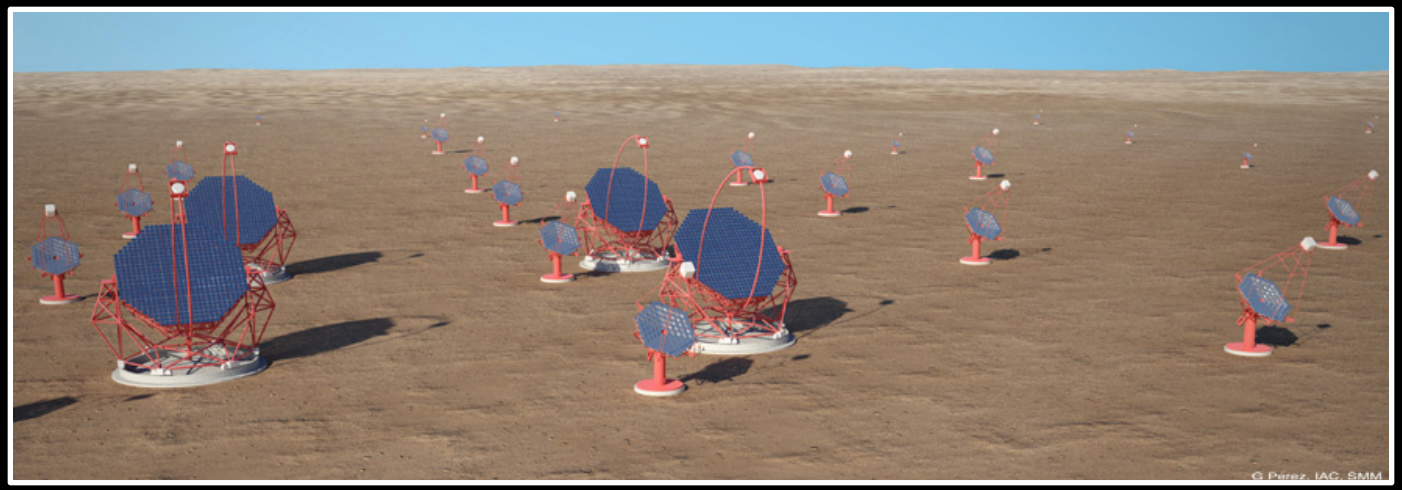
OUTLINE

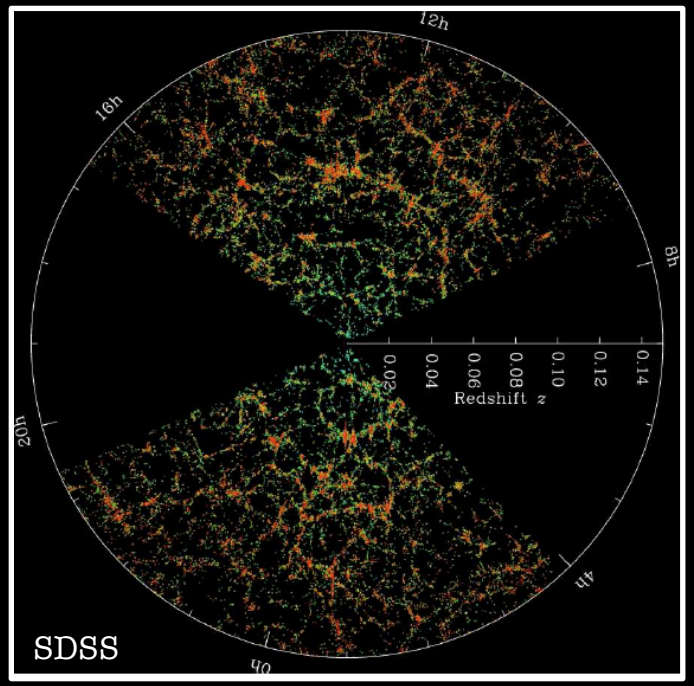
- The Latest & Largest Structures: Clusters of Galaxies
- Gamma-ray Emission from Structure Formation
- State-of-art of Observations
- Implications, Predictions & Future Prospects for CTA

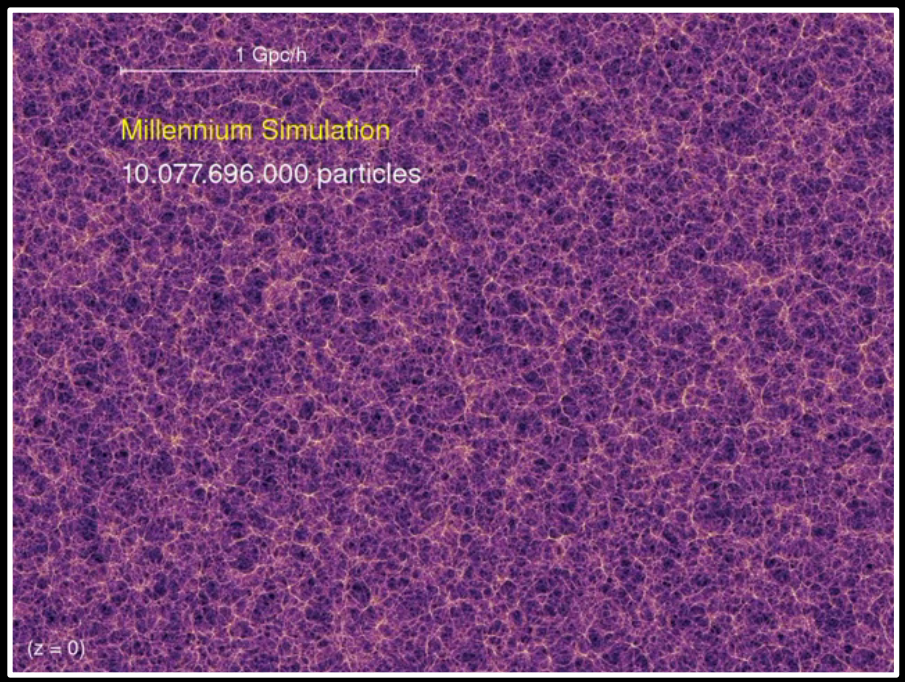


Structure Formation

Non-baryonic Cold Dark Matter (DM) is the dominant matter in the Universe and drives the structure formation

Hierarchical Scenario: structures grow via gravitational instability from initial small density fluctuations → large-scale structures grow through merging and accretion of smaller systems



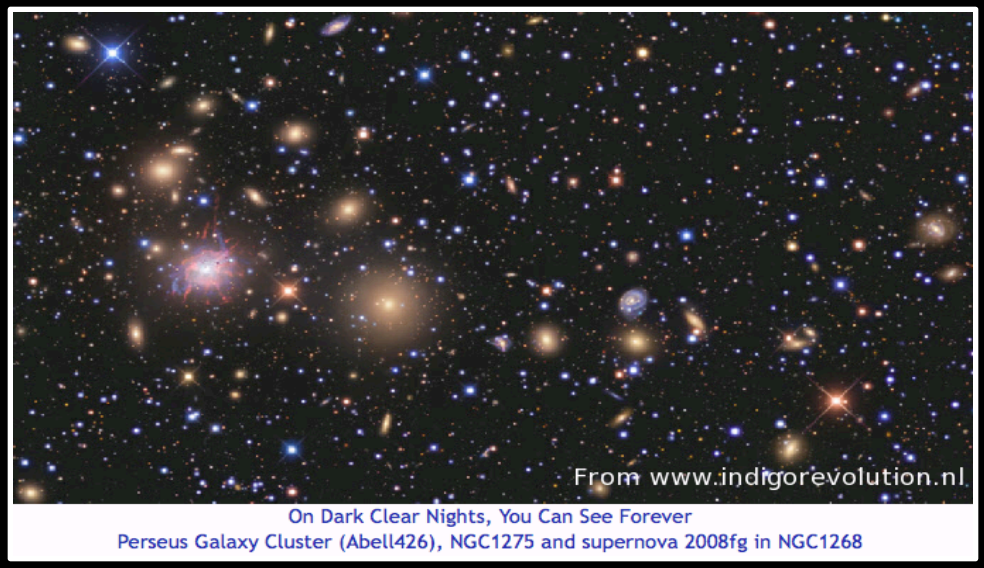


Clusters of Galaxies

Largest gravitationally bound systems in the Universe with mass of 10^{14}–10^{15} $M_\odot$ and radius of few Mpc

Actively evolving objects

Cosmic energy reservoirs



On Dark Clear Nights, You Can See Forever
Perseus Galaxy Cluster (Abell426), NGC1275 and supernova 2008fg in NGC1268

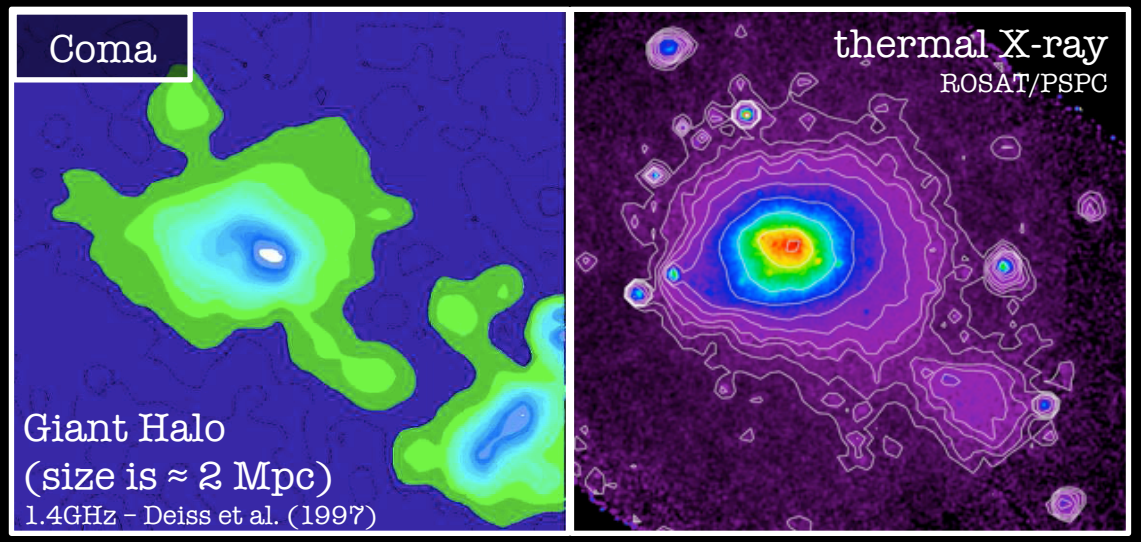
Expected to contain substantial populations of cosmic rays (CRs) and dark matter (DM) → can generate non-thermal emission from radio to gamma-ray frequencies

Powerful cosmological tools to test models on the origin and evolution of the Universe → via thermal X-ray emission and Sunyaev-Zel'dovich effect

Observed Non-thermal Emission in Radio

Radio Relics
- at the cluster periphery
- irregular morphology
- highly polarized
- seems to trace structure formation shocks

Radio (Mini-)Halos
- at the cluster center
- regular morphology
- un-polarized
- similar to thermal X-ray emission



CRs in Clusters – Processes & Emission

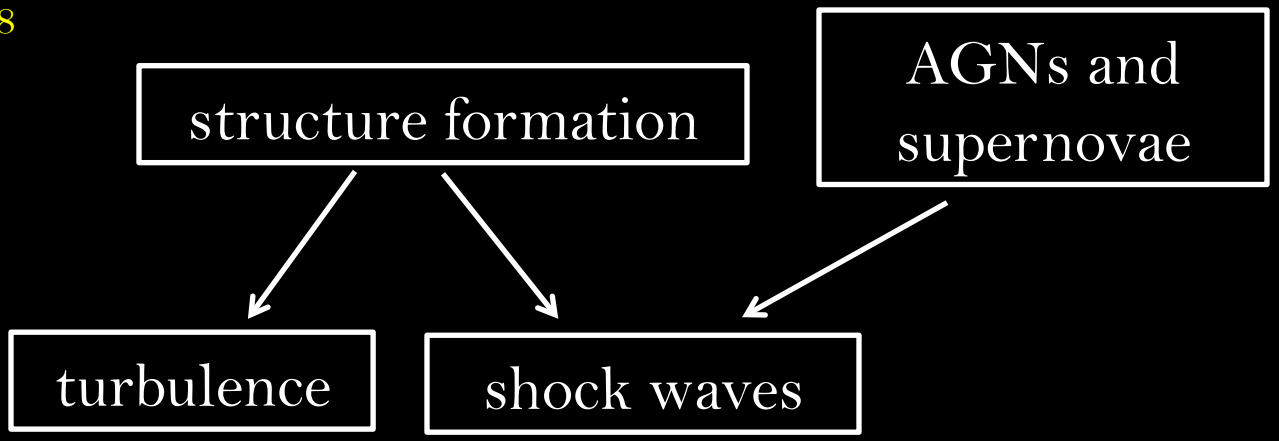
from Pfrommer et al. 2008

energy and particle sources

acceleration processes

relativistic populations

expected emission



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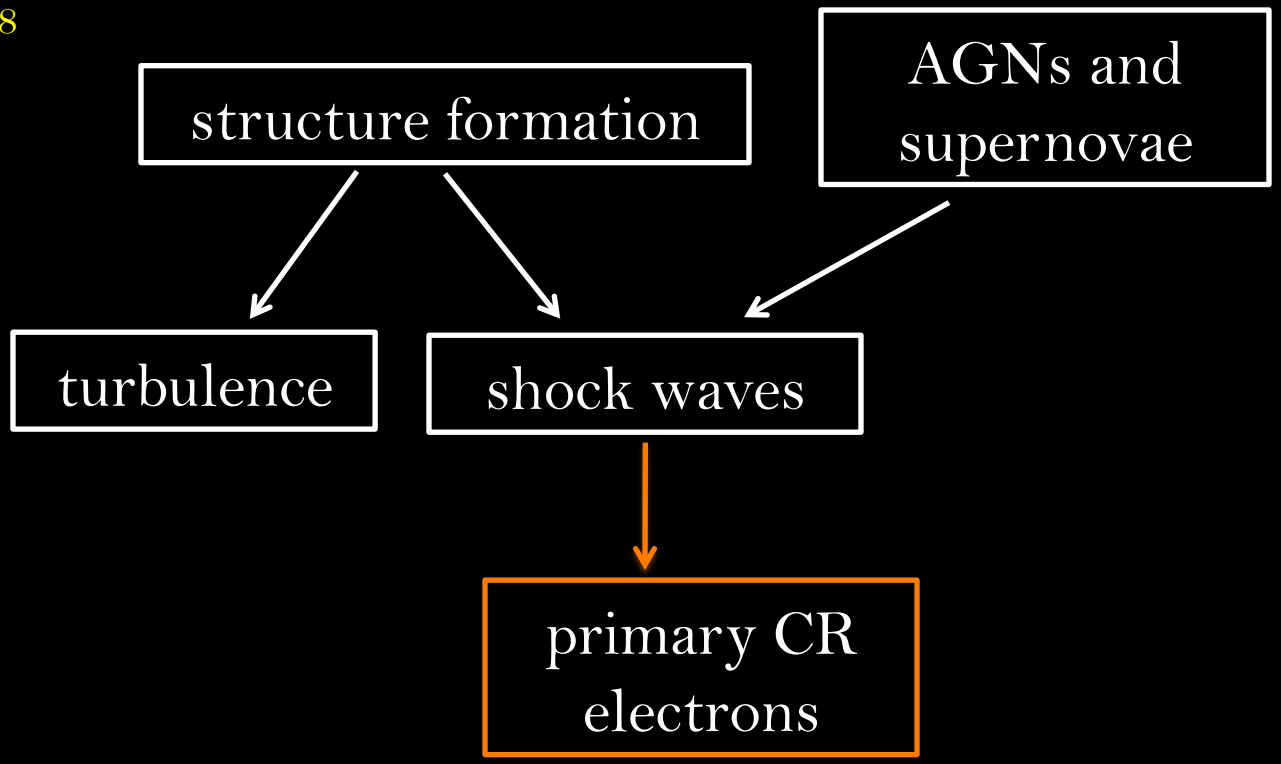

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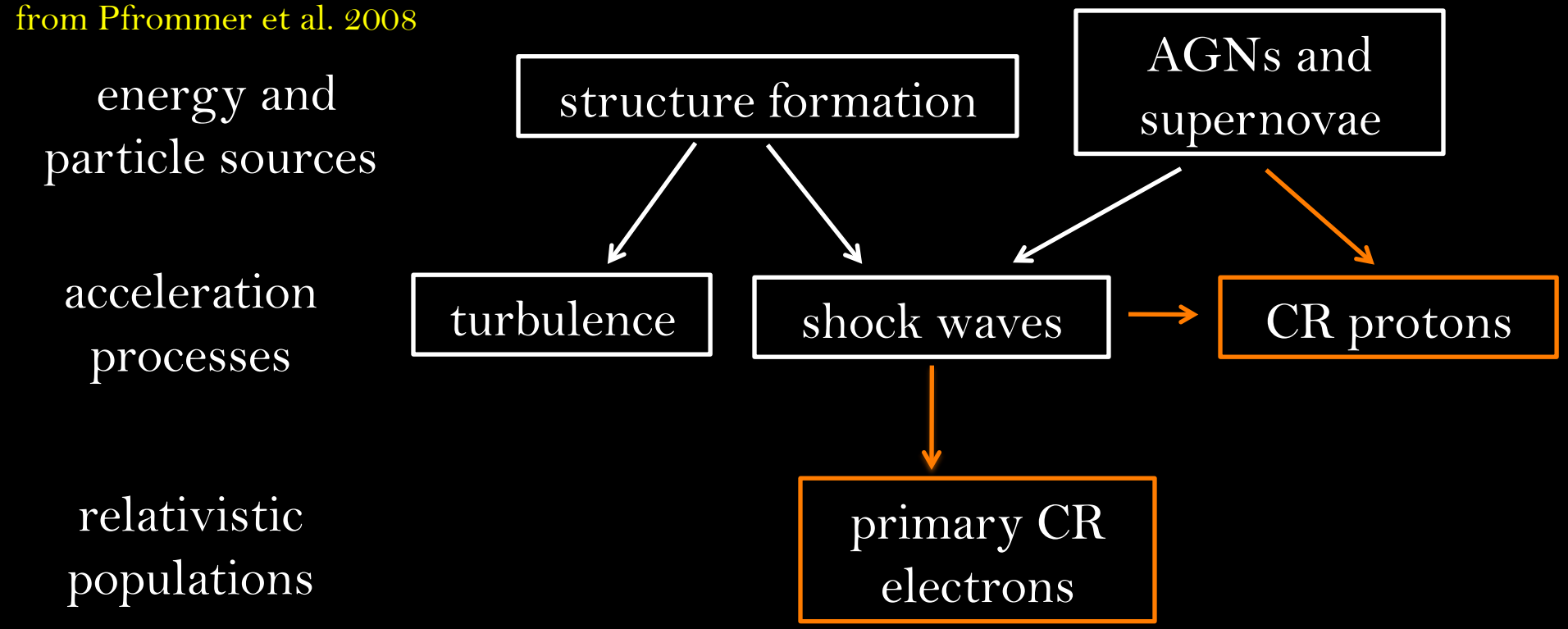

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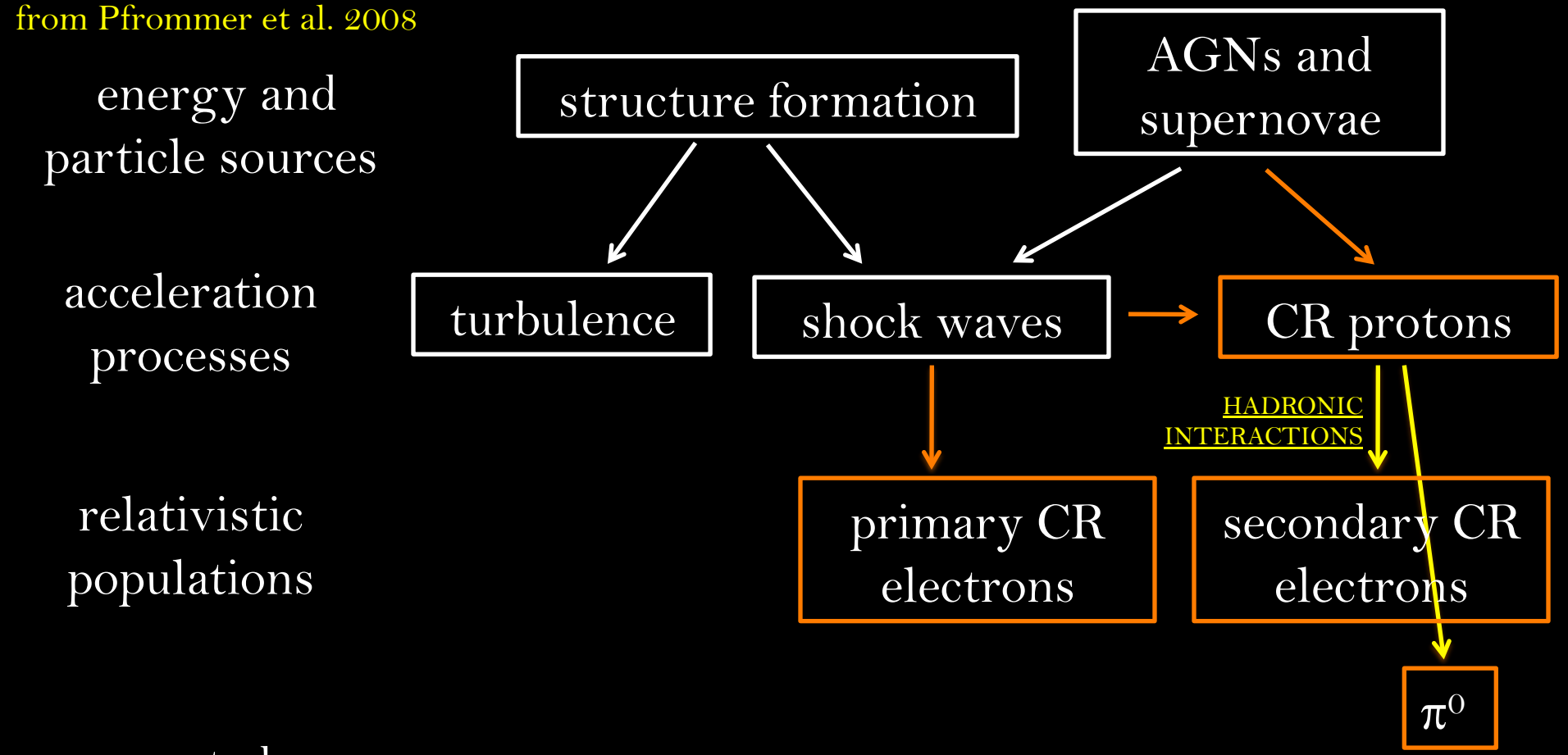

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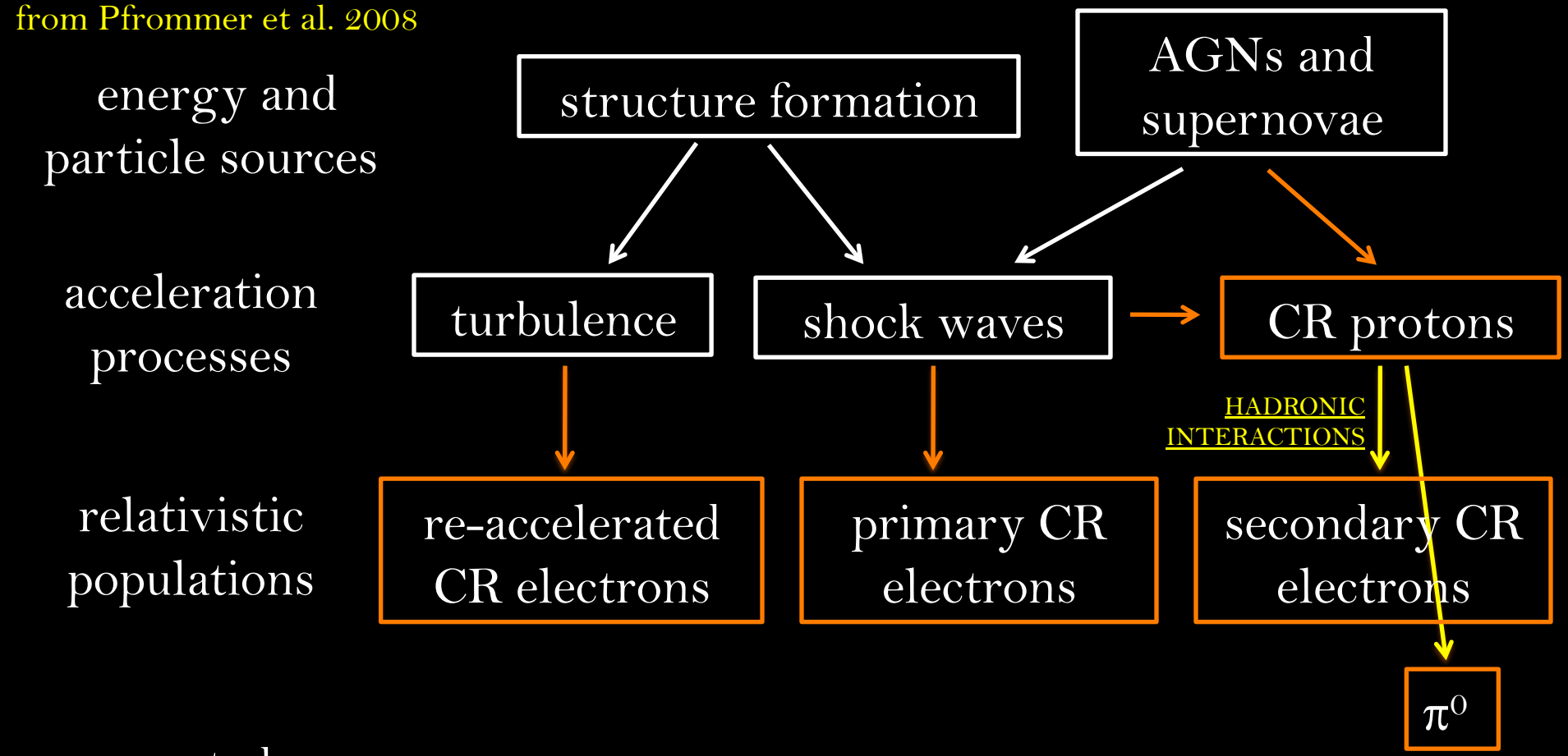

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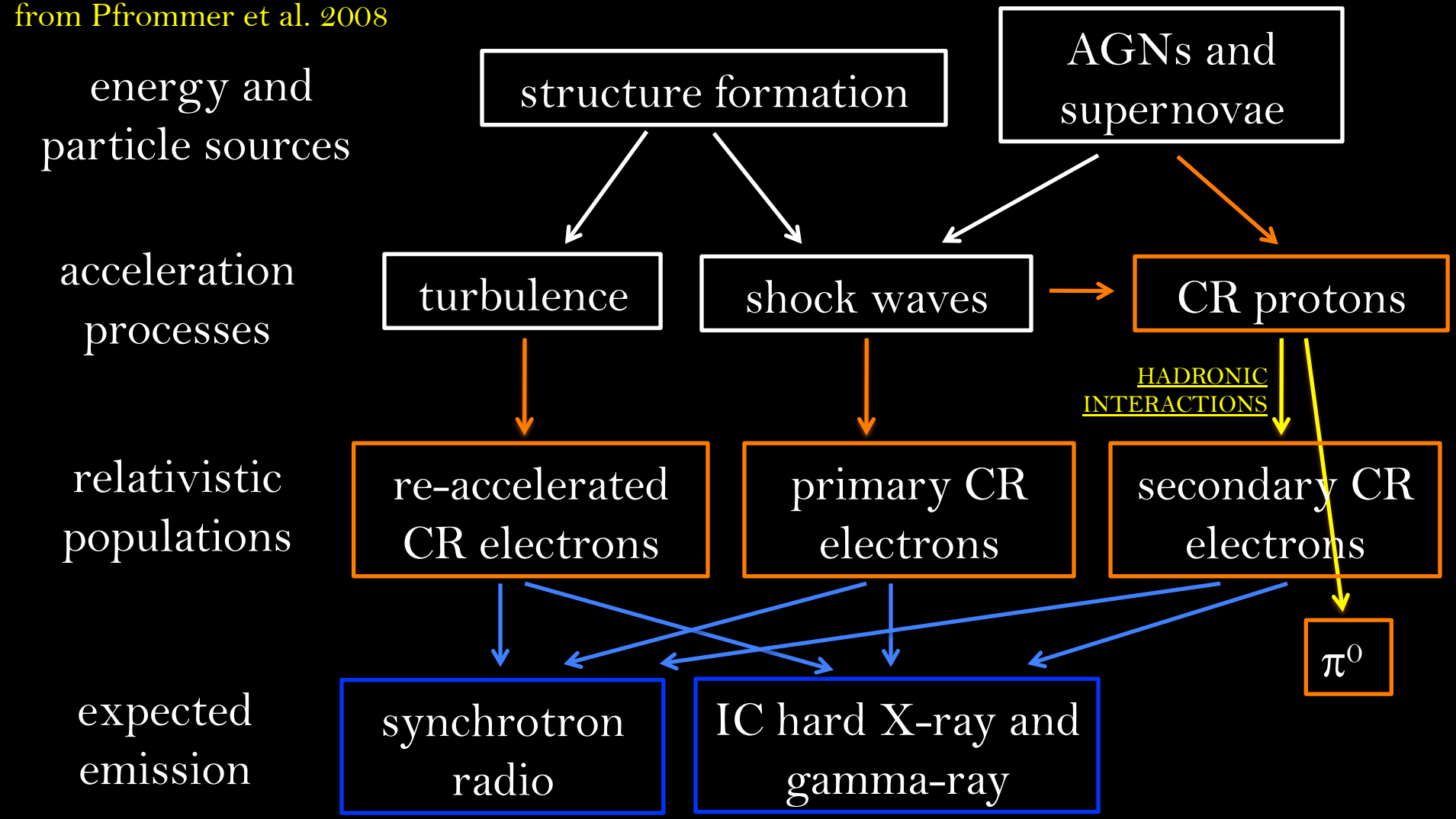

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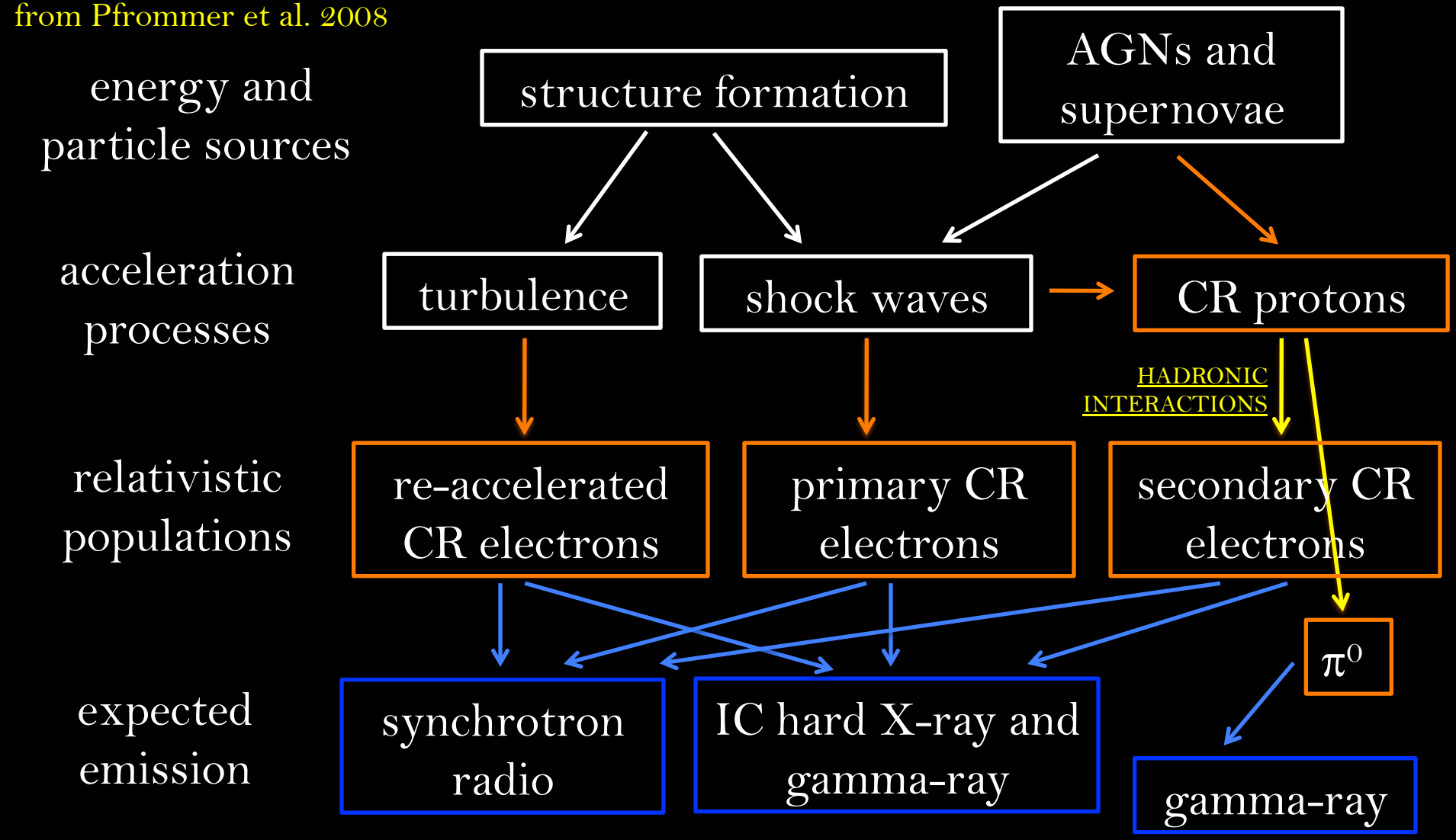


“Reference” CR Model in Gamma-rays

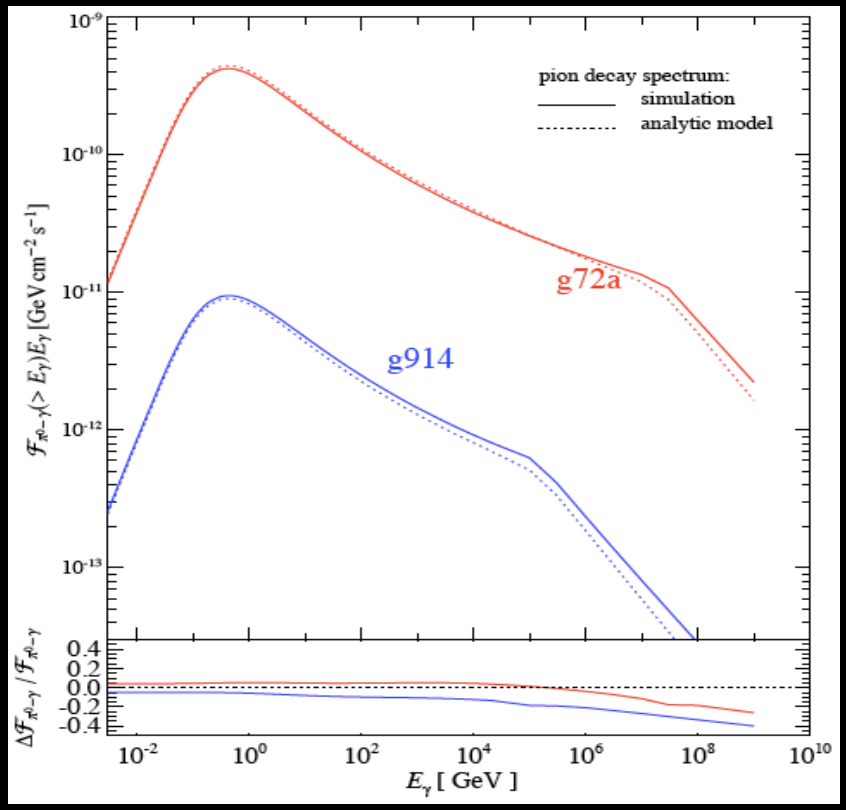
Pinzke & Pfrommer (2010)

Most important energy and particle sources in the simulation are diffusive shock acceleration at cosmological structure formation shocks and supernovae injection

Pion-decay dominates over primary and secondary IC emission

This obeys to a universal CR spectrum and spatial distribution

Characteristic pion-bump + spectral index of about *2.2* at TeV energies



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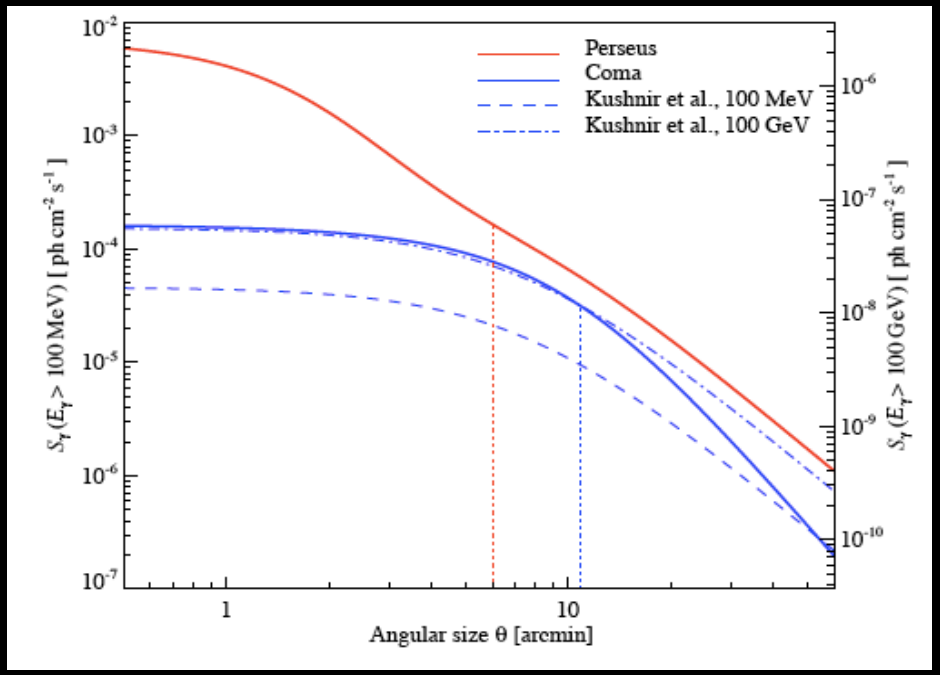


Existing Gamma-ray Instruments

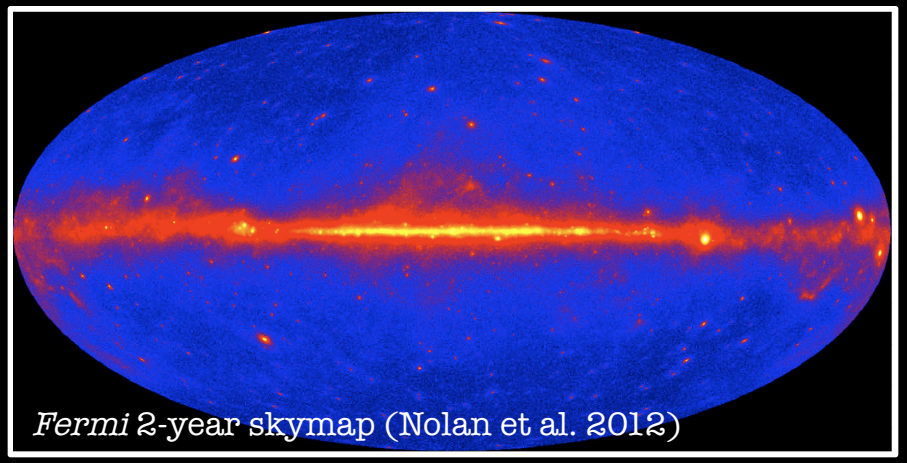
Fermi-Large Area Telescope NASA satellite

Constantly survey the sky (full coverage in 3 hours)

100 MeV – 300 GeV

Angular resolution 0.1 deg @ 10 GeV

Energy resolution 10% @ 10 GeV

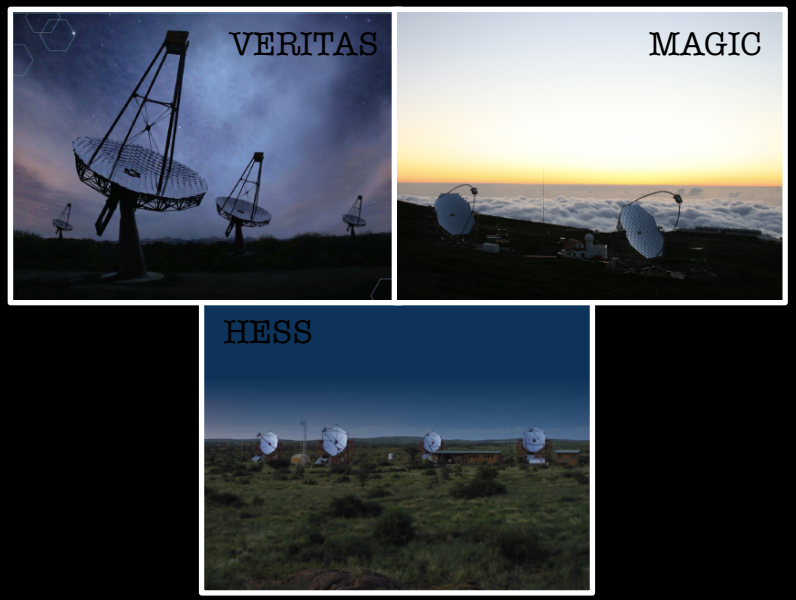

Fermi 2-year skymap (Nolan et al. 2012)

Imaging Atmospheric Cherenkov Telescopes

> 50 – 100 GeV

Angular resolution 0.1 deg

Energy resolution 15%

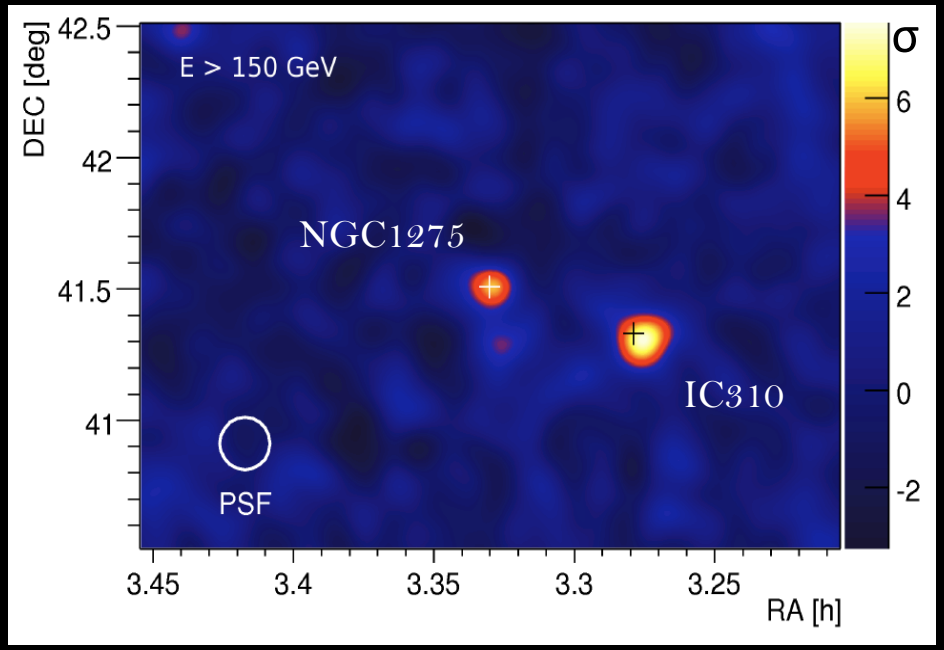


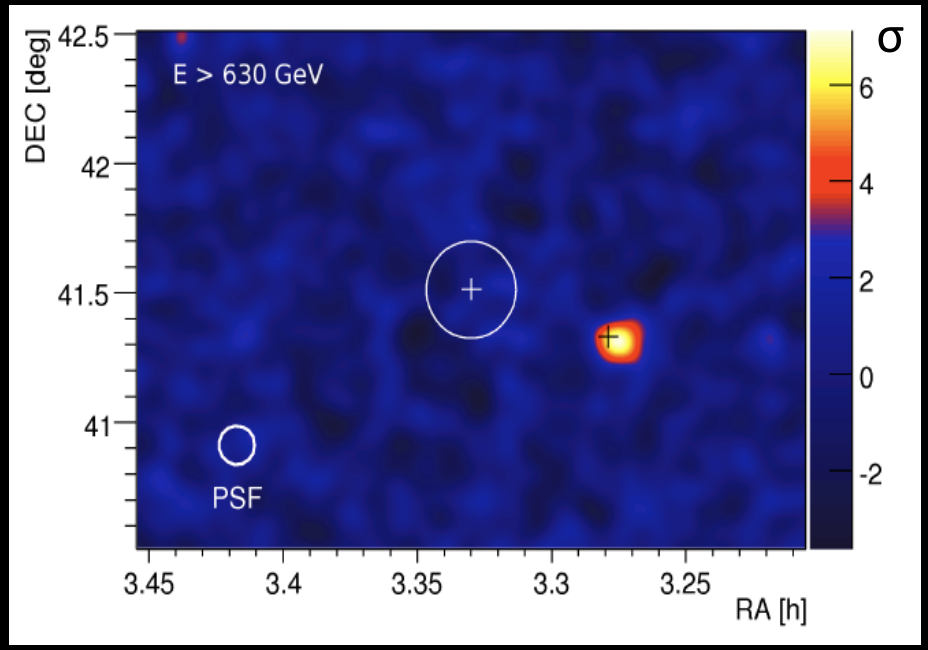
State of Art of Observations - IACTs

Best Constraints: MAGIC observation campaign of the Perseus cluster of galaxies

Total of 85 hours of data from Oct 2009 to Feb 2011

Deepest cluster observation ever at very high energy





MAGIC Coll. (2012) – FZ as corr. author

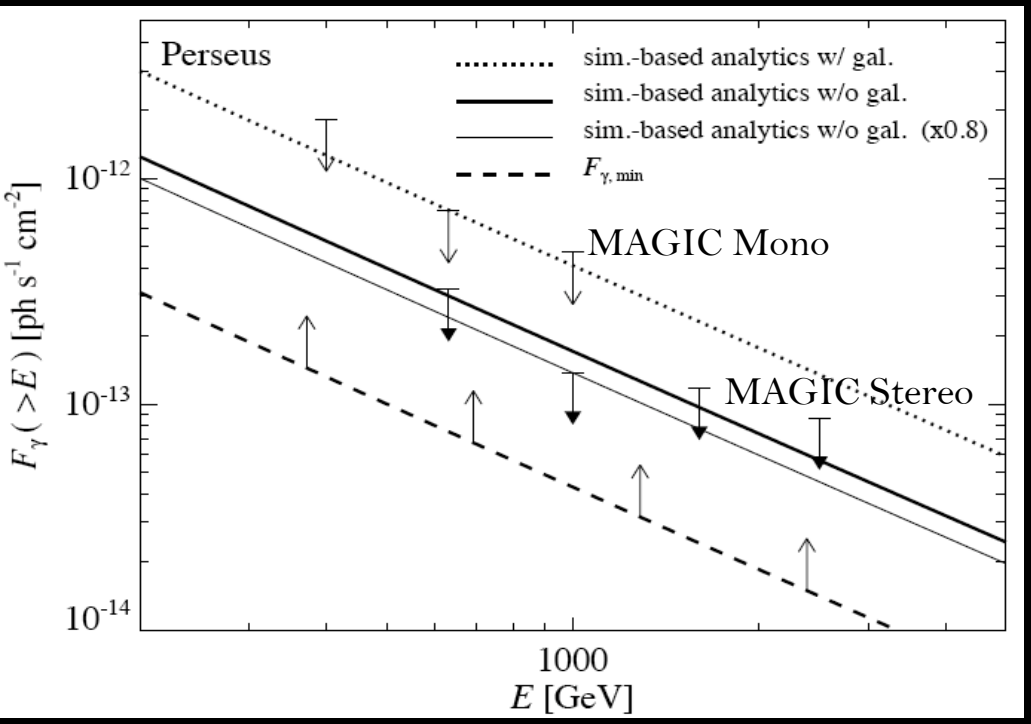
State of Art of Observations - IACTs

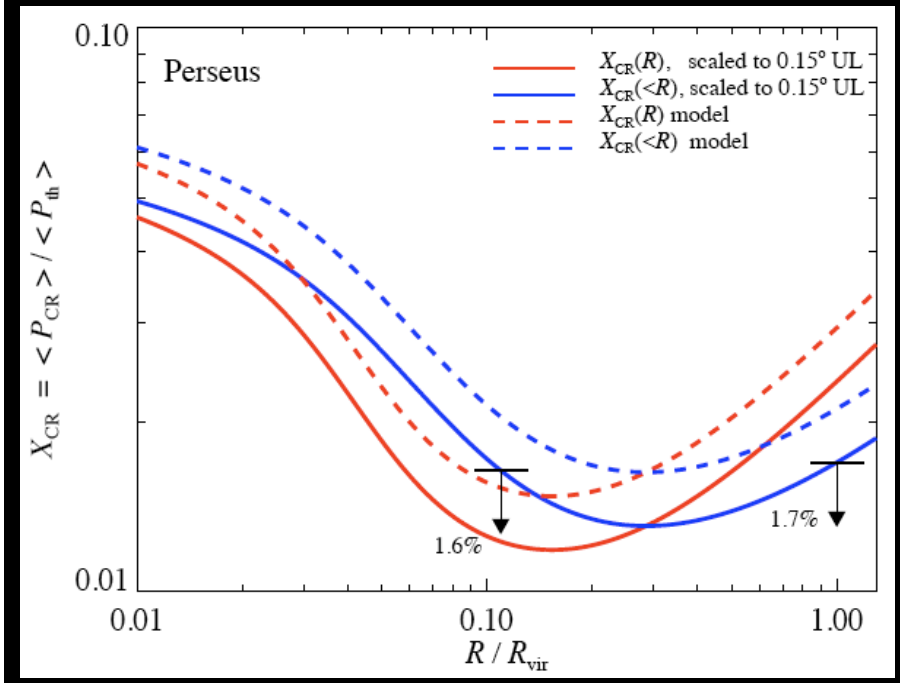
Predictions (Pinzke & Pfrommer 2010) were constrained for the first time

the maximum CR acceleration efficiency at shocks is < 50%

OR

significant CR propagation out of the cluster core





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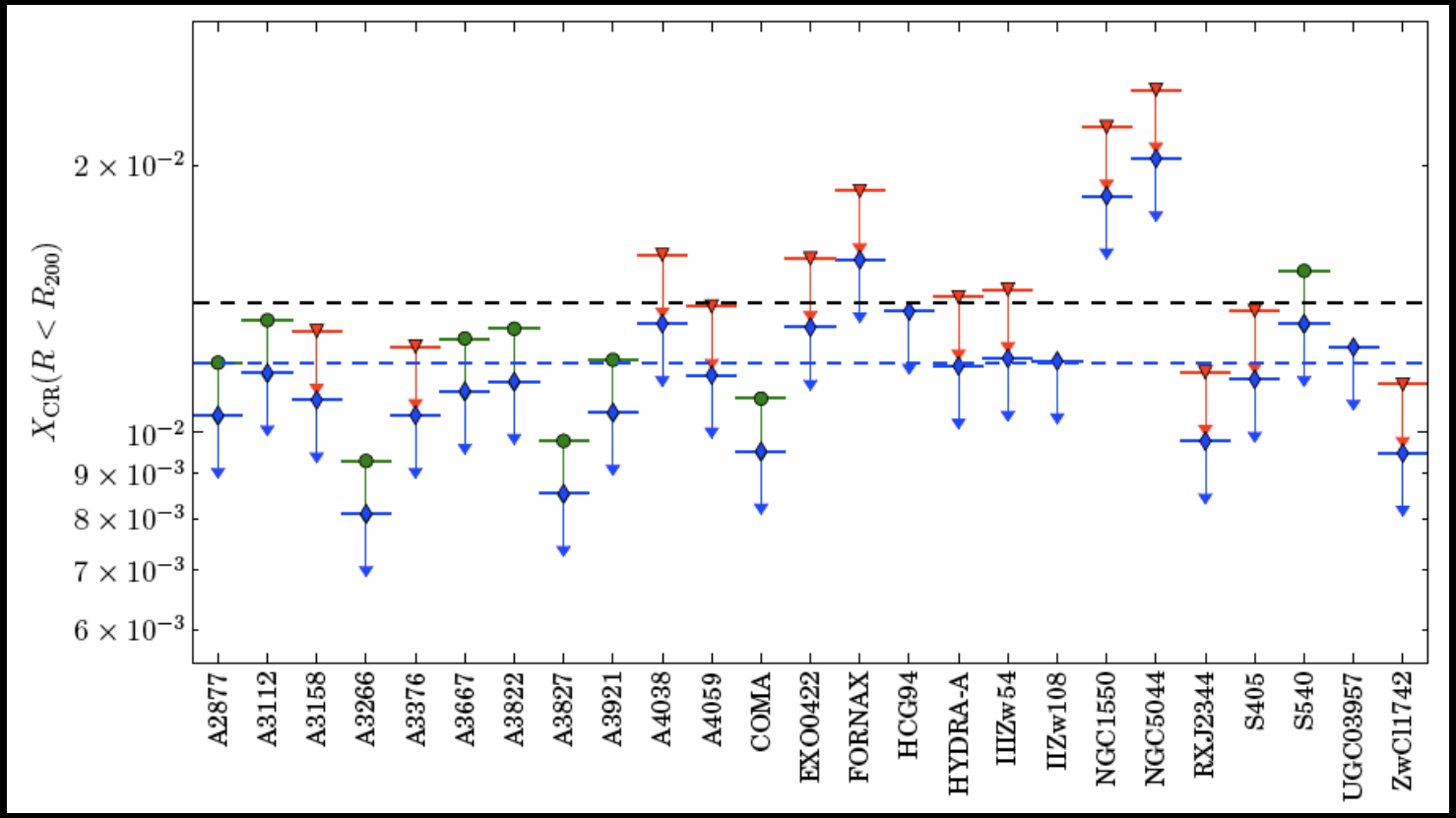
State of Art of Observations - *Fermi*

Fermi Coll. stacked analysis of 50 HIFLUGCS clusters (arXiv:1308.5654)



maximum acceleration efficiency is < 25% + CR-to-thermal pressure < 1.5%

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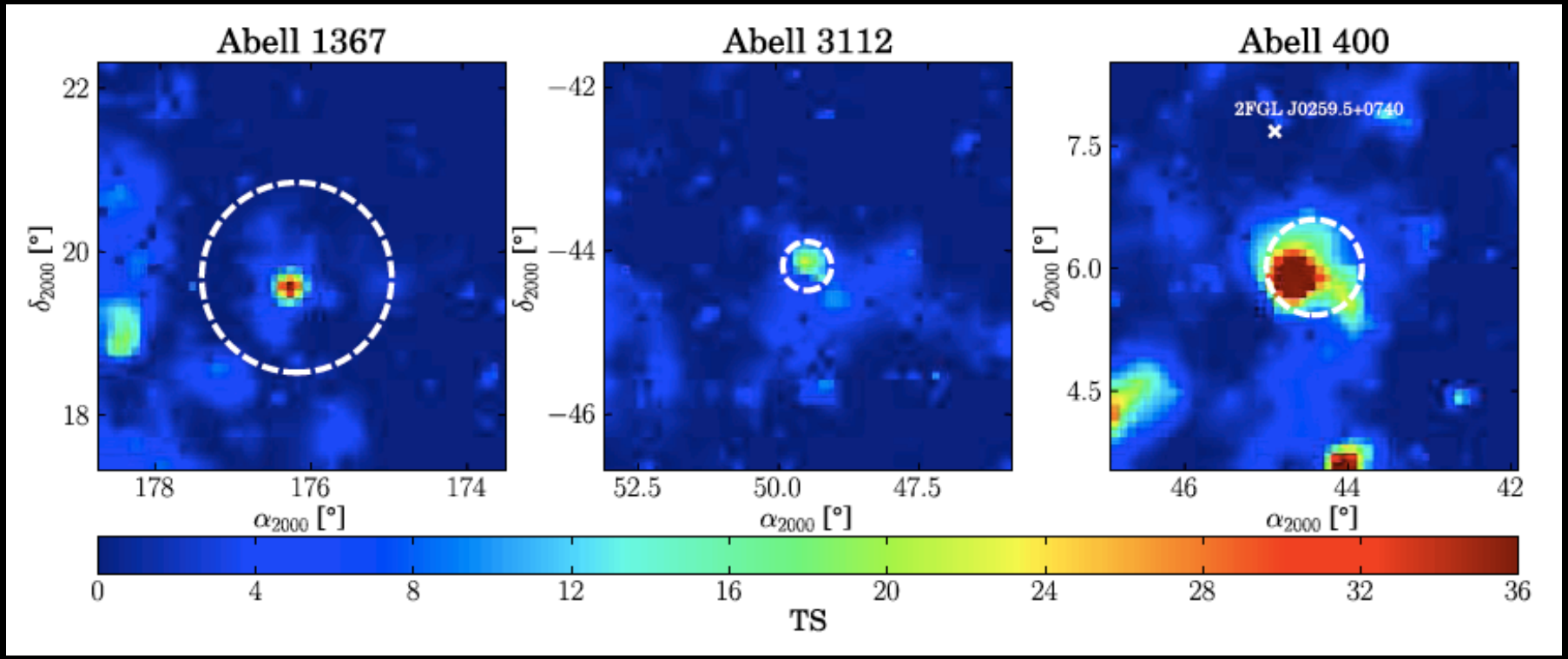
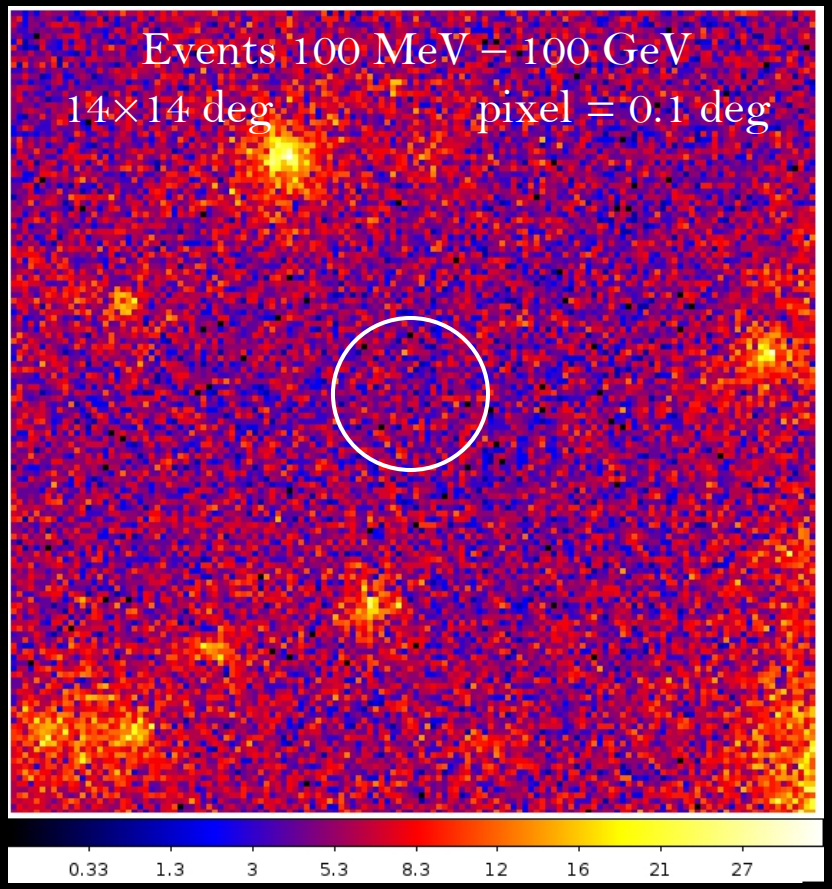


see also Huber et al. (2013) and Prokhorov & Churazov (2013)

State of Art of Observations - *Fermi*

Fermi analysis of the Coma cluster of galaxies
FZ & Ando 2013, arXiv:1312.1493



Test different (diffuse) models:

- Point Source
- Disk
- Pinkze & Pfrommer (2010)
- FZ, Pfrommer & Prada (2012)
- Radio Relic template
- Ring-like template (Keshet et al. 2003)

→ NOT DETECTED (TS ≤ 2)

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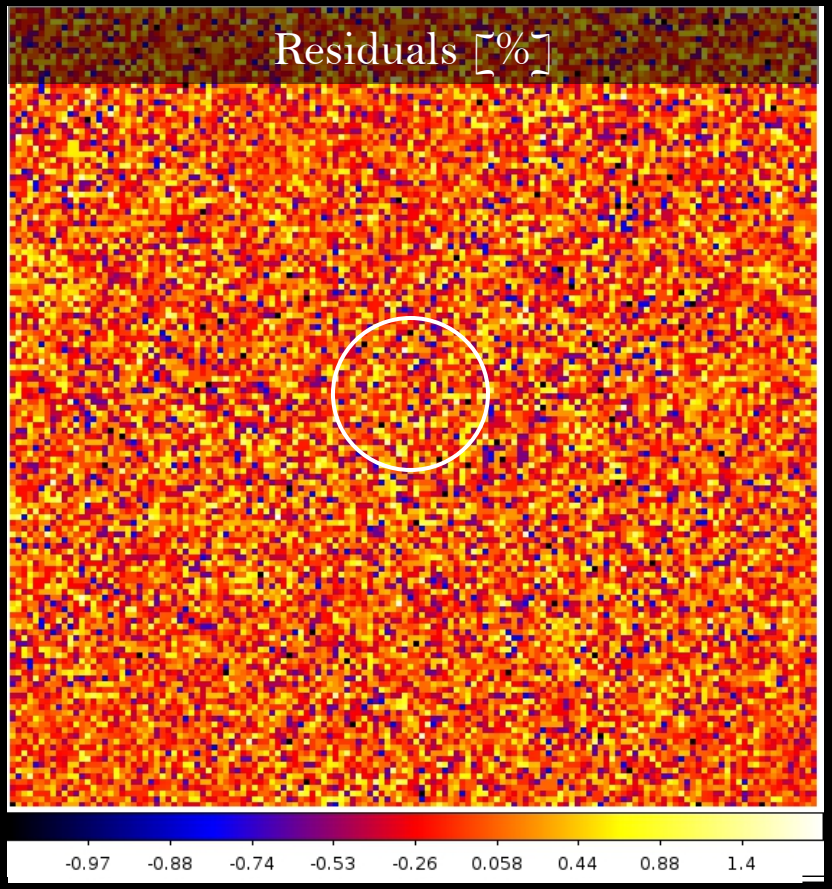


CR protons acceleration efficiency < 15%

CR electrons acceleration efficiency < 1%

CR-to-thermal pressure < 1.5%

CR Protons in Clusters: a Summary

CR-to-thermal pressure $< 1\%$ ($\alpha_p = 2.1$) to $< 10\%$ ($\alpha_p = 2.5$)

Maximum CR proton acceleration efficiency $<< 50\%$

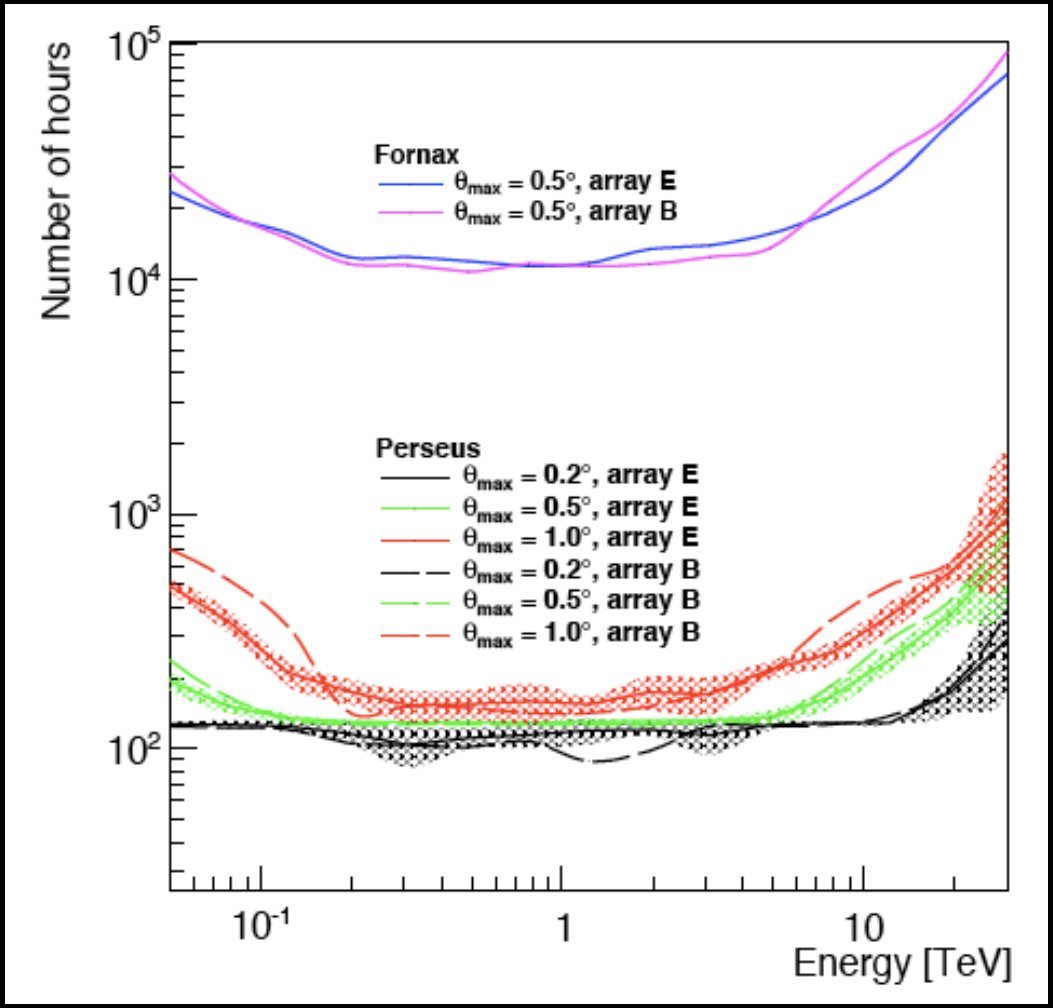
Gamma-ray Emission:

- CRp could have a very low acceleration efficiency
- CRp could diffuse/stream out of the cluster core
- CRp could have a different/varying spectral index

+ need to "match" the radio data where the magnetic field enters the game

Detectability – Predictions for CTA

Doro et al. (2013) for the CTA Collaboration – $\xi_p = 50\%$



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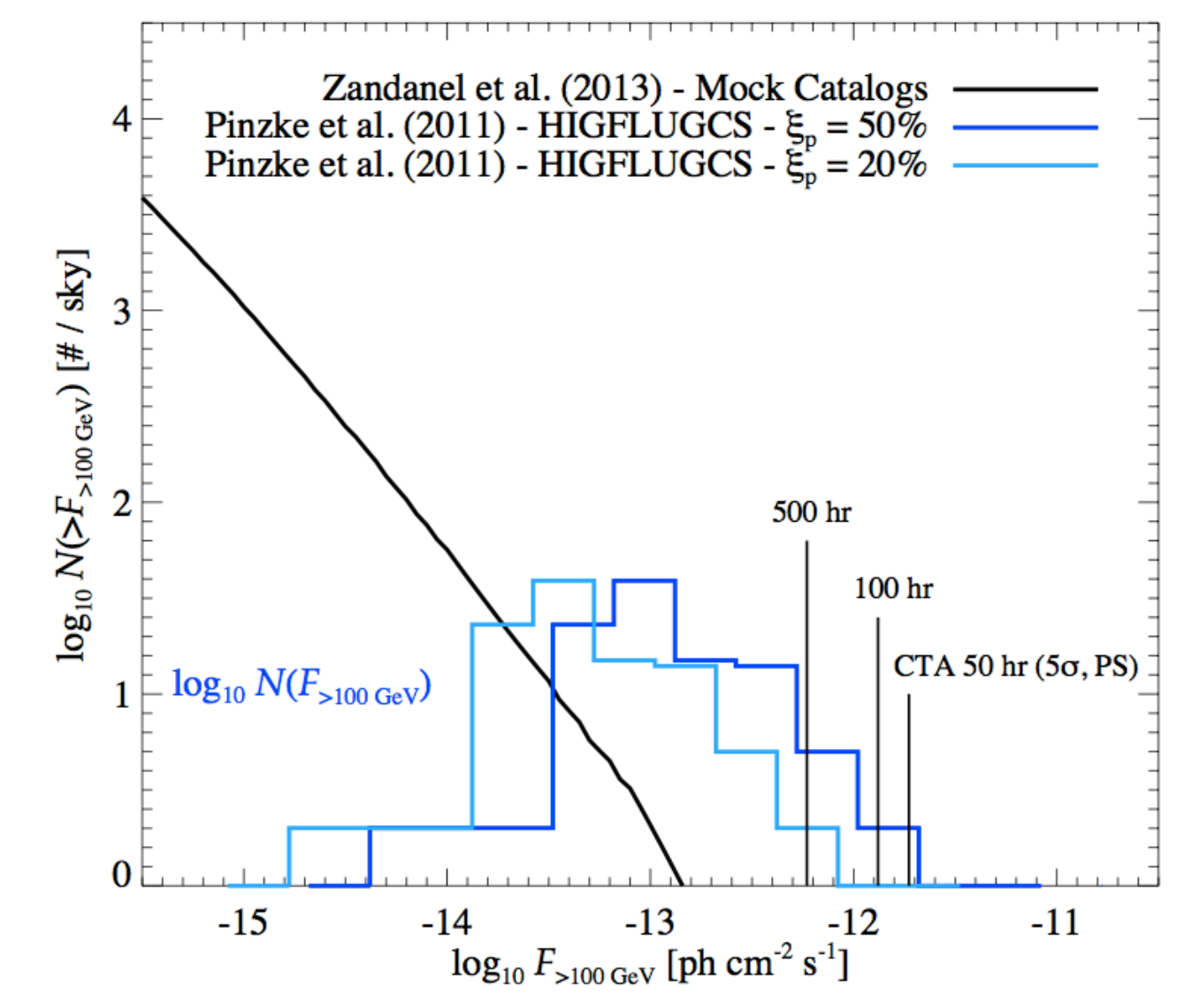
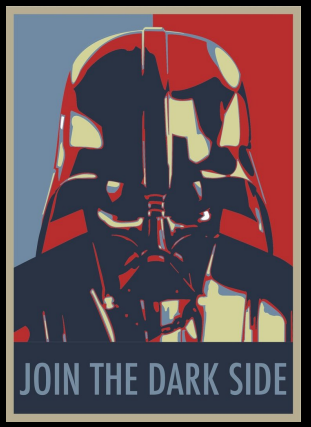


What needs to be done *now* in CTA?

Model nearby clusters with
available radio and X-ray data

Make detailed sensitivity study for
CTA and select suitable targets



Promote clusters of galaxies as key science case
(proprietary data), not only for CRs but also field galaxies
and DM, within CTA and make sure that they are observed

→ Lots of science work to be done right now ←

Collaboration commitment is important as the required
observation time is likely very high (> 100 hr)

Summary & Future Prospects

We DO expect CR protons to accumulate in clusters and electrons to be accelerated directly at accretion and merger shocks

We DO expect a correspondent induced gamma-ray emission

Emission may be much lower than thought before (CR acceleration efficiency, transport properties…)

BEST SCENARIO for CTA is to detect a handful of clusters

Summary & Future Prospects

Gamma-rays (*Fermi* & IACTs) are starting to put stringent constraints on various acceleration scenarios and on the CR content in clusters of galaxies

Detection of cluster gamma-ray emission would be a major scientific discovery!!!

Open up a new window to study:

- non-thermal processes in clusters
- high-energy physics in the largest structures
- DM, CR, ICM, and cluster magnetic field
- formation and evolution of clusters, and of the Universe itself

Thanks!