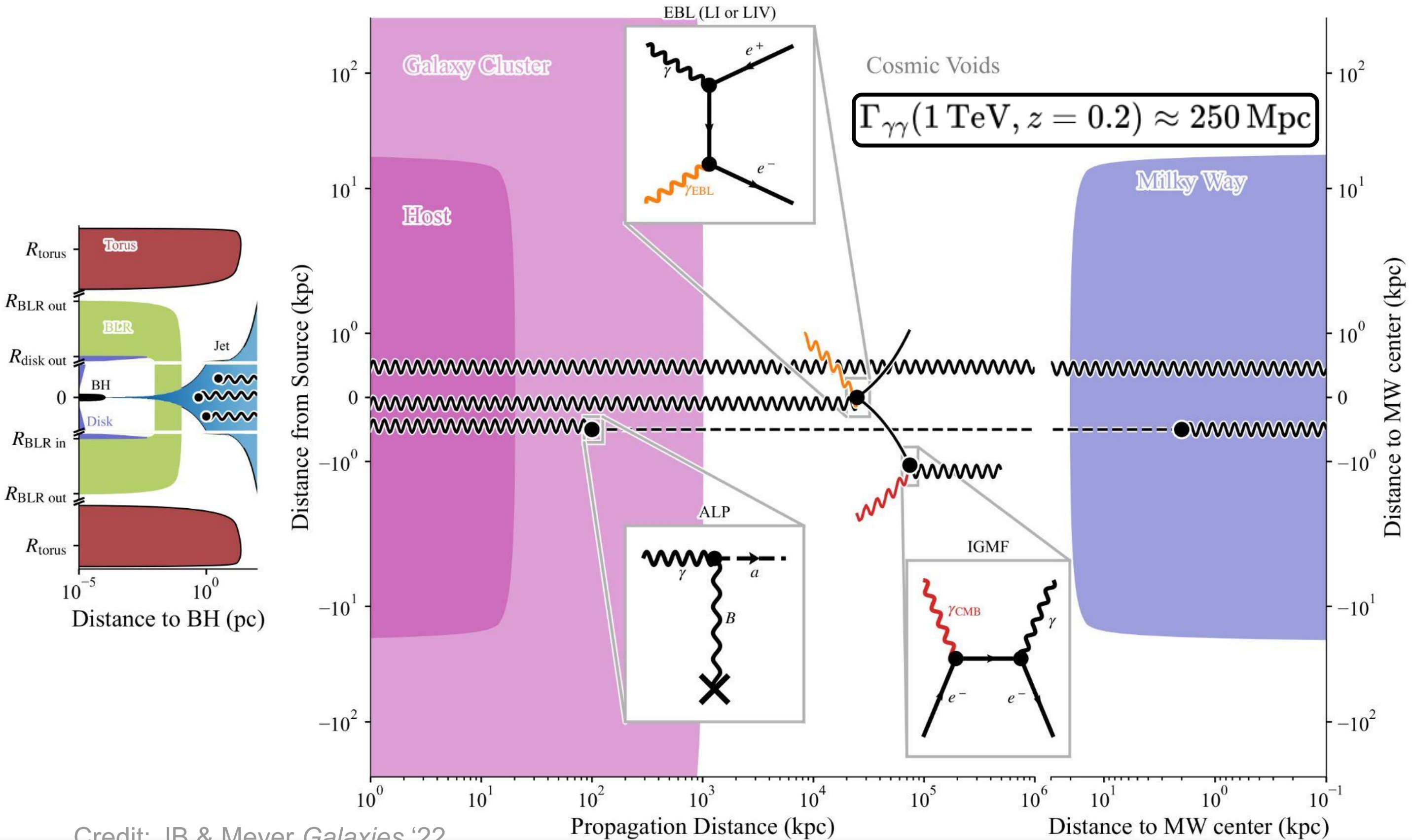
Gamma-ray Cosmology

EBL and B-field constraints from GeV-TeV observations

2024.09.04, Gamma2024 @ Milano

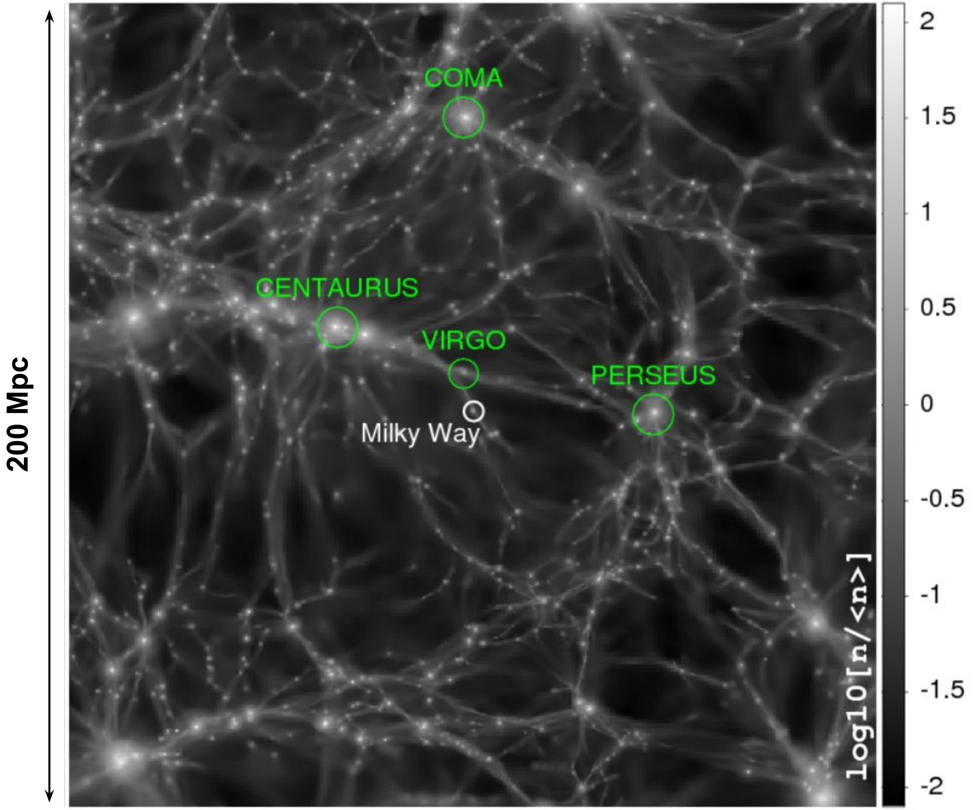
Jonathan Biteau

Gamma-ray propagation on cosmic scales



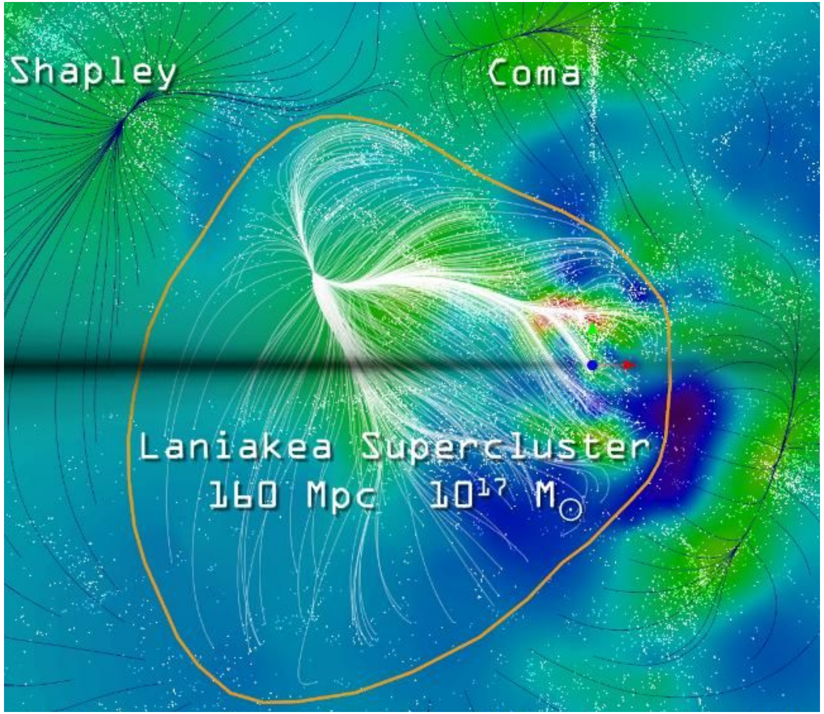
Credit: JB & Meyer *Galaxies* '22

Cosmic web: relevant scales



Credit: Hackstein+ *MNRAS* ‘18 (Cosmic V-web constrained sim. / CLUES)

Our supercluster (*d* < 100 Mpc)

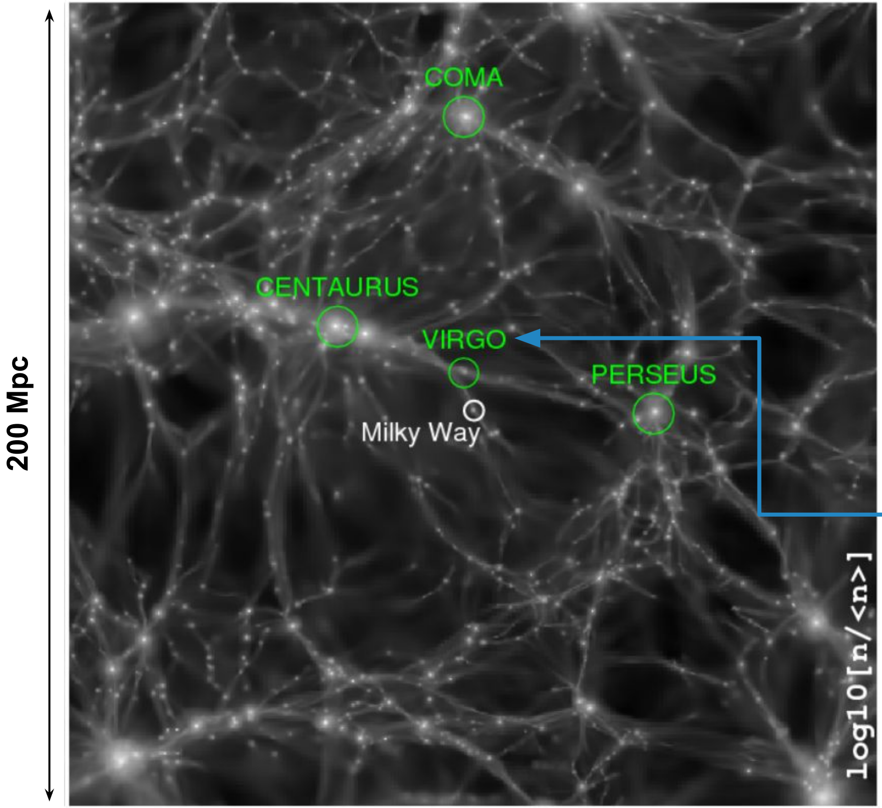


Note: closest TeV blazar Mrk 421 @ 130 Mpc (*z* ~ 0.03)

Credit: Tully+ *Nature* ‘14 (Cosmic V-web)

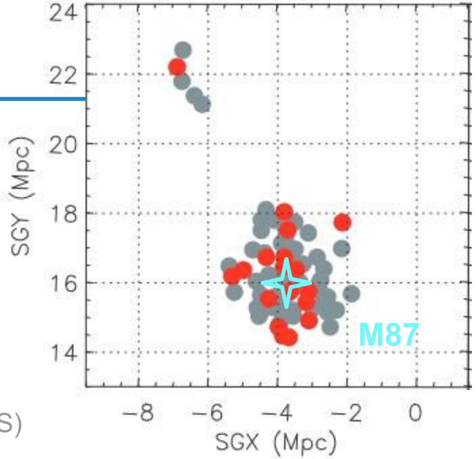
Cosmic web: relevant scales

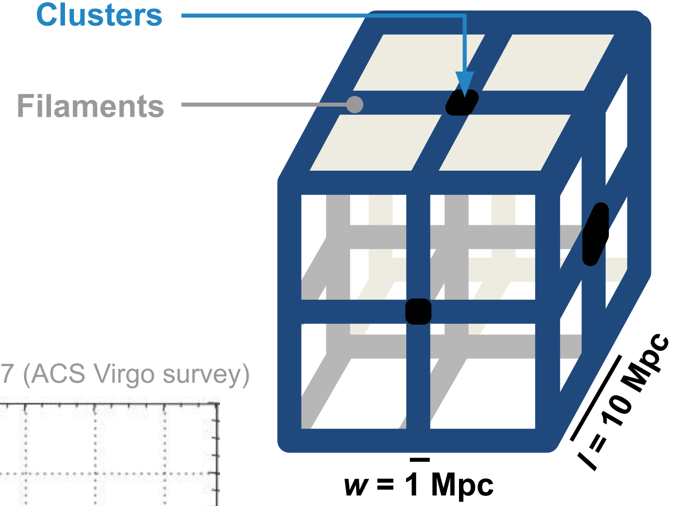
TeV emitter



Credit: Hackstein+ *MNRAS* '18 (Cosmic V-web constrained sim. / CLUES)

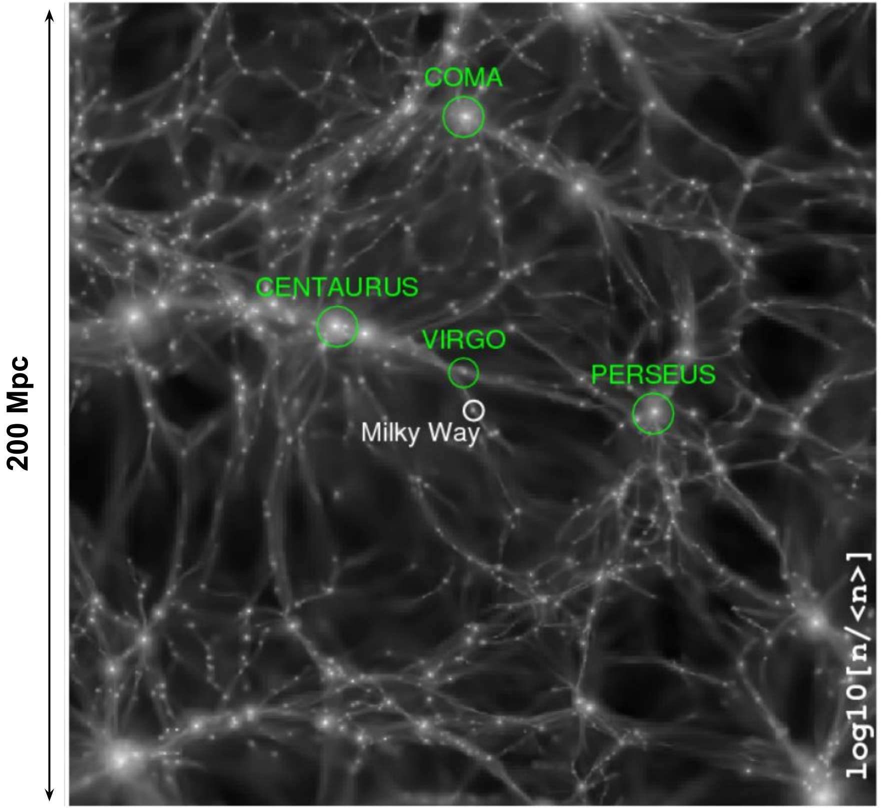
Credit: Mei+ *ApJ* '07 (ACS Virgo survey)





Cosmic web: relevant scales

TeV emitter



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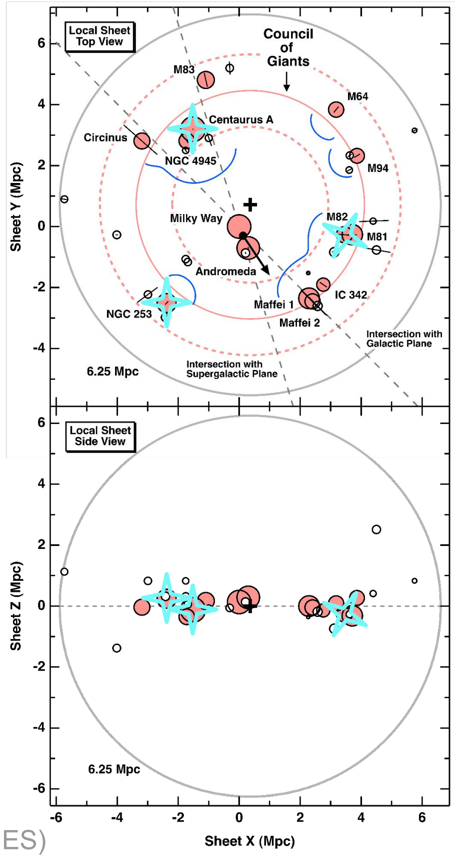
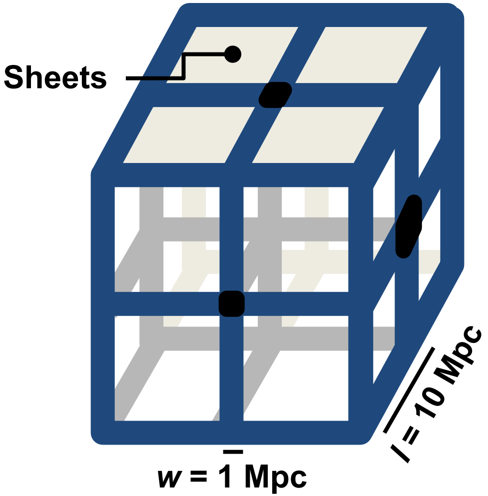
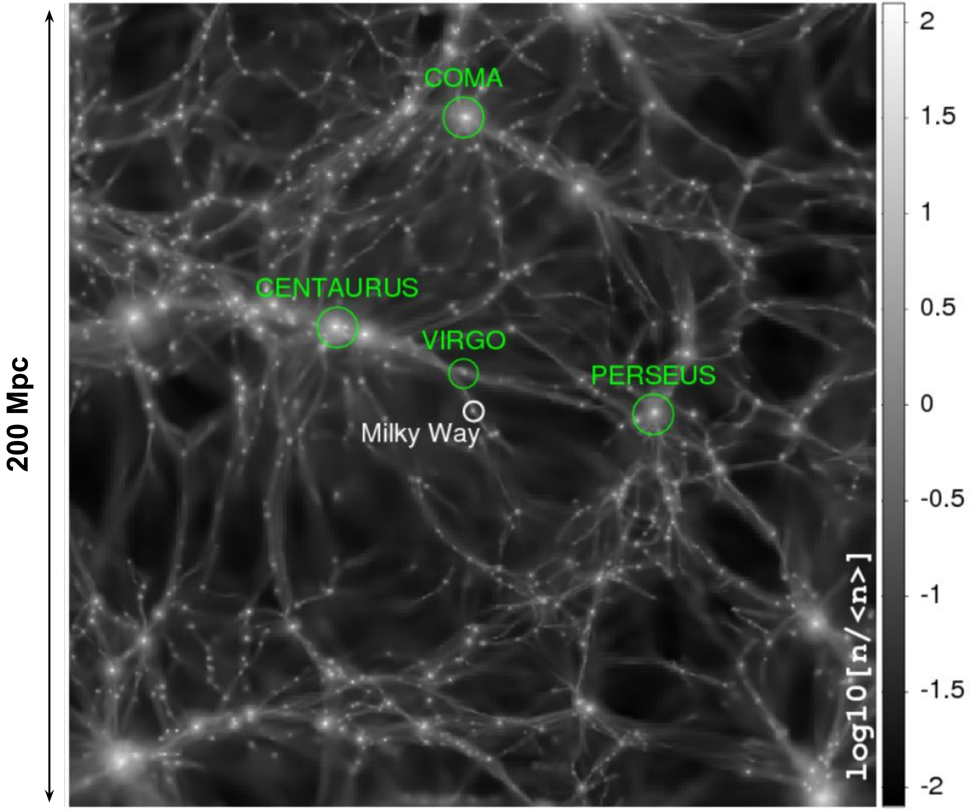


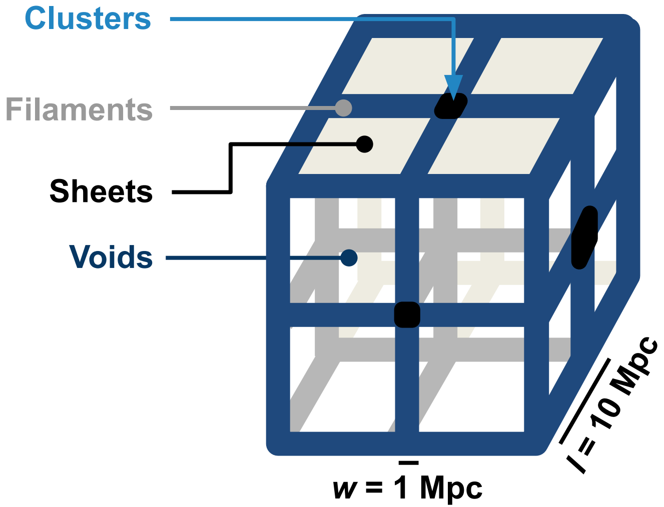


Credit: McCall *MNRAS* ‘14
(The Council of Giants)

Cosmic web: relevant scales



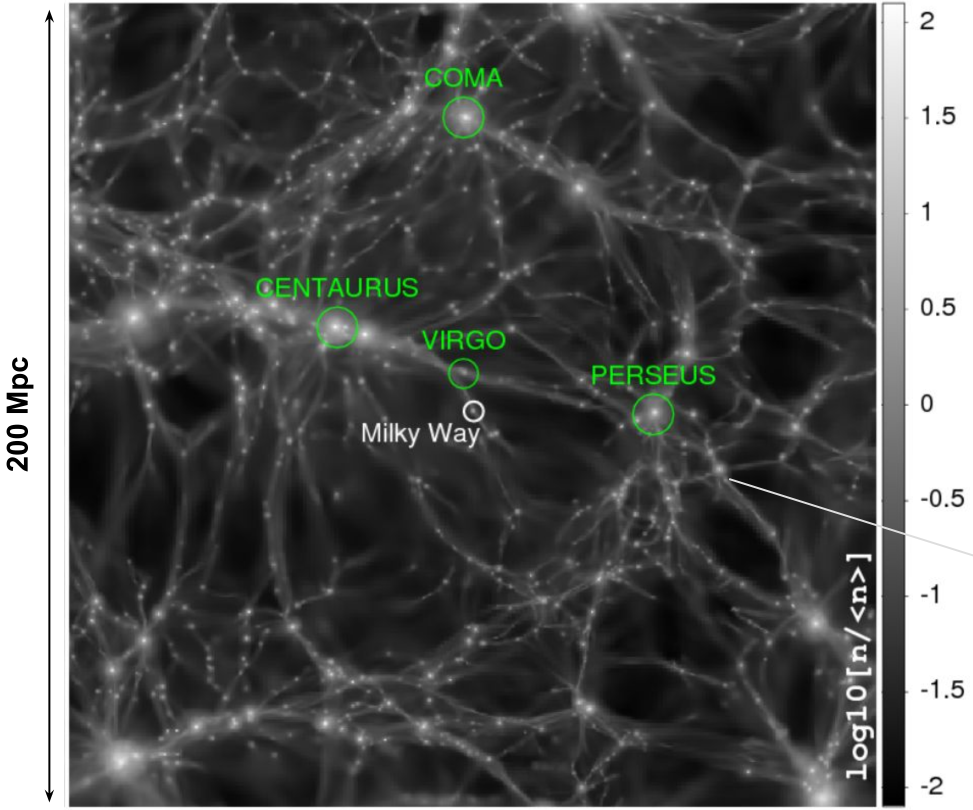
Credit: Hackstein+ *MNRAS* ‘18 (Cosmic V-web constrained sim. / CLUES)



Structure	Volume filling fraction	VFF, cubic $w/l = 0.1$	VFF, simulation
Clusters	$(w/l)^3$	0.1%	0.5%
Filaments	$3(w/l)^2(1-w/l)$	2.7%	5%
Sheets	$3(w/l)(1-w/l)^2$	24.3%	18%
Voids	$(1-w/l)^3$	72.9%	76%

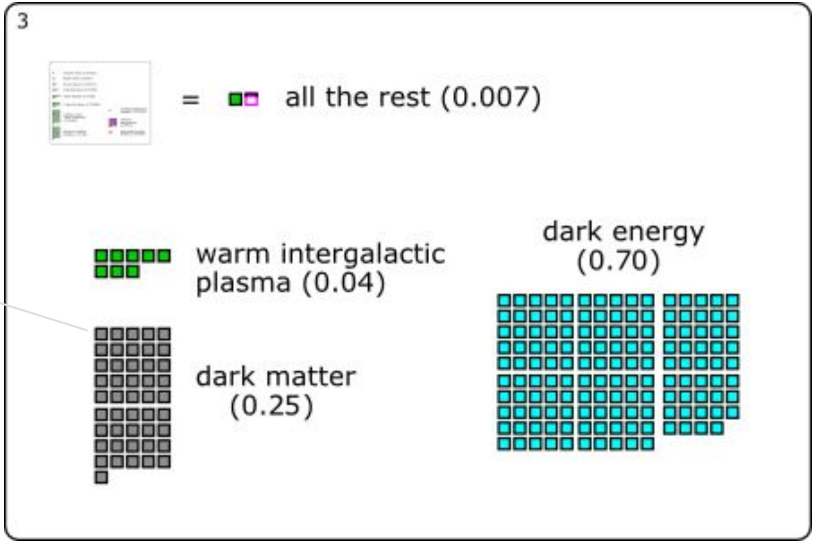
Credit: Oei+ *A&A* ‘22

Cosmic web: contents



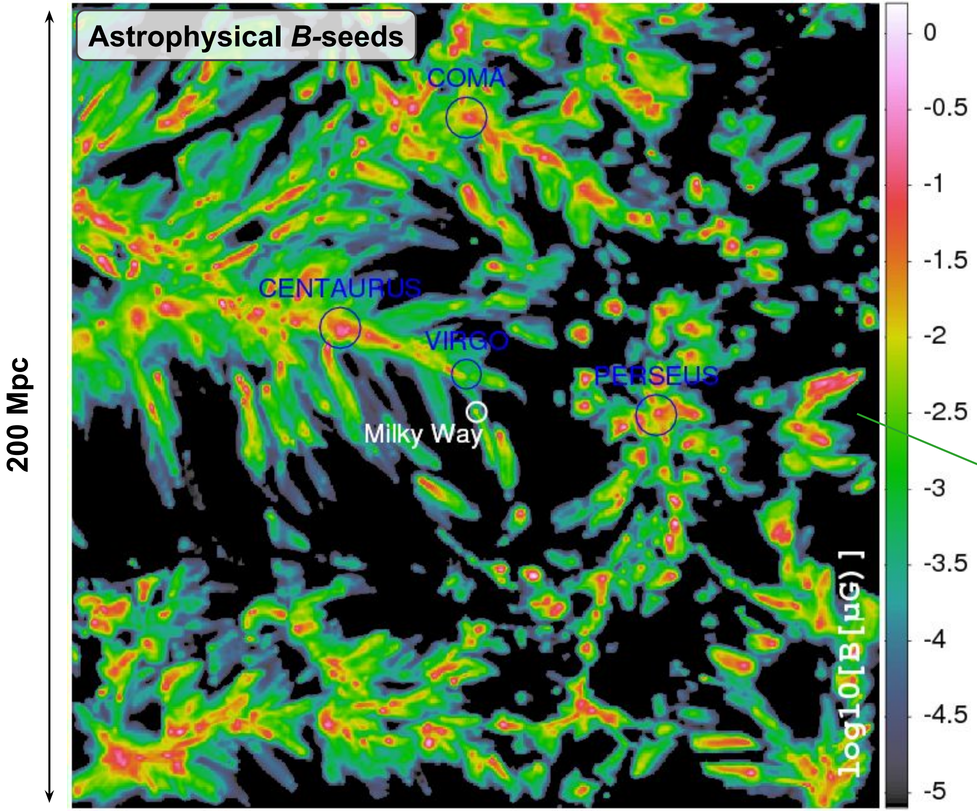
Credit: Hackstein+ *MNRAS* ‘18 (Cosmic V-web constrained sim. / CLUES)

$$\rho_c c^2 = \frac{3H^2}{8\pi G} c^2 \approx 4.8\,\mathrm{GeV\,m^{-3}}$$



Credit: Fukugita & Peebles *ApJ* ‘04 (Cosmic energy inventory)

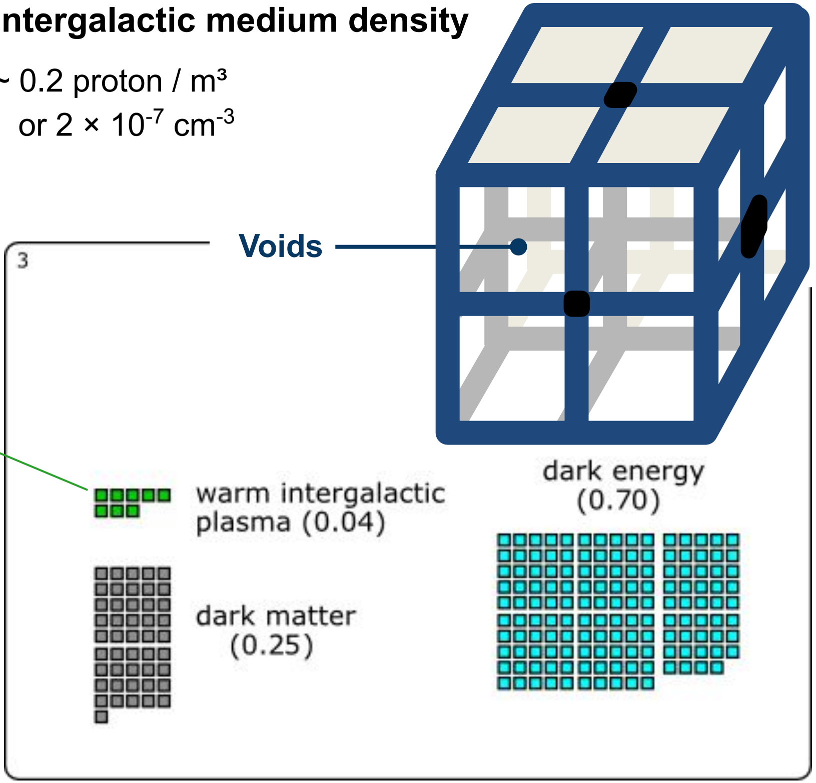
What's in the voids?



Credit: Hackstein+ *MNRAS* '18 (Cosmic V-web constrained sim. / CLUES)

Intergalactic medium density

~ 0.2 proton / m^3
or 2×10^{-7} cm^{-3}



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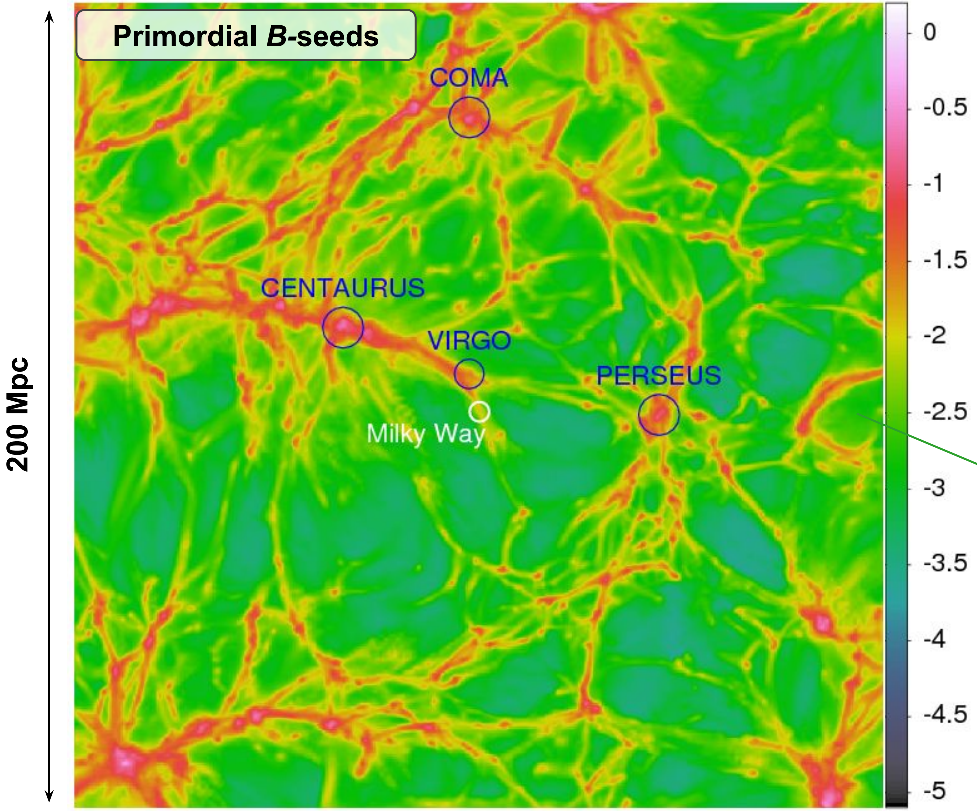

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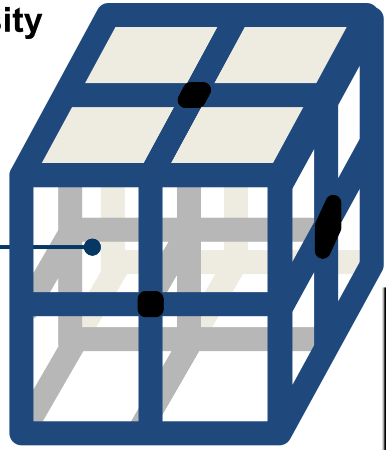

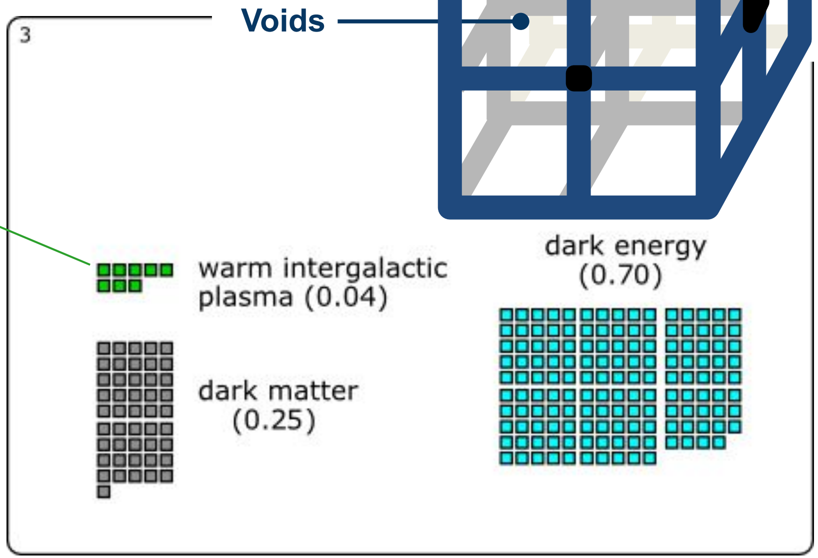

Credit: Fukugita & Peebles *ApJ* '04 (Cosmic energy inventory)

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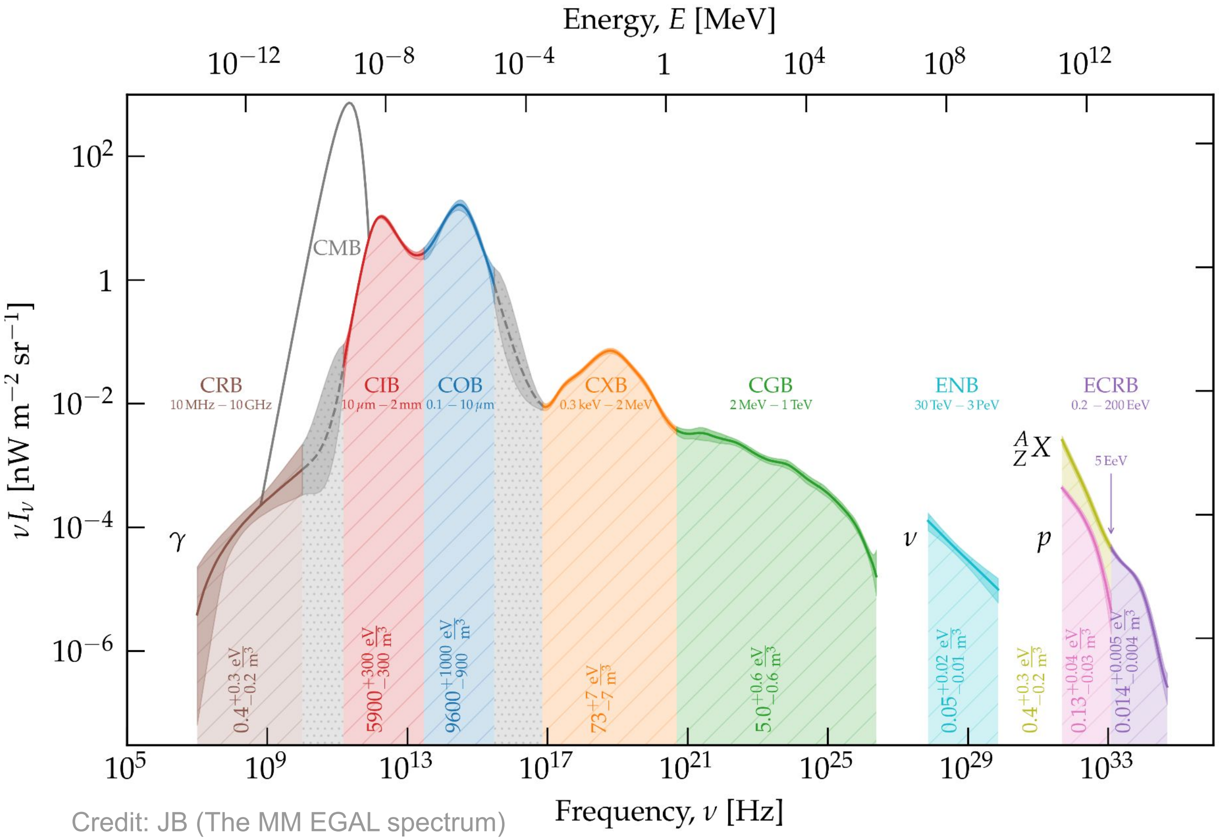
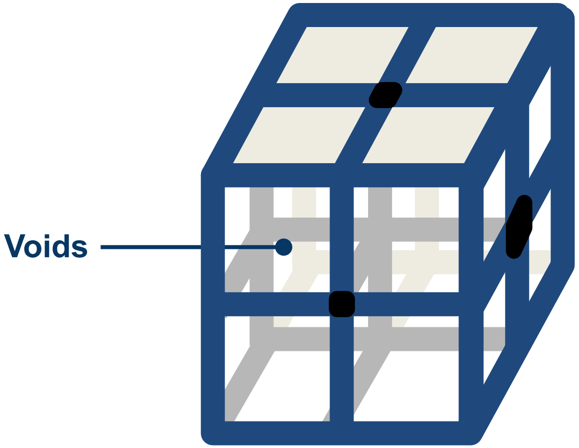


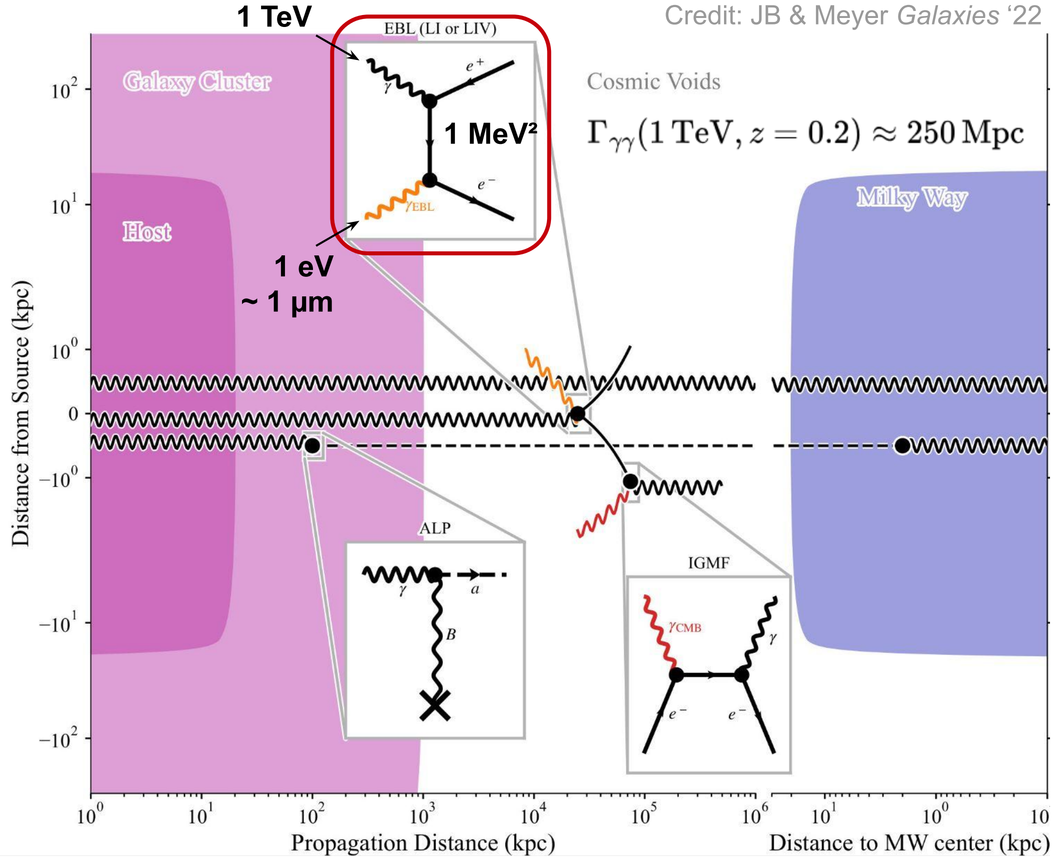
DOI 10.5281/zenodo.7842239

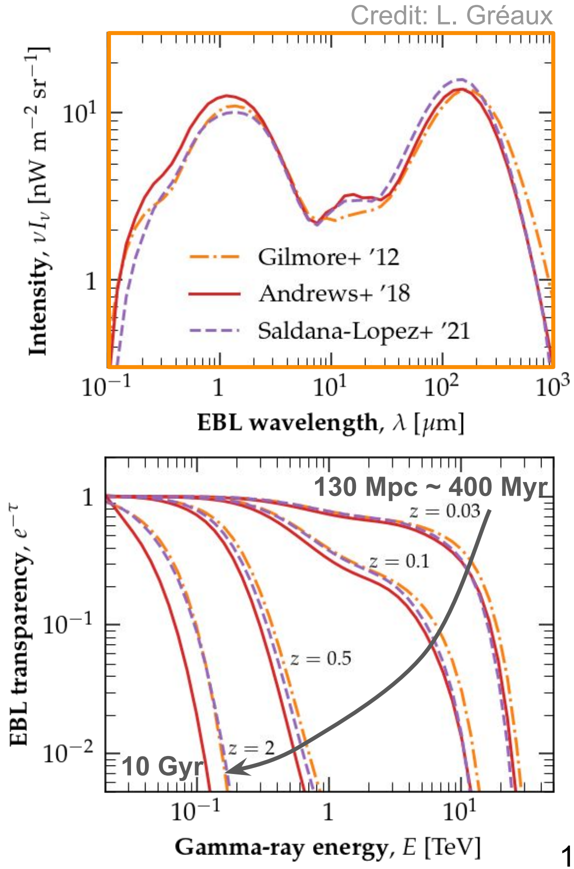


$$\int \nu I_\nu \, \mathrm{d}\ln\nu = \int I_\nu \, \mathrm{d}\nu = \frac{c}{4\pi} u$$

Credit: JB (The MM EGAL spectrum)

Probe of O-IR extragalactic background light in voids





TeV ɣ-ray flux suppression

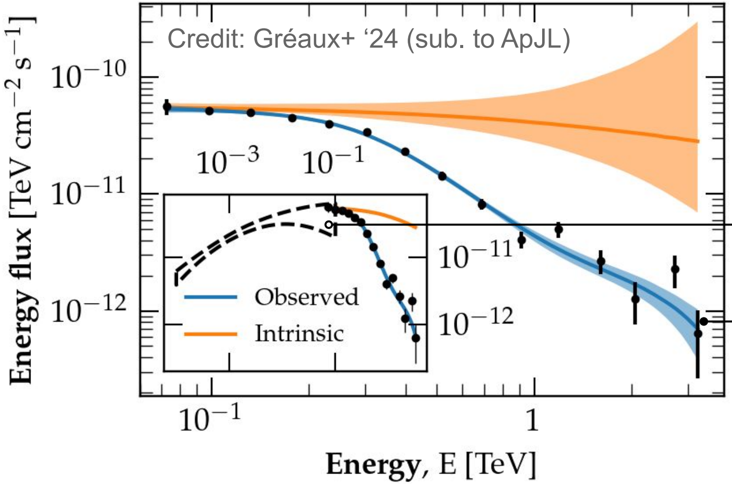
Optical depth $\tau(E, z) = \int_0^z \mathrm{d}z' \, \frac{\partial L}{\partial z'} \Gamma^{-1}_{\gamma\gamma}(E(1+z'), z')$

Light travel distance (ΛCDM)

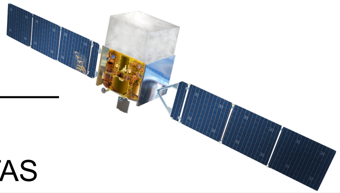
$$\frac{\partial L}{\partial z} = \frac{c}{H_0} \frac{1}{1+z} \frac{1}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

Mean free path (EBL photon density, Breit-Wheeler cross section)

$$\Gamma^{-1}_{\gamma\gamma}(E', z) = \int_0^{+\infty} \mathrm{d}\epsilon \, \frac{\partial n}{\partial \epsilon} \int_{-1}^{1} \mathrm{d}\mu \, \frac{1-\mu}{2} \sigma_{\gamma\gamma}\left[E', \epsilon, \mu\right]$$



Observed flux $\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$



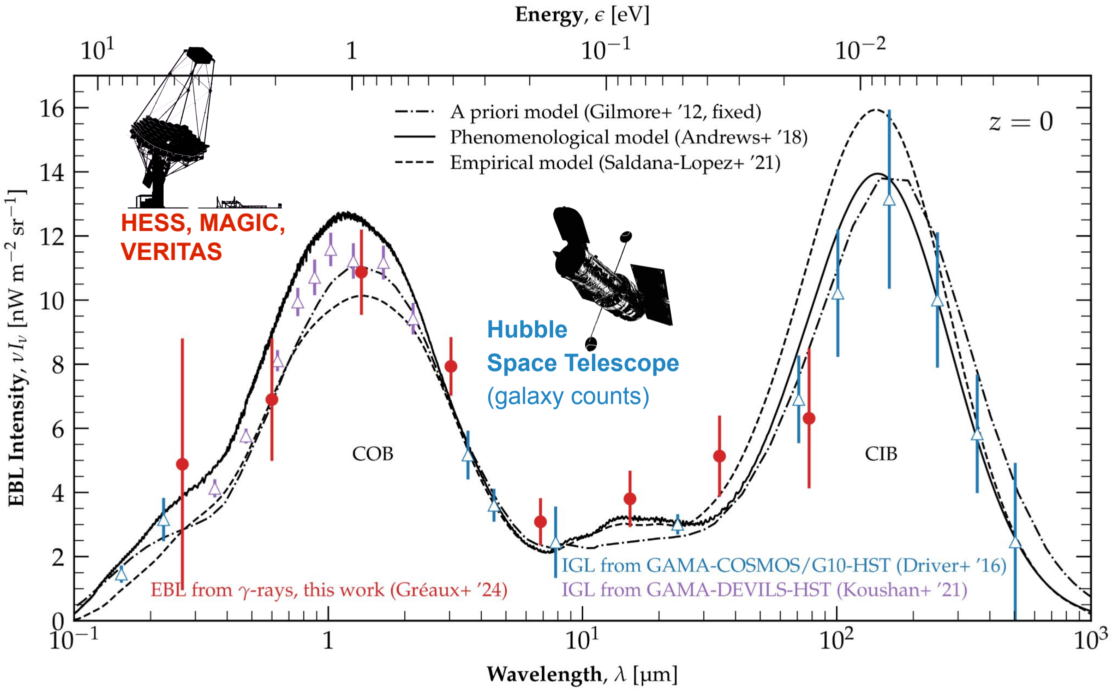
Fermi-LAT
(GeV range)

HESS, MAGIC, VERITAS
(TeV range)

New ɣ-ray reconstruction of the COB and CIB

Fully model-independent reconstruction using STeVECat database

i.e. 268 TeV spectra (HESS/MAGIC/VERITAS) from 45 sources a z = 0.02 - 0.94

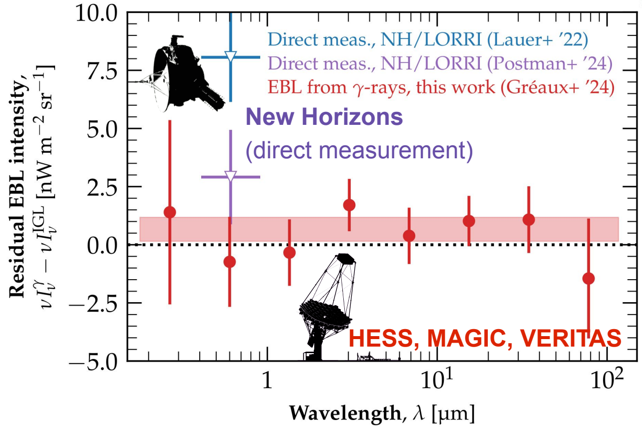


from Cosmic Optical Controversy

see Driver '21

to Cosmic Optical Convergence

Aspen Winter Meeting, [April 2024]()



Credit: Gréaux+ '24 (sub. to ApJL)

Diffuse components and Hubble constant

Ratio of model-independent EBL from TeV spectra and from accumulated galaxy flux at *z* = 0 (Gréaux+ ‘24)

- Unresolved diffuse components = small fraction of the EBL: $f_{\rm diff} < 20\%$ at 95% C.L. for $\nu I_\nu^\gamma = \nu I_\nu^{\rm IGL} \times (1 + f_{\rm diff})$

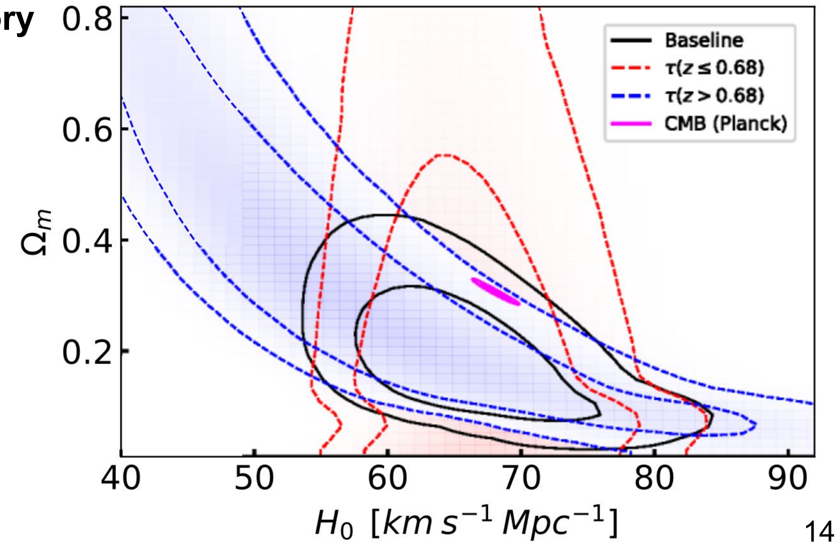
  → already constraining for **intra-halo / circum-galactic light** models

  → not constraining (yet?) for *relic radiation from reionization* (few tenths of nW m^{-2} sr^{-1}, Cooray+ *ApJ* ‘12)
- ɣ-ray optical depth ∝ *d* ∝ *c* / H_0 while IGL = sum of observed flux: $H_0 = 67^{+7}_{-6}\,{\rm km\,s^{-1}\,Mpc^{-1}} \times (1 + f_{\rm diff})$

Model of galaxy luminosity density & star formation history
(Saldana-Lopez+ 2021)

vs optical depth inferred from GeV and TeV spectra
(*Fermi*-LAT 2018, Desai+ 2019)

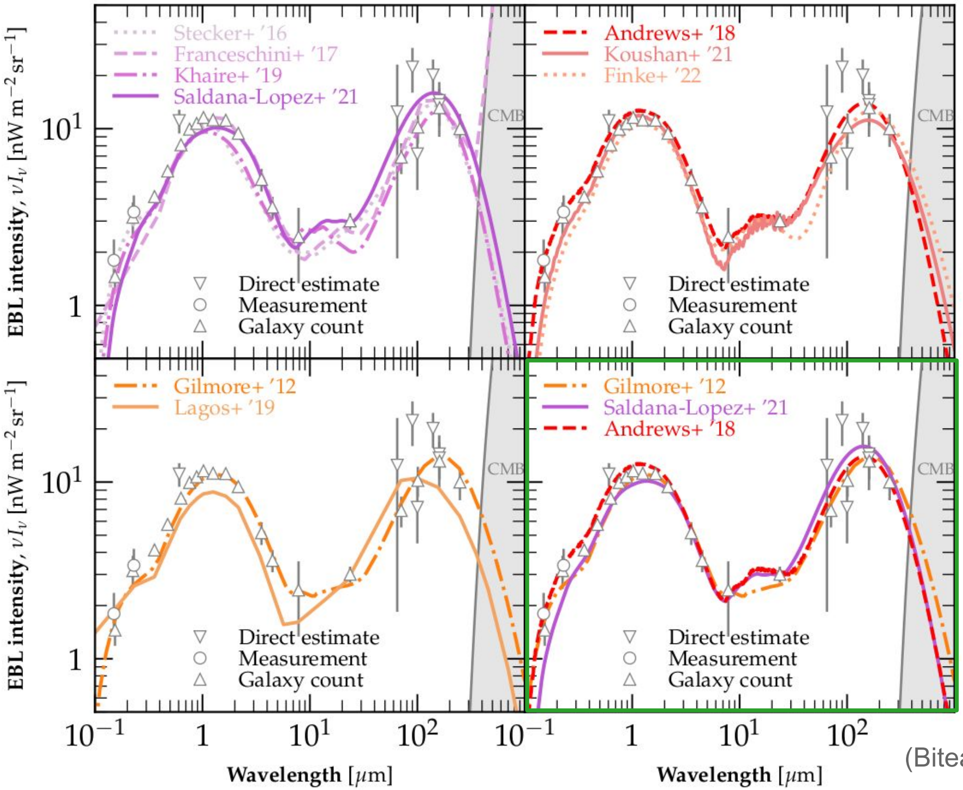
- Fixed dark + baryonic matter density
  $H_0 = 62 \pm 4\,{\rm km\,s^{-1}\,Mpc^{-1}}$ for $\Omega_{\rm m} = 0.32$
- Free dark + baryonic matter density
  $H_0 = 65^{+6}_{-5}, {\rm km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_{\rm m} = 0.19 \pm 0.08$



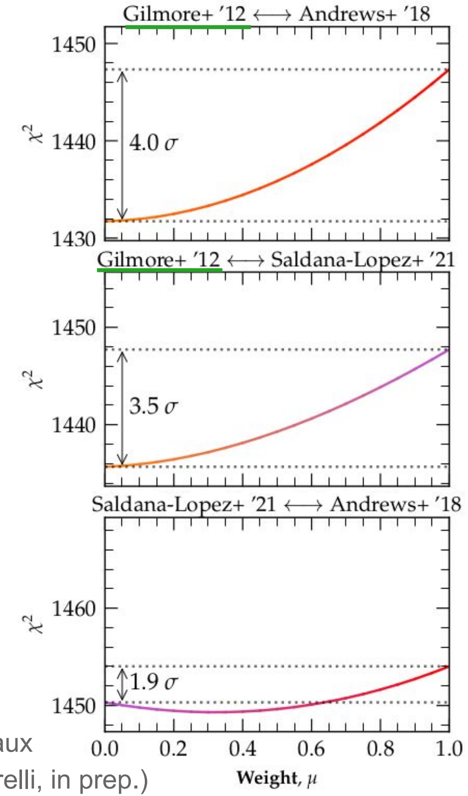
Credit: Dominguez+ *MNRAS* ‘24

Status of COB-CIB models: a TeV appraisal @ $z < 1$

Lowest tension with direct measurements and galaxy counts @ $z = 0$

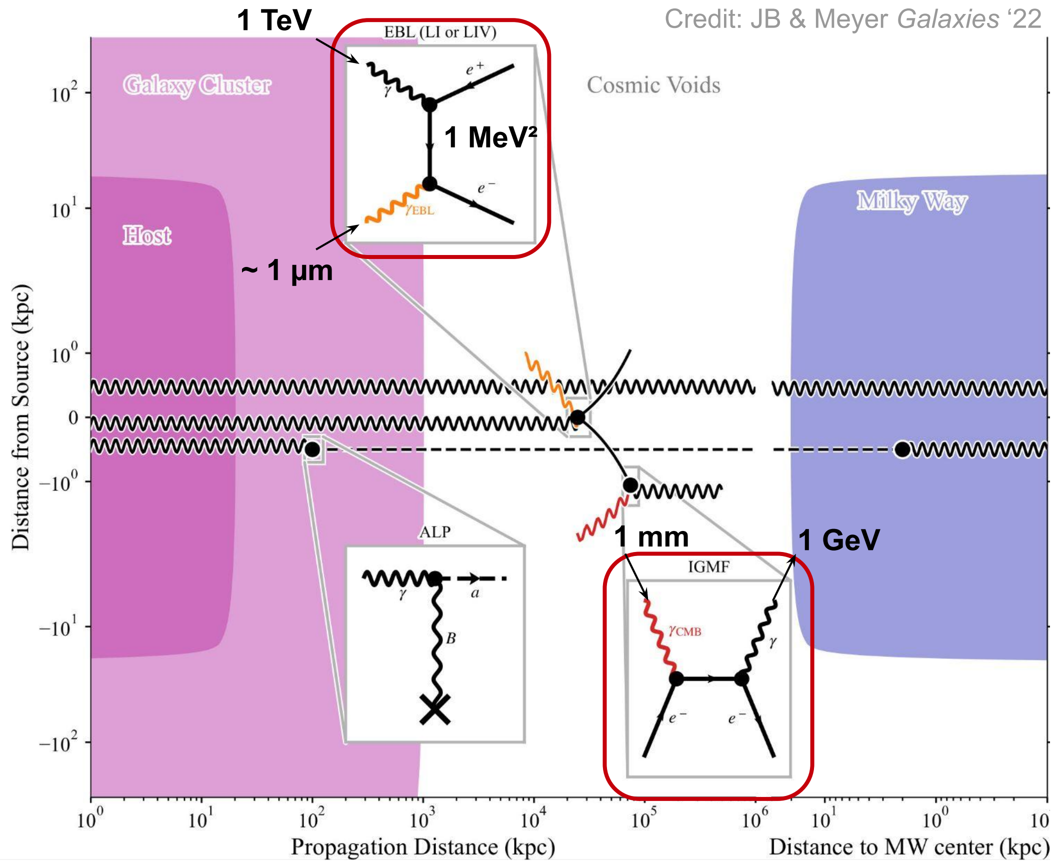


Lowest tension with TeV ɣ rays



Credit: L. Gréaux
(Biteau, Gréaux, Condorelli, in prep.)

Probe of the intergalactic plasma in voids



Gen. 1: TeV gamma-ray

$$\Gamma_{\gamma\gamma}(1\,\mathrm{TeV}, z=0.2) \approx 250\,\mathrm{Mpc}$$

Gen. 2: pair e^+e^-

- Diffuse in $\langle B^2 \rangle$
  $r_L(\gamma_e = 10^6) \approx 0.5\,\mathrm{Mpc}(B_{IGM}/10^{-15}\,\mathrm{G})^{-1}$
- Excite electrostatic instability of beam (~ 10^{-22} cm^{-3}) intergalactic plasma (~ 10^{-7} cm^{-3})
  - ➔ Inefficient *E*-loss mechanism due to
    - ◆ background MeV e^- (Yang+ *ApJ* '24)
    - ◆ non-linear feedback (Alawashra & Pohl *ApJ* '24)
    - ◆ $B > 10^{-17}$ G $(\lambda_B/1\,\mathrm{pc})^{-1/2}$ (Alawashra & Pohl *ApJ* '22)
- Inverse Compton on CMB photons
  $\Gamma_{e\gamma}(\gamma_e = 10^6) \approx 0.75\,\mathrm{Mpc}$

Gen. 3: GeV gamma-ray

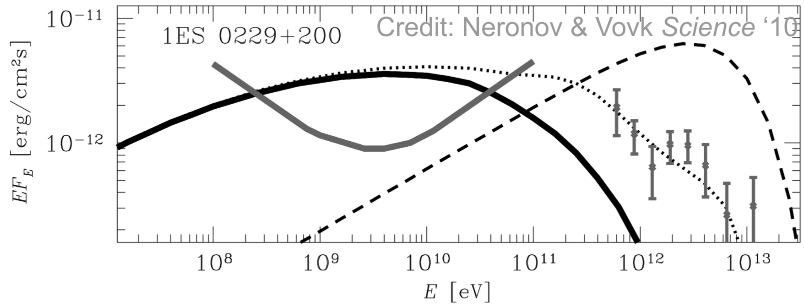
$$E_1 = \frac{4}{3}\gamma_e^2 \epsilon_{\mathrm{CMB}} \approx 1\,\mathrm{GeV}\left(\frac{E_0}{1\,\mathrm{TeV}}\right)^2$$

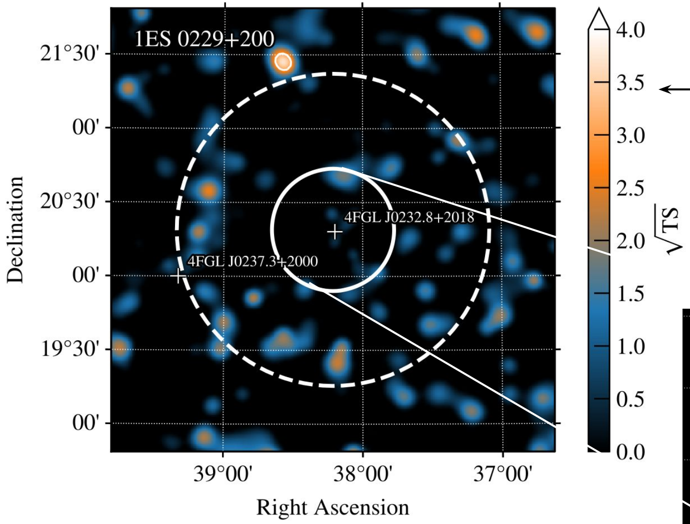
Absence of secondary signal

Discovery of extreme TeV blazars in 2006

Hard TeV photon spectrum when corrected for absorption

Intrinsic emission expected in the GeV band,
not seen in 2010 nor in 2024

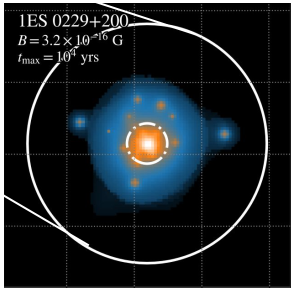


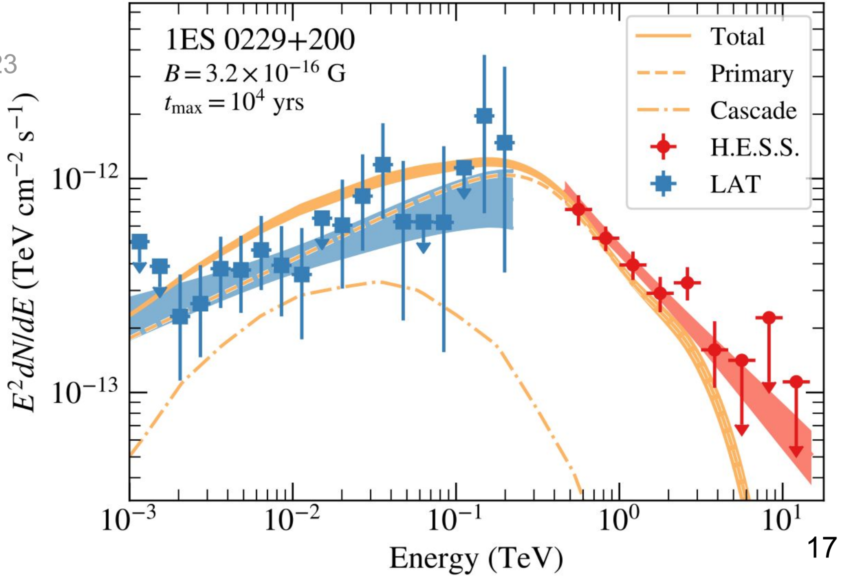


Observed

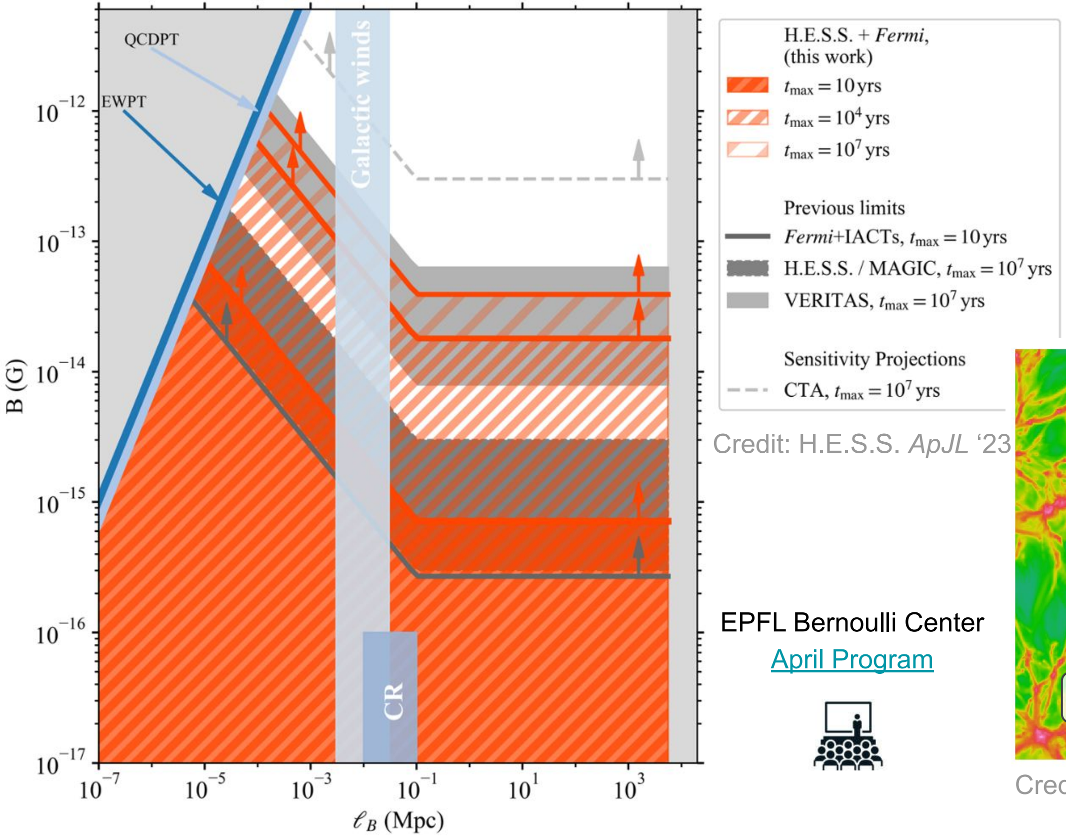
Credit: H.E.S.S. *ApJL* '23

Expected for
$B \sim 3 \times 10^{-16}$ G





Magnetic fields in voids



Credit: H.E.S.S. *ApJL* '23

EPFL Bernoulli Center

April Program

Status and expectations

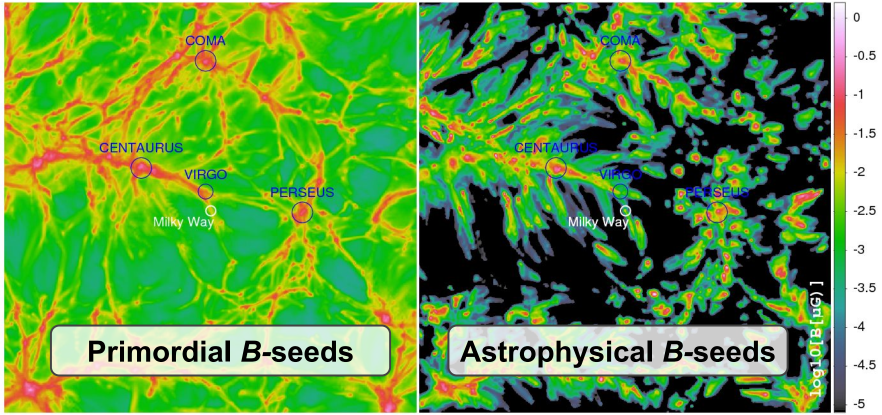
Current-generation: *B* > 10-100 fG,

CTAO discovery at 5σ up to 300 fG (CTAO *JCAP* '21)

Patchy *B*-field generation models disfavored:

VFF < 0.67 excluded at 95% C.L. (Tjemsland+ *ApJ* '24)

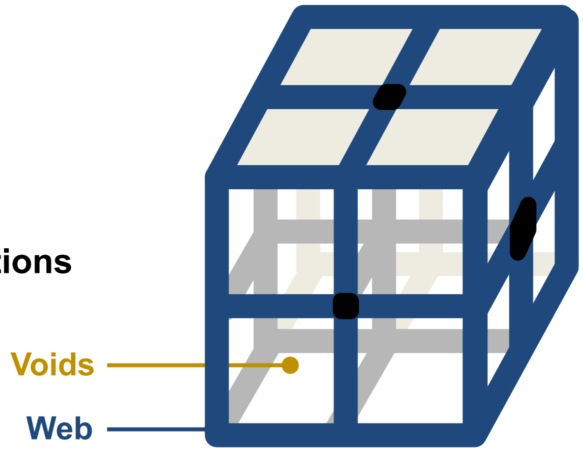
Primordial ↗ - Astrophysical ↘



Credit: Hackstein+ *MNRAS* '18

Conclusions and outlook

- ❏ Model-independent measurement of **Extragalactic Background Light**:
  O-IR backgrounds at $z = 0$ with **10-25% precision depending on λ**
- ❏ Precision on **Hubble constant:** 5% (model-dep.) to 10% (model-indep.)
  assuming no unresolved diffuse component in galaxy counts
  → could become relevant if Hubble tension not solved by **JWST observations**
- ❏ Probe of UV emissivity at high z (e.g. $z \sim 6$ in *Fermi*-LAT Science '18)
  room for improvement with archival and upcoming CTAO data?
  → timely in the **context of JWST observations**



- ❏ opportunity to probe ***B*-field in voids** (and study the intergalactic plasma)
  little room left for plasma instabilities as main *E*-loss or *p*-diffusion mechanism
  → comparison with models goes in the direction of primordial origin of *B*-fields,
  but without clearly preferred mechanism and (!) **without irrefutable observations**
- ❏ growing body of studies of **cosmic-web impact** on propagation (e.g. Bondarenko+ *A&A* '22, Abdalla+ *MNRAS* '24)
  → timely in the **context of LSST and Euclid observations**

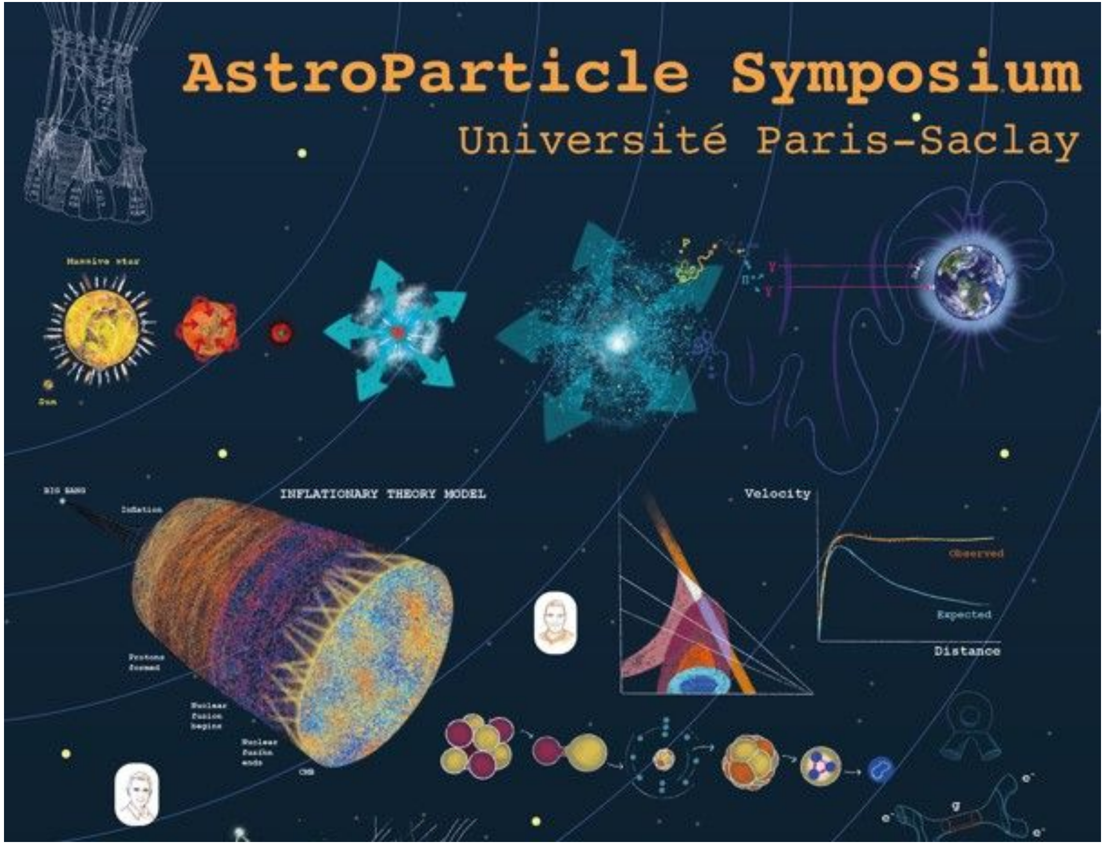
Upcoming EBL workshop in Paris area

November 12th to 15th, 2024

Limited # of on-site attendants

Remote participants also welcome

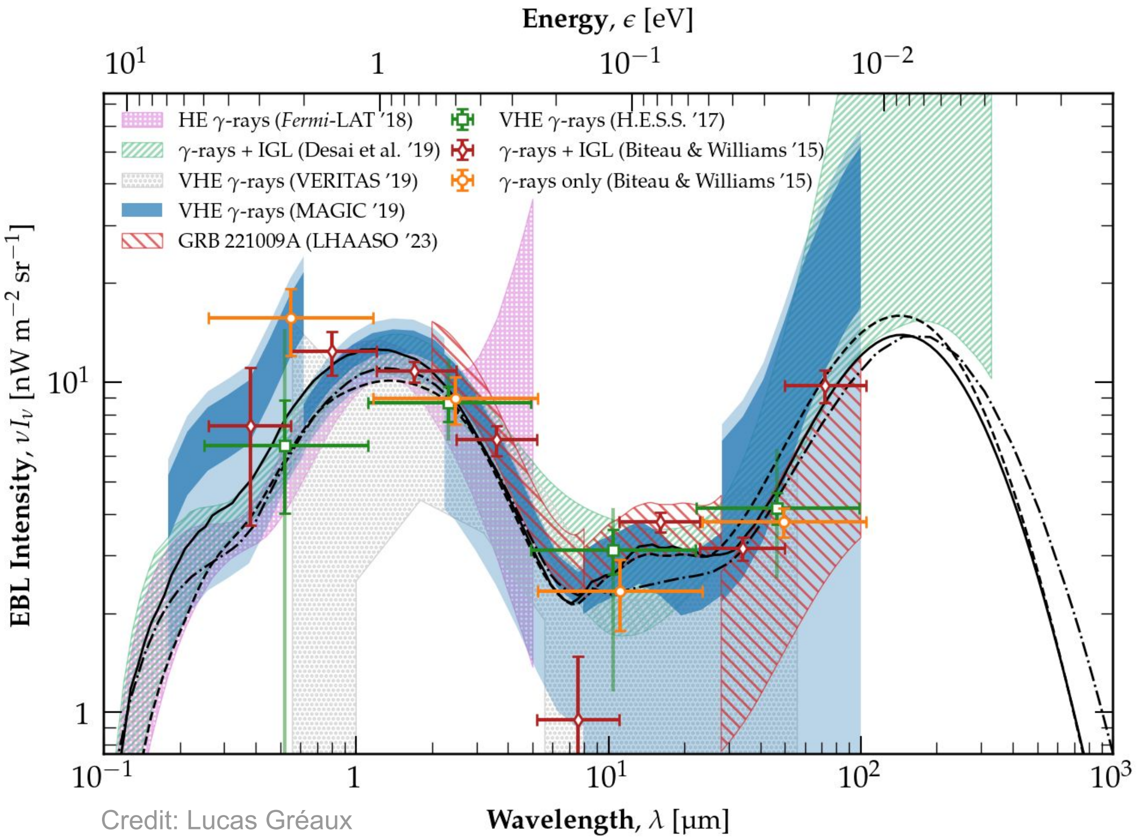
Please reach out if interested!



Jonathan Biteau

Backup

Overview of COB-CIB constraints at z=0



Credit: Lucas Gréaux

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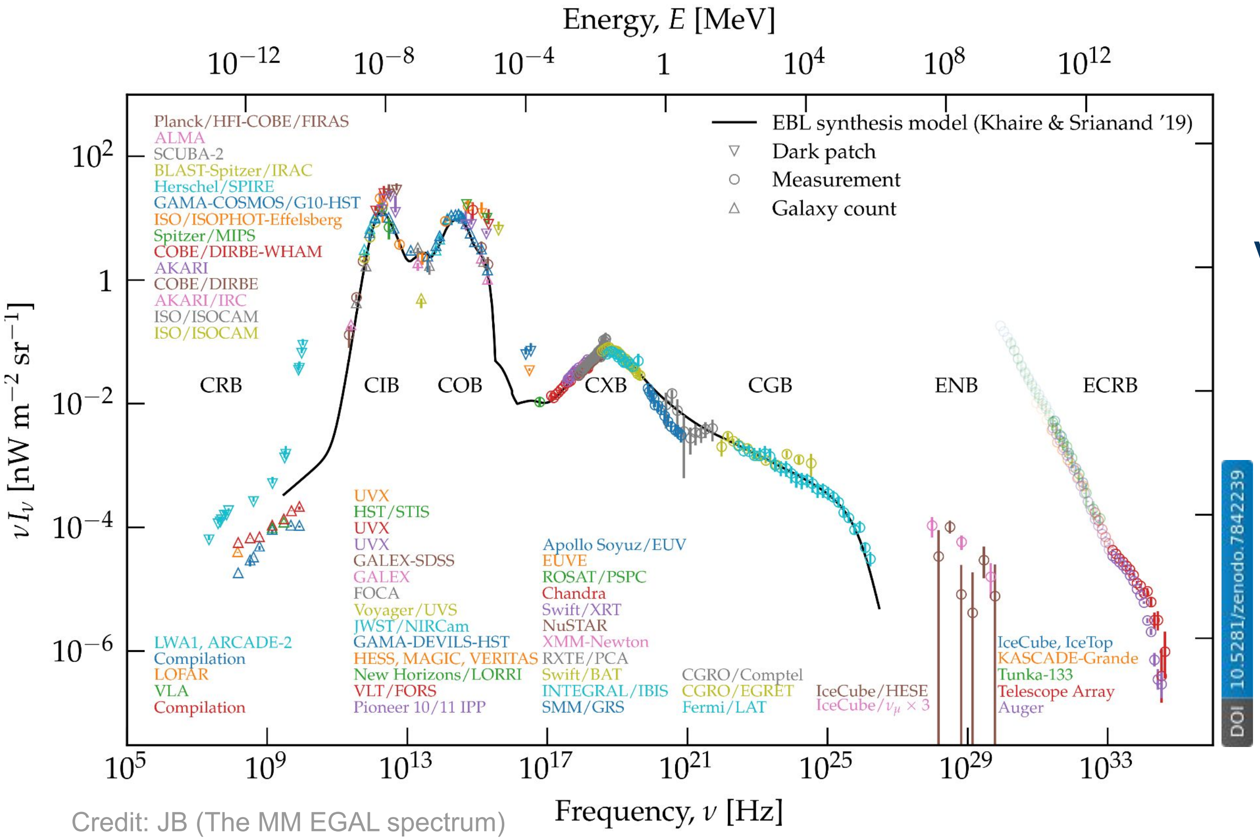
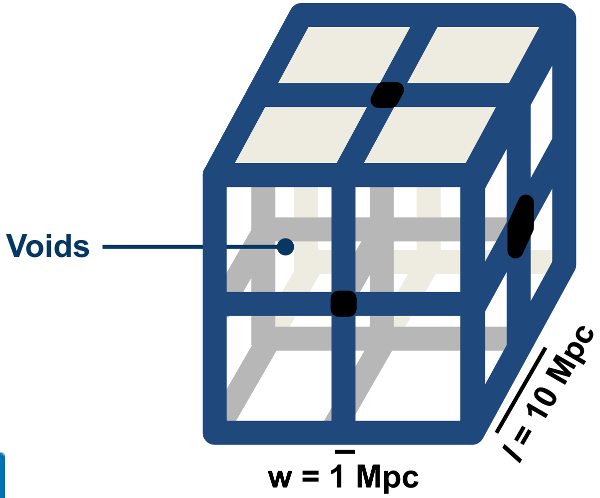
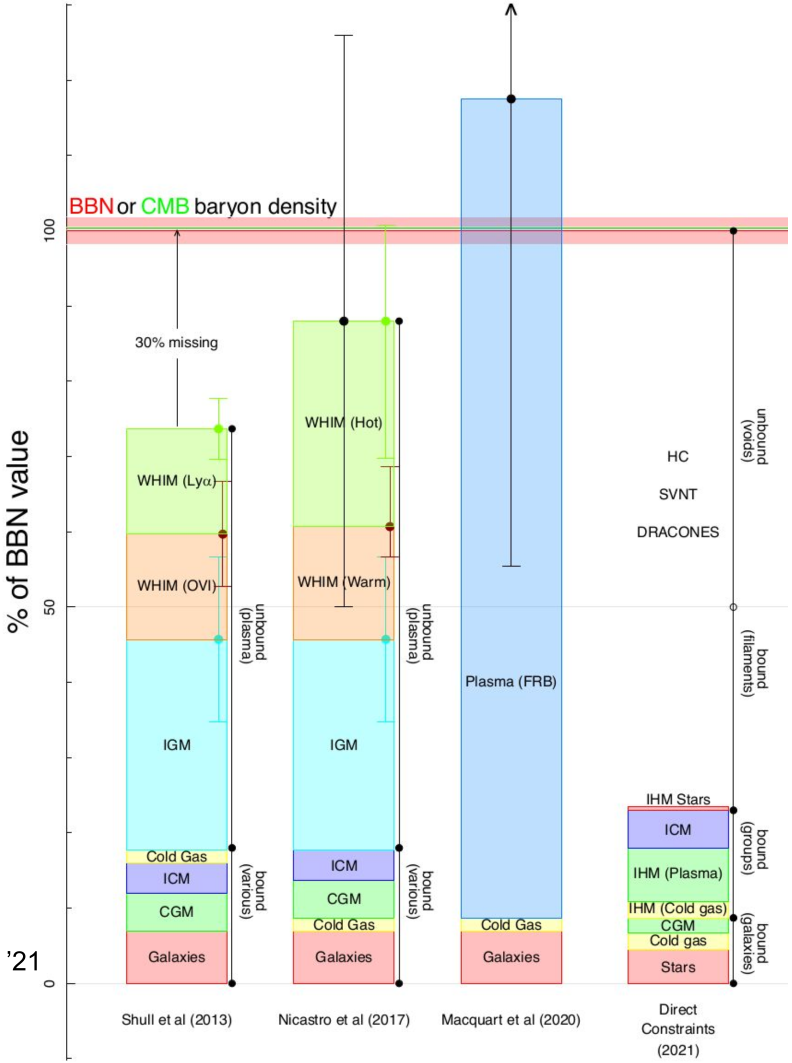


Credit: JB (The MM EGAL spectrum)



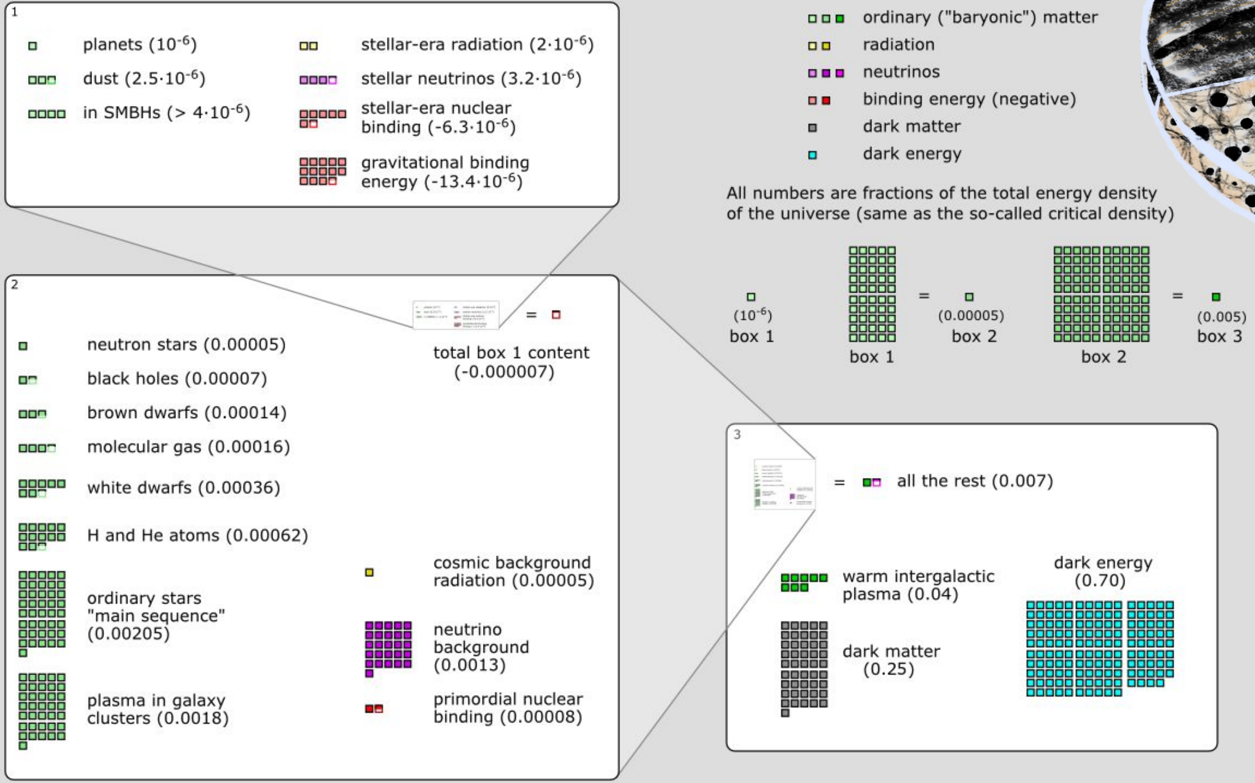
$$\int \nu I_\nu \, \mathrm{d}\ln\nu = \int I_\nu \, \mathrm{d}\nu = \frac{c}{4\pi} u$$

Missing baryons



Credit: Driver Nature Comments ’21

Cosmic energy inventory



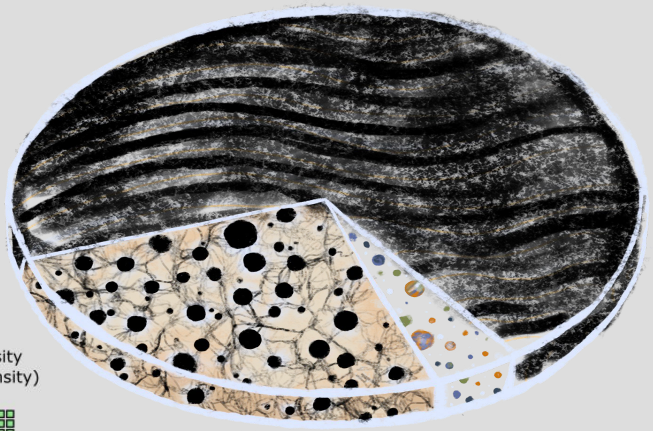


Chart by Markus Pössel [www.haus-der-astronomie.de] - Published under CC BY-NC-SA 3.0
Data from M. Fukugita & P.J.E. Peebles, "The Cosmic Energy Inventory" (2004) [adsabs.harvard.edu/abs/2004ApJ...616..643F]
Chart style following Randall Munroe's xkcd.com/radiation