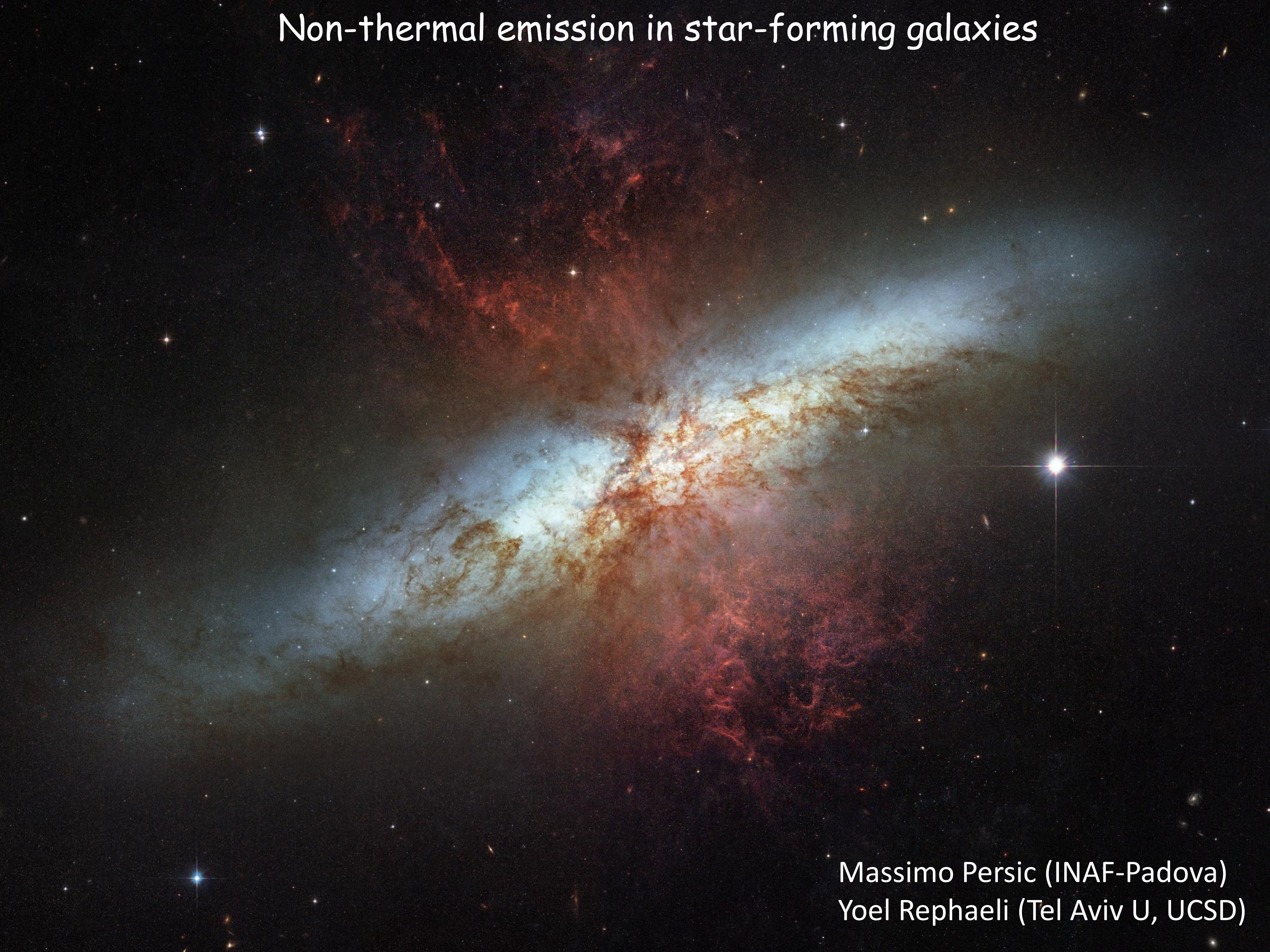
Non-thermal emission in star-forming galaxies



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Outlook

- Why non-thermal side of gal's (CR, mag fields) important?
  - acceleration mechanism(s)
  - E_{max} of CR
  - CR, scattering off magnetized plasma, affect gas dynamics
  - affect μ (mean mol mass), T in fragmentation mass, $M_{fragm} \propto \mu^{-2}\, T^{1/4}$
- Most desirable: solving individual cases
- Relevant NT emission processes
- Relevant radiation & matter fields
- SED-modeling procedure
- Source sample:
  - Magellanic Clouds (A&A 2022), M31 & M33 (A&A 2024)
  - M82 (to be submitted), NGC 253 (planned), NGC 2146 (planned)
- SED-modeling results
  - lepto-hadronic
  - NT energy budget: particles-field equipartition?

Electrons: radiative yields ❶

Blumenthal & Gould 1970

CRe: $N_e(\gamma) = N_{e,0}\,\gamma^{-q_e} \quad \ldots \quad \gamma_{min} < \gamma < \gamma_{max}$

simplest EED: truncated single PL
BUT more structured EED also OK

Synchrotron

Synchrotron emissivity

$$j_s(\nu) = \frac{\sqrt{3}e^3 B N_{e,0}}{4\pi\, m_e c^2} \int_\Omega \sin\theta\, d\Omega_\theta \int_{\gamma_{min}}^{\gamma_{max}} \gamma^{-q_e} d\gamma\, \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\xi)\, d\xi \quad \mathrm{erg\,cm^{-3}\,s^{-1}\,Hz^{-1}}$$

$$x = \nu/\nu_c = \nu/[\nu_0\gamma^2 \sin\theta]$$

$$\nu_0 = \frac{3eB}{4\pi m_e c}$$

modif Bessel funct 2 kind

$$K_{5/3}(\xi) = \int_0^\infty e^{-\xi\,\cosh(t)} \cosh\left(\frac{5}{3}t\right) dt$$

$$j_s(\nu) = N_{e,0} \frac{\sqrt{3}}{4}\frac{e^3 B}{m_e c^2}\left(\frac{\nu}{\nu_0}\right)^{-\frac{q_e-1}{2}} \int_0^\pi \sin\theta^{\frac{q_e+3}{2}} \int_{\frac{\nu}{\nu_0\gamma_{max}^2\sin\theta}}^{\frac{\nu}{\nu_0\gamma_{min}^2\sin\theta}} x^{\frac{q_e-1}{2}} \int_x^\infty \int_0^\infty e^{-\xi\,\cosh(t)} \cosh\left(\frac{5}{3}t\right) dt\, d\xi\, dx\, d\theta \quad \frac{\mathrm{erg}}{\mathrm{cm^3 s\,Hz}}$$

$$j_s(\nu) = N_{e,0} \frac{\sqrt{3}}{4}\frac{e^3 B}{m_e c^2}\left(\frac{\nu}{\nu_0}\right)^{-\frac{q_e-1}{2}} \int_0^\pi \sin\theta^{\frac{q_e+3}{2}} \int_{\frac{\nu}{\nu_0\gamma_{max}^2\sin\theta}}^{\frac{\nu}{\nu_0\gamma_{min}^2\sin\theta}} x^{\frac{q_e-1}{2}} \int_0^\infty e^{-x\,\cosh(t)} \frac{\cosh\left(\frac{5}{3}t\right)}{\cosh(t)} dt\, dx\, d\theta \quad \frac{\mathrm{erg}}{\mathrm{cm^3 s\,Hz}}$$

Compton

$$\frac{d^2N_{\gamma,\epsilon}}{dt\,d\epsilon_1} = \int_{\epsilon_{min}}^{\epsilon_{max}} \int_{\max\{\frac{1}{2}\sqrt{\frac{\epsilon_1}{\epsilon}},\,\gamma_{min}\}}^{\gamma_{max}} N_e(\gamma)\,\frac{\pi r_0^2 c}{2\gamma^4}\,\frac{n(\epsilon)}{\epsilon^2}\left(2\epsilon_1 \ln\frac{\epsilon_1}{4\gamma^2\epsilon} + \epsilon_1 + 4\gamma^2\epsilon - \frac{\epsilon_1^2}{2\gamma^2\epsilon}\right) d\gamma\, d\epsilon$$

Thermal: diluted BB

$$n(\epsilon) = C_{\mathrm{dil}}\,\frac{8\pi}{h^3c^3}\,\frac{\epsilon^2}{e^{\epsilon/k_BT}-1}$$

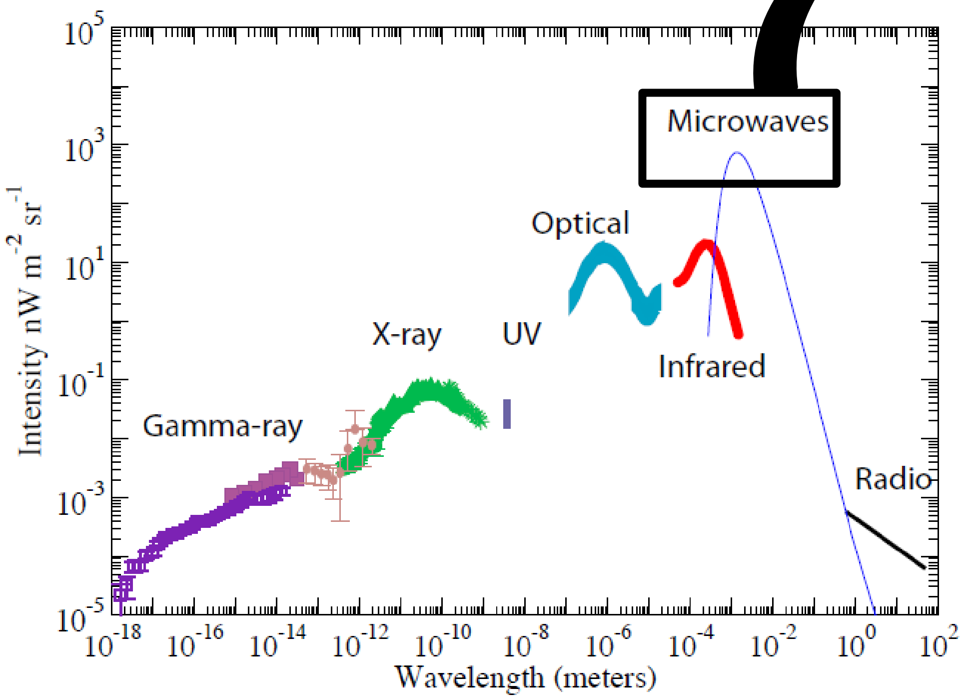
$$u = C_{\mathrm{dil}}aT^4$$

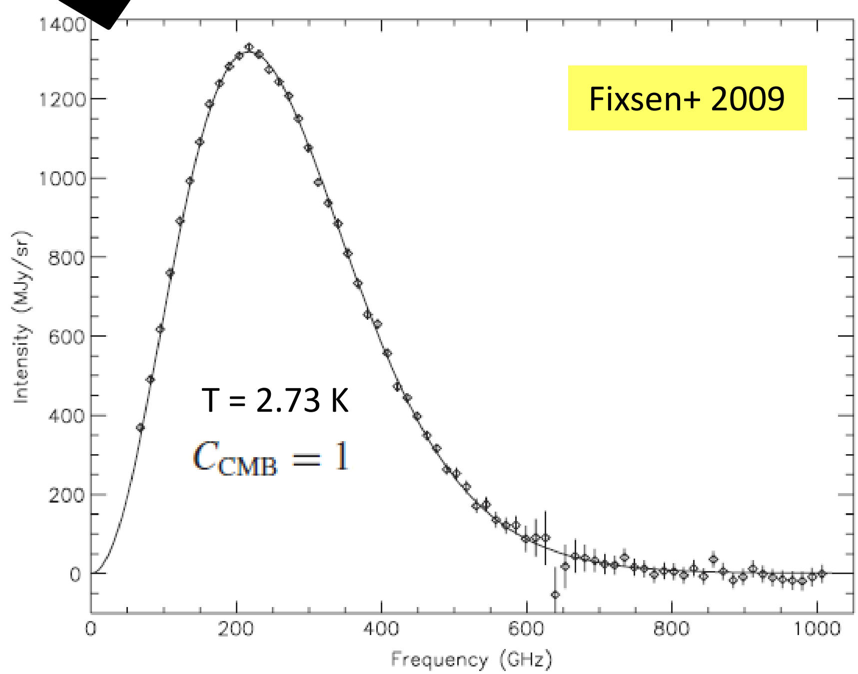
$$n_{\mathrm{EBL}}(\epsilon) = \sum A_j\,\frac{8\pi}{h^3c^3}\,\frac{\epsilon^2}{e^{\epsilon/k_BT_j}-1} \quad \mathrm{cm}^{-3}\,\mathrm{erg}^{-1}$$

... or NT: synchrotron

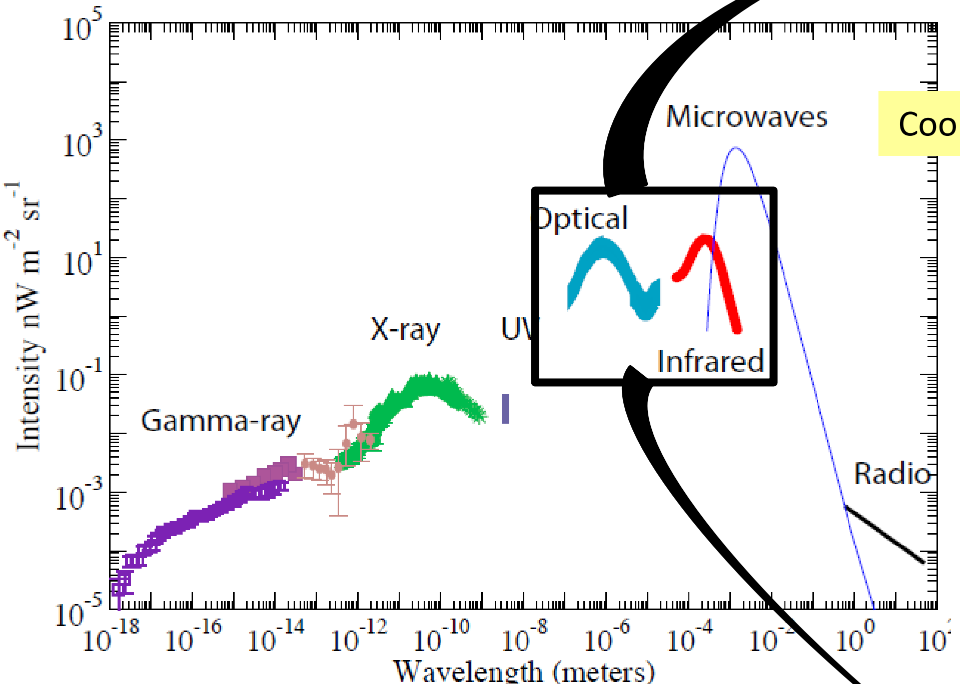
Radiation fields

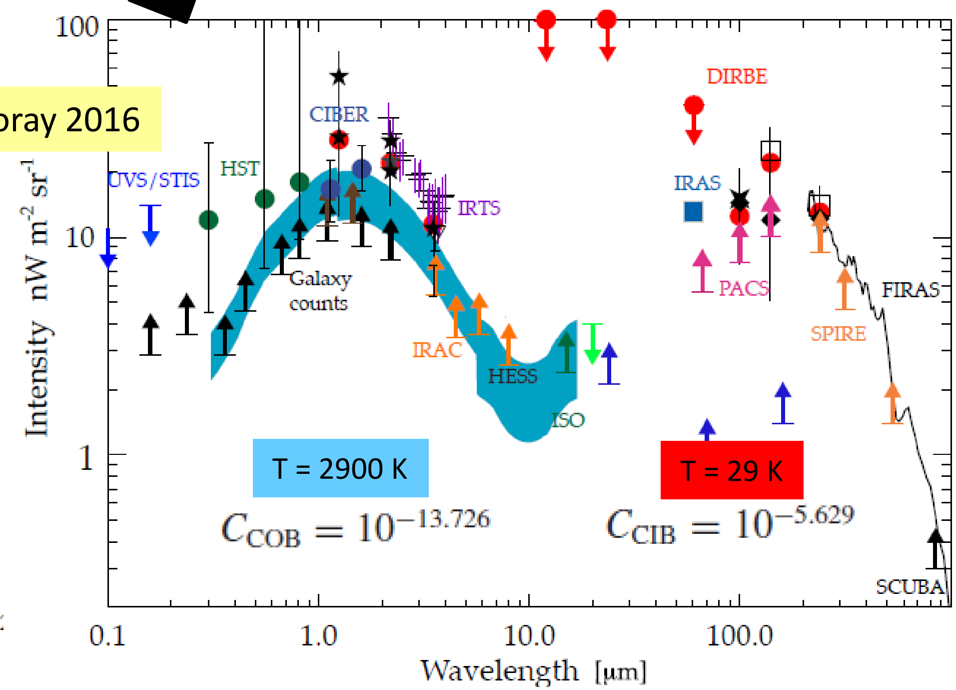
① CMB - Cosmic Microwave Background

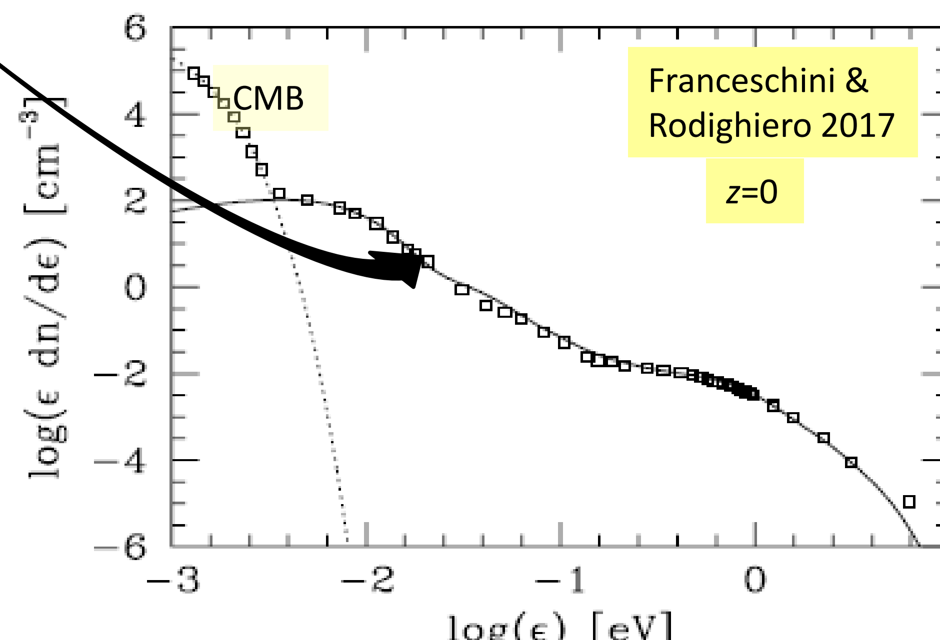




② EBL - Extragalactic Background Light





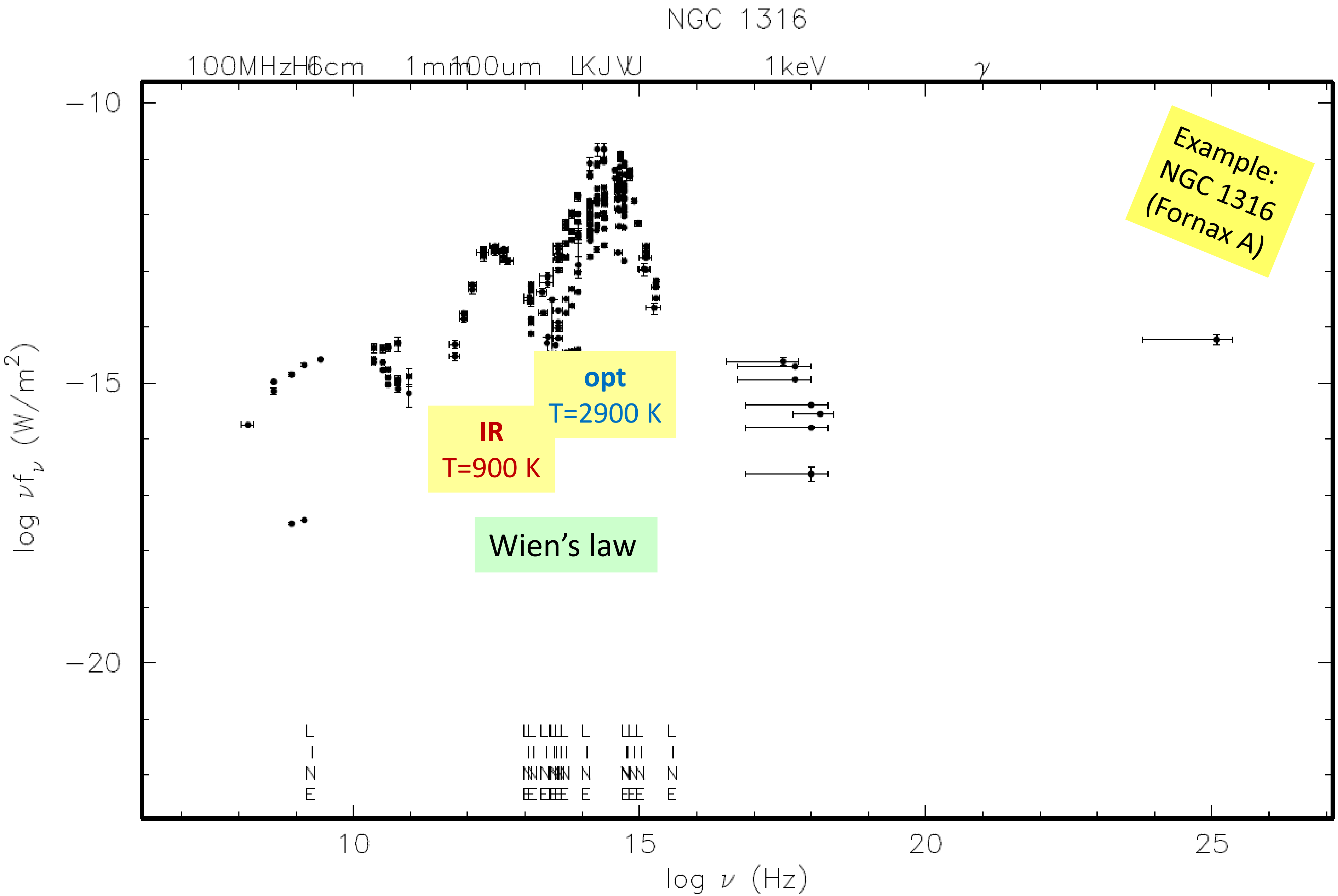


Numerical fit to EBL: sum of diluted planckians

$$n_{\rm EBL}(\epsilon) = \sum_{i=1}^{8} A_j \frac{8\pi}{h^3c^3}\frac{\epsilon^2}{e^{\epsilon/k_BT_j}-1} \qquad {\rm cm}^{-3}\,{\rm erg}^{-1}$$

with: $A_1 = 10^{-5.629}$, $T_1 = 29\,$K; $A_2 = 10^{-8.522}$, $T_2 = 96.7\,$K; $A_3 = 10^{-10.249}$, $T_3 = 223\,$K; $A_4 = 10^{-12.027}$, $T_4 = 580\,$K; $A_5 = 10^{-13.726}$, $T_5 = 2900\,$K; $A_6 = 10^{-15.027}$, $T_6 = 4350\,$K; $A_7 = 10^{-16.404}$, $T_7 = 5800\,$K; $A_8 = 10^{-17.027}$, $T_8 = 11600\,$K.

③ GFL - Galaxy Foreground Light



Protons: pion-decay yields

Stecker 1971

$\pi^0 \rightarrow 2\gamma$ $\pi^\pm \rightarrow e^\pm$

CRp: $N_p(E_p) = N_{p,0}\, E_p^{-q_p} \quad \ldots \quad E_p^{min} < E < E_p^{max}$

① Production of π^0-decay γ-rays

γ-ray photon emissivity

$f(m_p, m_{\pi 0}) \sim E_p(\text{max})$

- $$Q_\gamma(E_\gamma)|_{\pi^0} = 2 \int_{E_{\pi^0}^{min}}^{E_{\pi^0}^{max}} \frac{Q_{\pi^0}(E_{\pi^0})}{\sqrt{E_{\pi^0}^2 - m_{\pi^0}^2}}\, dE_{\pi^0}$$ π^0-decay γ-ray emissivity

$$E_{\pi^0}^{min} = E_\gamma + m_{\pi^0}^2/(4E_\gamma)$$

π^0 ED

$$Q_{\pi^0}(E_{\pi^0}) = \frac{4}{3}\pi n_H \int_{E_p^{thr}(E_{\pi^0})}^{E_p^{max}} J_p(E_p)\, \frac{d\sigma(E_{\pi^0}, E_p)}{dE_{\pi^0}}\, dE_p$$

π^0 production rate

ambient

$$J_p = \frac{c}{4\pi} N_p$$

0.17

δ-approx

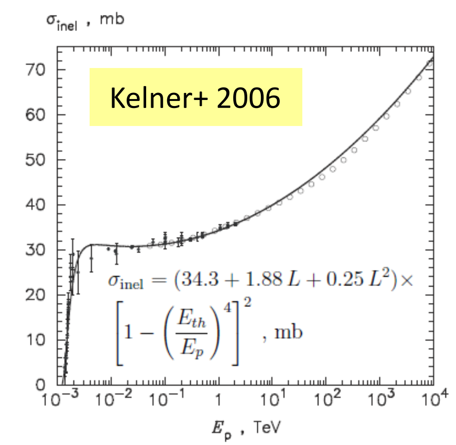
$$d\sigma(E_{\pi^0}, E_p)/dE_{\pi^0} \sim \delta(E_{\pi^0} - \kappa_{\pi^0} E_p^{kin})\, \sigma_{pp}(E_p)$$

$$E_p^{thr} \simeq 1.22 \text{ GeV}$$

differential cross-section for production of neutral pions with energy E_{π^0} from a collision of a proton with energy E_p with a proton (essentially) at rest

$\sigma_{pp}(E_p)$ can be analytically approximated

$\sigma_{pp} \approx 30$ mbarn $\quad 5 \lesssim E_p/\text{GeV} \lesssim 50$



$$Q_{\pi^0}(E_{\pi^0}) = \frac{c\, n_H}{3\,\kappa_{\pi^0}} N_p\left\{m_p + \frac{E_{\pi^0}}{\kappa_{\pi^0}}\right\} \sigma_{pp}\left\{m_p + \frac{E_{\pi^0}}{\kappa_{\pi^0}}\right\}$$

- $$Q_\gamma(E_\gamma)|_{\pi^0} = \frac{2}{3}\frac{c}{\kappa_{\pi^0}} n_H\, N_{p,0}\, \sigma_{pp,0} \int_{E_{\pi^0}^{min}}^{E_{\pi^0}^{max}} \frac{(m_p + E_{\pi^0}/\kappa_{\pi^0})^{-q_p}}{\sqrt{E_{\pi^0}^2 - m_{\pi^0}^2}}\, dE_{\pi^0}$$

② Production of $\pi^{\pm}$-decay secondary $e^{\pm}$

$\pi^{\pm}$ decay rate density

- $$Q_{\pi^\pm}(E_{\pi^\pm}) = \frac{2}{3} c n_H \int_{E_{\rm thr}} N_p(E_p)\, f_{\pi^\pm,p}(E_p, E_{\pi^\pm})\, dE_p$$

$$f_{\pi^\pm,p}(E_p, E_{\pi^\pm}) = \sigma_{pp}(E_p)\, \delta(E_{\pi^\pm} - k_{\pi^\pm} E_p^{\rm kin})$$

$\pi^{\pm}$ energy distribution for an incident proton energy E_p

0.25

$$Q_{\pi^\pm}(E_{\pi^\pm}) = \frac{2}{3} \frac{c}{k_{\pi^\pm}} n_H N_{p,0} \left(m_p + \frac{E_{\pi^\pm}}{k_{\pi^\pm}} \right)^{-q_p} \sigma_{pp}\left\{ m_p + \frac{E_{\pi^\pm}}{k_{\pi^\pm}} \right\}$$

Ramaty & Lingenfelter 1966; *see next slide for details*

- $$Q_{se}(E_e) \approx \frac{8}{3} \frac{c}{k_{\pi^\pm}} n_H N_{p0}\, \sigma_{pp,0} \left(\frac{4E_e + m_{\pi^\pm}}{\kappa_{\pi^\pm}} + m_p \right)^{-q_p}$$ source rate density of the secondary $e^{\pm}$

- $$N_{se}(\gamma) = \frac{\int Q_{se}(\gamma)\, d\gamma}{b(\gamma)}$$ steady-state secondary electron density

diffusion-loss eqn.

$$b(\gamma) = b_0 + b_1(\gamma) + b_2(\gamma)$$

radiative energy loss

$$b_0(\gamma) = 1.2 \cdot 10^{-12} n_e \left[1 + \ln(\gamma/n_e)/84\right]$$ coulomb

$$b_1(\gamma) = 10^{-16}\, \gamma n_e$$ ionized gas — bremsstr

$$b_2(\gamma) = 1.3 \cdot 10^{-9} \gamma^2 \left(B^2 + 8\pi\rho_r\right)$$ CS

(coulomb, bremsstr: ionized gas)

- The resulting $N_{se}(\gamma)$ can be approximated by

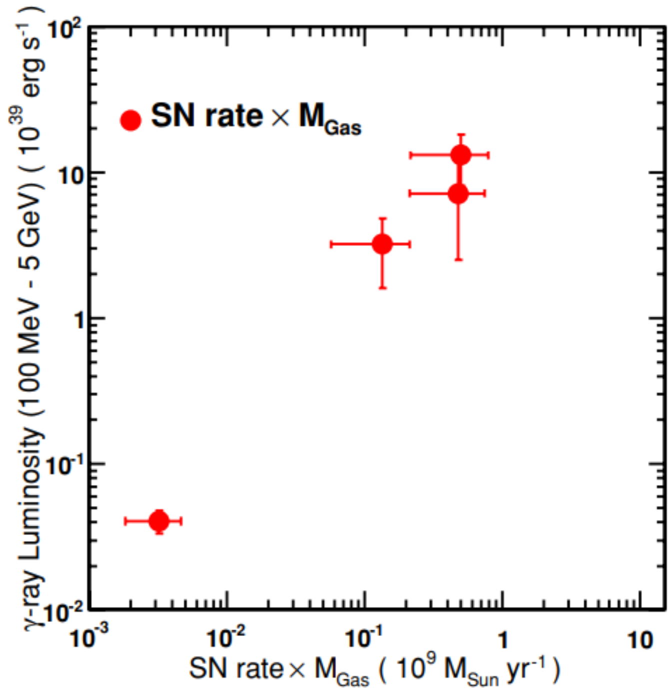
$$N_{se}^{\rm fit}(\gamma) = N_{se,0} \left[1 + \left(\frac{\gamma}{\gamma_f} \right)^{\tau} \right]^{-(q_p+1)} .$$

e.g.: ¾ in Fornax A

Star-forming galaxies

General properties:

- high density ISM → high SFR → high SNr → high CR density → high pp interaction rate → high π production
- B field (~ 10-100 μG)
- CRe → synchrotron (radio), Compton (X, γ), bremsstrahlung (radio, γ)
- CRp → π^0-decay (γ)



P & Rephaeli 2014, A&A, 567, A101

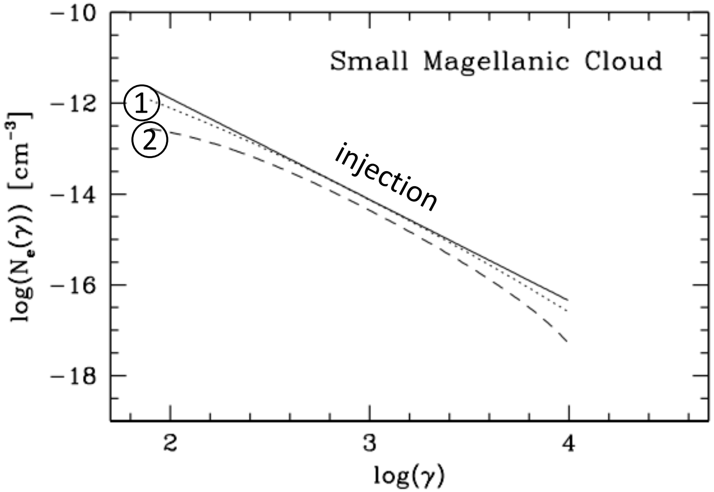
Starburst galaxies

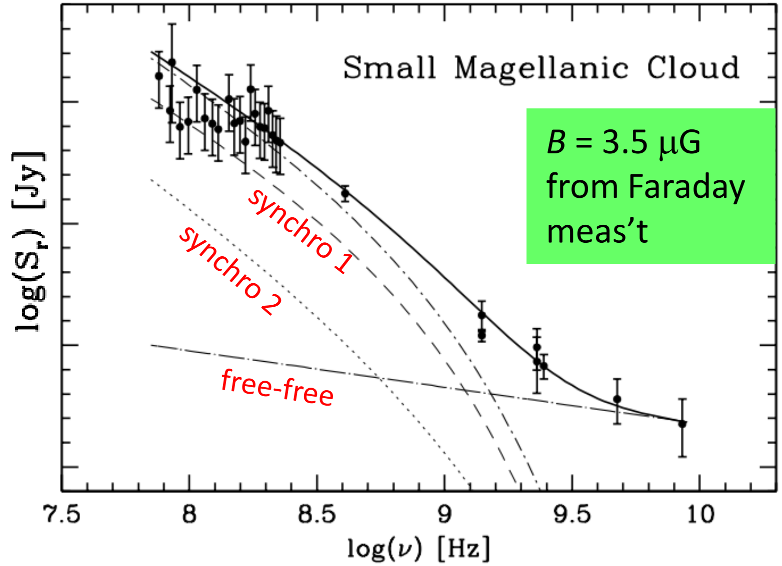
$$\kappa(q) \simeq \left(\frac{m_p}{m_e}\right)^{(3-q)/2}$$ → κ

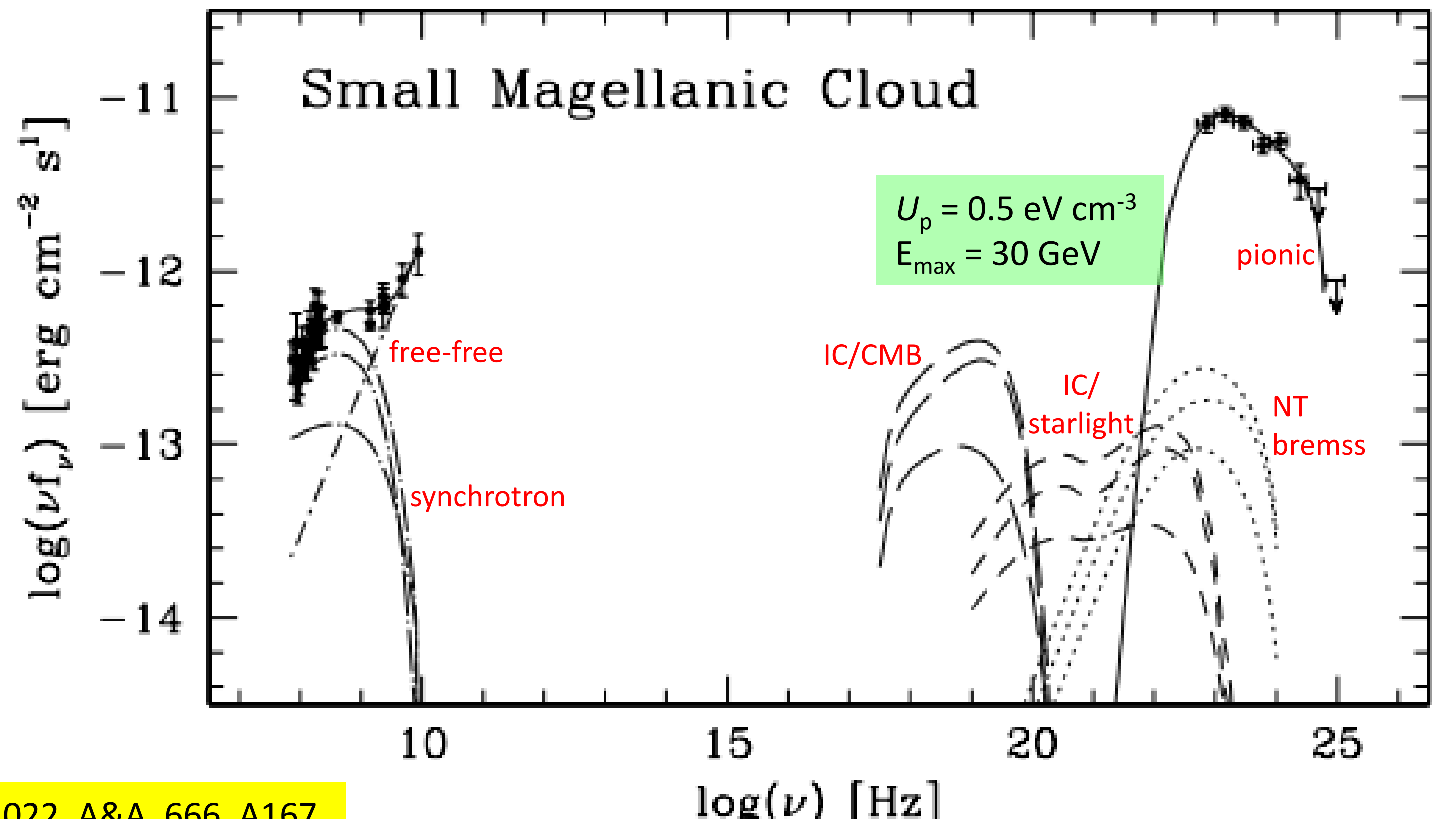
equipartition → B

Object	D_L [1]	R_{SB} [2]	h_{SB} [3]	f_5 [4]	α [5]	n_e [6]	L_{IR} [7]	M_{SB} [8]	χ [9]	κ [10]	γ_1 [11]	B [12]	U_p [13]	Notes [a]
Arp 220 E	74.7	114⁺	–	0.08	0.70	3000⁺	44.91	9.3	24	48	21000	155	390	
Arp 220 W	74.7	70⁺	–	0.10	0.70	3000⁺	45.08	9.1	40	48	15000	230	730	
Arp 299-A	43.0	140	200⋆	0.10	0.60	250	44.88	9.0	8	20	8700	145	365	=IC 694
NGC 253	2.5	180	150	1.80	0.70	100	43.62	7.7	0.3	48	8300	100	235	
NGC 3034	3.4	300	200	3.70	0.71	200	43.96	8.1	0.3	51	6600	100	250	=M 82
NGC 3628	7.6	135	200⋆	.065	0.86	100	43.30	7.3	0.1	120	7600	65	100	
NGC 4945	3.7	250	200⋆	2.25	0.60	300	43.72	7.4	0.1	20	4700	110	270	
NGC 5236	3.7	180	200⋆	0.75	0.80	200	43.45	7.3	0.1	90	5000	105	260	=M 83
NGC 6946	5.5	150	200⋆	.045	0.74	100	43.51	7.0	0.7	60	4000	65	110	

Small Magellanic Cloud



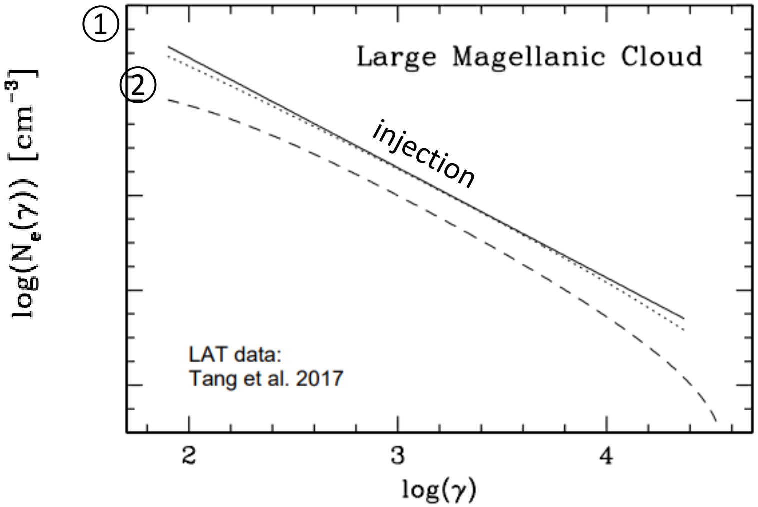


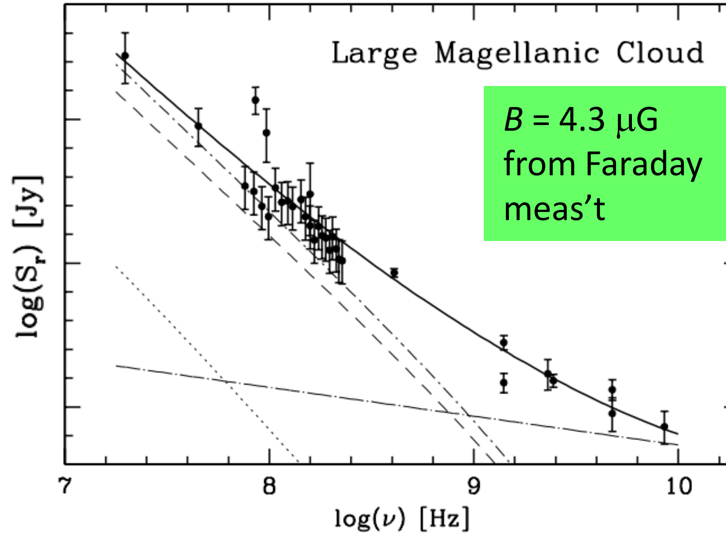


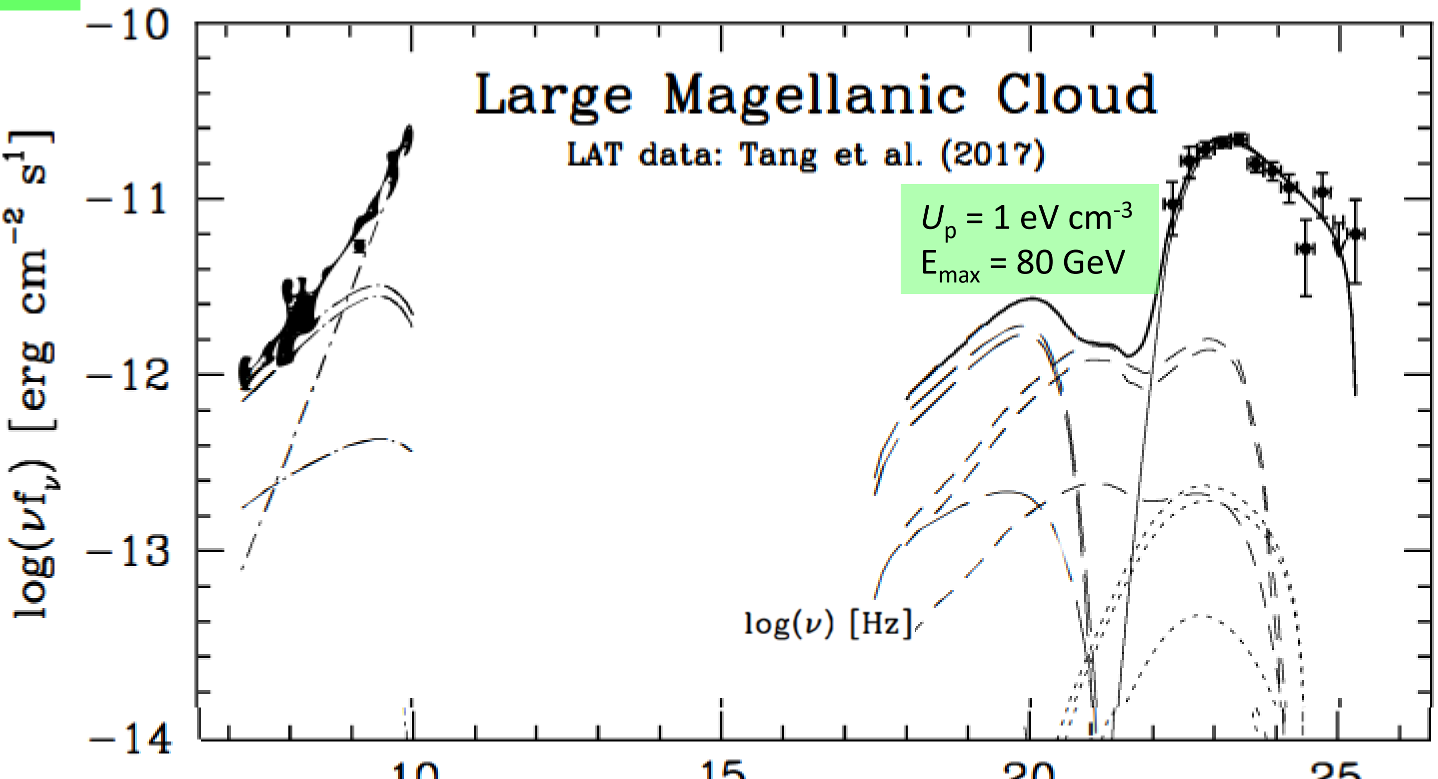
P & Rephaeli 2022, A&A, 666, A167

Large Magellanic Cloud

U_p = 1 eV cm^{-3}







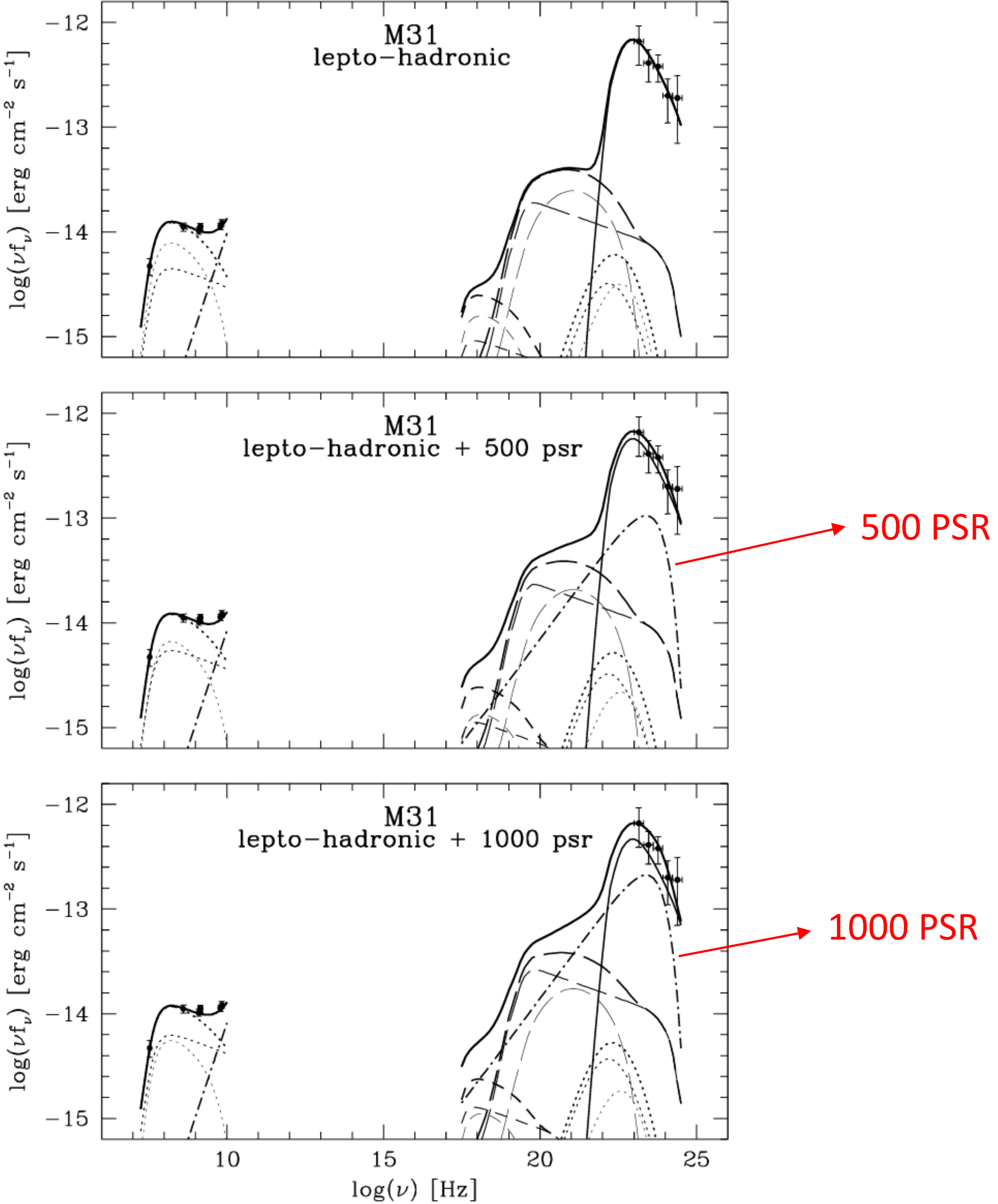
P & Rephaeli 2022, A&A, 666, A167

M31

P & Rephaeli 2024
A&A, 685, A47

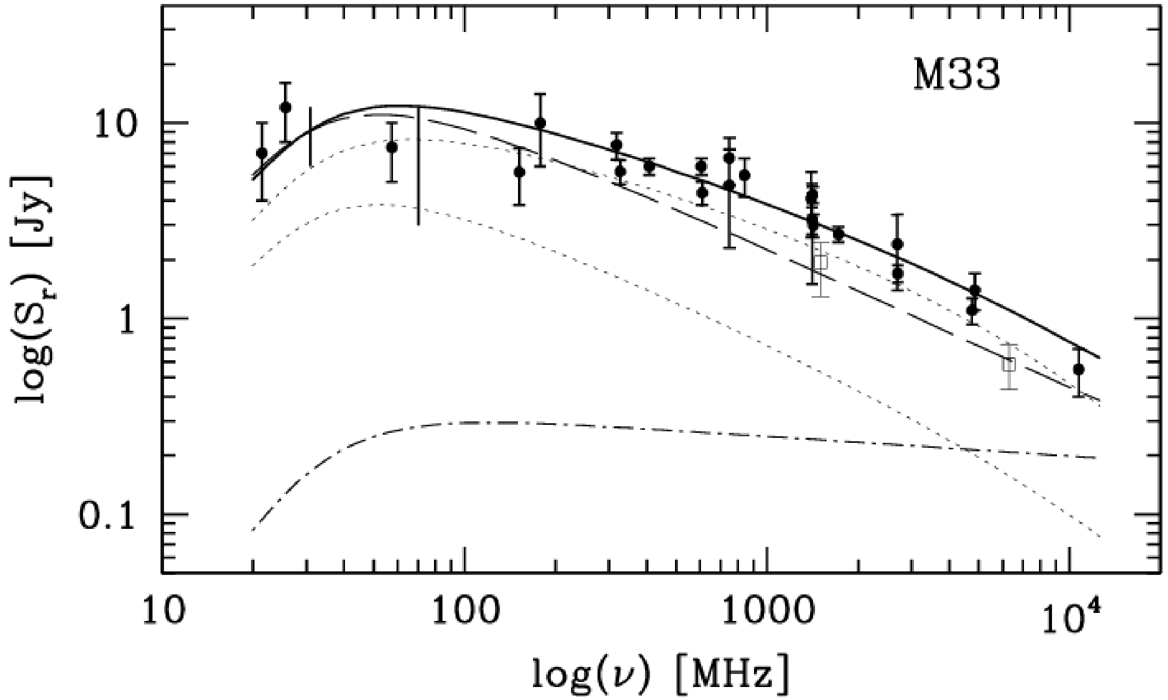
Central region, < 5.5 kpc

$U_p \sim 5$ eV cm^{-3}
E_{max} = 30 GeV

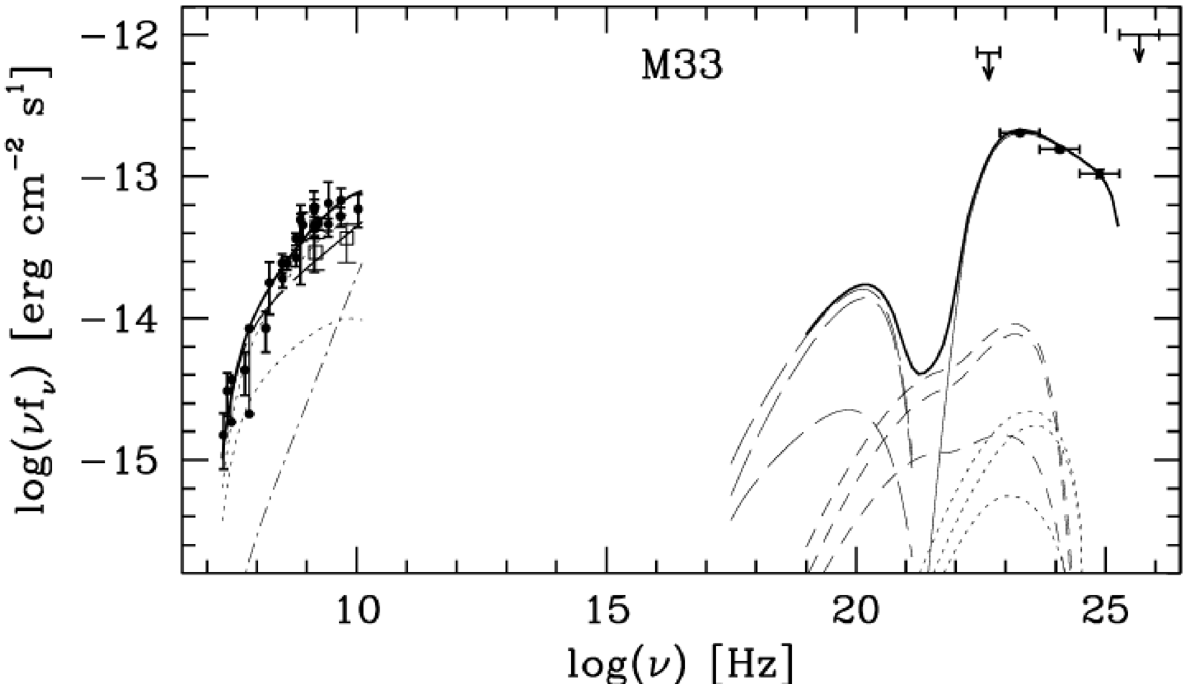


M33

P & Rephaeli 2024
A&A, 685, A47



U_p = 0.5 eV cm^{-3}
E_{max} = 100 GeV



M82

Physics Today (2010) 63, 13

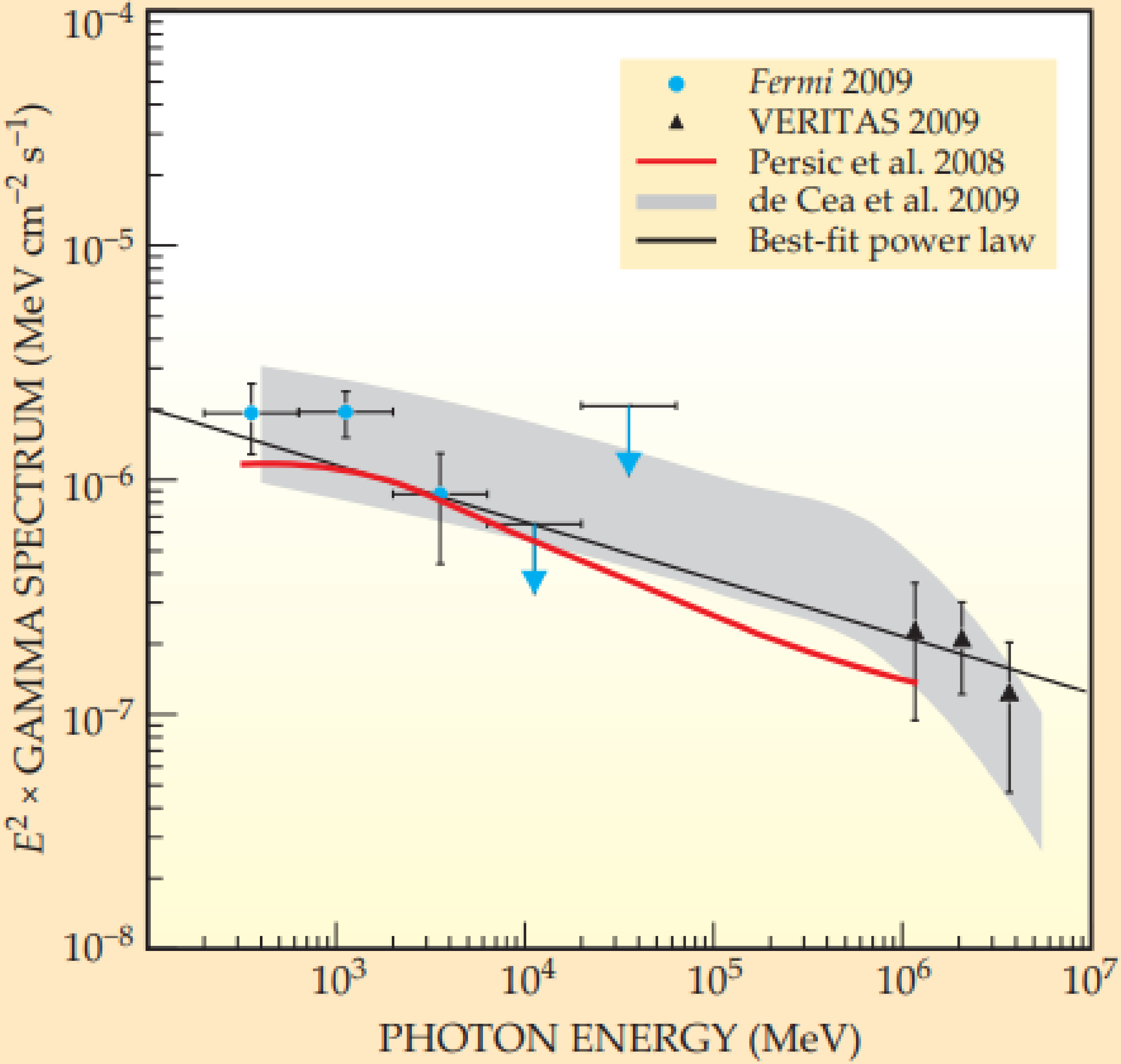
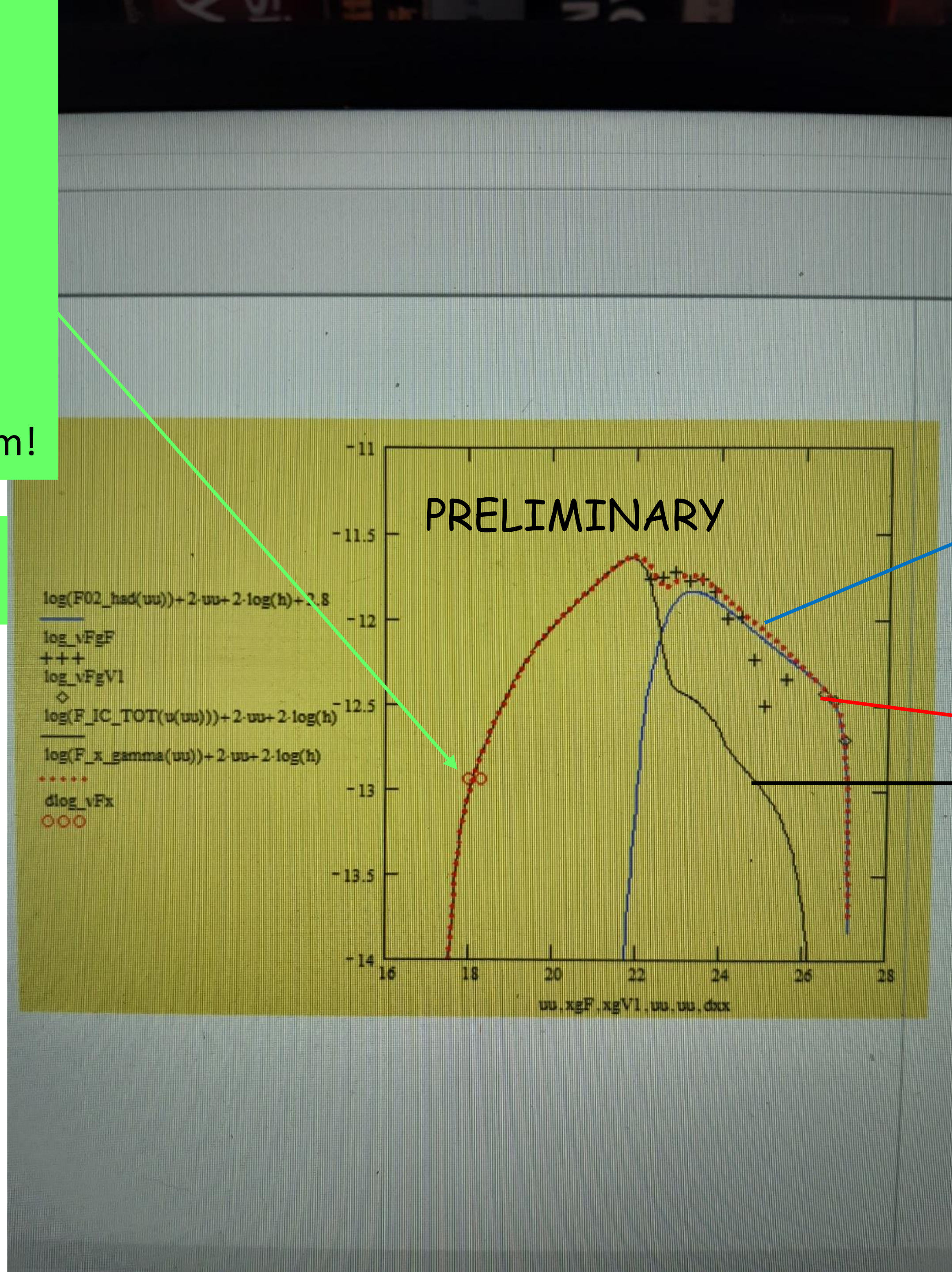


Figure 1. Gamma-ray spectrum of the starburst galaxy M82 measured by the *Fermi* and VERITAS telescopes[1,2] and compared with detailed theoretical predictions.[4] The simple power-law fit gives an energy dependence of $E^{-2.2}$. For clarity, the spectrum is multiplied in the plot by E^2. (Adapted from ref. 1.)

Breakthrough: non-thermal X-ray emission (Iwasawa+ 2023; *Chandra* 520ks)
→ Compton/FIR
$j_{IC}(\nu) \propto n_e$
→ normalize electron spectrum!

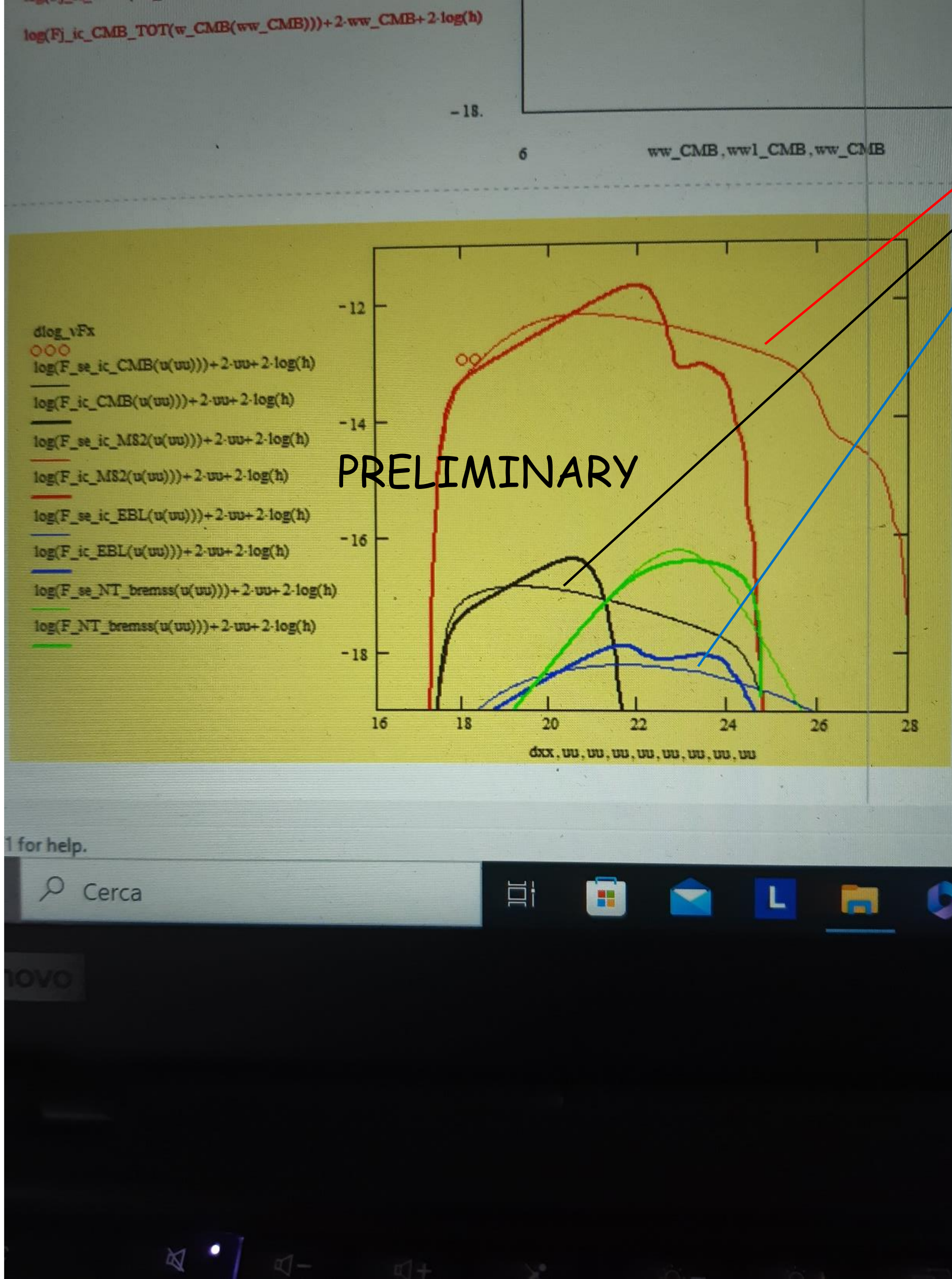
P., Rando (UniPD), Rephaeli 2024 in prep



Pionic
Fermi-LAT 16yr
VERITAS 137hr

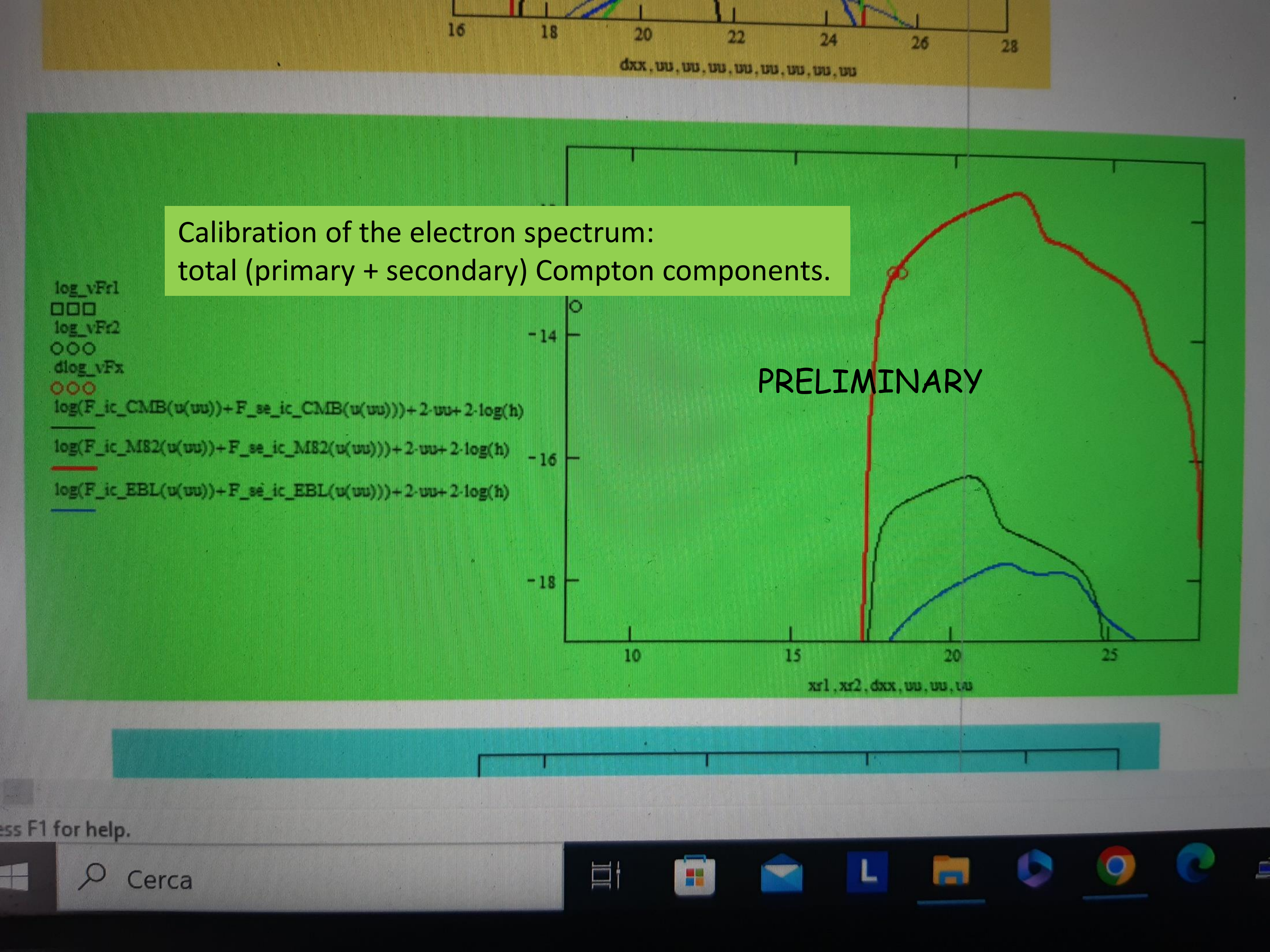
E_{max} = 7 TeV

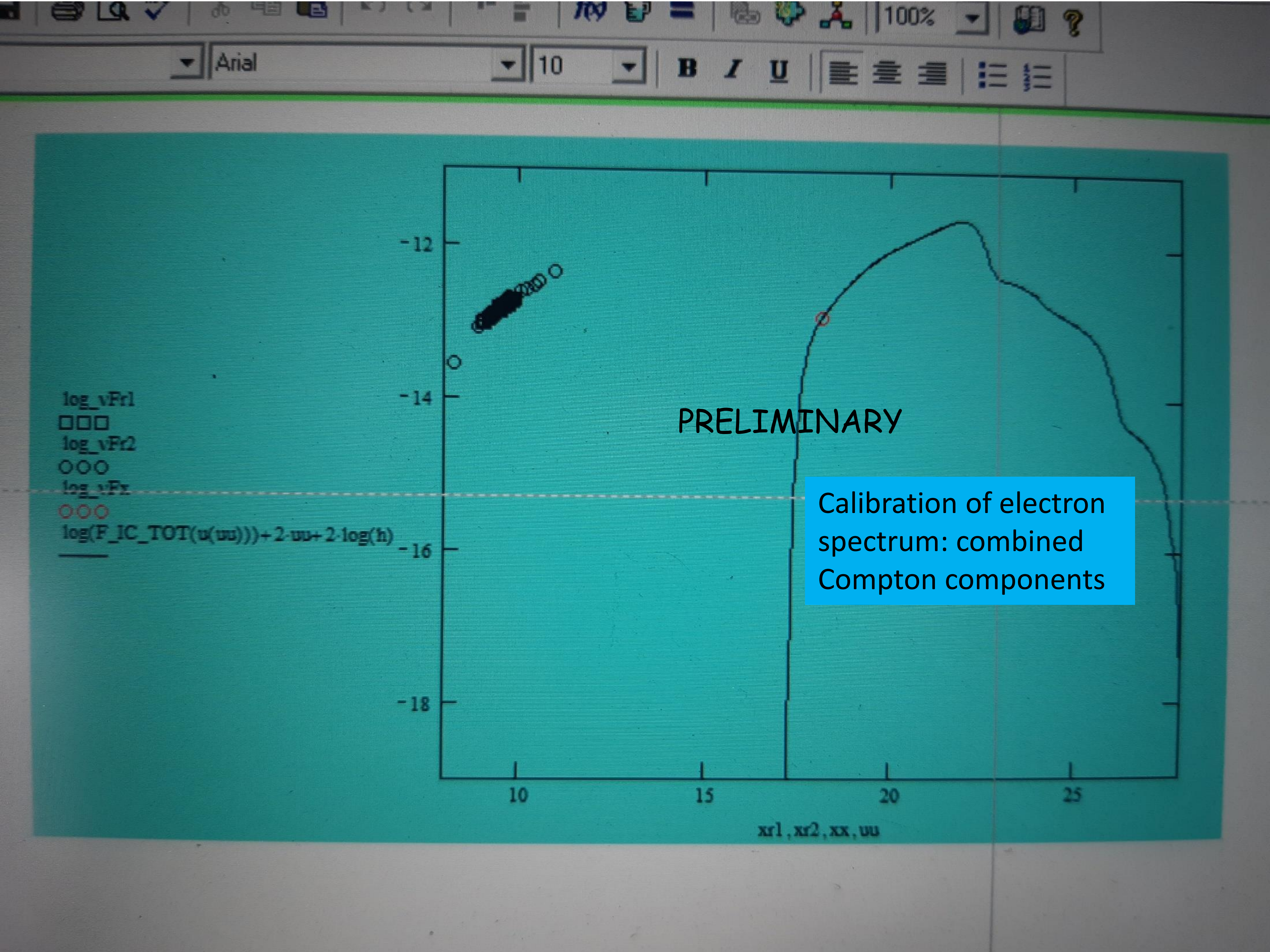
Compton/starlight
(**total**:
M82 + EBL + CMB,
primary + secondary)



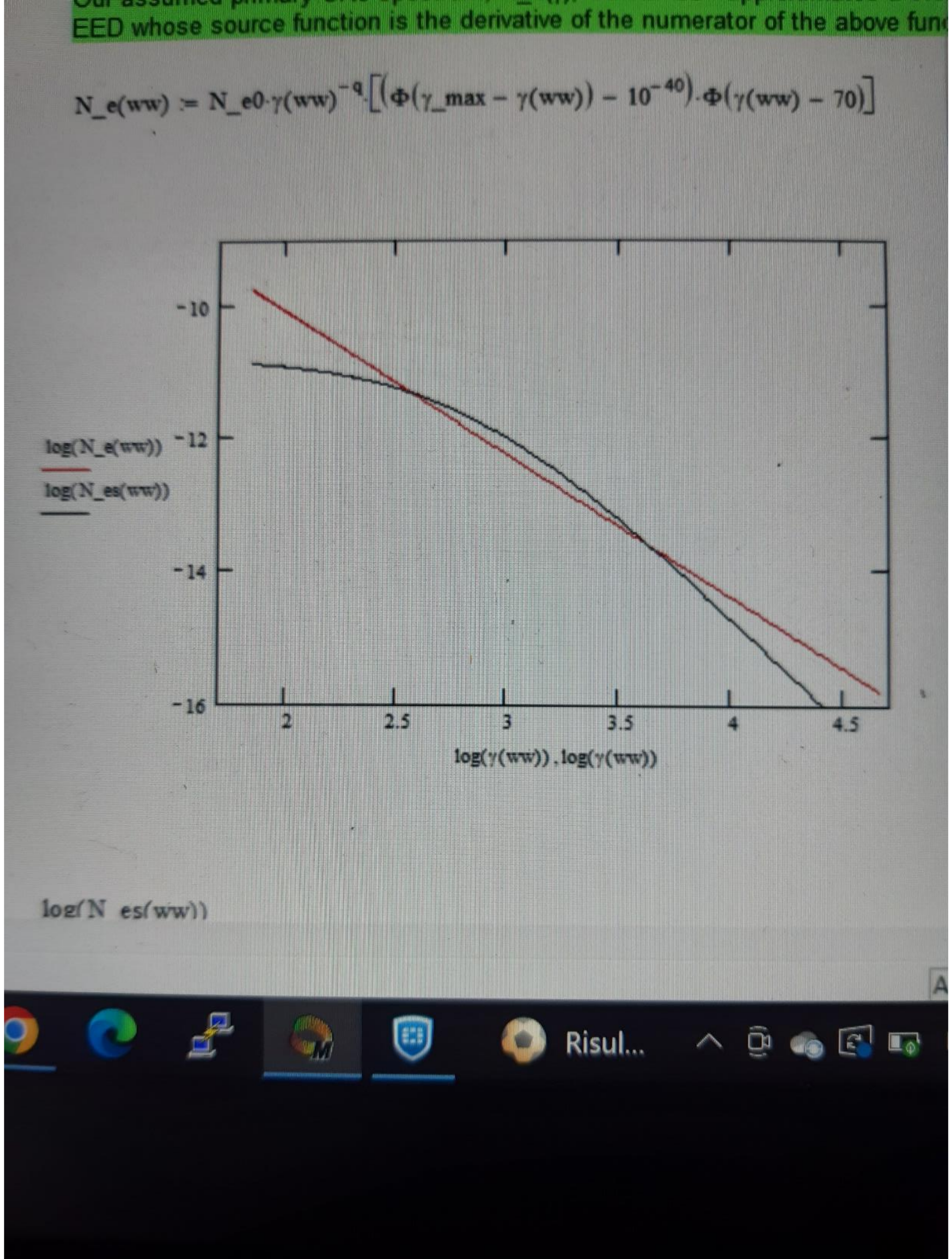
Calibration of *assumed primary* electron spectrum : X-ray flux is Comptonized starlight, EBL, CMB emission off radio electrons – separate primary & secondary components.

Calibration of the electron spectrum:
total (primary + secondary) Compton components.




100%
Arial
10
log_vFr1
log_vFr2
log_vFx
log(F_IC_TOT(u(uu)))+2·uu+2·log(h)
-12
-14
-16
-18
10
15
20
25
xr1 , xr2 , xx , uu
PRELIMINARY
Calibration of electron spectrum: combined Compton components

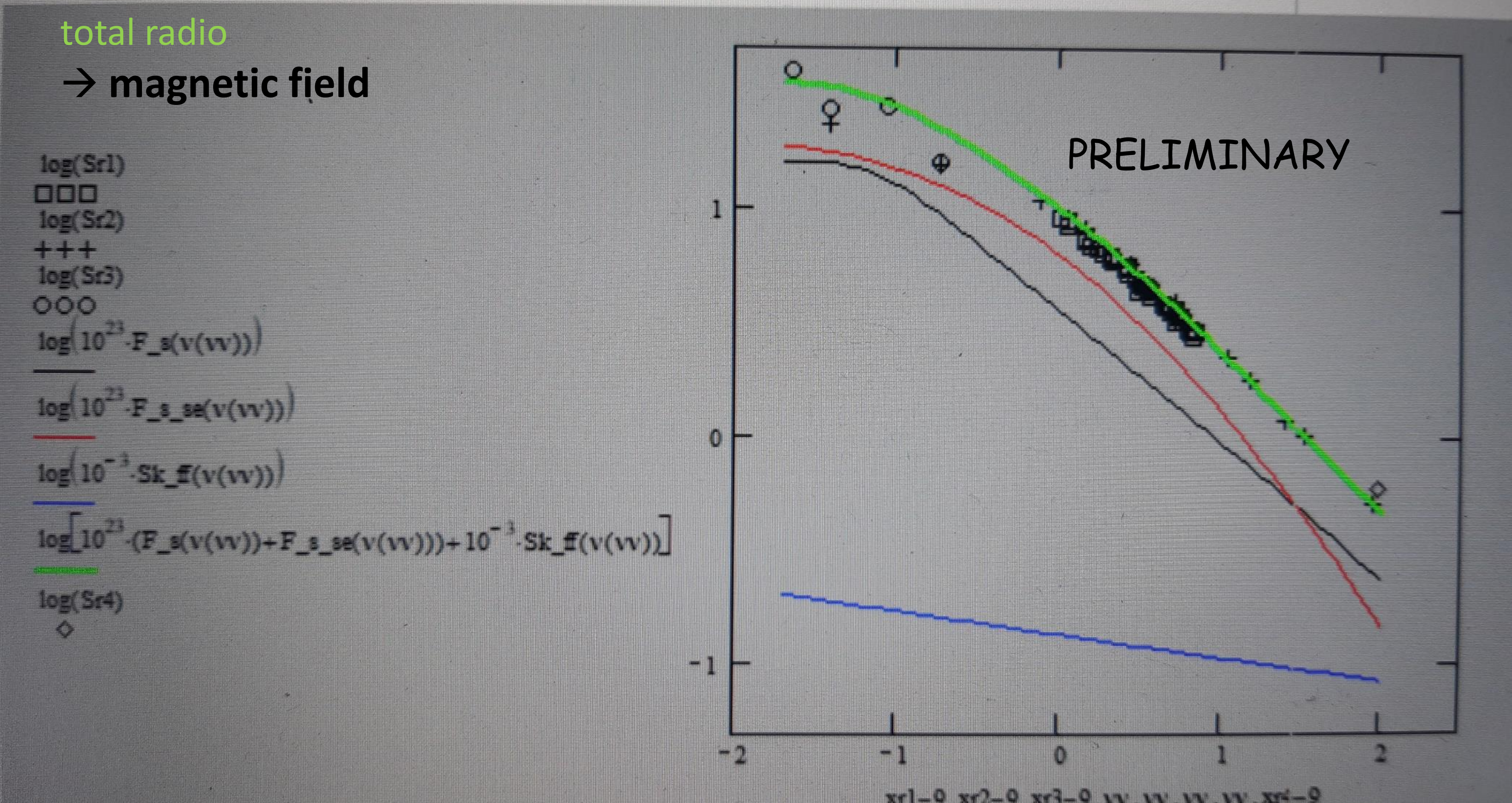
PRELIMINARY

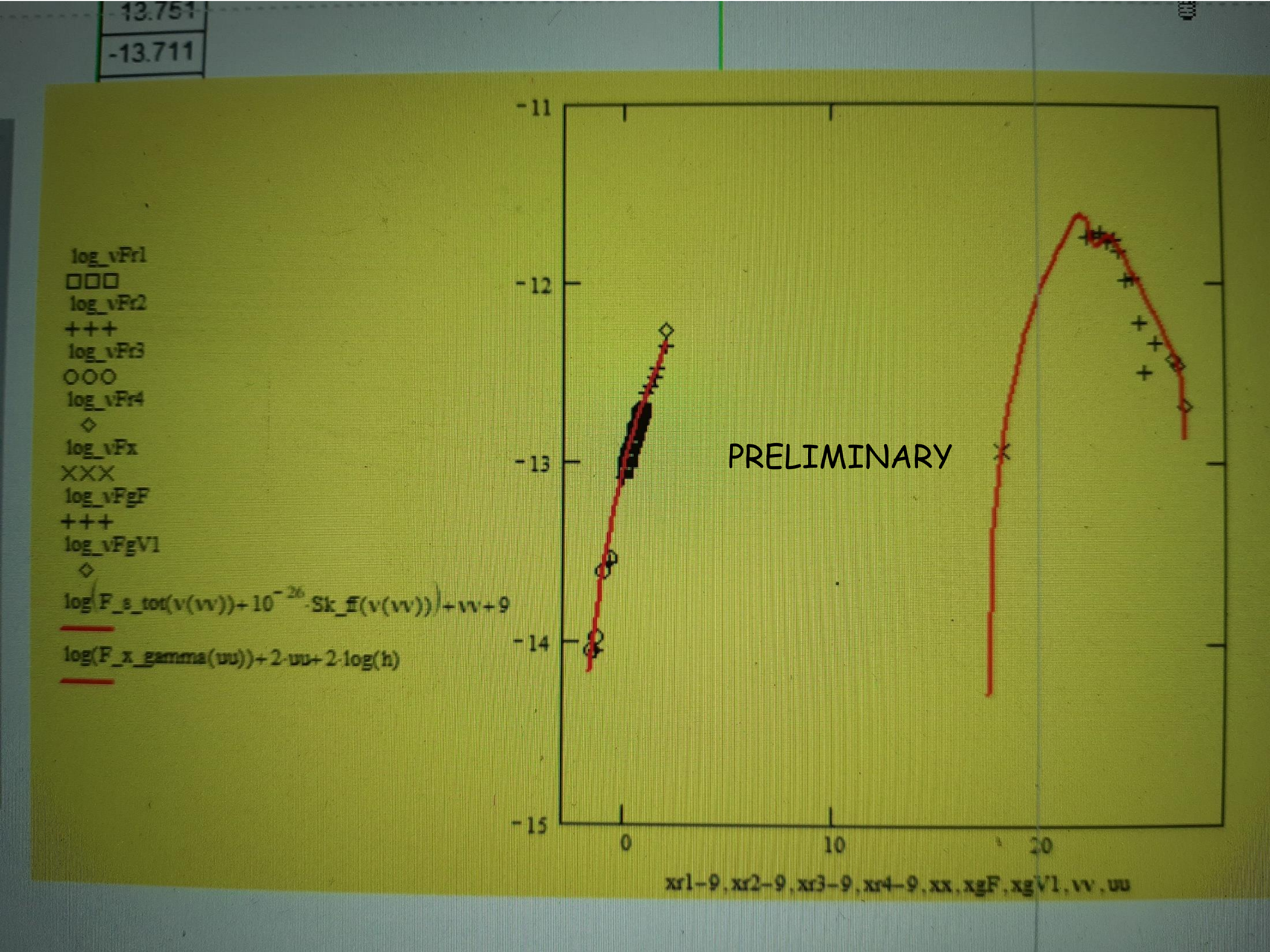


Primary electrons

Secondary electrons

Radio model:
primary & secondary synchrotron
thermal free-free emission
total radio
→ **magnetic field**





13.751
-13.711
log_vFr1
log_vFr2
log_vFr3
log_vFr4
log_vFx
log_vFgF
log_vFgV1
log(F_s_tot(v(vv))+10^-26·Sk_ff(v(vv)))+vv+9
log(F_x_gamma(uu))+2·uu+2·log(h)
PRELIMINARY
-11
-12
-13
-14
-15
0
10
20
xr1−9, xr2−9, xr3−9, xr4−9, xx, xgF, xgV1, vv, uu

M82: summary

PRELIMINARY

$B = 360\ \mu G$

$U_p = 777$ eV cm^{-3}
$U_e = 3$ eV cm^{-3} } $U_{CR} = 780$ eV cm^{-3} → $B_{eq} = 177\ \mu G \sim ½ B$

Primary electon spectral index: $q_e = 2.25$
Proton spectral index $q_p = 2.25$ } → $q_p \sim q_e \sim$ injection index

Electron timescales:
primary : $t_{inj} << t_{energy\ loss}$ → injection (PL) spectrum
secondary: $t_{inj} >> t_{energy\ loss}$ → steady-state (=curved) PL

Proton timescale: $t_{inj} << t_{energy\ loss}$ → injection (PL) spectrum

Low fraction of proton energy into $\pi^{0\pm}$-decay products (γ rays, secondaries)

Conclusions

- homogeneous SED modeling of SFG sample.
  - no minimum–χ^2 fit, physically motivated model matching data.
- theoretically motivated (primary) electron spectrum.
- exact calculations of electron radiative yields, pion-decay yields.
- EBL model (Franceschini & Rodighiero 2017).
- source-specific FGL.
- NT X-rays: Compton/(starlight+CMB) → N_{e0}, γ_{min}.
- radio → q_e , γ_{max}.

(both) → B

- Electron Compton scattering of CMB/EBL/FGL photons → γ rays.
- γ rays: hadronic in SFG ($u_p \sim \mathcal{O}(1)$ eV cm^{-3}), SBG ($u_p \sim \mathcal{O}(10^2)$ eV cm^{-3})
- X-ray data *crucial* (to calibrate NT electron spectrum):

Current: *Chandra*, XMM: 1999; INTEGRAL: 2002; *Swift*: 2004; NuSTAR: 2012; [eRosita: 2019, but stopped since Feb 2022]; XRISM: 2023; Athena: 2035?

- GeV data *crucial* (to probe CRp): what after *Fermi* (2008)?

The End
Thank you!