

Materia Oscura:
alla Ricerca di una Tenue Luce

Capitolo 1

Misurare la Massa dell'Universo
o almeno di una galassia



NIST's Eddie Mulhern holding K92, one of the agency's kilogram samples.

Credit: J.L. Lee/NIST

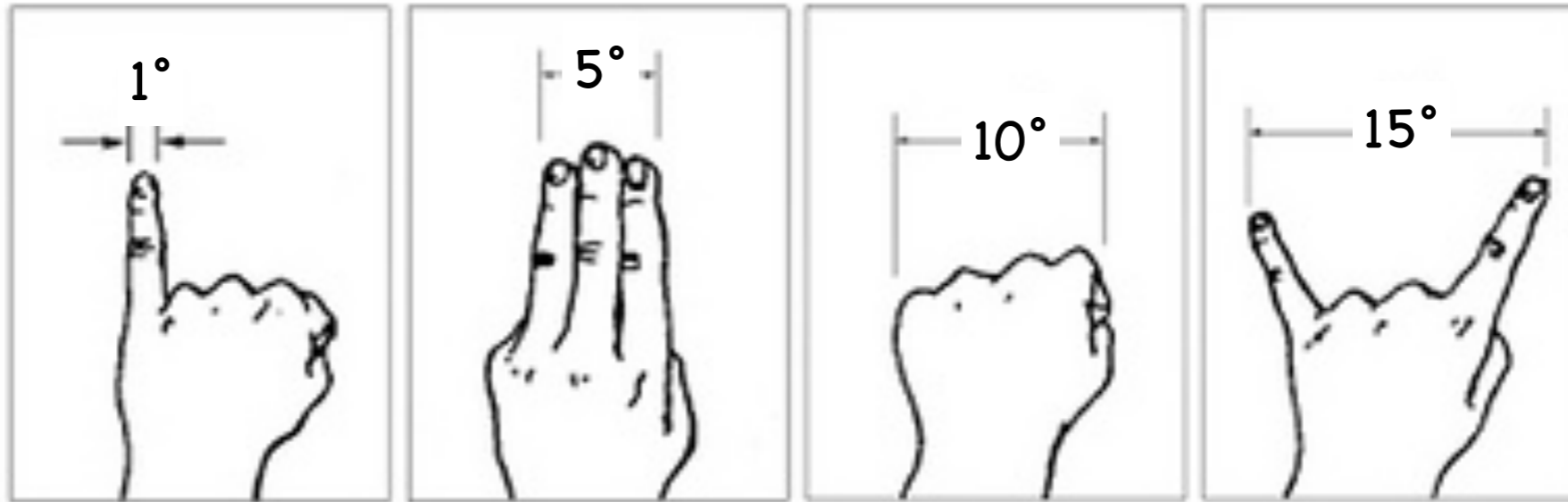
Notte Stellata sul Rodano (V. van Gogh 1888)

Cosa Possiamo Misurare Direttamente?

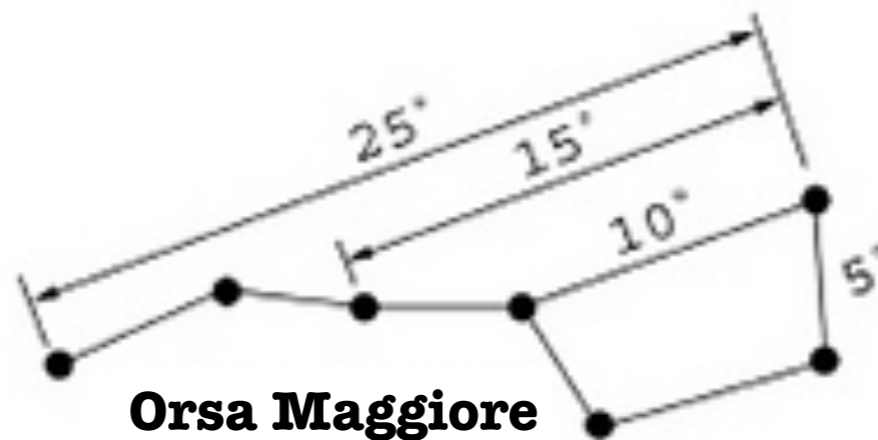
- Fino a poco tempo fa non molto oltre:
 - la distanza angolare apparente fra due galassie
 - l'intensità luminosa apparente di ciascuna galassia
 - il colore apparente di ciascuna galassia

Distanza angolare apparente

- Misure angolari per astrofili dilettanti

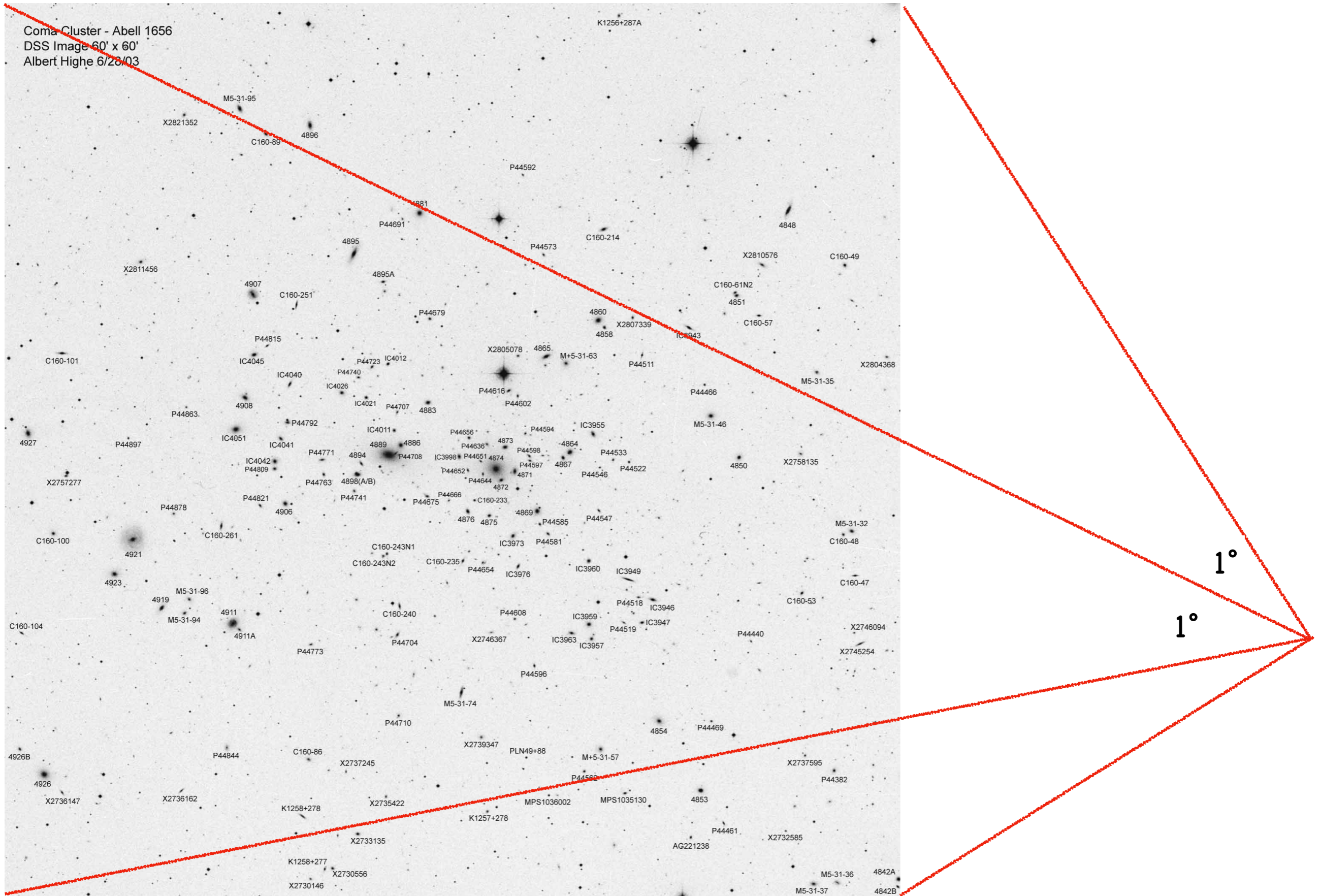


Tenete il braccio completamente teso e guardate il cielo attraverso le mire

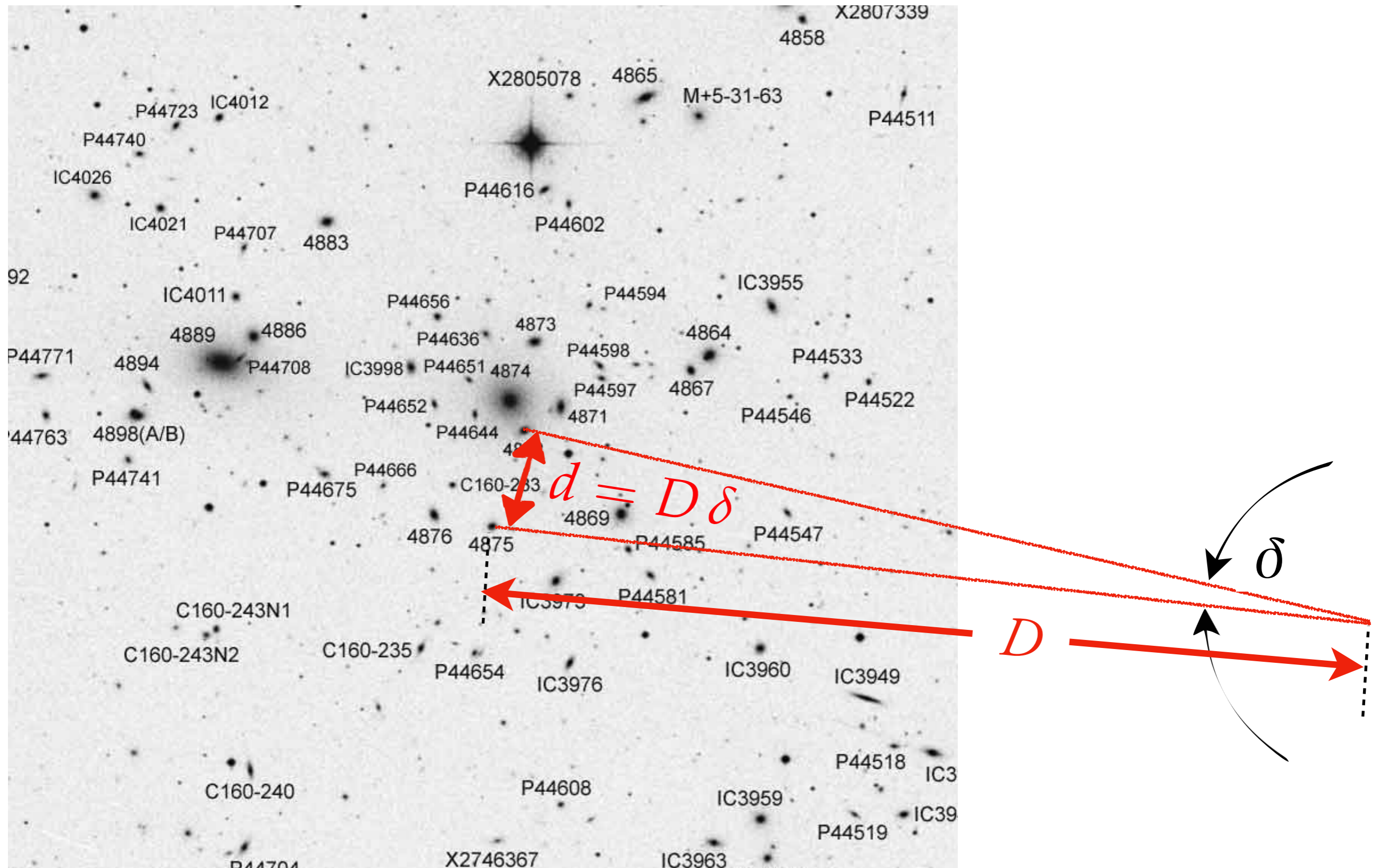


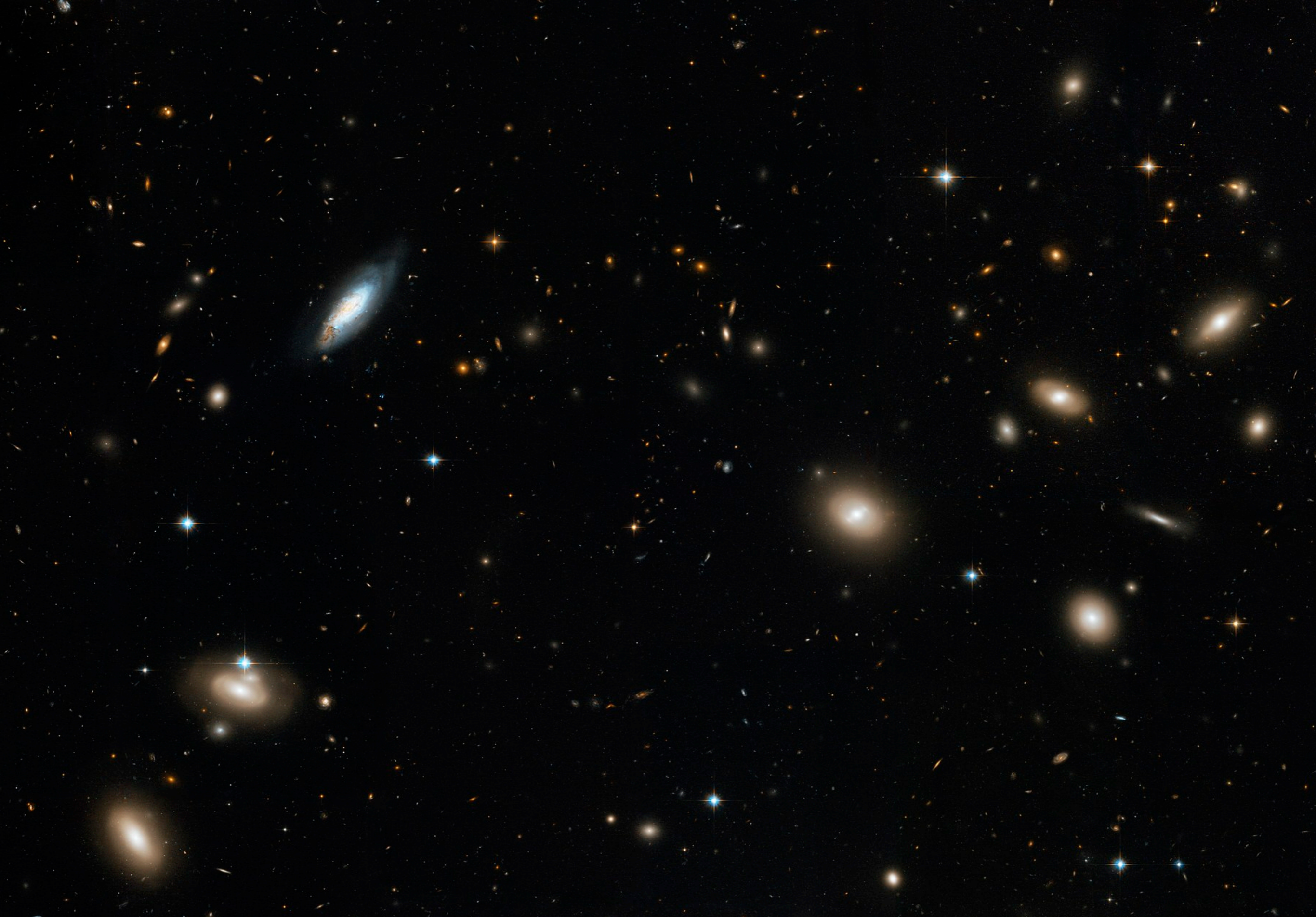
Campioni angolari a portata di mano (letteralmente)

Il Cluster di Galassie nella Chioma di Berenice



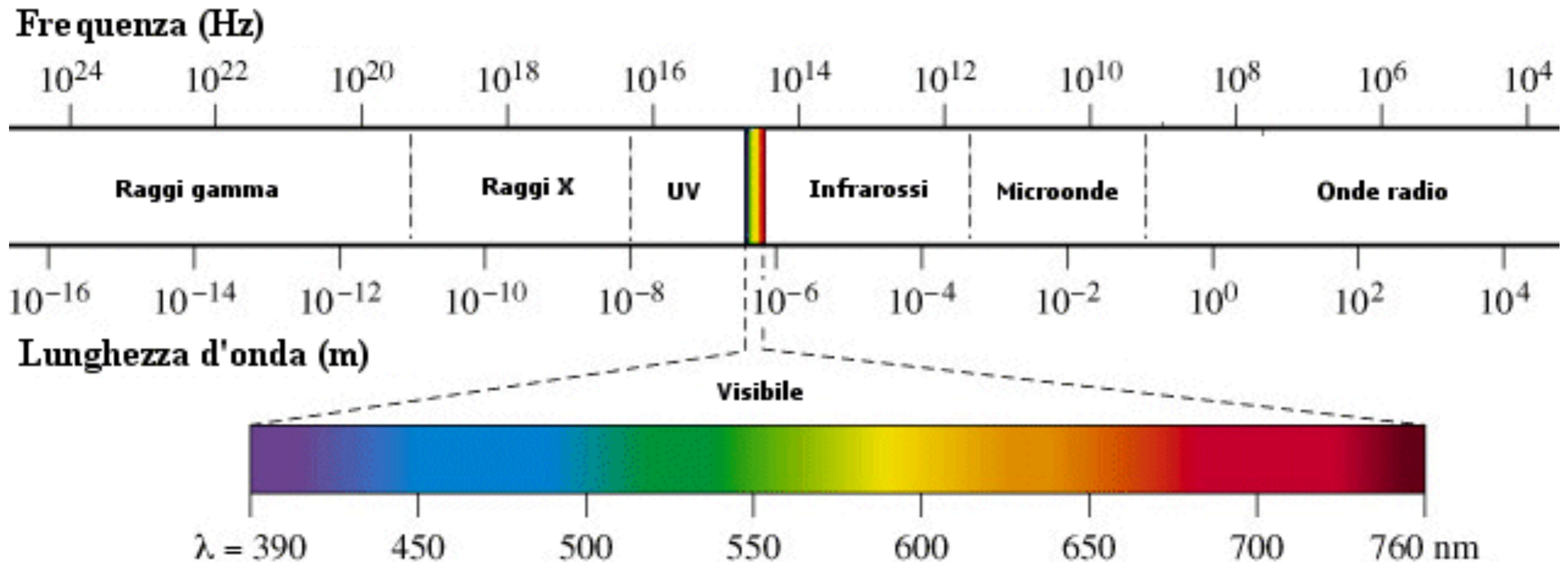
Il Cluster di Galassie nella Chioma di Berenice





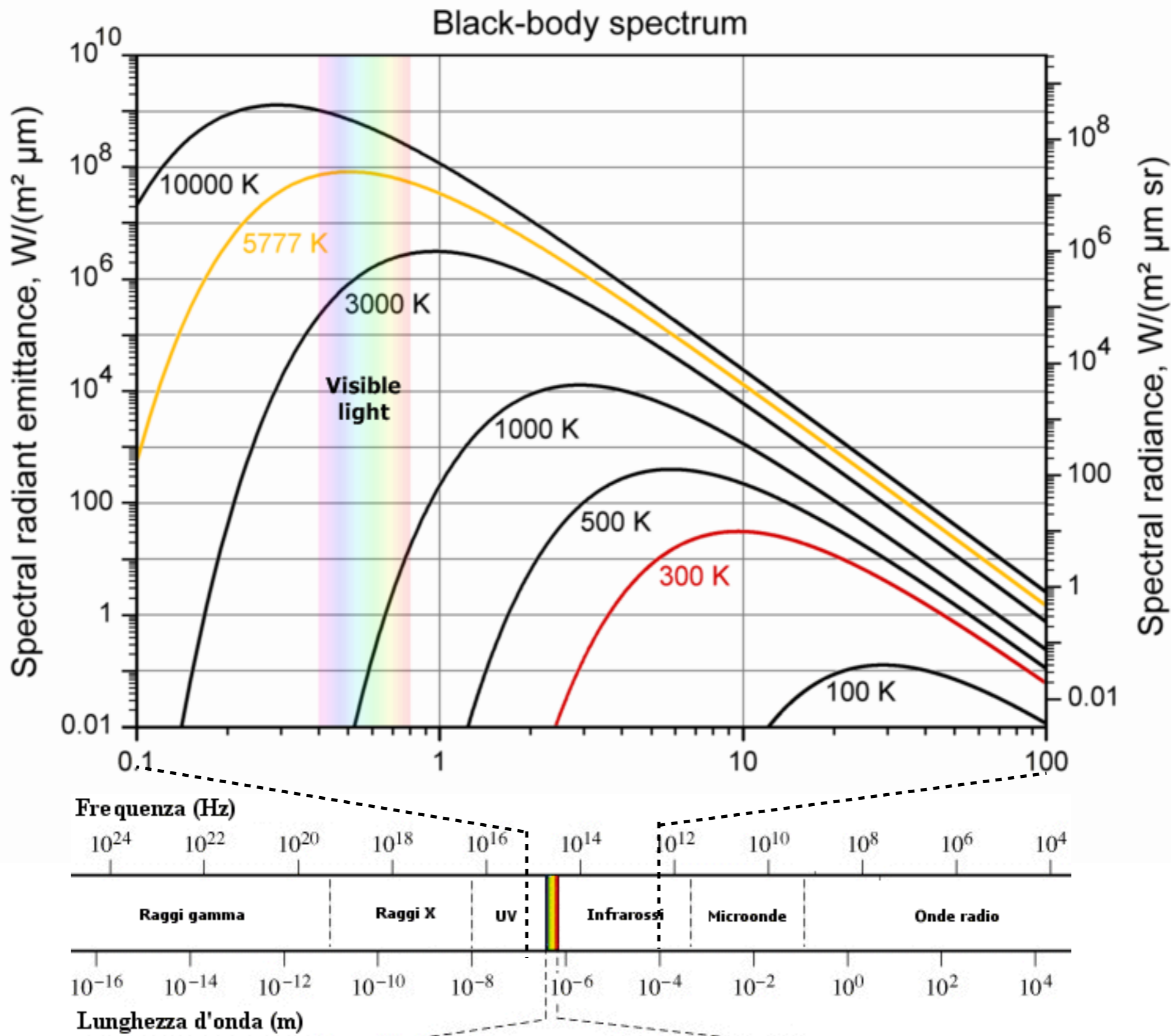
Ammasso di Galassie nella Costellazione "Coma Berenices" (Chioma di Berenice)
visto dall' Hubble's Advanced Camera for Surveys

Il Colore di Una Galassia



- Lo spettro delle onde elettromagnetiche su 20 ordini di grandezza

Radiazione di Corpo Nero



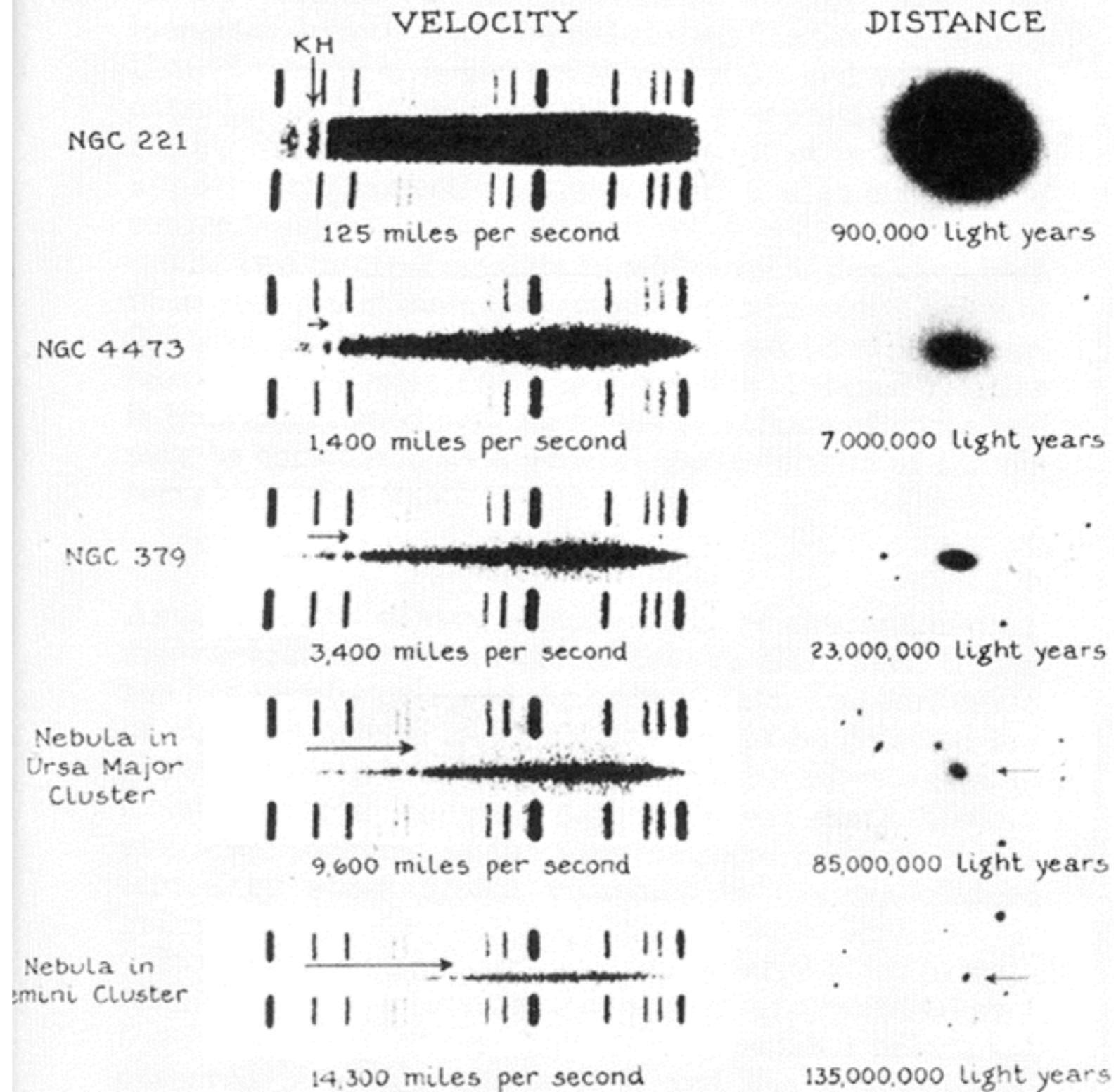
Spettri di emissione degli elementi

H																He	
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Hubble

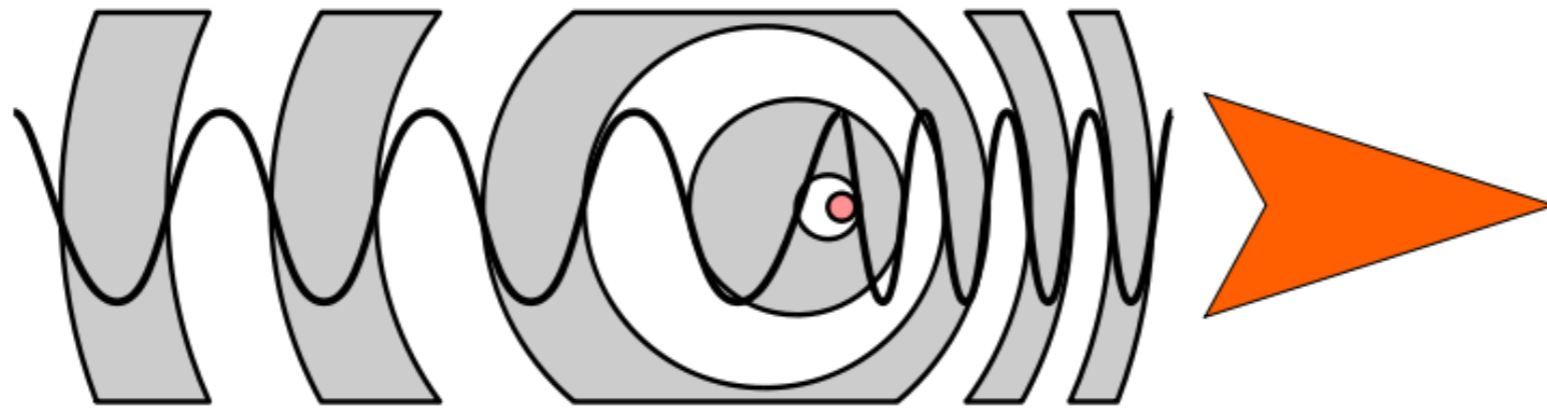
THE VELOCITY-DISTANCE RELATION FOR EXTRA-GALACTIC NEBULAE



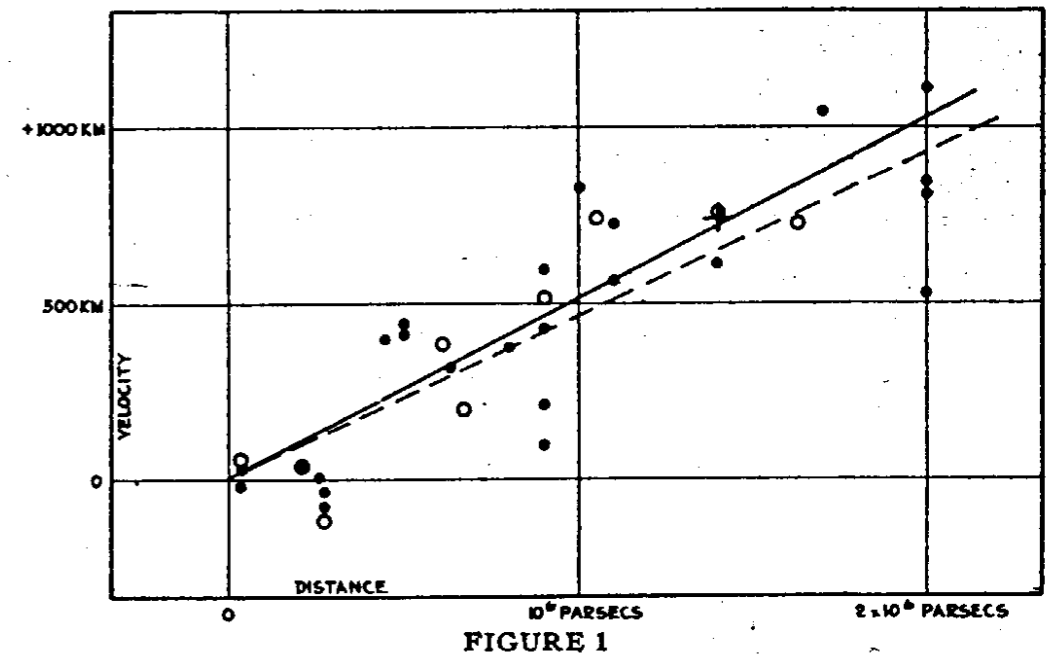
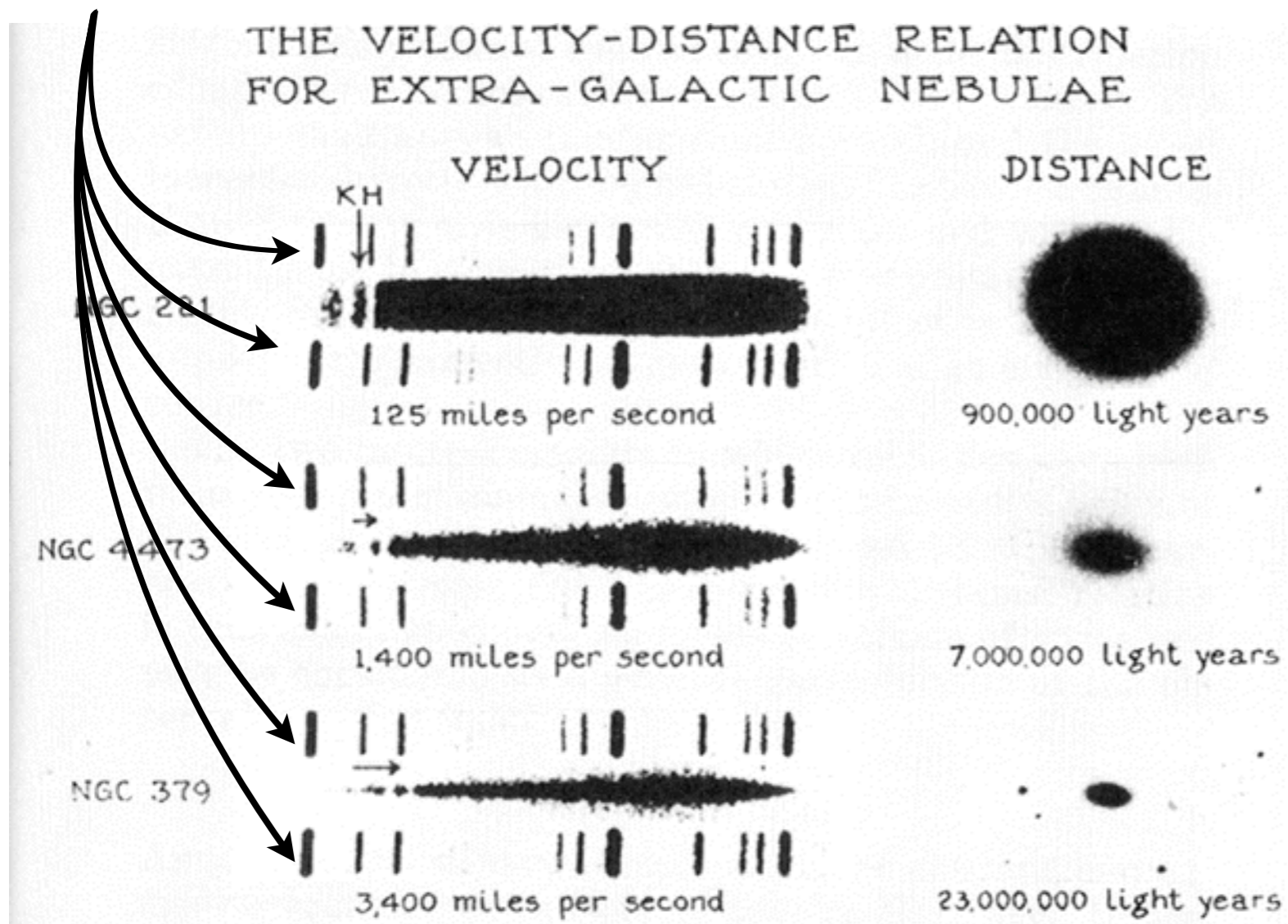
The arrows above the nebular spectra point to the H and K lines of calcium and show the amounts these lines are displaced toward the red end of the spectra. The comparison spectra are of helium.

The direct photographs (on the same scale and with approximately the same exposure times) illustrate the decrease in size and brightness with increasing velocity or red-shift.

Effetto Doppler: misure di velocità & distanza



Spettro dell'Elio (sorgente in lab)



Distanza valutata dal red shift
Velocità lungo la linea di vista valutata dall'effetto Doppler
Dimensione valutata dall'estensione angolare dell'ammasso

$$\overline{\sum_i \frac{1}{2} m_i v_i^2} = \overline{\sum_i \sum_{j < i} \frac{G m_i m_j}{r_{ij}}}$$

$$M v^2 \simeq \frac{G M^2}{R}$$

$$M \simeq \frac{v^2 R}{G}$$

Fritz Zwicky al telescopio da 18 pollici del Palomar Observatory negli anni trenta.

L'Interpretazione di Zwicky

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

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NUMBER 3

ON THE MASSES OF NEBULAE AND OF
CLUSTERS OF NEBULAE

F. ZWICKY

$$\overline{\sum_i \frac{1}{2} m_i v_i^2} = \overline{\sum_i \sum_{j<i} \frac{G m_i m_j}{r_{ij}}}$$

$$M v^2 \simeq \frac{G M^2}{R}$$

$$M \simeq \frac{v^2 R}{G}$$



Combining (33) and (34), we find

$$M > 9 \times 10^{46} \text{gr}. \quad (35)$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\bar{M} > 9 \times 10^{43} \text{gr} = 4.5 \times 10^{10} M_{\odot}. \quad (36)$$

[...]

This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

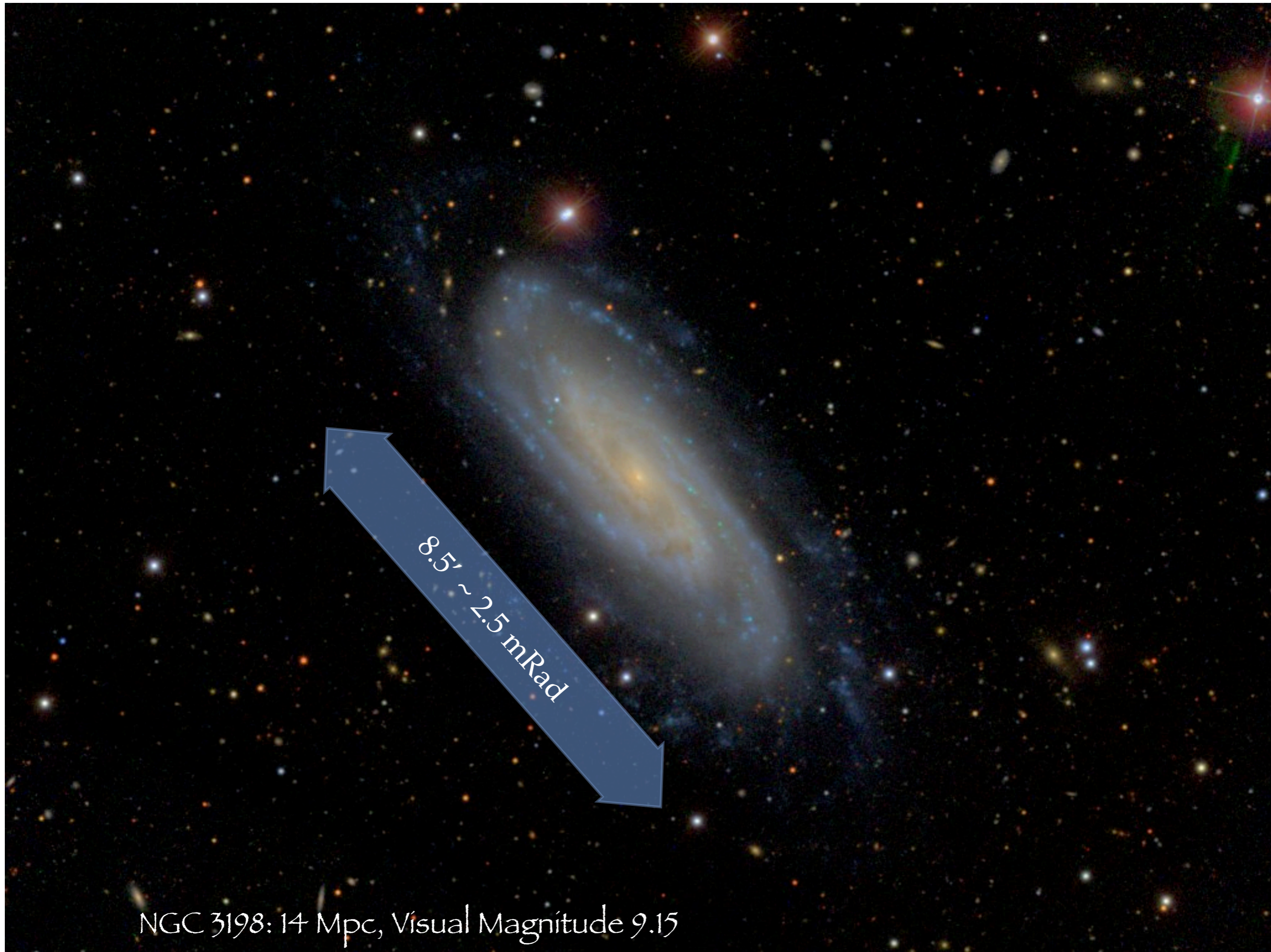
Curve di Rotazione

- Ciò che tiene assieme le galassie in un ammasso è ciò che tiene assieme le stelle in una galassia

$$\mathbf{f} = -\hat{r} m \frac{v^2}{r} \simeq -\hat{r} G \frac{m M}{r^2}$$

$$M \simeq \frac{r v^2}{G}$$

Vera Rubin (circa 1947)



NGC 3198: 14 Mpc, Visual Magnitude 9.15



Vera Rubin (circa 1955)

DISTRIBUTION OF DARK MATTER IN THE SPIRAL GALAXY NGC 3198

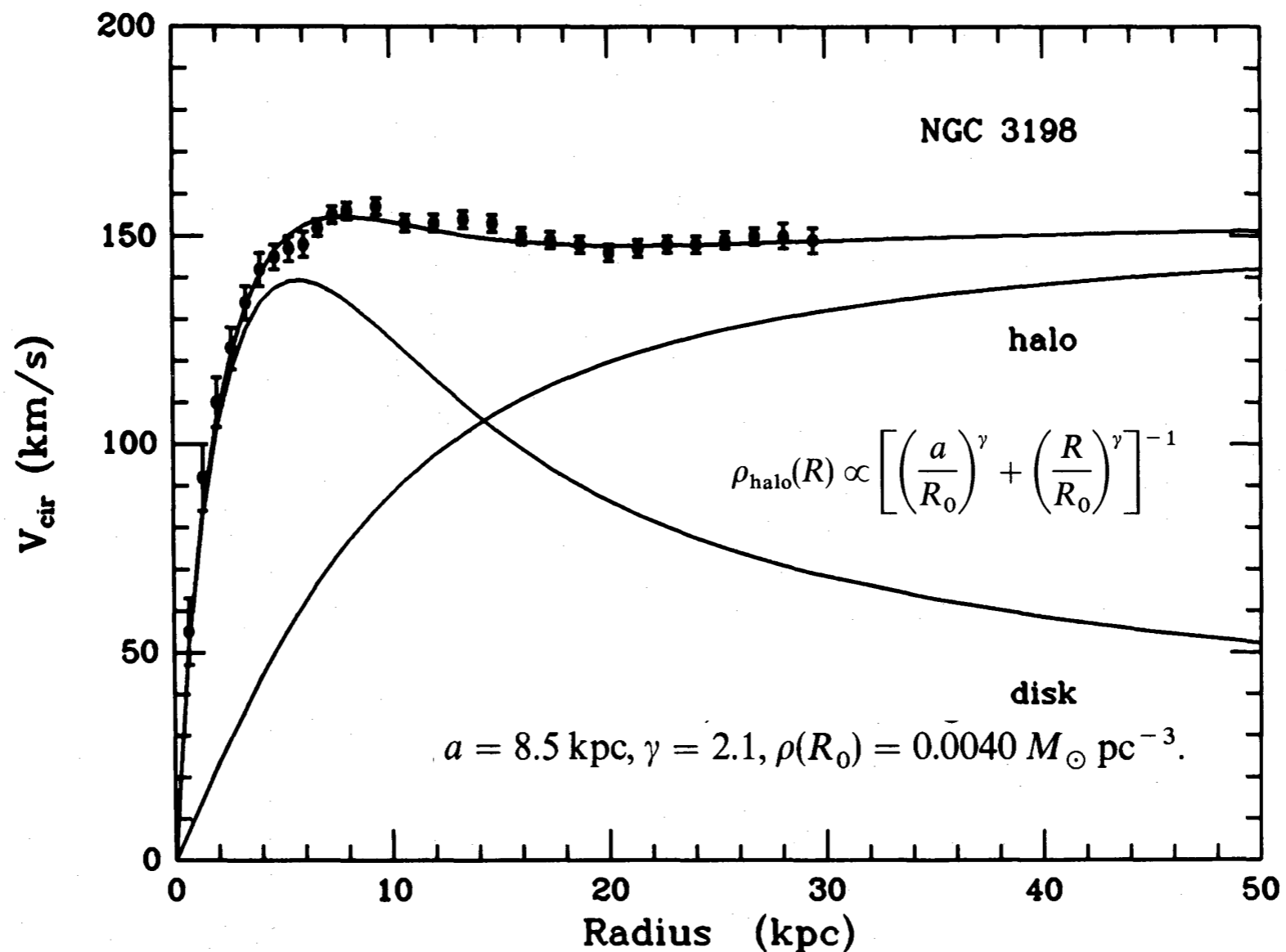
T. S. VAN ALBADA,¹ J. N. BAHCALL,² K. BEGEMAN,¹ AND R. SANSCISI¹

Received 1984 August 13; accepted 1985 February 26

ABSTRACT

Two-component mass models, consisting of an exponential disk and a spherical halo, are constructed to fit a newly determined rotation curve of NGC 3198 that extends to 11 disk scale lengths. The amount of dark matter inside the last point of the rotation curve, at 30 kpc, is at least 4 times larger than the amount of visible matter, with $(M/L_B)_{\text{tot}} = 18 M_{\odot}/L_{B\odot}$. The maximum mass-to-light ratio for the disk is $M/L_B = 3.6$. The available data cannot discriminate between disk models with low M/L and high M/L , but we present arguments which suggest that the true mass-to-light ratio of the disk is close to the maximum computed value. The core radius of the distribution of dark matter is found to satisfy $1.7 < R_{\text{core}} < 12.5$ kpc.

Subject headings: galaxies: individual — galaxies: internal motions — interstellar: matter

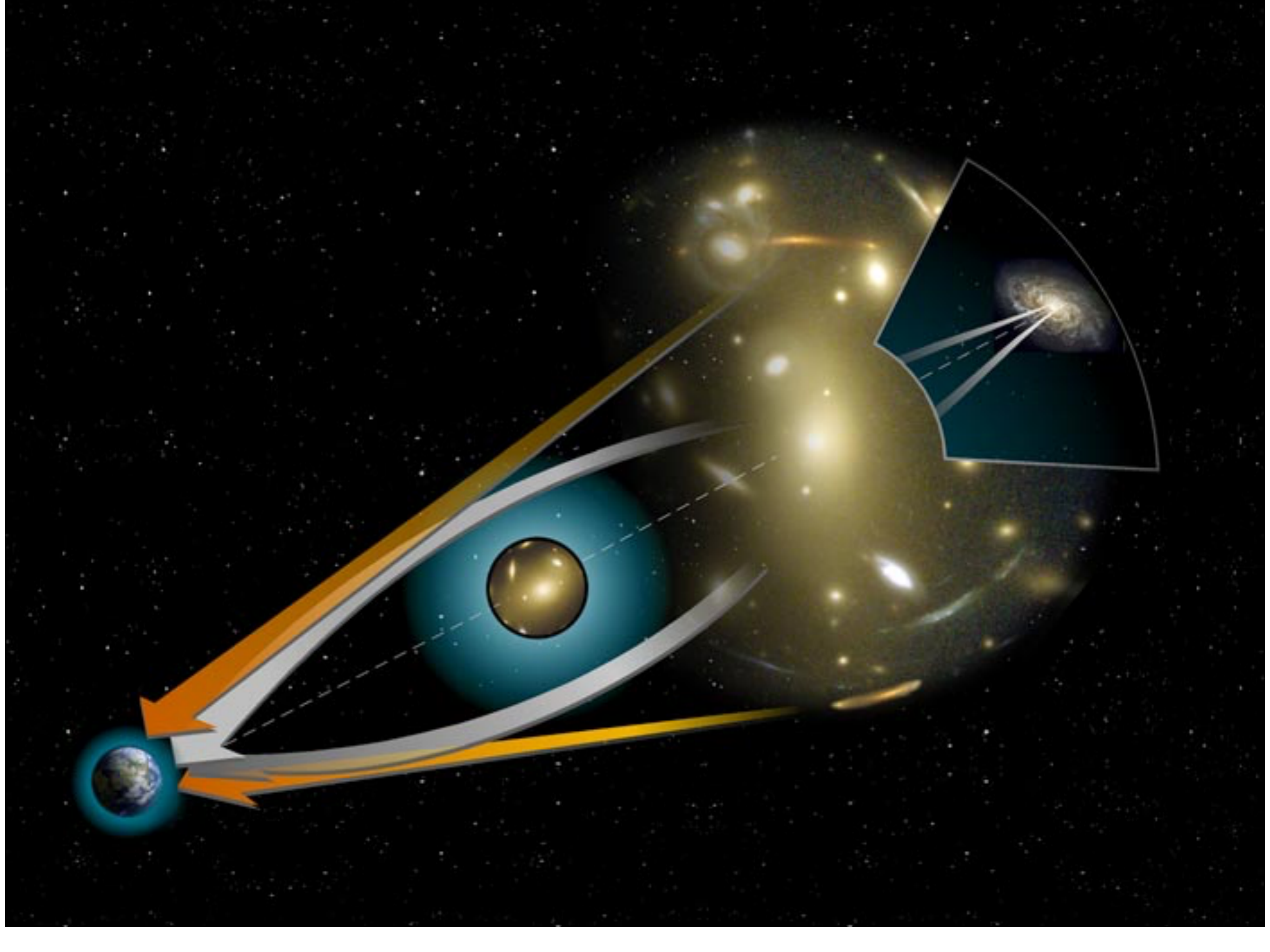


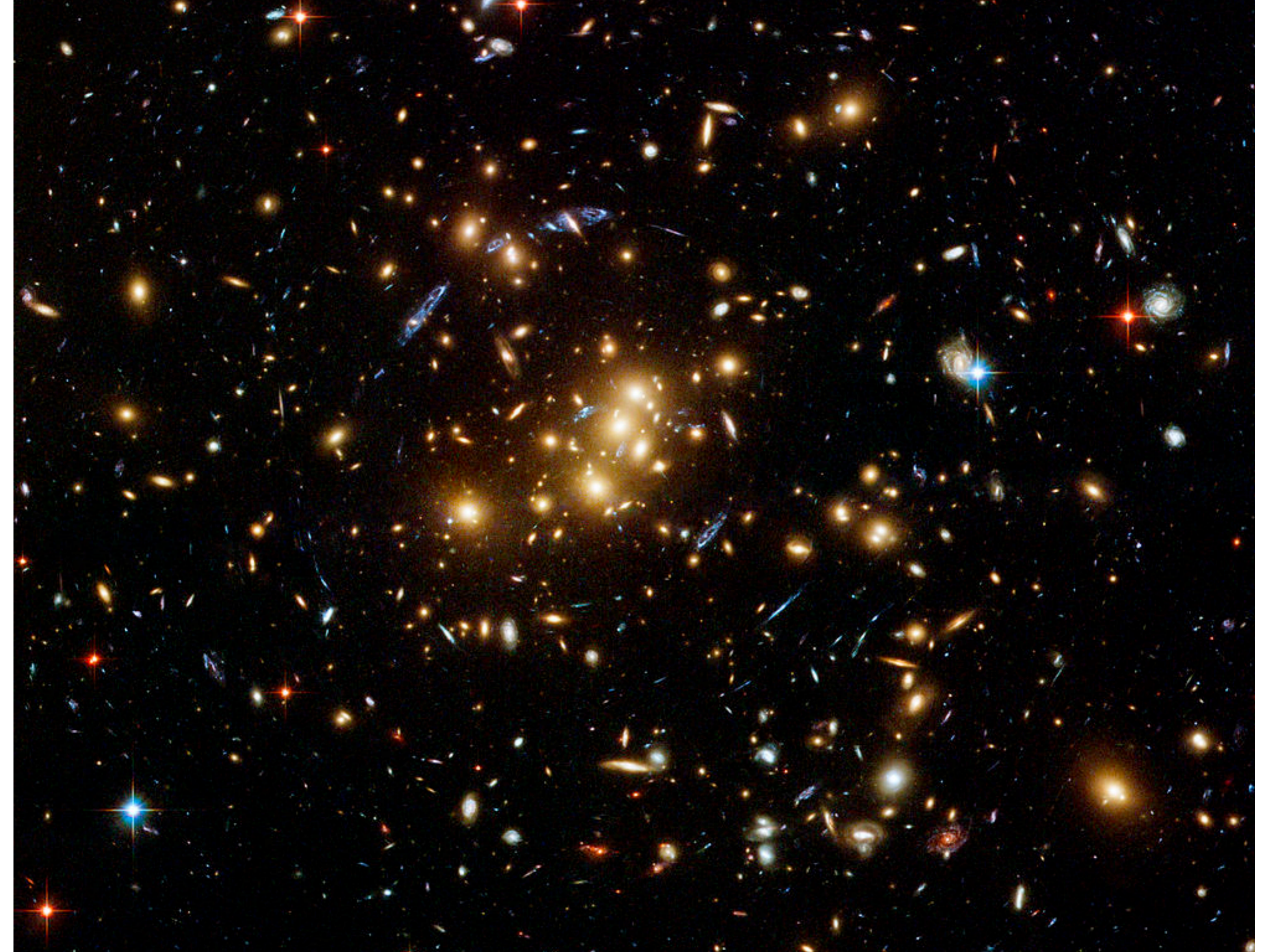
Lensing Gravitationale

- La luce (per definizione) segue nel vuoto una traiettoria rettilinea
- Non sempre la geometria descritta da queste rette è euclidea

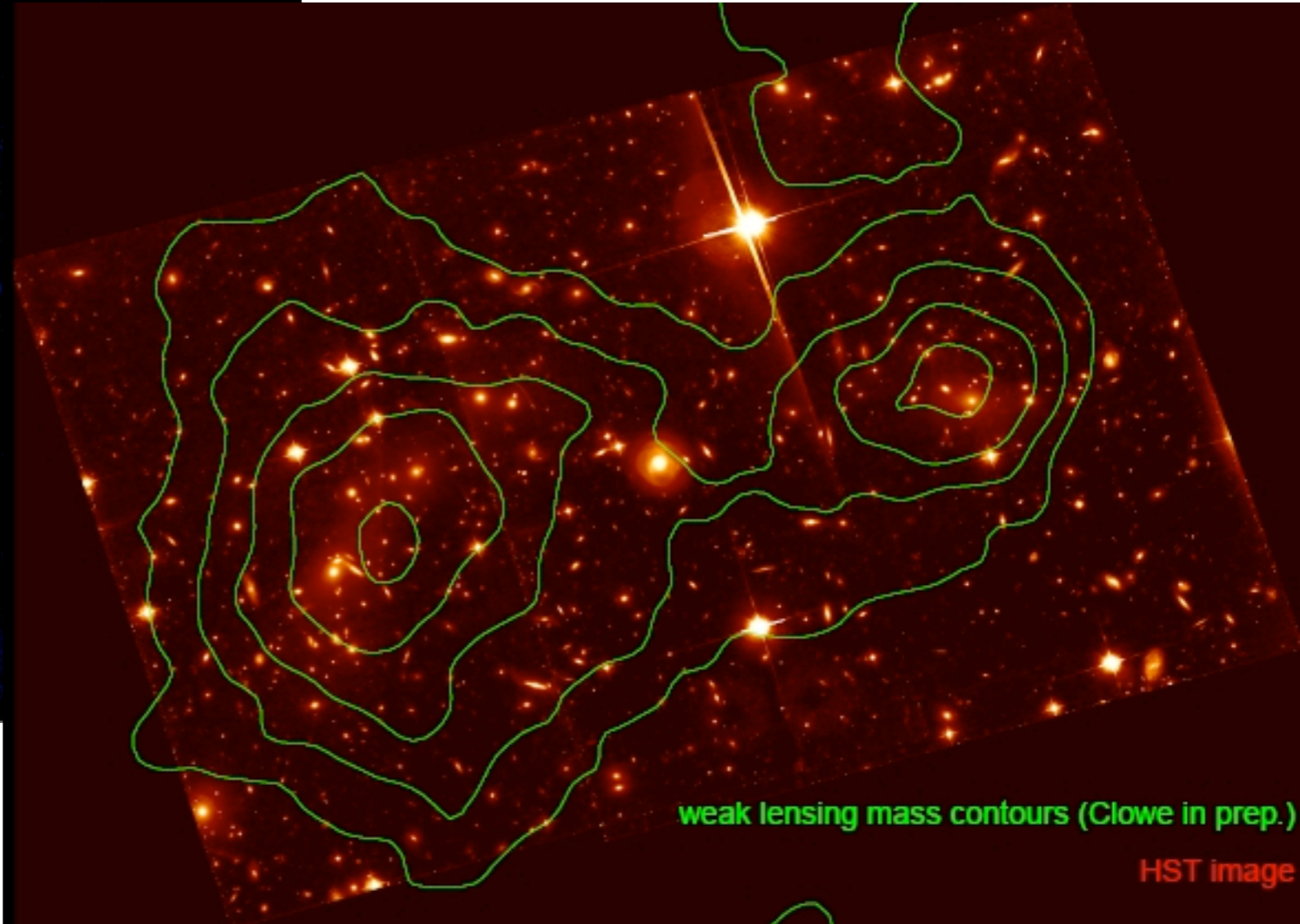
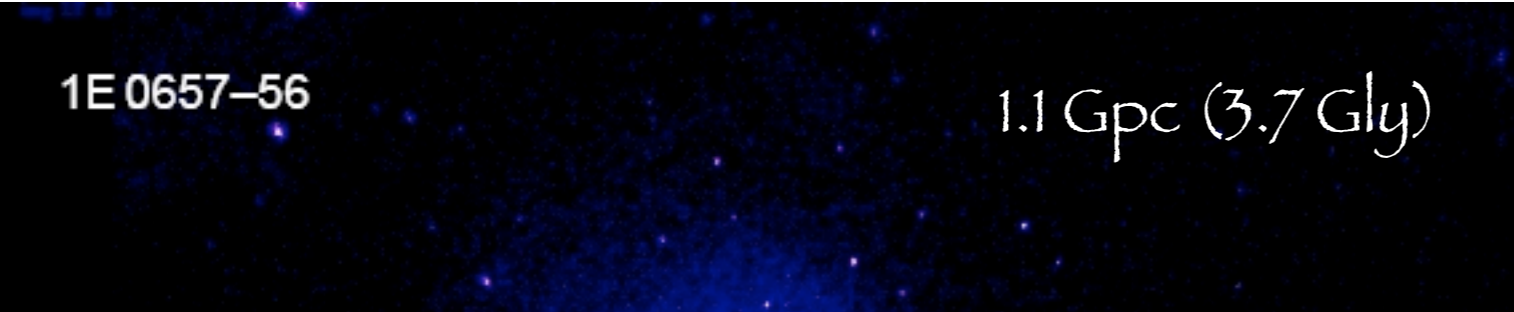


Photographer Shawn Malone captured this Fata Morgana of an ore boat on Lake Superior on May 22, 2015 in Marquette, Michigan.





WEAK-LENSING MASS RECONSTRUCTION OF THE INTERACTING CLUSTER 1E 0657–558: DIRECT EVIDENCE FOR THE EXISTENCE OF DARK MATTER¹

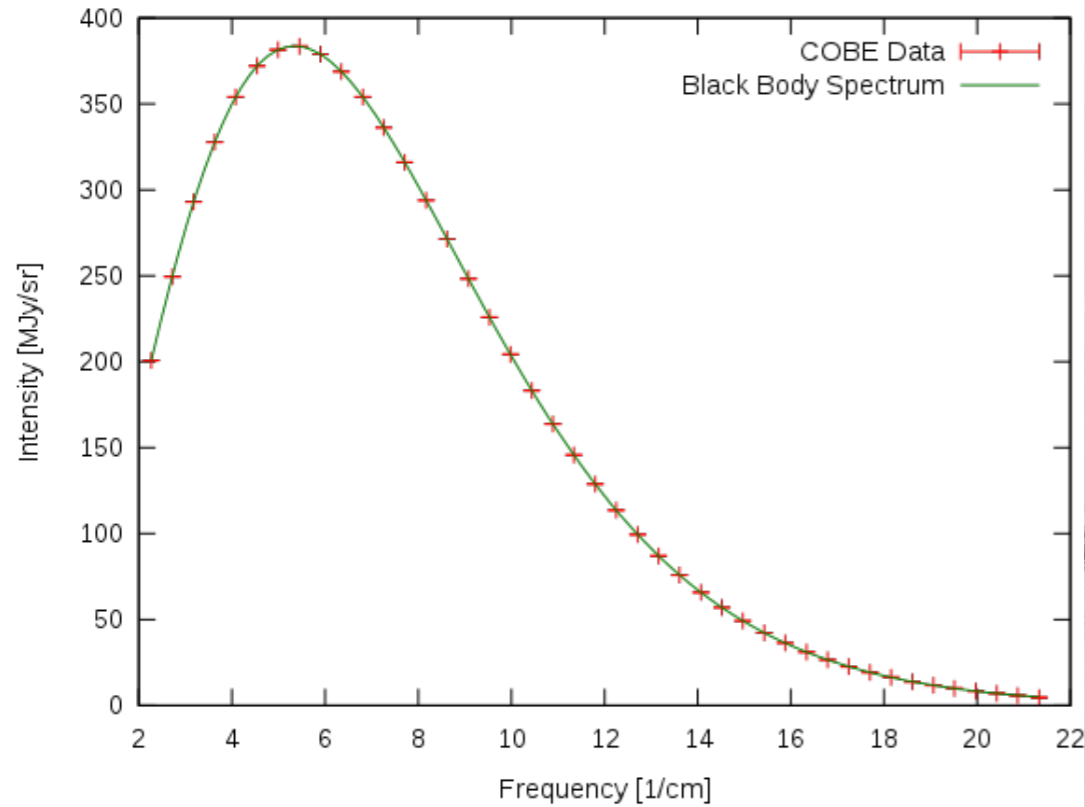


La combinazione delle due foto

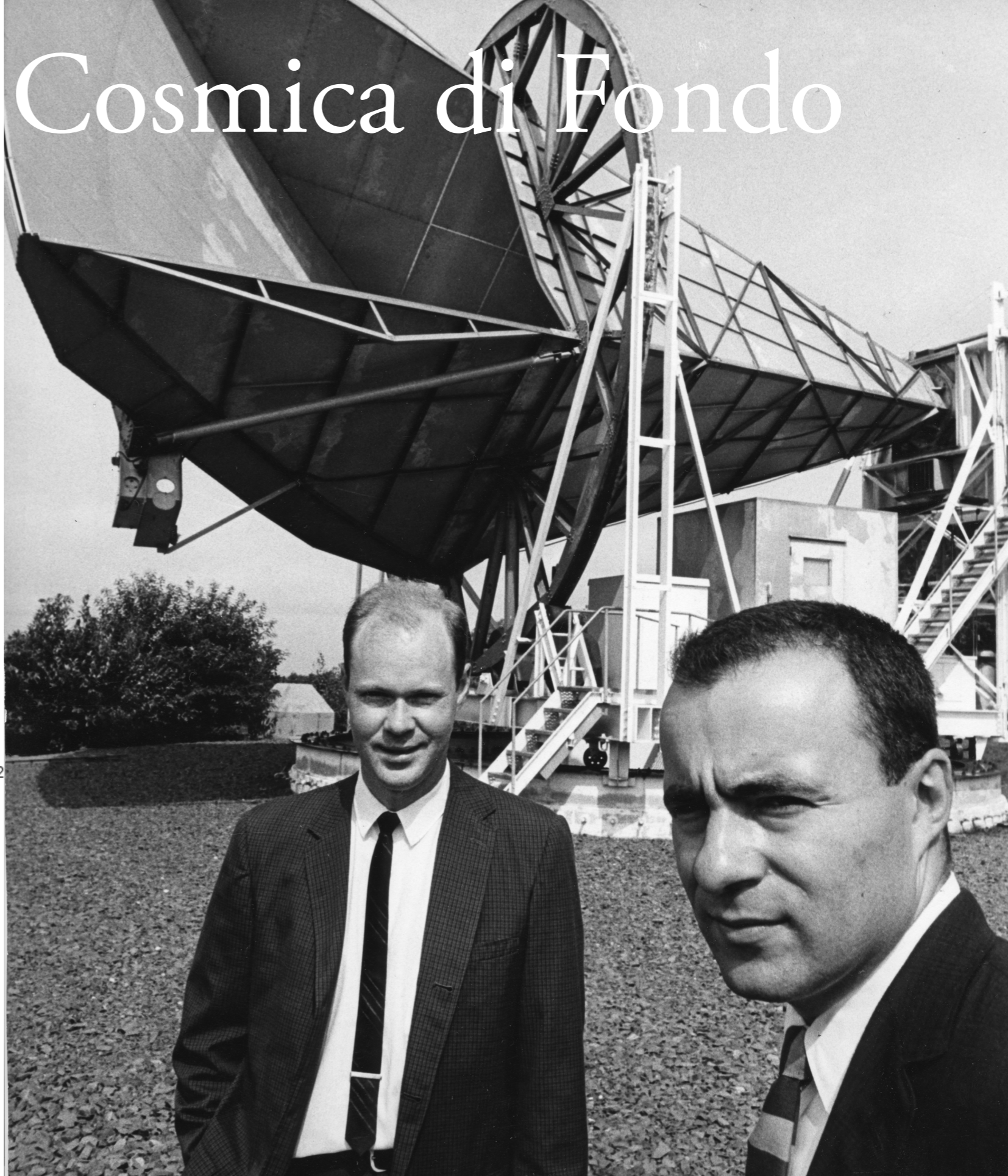


Radiazione Cosmica di Fondo

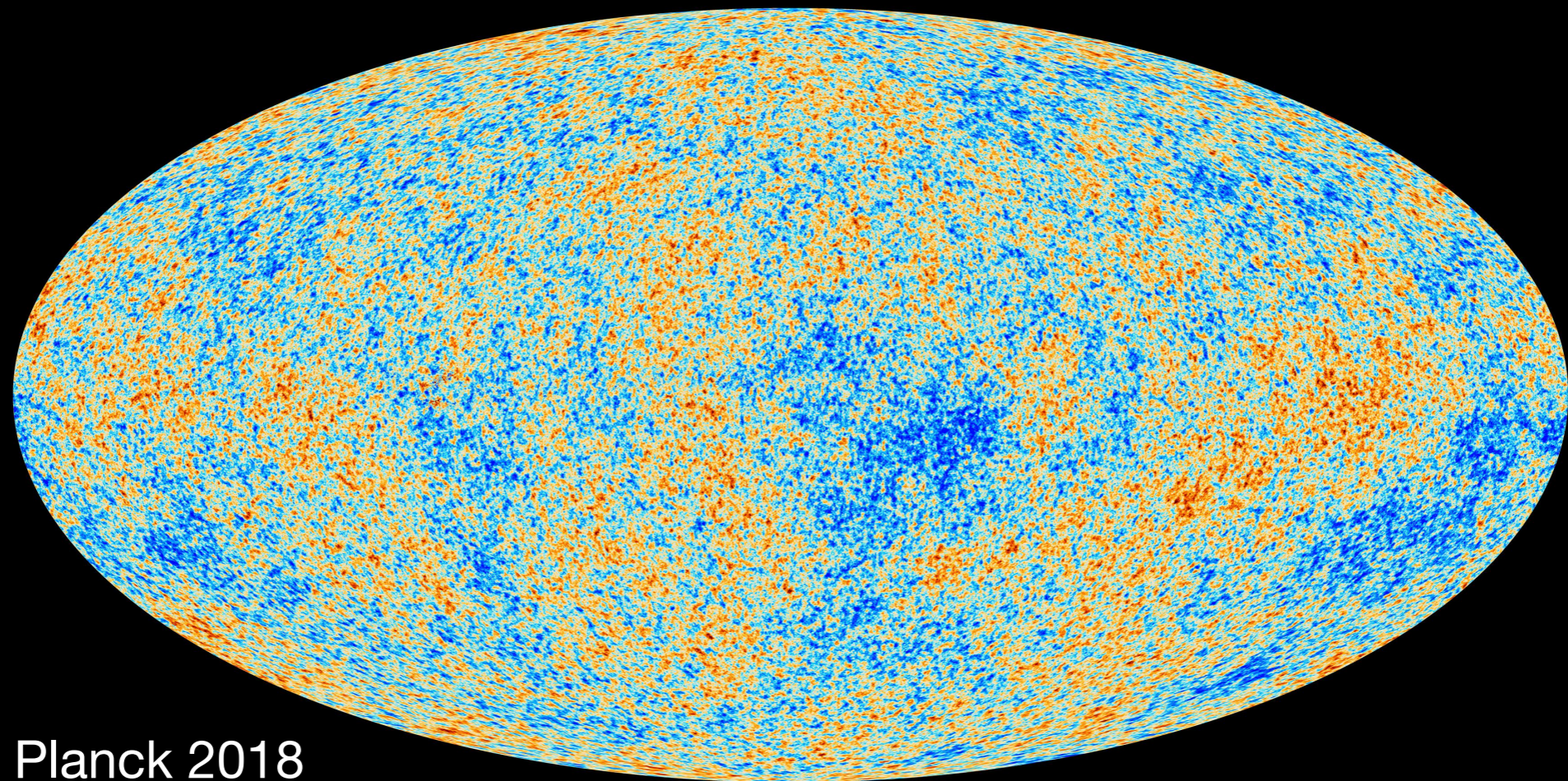
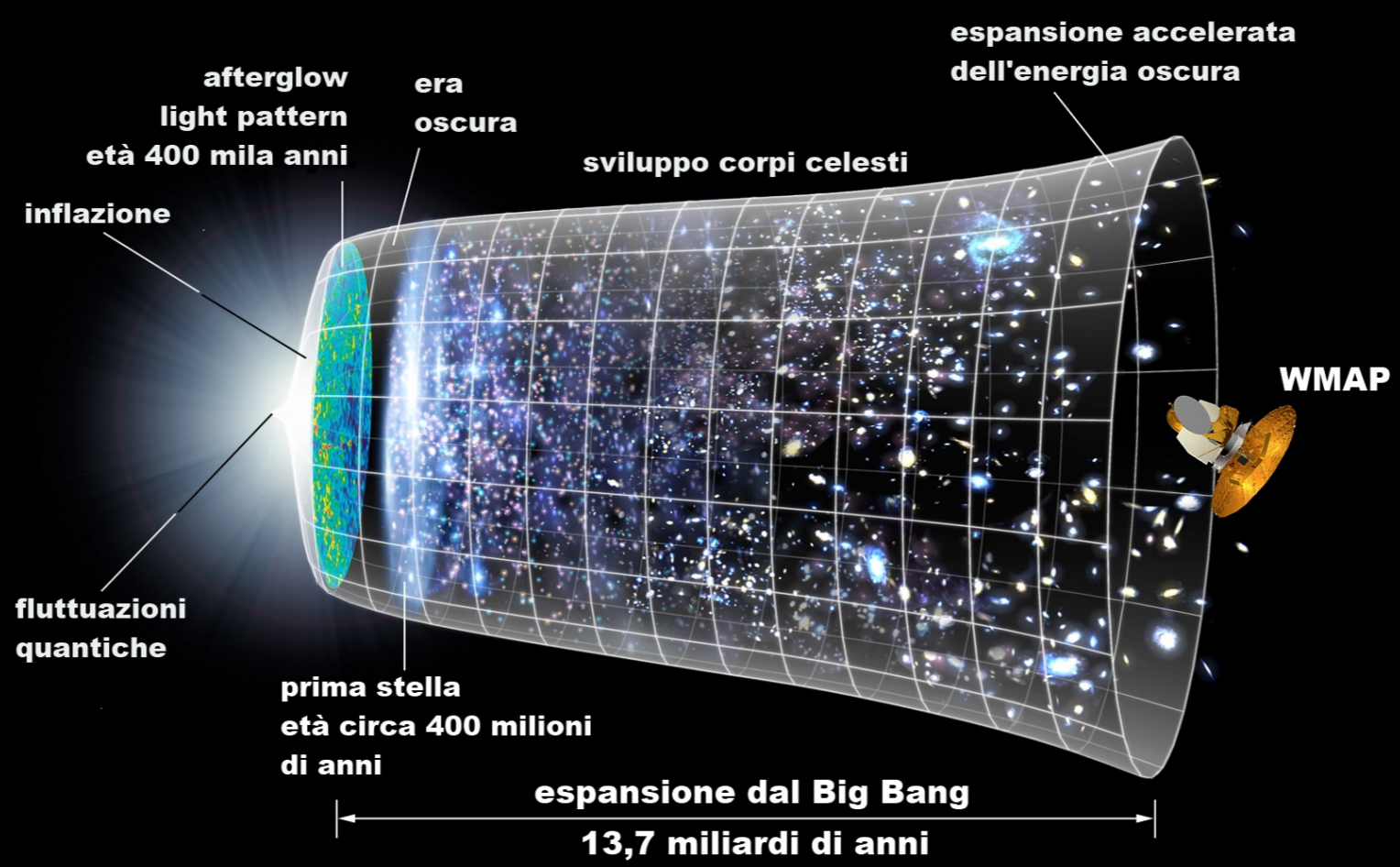
Cosmic Microwave Background Spectrum from COBE



Radiazione di corpo nero
temperatura ~ 2.72 K



Robert Woodrow Wilson and Arno A. Penzias stand in front of the horn reflecting antenna at the Homdel Horn in Crawford Hill, New Jersey.

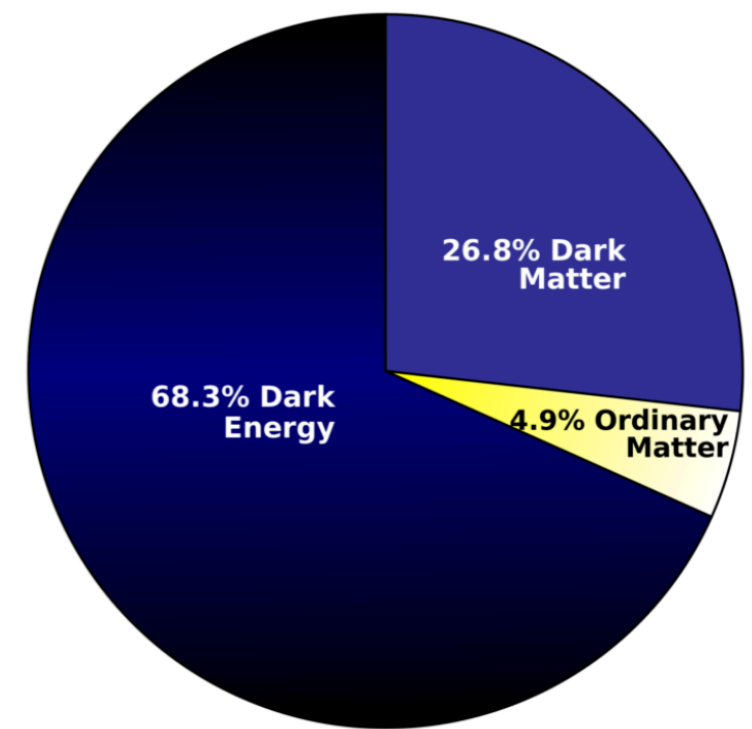


Planck 2018

Table 17. Cosmological Parameter Summary

Parameter	Symbol	WMAP ^a	WMAP+eCMB+BAO+ H_0 ^{a b}
6-parameter ΛCDM fit parameters^c			
Physical baryon density	$\Omega_b h^2$	0.02264 ± 0.00050	0.02223 ± 0.00033
Physical cold dark matter density	$\Omega_c h^2$	0.1138 ± 0.0045	0.1153 ± 0.0019
Dark energy density ($w = -1$)	Ω_Λ	0.721 ± 0.025	$0.7135^{+0.0095}_{-0.0096}$
Curvature perturbations ($k_0 = 0.002 \text{ Mpc}^{-1}$) ^d	$10^9 \Delta_{\mathcal{R}}^2$	2.41 ± 0.10	2.464 ± 0.072
Scalar spectral index	n_s	0.972 ± 0.013	0.9608 ± 0.0080
Reionization optical depth	τ	0.089 ± 0.014	0.081 ± 0.012
Amplitude of SZ power spectrum template	A_{SZ}	< 2.0 (95% CL)	< 1.0 (95% CL)
6-parameter ΛCDM fit: derived parameters^e			
Age of the universe (Gyr)	t_0	13.74 ± 0.11	13.772 ± 0.059
Hubble parameter, $H_0 = 100h \text{ km/s/Mpc}$	H_0	70.0 ± 2.2	69.32 ± 0.80
Density fluctuations @ $8h^{-1} \text{ Mpc}$	σ_8	0.821 ± 0.023	$0.820^{+0.013}_{-0.014}$
Velocity fluctuations @ $8h^{-1} \text{ Mpc}$	$\sigma_8 \Omega_m^{0.5}$	0.434 ± 0.029	0.439 ± 0.012
Velocity fluctuations @ $8h^{-1} \text{ Mpc}$	$\sigma_8 \Omega_m^{0.6}$	0.382 ± 0.029	0.387 ± 0.012
Baryon density/critical density	Ω_b	0.0463 ± 0.0024	0.04628 ± 0.00093
Cold dark matter density/critical density	Ω_c	0.233 ± 0.023	$0.2402^{+0.0088}_{-0.0087}$
Matter density/critical density ($\Omega_c + \Omega_b$)	Ω_m	0.279 ± 0.025	$0.2865^{+0.0096}_{-0.0095}$
Physical matter density	$\Omega_m h^2$	0.1364 ± 0.0044	0.1376 ± 0.0020
Current baryon density (cm^{-3}) ^f	n_b	$(2.542 \pm 0.056) \times 10^{-7}$	$(2.497 \pm 0.037) \times 10^{-7}$
Current photon density (cm^{-3}) ^g	n_γ	410.72 ± 0.26	410.72 ± 0.26
Baryon/photon ratio	η	$(6.19 \pm 0.14) \times 10^{-10}$	$(6.079 \pm 0.090) \times 10^{-10}$
Redshift of matter-radiation equality	z_{eq}	3265^{+106}_{-105}	3293 ± 47
Angular diameter distance to z_{eq} (Mpc)	$d_A(z_{\text{eq}})$	14194 ± 117	14173^{+66}_{-65}
Horizon scale at z_{eq} (h/Mpc)	k_{eq}	0.00996 ± 0.00032	0.01004 ± 0.00014
Angular horizon scale at z_{eq}	l_{eq}	139.7 ± 3.5	140.7 ± 1.4

Capitolo 2

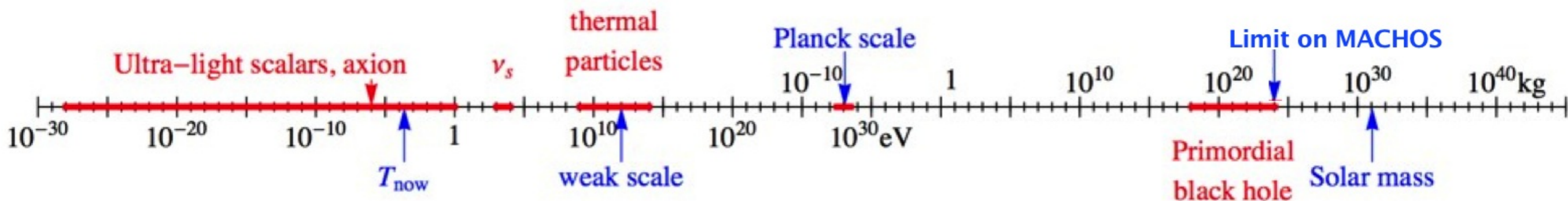


Cosa sappiamo della Dark
Matter
(capitolo molto breve)

After 80 years, what we know about DM:

- Attractive gravitational interactions and stable (or lifetime $\gg t_U$)
- DM and not MOND + only visible matter (“Bullet Cluster”)
- $10^{-31} \text{ GeV} \leq \text{mass} \leq 10^{-7} M_\odot = 10^{50} \text{ GeV}$ (limits on MACHOS [astro-ph/0607207](#))
 (“Fuzzy DM”, boson de Broglie wavelength = 1 kpc [Hu, Barkana, Gruzinov, astro-ph/0003365](#))
 or $0.2\text{-}0.7 \times 10^{-6} \text{ GeV} \leq \text{mass}$ (for particles which reached equilibrium - depending on boson-fermion and d.o.f. [Tremaine-Gunn 1979; Madsen, astro-ph/0006074](#))

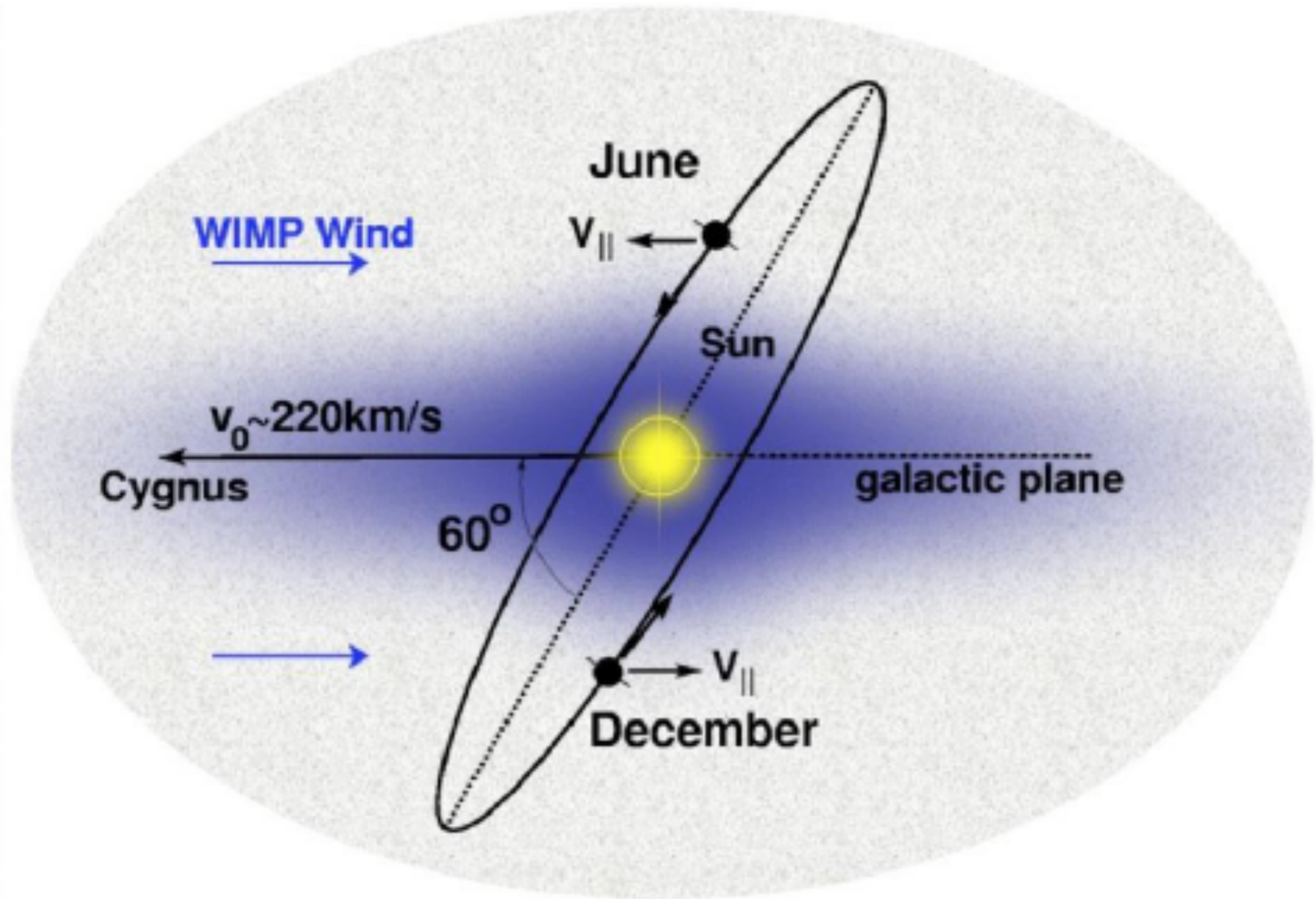
DM particle mass: 80 orders of magnitude!



Capitolo 3

Ricerca sotto ogni pietra





Darkside

36 Ar 35.96754 0.337% Stabile	37 Ar $t_{1/2}=35$ days Radioattivo	38 Ar 37.96273 0.063% Stabile
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39 Ar $t_{1/2}=269$ yrs Radioattivo	40 Ar 39.96238 99.60% Stabile
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Obiettivo:

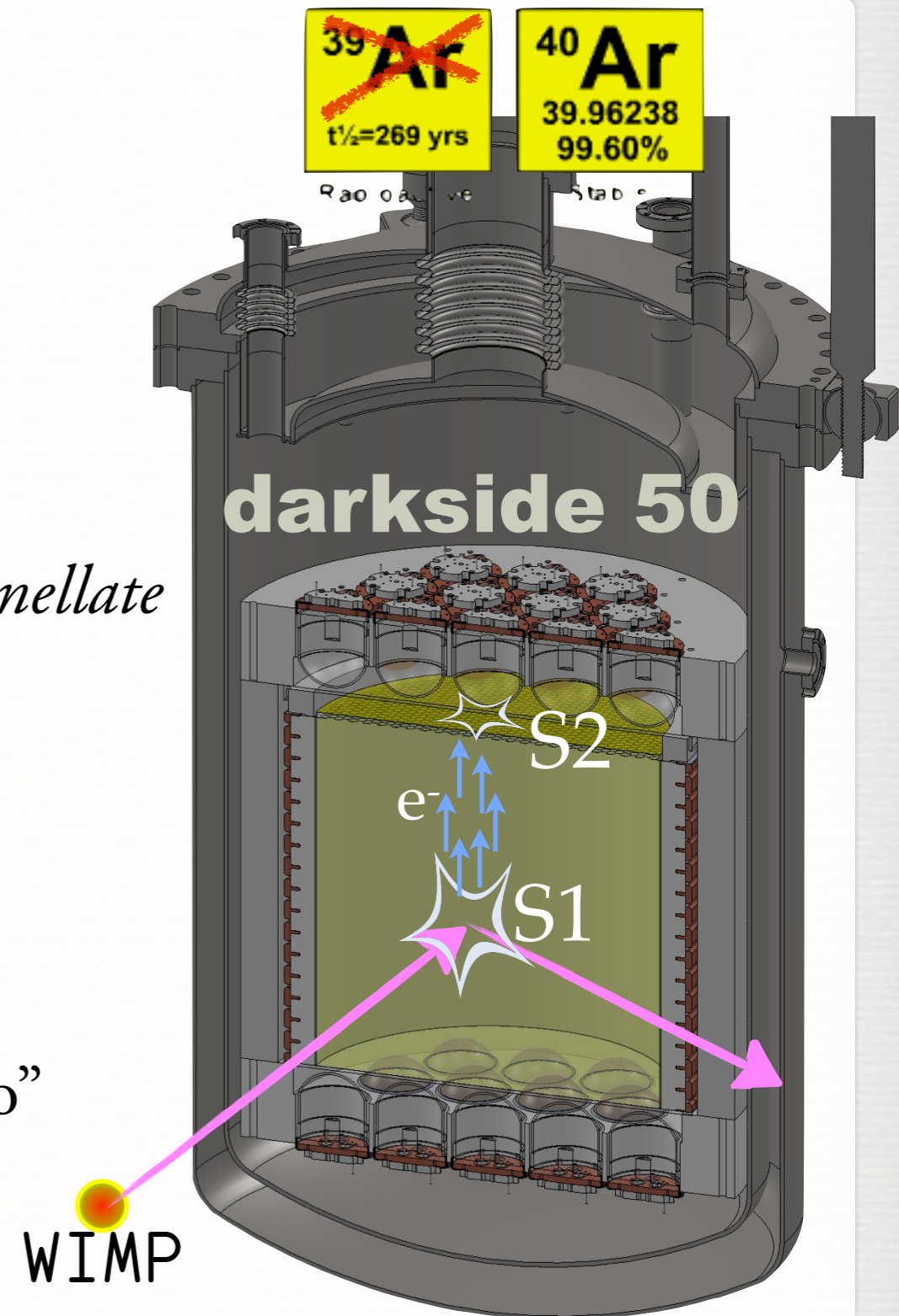
- ◆ Ricerca Diretta di materia oscura (WIMP)

Detector:

- ◆ TPC Argon bifase (liquido + gas) di 20 tonnellate con rivelazione del segnale di scintillazione e ionizzazione

Strategia per Darkside 20k:

- ◆ Osservazione di un segnale su fondo “nullo”



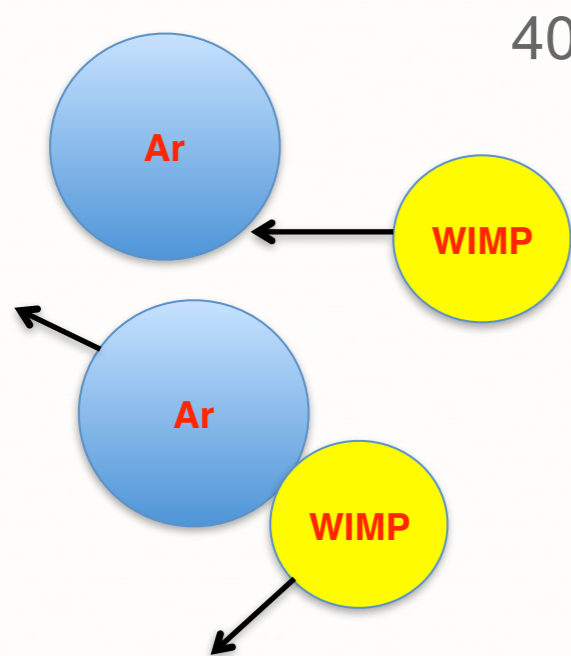
Darkside: Il Segnale

Urto *elastico* di WIMP su *nucleo* di ^{40}Ar :

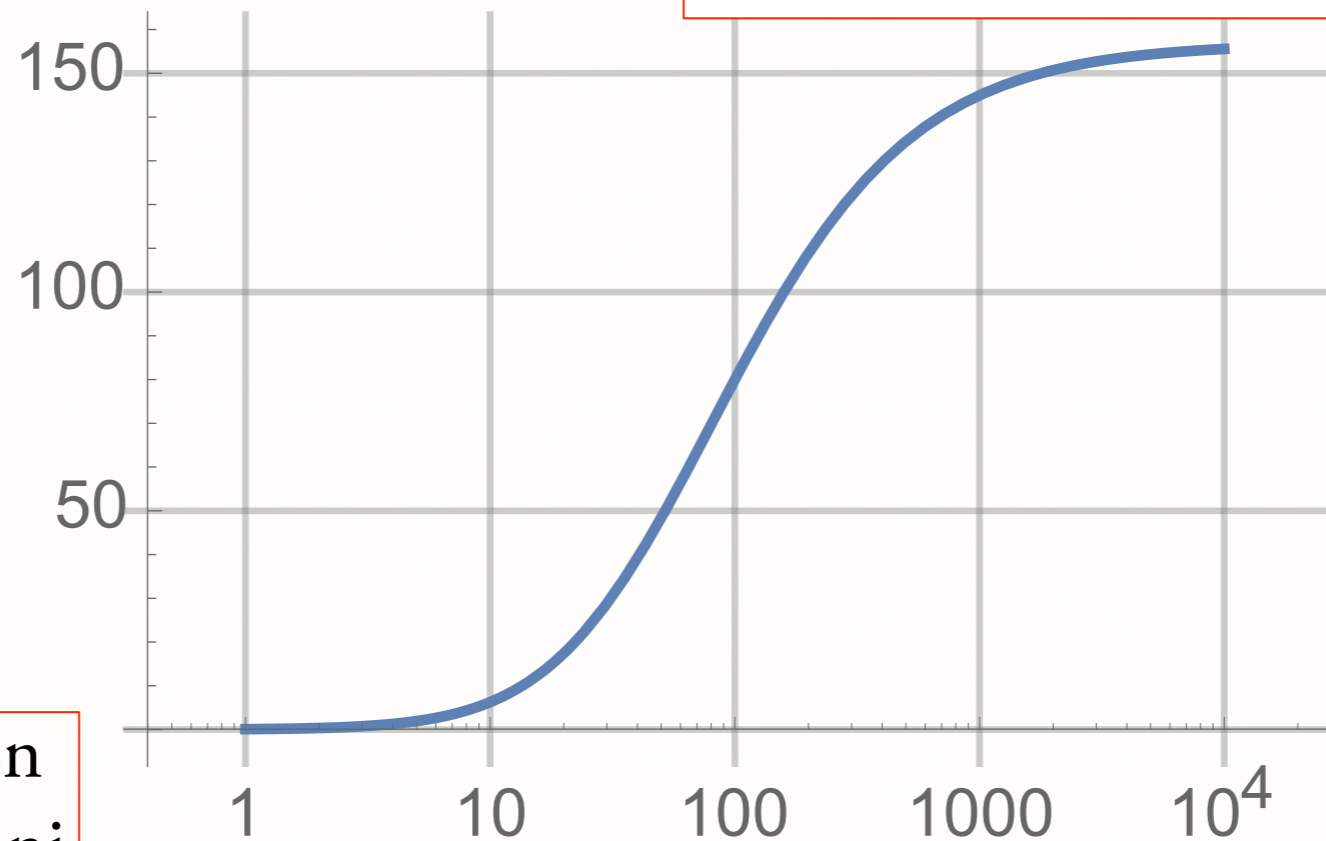
$$\langle \beta_{\text{WIMP}} \rangle \sim \frac{220 \pm 30 \text{ km/s}}{c} \sim (7.3 \pm 1.0) \cdot 10^{-4}$$

Massima energia trasferita :

$$\frac{1}{2} M_W c^2 \beta_W^2 \frac{4 M_W M_{\text{Ar}}}{(M_W + M_{\text{Ar}})^2} + \mathcal{O}(\beta^4)$$



^{40}Ar Kin En (keV)

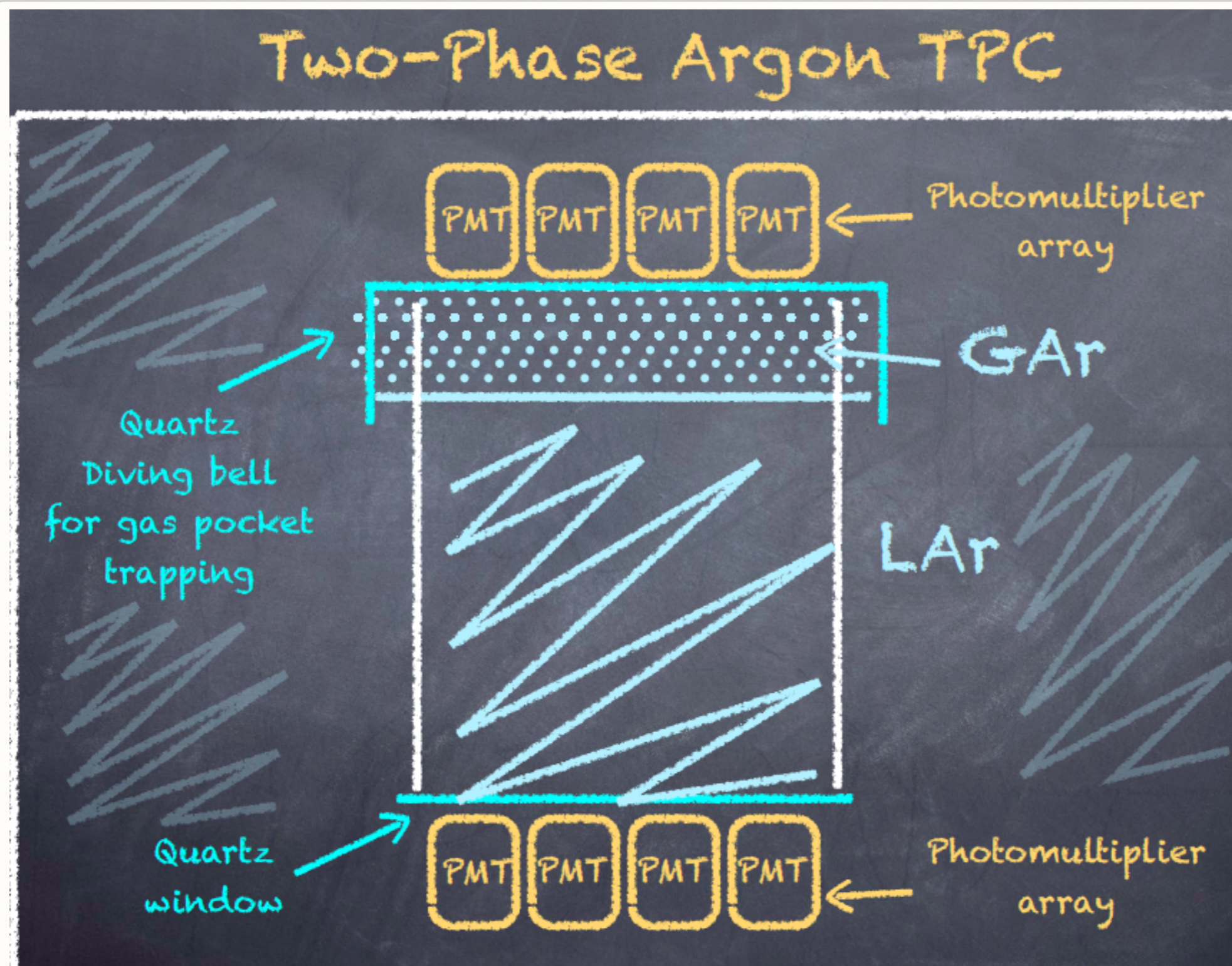


In LAr il range del nucleo è $< 100\mu\text{m}$, **direzionalità** (forse) su base statistica

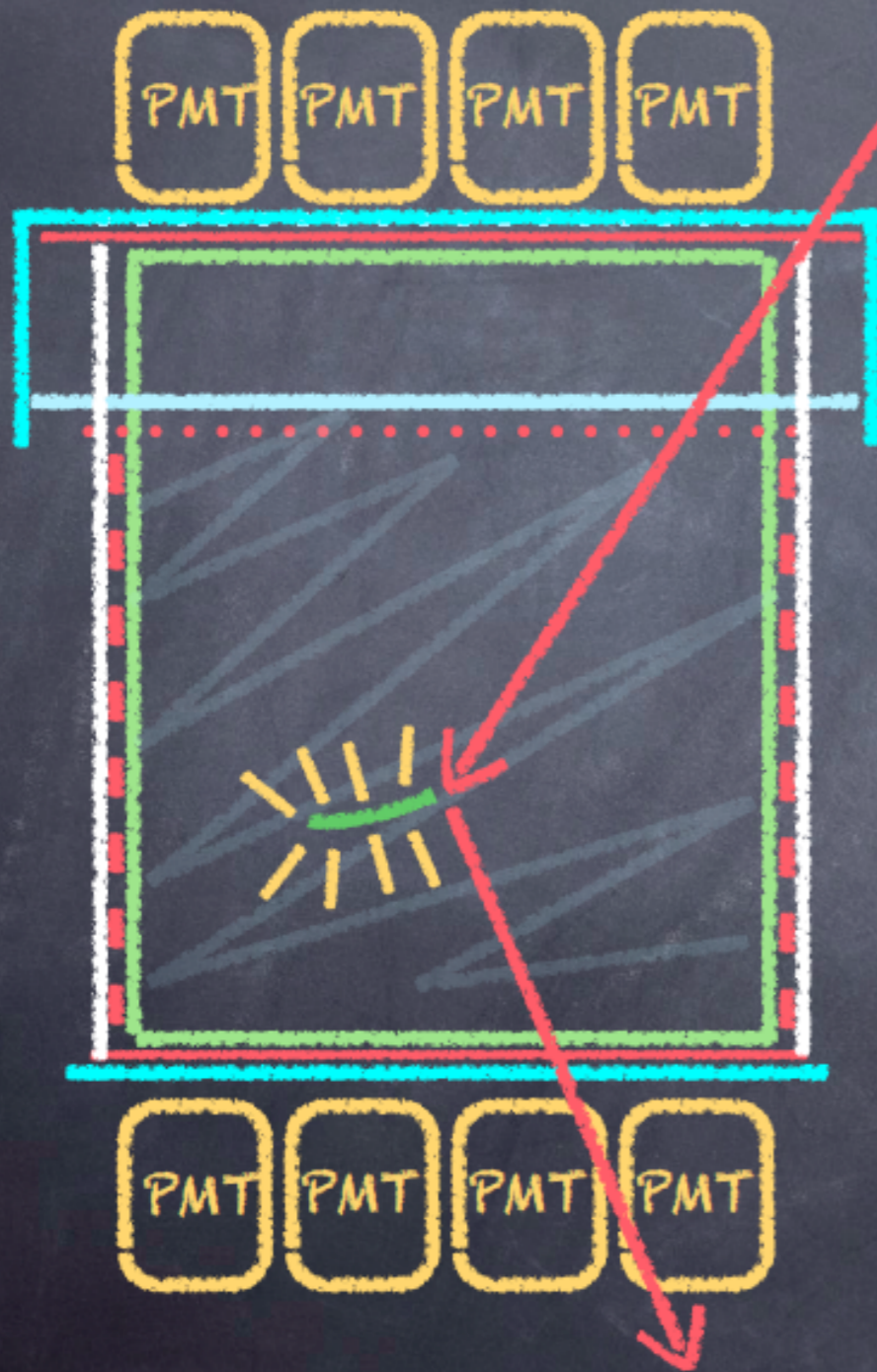
Segnale **simulabile** con urto elastico di neutroni

DM_{Mass} (GeV)

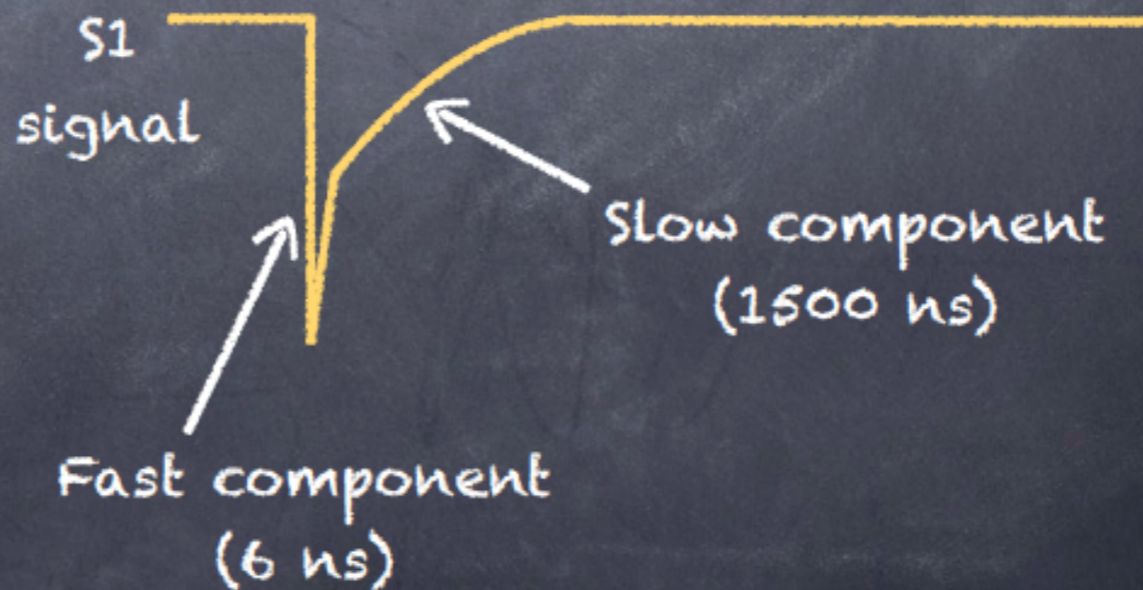
Darkside: Metodo Misura



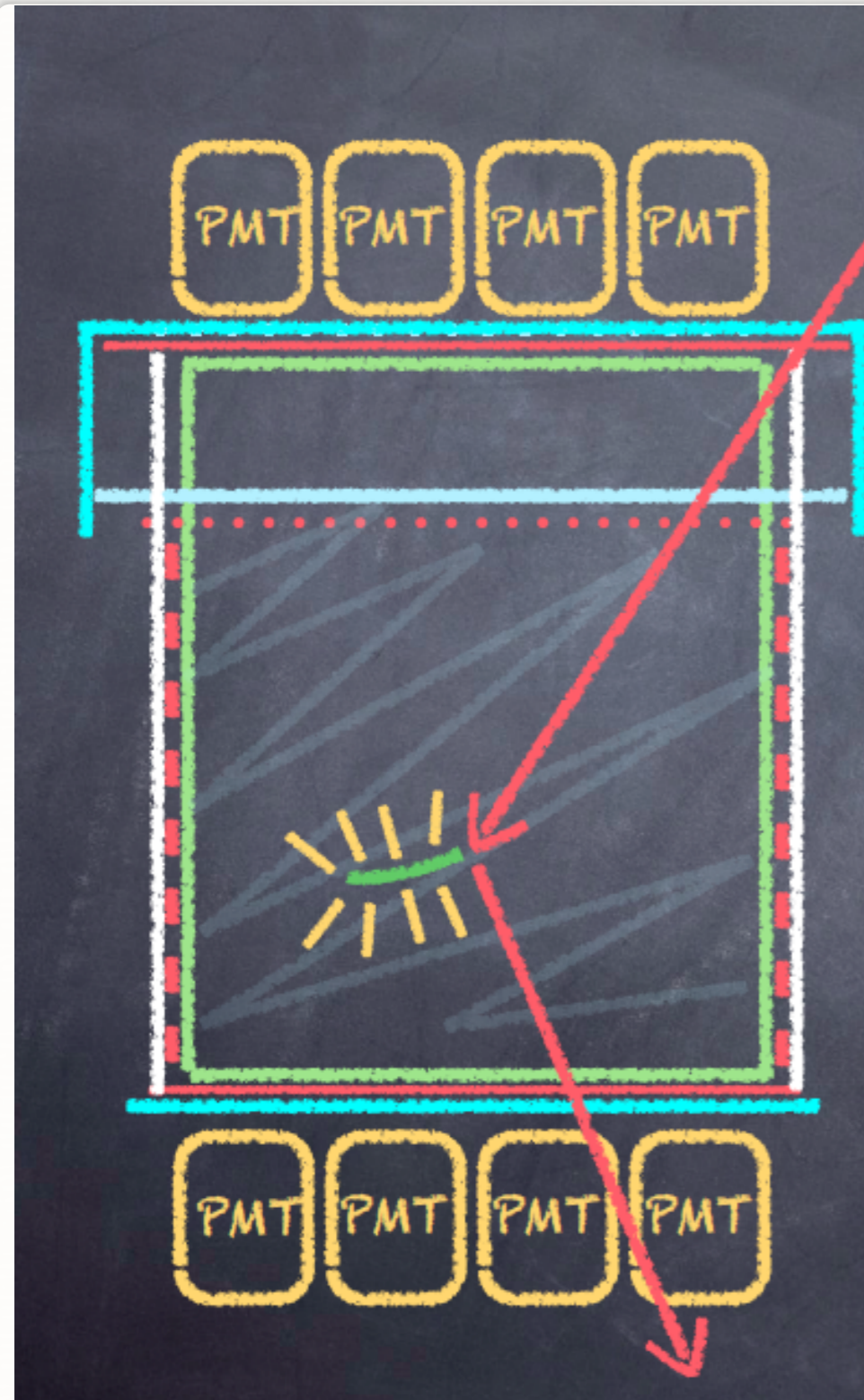
Scintillazione (Immediata)



The primary ionizing particle (nuclear recoil or electron recoil) produces ionization and excitation along its track. Excited argon dimers are formed and their de-excitation leads to the emission of scintillation light presenting a fast and slow component (associated Ar_2^* singlet and triplet state) whose average ratio depends on the nature and energy of the ionizing particle.



Scintillazione (Immediata)



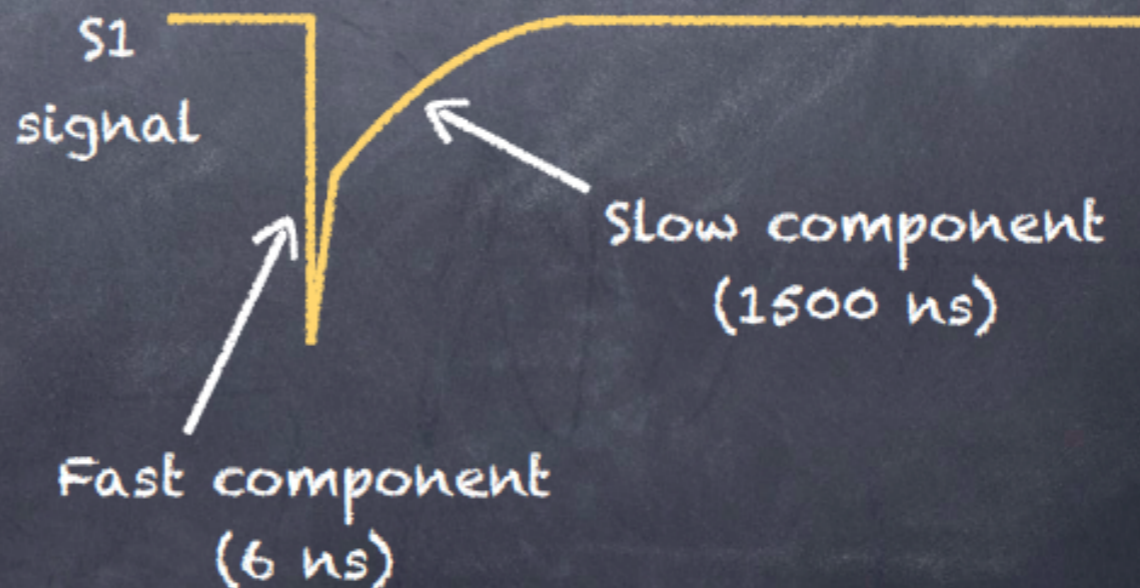
Circa **40 fotoni UV (128nm) / keV**

TMP per shift da 128 nm a ~ 400 nm

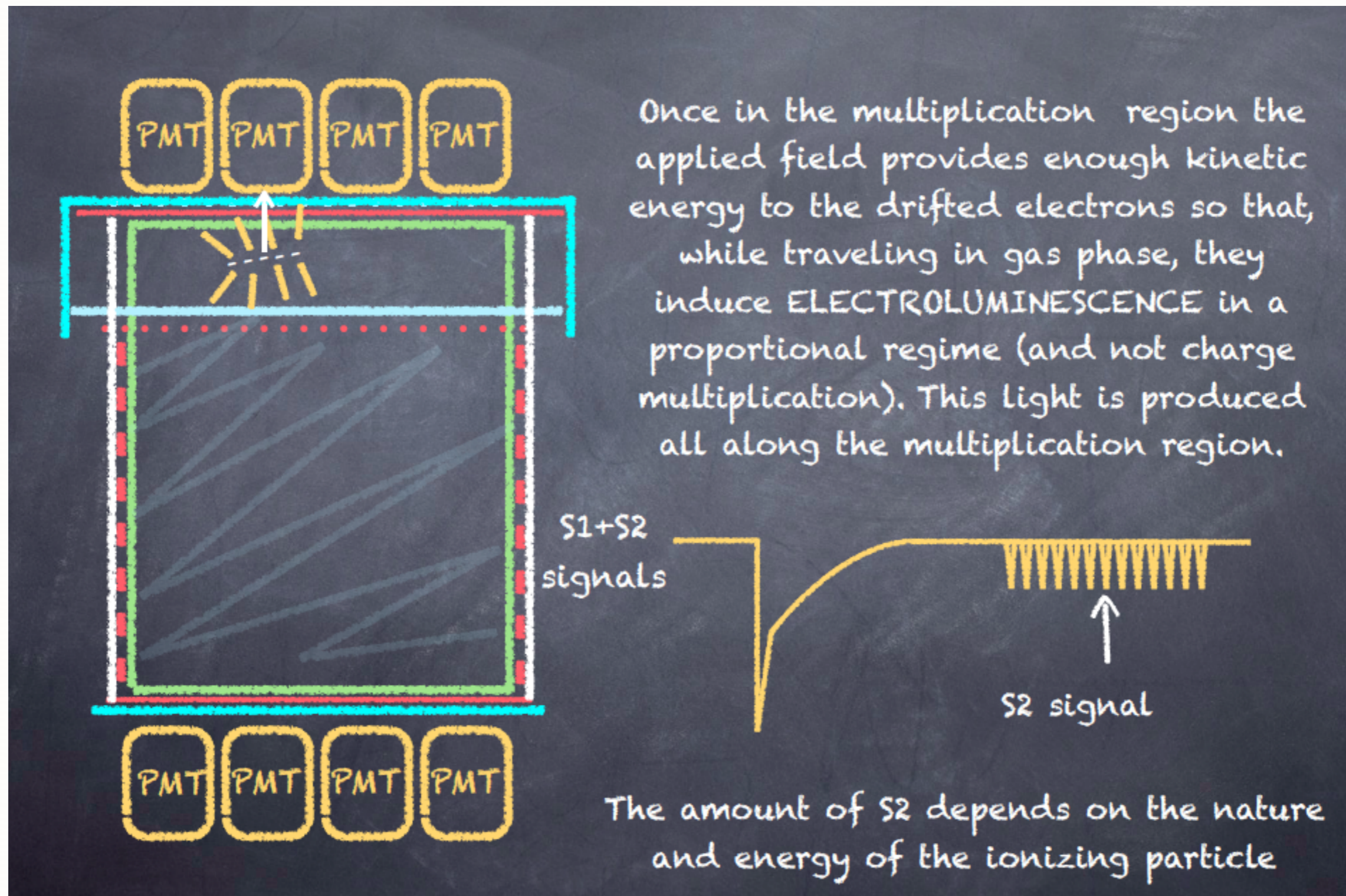
Segnale S1 con componenti fast e slow.

Fotoni visibili nei SiPM: **4.7/KeV**

Rapporto **FAST/SLOW** dipende dalla
particella ionizzante (nucleo/elettrone) \Rightarrow
potente mezzo per **discriminare recoil su
elettrone (i.e. fondo da neutrini)**



Ionizzazione (Tpc) Ritardata

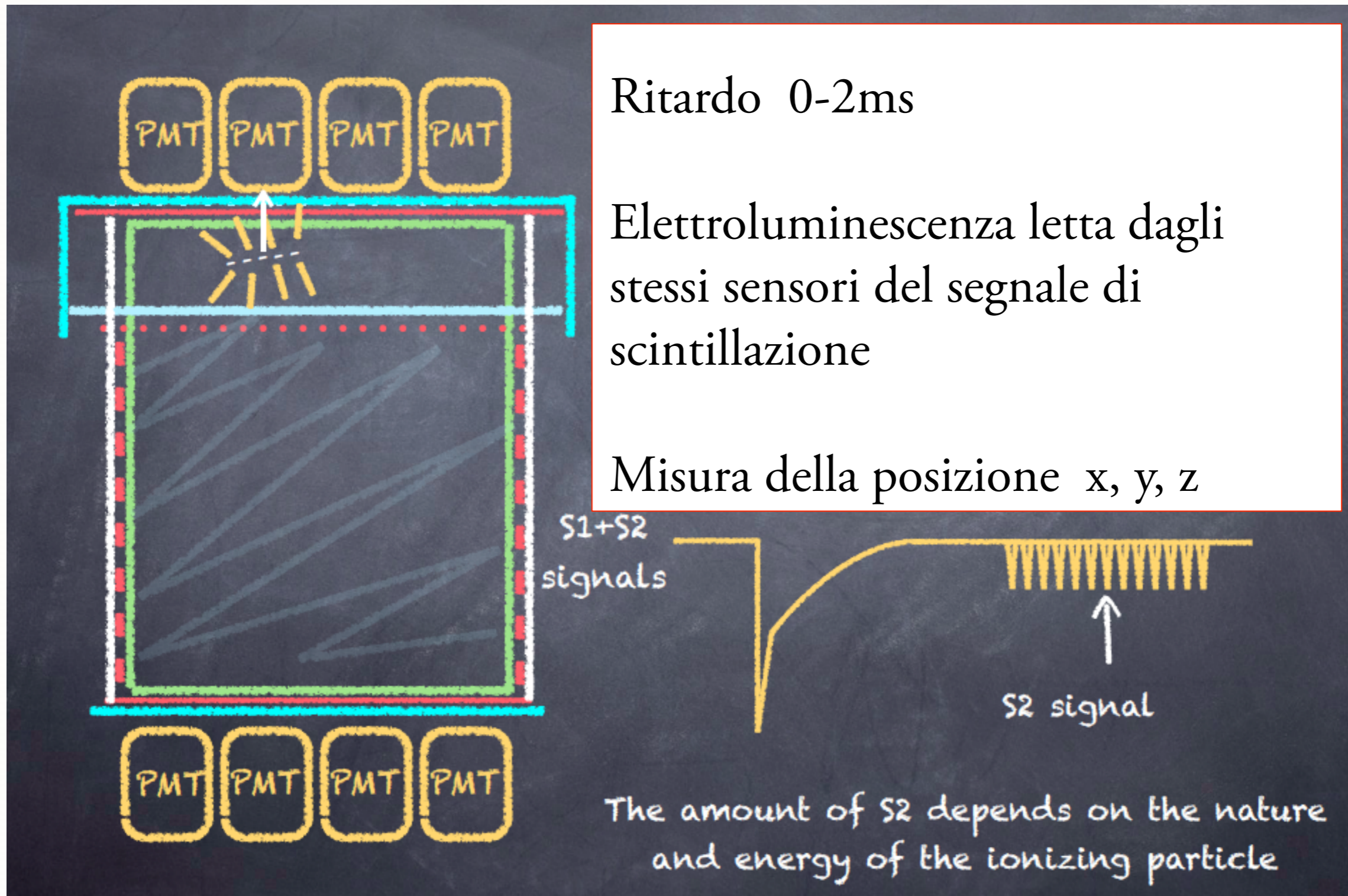


Ionizzazione (Tpc) Ritardata

Ritardo 0-2ms

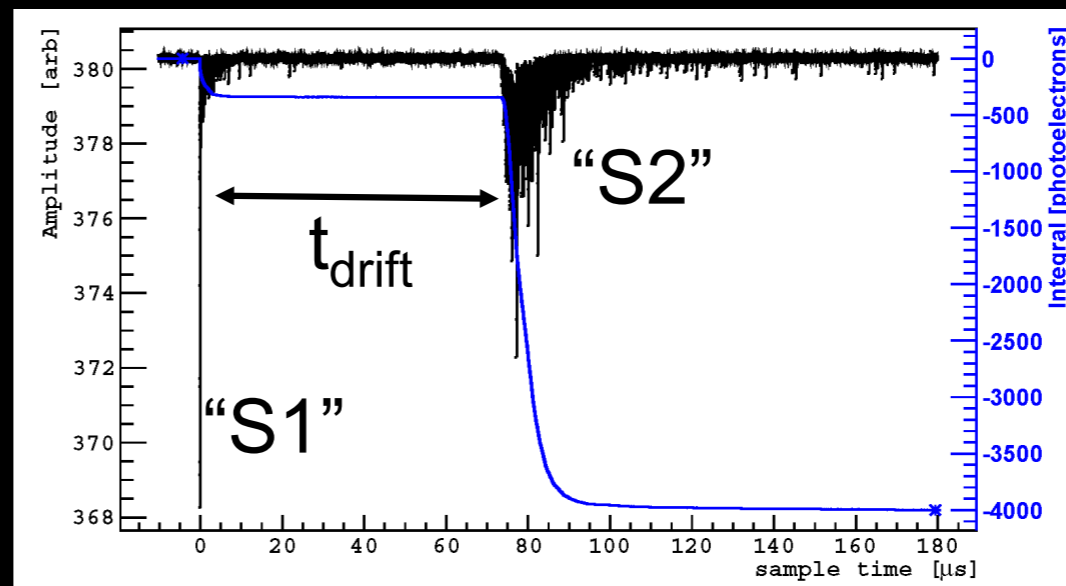
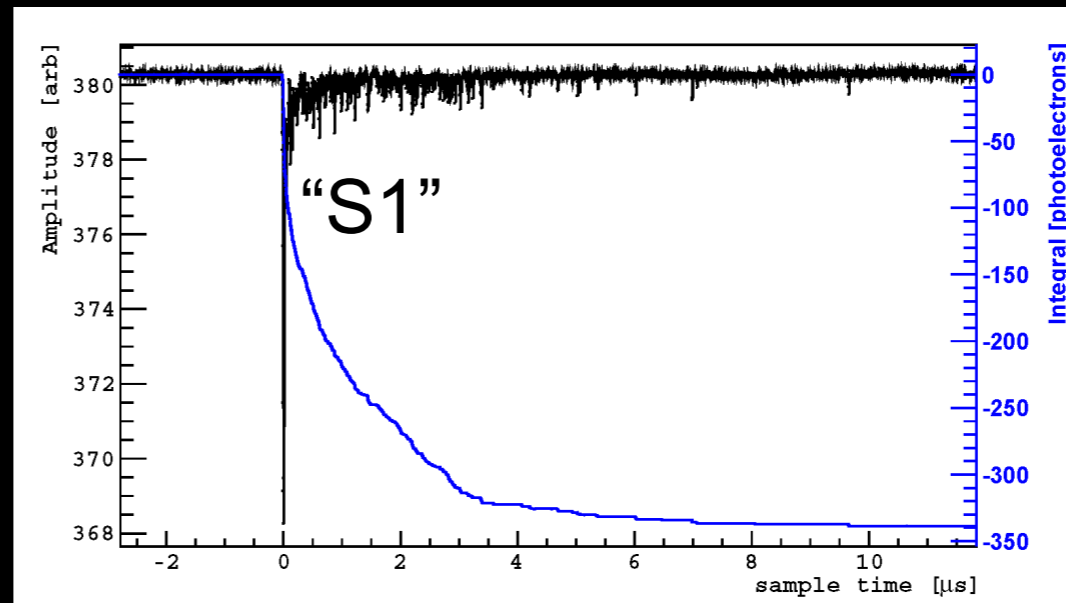
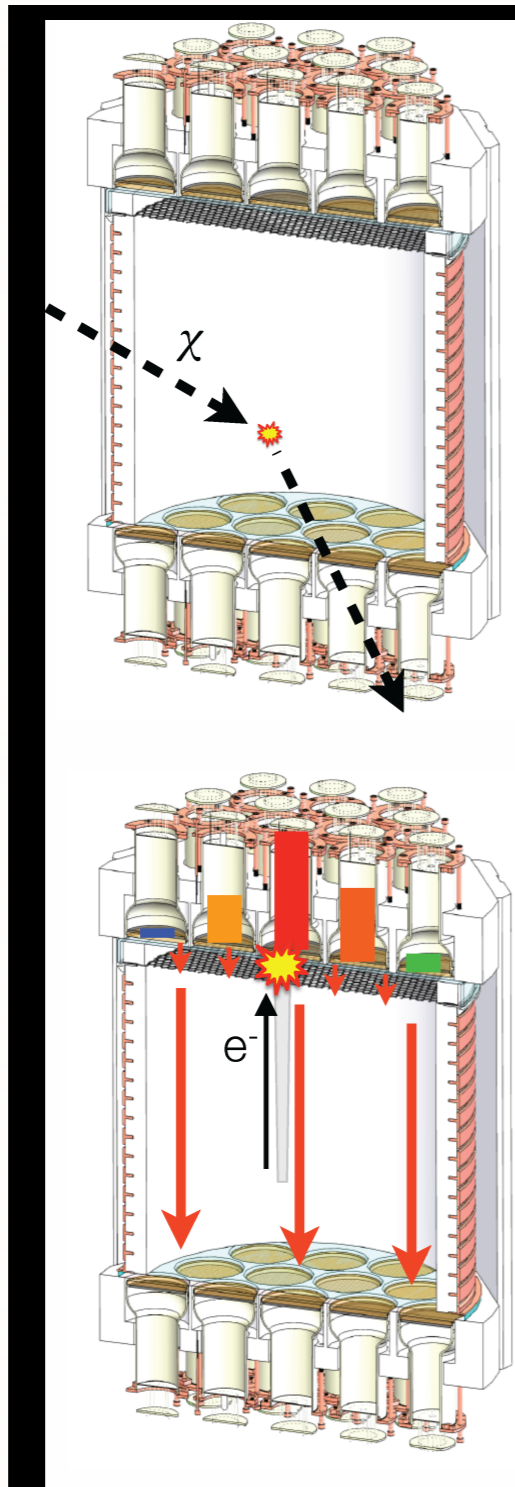
Elettroluminescenza letta dagli stessi sensori del segnale di scintillazione

Misura della posizione x, y, z

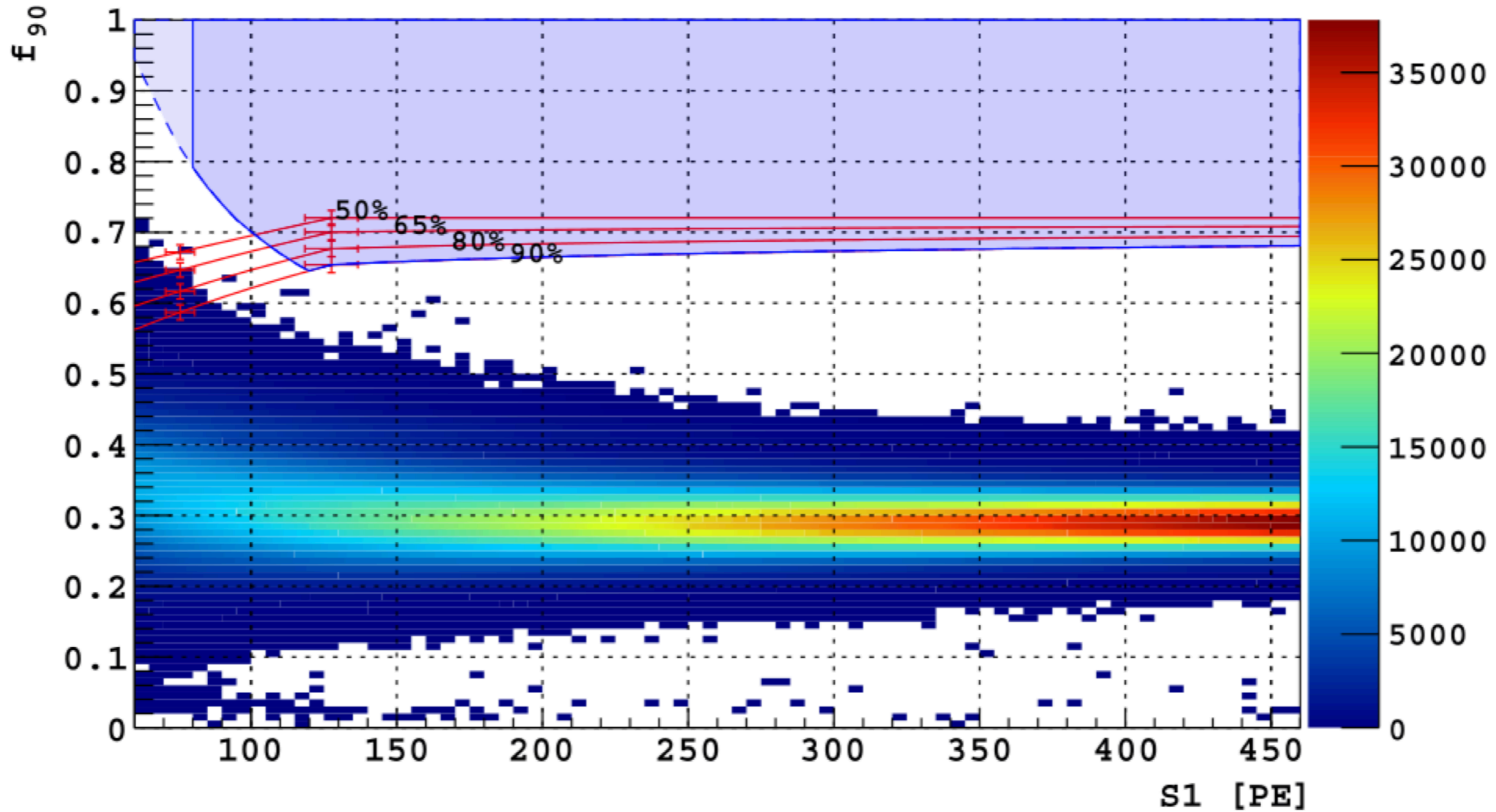


The amount of $S2$ depends on the nature and energy of the ionizing particle

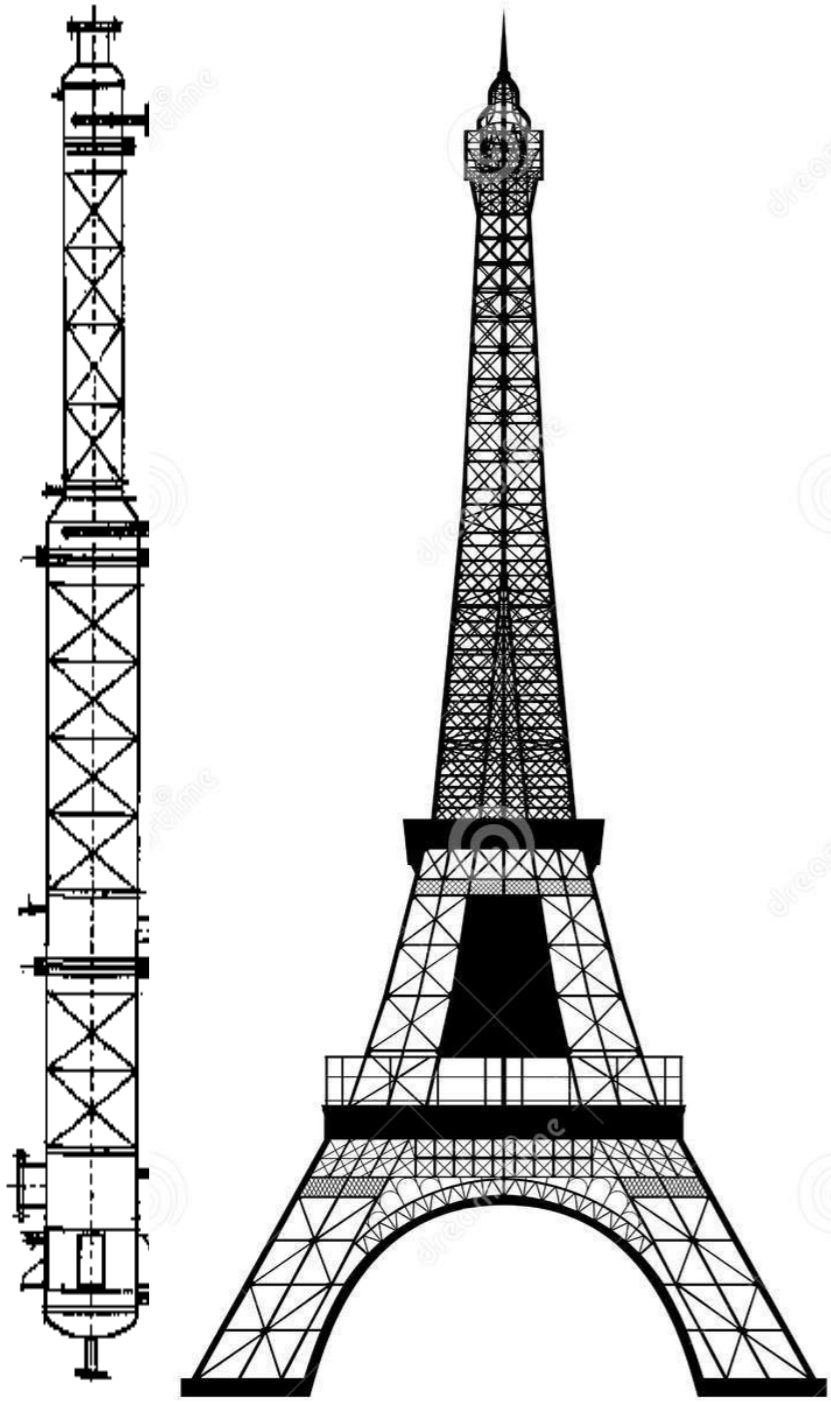
Fondi Da Neutrini Solari



Darkside 50 results



Darkside 20K – Altri Fondi



Decadimento β ^{39}Ar

($T_{1/2} \sim 269$ anni, $Q = 565$ keV)

- ◆ Darkside 50 usa Argon da miniere sotterranee impoverito UAr
- ◆ Per Darkside 20k impianto distillazione per rimuovere la componente radioattiva

*Fondi da contaminazioni
(U, Th, Rn, ...beta),*

Conclusioni

- La natura della Dark Matter rimane a tutt'oggi quasi completamente ignota e rappresenta uno dei più affascinanti temi di ricerca attuali.

