Darkside: a Two Phases Argon Time Projection Chamber for Dark Matter Searches

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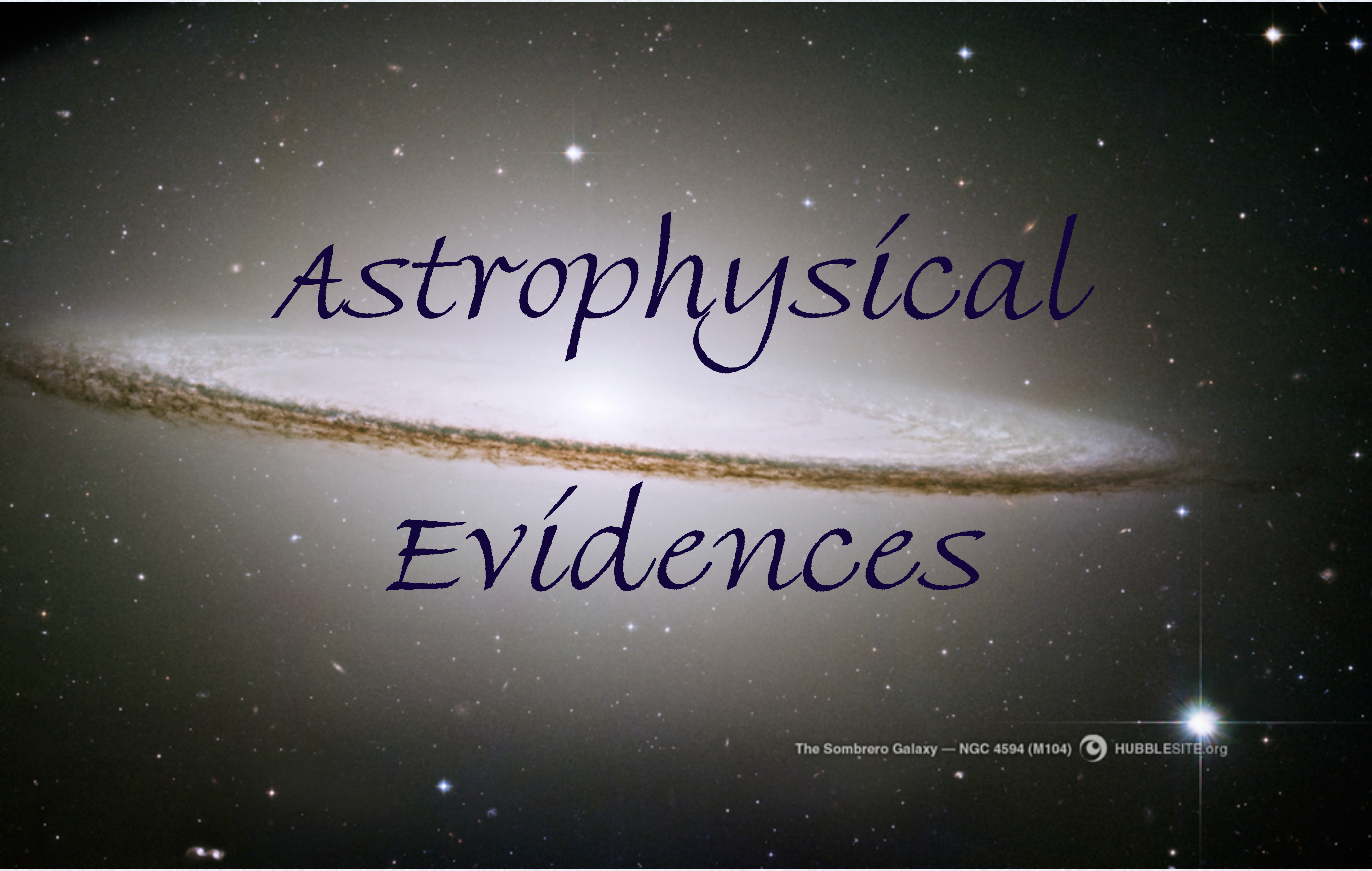
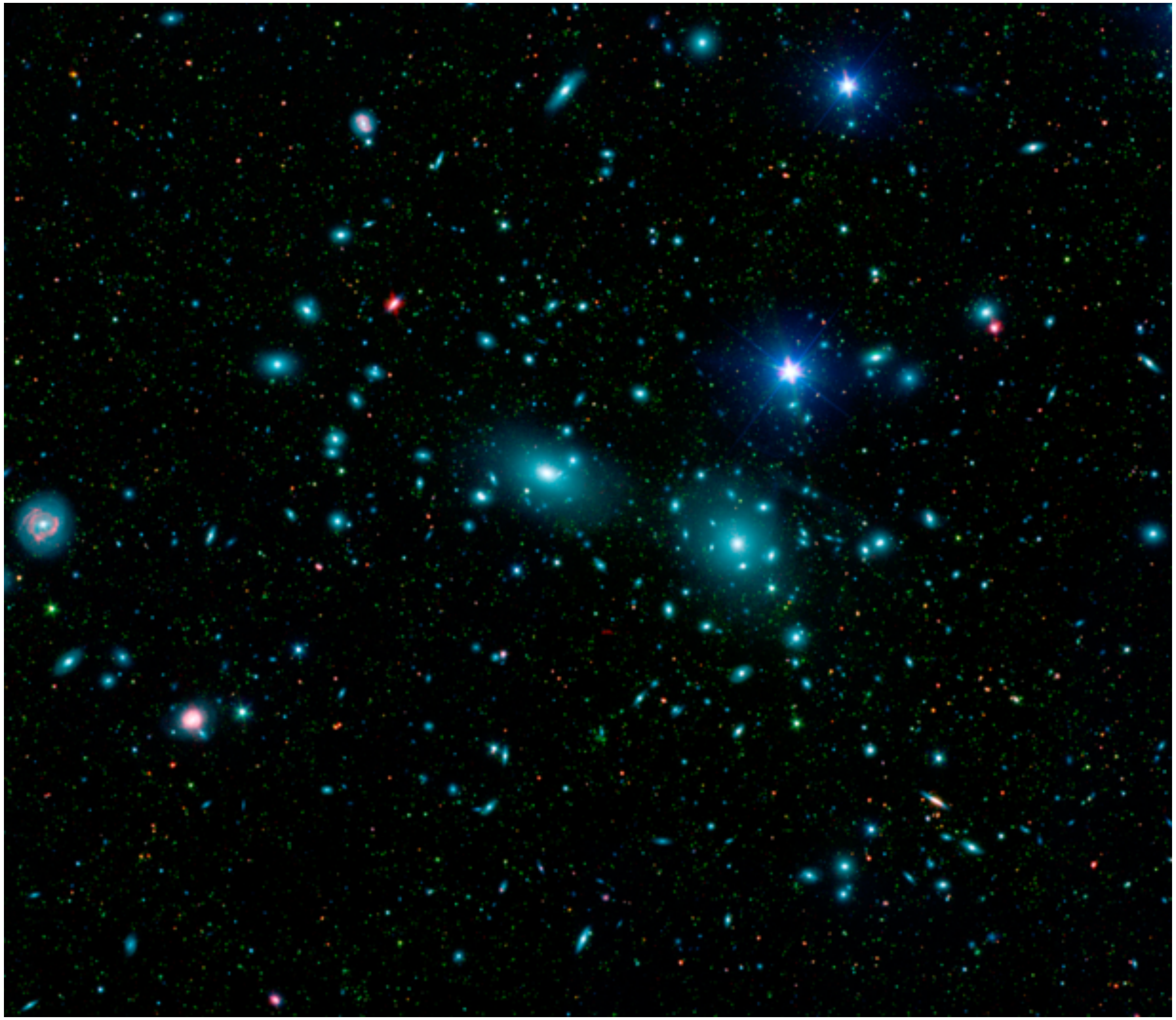
Plan For this Tour de Force

- Why are we searching for Dark Matter?
  - Astrophysical and cosmological evidences.
- Noble liquids Time Projection Chambers (TPC) for Dark Matter search
  - Prototypical example: Darkside 50
  - Some neat features of Argon
  - Backgrounds and backgrounds rejection
- Darkside 50 preliminary results
- Toward a multi tonne background free experiment: Darkside 20k

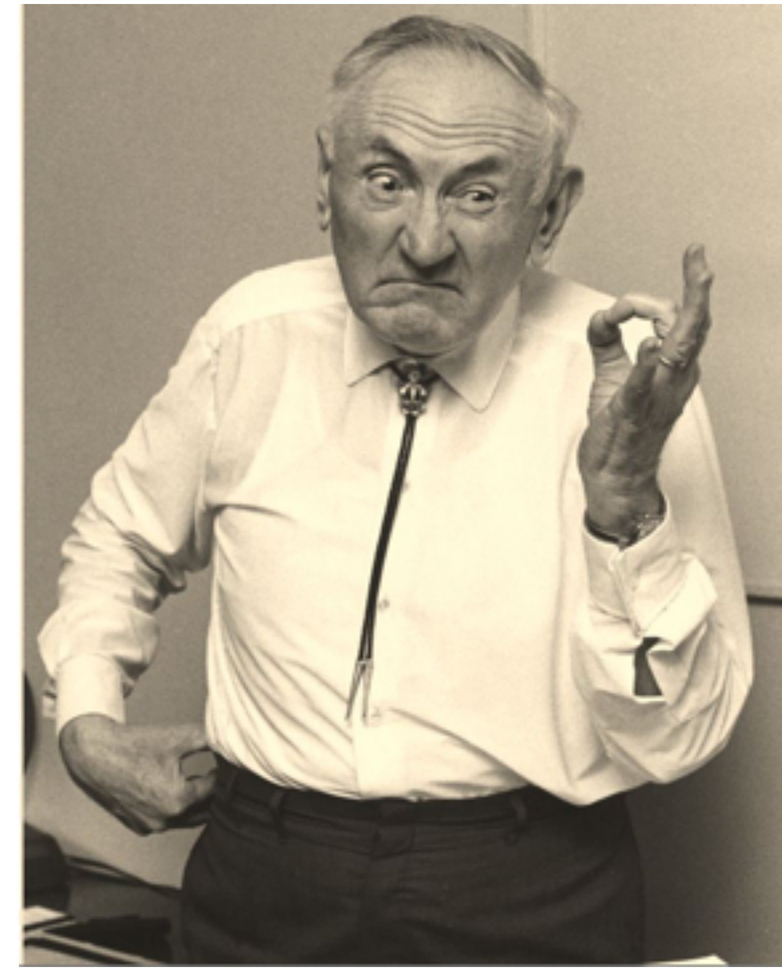
Astrophysical Evidences



Zwicky Analysis of the Coma Cluster Dynamics



O(1000) galaxies. 46’ ~ 13 mRad



Fritz Zwicky,
(Varna 1898, Pasadena 1973)
Postulated the existence of Dark Matter in 1930’s to explain the dynamic behavior of the Coma cluster

The Coma Cluster: Mosaic in false color (Red long waves infrared, Green short waves infrared, visibile light)

Credit: NASA/JPL-Caltech/GSFC/SDSS

Put 1000 Galaxies on a Scale: Virial Theorem

- Assuming that the Coma cluster is held together by classical gravitational forces and that it reached equilibrium, then the virial theorem states that for a single galaxy of mass *m*:

$$\frac{1}{2}m(3\sigma^2) \qquad\qquad G\frac{M_{tot}(r)m}{r}$$

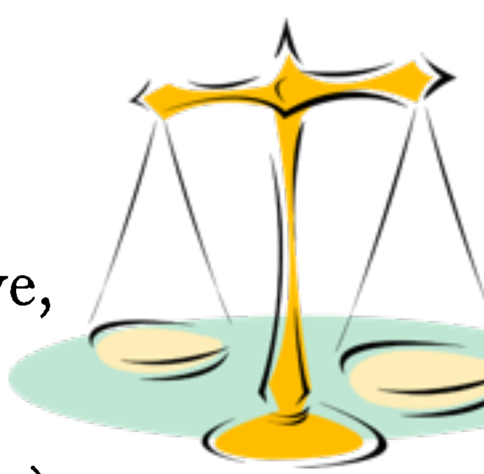
$$2\langle T\rangle = -\langle V\rangle$$

Velocities ~ 1000 km/s
R ~ Mpcs
Distance ~100 Mpc
(1 pc = 3.26 light yrs)

- *By* measuring the velocity dispersion σ (Doppler shift) and the distance *r* from the cluster center Zwicky was able to measure M_{tot}, ie. the total mass of the cluster

From the observations of the Coma cluster so far available we have, approximately,[5]

$$\overline{\overline{v_s^2}} = 5 \times 10^{15}\mathrm{cm}^2\ \mathrm{sec}^{-2}\ . \qquad (34)$$



F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)

[...] The mass $\mathscr{M}$, as obtained from the virial theorem, can therefore be regarded as correct only in order of magnitude.

Combining (33) and (34), we find

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

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

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

[...] 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 to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500 , \qquad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order.

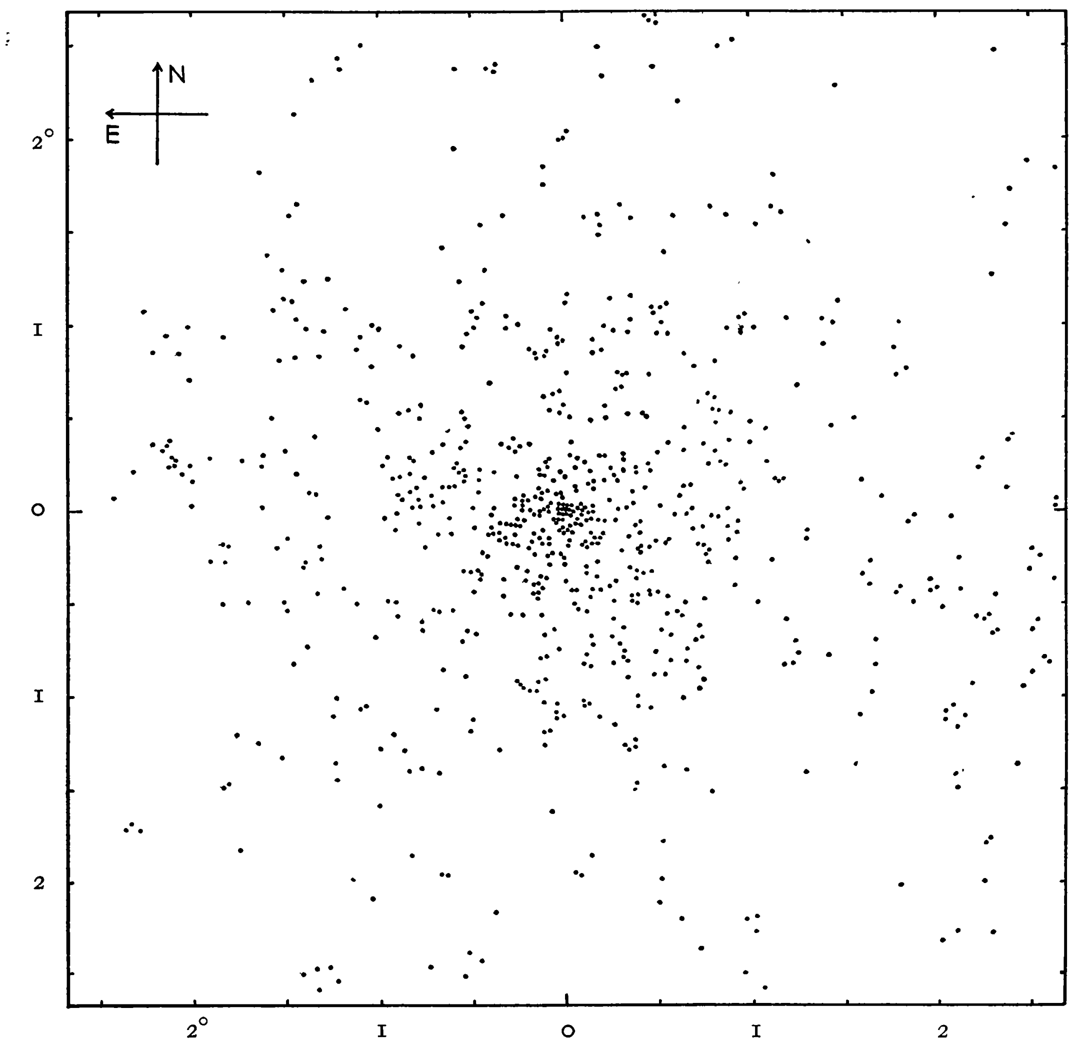


Fig. 3.—The Coma cluster of nebulae

Rotation Curves of Galaxies

- Measure line of sight velocity of stars and gas via Doppler shift (Hα in optical and HI 21 cm line in radio)
- Infer the tangential velocity, apply classical mechanics

M31 (Andromeda)

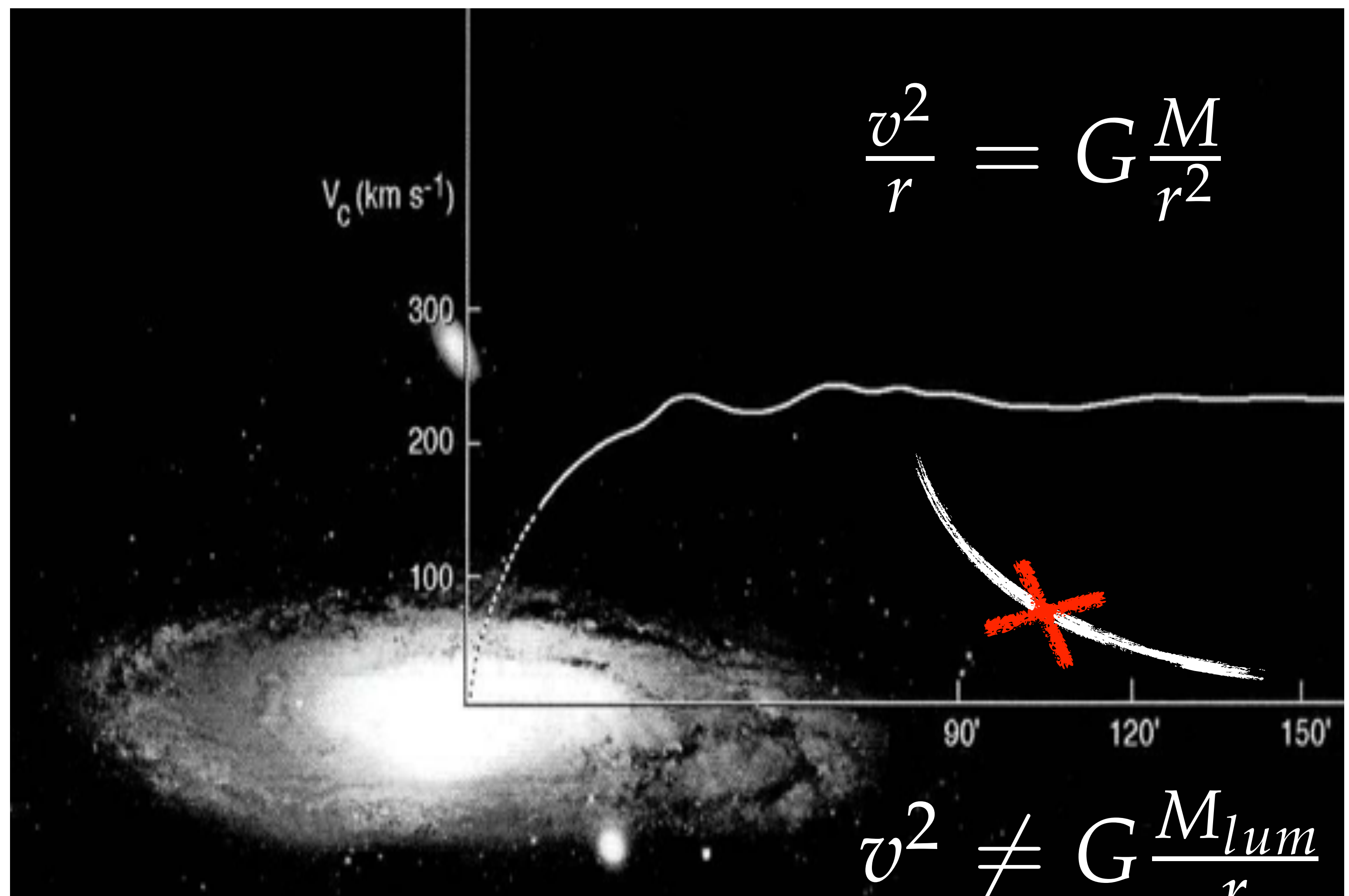
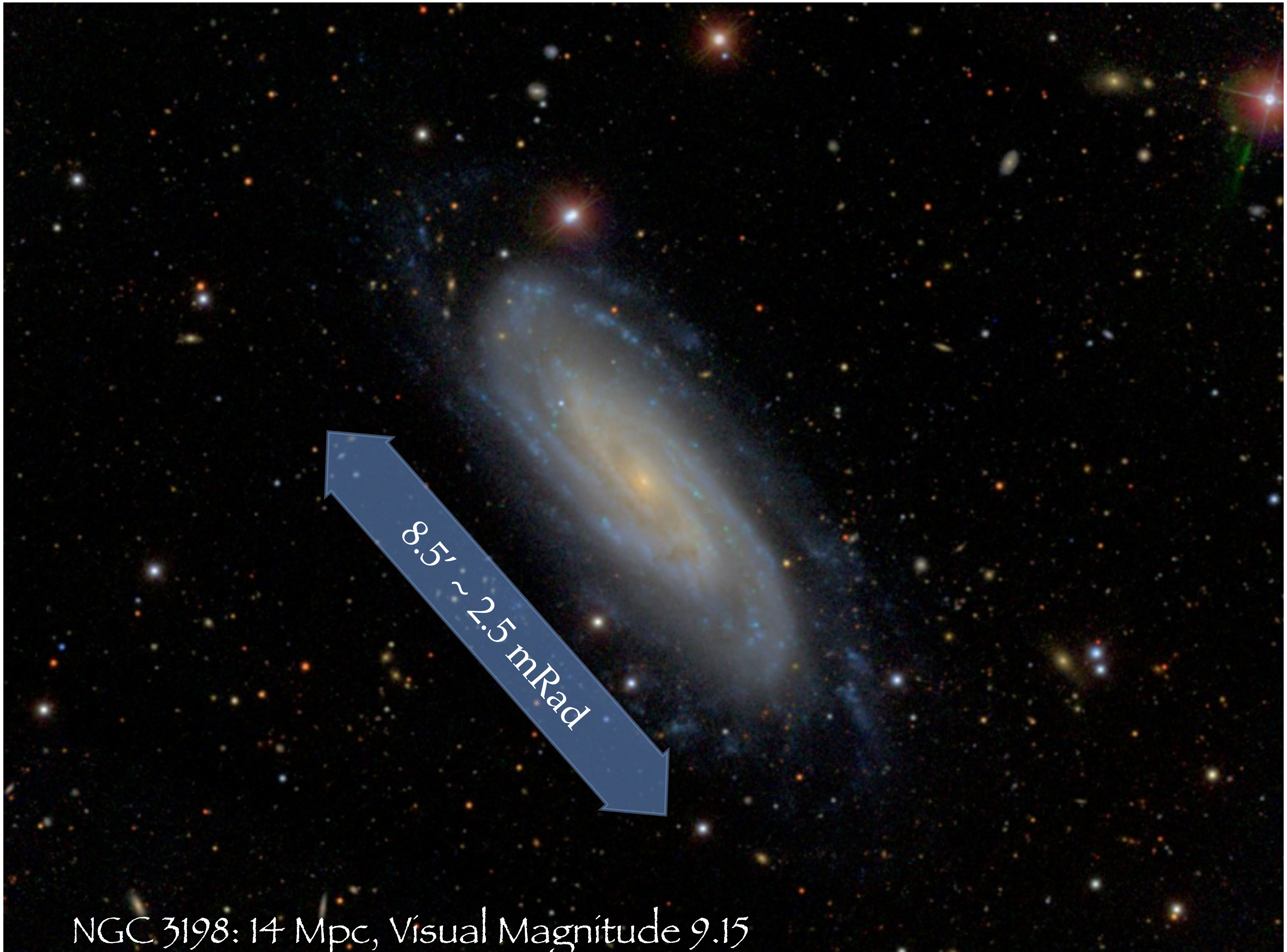


Image of the Andromeda galaxy (M31)
with rotation curve superimposed (Turner,2000)

NGC 3198



Astronomy & Astrophysics manuscript no. N3198A_A2col
April 13, 2015

The dark matter distribution in the spiral *NGC* 3198 out to 0.22 R_{vir}

E.V. Karukes[1,2], P. Salucci[1,2] and G. Gentile[3,4]

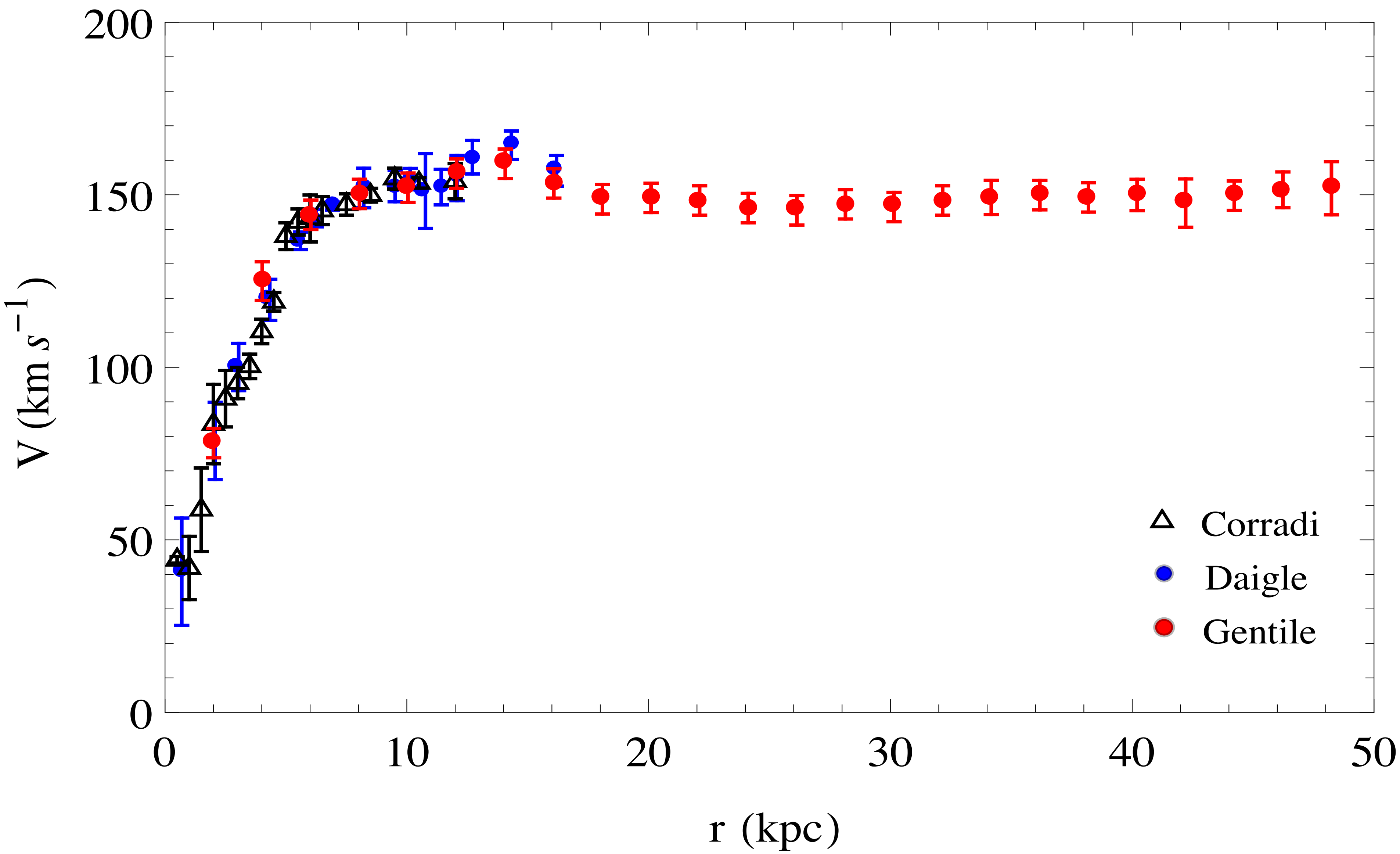


Fig. 1. Comparison between Hα and HI RCs black open triangles with error bars from Corradi et al. (1991), blue circles with error bars are from Daigle et al. (2006), and red circles with error bars are from Gentile et al. (2013).

NGC 3198 components

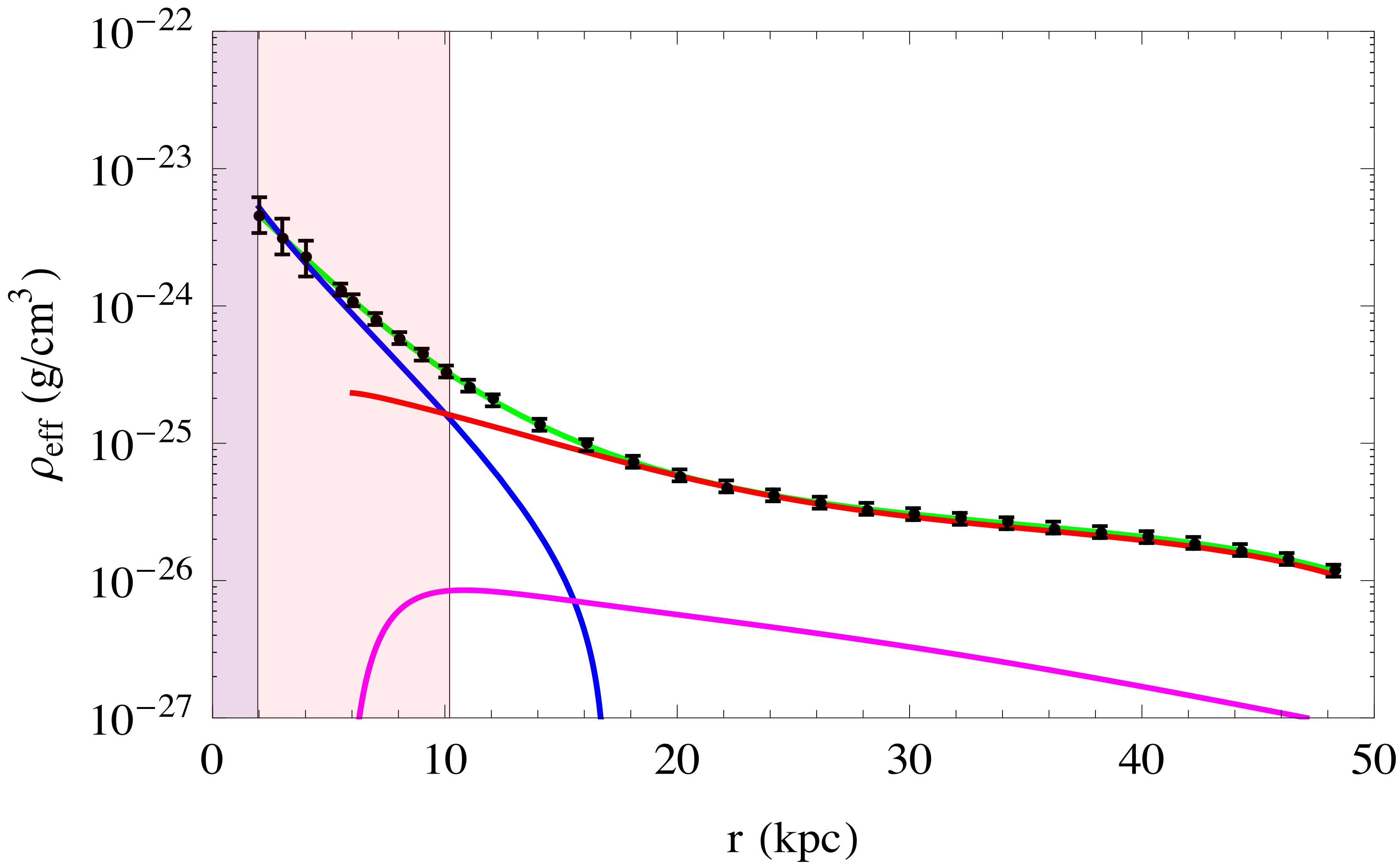


Fig. 7. Density profile of the DM halo of NGC 3198 and the *effective* density of the other components. We assume $M_{\rm D} = 4.4 \times 10^{10} M_\odot$. The stellar disk (Blue line), the HI disk (magenta line), the dark halo (red line) and the sum of all components (green line). The different colour regions correspond to the regions a) where we do not have any kinematical information due to the lack of data (dark purple), b) where the stellar disk dominates the DM density profile (light purple) and c) where DM dominates (white).

Similar exercise for the Milky Way yields local DM density:
ρ(8.5 kpc)~0.2-0.5 GeV/cm^3 (direct detection)

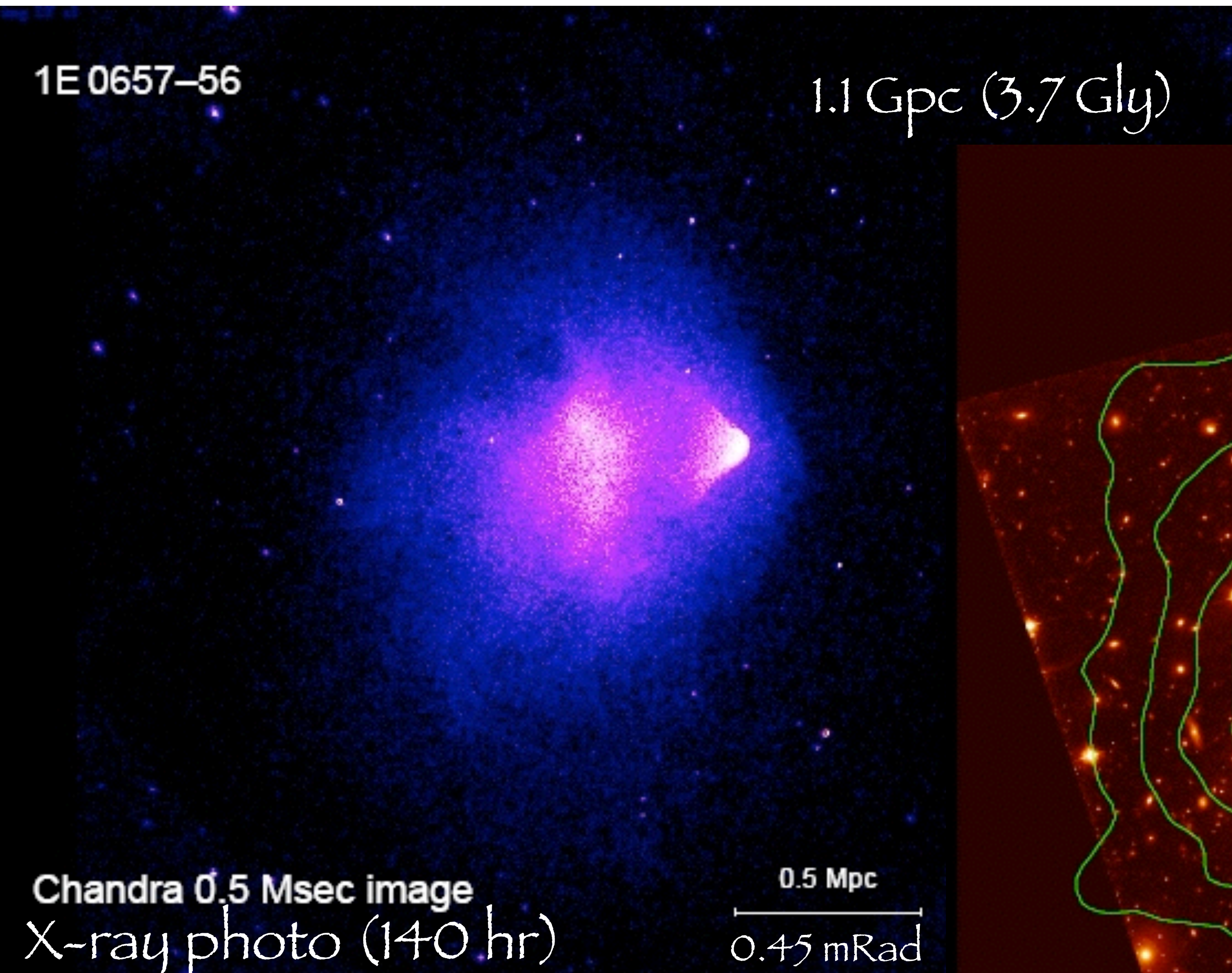
- For constant v:

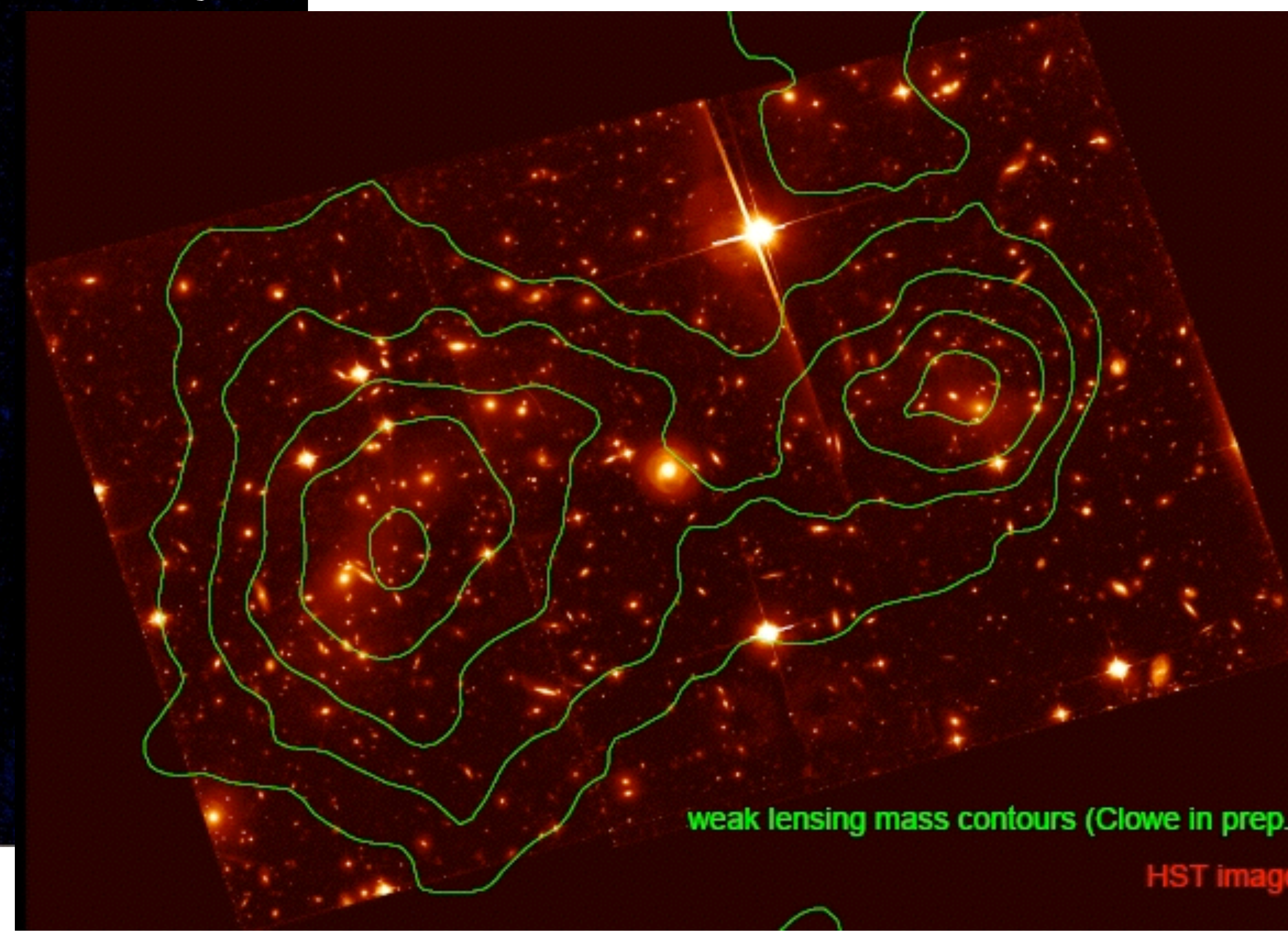
$$M(r) \propto r \qquad \rho(r) \propto r^{-2}$$

The Bullet Cluster Smoking Gun Evidence

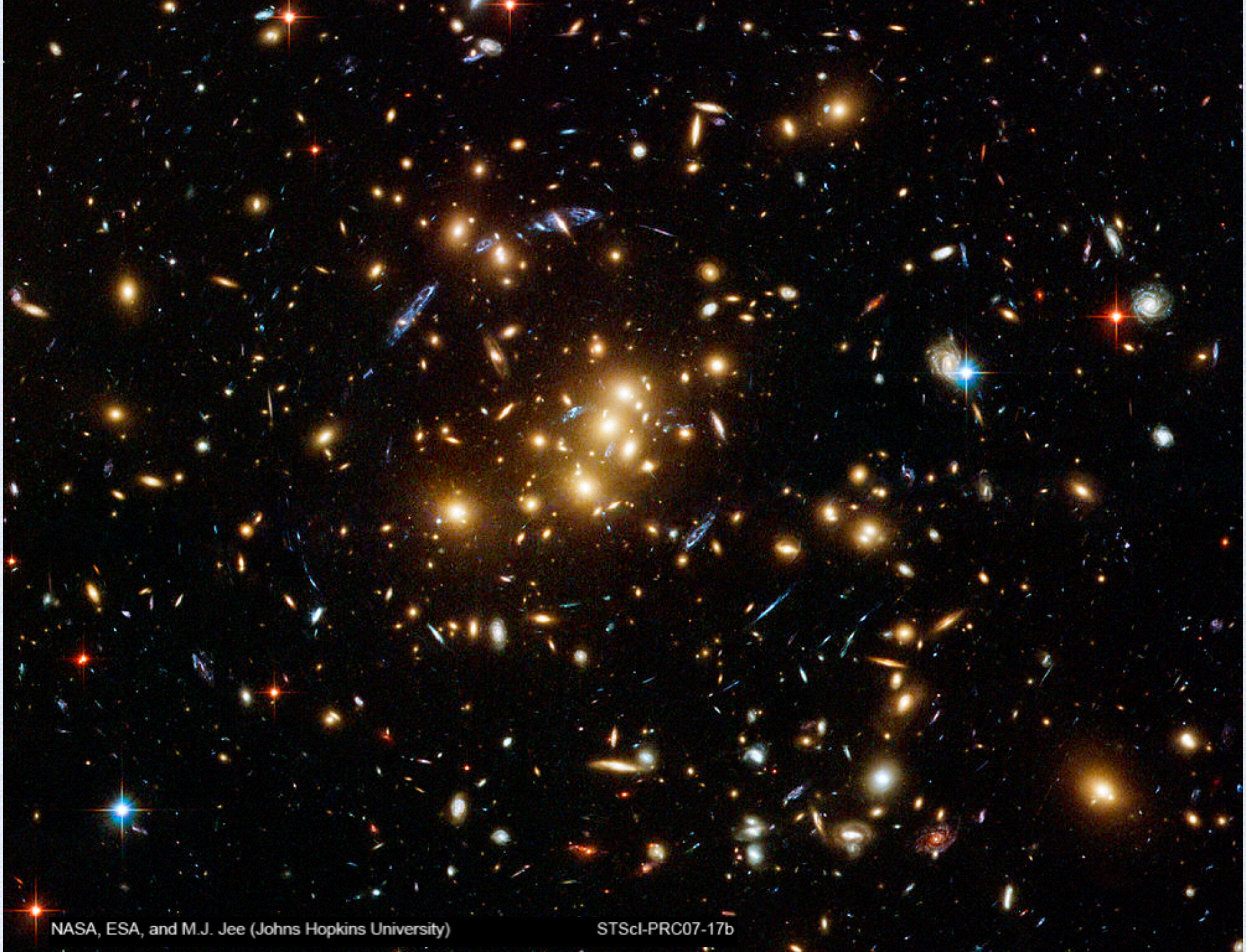
THE ASTROPHYSICAL JOURNAL, 604:596–603, 2004 April 1

WEAK-LENSING MASS RECONSTRUCTION OF THE INTERACTING CLUSTER 1E 0657−558: DIRECT EVIDENCE FOR THE EXISTENCE OF DARK MATTER[1]





Superimposing the 2 Pictures


NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

Dark Matter Ring

The ring, 2.6-million light-years wide, formed when two huge clusters of galaxies slammed together in a head-on collision 6 to 7 billion years ago, puffing the mysterious matter outward, the astronomers figure. If the galactic hit-and-run had occurred outside of Earth's line-of-sight, the result might look more like the "Bullet cluster"-- another cosmic impact site that astronomers view as strong evidence for dark matter. *(from NBC news)*

DISCOVERY OF A RINGLIKE DARK MATTER STRUCTURE IN THE CORE OF THE GALAXY CLUSTER Cl 0024+17

M.J. JEE[1], H.C. FORD[1], G.D. ILLINGWORTH[2], R.L. WHITE[3], T.J. BROADHURST[4], D.A. COE[1,5], G.R. MEURER[1], A. VAN DER WEL[1], N. BENÍTEZ[5], J.P. BLAKESLEE[6], R.J. BOUWENS[2], L.D. BRADLEY[1], R. DEMARCO[1], N.L. HOMEIER[1], A.R. MARTEL[1], AND S. MEI[1]

ABSTRACT

We present a comprehensive mass reconstruction of the rich galaxy cluster Cl 0024+17 at $z \simeq 0.4$ from ACS data, unifying both strong- and weak-lensing constraints. The weak-lensing signal from a dense distribution of background galaxies (~ 120 arcmin^{-2}) across the cluster enables the derivation of a high-resolution parameter-free mass map. The strongly-lensed objects tightly constrain the mass structure of the cluster inner region on an absolute scale, breaking the mass-sheet degeneracy. The mass reconstruction of Cl 0024+17 obtained in such a way is remarkable. It reveals a ringlike dark matter substructure at $r \sim 75''$ surrounding a soft, dense core at $r \lesssim 50''$. We interpret this peculiar sub-structure as the result of a high-speed line-of-sight collision of two massive clusters $\sim 1-2$ Gyr ago. Such an event is also indicated by the cluster velocity distribution. Our numerical simulation with purely collisionless particles demonstrates that such density ripples can arise by radially expanding, decelerating particles that originally comprised the pre-collision cores. Cl 0024+17 can be likened to the bullet cluster 1E0657-56, but viewed *along* the collision axis at a much later epoch. In addition, we show that the long-standing mass discrepancy for Cl 0024+17 between X-ray and lensing can be resolved by treating the cluster X-ray emission as coming from a superposition of two X-ray systems. The cluster's unusual

Cosmology (From Astrophysical Observation)

Nine-Year Wilkinson Microwave Anisotropy Probe (*WMAP*) Observations: Final Maps and Results

Sky in different microwaves bands

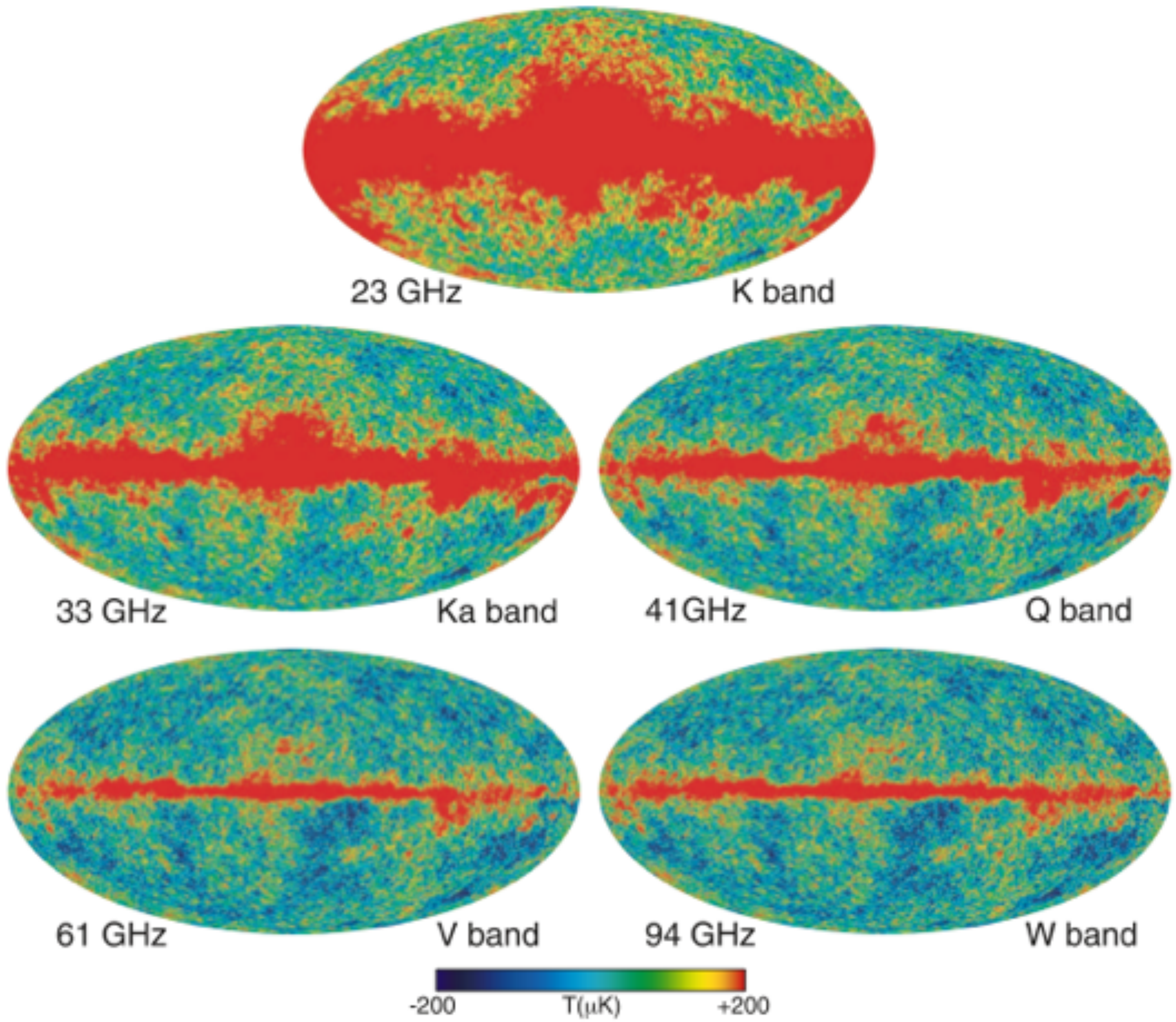
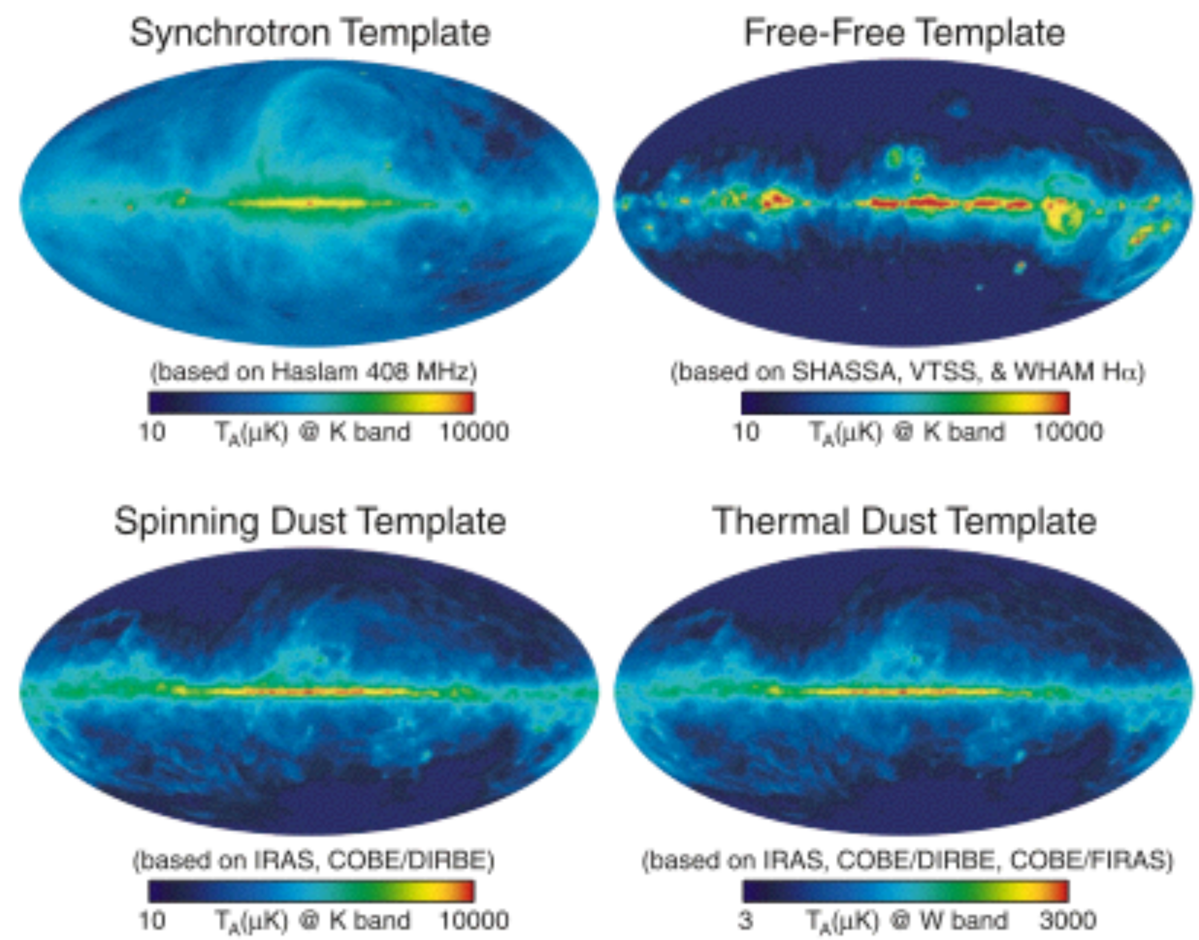
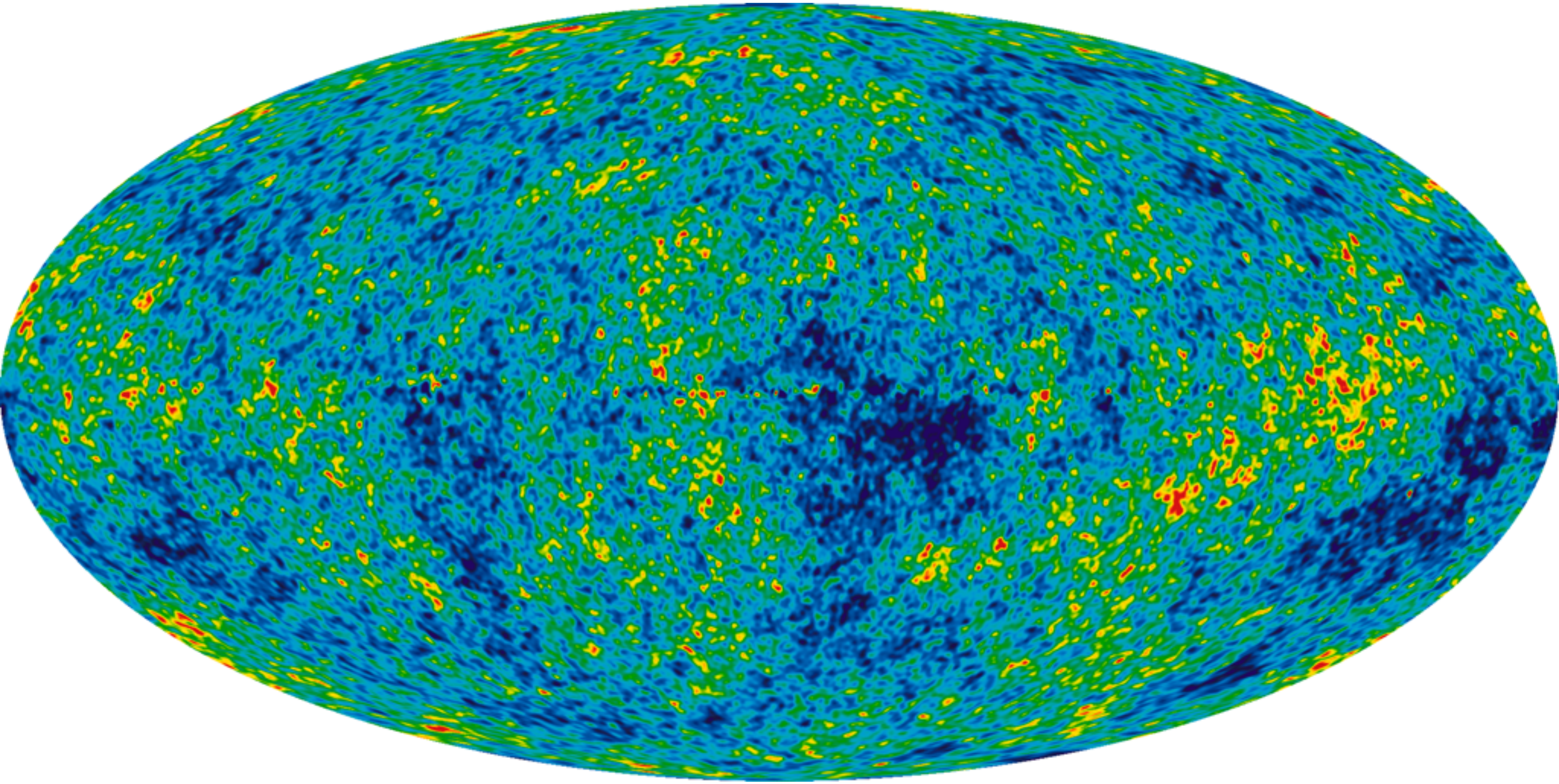


Fig. 3.— Nine-year temperature sky maps in Galactic coordinates shown in a Mollweide projection. Maps have been slightly smoothed with a 0°2 Gaussian beam.



Backgrounds to subtract

Temperature Fluctuations of The Early Universe As Seen Now



WMAP (NASA). Temperature Range +/- 200 μK

Angular Correlations of The Temperature Fluctuations

$$T(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{T,lm} Y_{lm}(\hat{n}) \qquad C_l^{TT} = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{T,lm} a^*_{T,lm}$$

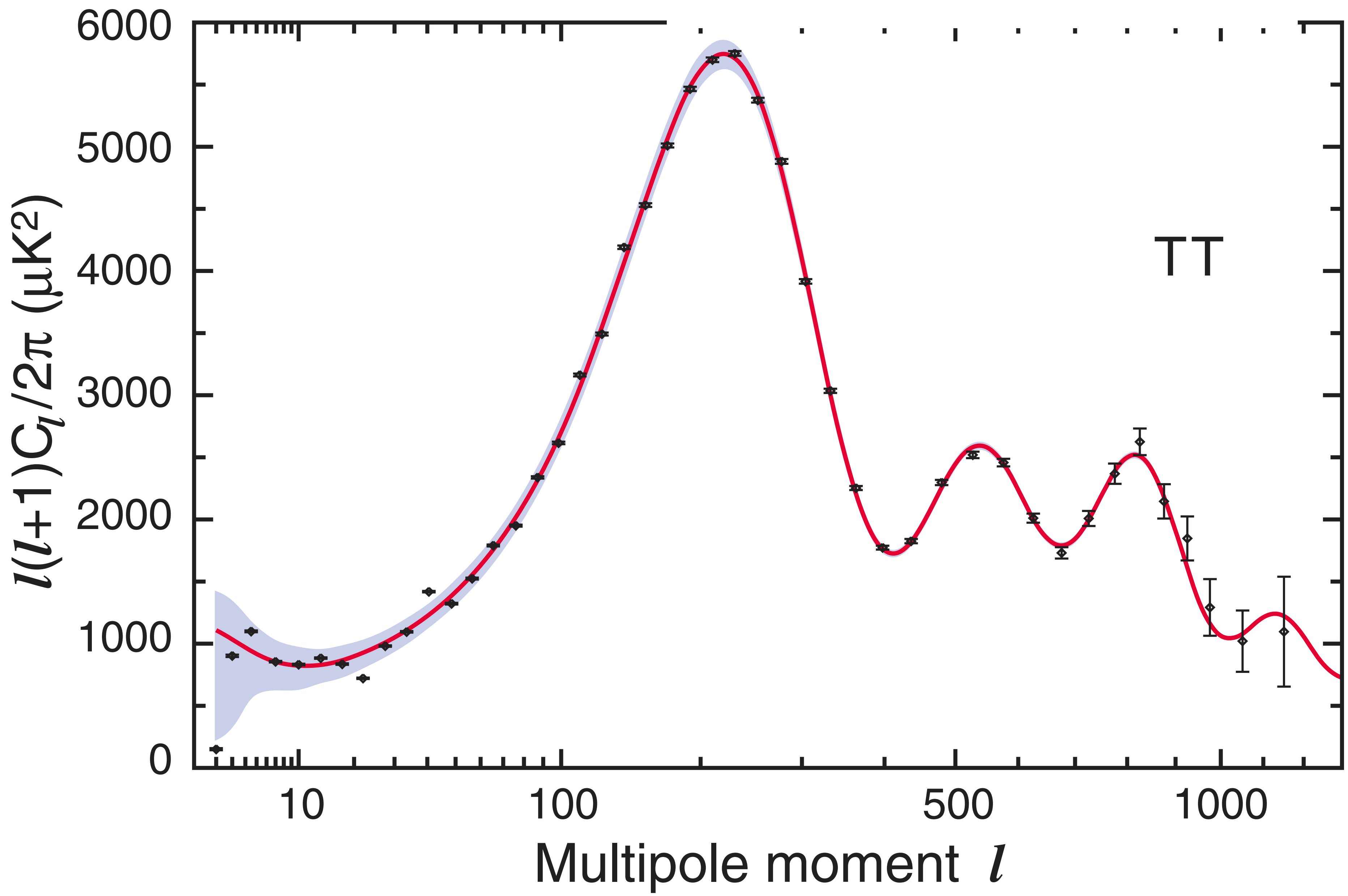


Fig. 32.— The nine-year *WMAP* TT angular power spectrum. The *WMAP* data are in black, with error bars, the best fit model is the red curve, and the smoothed binned cosmic variance curve is the shaded region. The first three acoustic peaks are well-determined.

Cosmological Parameter Summary (PDG)

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 ($k_0 = 0.002$ Mpc^{-1})[d]	$10^9 \Delta^2_{\mathcal{R}}$	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, $H_0 = 100h$ km/s/Mpc	H_0	70.0 ± 2.2	69.32 ± 0.80
Density fluctuations @ $8h^{-1}$ Mpc	σ_8	0.821 ± 0.023	$0.820^{+0.013}_{-0.014}$
Velocity fluctuations @ $8h^{-1}$ Mpc	$\sigma_8 \Omega_m^{0.5}$	0.434 ± 0.029	0.439 ± 0.012
Velocity fluctuations @ $8h^{-1}$ 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)	$d_A(z_{\mathrm{eq}})$	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
Tensor spectral index[l]	n_t	> -0.048 (95% CL)	> -0.016 (95% CL)
Curvature ($1 - \Omega_{\mathrm{tot}}$)[m]	Ω_k	$-0.037^{+0.044}_{-0.042}$	$-0.0027^{+0.0039}_{-0.0038}$
Fractional Helium abundance, by mass	Y_{He}	< 0.42 (95% CL)	0.299 ± 0.027
Massive neutrino density[n]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0047 (95% CL)
Neutrino mass limit (eV)[n]	$\sum m_\nu$	< 1.3 (95% CL)	< 0.44 (95% CL)
Limits on parameters beyond ΛCDM			
Dark energy (const.) equation of state[o]	w	$-1.71 < w < -0.34$ (95% CL)	$-1.073^{+0.090}_{-0.089}$
Uncorrelated isocurvature modes	α_0	< 0.15 (95% CL)	< 0.047 (95% CL)
Anticorrelated isocurvature modes	α_{-1}	< 0.012 (95% CL)	< 0.0039 (95% CL)

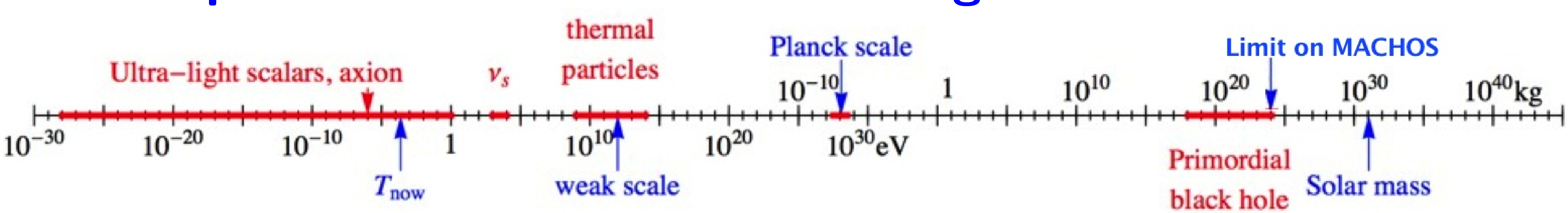
Ok… let's say that DM exists,
what
the heck is it anyhow ???

Graciela Gelmini-UCLA

After 80 years, what we know about DM:

- **Attractive gravitational interactions and stable (or lifetime $>> t_U$)**
- **DM and not MOND + only visible matter ("Bullet Cluster")**
- 10^{-31} GeV $\leq$**mass**$\leq 10^{-7} M_\odot = 10^{50}$GeV (limits on MACHOS astro-ph/0607207) ("Fuzzy DM", boson de Broglie wavelength= 1 kpc Hu, Barkana, Gruzinov, astro-ph/0003365) or 0.2-0.7 $\times 10^{-6}$ GeV$\leq$ 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!



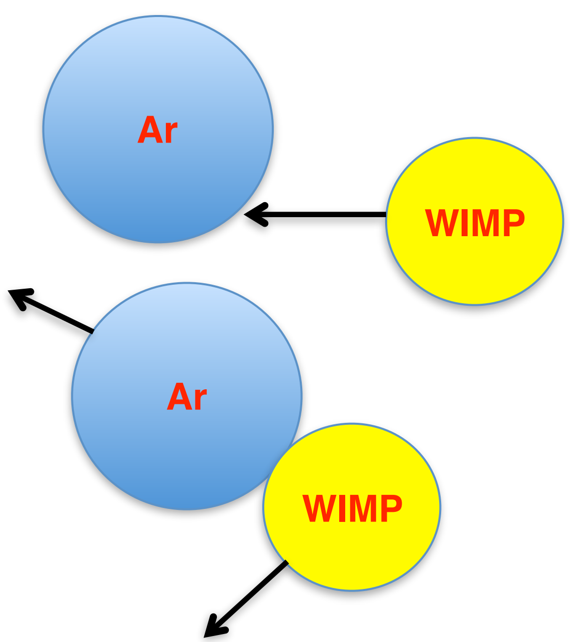
Hopefully DM Interacts with Ordinary Matte

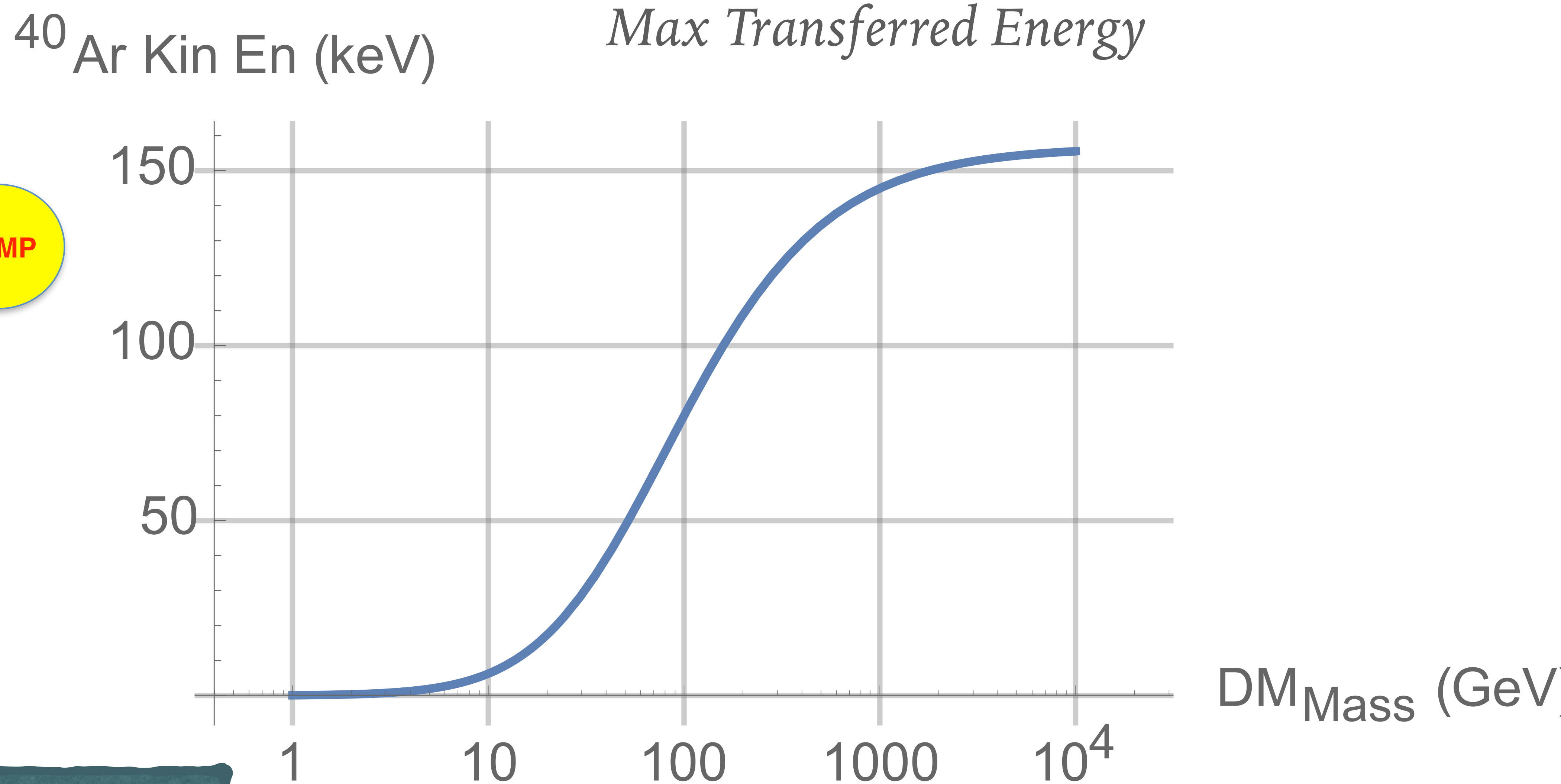
KIS (Keep It Simple)/
Occam's Razor:
WIMP - Nucleus
Elastic Collision

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

$$\frac{1}{2} M_{\mathrm{W}}\, c^2\, \beta_{\mathrm{W}}^2\, \frac{4\, M_{\mathrm{W}}\, M_{\mathrm{Ar}}}{(M_{\mathrm{W}}+M_{\mathrm{Ar}})^2} + \mathcal{O}(\beta^4)$$

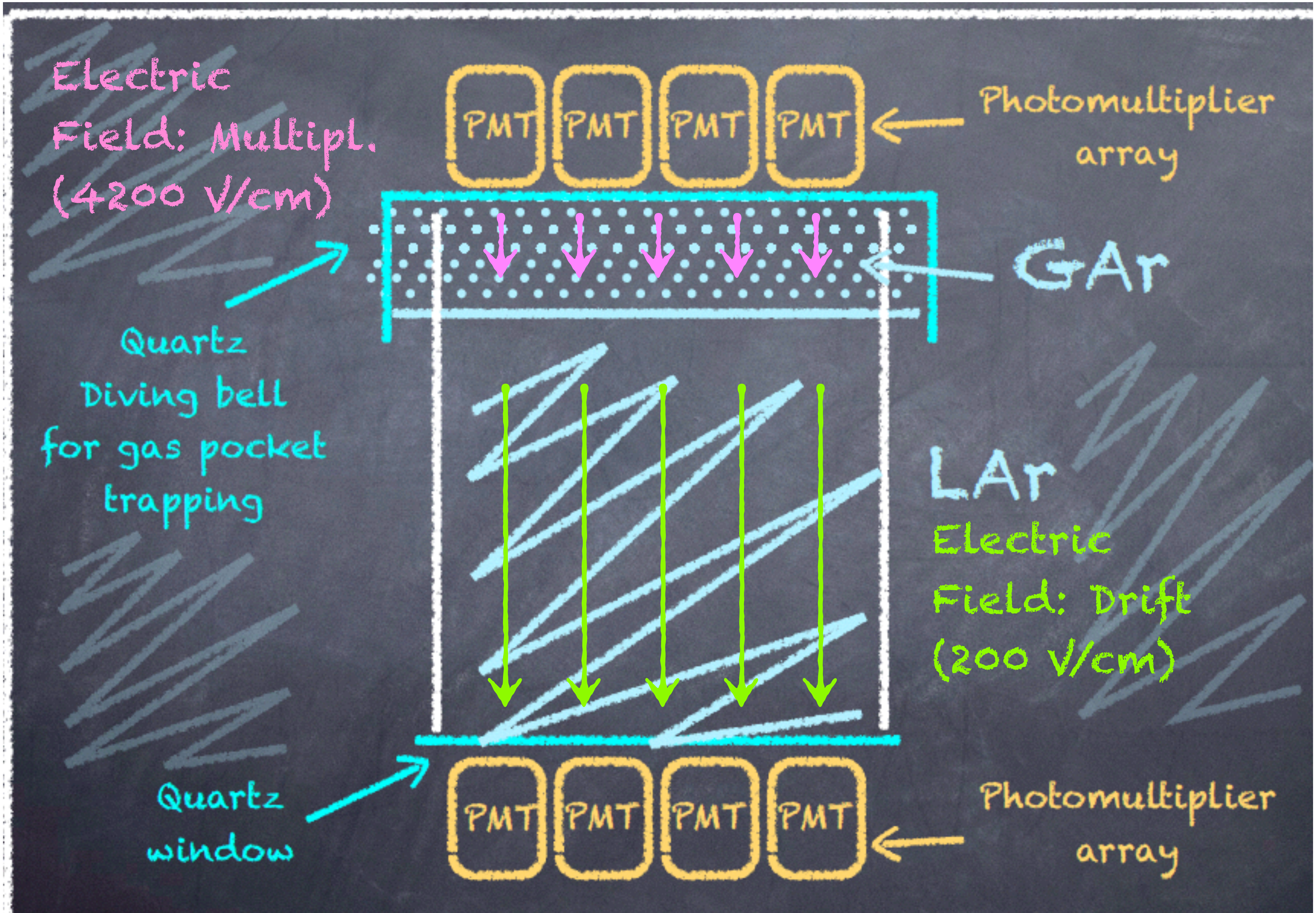
Max Transferred Energy



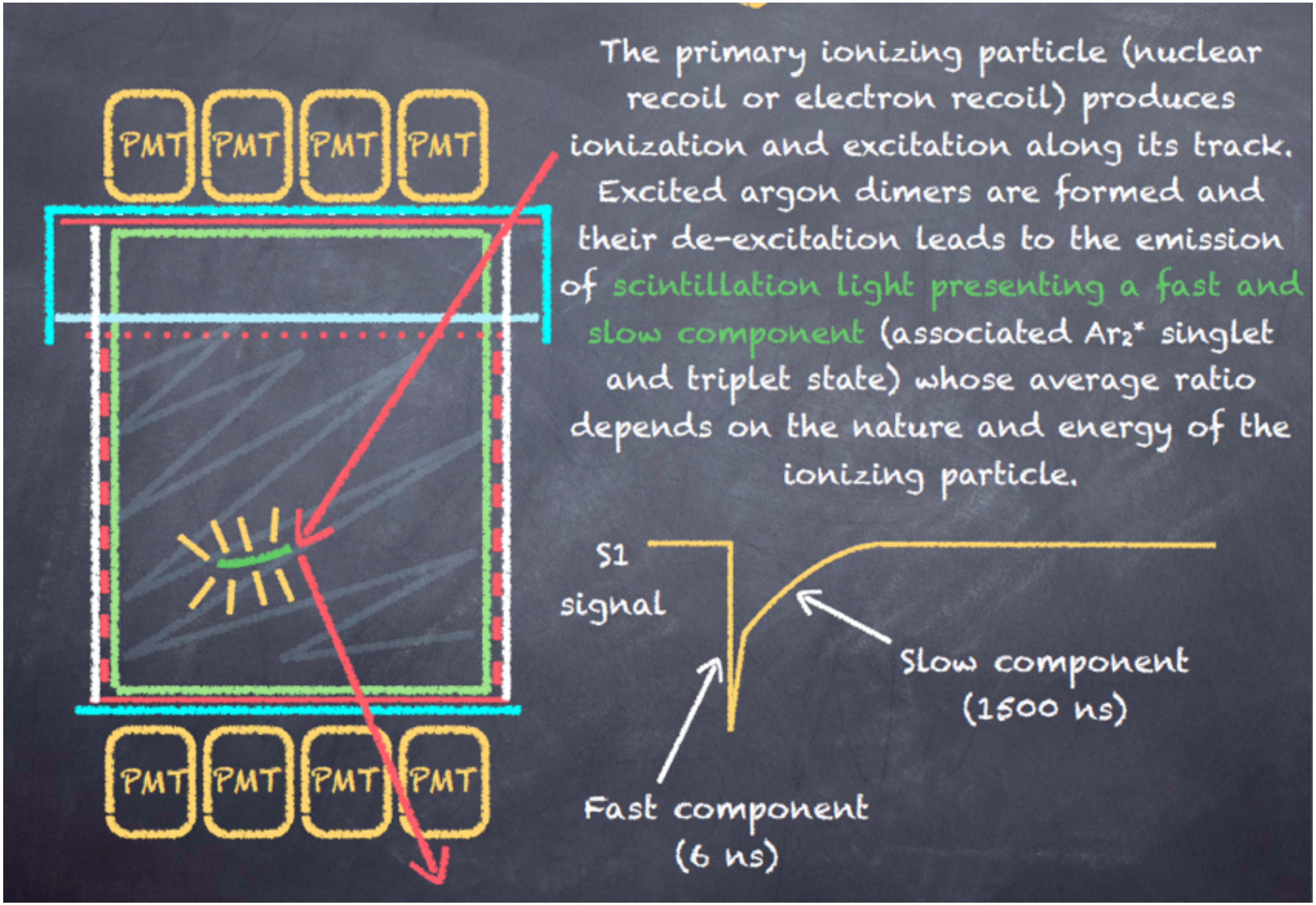


Use neutrons to mimic WIMPs
for calibrations

Two Phases Time Projection Chamber (Darkside 50)

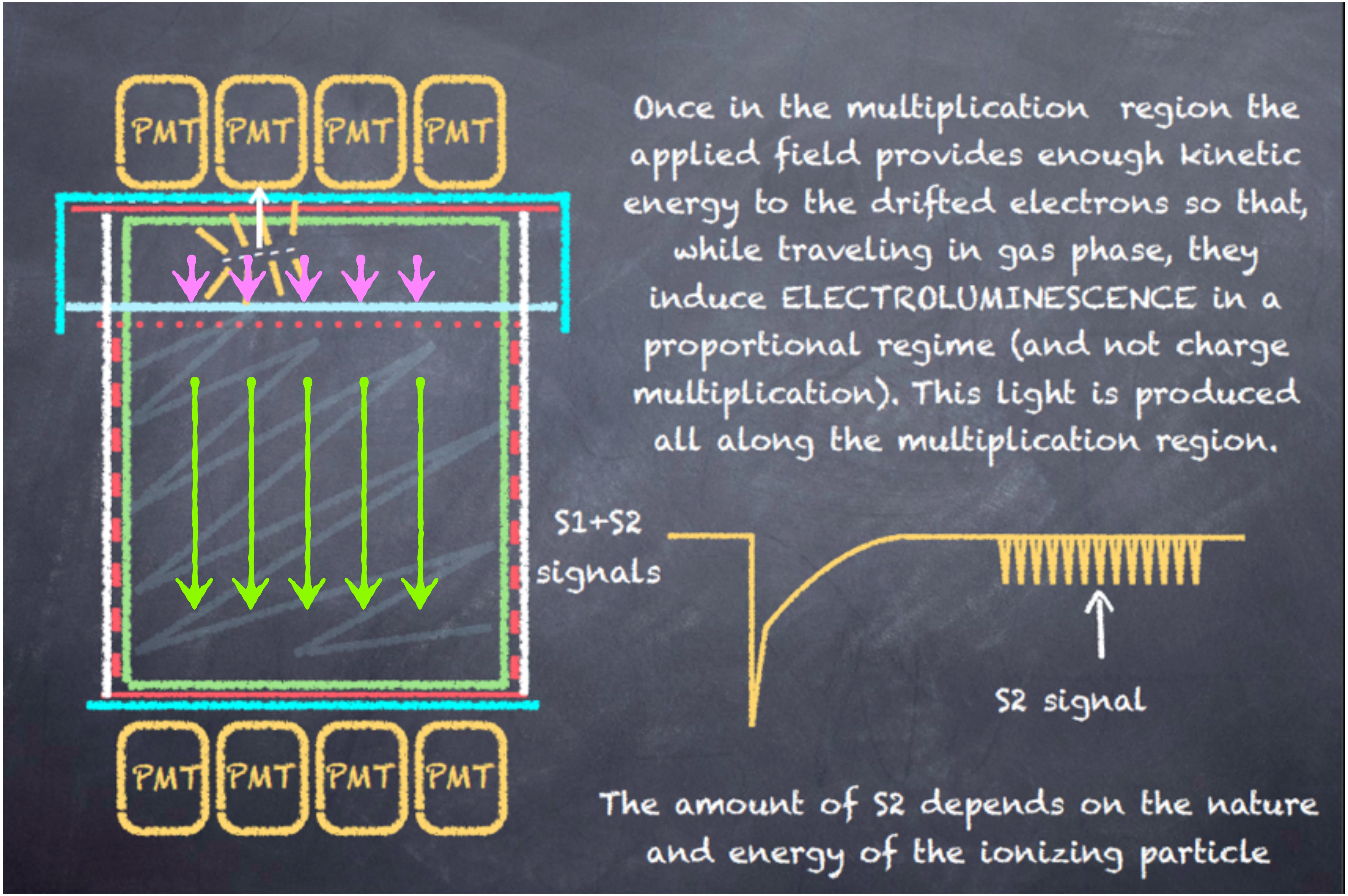


The Prompt Signal

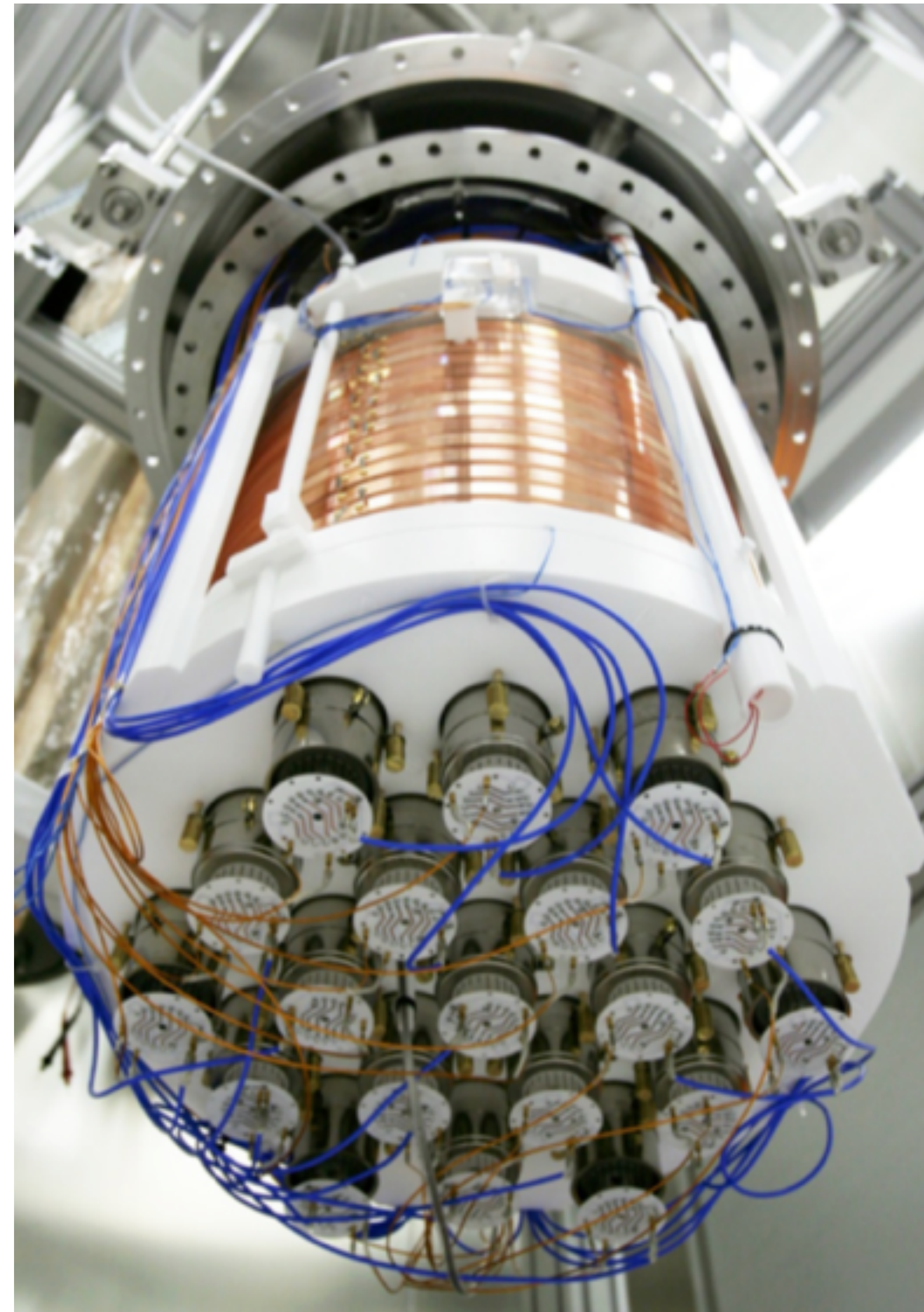


~ 40 primary photons UV (128nm) / keV

The Delayed Signal



The Darkside PMT array and the whole TPC



Backgrounds

- We are looking for extremely rare events consisting of a few 10s of keV released in the detector, that is a few tens of photons on the PMT
- The signal must come out of the blue in the core of the detector
  - radioactive decays inside the detector
  - neutrons (cosmogenic, radiogenic)
  - γ rays
  - neutrino - electron scattering
  - neutrino floor (coherent neutrino - nucleus scattering)

Clean Construction

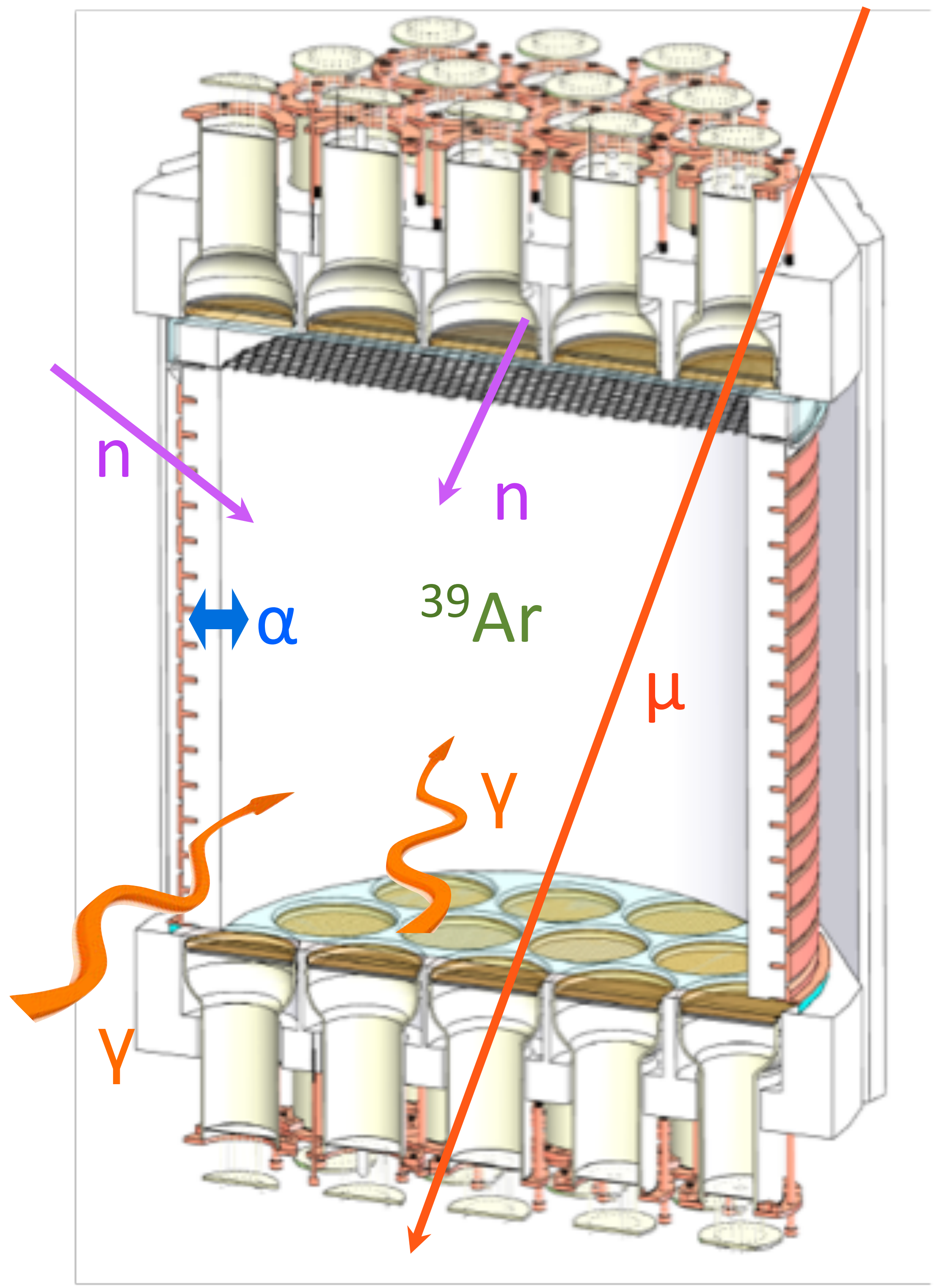
Shielding+Veto + Background rejection

Backgrounds

ELECTRON RECOILS

^{39}Ar
~9x10^4 evt/kg/day

γ
~1x10^2 evt/kg/day



NUCLEAR RECOILS

μ
~30 evt/m^2/day

Radiogenic n
~6x10^{-4} evt/kg/day

α
~10 evt/m^2/day

100 GeV, 10^{-45}cm^2 WIMP Rate ~ 10^{-4} evt/kg/day

Darkside 50 Vetos Systems

DarkSide-50

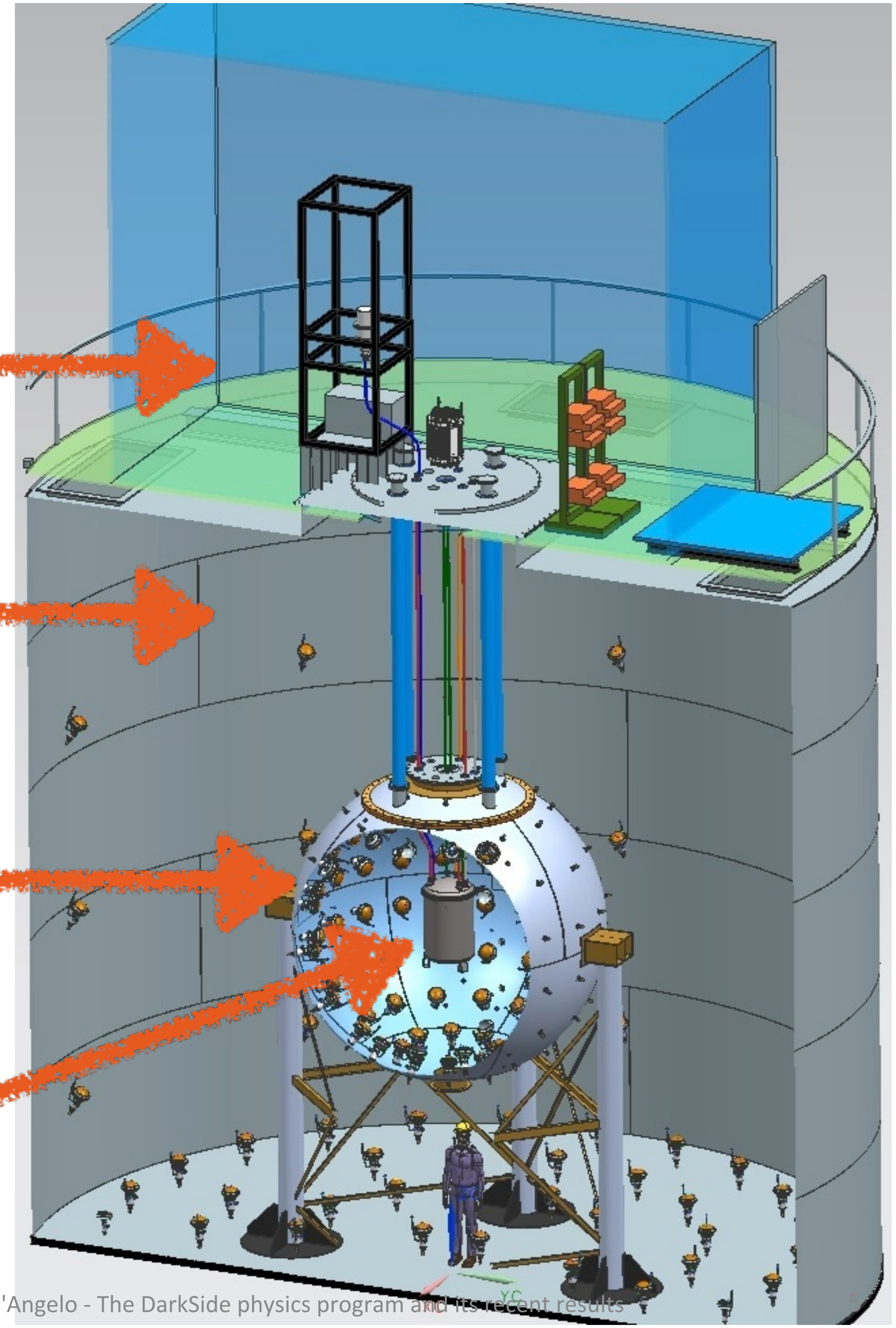
Housed in CTF
Borexino Counting Test Facility

Radon-free (Rn levels < 5 mBq/m^3)
Clean Room

1,000-tonne Water-based
Cherenkov **Cosmic Ray Veto**

30-tonne Liquid Scintillator
Neutron and γ's Veto

Inner detector **TPC**



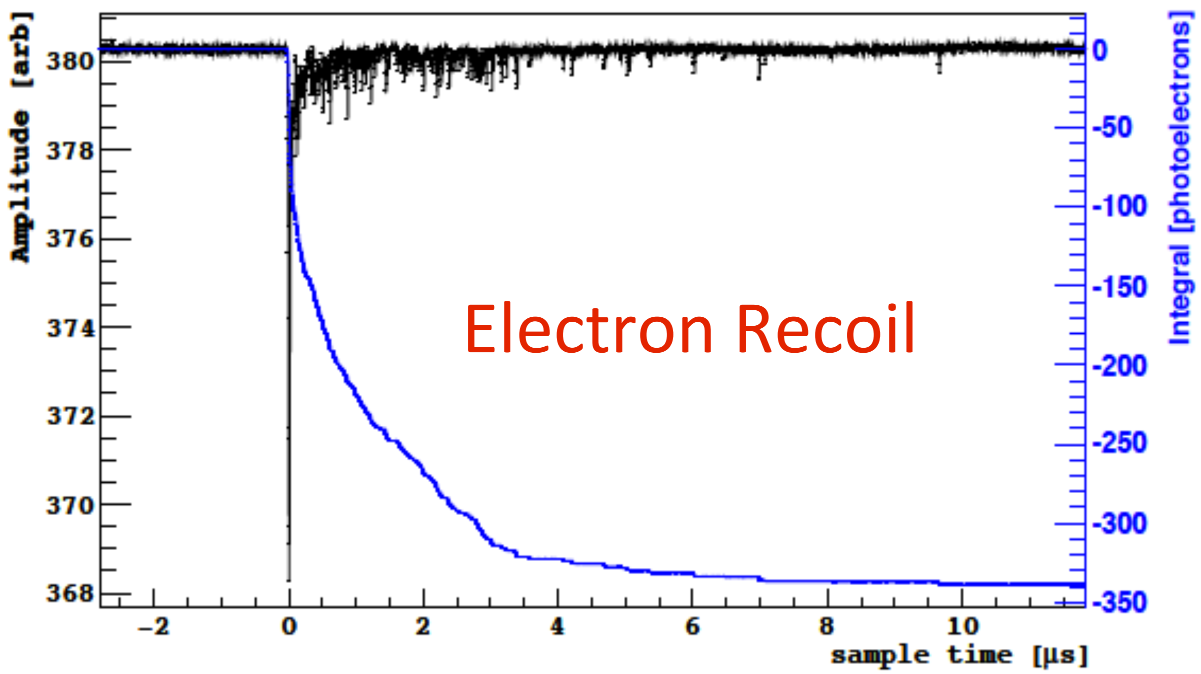

Gran Sasso
Under 3800 meters of equivalent water shield in LNGS

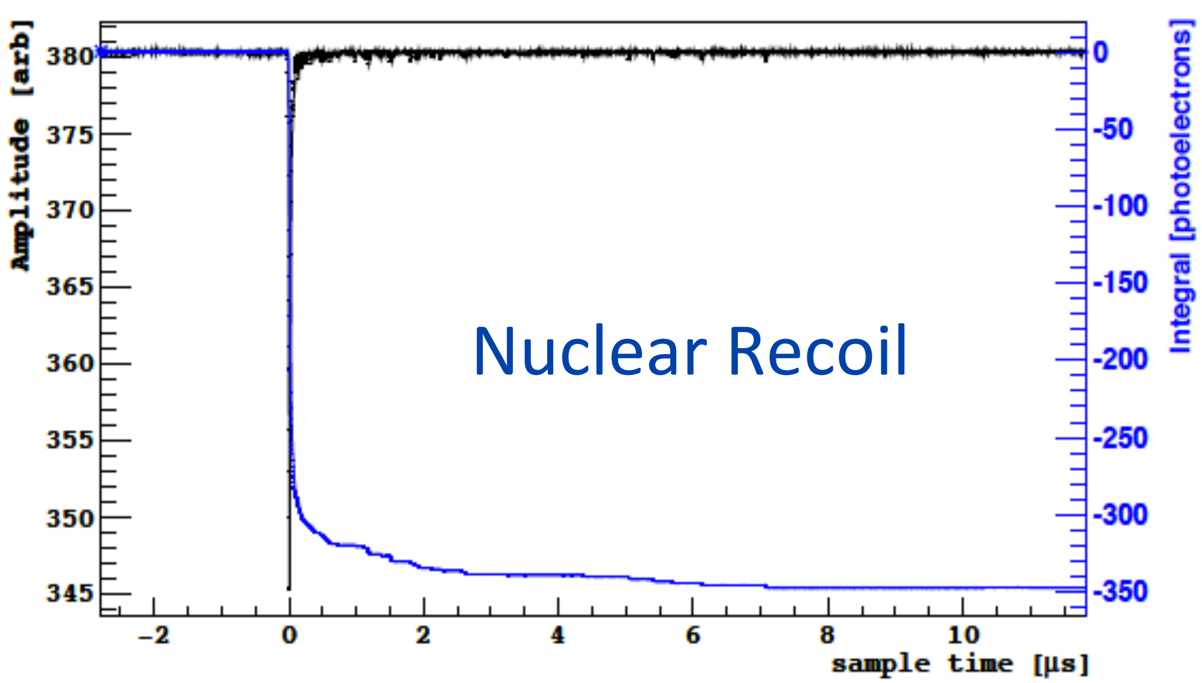
Pulse Shape Discrimination

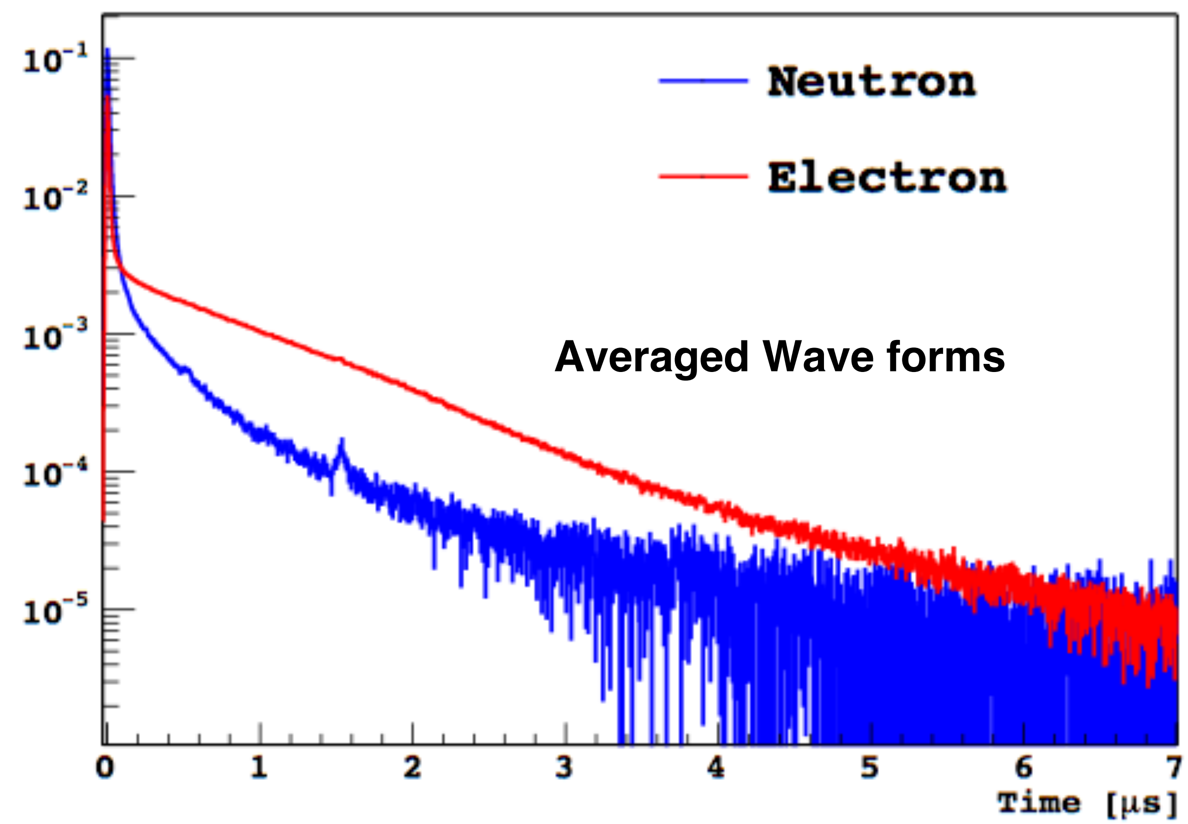
$T_{singlet} \sim 7$ ns

$T_{triplet} \sim 1500$ ns

$$F_{90} = \frac{\int_0^{90ns} dt\, f(t)}{\int_0^{\infty} dt\, f(t)} = \begin{cases} 0.3 \text{ ER} \\ 0.7 \text{ NR} \end{cases}$$

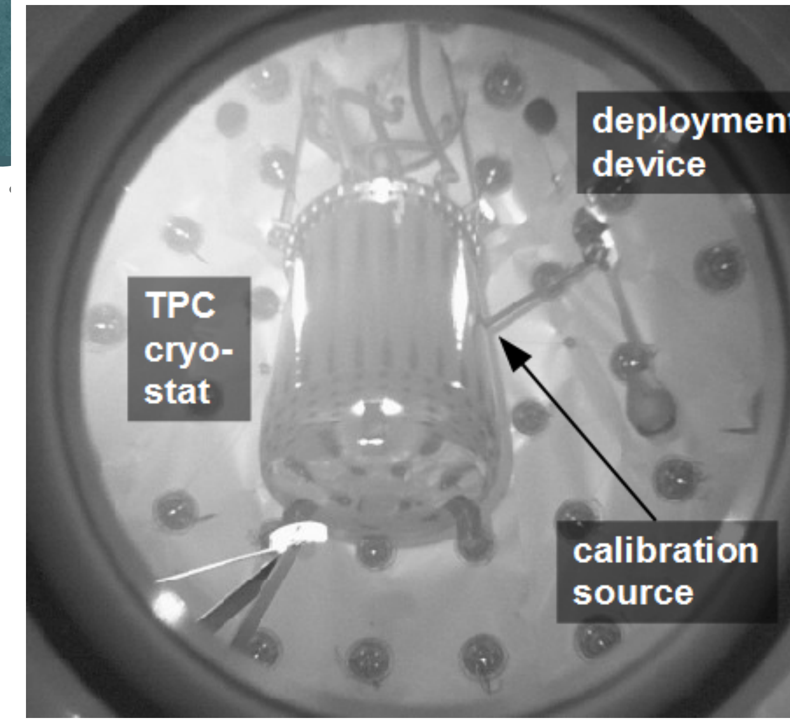






Different singlet/triplet excitations ratio.
Electron recoil pulse shape is longer

Calibration And Cross-checks

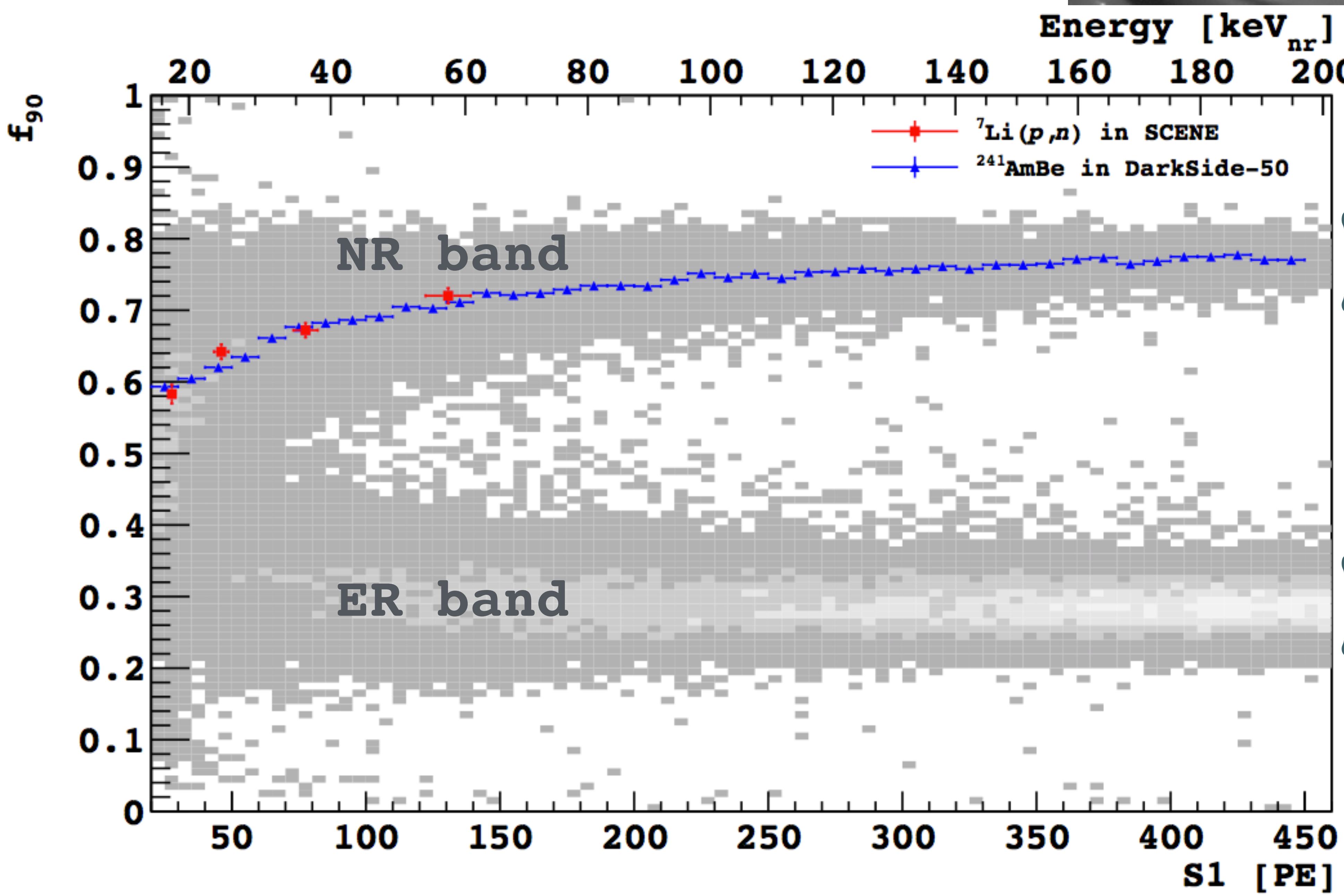


CALIS

CALibration Insertion System

Calibrate both **TPC** and **Neutron veto**

- **Gamma sources:** ^{57}Co (122 keV), ^{133}Ba (356 keV), ^{137}Cs (663 keV)
- **Neutron source:** AmBe

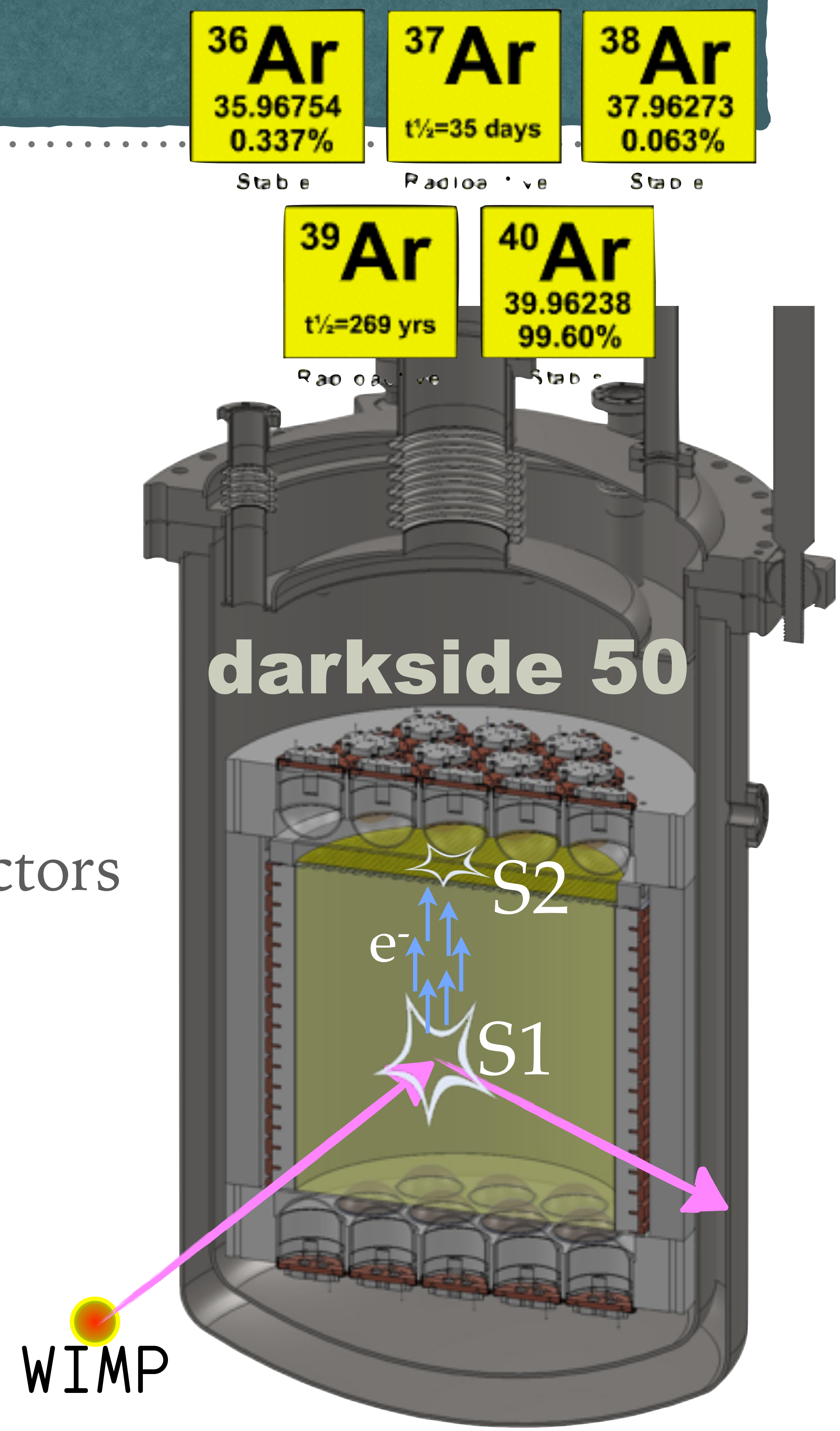


Signal Band

Bkg. Band

Argon Isotopical Composition

- ^{39}Ar (Cosmogenic Isotope) is a contaminant of Argon extracted from atmosphere
  - β emitter
    (565 keV head of the spectrum)
  - Intrinsic radioactivity 1Bq/kg
    - Limiting factor for multi ton detectors
- The activity of Argon from the deep underground CO_2 mine in Colorado is ~ 150 times lower
- Distillation plant produces 0.5 kg/d of underground Argon (uAr)



Underground Ar

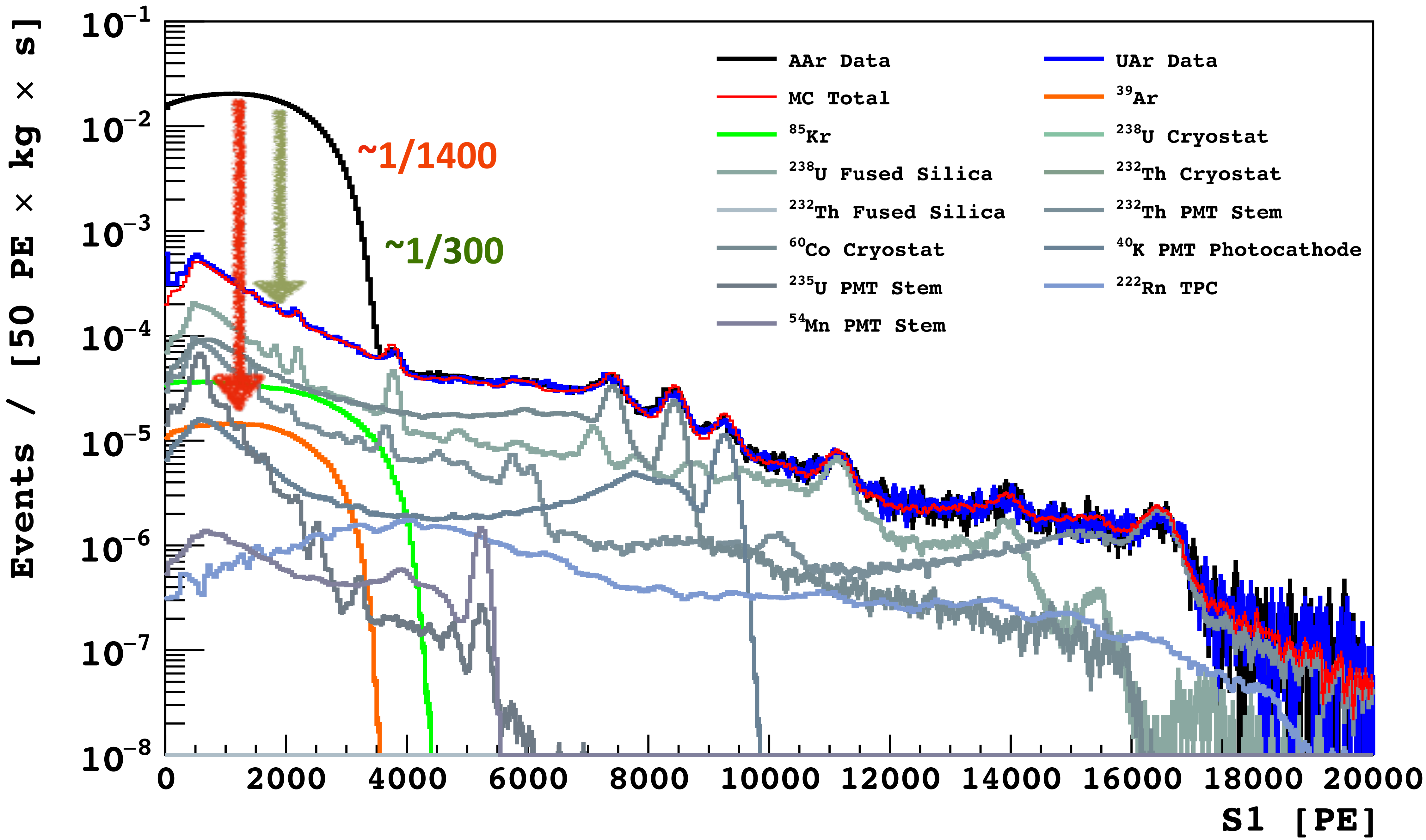
1. **Extraction at Colorado (CO_2 Well)**
   Extract a crude argon gas mixture (Ar, N_2, and He)

2. **Purification at Fermilab**
   Separate Ar from He and N_2

3. **Arrived at LNGS**
   Ready to fill into DS-50

UAr vs Atmospheric Argon (AAr)

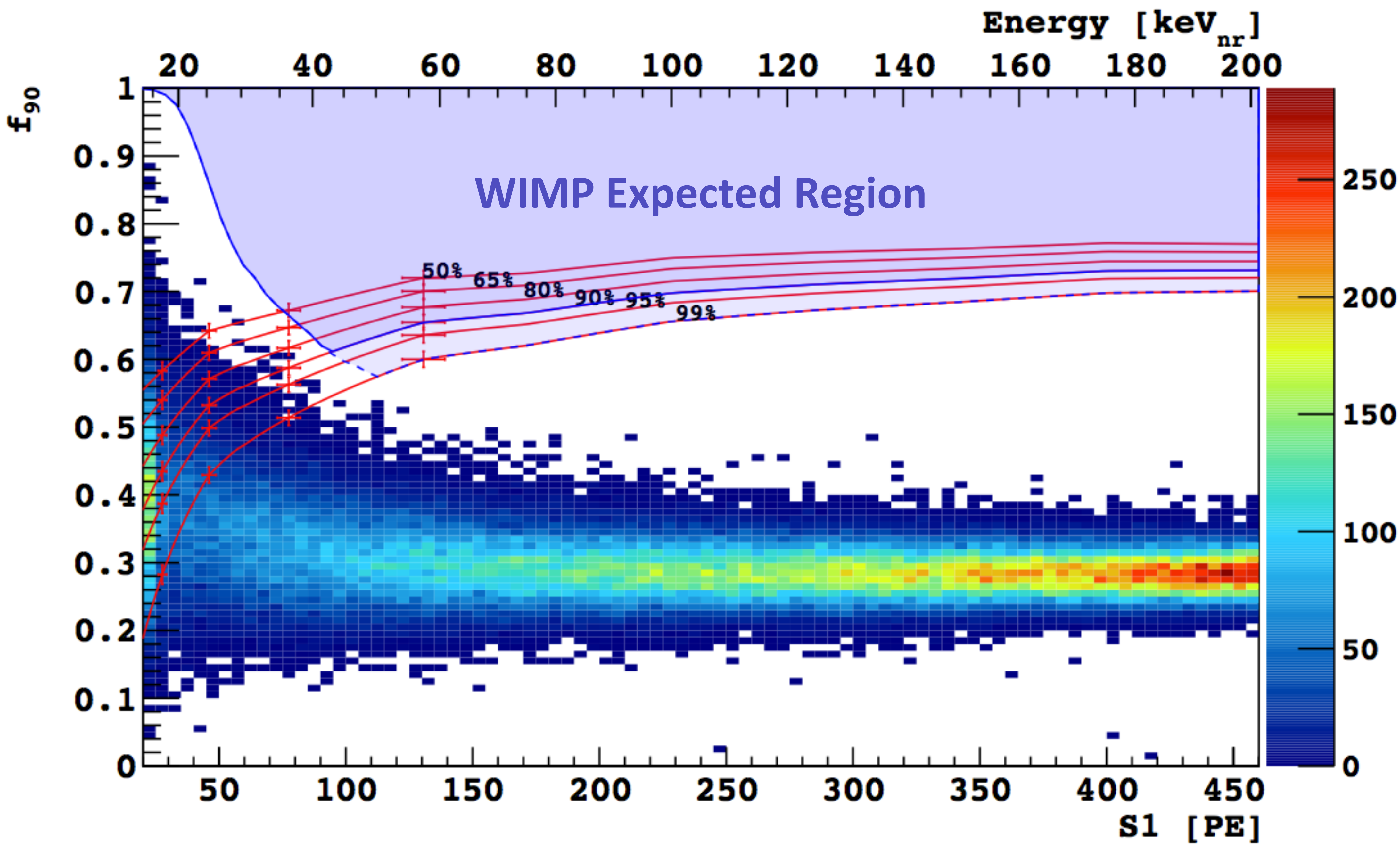
AAr vs UAr. Live-time-normalized S1 pulse integral spectra at Zero field.



Low level of ^{39}Ar allows extension of DarkSide program to ton-scale detector.

Darkside with Underground Argon First results

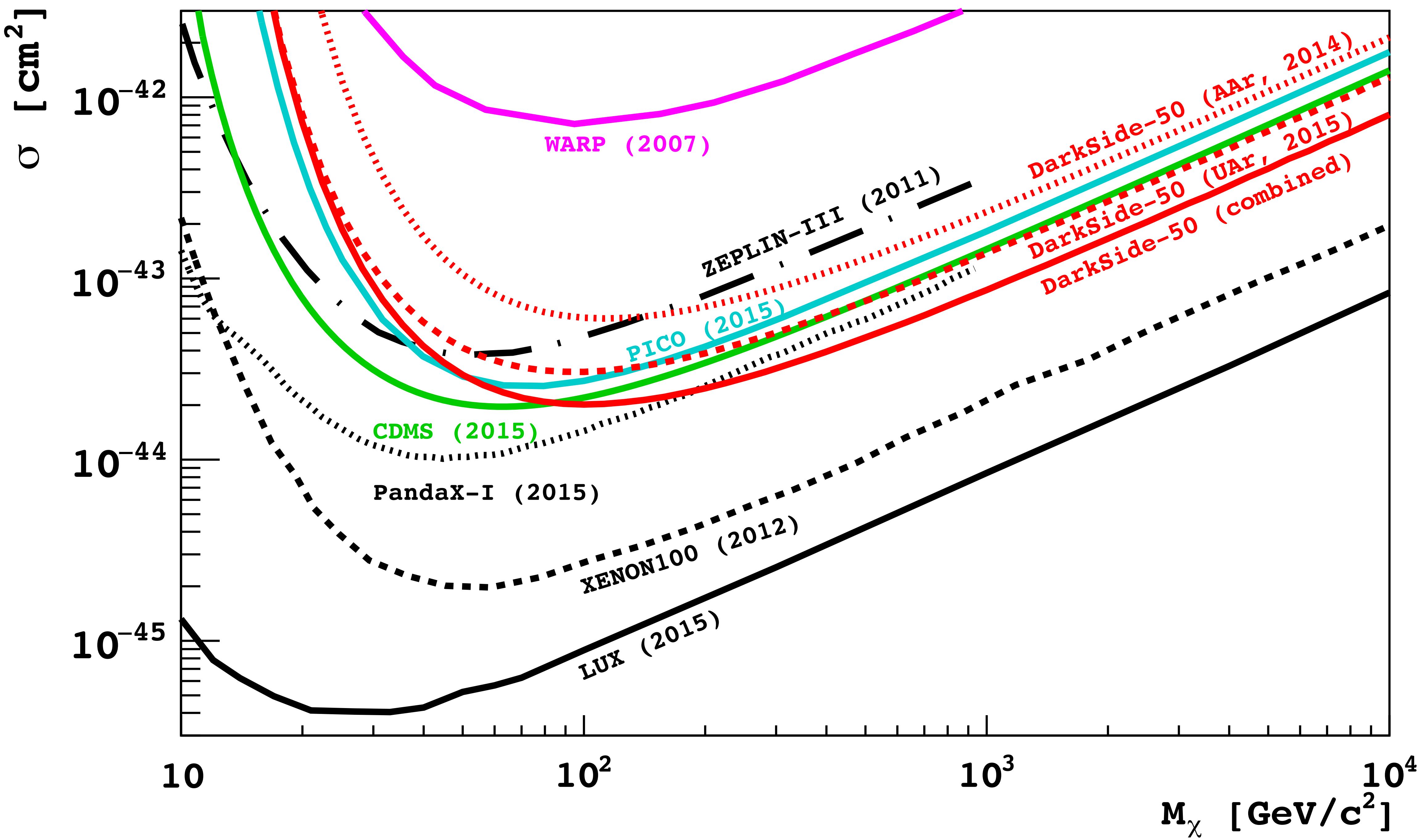
No background events in nuclear recoil (WIMP) region!



71 live-days after all cuts. (2616±43) kg day exposure.
Single-hit interactions in the TPC, no energy deposition in the veto

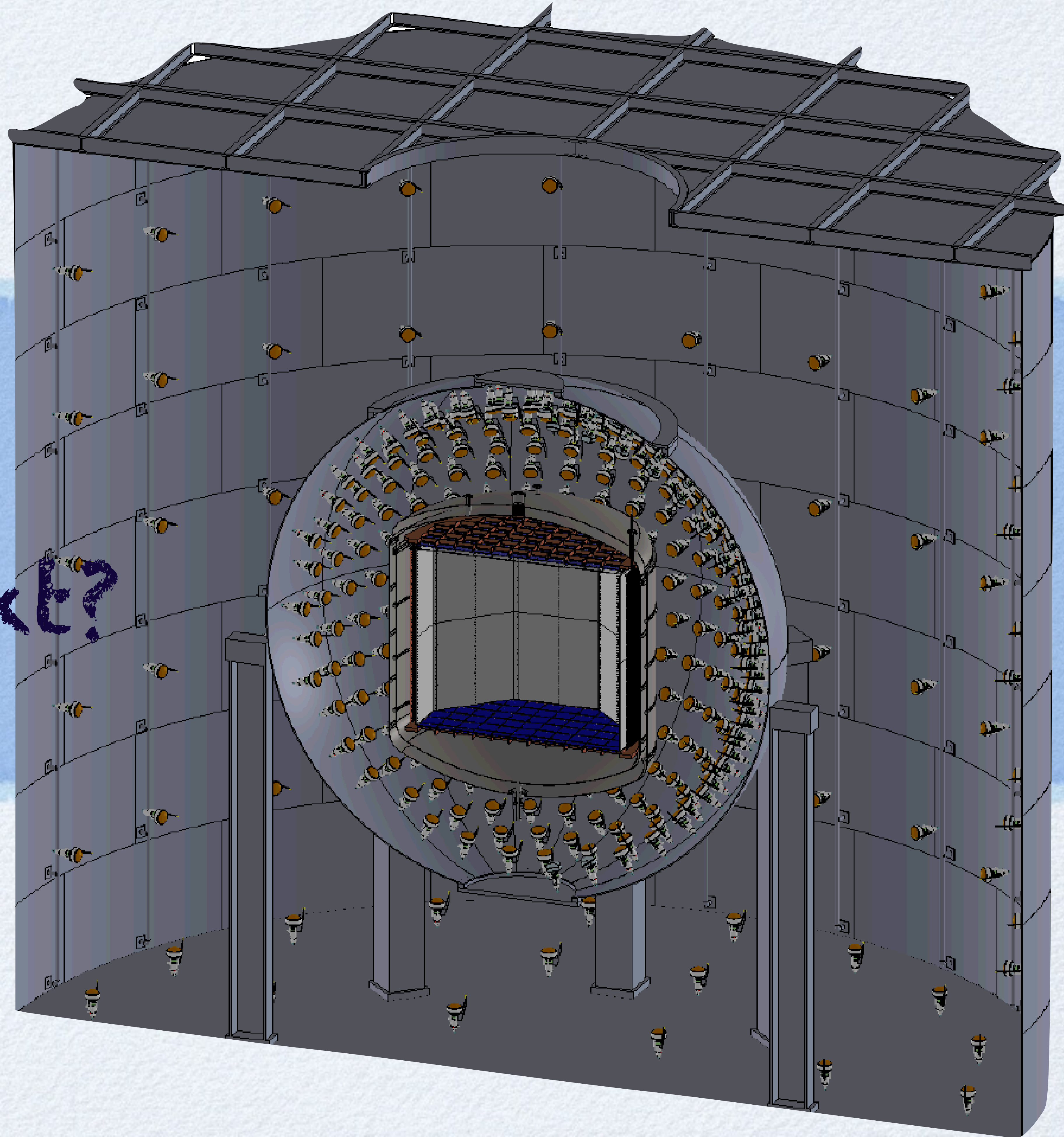
arXiv:1510.00702

Darkside 50 Exclusion Region



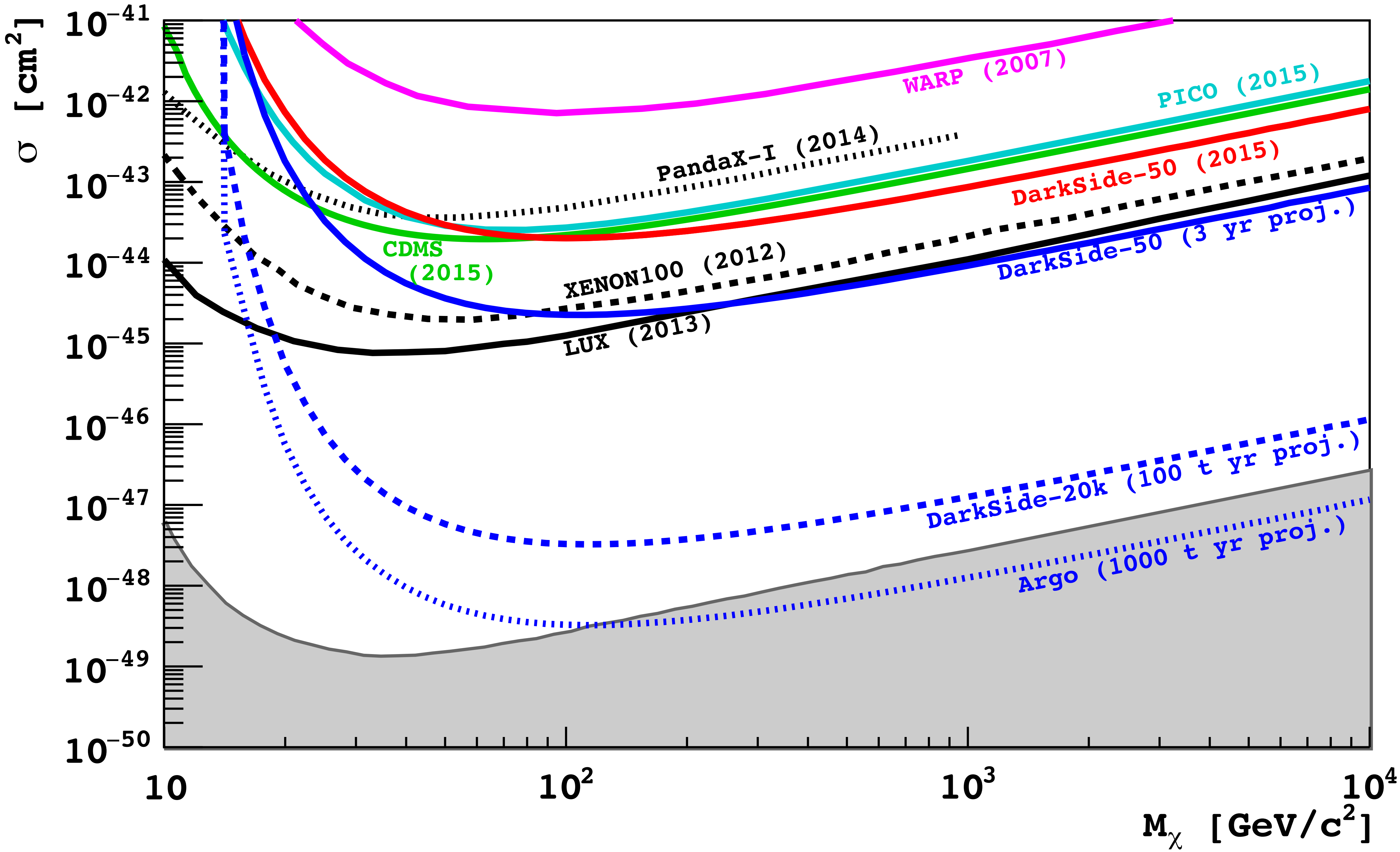
Best limit to date, with argon target, third best limit behind LUX & Xenon100.

Ok...
What Next?



Future Searches using 2 phases Argon TPC

- Longer exposure, then larger detector



Darkside Past, Present, Future

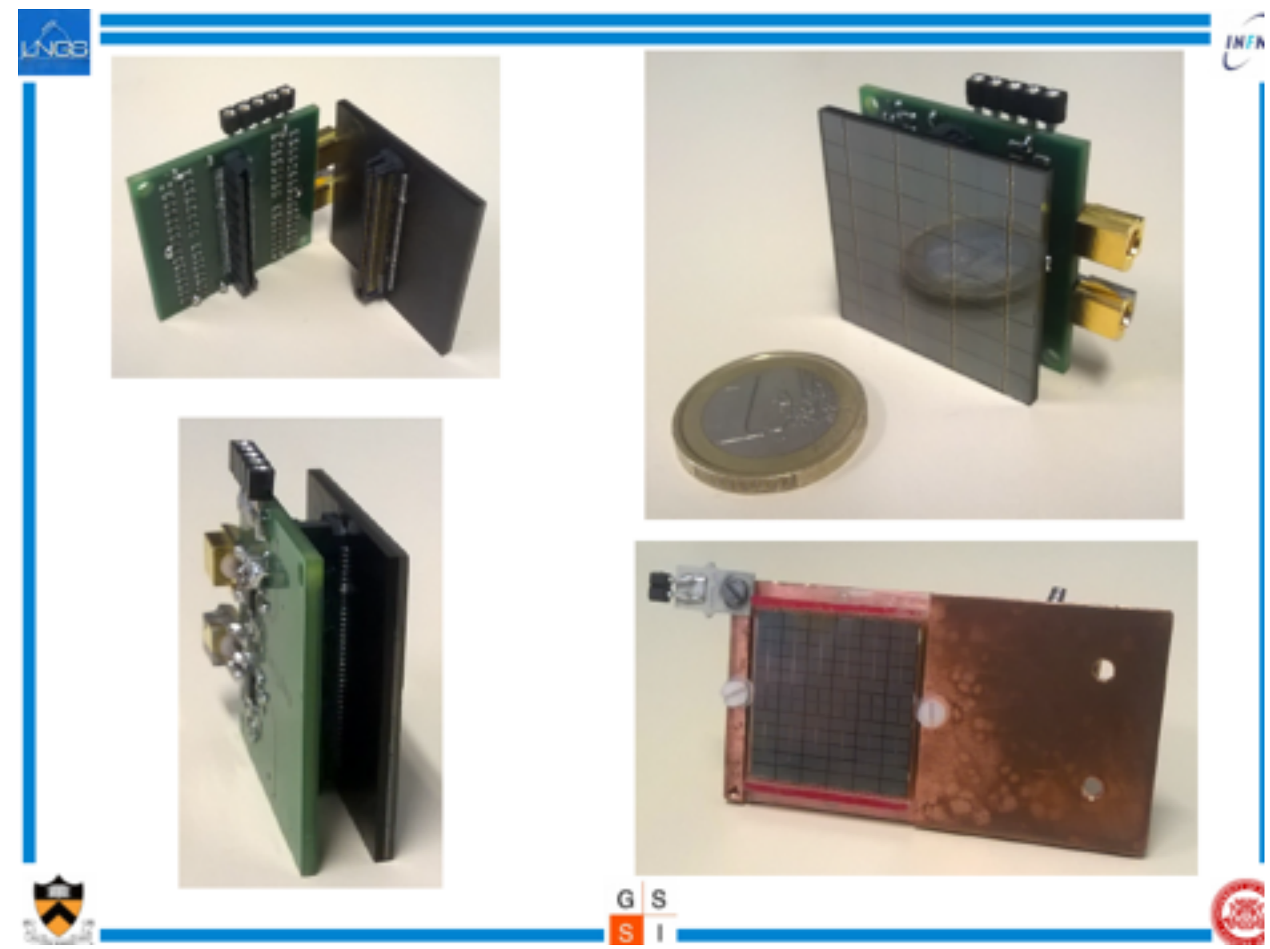
- 2010-2012; DS-10 at Princeton-> LNGS 10 kg normal Ar not radiopure, water-block shielding, 8 PMTs
- 2013-present; DS-50 at LNGS
  153 kg total, 36.9 kg fiducial
  radiopure construction, UAr target (arXiv 1204.6024; see below) high efficiency neutron shield/veto
  currently: > 4000 kg-day analyzed, planned exposure 3 years
  8.6×10^{-44} cm2 @ 1 TeV/c2, world's 3rd best current limit
- ~2020 DS-20k at LNGS (proposed to NSF & INFN 2015)
  30 ton total, 20 ton fiducial
  radiopure construction, Depleted Ar target, SiPM sensors high efficiency neutron shield/veto
  100 ton-year planned exposure 10^{-47} (10^{-46}) cm2 at 1(10) Tev/c2
- 202x ARGO at LNGS
  1000 ton-year planned exposure
  to reach the solar ν coherent scattering floor detailed solar ν studies possible (arXiv 1510.04196)

Toward a MultiTonne Background Free 2 Phases Ar TPC

- Background free:
  - Darkside 50 collected 47.1 live days (1422 kg x day fiducial) of Atmospheric Argon data
  - The sample corresponds to the expected background of 180 live years of UAr operations
  - Darkside demonstrated complete background rejection of ^{39}Ar bkg. at level of 5.5 ton x year
- Project Urania (Underground Argon):
  - Expansion of the argon extraction plant in Cortez, CO, to reach capacity of 100 kg/day of UArg
- Project Aria (UAr Purification):
  - 100s meters tall distillation column in the Seruci mine (Sardinia) for further reduction of UAr contaminants
  - First test facility funded by INFN, Sardinia regional funds for the construction of the complete facility

Photo sensors

- Replace PMT with SiPM
  - Pros:
    - Cheaper
    - More efficient (filling factor)
    - More radiopure
  - Cons:
    - 15 m^2 of SiPM arrays: hundred thousands of devices
    - Cold front end electronic to sum SiPM output
    - Intense R/D ongoing

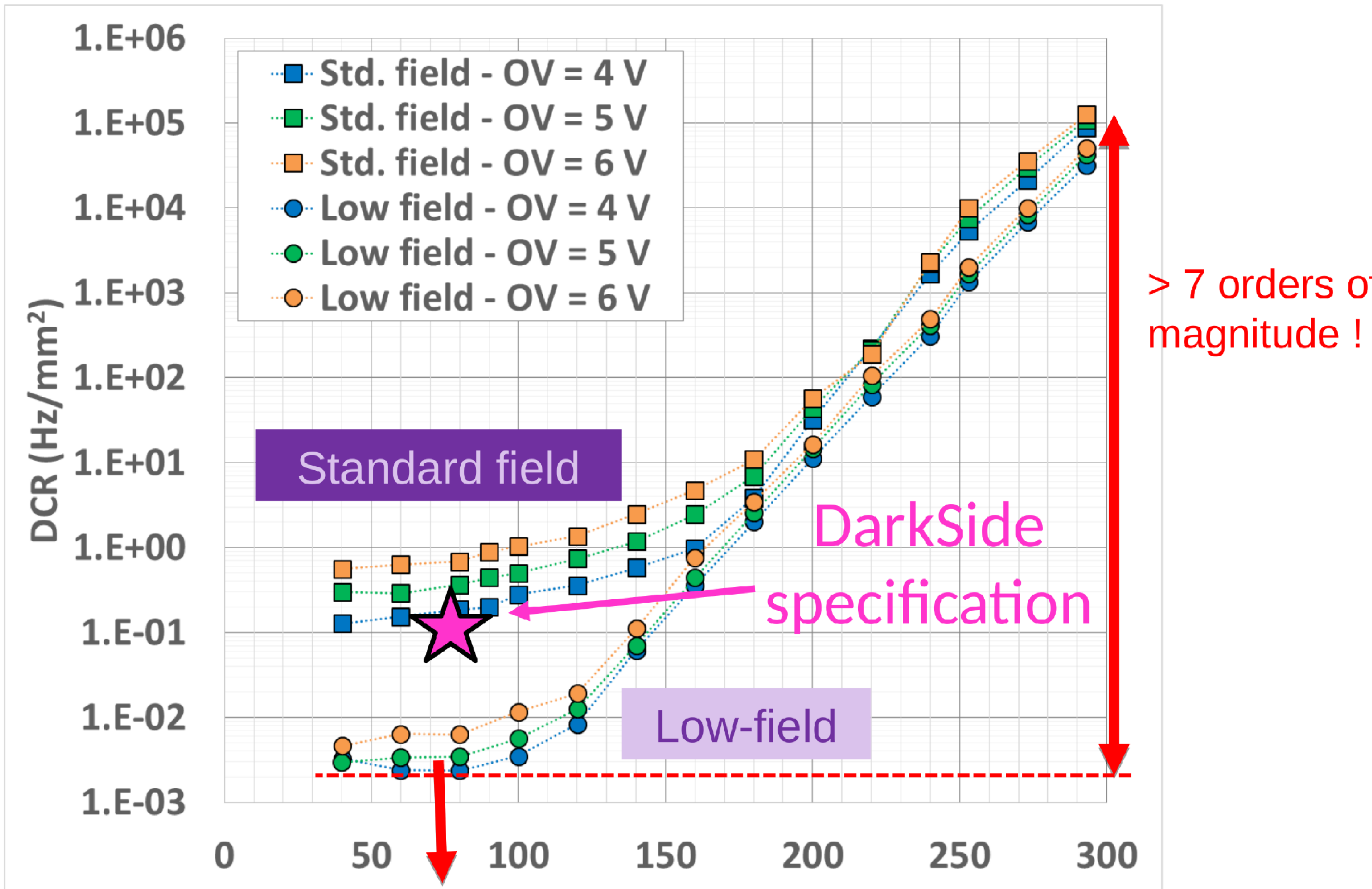


SiPM At Cryogenic Temperature Can be Quie

FONDAZIONE BRUNO KESSLER

NUV-HD: DCR @ LN

INFN Istituto Nazionale di Fisica Nucleare



A 10x10 cm^2 SiPM array would have a total DCR < 100 Hz!

Conclusions

- I tried to cover lot of material today
  - The astrophysical and cosmological evidences of the existence of Dark Matter together with an estimate of the local density
  - The concept of 2 phases noble gas TPC for DM searches
  - The main characteristics of a prototypical TPC: Darkside
  - The latest results from Darkside
  - The plans for the next generation of Darkside
- I hope you survived the tour de force


That's all Folks!

DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

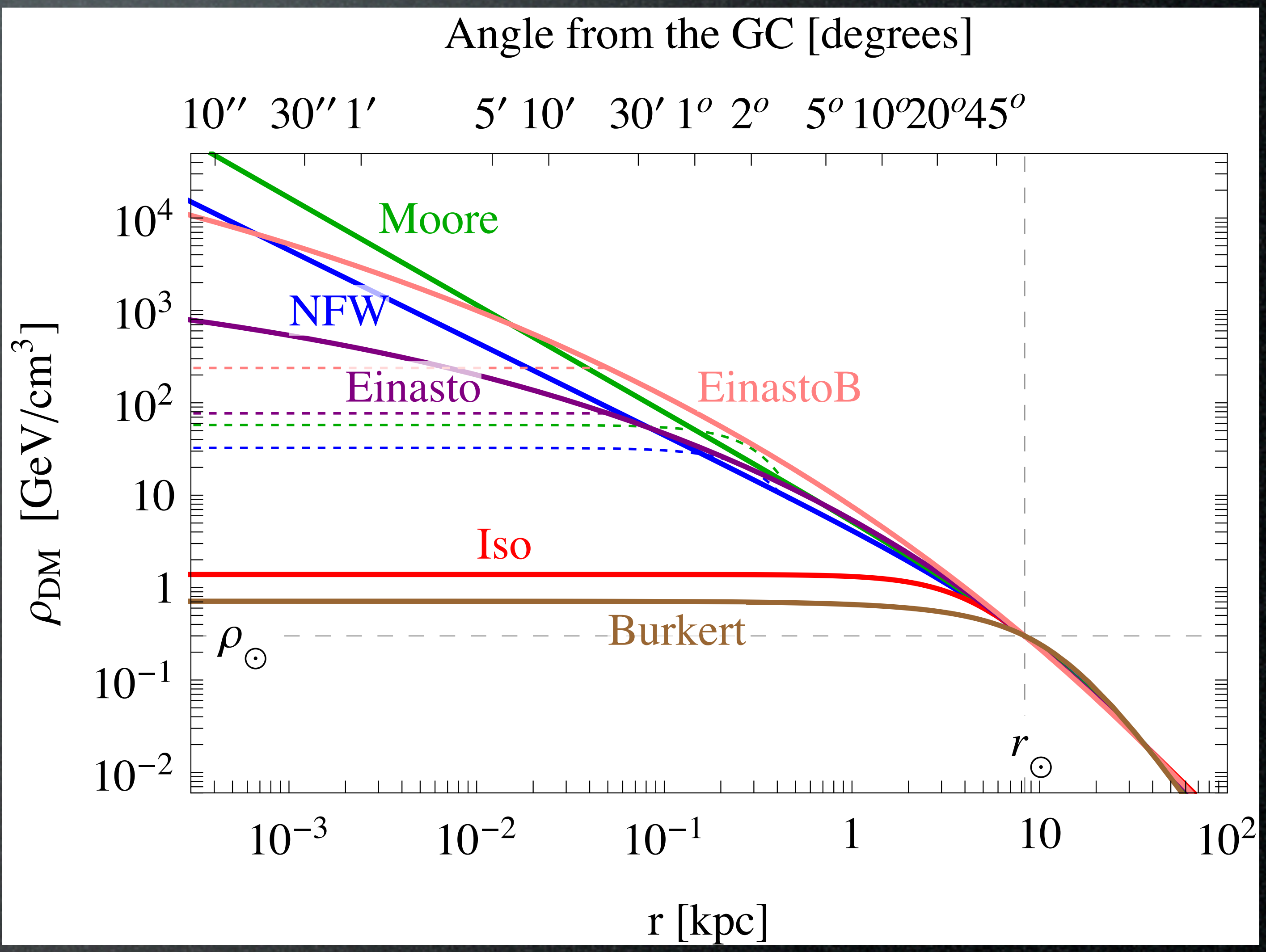
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	—	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	—	4.38	1.387
Burkert	—	12.67	0.712
Moore	—	30.28	0.105

At small r: $\rho(r) \propto 1/r^{\gamma}$



6 profiles:

cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)