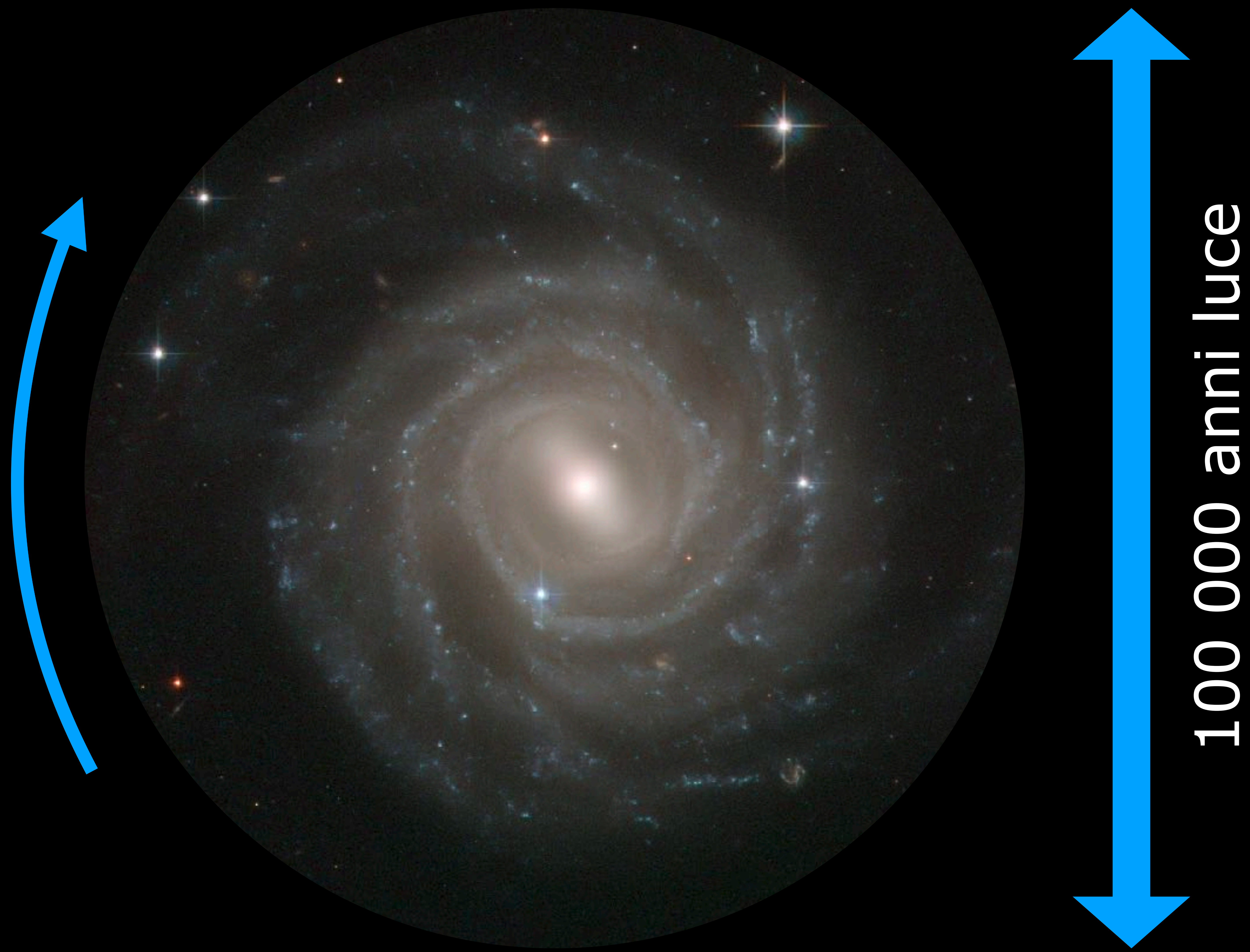
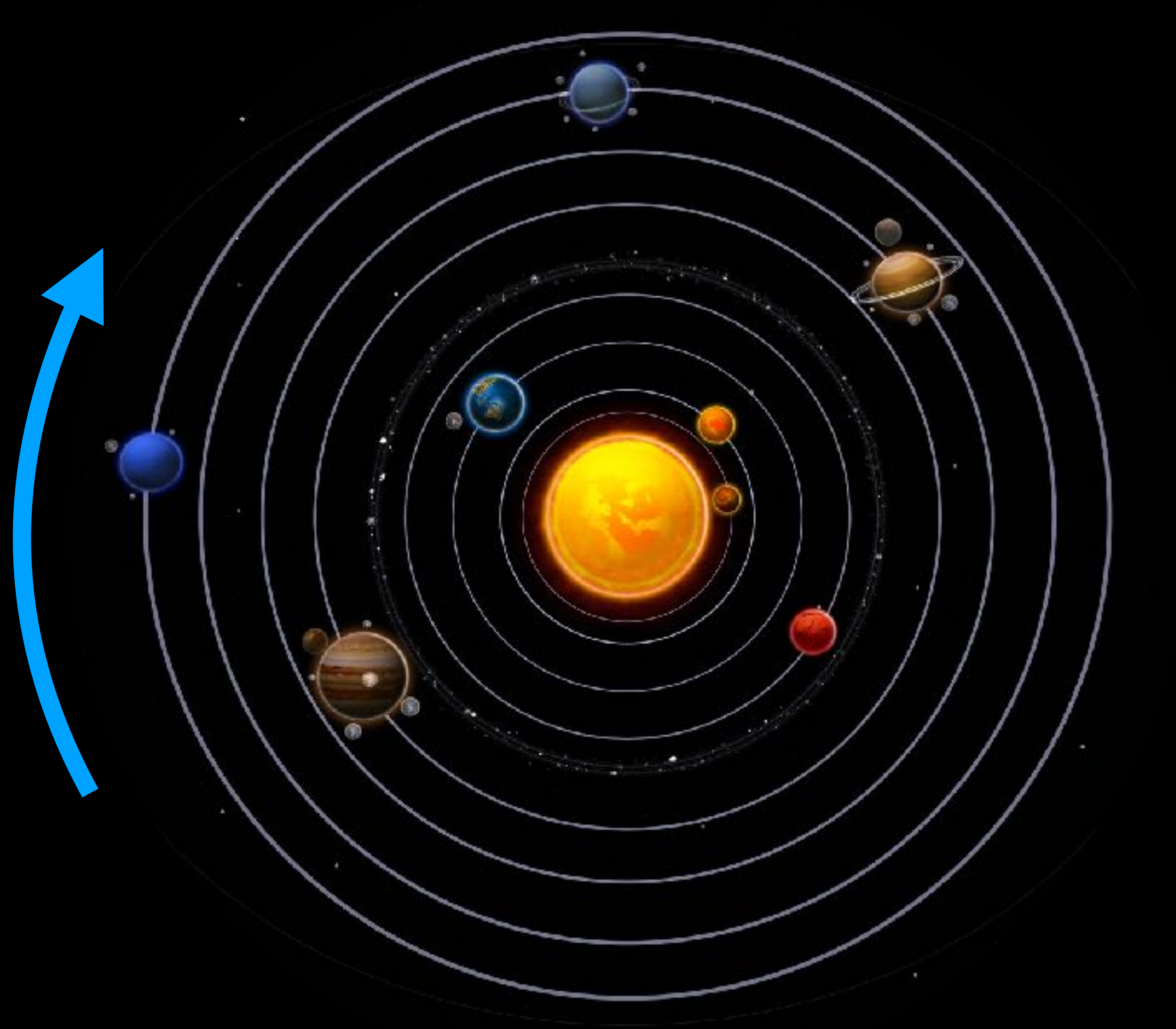
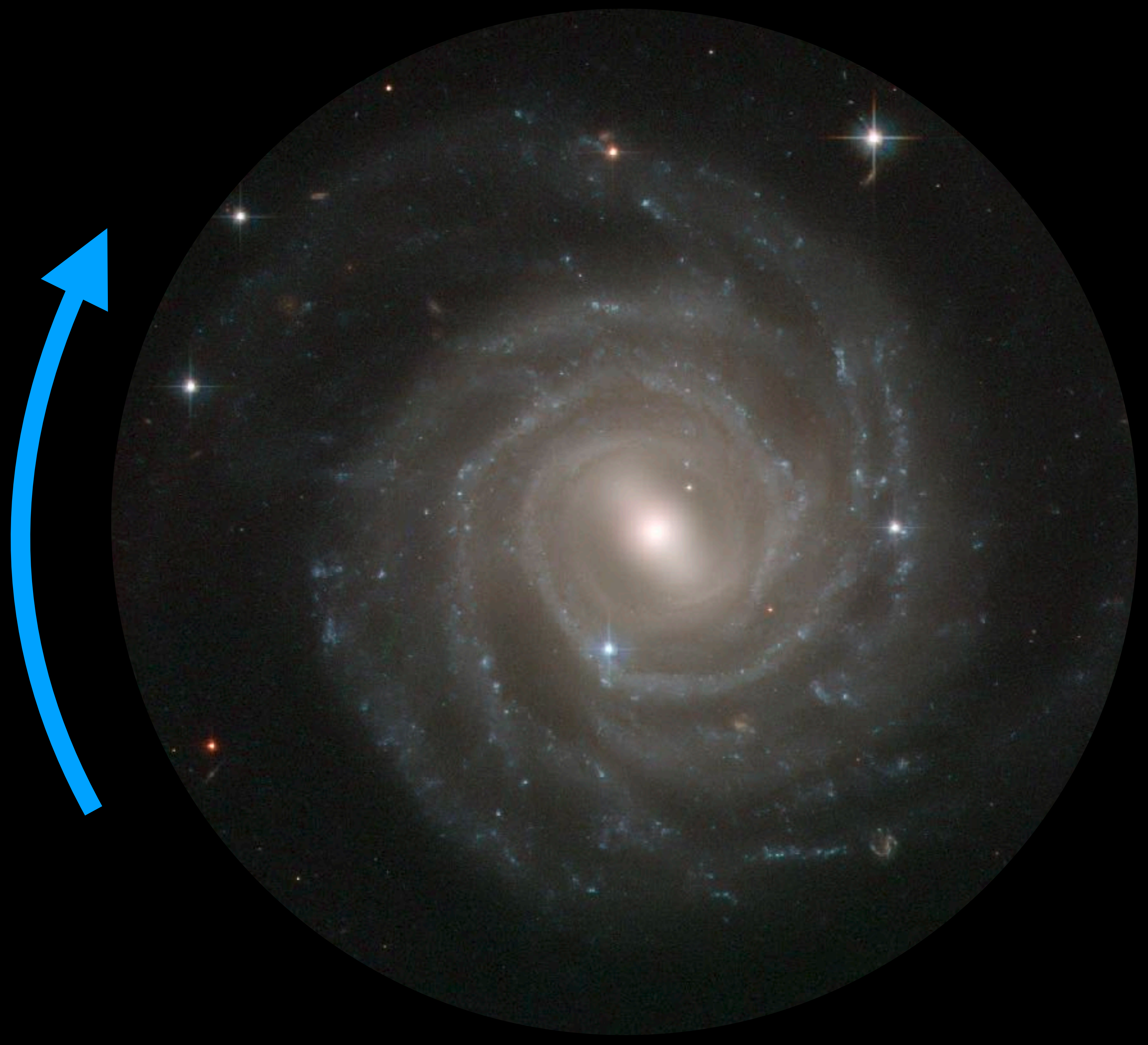
Galassie



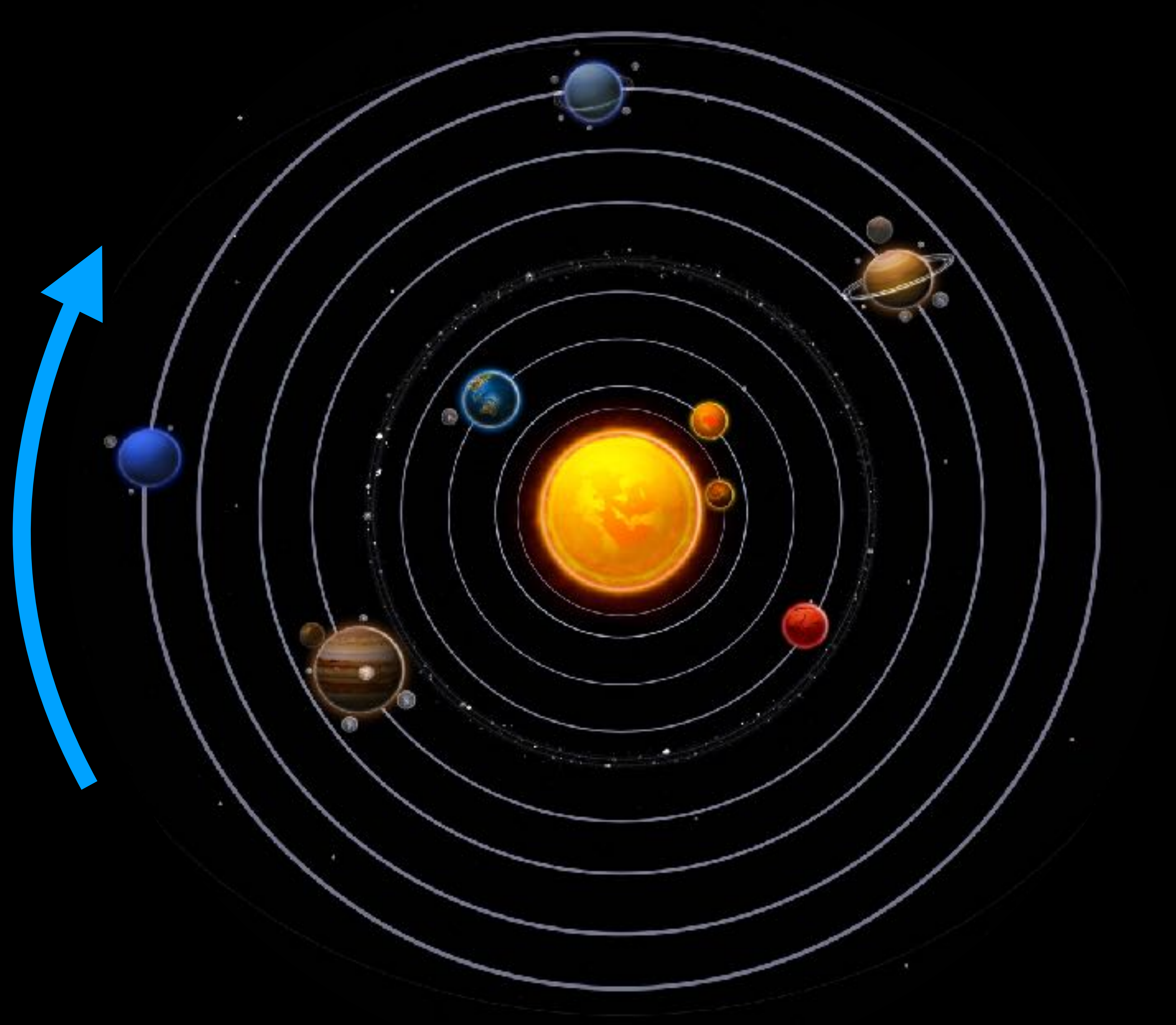
$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

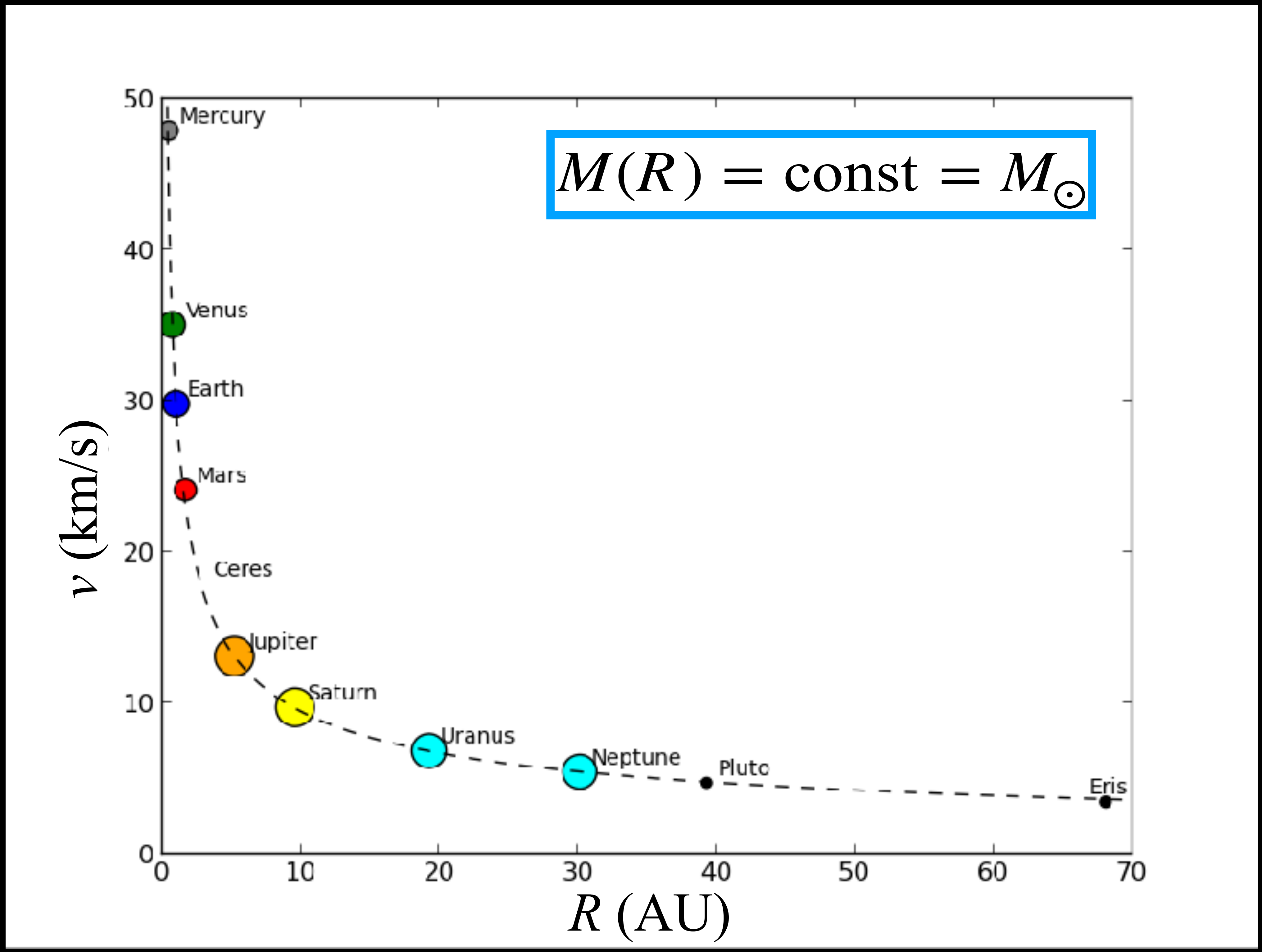




Un sistema semplice: curva di rotazione Kepleriana

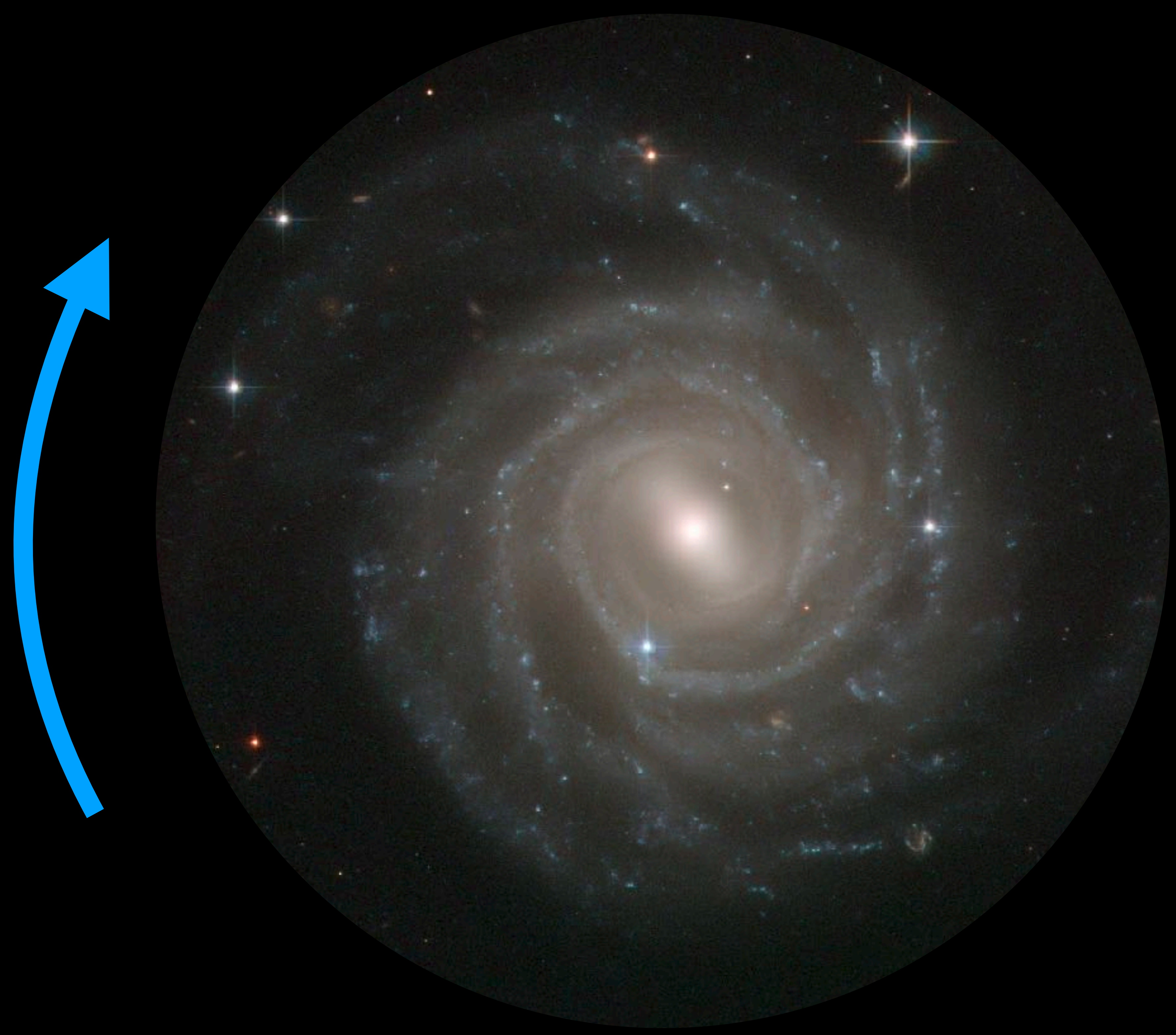
$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

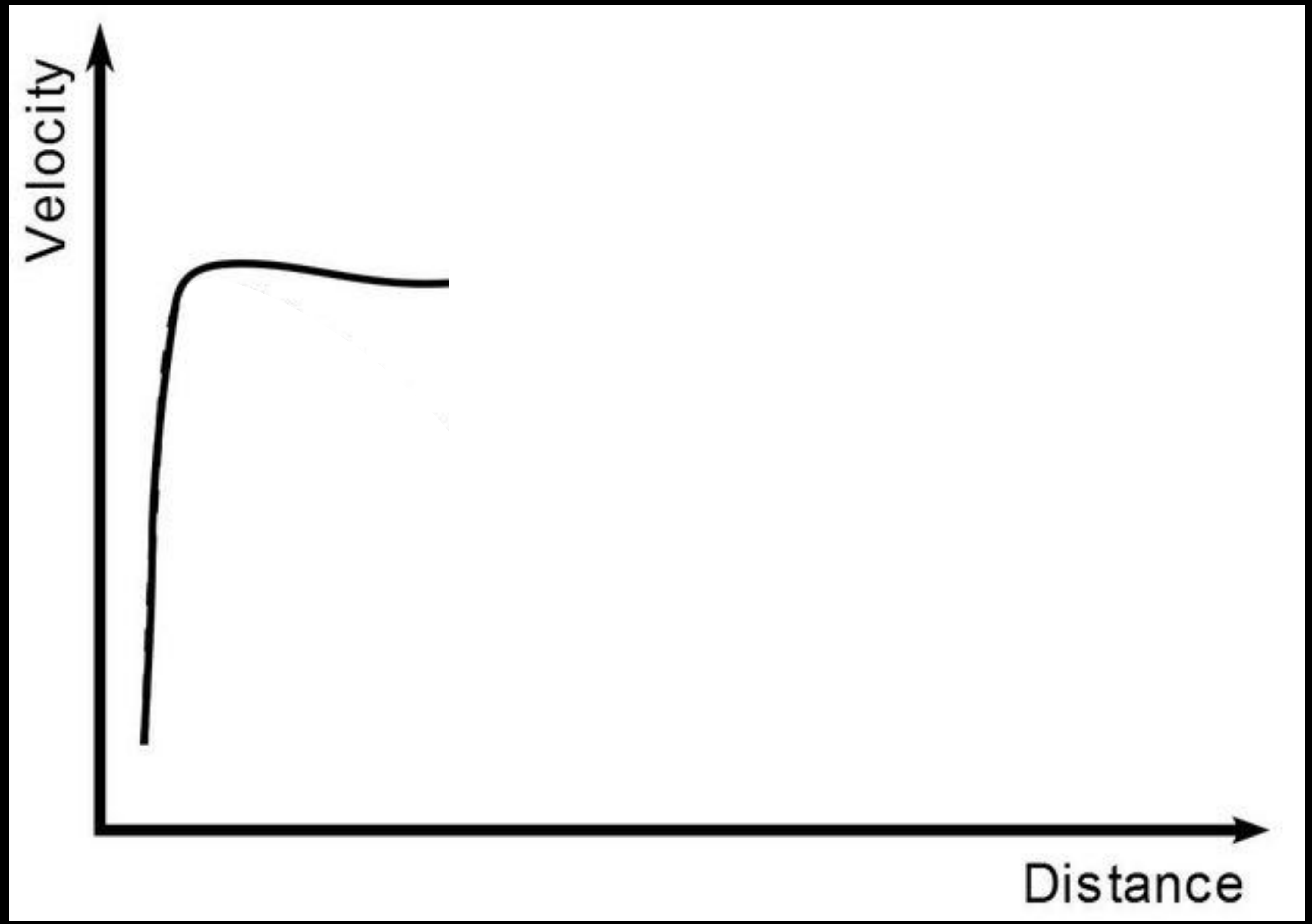




Curva di rotazione galattica

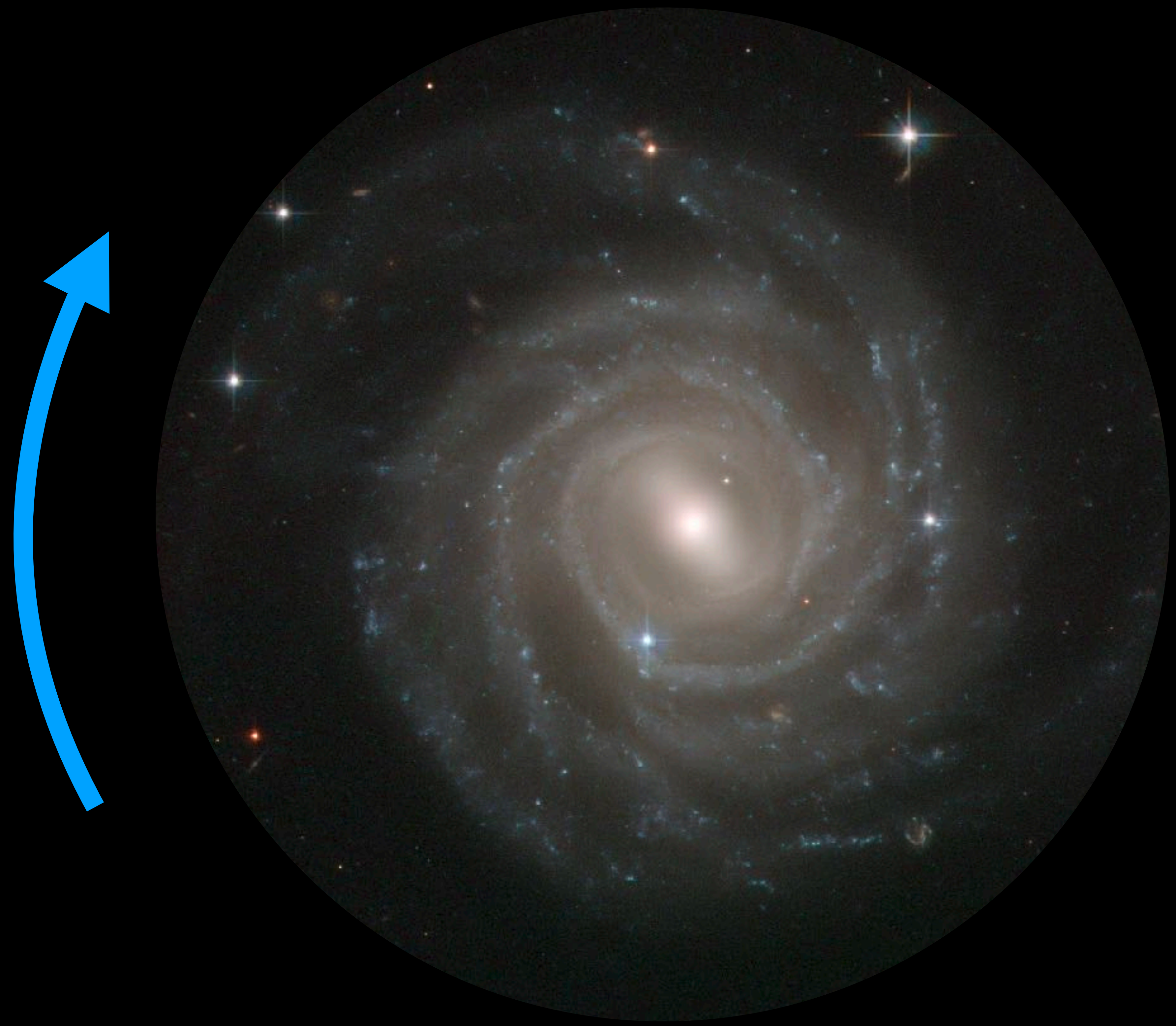
$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

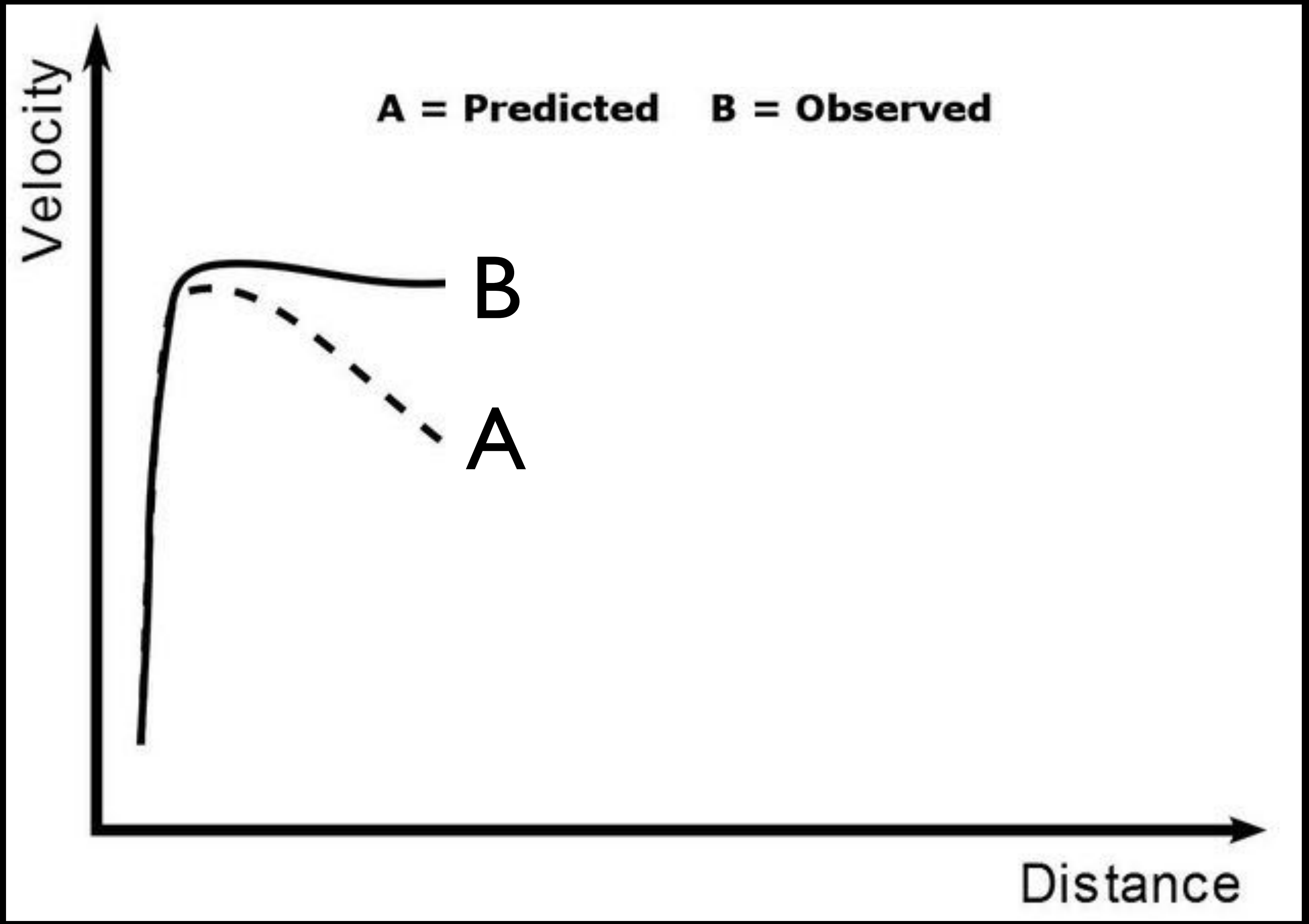




Massa mancante

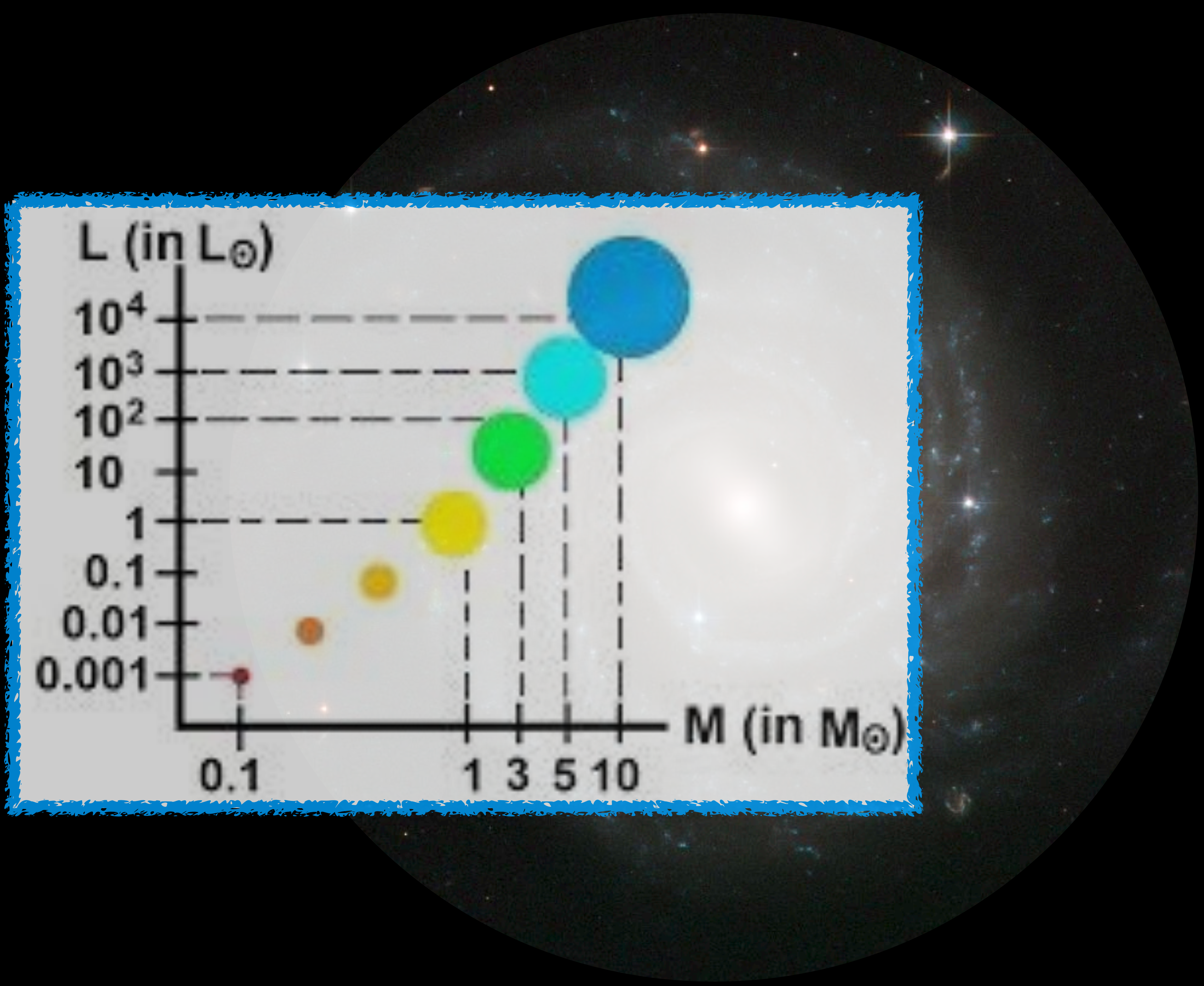
$$v_{\text{pred}}(R) = \sqrt{\frac{GM_{\text{pred}}(R)}{R}} < v_{\text{obs}}(R)$$

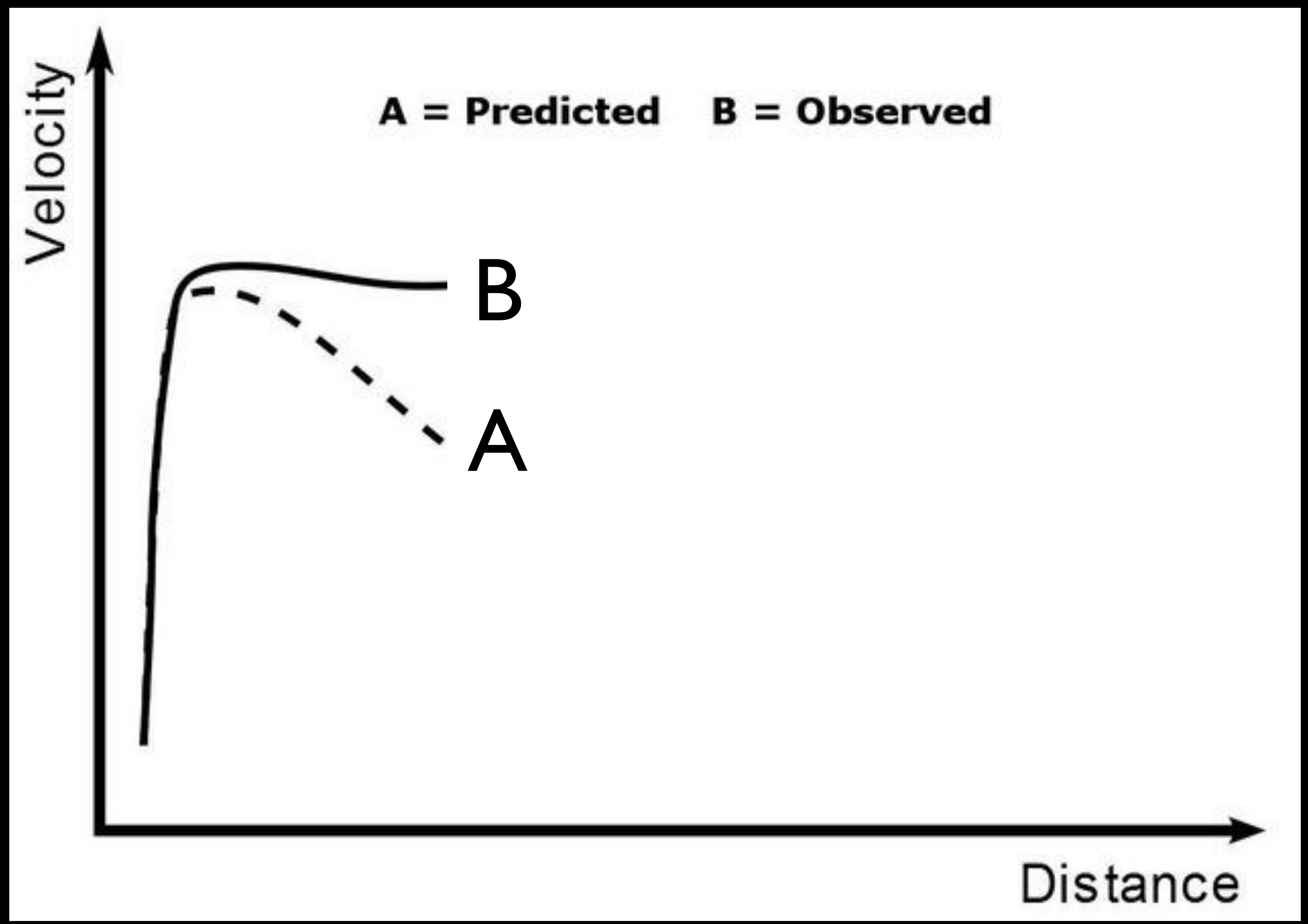




Massa mancante o predizione sbagliata?

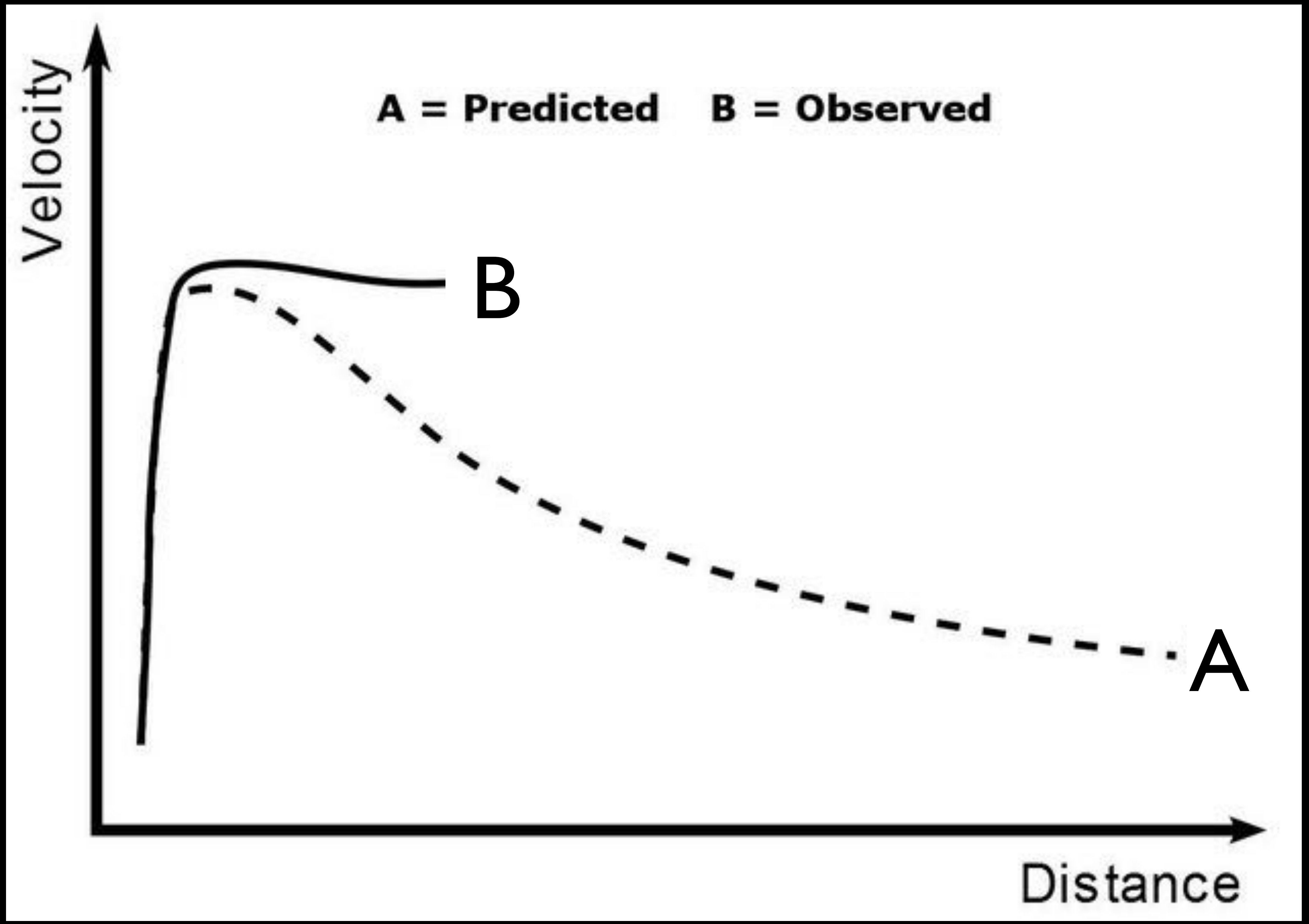
$$v_{\rm pred}(R) = \sqrt{\frac{GM_{\rm pred}(R)}{R}} < v_{\rm obs}(R)\ ; \quad M_{\rm pred}(R) = \gamma L(R)$$





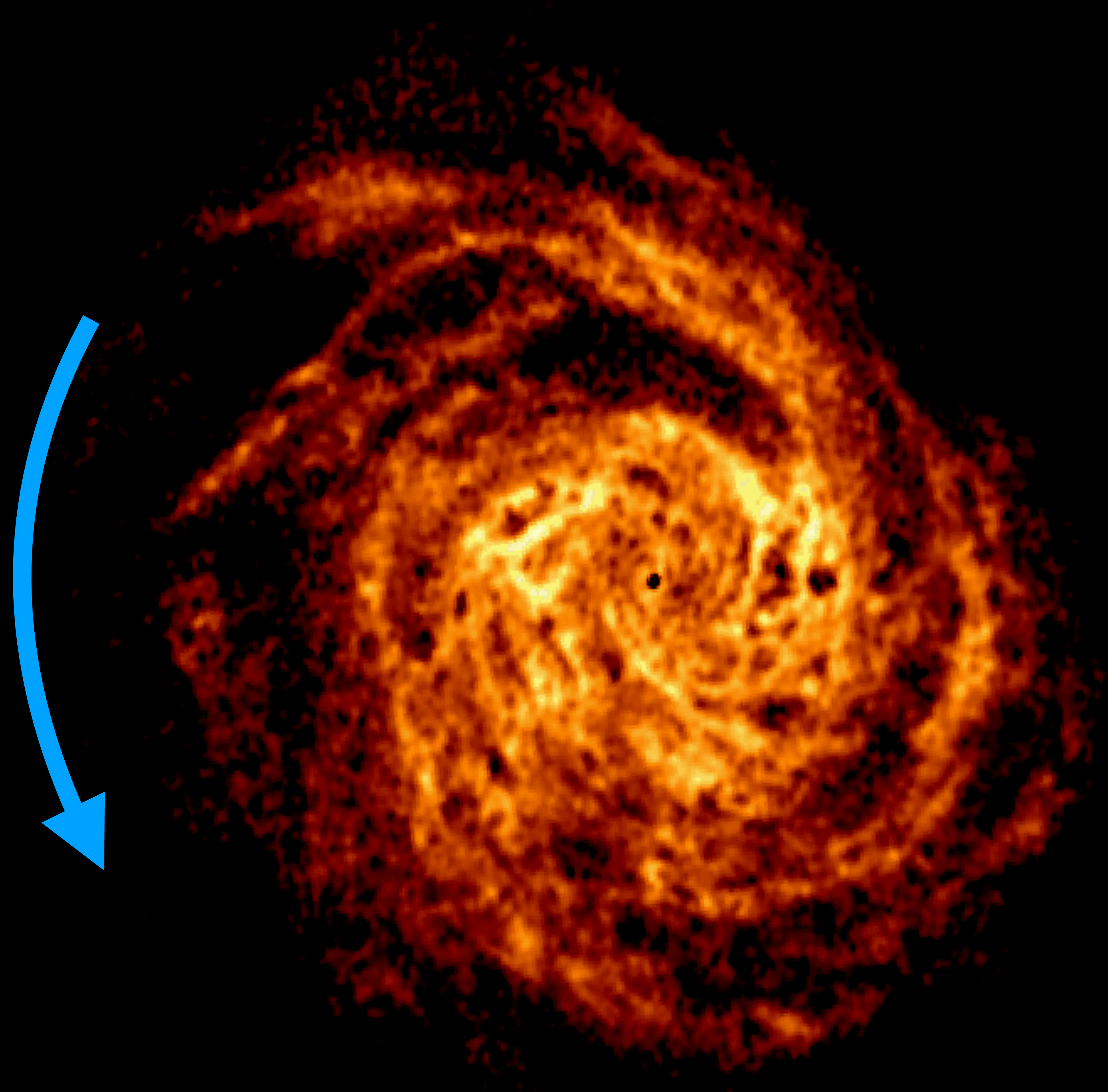
Oltre il limite visibile delle galassie: curve Kepleriane

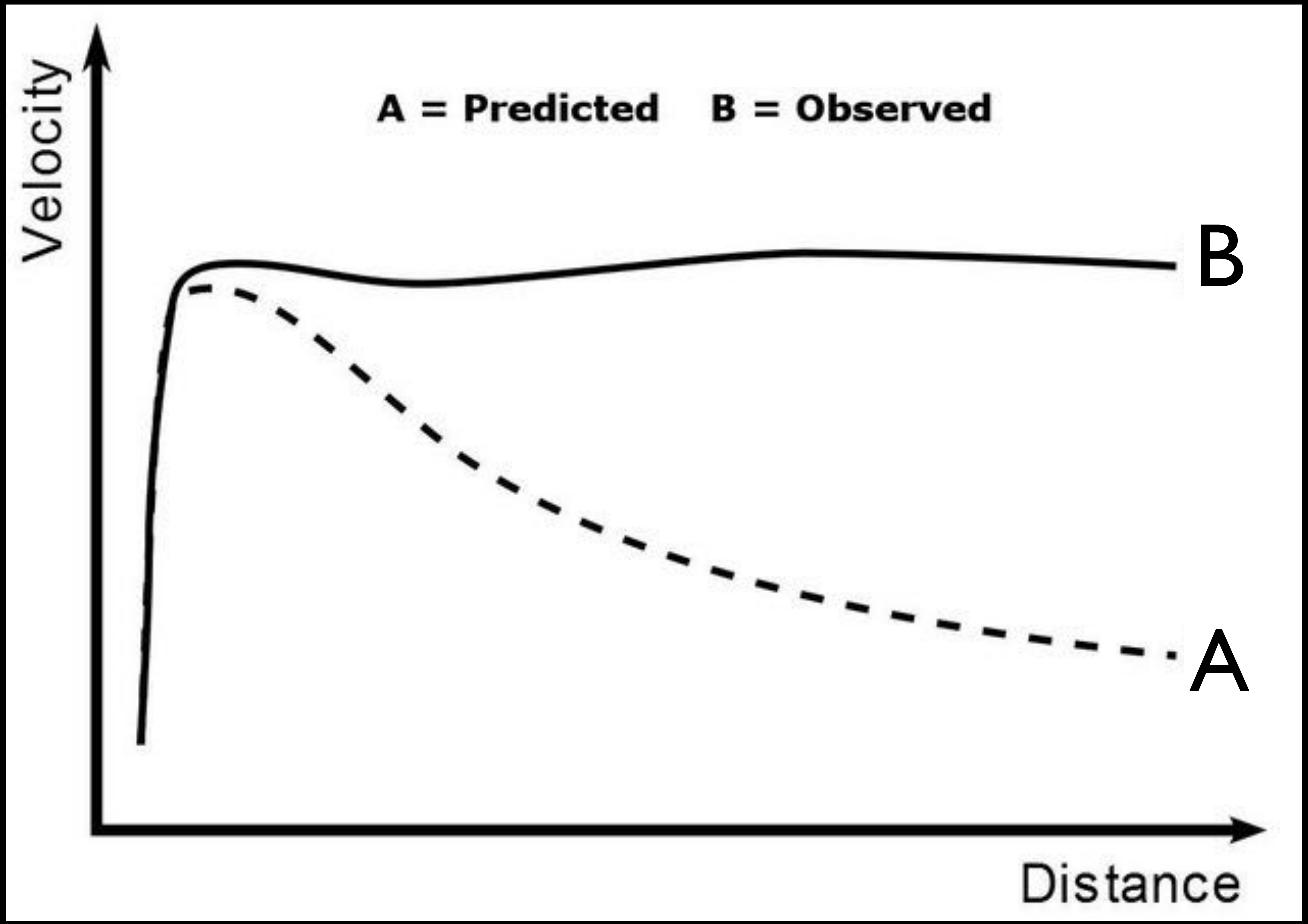
$$v(R) = \sqrt{\frac{GM(R)}{R}}$$

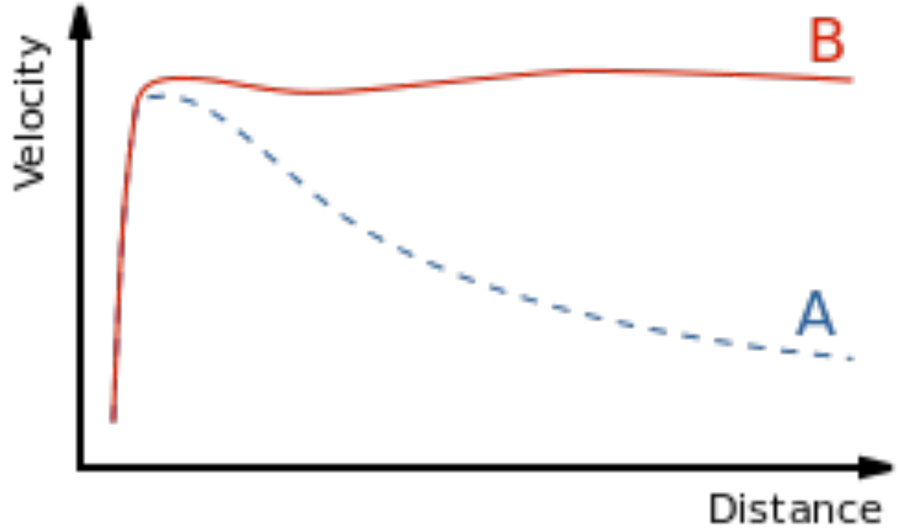


Oltre il limite visibile della galassie: osservazioni radio

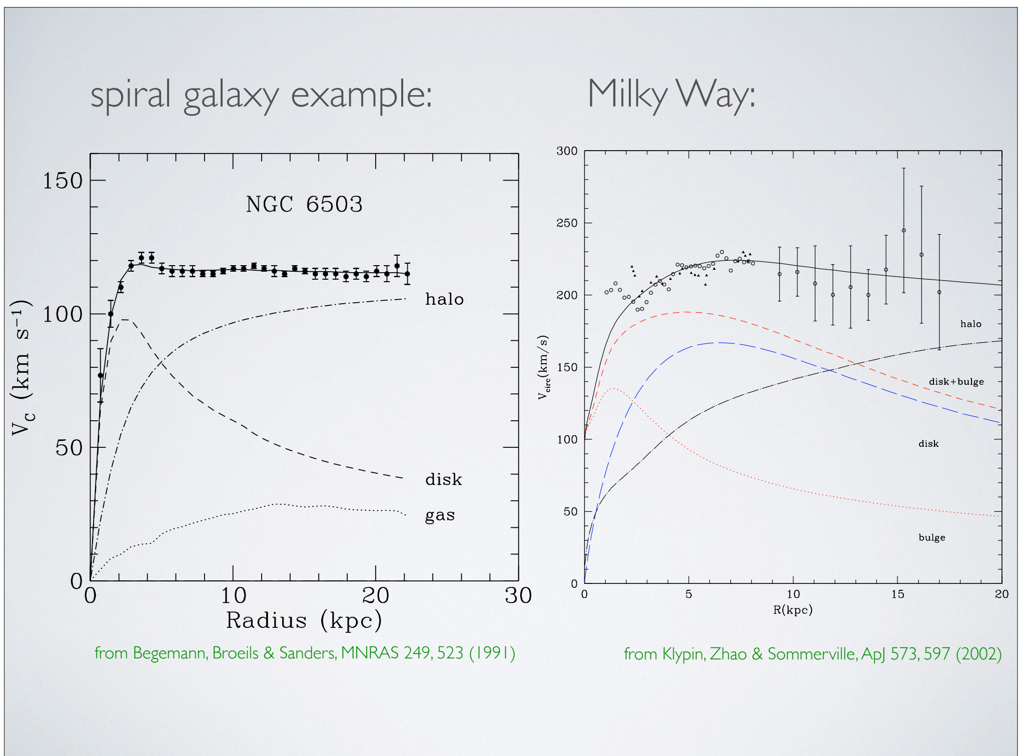
$$v(R) = \sqrt{\frac{GM(R)}{R}}$$







Velocity
Distance
B
A



spiral galaxy example:
Milky Way:
NGC 6503
150
100
50
0
10
20
30
Radius (kpc)
V_c (km s^{-1})
halo
disk
gas
300
250
200
150
100
50
0
5
10
15
20
R(kpc)
V_{circ}(km/s)
halo
disk+bulge
disk
bulge
from Begemann, Broeils & Sanders, MNRAS 249, 523 (1991)
from Klypin, Zhao & Sommerville, ApJ 573, 597 (2002)

- PER FAR TORNARE I CONTI SERVE ALMENO 5-6 VOLTE LA QUANTITA' DI MATERIA CHE SI VEDE! MATERIA OSCURA?

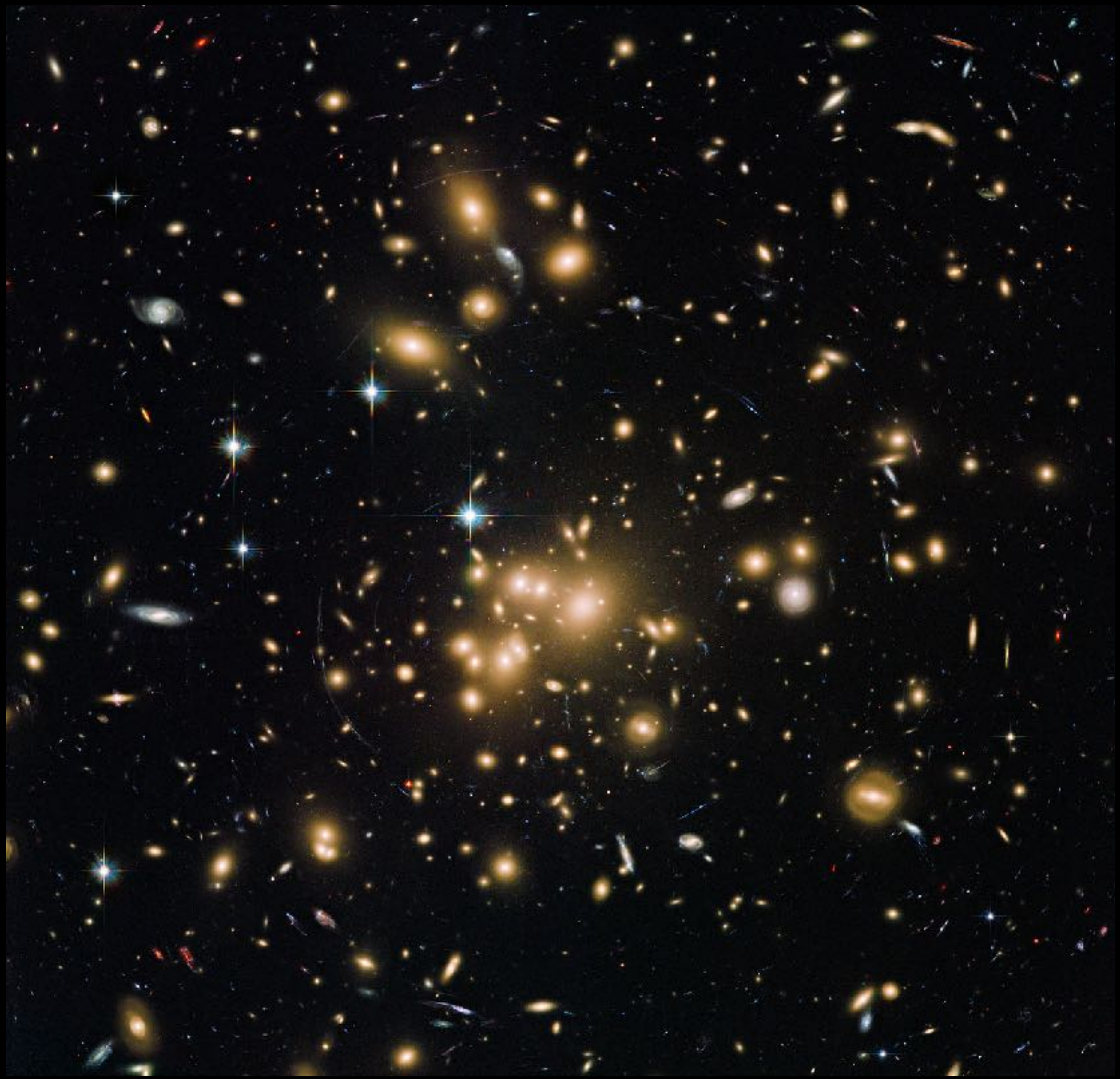
- DA NOTARE CHE L'APPIATTIMENTO DELLA CURVA PUO' ESSERE SPIEGATO DA (MOND)

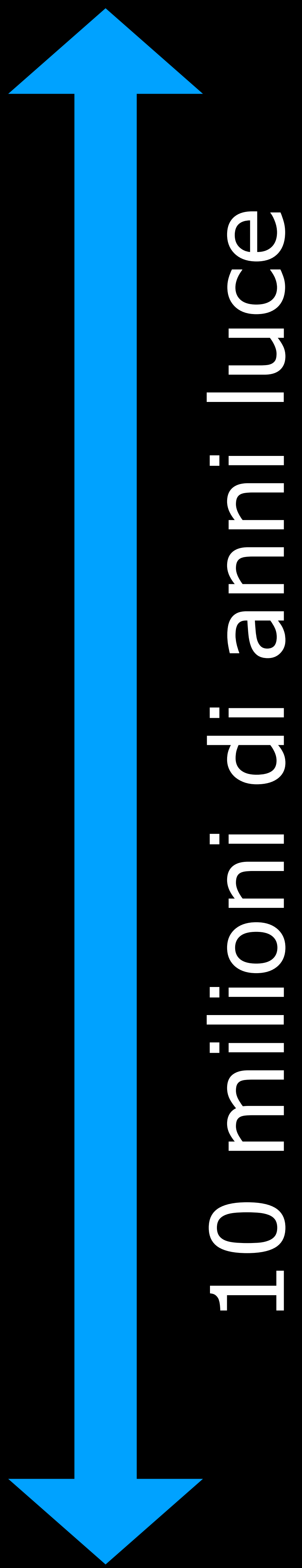
$$M(r) = kr$$

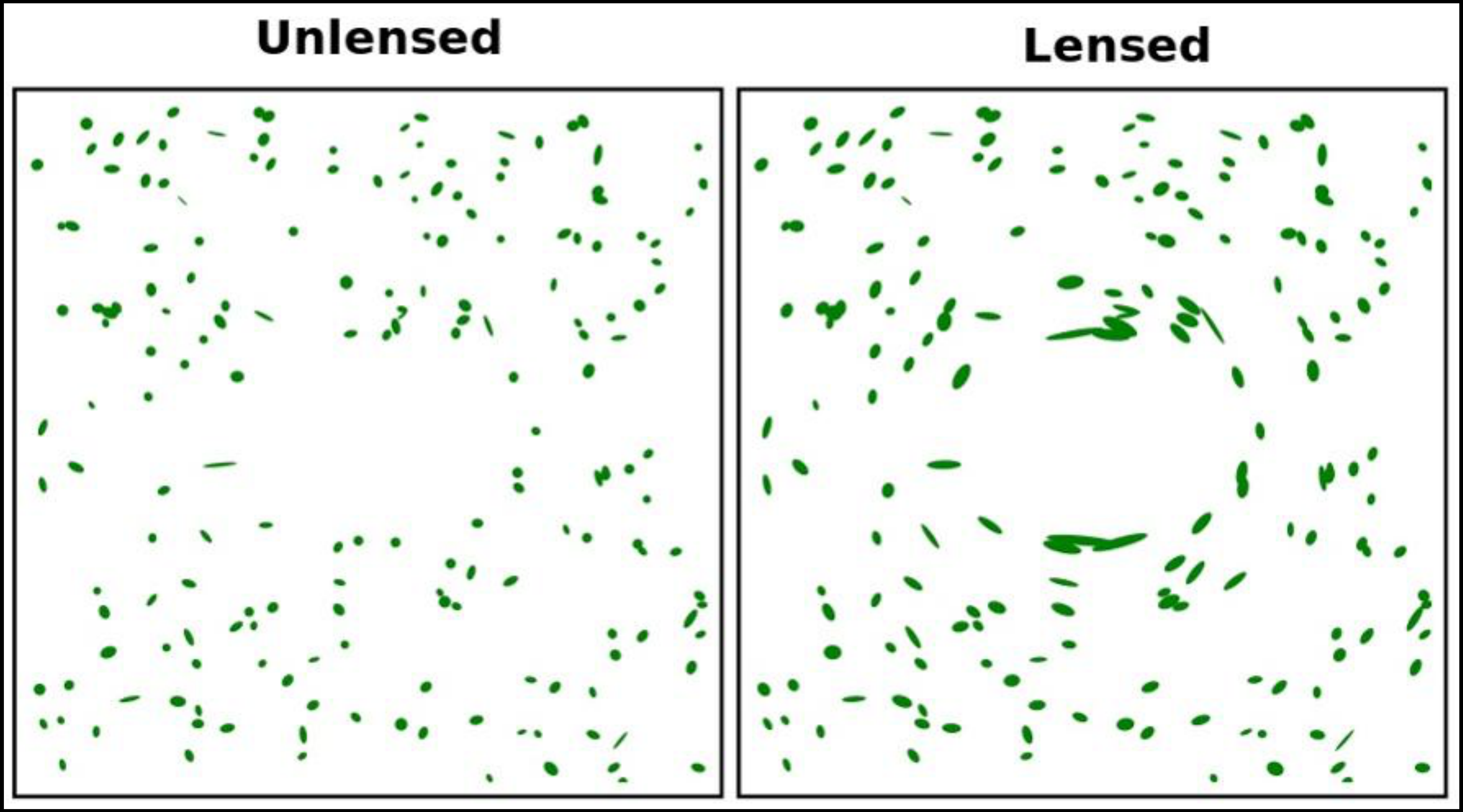
LA MANCANZA DI MASSA E' CONFERMATA ANCHE DAL **LENSING GRAVITAZIONALE**

Ammassi di galassie

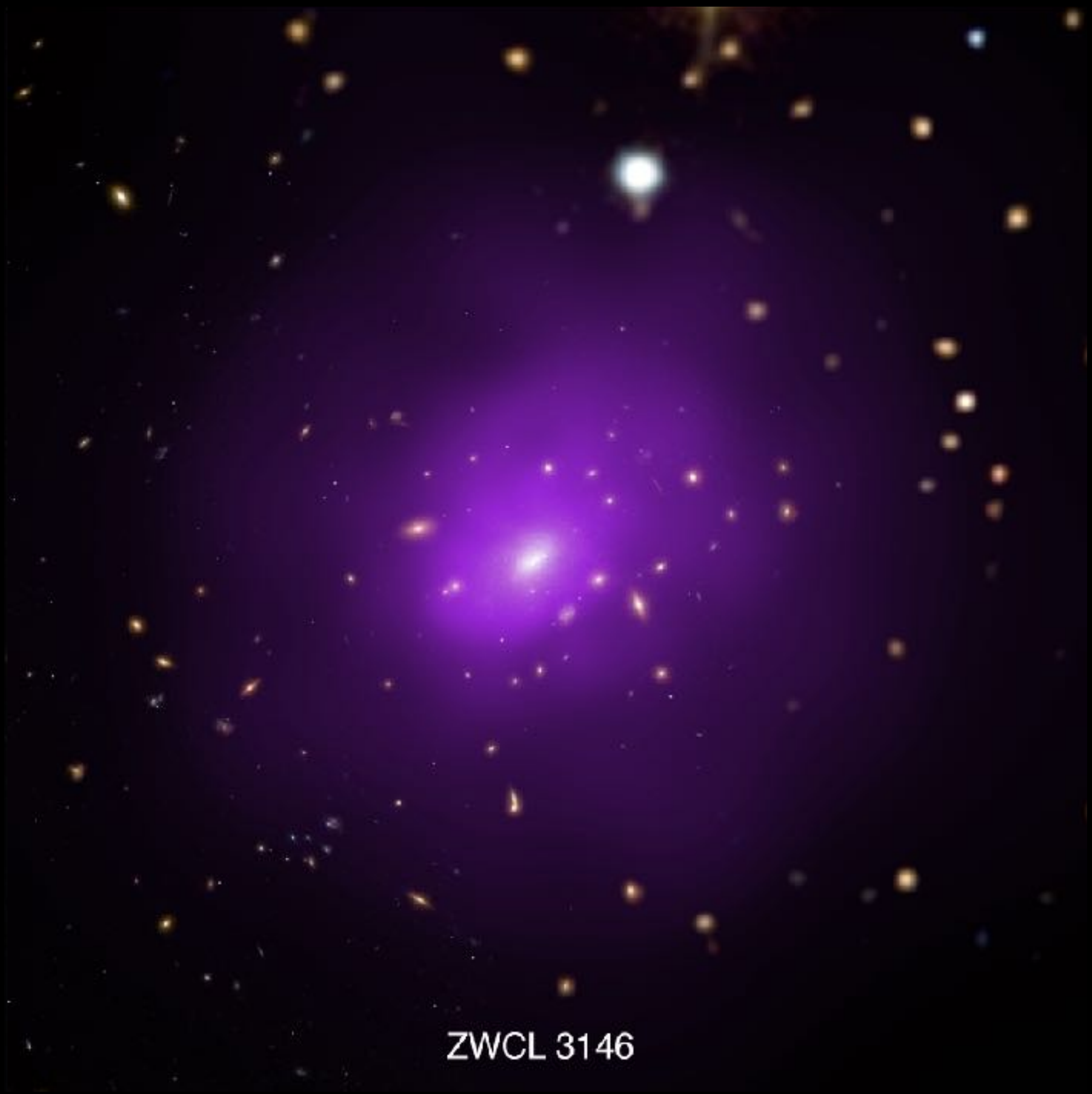
Ammassi di galassie



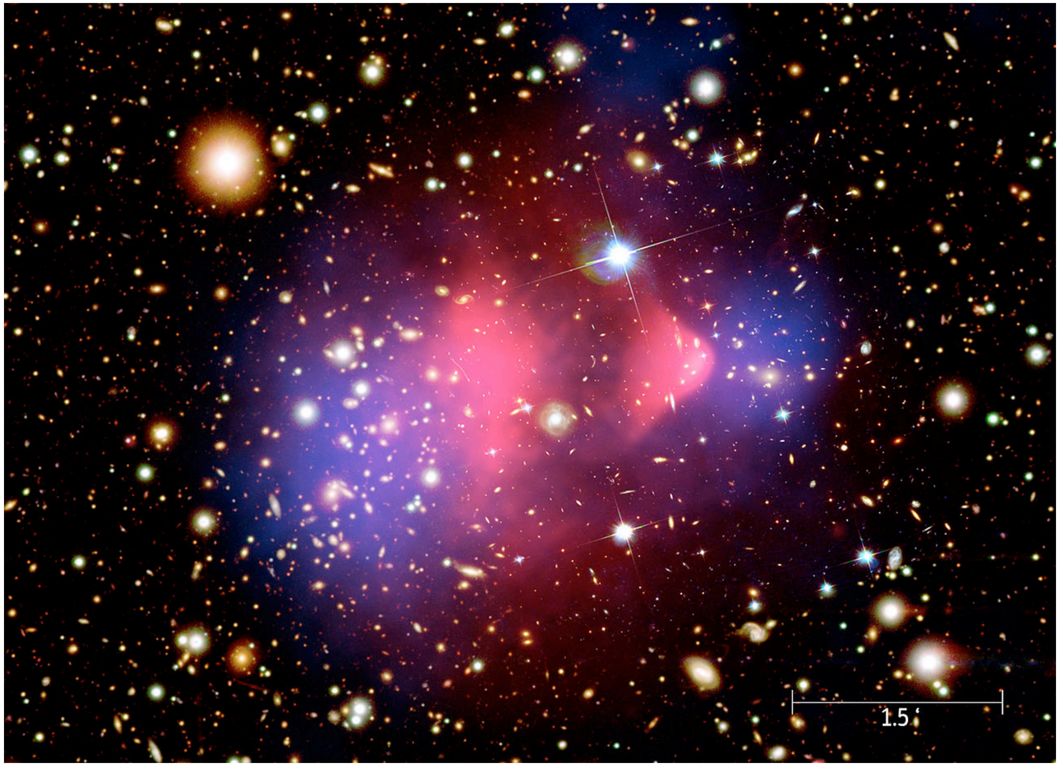



Unlensed
Lensed

Gas caldo o materia oscura?

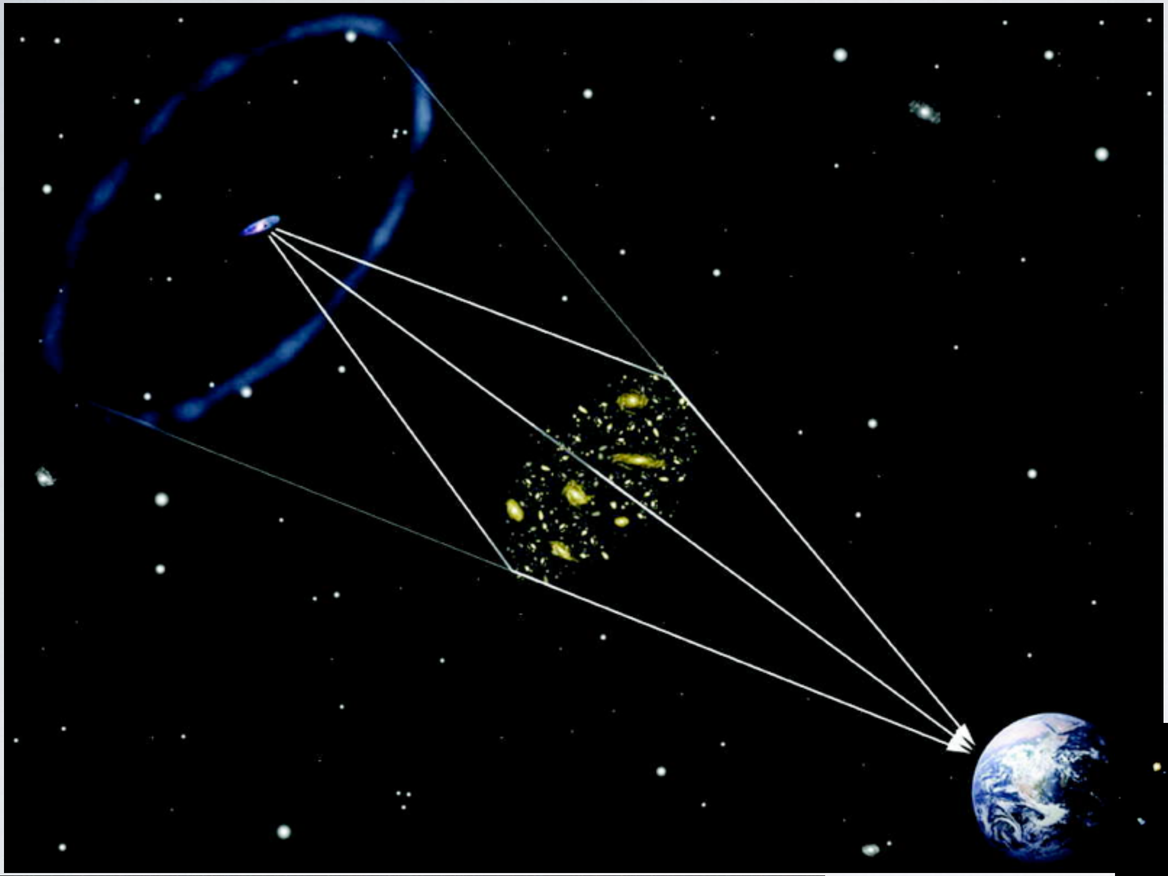


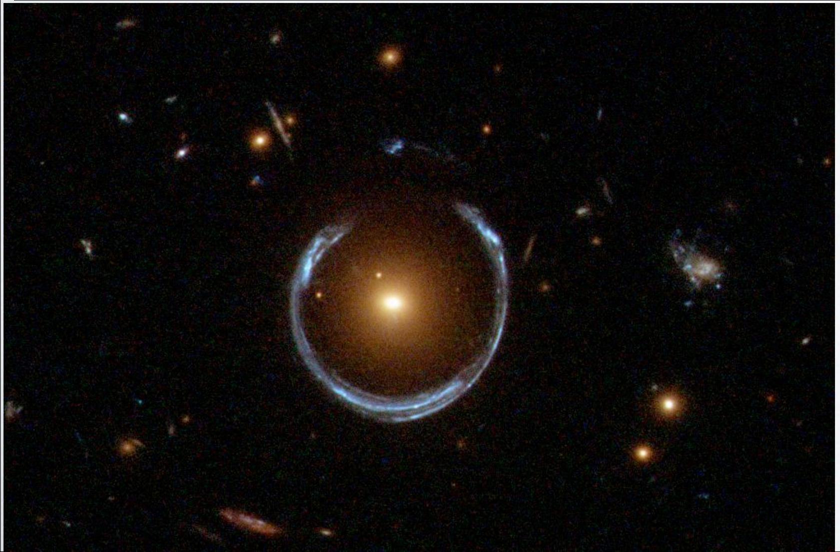
BULLET CLUSTER



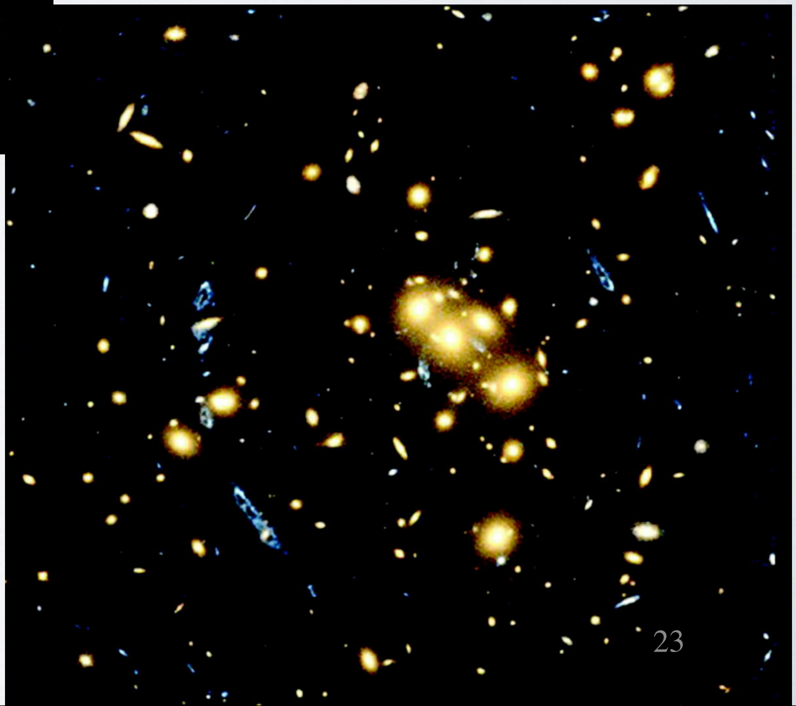
DUE CUSTER CHE COLLIDONO 1E 0657-56. L’ALONE DI MATERIA OSCURA (BLU), RICOSTRUITO TRAMITE IL LENSING DEGLI OGGETTI SULLO SFONDO, E’ DEL TUTTO DISLOCATO RISPETTO ALLA MATERIA VISIBILE, BARIONICA (ROSA).

Gravitational lensing





Hubble view of CL0024+1654



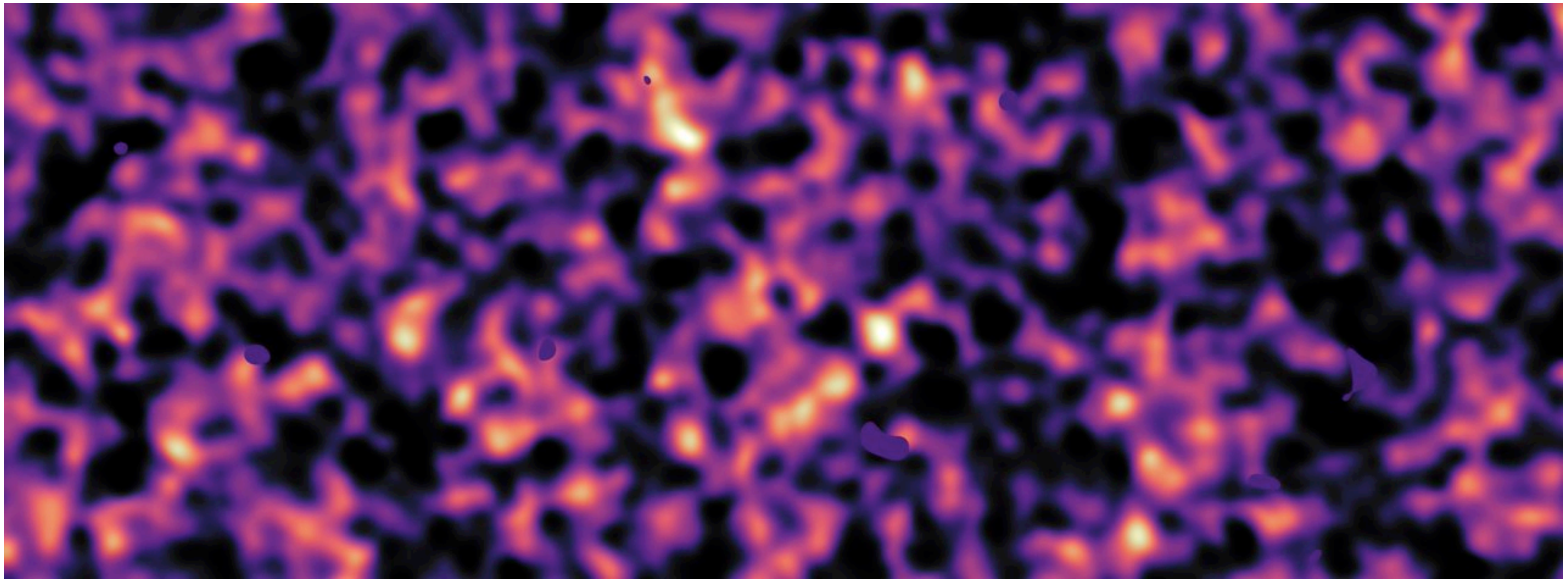


Immagine di tre milioni di galassie distanti 6 miliardi di anni luce ricostruita usando il fatto che la materia oscura (regioni viola) curva la luce [osservatorio Paranal Cile]

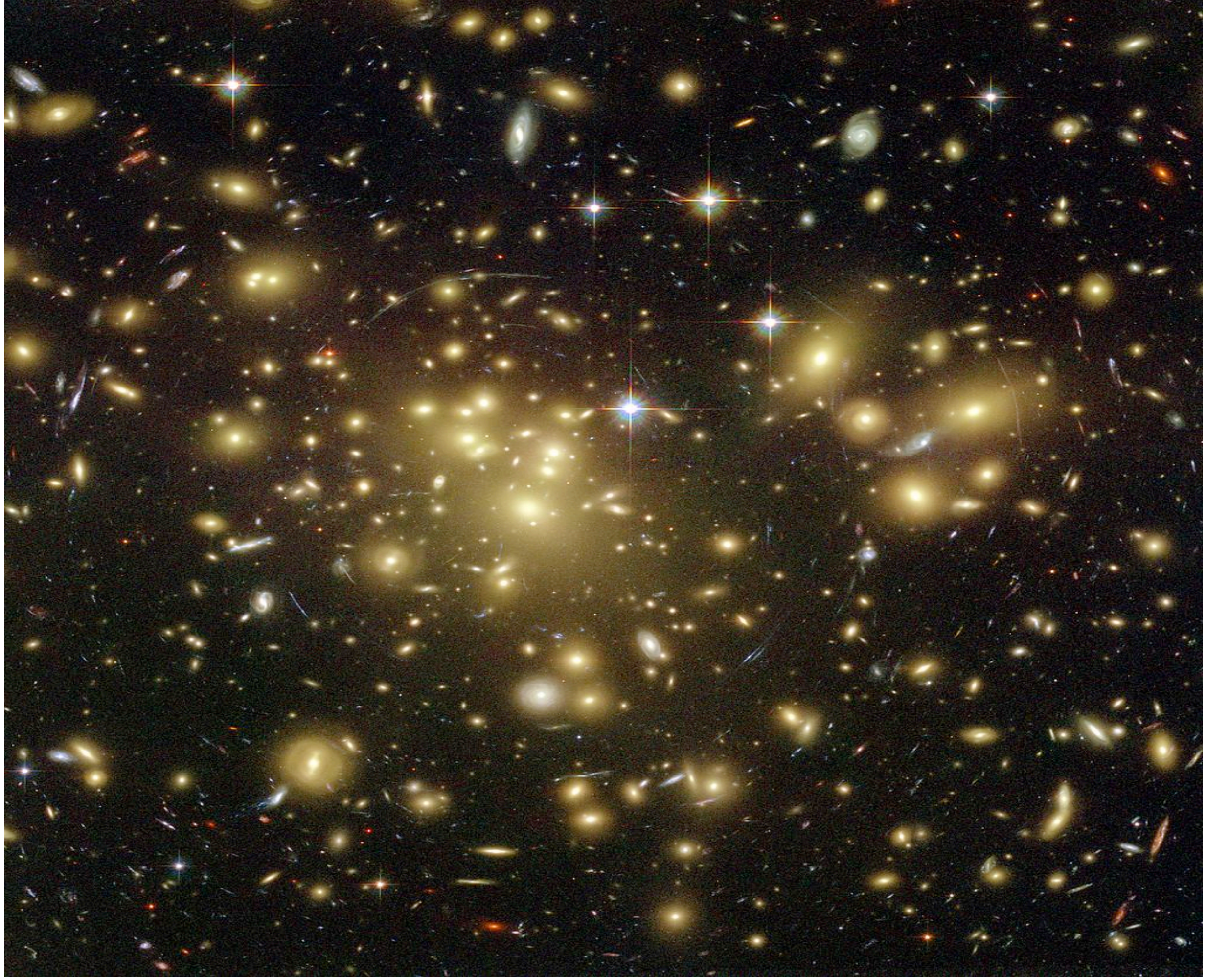


Immagine del Galaxy cluster Abell 1689 fatta dal Hubble space Telescope. La gravità di 3 miliardi di stelle + Materia oscura agisce come una lente larga 2 milioni di anni luce. Gli oggetti piu' lontani distano 13 Miliardi di AL (z=6).

La massa stimata in base alle leggi della gravità
(curve di rotazione, dispersione di velocità, lenti gravitazionali)

è maggiore

della massa stimata in base alla luce

Struttura su larga scala dell'Universo

FORMAZIONE STRUTTURE

- LA FORMAZIONE DI STRUTTURE NELL'UNIVERSO PRIMORDIALE AVVIENE DOPO IL BIG BANG A PARTIRE DA PICCOLE PERTURBAZIONI DI DENSITÀ NELL'UNIVERSO OMOGENEO CHE CRESCONO FINO A FORMARE STELLE, GALASSIE,CLUSTERS

SE IL PLASMA PRIMORDIALE FOSSE STATO SOLO COMPOSTO DA MATERIA VISIBILE L'INTERAZIONE CON LA RADIAZIONE AVREBBE CANCELLATO QUESTE PERTURBAZIONI

LA PRESENZA DI MATERIA OSCURA, CHE NON INTERRAGISCE CON LA RADIAZIONE AGISCE COME UNA BUCA DI POTENZIALE RENDENDO POSSIBILE LA FORMAZIONE DELLE STRUTTURE

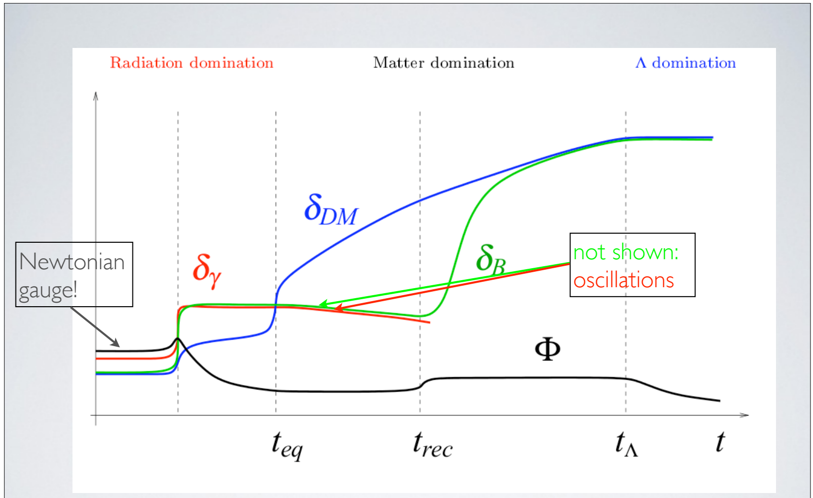
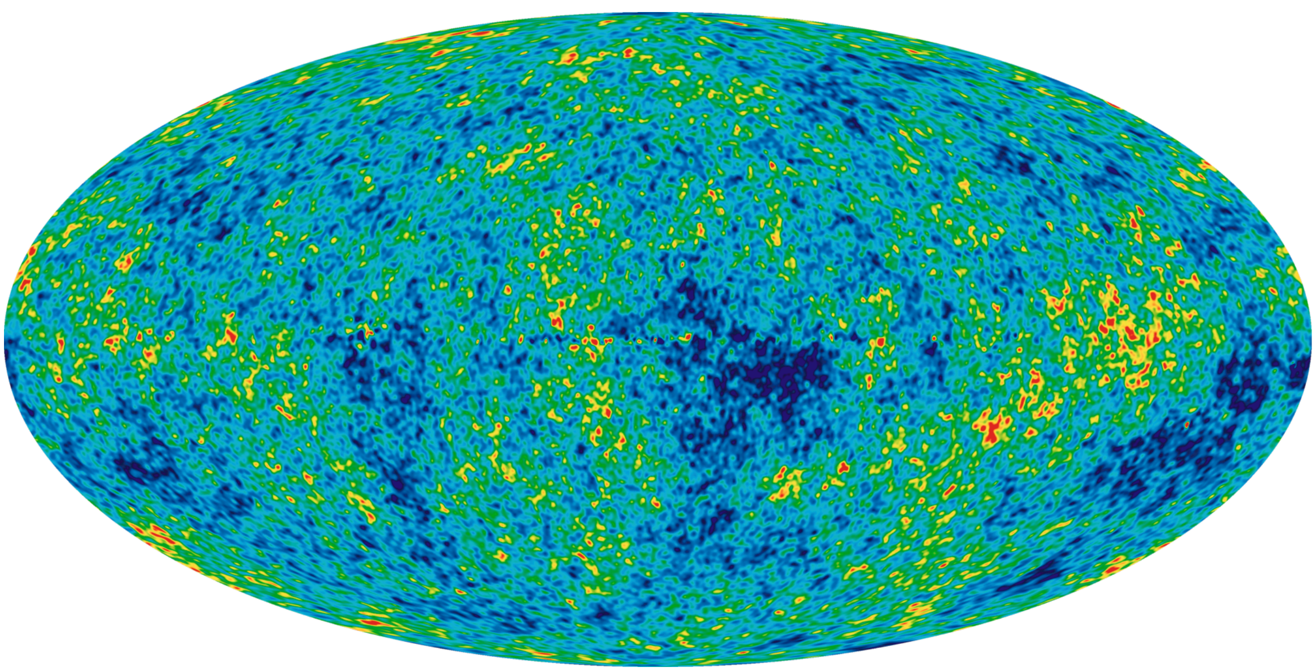


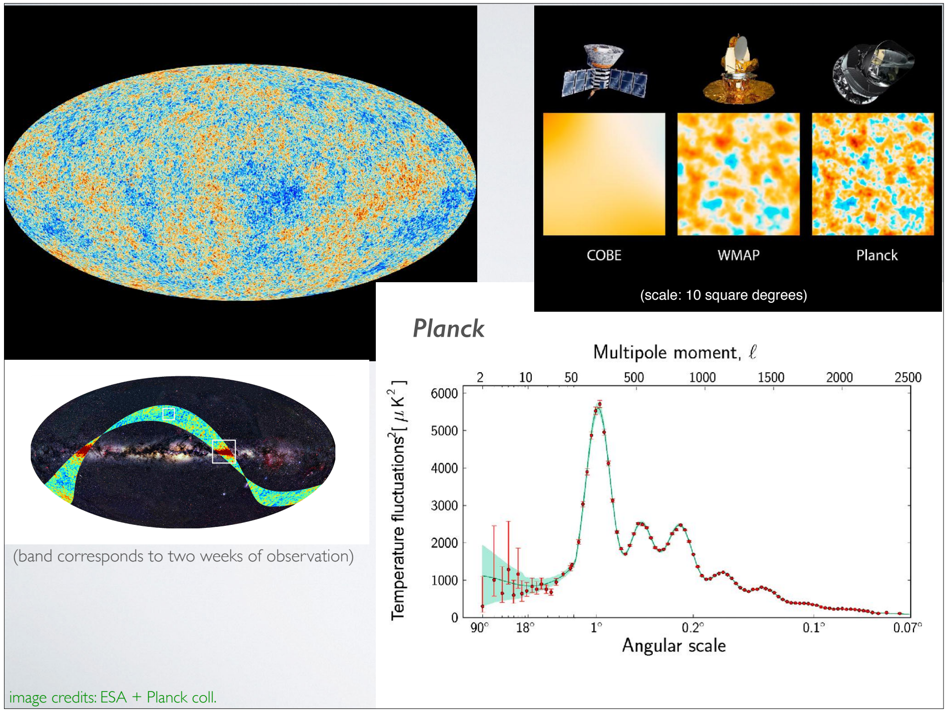
Figure 5: Schematic plot of the evolution of density pertirbations in different components. Here, $\delta = \delta\rho/\rho$, and Φ is the gravitational potential. The left dashed vertical line is the time of horizon crossing of a mode considered.

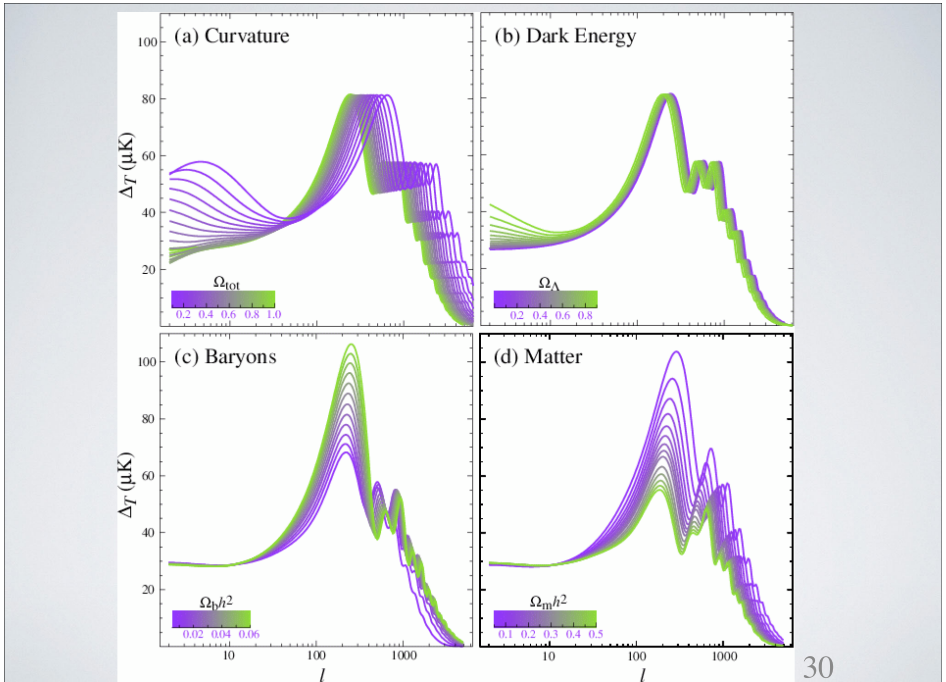
Rubakov & Vlasov, 1008.1704

- L'INFORMAZIONE SULLE PERTURBAZIONI PRIMORDIALI È CONTENUTA NELLE ANISOTROPIE DELLA RADIAZIONE COSMICA DI FONDO (la radiazione fossile che osserviamo oggi, originata 380.000 dopo il BB quando materia e radiazione si sono separati)



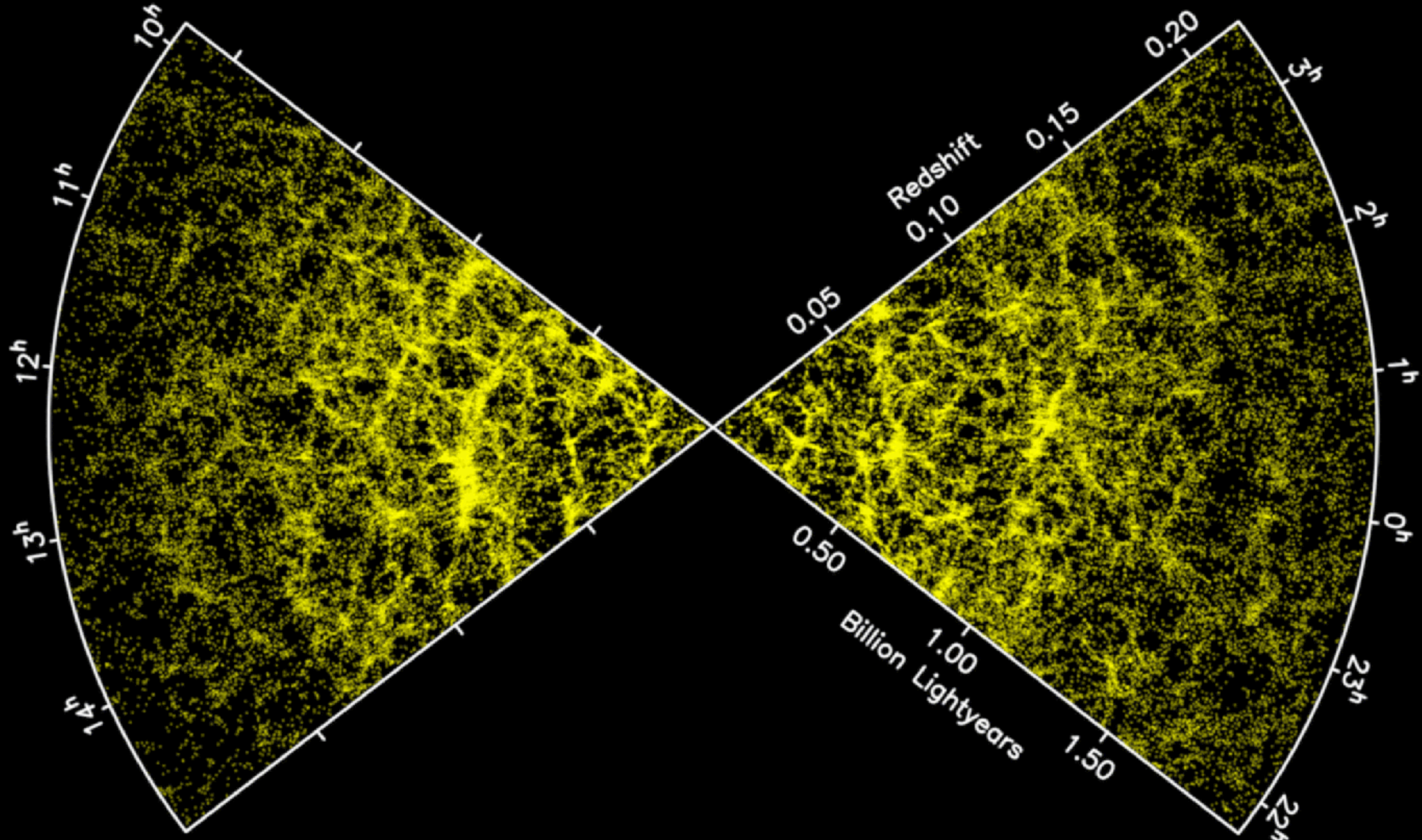
- MATEMATICAMENTE QUESTO PUO' ESSERE DESCRITTO USANDO LO "SPETTRO" DELLA CMB
- IL PRIMO PICCO DA INFORMAZIONI SULLA MATERIA VISIBILE, QUELLI SUCCESSIVI SULLA MATERIA OSCURA



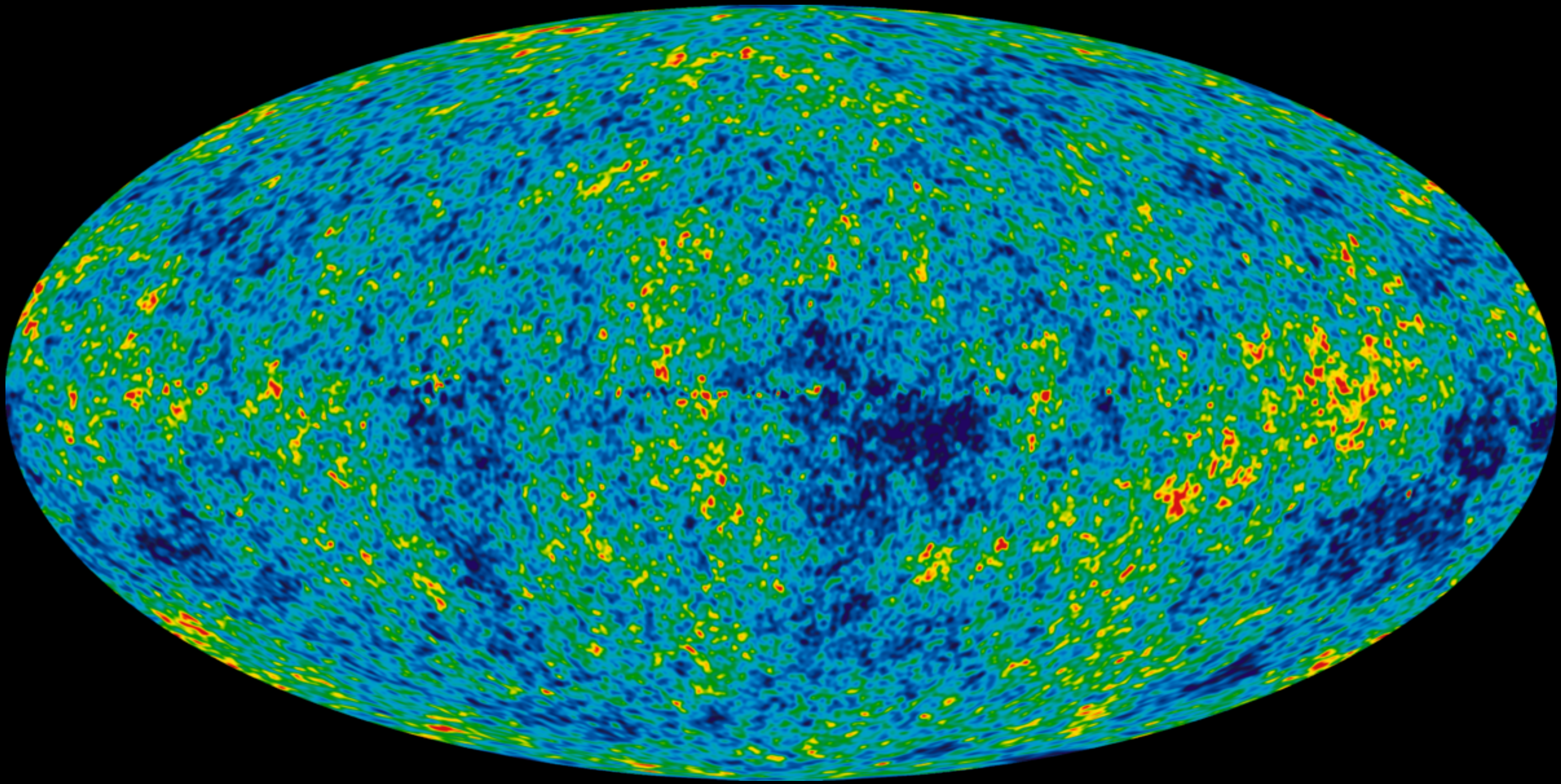


Hu & Dodelson, ARAA 40, 171 (2002)

Struttura su larga scala dell'Universo

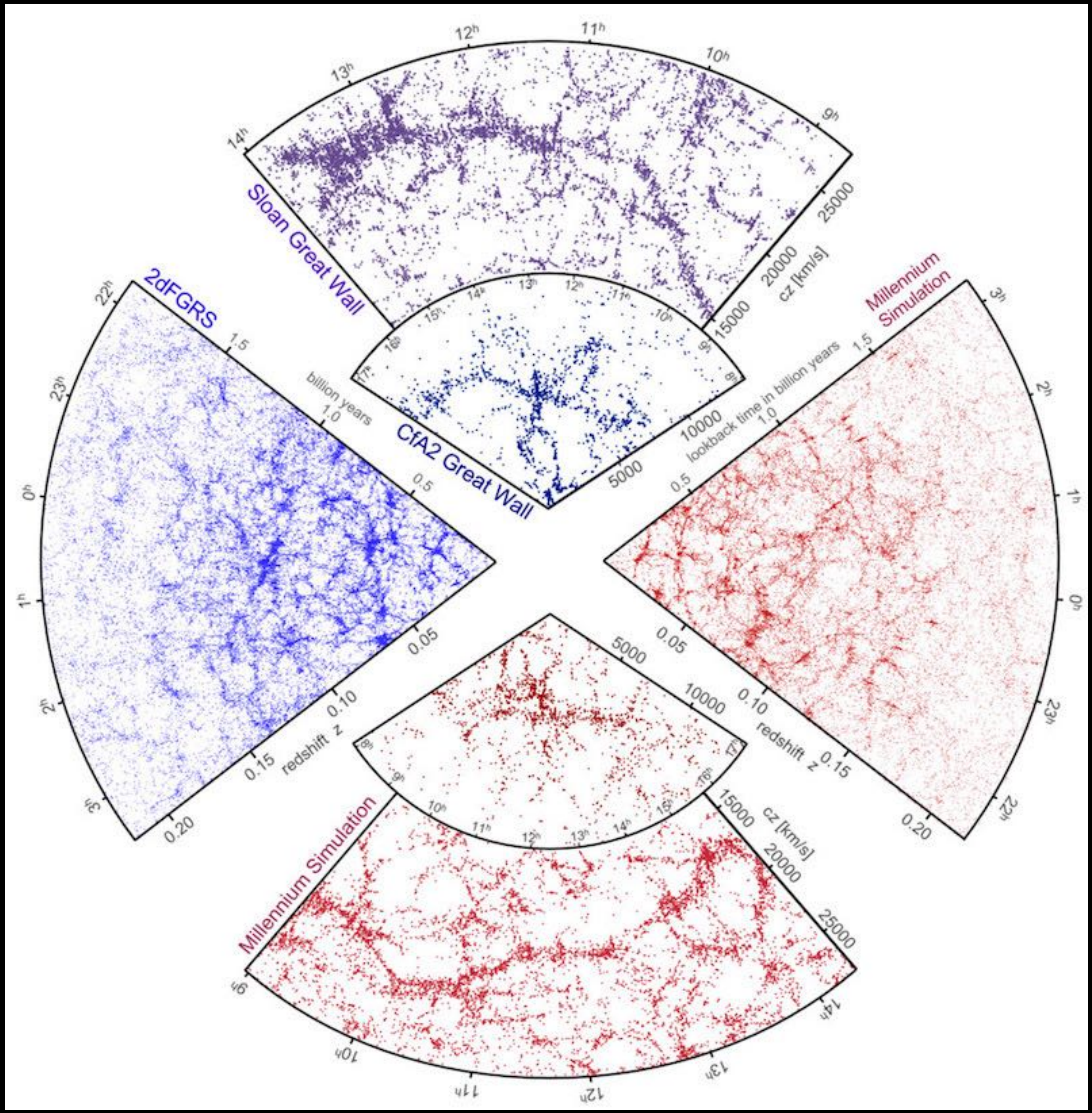


Formazione della ragnatela cosmica: condizioni iniziali



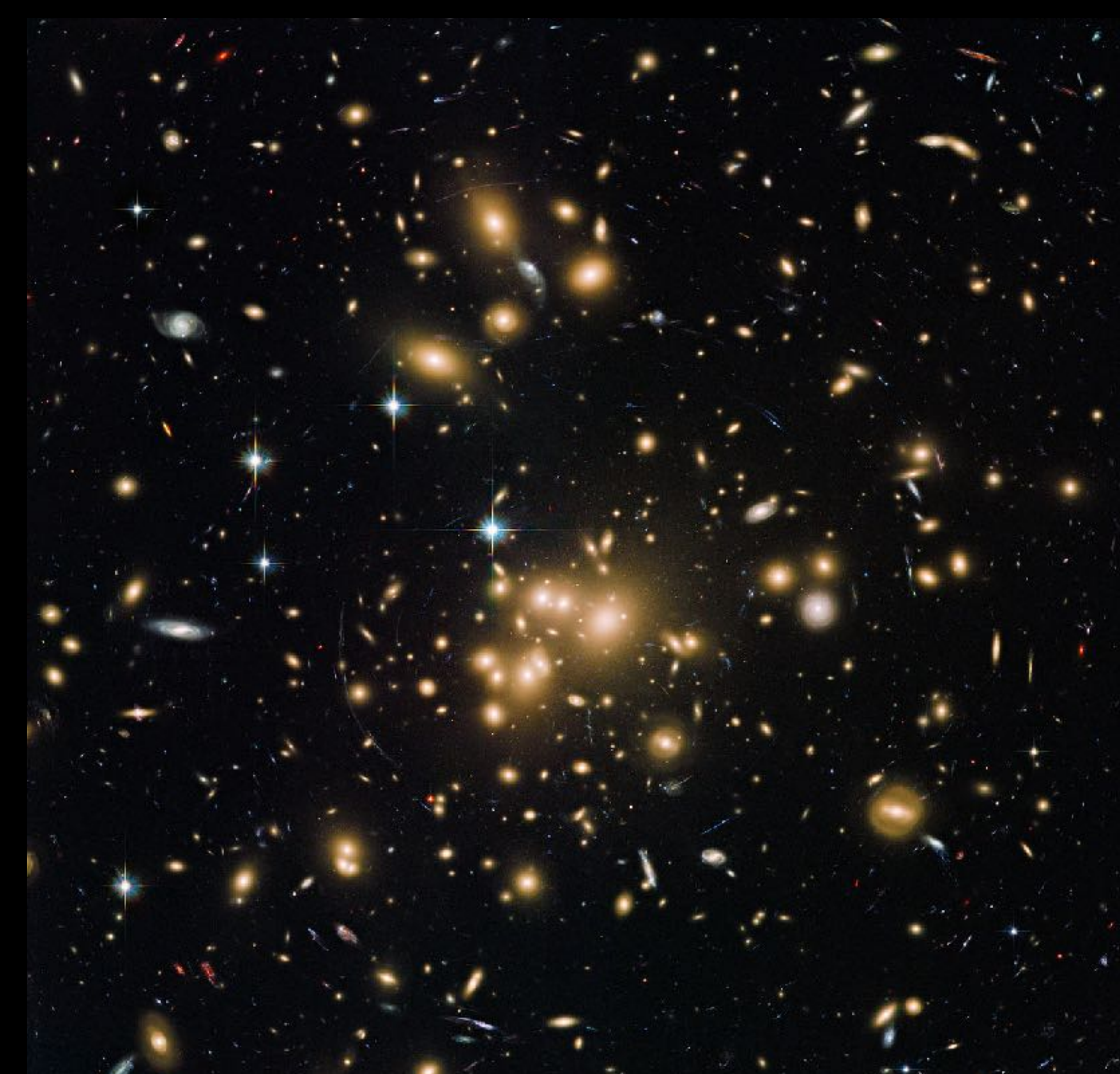
Formazione della ragnatela cosmica (materia oscura)

Il successo su larga scala della materia oscura



Materia oscura su diverse scale

100 000 anni luce

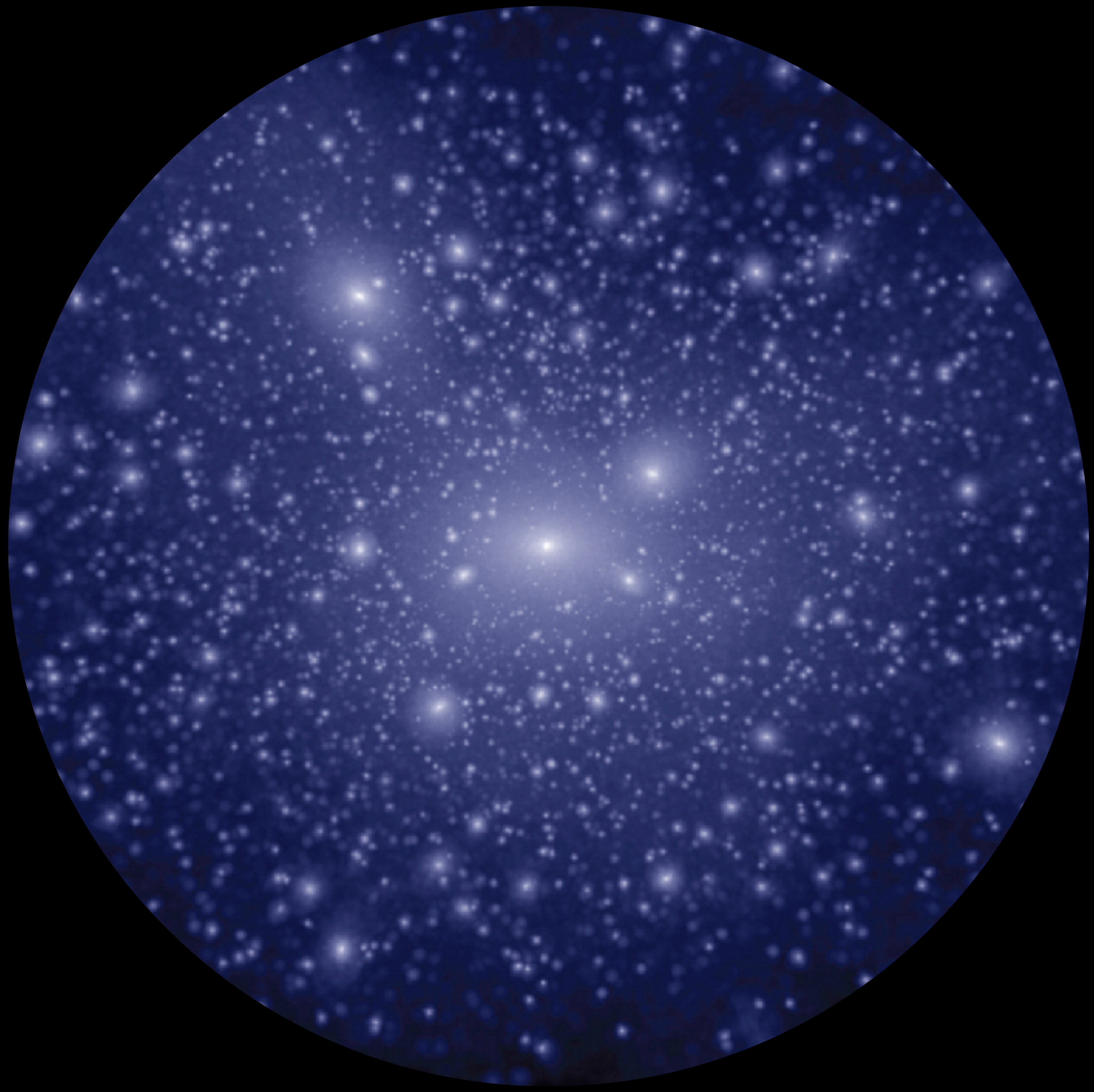


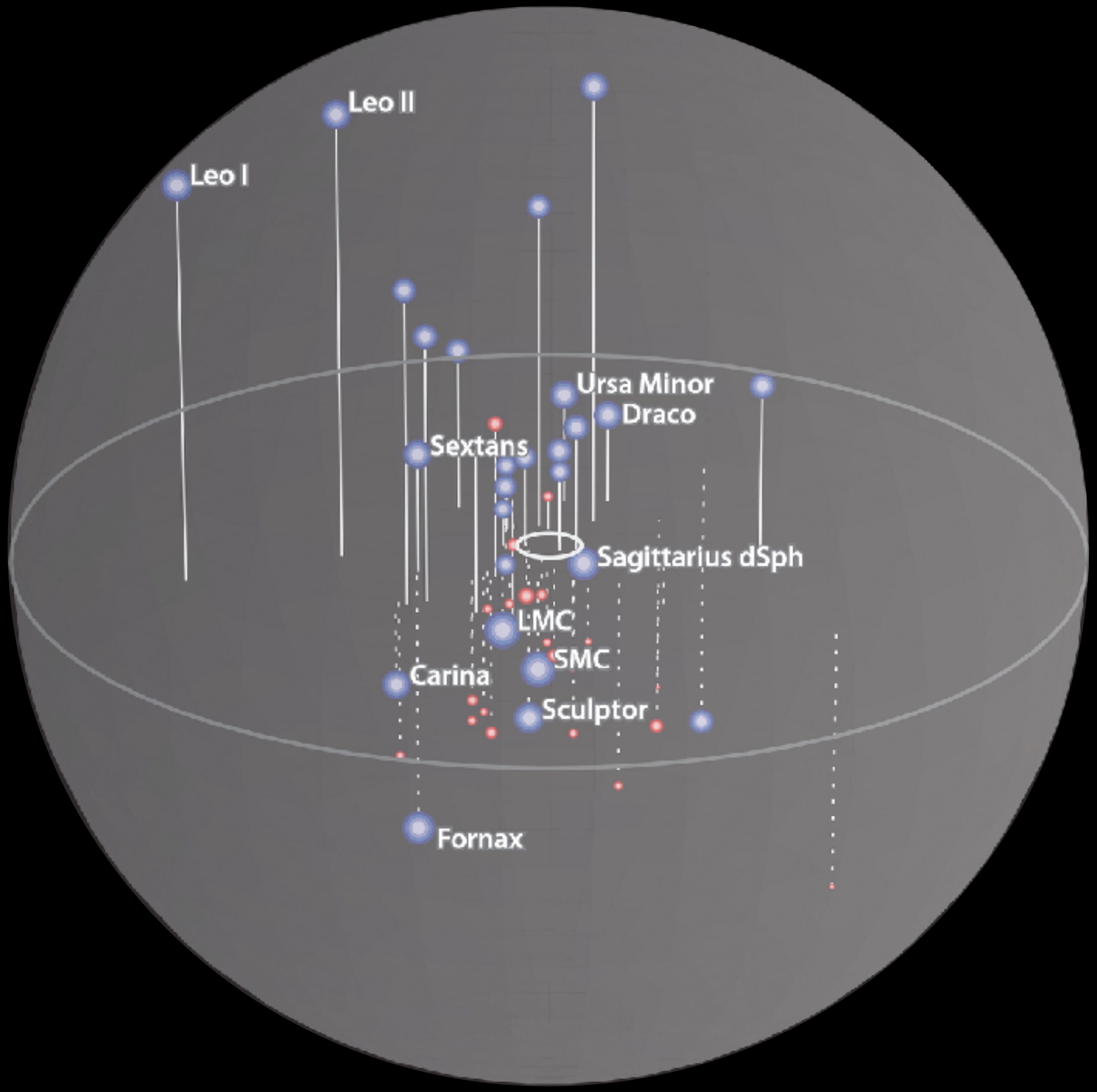
10 milioni di anni luce

1 miliardo di anni luce

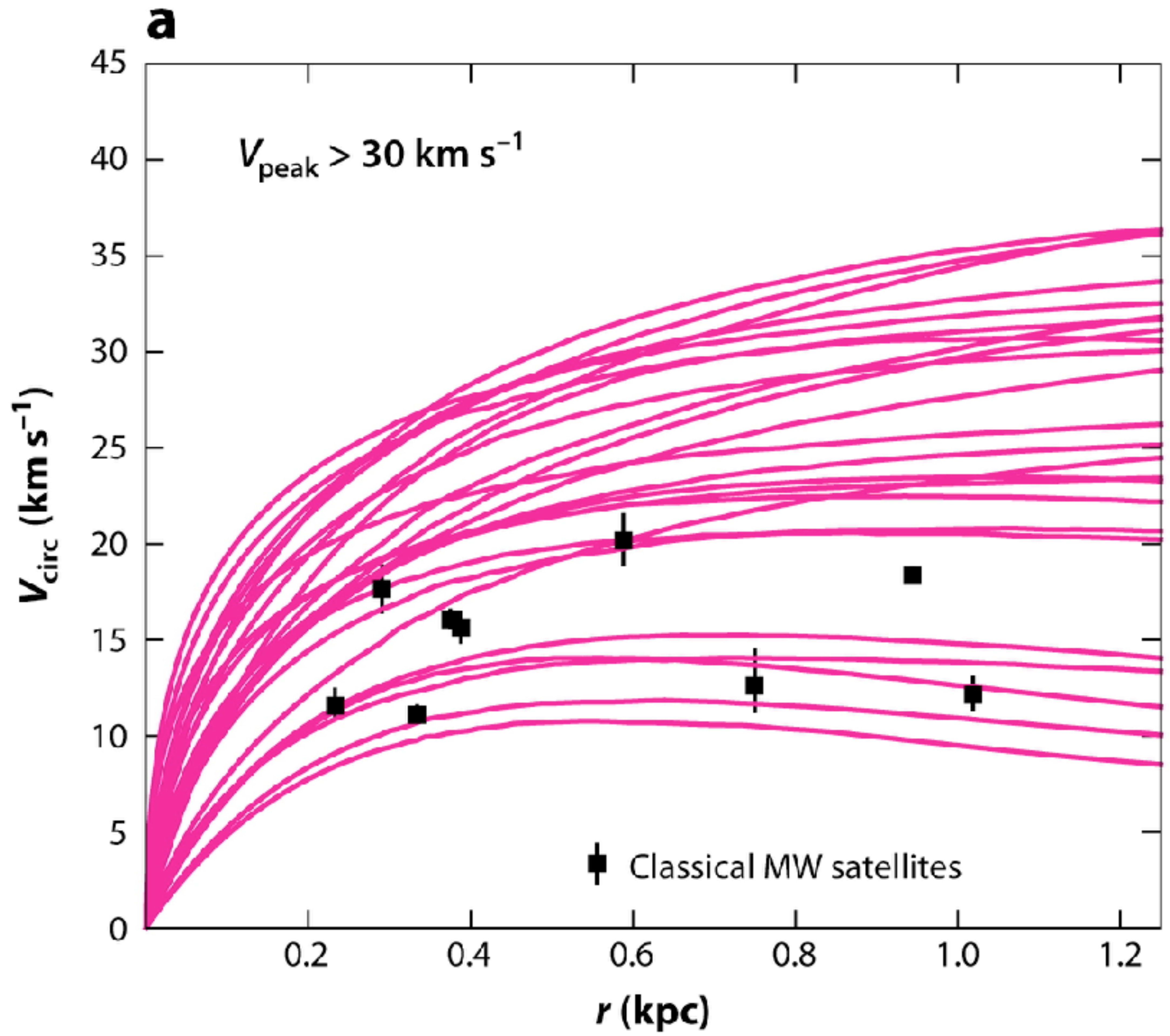
Alcuni problemi irrisolti

I satelliti mancanti



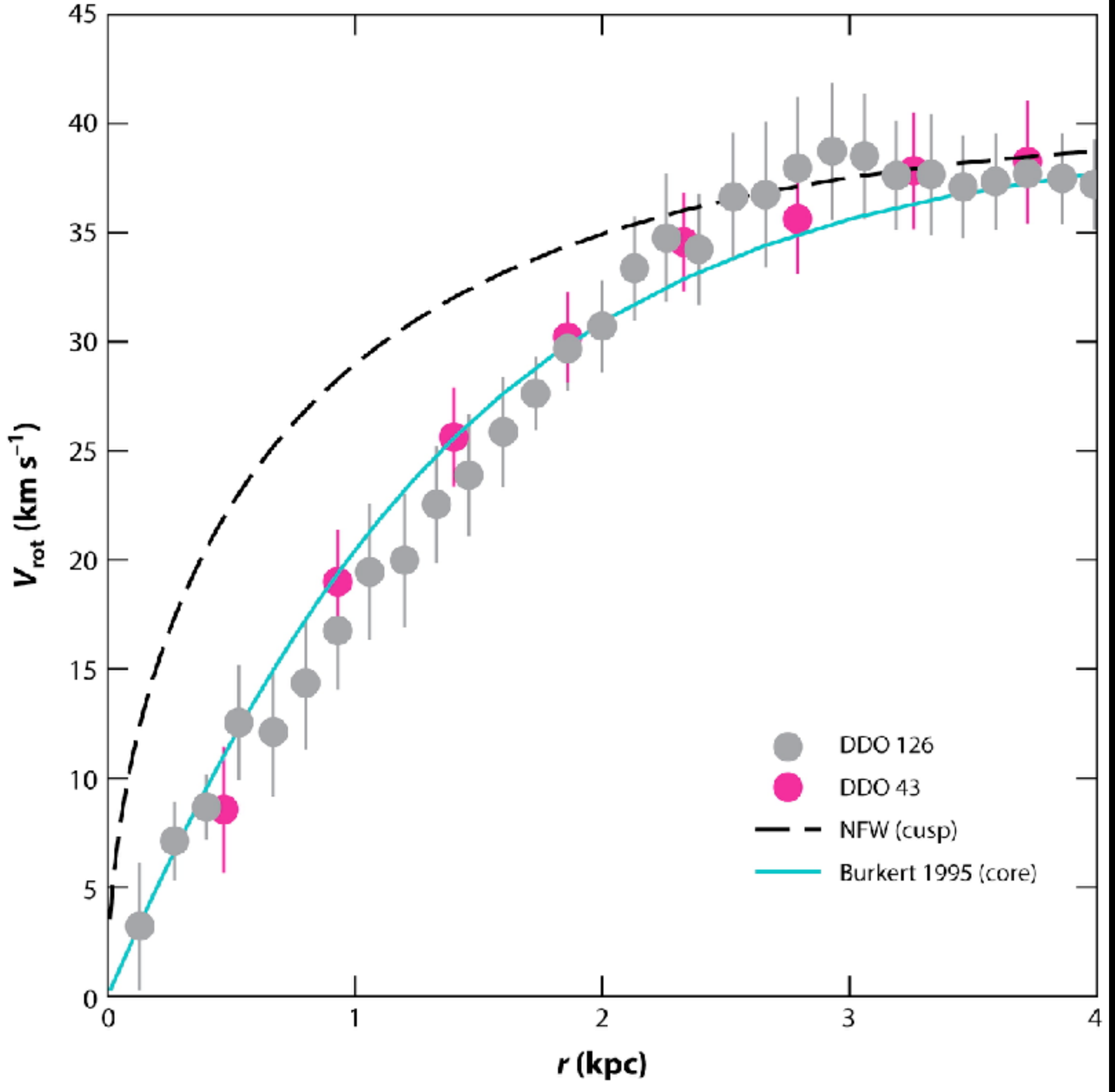


Densità centrale delle galassie satellite



Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

Profili di densità delle galassie nane



Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

Conclusione

La massa stimata in base alle leggi della gravità è maggiore della massa stimata in base alla luce visibile

Una materia oscura composta di particelle debolmente interagenti spiega sia queste osservazioni sia la forma della struttura su larga scala dell'Universo

Le discrepanze con le osservazioni sono probabilmente risolvibili migliorando la nostra comprensione del processo di formazione delle galassie

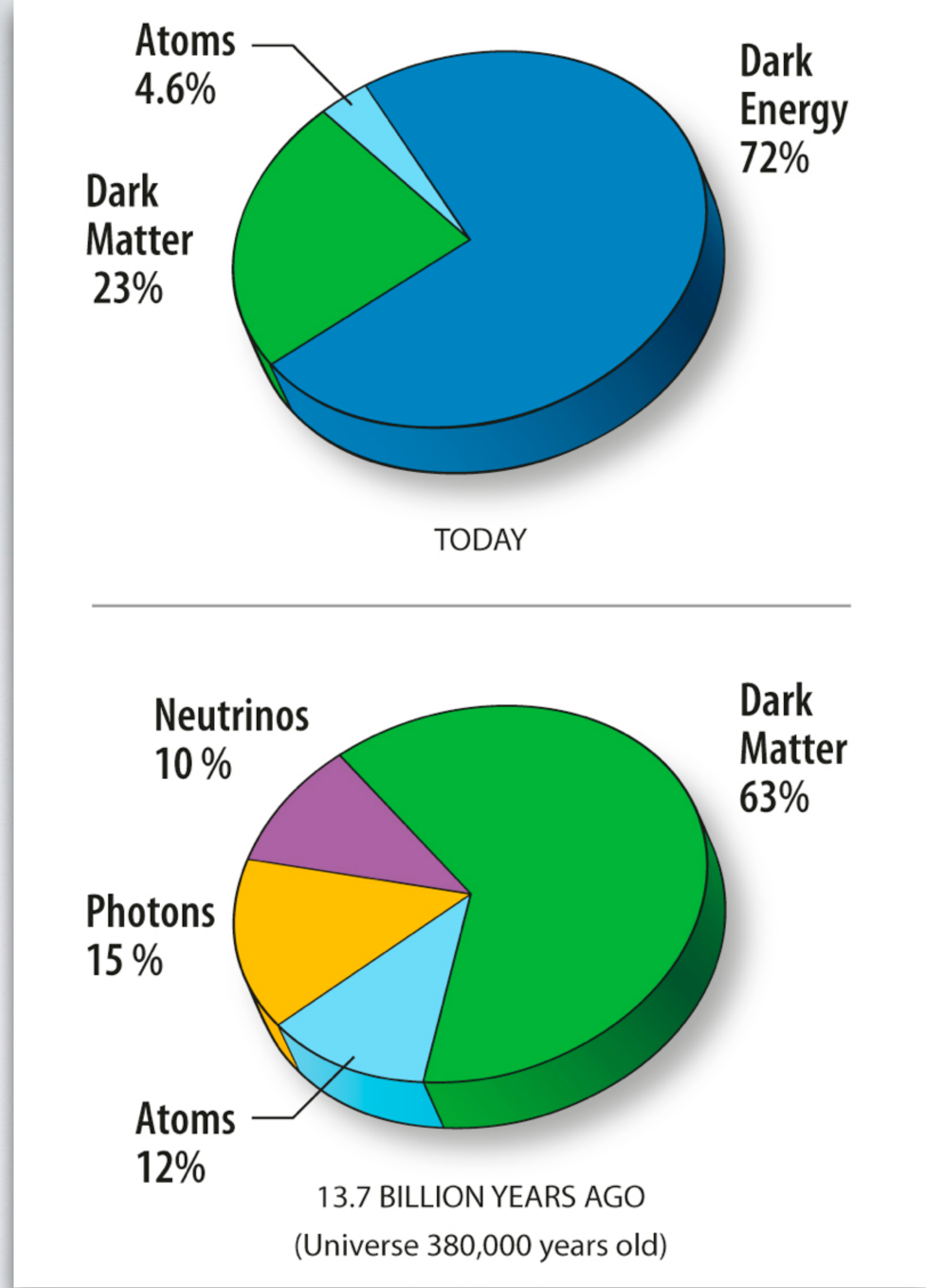
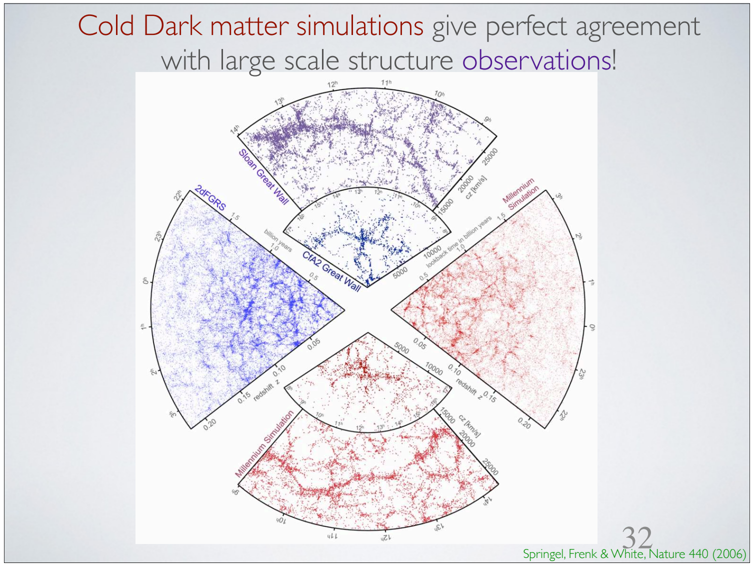


image credit: NASA

MATERIA OSCURA CALDA O FREDDA?

- PER LA FORMAZIONE DELLE STRUTTURE È MOLTO IMPORTANTE SE LA MATERIA OSCURA PRIMORDIALE FOSSE CALDA O FREDDA (PIÙ PRECISAMENTE BISOGNEREBBE PARLARE DI CAMMINO LIBERO MEDIO)
- LE OSSERVAZIONI PREFERISCONO DI GRAN LUNGA MATERIA OSCURA FREDDA (CDM=COLD DARK MATTER)

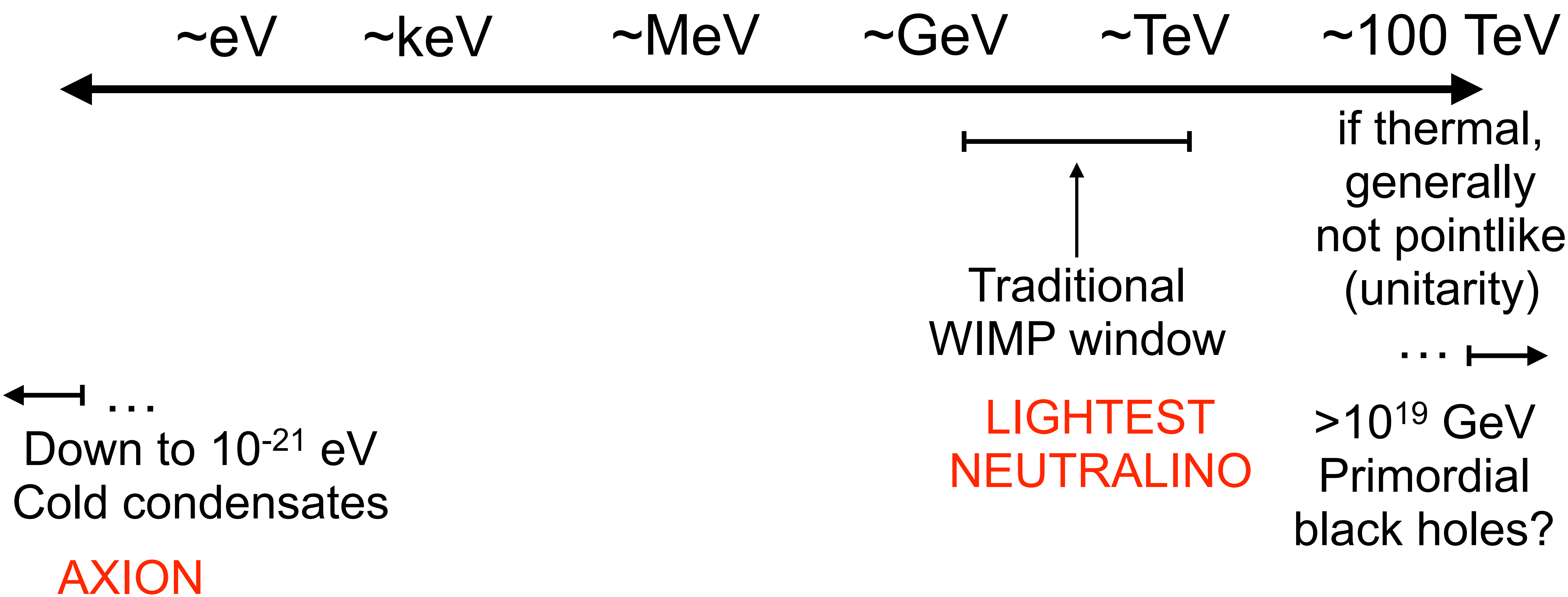


DI COSA E' FATTA LA MATERIA OSCURA?

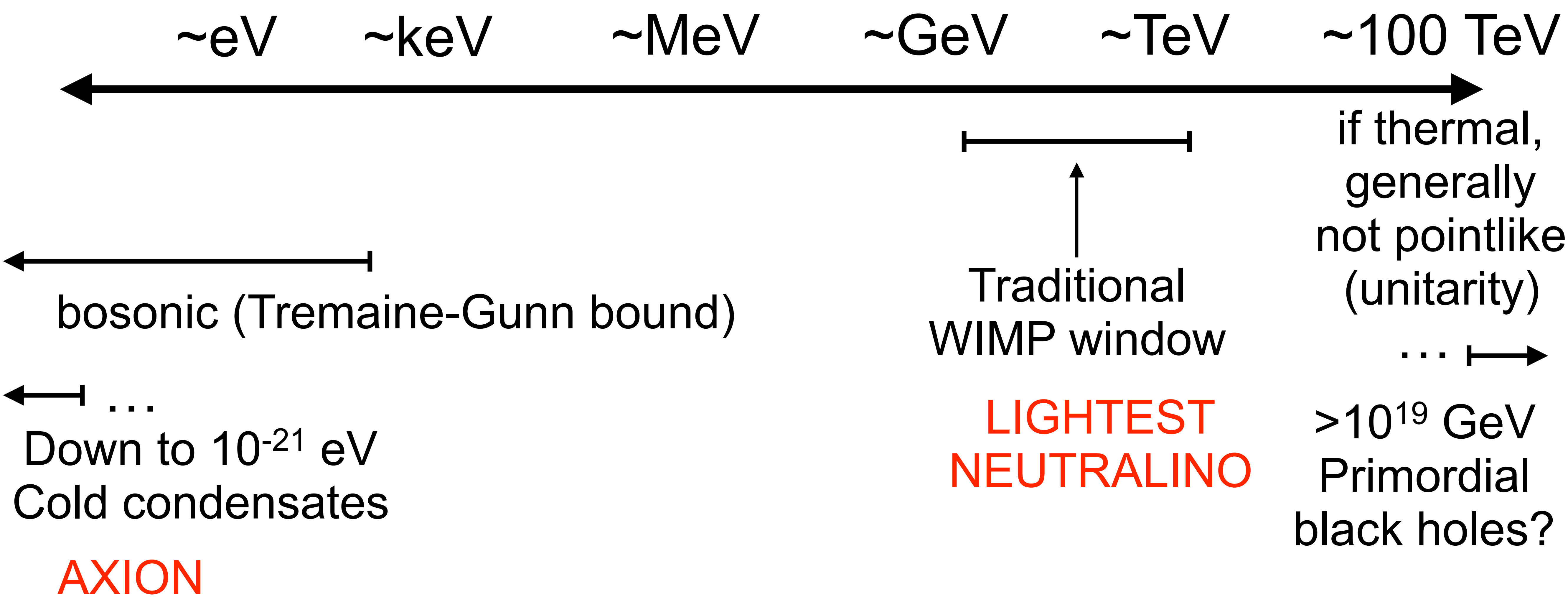
- CI SONO FORTI INDICAZIONI PROVVENIENTI DA TUTTE LE SCALE NEL NOSTRO UNIVERSO SULL'ESISTENZA DI UNA FORMA NON VISIBILE DI MATERIA MEDIAMENTE 5 VOLTE LA MATERIA VISIBILE (E' MOLTO MENO NELLA NOSTRA GALASSIA E DIVENTA 1000 PER LE DWARF)
- MA SAPPIAMO MOLTO POCO SULLA SUA NATURA

1. DEVE ESSERE ELETTRICAMENTE NEUTRA (altrimenti sarebbe visibile)
2. NON DEVE AVERE CARICA DI COLORE (nessuna interazione forte, altrimenti cambierebbe la NUCLEOSINTESI PRIMORDIALE)
3. INTERAGIRE MOLTO DEBOLMENTE CON I BOSONI DEL SETTORE DEBOLE (altrimenti sarebbe gia' stata rivelata dagli esperimenti)
4. INTERAZIONE CON MATERIA BARIONICA SOLO GRAVITAZIONALE

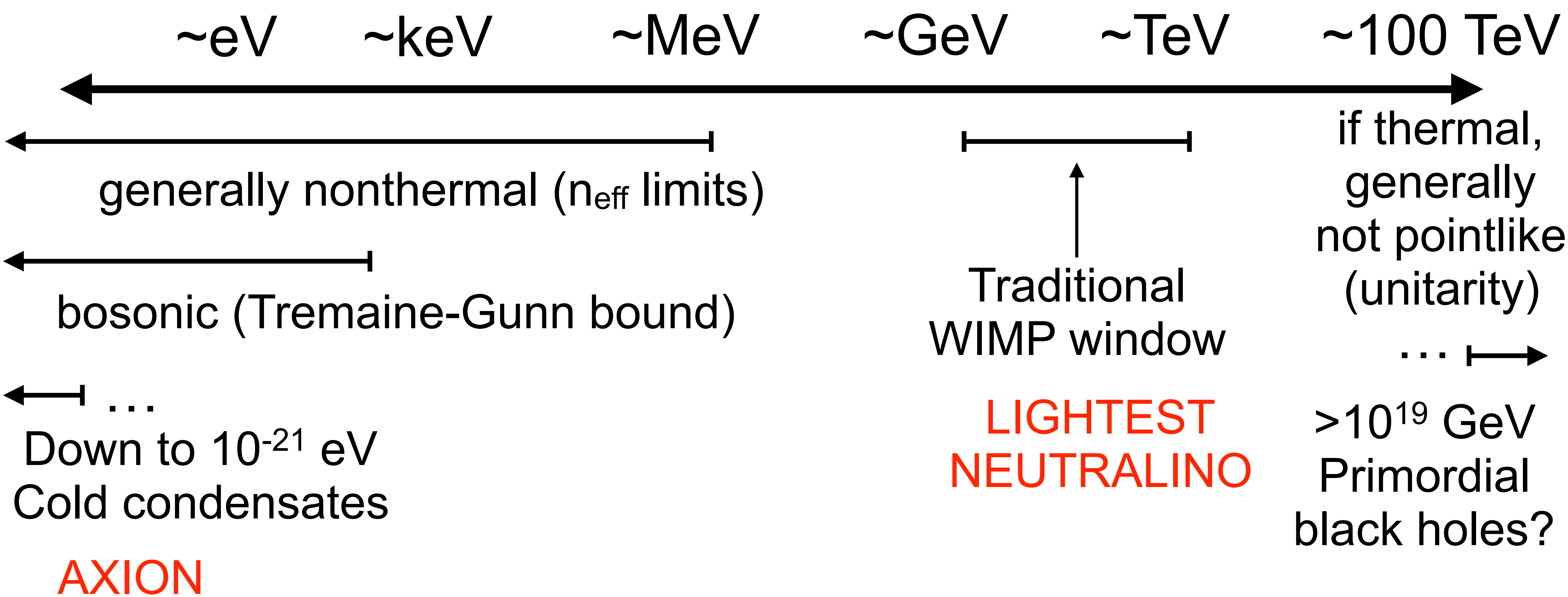
Dark matter mass scales



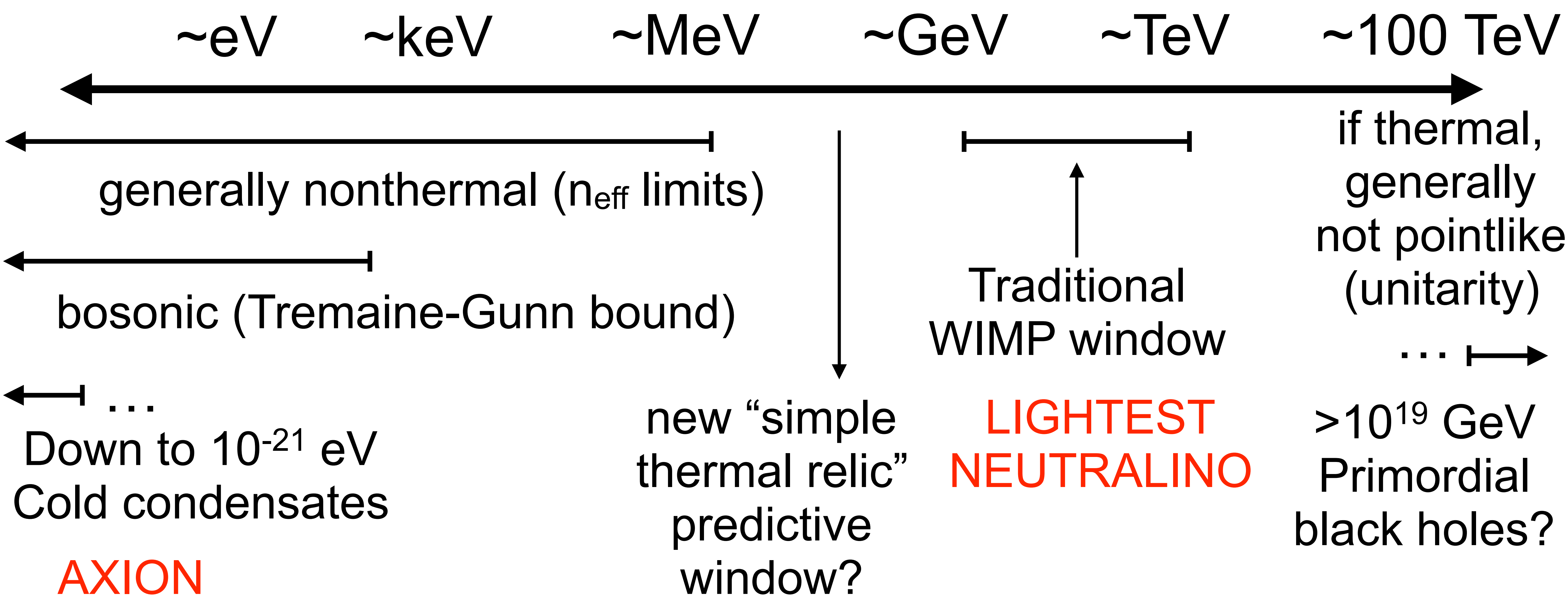
Dark matter mass scales



Dark matter mass scales



Dark matter mass scales



Thermal freezeout

- In the early universe, suppose DM & Standard Model (SM) particles are in thermal equilbrium.
- DM can annihilate to SM particles, or SM particles can collide and produce DM.

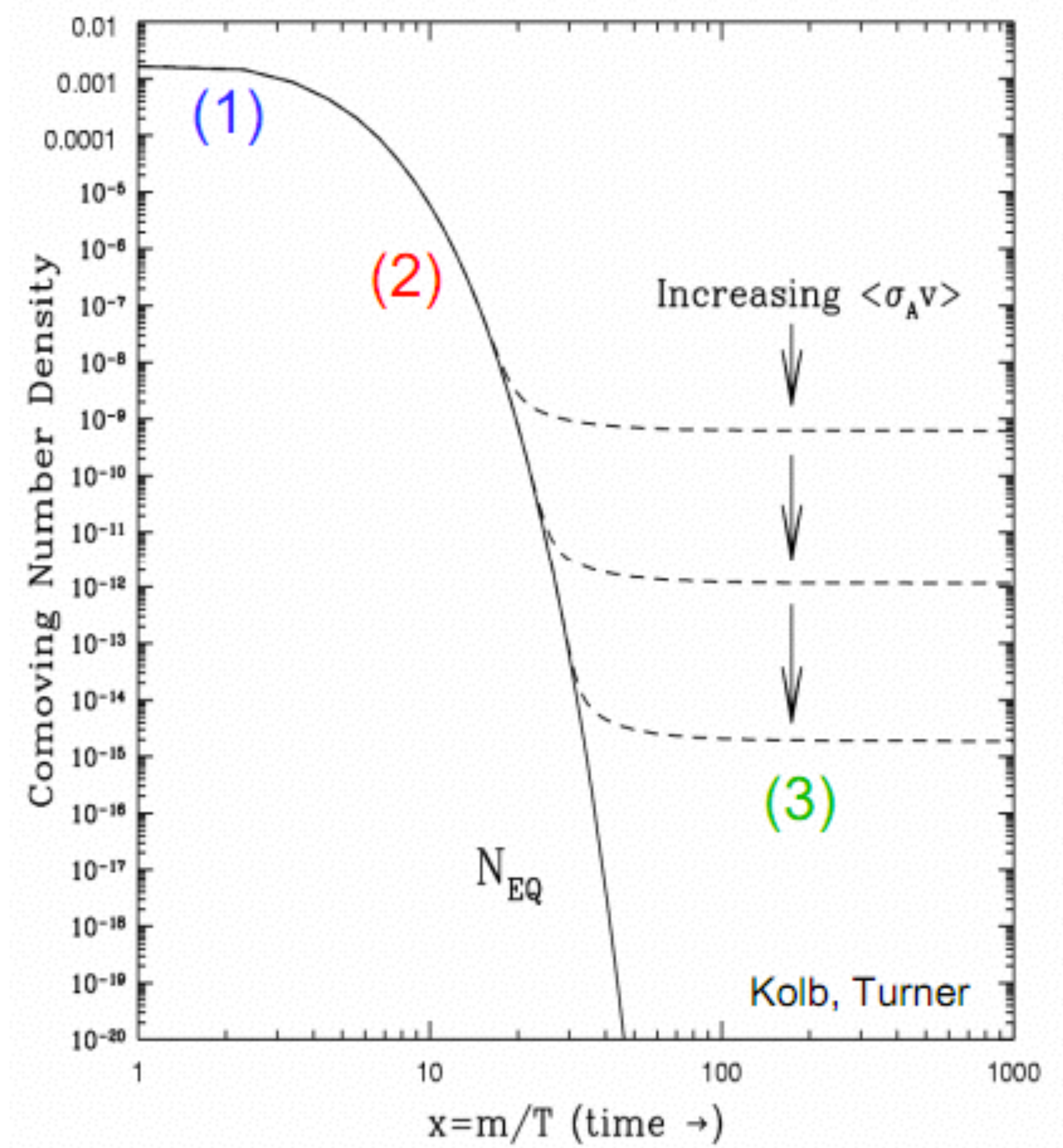
$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => DM can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The comoving dark matter density then freezes out.

$$(3)$$



The WIMP miracle

$$n_f \langle \sigma v \rangle \sim H \sim T_f^2 / m_{\rm Planck} \sim m_\chi^2 / m_{\rm Planck}$$

$$n_f = \rho_f / m_\chi \sim (m_\chi / T_{\rm eq})^3 \rho_{\rm eq} / m_\chi \sim m_\chi^2 T_{\rm eq}$$

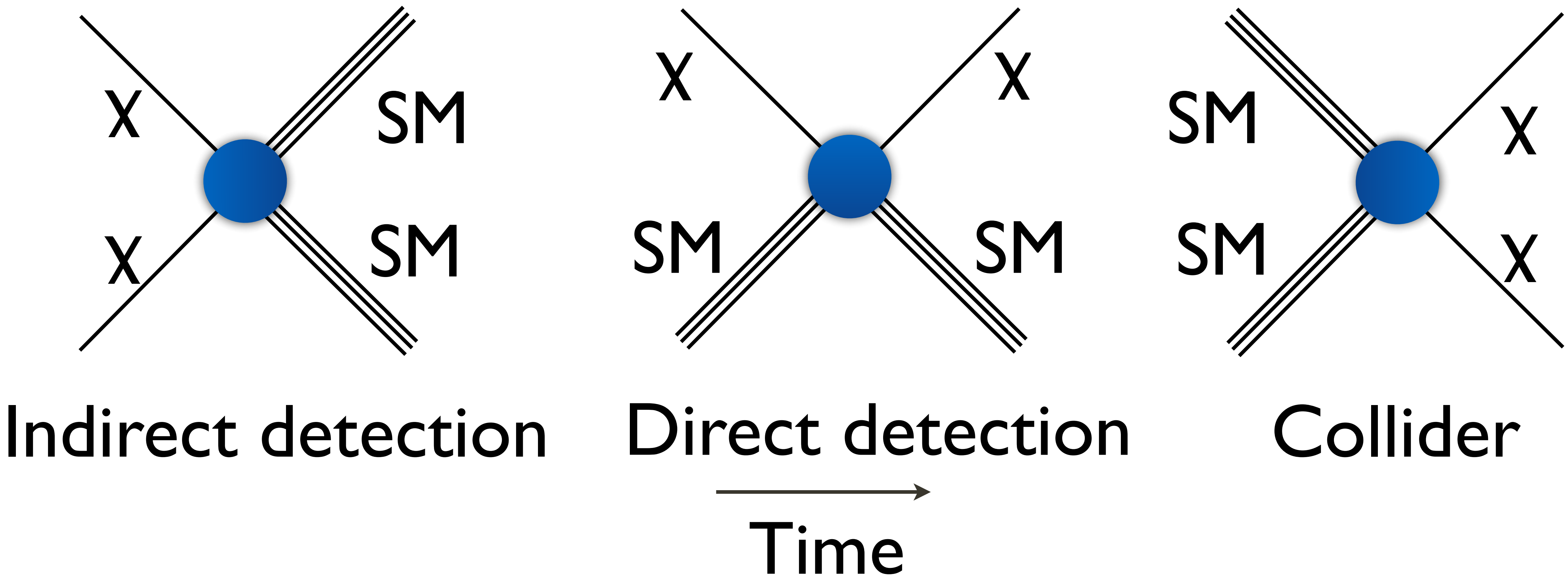
$$\langle \sigma v \rangle \sim \frac{1}{m_{\rm Planck} T_{\rm eq}} \sim \frac{1}{(10^{19}{\rm GeV} \times 1{\rm eV})} \sim \frac{1}{(10^{14}{\rm eV})^2}$$

$$\sim \frac{1}{(100{\rm TeV})^2} \sim \left(\frac{10^{-2}}{1{\rm TeV}} \right)^2 \sim \frac{\alpha^2}{m_\chi^2}$$

- Perturbativity requires DM mass below ~100 TeV (unitarity bound ~200 TeV [von Harling & Petraki '14]). Some caveats exist: e.g. late-time entropy injection can relax bound by many orders of magnitude [Bramante & Unwin '17].

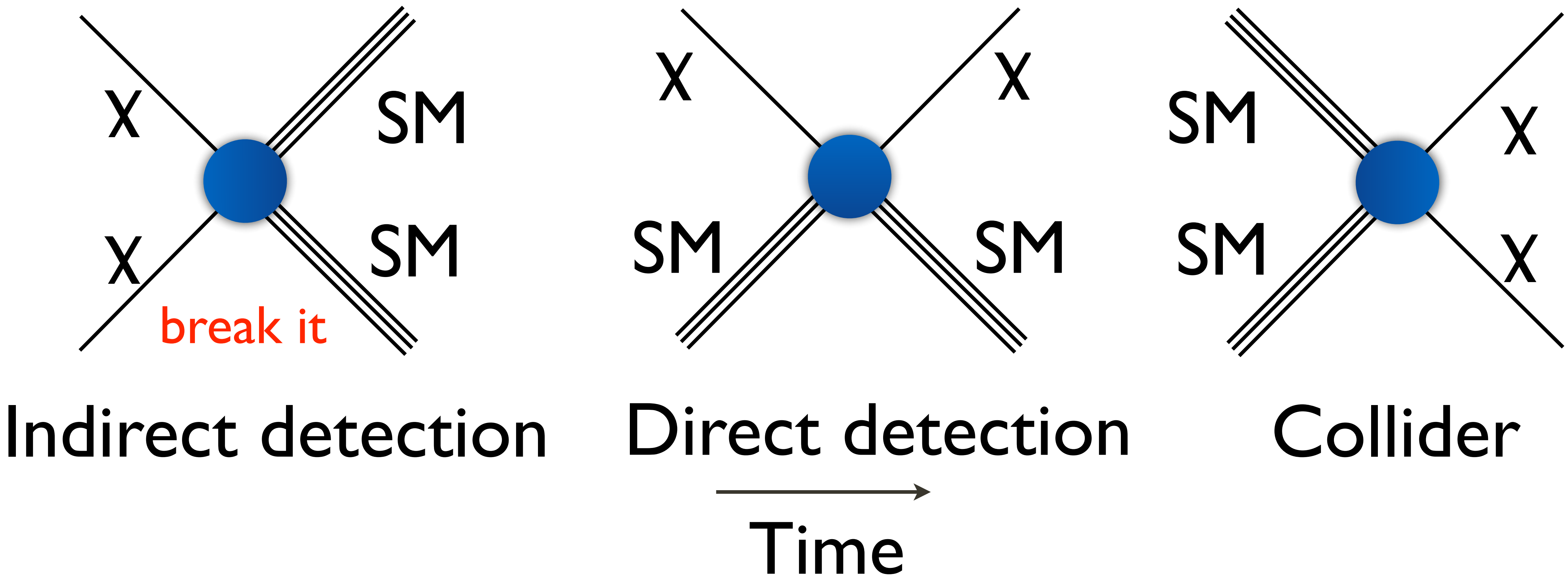
- The thermal cross section is naturally obtained for electroweak-scale couplings and masses - suggests a possible connection to electroweak physics + hierarchy problem.

WIMP searches



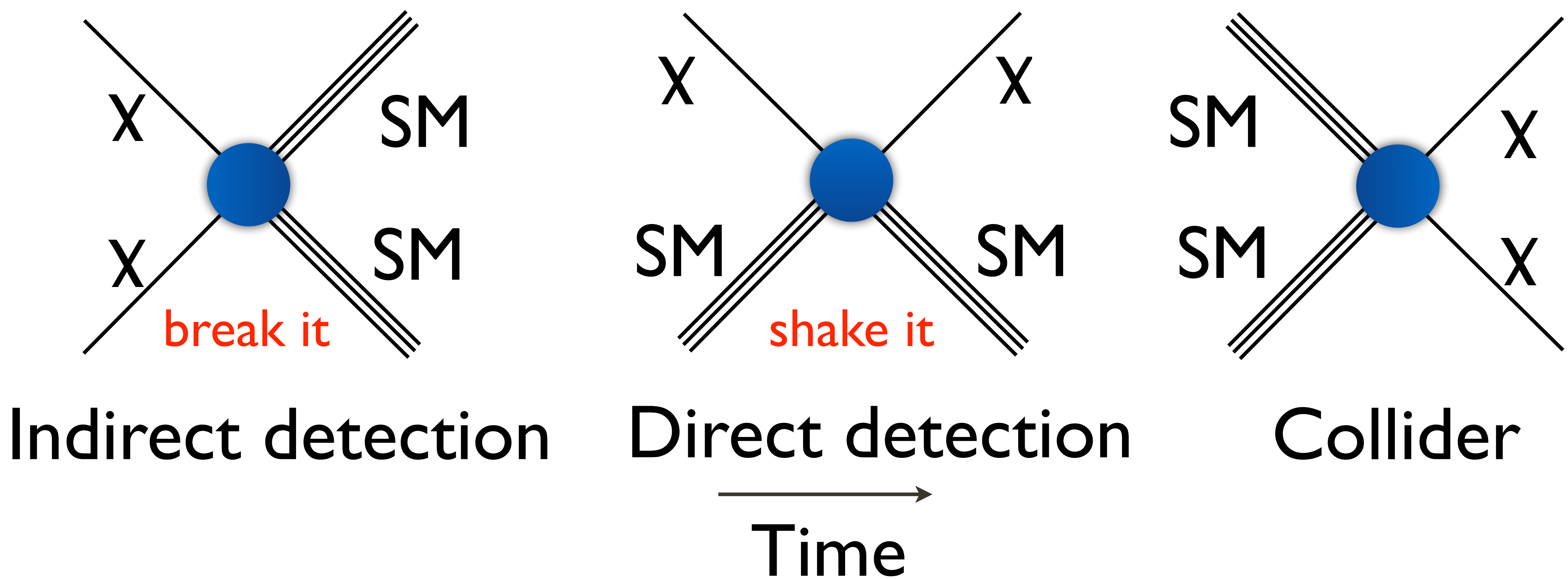
- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

WIMP searches



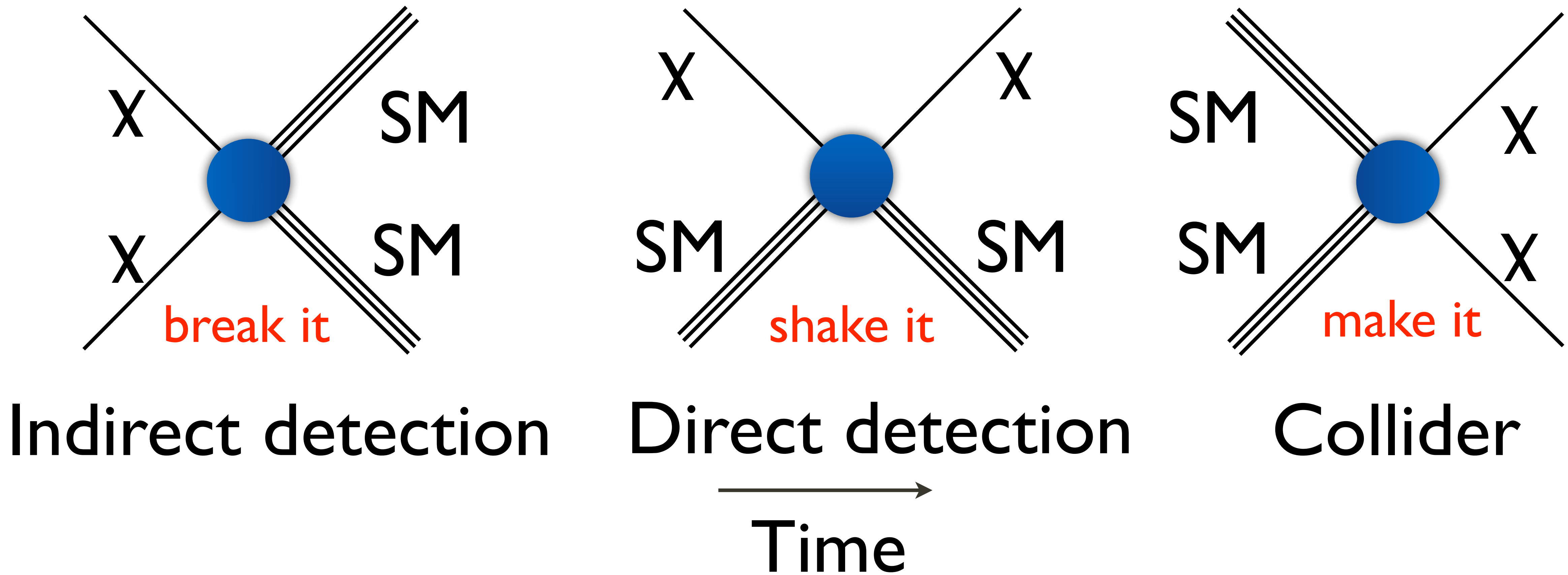
- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

WIMP searches



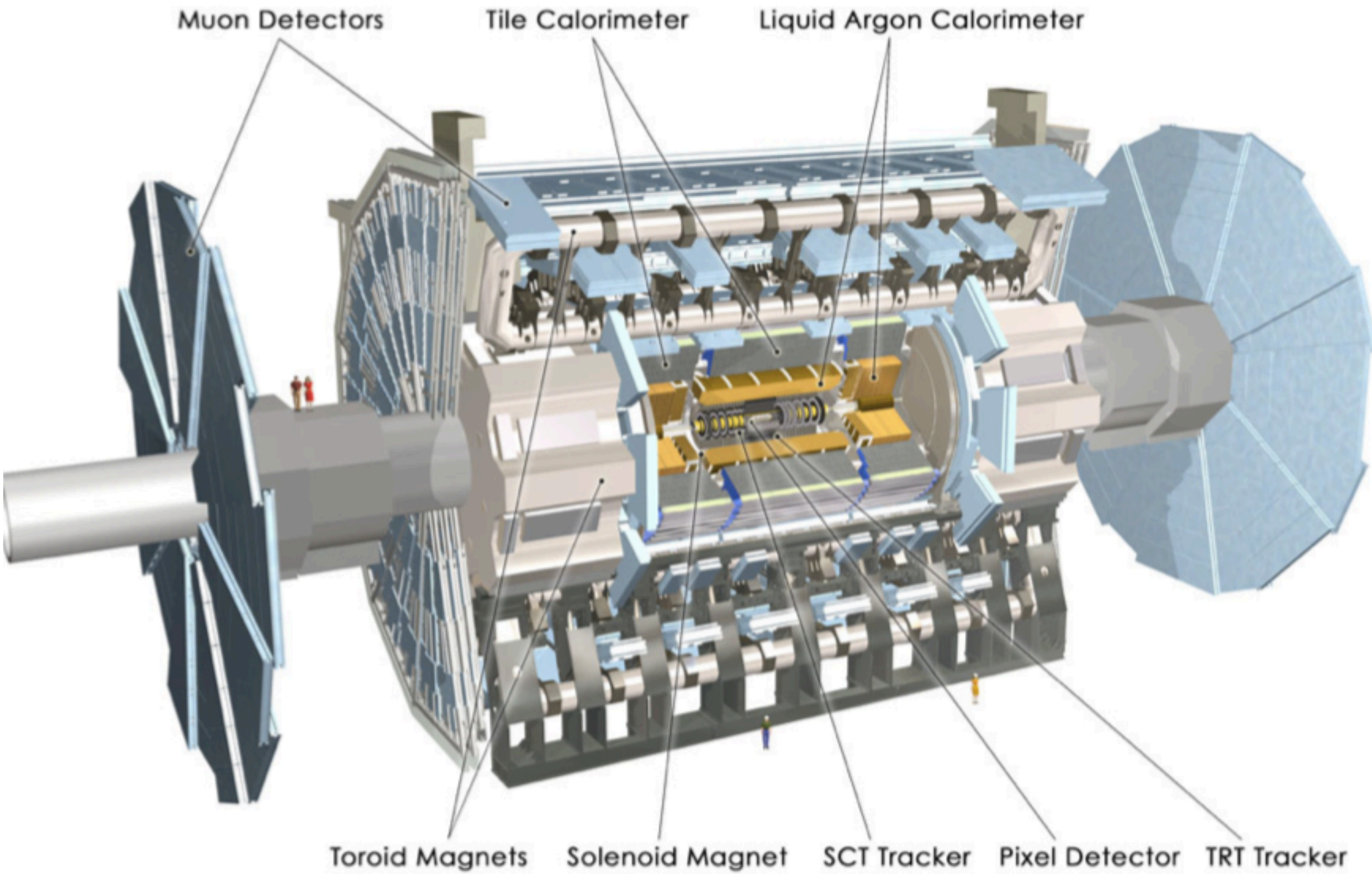
- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.

WIMP searches



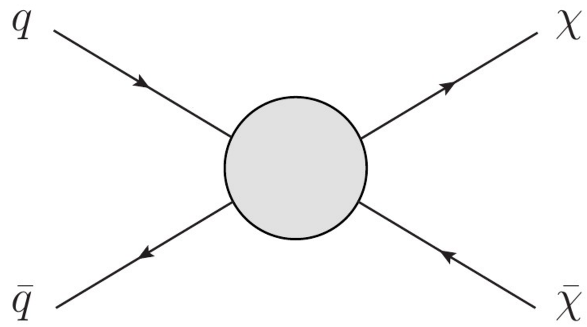
- Indirect detection: look for SM particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Colliders: produce DM particles in high-energy collisions and look for missing energy (e.g. at the LHC), or search for new light dark-sector particles.


LHCb
ATLAS
CERN
CERN
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

Mono-X

Simplest mode of DM production *unobservable* @ LHC



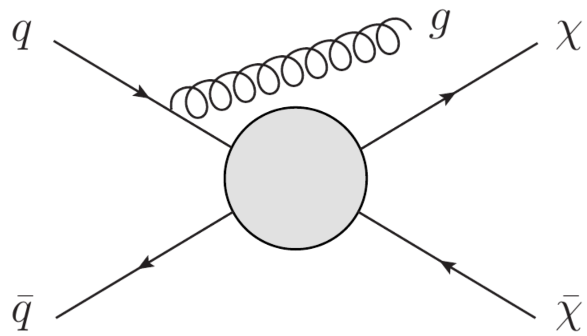
Dark Matter is **DARK**

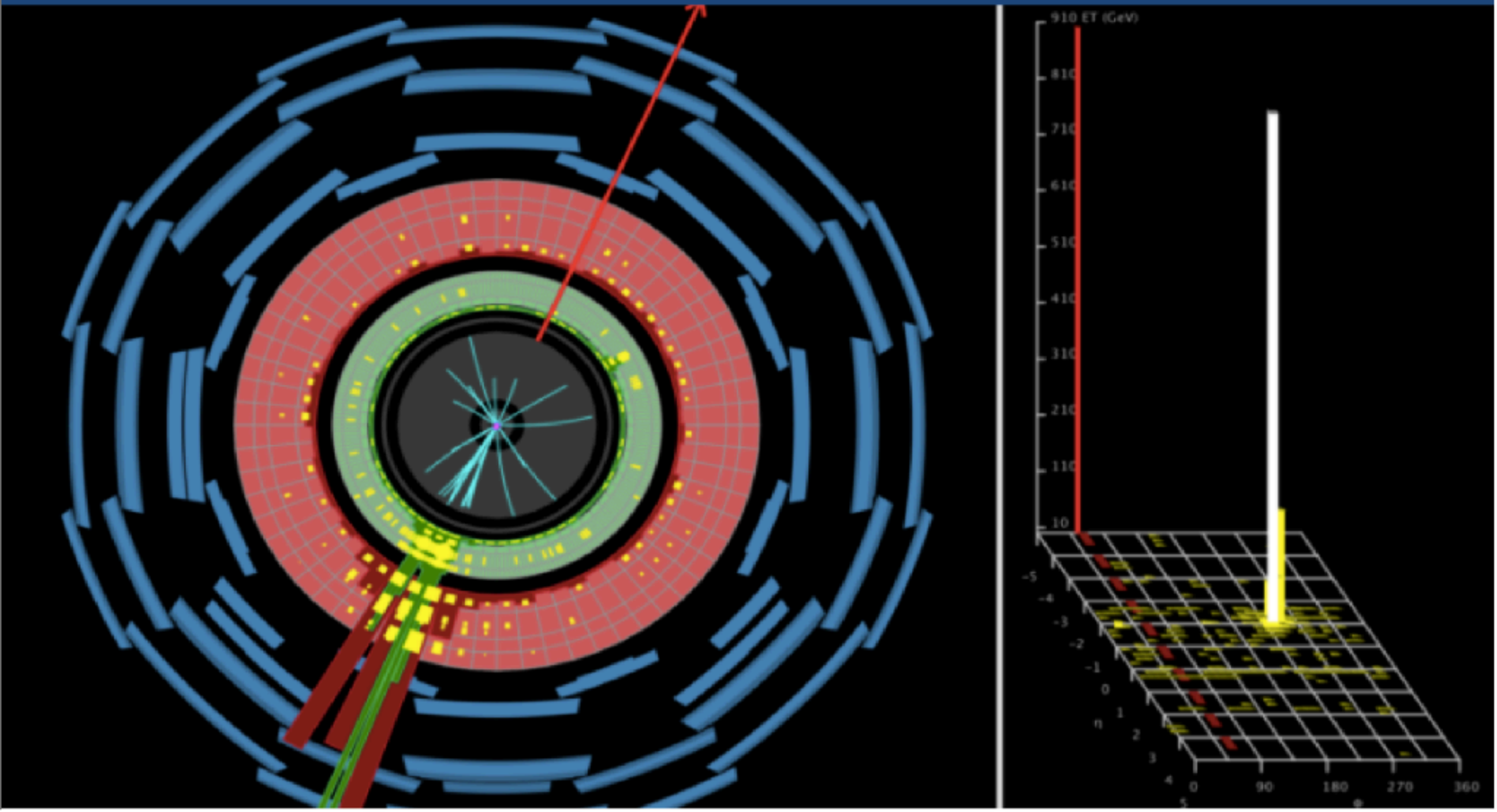
- Leaves no activity in the detector
- Nothing to trigger on / reconstruct above

DM must instead recoil against *something* to become "visible"

"Mono-X" (or "MET+X") includes "X" for viable detection

- X: quarks/gluons, photons, W/Z …





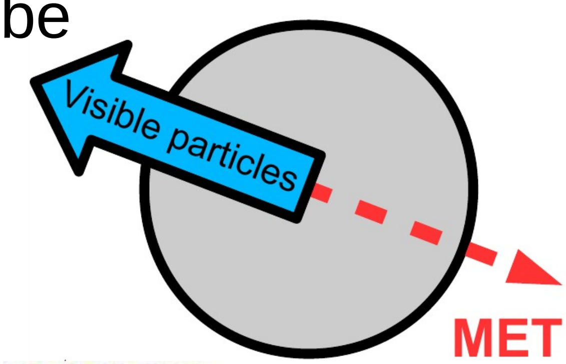
910 ET (GeV)
810
710
610
510
410
310
210
110
10
-5
-4
-3
-2
-1
0
η
1
2
3
4
5
0
90
180
270
360
φ

Non-interacting particles escape the detector

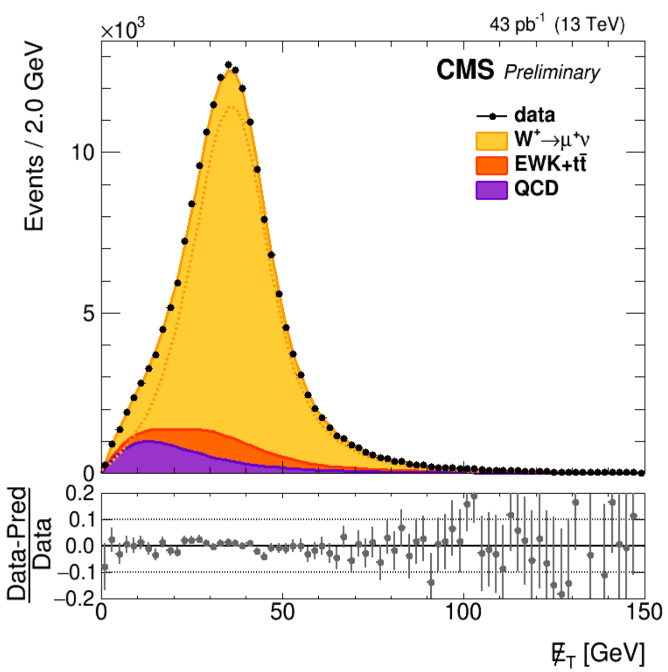
- Their presence inferred from energy/momentum imbalance

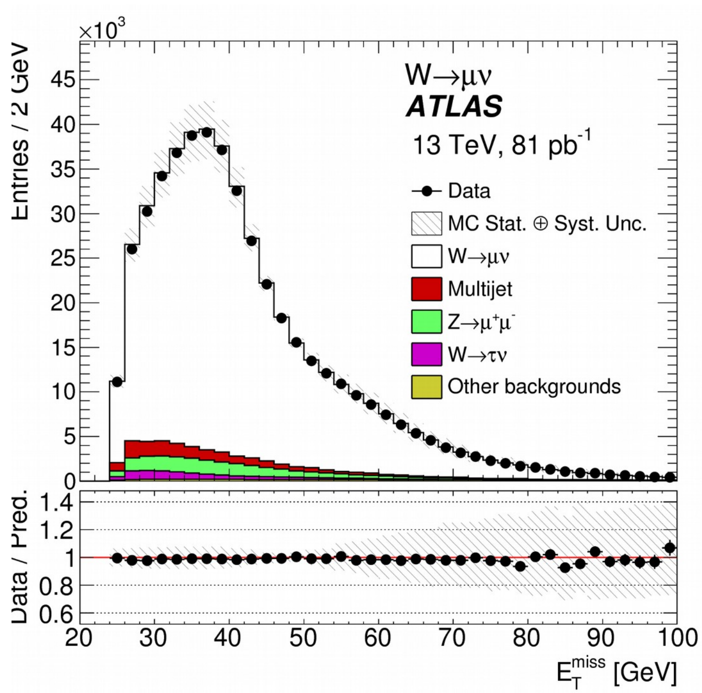
(Transverse) analog of nuclear recoil in DD …

- Transverse → because final state particles can be lost in the beampipe
- E_T^{miss} = Negative vector sum of all visible pT



$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{\text{all visible}} \vec{E}_T$$



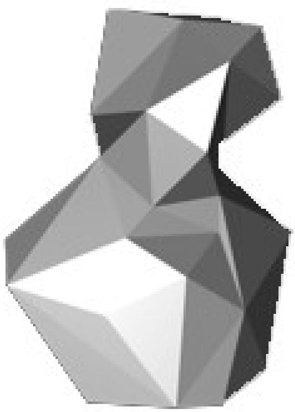


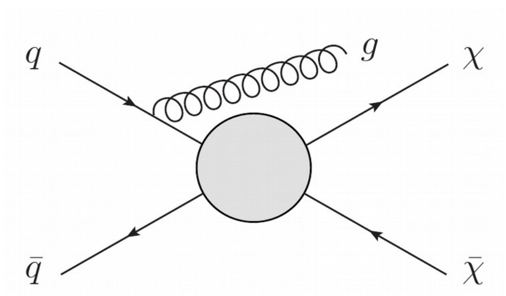
A well understood collider observable

- Wide use in SM measurements

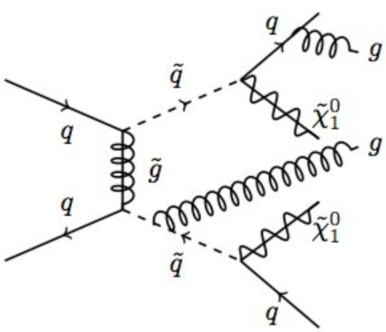
Modeling DM Collider Production

- Models used in the design and interpretation of DM searches
- Need to balance model complexity with predictive accuracy ...





EFTs



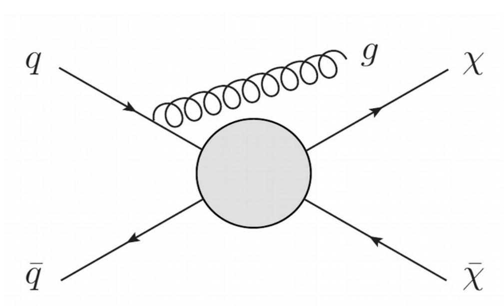
UV-complete Models

Validity issues @ LHC ..
cf: 1307.2253, 1308.6799

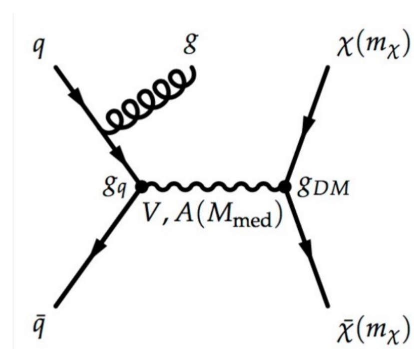
Too specific?
Theory baggage?

Modeling DM Collider Production

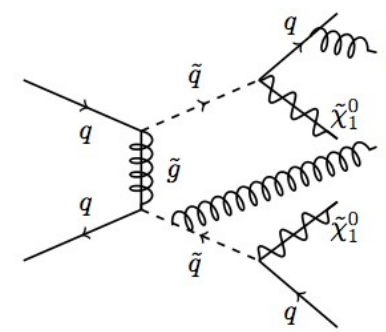
- Models used in the design and interpretation of DM searches
- Need to balance model complexity with predictive accuracy ...



EFTs



Simplified Models



UV-complete Models

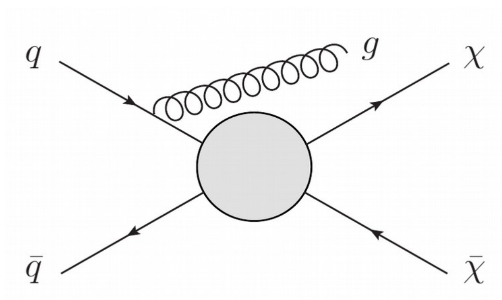
Validity issues @ LHC ..
cf: 1307.2253, 1308.6799

Just right?

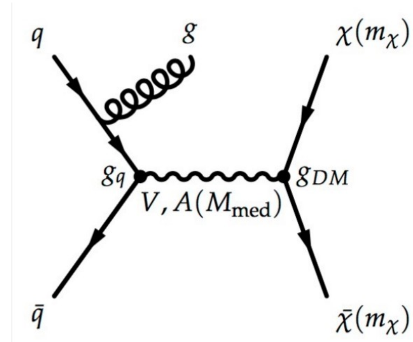
Too specific?
Theory baggage?

Modeling DM Collider Production

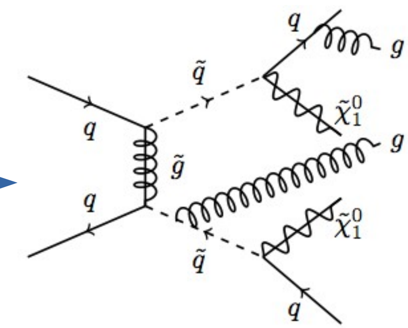
- Models used in the design and interpretation of DM searches
- Need to balance model complexity with predictive accuracy ...



EFTs



Simplified Models



UV-complete Models

Simplified models: capture kinematics, lack completion

- Pair-produced DM Dirac fermions, χ
- Massive DM↔SM mediator, on/off-shell production
- Couplings: vector/axial/scalar/pseudo
- Minimal flavor violation
- Minimal mediator width: couples only to SM and χ

Only four parameters:

g_q, g_{DM}, m_χ, M_{med}

LHC DM searches using simplified models/benchmarks from the LHC Dark Matter Forum: 1507.00966

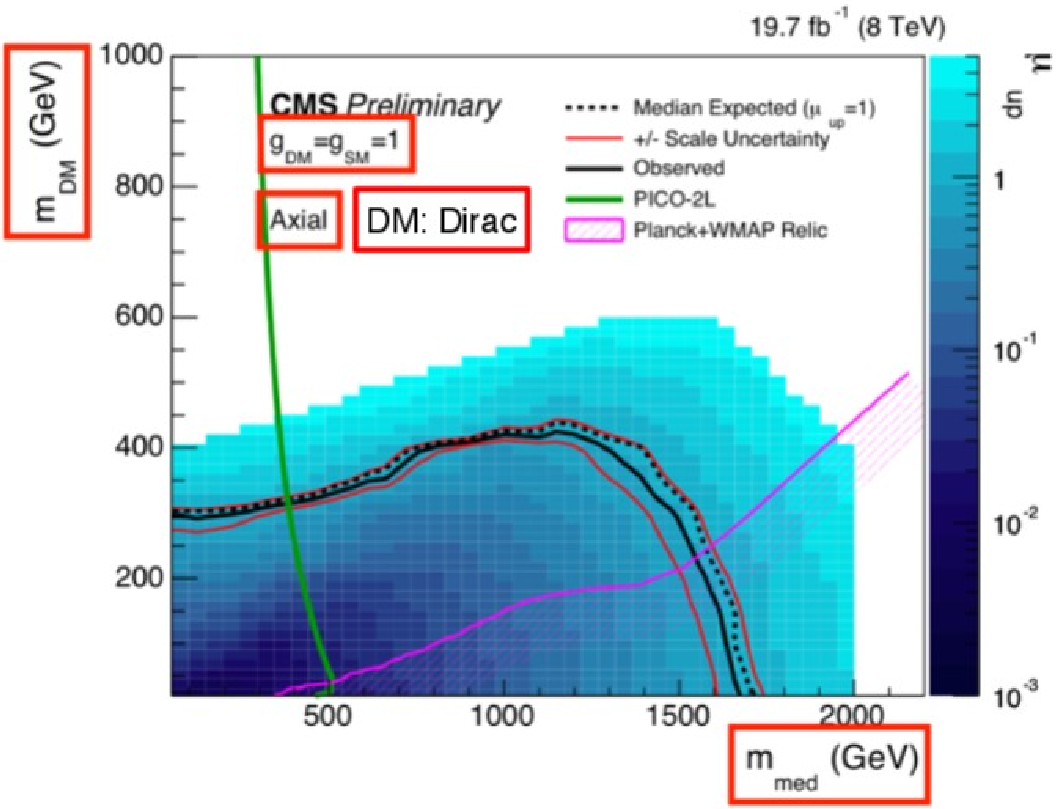
Extraction of potential DM signals …

In absence of excess: limit setting, model constraints

- NB: 95% CLs limits are standard in collider world

m(Med)-m(DM) plane: provides natural representation of collider results

- Results shown as limit on signal cross section or on signal strength ($\mu = \sigma_{obs}/\sigma_{th}$)
- Fixed gDM & gSM
- All model assumptions (eg: mediator & DM type) specified



Comparison of collider results with (in)direct detection

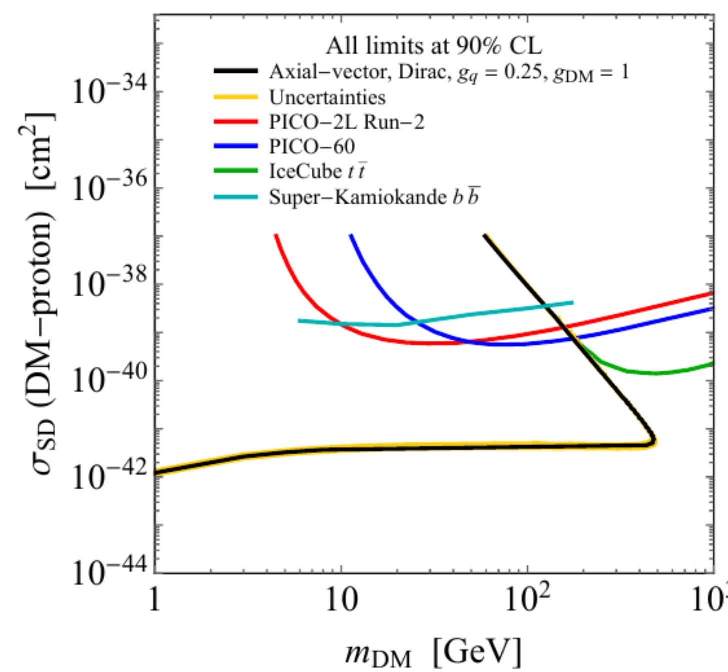
- Recent focus of LHC Dark Matter Working Group (DMWG)
- Developed recommendations for collider/non-collider comparison

Translate collider limits to $\sigma_{DM\text{-}N}$ & σv_{rel} , rather than reverse

- Avoid subtleties and assumptions involved in mapping DD/ID to collider
- DD: vector/scalar (SI) axial (SD) mediators
- ID: pseudoscalar mediators

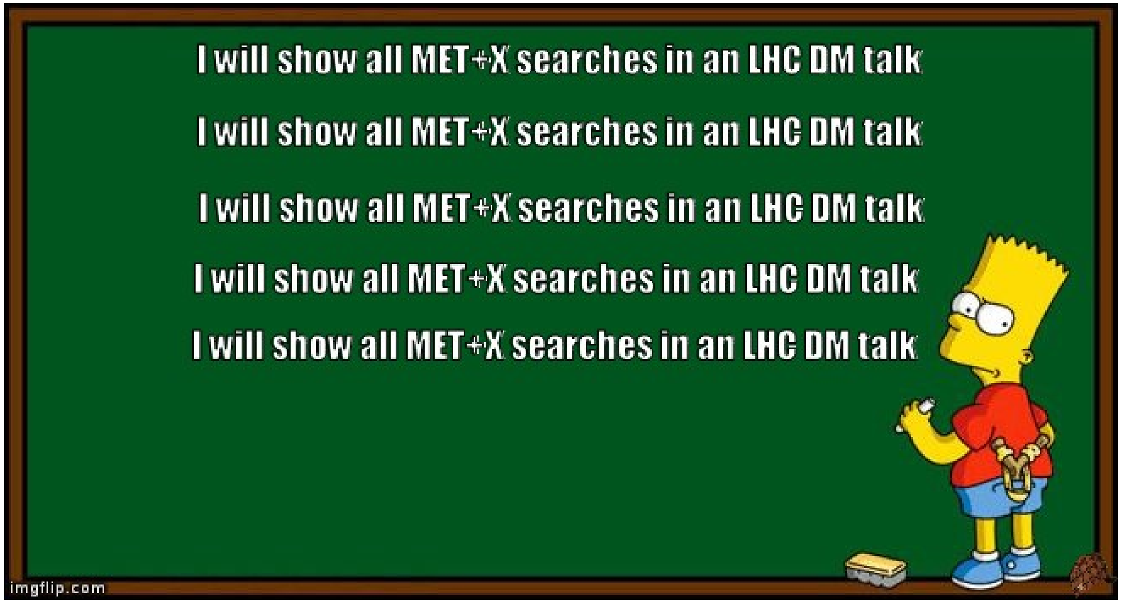
Recommendations on presenting LHC searches for missing transverse energy signals using simplified *s*-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]



arxiv://1603.04156, CERN-LPCC-2016-001

Recent ATLAS & CMS DM Results



Focusing on the hadronic search channels

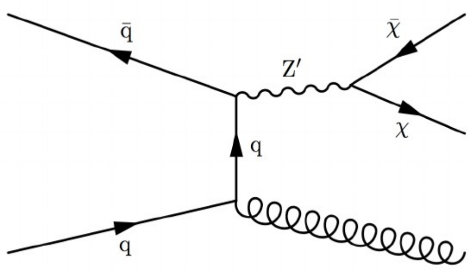
- Monojet, tt/bb + DM, dijet
- In the simplified model framework, these provide most of the DM reach at the LHC

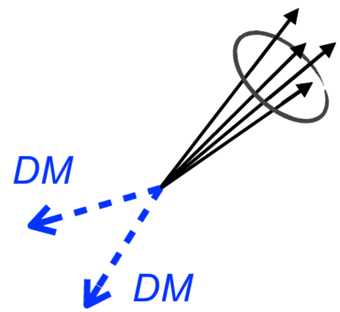
Complete list of recent results in the backups

Monojet

A generic & powerful DM search strategy at the LHC

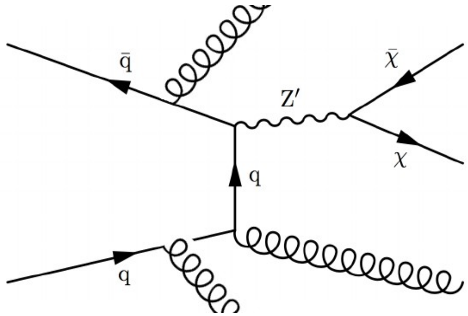
- Assumes only that DM couples in someway to incoming quarks
- Require energetic recoiling jet to trigger detector

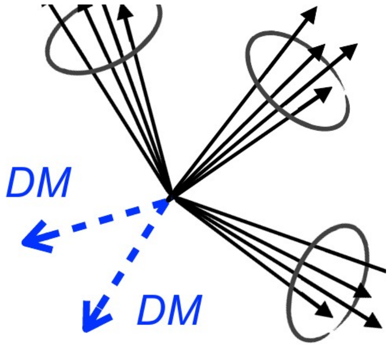




But no need to limit to a single recoiling jet ...

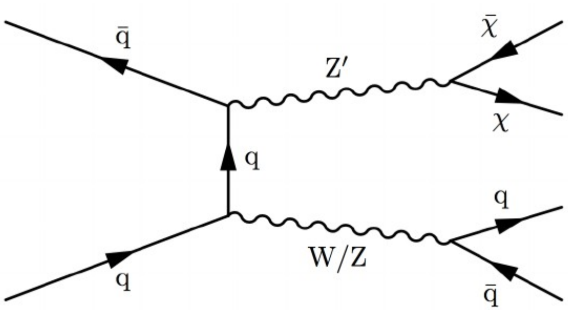
- The “monojet” search actually targets multijet + E_T^{miss} !

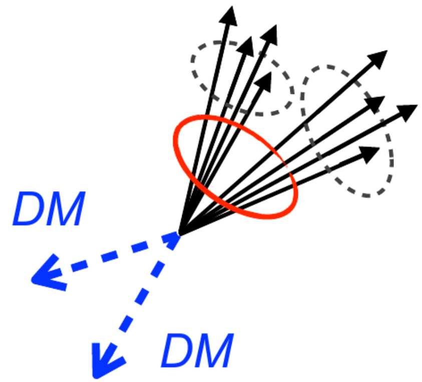


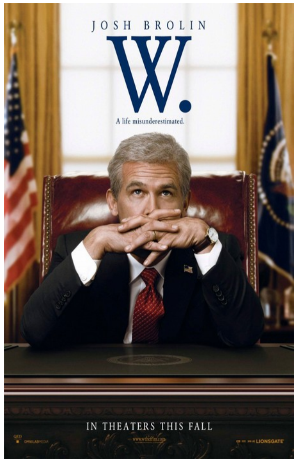


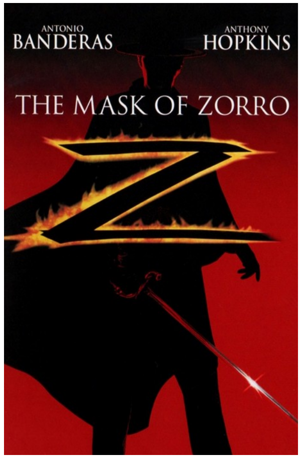
Monojet / Mono-V

DM + hadronic decays of EWK bosons can also produce a multijet + E_T^{miss} signature … mono-V

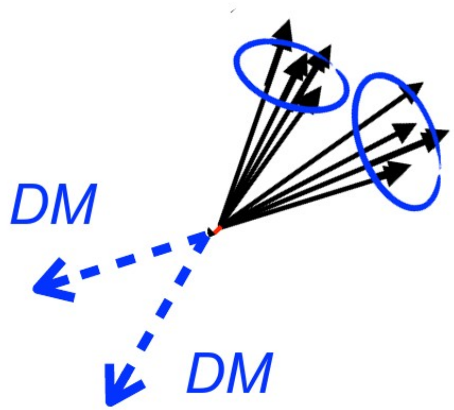






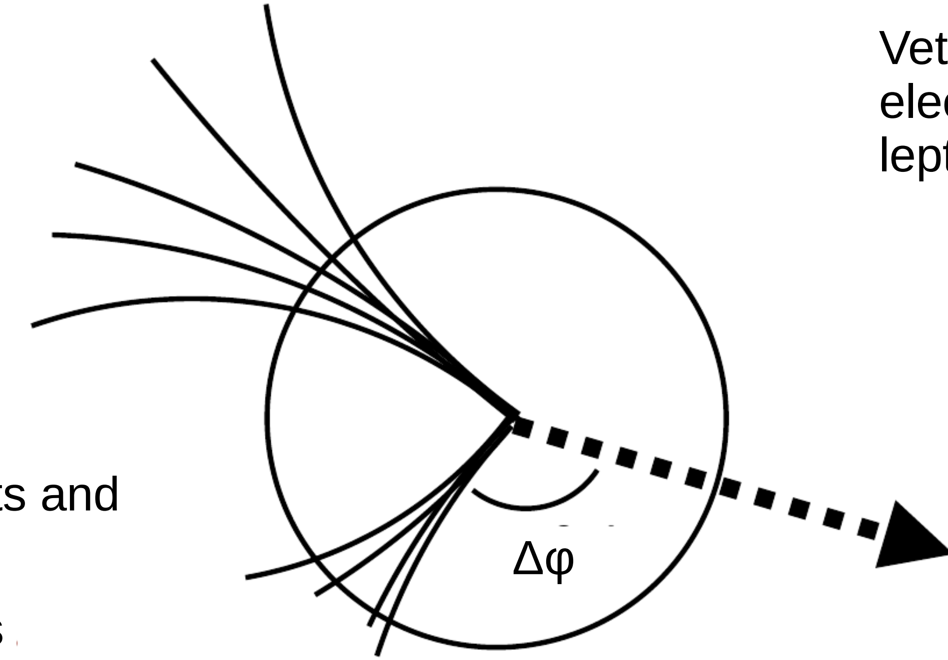


- W/Z decay products will be **boosted** when DM recoil is significant
- Reconstruction algorithms can merge these into a ~small radius jet
- But can use jet grooming / substructure techniques to identify the underlying 2-prong nature



Monojet : general strategy

At least one
central ($|\eta| < 2.4$),
good-quality,
high-pT (eg >250 GeV)
jet



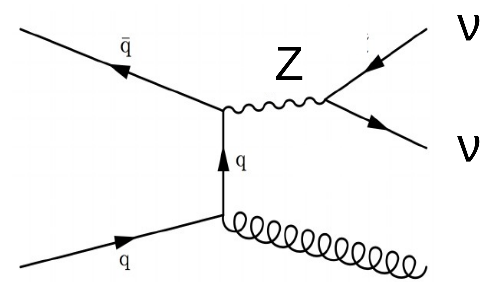
Veto additional objects:
electrons, muons, tau
leptons, photons, bjets ...

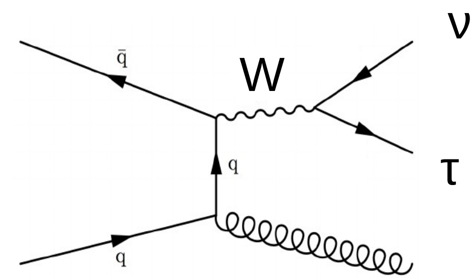
Require minimum Δφ separation between jets and E_T^{miss} to suppress misreconstruction BGs

Significant E_T^{miss}
(eg >200 GeV)

Dominant backgrounds from SM processes with real E_T^{miss} and/or leptons out of detector acceptance

- Z(νν) + jets, W(τ[qq'] ν) + jets, W(lν) + jets
- Bread & butter EWK processes @ the LHC
- Wealth of precise calculations & simulation tools available

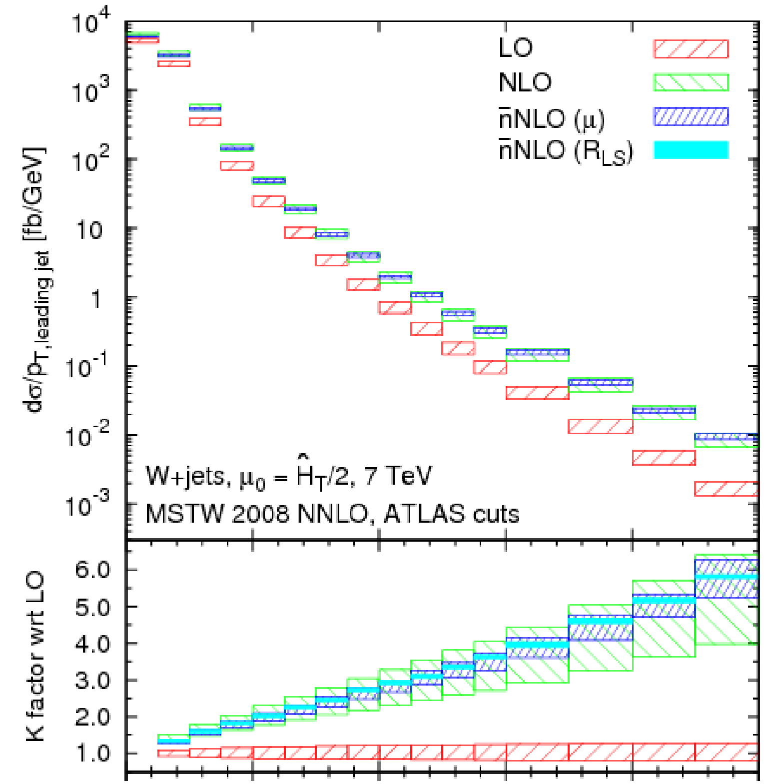


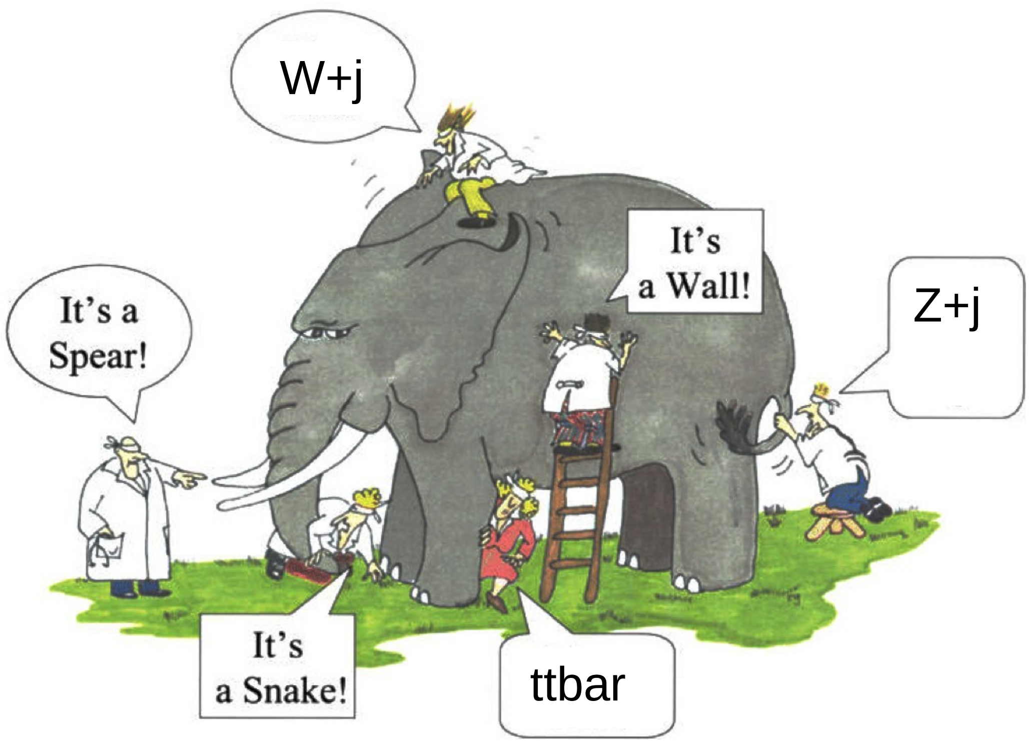


Monojet : general strategy

Selections define signal enriched regions (SR) in data

- Residual backgrounds in these regions from events in tails of E_T^{miss} kinematic distributions
- Associated SM theory uncertainties are typically large here ...





BG dominated control regions (CR) help constrain SM rates & kinematics in the SRs

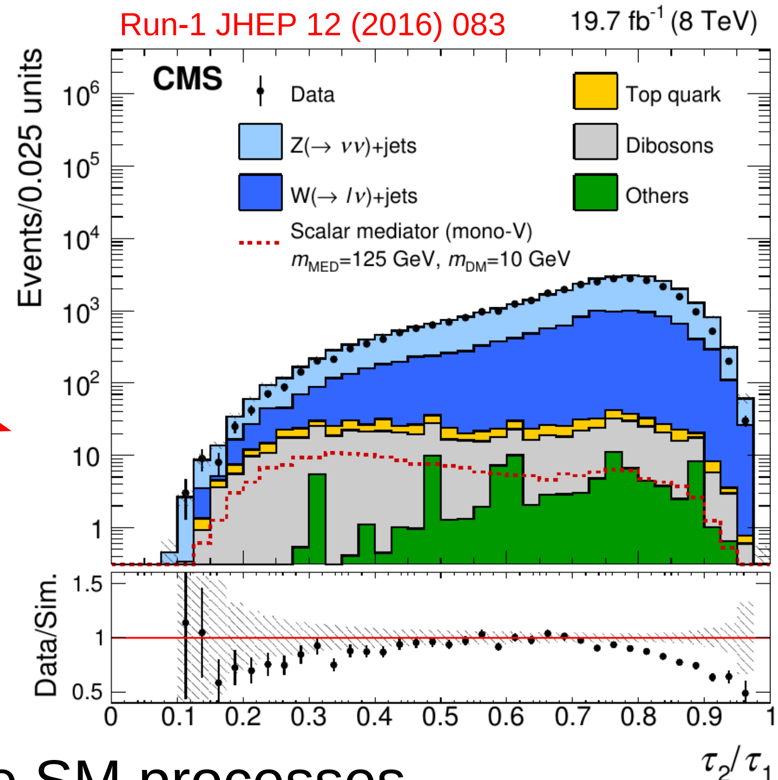
- *Augment* precise calculations of EW processes with measurements!

CMS Monojet / Mono-V

35.9 fb-1 : CMS-PAS-EXO-16-048, 12.9 fb-1: JHEP 07 (2017) 014, 1703.01651

SR selection : large E_T^{miss}, ≥ 1 high-p_T jet, Δφ > 0.5 radian

- Mono-V : p_T^{AK8}, E_T^{miss} > 250 GeV, m_{jj} 65-105 GeV, τ_{12} < 0.6 ("n-subjettiness")
- Mono-jet : remaining events, p_T^{AK4} > 100 GeV, E_T^{miss} > 250 GeV



5 (categorized) SM control regions to constrain high-E_T^{miss} BGs

- Use observable analogues of the invisible SM processes
  - Z(μμ), Z(ee), W(μν), W(eν) + jets, high-stat γ+jet
- Subtract visible signatures → hadronic recoil, a proxy for E_T^{miss}
- Use NLO QCD + NLO EWK calculations to translate rates + distributions in CRs into SR predictions!

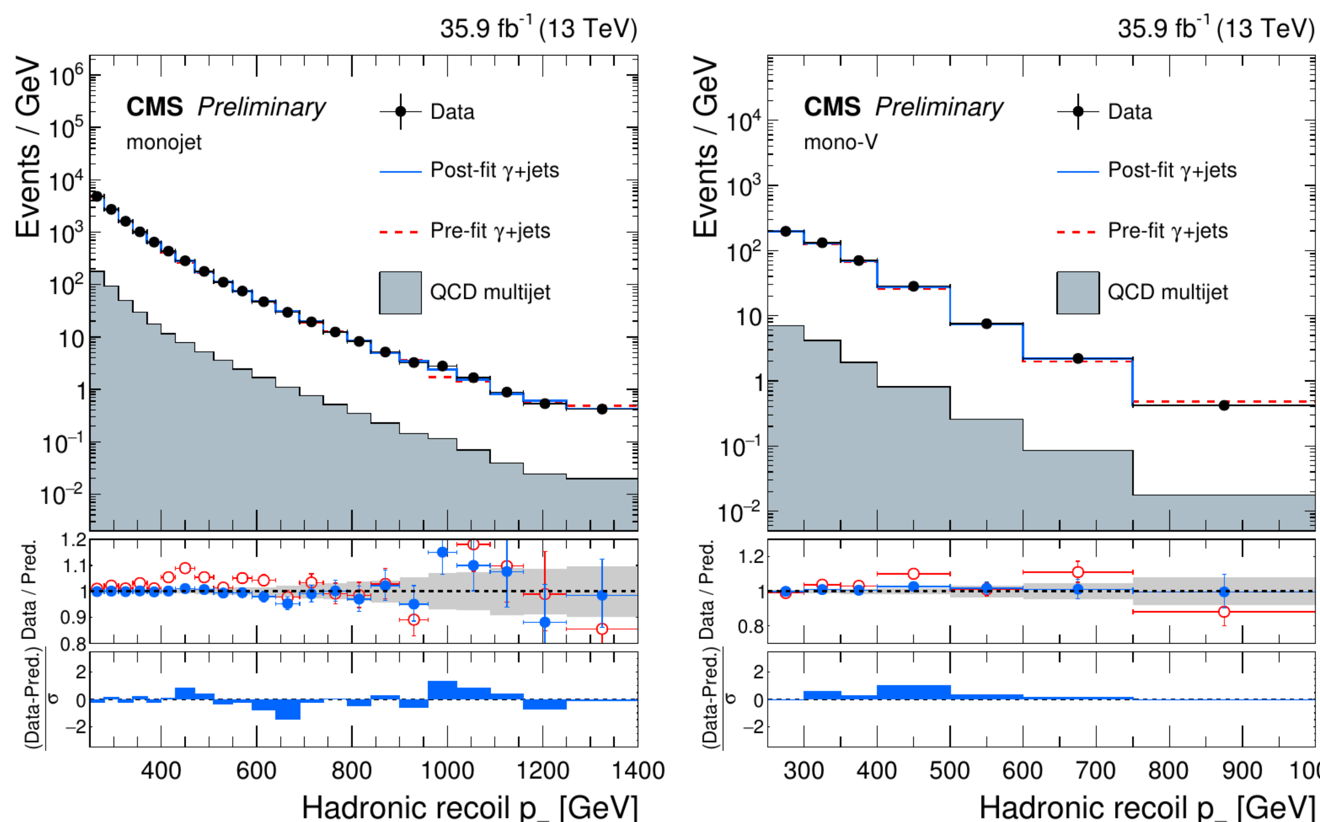
Extract signal from combined likelihood fit to E_T^{miss} distributions

Uncertainties & correlations on transfer factors (see 1705.04664)

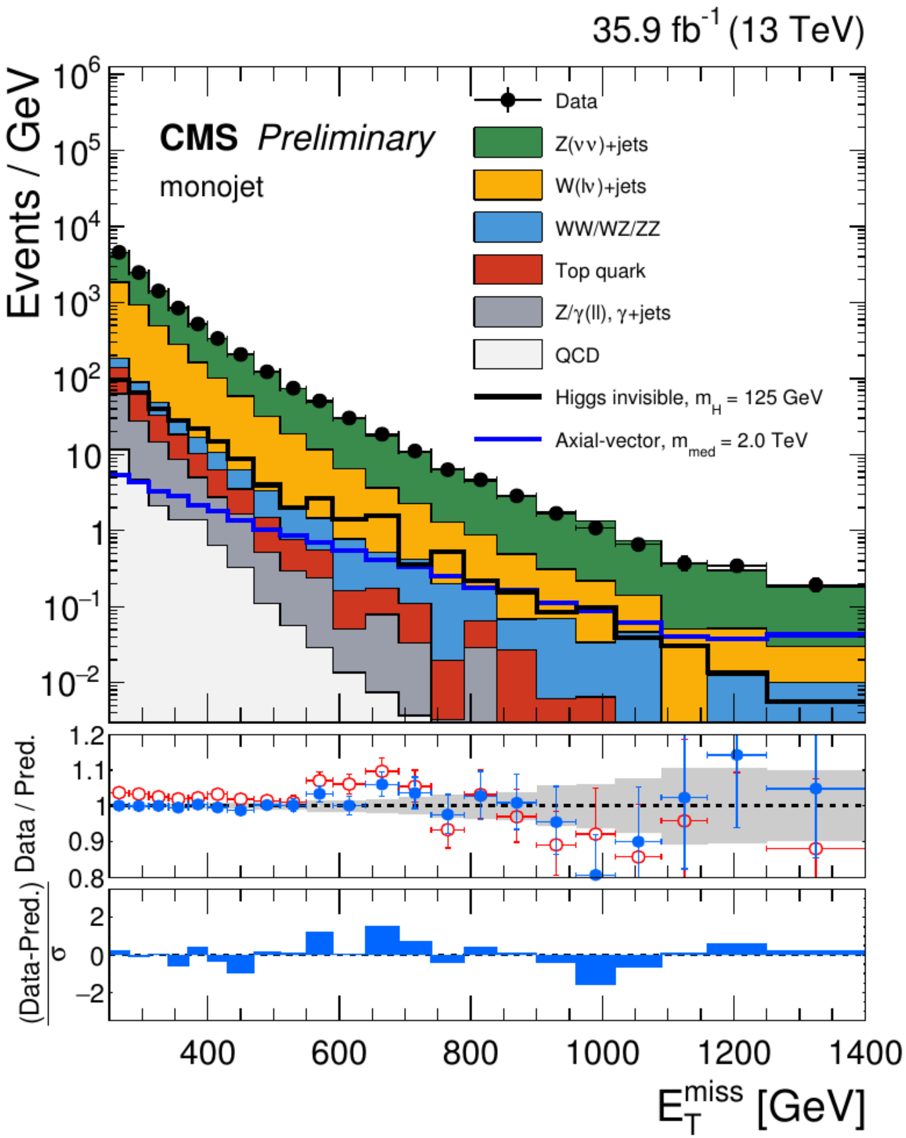
- Incorporated as nuisance parameters in the fit
- Pure QCD effects: scale/normalization, recoil shape pT dependence, cross section ratios
- Pure EWK effects: missing NNLO, unknown Sudakov logs, NLL Sudakov approximation
- Combined multiplicatively, nuisance added for possible non-factorization

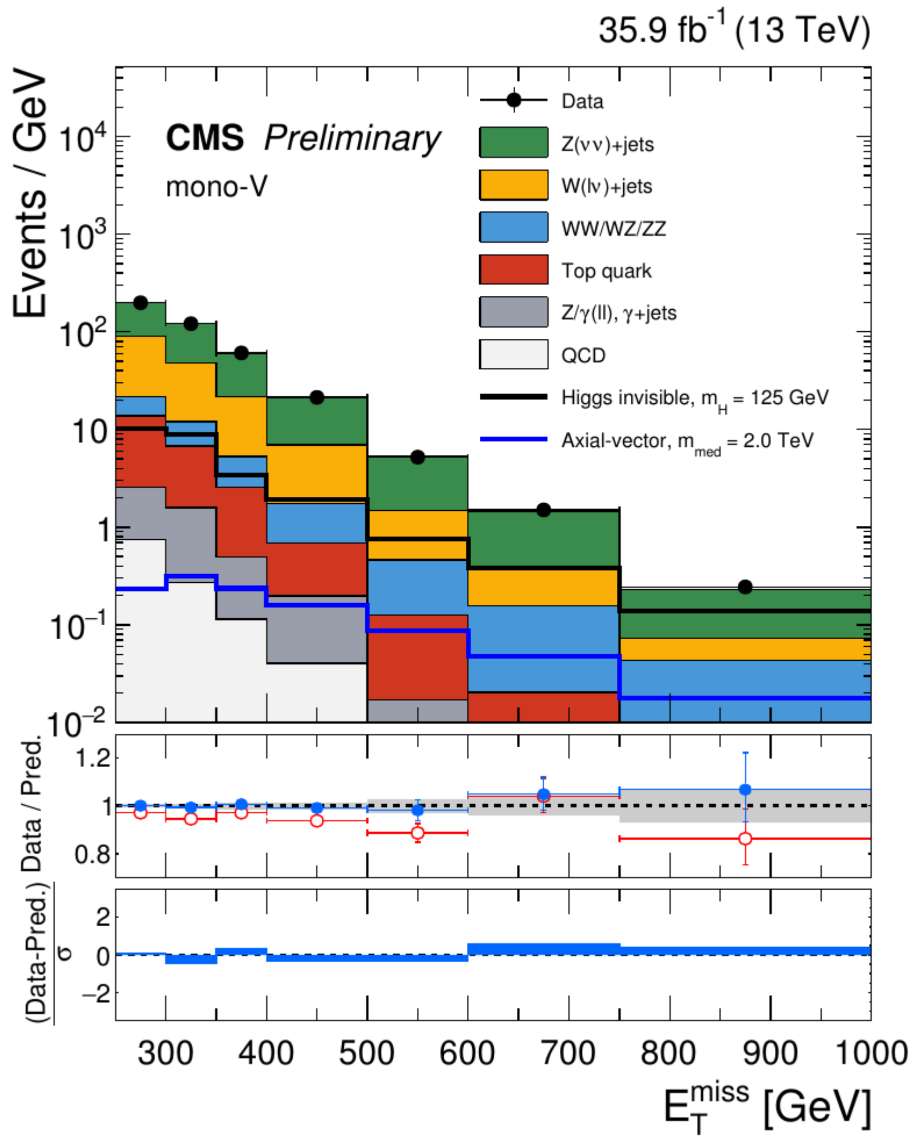
Control regions fit simultaneously with the signal regions

- Excellent post-fit agreement in CRs



Data in signal region consistent w/ post-fit SM expectations …

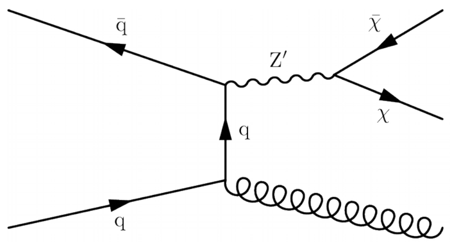


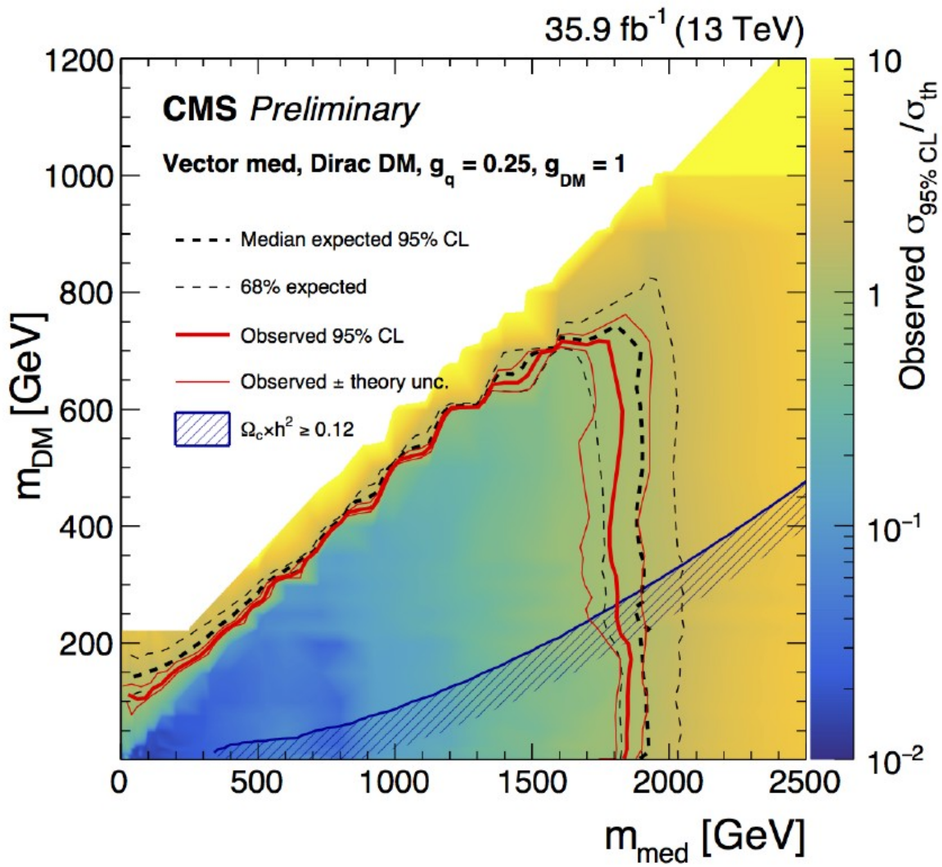


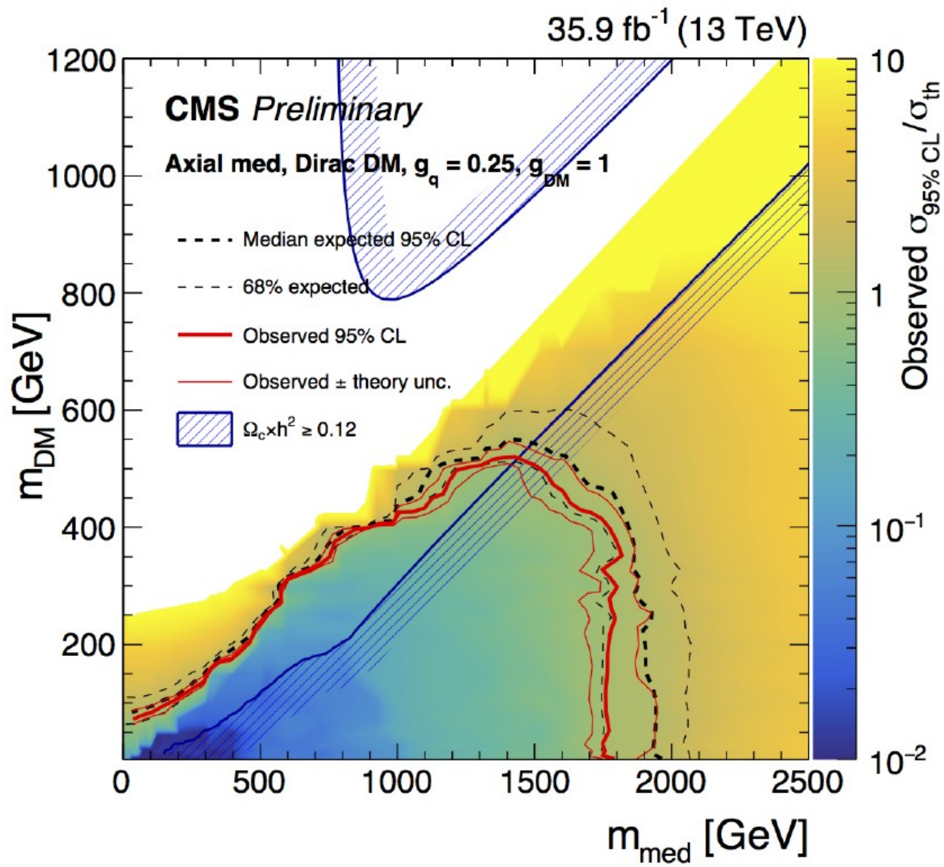
CMS Monojet / Mono-V

Limits on both spin-1 and spin-0 mediators

- Vector/Axial exclusion (this slide) up to 1.8 TeV
- Pseudoscalar (backup) up to 400 GeV

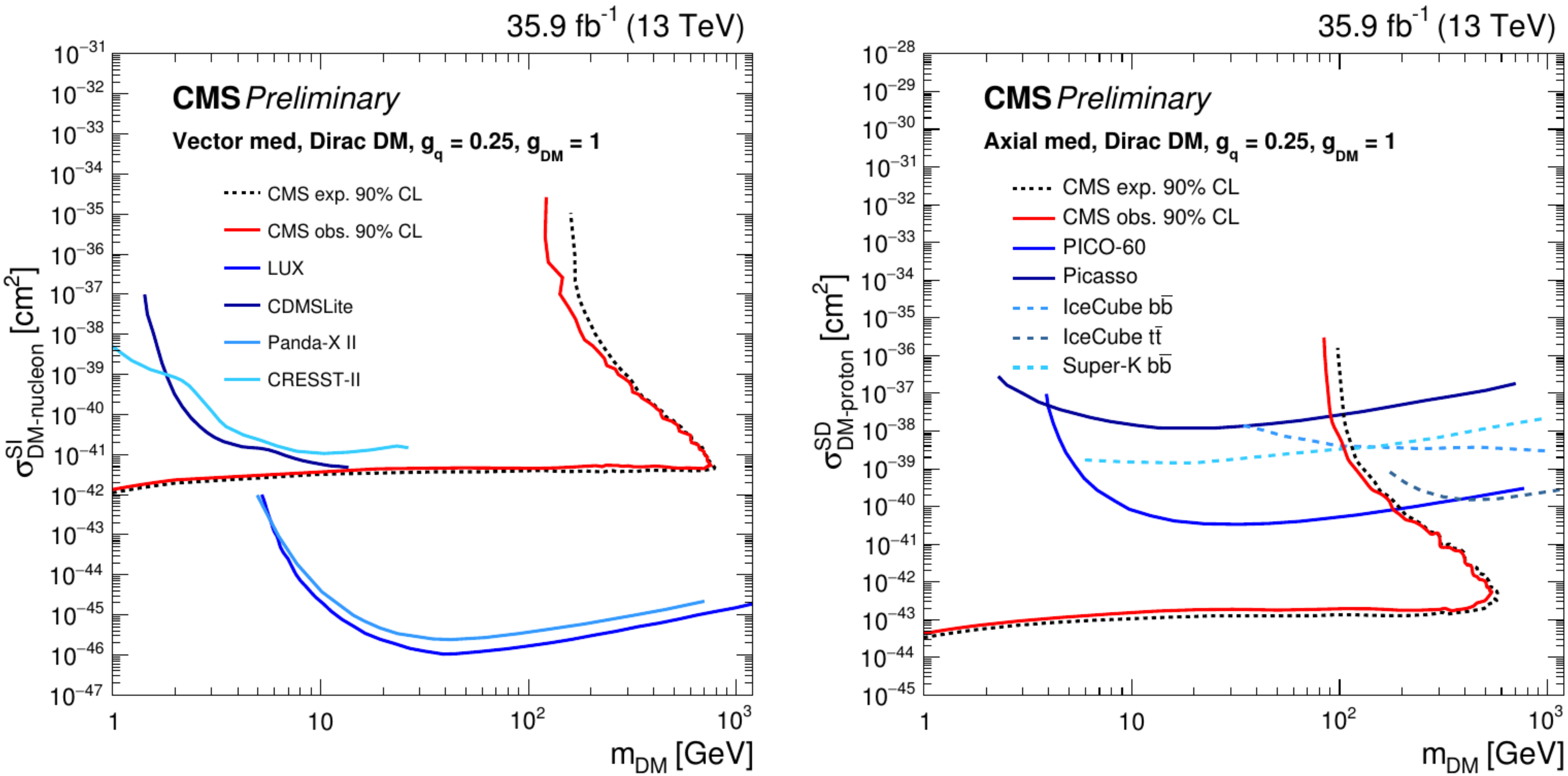






Reinterpret as invisible Higgs : BR(h→inv.) < 0.53 (0.4 exp.)

And recast as limits on SI/SD DM-nucleon cross section (1603.04156)

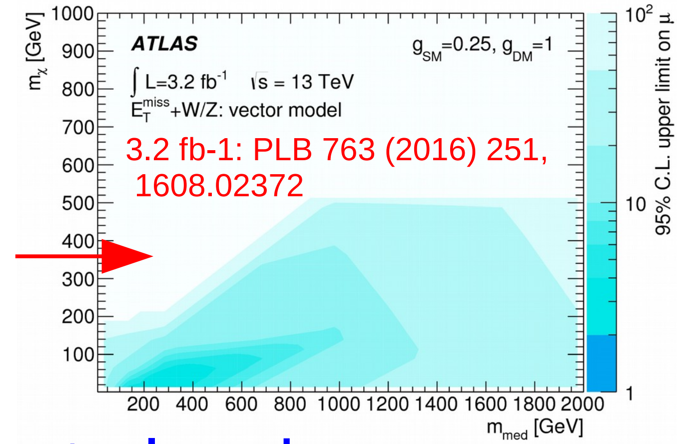


Low-mDM reach complementary to direct detection!

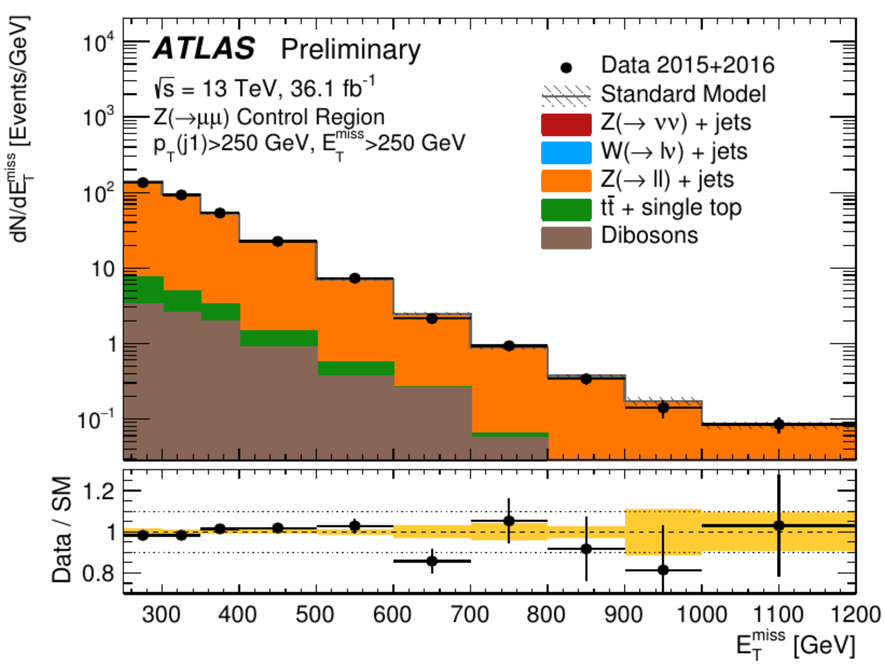
36.1 fb-1 : ATLAS-CONF-2017-060, 3.2 fb-1: PRD 94 (2016) 032005, 1604.07773

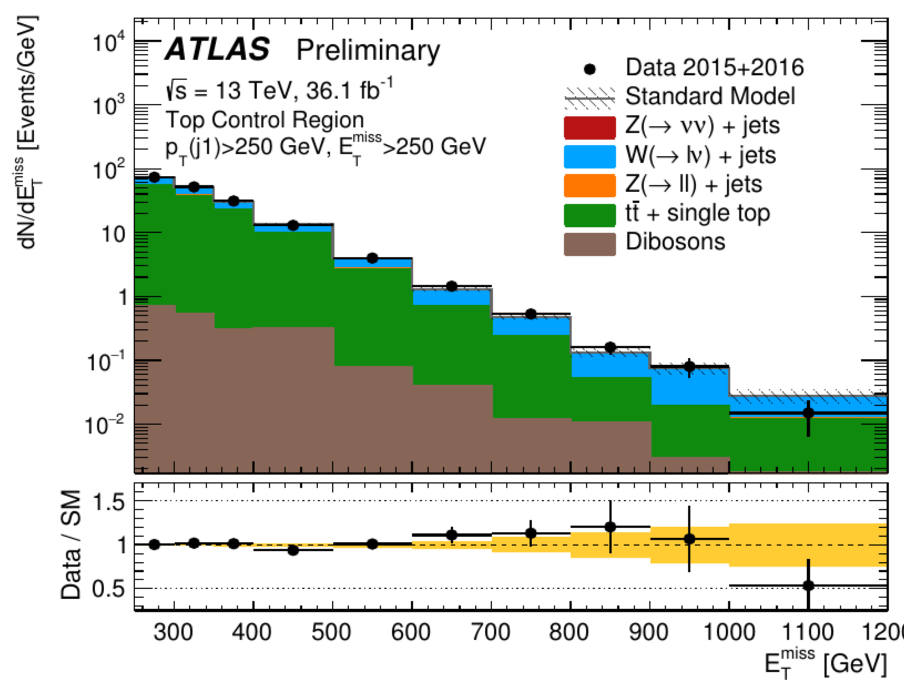
Similar monojet search strategy pursued in ATLAS:

- p_T^{AK4} , E_T^{miss} > 250 GeV, Δφ > 0.4 radian, vetos
- Simultaneous binned likelihood fit to E_T^{miss}
- No mono-V category, dedicated mono-W search
- No Z(ee) + jets, γ+jets CRs, adds ttbar CR



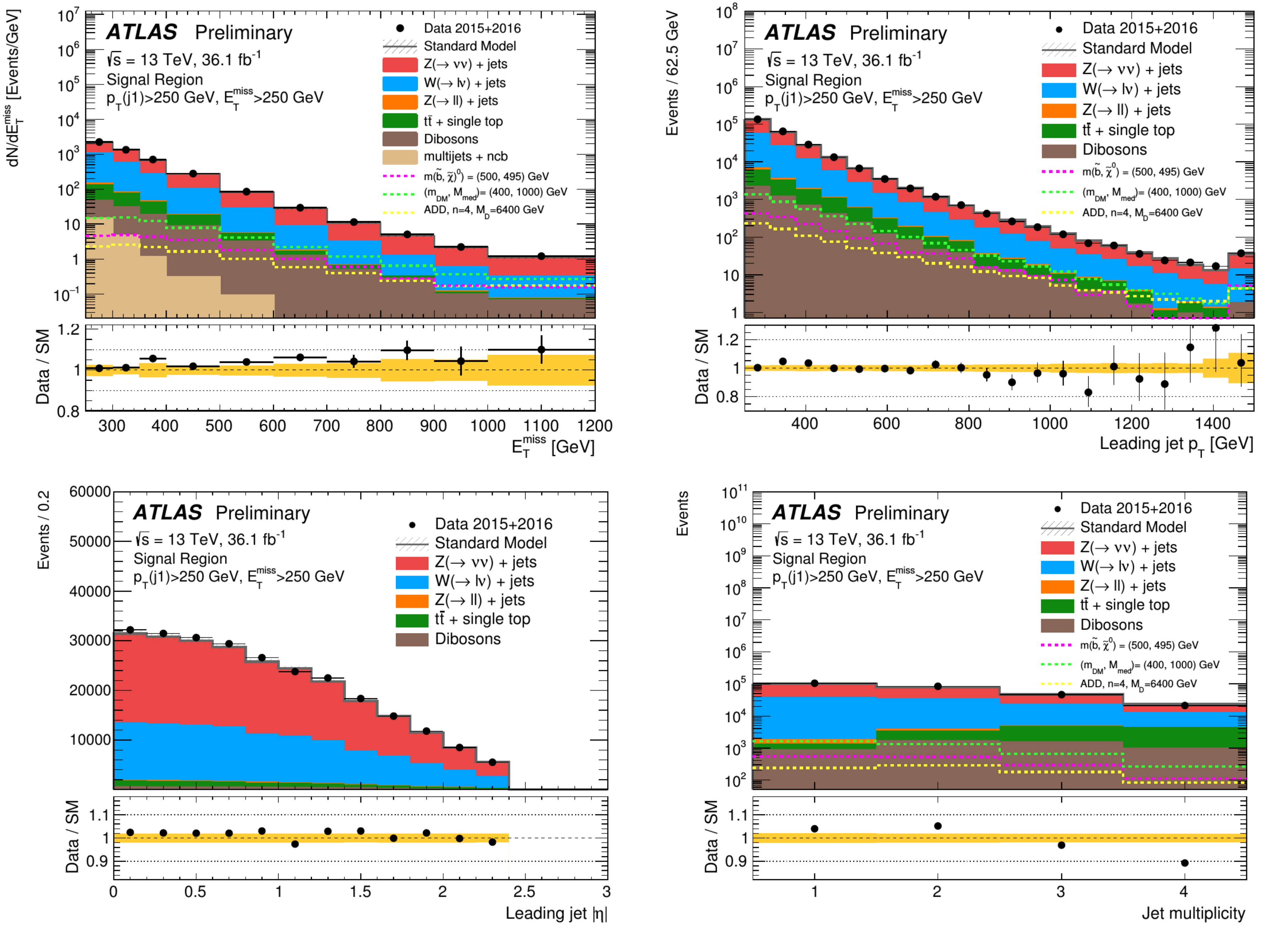
Good agreement in Z(ll)+jets & W(lν)+jets control regions





ATLAS Monojet

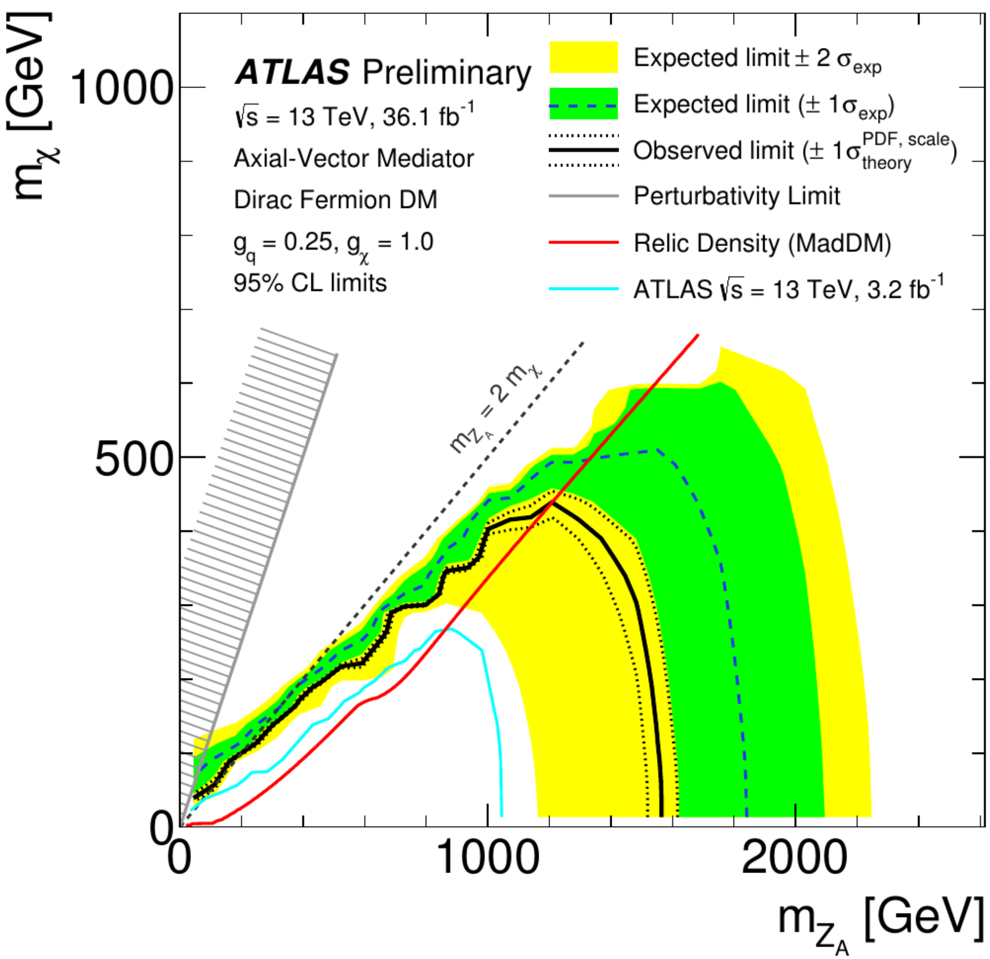
And good agreement in the signal region ...

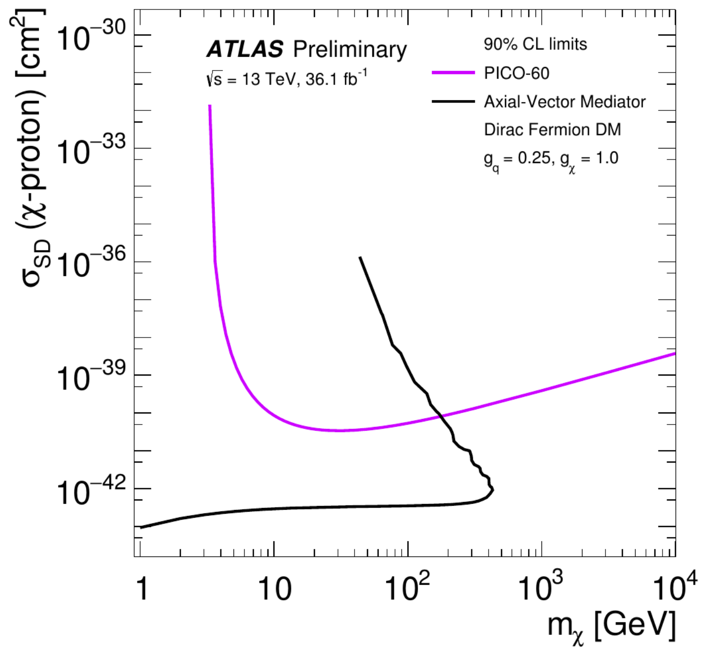


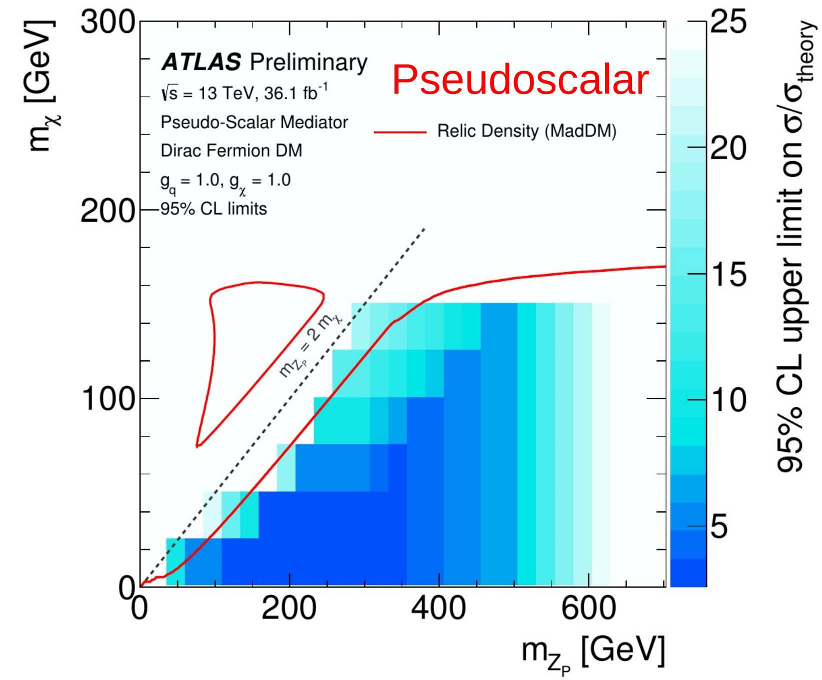
ATLAS Monojet

Limits on both spin-1 and spin-0 mediators

- Axial-vector exclusion up to 1.55 TeV
- Not yet sensitive to pseudoscalars

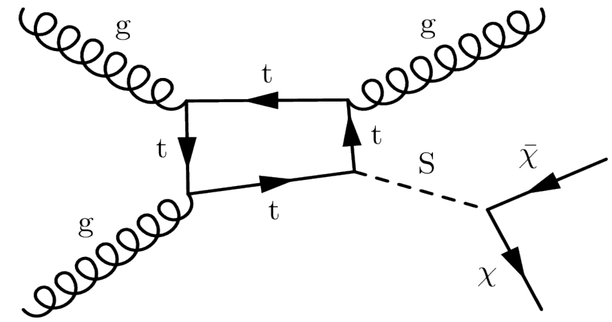


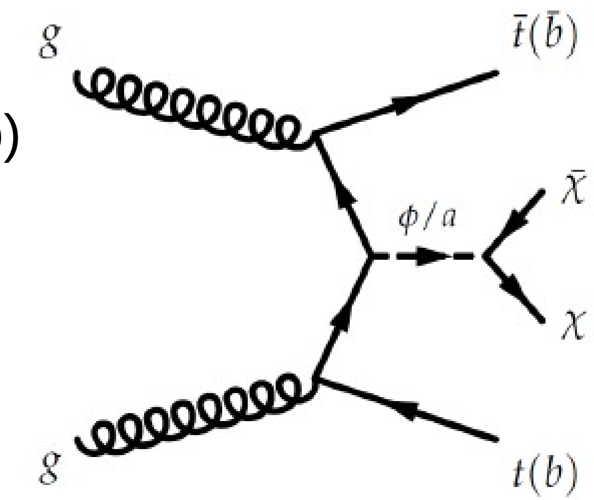




Monojet drives sensitivity to spin-1 mediator scenarios

- Picture more nuanced for spin-0 models ...
  - MFV → mediator has Yukawa coupling
  - Monojet through heavy quark loops
- Implies tree-level couplings to top and bottom
  - Same mediator as in monojet
  - Yukawa enhancement → tt+DM competitive with monojet at low mMed!
- Can also anticipate a "monotop" signature …
  - Assumes specialized signal model (see backup)





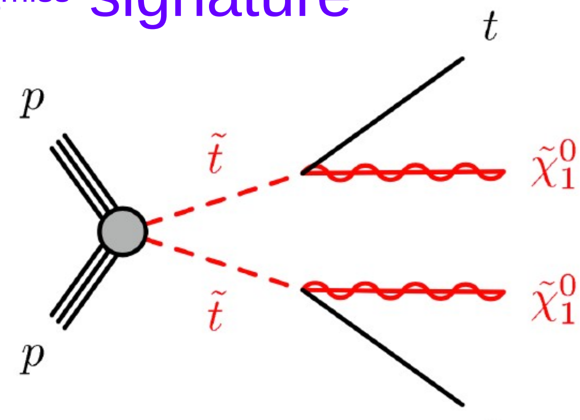
DM+ heavy quarks = rich signatures!

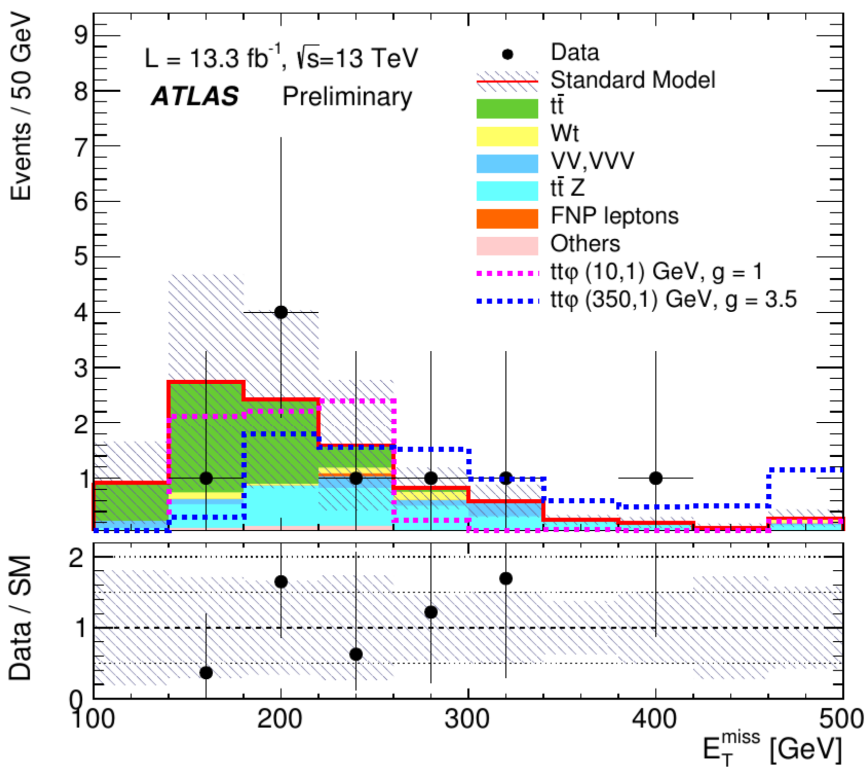
- tt final states: all-hadronic, semileptonic, dileptonic
  - Produces leptons, high-pT jets, b jets, E_T^{miss}
- Many experimental handles → many viable DM search strategies

Backgrounds : mostly SM ttbar (with a lost lepton), single top, ttV

SUSY stop searches also looking for the tt+E_T^{miss} signature

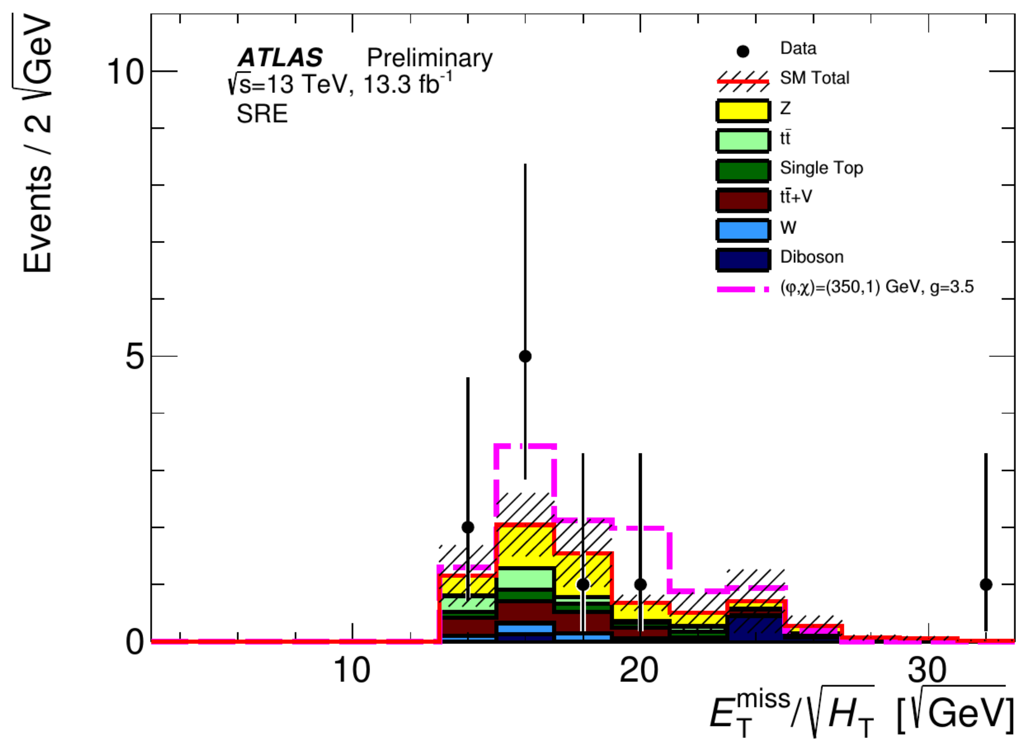
- These generally involve many SRs & CRs to explore wide range of SUSY scenarios
- Leverage SUSY observables (eg: mT2) optimized for selecting E_T^{miss} from decays of heavy particles
- Extend SUSY search with regions that target DM production, add DM interpretation





ATLAS-CONF-2016-076 (13.3 fb-1)

ttbar (dilepton) + E_T^{miss}



ATLAS-CONF-2016-076 (13.3 fb-1)

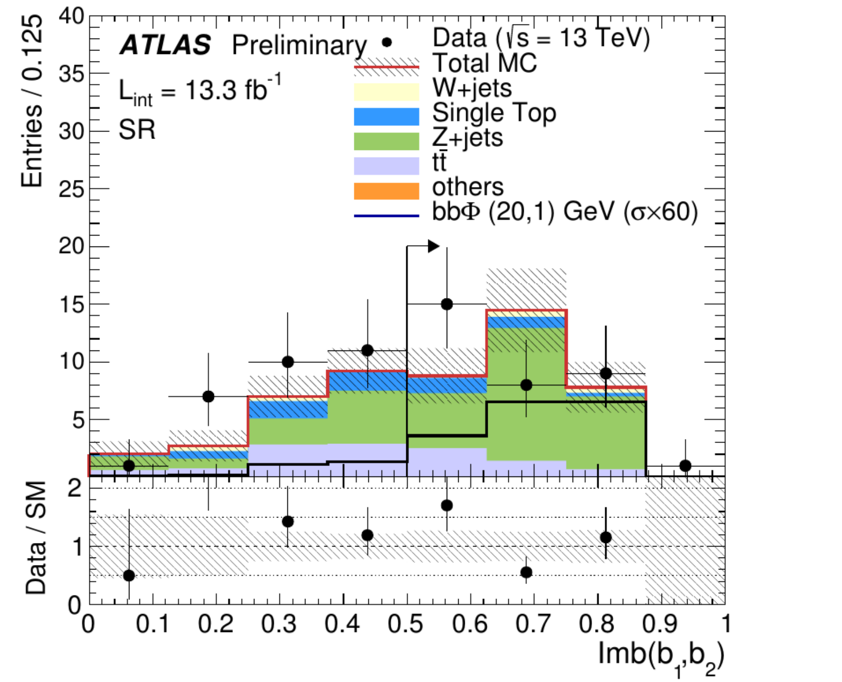
ttbar (dilepton) + E_T^{miss}

ATLAS tt/bb + DM

ATLAS-CONF-2016-086 (13.3 fb-1)

Dedicated bb+E_T^{miss} search

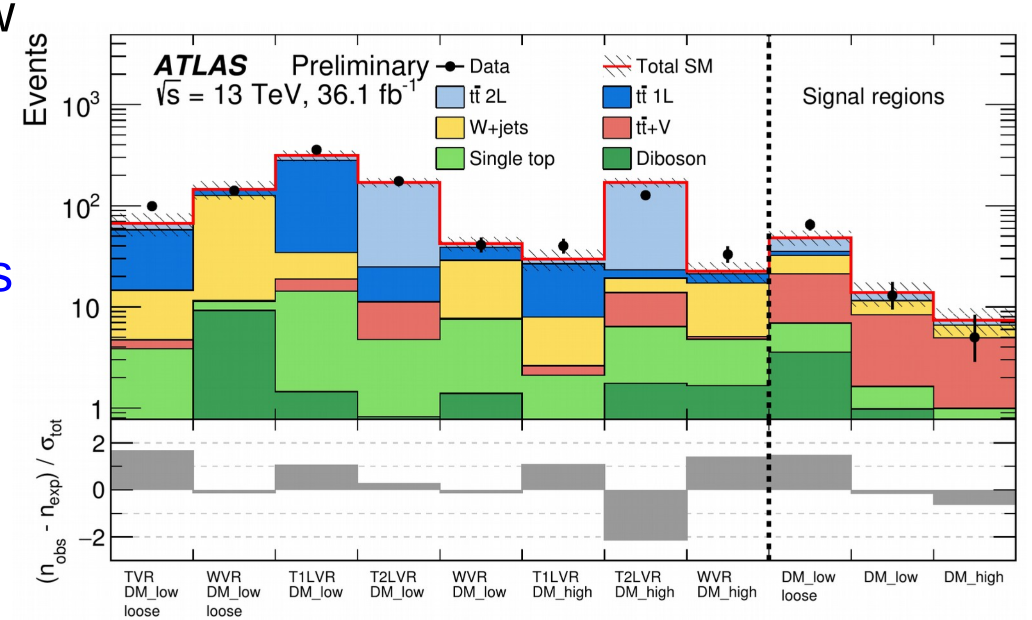
- Sensitive to models (eg: 2HDM w/ large tanβ) in which coupling to down-type quarks enhanced
- Select events with large pT imbalance between 2 high-pT b-tagged jets
- 3 CRs to control Z+jets, W+jets and ttbar



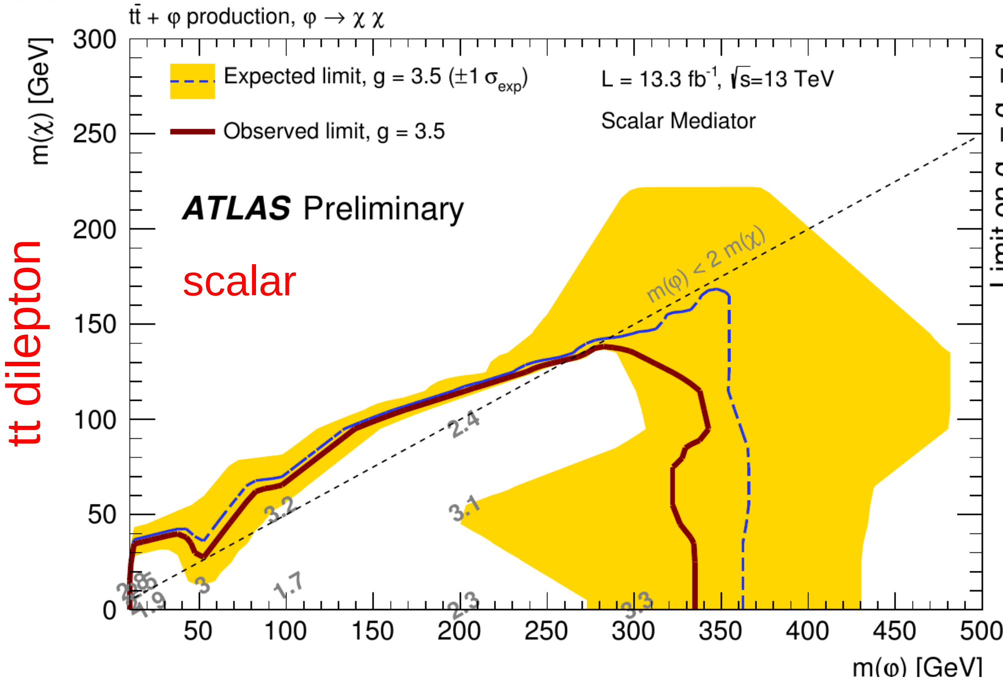
ATLAS-CONF-2017-037 (36.1 fb-1)

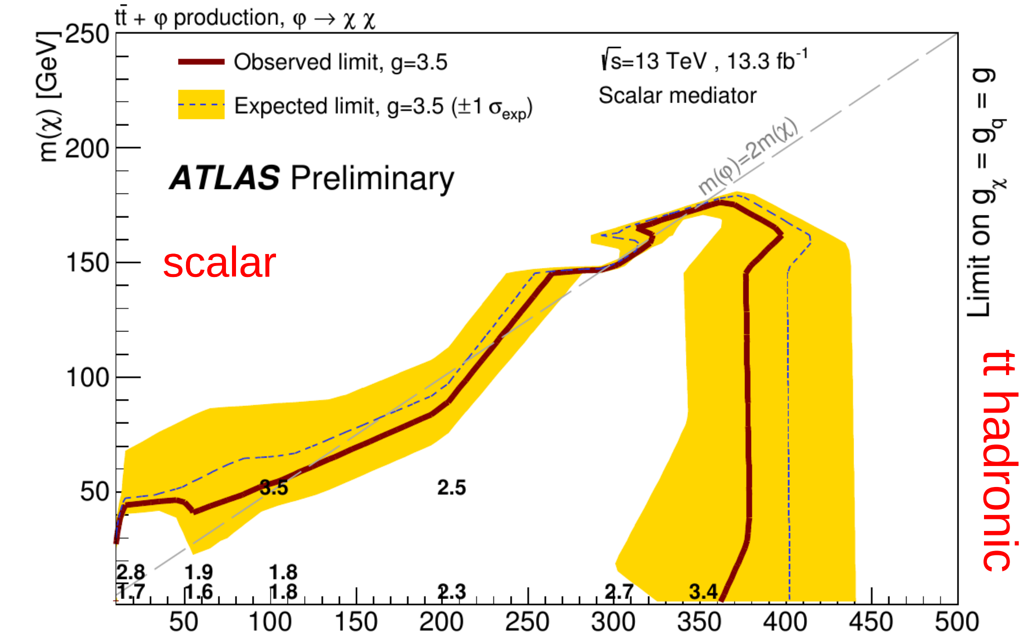
Update: tt(semileptonic)+E_T^{miss} search

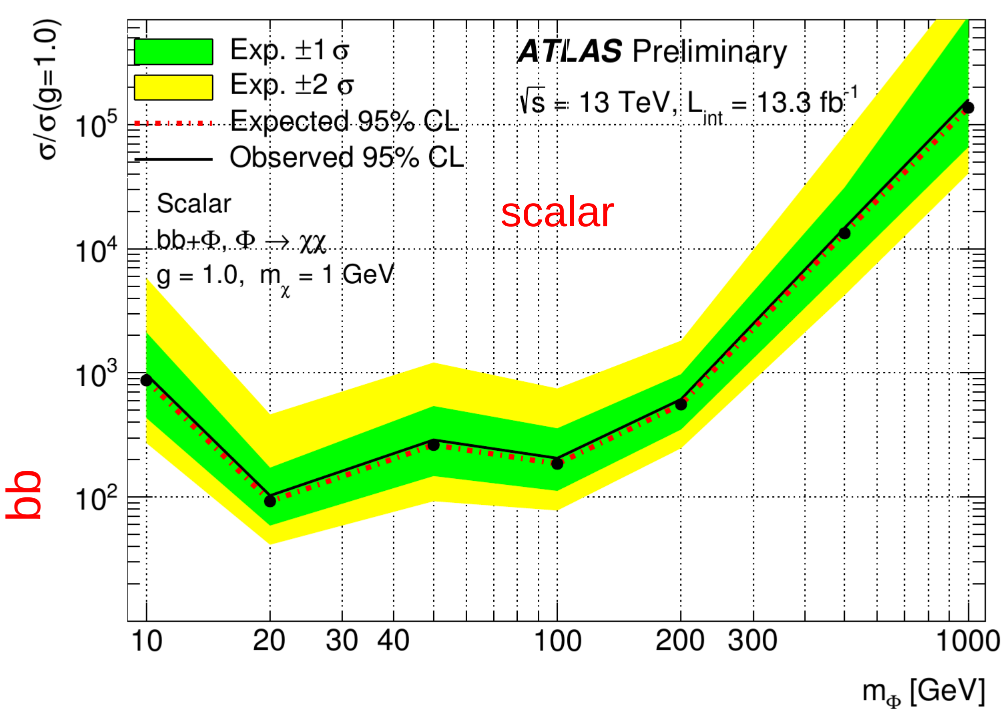
- DM categories provide sensitivity to low (~20 GeV) and high (~300 GeV) mass DM mediators
- New SRs use boosted top-tagging discriminant to identify hadronic decays of high-pT top quarks
- ttbar normalized via CR fit, signal extraction from 3 bin cut & count analysis

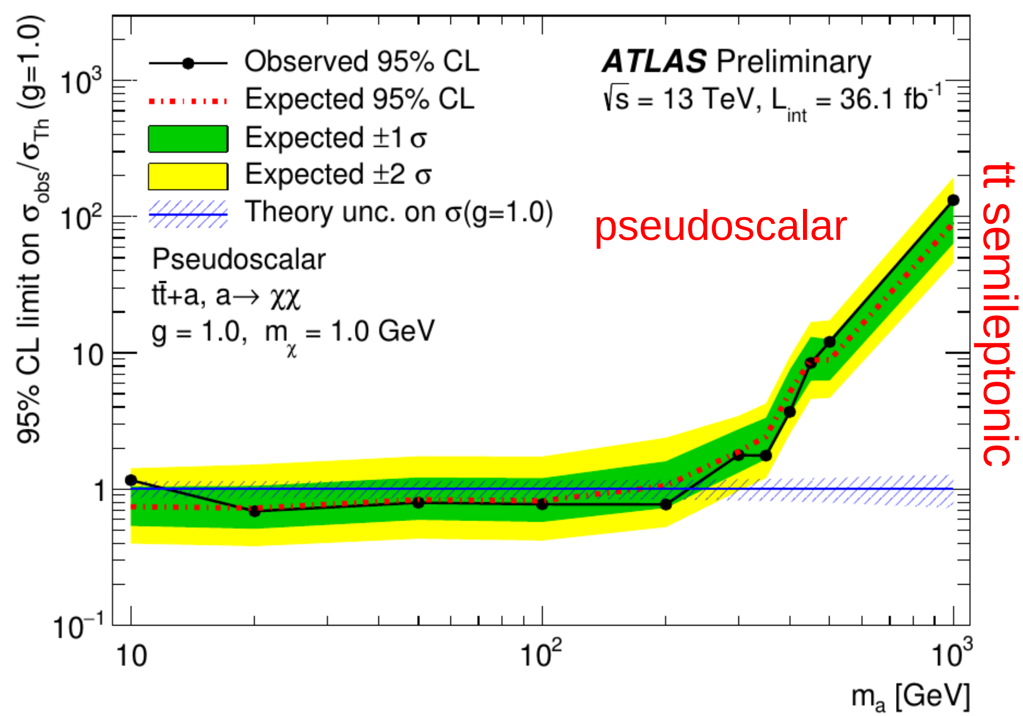


ATLAS tt/bb + DM Limits

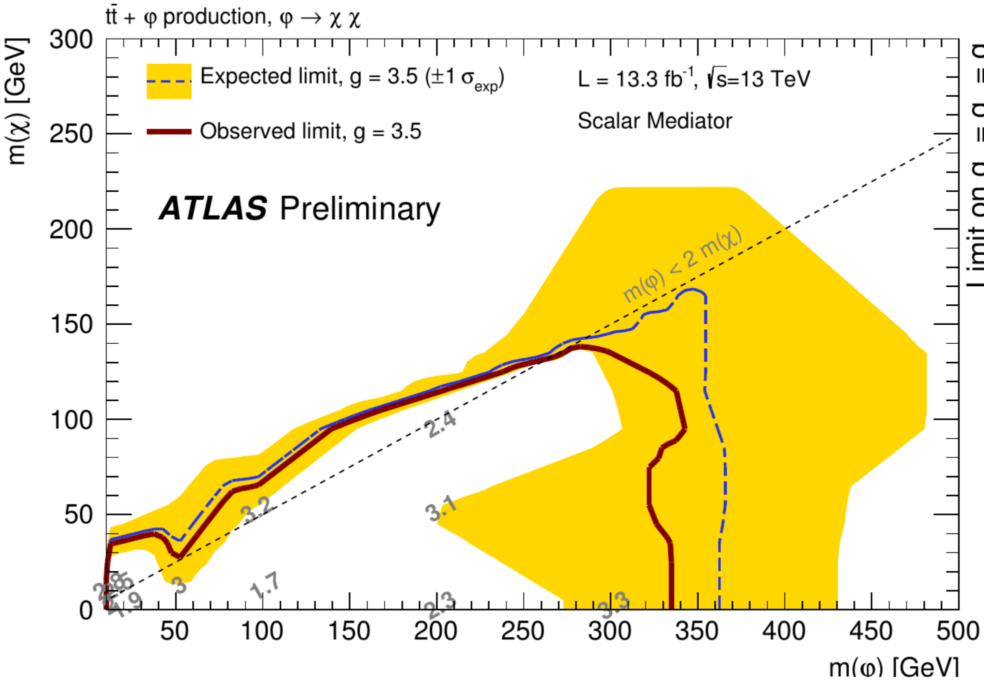


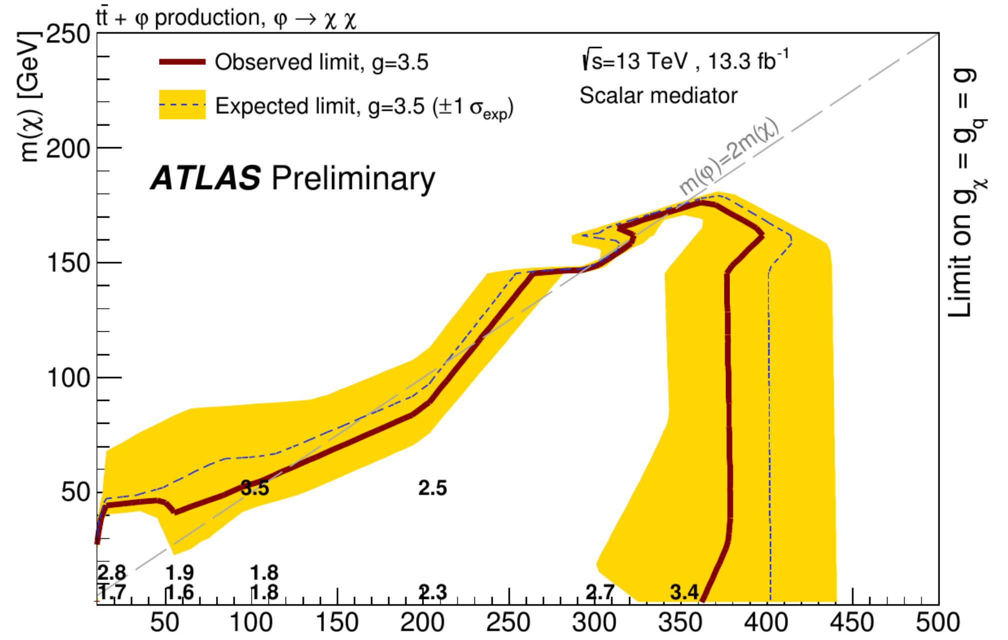


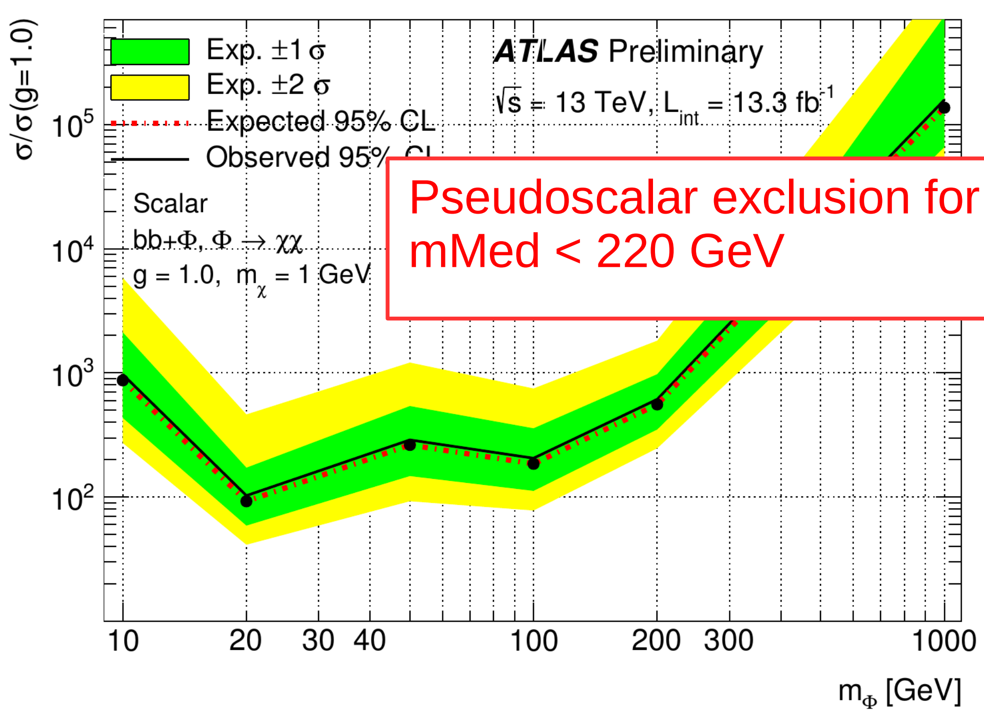




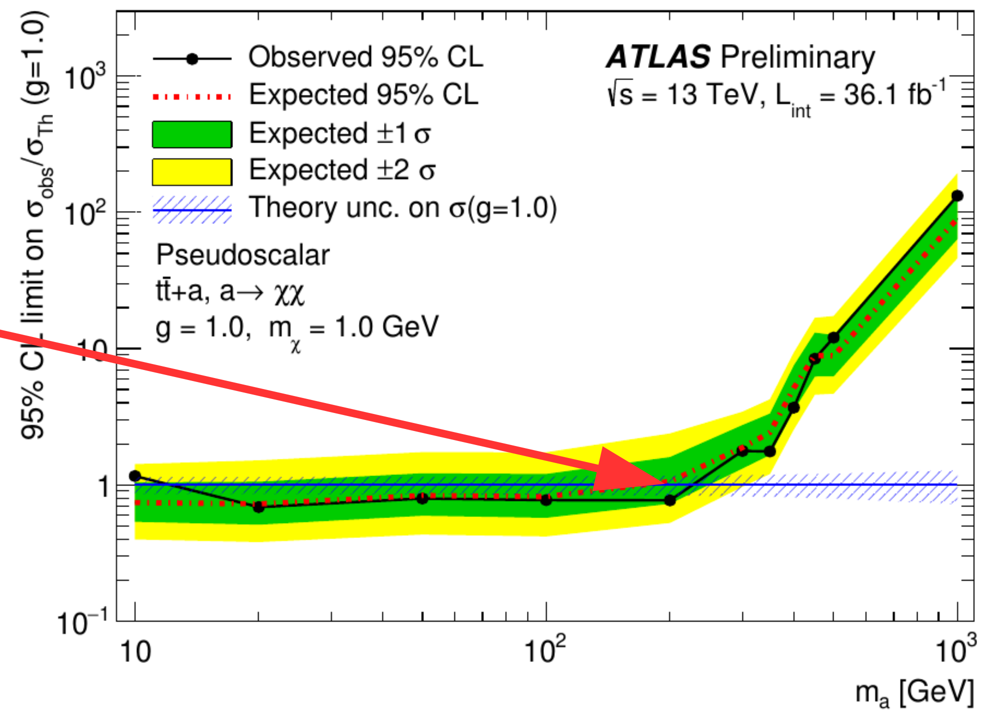
ATLAS tt/bb + DM Limits







Pseudoscalar exclusion for mMed < 220 GeV



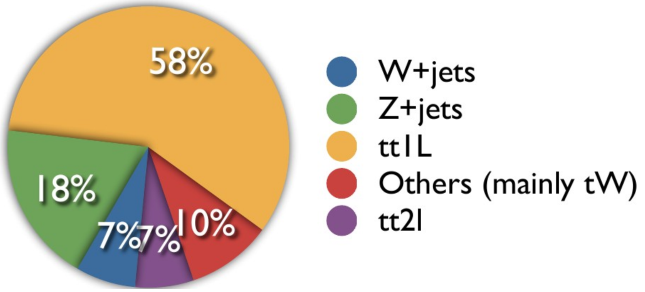
CMS tt/bb + DM

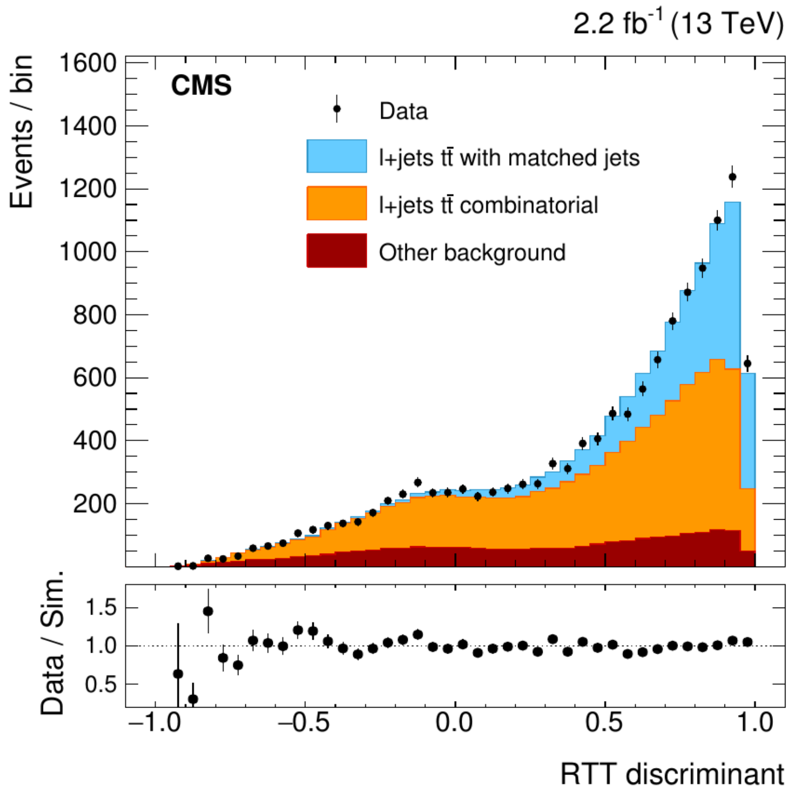
2.2 fb-1 : 1706.02581, CMS-PAS-EXO-16-005, CMS-PAS-EXO-16-028

Combined search using all tt+E_T^{miss} and bb+E_T^{miss} channels

- E_T^{miss} > 200 for bb & all-hadronic tt, E_T^{miss} > 160 GeV for semileptonic tt, E_T^{miss} > 50 GeV for dileptonic tt
- Employs novel *resolved* top quark tagger to reconstruct low/moderate pT hadronic decays
  - Top pT is soft in for mediator masses for which there is LHC sensitivity
  - BG from SM tt with missing lepton
  - Categorize signal and bkg according to number of top tags
- Simultaneous E_T^{miss} fit using 8 SRs + 19 CRs

BG yields in all-hadronic tt+DM



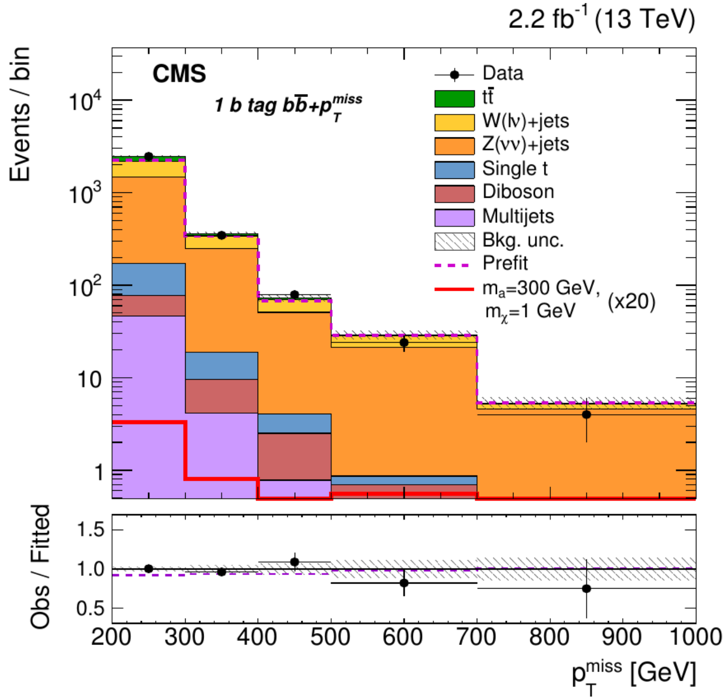


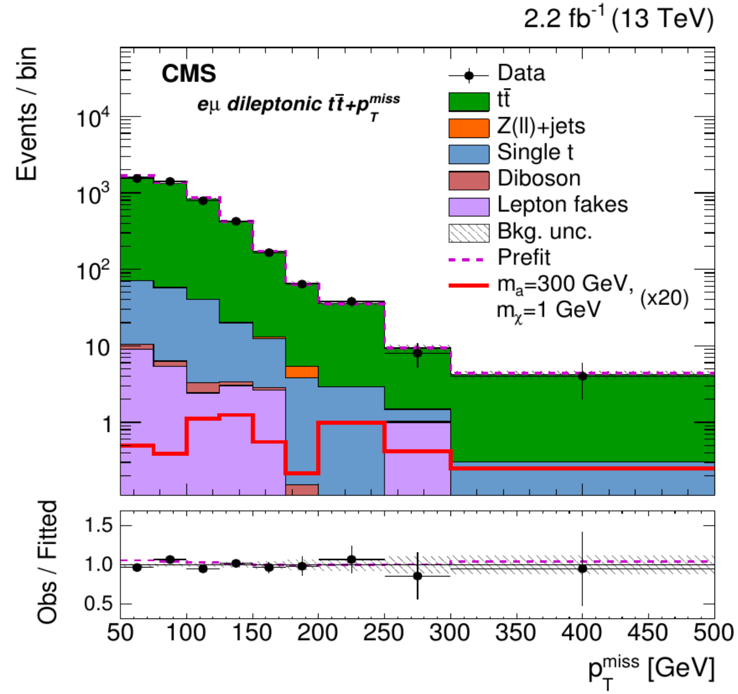
Search uses just 2.2 fb-1 from Run2

- Analysis of full 35.9 fb-1 in progress

CMS tt/bb + DM

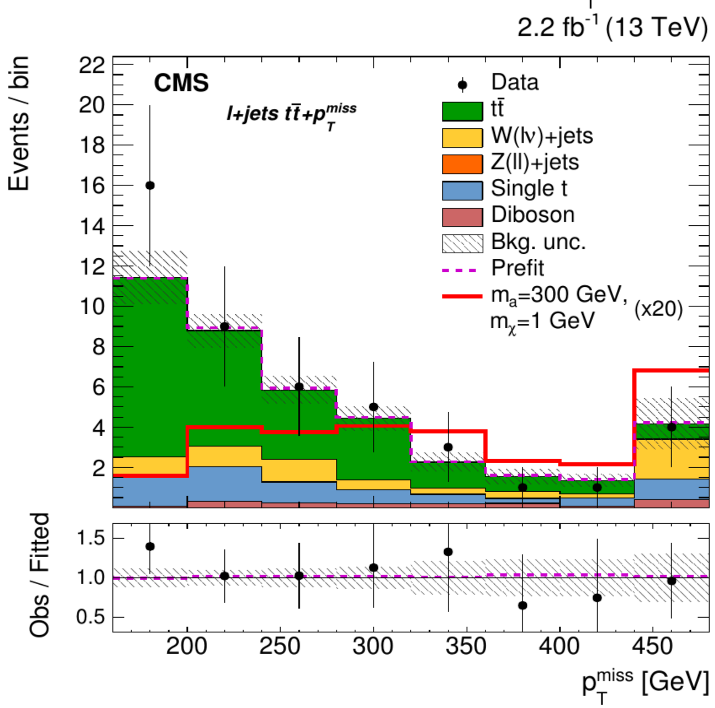
bb signal region

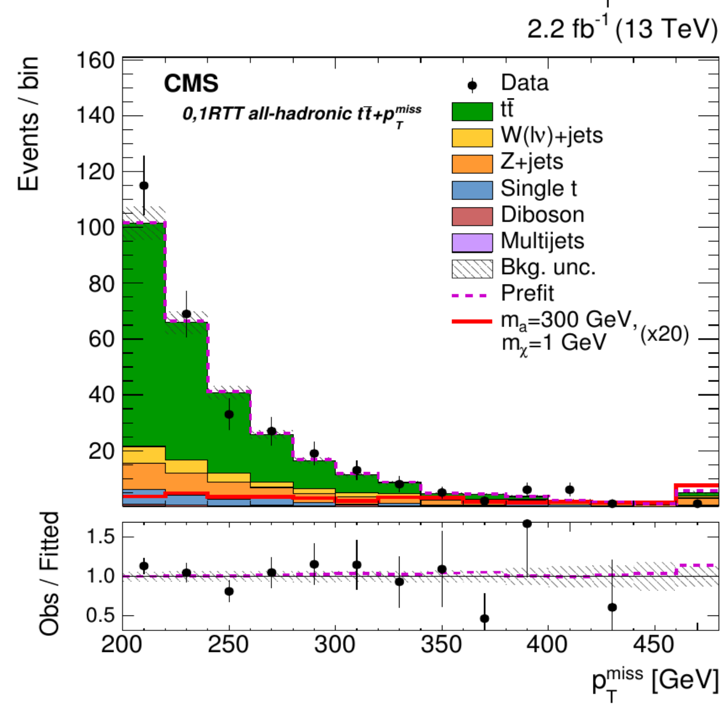




dileptonic eμ signal region

semileptonic signal region

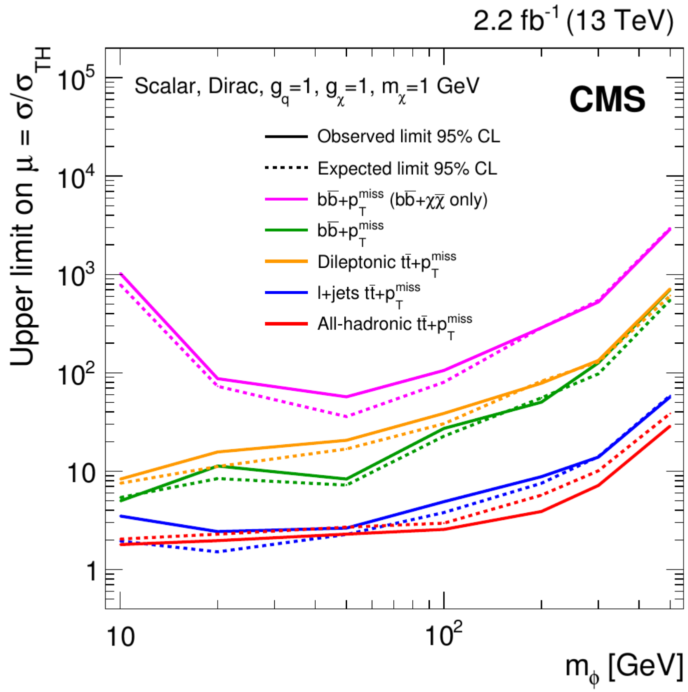




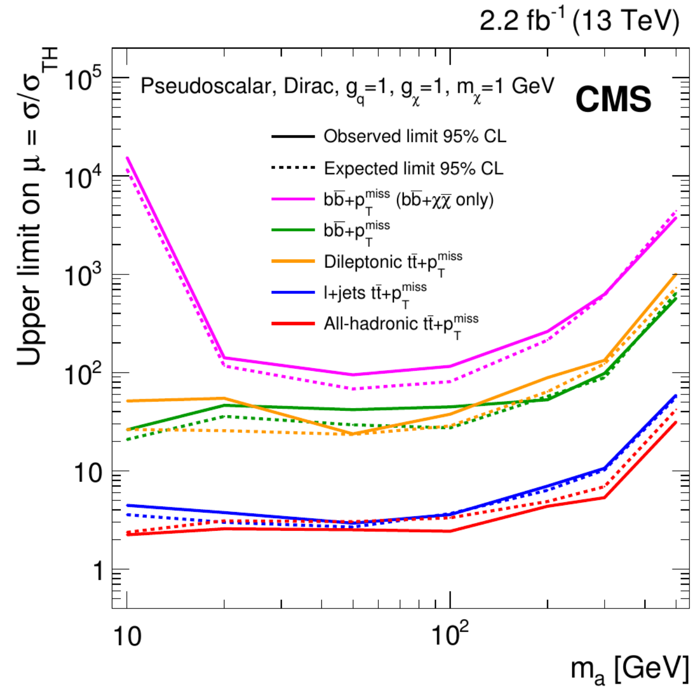
all-hadronic 01RTT signal region

CMS tt/bb + DM Limits

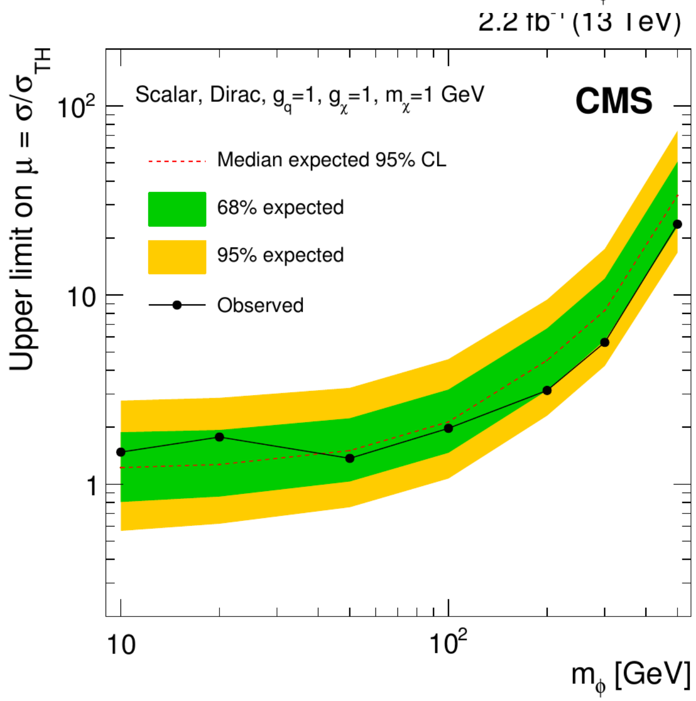
Per-channel, scalar



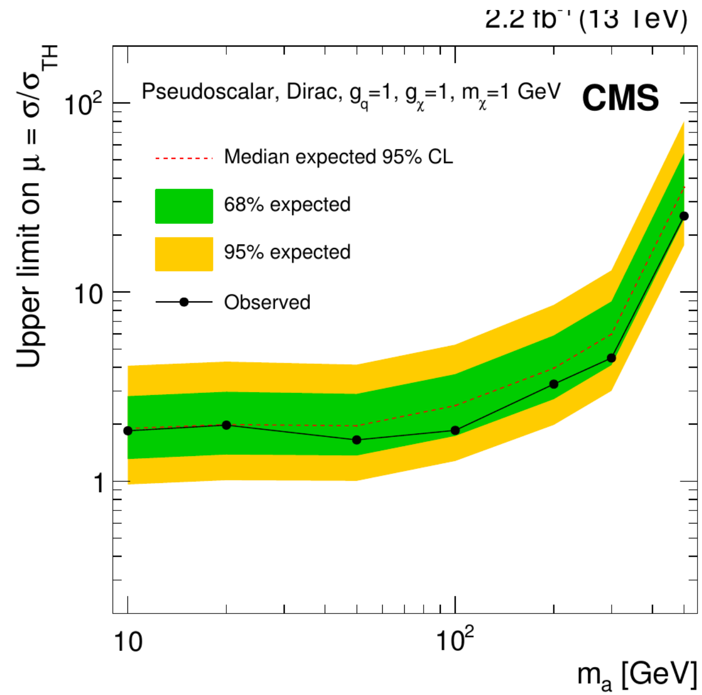
Per-channel pseudoscalar



Full combination, scalar



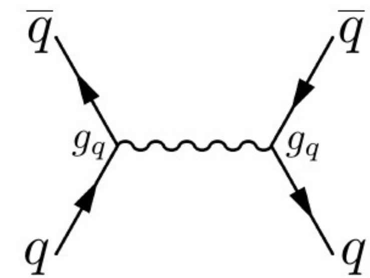
Full combination, pseudoscalar



Direct Mediator Searches

If mediator couples to quarks, then also decay to SM particles

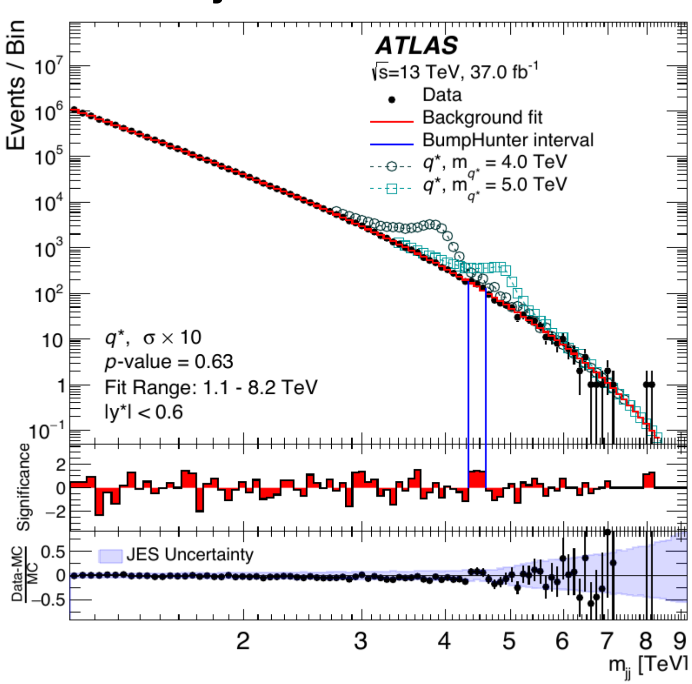
- Search for the DM mediators directly via traditional LHC “bump hunts”
  - Dijet (+ISR), dilepton, di-bjet, etc … eg:

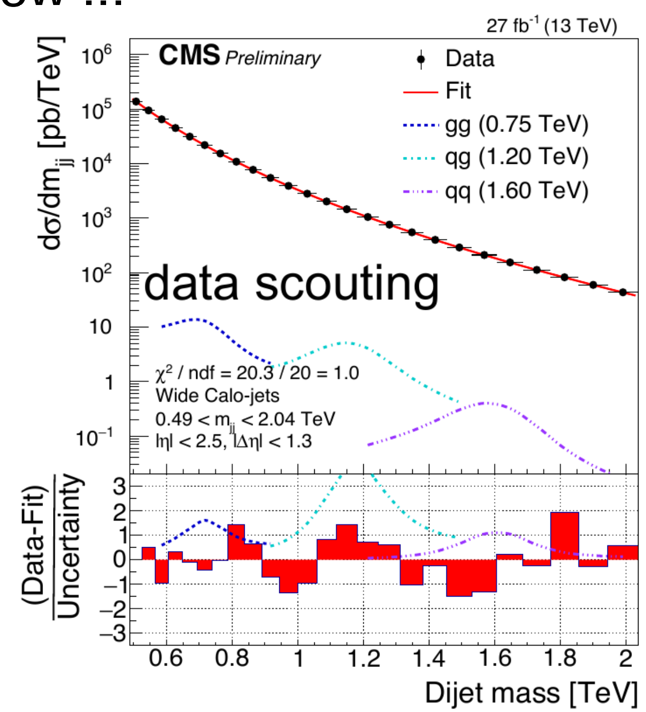


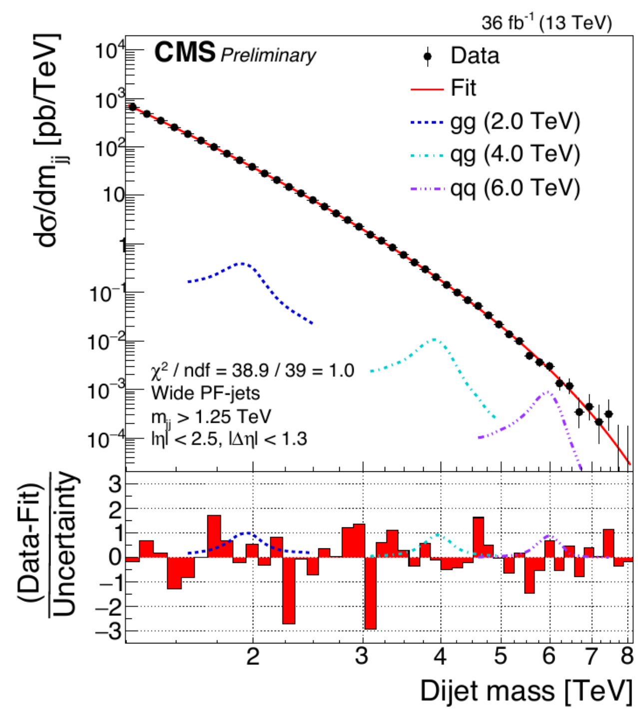
Dijet : 15.7 fb -1 ATLAS-CONF-2016-069, 27 & 36 fb-1 CMS-PAS-EXO-16-056
Dijet angular, 3.6 fb -1 (ATLAS) PLB 754 (2016) 302-322, 36 fb-1 CMS-PAS-EXO-16-046
Boosted dijet : 3.2 fb-1 (bjets) ATLAS-CONF-2016-031, 36 fb-1 CMS-PAS-EXO-17-001
Dilepton :: 36 fb-1 (ATLAS) 1707.02424, 2.9+19.7 fb-1 (CMS) PLB 768 (2017) 57

-

- New techniques (data scouting [CMS], Trigger Level Analysis [ATLAS]) allows searches to now push to lower mediator masses
- Dijet search results below ...



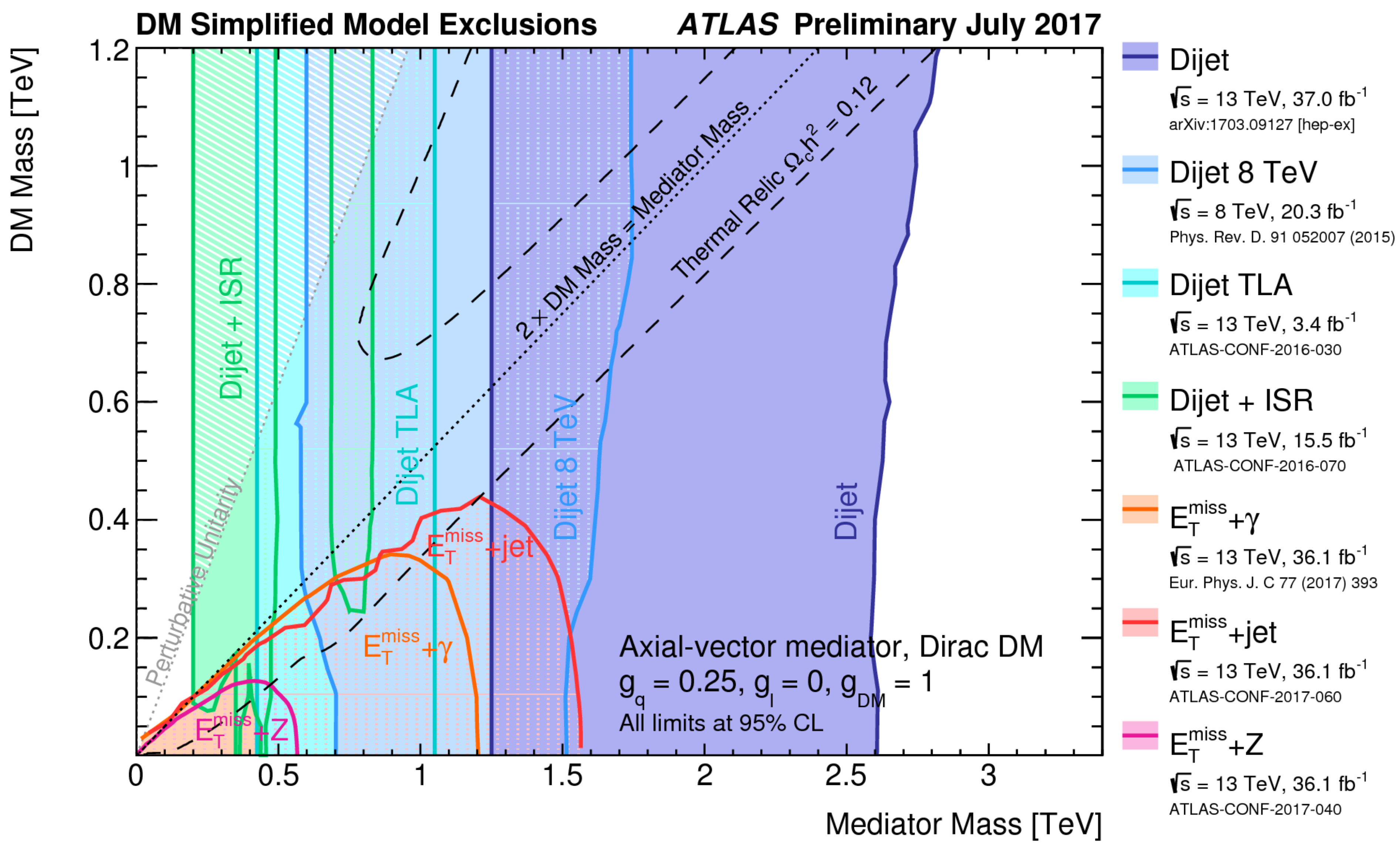




Collider DM Summaries

Comprehensive picture of LHC sensitivity to DM simplified models

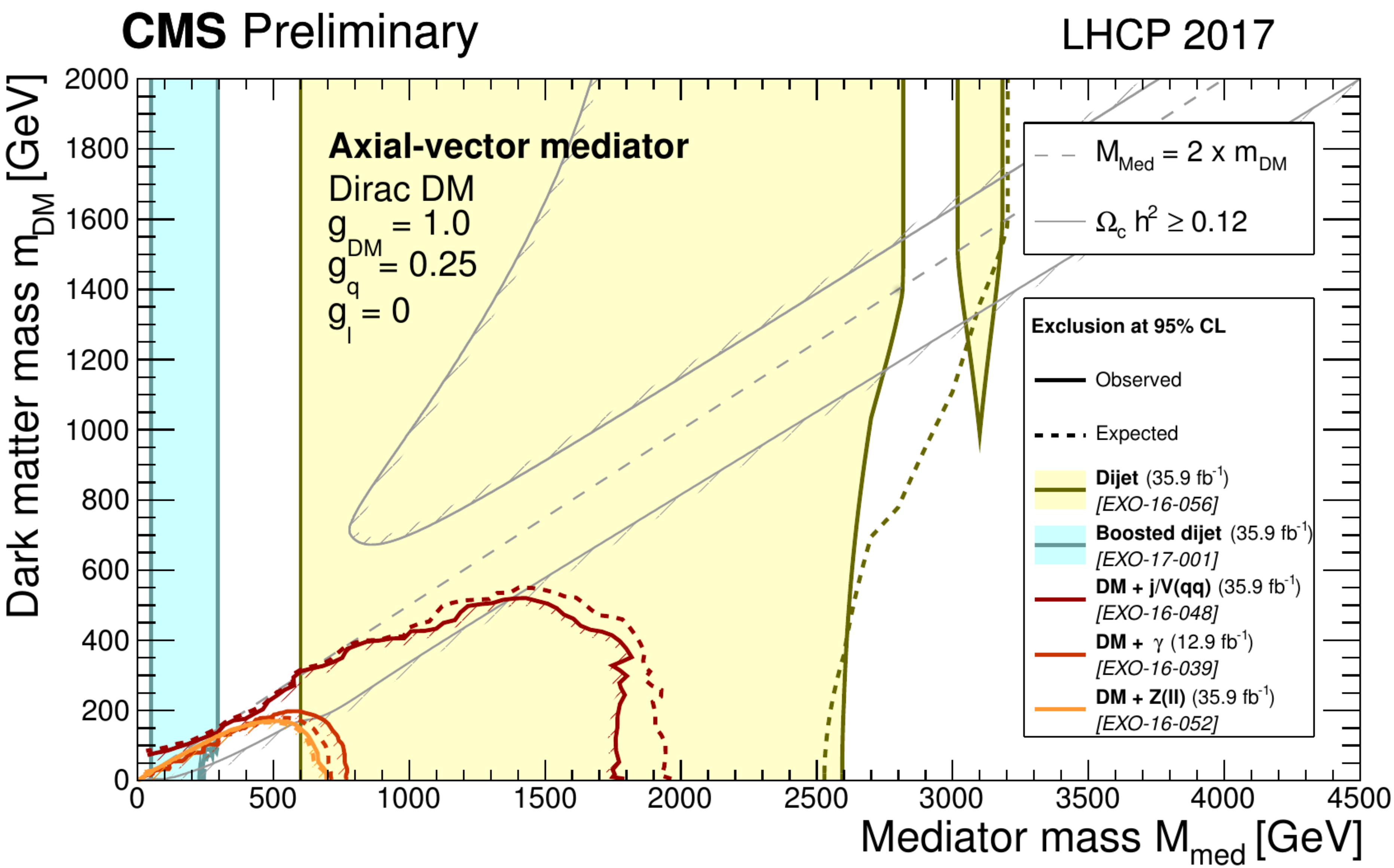
- Axial-vector mediator shown here (see ATLAS Exotica Summaries)



Collider DM Summaries

Comprehensive picture of LHC sensitivity to DM simplified models

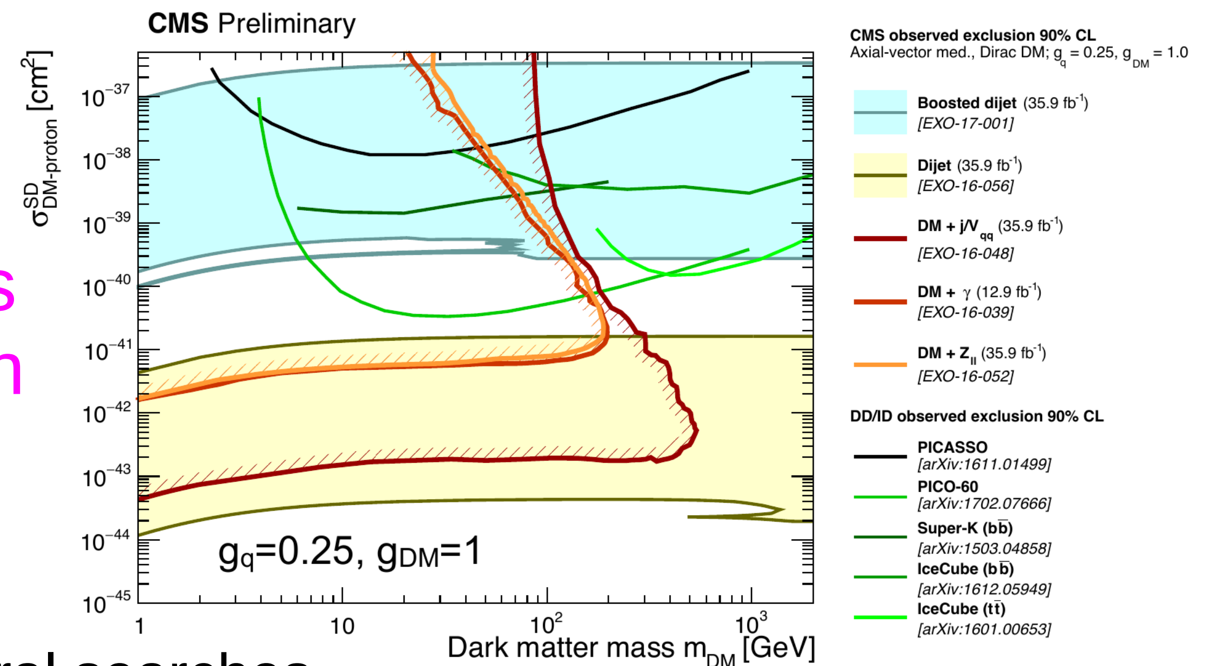
- Axial-vector mediator shown here (see CMS DM Summaries)



Robust program of E_T^{miss} +X DM searches at the LHC

Run 2 results pushing into new territory, limits on

- Multi-Tev spin-1 mediators
- Low-mass spin-0 mediators

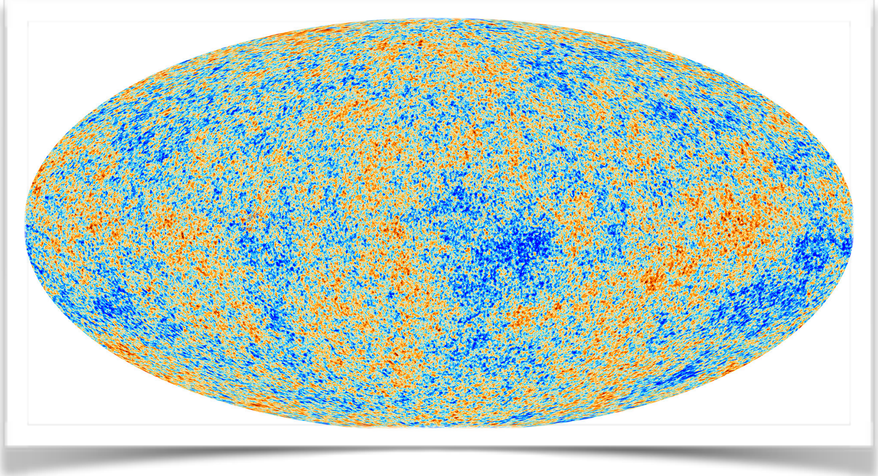


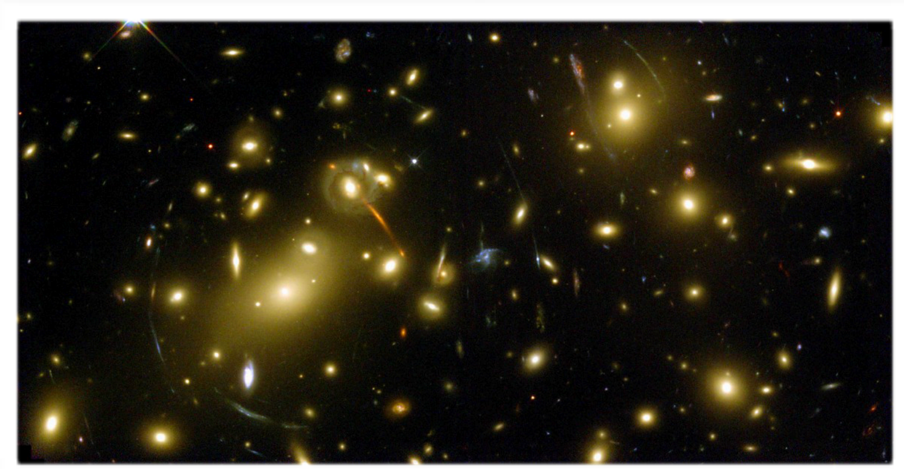
Complementary strengths vs direct/indirect detection

On the horizon:

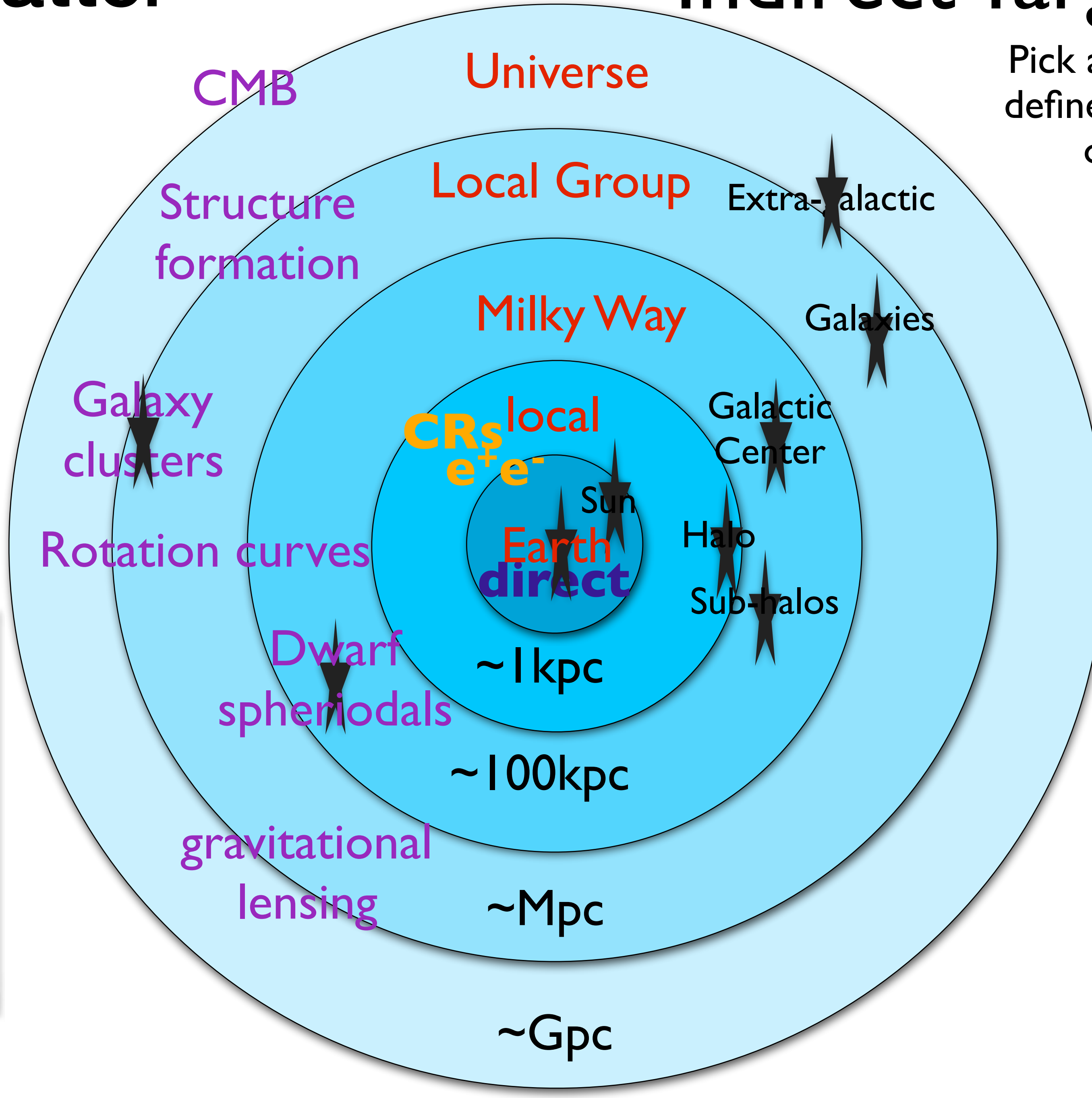
- Large bump in stats for several searches
- Stronger interplay between DM channels
- New methods for treating SM systematics (eg: arxiv: 1705.04664)
- Interpretations with somewhat-less-simplified models (eg: 1701.07427)

Evidence for Dark Matter





“Indirect Targets”



Pick a target that is well defined and that has low or understood astrophysical backgrounds

- Dark Matter already gravitationally “observed”, but ...
  - What is it ?
  - What are it’s properties ?

χ

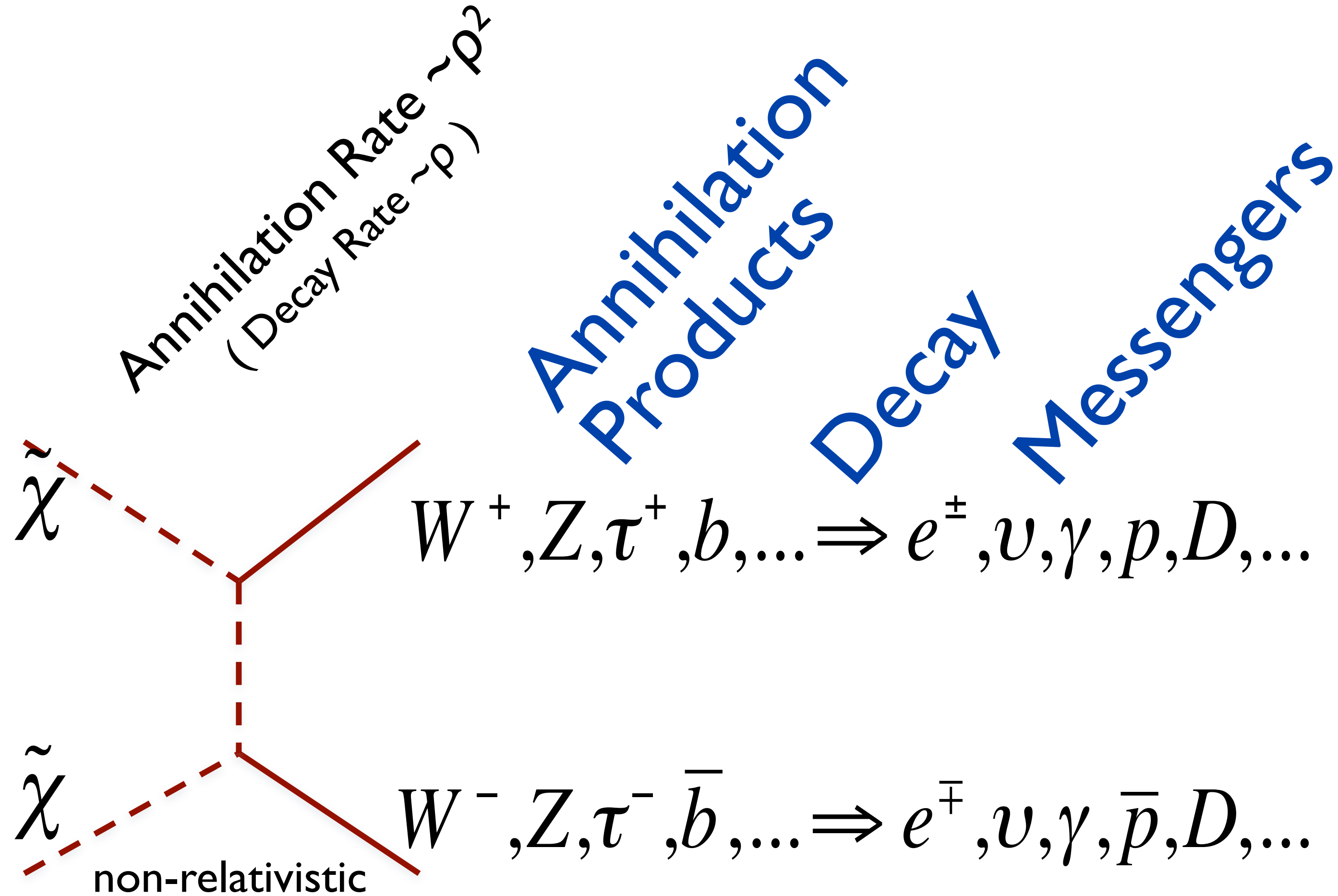
Some of us like WIMPs <σv>~3x10^{-26}cm^{3}s^{-1}

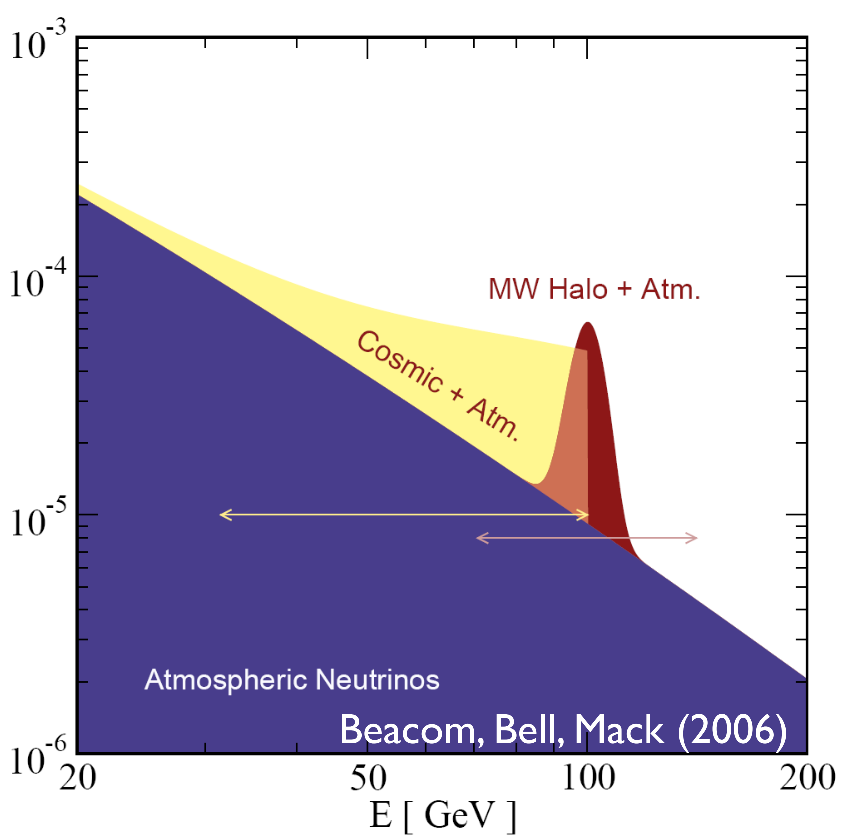
Indirect Dark Matter Searches

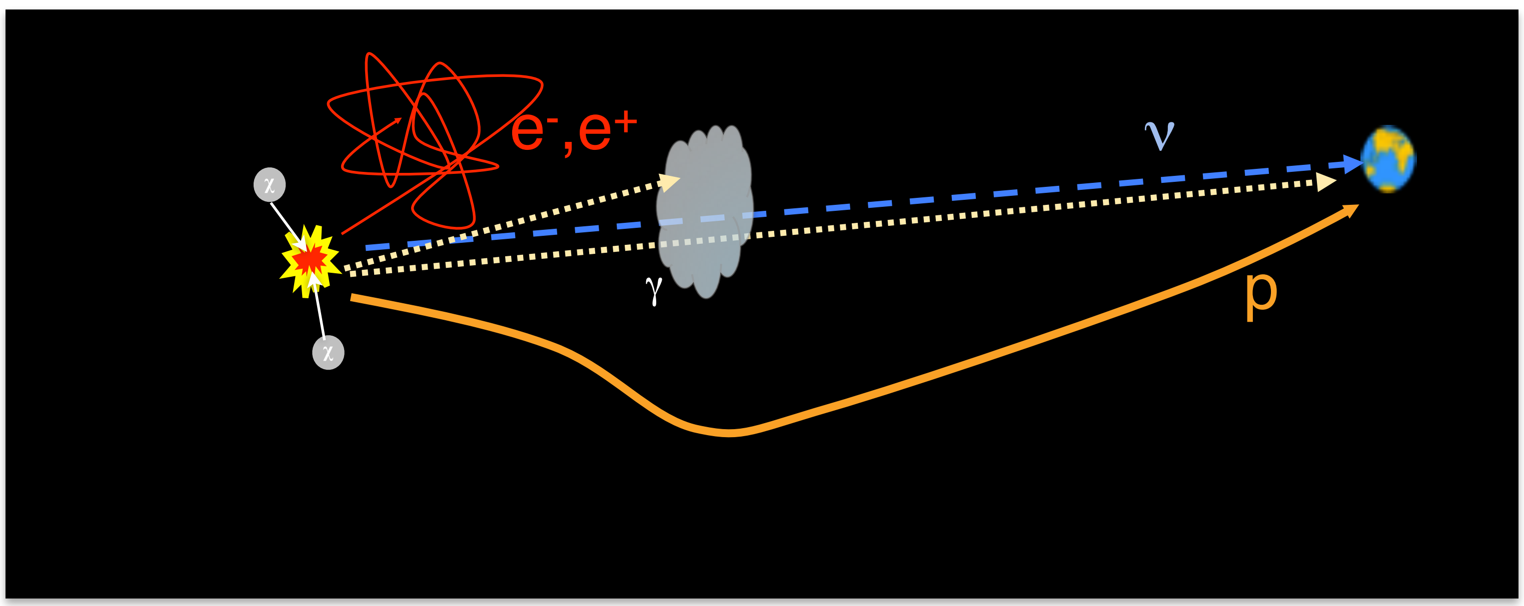
Dark Matter Signals

- Identify overdense regions of dark matter

  ⇒self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds







Targets - Dark Matter Annihilations

Small halo model dependence, boost factors

Diffuse flux, spectral feature

Signal weak compared to Galactic signal

Large DM content, nearby source, O(10) larger flux than extra-galactic

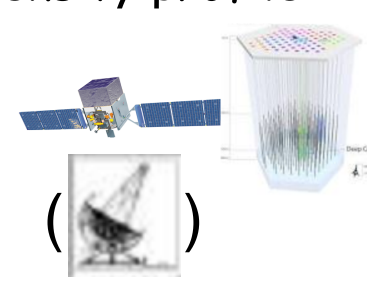
Anisotropy

Relatively independent from DM halo profile

Very dense DM accumulation, nearby source

Extended Source

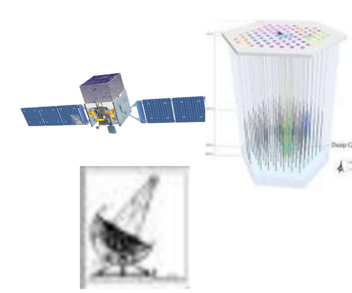
Very strong dependence on DM density profile

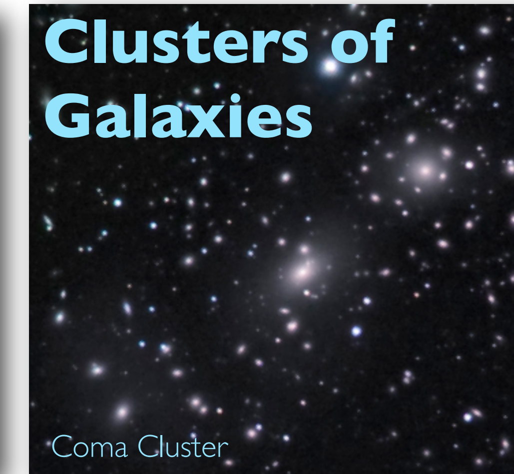


No astrophysical backgrounds

Point source

Cored profiles favored, less flux

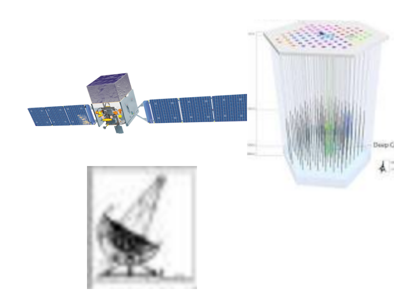




Large DM content, high boost factors from sub structure

Extended source

Understanding of boost factors



For discovery observations at multiple sources with different observatories (Multiwavelength !) that yield a consistent picture

Dark Matter Distributions / Halo Profiles

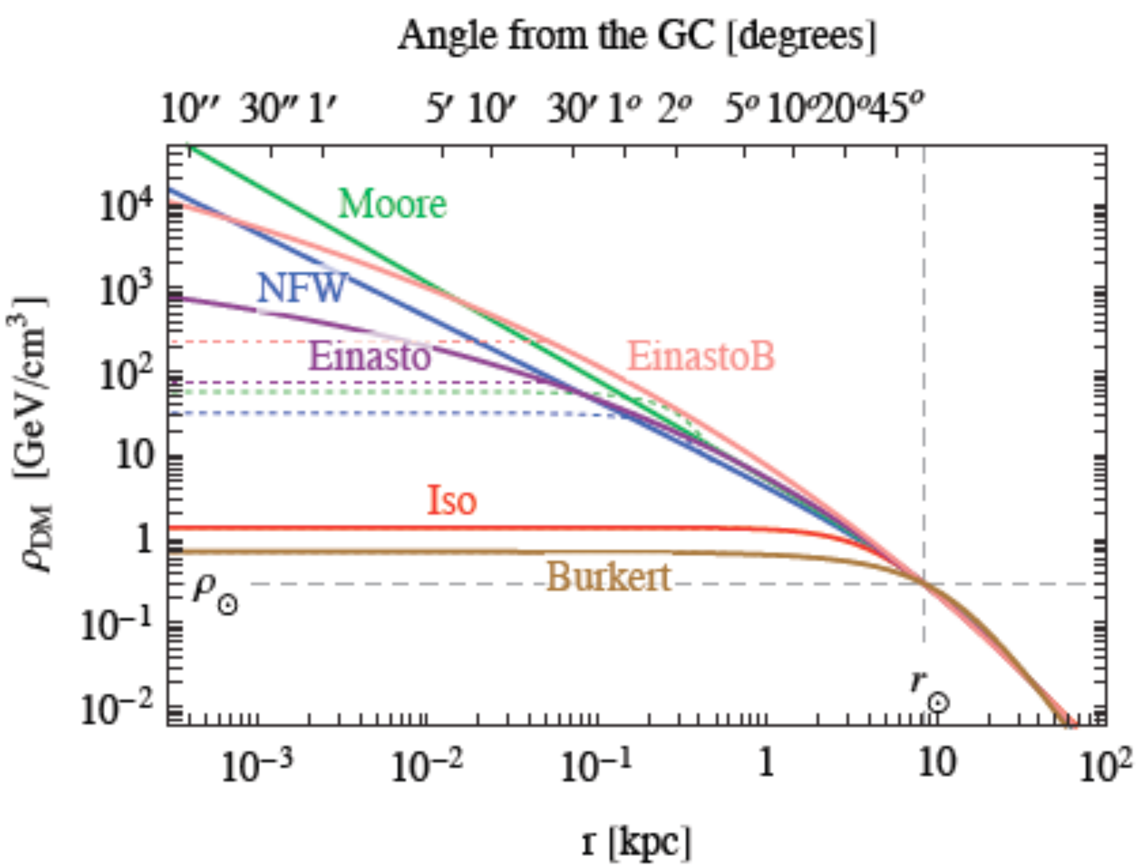
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

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

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

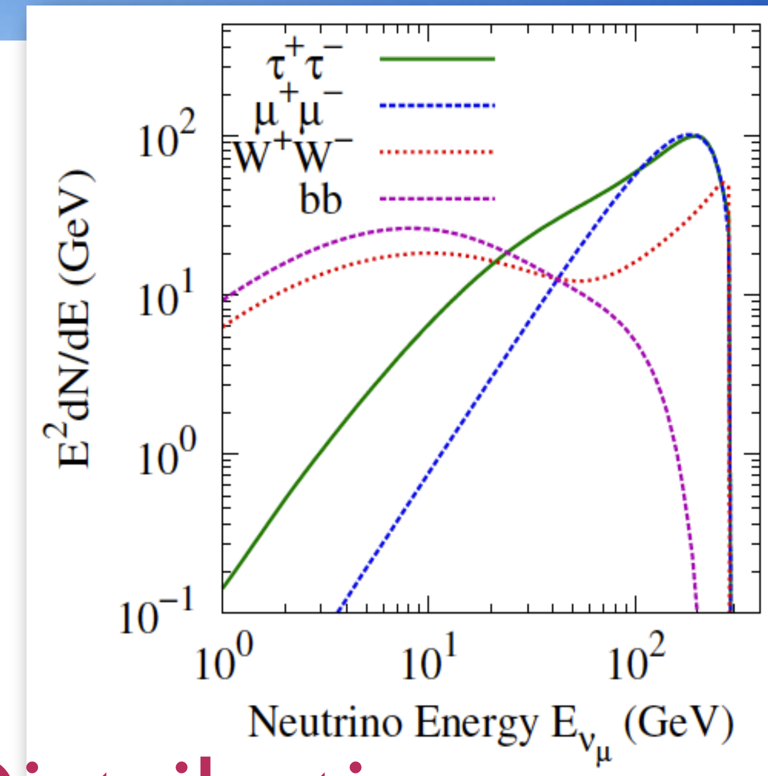
$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

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



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

Dark Matter Annihilation



Measure Flux

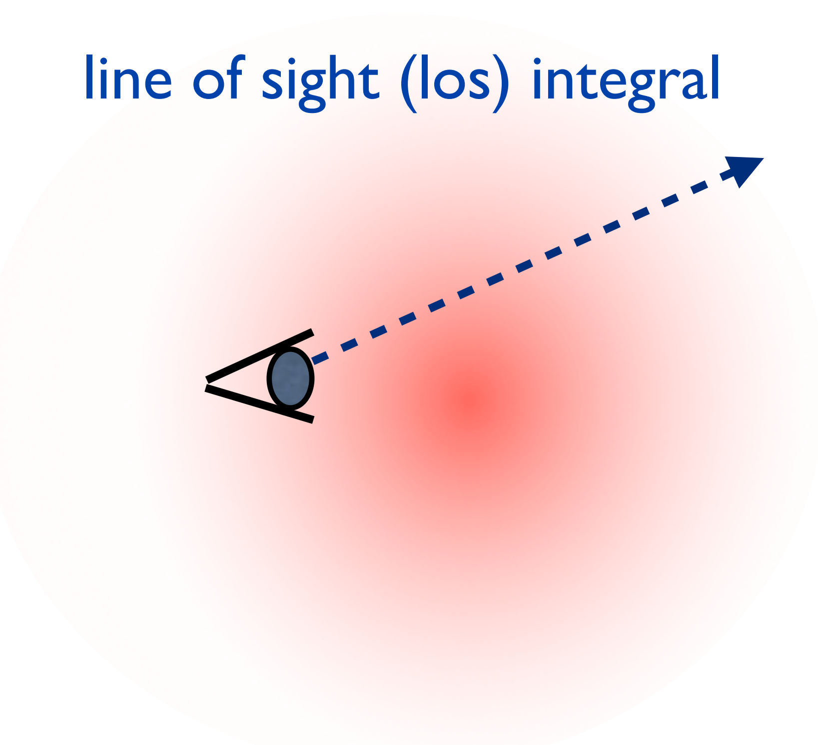
Particle Physics

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$

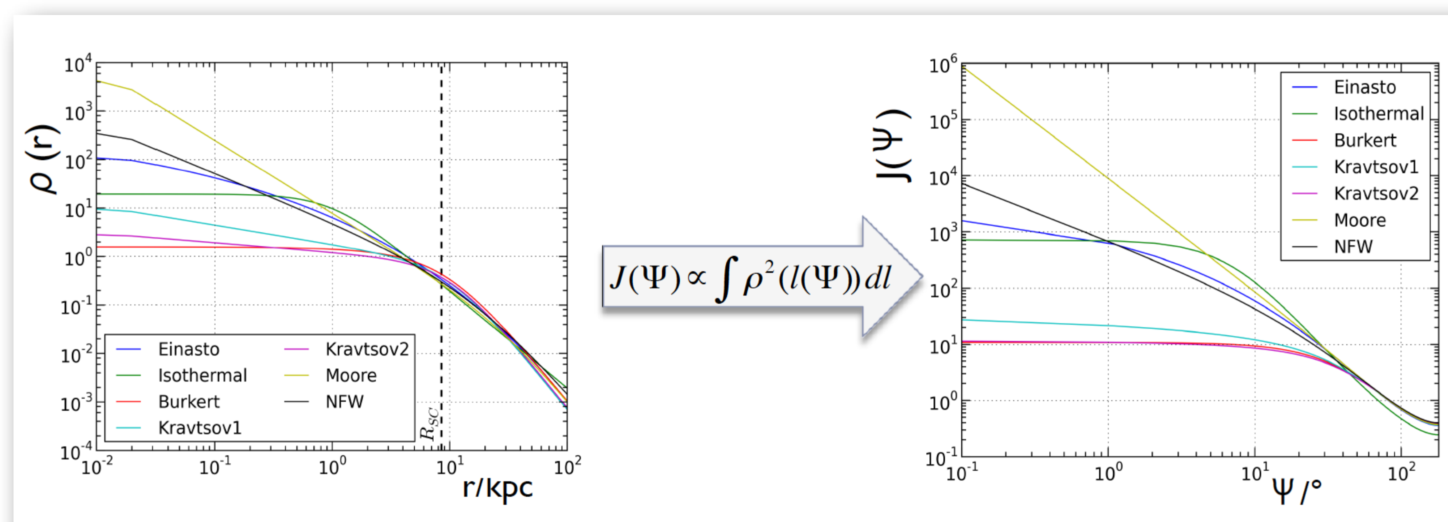
x

Dark Matter Distribution

line of sight (los) integral

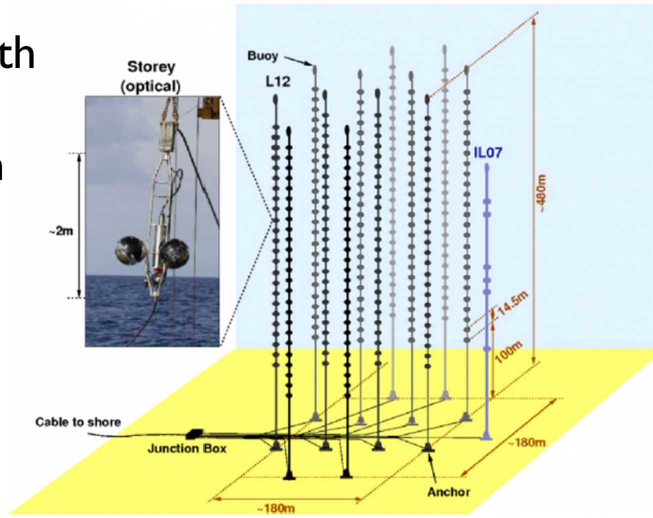


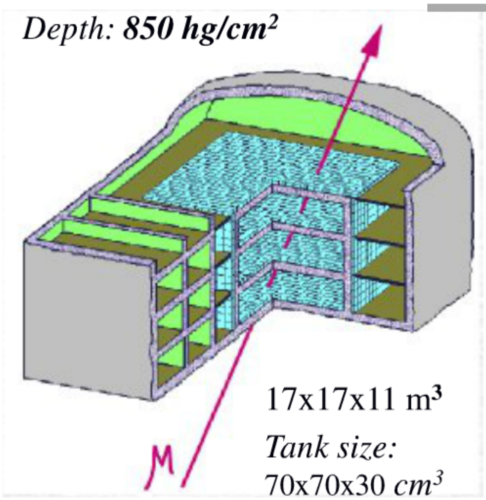
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



Neutrino Telescopes / Detectors

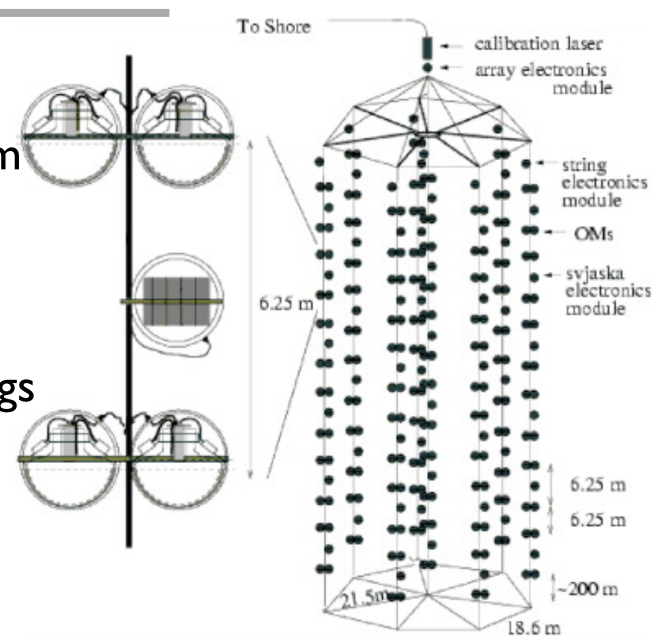
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10”PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



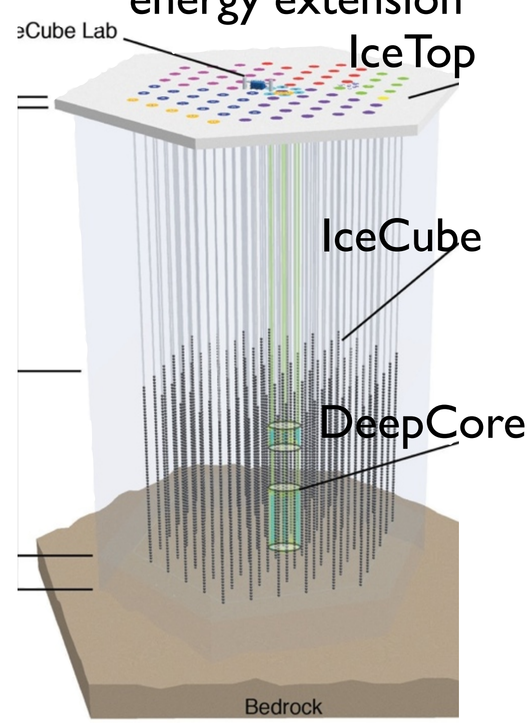


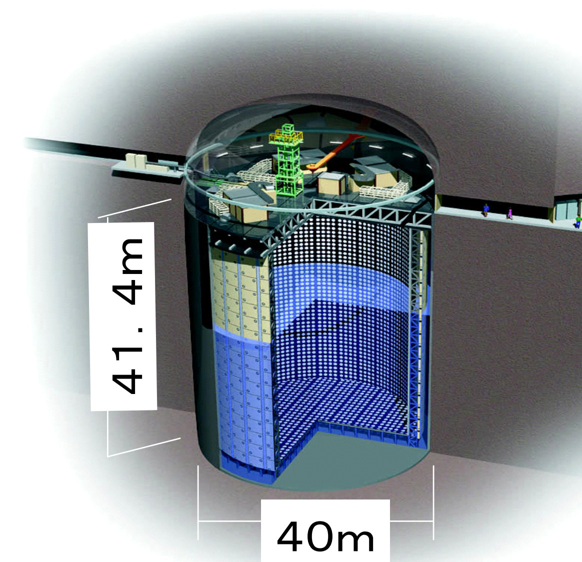
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



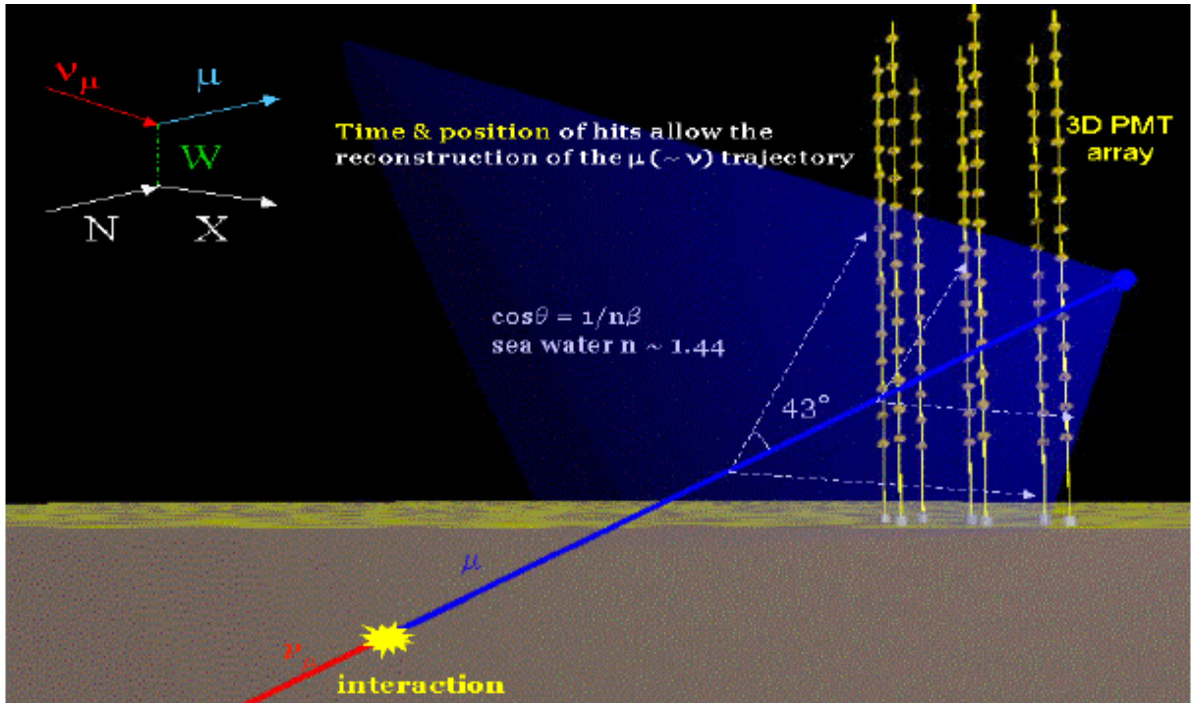
- **IceCube** at the Geographic South Pole
- 5160 10”PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension

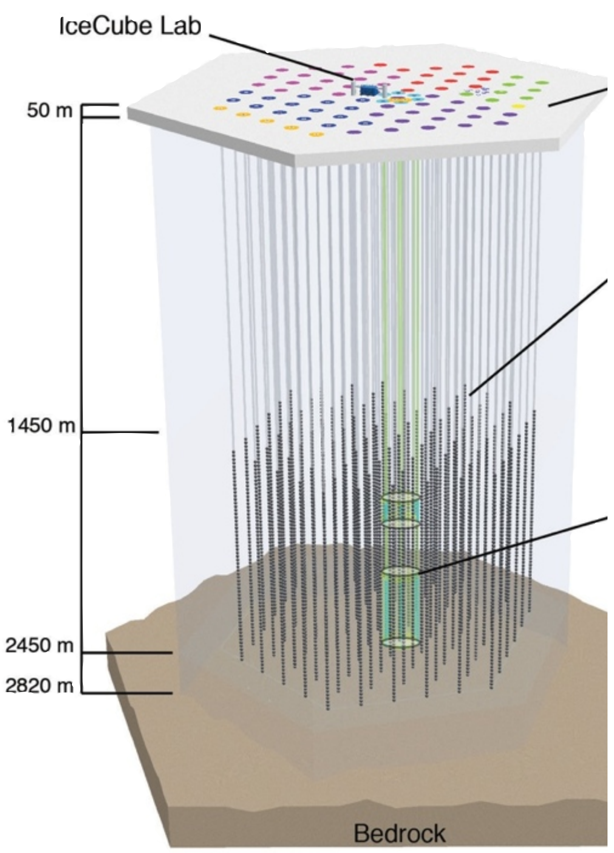




- **Super-Kamiokande** at Kamioka uses 11K 20” PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

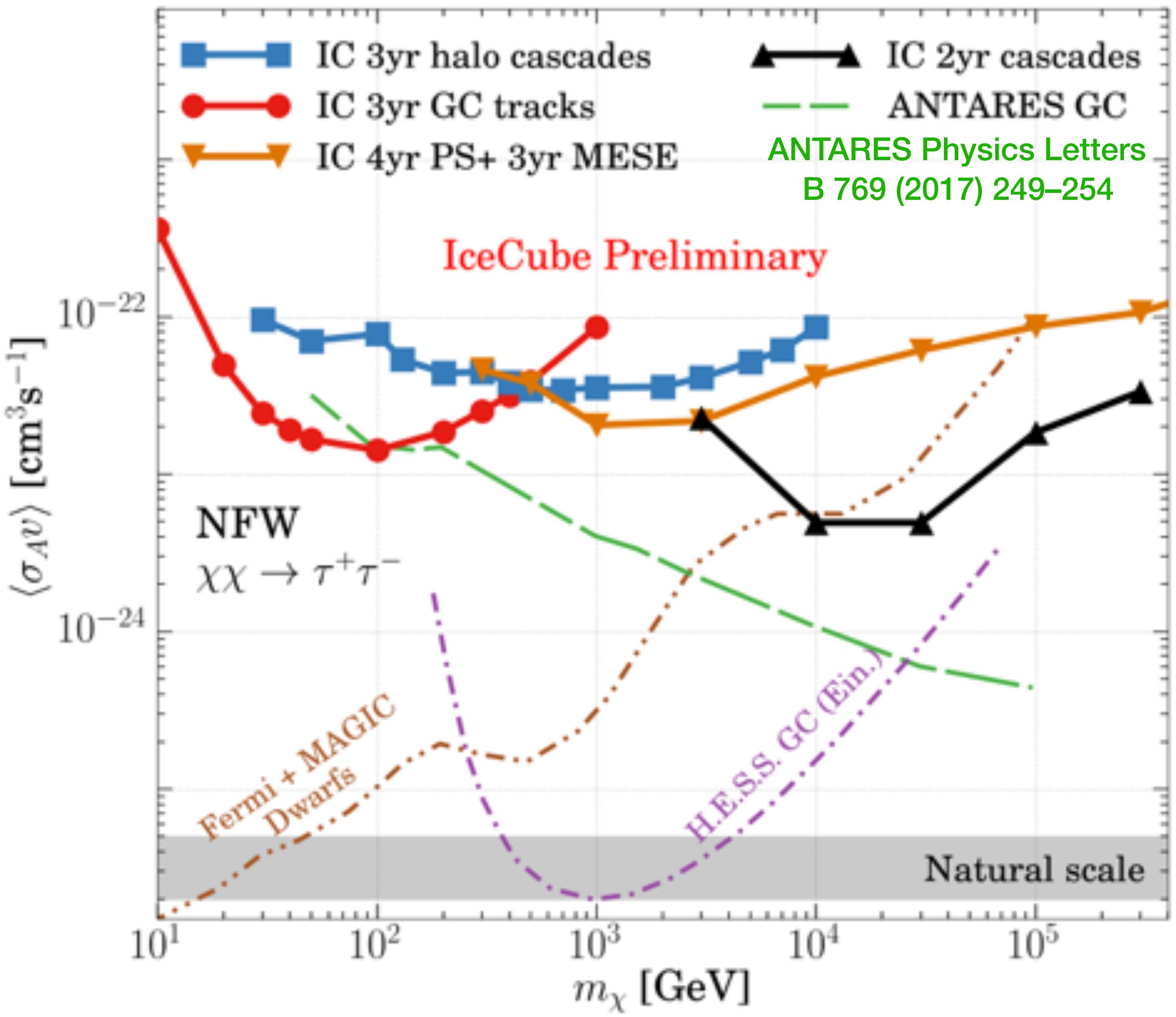




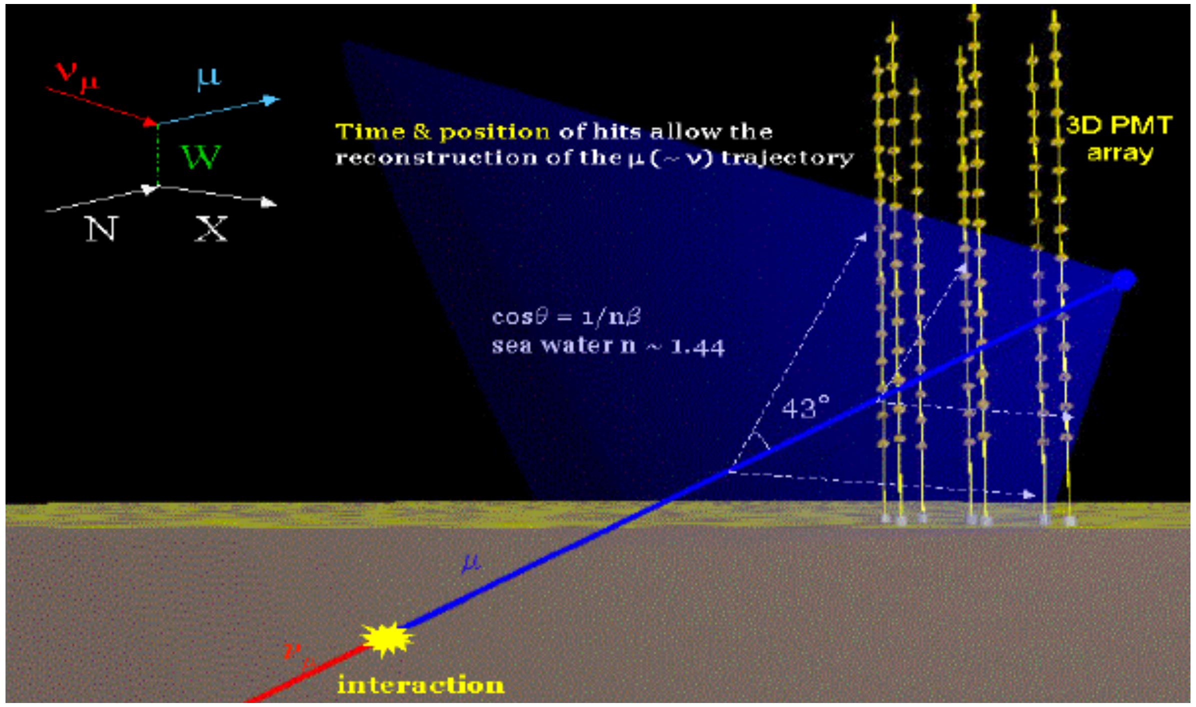
- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

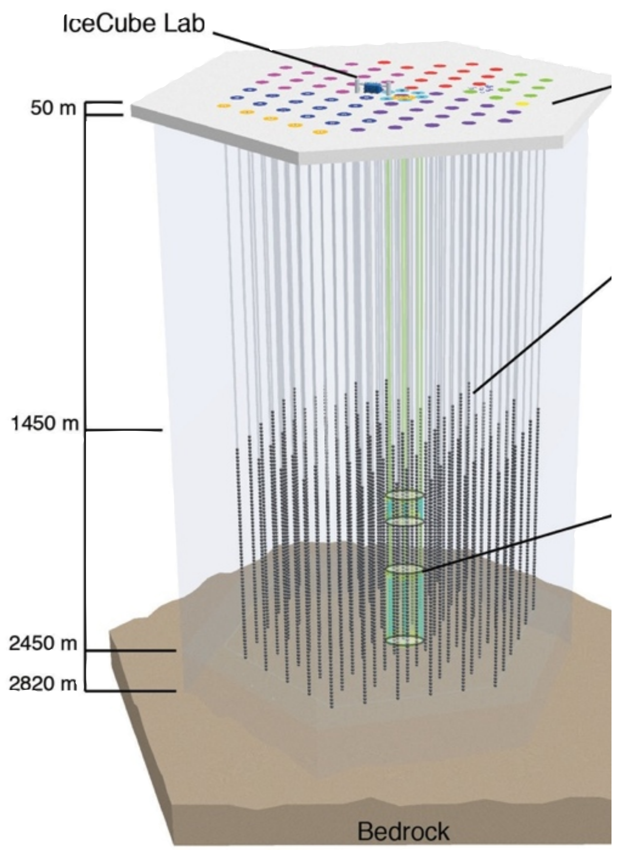
Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103]



INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

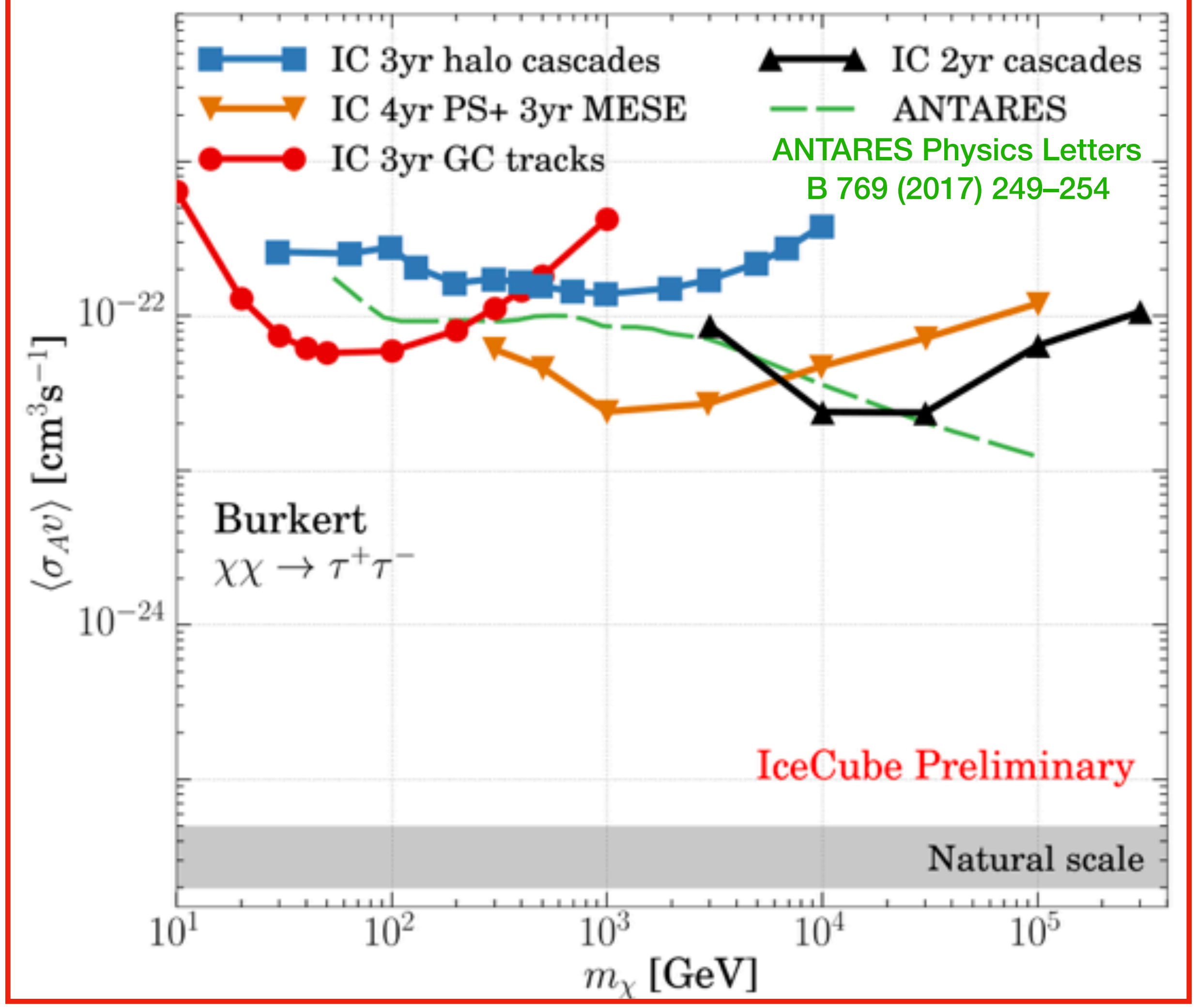




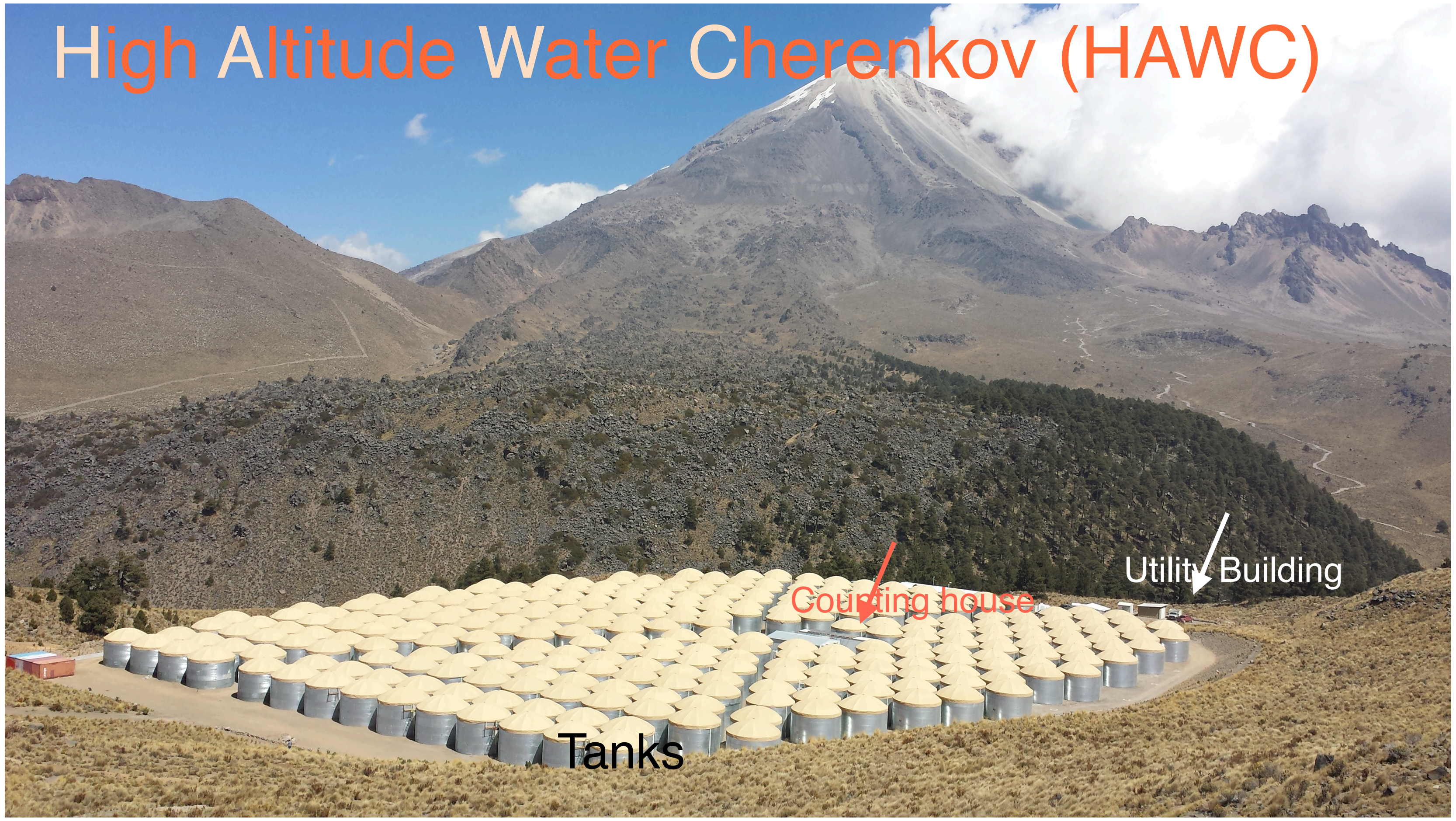
- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103]



High Altitude Water Cherenkov (HAWC)

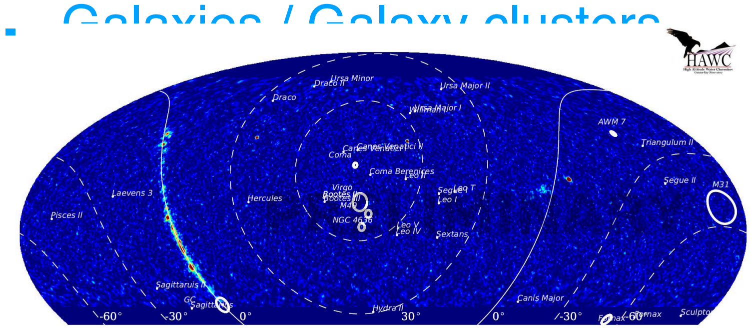


- Located at 97.5° W, 18.9° N (Parque Nacional Pico de Orizaba) at 4100m
- 300x 7.3 m diameter, 5 m height tanks,
  - 3x 8" R5912 PMTs and 1x 10" R7081-HQE PMT
- In total: 55kT of water
- Covers 22000 m^2
- Completed in 2016
- Trigger rate: 24kHz
- Data rate: 2TB of data per day, 95% livetime

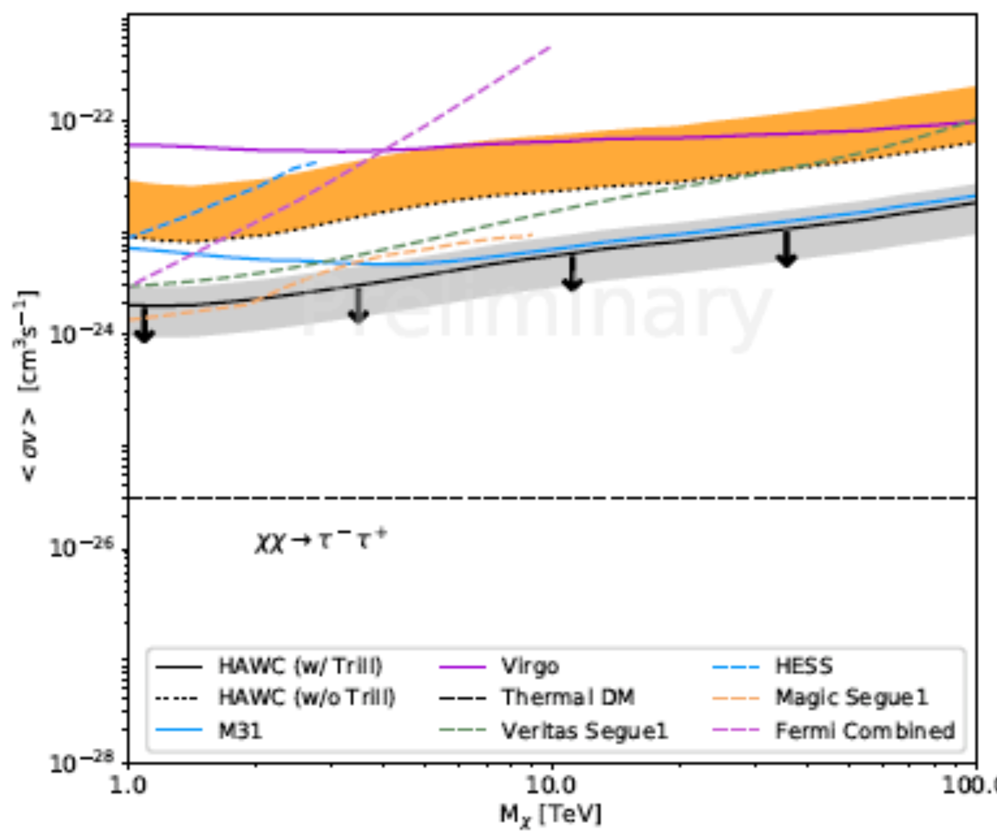
507 days of HAWC data analyzed

Targets:

- Dwarf spheroidal (dSph)galaxies
  - Combined results were computed for 15 dSph
- Galaxies / Galaxy clusters



Potential sources to look for dark matter signature



Future improvements:

- include more dSph
- extended source analysis
- more data …

Also measurements on:

- TeV γ emission from pulsars
- Dark Matter Decay

Dark Matter Annihilation Search with VERITAS

Array of four IACTs in Southern AZ, USA

- Energy Range: 85 GeV to > 30 TeV
- Energy Resolution: 15-25%
- Pointed observation (FOV~3.5°)

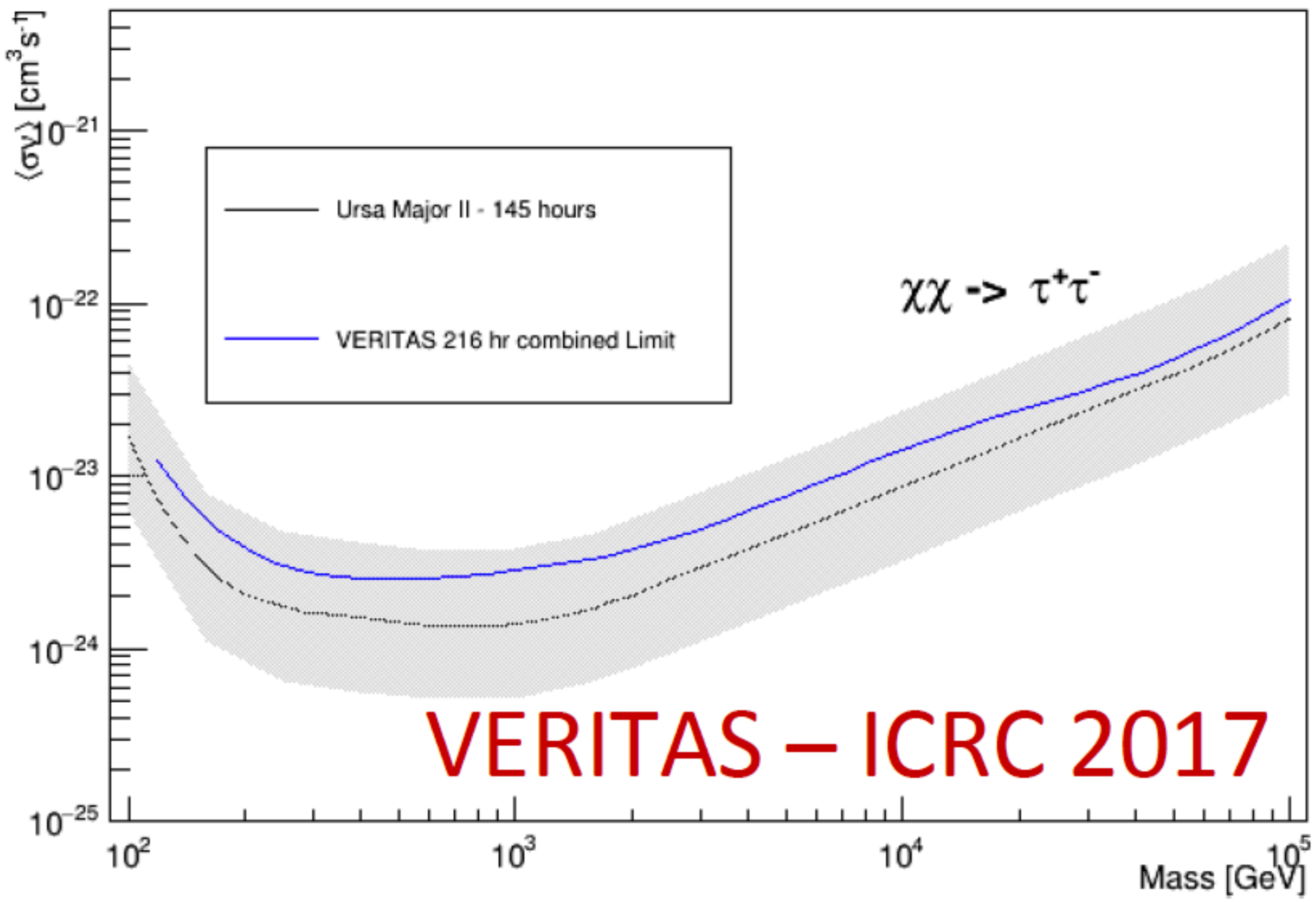
Targets

- Dwarf Spheriodal Galaxies
- Fermi-LAT unidentified sources
- Galactic Center (soon)
    - Galactic Center region does not transit above 30°elevation at VERITAS site

Five **dSphs** observed by VERITAS between 2007 and 2013

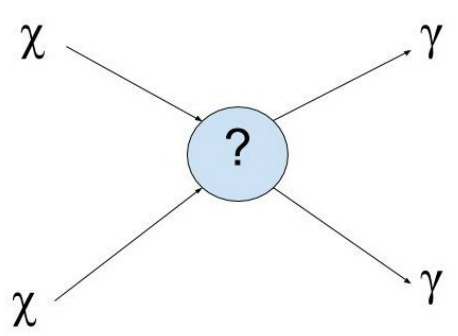
- Total of 230 hours after data quality selection
- 92 hours for Segue 1

Benjamin Zitzer [VERITAS]. ICRC2017 (904)



see also Archambaultet al. [VERITAS] Phys. Rev. D 95, 082001

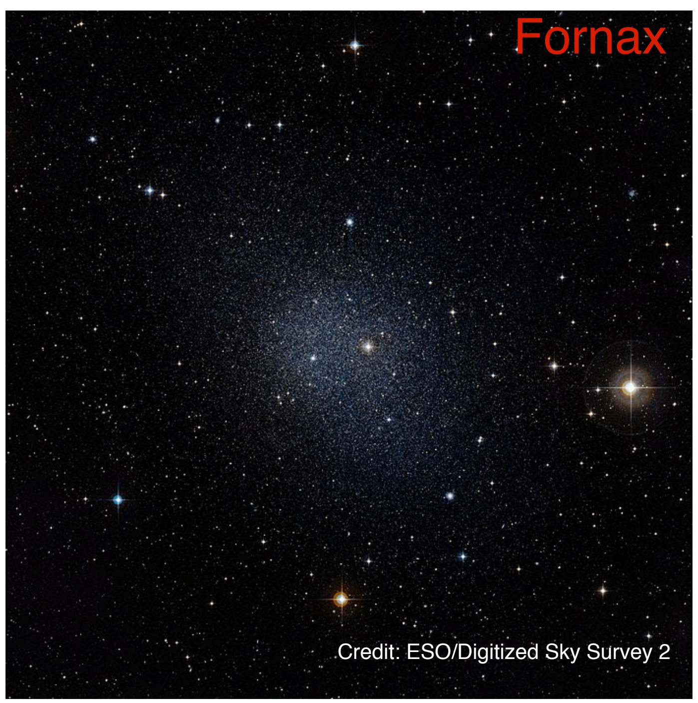
Line Searches

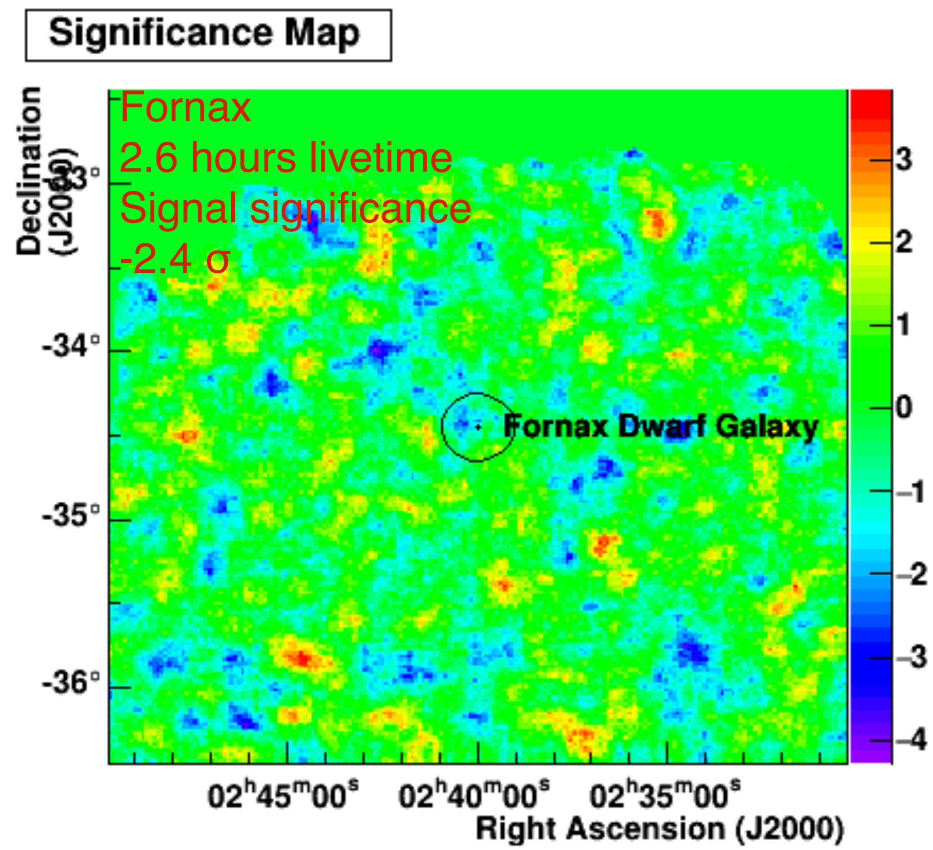


Peak in the γ energy distribution at the WIMP mass ("γ-ray line") would be clear signal for DM annihilations.

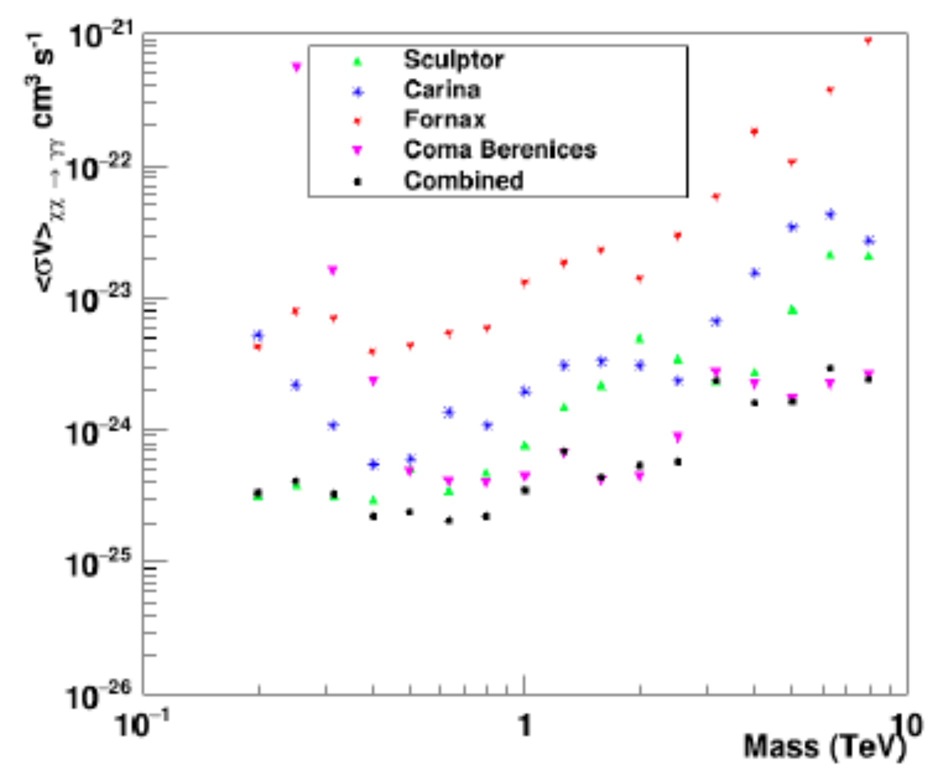
Dwarf Spheroidal Galaxies (dSphs)

- Low/no gas, dust or recent star formation
- DM dominated
- Several large datasets already recorded



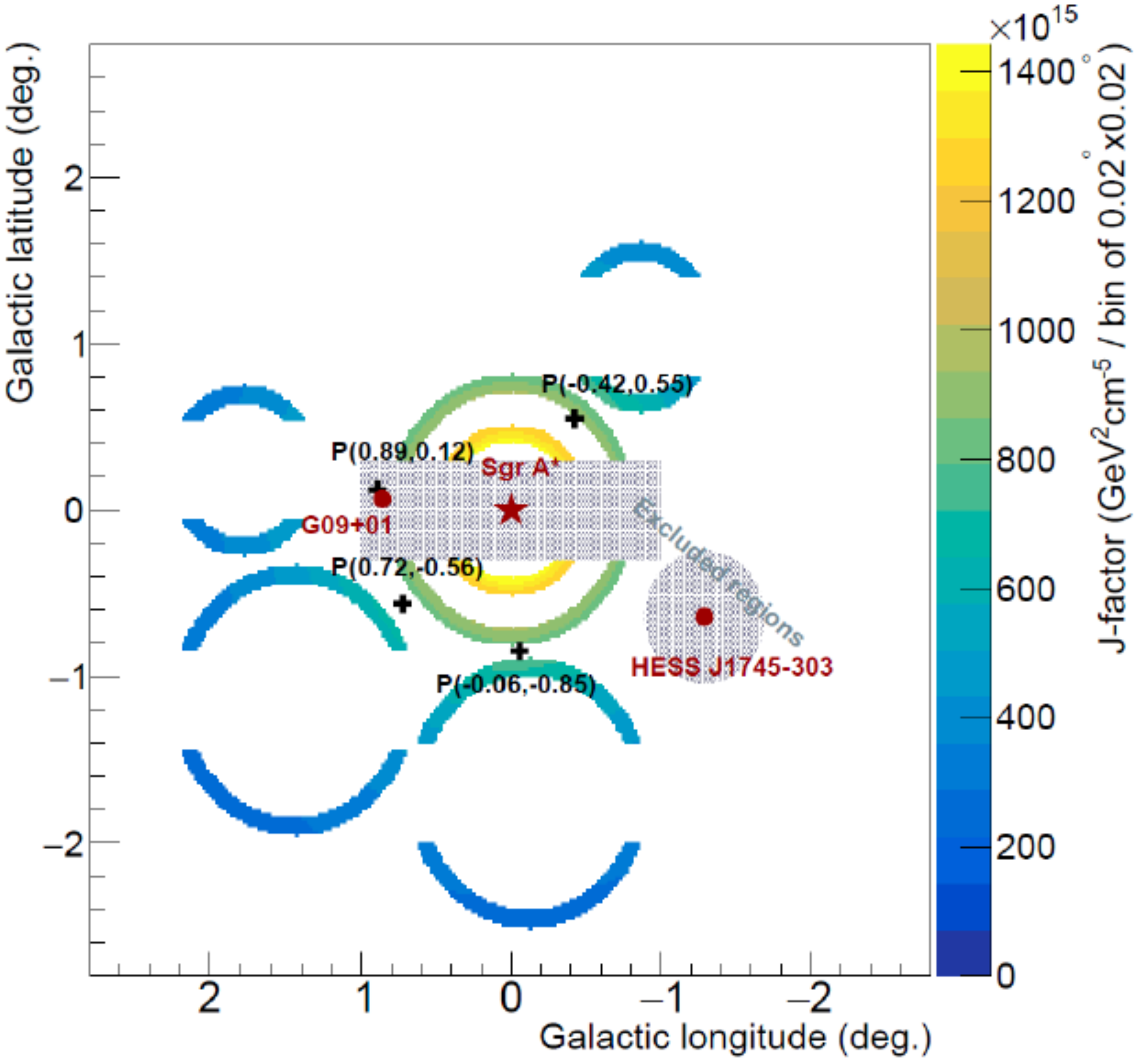


L. Oakes [H.E.S.S.] ICRC2017 (905)

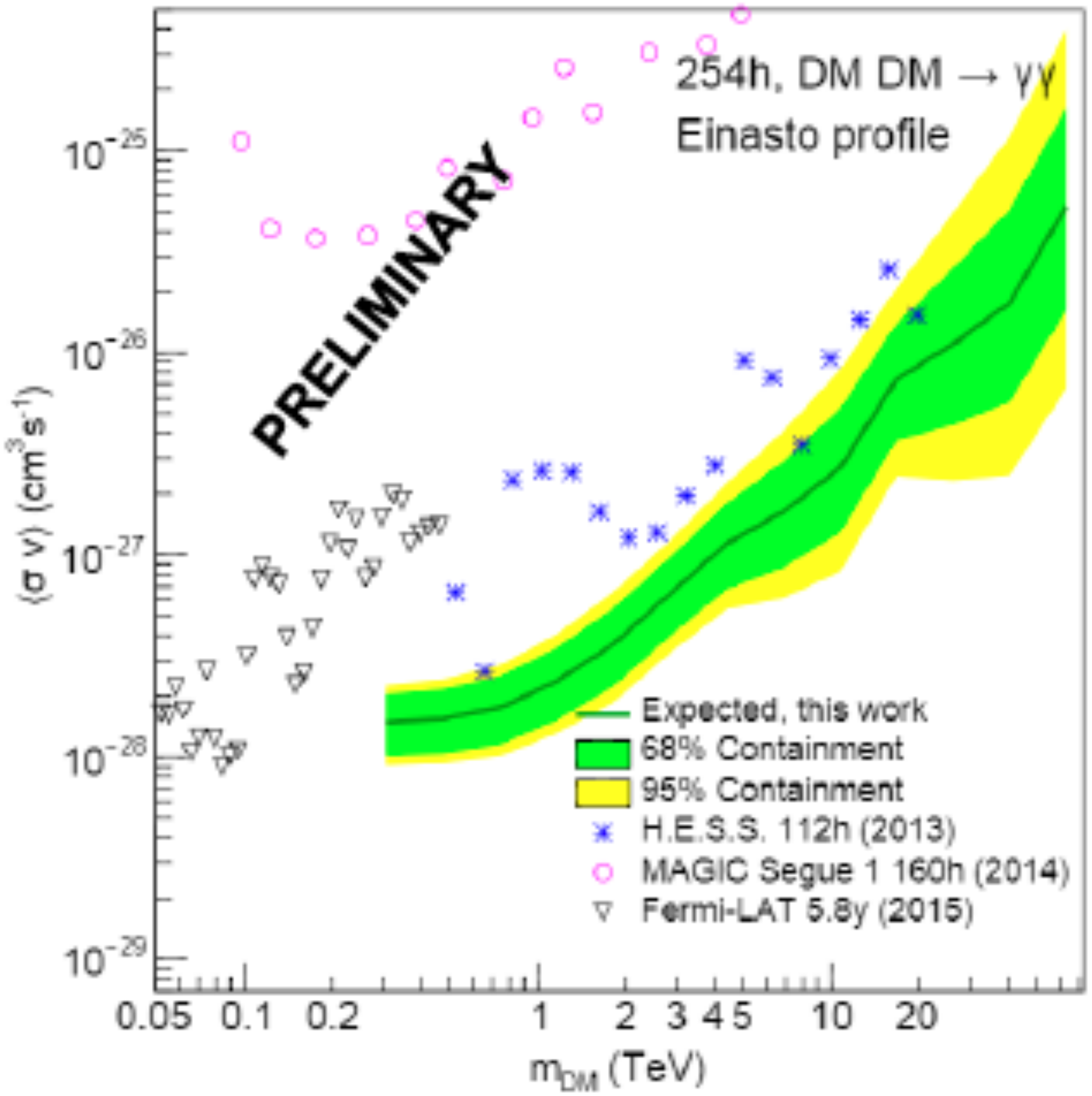


- Limit on <σv> of 3×10^{-25} $cm^3 s^{-1}$ reached for M_χ range 0.4-1.0 TeV
- First H.E.S.S. DM line search from dwarf galaxies and first combined DM line search
- More complex line-like models to be included for upcoming paper

Line Searches



Emmanuel Moulin [H.E.S.S.] ICRC2017 (893)



- Sensitivity only (2×10^{-28} $cm^3 s^{-1}$ @1TeV) , unblinding in progress … expect results soon
- lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV

Dark Matter Decay

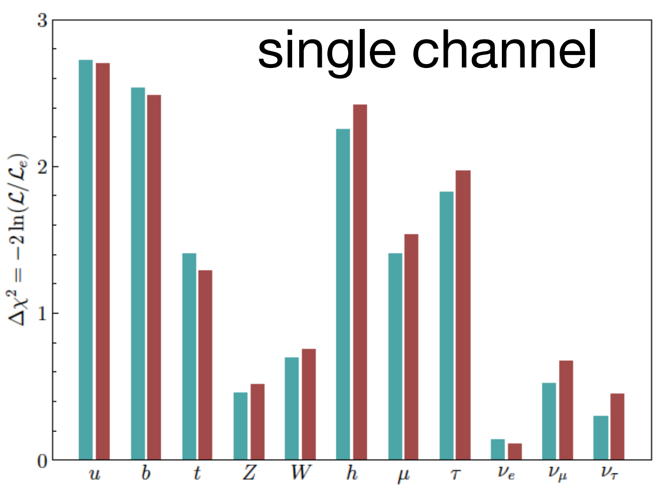
Heavy Decaying Dark Matter

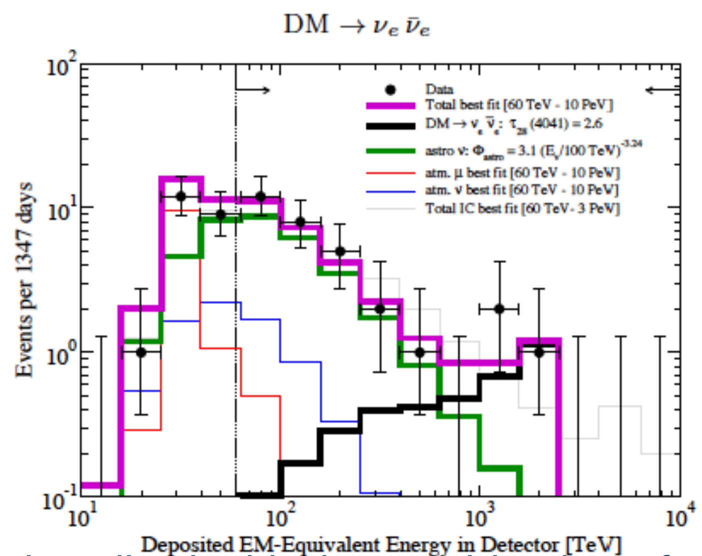
Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

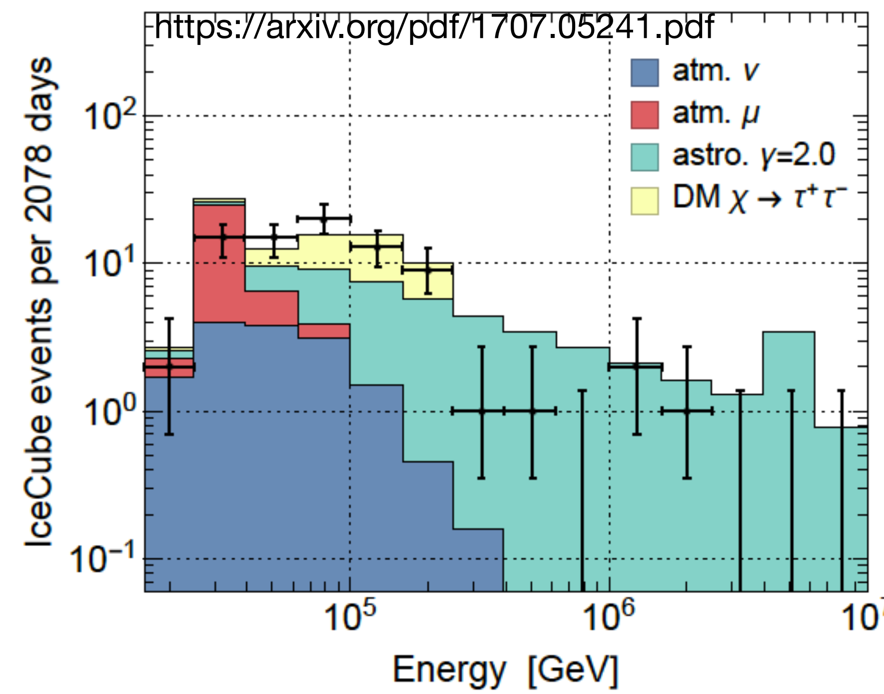
$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

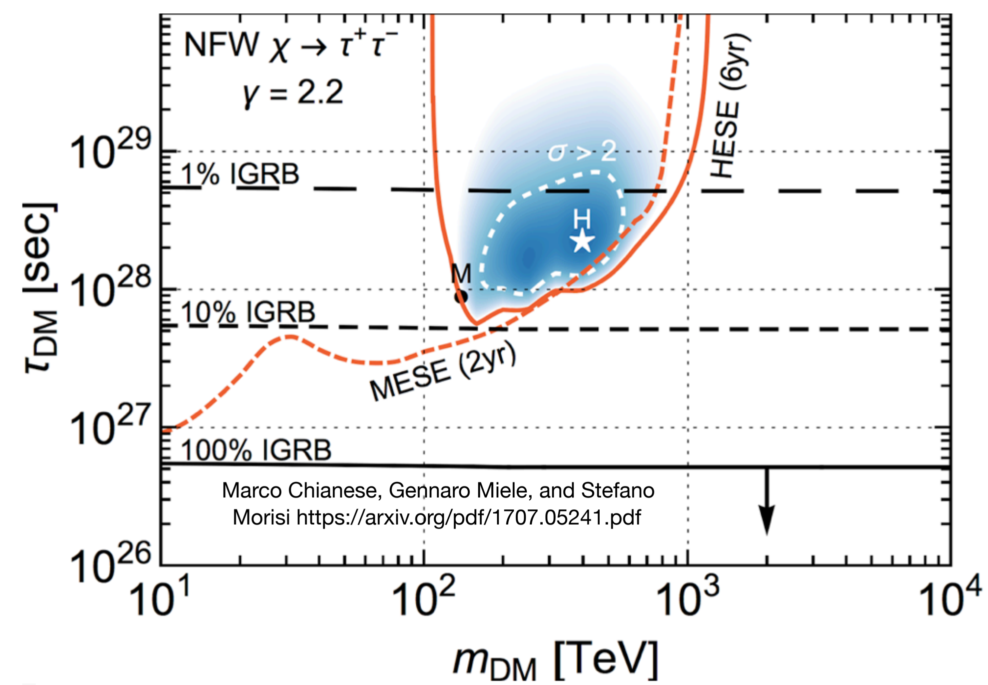
Take Galactic and Extra galactic contributions into account

Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv:1706.05746









Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome strongly depends on background assumption

Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
Rott, Kohri, Park PRD92, 023529 (2015)
El Aisati, Gustafsson, Hambye 1506.02657

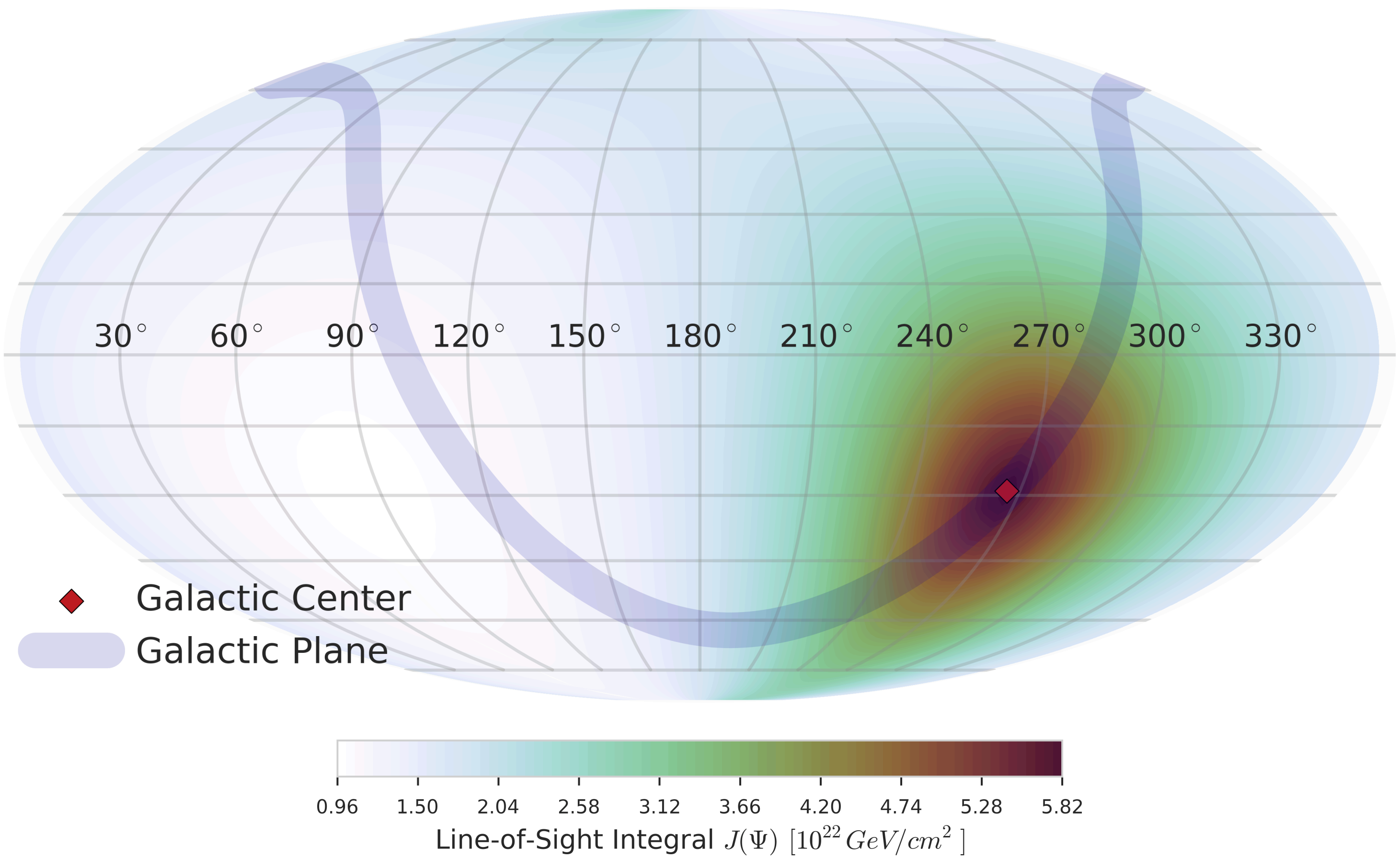
Dark Matter Decay with IceCube

- Two expected flux contributions:
  - Dark Matter decaying in the Galactic Halo (Anisotropic flux + decay spectrum)

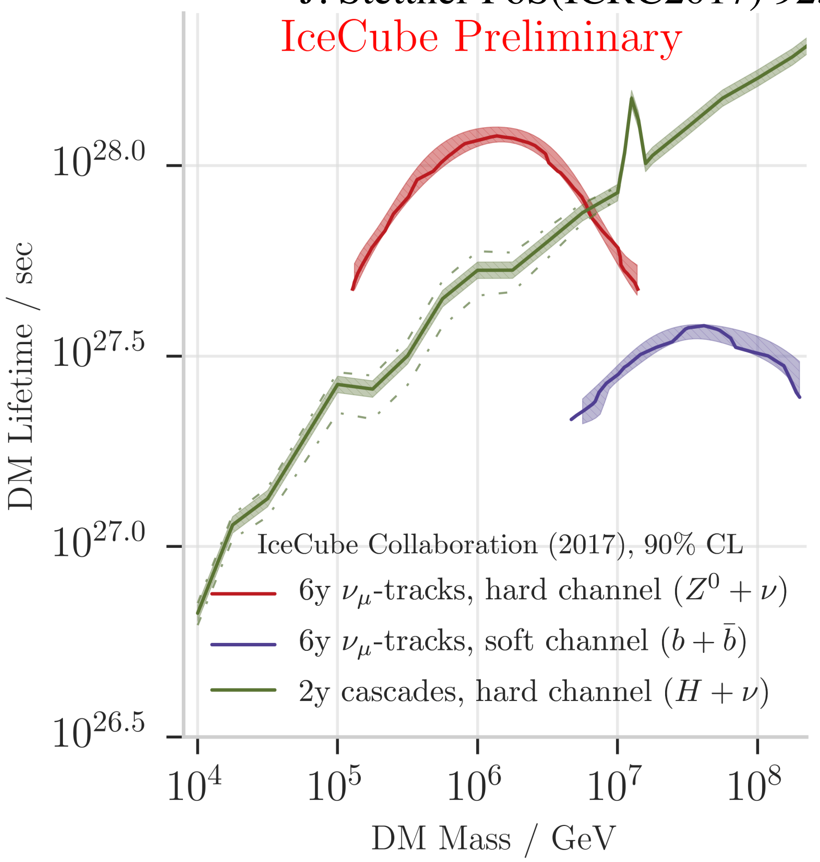
$$\frac{d\Phi^{G}}{dE_\nu} = \frac{1}{4\pi\, m_{DM}\, \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty \rho(r(s,l,b))\, ds$$

  - Dark Matter decaying at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{d\Phi^{EG}}{dE} = \frac{\Omega_{DM}\, \rho_c}{4\pi\, m_{DM}\, \tau_{DM}} \int_0^\infty \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu} [(1+z)E_\nu]\, dz$$



J. Stettner PoS(ICRC2017) 923

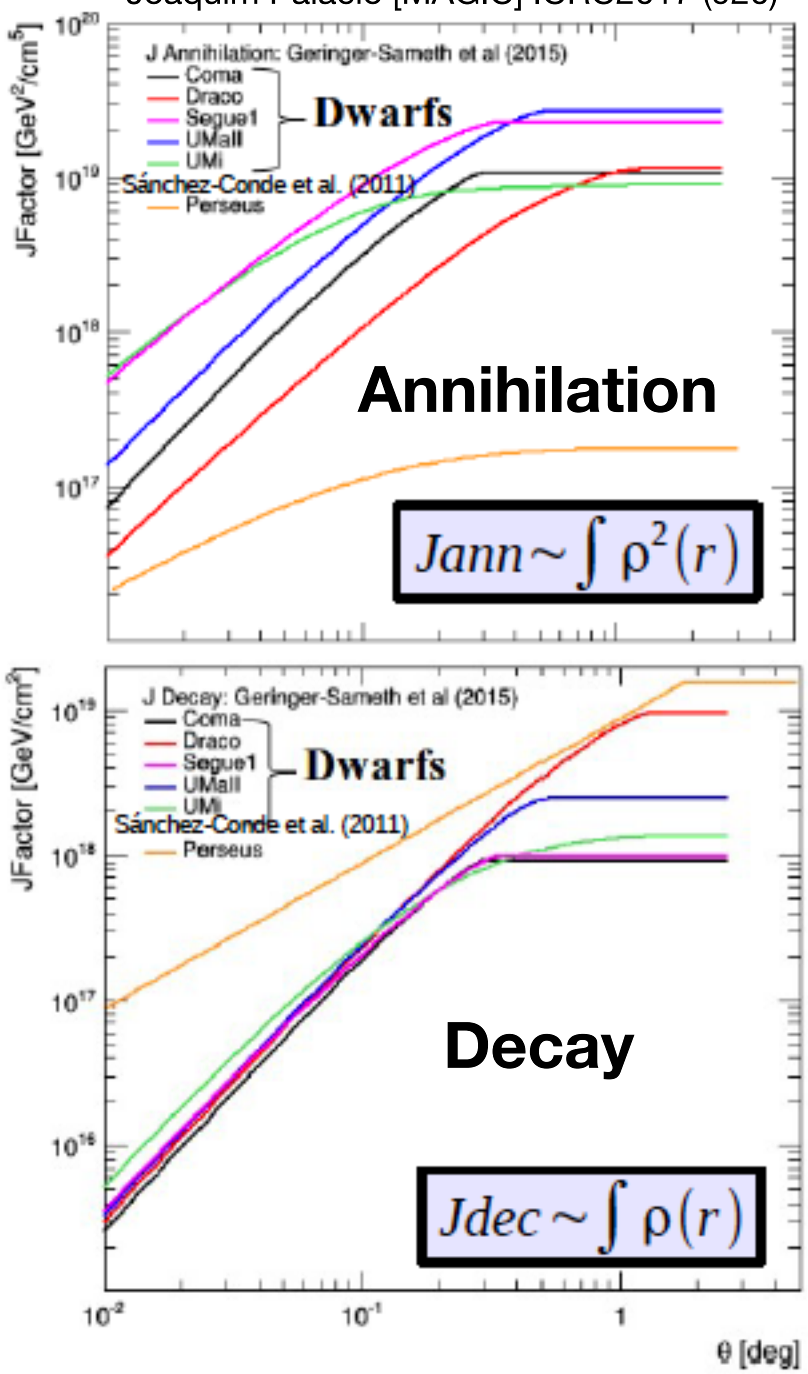


Test-Statistic: $TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM}=\infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$

Bound on DM lifetime up to $10^{27.5}$s obtained with IceCube data for m_{DM}>100TeV

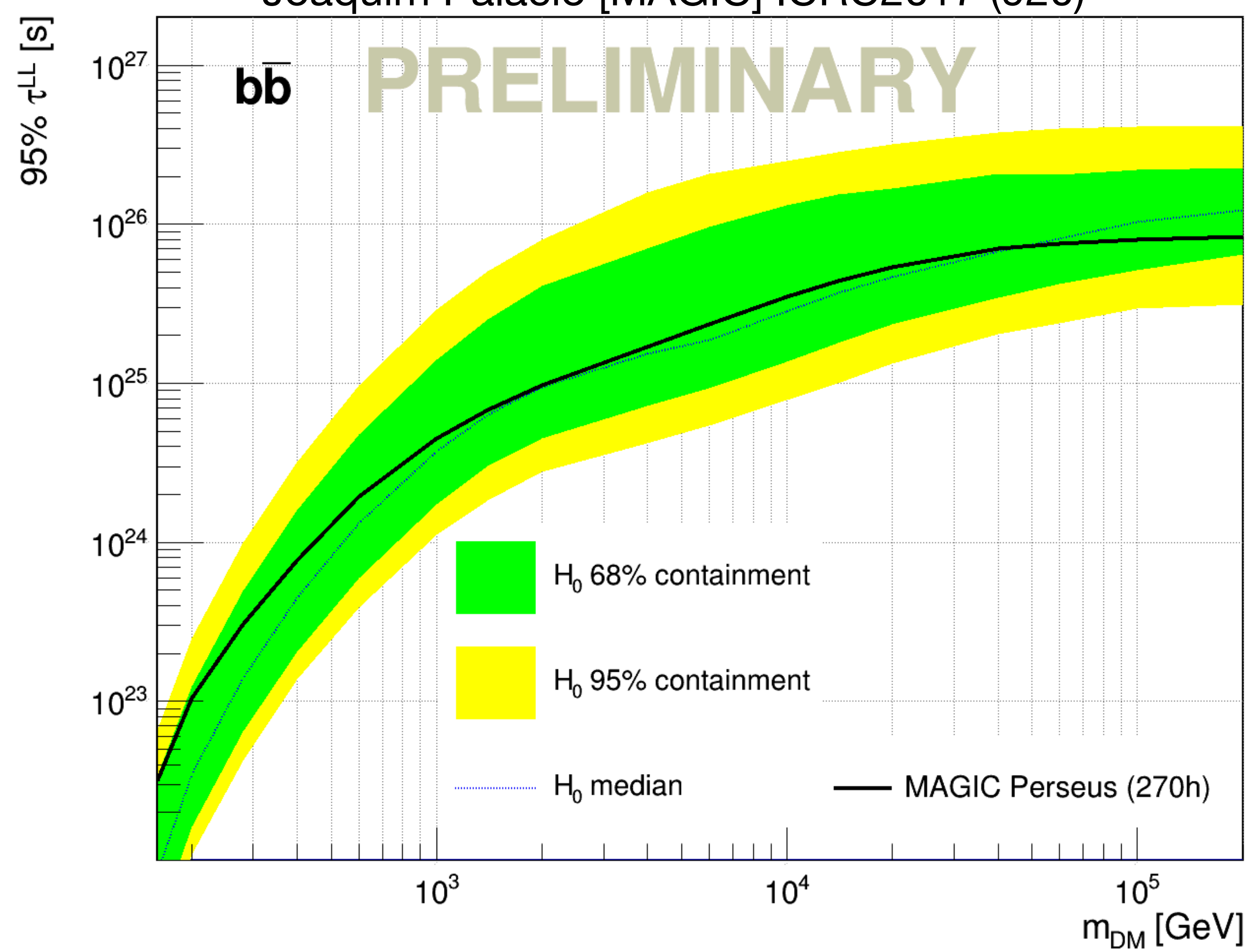
MAGIC - Perseus Cluster

Joaquim Palacio [MAGIC] ICRC2017 (920)



Results from 270h of good quality data (from 2009-2017)

Joaquim Palacio [MAGIC] ICRC2017 (920)

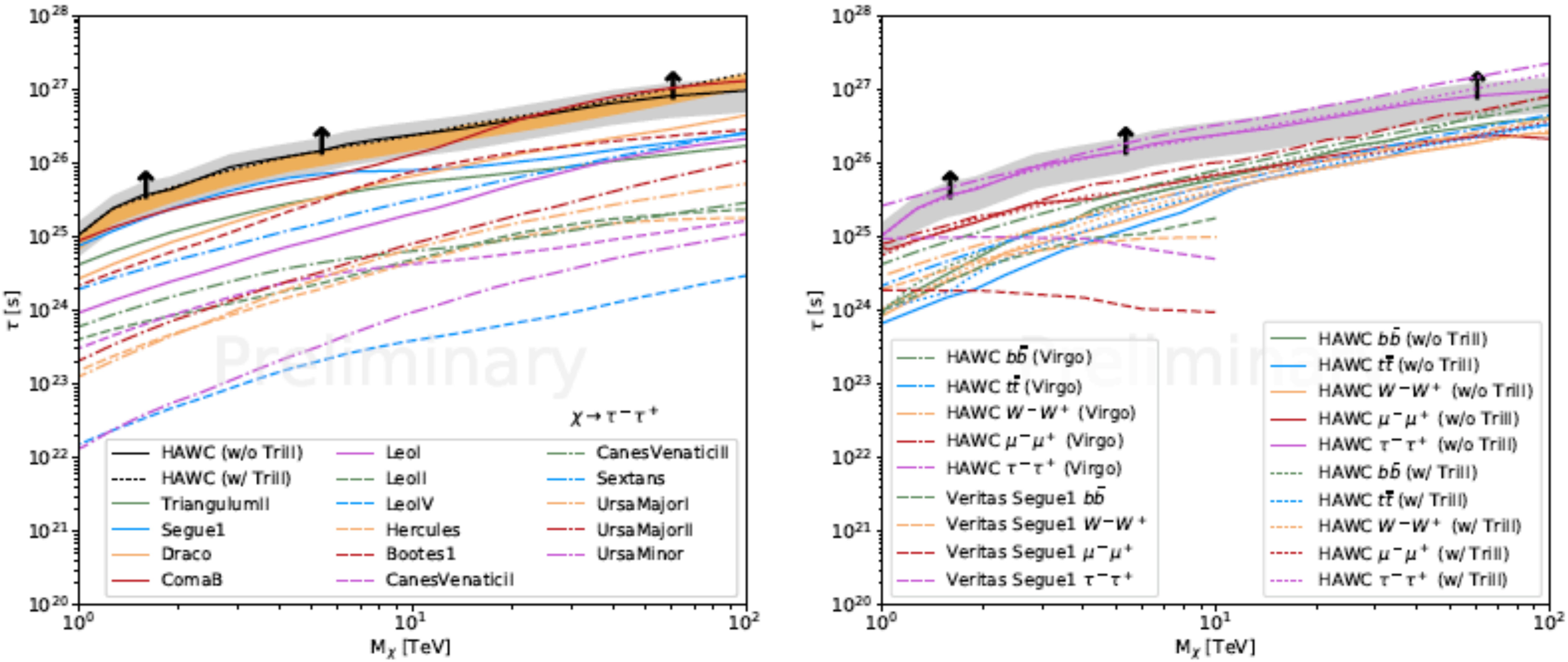


No evidence of dark matter decay observed

Obtain limit on DM life times of ~8 $\cdot 10^{25}$ s for bb and ττ

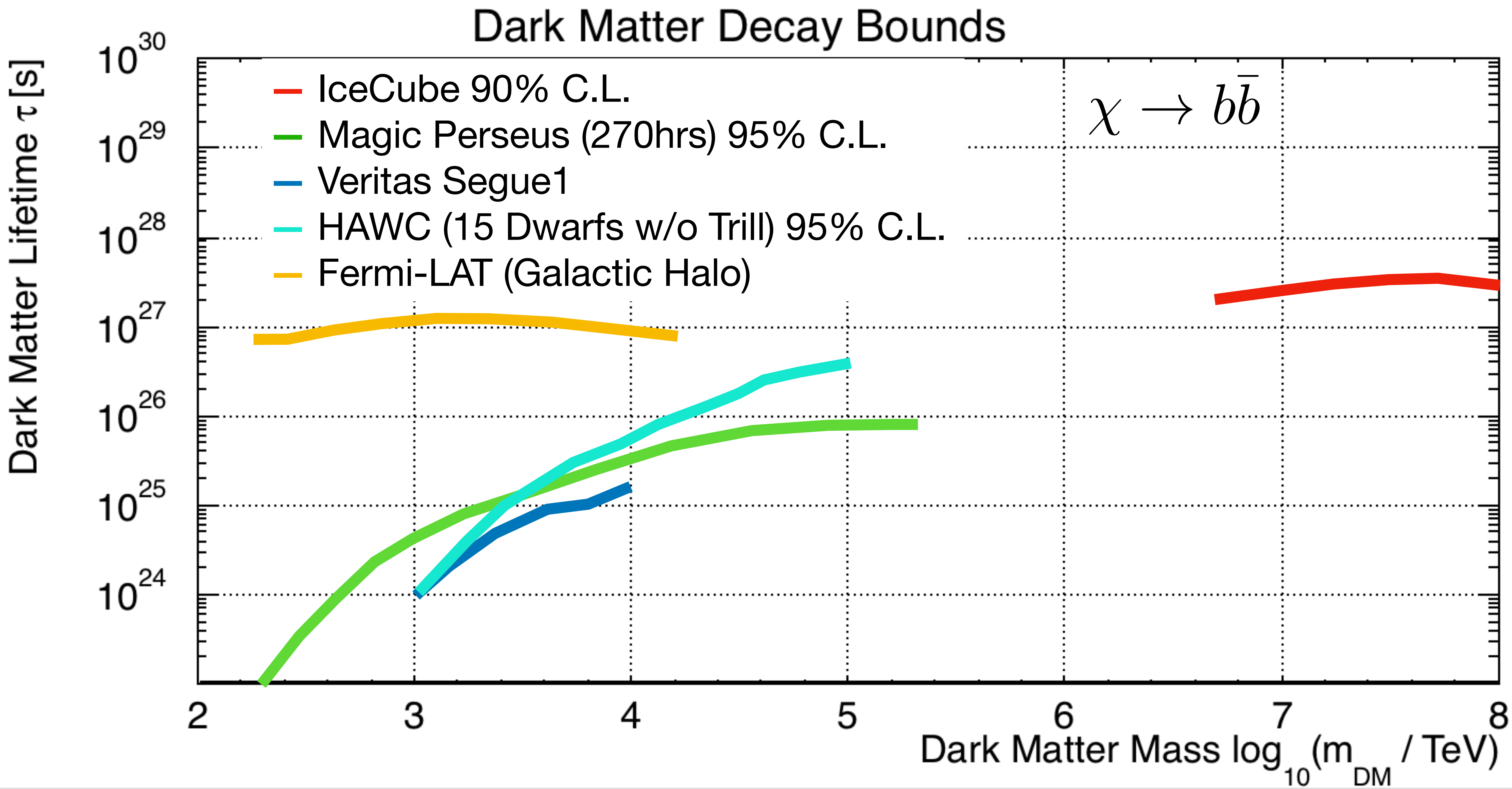
Dark Matter Decay with HAWC

T. Yapici [HAWC] ICRC2017 (891)



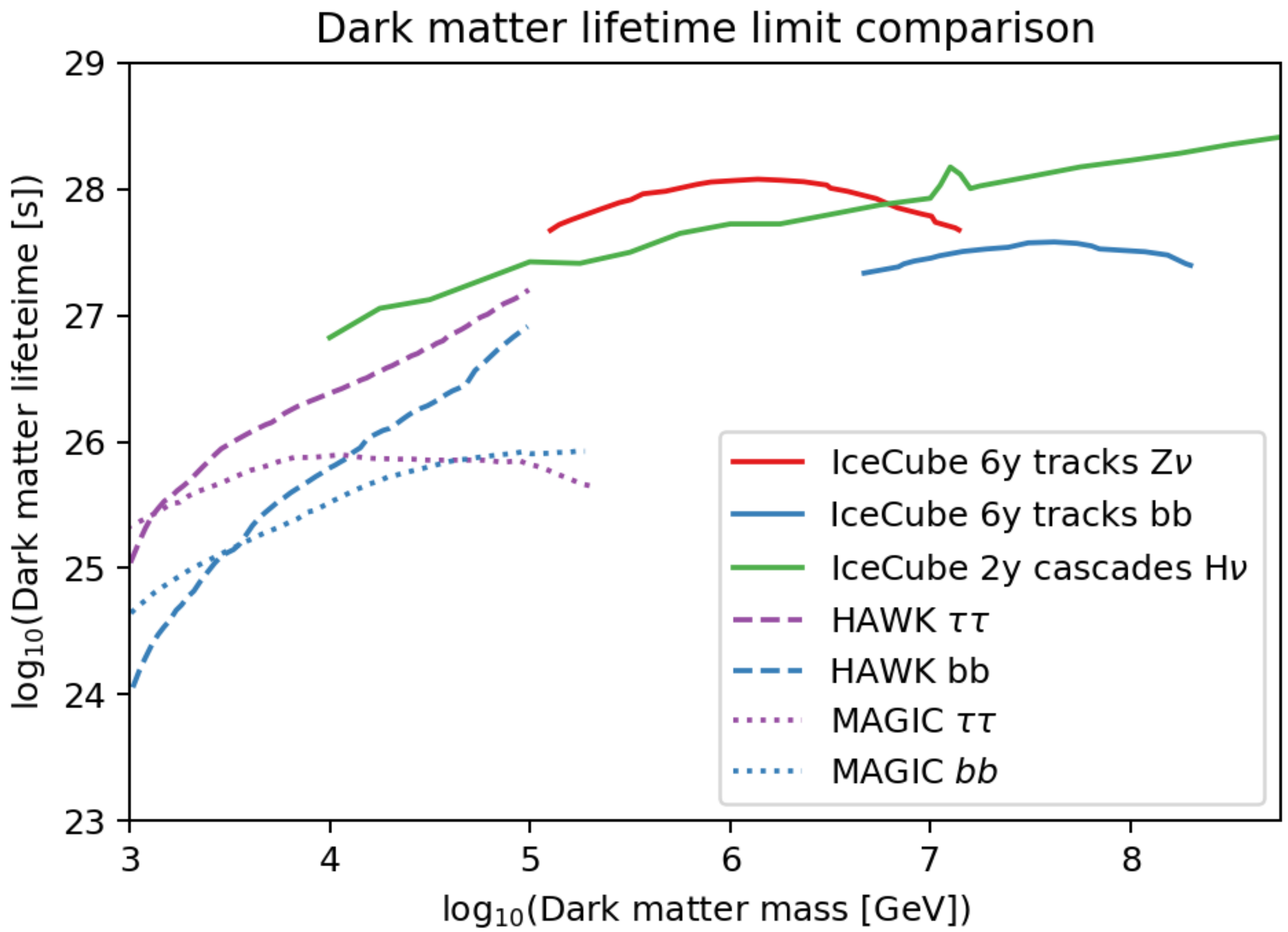
Results for 15 dSph, Virgo Cluster and M31

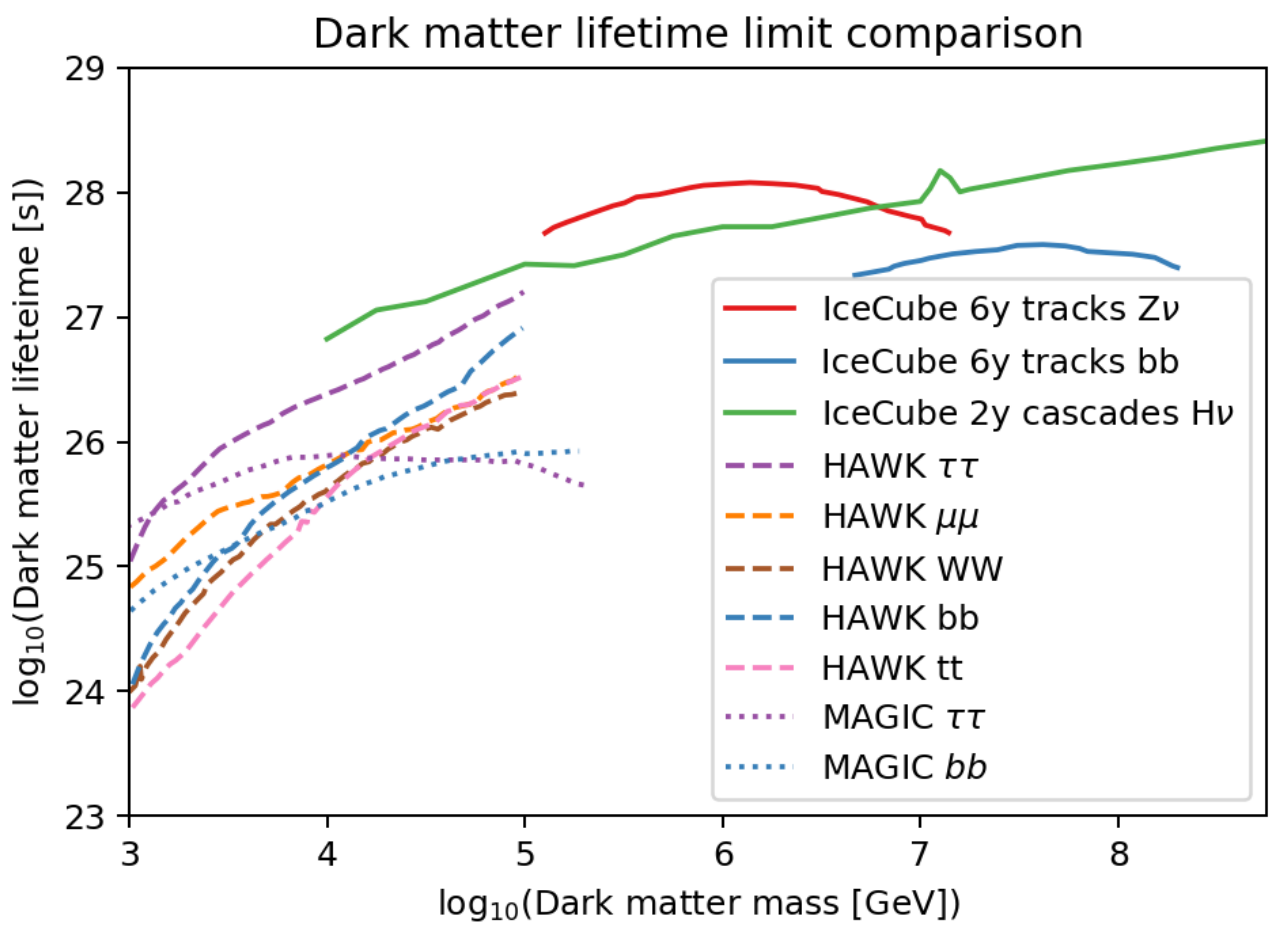
Dark Matter Decay Bounds



see also Fermi-LAT Astrophys.J. 761 (2012) 91

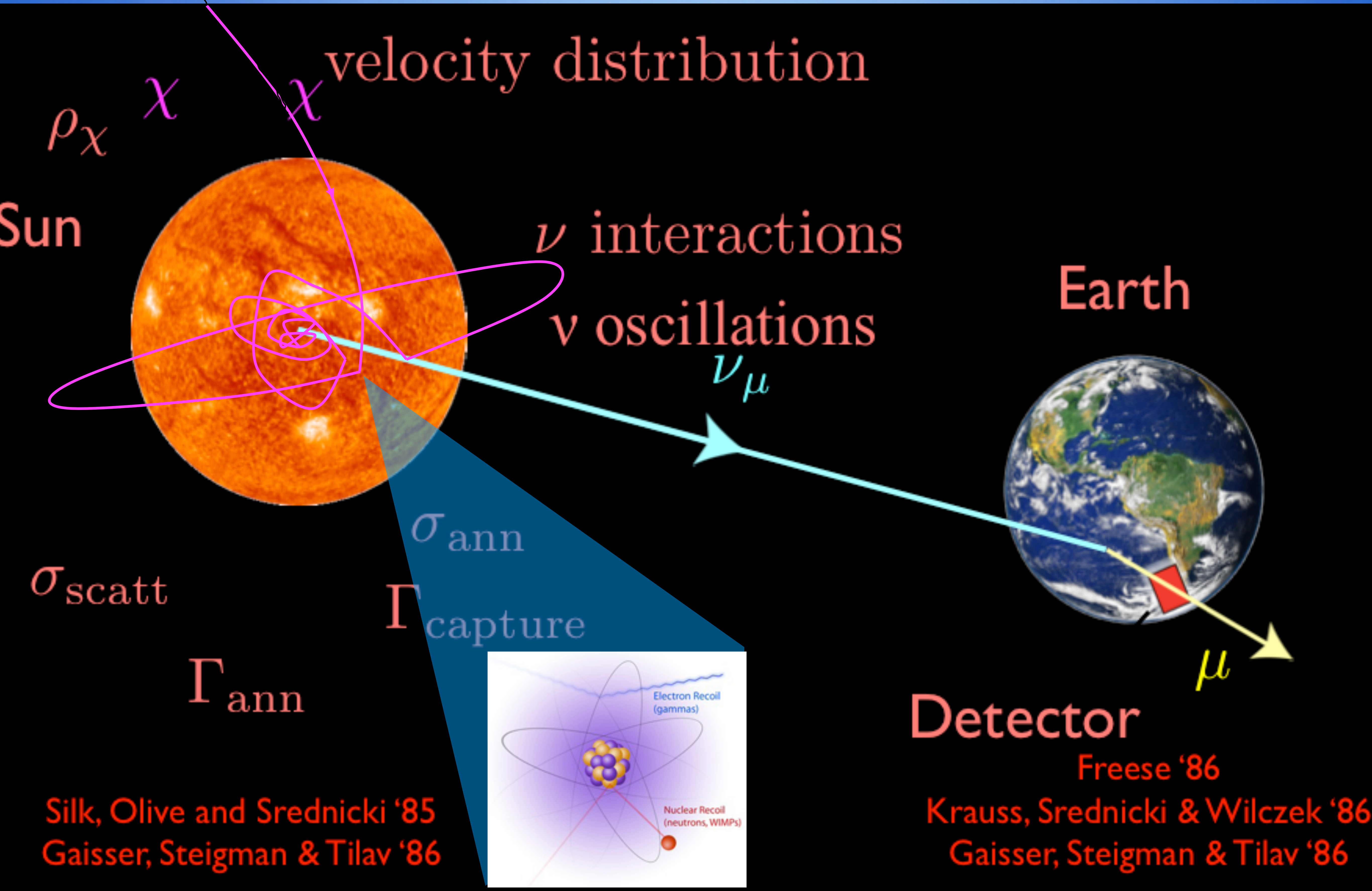
Dark Matter Decay Bounds



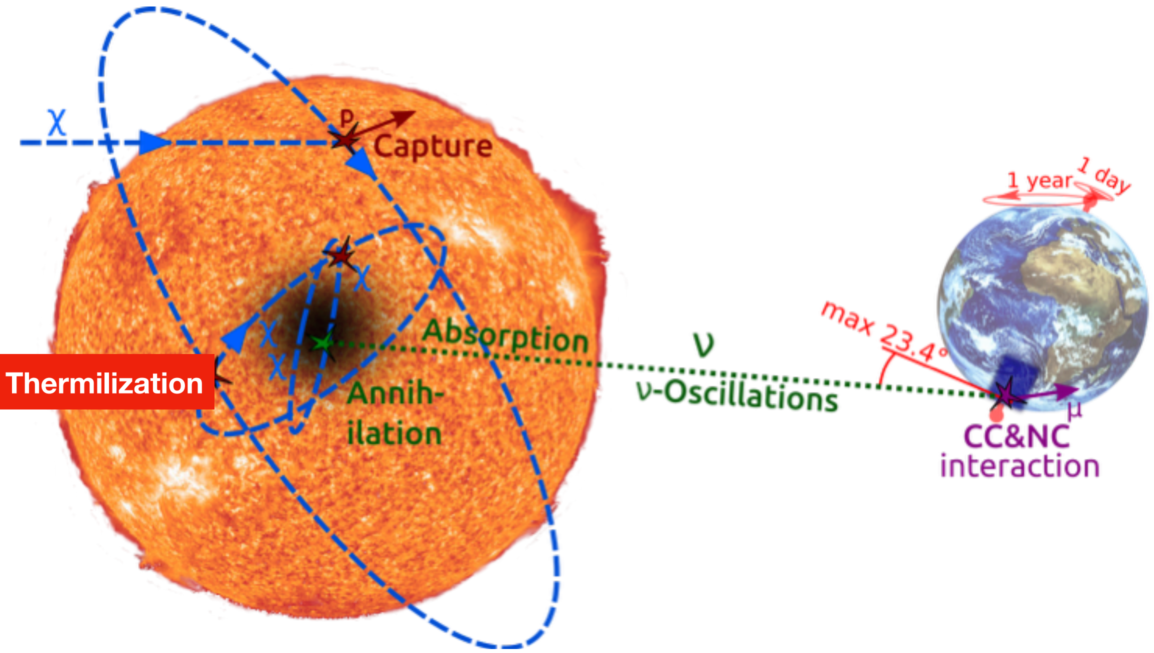


Solar Dark Matter Searches

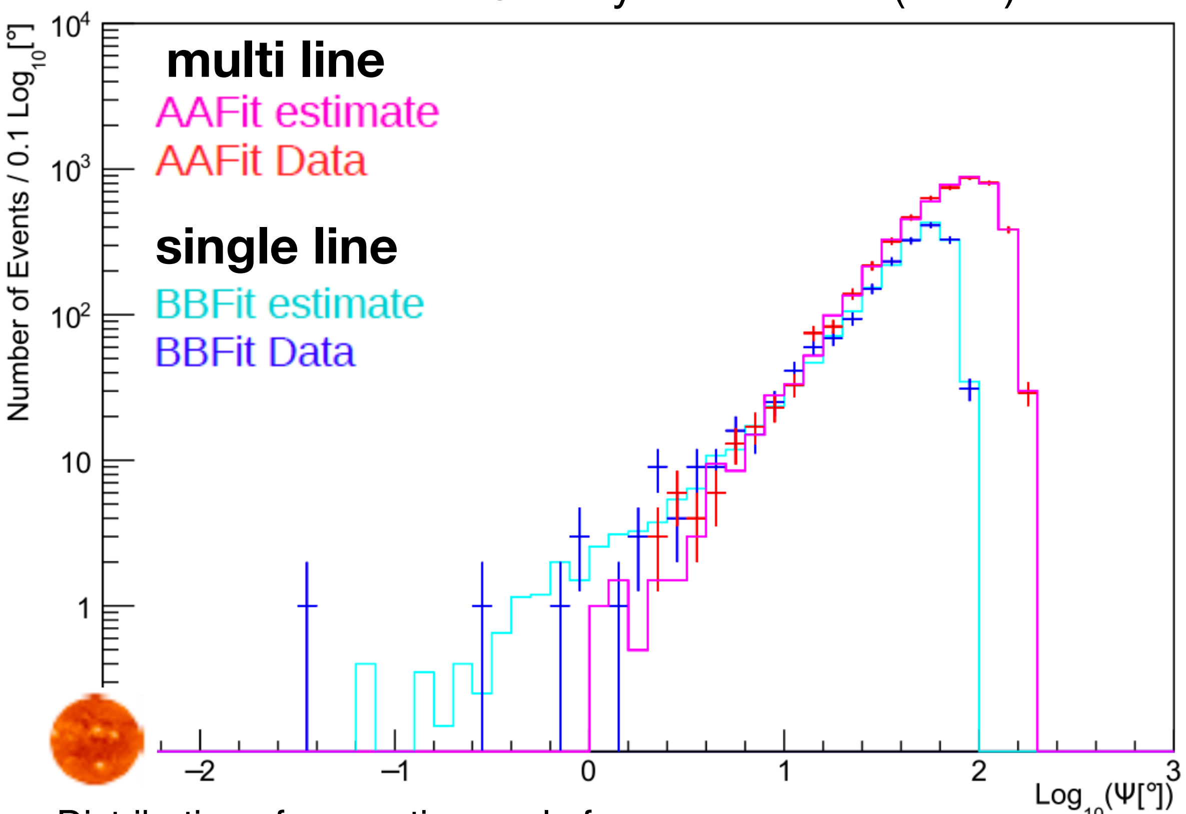
Solar Dark Matter



Solar Dark Matter - IceCube/ANTARES

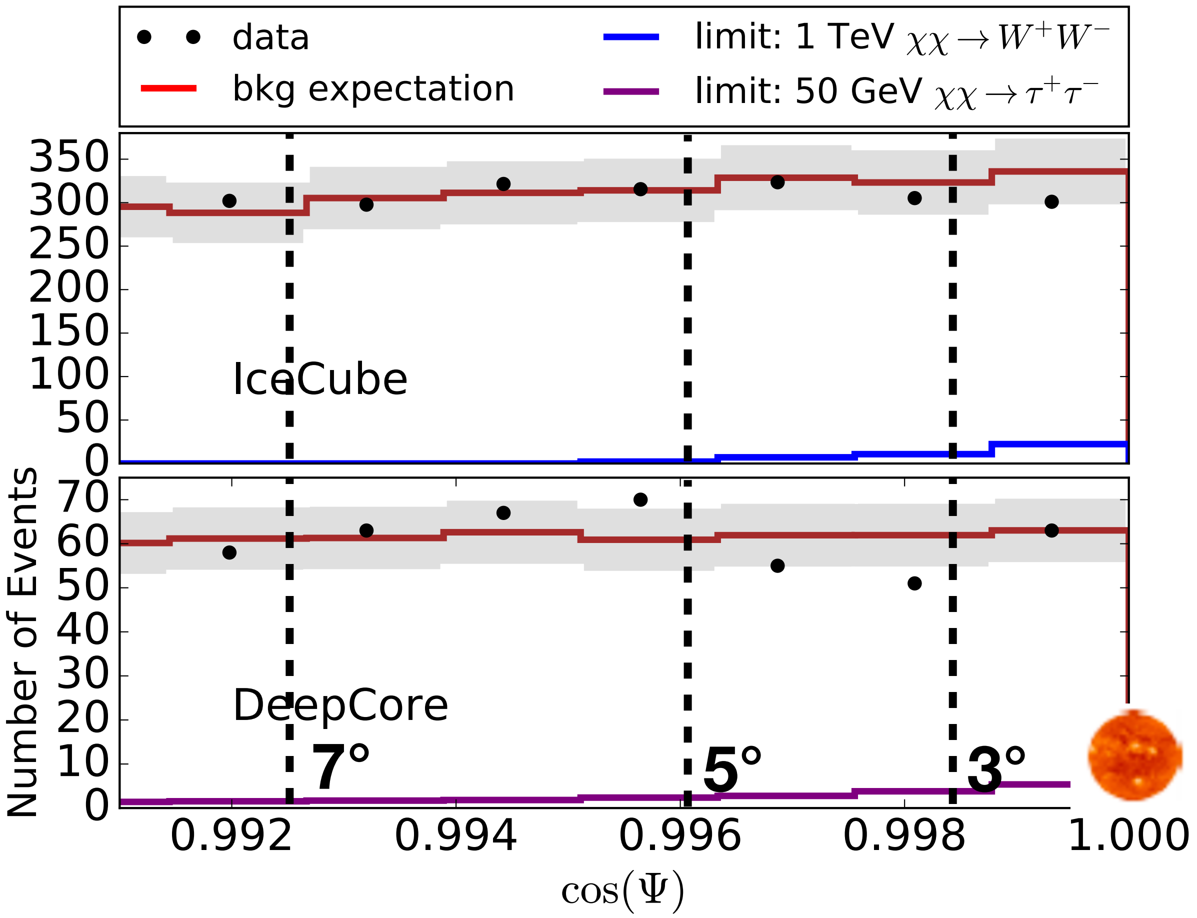


ANTARES - Phys.Lett. B759 (2016) 69-74



Distribution of separation angle for 2007-2012 ANTARES data

IceCube Eur.Phys.J. C77 (2017) no.3, 146

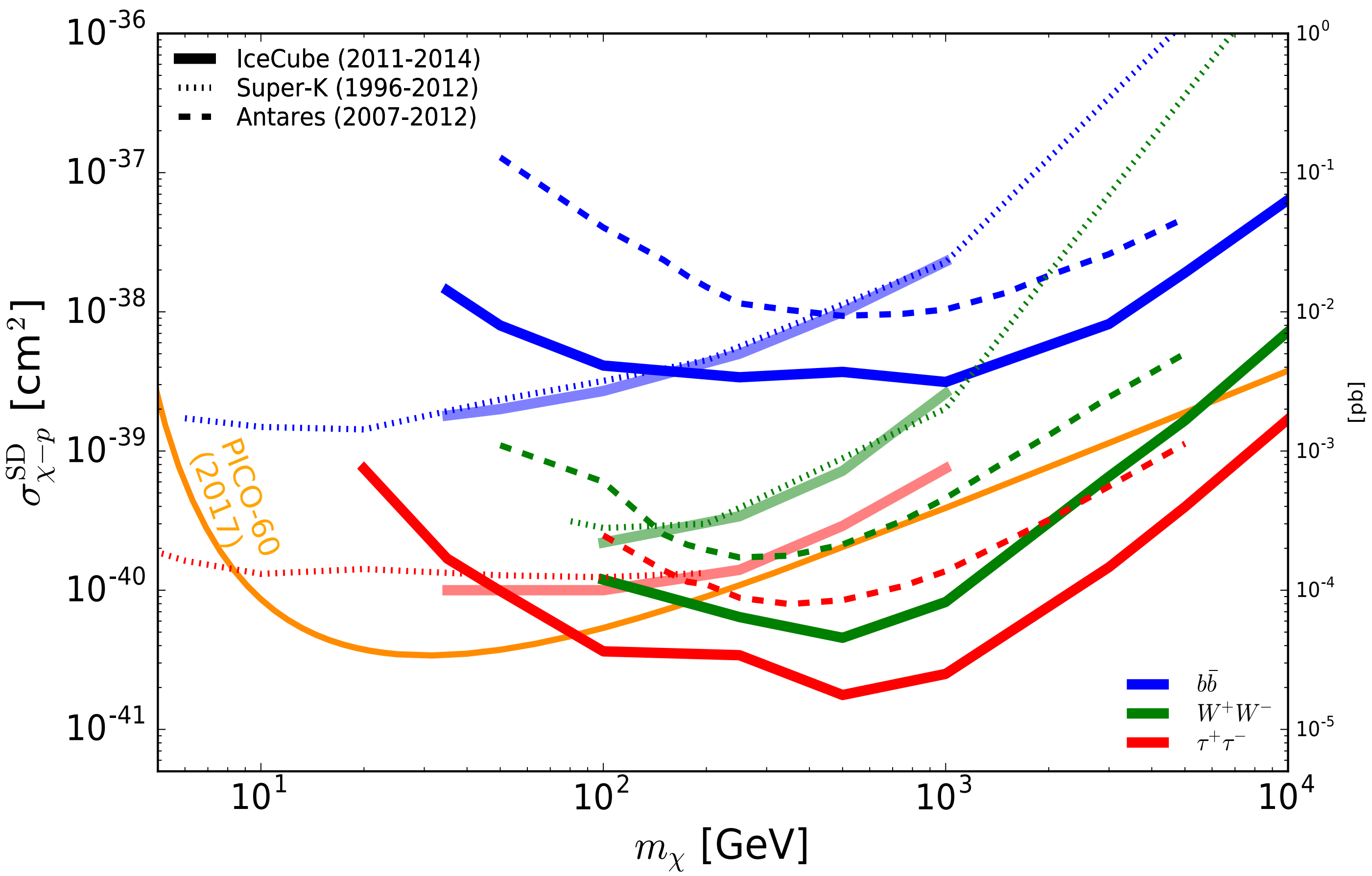


- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data

Solar Dark Matter - IceCube/ANTARES

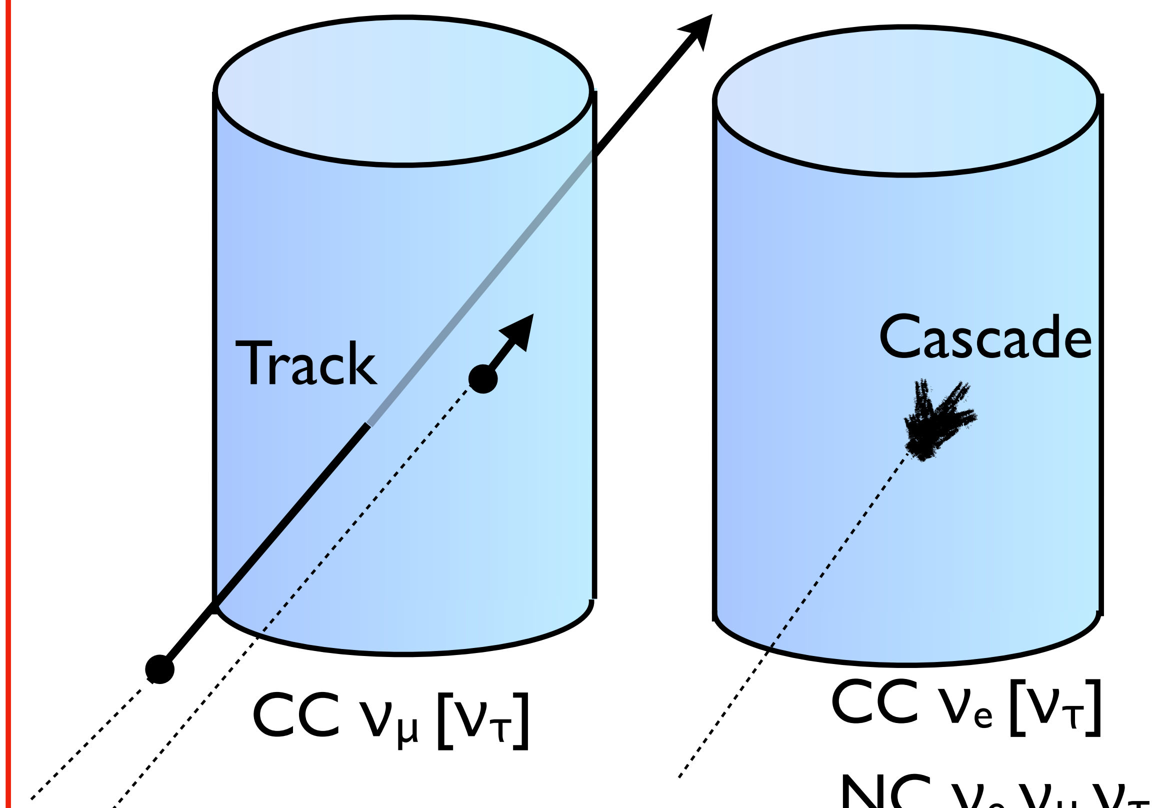
- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

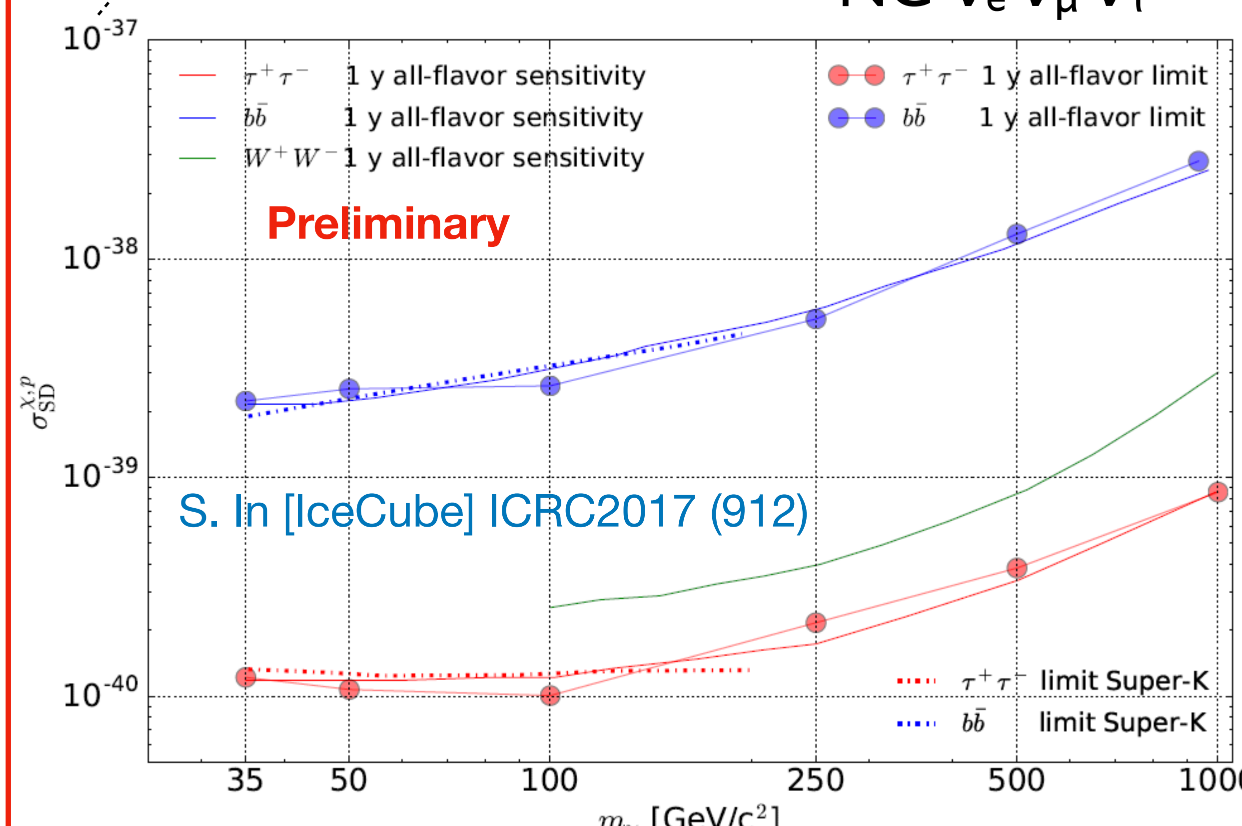
IceCube Eur.Phys.J. C77 (2017) no.3, 146



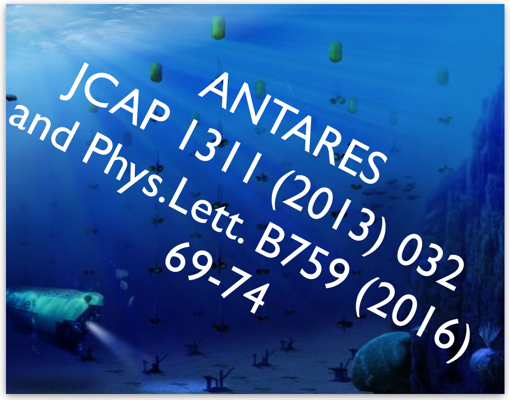
Solar WIMPs
- ANTARES - Phys.Lett. B759 (2016) 69-74
- IceCube Eur.Phys.J. C77 (2017) no.3, 146
- S. In and K. Wiebe [IceCube] ICRC2017 (912)

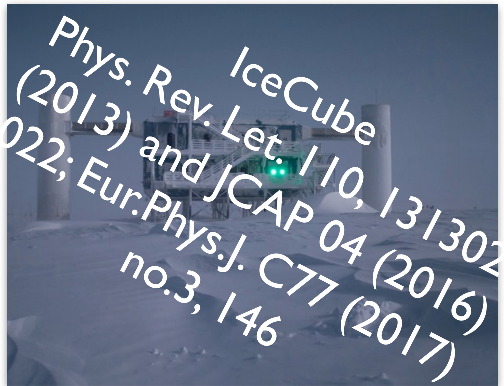
All flavor Solar WIMP - IceCube

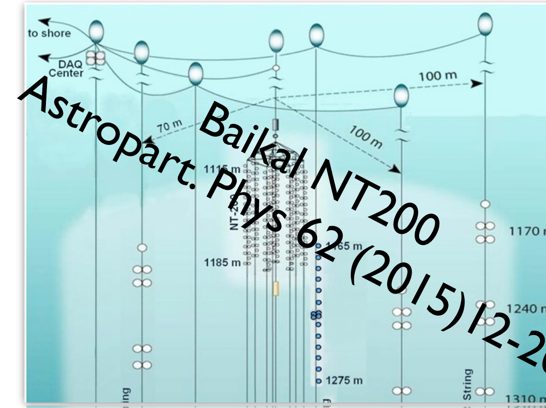




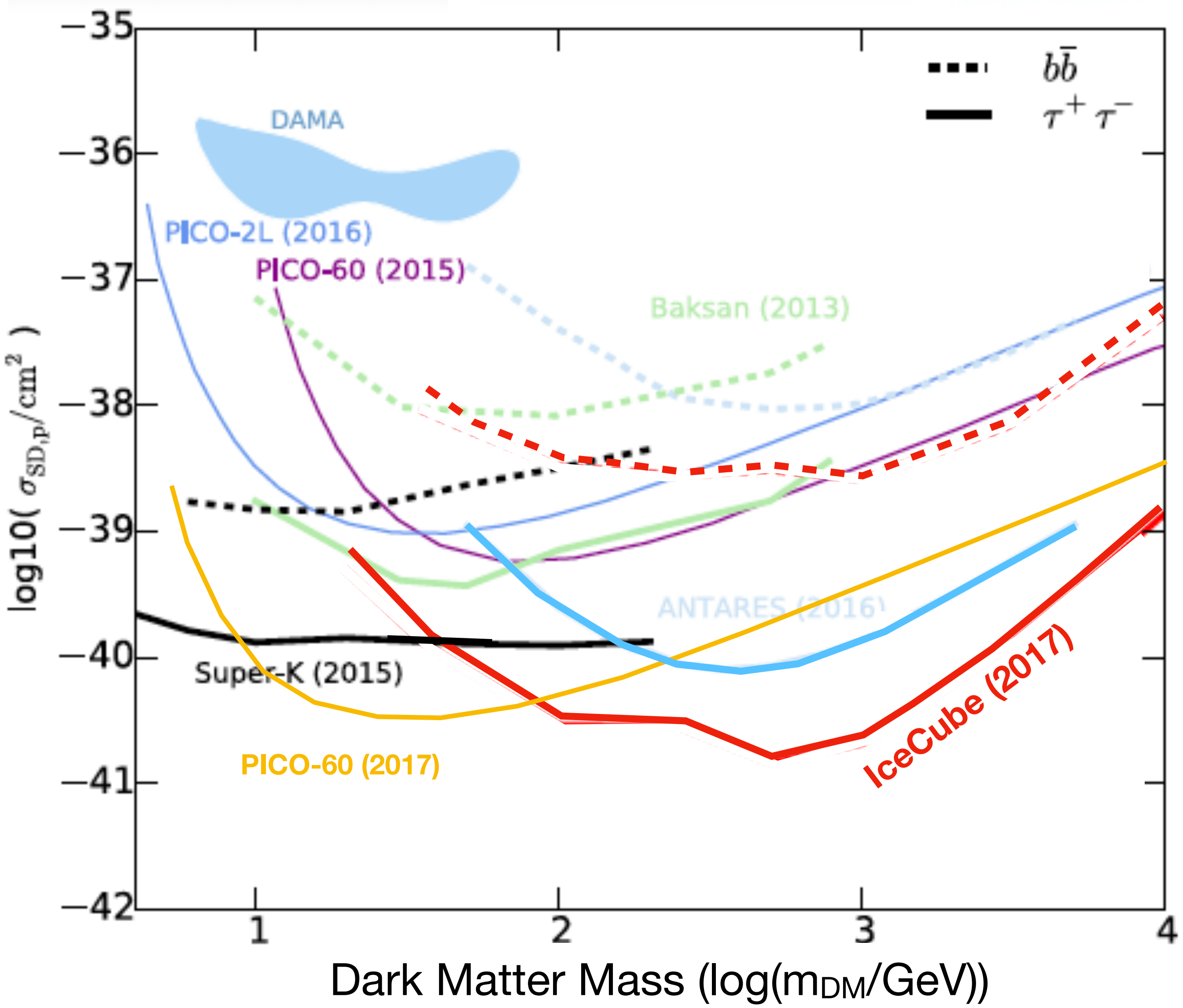
Solar Dark Matter Summary



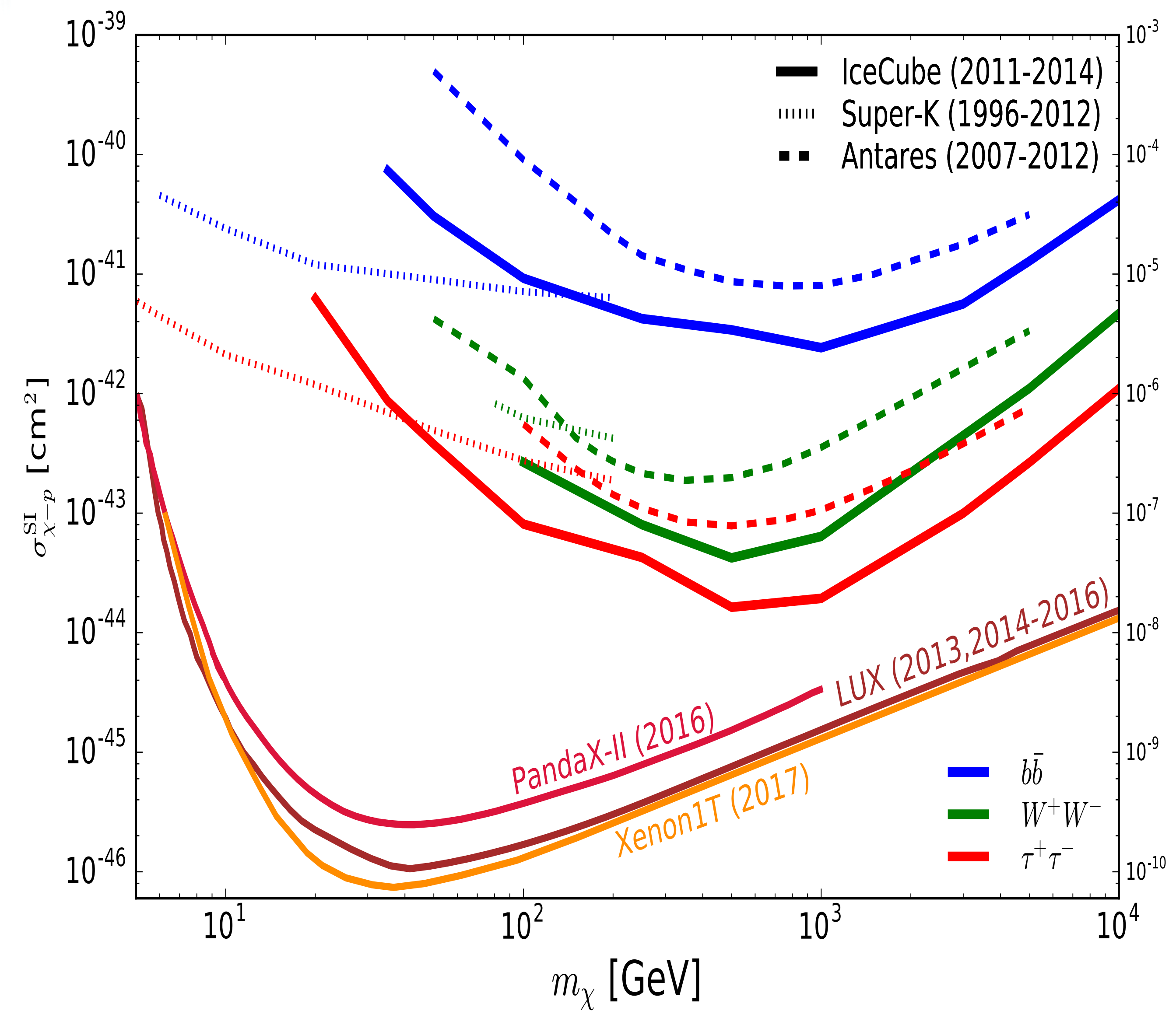




Spin-dependent scattering

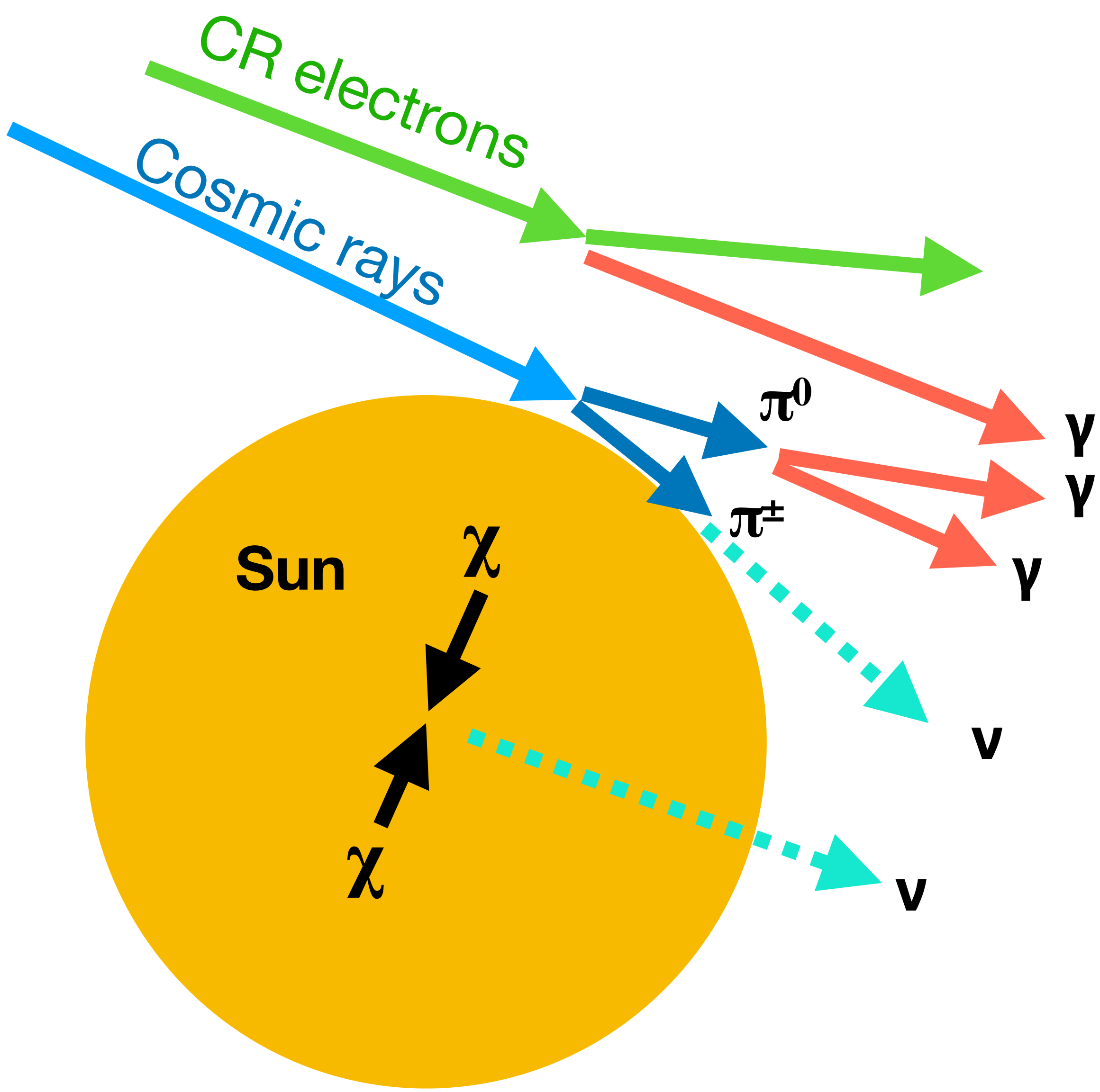


Spin-independent scattering

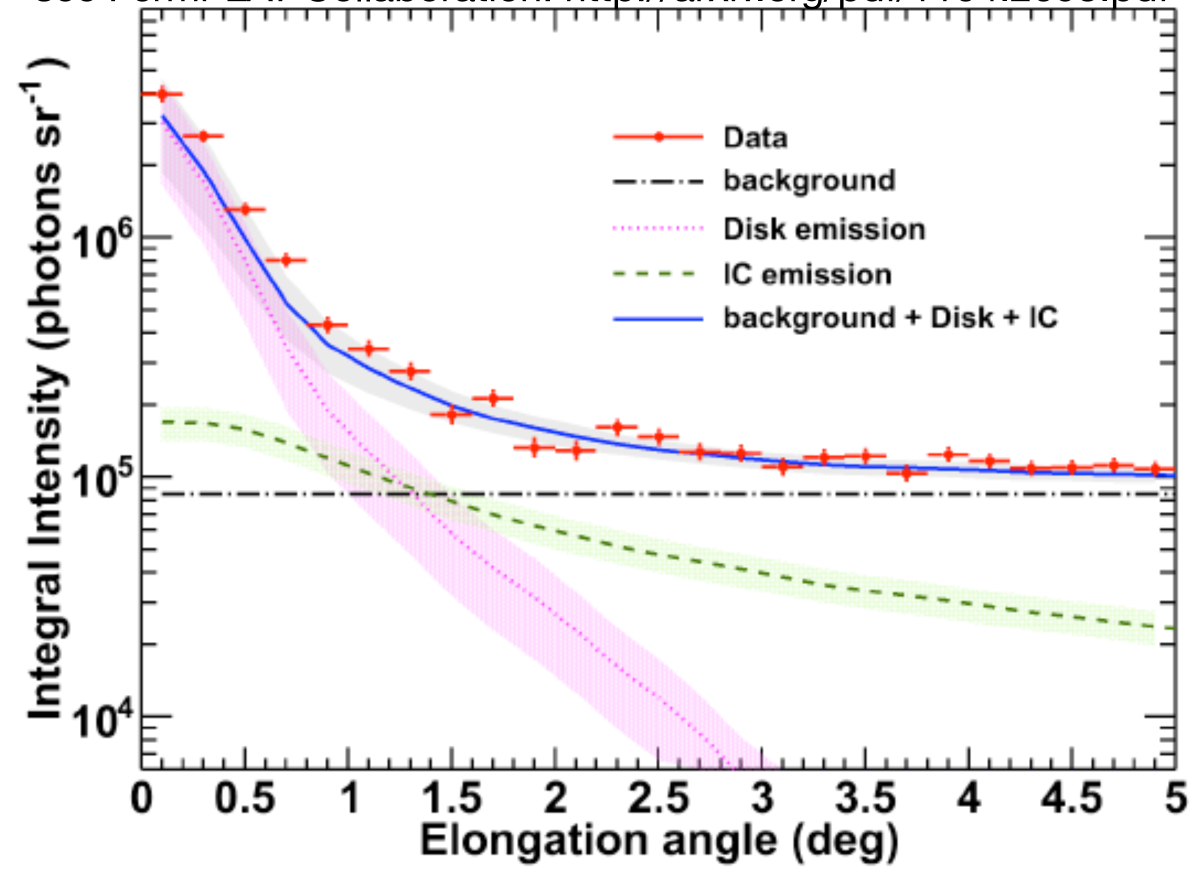


Solar Atmospheric Neutrino Floor

Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: http://arxiv.org/pdf/1104.2093.pdf



- CR interaction in the Solar atmosphere result produce gamma-rays and neutrinos
- Background to dark matter search from the Sun, that soon will be relevant (and first high-energy neutrino point source ??)

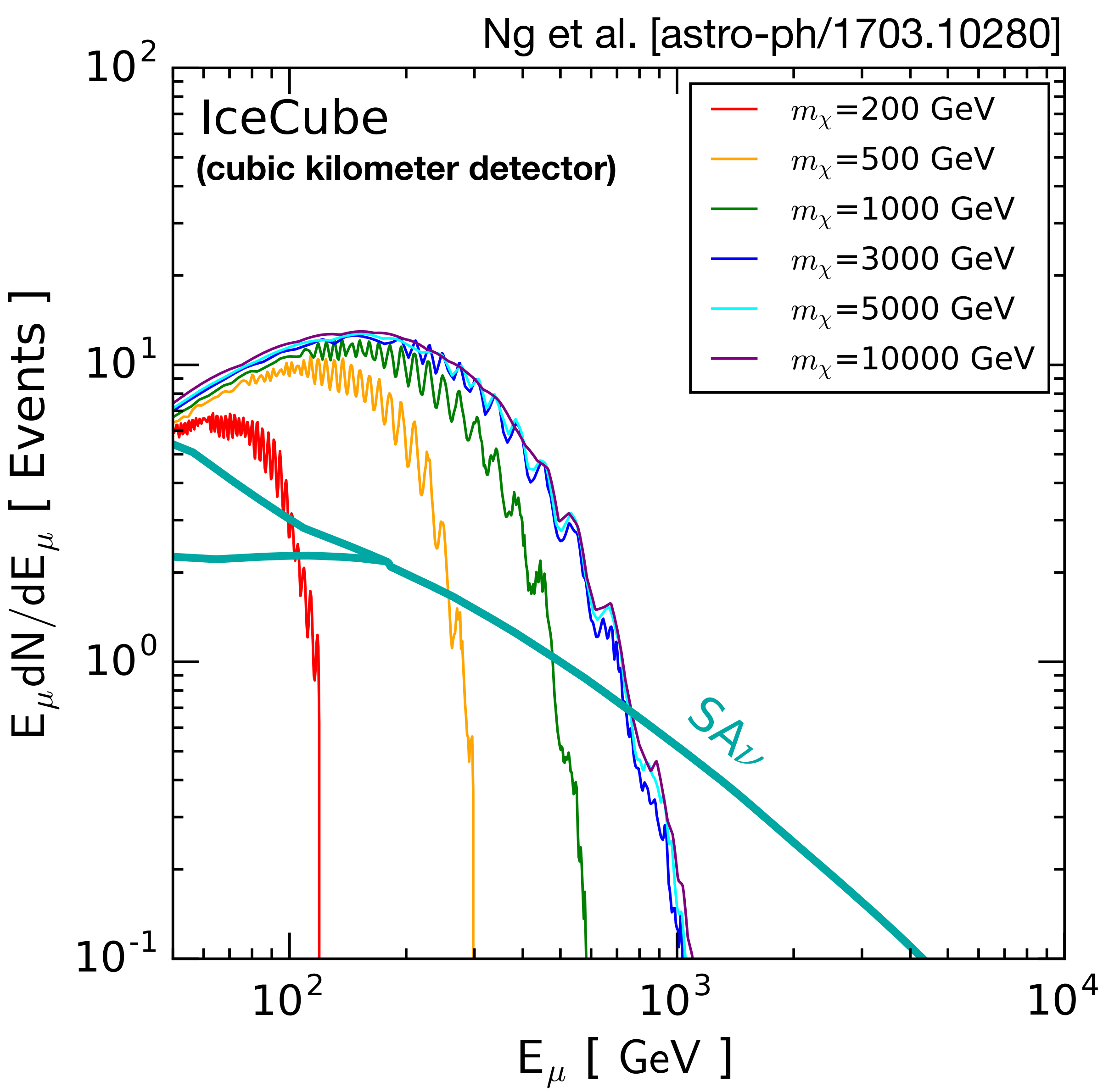
Leptonic

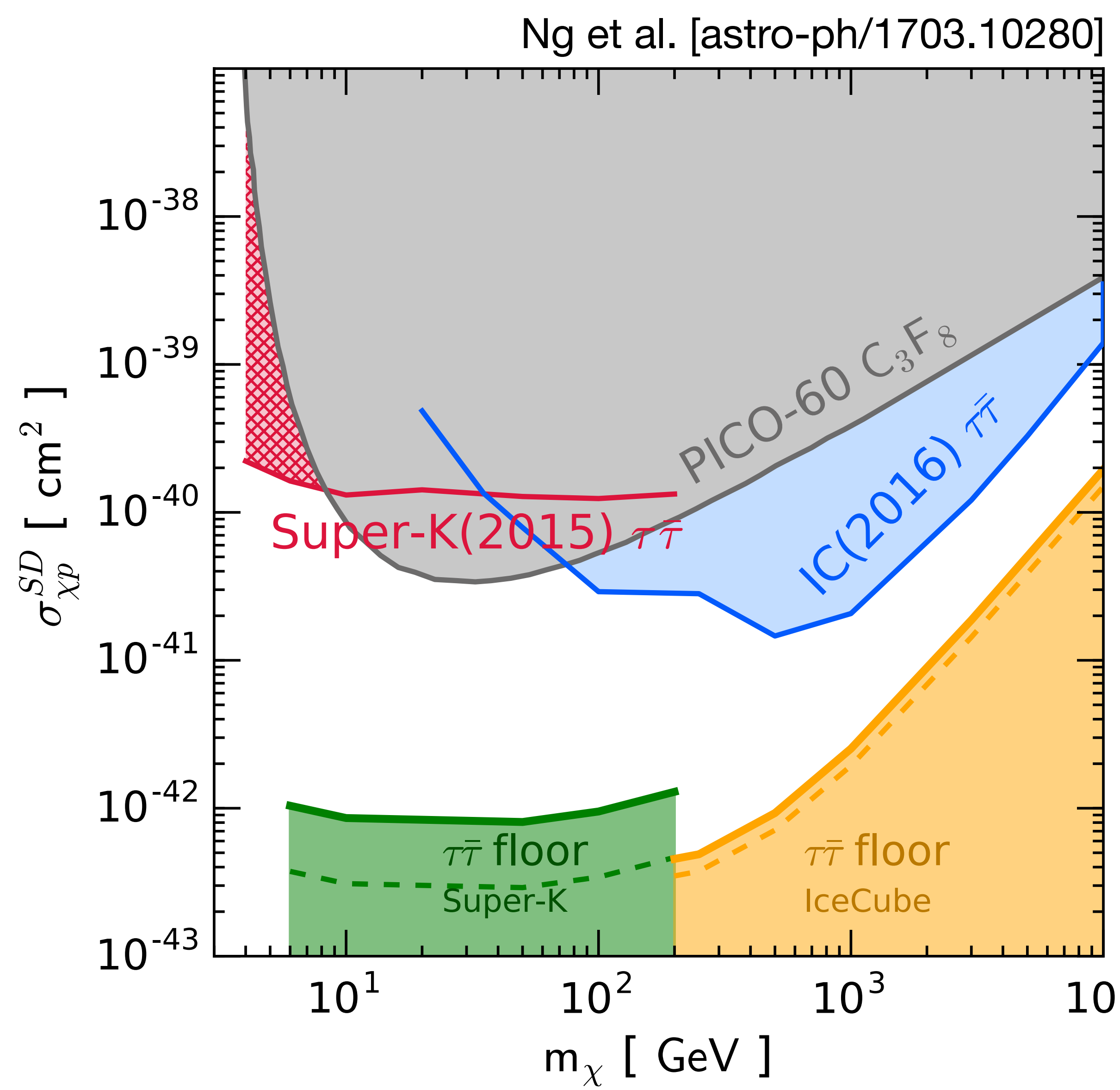
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic

- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

Cosmic background from the Sun





- Natural background to Solar Dark Matter Searches !
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2events per year at cubic kilometer detector

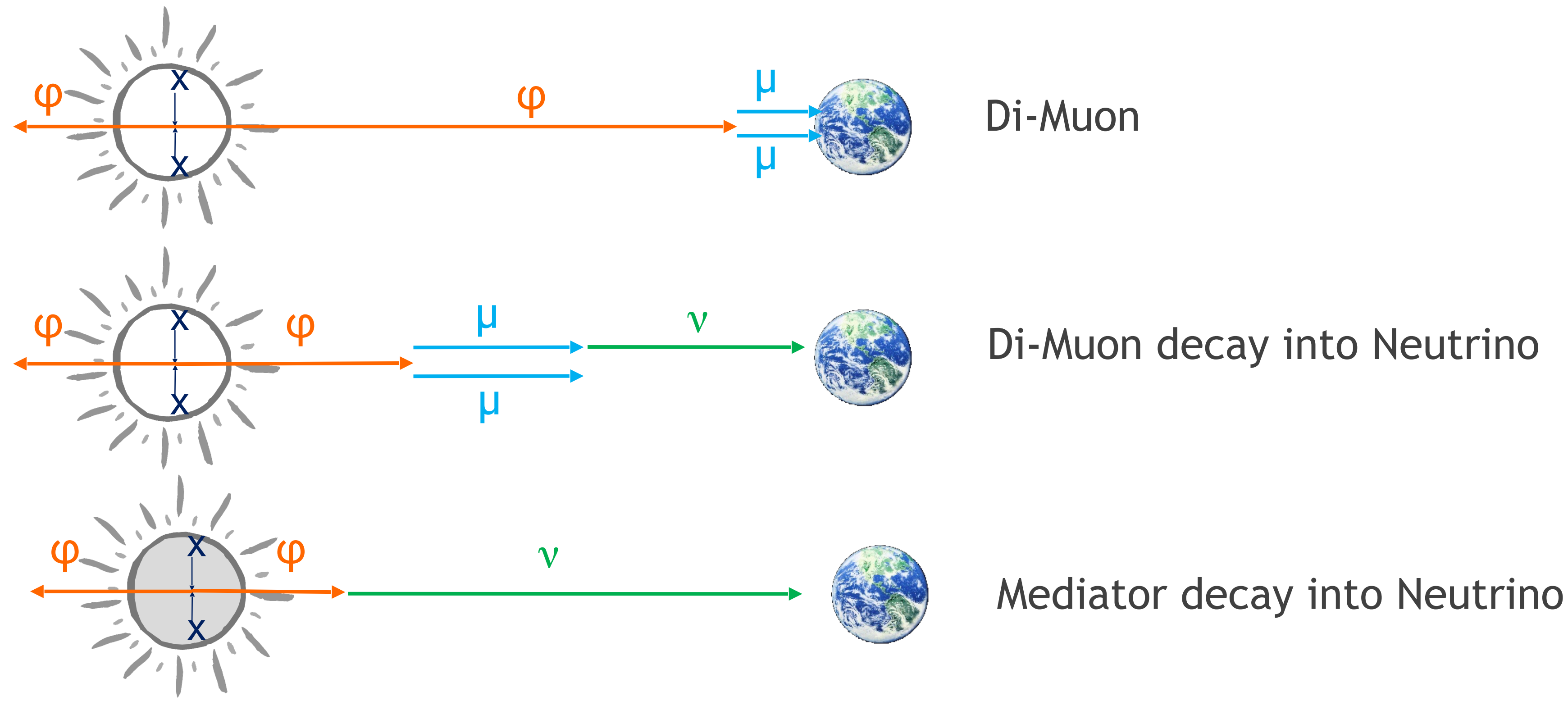
Recent works on the Solar Atmospheric Neutrino Floor

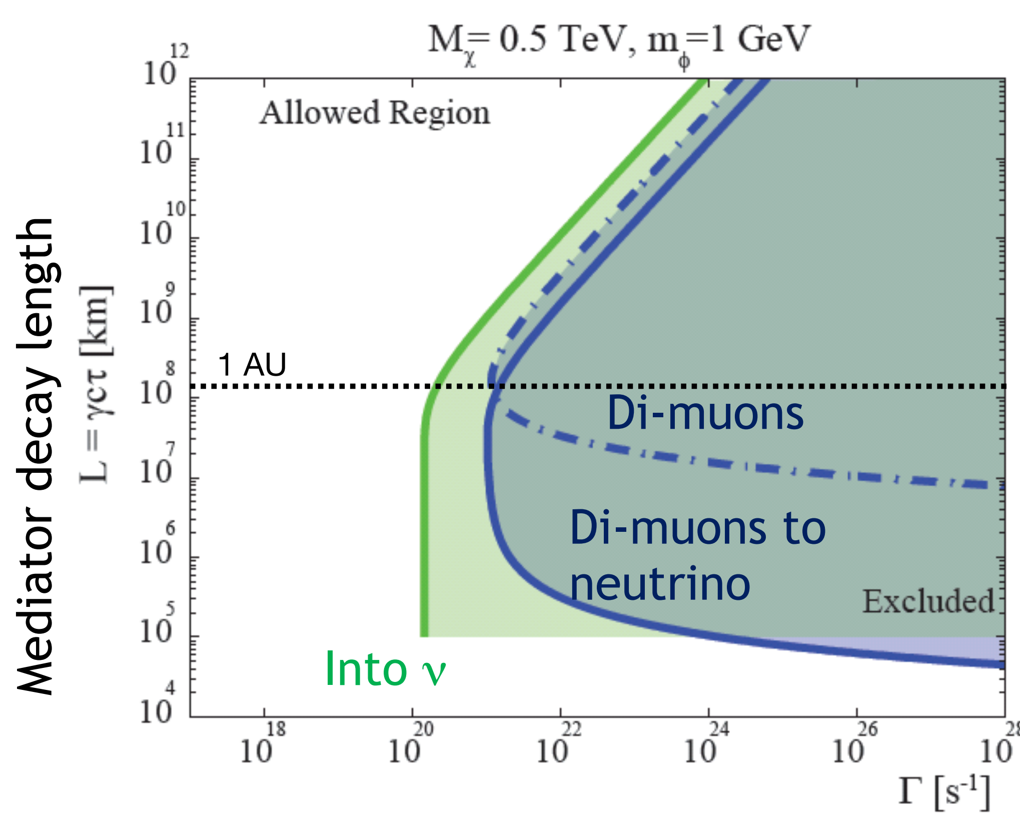
- Argüelles et al. [astro-ph/1703.07798]
- Ng et al. [astro-ph/1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, JCAP 2017 .06 (2017), p. 033, [astro-ph/1704.02892]
- M. Masip (2017), [hep-ph/1706.01290]

ANTARES Coll. JCAP 1605 (2016) no.05, 016

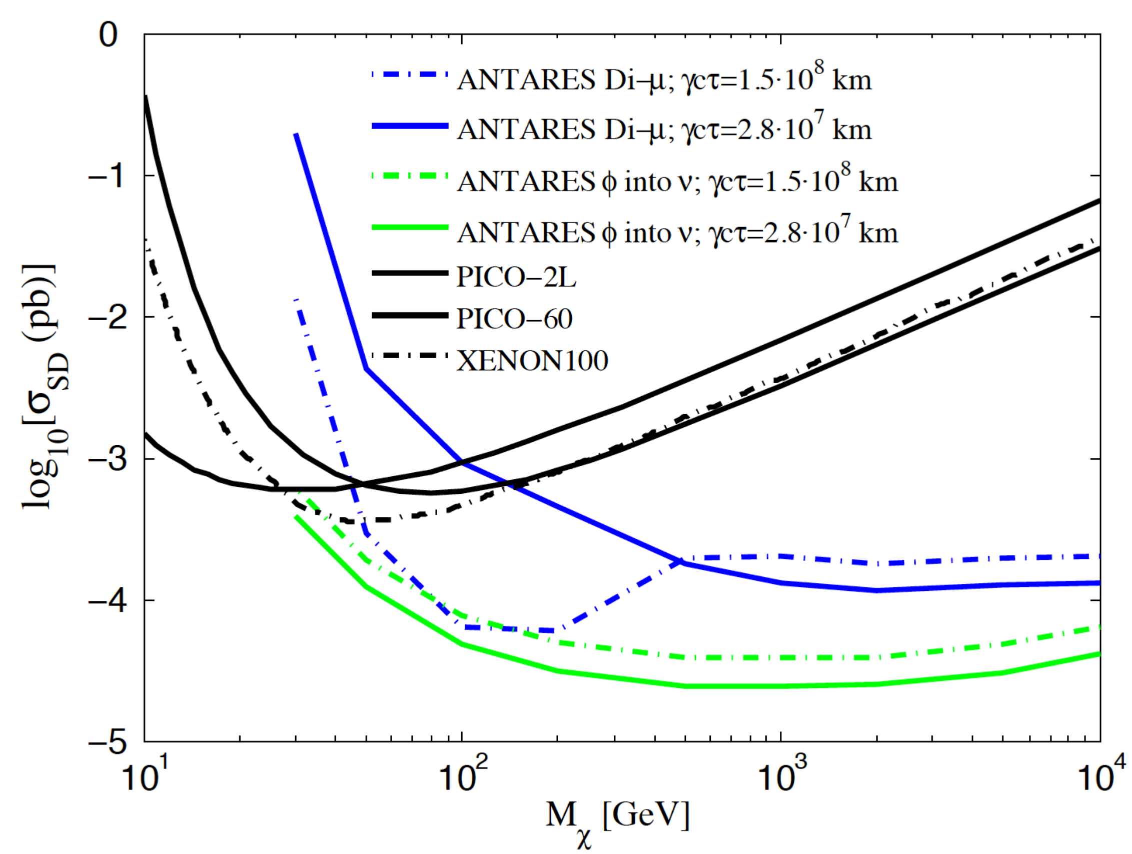
ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
  - χχ annihilates into mediator ϕ
    - ϕ → νν or μμ
- Livetime of 1321 days (Jan 2007 to Oct 2012)



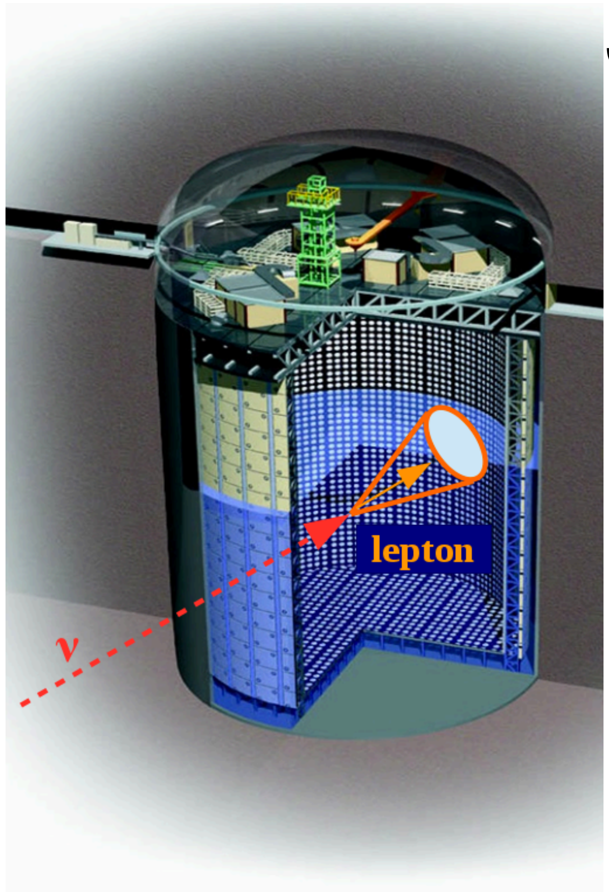


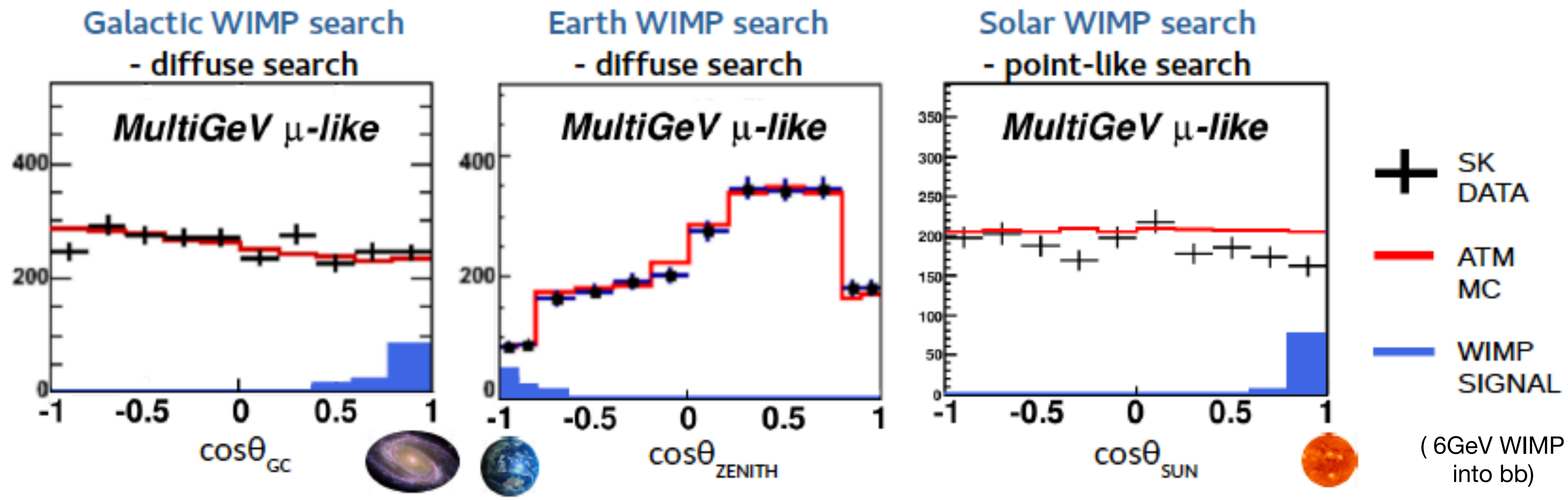
Annihilation of DM in the Sun x Branching ratio



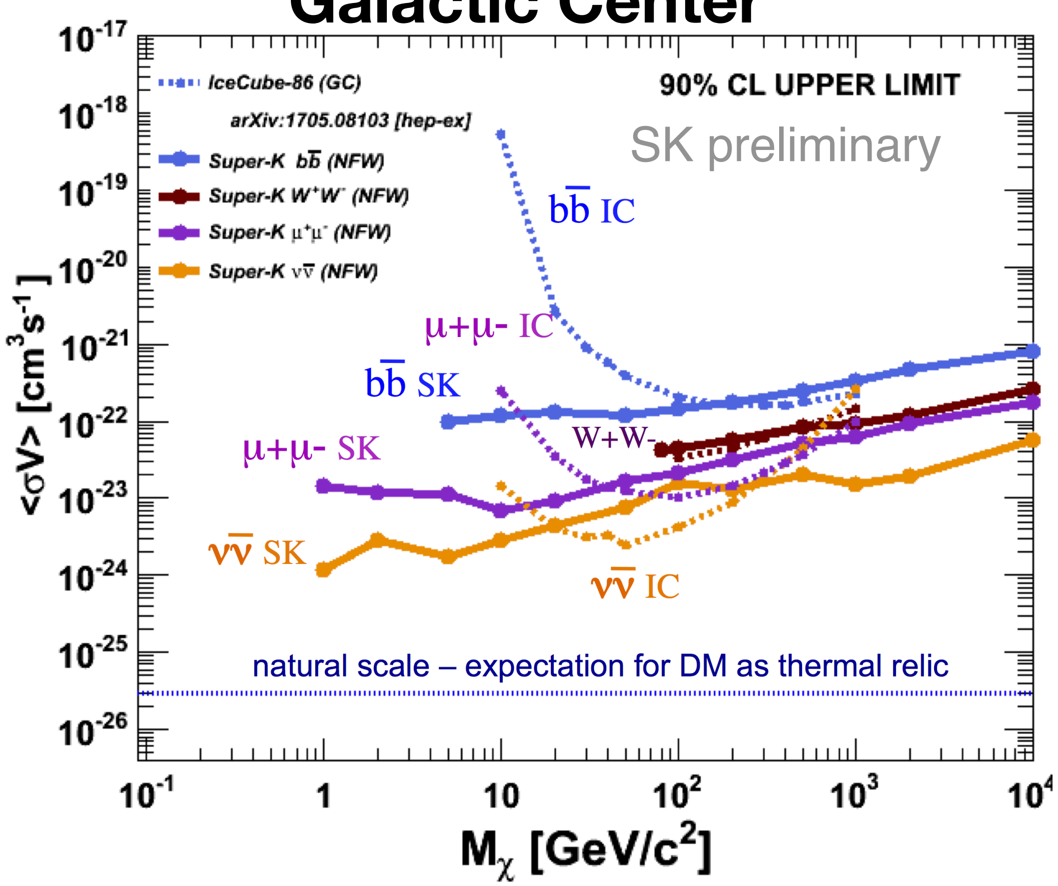
Piotr Mijakowski

Super-K Dark Matter Searches





Galactic Center



Earth WIMPs