Fundamental physics and X-ray astrophysics

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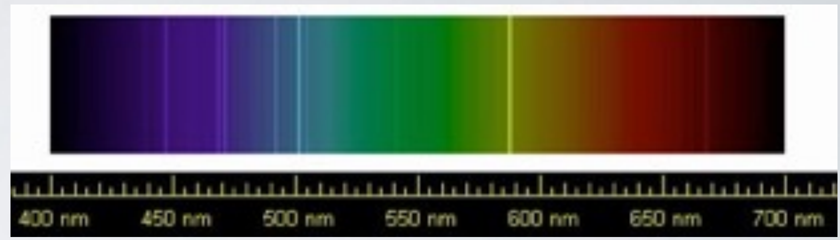
PROLOGUE
(FOR SKEPTICS)

FINDING NEW PHYSICS FROM ASTROPHYSICS?

History would invite us to be optimists!

1868: soon after new tool (spectroscopy) introduced in astro, *new "particle"* (atom) identified *first via astrophysics*: **He** in solar spectrum (***Janssen** & **Lockyer*****) only discovered on Earth in 1882 (by Neapolitan physicist Luigi Palmieri, in Vesuvius lava)

587.49 nm

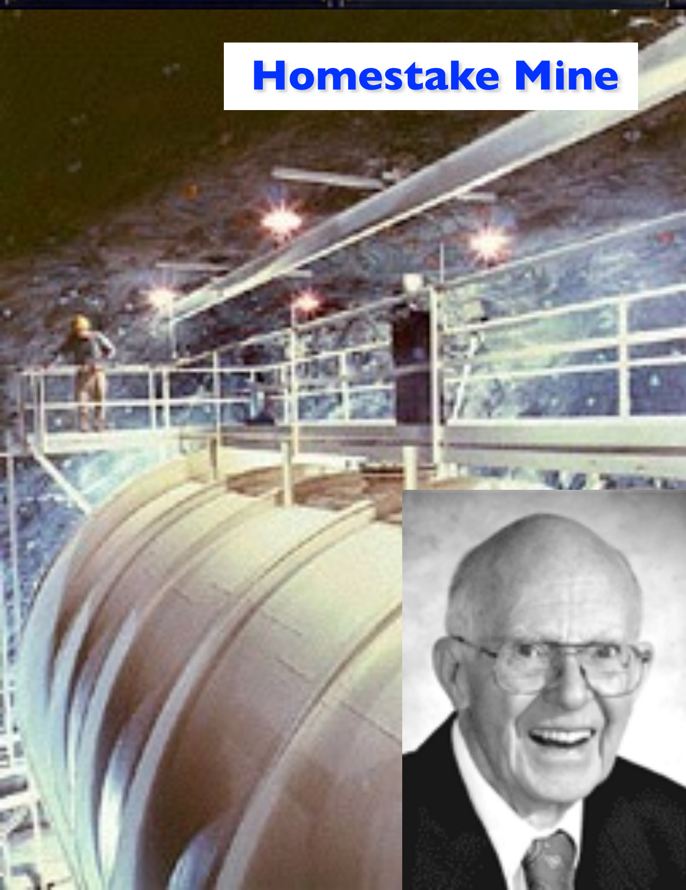


*founder and first chief editor of "Nature"

~1932-53: Particle zoo in cosmic rays such as *positron* e^+ (***Anderson*** '32), predicted by ***Dirac*** in 1930, but also μ, π, strange particles (K, Λ, Ξ, Σ)...

Last decades: systematically detected less ν's than predicted from the sun: ν *oscillations (hence $m\neq0$)!*

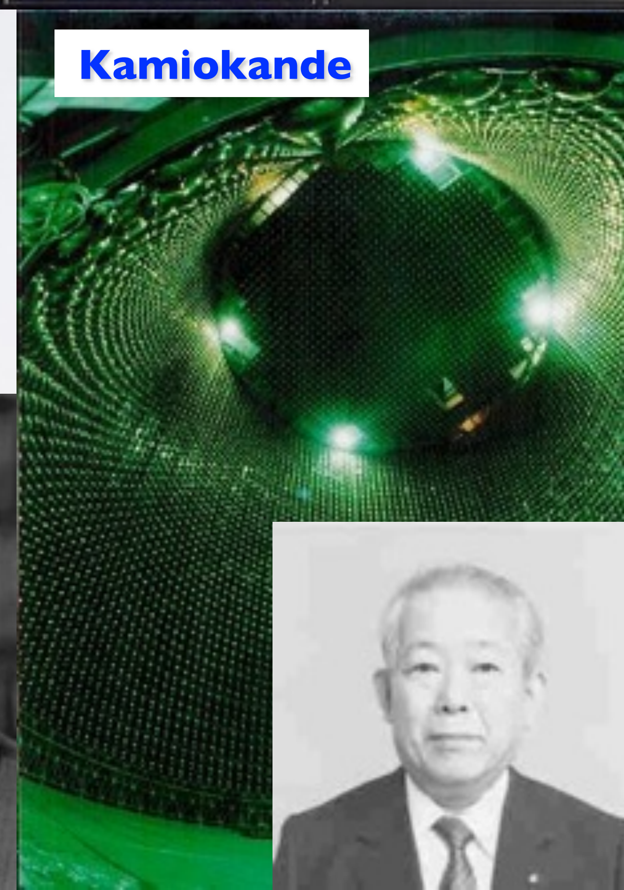
...INCLUDING X-RAY ASTROPHYSICS!



X-ray astrophysics

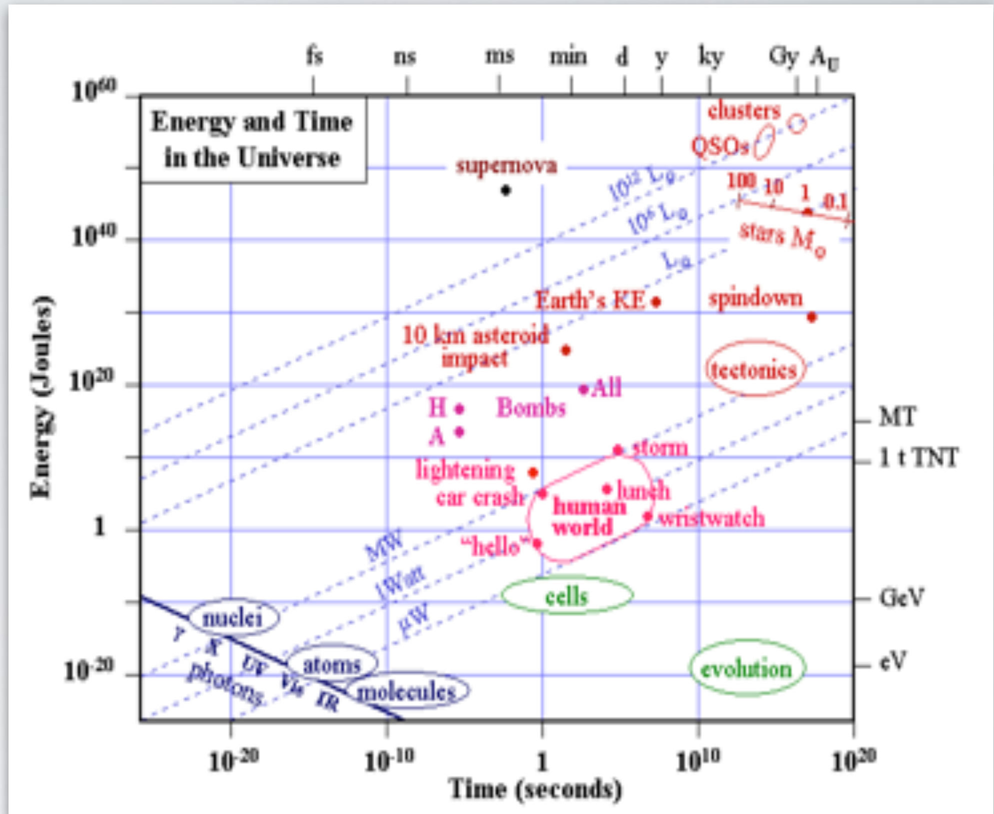
ν astrophysics

Nobel Prize 2002



WHY IT IS SO?

- Not surprising, if we think of the unusual scales of density, temperature, size, time, energy… if compared with what achievable in terrestrial laboratories!
- Many orders of magnitude away from familiar ranges: conceivable that extrapolations of some physics may fail, highlighting new phenomena, or regimes



My goal in the following

to provide a quick (necessarily only semi-quantitative) overview of a few discovery (or constraining) possibilities for X-ray astrophysics inspired by some open issues in theoretical physics. Take it as "food for thought", an invitation to keep an open mind!

END OF PROLOGUE

PLAN OF MY LECTURE

Dark Matter: evidence & diagnostics

X-rays to identify particle DM candidates?

- Why not great for WIMPs
- Sterile Neutrinos (& others)

Axions & Axion-like particles

Compact objects, EOS dense matter…

testing gravity in new regimes…

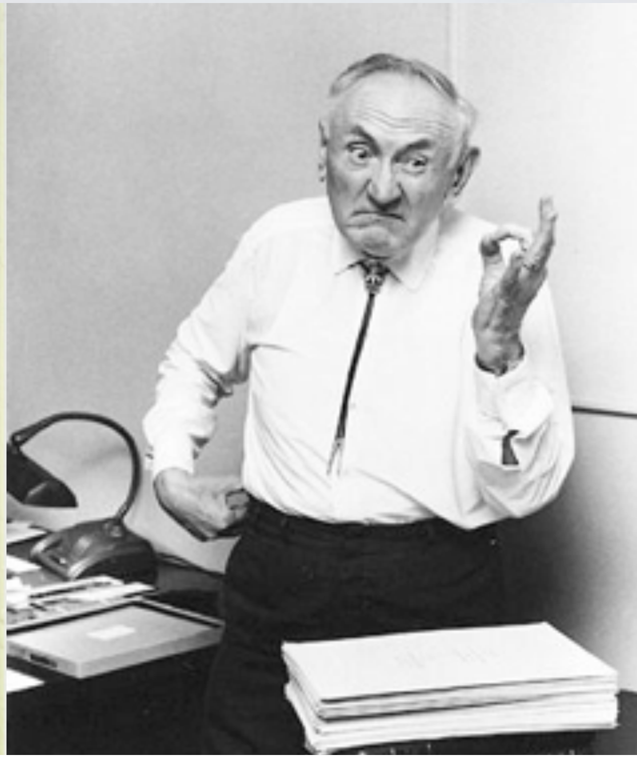
Forthcoming cosmological probes

PART I. DARK MATTER

DARK MATTER ENTERS THE SCENE...

DM "DISCOVERY" IN COMA CLUSTER (~1933)

Varna, Bulgaria



~10^3galaxies in ~1 Mpc radius region

We remember F. Zwicky here for two important discoveries:

- "Astronomers are spherical bastards. No matter how you look at them they are just bastards."
- Inferred the mass of the Coma cluster from the proper motion of the Galaxies, finding that the required mass is much larger than what could be accounted for

Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta (1933)* ***6****, 110–127.*

"On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal (1937)* ***86****, 217*

*Nebula=Early XXth century name for what we call now galaxy

I. No "physics beyond the standard model" (yet)

II. How did he do it? Clever & original application of Virial Theorem

SKETCH OF THE METHOD

Expression of time average of total kinetic energy T of N particles bounded by conservative forces F

$$2\langle T\rangle = -\sum_{k=1}^{N}\langle \mathbf{r}_k \cdot \mathbf{F}_k\rangle$$

Average total potential energy <U>

$$U(r) = A\,r^n \Longrightarrow -\sum_{k=1}^{N}\langle \mathbf{r}_k \cdot \mathbf{F}_k\rangle = n\langle U_{tot}\rangle$$

For Gravity, U~ r $^{-1}$

$$2\langle T\rangle + \langle U_{tot}\rangle = 0$$

$$\langle T\rangle = N\frac{\langle m\,v^2\rangle}{2}$$

$N^2/2$ pairs of Galaxies

$$\langle U_{tot}\rangle \simeq -\frac{N^2}{2}G_N\frac{\langle m^2\rangle}{\langle r\rangle}$$

doppler shifts in galactic spectra

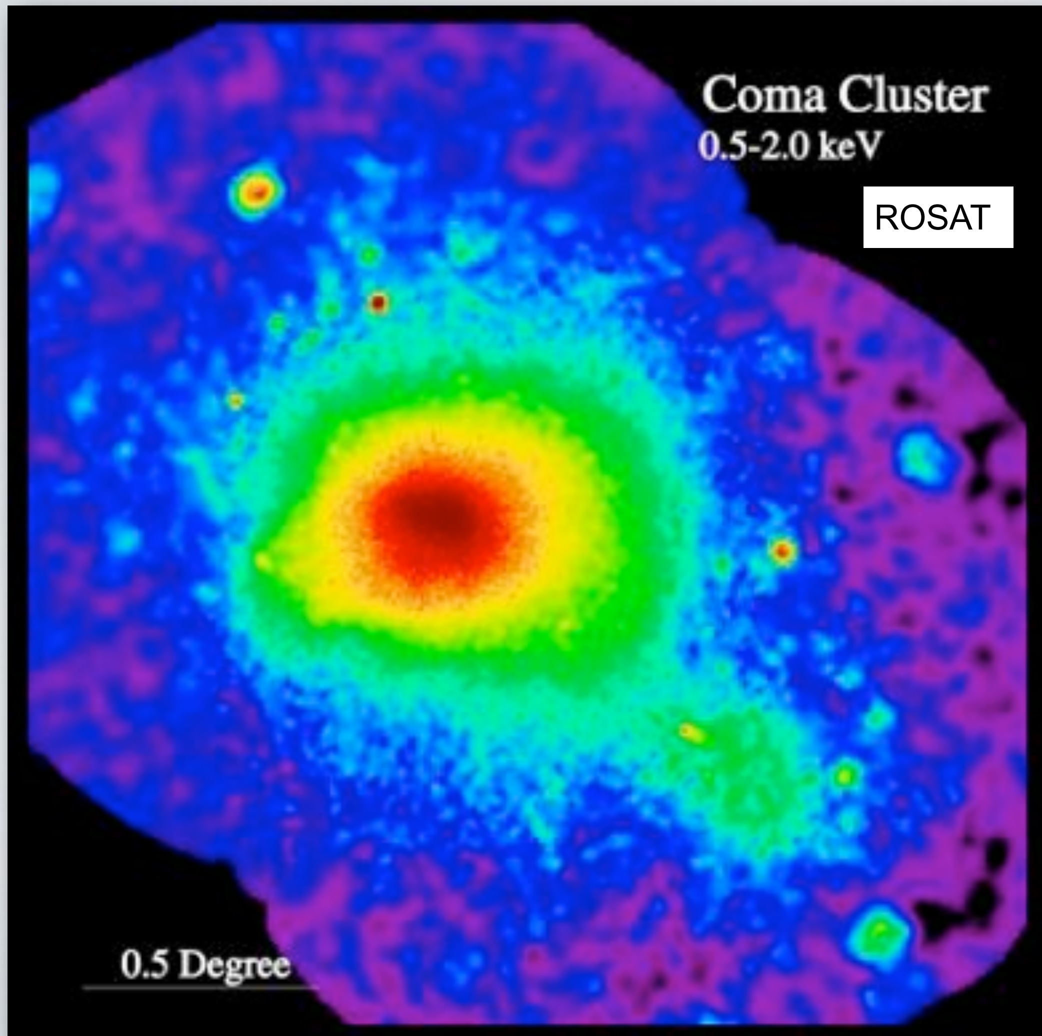
$$M_{tot} \simeq N\langle m\rangle \simeq -\frac{2\langle v^2\rangle\,\langle r\rangle}{G_N}$$

inferred geometrically

found a factor ~400 larger mass than the one from converting luminosity into mass!

MODERN PROOFS FROM CLUSTERS: X-RAYS

We know today that most of the mass in clusters (not true for galaxies!) is in the form of hot, intergalactic gas, which can be traced via X rays: bolometric X-luminosity can be eventually converted into gas density maps, spectral info into pressure information (or potential depth)



$$\frac{dP_{gas}}{dr} = G_N \frac{M(<r)\rho_{gas}}{r^2}$$

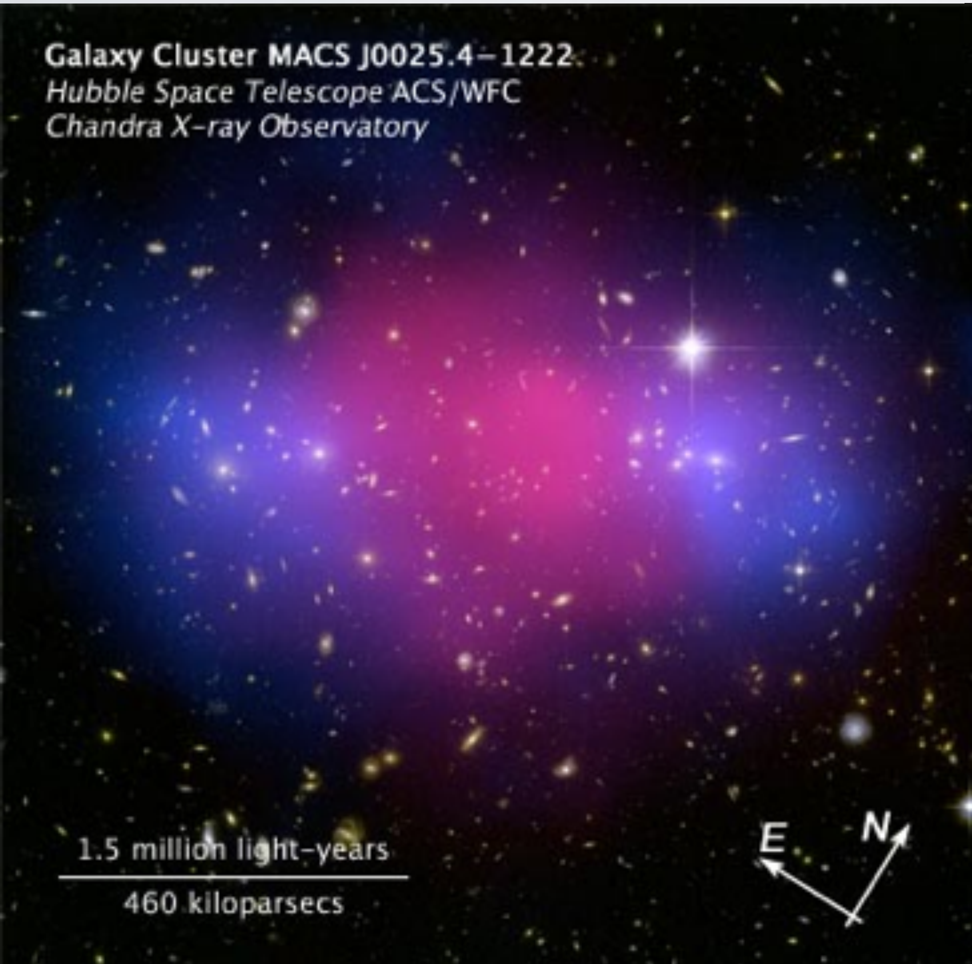
See for example
Lewis, Buote, and Stocke, ApJ (2003), 586, 135

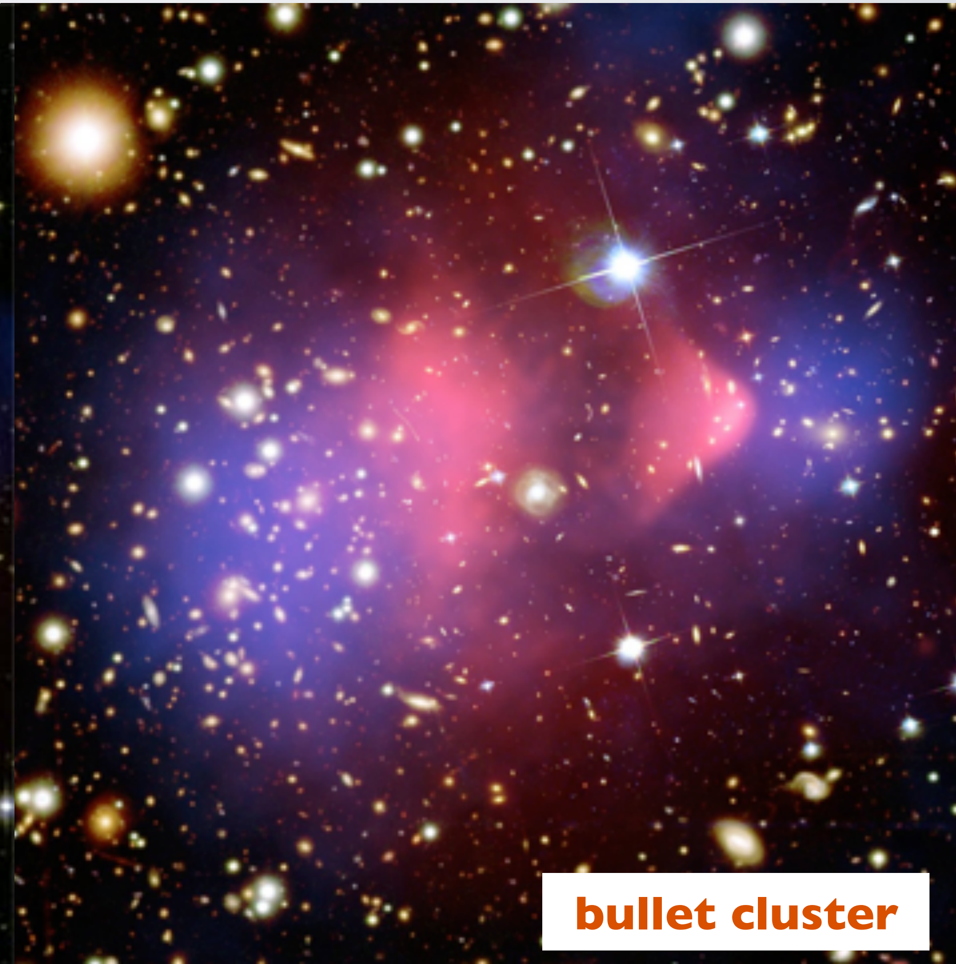
Again, a factor ~7 more mass than those in gas form is inferred (also its profile can be traced...)

MORE SPECTACULAR: SEGREGATION!

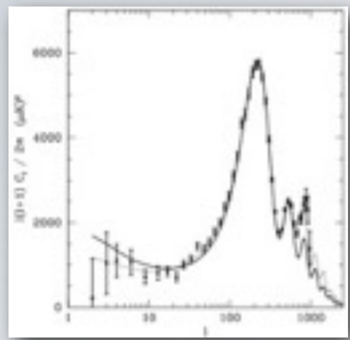
Baryonic gas gets “shocked” in the collision and stays behind. The mass causing lensing (as well as the subdominant galaxies) pass trough each other (non-collisional)

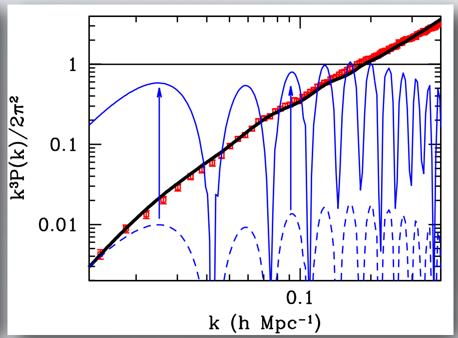
(most of the) Mass is not in the collisional gas, as would happen if law of gravity were altered!

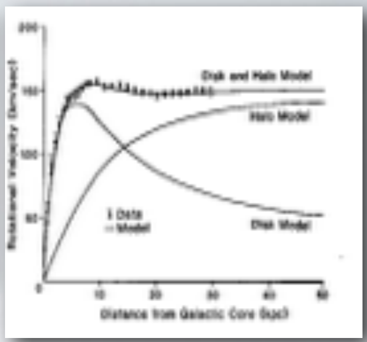




DM EVIDENCE @ MANY SCALES







CMB anis.

(Growth & Pattern of) Large Scale Structures

Clusters (X-rays, lensing)

Galaxies **Dwarfs (rotation curves, fits...)**

(growing effect of non-linearities, baryonic gas dynamics, feedbacks...)

"Cosmological" → **"Astrophysical"**

Especially cosmological evidence of paramount importance for Particle Physics!

- Exact solutions or linear perturbation theory applied to simple physical systems: credible and robust!
- Many would say: Suggests **"cold" collisionless additional species**, rather than a modification of GR

(IMHO: academic debate mostly influenced by "classical" thinking… the ***need for new d.o.f.*** *is key observation!)*

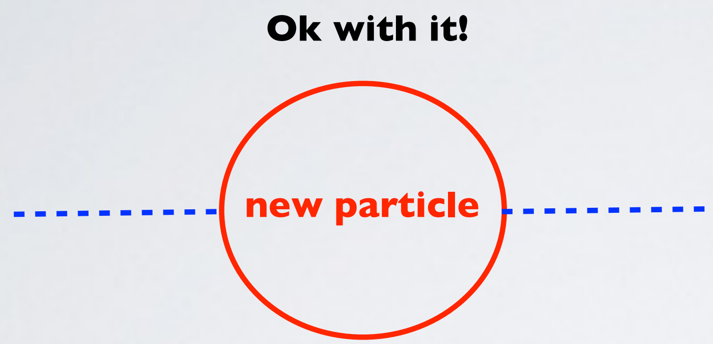
- Tells that its majority is **non-baryonic**, rather than e.g. brown dwarf stars, planets...

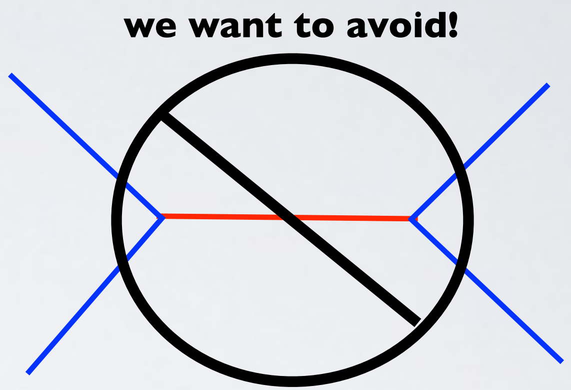
Beyond SM explanation **needed**, but **gravity is universal**: no particle identification!
discovery via other channels is needed **to clarify** **particle physics** framework

But **what to look for depends on "theoretical prejudice"** (*curse* of DM searches)

"TRADITIONAL" LINK WITH PARTICLE PHYSICS

Strong *__prior for new TeV-scale physics (with SM-like couplings)__* ***to cure the hierarchy problem***
precision data (e.g. from LEP) suggest that tree-level couplings SM-SM-BSM should be avoided!





One straightforward solution is to impose ***some symmetry*** (often "parity-like", relic from some UV-sym): SUSY R-parity, K-parity in ED, T-parity in Little Higgs. New particles only appear in pairs!

➡ Automatically makes lightest new particle stable!
➡ It has other benefits, e.g. respect proton stability bounds!

Cosmology tells us that the early universe was a hot plasma, in which all "thermally allowed" species should be populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

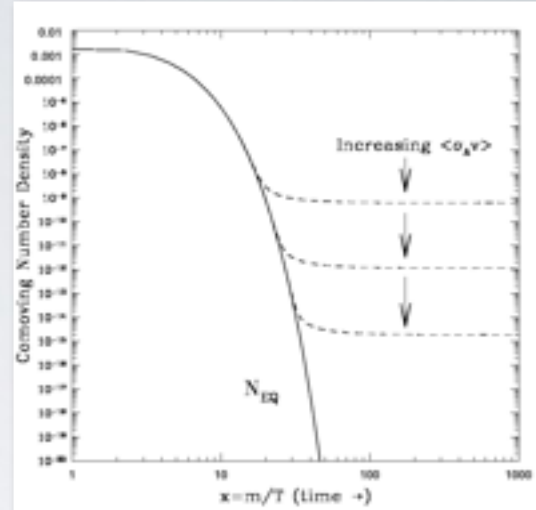
What happens if we extrapolate further backwards and account for the hypothetical presence of this new, stable weakly interacting massive particle?

THE WEAKLY INTERACTING MASSIVE PARTICLE PARADIGM

$$X\bar{X} \longleftrightarrow \ell\bar{\ell}$$

Stable, massive particles in chemical equilibrium down to $T<<m$ (required for **cold** DM, i.e. non-relativistic distribution function!), suffer exponentially suppression of their abundance

So, what is left depends on the decoupling time, or their annihilation cross section: the weaker, the more abundant...



A textbook calculation yields the current average cosmological energy density

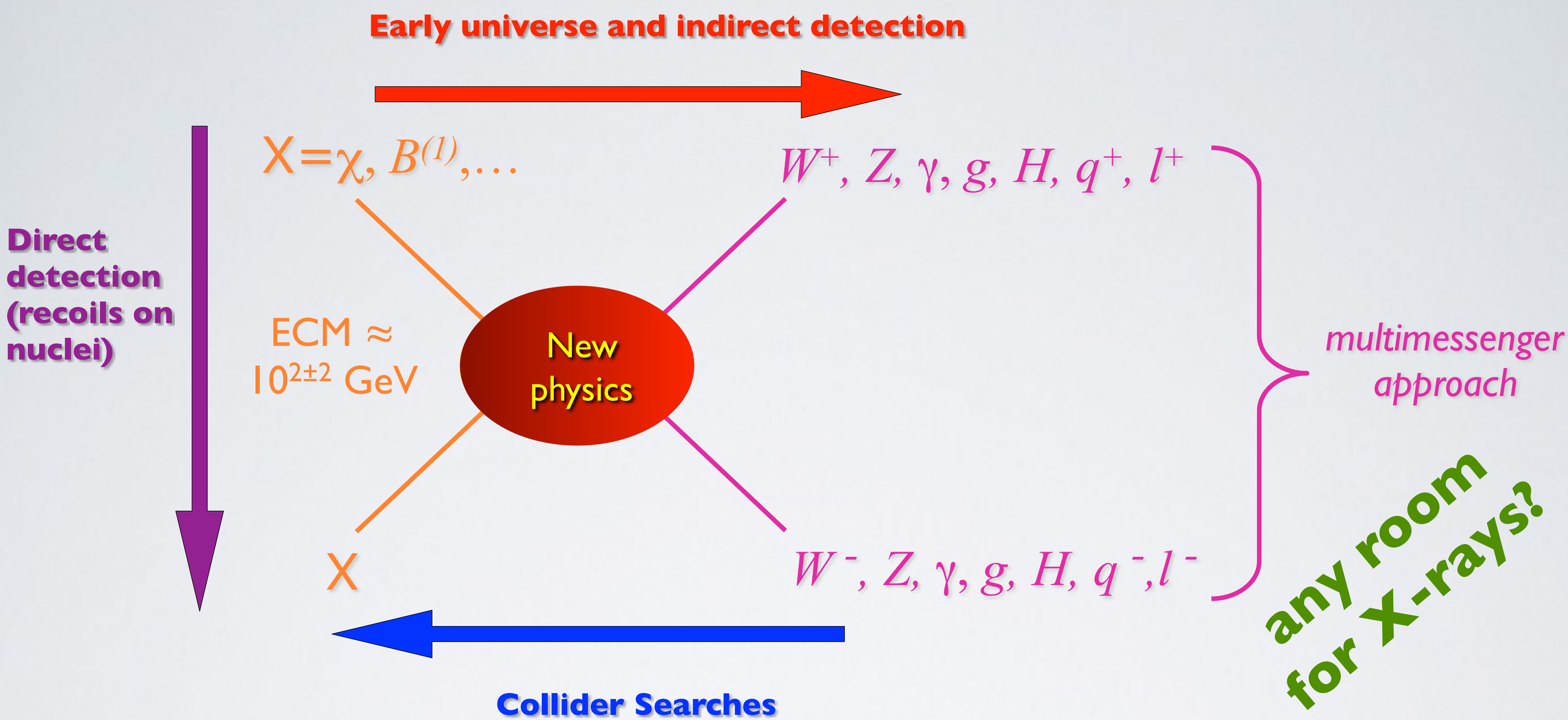
$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle\sigma v\rangle}$$

Observationally inferred $\Omega_{DM}h^2 \sim 0.1$ recovered for EW scale masses & couplings (aka **WIMP miracle**)!

$$\langle\sigma v\rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

- Stability results e.g. from the same **discrete "parity" symmetry** previously invoked
- Matches (old?) **theoretical prior for BSM at EW scale**
- Leads to a number of interesting, testable phenomenological consequences

WIMP (NOT GENERIC DM!) SEARCH PROGRAM



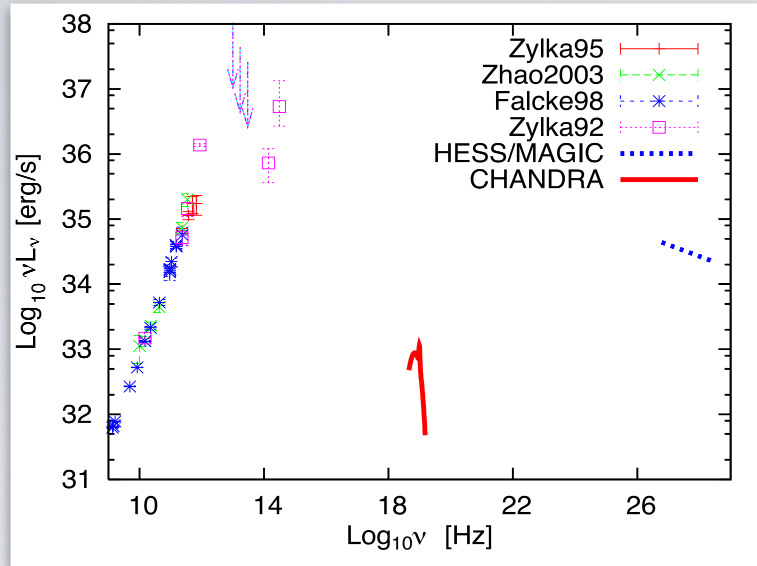
✓ demonstrate the "particle physics" nature of astrophysical DM (locally, via DD; remotely, via ID)

✓ Possibly, create DM candidates in the controlled environments of accelerators (but not enough! Neither stability nor relic density "directly tested", for instance…)

✓ Find a consistency between properties of the two classes of particles. Ideally, we would like to calculate abundance and DD/ID signatures → link with cosmology/test of production

WHY X-RAYS AT THE MARGIN OF THIS PROGRAM?

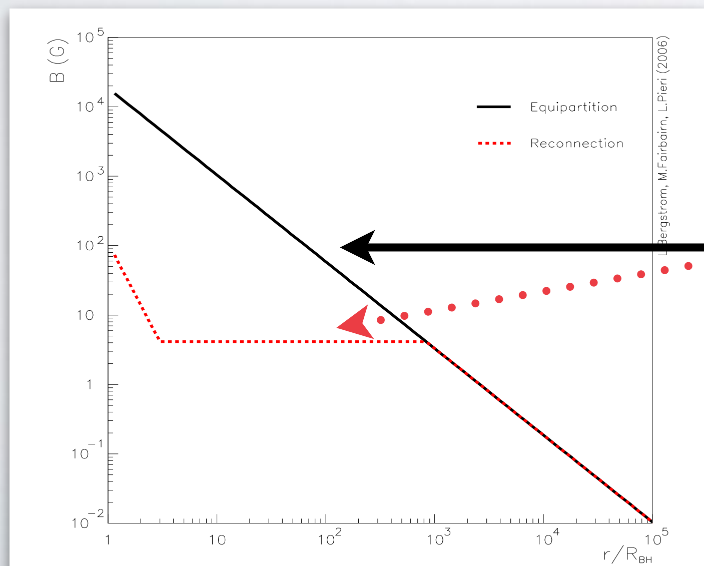
E-scale mismatch: 4 to 7 o.o.m. below the expected range of emitted <u>prompt</u> γ's!



only proposed exception: models emitting energetic leptons (e.g. KK DM candidates) in environment with large B-fields (synchrotron). Possibly Gal. Center?

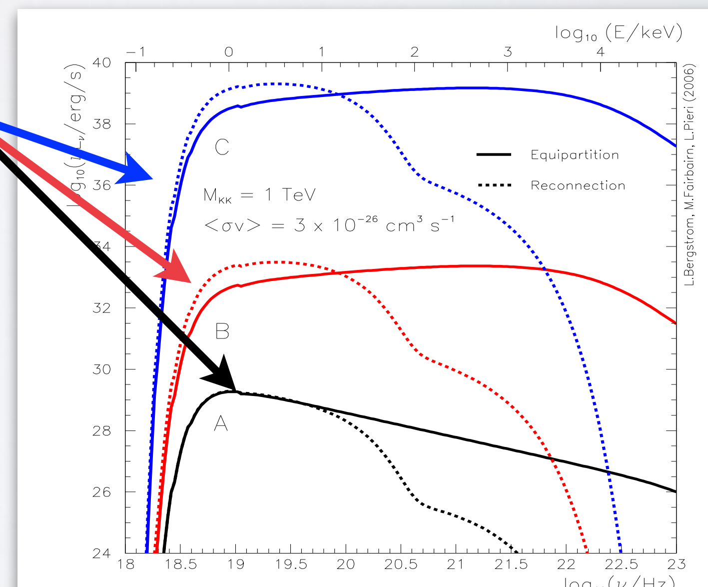
L. Bergstrom, M. Fairbairn and L. Pieri, "X-ray Radiation from the Annihilation of Dark Matter at the Galactic Center," PRD 74, 123515 (2006) [astro-ph/0607327]

Strong dependence from B-field & DM distribution profile! useful to check DM hints @ other wavelengths (e.g. radio)



different DM density profiles

different B-field really near the BH….



BUT REMEMBER: THEORY BIAS!

Different motivations for alternative DM (in fact, beyond-the-standard-model) models exist, in other scenarios signatures in X-rays may be natural!

NEUTRINOS AS DARK MATTER?

Condition 1. Must be massive (which is already a departure from SM...)

Fulfilled! Oscillations established…implying mass for at least two states (mismatch between flavour and mass basis is in fact necessary!)

- Take the 2-flavour mixing for simplicity
- Account for flavor states being superposition of mass states, which are the true propagating states
- Each mass eigenstate propagates as $\sim e^{ipz}$…

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

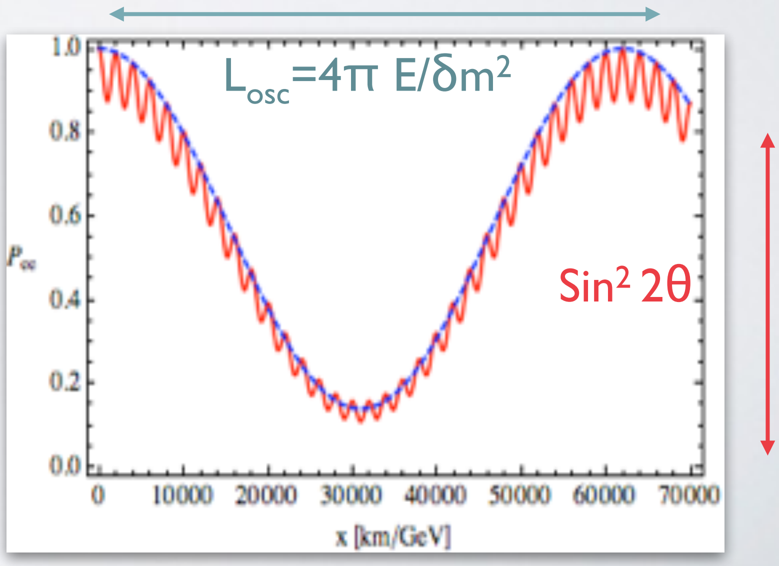
$$|\nu_\mu(\ell)\rangle = -\sin\theta\, e^{-ip_1\ell}|\nu_1\rangle + \cos\theta\, e^{-ip_2\ell}|\nu_2\rangle$$

$$p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$$

It implies the survival probability

$$P_{ee}(\ell) = 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2\,\ell}{4E}\right)$$

<1 only if $\delta m^2 \neq 0$



NEUTRINOS AS DARK MATTER?

Condition 1. Must be massive (which is already a departure from SM...)

Fulfilled! Oscillations established, at least 2 massive states, measured splitting implies at least one state heavier than 0.05 eV

$$\Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3}\,{\rm eV}^2$$

Condition 2. Must match cosmological abundance

Failed! Direct mass limits combined with splittings from oscillation experiments impose upper limit of about 7 eV to the sum (After KATRIN, potentially improved to ~0.7 eV)

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} \simeq \frac{\sum_i m_i}{45\,{\rm eV}}$$

$$\boxed{\Omega_{DM} \approx 0.3\,(\text{Planck}) \Rightarrow \sum m_i \approx 15\ \text{eV}}$$

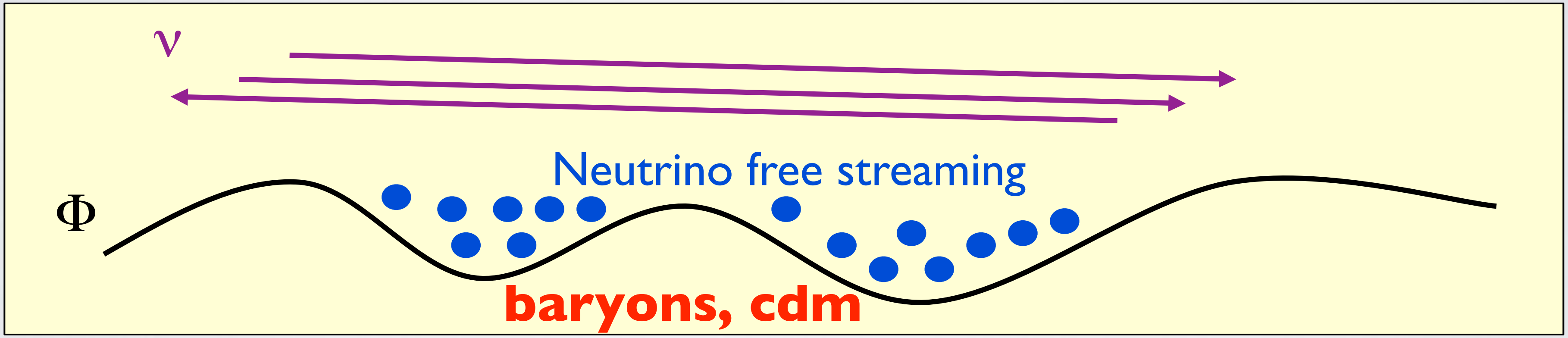
Condition 3. Must allow for structure formation (of the right kind)

Failed! Why?

DM IS NOT "HOT" (IT IS NOT RELATIVISTIC)!

DM cannot have a relativistic velocity distribution
(at least from matter-radiation equality for perturbation to grow)

This is the more profound reason why neutrinos would not work as DM, even if they had the correct mass: they were born with relativistic velocity distribution which prevents structures below O(100 Mpc) to grow till late!

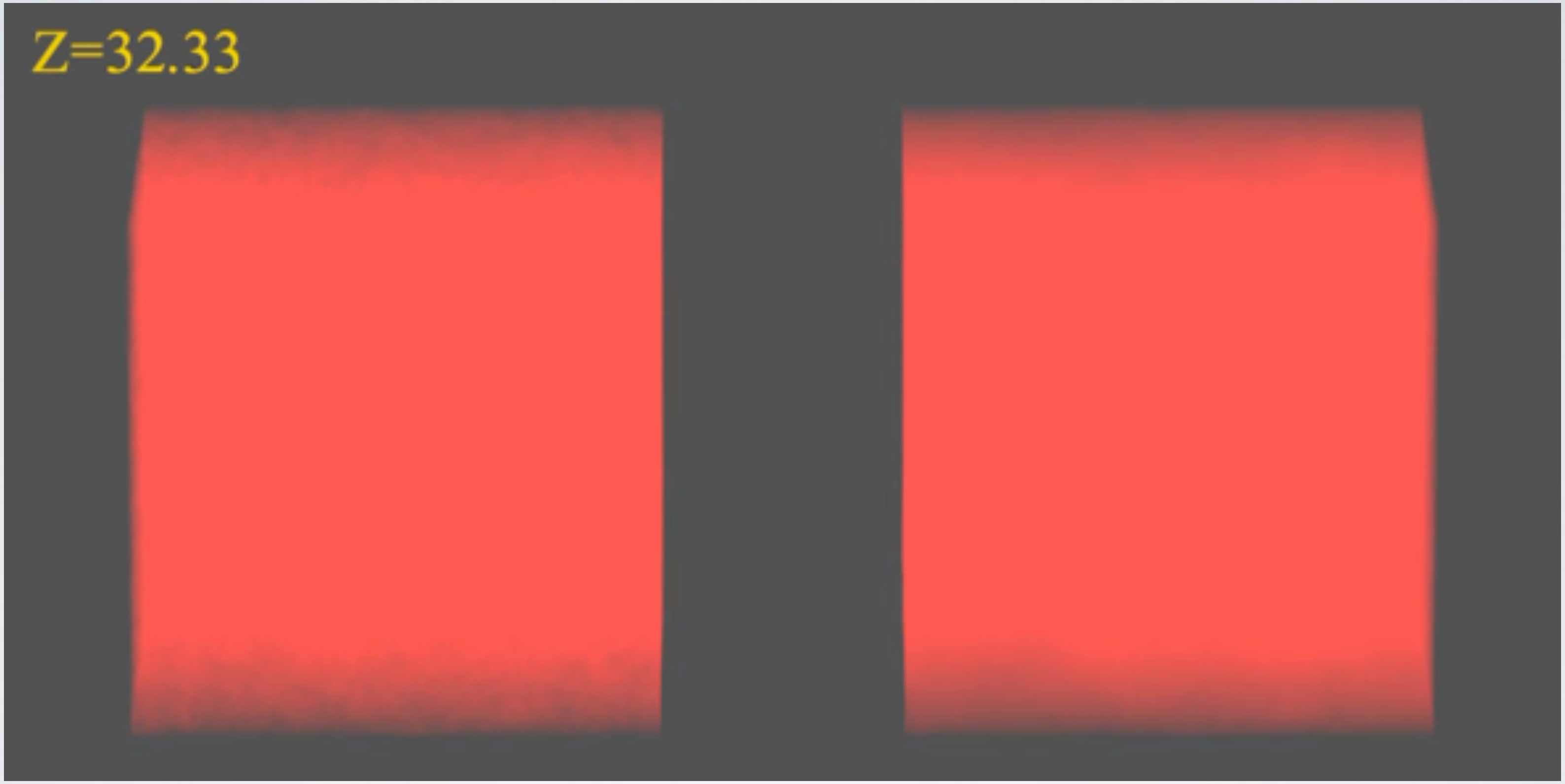


Cartoon Picture:

ν's "do not settle" in potential wells that they can overcome by their typical velocity: compared with CDM, they suppress power at small-scales

THE NUMERICAL PROOF

ΛCDM run vs. cosmology including neutrinos (total mass of 6.9 eV)



simulation by Troels Haugbølle, see

http://users-phys.au.dk/haugboel/projects.shtml

MINIMALISTIC APPROACH

- SM Neutrinos do not work as DM, but have some good properties (almost Ok!)
Easy to add one extra neutrino state which works (=**heavier & suppressed interactions**)!

- **SM gauge singlet**, but mixes with active (one needs ≥2 of these to give mass to ν's...)

$$\delta\mathcal{L} = \bar{N} i \partial_\mu \gamma^\mu N - \lambda_\ell H \bar{N} L^\ell - \frac{M}{2} \bar{N}^c N + h.c.$$

- Production via oscillations, suppressed by the small mixing (~10^{-4})
(never in equilibrium, non-thermal spectrum, avoid "hot-ness")

$$\theta \sim \lambda v / M$$

- Further adjust mass *M* to obtain right abundance, keV range selected.

- Still **not exceeding MeV scale** in a more general (EFT) analysis of its production & decay mechanism

F. Bezrukov, D. Gorbunov. M. Shaposhnikov, JCAP 0906, 029 (2009) [0812.3622] JCAP 1110, 001 (2011) [1106.5019]

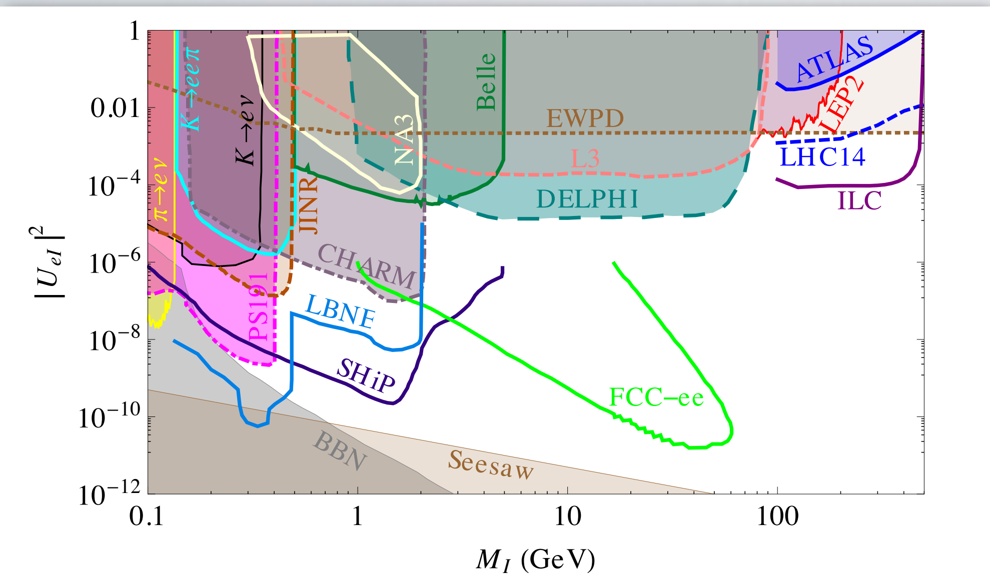
- Interesting astrophysical candidate:
- "cold-to-warm", may suppress structures at sub-kpc scales
(as in simulations I showed, but at sub-Galactic scales due to higher masses)
- can be searched for via X-ray line (rare loop-suppressed decay)
- can be embedded in a "minimal extension" of the SM with only 3 right-handed neutrinos (two GeV-ish ones explaining baryon asymmetry...)

$$N \to \nu + \gamma$$

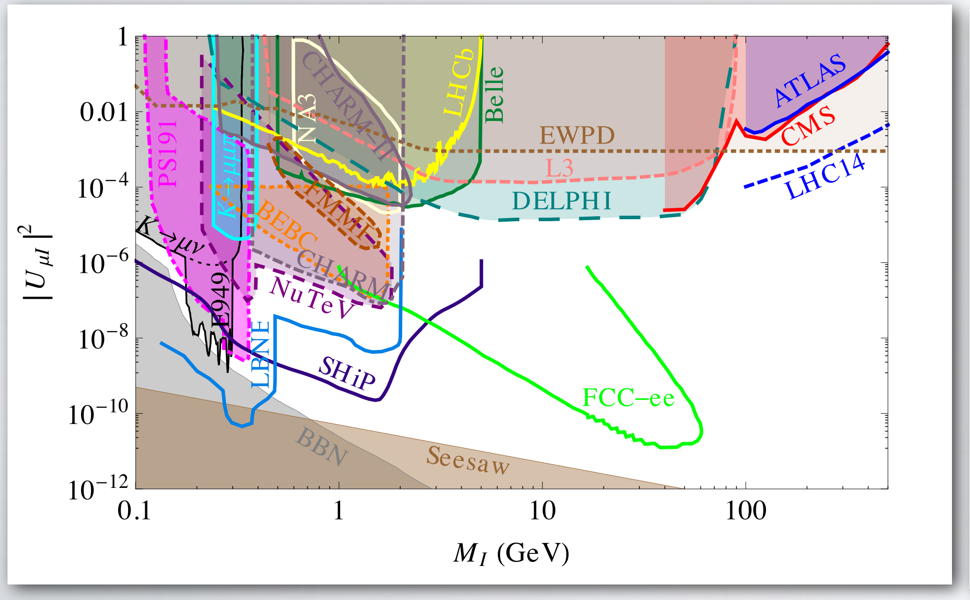
in principle accessible to colliders…
possible interplay X-ray astro/colliders!

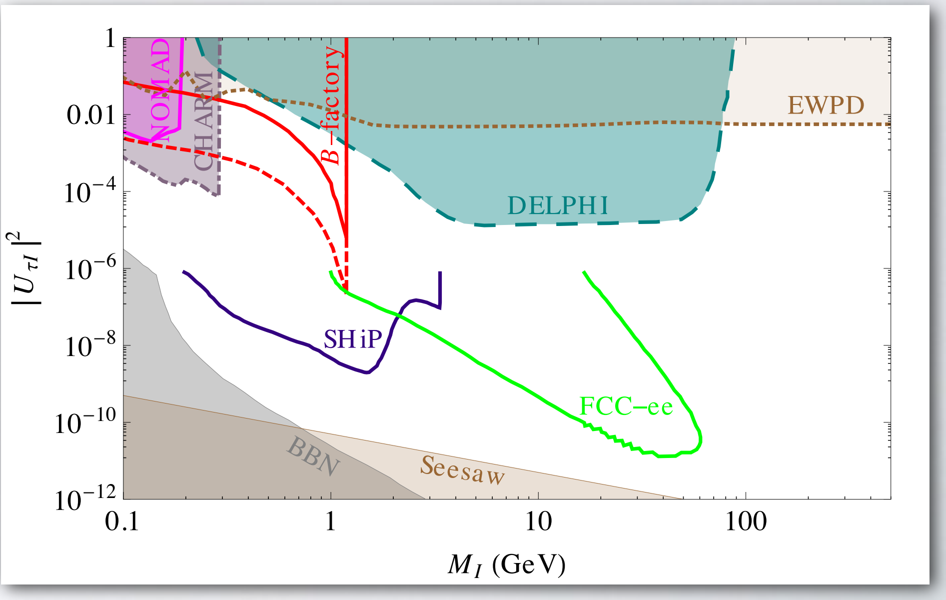
νMSM, *for a review, A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)*

GEV NEUTRAL LEPTONS AT COLLIDERS?



A number of different probes possible
(From 1504.04855)





DEDICATED EXPERIMENTS POSSIBLE

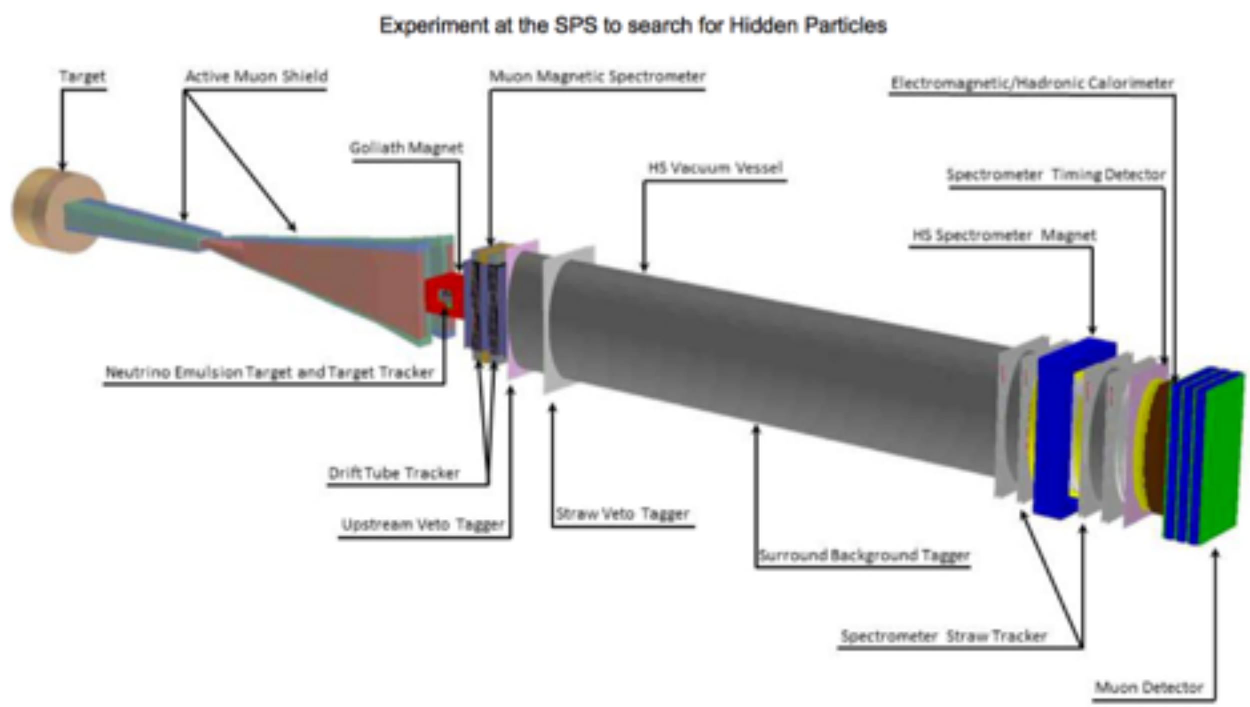
Proposed fixed target experiment at CERN

http://ship.web.cern.ch/ship/

Physics paper at 1504.04855, Technical paper at 1504.04956

SHiP
Search for Hidden Particles

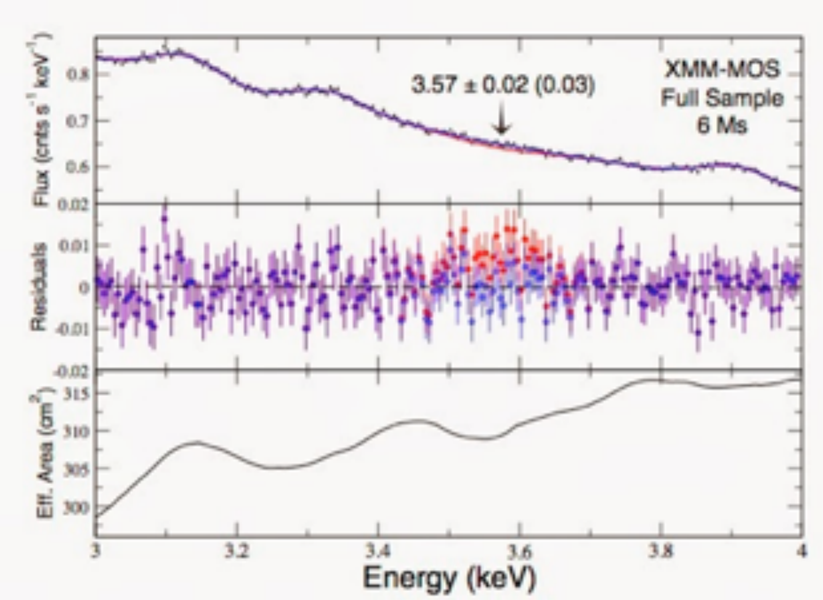
SHiP - Search for Hidden Particles



HINTS IN 2014?

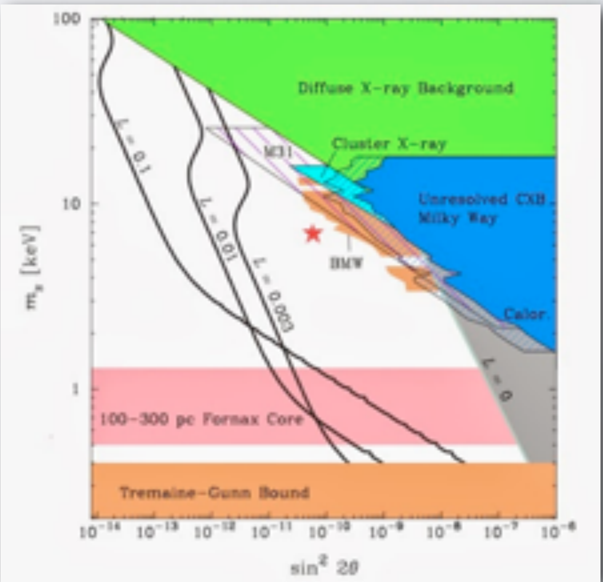
2 analyses of X-ray spectra of galaxy clusters claim the presence of a monochromatic 3.55 keV line which can be interpreted as a decay signal of a 7.1 keV sterile neutrino

- ~5 σ, but look elsewhere (~3 σ)
- stack clusters ("shuffling" via z-dependence)
- need to parameterize "effective" background to better than % level (but argued OK)
- Overall consistent with DM, but some anomaly in normalization of Perseus?
- Not confirmed (excluded?) by other searches…
- Further tests needed (unfortunately *Astro-H/Hitomi was lost soon after launch!*)



E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S.W. Randall, "Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters,"   arXiv:1402.2301, ApJ 789 (2014) 13

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, "An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster,"   1402.4119, PRL 113 (2014) 251301



I won't discuss about its status, or the analysis… let me just mention what kind of signatures (and model alternatives) may be out there

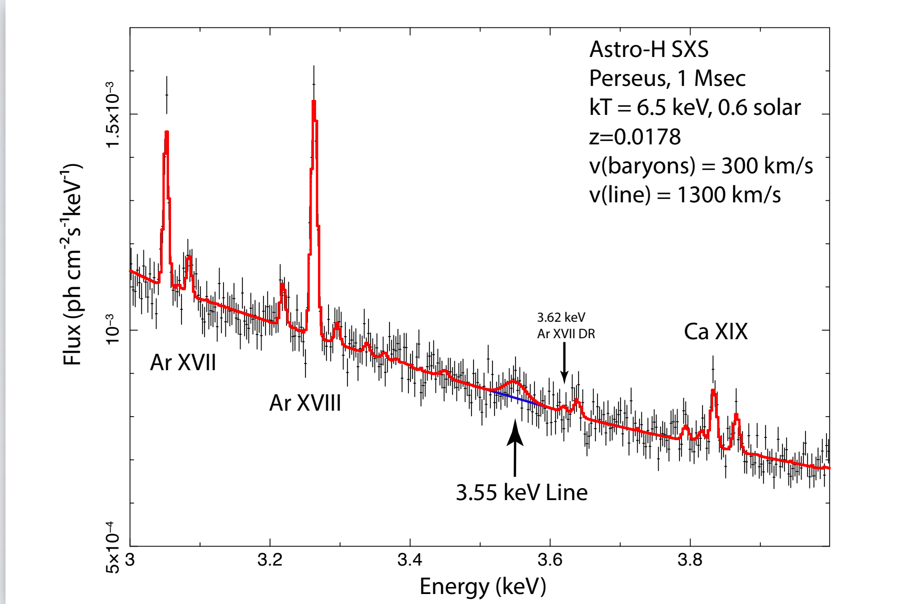
WHAT KIND OF CONFIRMING SIGNATURES?

Require increased exposure, plus improved angular resolution, spectral one (or both!)

1. That a line is really there (no statistical fluke)

2. Hitomi would have had sufficient E-resolution to resolve the x-ray line shape: if the width of the line is relatively broad ⇒ consistent with the expected ***Doppler broadening of virialised DM particles***.

Narrower line(s) would suggest emission from normal atomic transitions (broadened through collisions)



E. Bulbul et al. ApJ 789 (2014) 13

3. Also, with increased exposure one could verify whether the line weakens toward the edges of a cluster or a galaxy in a way that matches the predicted dark matter density profile of these objects.

A. Boyarsky et al.
PRL 113 (2014) 251301

OTHER THEORETICAL MODELS WITH X-RAY SIGNALS

Ex. 1: Exciting dark matter

Finkbeiner & Weiner 1402.6671, Cline & Frey 1410.7766
DM has an excited state ~ 3.5 keV above the ground state, which can be excited by DM-DM collisions. The X-ray photon is emitted by subsequent decay. Rate of excitation scales as **density^2 x f(velocity)** - much less constrained than just DM density, seems to allow compatibility with data.

Ex. 2: Axion-like particle as byproduct of DM decay

Dark matter decays into axion-like particles, which can convert into X-ray photon in the presence of magnetic fields (e.g. *Conlon & Day 1404.7741*). Due to different B-fields, can lead to brighter signals in clusters, fainter in dwarfs and galaxies (*Alvarez et al 1410.1867*).

These models predict a different scaling with mass, for instance (and may be a way to reconcile apparently conflicting observations… at the expenses of some generic predictivity)

2. AND NOW FOR SOMETHING COMPLETELY DIFFERENT: AXIONS & ALPS

THE STRONG CP PROBLEM

$$L_{CP} = \theta \frac{N_f g^2}{32\pi^2} Tr(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Standard QCD Lagrangian contains a CP, P & T violating term*

$$\theta \to \bar{\theta} = \theta - Arg(\det M_q)$$

Due to non-trivial topological structure of QCD vacuum, $0<\theta_{QCD}<2\pi$

Phase "rotated away" from quark mass matrix (complex couplings in Higgs sector)

$\bar{\theta}$ induces a neutron EDM violating experimental limits unless $\bar{\theta}<10^{-10}$

Again, one of the nasty "fine-tuning" problems of the SM asking for an explanation (like hierarchy, cosmological constant…)

Maybe a window on high-energy physics? Some dynamical solution?

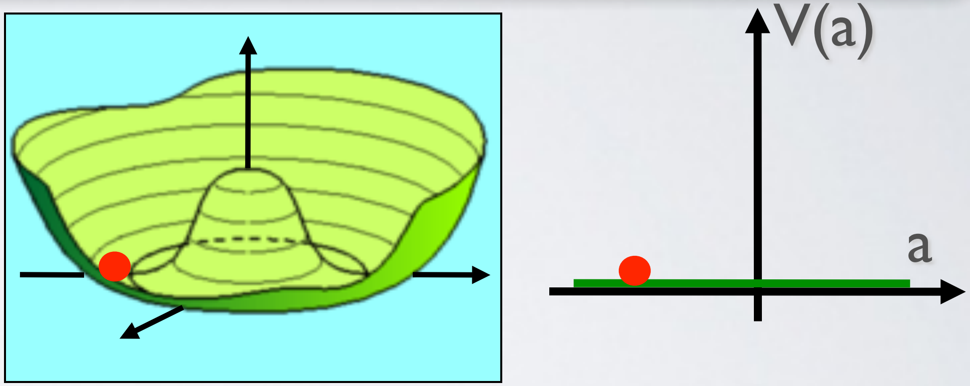
*despite being a total derivative, there are topologically inequivalent gauge configuration at infinity that make this term physical

INTRODUCING AXIONS

- One cannot solve the problem with known symmetries. Peccei, Quinn '77 proposed to solve it by a new global, axial $U(1)_{PQ}$ symmetry (1977), requiring a 2nd Higgs doublet.
- This symmetry is spontaneously broken at a scale f_a : axions a are the corresponding Nambu-Goldstone mode (Weinberg, Wilczek '78)

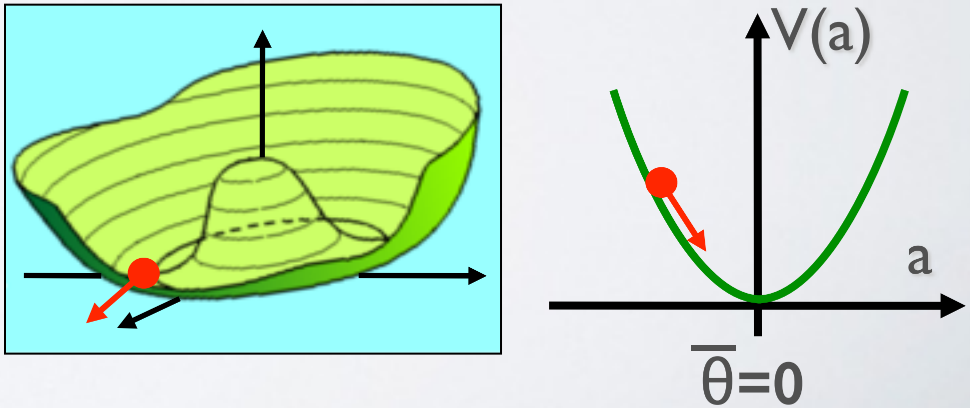
At $E \approx f_a$

- $U_{PQ}(1)$ spontaneously broken
- The axion is the m=0 mode settling at some value "θ" in the "Mexican hat"



At $E \approx \Lambda_{QCD} \ll f_a$

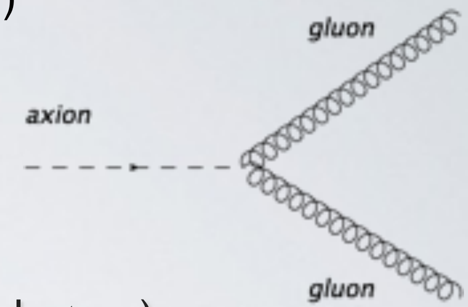
- $U_{PQ}(1)$ explicitly broken by chiral SSBthe Mexican hat tilts ("a mixes with π^0")
- In the potential induced by L_{CP} the (now-massive) $a(x)$ dynamically restores the CP-conserving minimum



NEW WINDOWS TO ALPS?

"Defining coupling": Axions couple to gluons (and mix with π^0)

$$L_{agg} = \frac{\alpha_s}{8\pi\ f_a} a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$



- Axions satisfy $m_\pi f_\pi \sim m_a f_a$
- They can couple to fermions, but more model-dependent (especially for leptons)
- effective 2-γ coupling $g_{a\gamma\gamma} = \xi\ \alpha/2\pi f_a \propto m_a$ (important for phenomenology)

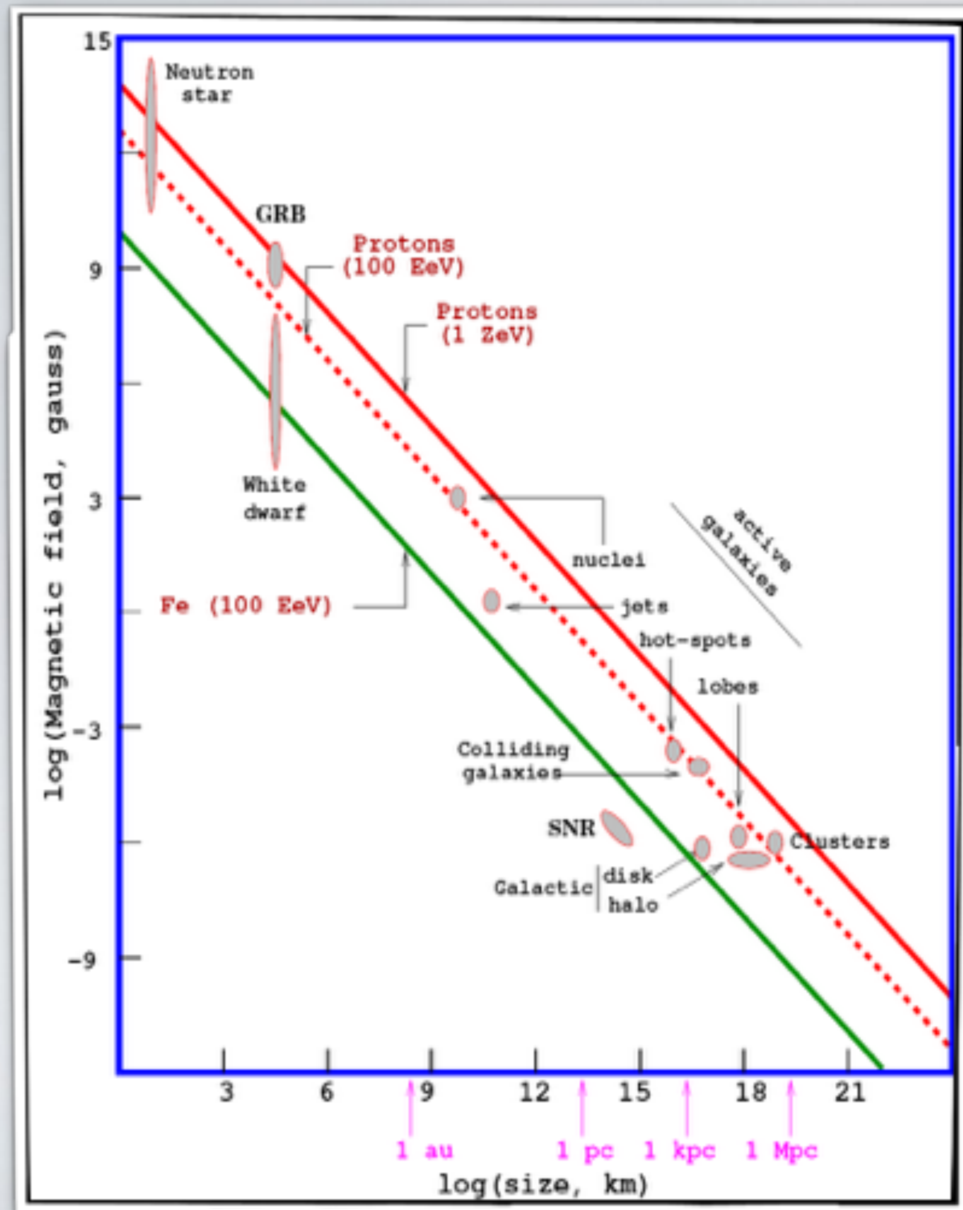
Search extended to axion-like particles (ALPs)≡ Light (pseudo)scalars with a 2-γ coupling $g_{a\gamma\gamma}$ with generic relation with m_a

Pseudoscalar fields with axion-like properties generically arise e.g. in string theory compactifications as Kaluza-Klein zero modes of antisymmetric tensor fields ("the phase" counterparts of the moduli describing the "size" of the compact manifolds)

P. Svrcek and E. Witten, "Axions In String Theory," JHEP 0606, 051 (2006) [hep-th/0605206];
A. Arvanitaki et al., "String Axiverse" PRD 81, 123530 (2010) [0905.4720]; ...

what has all this to do with high energy astrophysics?

UNRELATED (?!) TOPIC: "HILLAS" PLOT



Any accelerator (including cosmic ones!) must be able to contain the particle: Larmor Radius must be smaller than the size of the accelerator: $s > r_L$

$$r_L = \frac{p_\perp}{Z\,e\,B} \approx \frac{1\,\mathrm{pc}}{Z}\left(\frac{p_\perp}{\mathrm{PeV}/c}\right)\left(\frac{1\mu\mathrm{G}}{B}\right)$$

UHECRs extend at least up to ~3 10^{20} eV

$$E_{\max} \approx 9.3 \times 10^{20} eV \times B_G s_{pc}$$

$$B_G s_{pc} \geq 0.3$$

should be realized in nature...

ALPS & GAMMA/X-RAY ASTROPHYSICS!

For a photon propagating in a domain of size s with uniform field B along its direction, neutrino-like oscillation probability formula holds (leading to ~30% flux distortions...)

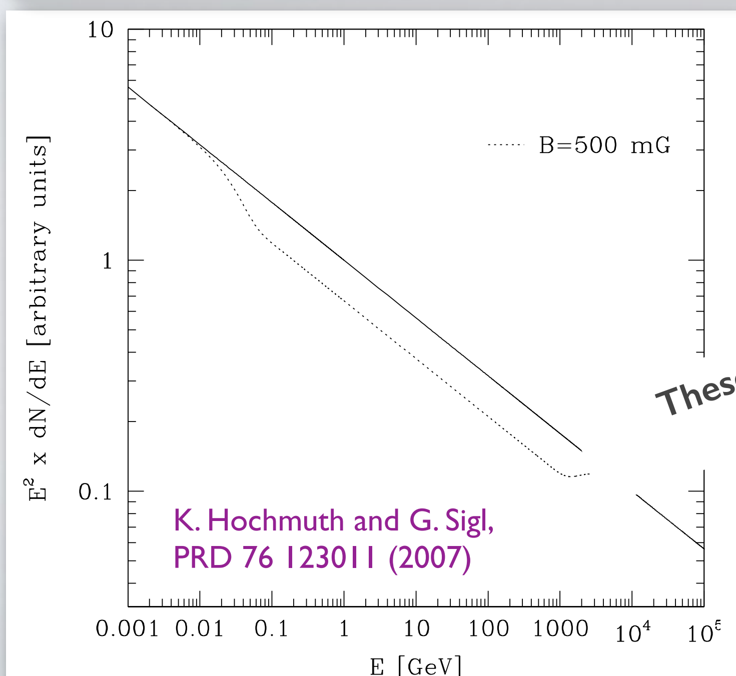
P.S. with D. Hooper, Phys. Rev. Lett. 99, 231102 (2007)

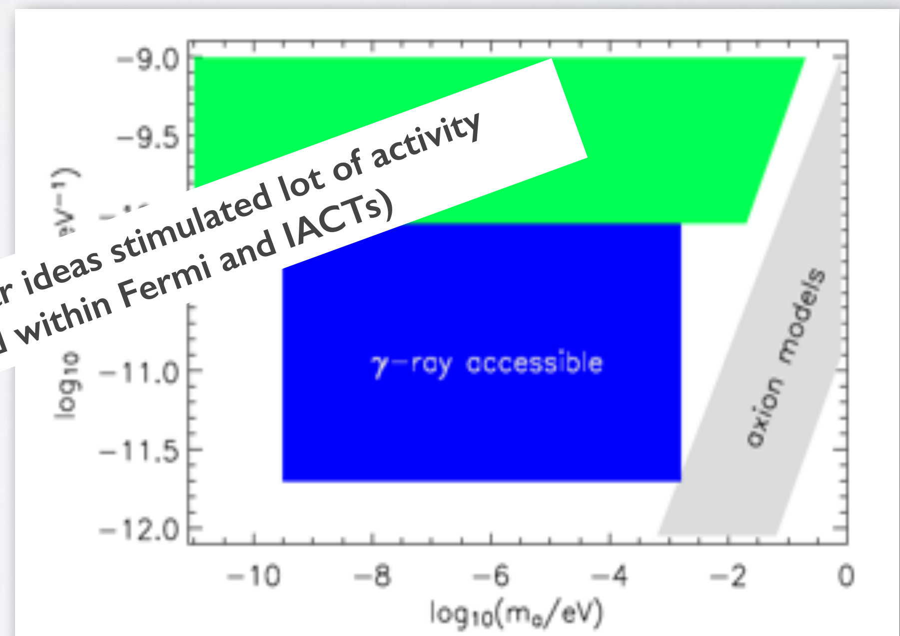
$$P_{osc} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma}Bs}{2}\sqrt{1+\left(\frac{K}{E}\right)^2}\right]$$

$$\sin^2(2\theta) = \frac{1}{1+(K/E)^2} \qquad K = \frac{m^2}{2g_{a\gamma}B}$$

Large phases (→large conversions) for unexplored range of coupling naturally expected for Hillas-efficient accelerators!

$$K_{GeV} = \frac{m^2_{\mu eV}}{0.4g_{11}B_G} \qquad 15g_{11}B_G s_{pc} \geq 1$$



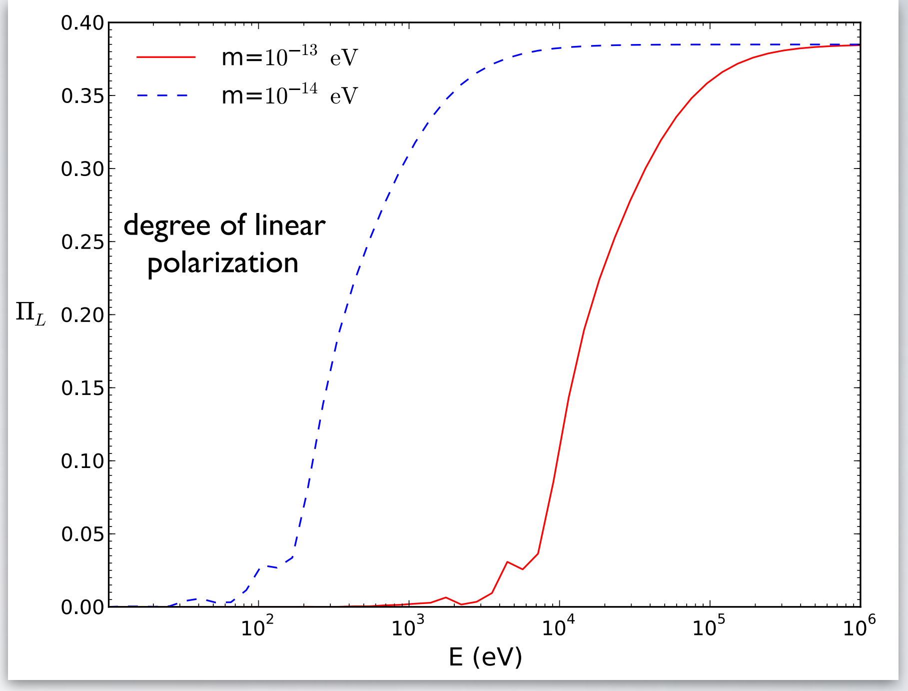


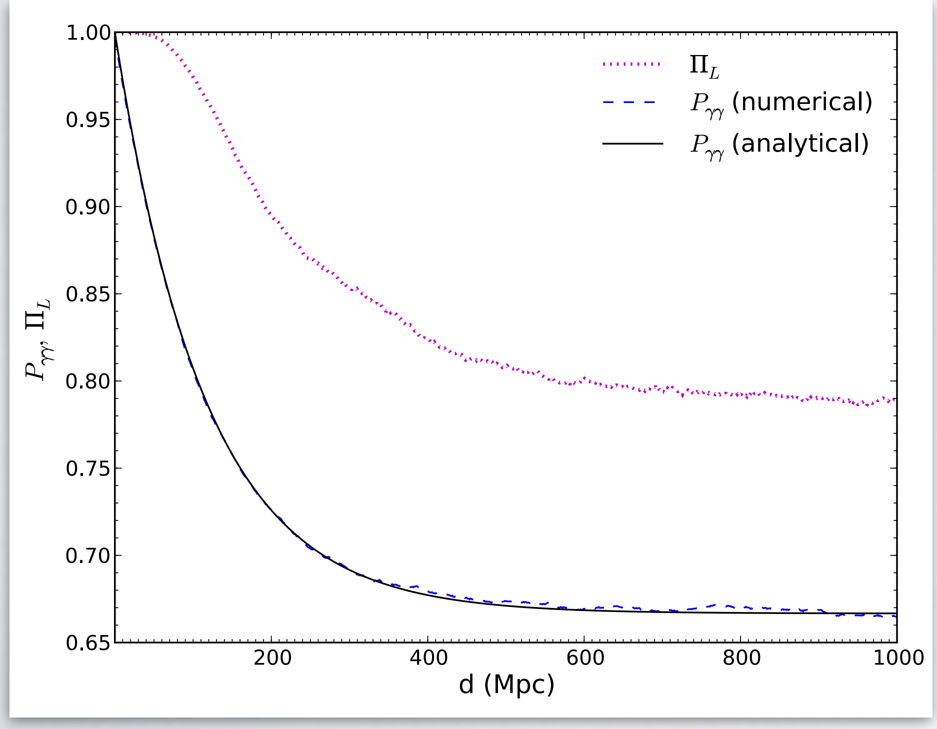
These and similar ideas stimulated lot of activity
(included within Fermi and IACTs)

X-RAY POLARIZATION

Propagation of X-rays from distant sources (e.g. GRBs)+ ALP conversion in extragalactic B-fields may yield peculiar polarization features wrt Energy and/or distance

(possibly analogous signatures associated to crossing of the Galactic magnetic field)





N. Bassan, A. Mirizzi and M. Roncadelli, "Axion-like particle effects on the polarization of cosmic high-energy gamma sources," JCAP 1005, 010 (2010) [1001.5267]

CASE OF COMPACT OBJECTS

clear advantage in celestial environments
due to large B fields coherent over large lengths

$$\frac{P_{\gamma\to a}^{\text{laboratory experiments}}}{P_{\gamma\to a}^{\text{celestial objects}}} \simeq \left(\frac{B_{\text{lab}}}{B}\right)^2 \left(\frac{R_{\text{lab}}}{R}\right)^2 \simeq \left(\frac{R_{\text{obj}}}{R_s}\right)^2 \frac{B_{\text{lab}}^2 R_{\text{lab}}^2}{c^4/8G} \ll 1$$

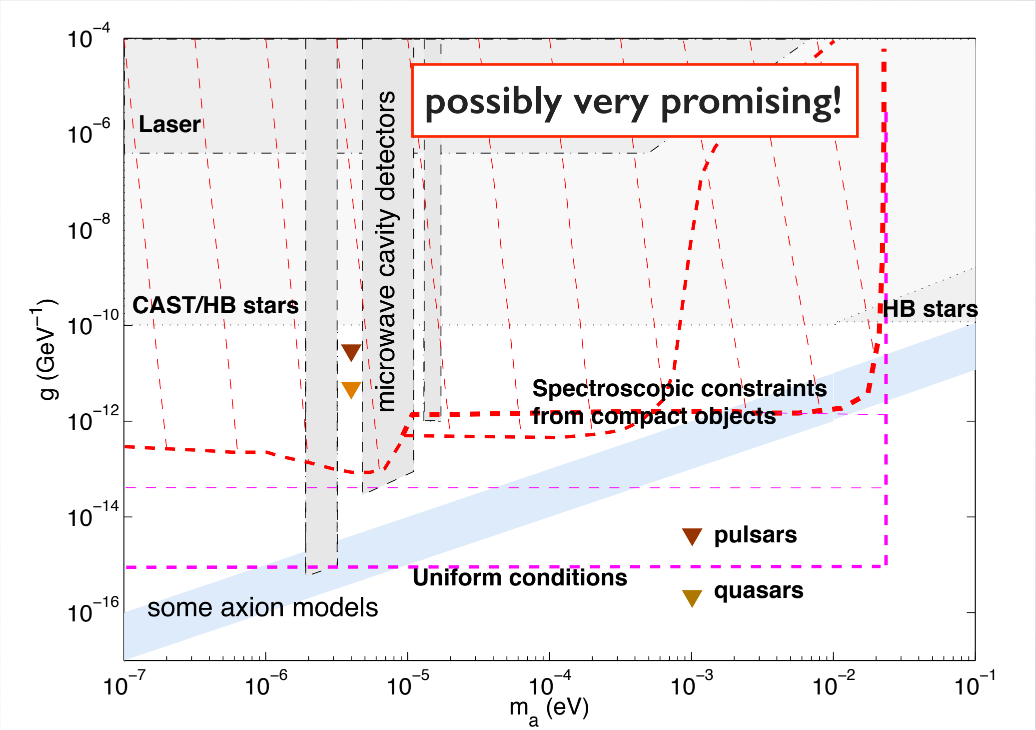
Relatively simple Schroedinger-like mixing equation leads to rich & complicated phenomenology, ***due to the medium***

$$(\omega - i\partial_\gamma + \Delta)\,\mathfrak{A} = 0$$

$$\begin{vmatrix} \Delta_{\perp\perp} & \Delta_{\perp\|} & 0 \\ \Delta^{\star}_{\perp\|} & \Delta_{\|\|} & \Delta_{\|a} \\ 0 & \Delta_{\|a} & \Delta_{aa} \end{vmatrix} \qquad \begin{bmatrix} A_\perp \\ A_\| \\ a \end{bmatrix}$$

e.m. field components & axion field
(acting as "additional polarization state")

Polarization-dependent refraction indexes, mass (and effective plasma mass) term, Faraday rotation and Cotton Mouton birefringence term…



D. Chelouche, R. Rabadan, S. Pavlov and F. Castejon, "Spectral Signatures of Photon-Particle Oscillations from Celestial Objects," ApJ. Suppl. 180, 1 (2009) [0806.0411]

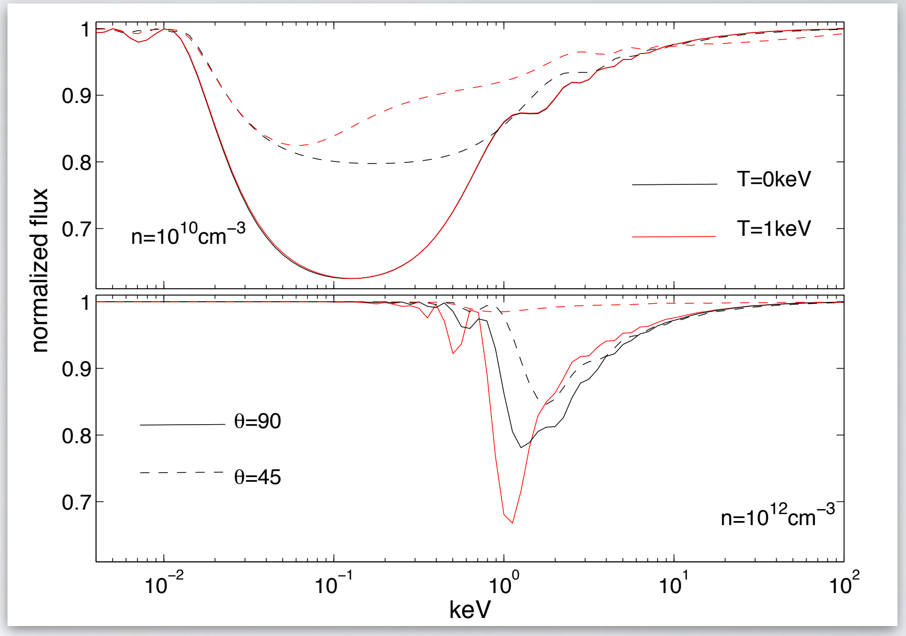
CASE OF COMPACT OBJECTS, CONT'D

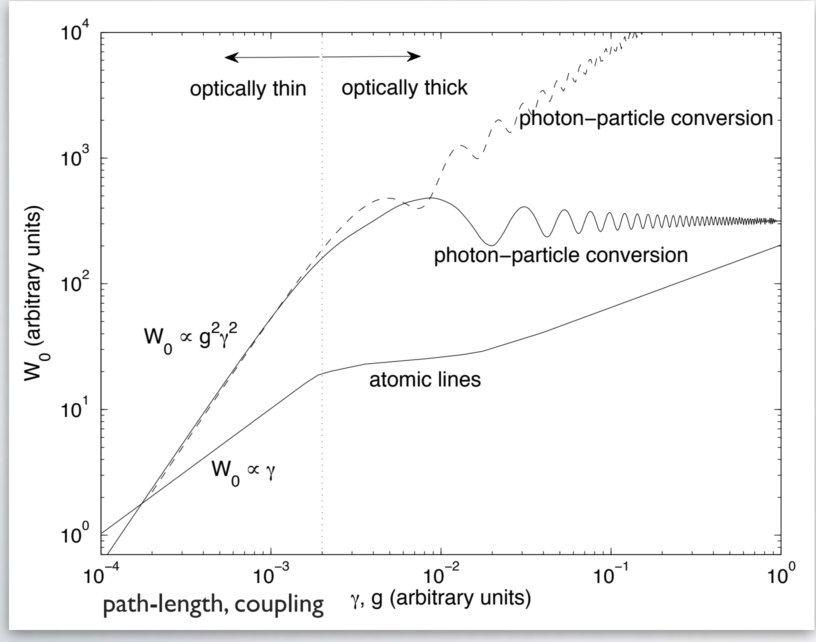
ex.: **X-ray binary** "conversion dips"
different densities and temperatures

$$m_a = 10^{-5}\,\mathrm{eV}$$

$$g = 10^{-9}\,\mathrm{GeV}^{-1}$$

D. Chelouche, R. Rabadan, S. Pavlov and F. Castejon, "Spectral Signatures of Photon-Particle Oscillations from Celestial Objects," ApJ. Suppl. 180, 1 (2009) [0806.0411].





Can be **identified**? May be difficult in practice, although argued that dependence of rest-equivalent width/signal from variables is very different from corresponding atomic lines: peculiar shape and variability features expected!

certainly deserves further studies, especially if puzzling features were to be observed!

3. COMPACT OBJECTS… ALSO PROBE DENSE MATTER!

EOS OF EXTREME MATTER

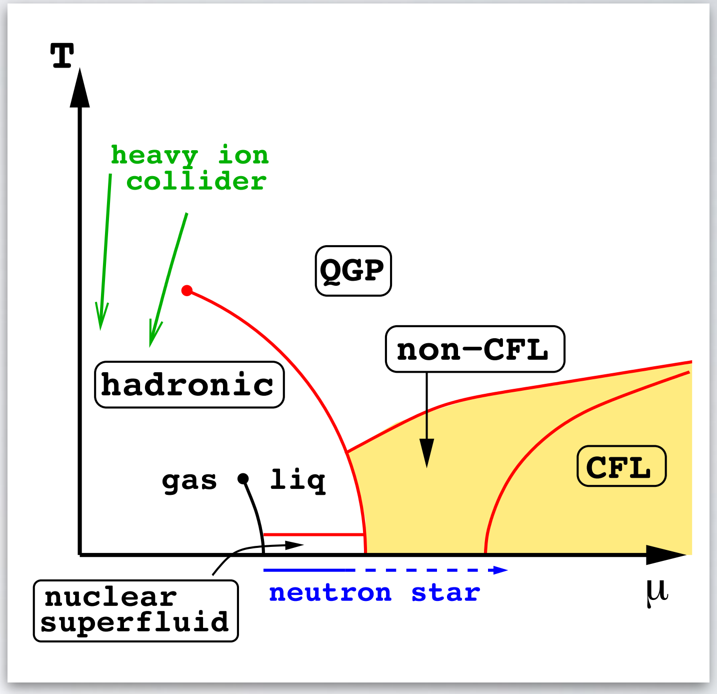
"what happens to matter if you squeeze it more and more?"

The QCD phase diagram is poorly known: no way to probe the high density regime (notably the "cold" one) in the lab! the EOS P=P(ρ) is an ex. of poorly known observable

P=P(ρ) can be constrained in astrophysics via the **mass-radius** relation, since it allows one to close the system

$$\frac{dP}{dr} = -\frac{G(mc^2 + 4\pi r^3 p)(\epsilon + p)}{rc^4(r - 2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi \frac{\epsilon}{c^2} r^2 \qquad \epsilon = n(m_b c^2 + E)$$



J. M. Lattimer and M. Prakash, "The Equation of State of Hot, Dense Matter and Neutron Stars," Phys. Rept. 621, 127 (2016) [1512.07820]

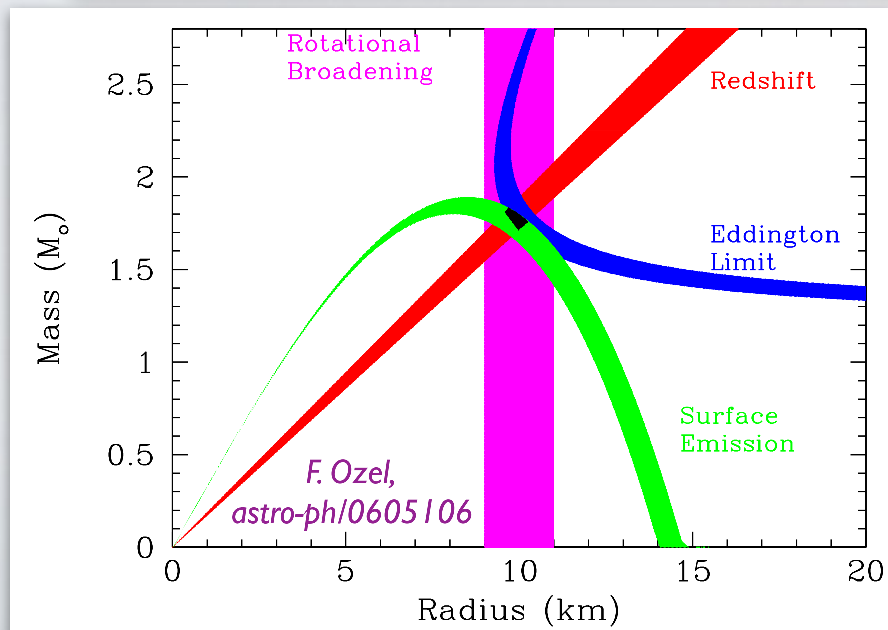
Andreas Schmitt,

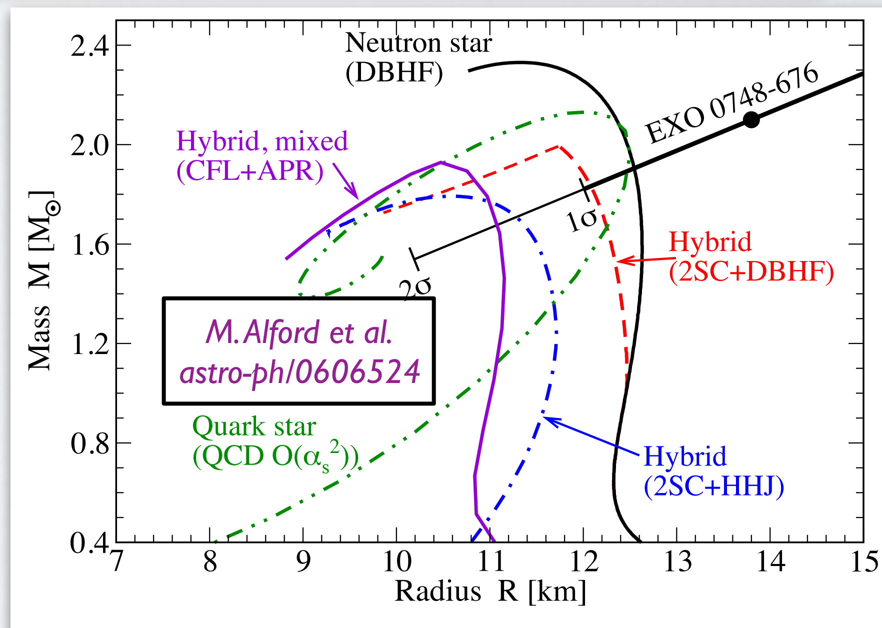
"Dense matter in compact stars - A pedagogical introduction" Springer

MASS-RADIUS RELATION

A number of observables have been proposed to determine masses & radii of NSs, with the latter usually more challenging. Some handles relying on (current or future) **X-ray observations** are:

- Gravitational redshift of lines $z = 1 - (1 - 2GM/Rc^2)^{-1/2}$
- linked to Stefan-Boltzmann blackbody formula (or modifs., provided it applies!) $L = 4\pi R^2 \sigma T^4$
- modulation of X-ray pulses in accreting systems via GR effects
- ...





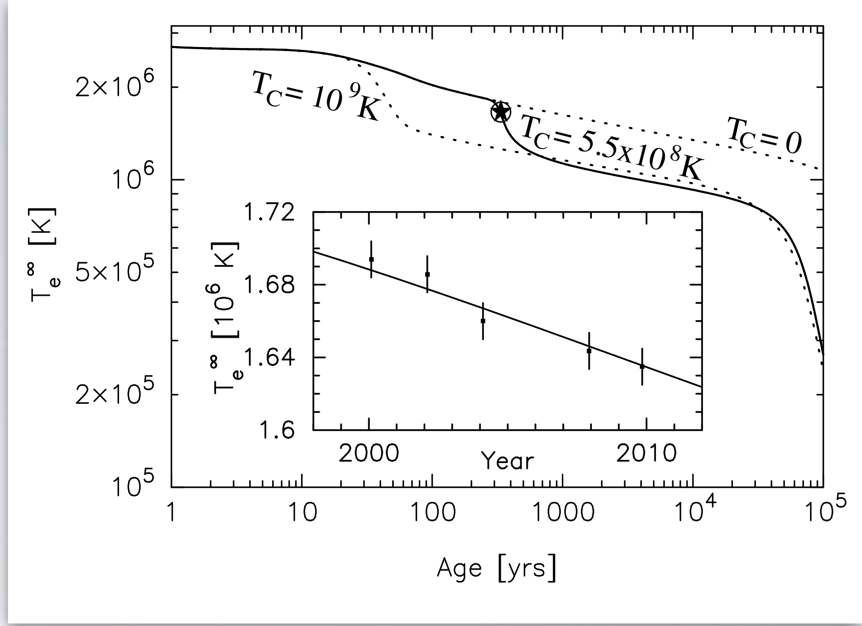
COOLING

Alternative diagnostics exploit cooling of NS

$$C_V \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

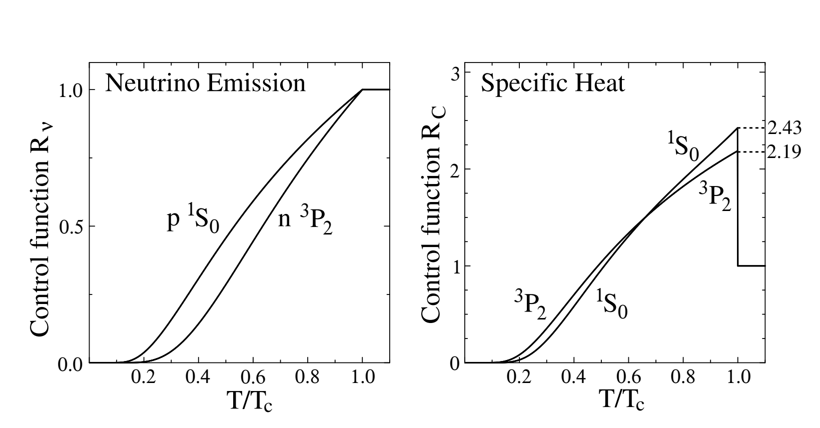
very fast one observed for Cas A! (**Chandra** data)

C. O. Heinke and W. C. G. Ho, "Direct Observation of the Cooling of the Cassiopeia A Neutron Star," ApJ 719, L167 (2010) [1007.4719]



most likely cause: recent transition of inner NS to a superfluid phase!

D. Page, M. Prakash, J. M. Lattimer and A.W. Steiner, "Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter," PRL 106, 081101 (2011) [1011.6142]; See also "Stellar Superfluids," [1302.6626]



4. GRAVITY

TESTING GRAVITY IN NEW REGIMES

No high precision GR tests, apart for specific conditions: Is GR altered for conditions very far away from solar system ones, for instance?

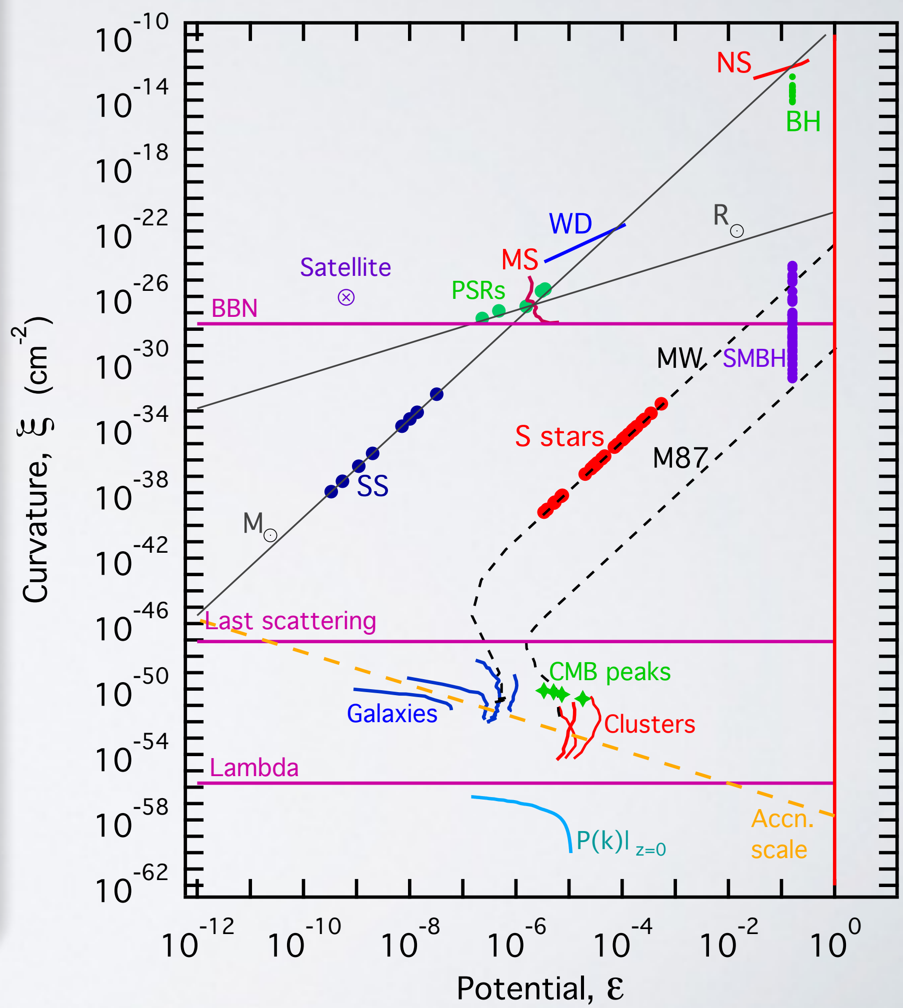
- Quasi-periodic oscillations of X-ray flux
- relativistically broadened Fe-lines,
- thermal emission from the innermost regions of the accretion disks

have all been proposed for such diagnostics, e.g. testing that BH are described by Kerr solution

C. Bambi and E. Barausse, "Constraining the quadrupole moment of stellar-mass black-hole candidates with the continuum fitting method," ApJ 731, 121 (2011) [1012.2007]

T. Johannsen and D. Psaltis, "Testing the No-Hair Theorem with Observations in the Electromagnetic Spectrum. IV. Relativistically Broadened Iron Lines," ApJ 773, 57 (2013) [1202.6069]

T. Baker, D. Psaltis, C. Skordis, "Linking Tests of Gravity On All Scales: from the Strong-Field Regime to Cosmology," ApJ 802, 63 (2015)1412.3455



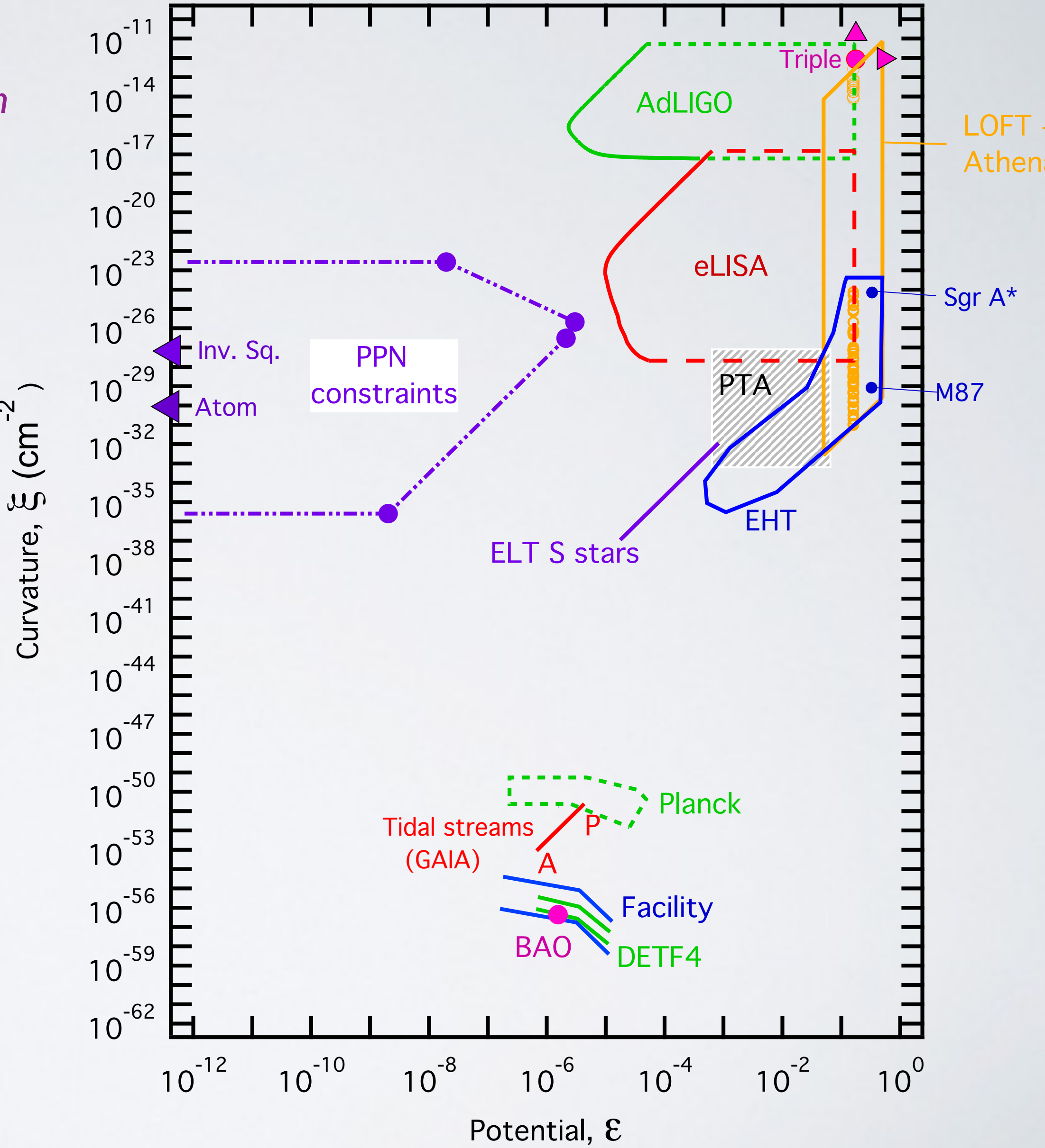
FORECAST FOR LOFT/ATHENA+

T. Baker, D. Psaltis, C. Skordis, "Linking Tests of Gravity On All Scales: from the Strong-Field Regime to Cosmology," ApJ 802, 63 (2015) 1412.3455

LOFT & Athena+ should be able to make these measurements for BH with masses from ~ 5 M⊙ to >10⁹ M⊙.

1-10 Schwarzchild radii mark the boundary of the yellow box.

Distances greater than 10 RS become difficult to probe, because the relativistic broadening of the ~ 6.5 keV Kα line cannot be disentangled from other astrophysical effects on its intrinsic width.



5. FULL CIRCLE, BACK TO COSMOLOGY

COSMOLOGY FROM F_{GAS} IN CLUSTERS

See Gabriel Pratt's lectures

Single cluster can be used to determine the fraction of mass in hot gas, whose z-evolution depends on cosmology!

$$f_{\rm gas}(z) = \Upsilon(z)\left(\frac{\Omega_{\rm b}}{\Omega_{\rm m}}\right)$$

$$L_X \propto n^2 V$$

(since due to collisional processes)

$$L_X = 4\pi d_L^2 F_X$$

by def. of luminosity distance

by equating and remembering that

$$V = 4\pi R^3/3 = 4\pi(\theta\, d_A)^3/3$$

one infers:

$$n \propto d_L/d_A^{1.5}$$

and

$$M_{\rm gas} \propto nV \propto d_L\, d_A^{1.5}$$

since total mass from hydrostatic Equilibrium scales as d_A

$$M(r) = -\frac{r\,kT(r)}{G\mu m_{\rm p}}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln T}{d\ln r}\right].$$

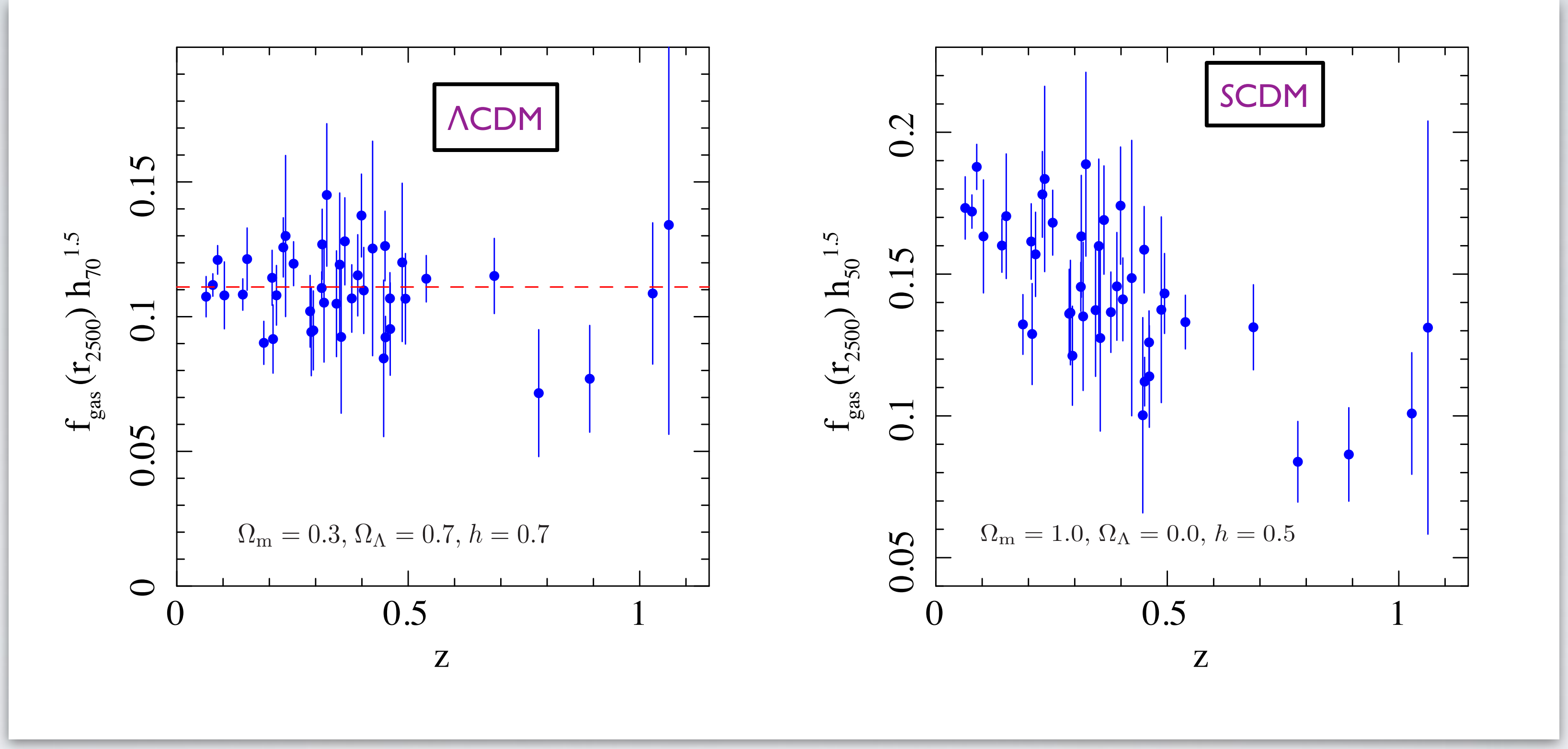
one gets the baryon to total-matter ratio, times a cosmo-dependent scaling factor

$$f_{\rm gas} \sim M_{\rm gas}/M \propto d_L d_A^{0.5}$$

S.W. Allen et al., "Improved constraints on dark energy from Chandra X-ray observations of the largest relaxed galaxy clusters," MNRAS 383, 879 (2008) [arXiv:0706.0033]

COSMOLOGY FROM F_{GAS} IN CLUSTERS

Comparison with data, for "cosmology-corrected" observable predicted to be constant with z (but correction dependent on actual cosmological model)



S.W. Allen et al., "Improved constraints on dark energy from Chandra X-ray observations of the largest relaxed galaxy clusters," MNRAS 383, 879 (2008) [arXiv:0706.0033]

X-RAY CLUSTER SURVEYS & COSMOLOGY

Essentially from endpoint of the halo mass function

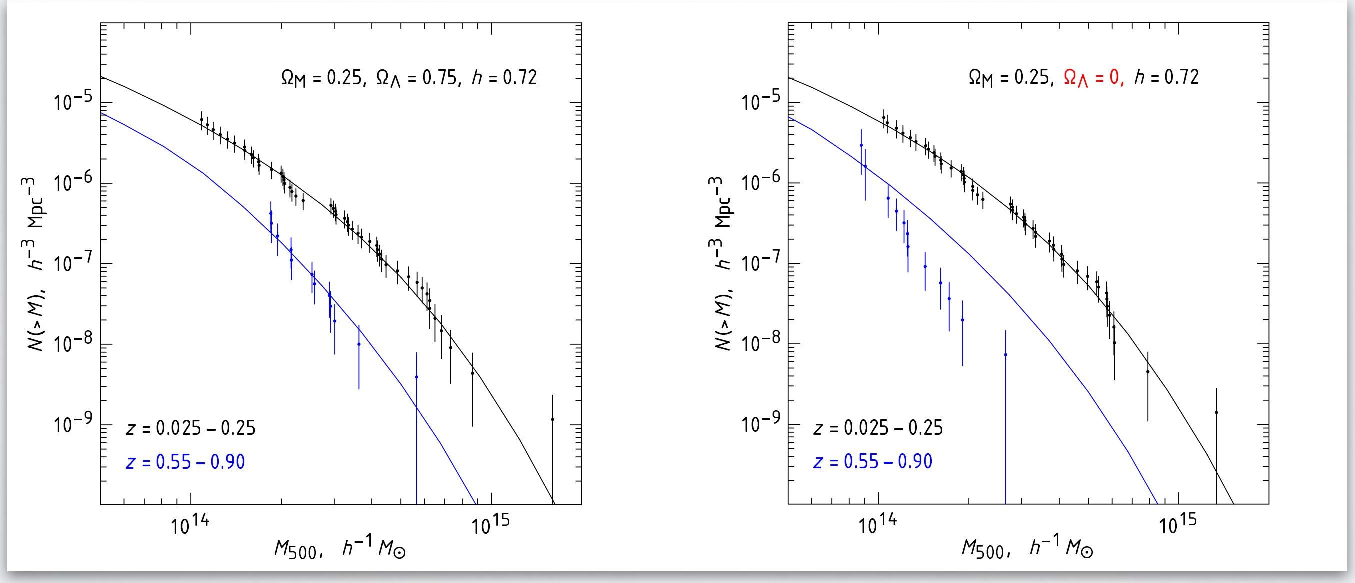
$$\frac{dn}{d\ln M} = \frac{\bar{\rho}_{\rm m}}{M} \left| \frac{d\ln\sigma}{d\ln M} \right| f(\sigma)$$

$$\sigma^2(M,a) = \int \frac{d^3k}{(2\pi)^3}\, W^2(kR)\, P_{\rm m}(k,a).$$

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2}$$

variance of linearly evolved fluctuations, filtered at some mass-scale.

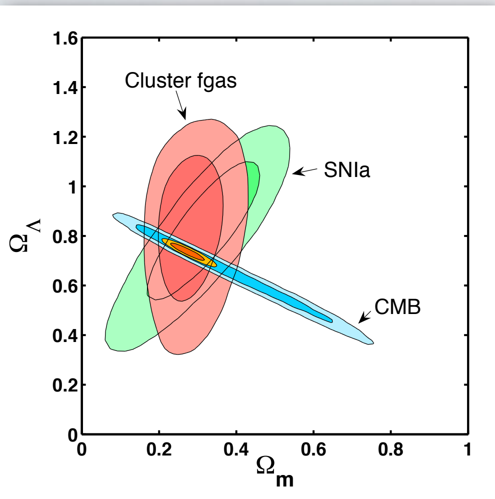
"theory"motivated function (excursion models, where halos collapse when above critical fluctuations) adjusted to simulations (e.g. Sheth Tormen, etc.)



S. W. Allen, A. E. Evrard and A. B. Mantz, "Cosmological Parameters from Observations of Galaxy Clusters," Ann. Rev. Astron. Astrophys. 49, 409 (2011) [arXiv:1103.4829]

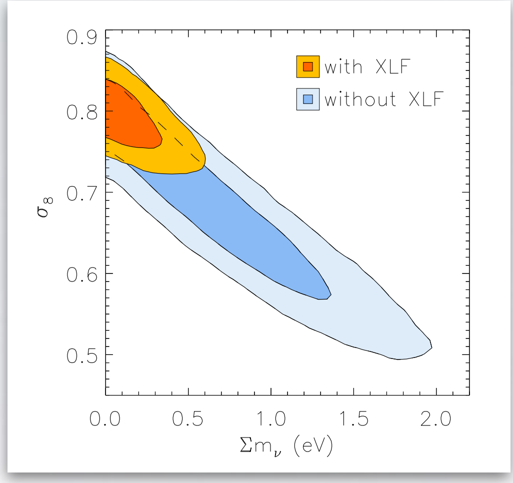
X-RAY CLUSTERS & COSMOLOGY

Relatively easy X-ray identification of clusters; relatively clean path to complete cluster catalogues (critical for cosmology with cluster counts); now currently used… even to constrain gravity to the largest scales!



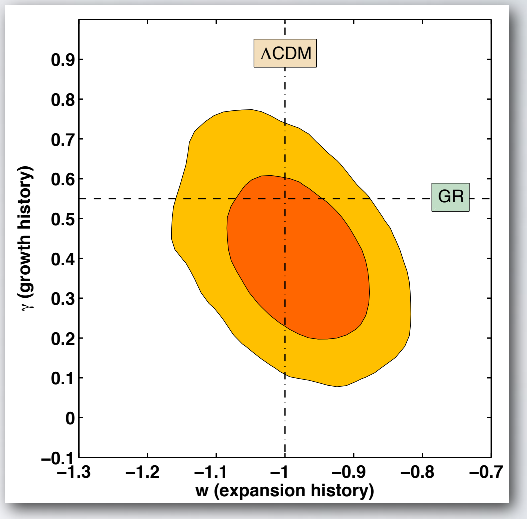
establishing ΛCDM

…



constraints to ν masses

…



constraints to modified gravity

Of course, many issues still to settle (e.g. bias!), especially for the forthcoming "high precision cosmology"! More on dedicated lectures…

S. W. Allen, A. E. Evrard and A. B. Mantz, "Cosmological Parameters from Observations of Galaxy Clusters," Ann. Rev. Astron. Astrophys. 49, 409 (2011) [arXiv:1103.4829]

CONCLUSIONS/TAKE-HOME MESSAGE

- ✓ Virtually any new astrophysical window has been exploited to learn about fundamental physics.
- ✓ X-ray astrophysics is no exception, since this emission is often associated to environmental conditions very far from the ones probed in terrestrial labs.
- ✓ I quickly recalled the role X-rays is currently play in mapping Dark Matter observables, alone or in conjunction with other probes (such as lensing)
- ✓ I have argued why X-rays are not usually a good probe for WIMP DM diagnostics… but does not mean that they cannot contribute to more exotic DM candidates (DM searches are "theory-biased", keep an open-mind!)
- ✓ X-rays can also probe new particles invoked in the solution of particle physics problems, such as axions, or generalizations of them arising e.g. in string-theory (axion-like particles). Usually, neutrino-like oscillations of photons into axions in external B-fields offer a great handle. We are also quite sure that Natural labs exceed the reach of terrestrial ones in parameter space (e.g. Hillas criterion & UHECRs) !
- ✓ Compact objects, notably neutron stars, offer one such environment; at the same time, unique lab to explore "standard physics" such as QCD in a density regime which is impossible to probe on Earth.
- ✓ X-rays are also messengers to probe gravity in poorly explored regimes of curvature/potential
- ✓ In current cosmological context, significant auxiliary tool to probe dark energy/modified gravity!