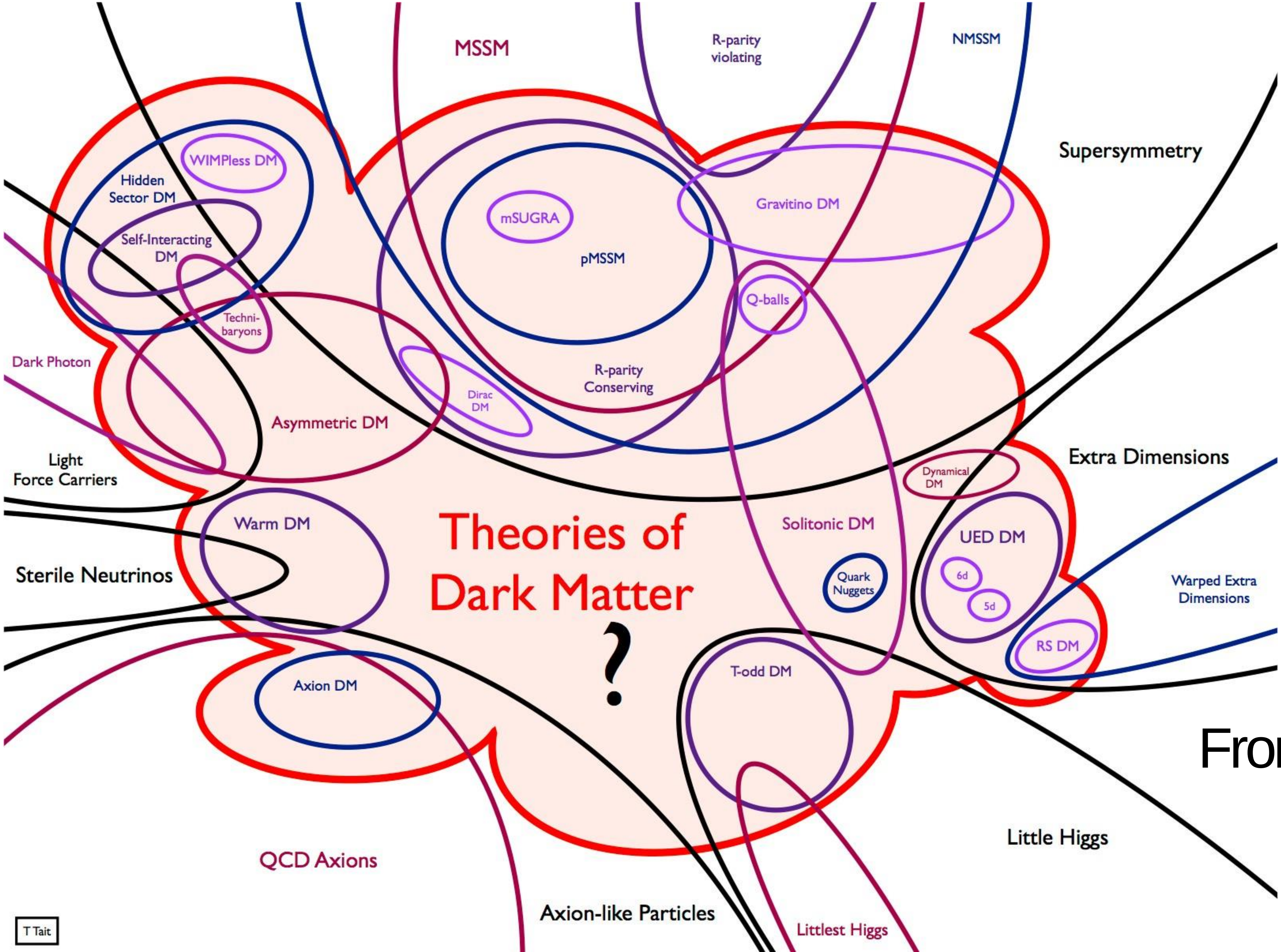
Fantastic Beasts and where to Find Them:-
1) CNO neutrinos
2) The Interaction of PBHs with stars

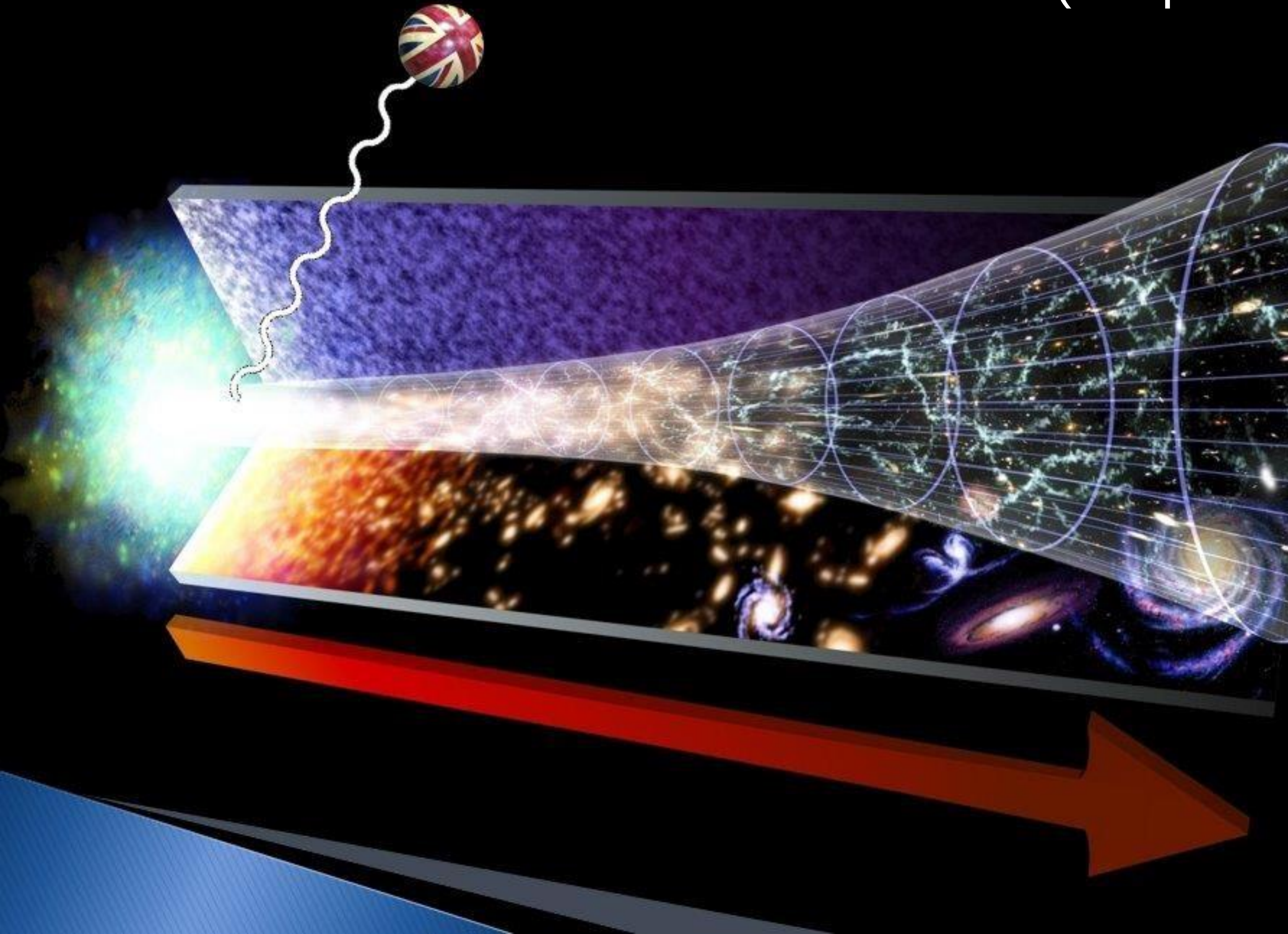
Malcolm Fairbairn

KING'S College LONDON



From Tim Tait

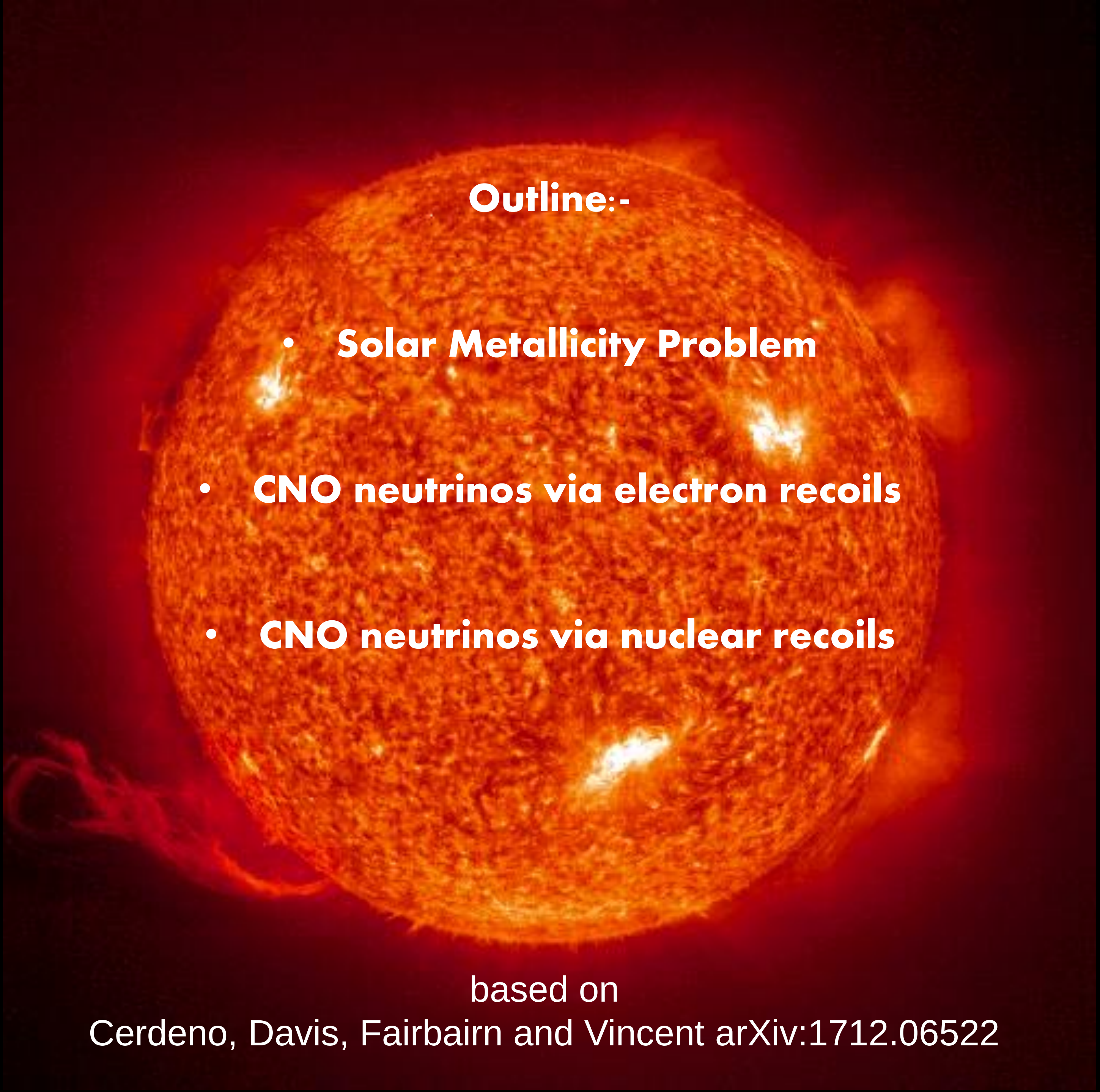
The Brexiton (Enqvist 2017, Rajantie 2017)



Goes out of thermal equilibrium then acts as a decoupled spectator field while it decays

Outline of Talk

- CNO neutrinos
  - Will the upcoming experiments find CNO neutrinos
  - What future experiments might discover neutrinos
- Interaction of Primordial Black Holes with Stars
  - Super-radiance in plasma as a source of Fast Radio Bursts
  - Black Hole in Stellar Atmosphere
  - Event Rate


Outline:-
• Solar Metallicity Problem
• CNO neutrinos via electron recoils
• CNO neutrinos via nuclear recoils
based on
Cerdeno, Davis, Fairbairn and Vincent arXiv:1712.06522

New Scientist

WEEKLY 21 October 2017

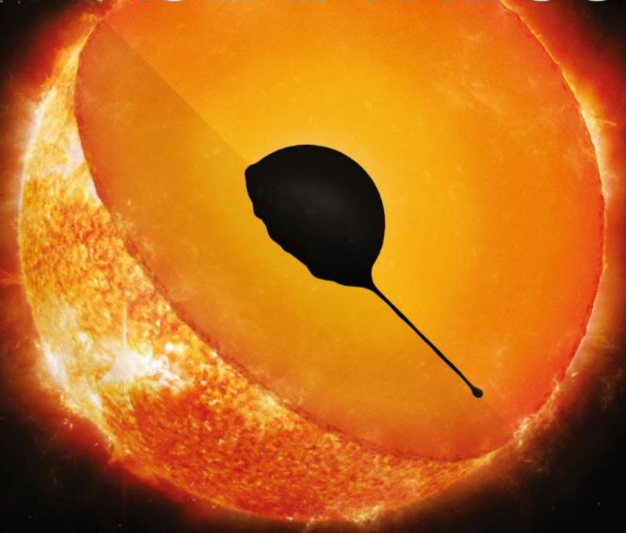
SPECIAL REPORT

GRAVITATIONAL WAVES

All the fallout from the neutron star smash-up

SWIPE LEFT! How online dating is making society more liberal

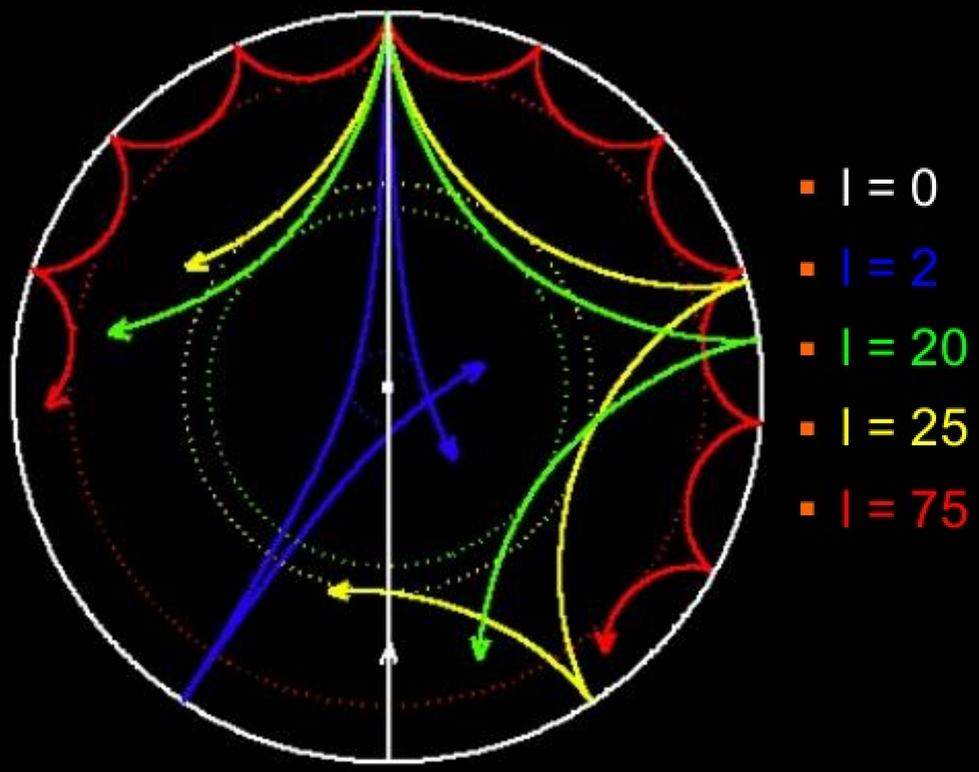
SOMETHING STRANGE IS GOING ON INSIDE THE SUN

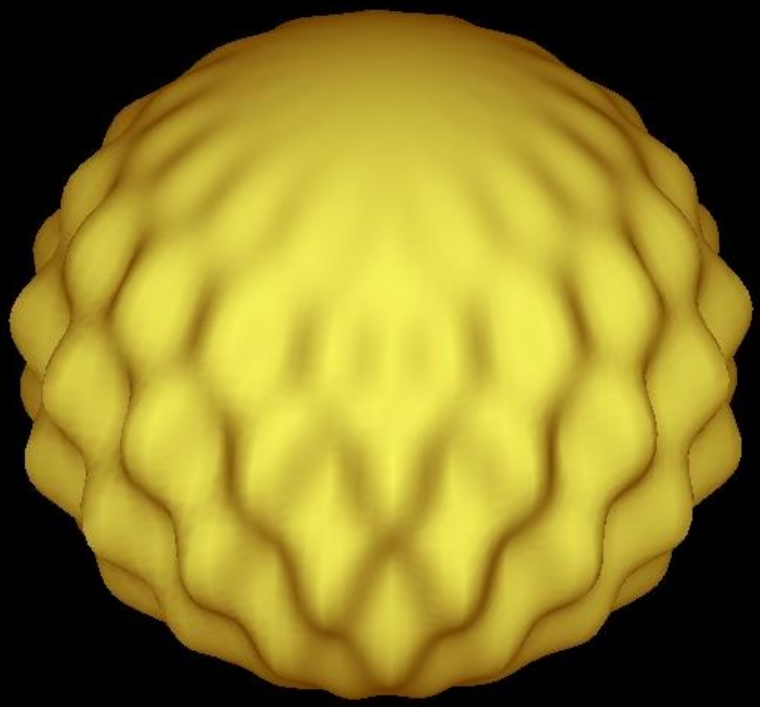


No3148 £4.10 US/CAN$6.99

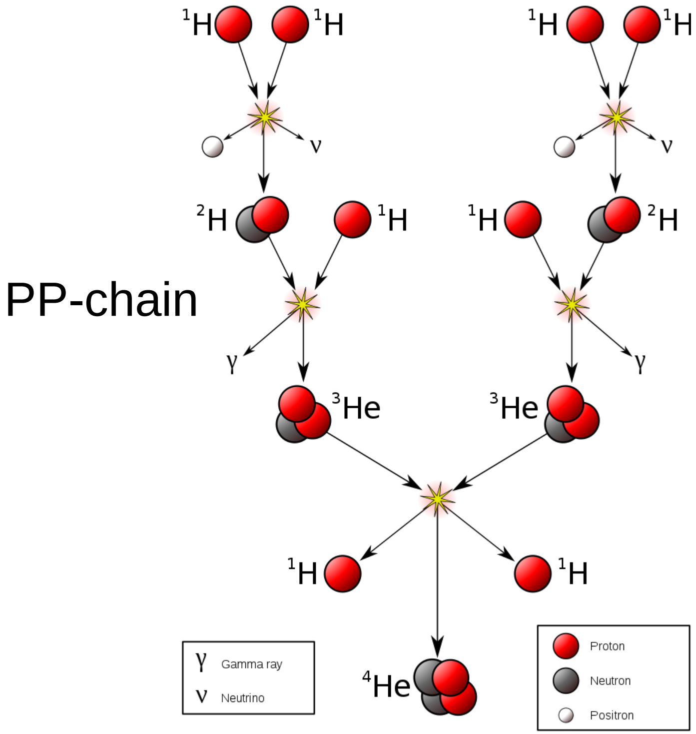
PLUS LONG-LOST SPECIES / **CANCER AND NERVES** / SEX ADDICTION / **MOON VS MARS** / **FEMALE ORGASM** / EPIGENETIC EVOLUTION / **SOVIET SCIENCE** / MATHS BEATS THE BOOKIES

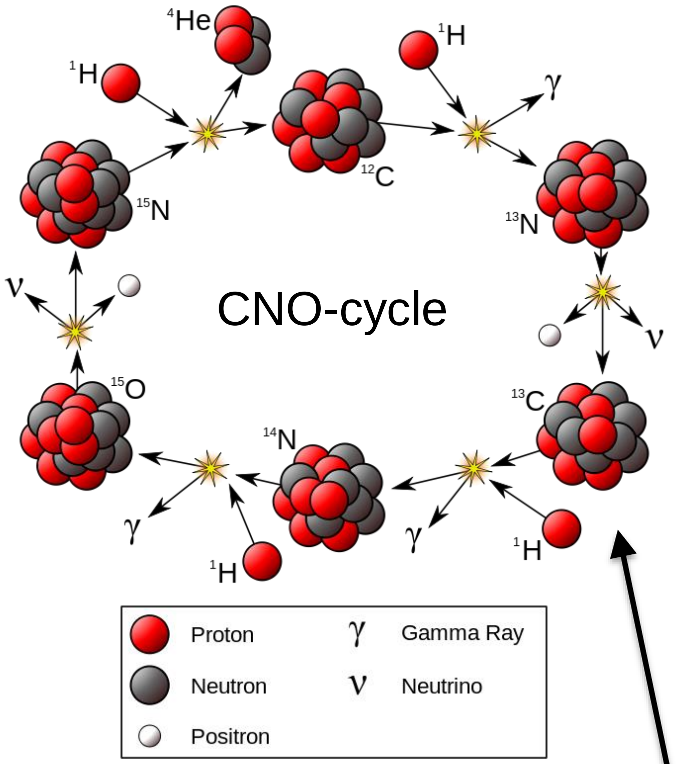
Helioseismology – vibrational modes of the Sun

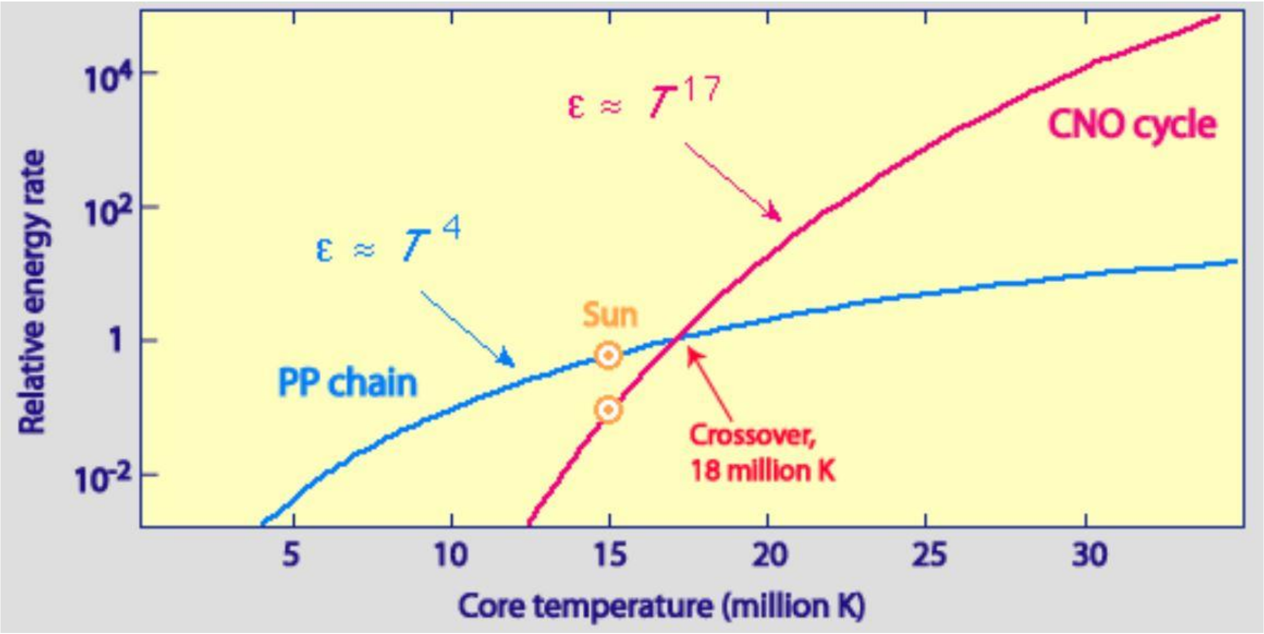




By its very nature it samples the speed of sound in the Sun at different depths







DEPENDS ON
METALLICITY
Z

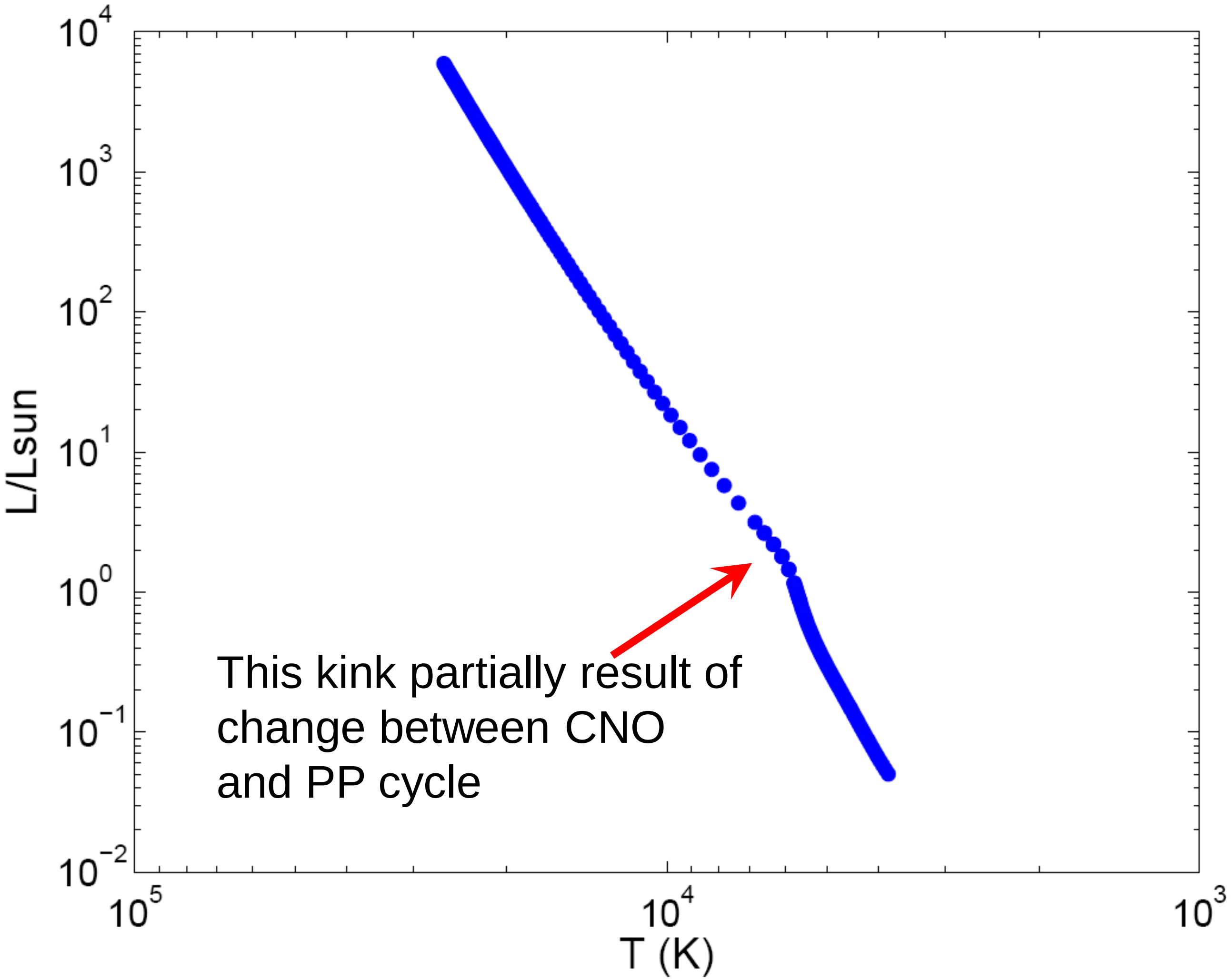
Equations of Stellar Structure have Solutions which are Stars

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

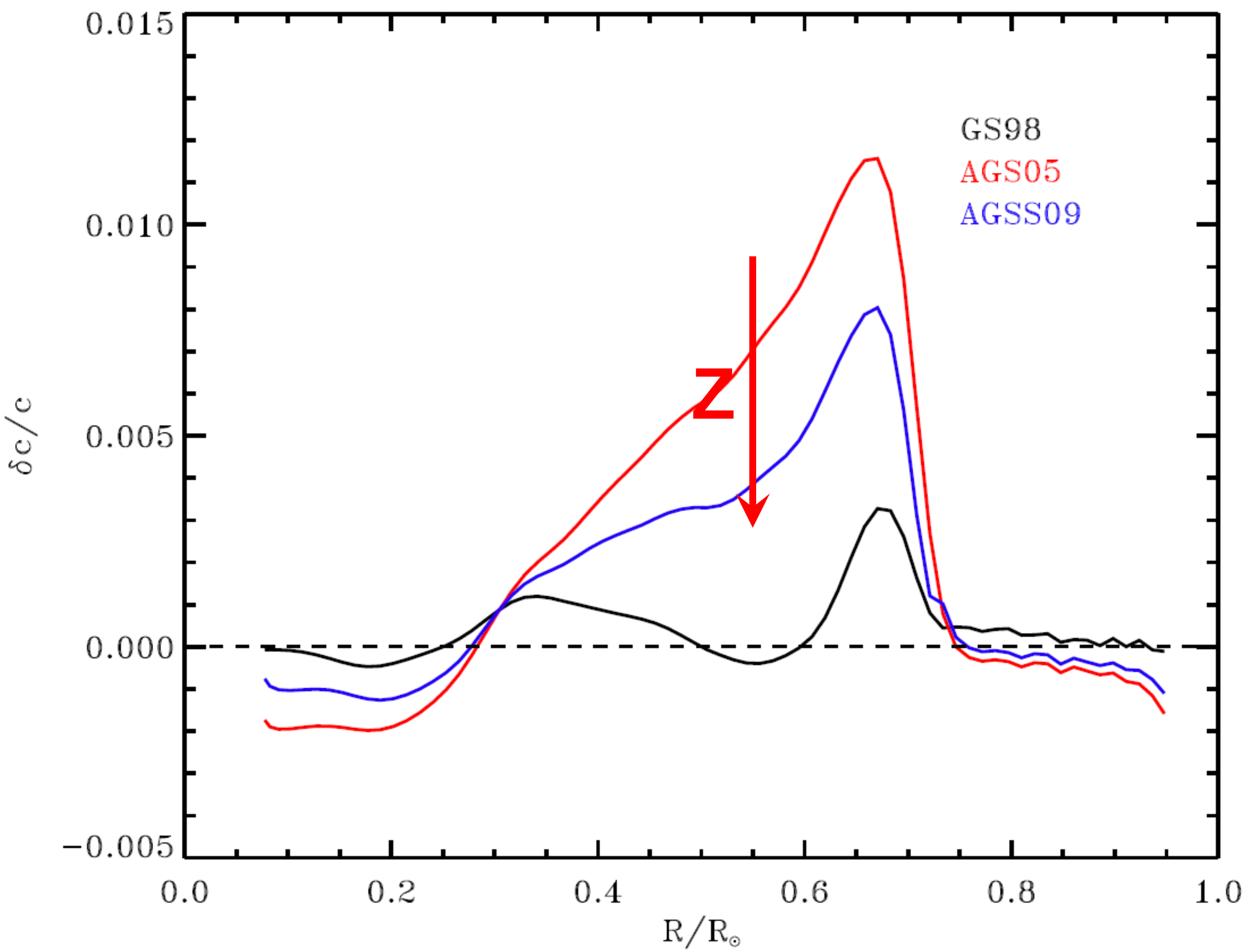
$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$



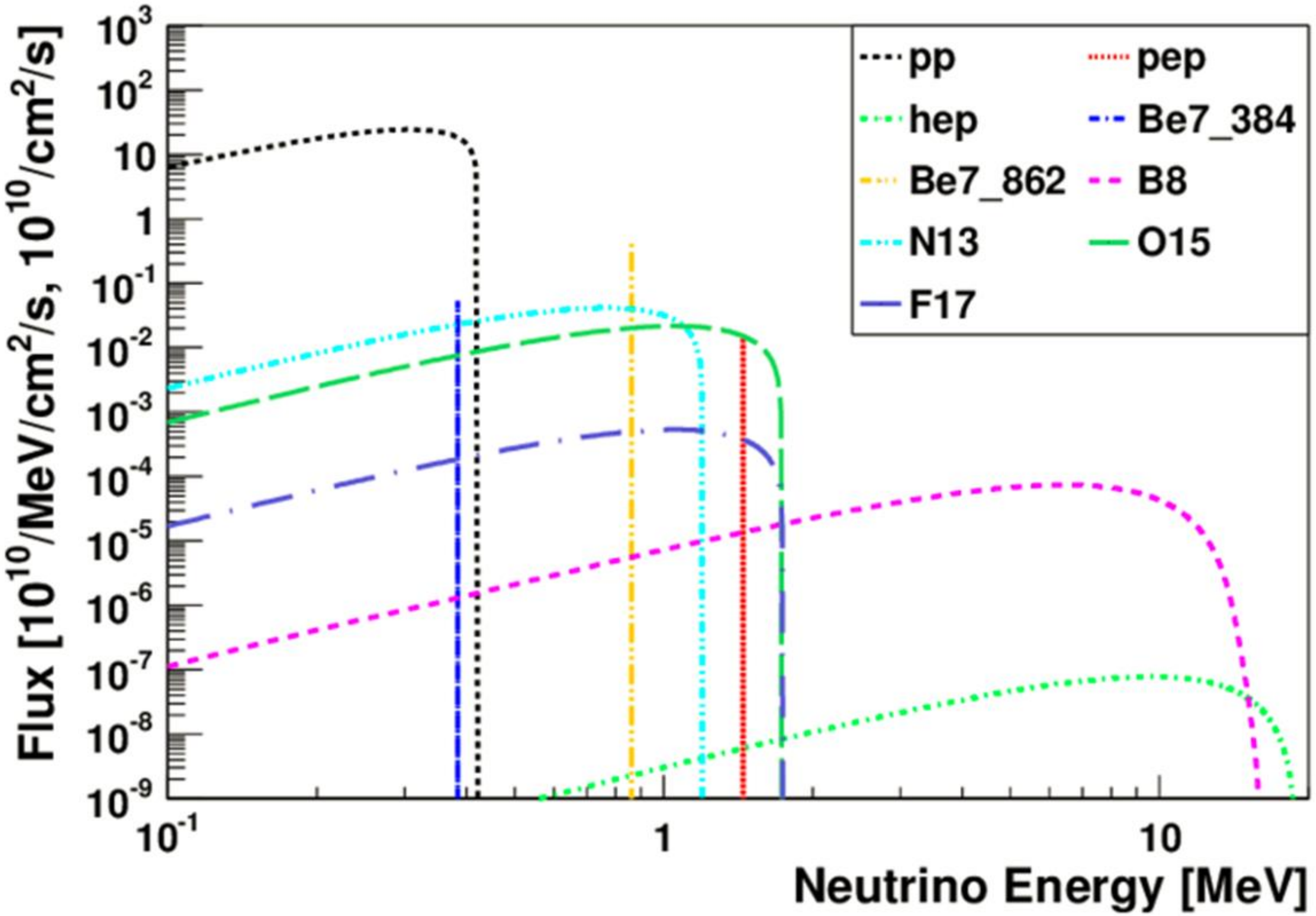
Observed abundances are not consistent with Solar Models which match Helioseismology constraints on speed of sound.



As we make conclusions about DM and DE using stars should worry about this.

Solar Metallicity	CNO Neutrino Flux [$cm^{-2}\ s^{-1}$]		
	^{13}N [10^8]	^{15}O [10^8]	^{17}F [10^6]
High	2.78 ± 0.42	2.05 ± 0.35	5.92 ± 1.06
Low	2.04 ± 0.29	1.44 ± 0.23	3.26 ± 0.59

One way to get a better hold on this is by measuring CNO neutrinos

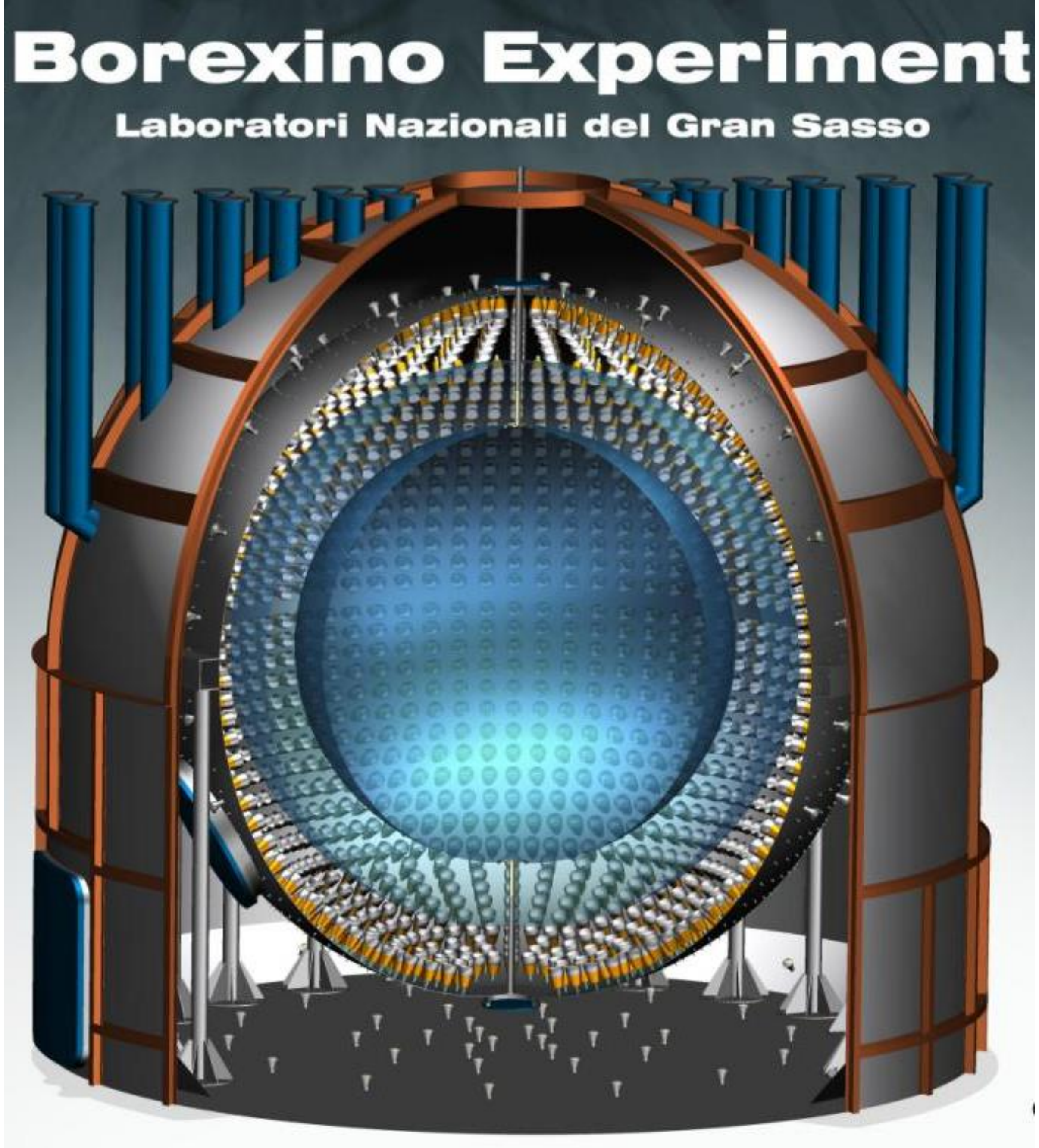


Let's estimate the sensitivity of Borexino and SNO+…

Our Statistical Analysis in the work

- We do Monte Carlo Markov Chains MCMC
- Some of our (Gaussian) priors based on actual measurements and their errors
- Other priors are based on expected backgrounds and the accuracy with which experiments will be able to measure these backgrounds
- We compare the spectra of the different sources with simulated data
- Each chain has one simulated data set, normalisations of the various spectra are allowed to vary within their priors
- We run 50 chains (50 fake experiments) for each situation

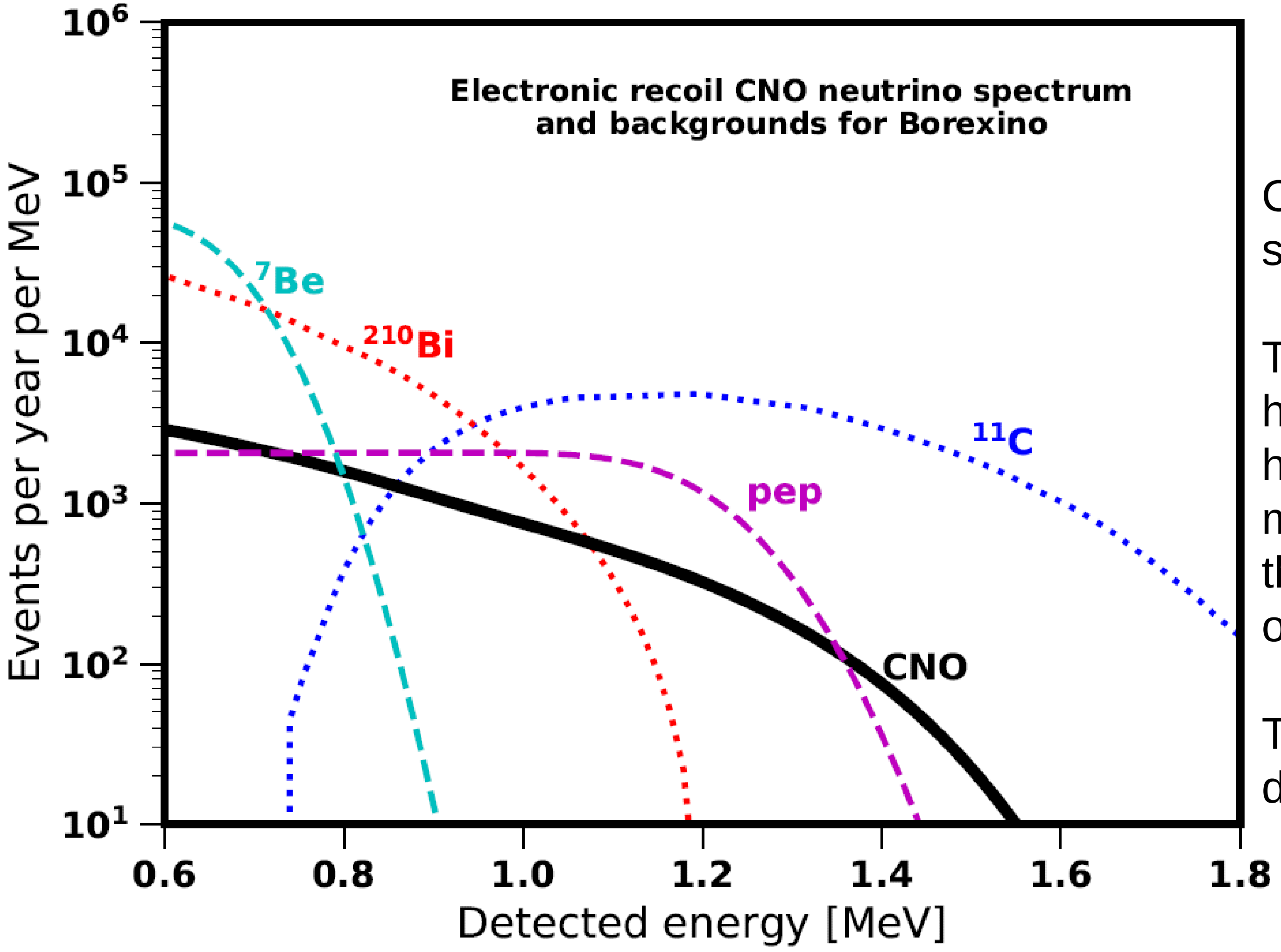
Andrey Markov



Liquid scintillator with 71 tons fiducial mass located in Gran Sasso Laboratory.

The liquid is a doped aromatic hydrocarbon.

Borexino CNO recoil spectrum and relevant backgrounds



CNO flux is rather similar to ^{210}Bi flux

This is a problem, however Borexino hope to be able to measure ^{210}Bi flux through observation of daughter nuclei.

They may be able to do this at 10% level.

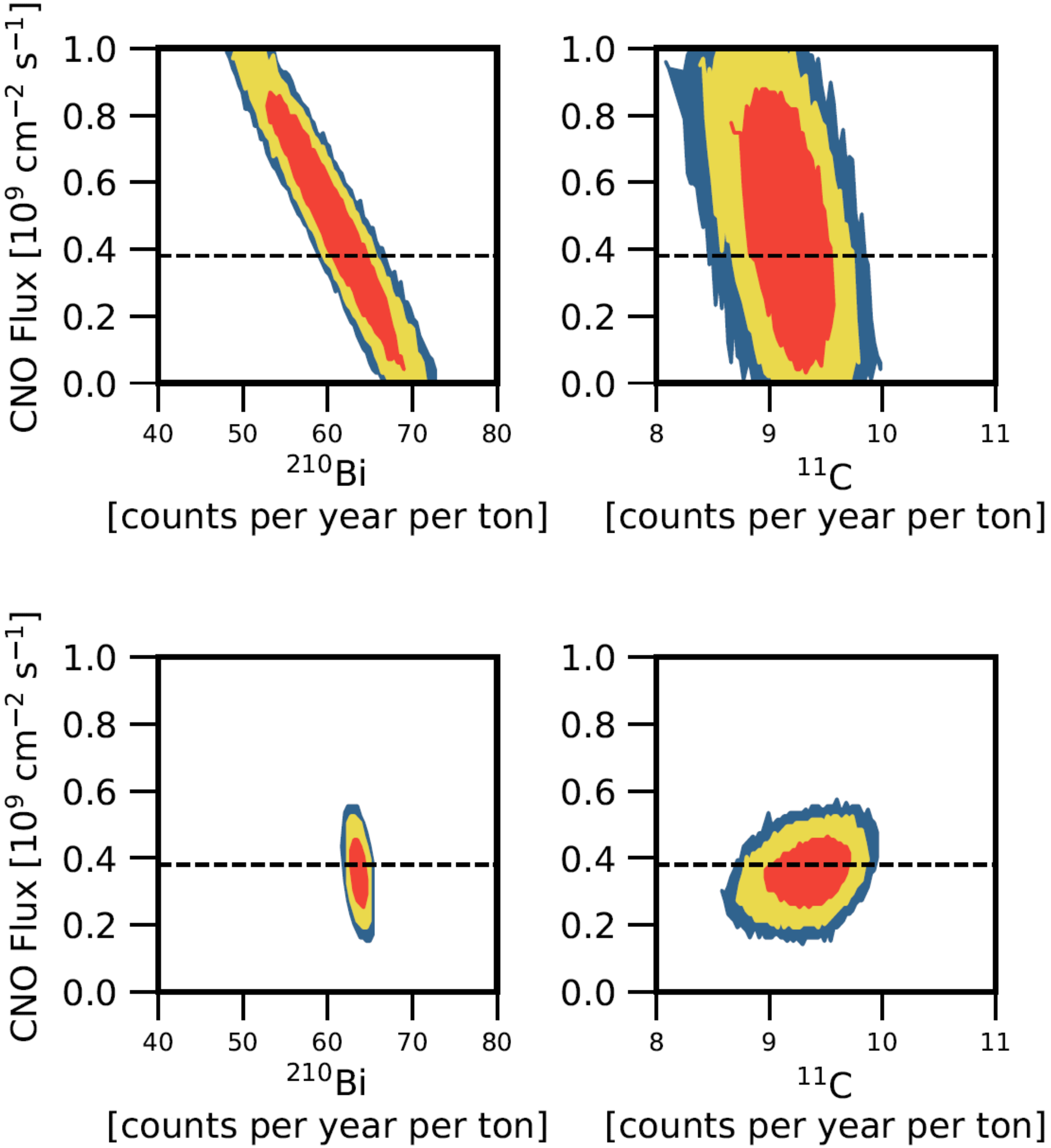
Borexino

Pessimistic (realistic) error Estimate, assumes Borexino Can measure ^{210}Bi flux to 10%

THIS IS AFTER 10 YEARS OF RUNNING.

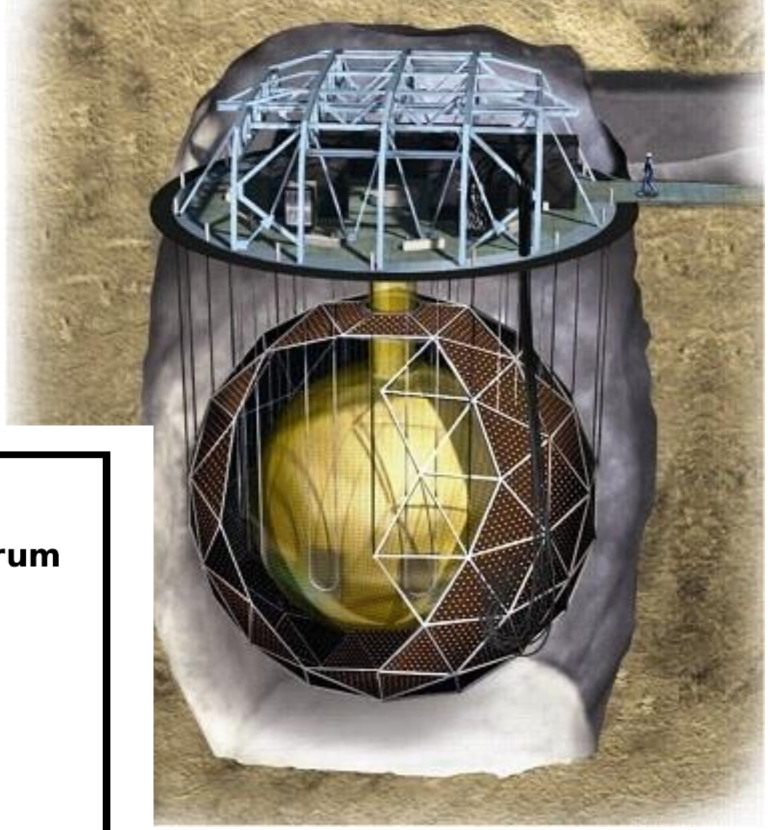
DASHED LINE IS HI-Z CNO FLUX.

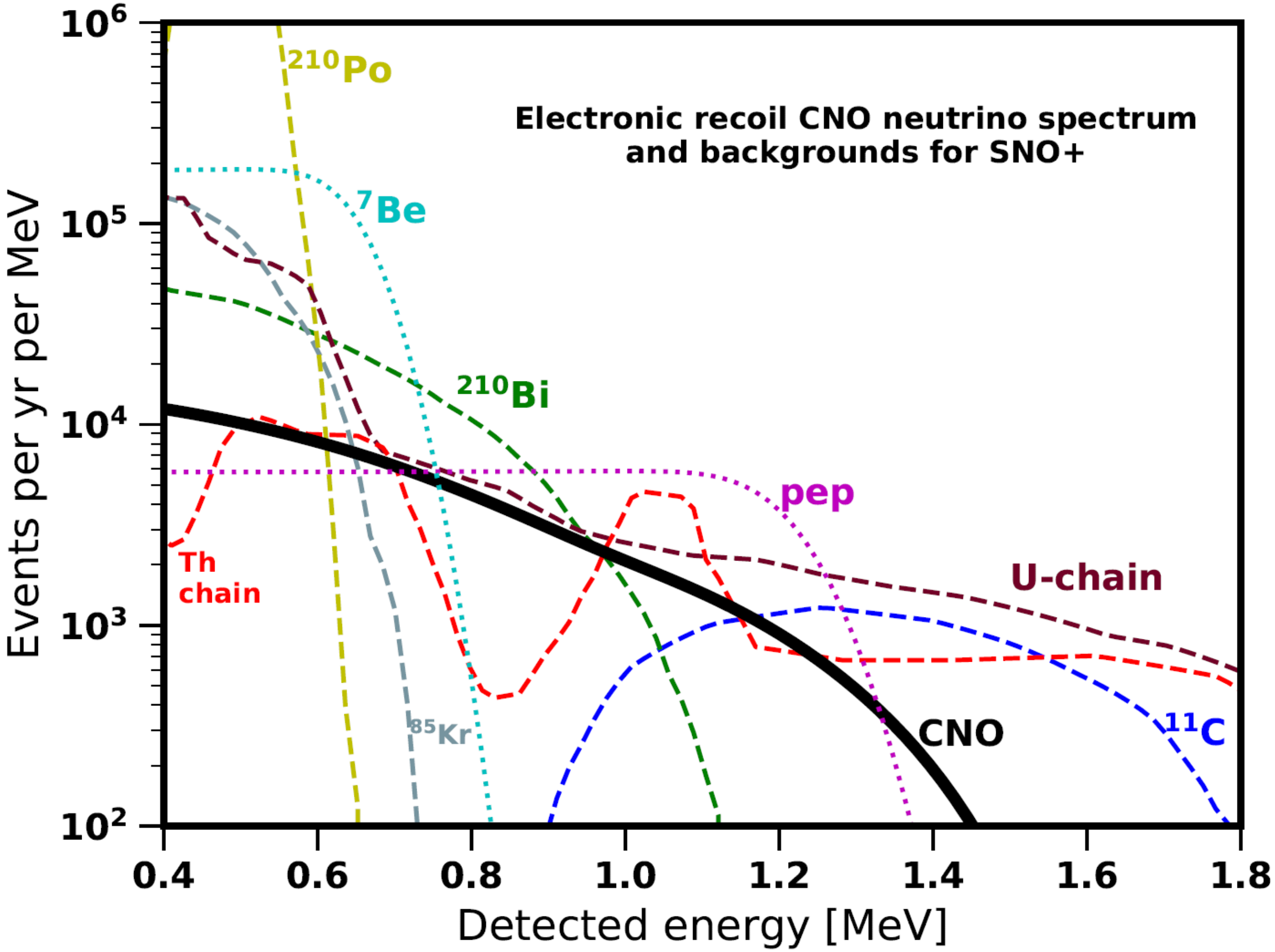
Optimistic (unrealistic?) error Estimate, assumes Borexino Can measure ^{210}Bi flux to 1%



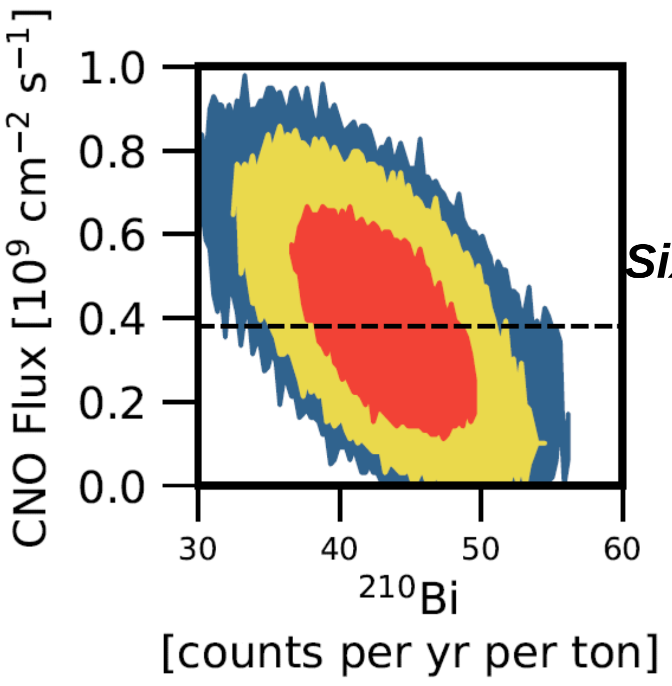
SNO+

Also has backgrounds but more importantly it is
Starting it's run with ^{130}Te for $0\nu\beta\beta$



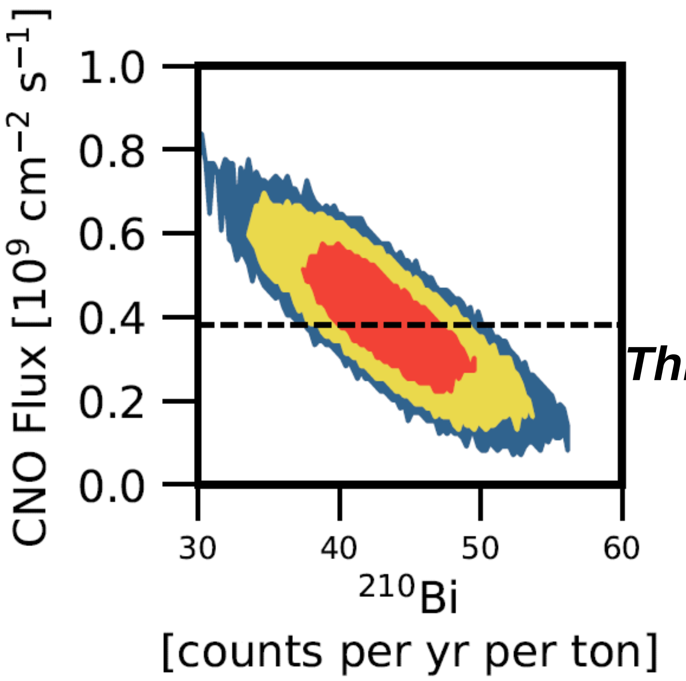


SNO+ runs without ^{130}Te



Six months running of SNO+ with pessimistic errors

Background	Pessimistic Value $[(\text{ton yr})^{-1}]$	Pessimistic Error $[1\sigma]$
^{210}Bi	45.4	10%
^{210}Po	1530	20%
^{11}C	1.74	Free
^{85}Kr	96.4	50%
U chain	74.4	7%
Th chain	11.1	25%



Three years running of SNO+ with pessimistic errors

HOWEVER – currently SNO+ plans to run with ^{130}Te in order to look for neutrinoless double beta decay

As it stands, SNO+ MAY detect CNO at low significance IF it decides to run without ^{130}Te for several years and they understand their backgrounds as well as they hope to.

However, they probably won’t be able to discriminate between low and high metallicities.

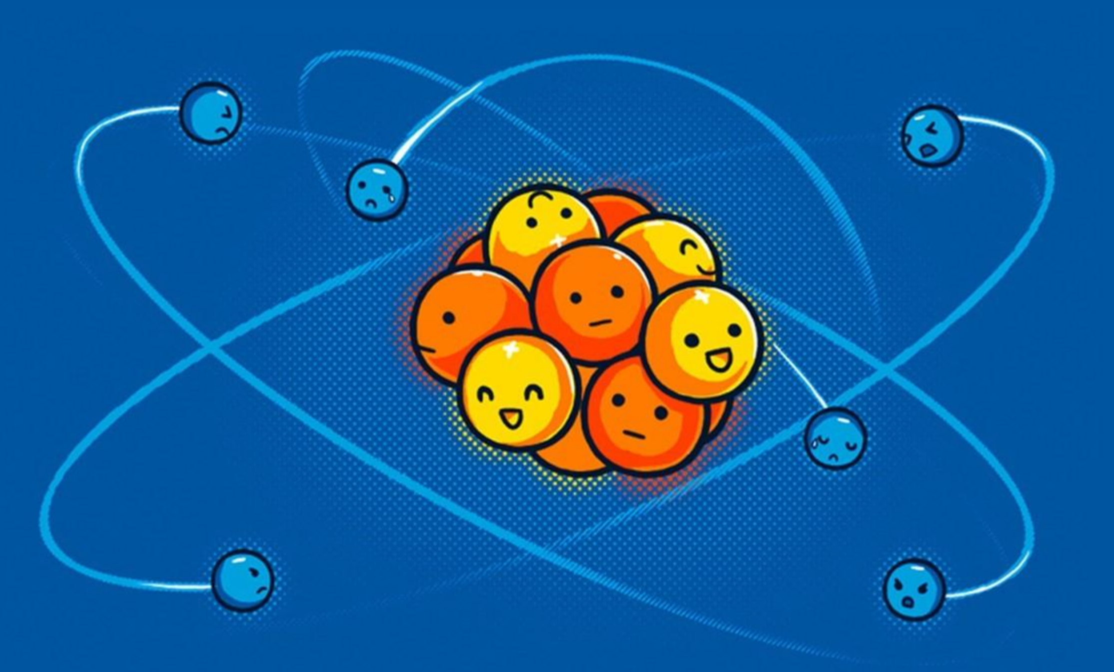
What about Dark Matter detectors?

CNO neutrinos give rise to

MeV electron recoils (above pp)
&
keV nuclear recoils (below 8B)

Lets start with electron recoils.

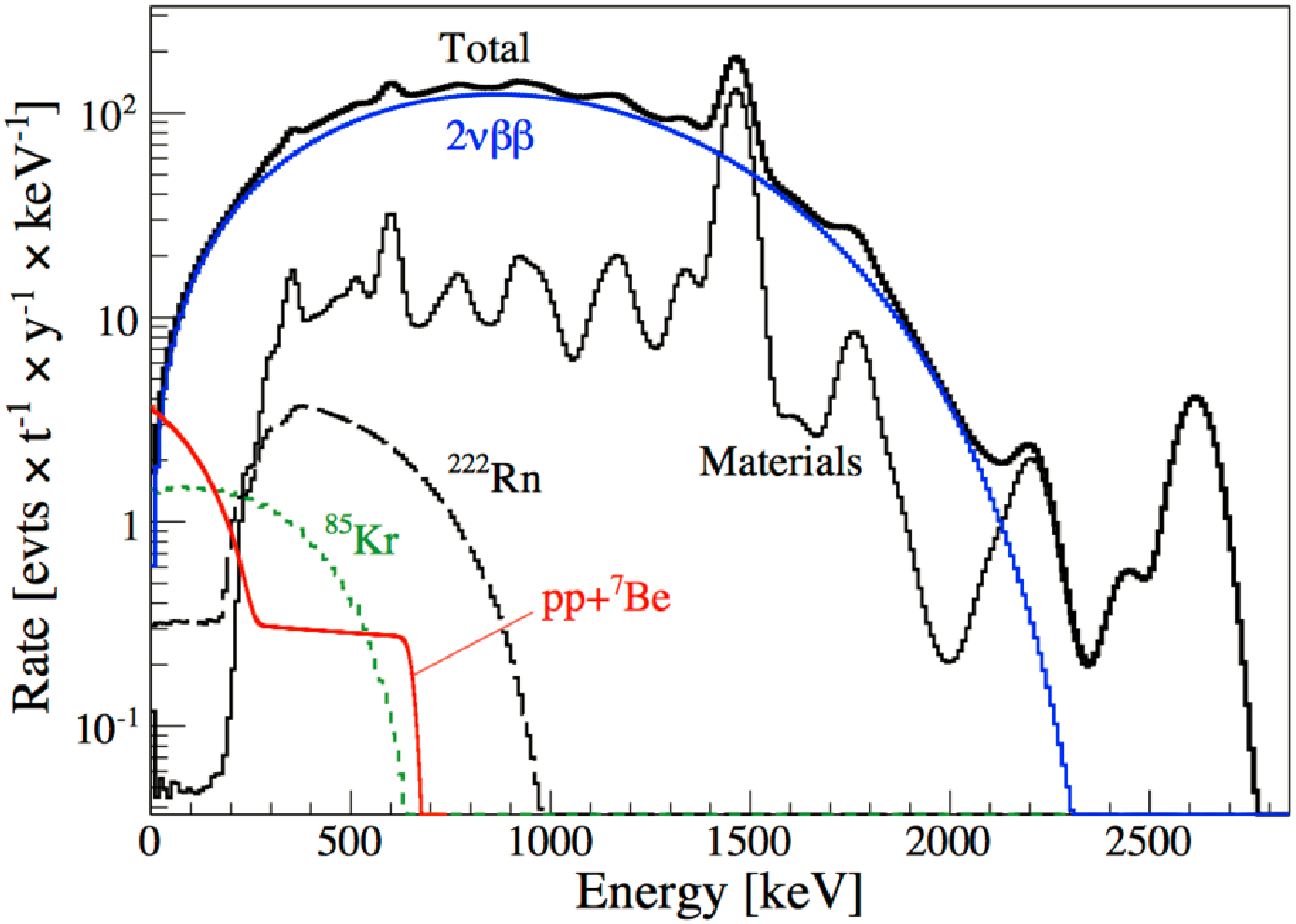
start with electron recoils



FUTURE ***XENON*** EXPERIMENTS (e.g. Darwin)

CNO neutrinos would be very difficult for a Xenon like experiment…

Electron recoils are in a region with a lot of background…



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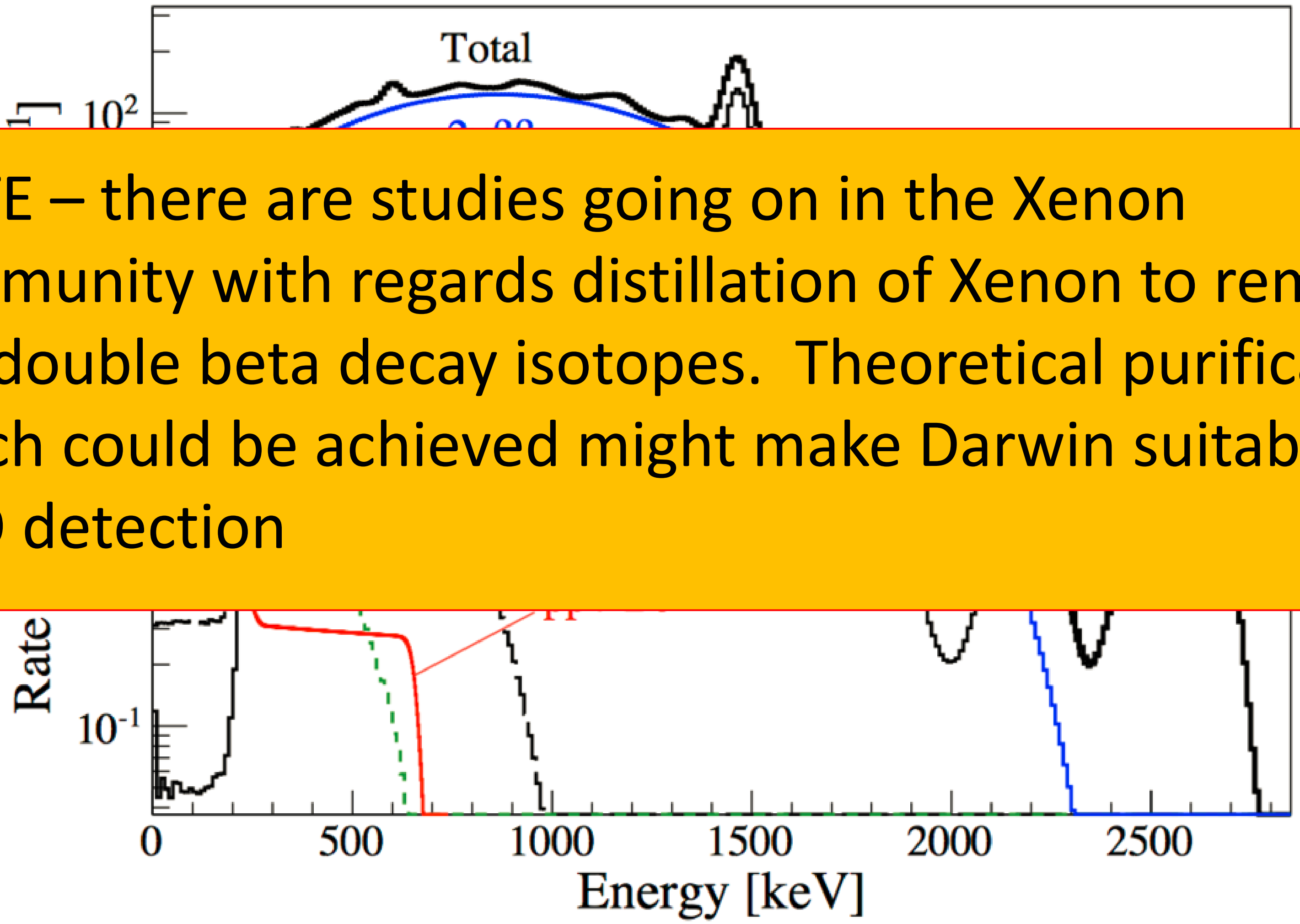


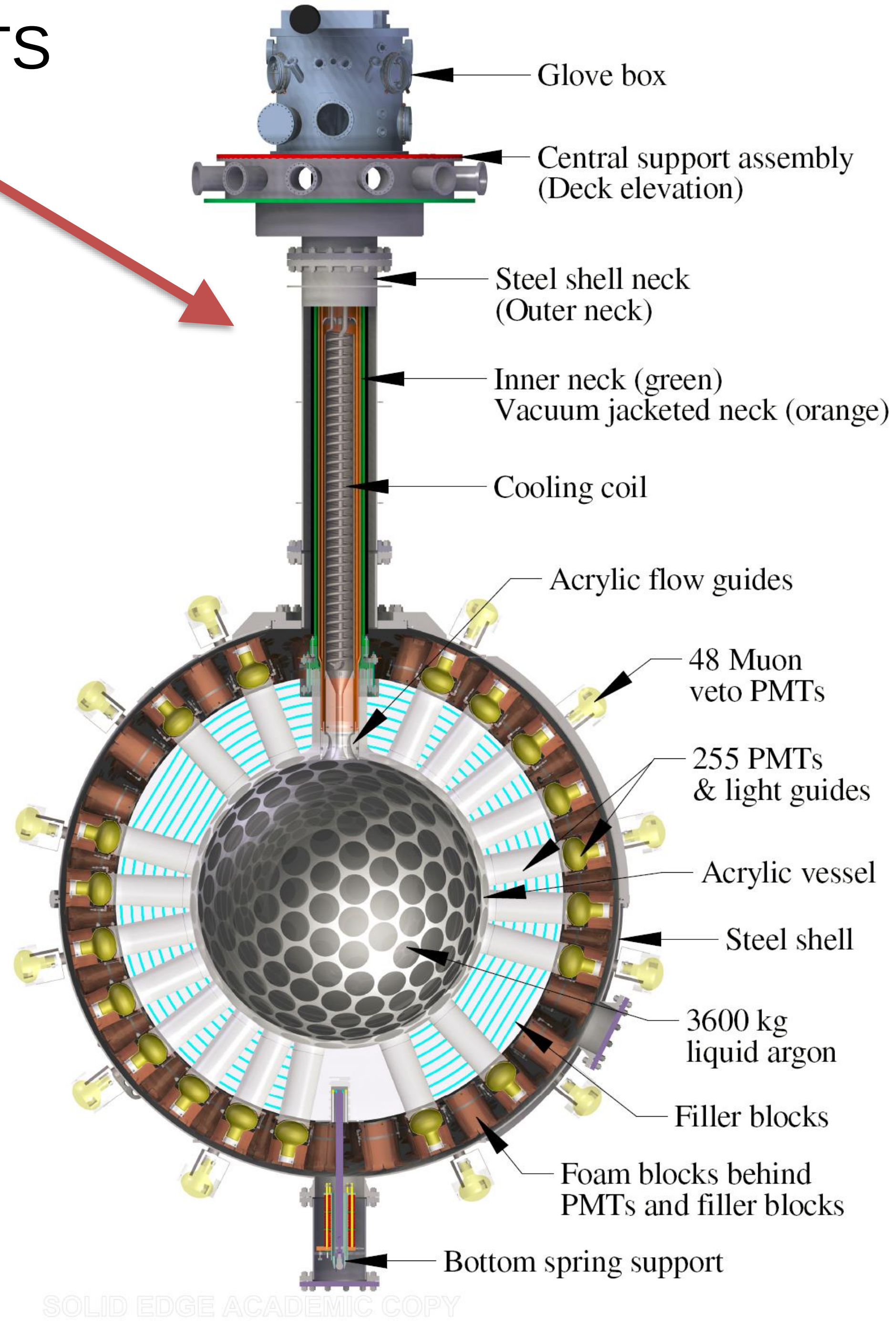
NOTE – there are studies going on in the Xenon community with regards distillation of Xenon to remove the double beta decay isotopes. Theoretical purification which could be achieved might make Darwin suitable for CNO detection

FUTURE ***ARGON*** EXPERIMENTS

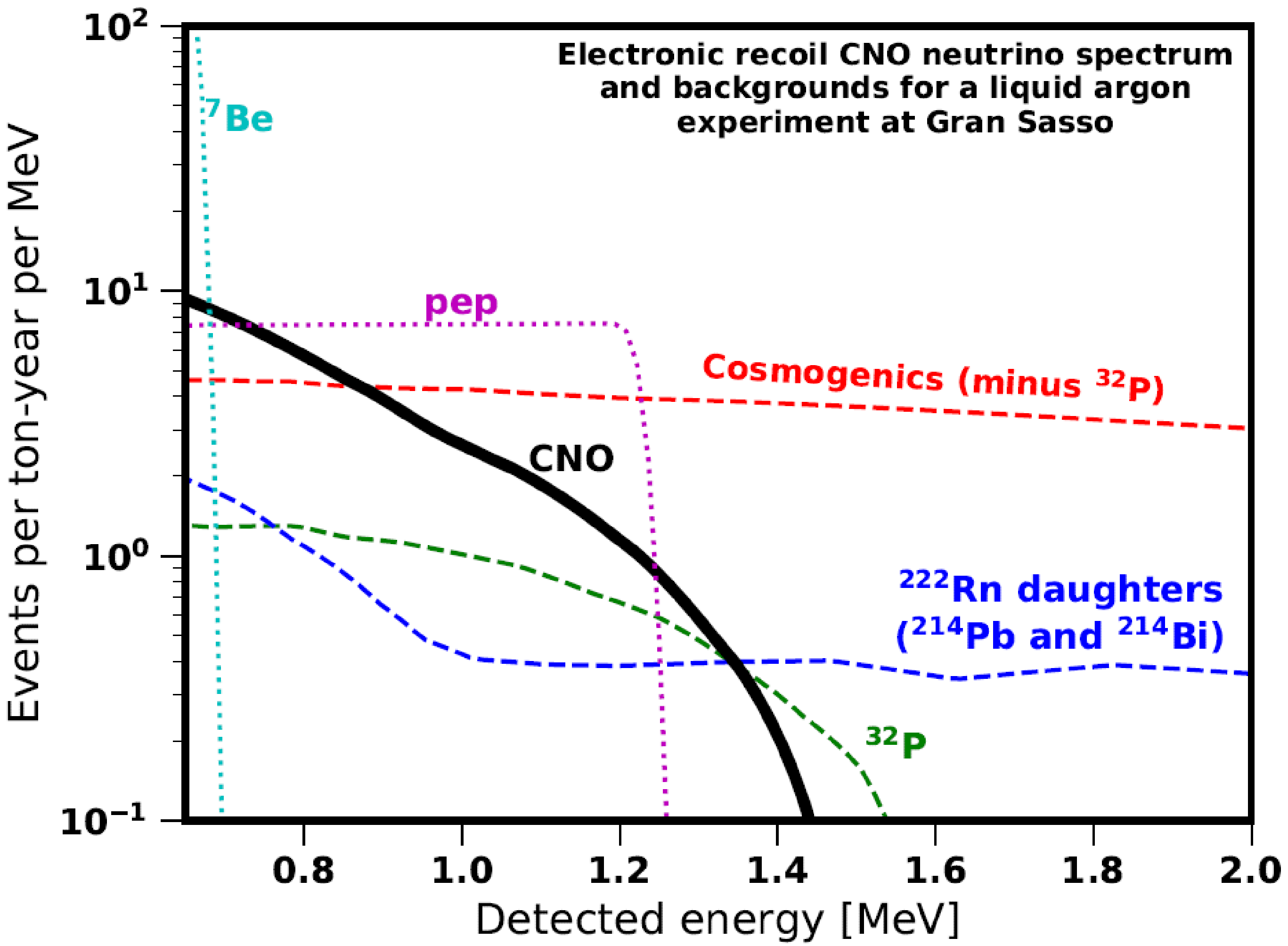
e.g. Deap 3600, already exists

Darkside 20 tons
will probably happen.
Located at Gran Sasso

Argo 100 tons ????

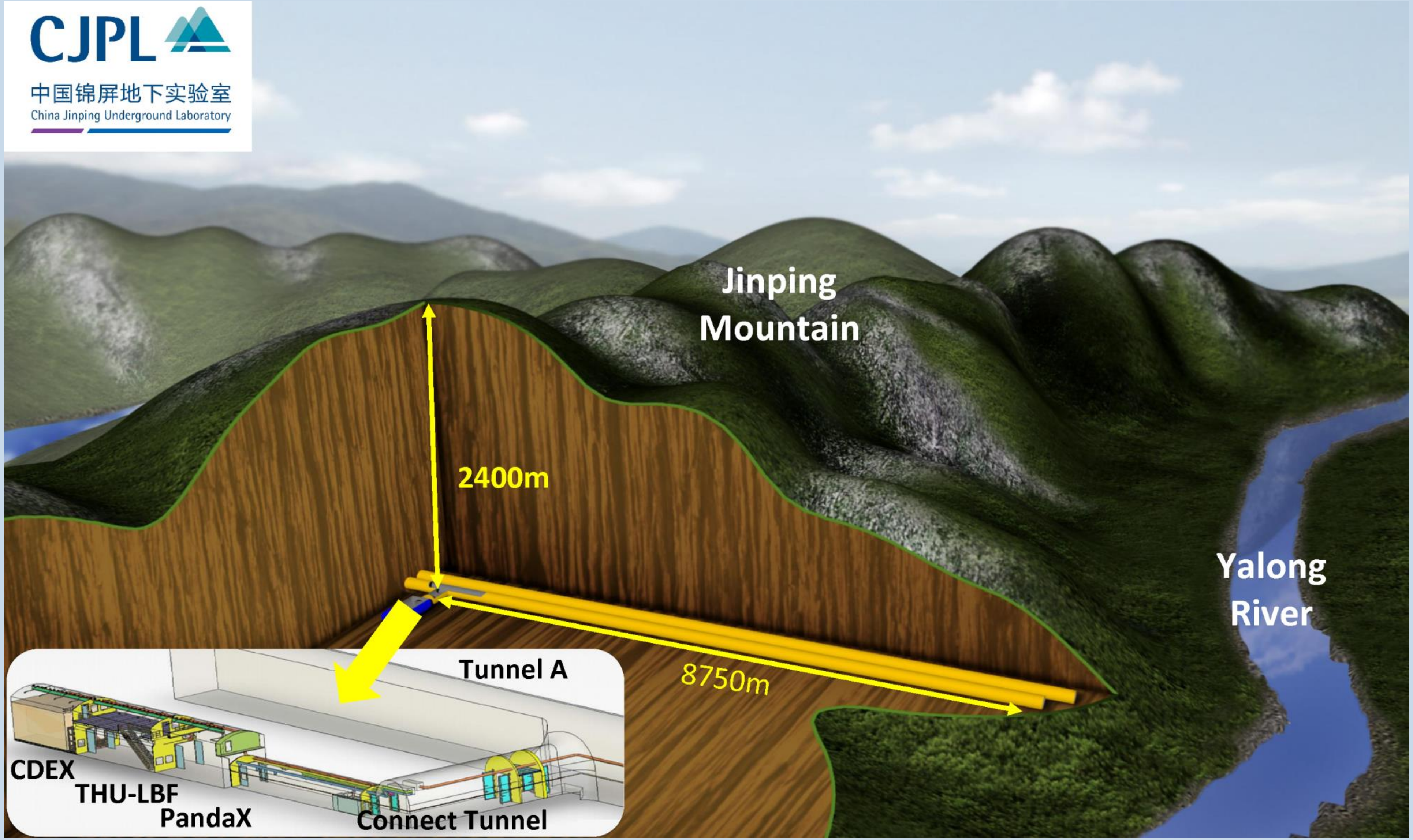


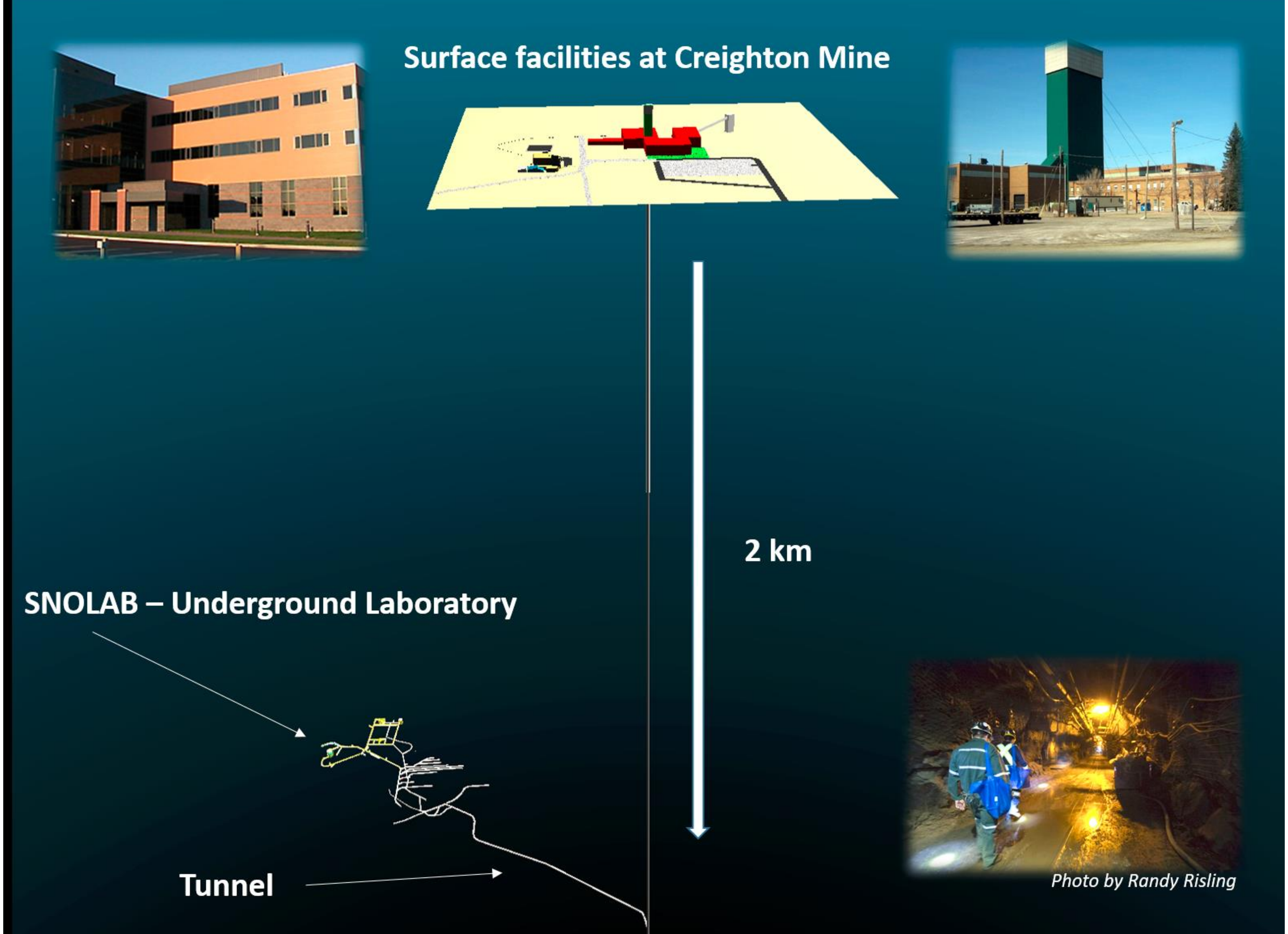
Backgrounds in Liquid Argon Experiment



Gran Sasso mountain

Jinping Laboratory




Surface facilities at Creighton Mine
2 km
SNOLAB – Underground Laboratory
Tunnel
Photo by Randy Risling

Gran Sasso

Radon chain Unmeasured

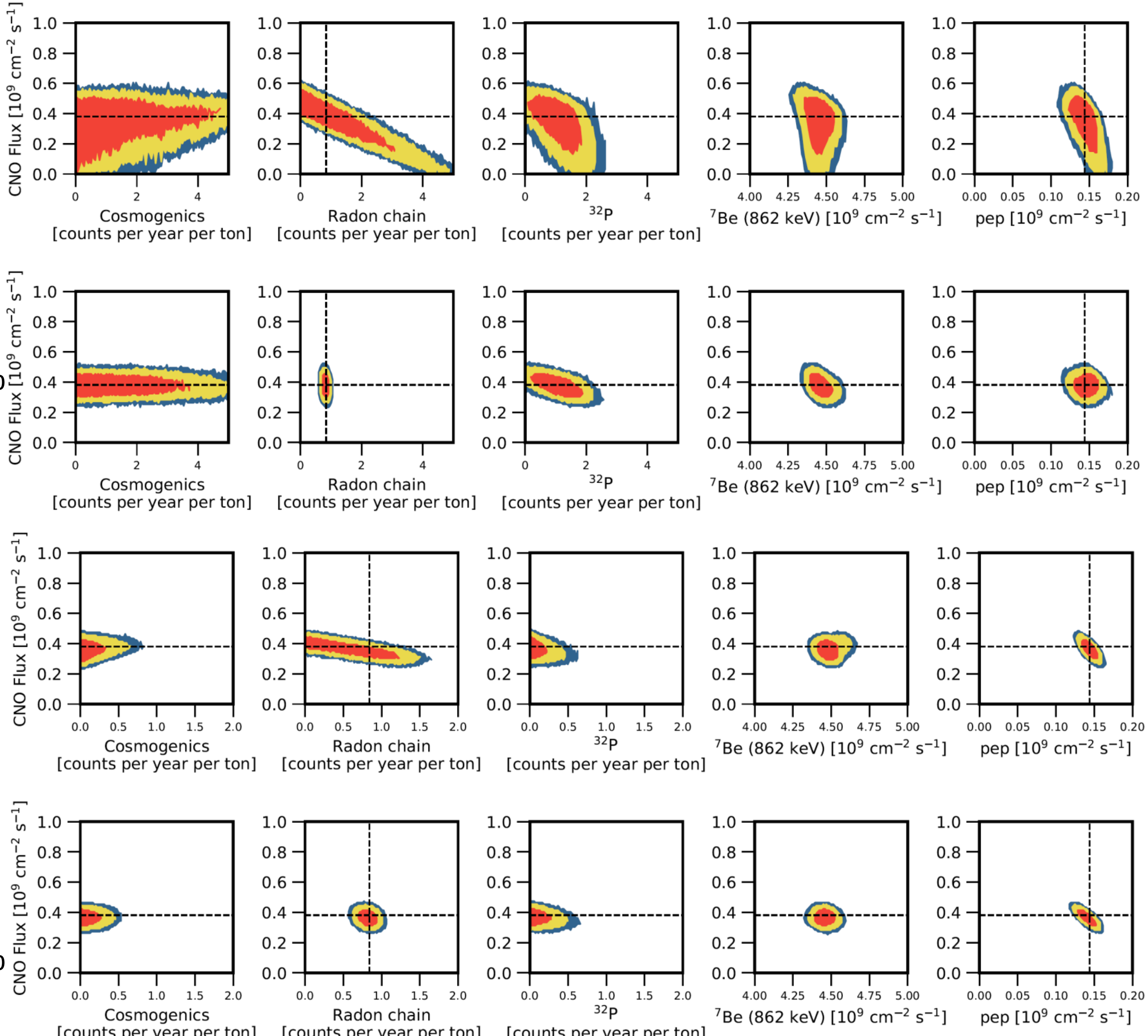
Radon Chain Known at 10%

1000 ton-yrs liquid argon

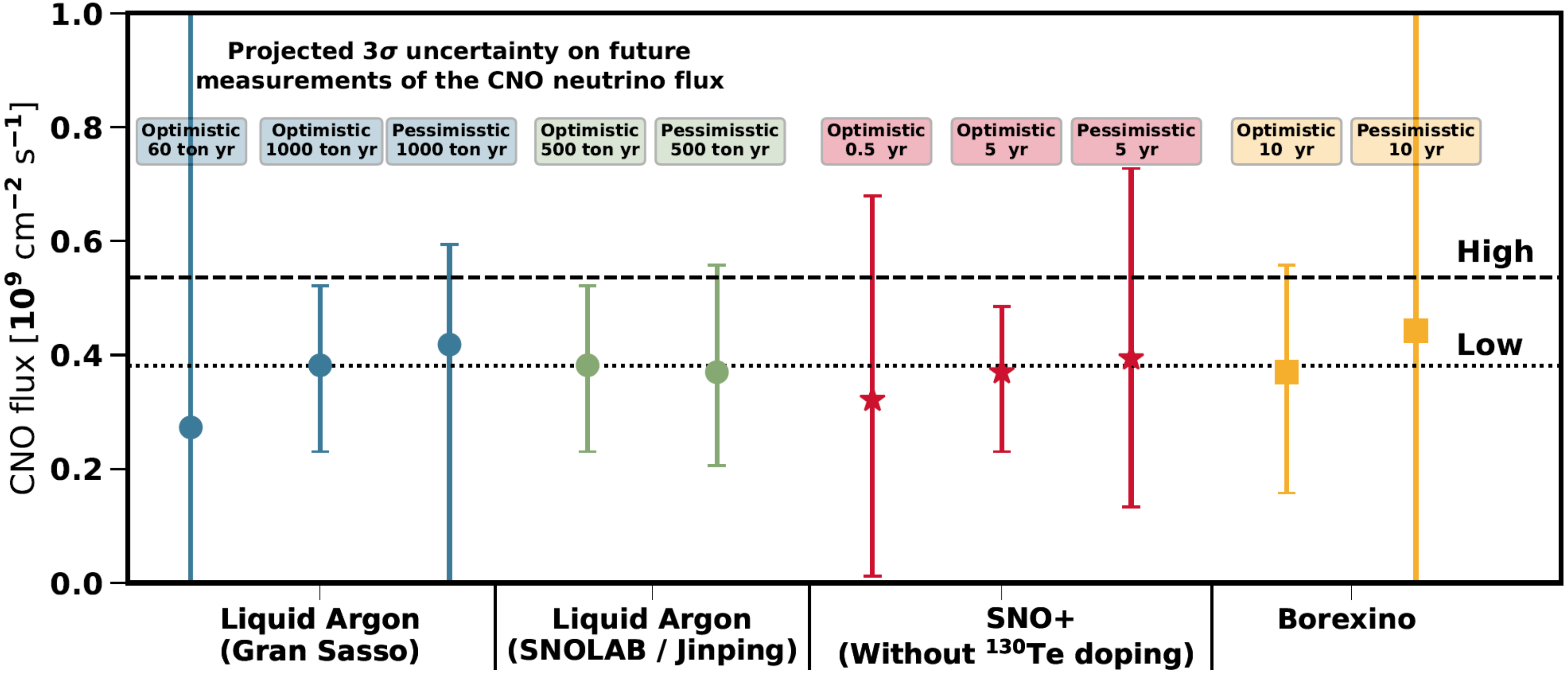
SNOLAB or Jinping

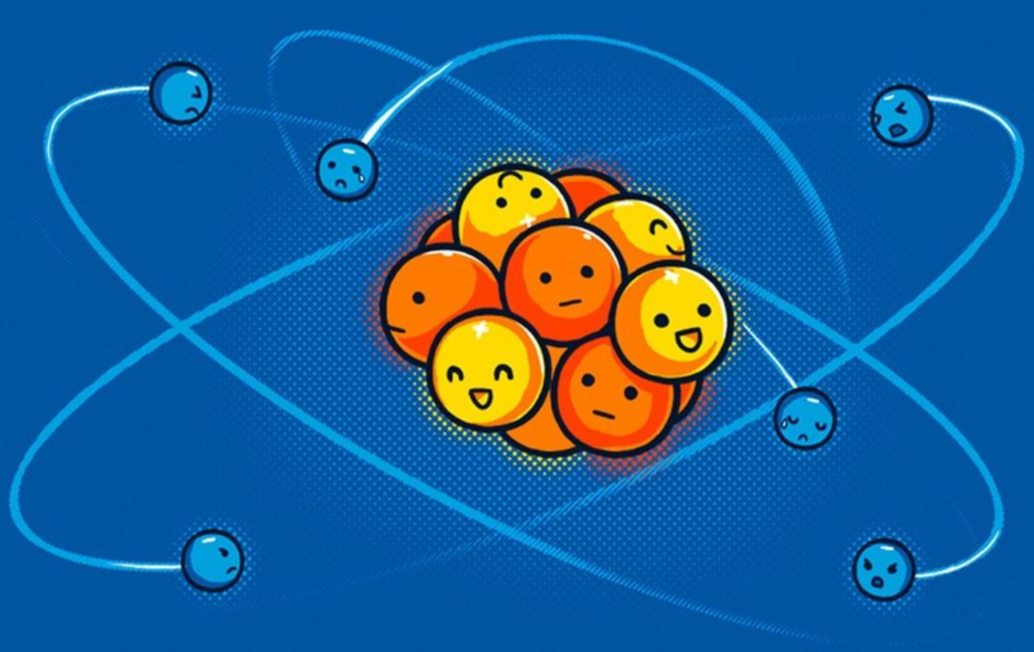
Radon chain Unmeasured

Radon Chain Known at 10%



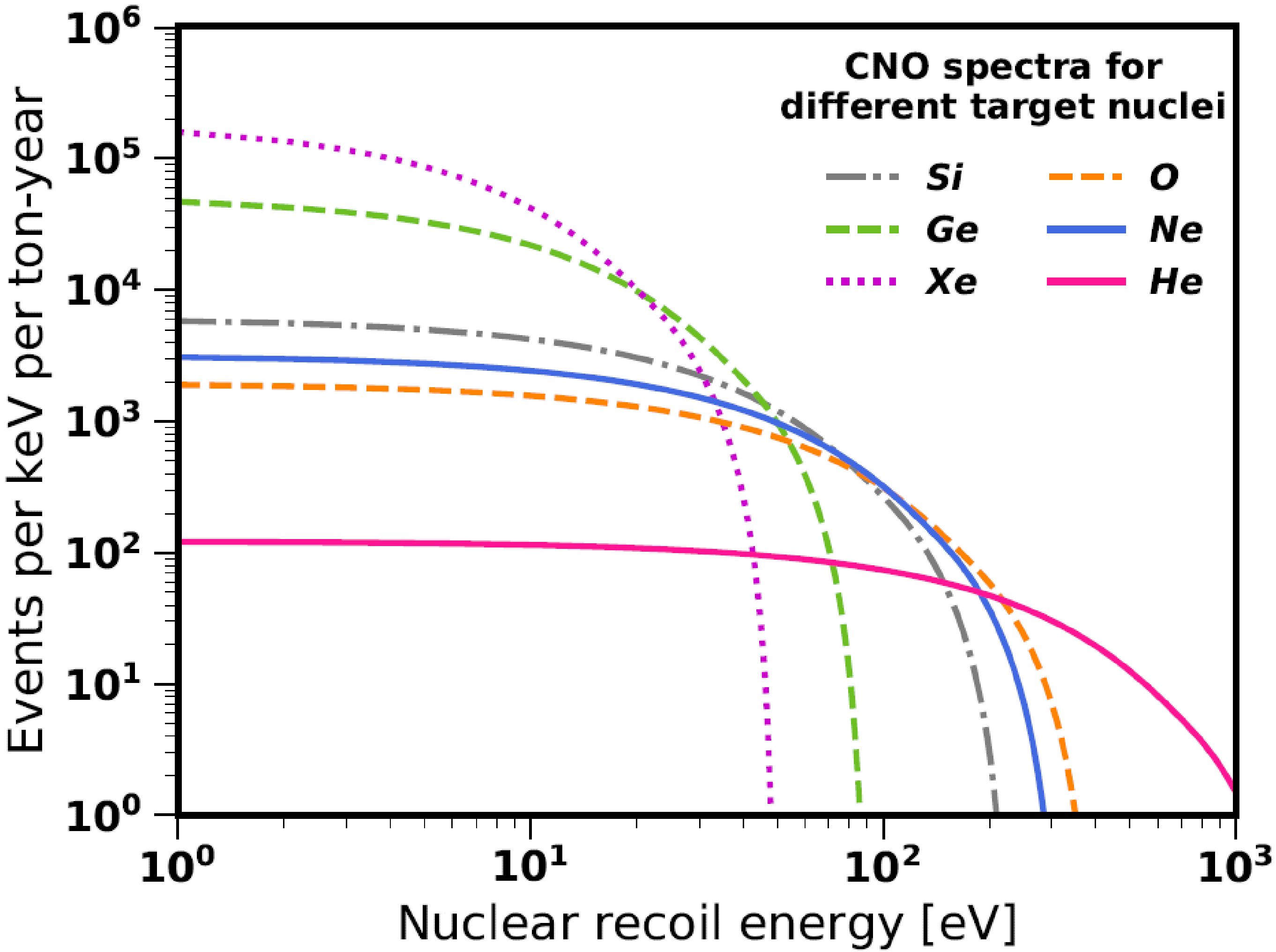
Summary of Electron Recoil Results



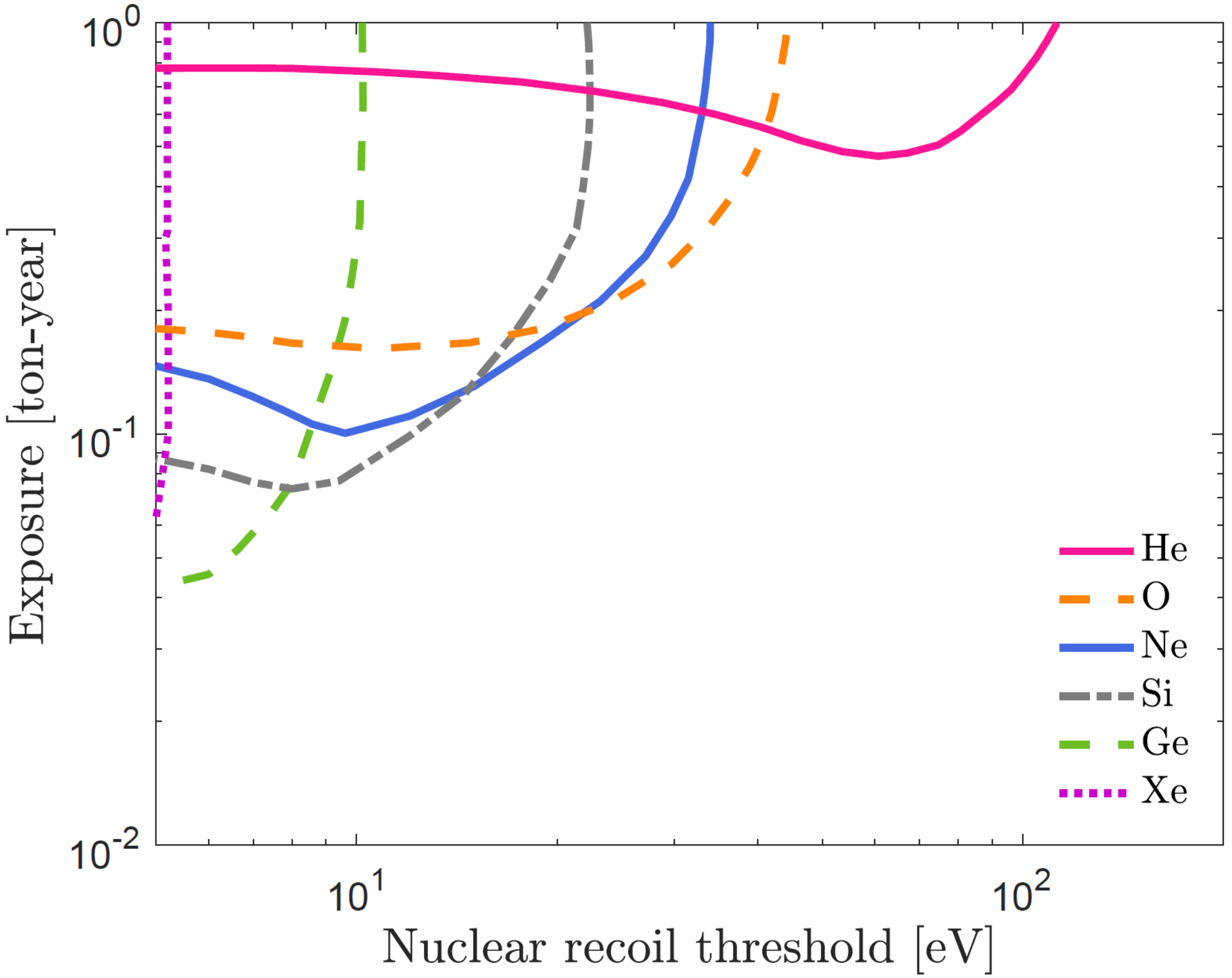


What about Nuclear recoils?

CNO Nuclear Recoil Energy Spectrum



CNO Nuclear Recoil Sensitivity requirements



Required combination of high target mass and VERY low threshold is challenging!

Conclusions

- Current experiment looking for CNO maybe can't see it (Borexino)
- Experiment which might be able to see it isn't looking (SNO+)
- Future large argon experiments will be able to see it if they can understand their backgrounds
- If current low threshold nuclear recoil experiments could be improved and scaled up they might also see it.

PEOPLE SHOULD TRY HARDER TO LOOK FOR CNO NEUTRINOS

THE DARK MATTER COMMUNITY MIGHT ONE DAY GET INVOLVED

Science & Technology Facilities Council

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Part II

Interaction of PBHs with Black Holes

Based on work with Katia Moskvitch and Mohammed Montadir al-Hakim

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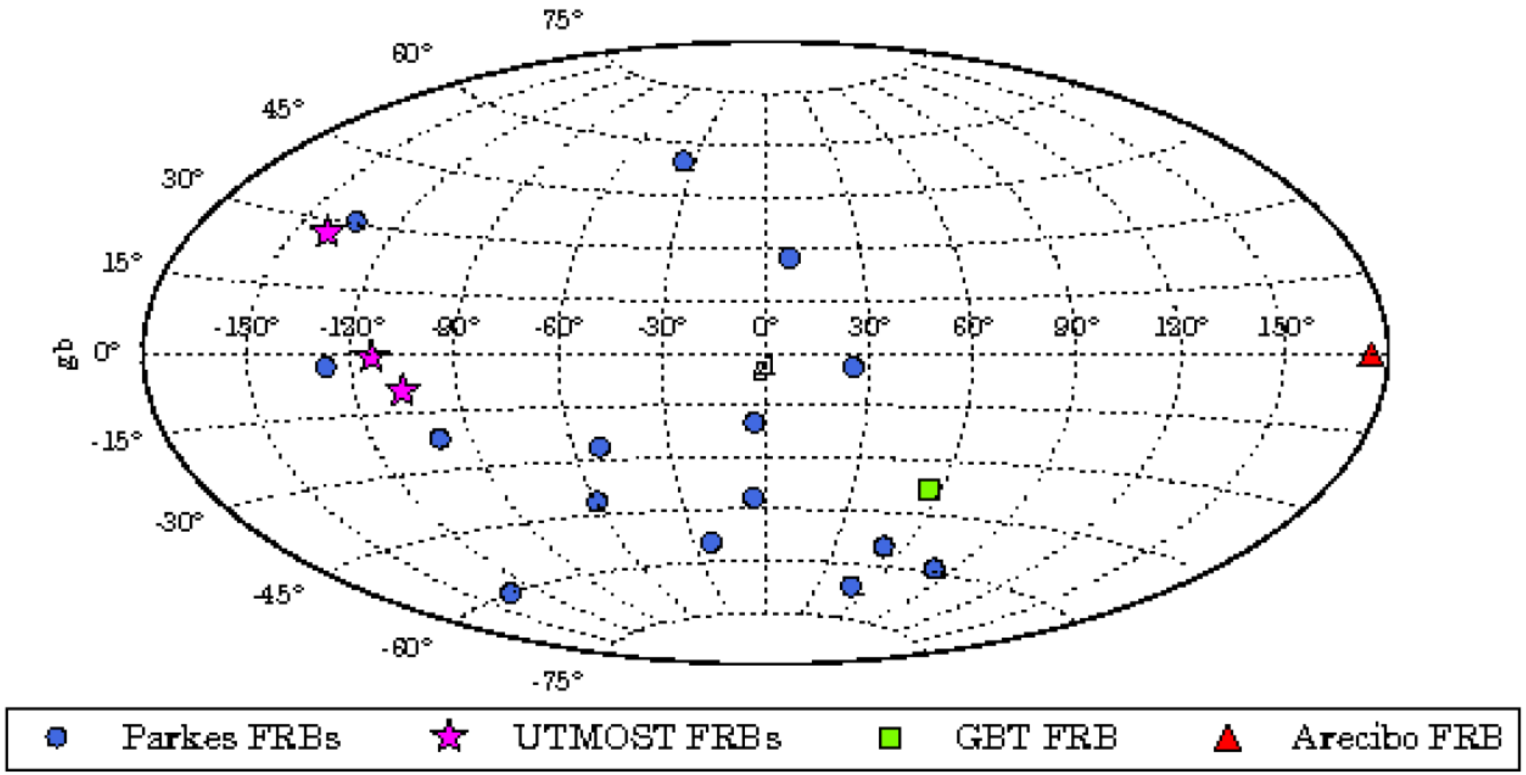
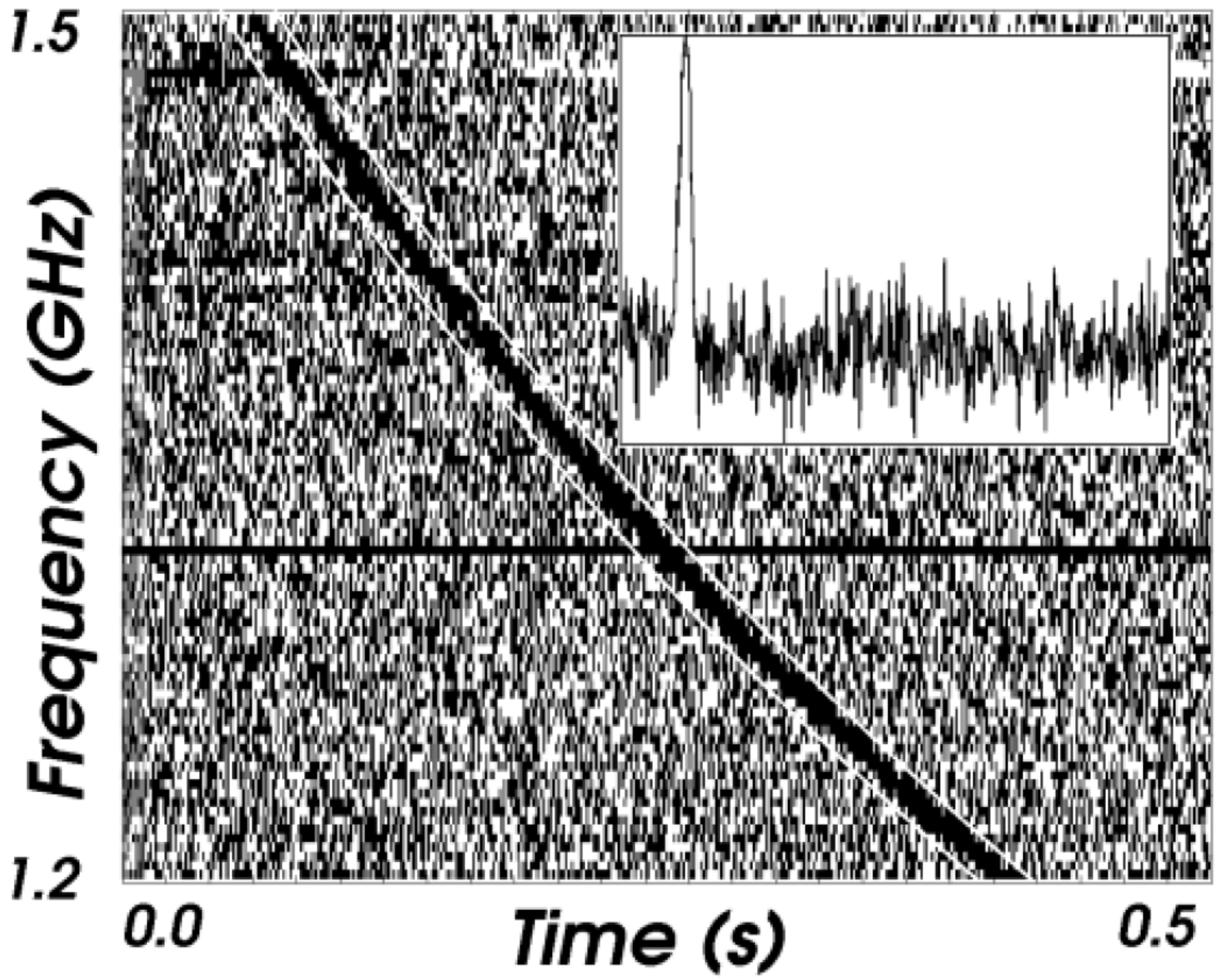
Fast Radio Bursts

- Intense bursts of radio waves located at cosmological distances
- Various theories as to their origin
  - Magnetars
  - Supernovae
  - Extra-terrestrial intelligence



The sky distribution of the first 18 FRBs Caleb et al. (2017)

Fast Radio Bursts



- Typical Frequency is 1 GHz
- Typical duration is very short at any one frequency (1 ms)
- Typical energy is 10^{33} Joules
- Dispersion is consistent with high redshift objects
- Could be magnetars, but galactic magnetars do not produce FRBs, even when they produce flairs of gamma rays.
- Repeating source now rules out models where FRBs result from destruction of progenitors
- Estimated to be about one every 25 seconds in the Universe (very rough)

Superradiance

Nice review – Brito, Cardoso and Pani arXiv:1501.06570

The angular momentum of a black hole can be converted into bosonic radiation if

1. The wavelength of the radiation is comparable to the radius of the Black Hole
2. The boson is kept trapped close to the blackhole, either by mass or by a mirror

Plasma frequency gives the photon an effective mass, equivalently, turns the plasma into a mirror

$$\omega_p = \sqrt{4\pi e^2 n / m_e}$$

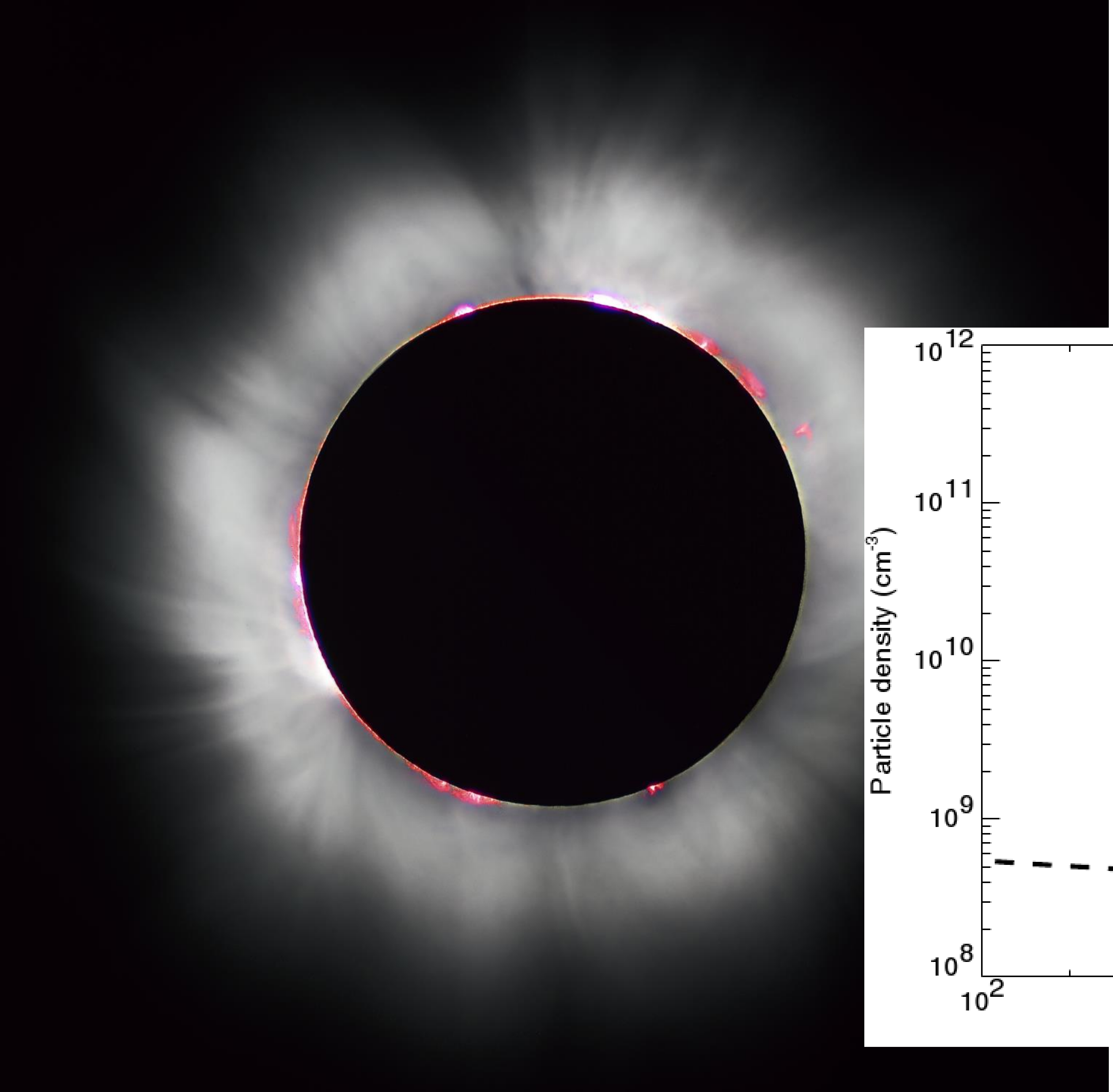
Radiation can then be produced resonantly on a very short timescale

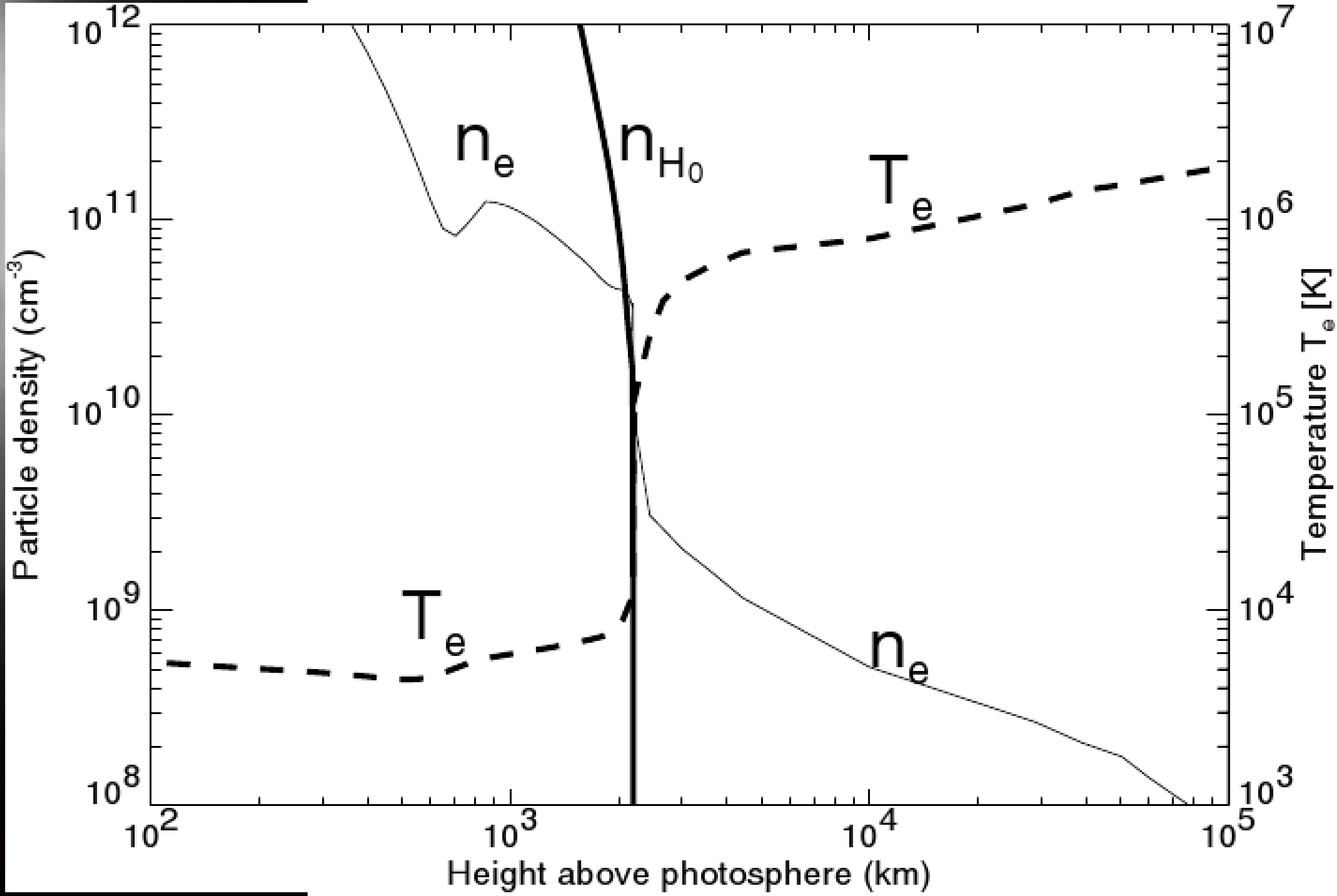
$$GM\tau^{-1} \sim c^3 \gamma_{S\ell} \left(\tilde{a}m - 2r_+\omega_p/c\right) \left(GM\omega_p/c^3\right)^{4\ell+5+2S}$$

Conlon and Herdeiro 2017 speculate that 10-100 solar mass black holes could become superradiant in plasmas with plasma frequencies of $10^{-12} – 10^{-10}$ eV. About a kHz

To get the right frequency, you need the right size black hole 10^{-4} M_{sun} and the right plasma frequency:-

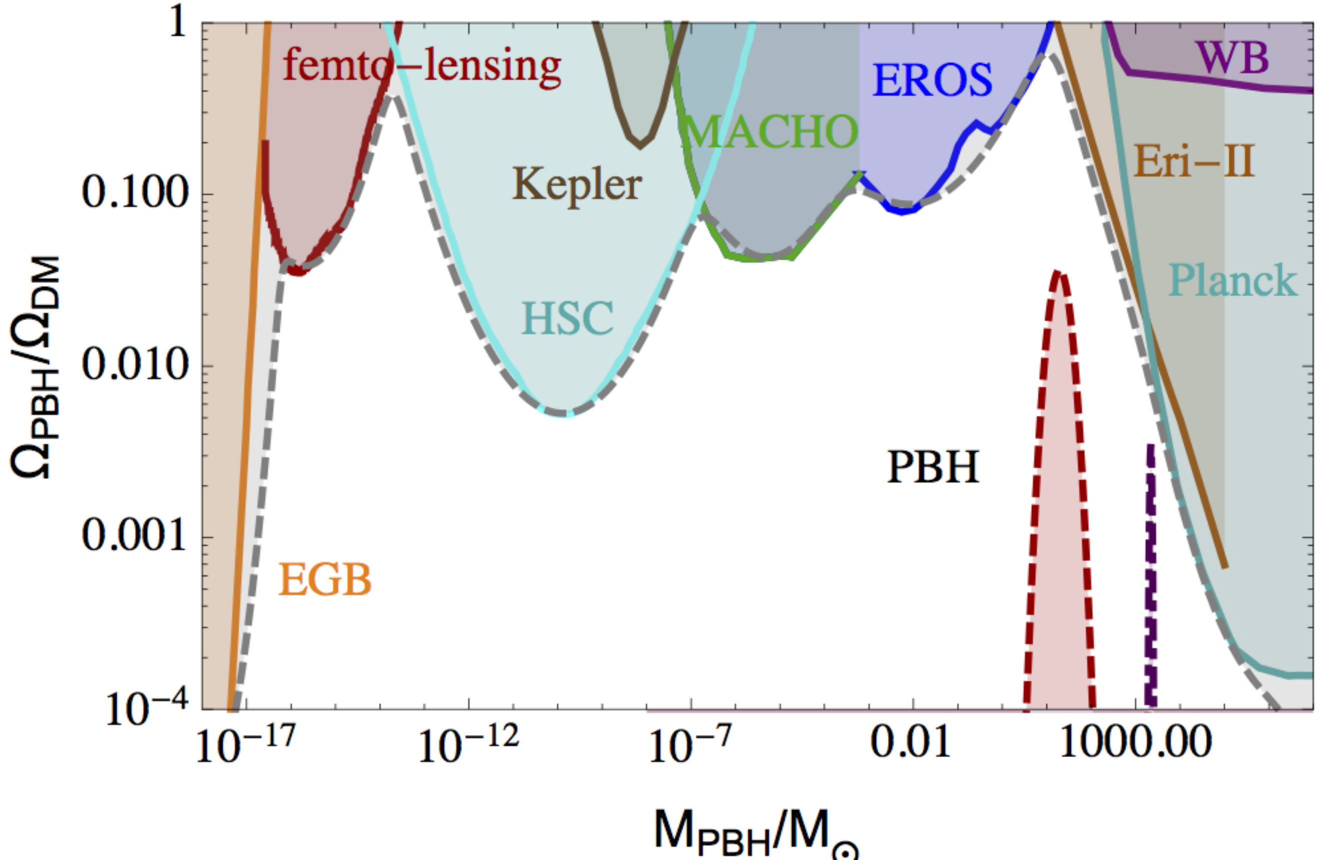
THE STELLAR CORONA…





The basic idea

- Some component of dark matter is made out of primordial black holes
- Periodically they will hit stars, as they move through the corona, they will become superradiant and create GHz radiation.
- The rotational energy in a 10^{-4} solar mass black hole with a=1 is around 10^{43} J, 10^{33} J required for a fast radio burst.



Need to work out if the rate is reasonable!!!

Collisions (of any dark particle) with Stars

The rate for a single dark matter particle of any kind (including black holes) to collide with a star can be estimated in the following way.

$$\Gamma(r, M_{vir}) = \frac{\rho_*(r, M_{vir})\sigma(r, M_{vir})}{\langle M_* \rangle} \int \xi(M_*) \underbrace{\pi R_*^2(M_*)}_{\text{Cross section}} \underbrace{\left(1 + \frac{v_{esc*}^2(M_*)}{\sigma^2(r, M_{vir}) + v_{circ}^2(r, M_{vir})}\right)}_{\text{Velocity enhancement (Safronov number)}} dM_*$$

Need to assume something about stellar mass distribution and also stellar radius.

$$\xi(M_*) \propto \begin{cases} M_*^{-0.3} & (M_* < 0.08) \\ M_*^{-1.3} & (0.08 \leq M_* < 0.5) \\ M_*^{-2.3} & (0.5 \leq M_*) \end{cases} \qquad R_*(M_*) = \begin{cases} R_\odot \left(\frac{M_*}{M_\odot}\right)^{3/7} & (M_* < 1.3) \\ 0.907 R_\odot \left(\frac{M_*}{M_\odot}\right)^{0.8} & (1.3 \leq M_*) \end{cases}$$

Collisions (of any dark particle) with Stars

$$\Gamma(r, M_{vir}) = \frac{\overbrace{\rho_*(r, M_{vir})}^{\text{Need stellar density}}\overbrace{\sigma(r, M_{vir})}^{\text{Also need velocity dispersion...}}}{\langle M_* \rangle} \int \xi(M_*)\pi R_*^2(M_*) \left(1 + \frac{v_{esc*}^2(M_*)}{\sigma^2(r, M_{vir}) + \underbrace{v_{circ}^2(r, M_{vir})}_{\text{... and circular velocity}}}\right) dM_*$$

Galactic Stellar Density

Need stellar density profiles for all galaxies, large and small.
Assume Plummer model for simplicity.

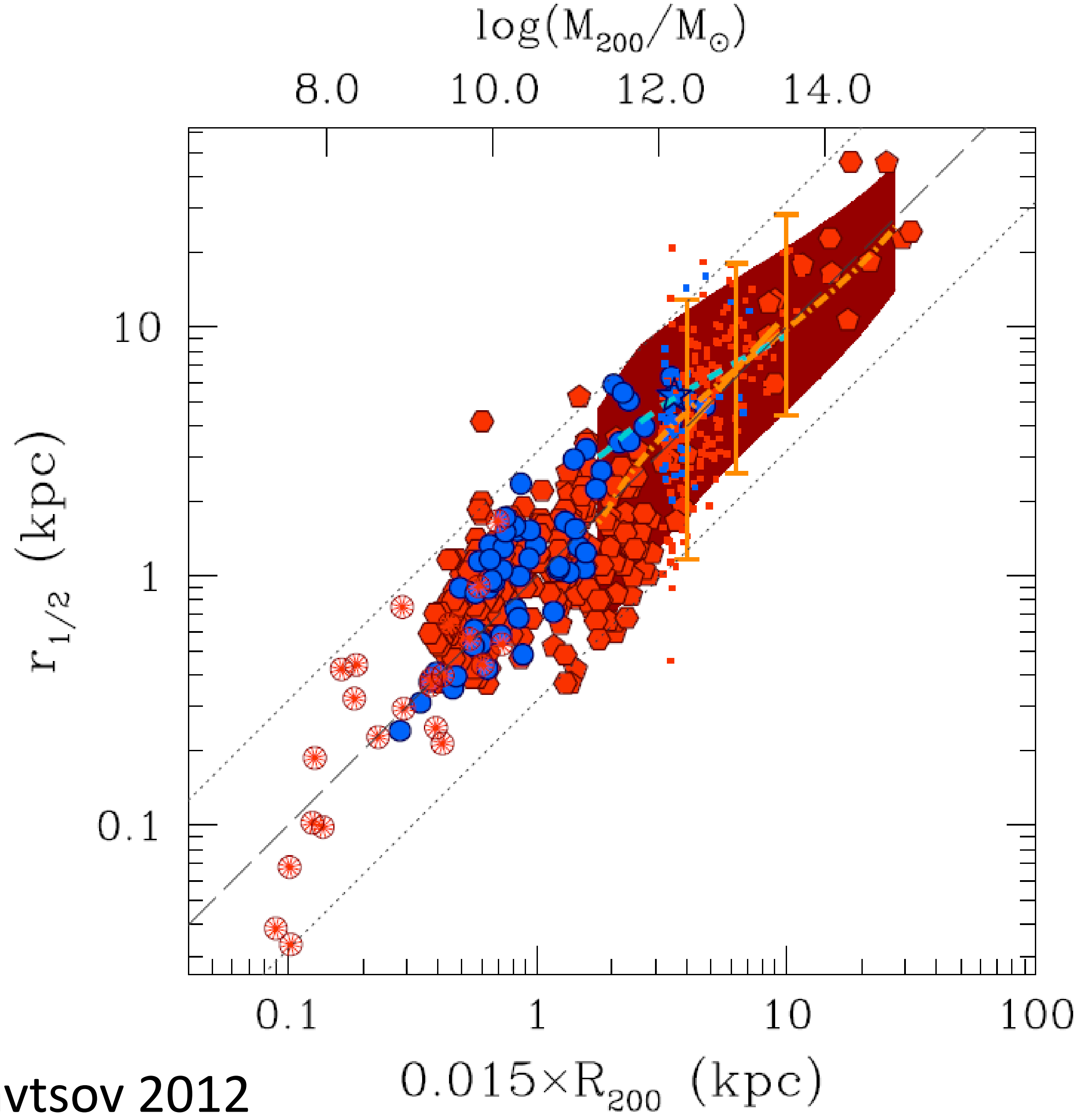
$$\rho_*(r) = \left(\frac{3M_S}{4\pi a^3}\right)\left(1 + \frac{r^2}{a^2}\right)^{-5/2}$$

Still need to define M_s for a given M_{vir} and also scale length a

Stellar half light radius vs. Dark Matter Mass

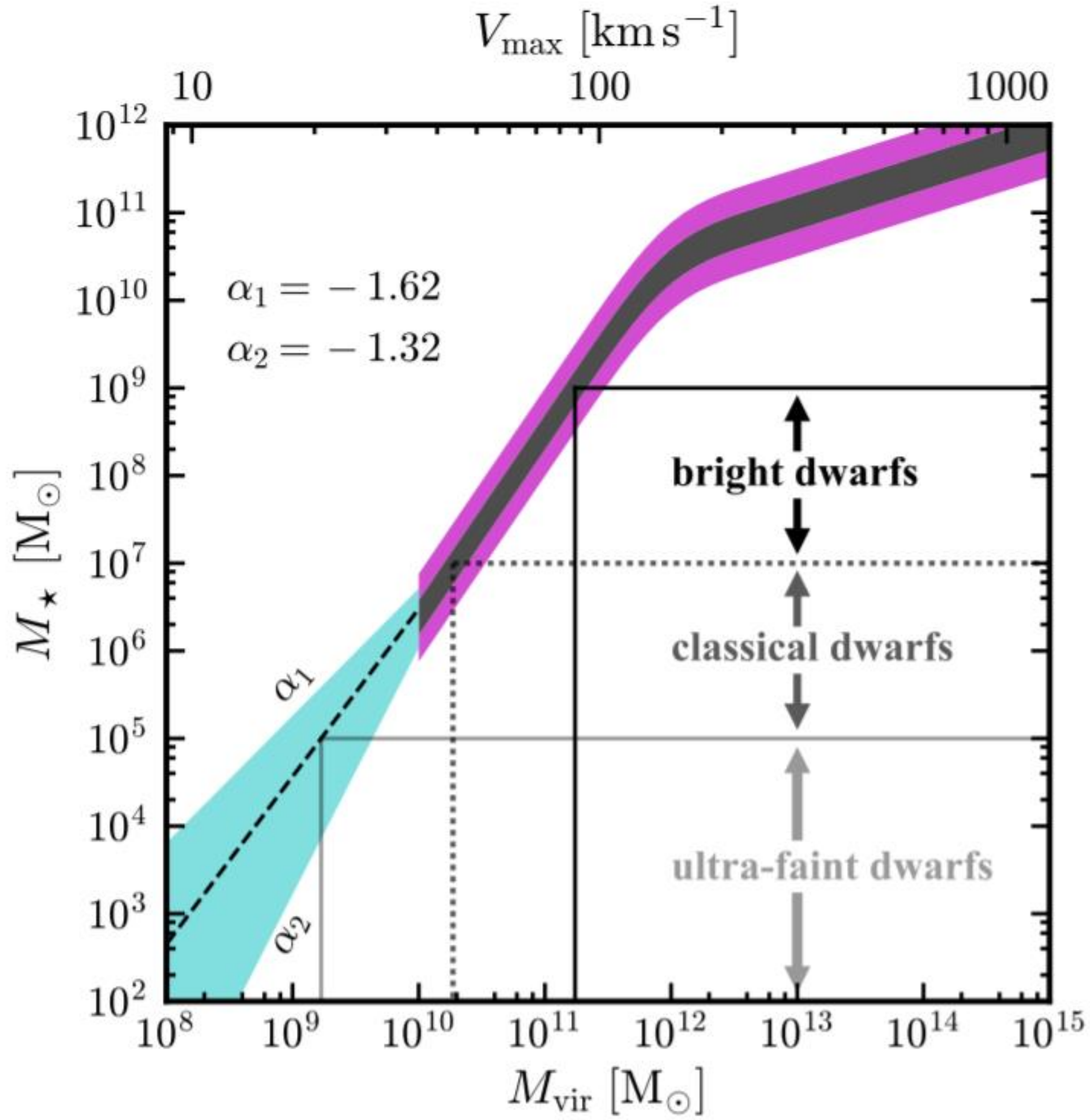
Survey of many galaxies over many orders of magnitude yields the approximate relation

$$r_{1/2} \simeq 0.015 \times R_{200}$$



Kravtsov 2012

Stellar Mass vs. Dark Matter Mass



Small halos don't have many stars!

Very hot topic.

Need relationship between the two quantities.

Follow abundance matching work.

Bullock and Boylan-Kolchin 2017
(see also Behroozi 2018)

Dark Matter Halos

Use NFW profile for simplicity with concentration parameter predicted by simulations

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_S}(1 + \frac{r}{R_S})^2}$$

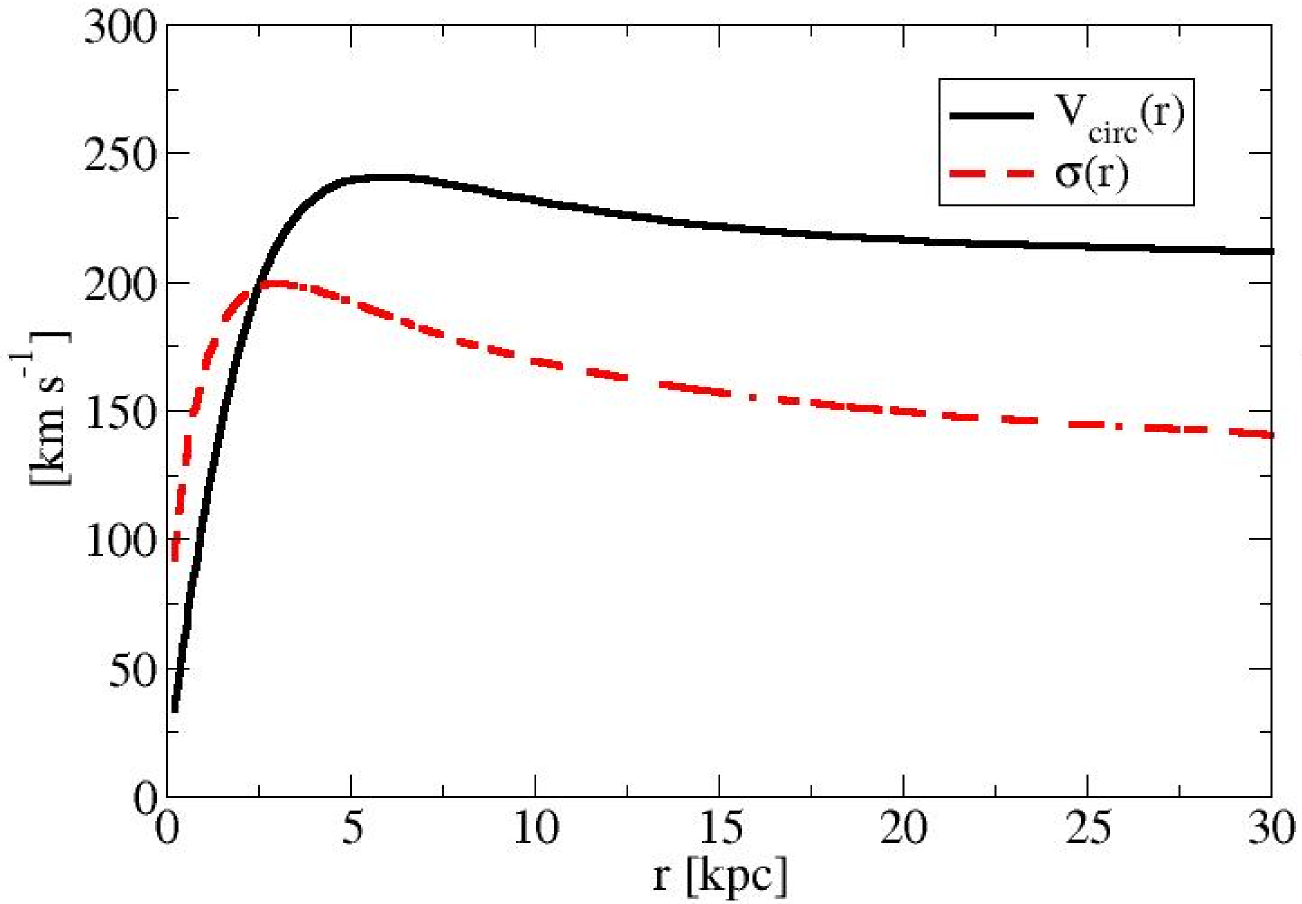
$$c(M_{vir}) = C_0 \left(\frac{M_{vir}}{10^{12} h^{-1} M_\odot} \right)^{-\gamma}$$

$$C_0 = 7.4, \gamma = 0.12$$

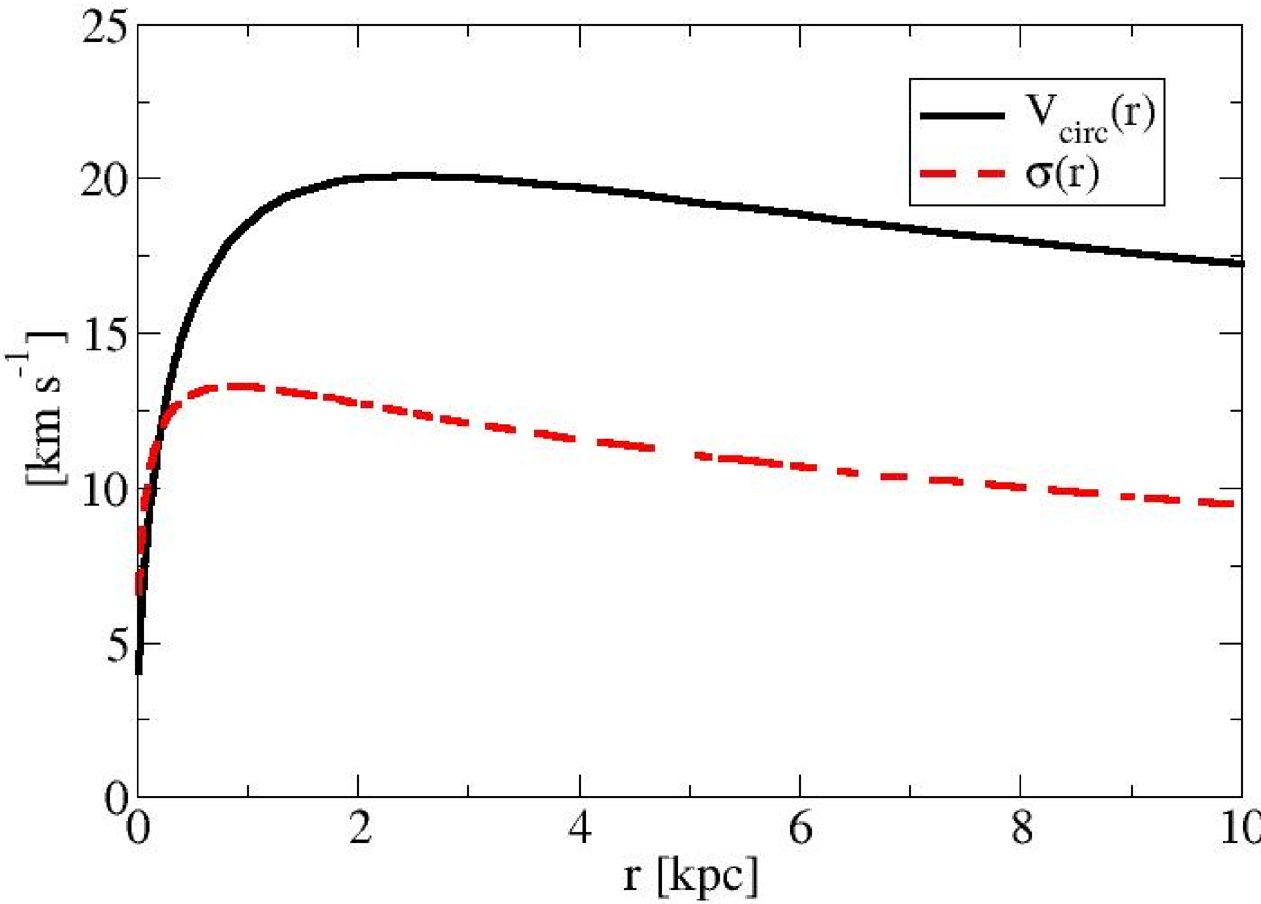
Now we can solve the Jeans equation, assuming that the anisotropy parameter β=0 to obtain $\sigma(r)$

$$\frac{d\sigma^2}{dr} = -\frac{\sigma^2}{\rho_{dm}} \frac{d\rho_{dm}}{dr} - \frac{GM(r)}{r^2}$$

Examples of rotation curves in our "Galaxies"



Milky Way type Galaxy, M_{vir}=1.5 x 10^{12} M_{sun}

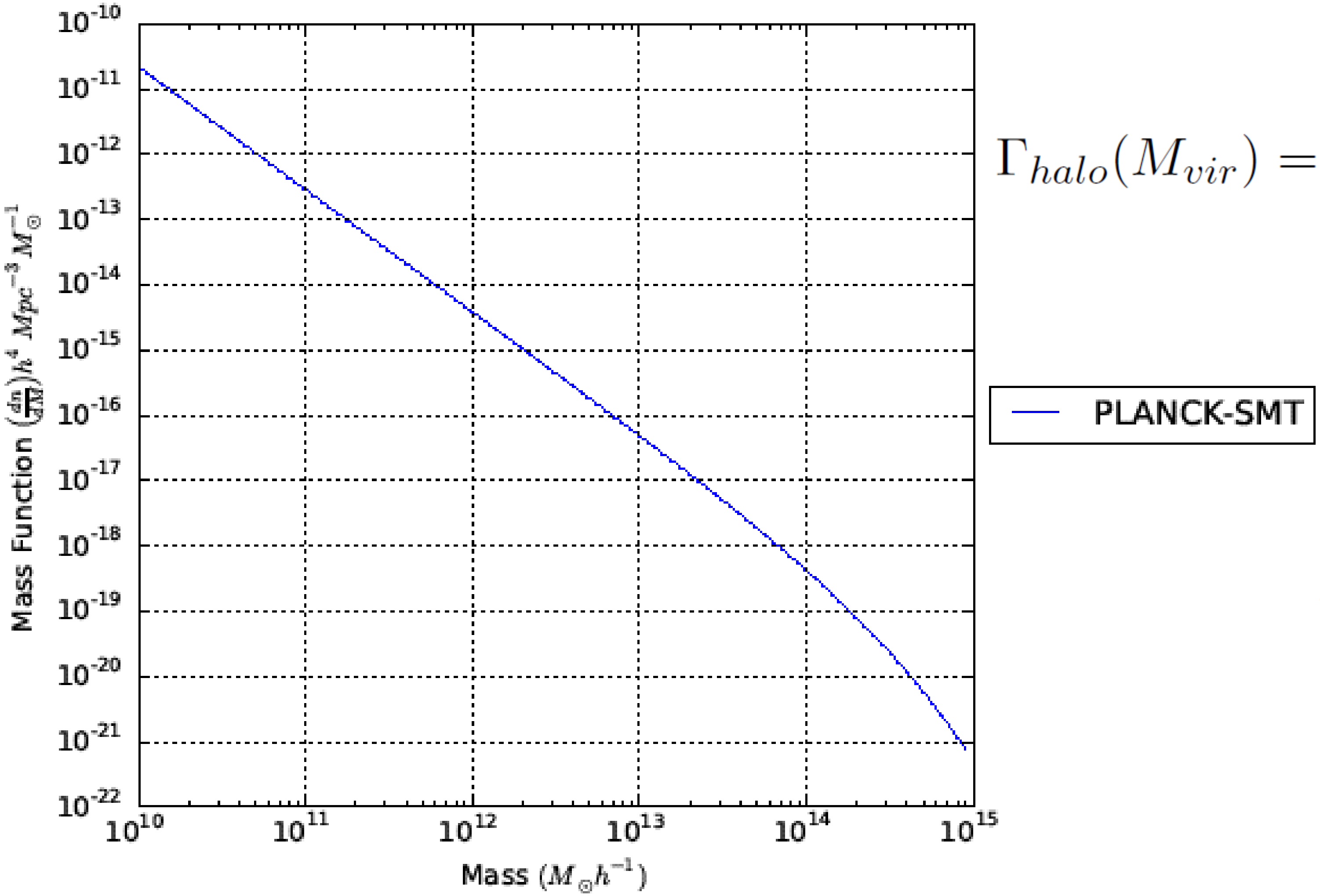


Dwarf type Galaxy, M_{vir}=1 x 10^{9} M_{sun}

Seems to work OK!

Finally need to integrate over all Galaxies/halos

Integrate throughout the halo for the rate for a single dark matter particle



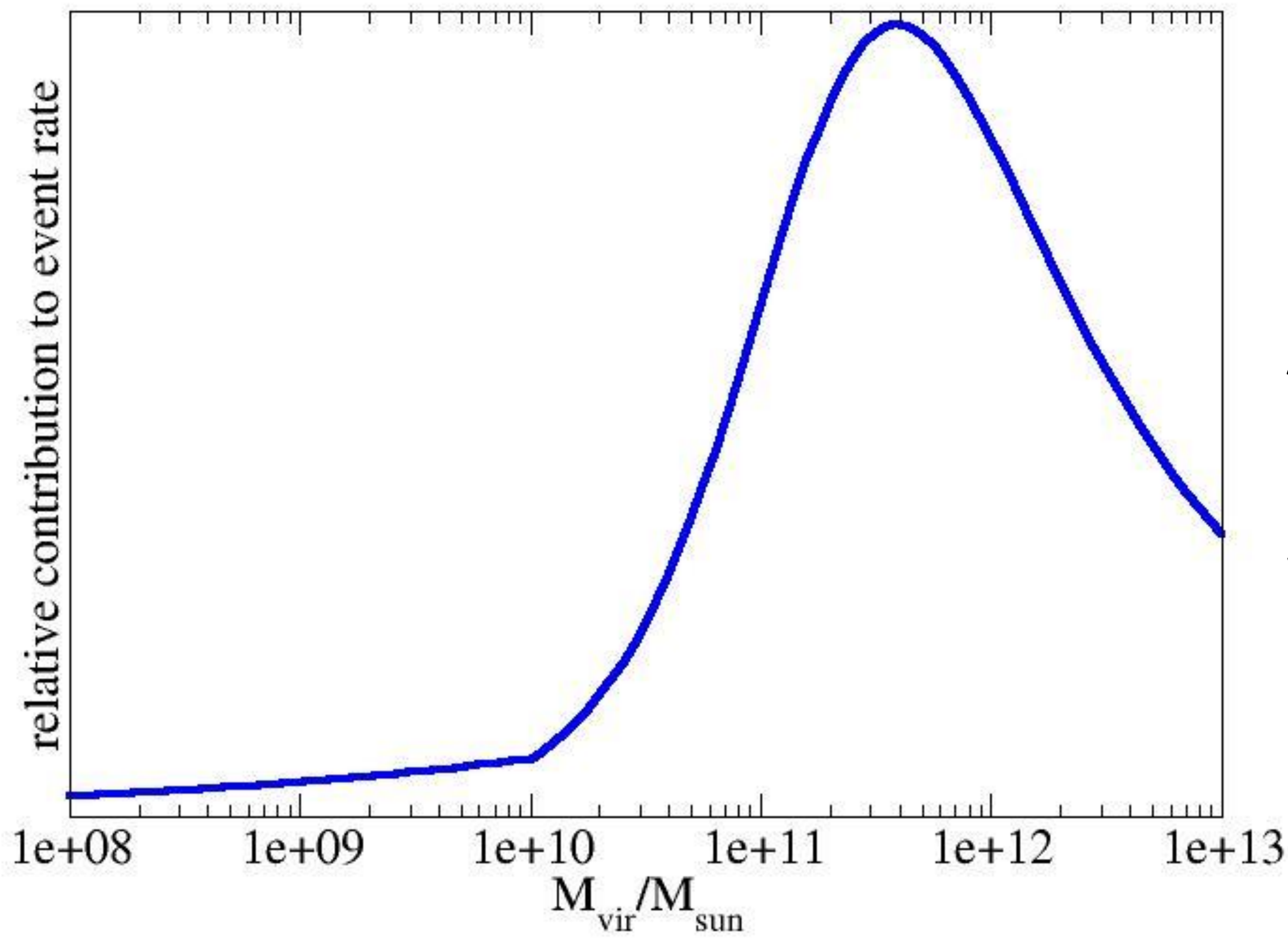
$$\Gamma_{halo}(M_{vir}) = \int_0^{R_{vir}} 4\pi r^2 \frac{\rho_{DM}(r, M_{vir})}{m_{DM}} \Gamma(r, M_{vir}) dr$$

Integrate over all the halos which exist in the halo mass function

$$A = \int_{M_{min}}^{M_{max}} \frac{dn}{dM_{vir}} \Gamma_{halo}(M_{vir}) dM_{vir}$$

Rate = 0.18 s^{-1} - about one every 5 seconds in the Universe

Which Galaxies Contribute the Most Events?



appropriately weighted graph
(linear vertical scale
Arbitrary units)

We therefore need not worry about low mass halo stellar occupation uncertainty

Assumptions and approximations

- No redshift evolution of concentration parameter and stellar mass/Mvir relation
- Assumes all dark matter is made out of 10^{-4} M_{sun} PBHs (ruled out!)
- No evolution of stellar mass function etc
- Integrates out to comoving Universe at z=2
- We make no attempt to take into account repeats (accretion leading to bound PBHs)

Conclusions

- Spinning Primordial black holes may superradiate in plasma
- To explain fast radio bursts the black holes must be roughly 10^{-4} M_{sun}
- The predicted rate is not then very far from the observed rate of FRBs in the Universe, if we assume these PBH are some fraction of the dark matter
- Many issues will have to be investigated further, for example:-
    - Backreaction of super-radiance on stars
    - Difference between superradiance of massive scalar and photon in plasma

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