PPC 2018

Interconnection between Particle Physics and Cosmology

Kfir Blum (CERN & Weizmann Institute)

Zurich, 20-24/8/2018

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Interconnection between Particle Physics and Cosmology

Dark matter

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Hierarchy problem

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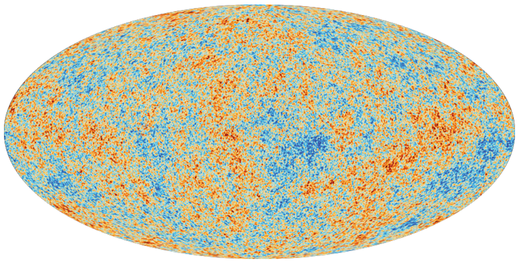
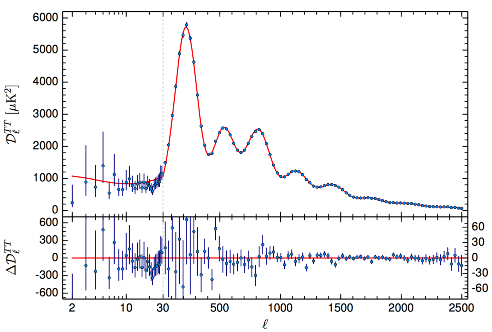
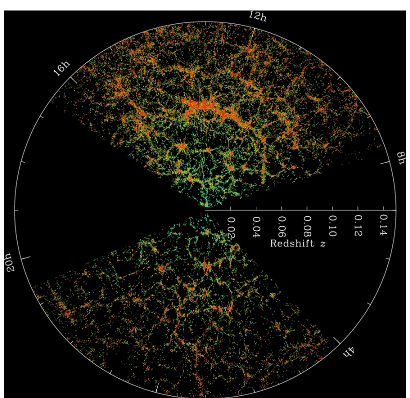
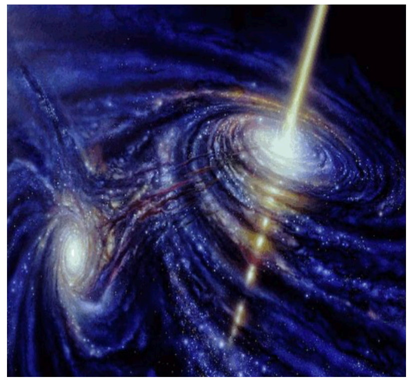
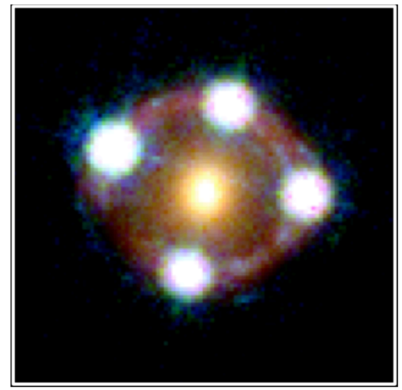
Unbelievably beautiful things to understand on the way:

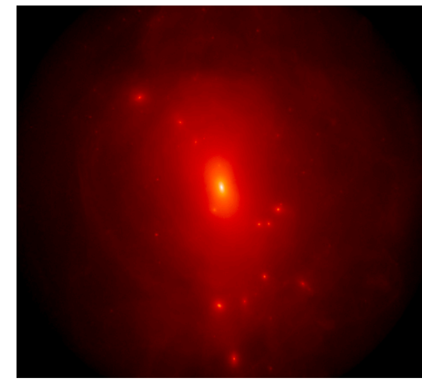


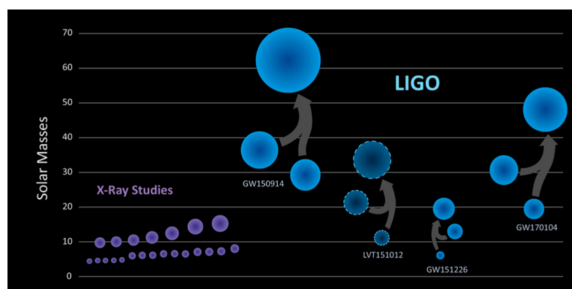












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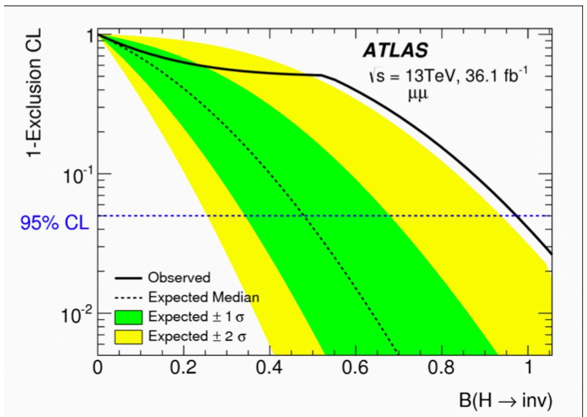
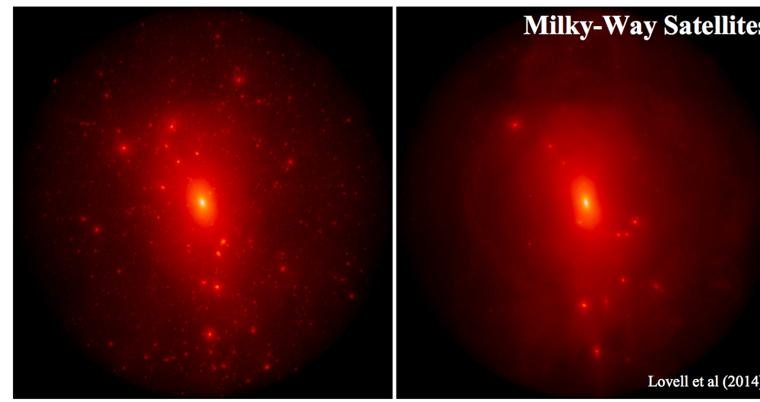
Where will new physics appear first?

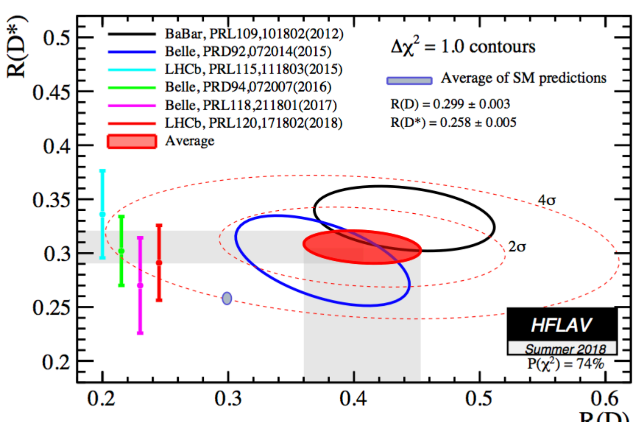
A. Jafari (22/8)



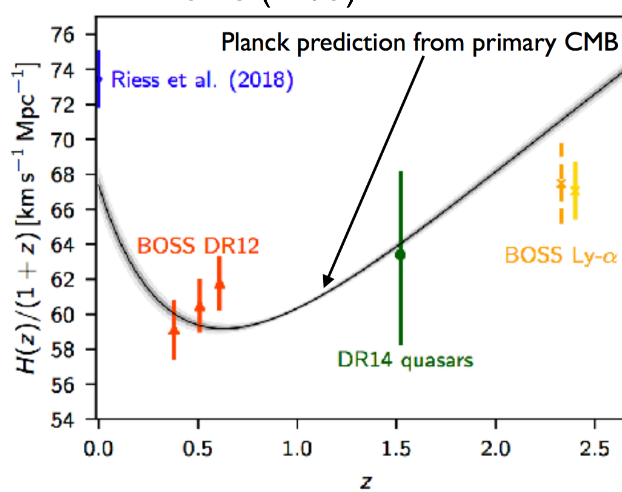
A. Schneider (21/8)



A. Buonaura (22/8)



H. Peiris (21/8)



PPC 2018

Interconnection between Particle Physics and Cosmology

Had a number of reviews
(CMB, galaxy surveys, GWs, LHC status, dark sectors, DM models, neutrinos, BSM,…)

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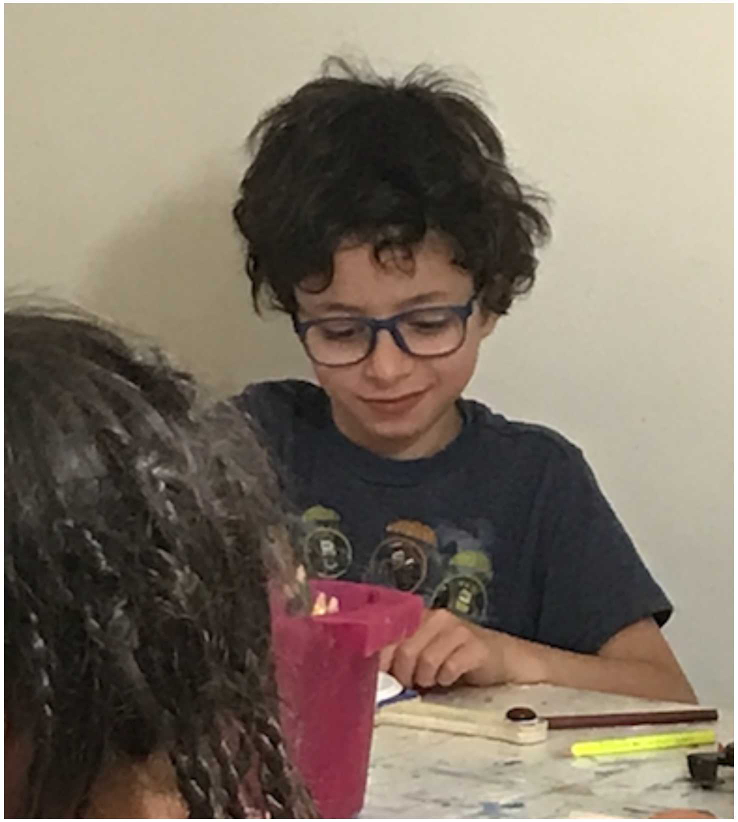
Interconnection between Particle Physics and Cosmology

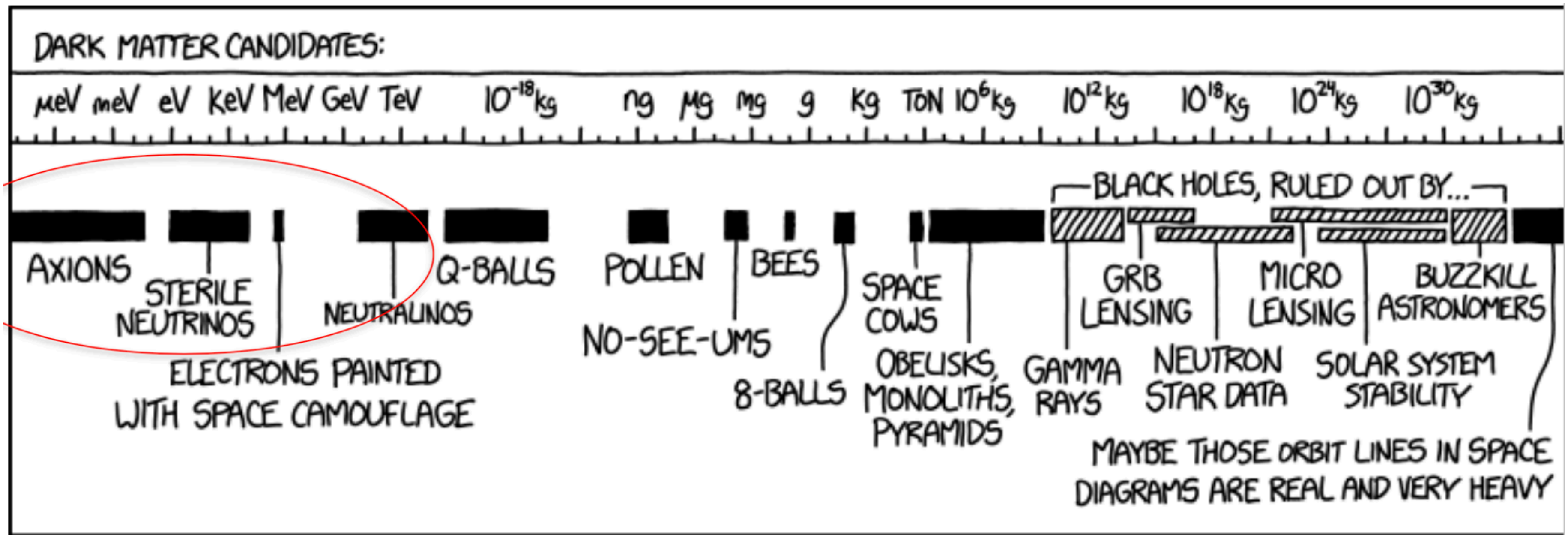
Had a number of reviews
(CMB, galaxy surveys, GWs, LHC status, dark sectors, DM models, neutrinos, BSM,…)

Choose something, and play with it:
It's a good way to find out,
what the world is made of



Dark matter

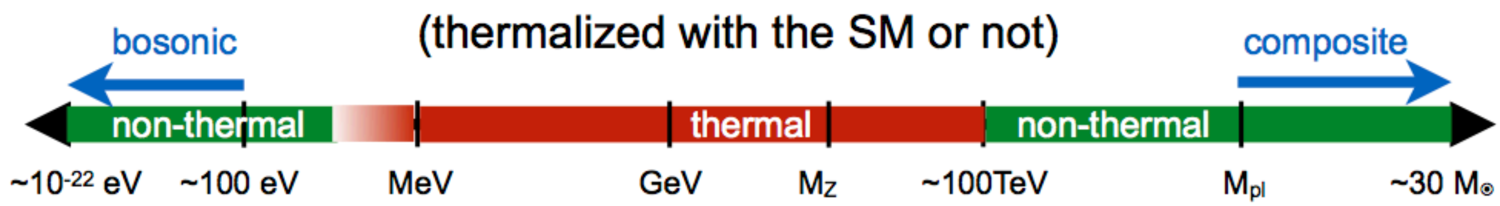
P. Hamilton (20/8)



A. Ritz (20/8)

Cold DM "Landscape"

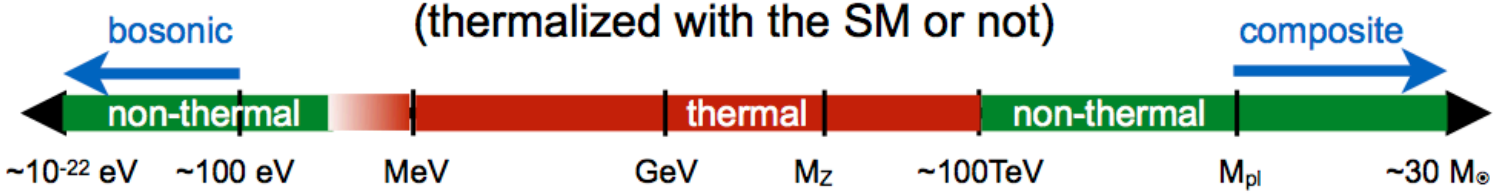
Classify models according to their thermal history in the early universe



Cold DM "Landscape"

Classify models according to their role in the Holy Grail

(thermalized with the SM or not)



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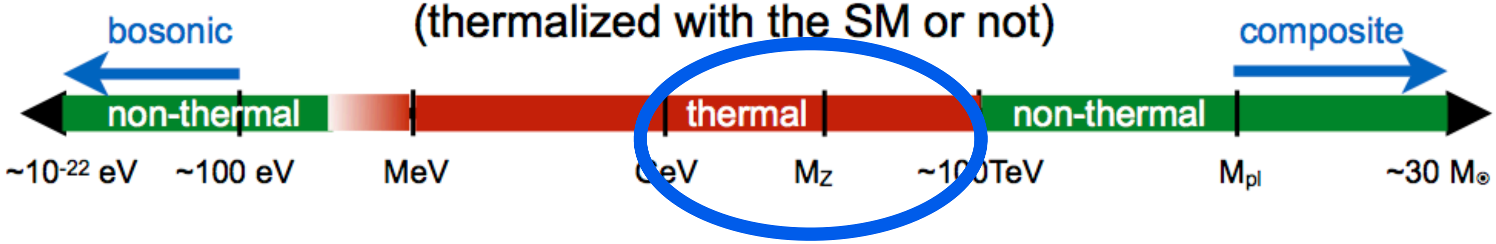

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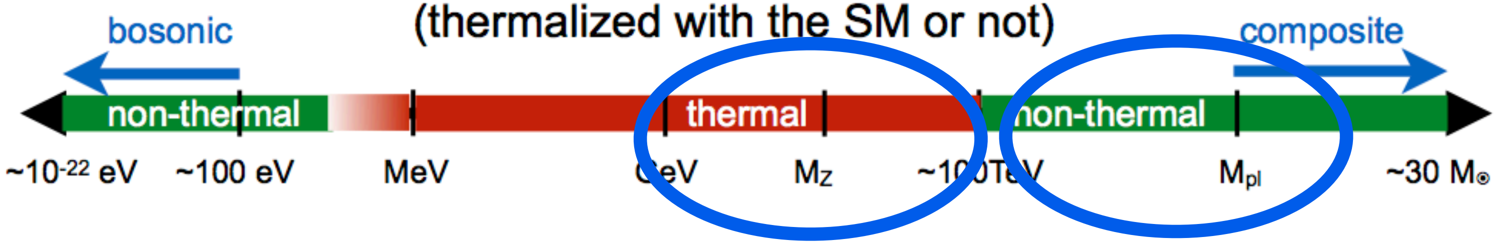

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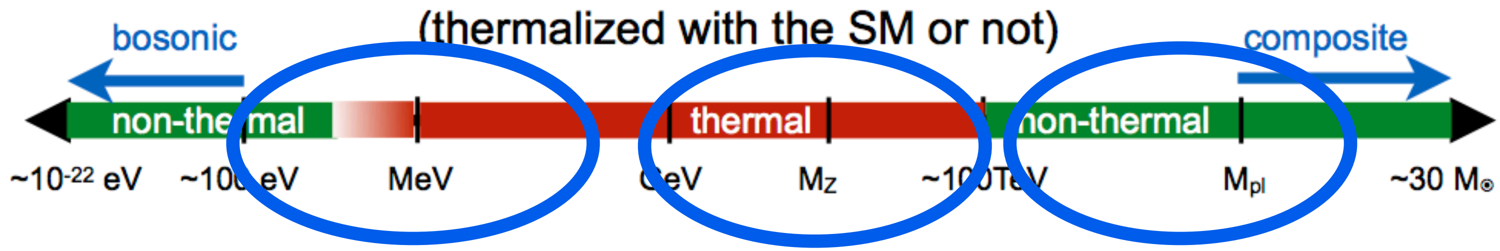

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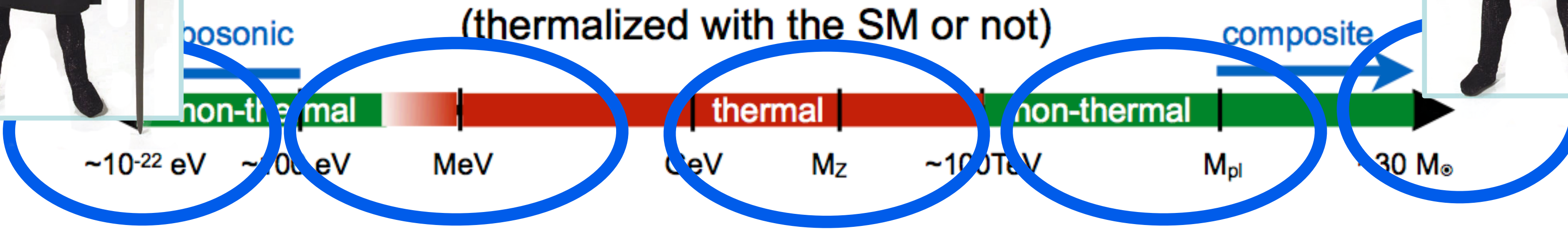

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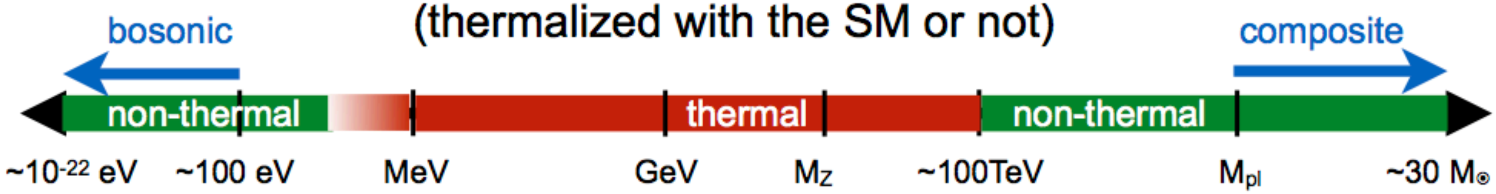

Clear holy grail
(unlike the case for hierarchy or DE problems)

But the road may be very long.

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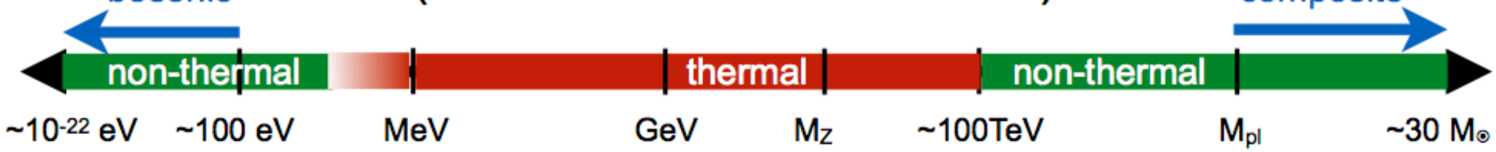

Clear holy grail
(unlike the case for hierarchy or DE problems)

But the road may be very long.

It’s a good idea to pay attention to *things* we find on the road.

Cold DM "Landscape"

Classify models according to their thermal history in the early universe

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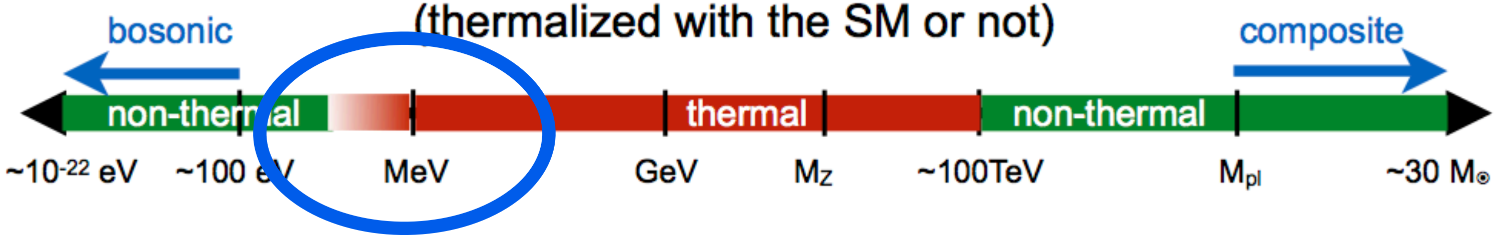


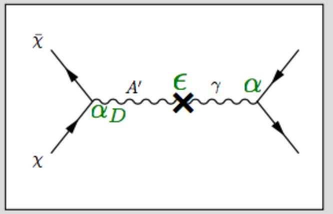
Dark photons/“dark sector”

R. Pottgen (23/8)

Simple, thermal, MeV DM

representative benchmark model: Dark Photon (A’)

- vector mediator
- kinetically mixes with photon (**ε**)
- annihilation cross section



$$\sigma v \sim \alpha_D \varepsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \alpha_D \varepsilon^2 \frac{m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \sim y \frac{1}{m_\chi^2}$$

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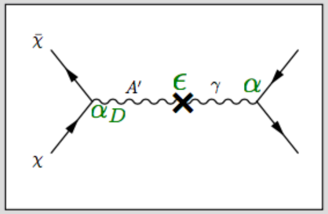

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A. Ritz (20/8)

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

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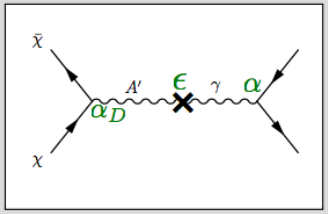

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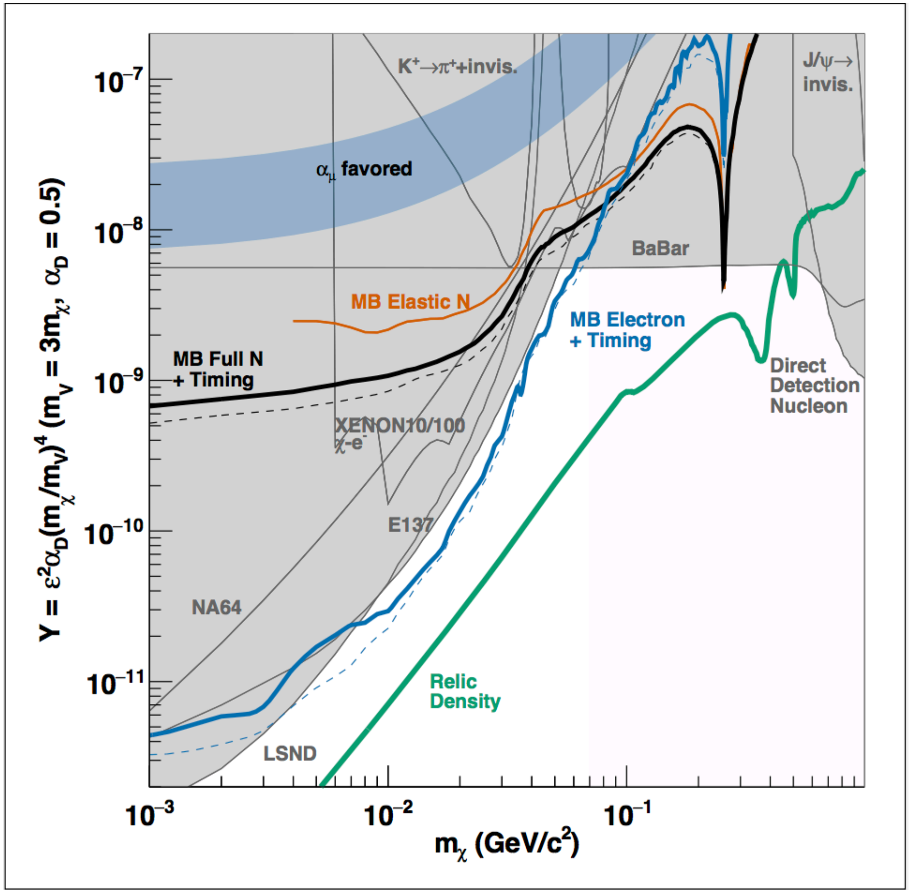
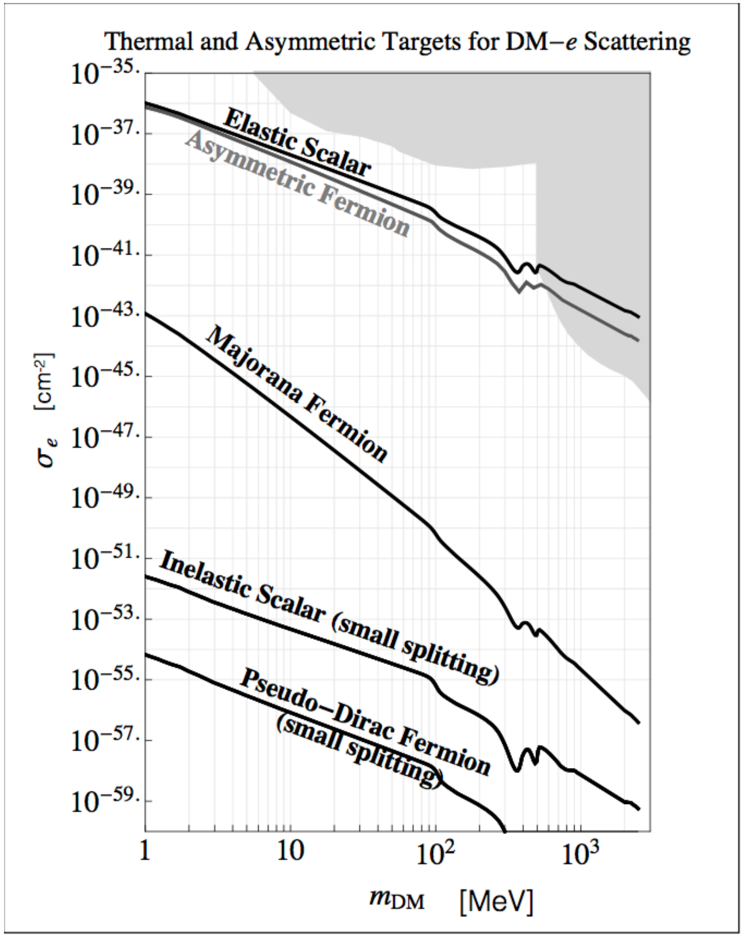
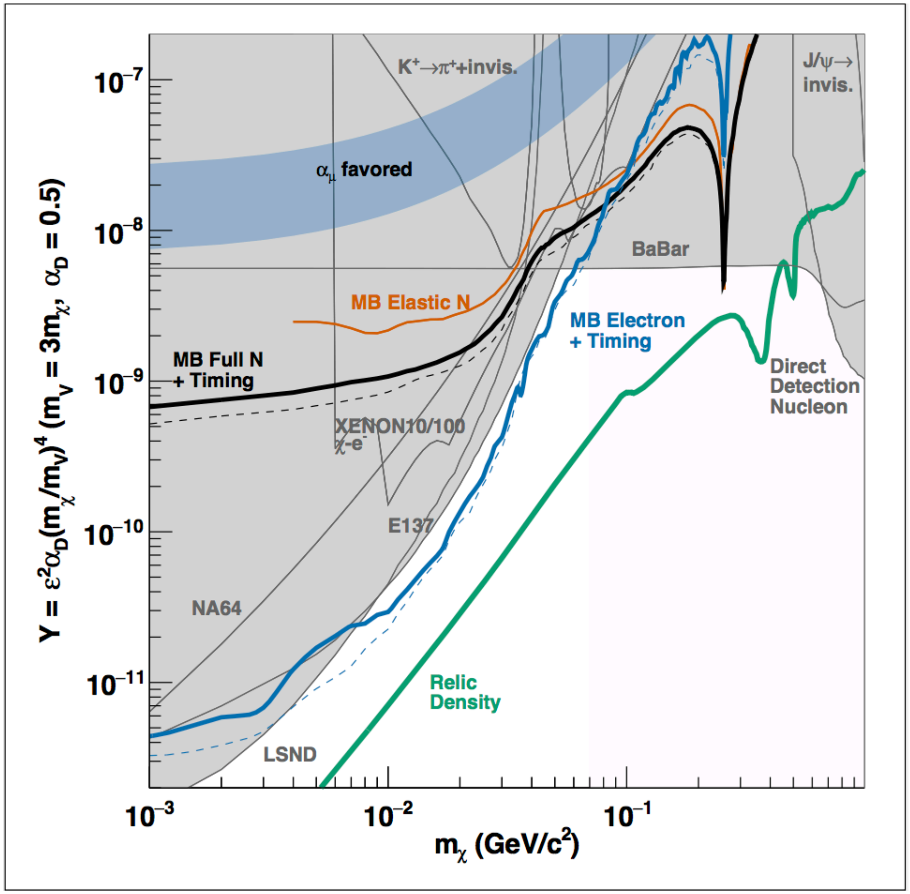
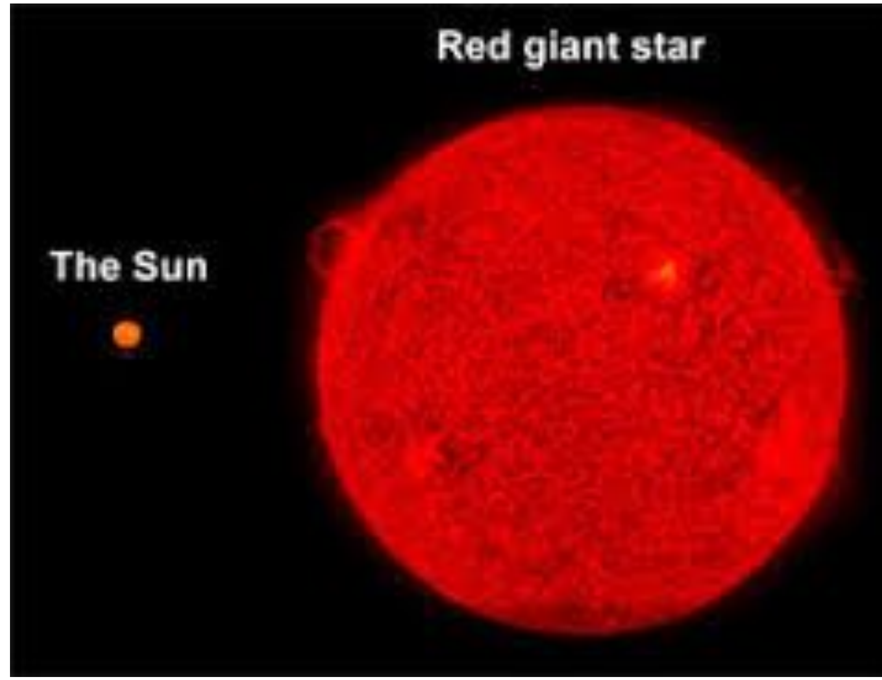




Dark photons/“dark sector”,
Laboratory vs. Astro constraints

R. Pottgen (23/8)
MiniBooNE 1807.06137





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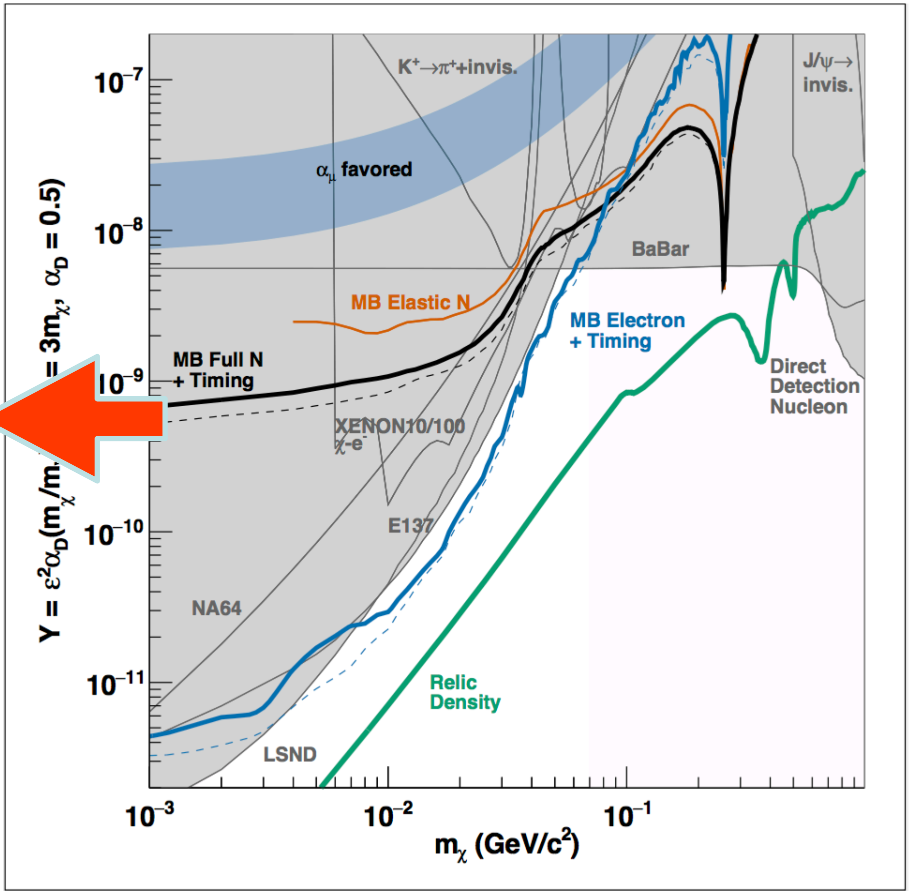
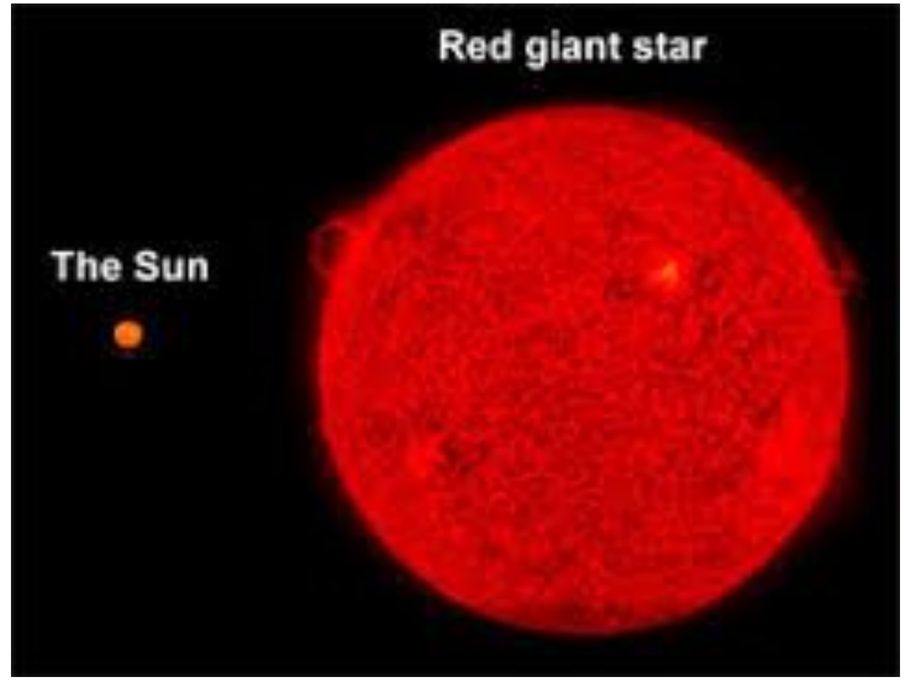


Stars are hot, but not 10MeV hot.
RG core is ~10KeV.



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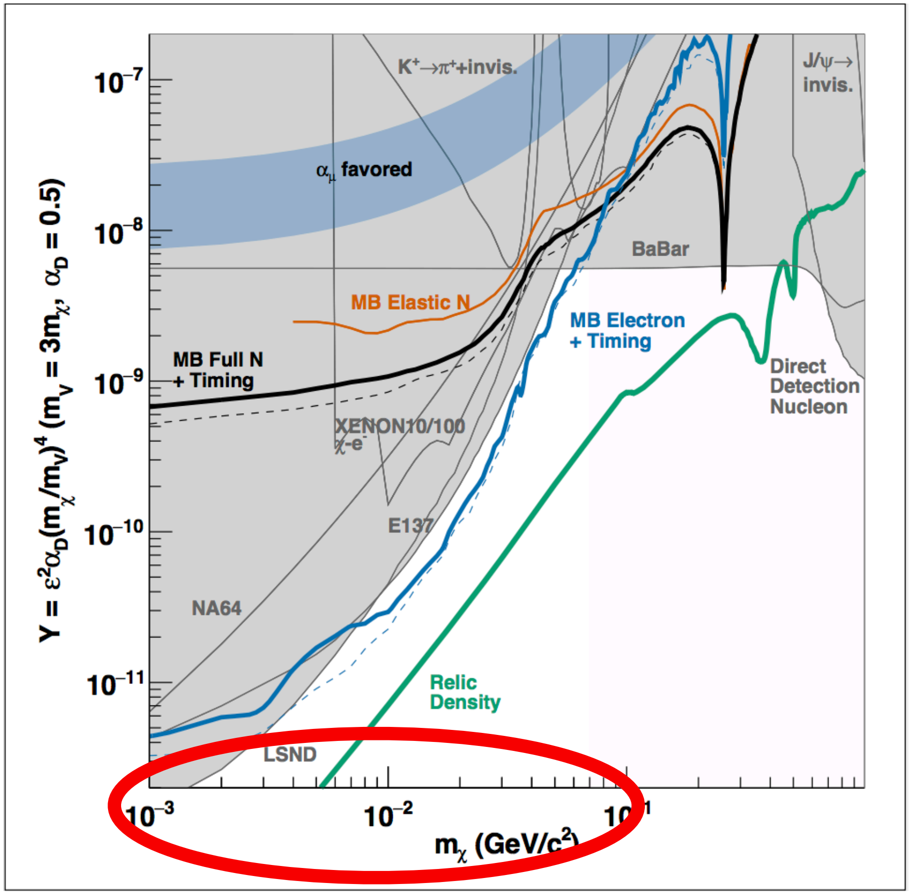
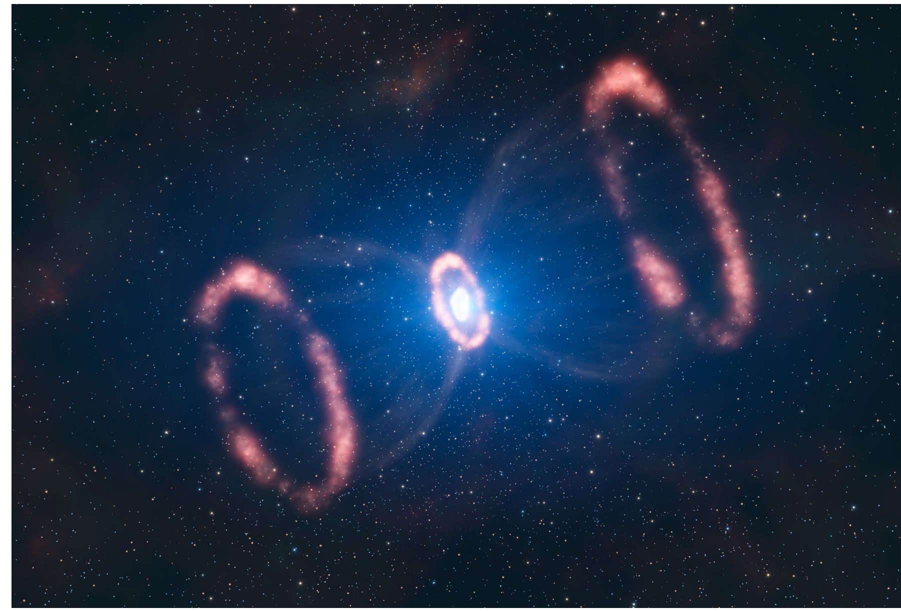


Supernova core is 10MeV hot:
Chang, Essig, McDermott 1803.00993



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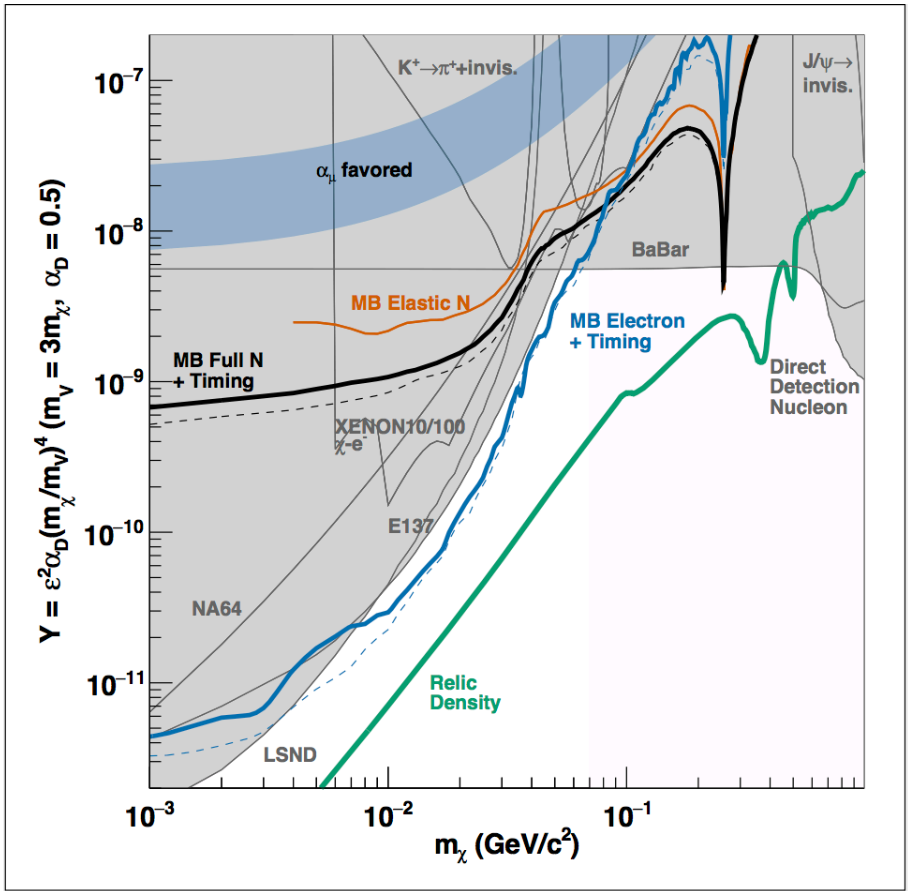

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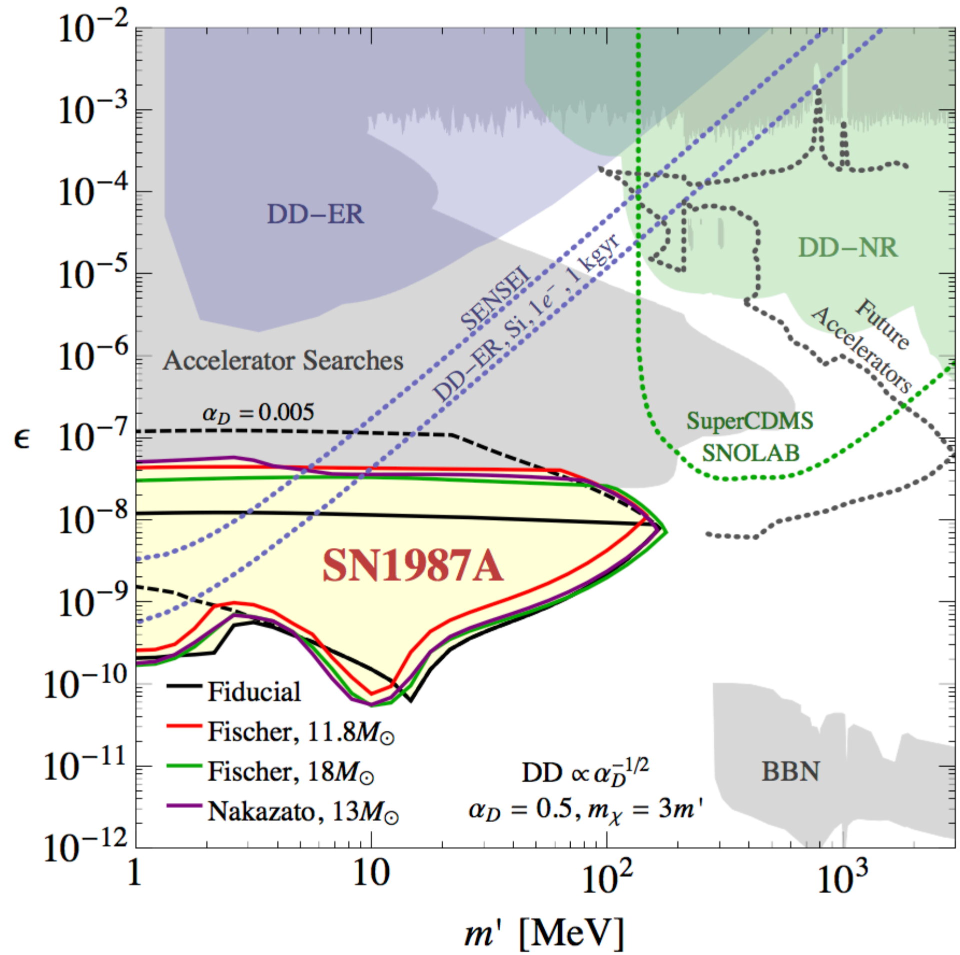

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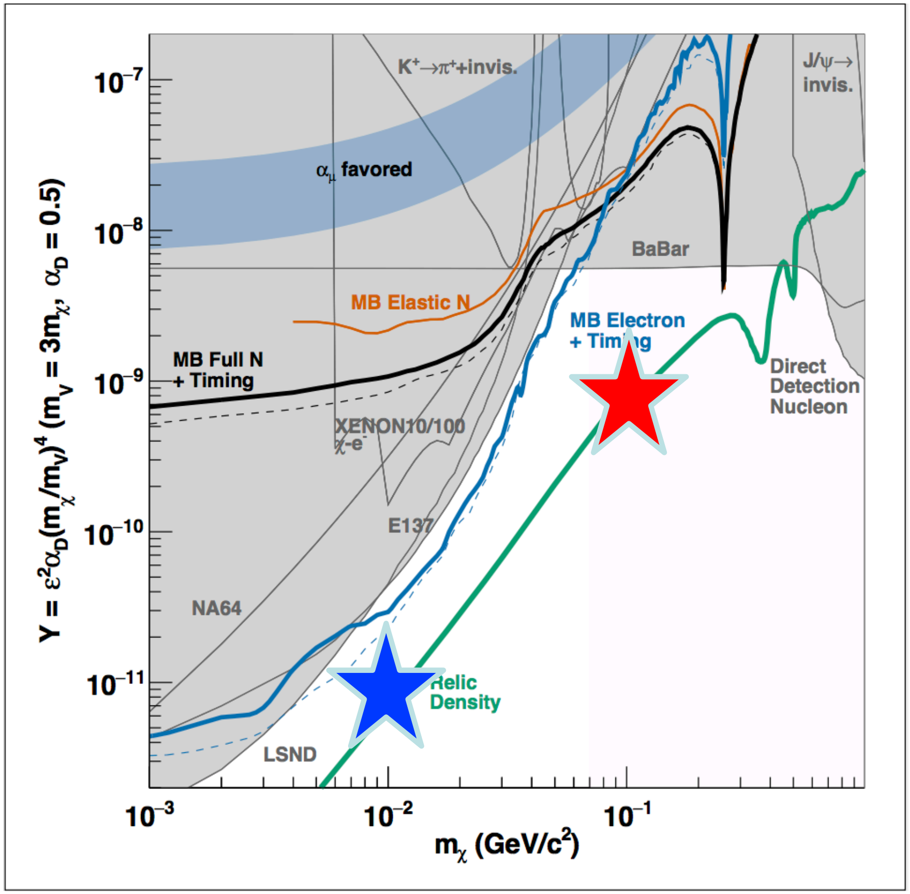

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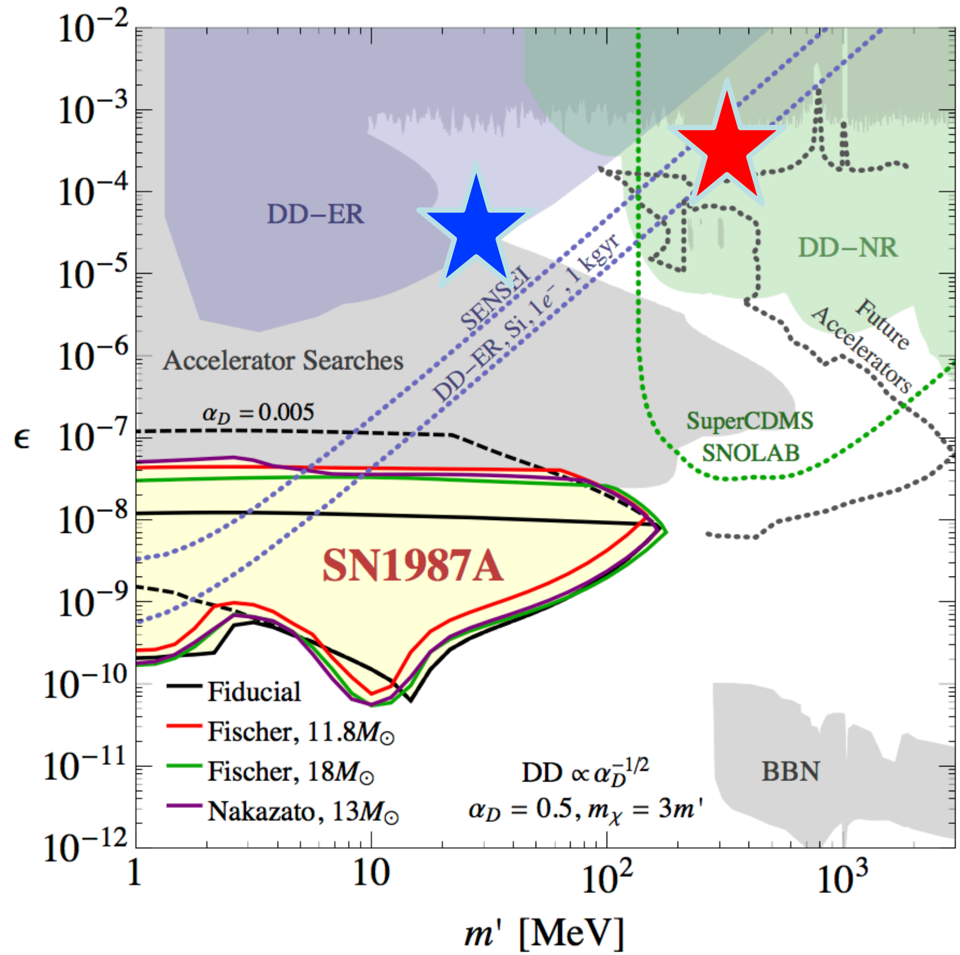

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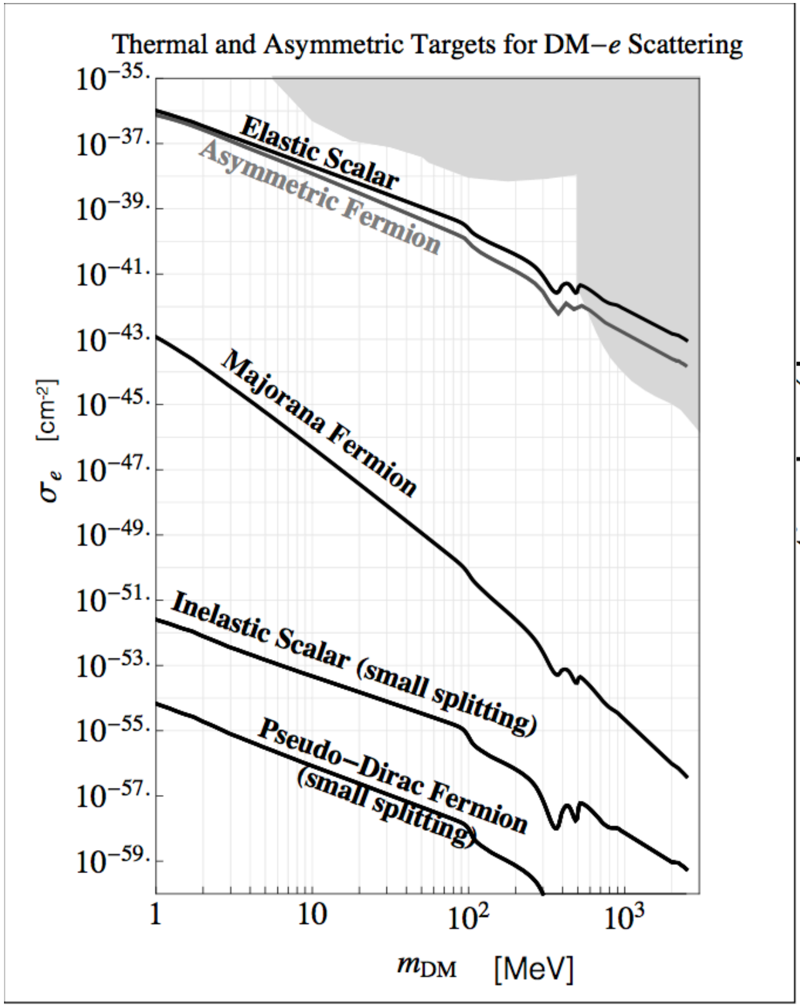
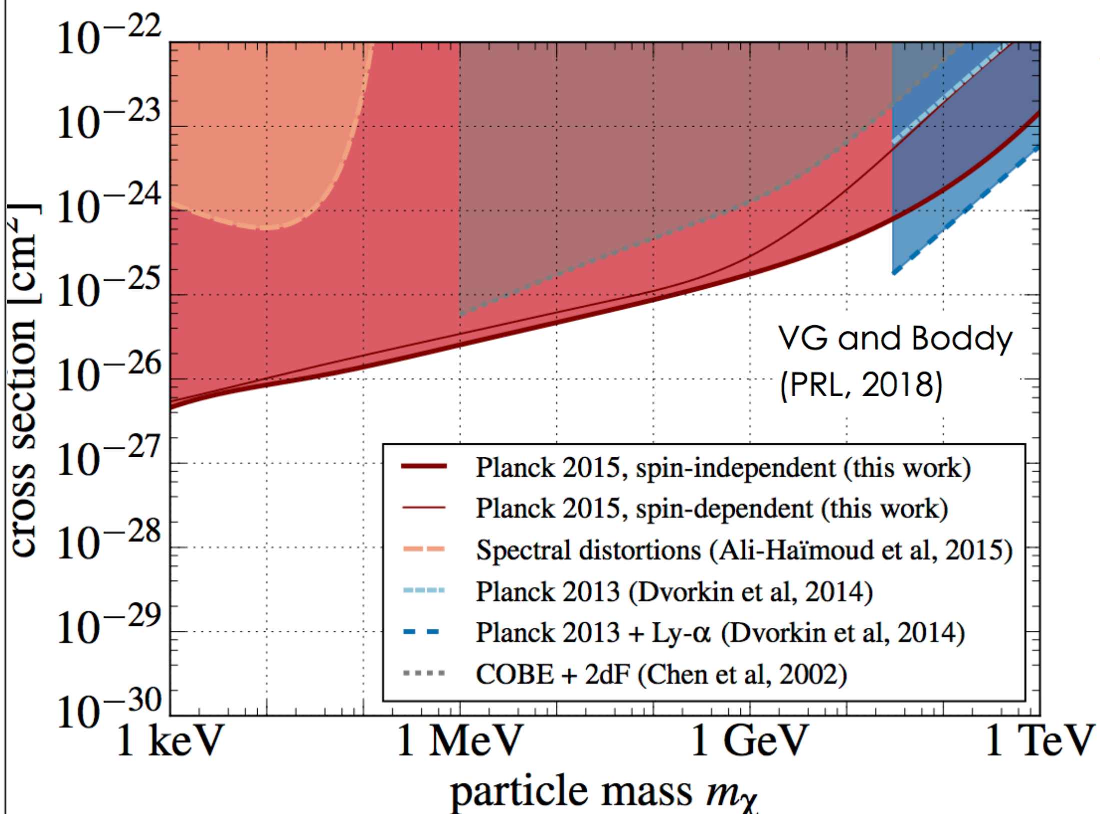


V. Gluscevic (21/8)

<u>DM-proton</u> scattering



Dark photons/“dark sector”,
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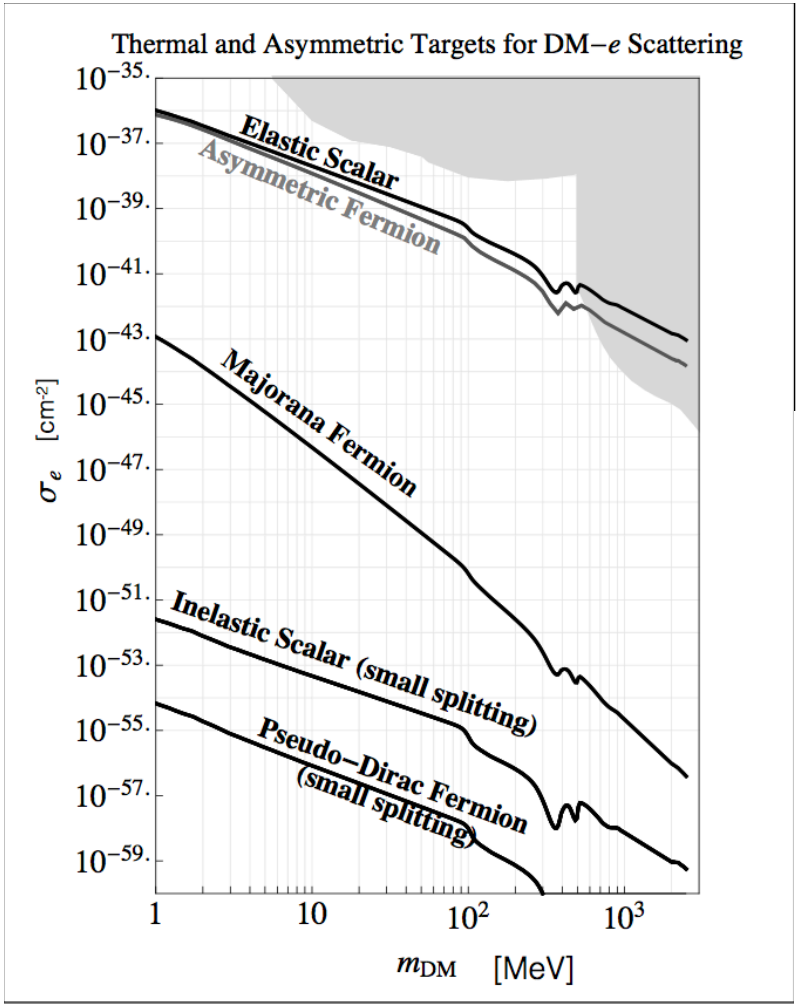
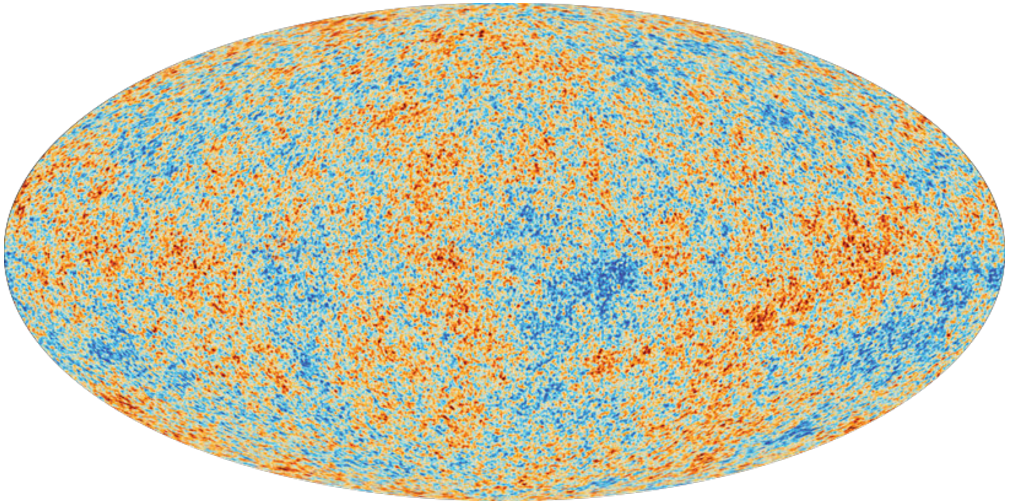
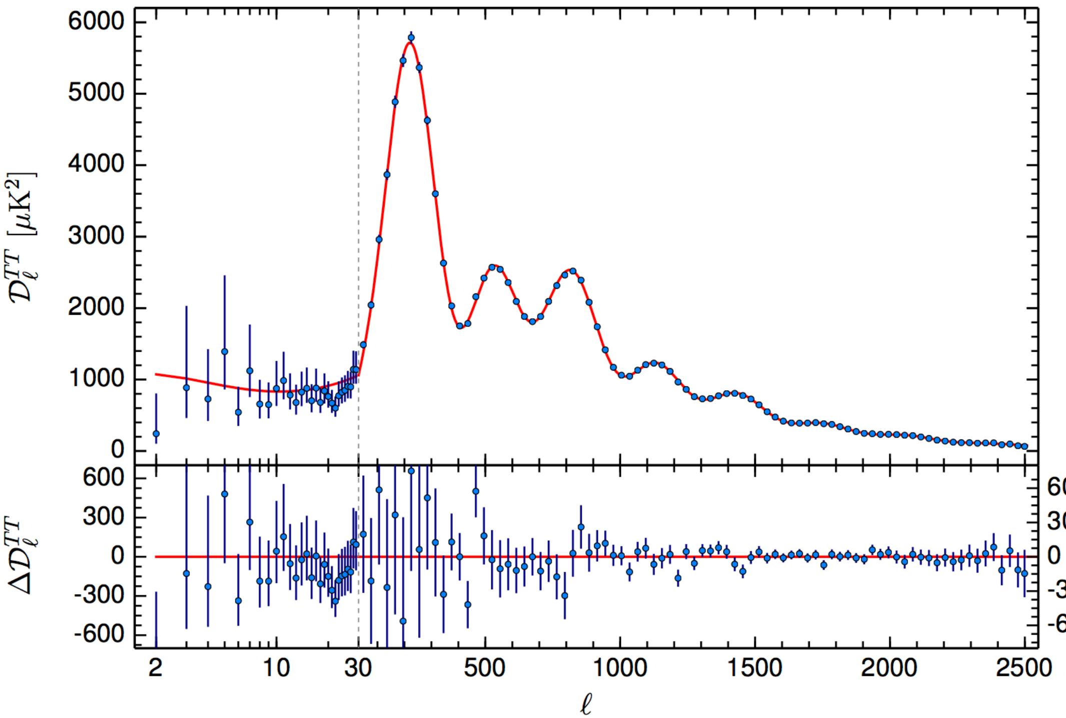
R. Pottgen (23/8)

R. Durrer (20/8)





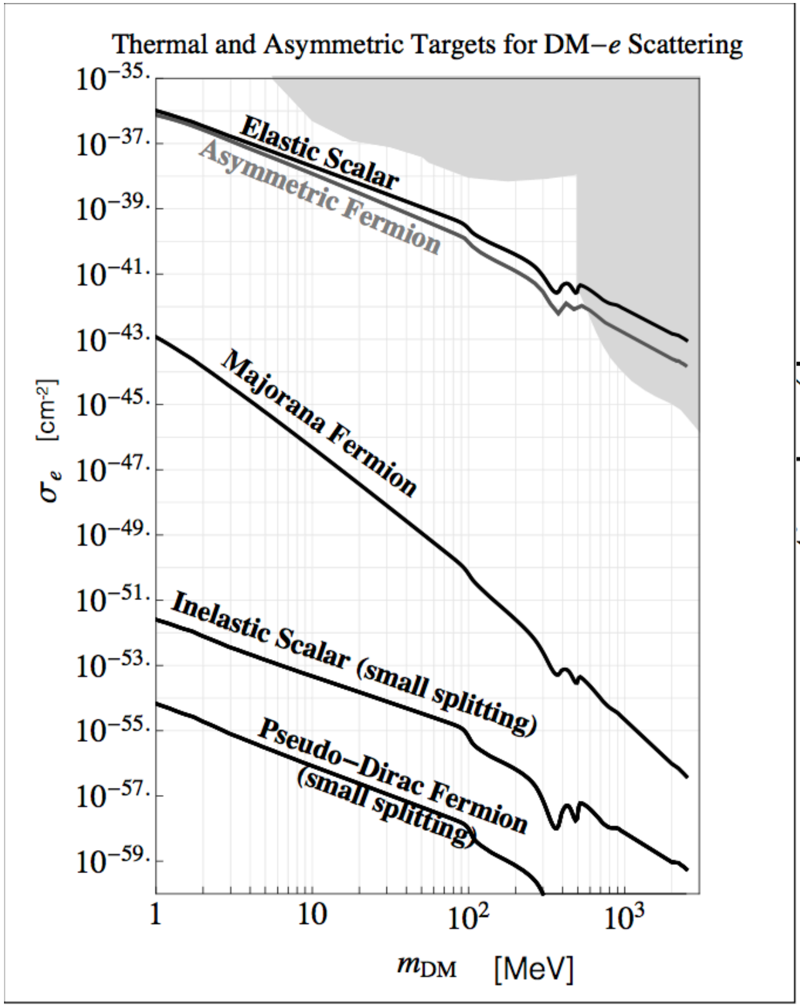


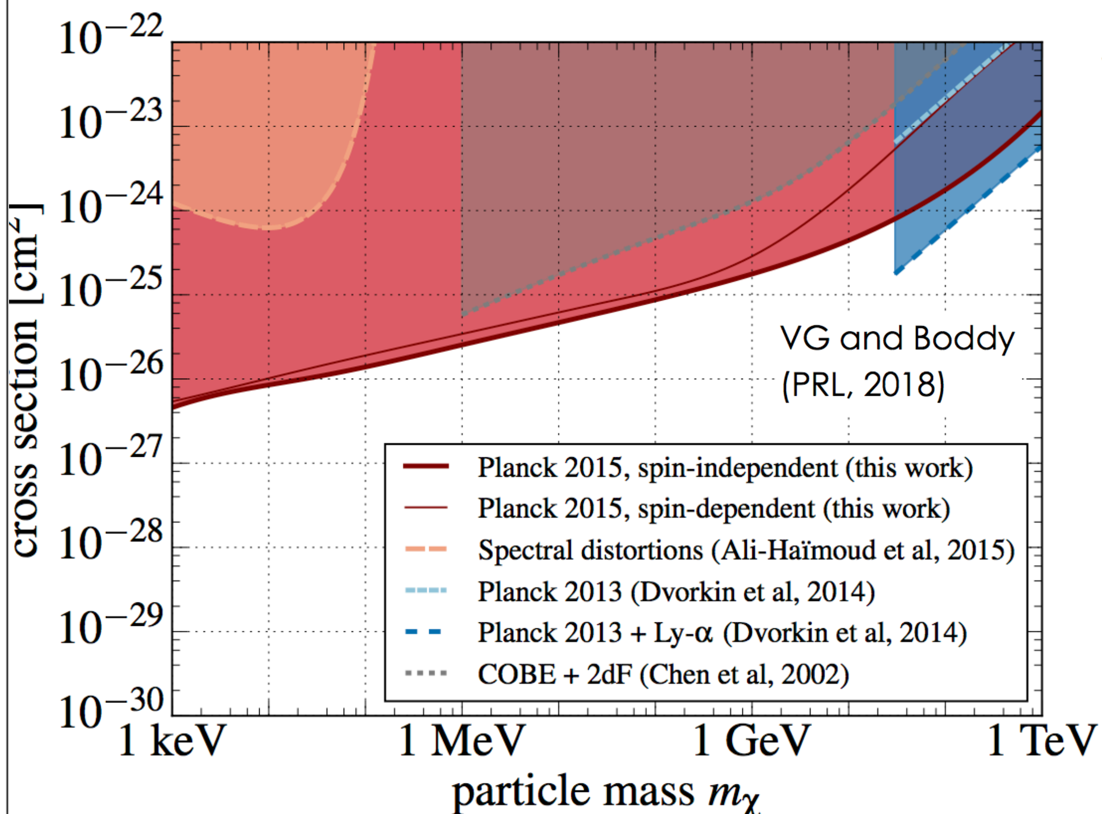
Dark photons/“dark sector”,
Laboratory vs. Astro constraints
R. Pottgen (23/8)

What about DM-electron scattering?

V. Gluscevic (21/8)

DM-proton scattering





Dark photons/“dark sector”,
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R. Pottgen (23/8)

What about DM-electron scattering?

①

DM-e scattering

$$\Delta \vec{p}_\chi = \frac{m_\chi m_e}{m_\chi + m_e} |\Delta \vec{V}_{\chi e}| \left(\hat{n} - \frac{\vec{V}_\chi - \vec{V}_e}{|\vec{V}_\chi - \vec{V}_e|} \right)$$ per collision.

$$\Rightarrow \frac{d\vec{V}_\chi}{dt} = n_e \frac{m_\chi m_e}{m_\chi + m_e} \int dv_e v_e^2 f_e(v_e) \int \frac{d\hat{n}_e}{4\pi} \int d\hat{n} \left(\frac{d\sigma}{d\hat{n}}\right) |\vec{V}_\chi - \vec{V}_e|^2 \left(\hat{n} - \frac{\vec{V}_\chi - \vec{V}_e}{|\vec{V}_\chi - \vec{V}_e|}\right)$$

bulk velocity V_χ:

$$\frac{d\vec{V}_\chi}{dt} = \int \frac{d\hat{n}_\chi}{4\pi} \int dv_\chi v_\chi^2 f_\chi(v_\chi) \frac{d\vec{v}_\chi}{dt}$$

$$\simeq -\vec{V}_\chi c_n \frac{\rho_e \sigma_0}{m_\chi + m_e} \left(\frac{\langle (\Delta \vec{V}_{\chi e})^2 \rangle}{3} \right)^{\frac{n+1}{2}}$$

where: $\bar{\sigma}(v) \equiv \int dc_\theta (1 - c_\theta) \left(\frac{d\sigma(v)}{dc_\theta} \right) \equiv \sigma_0 v^n$

note: $z \gtrsim 300 \Leftrightarrow \frac{\langle (\Delta V_{\chi e})^2 \rangle}{3} \simeq \frac{T_b}{m_e} + \frac{T_\chi}{m_\chi}$

$\Rightarrow$ below, let $m_\chi > m_e$; neglect $\frac{T_\chi}{m_\chi}$ vs. $\frac{T_b}{m_e}$.

cosmo. pert.: velocity divergence EOM:

$$\begin{cases} \dot{\theta}_\chi = -\mathcal{H}\theta_\chi + R_\chi^{(e)}(\theta_b - \theta_\chi) & \text{DM} \\ \dot{\theta}_b = -\mathcal{H}\theta_b + \frac{\rho_\chi}{\rho_b} R_\chi^{(e)} (\theta_\chi - \theta_b) + \ldots & \text{SM baryons} \end{cases}$$

easy to see:

$$R_\chi^{(e)} \simeq \frac{\rho_e}{\rho_b} \cdot \left(\frac{m_p}{m_e}\right)^{\frac{n+1}{2}} \cdot \frac{(\sigma_0^{(e)}/m_\chi)}{(\sigma_0^{(p)}/m_\chi)} \cdot R_\chi^{(p)} \simeq \left(\frac{m_p}{m_e}\right)^{\frac{n-1}{2}} \frac{(\sigma_0^{(e)}/m_\chi)}{(\sigma_0^{(p)}/m_\chi)} R_\chi^{(p)}$$

②

limit is set (roughly) by noting: $\left.\frac{R_\chi}{\mathcal{H}}\right|_{z \simeq 10^4} < 1$. $\quad \mathcal{H} = \left(\frac{da/d\eta}{a}\right)$

(*) extract $(\sigma_0^{(e)}/m_\chi)$ limit at $m_\chi > m_e$ from constraint on $(\sigma_0^{(p)}/m_\chi)$ limit at $m_\chi = 1\,\text{GeV} = m_p$.

$\Rightarrow R_\chi^{(e)}\big|_{lim} = R_\chi^{(p)}\big|_{lim}$. for $n = 0$:

$$\left(\sigma_0^{(e)}/m_\chi\right)_{lim,\, m_\chi = 1\,\text{GeV}} \simeq \left(\sigma_0^{(p)}/m_\chi\right)_{lim,\, m_\chi = 1\,\text{GeV}} \cdot \left(\frac{m_p}{m_e}\right)^{\frac{1}{2}}$$

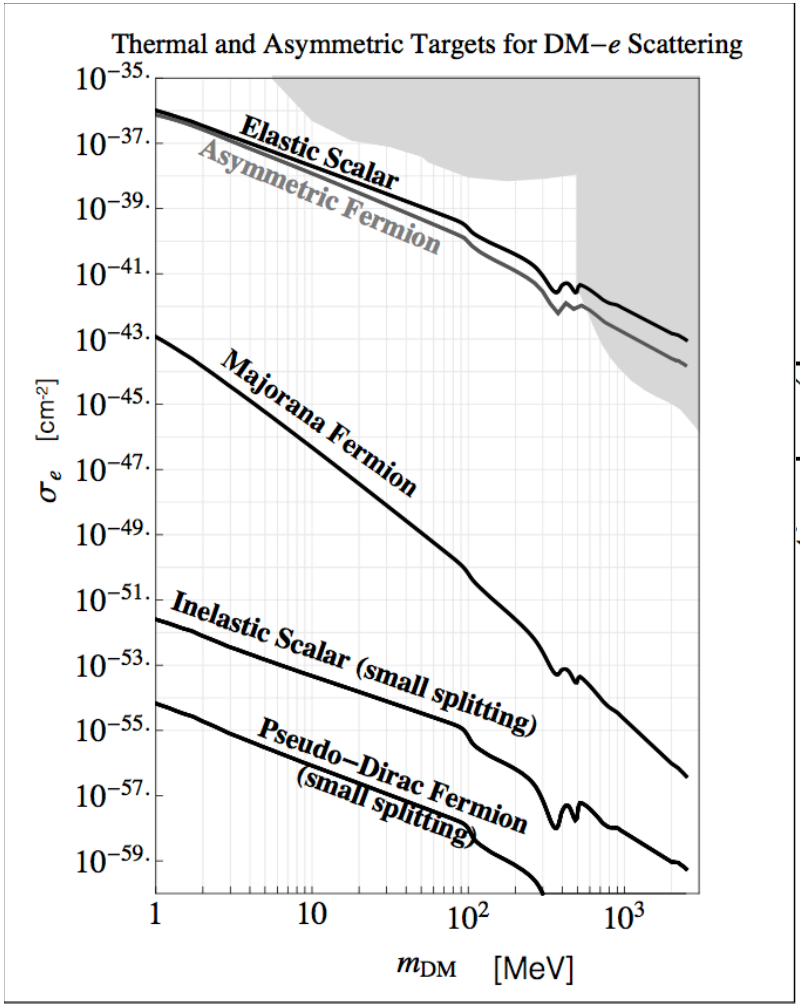
$$\simeq 40 \left(\frac{\sigma_0^{(p)}}{m_\chi}\right)_{lim,\, m_\chi = 1\,\text{GeV}}$$

$\Rightarrow$ constraint on $\left(\frac{\sigma_0^{(e)}}{m_\chi}\right)$ is independent of m_χ for $m_\chi > m_e$.

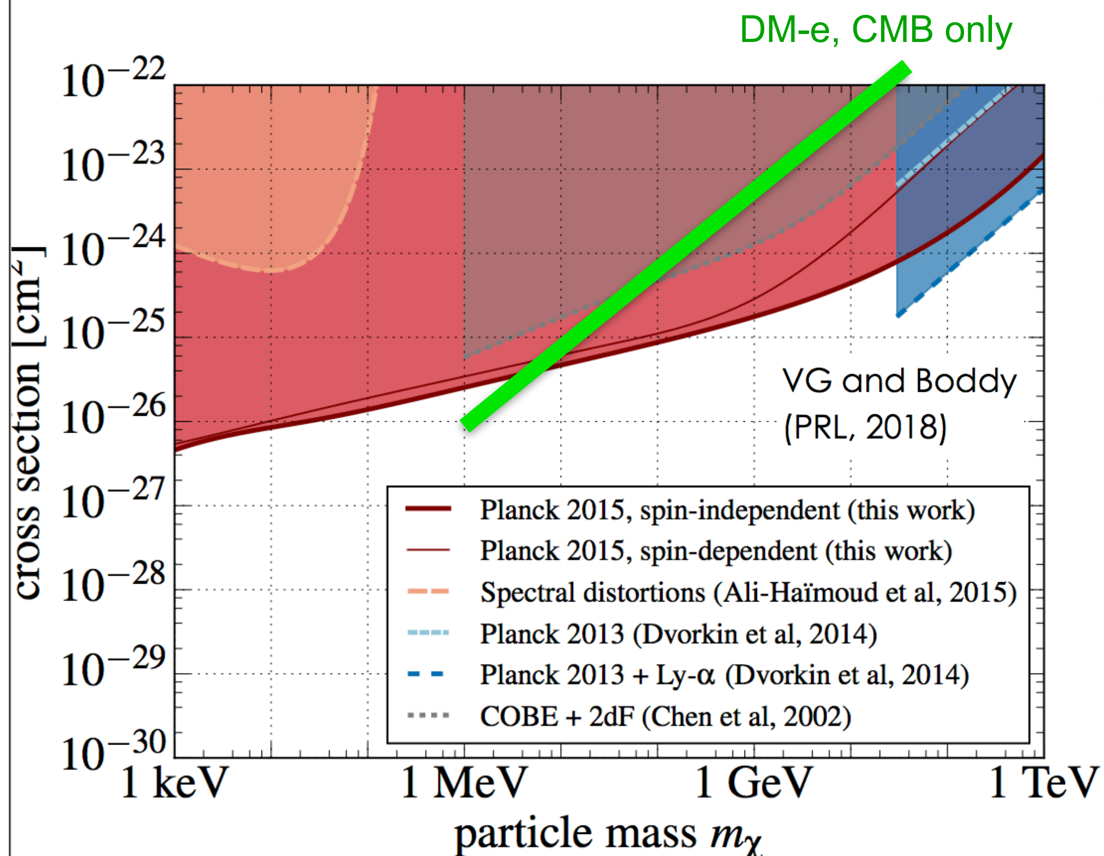
Dark photons/“dark sector”,
Laboratory vs. Astro constraints
R. Pottgen (23/8)

What about DM-electron scattering?

V. Gluscevic (21/8)



DM-proton scattering



(velocity-indep. cross sec.)

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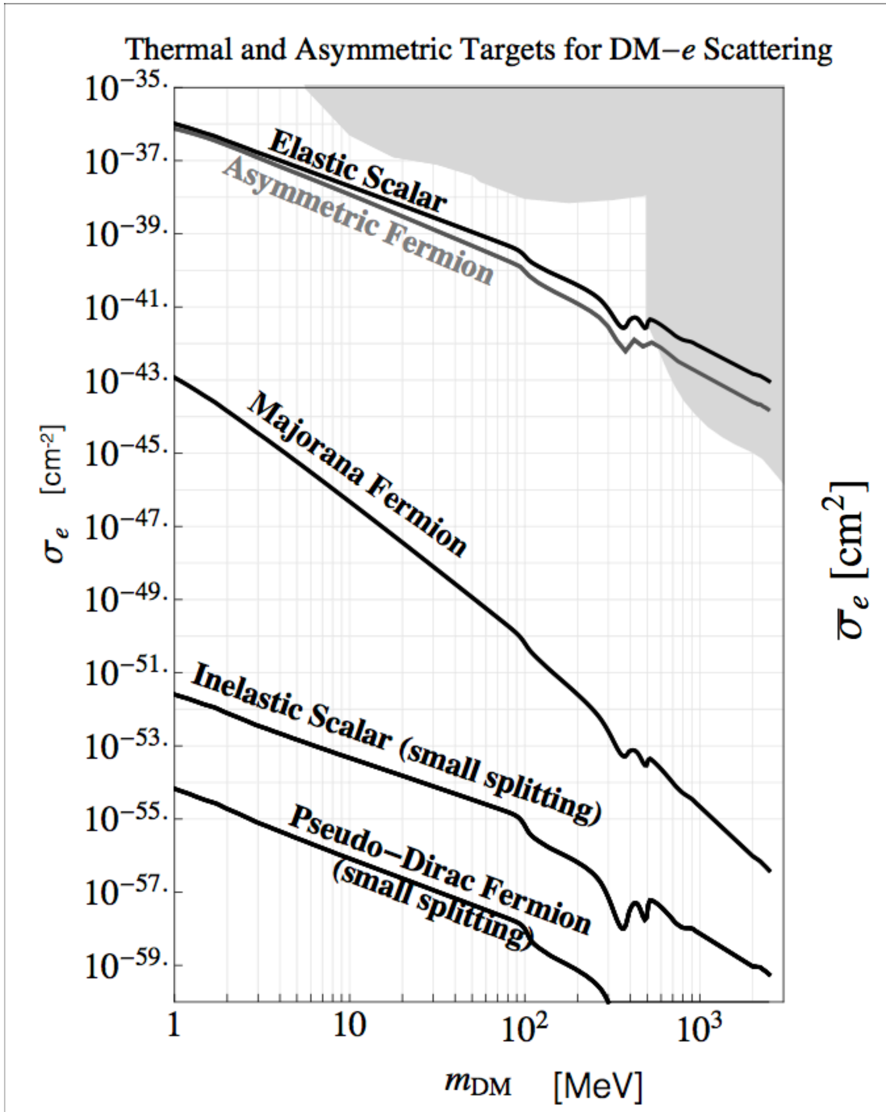
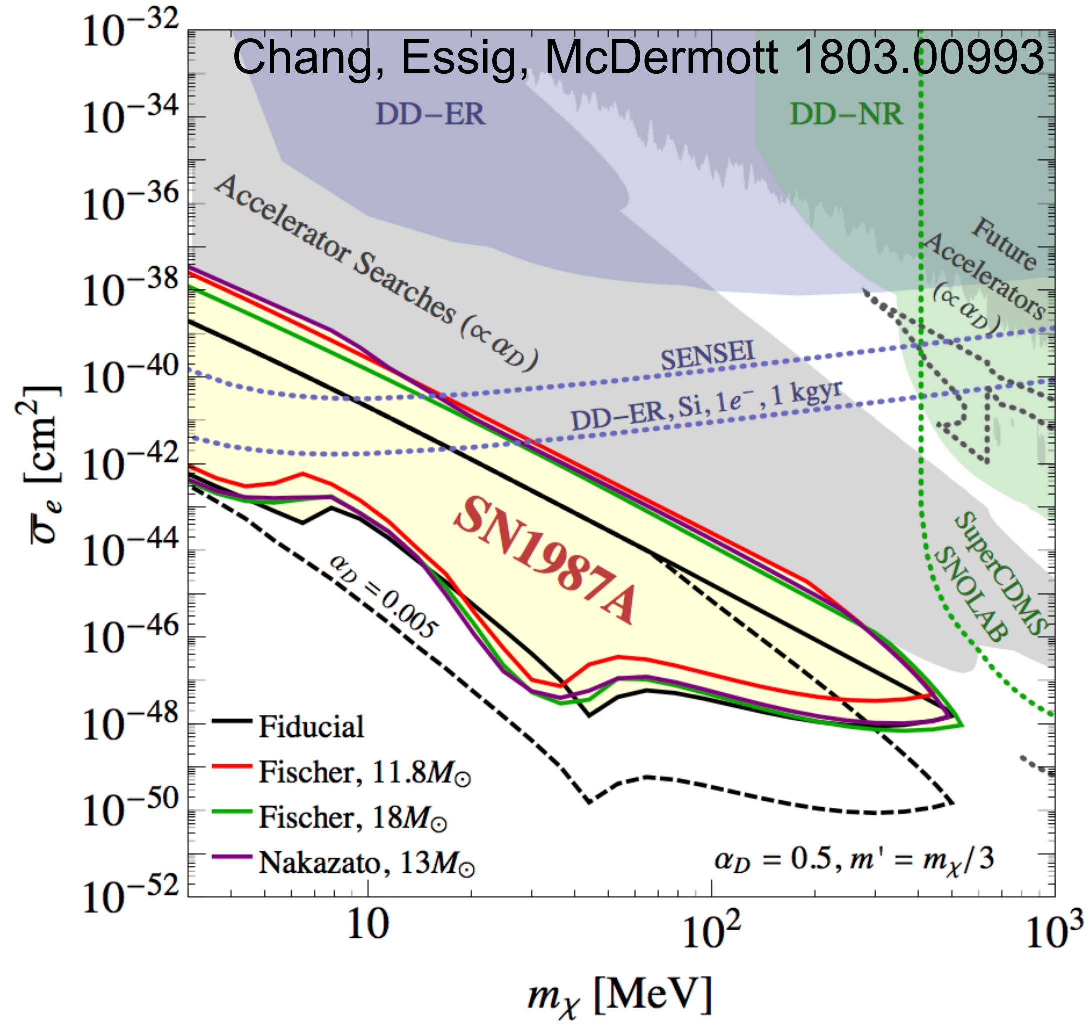
R. Pottgen (23/8)





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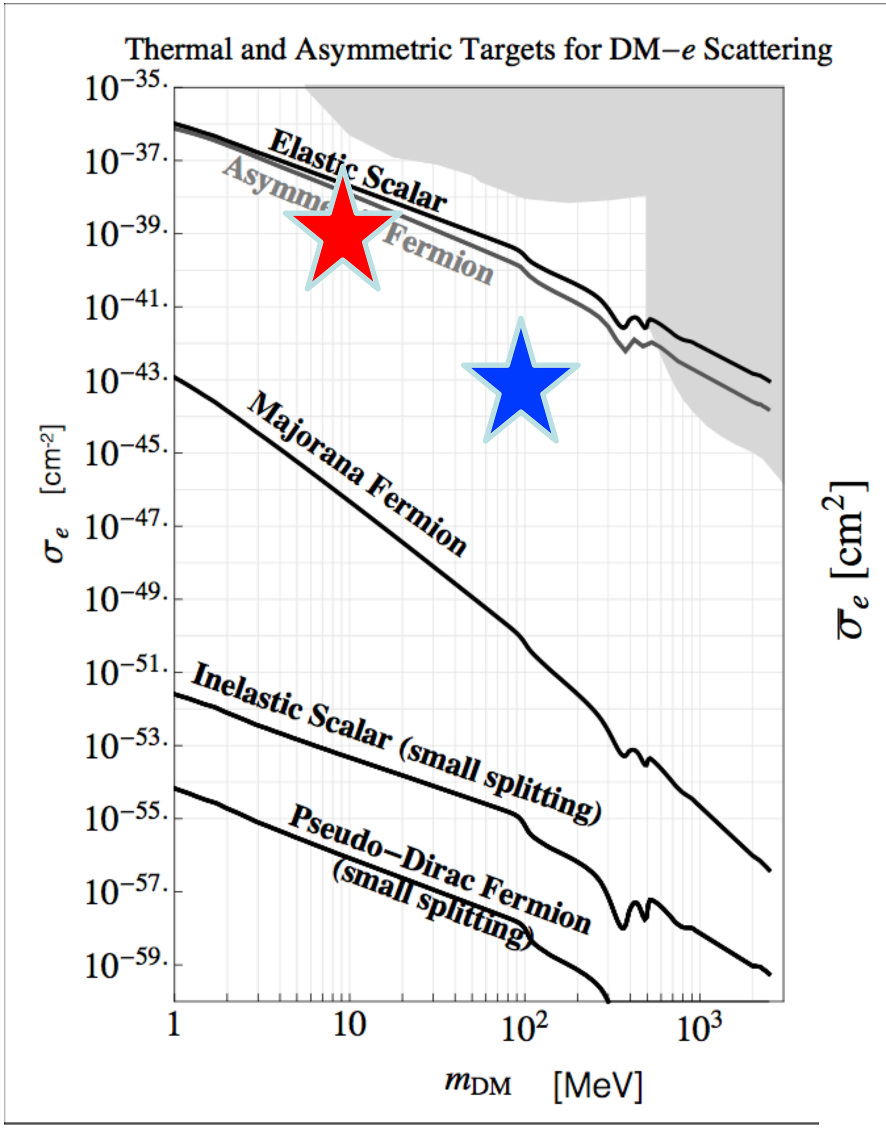
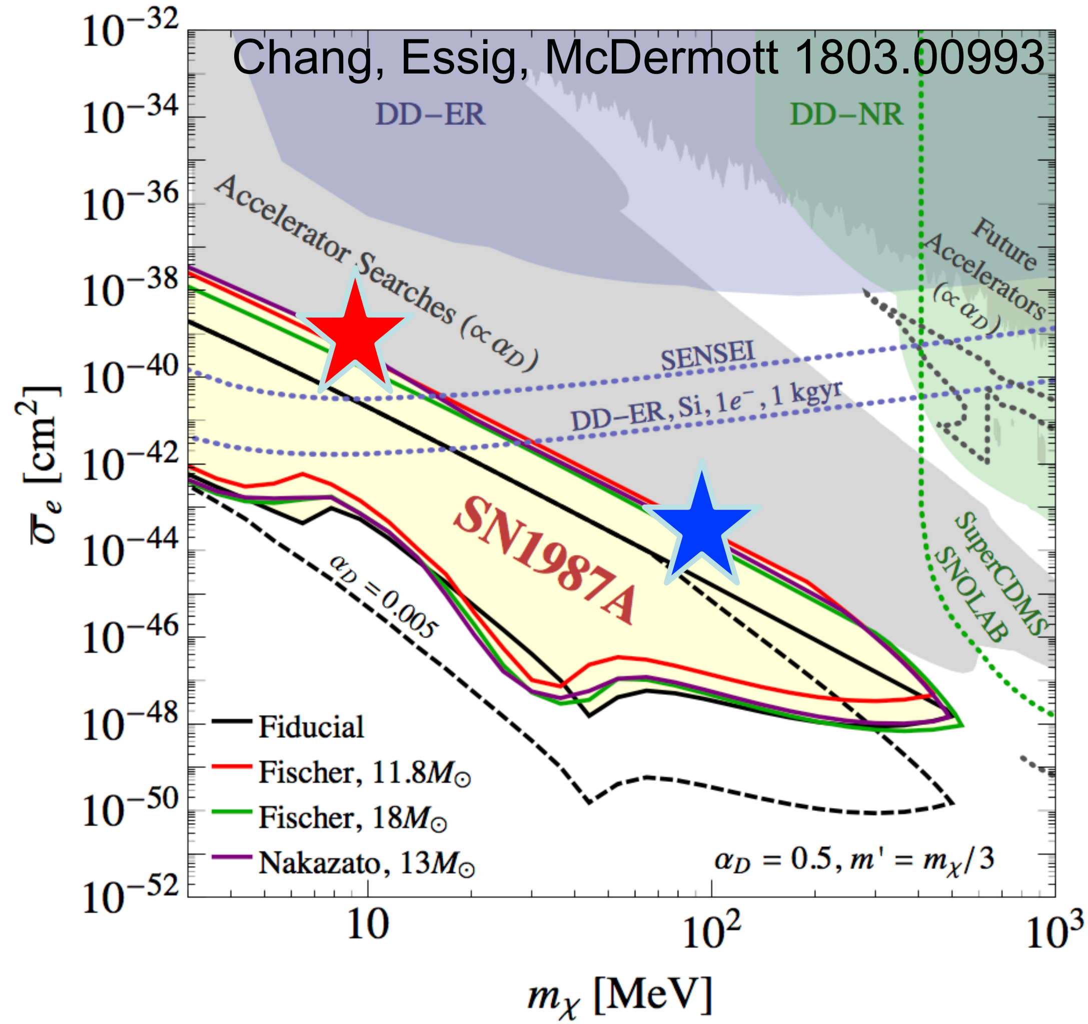
R. Pottgen (23/8)

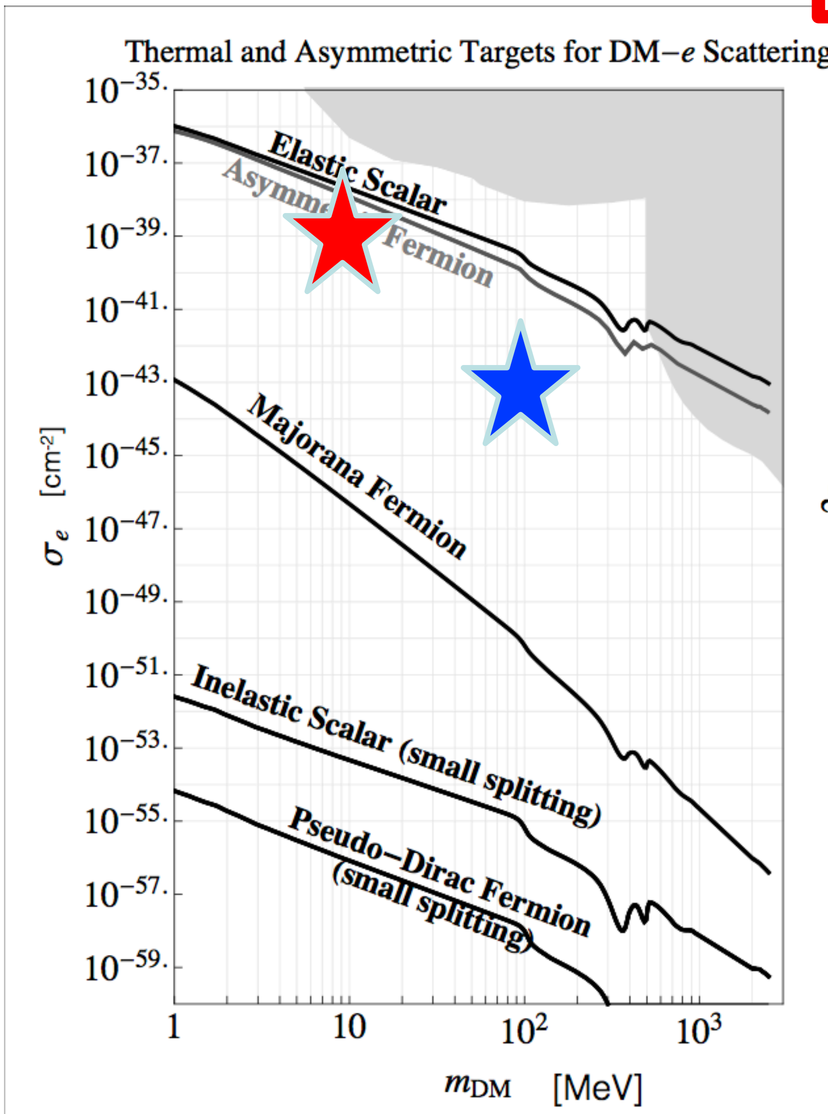


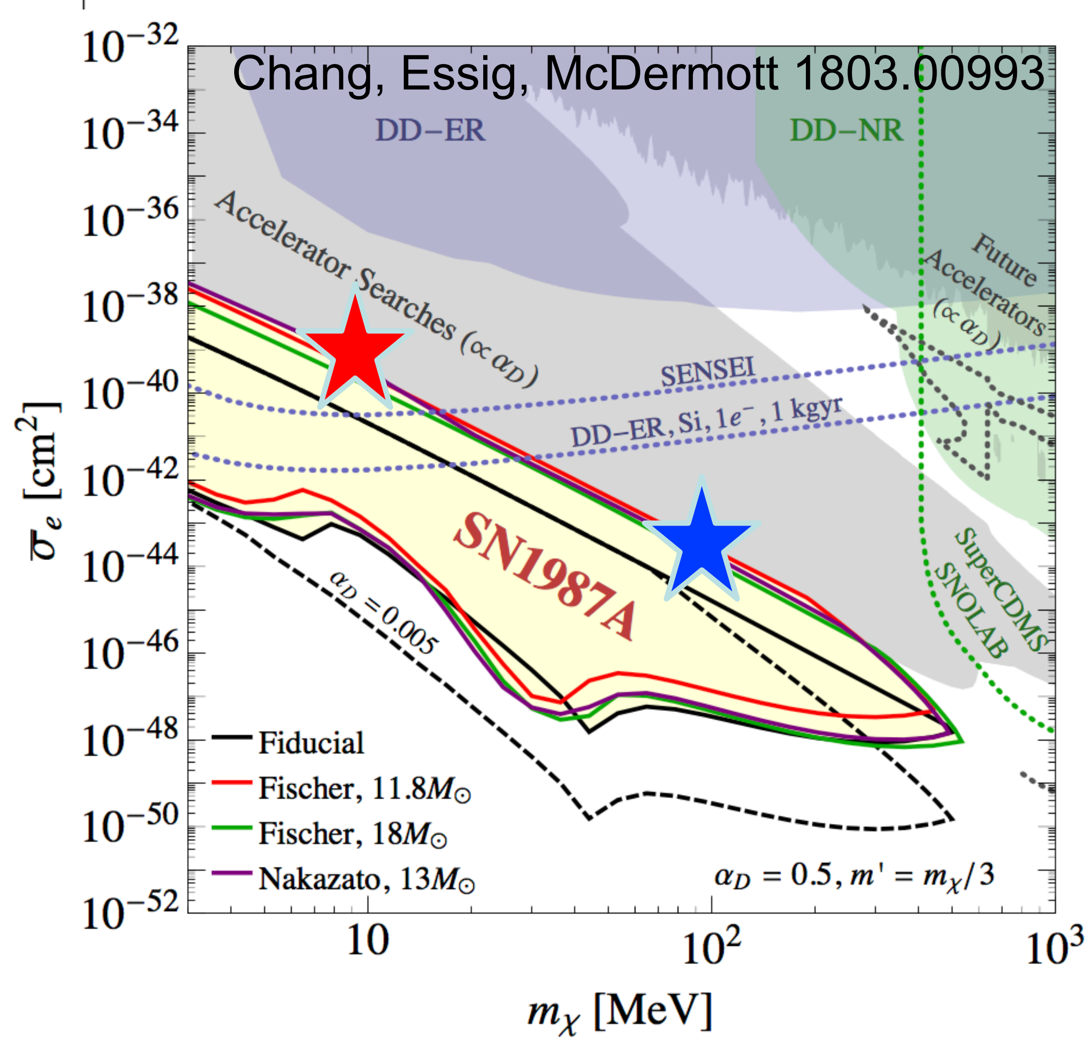


Dark photons/“dark sector”,
Laboratory vs. Astro constraints

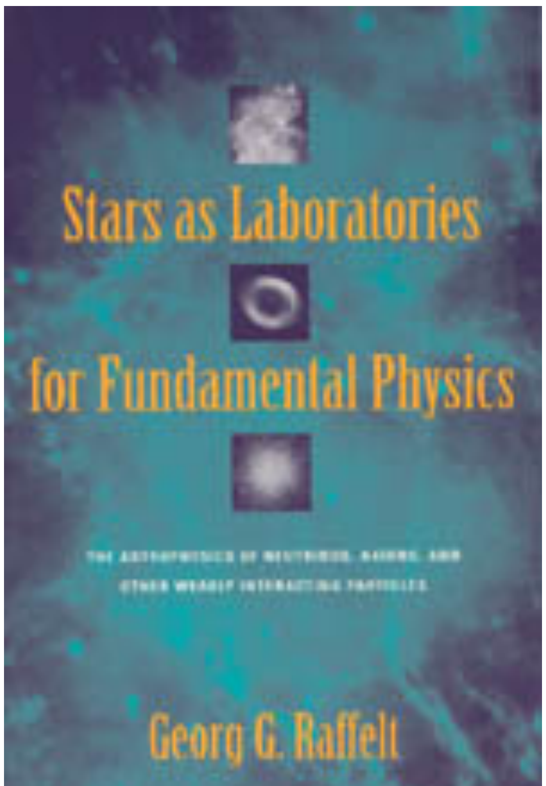
R. Pottgen (23/8)

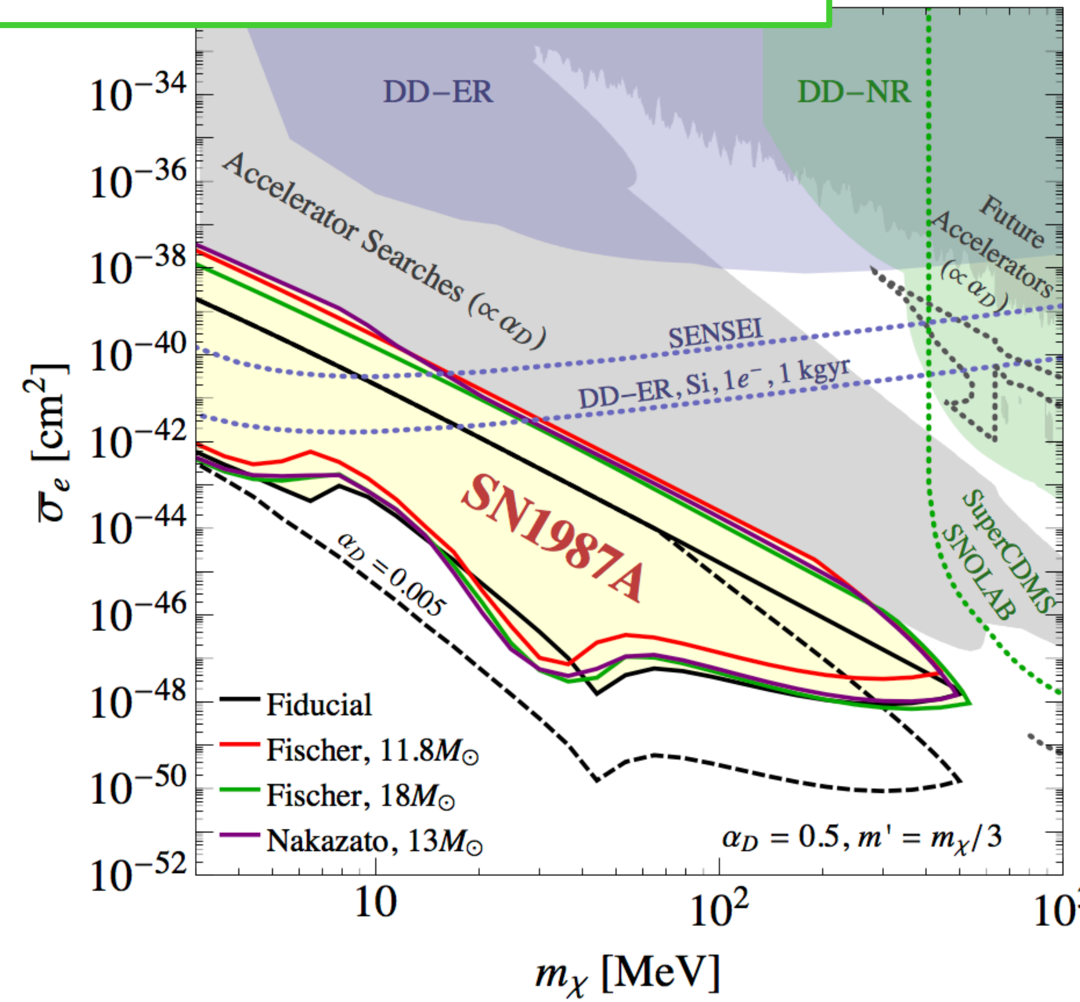
…do we understand core-collapse supernovae well enough?





The existence of new, weakly-coupled particles could provide novel channels to "cool" the proto-neutron star and change the neutrino emission from SN1987A. Constraints in this context are derived from the "Raffelt criterion": the luminosity carried by the new particles from the interior of the proto-neutron star environment to the outside of the neutrinosphere must be smaller than the luminosity carried by neutrinos [2]. The observed cooling time of the supernova agrees within uncertainties with the SM prediction [3, 4]. However, if there were an additional efficient channel for energy flow that could compete with neutrinos, the cooling time of the supernova would have been shorter than observed.





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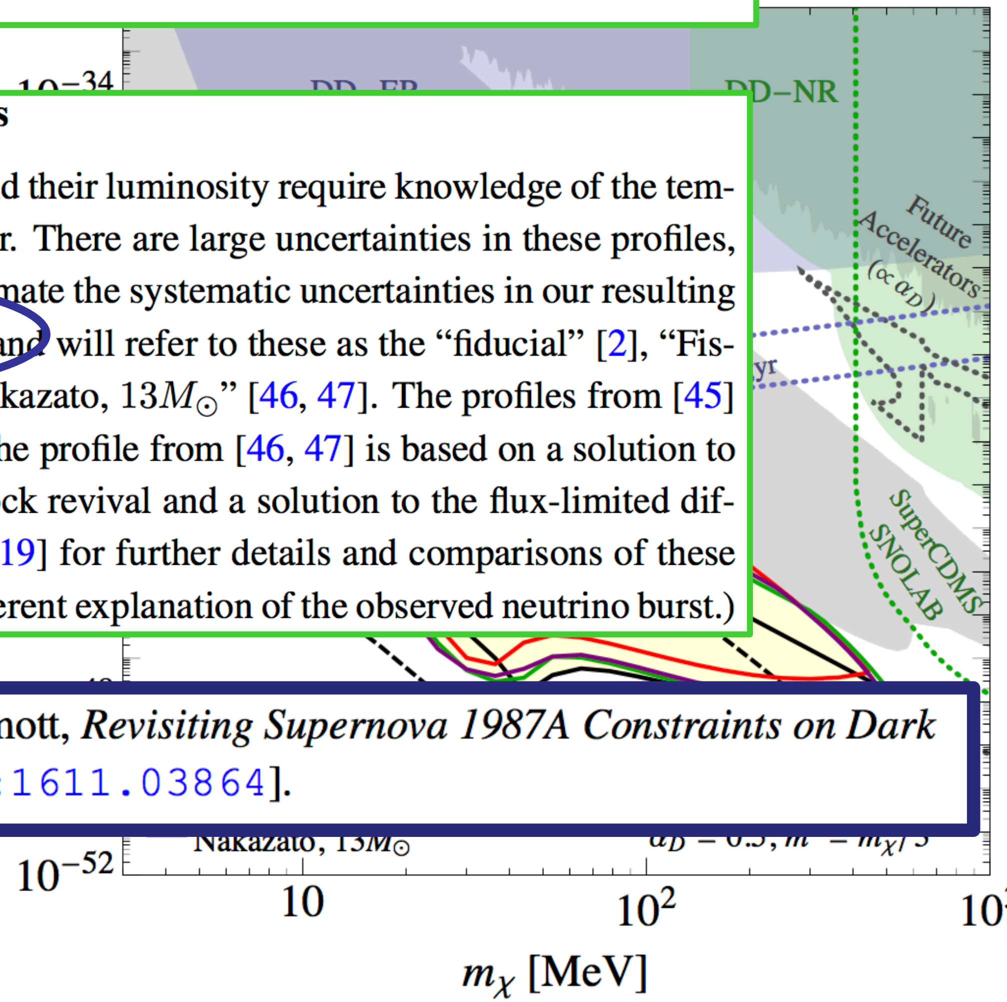

2.6 Supernova Temperature and Density Profiles

The calculations of dark-sector particle production and their luminosity require knowledge of the temperature and density profiles of the proto-neutron star. There are large uncertainties in these profiles, and we thus use four different profiles in order to estimate the systematic uncertainties in our resulting constraints. We choose the same profiles as in [19], and will refer to these as the "fiducial" [2], "Fischer, $11.8M_\odot$" [45], "Fischer, $18M_\odot$" [45], and "Nakazato, $13M_\odot$" [46, 47]. The profiles from [45] use the AGILE-BOLTZTRAN code [48–52], while the profile from [46, 47] is based on a solution to a neutrino radiative hydrodynamical code before shock revival and a solution to the flux-limited diffusion equation after cooling has commenced. See [19] for further details and comparisons of these simulations. (See also [53–55] for a qualitatively different explanation of the observed neutrino burst.)

[19] J. H. Chang, R. Essig, and S. D. McDermott, *Revisiting Supernova 1987A Constraints on Dark Photons*, *JHEP* **01** (2017) 107, [arXiv:1611.03864].

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pg. 9 (of 33):

Our fiducial model, while convenient for analytic purposes, will inevitably mischaracterize the core collapse to some degree. To parameterize the uncertainties arising from the exact nature of the supernova explosion, we will also show bounds using numerical profiles from a variety of different sources [31–33]. The profile from [32, 33] is the 13 solar mass progenitor at $t = 1$ sec post bounce and with a 100 msec shock revival time inserted by hand. This work

?

[19] J. H. Chang, R. Essig, and S. D. McDermott, *Revisiting Supernova 1987A Constraints on Dark Photons*, *JHEP* **01** (2017) 107, [arXiv:1611.03864].

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SUPERNOVA NEUTRINO LIGHT CURVES AND SPECTRA FOR VARIOUS PROGENITOR STARS: FROM CORE COLLAPSE TO PROTO-NEUTRON STAR COOLING

Ken'ichiro Nakazato[1], Kohsuke Sumiyoshi[2], Hideyuki Suzuki[1], Tomonori Totani[3], Hideyuki Umeda[4] and Shoichi Yamada[5,6]

January 10, 2013

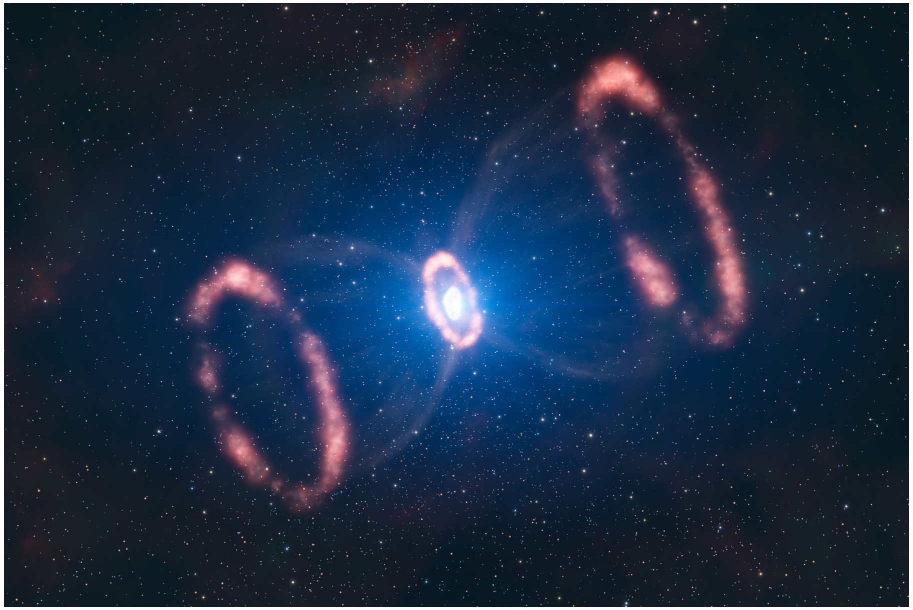
ABSTRACT

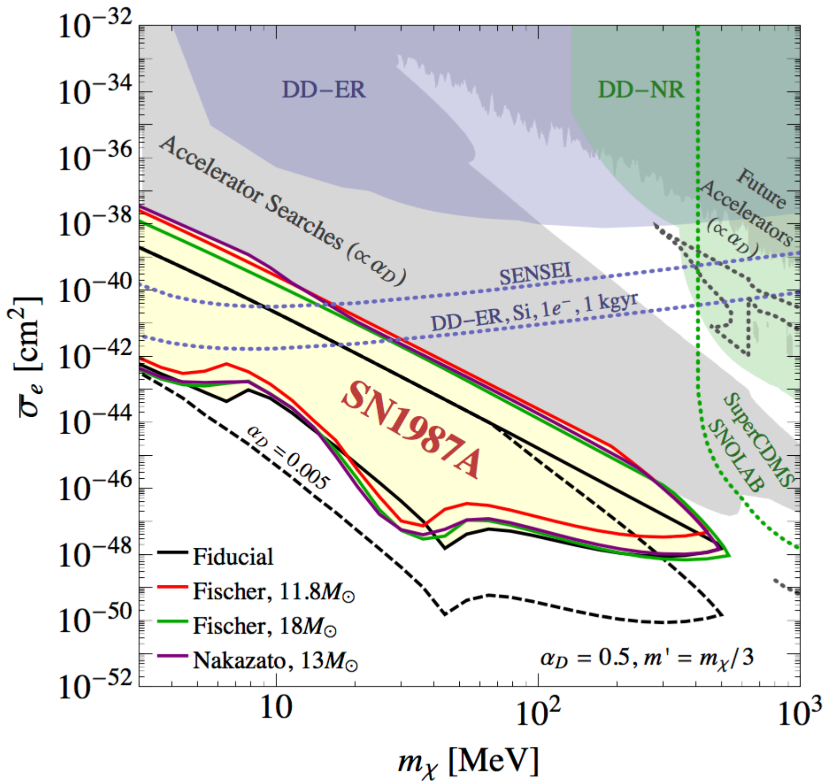
We present a new series of supernova neutrino light curves and spectra calculated by numerical simulations for a variety of progenitor stellar masses ($13\text{-}50 M_\odot$) and metallicities ($Z = 0.02$ and 0.004), which would be useful for a broad range of supernova neutrino studies, e.g., simulations of future neutrino burst detection by underground detectors, or theoretical predictions for the relic supernova neutrino background. To follow the evolution from the onset of collapse to 20 s after the core bounce, we combine the results of neutrino-radiation hydrodynamic simulations for the early phase and quasi-static evolutionary calculations of neutrino diffusion for the late phase, with different values of shock revival time as a parameter that should depend on the still unknown explosion mechanism. We here describe the calculation methods and basic results including the dependence on progenitor models and the shock revival time. The neutrino data are publicly available electronically.

<u>My take:</u>

How CCSNe explode is a fascinating open question.

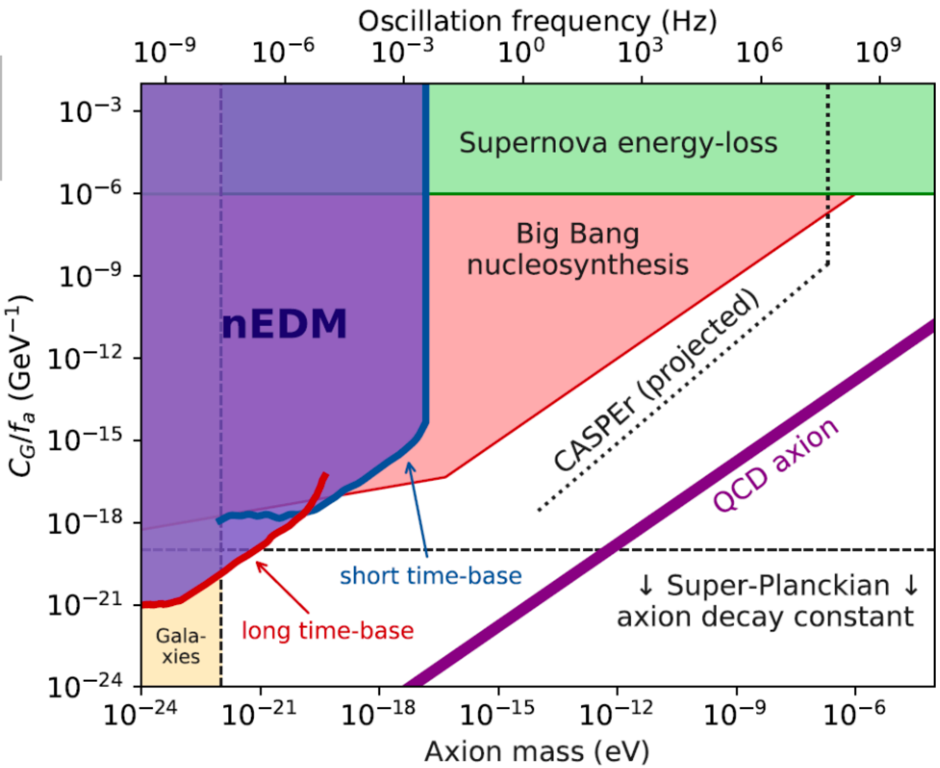
When we know the answer, possibly we'll have a supernova dark photon bound.

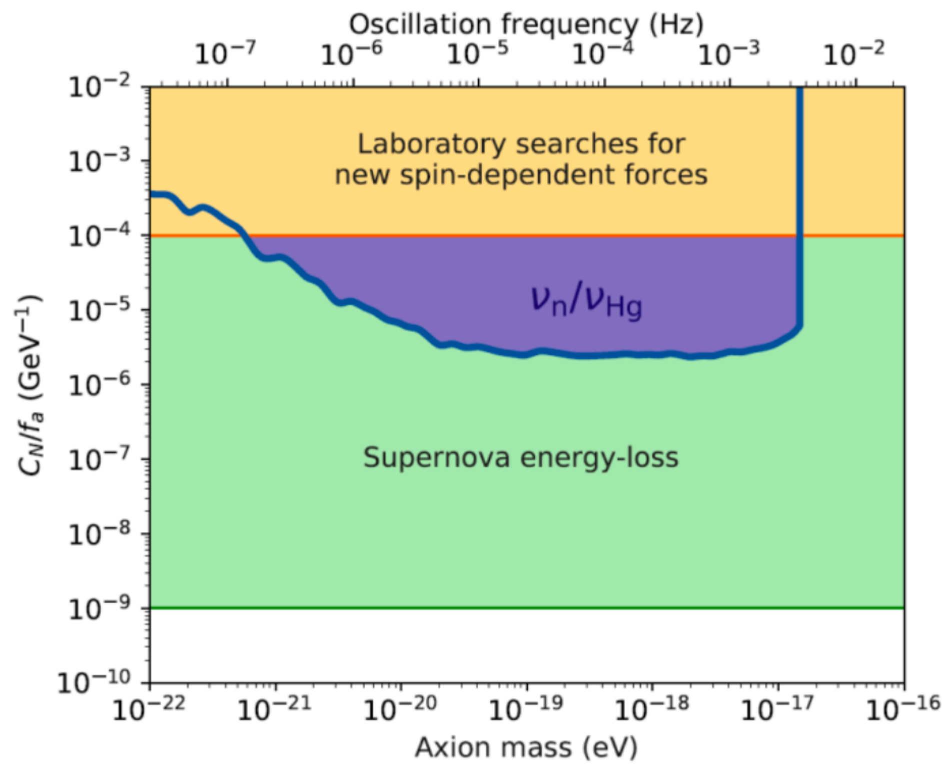




Are we "excluding" axions where they may still exist?

Schmidt-Wellenburg (20/8)



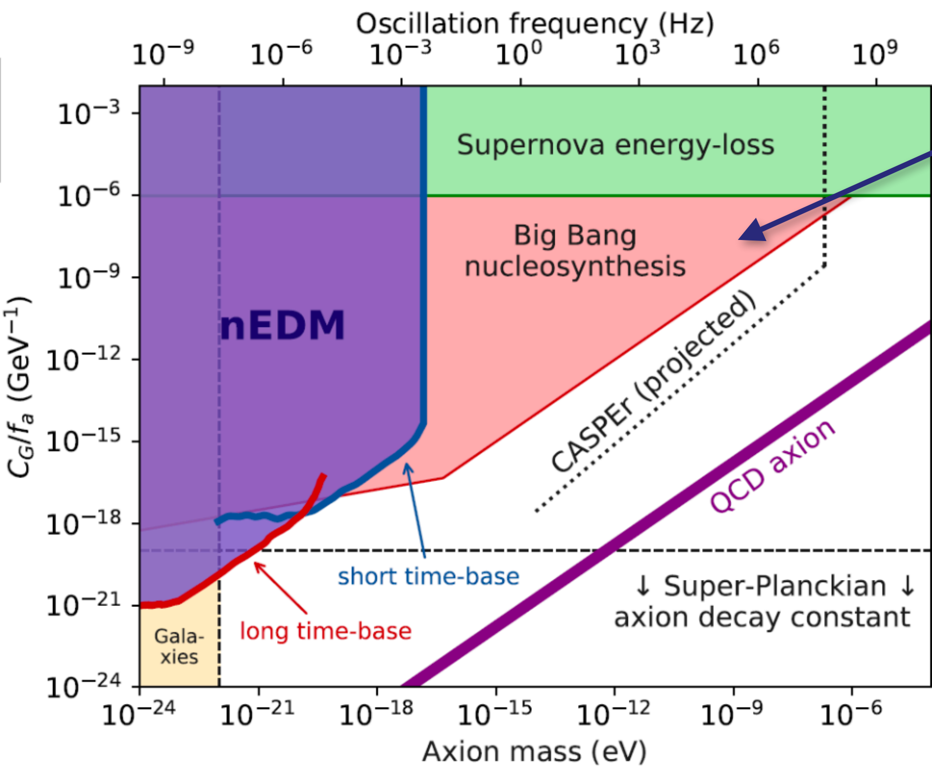


First experimental limits on gluonic coupling

40 times better limit on fermionic coupling

We *do* look for axion(-like?)s where they don't exist.

Schmidt-Wellenburg (20/8)



Phys.Lett. B737 (2014) 30-33

$$\Delta_{mass} \sim \frac{f_a^2\, m_a^2}{f_\pi^2 m_\pi^2} \sim 10^{-14} \left(\frac{f_a\, m_a}{10^{-9}\ \mathrm{GeV}^2} \right)^2$$

First experimental limits
on gluonic coupling

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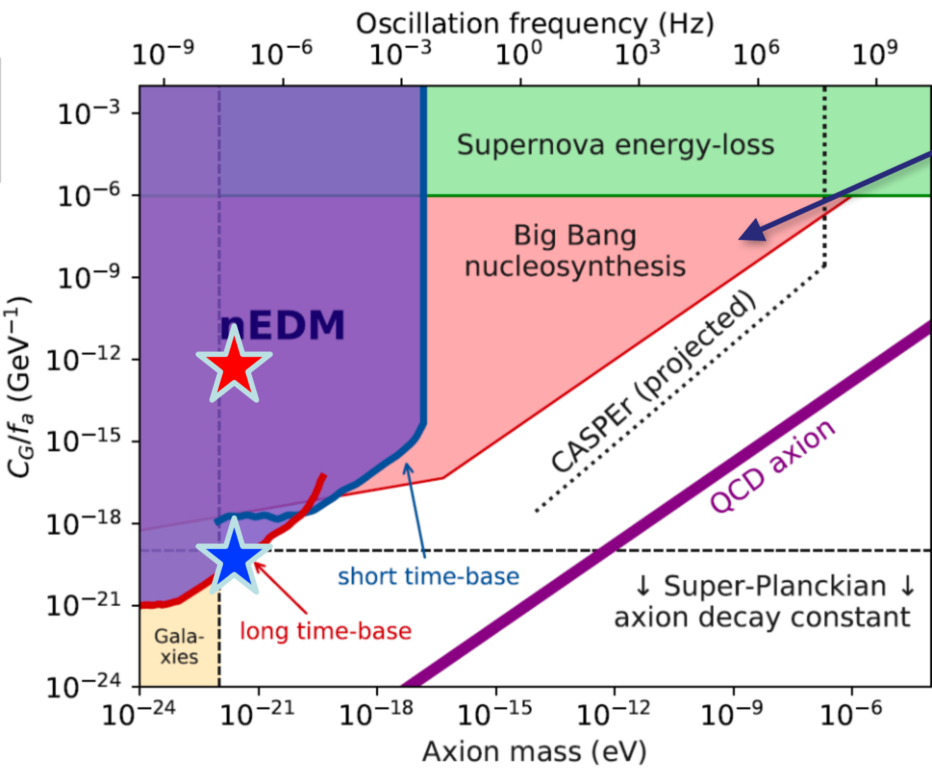

First experimental limits on gluonic coupling

Phys.Lett. B737 (2014) 30-33

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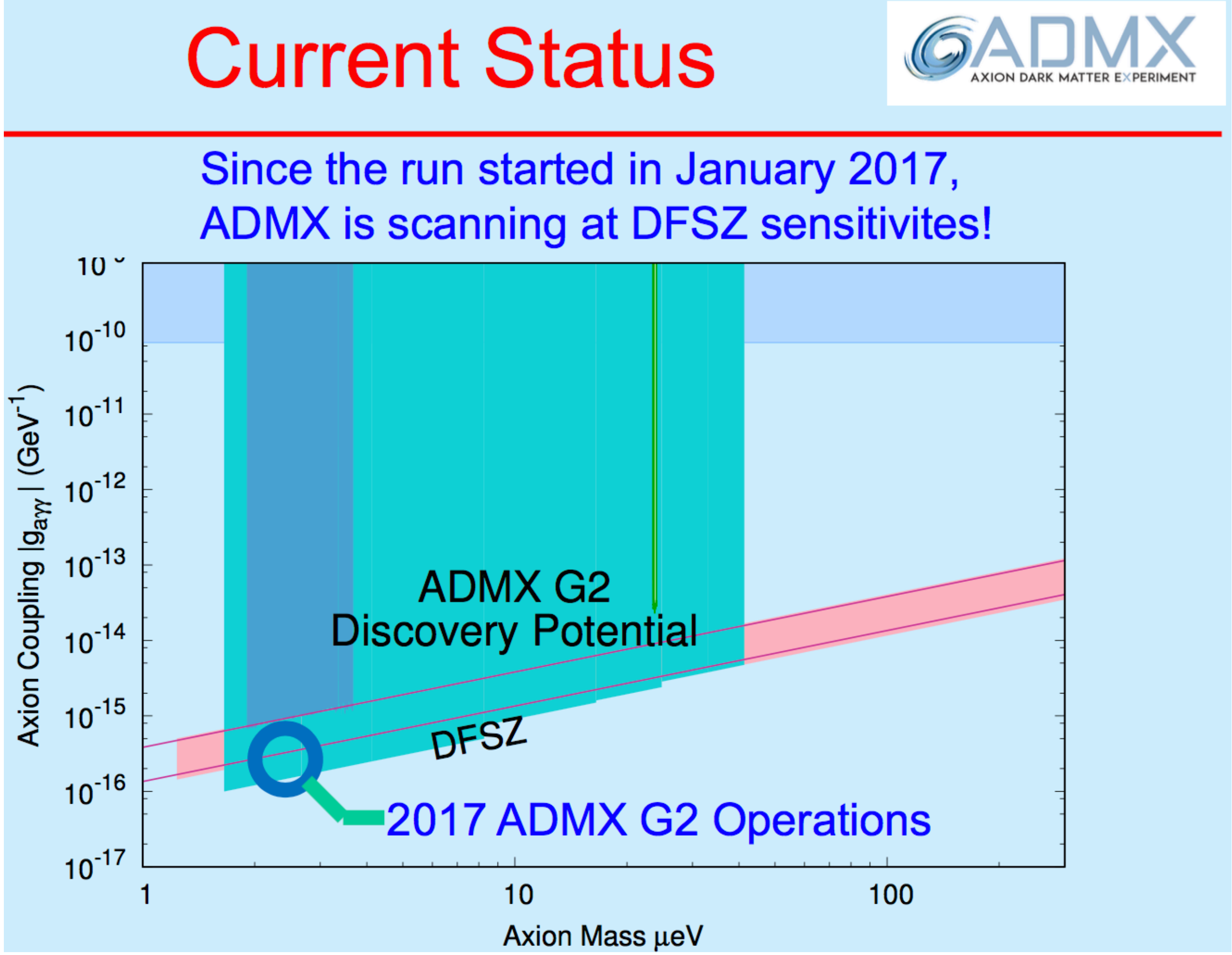
=> putting a state, e.g., here ★ (★) means fine-tuning the mass-squared by ~ 10^-20 (~10^-32)

…without even counting the loss of the solution of the strong CP problem.

Are ADMX (or CASPErII, …) done, when they cover the QCD line?

William Wester (21/8), ADMX

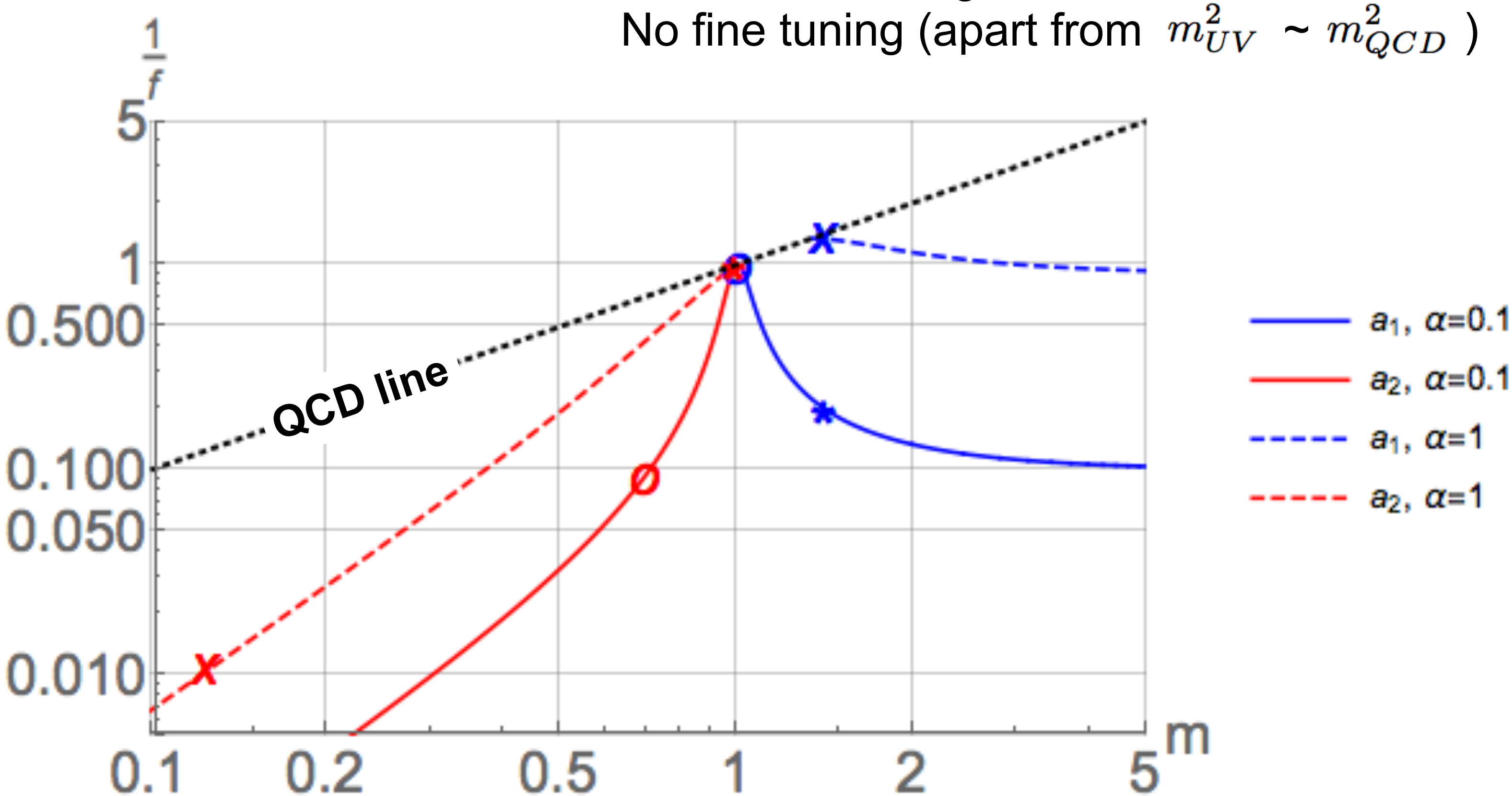


Are ADMX (or CASPErII, …) done, when they cover the QCD line?

What if there are >1 axions?

$$V = \frac{\Lambda_{QCD}^4}{2}\left(\frac{a}{f}+\frac{A}{F}\right)^2 + \frac{\Lambda_{UV}^4}{2}\left(\frac{A}{F}\right)^2$$

Still solves strong CP as before.
No fine tuning (apart from $m_{UV}^2 \sim m_{QCD}^2$)



Are ADMX (or CASPErII, …) done, when they cover the QCD line?

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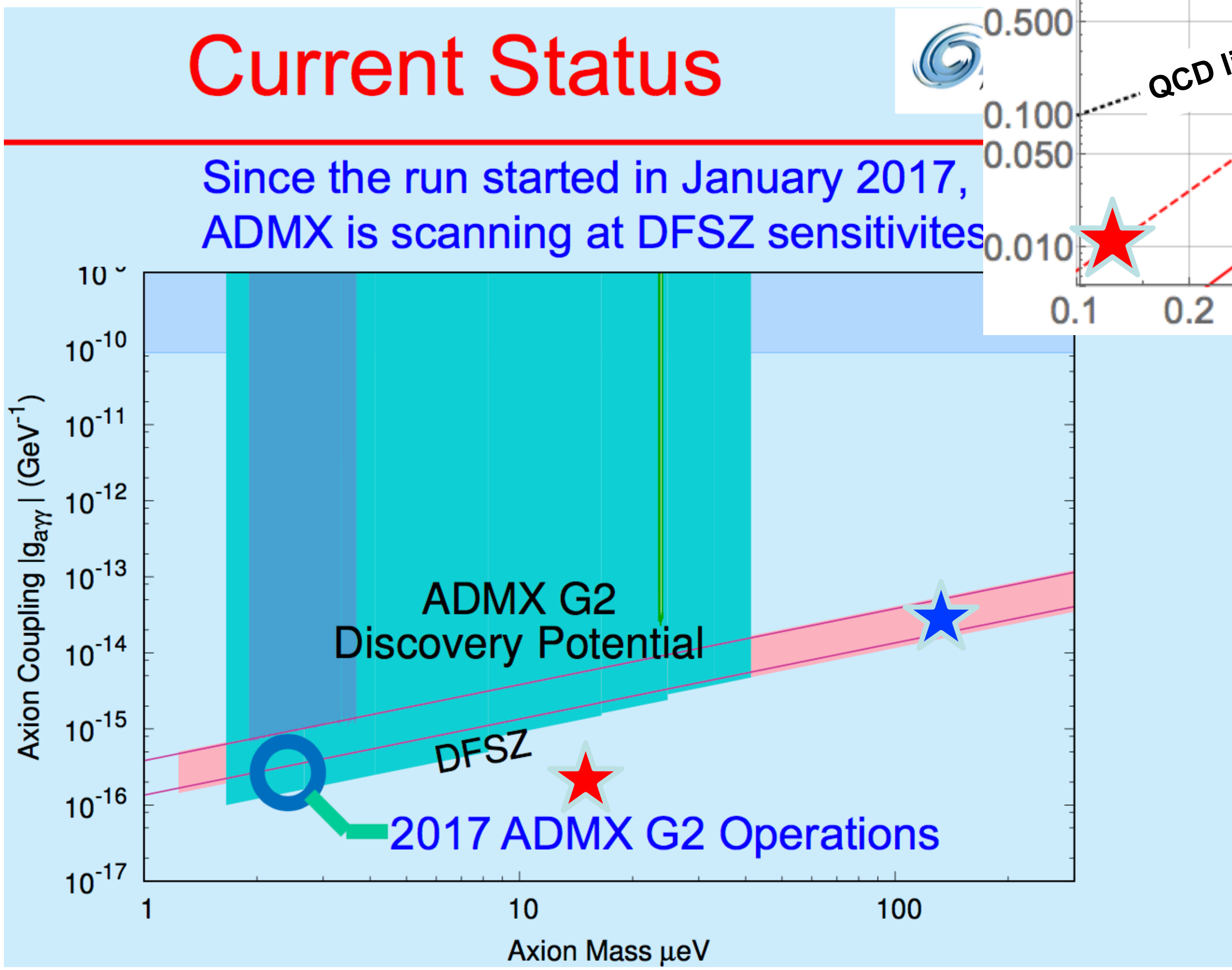
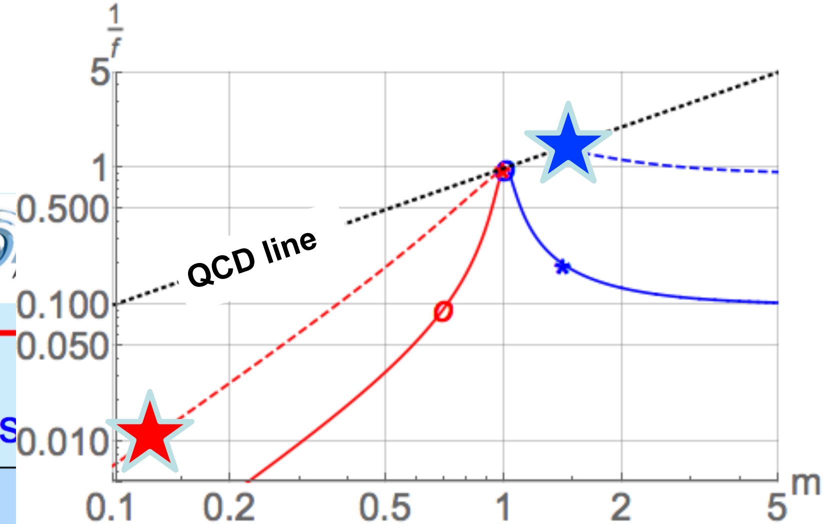




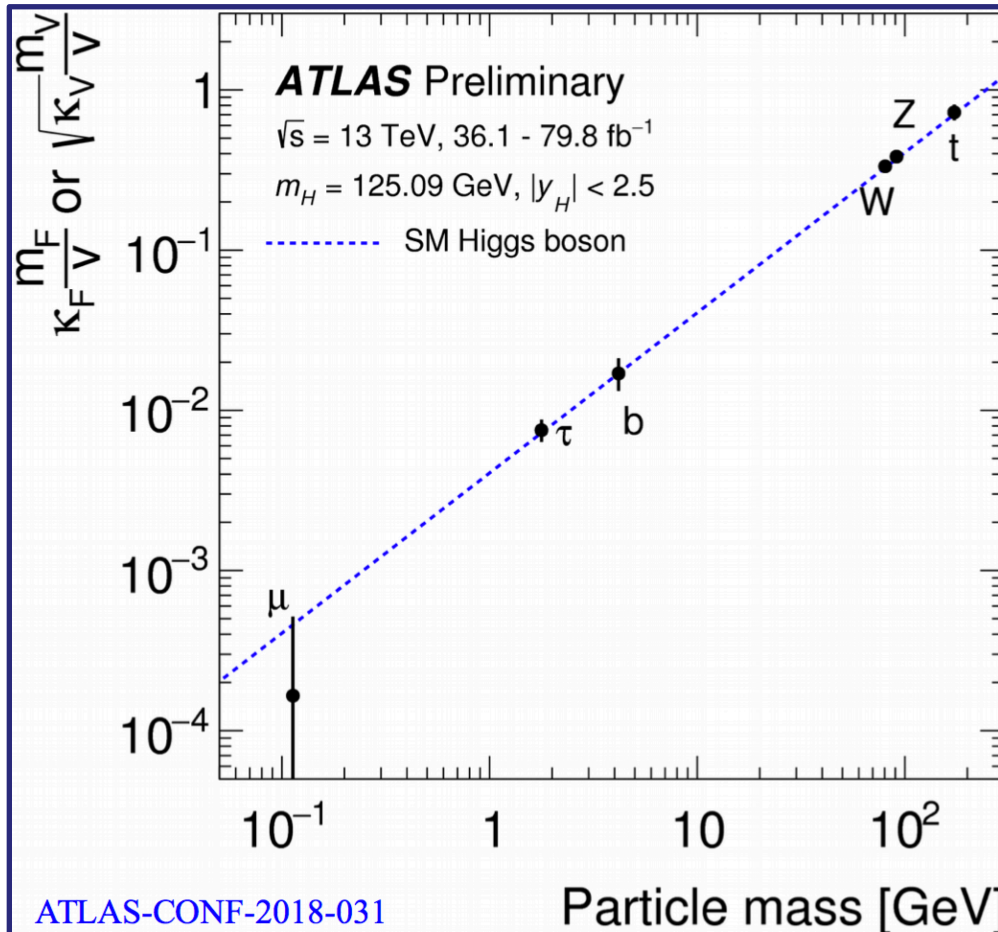
Higgs portal

A. Ritz (20/8)

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

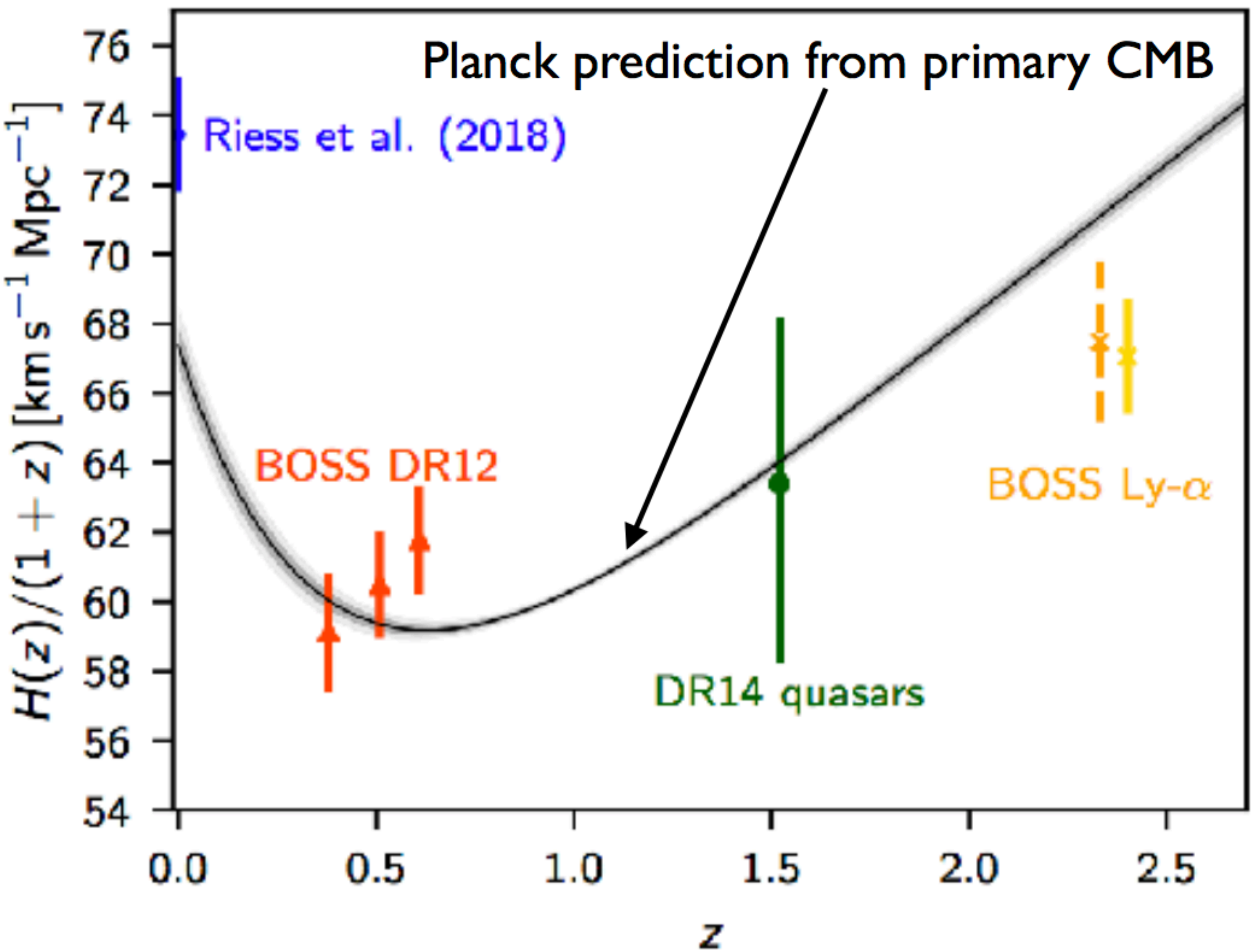
$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

A. Jafari (22/8)



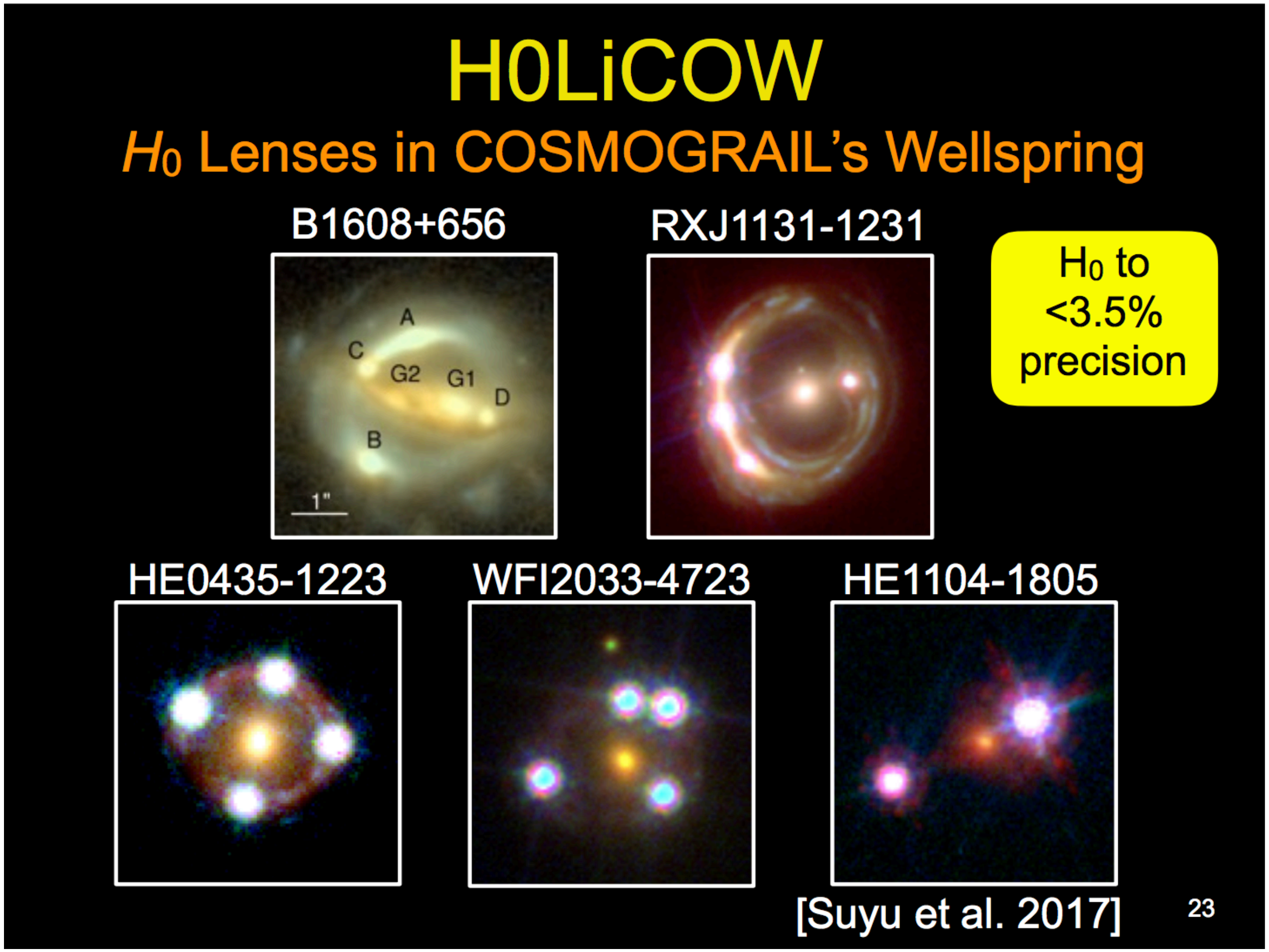
Dark energy

H. Peiris (21/8)



Planck prediction from primary CMB
Riess et al. (2018)
BOSS DR12
DR14 quasars
BOSS Ly-α
$H(z)/(1+z)$ [km s^{-1} Mpc^{-1}]
76
74
72
70
68
66
64
62
60
58
56
54
0.0
0.5
1.0
1.5
2.0
2.5
z

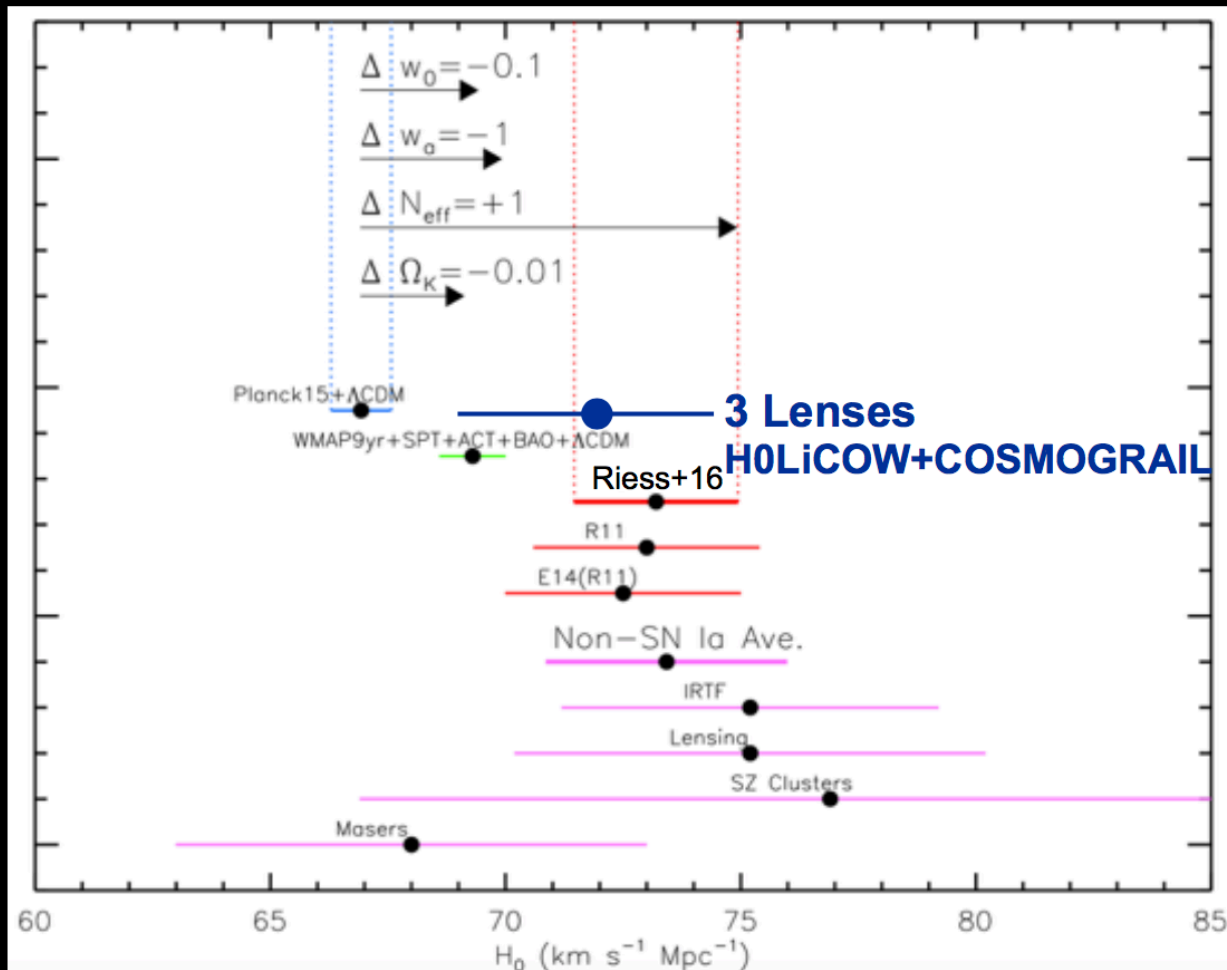
S. Suyu (20/8)



H0LiCOW
H0 Lenses in COSMOGRAIL's Wellspring
B1608+656
A
C
G2
G1
D
B
1"
RXJ1131-1231
H0 to <3.5% precision
HE0435-1223
WFI2033-4723
HE1104-1805
[Suyu et al. 2017]
23

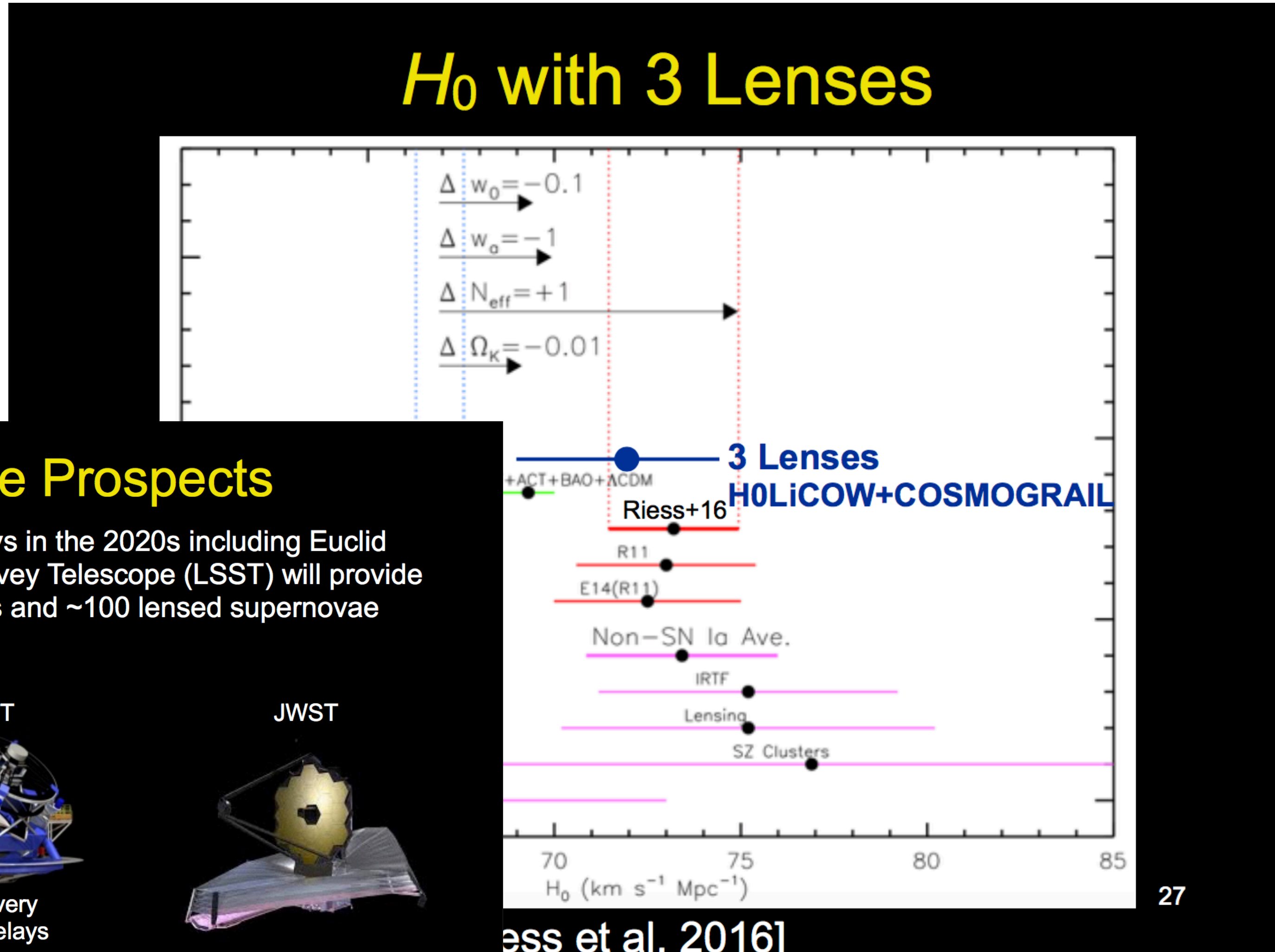
S. Suyu (20/8)

H_0 with 3 Lenses

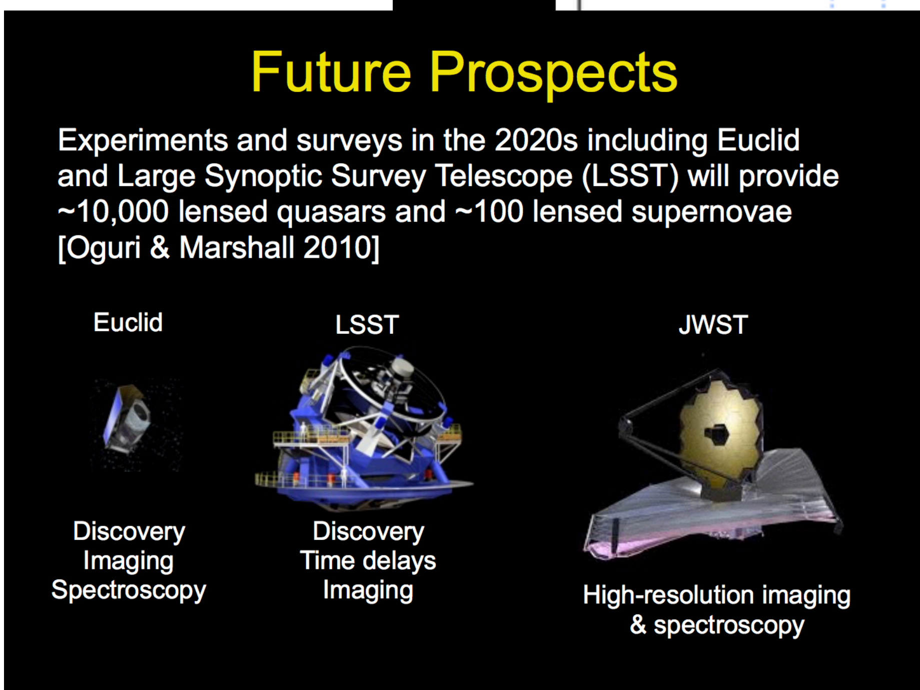


[Riess et al. 2016]

S. Suyu (20/8)



H_0 with 3 Lenses
$\Delta\ w_0 = -0.1$
$\Delta\ w_a = -1$
$\Delta\ N_{eff} = +1$
$\Delta\ \Omega_K = -0.01$
3 Lenses
H0LiCOW+COSMOGRAIL
+ACT+BAO+ΛCDM
Riess+16
R11
E14(R11)
Non−SN Ia Ave.
IRTF
Lensing
SZ Clusters
70
75
80
85
H_0 (km s^{-1} Mpc^{-1})
27
ess et al. 2016]

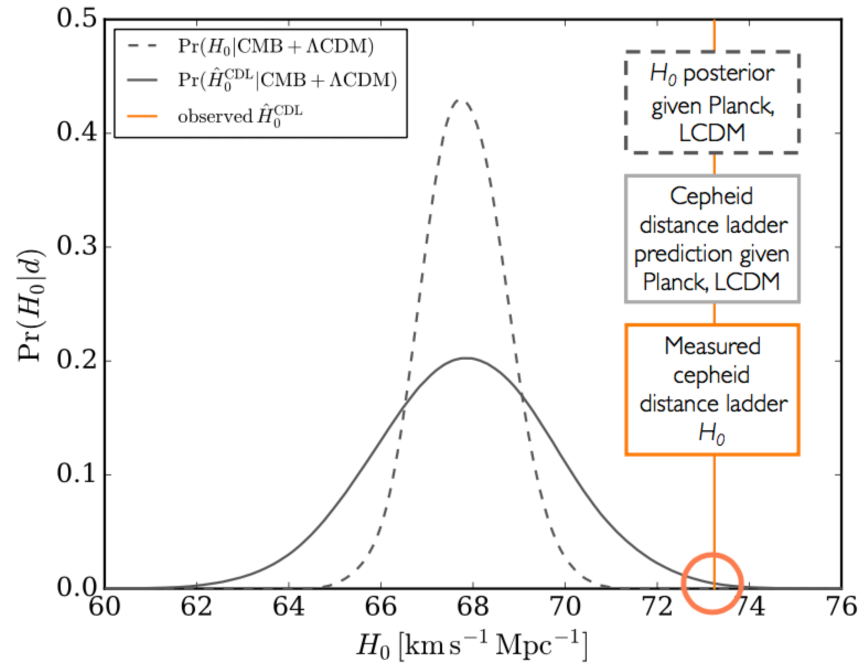


Future Prospects
Experiments and surveys in the 2020s including Euclid and Large Synoptic Survey Telescope (LSST) will provide ~10,000 lensed quasars and ~100 lensed supernovae [Oguri & Marshall 2010]
Euclid
LSST
JWST
Discovery
Imaging
Spectroscopy
Discovery
Time delays
Imaging
High-resolution imaging
& spectroscopy

H. Peiris (21/8)

Quantifying tension with PPD

- Treat Cepheid distance ladder H_0 as data: $\hat{H}_0^{\mathrm{CDL}}$
- PPD: predicted sampling distribution of $\hat{H}_0^{\mathrm{CDL}}$ given Planck CMB data, LCDM
- Is SH_0ES measurement consistent with draw from PPD?
- Summarize tension using PPD(observed H_0) / max(PPD) = **1/45**



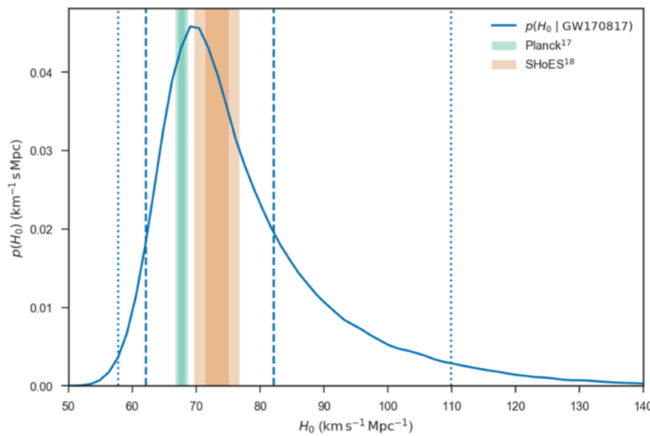
- NB: standard Gaussian 3-sigma threshold corresponds to **1/90**.

Completely independent GW data will arbitrate within a decade.

GWs as a tool to solve a (potentially fundamental) question

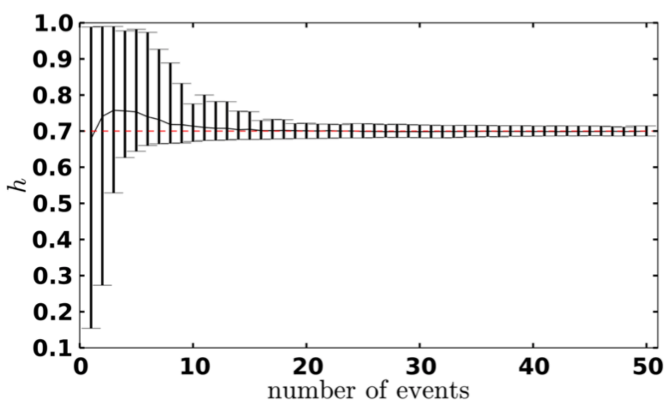
C. Van Den Broeck (20/8)

A new cosmic distance marker



LIGO+Virgo *et al.*, Nature **551**, 85 (2017)

- Measurement of the local expansion of the Universe: The Hubble constant
  - Distance from GW signal
  - Redshift from EM counterpart (galaxy NGC 4993)



Del Pozzo, PRD **86**, 043011 (2012)

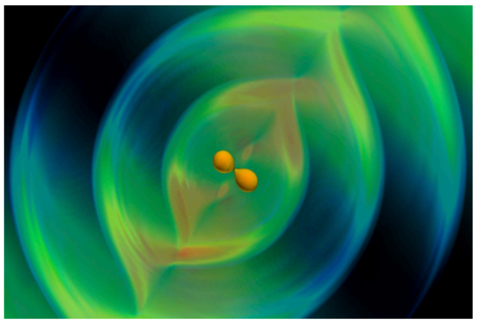
- One detection: limited accuracy
- Few tens of detections: O(1%) accuracy after few tens of detections

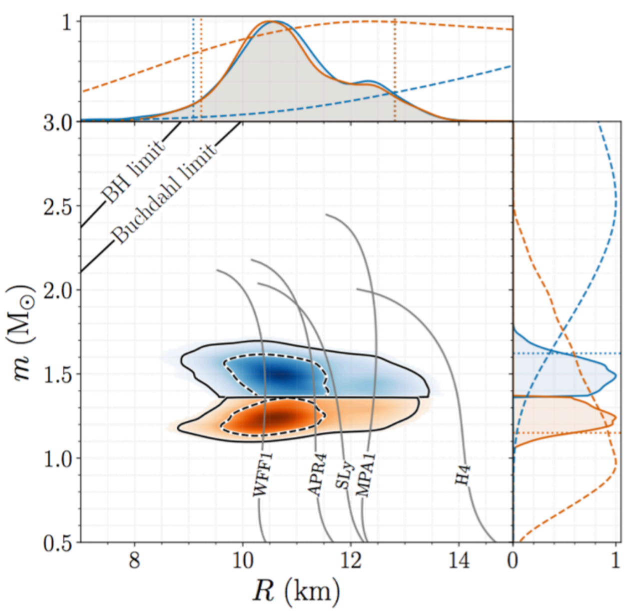
GWs as a tool to solve a decades-old question

Solving core-collapse supernovae <==> understanding EoS

C. Van Den Broeck (20/8)

Probing the structure of neutron stars



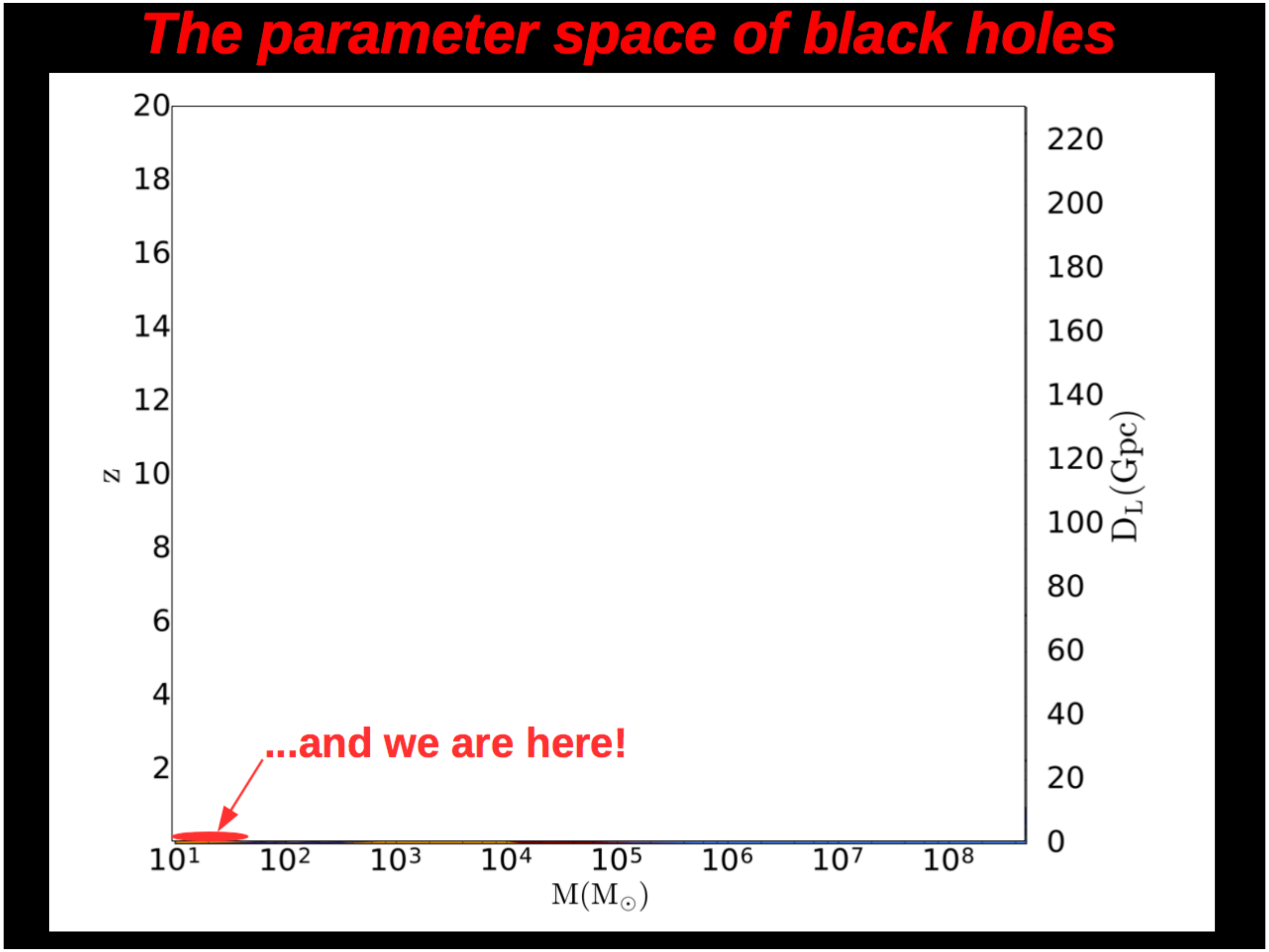


- Gravitational waves from inspiralling binary neutron stars:
  - When close, the stars induce tidal deformations in each other
  - These affect orbital motion
  - Tidal effects imprinted upon gravitational wave signal
  - *Tidal deformability maps directly to neutron star equation of state*
- Measurement of tidal deformations on GW170817
  - Infer mass, radius of the two stars
  - Compact neutron stars favored
  - Some equations of state already eliminated

LIGO+Virgo, arXiv:1805.11579

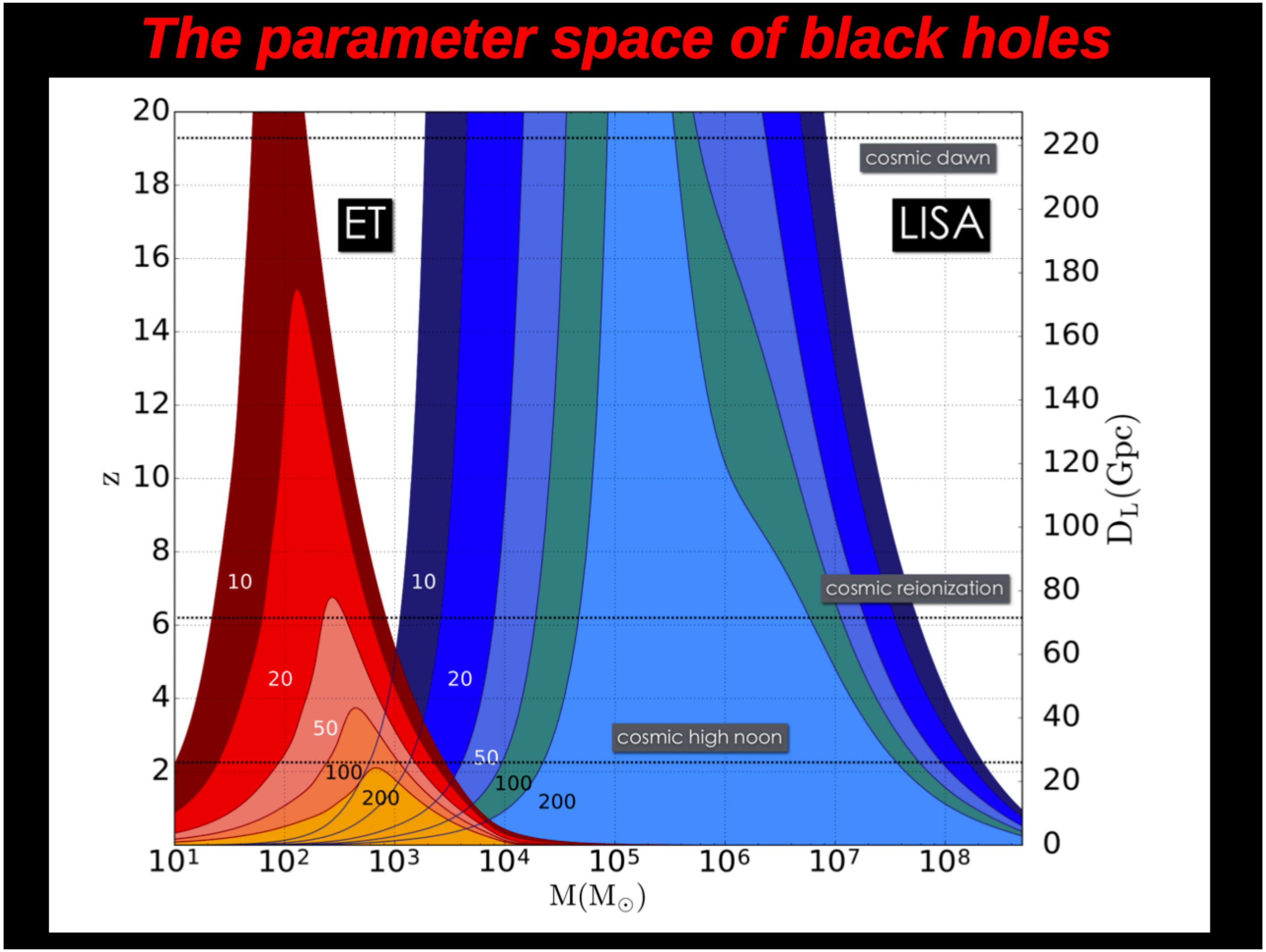
GWs as a door into the unknown

A. Sesana (20/8)



GWs as a door into the unknown

A. Sesana (20/8)



Summary

What is DM?
What is the origin of the baryon asymmetry?
Why is the DM energy density ~ baryon energy density? (and ~ DE density?)
What stabilises the Weak Scale?
What is the origin of neutrino masses?
What solves the strong CP problem?
How do supernovae explode?
When will 30Msol primordial BH DM be excluded?
When will 10^-22eV ultra-(super-fuzzy)-light DM be excluded?
What is the story with keeping the Zurich Guilds running in 2018?

Some of the answers will involve New Physics.
Most of the answers will be unbelievably beautiful and take us to new places.
Some of the answers may be found next year, but some will keep us company for many years.

Summary

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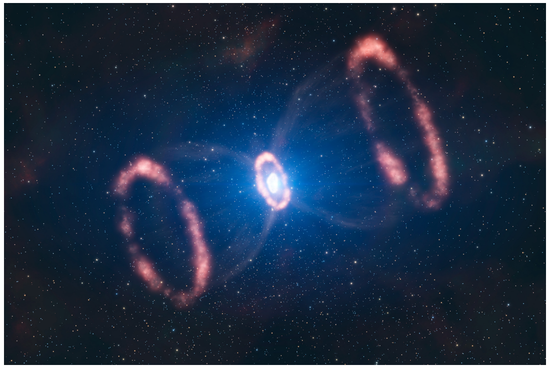
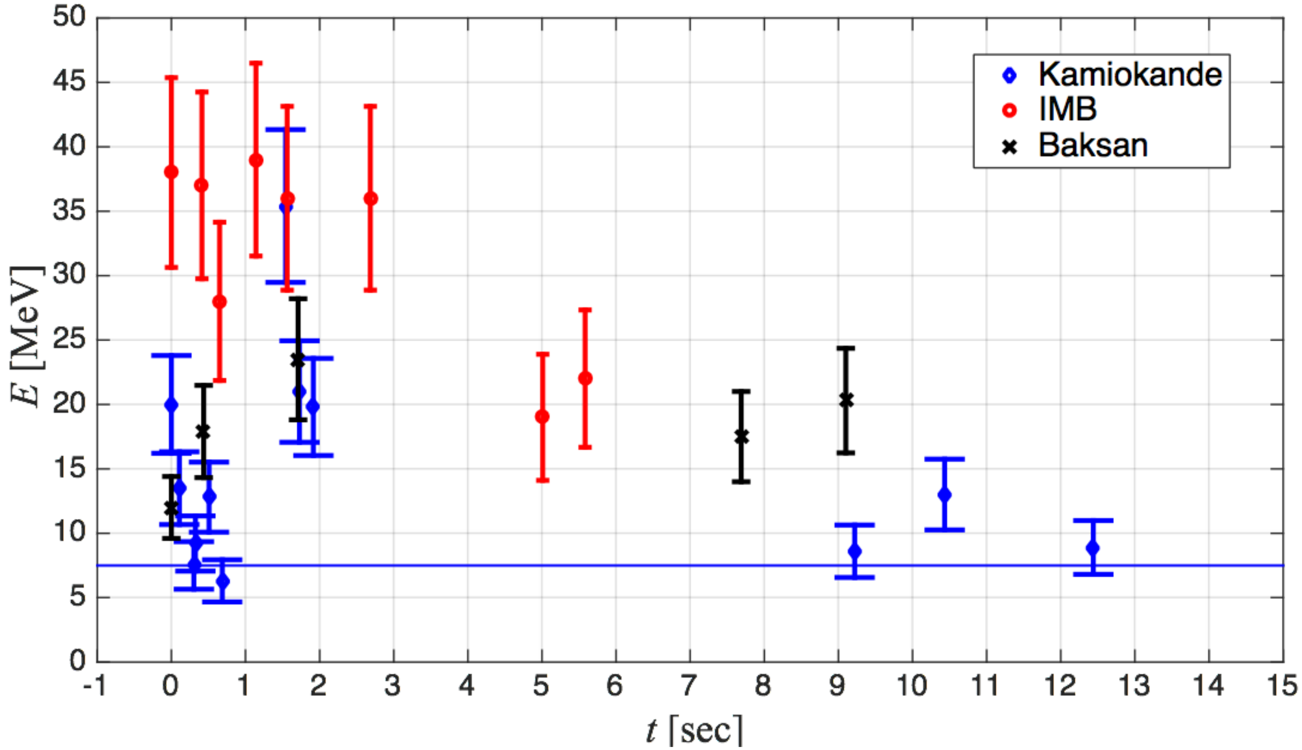
Thanks Zurich PPC2018
for assembling together very interesting presentations, spanning a significant part of our field!

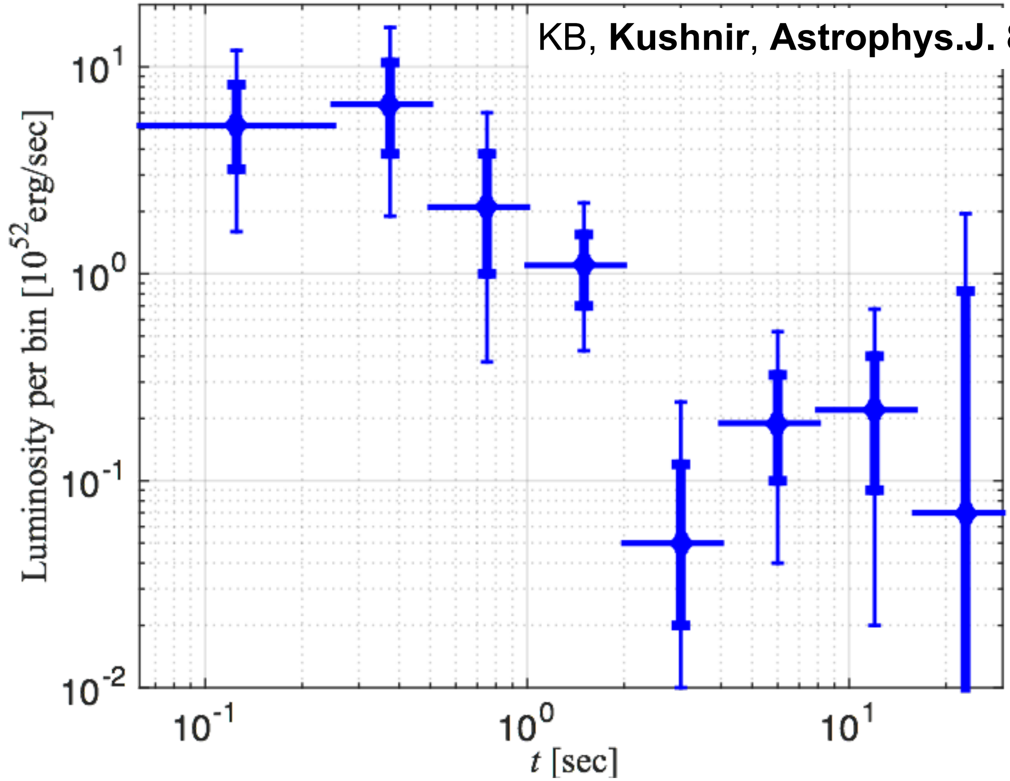
SN1987A

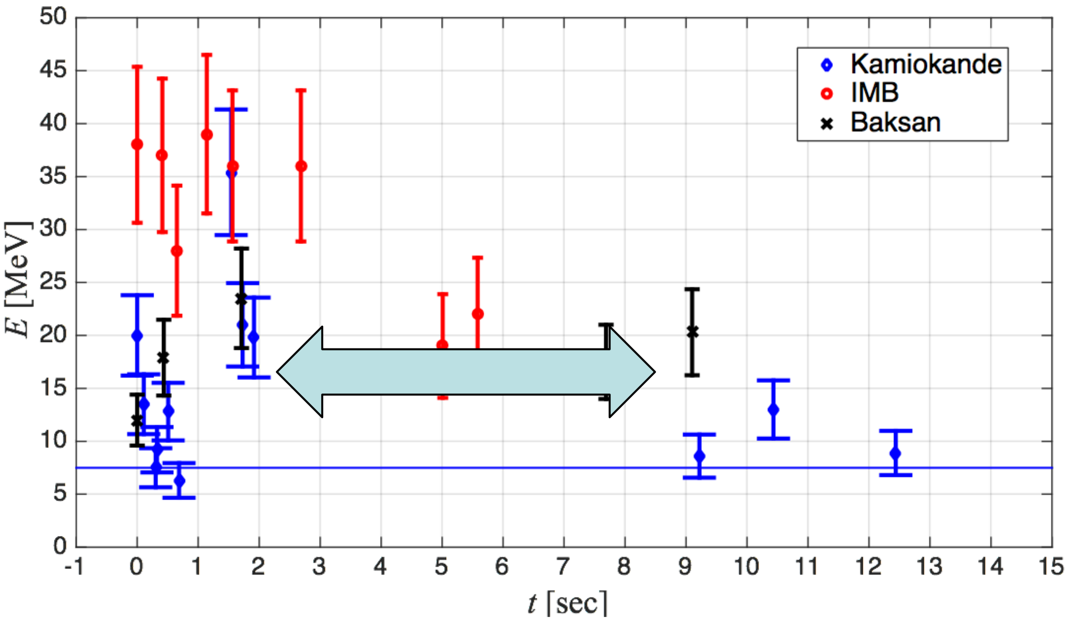


Do we understand CCSNe well enough?



KB, **Kushnir**, **Astrophys.J. 828 (2016) no.1, 31**

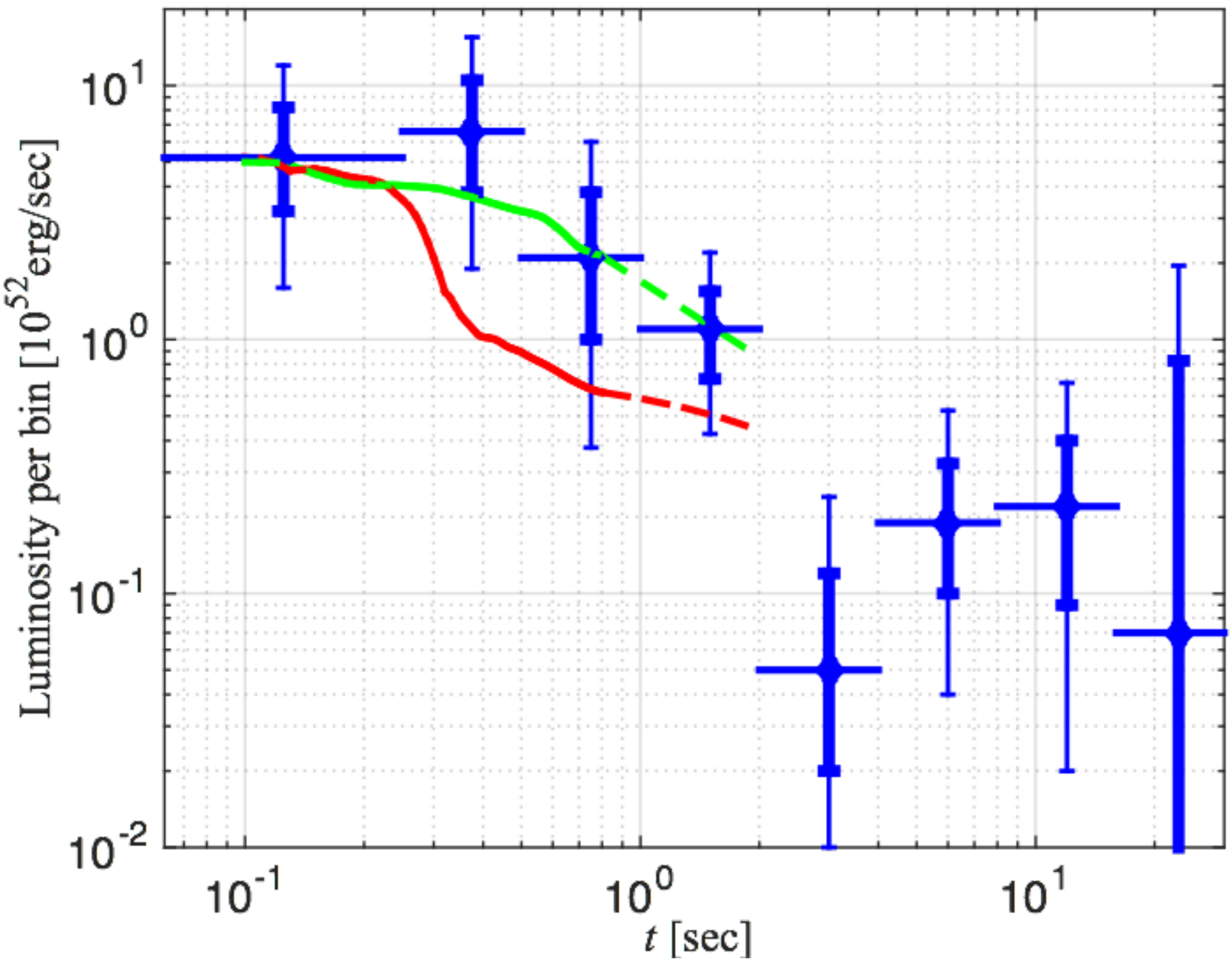




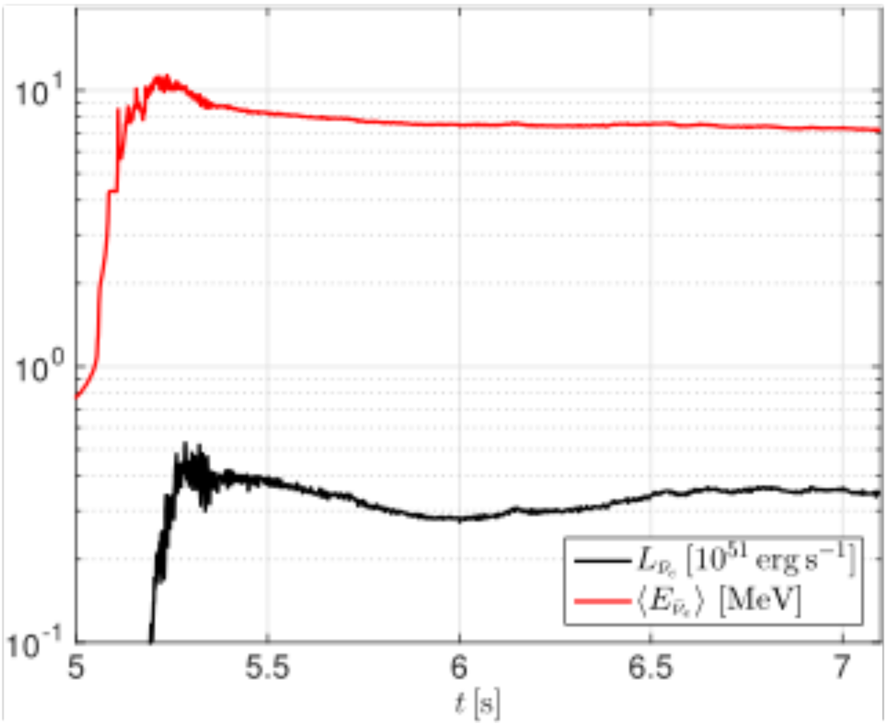
numerical simulations: e.g. Perego et al, **Astrophys.J. 806 (2015) 2, 275** (1D)

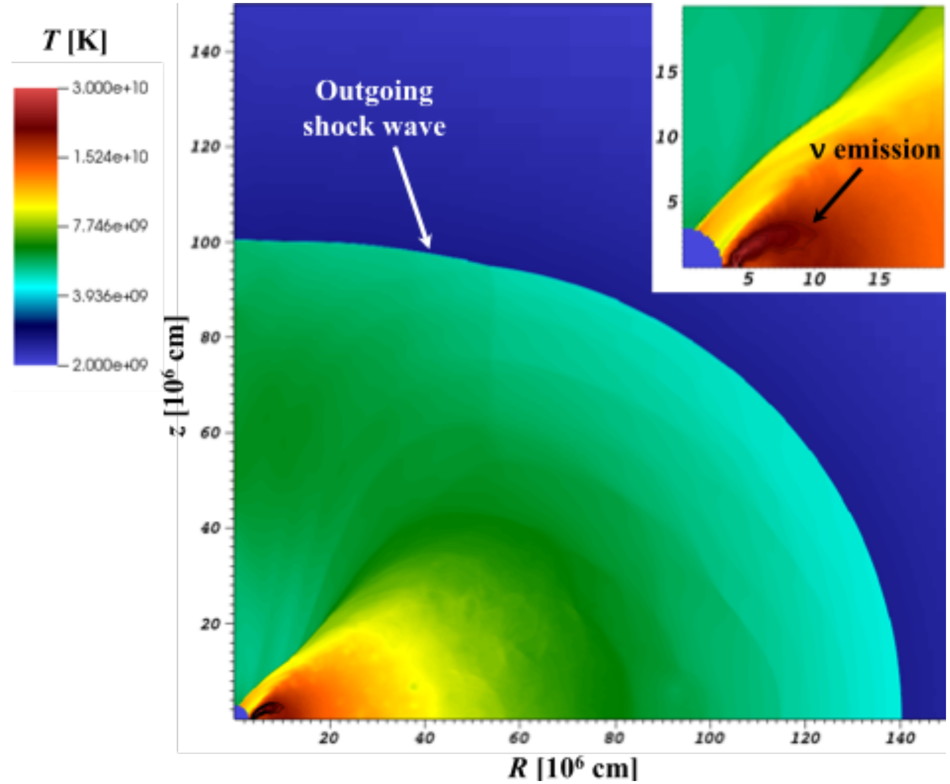
Red: "PUSH"
Green: "No PUSH"

➔ early phase <1-2 sec can't tell NM vs. Late explosion



KB, **Kushnir**, **Astrophys.J. 828 (2016) no.1, 31**





<u>Collapse-induced thermonuclear explosion **(CITE)**</u>:
Kushnir, 1506.02655
Kushnir, 1502.03111
Kushnir & Katz, ApJ. 811 (2015) no.2, 97
Burbidge et al, Rev. Mod. Phys. 29, 547 (**1957**)
Hoyle & Fowler, ApJ 132, 565 (**1960**)
Fowler & Hoyle, ApJS 9, 201 (**1964**)

Ultra-light DM:

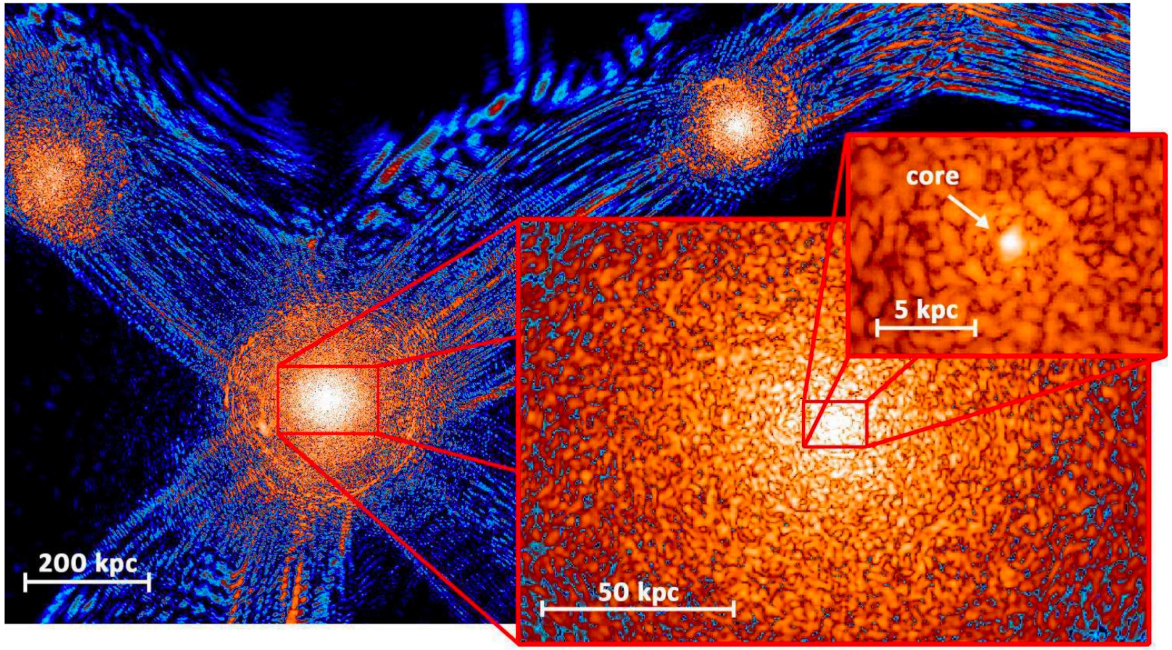
In the last ~five years, numerical structure formation simulations with ULDM have become available.

Schive 1406.6586, Schive 1407.7762, Mocz 1705.05845, Veltmaat 1804.09647, Levkov 1804.05857 (partial list…)

The inner part of simulated galaxies forms a core: "soliton".

Simulations have discovered a scaling relation, connecting the core to the host halo.

Schive 1406.6586, Schive 1407.7762, Veltmaat 1804.09647



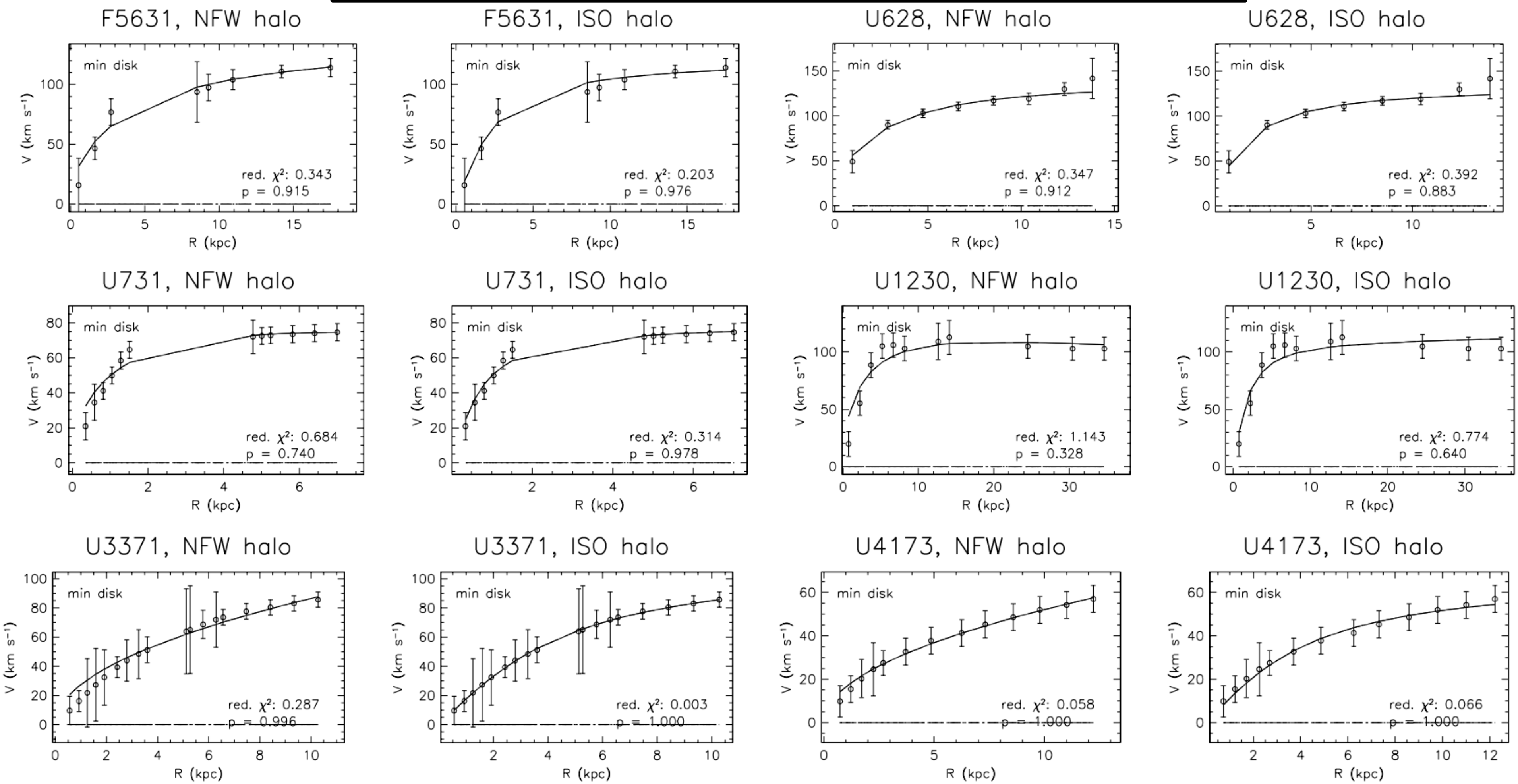
Schive 1406.6586

A&A 385, 816–846 (2002)
DOI: 10.1051/0004-6361:20020080

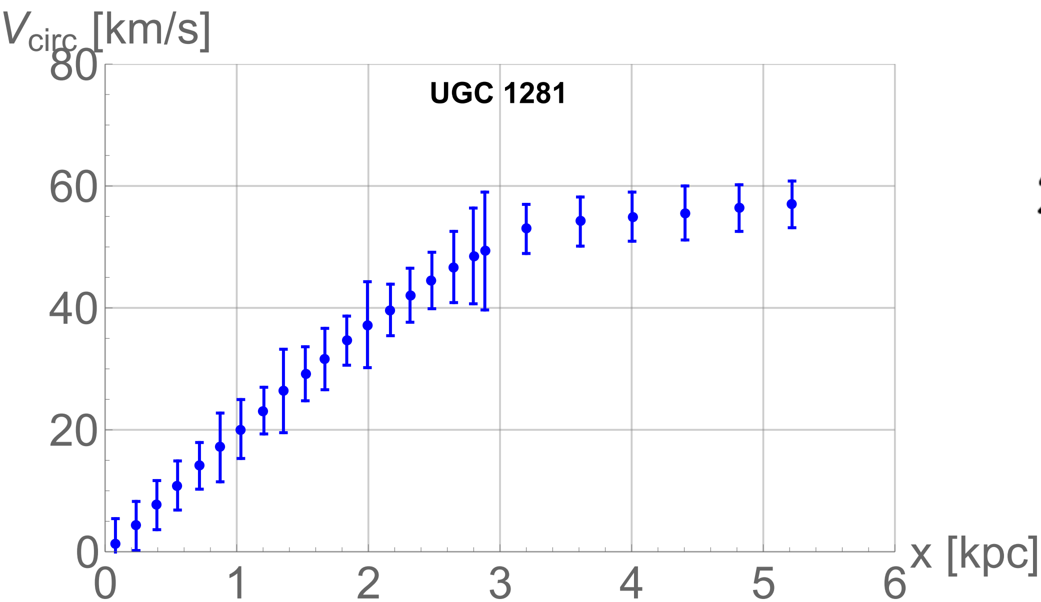
Astronomy & Astrophysics

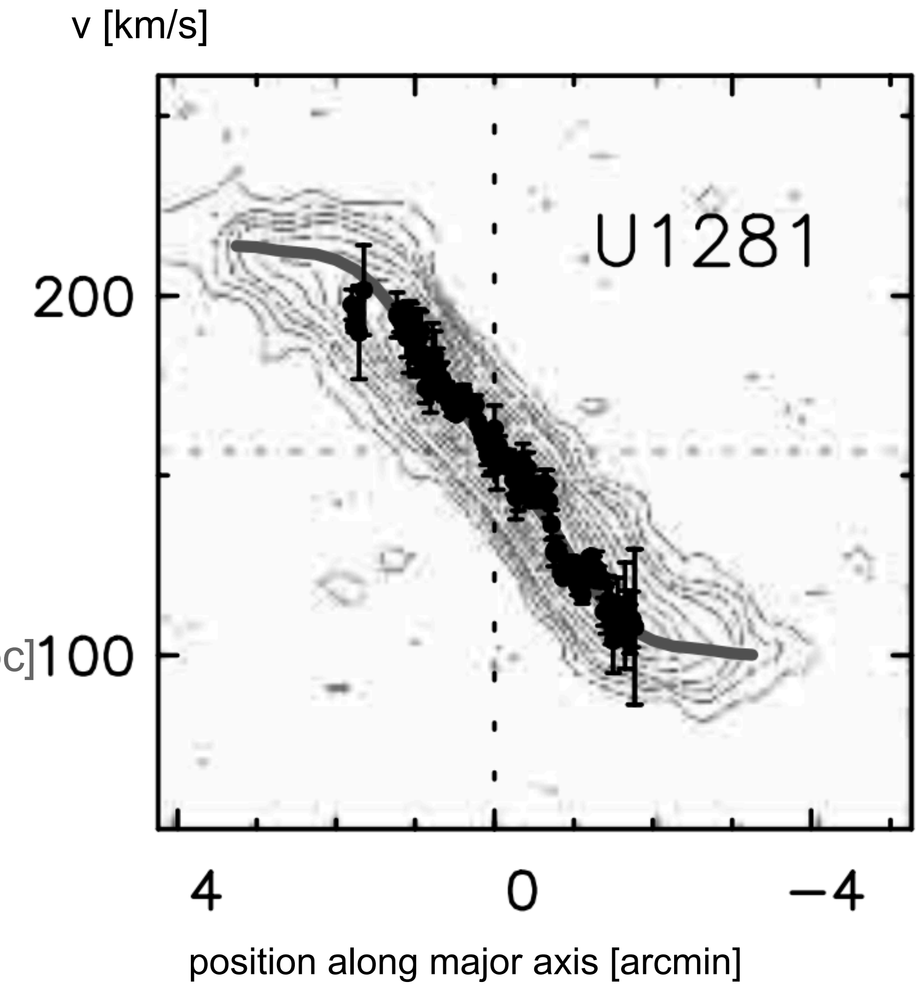
High-resolution rotation curves of low surface brightness galaxies*

W. J. G. de Blok[1] and A. Bosma[2]



Bosma & de Block 2002
HI+Halpha





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