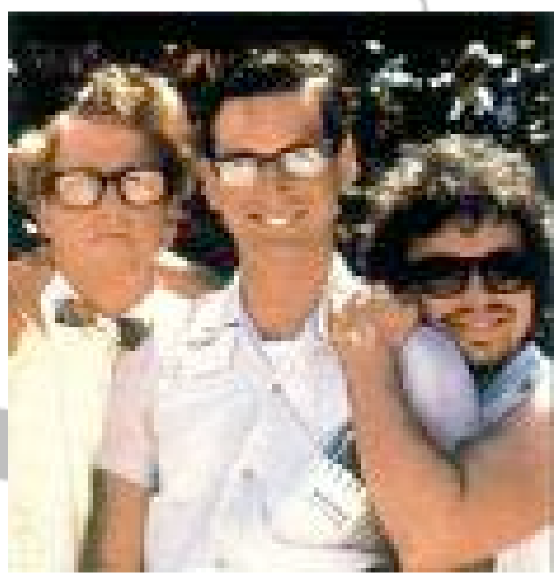
WIMP Dark Matter

Christopher Rogan

Ph135c - 04/27/07

What is a WIMP?

A.

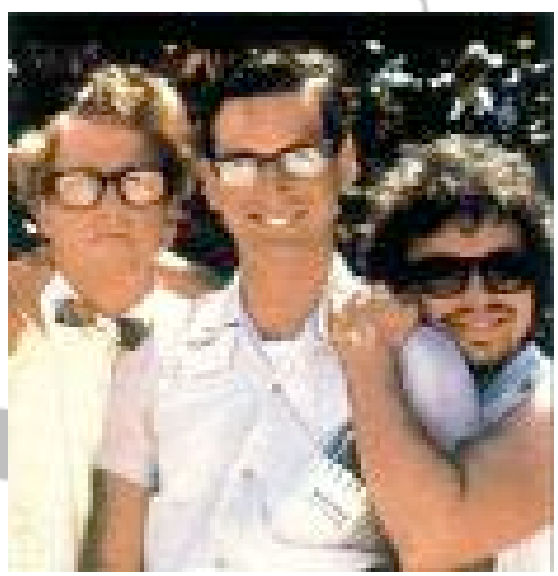


B.

C. Weakly interacting massive particle

What is a WIMP?

A.



B.

C. Weakly interacting massive particle

Evidence for CDM

- See Matt’s talk from 04/24/07
- In a nutshell, estimated that ~25% of critical density must be nonrelativistic nonbaryonic matter
- => *Cold Dark Matter*

WIMP candidates

- Many theories for physics beyond the Standard Model feature stable lightest particles (KK neutrinos, gravitinos, neutralinos)

- Often potential WIMP CDM candidates

Example: MSSM

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0\ H^0\ A^0\ H^\pm$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	" "
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	" "
			$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$	$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
charginos	1/2	-1	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
gluino	1/2	-1	$\widetilde{g}$	" "
gravitino/ goldstino	3/2	-1	$\widetilde{G}$	" "

WIMPs in early universe

Early hot universe, WIMPs effectively mass-less, in thermal equilibrium with SM particles

$$T >> m_\chi$$

$$\chi\chi \leftrightarrow l\bar{l}$$

WIMPs go to SM particles and vice-versa

$$l = (e^{\pm}, \mu^{\pm}, \tau^{\pm}, u, d, s, c, b, t, W^{\pm}, Z^0)$$

$$\Gamma_{\chi\chi\rightarrow l\bar{l}} = \langle \sigma_{\chi\chi\rightarrow l\bar{l}} |v| \rangle n_\chi$$

$$\sigma_{ann} \equiv \sigma_{\chi\chi\rightarrow l\bar{l}}$$

WIMPs in early universe

Satisfy Boltzman equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{ann}|v| \rangle [n_{chi}^2 - (n_\chi^{eq})^2]$$

Expansion rate $H = 1.66 g_*^{1/2} T^2 / m_{pl}$

Actual number density n_χ

Thermal equilibrium number density @ *T* n_χ^{eq}

WIMPs in early universe

In hot universe $\Gamma \geq H$

As the universe expands, temperature drops, and eventually (about when $T \leq m_\chi$) $H(T_f) = \Gamma(T_F)$, or:

$$1.66 g_*^{1/2} \frac{T_f^2}{m_{pl}} = g \left(\frac{m_\chi T_f}{2\pi} \right)^{3/2} e^{-m_\chi / T_f} \langle \sigma_{ann} |v| \rangle$$

Freeze-out! Thermal bath of particles becomes nearly transparent to WIMPs. Ratio of number density to entropy density remains constant.

WIMPs in early universe

What we find is:

$$T_f \approx m_\chi/20$$

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{(\rho_c/h^2)} \approx \left(\frac{\langle\sigma_{ann}|v|\rangle}{2.5\times10^{-10}\ GeV^{-2}}\right)^{-1}$$

WIMPs in early universe

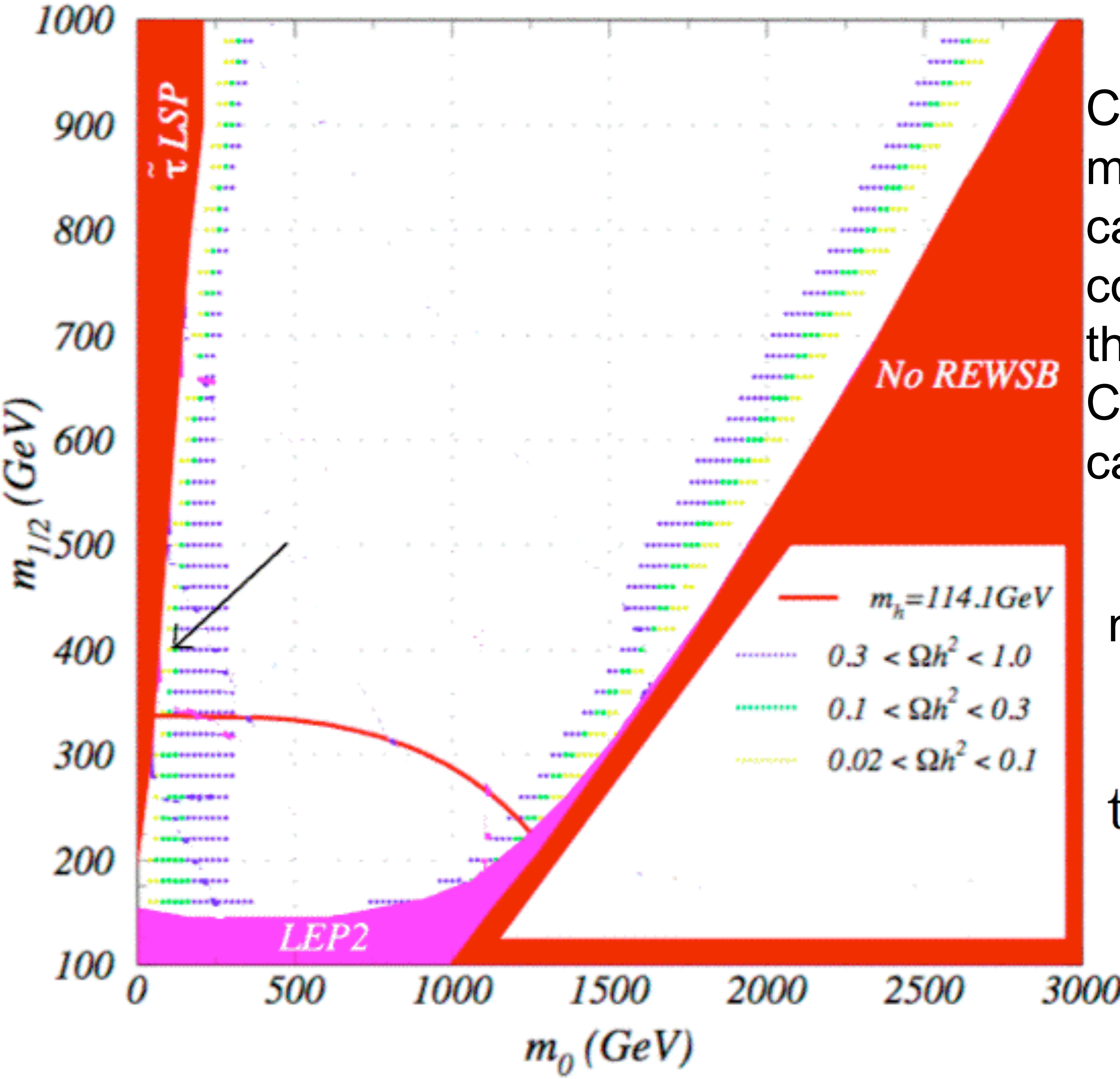
Hence very interesting results:

- WIMPs are well within non-relativistic regime

- A value of the relic density corresponding to that expected for CDM implies an annihilation cross section on the order of the weak interaction

$$\Omega_\chi h^2 \approx 0.1 \rightarrow \langle \sigma_{ann} |v| \rangle \approx \alpha^2/(100\ GeV)^2$$

- New physics at electroweak scale with stable neutral particle => CDM WIMP candidate



CMB measurements can be used to constrain theories with CDM candidates

mSUGRA with

$$A_0 = 0$$

$$\tan\beta = 10$$

$$\mu = 1$$

WIMP CDM Direct Detection

- Look for nuclear recoils in terrestrial detectors
- Rates depend on local halo density, velocity distribution in Milky Way, the WIMP mass, and the cross section on the target nuclei

Techniques for dark matter direct detection

TYPE	DISCRIMINATION TECHNIQUE	TYPICAL EXPERIMENT	ADVANTAGE
Ionization	None (Ultra Low BG)	MAJORANA, GERDA	Searches for ββ-decay, dm additional
Solid Scintillator	pulse shape discrimination	LIBRA/DAMA, NAIAD	low threshold, large mass, but poor discrim
Cryogenic	charge/phonon light/phonon	CDMS, CRESST EDELWEISS	demonstrated bkg discrim., low threshold, but smaller mass/higher cost
Liquid noble gas	light pulse shape discrimination, and/or charge/light	ArDM, LUX, WARP, XENON, XMASS, XMASS-DM, ZEPLIN	large mass, good bkg discrimination
Bubble chamber	super-heated bubbles/ droplets	COUPP, PICASSO	large mass, good bkg discrimination
Gas detector	ionization track resolved	DRIFT	directional sensitivity, good discrimination

R.J. Gaitskell, Ann. Rev. Nucl. Par. Sci, 54 (2004) 315

XENON Event Discrimination: Electron or Nuclear Recoil?

Within the xenon target:

- **Neutrons, WIMPs => Slow nuclear recoils => strong columnar recombination**

=> Primary Scintillation (S1) preserved, but Ionization (S2) strongly suppressed

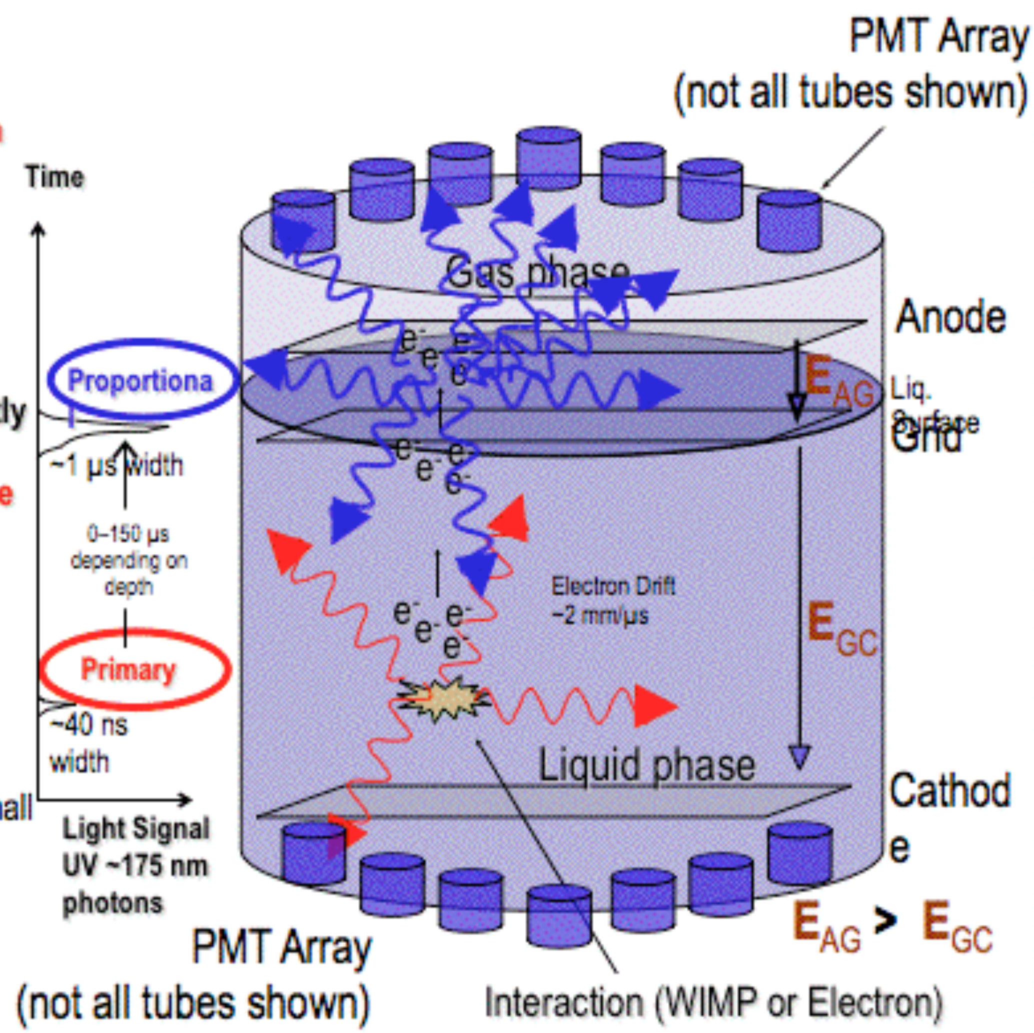
- **γ, e-, μ, (etc) => Fast electron recoils =>**

=> Weaker S1, Stronger S2

Ionization signal from nuclear recoil too small to be directly detected => extract charges from liquid to gas and detect much larger proportional scintillation signal => dual phase

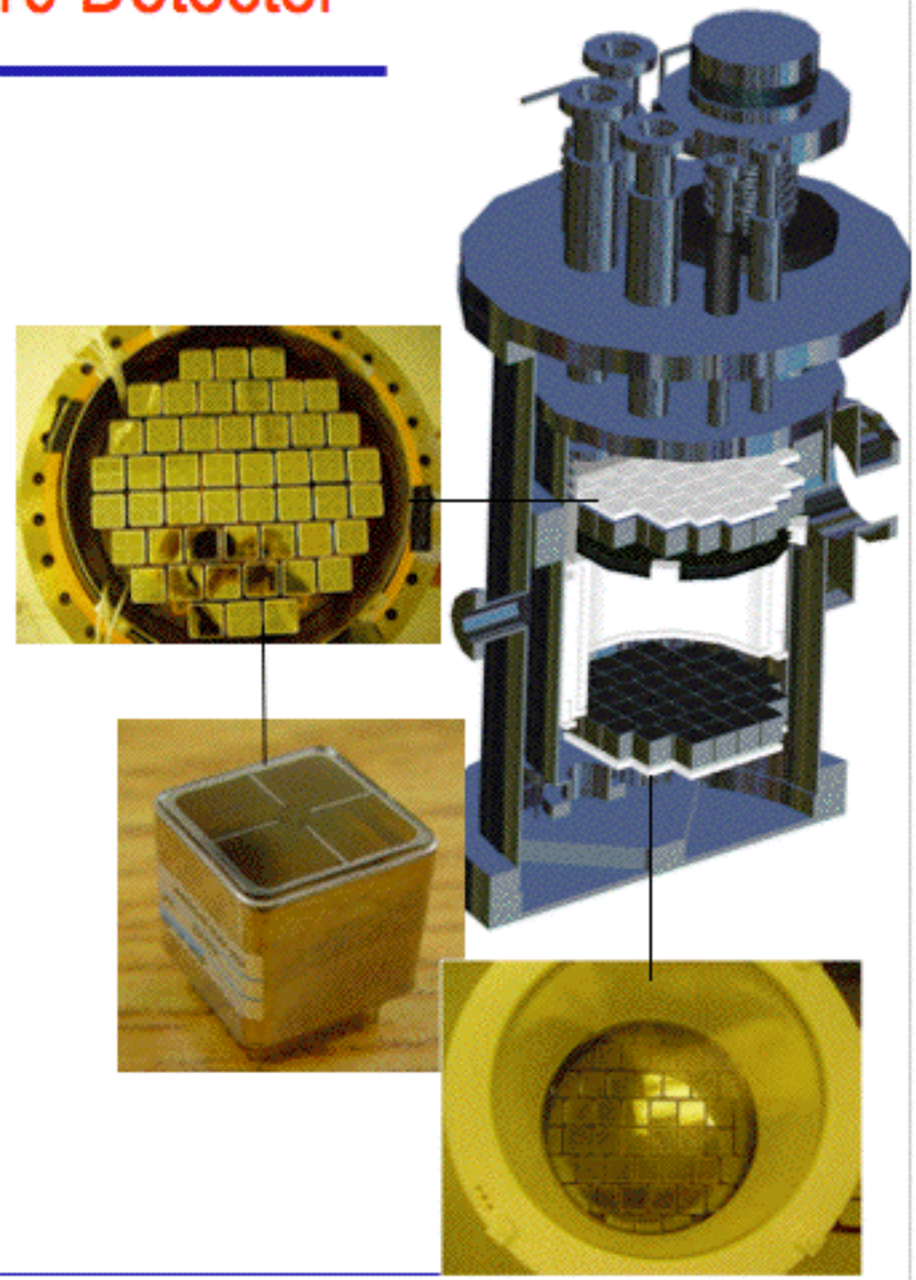
Simultaneously detect (array of UV PMTs) primary (S1) and proportional (S2) light =>
Distinctly different S2 / S1 ratio for e / n recoils provide basis for event-by-event discrimination.

Challenge: ultra pure liquid and high drift field to preserve small electron signal **(~20 electrons)**; efficient extraction into gas; efficient detection of small primary light signal **(~ 200 photons)** associated with **16 keVr**



The XENON10 Detector

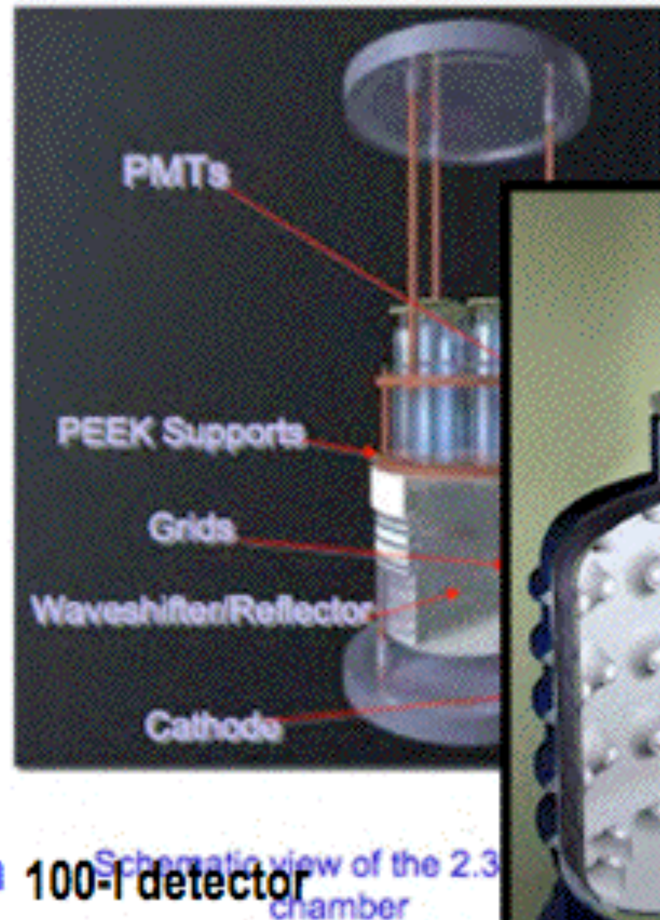
- 22 kg of liquid xenon
  - 15 kg active volume
  - 20 cm diameter, 15 cm drift
- Hamamatsu R8520 1"×3.5 cm PMTs
  - bialkali-photocathode Rb-Cs-Sb,
  - Quartz window; ok at -100ºC and 5 bar
  - Quantum efficiency > 20% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
  - x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx 1$ mm
  - z-position from Δt_{drift} ($v_{d,e^-} \approx 2$ mm/μs), $\sigma_Z \approx 0.3$ mm
- Cooling: Pulse Tube Refrigerator (PTR),
- 90W, coupled via cold finger (LN2 for emergency)



Two-phase Argon Detectors: WARP and ArDM

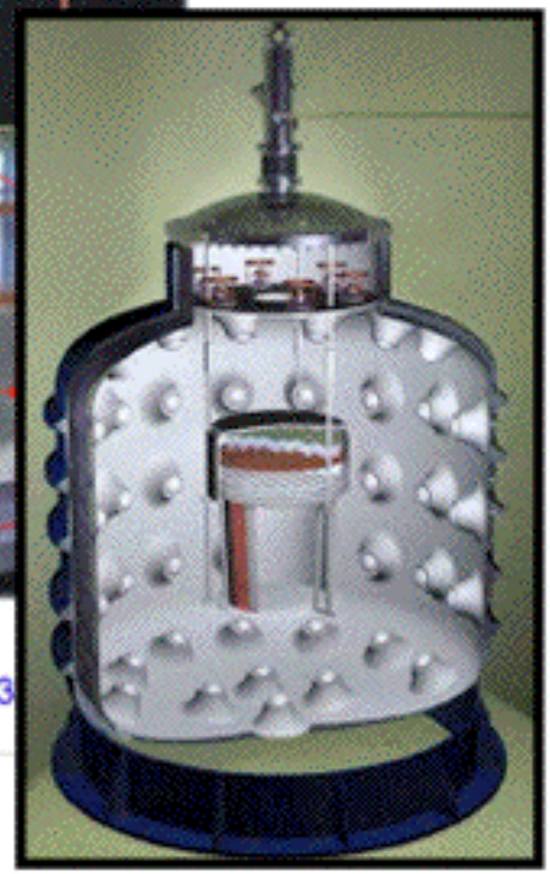
- **PSD and secondary scintillation from ionization drift**
- **WARP (Carlo Rubbia)**
  - 3.2 kg prototype running at Gran Sasso
  - Preliminary results reported
  - 140-kg detector w/800-kg active veto under construction
- **ArDM (Andre Rubbia)**
  - LEMs for ionization readout
  - PMTs for primary scintillation
  - 1 ton prototype in construction

WARP Prototype



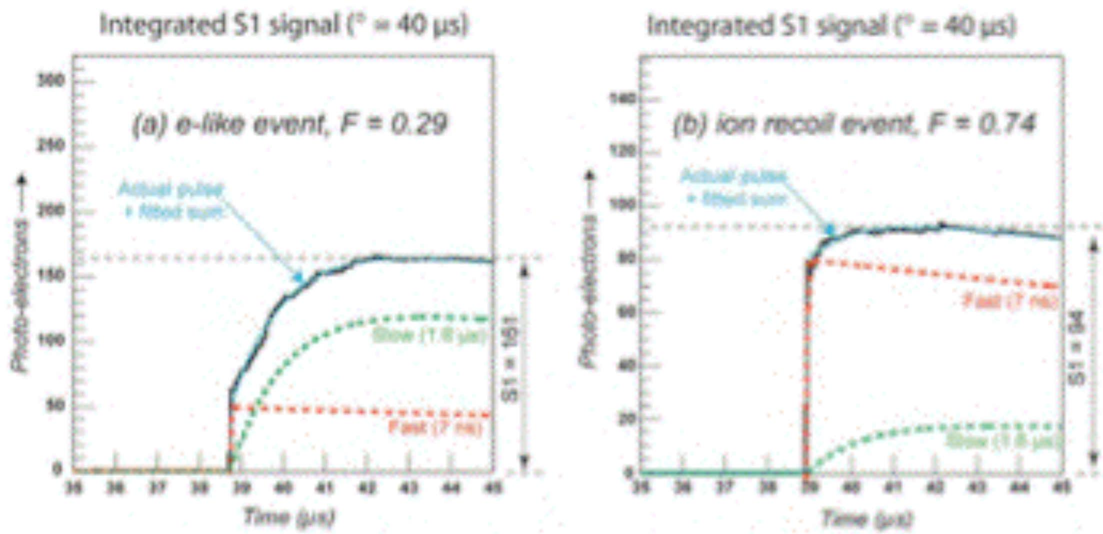
100-l detector

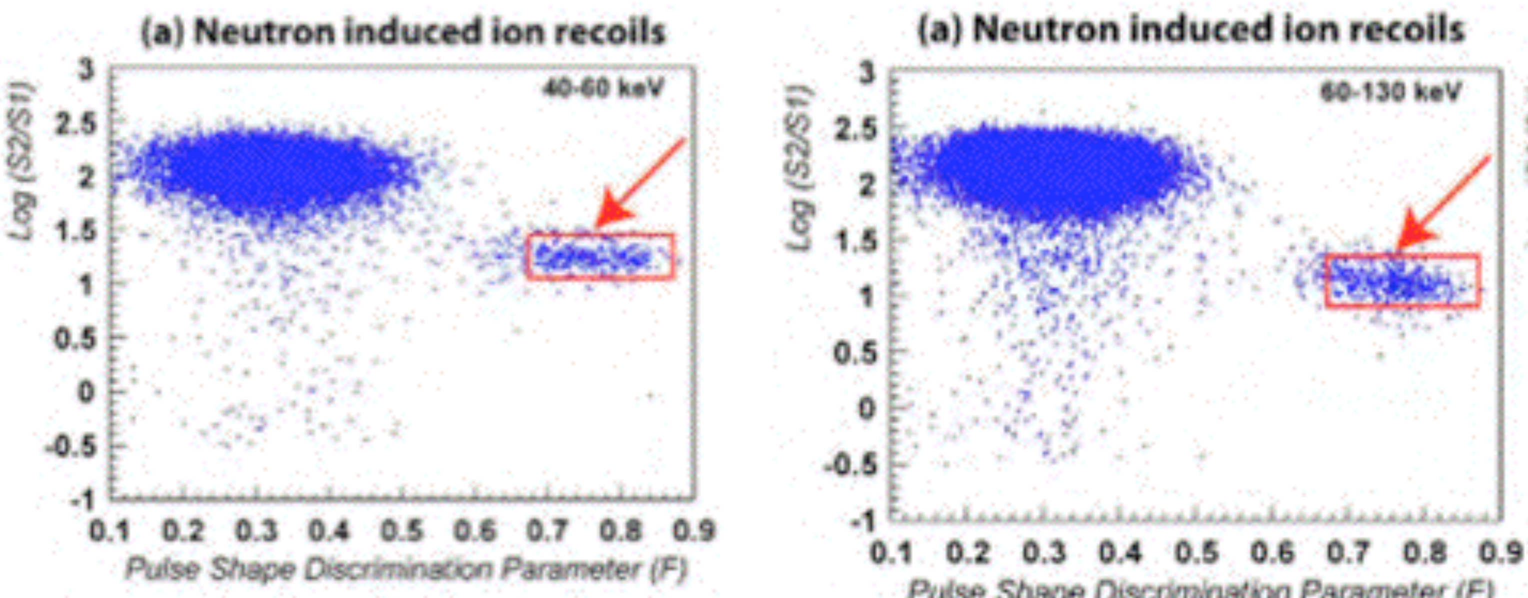
WARP



WARP - Dual Methods of Discrimination

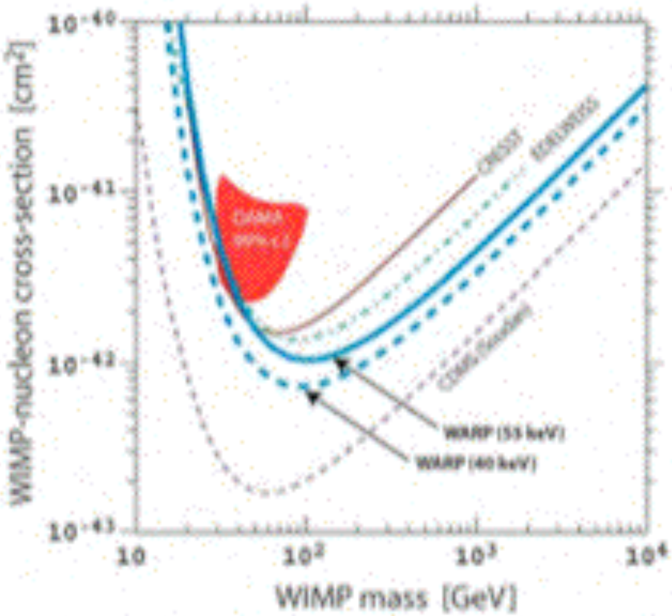
- PSD
  - Nuclear Recoil "Ion" has larger prompt component as in single phase
- S2/S1
  - Also have Ionization/ Scintilation

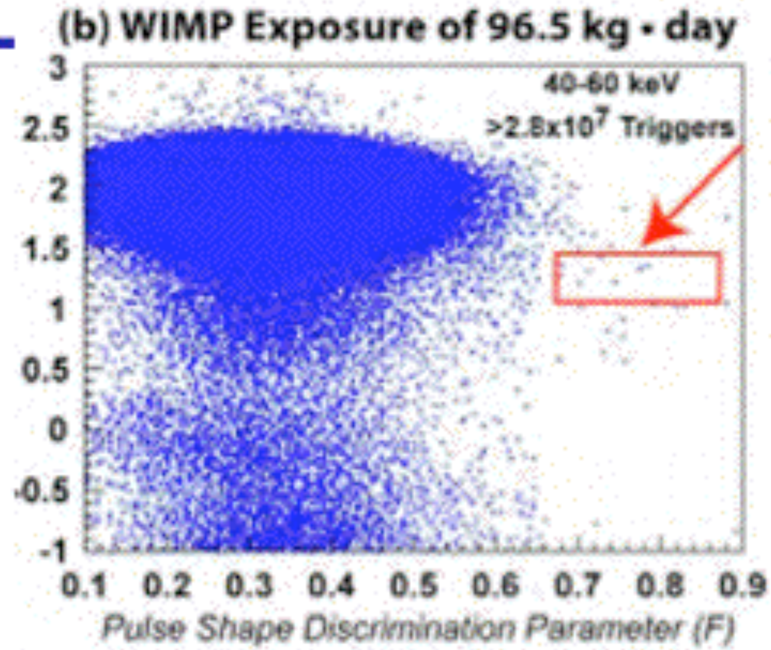


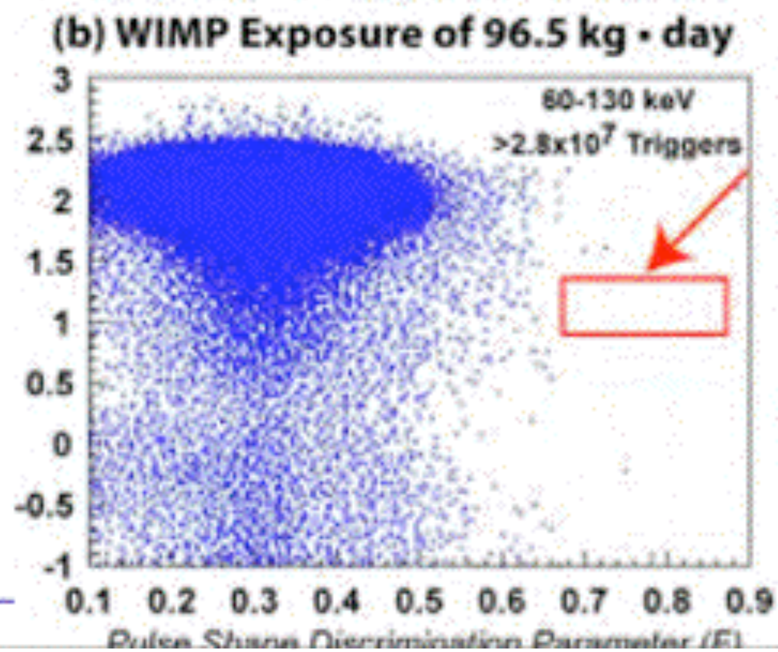


WARP Recent Results (Jan 07) astro-ph/0701286

- Analysis with no events above 55 keV (energy threshold selected a posteriori) yields limit at cyan line (5x above CDMS).
  - At this threshold energy Ar is 1/10 as sensitive to WIMPs per unit mass as Ge E>10 keV
  - The 40 keVr cyan dashed line is a simple a "what if" there were no events above 40 keVr
- Have new data run of ~50 kg-days with improved electronics - suggest that it will remove some/all of low energy events. (Announce soon)

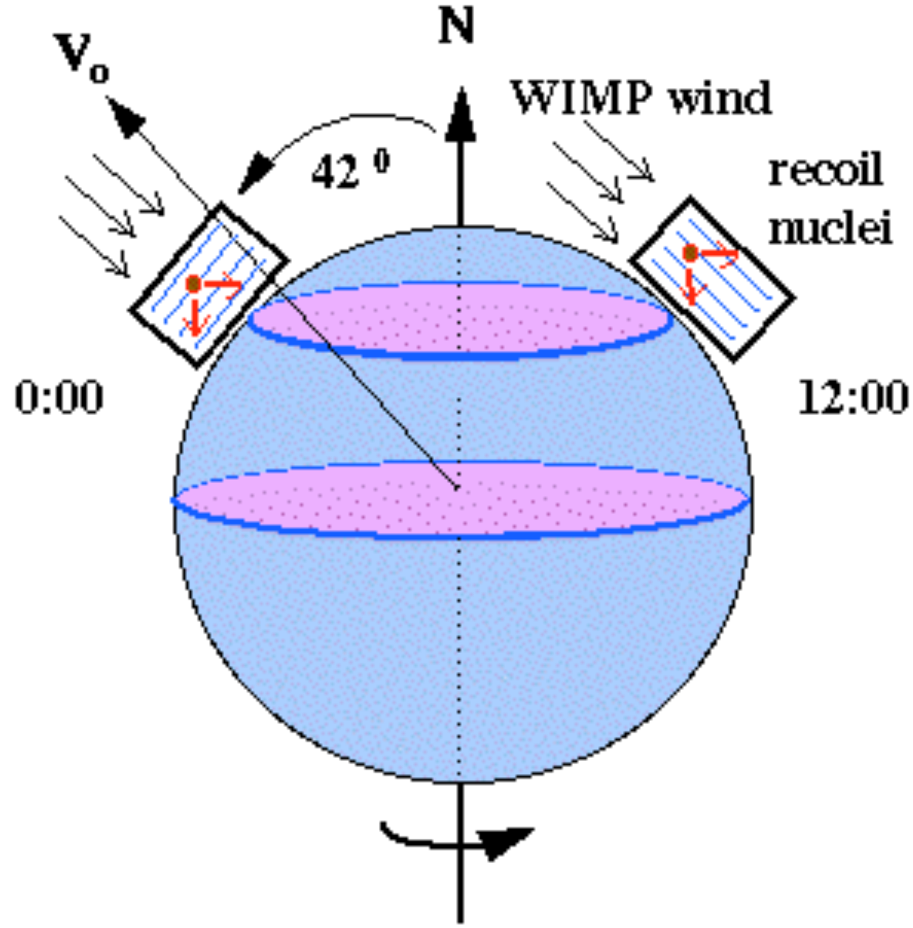






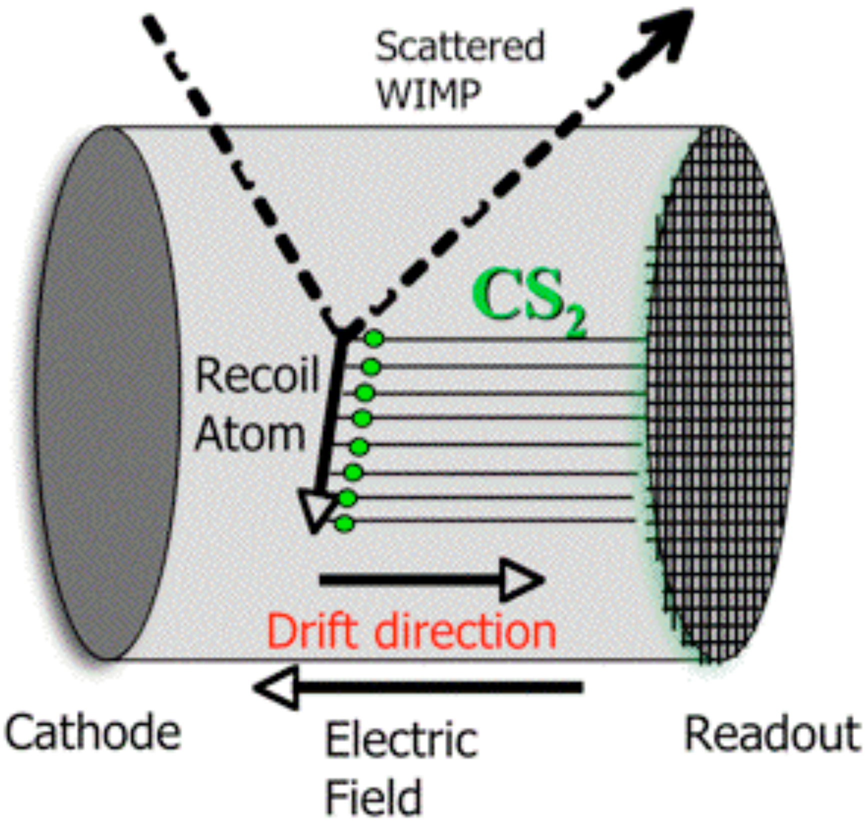
Diurnal Modulation

- Because of motion of solar system through galaxy, WIMPs are very directional in terrestrial frame (from Cygnus)
- Direction of WIMP wind varies diurnally due to Earth's rotation
- Recoiling nucleus will to a large extent preserve this directionality
- Large modulation (~ DC signal) possible in theory
- Backgrounds will be unmodulated
- Demonstrator experiment running (DRIFT), large masses still a challenge



DRIFT Time Projection Chamber

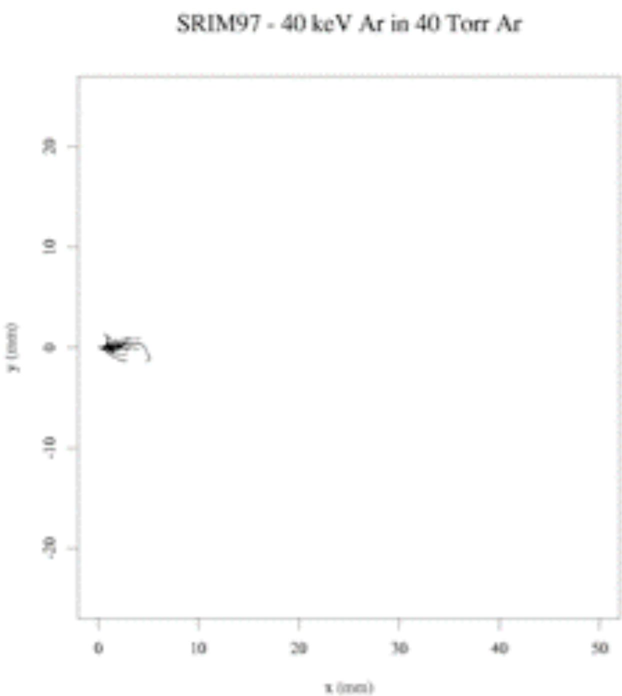
- DRIFT collaboration:
  - $e^- + CS_2 \rightarrow CS_2^-$: drifting of heavy ion suppresses charge diffusion
  - 1 m^3 40 Torr CS_2 gas (0.17 kg)
  - underground in Boulby (UK)

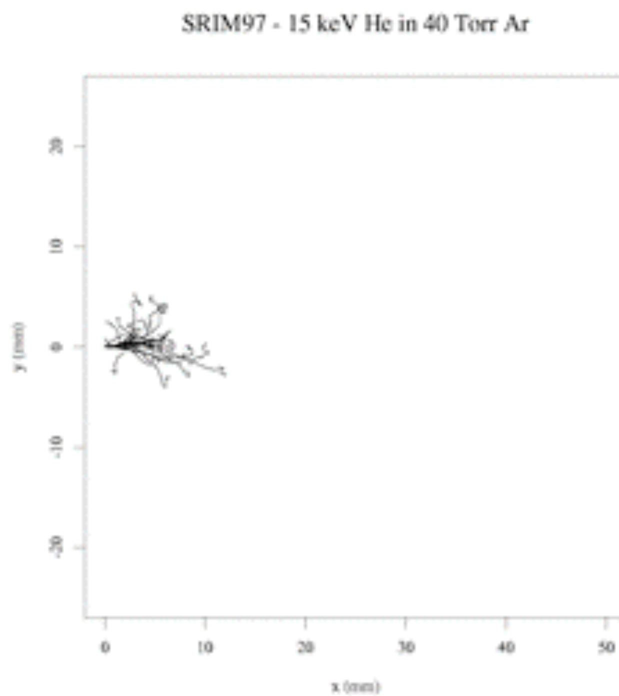


DRIFT Time Projection Chamber

Nuclear Recoils

40 keV nuclear recoils 500 electron-ion pairs	15 keV αs 500 electron-ion pairs	13 keV e^- 500 electron-ion pairs

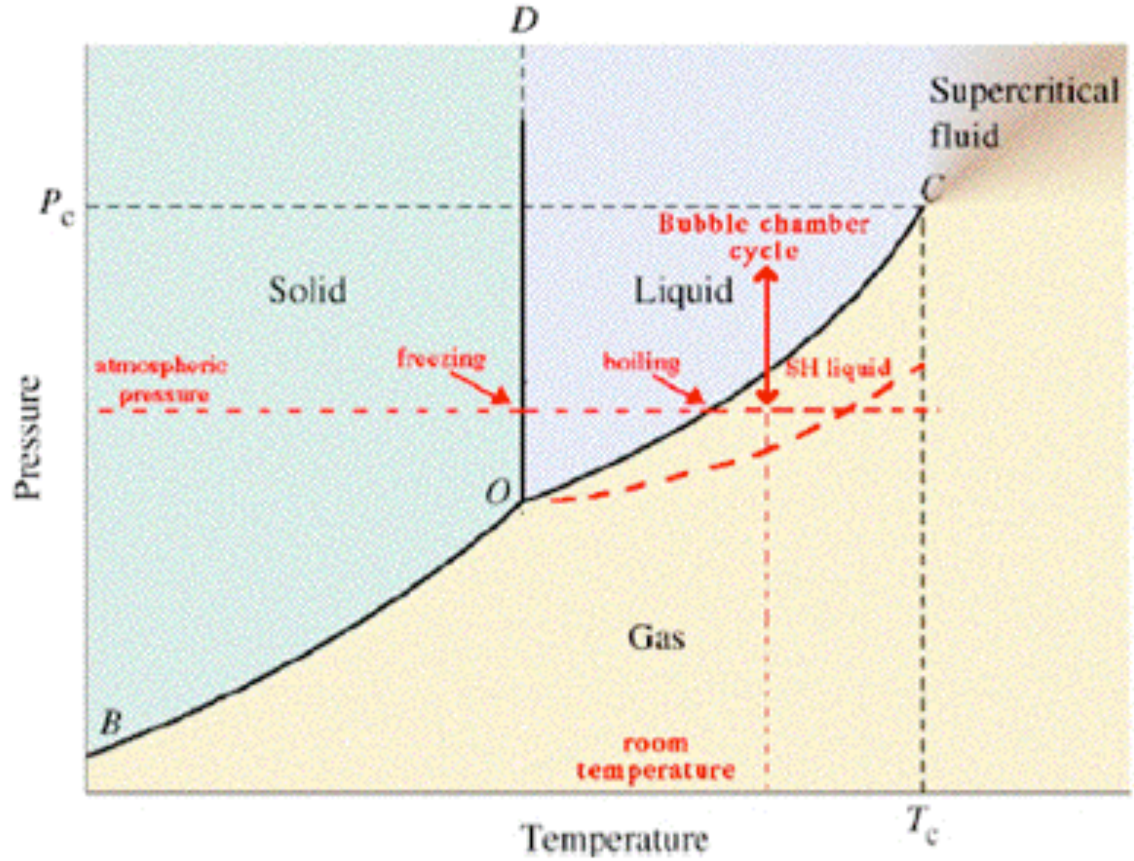




… Maybe even the direction of the recoil can be reconstructed

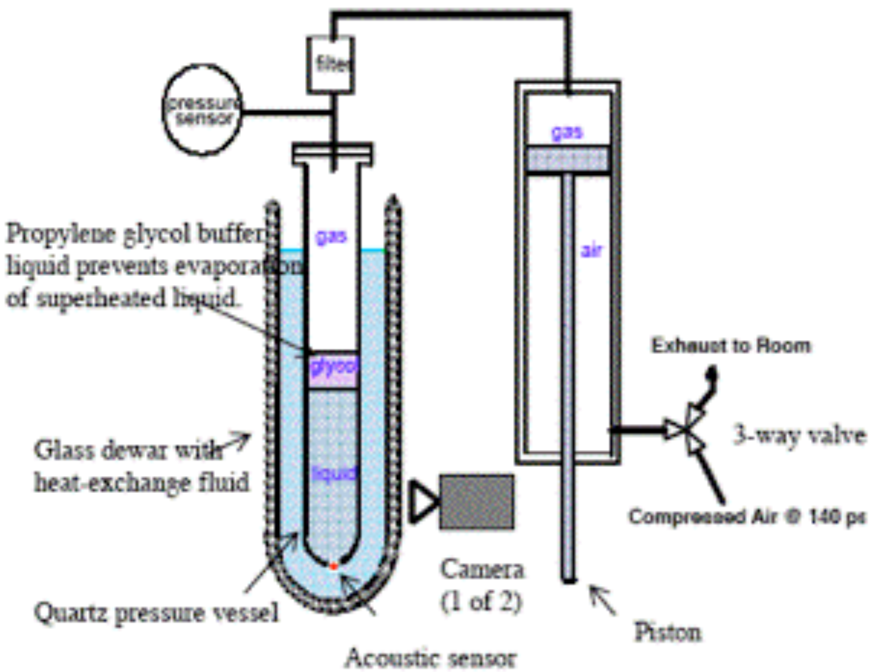
NR Discrimination in Bubble Chambers

- Superheated liquid
- Energy density effect: ER energy deposition density too small to nucleate bubbles
- Excellent rejection of ER backgrounds (lower limit of 10^9 demonstrated))
- Threshold detector, controlled by temperature & pressure

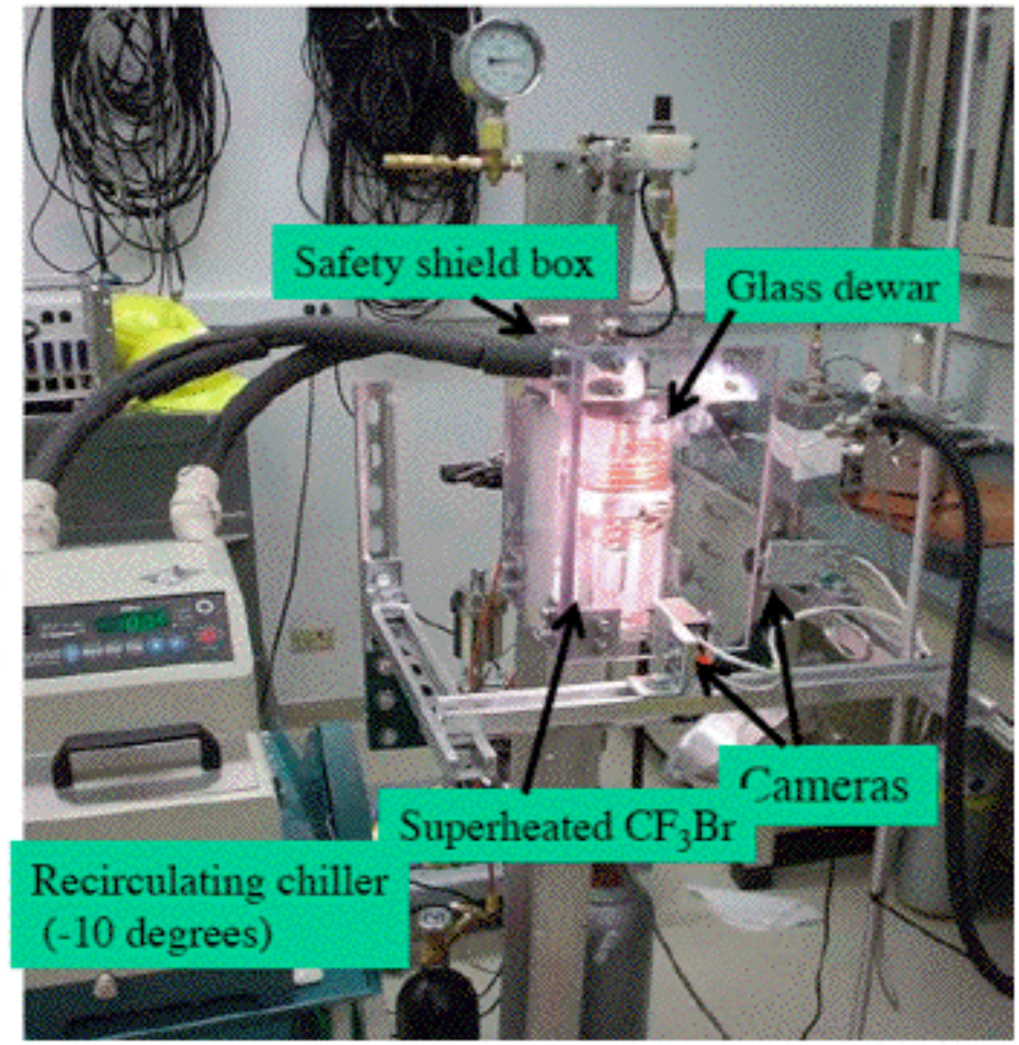


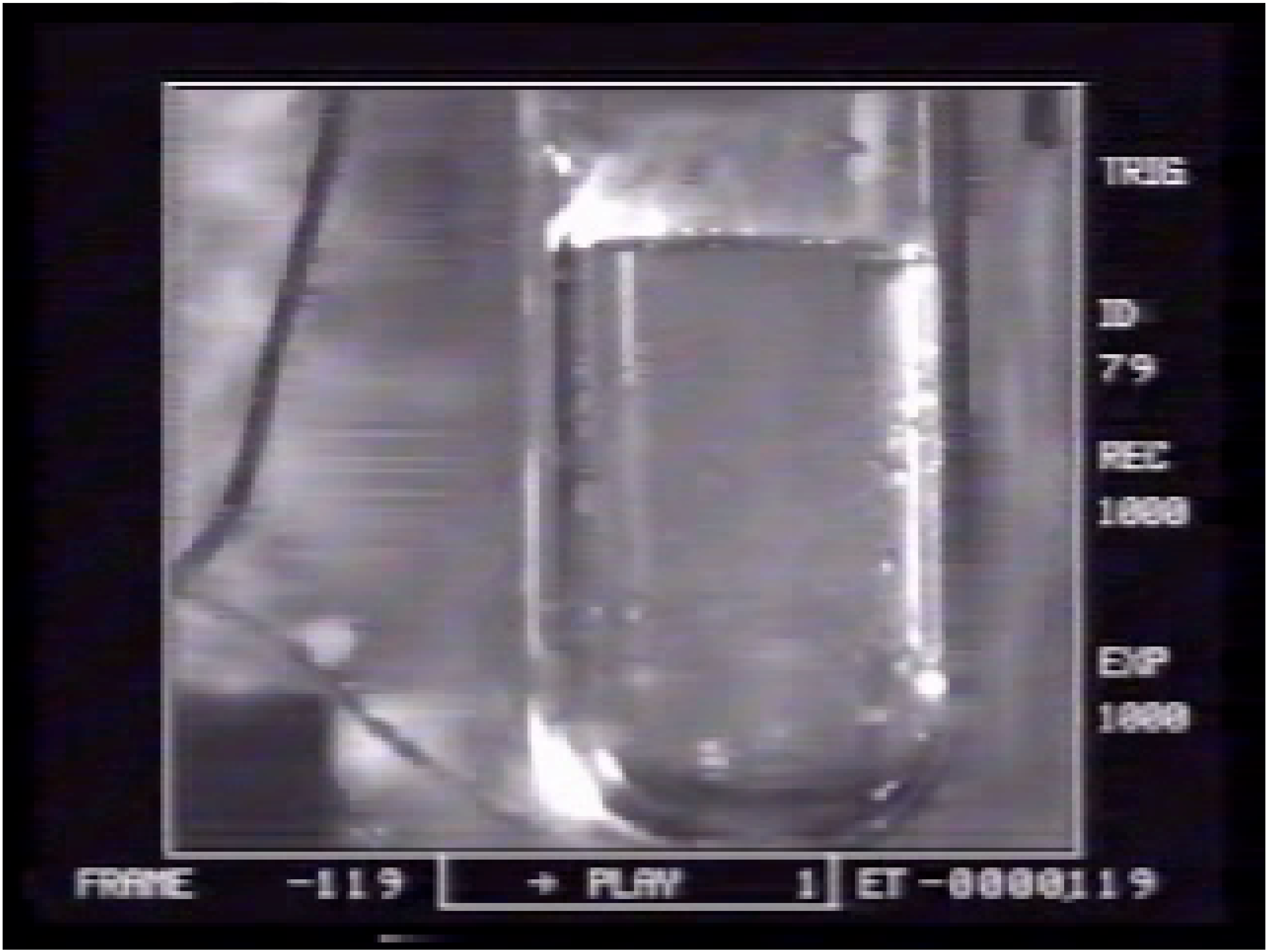
- Spin-independent (I and Br) and spin-dependent (F) targets work
- Scalable
- Many inexpensive modules to do energy scan
- COUPP: Collar (Chicago), Sonnenschein, Crisler, et al (FNAL) SIMPLE, PICASSO

NR Discrimination in Bubble Chambers



Collar group, Chicago

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CDMS

- Z(depth)-sensitive Ionization and Phonon detectors (ZIPs) measure the ionization and athermal phonon
- Six Ge (250 g each) and six Si (100 g each) ZIPs @ 50 mK

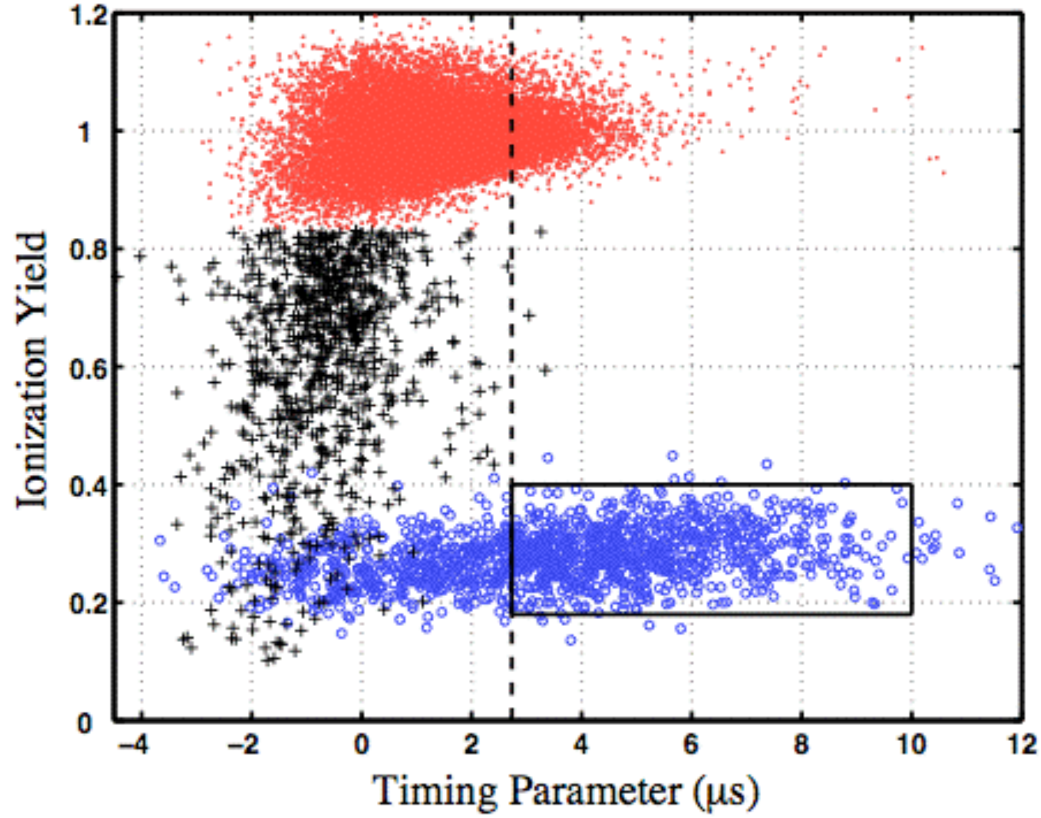


FIG. 1: Ionization yield versus timing parameter (see text) for calibration data in T2Z3(Ge), with recoil energies in the range 10–100 keV. Typical bulk-electron recoils from the ^{133}Ba source of gamma rays are dots (red), with yield near unity. Low-yield ^{133}Ba events (+, black), attributed to surface electron recoils, have small values of timing parameter, allowing discrimination from neutron-induced nuclear recoils from ^{252}Cf (∘, blue), which show a wide range of timing parameter values. The vertical dashed line shows the minimum timing parameter allowed for WIMP candidates, and the box shows the approximate signal region, which is in fact weakly energy dependent. (Color online.)

Use time delay, pulse rise time and energy distribution 'partition' to discriminate between electron and nuclear recoils

Spin dependent cross-sections

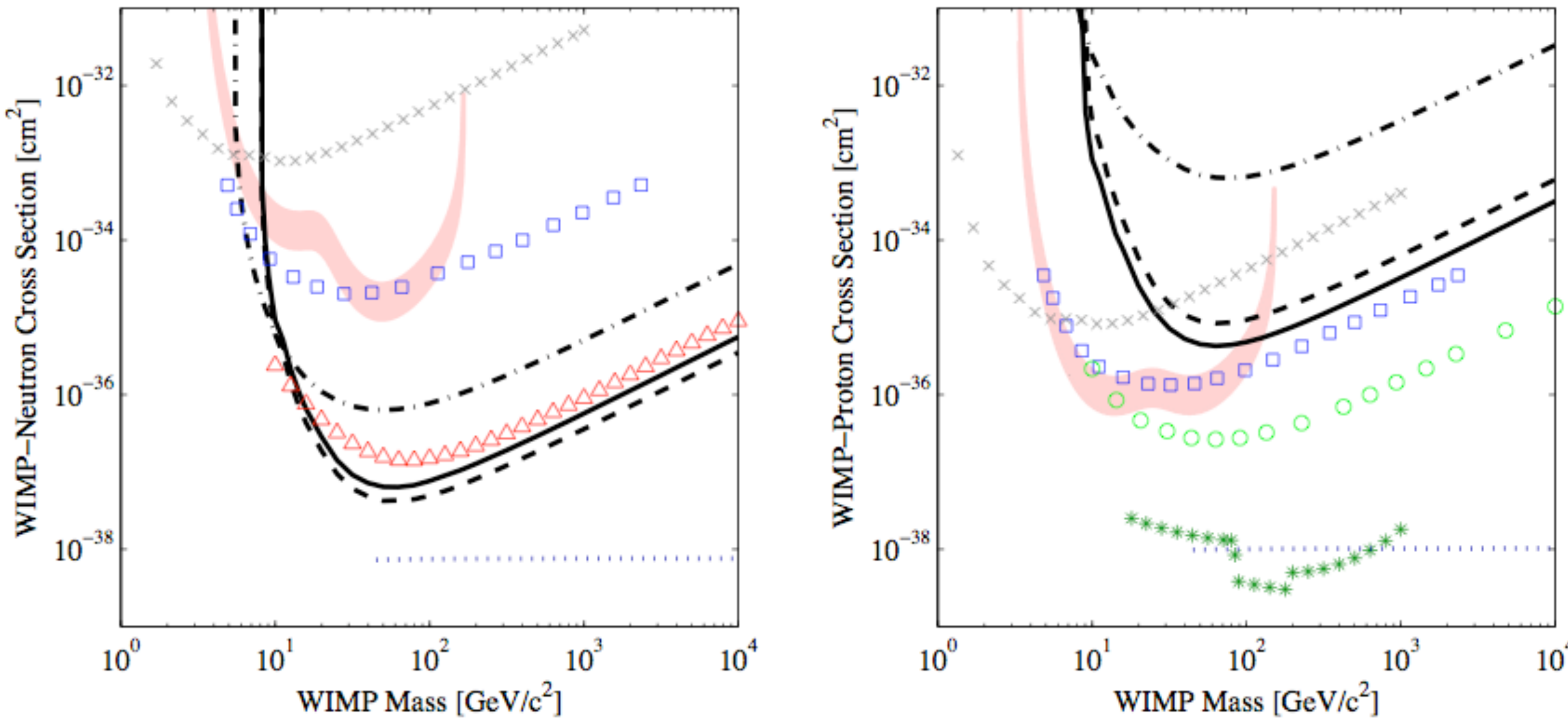
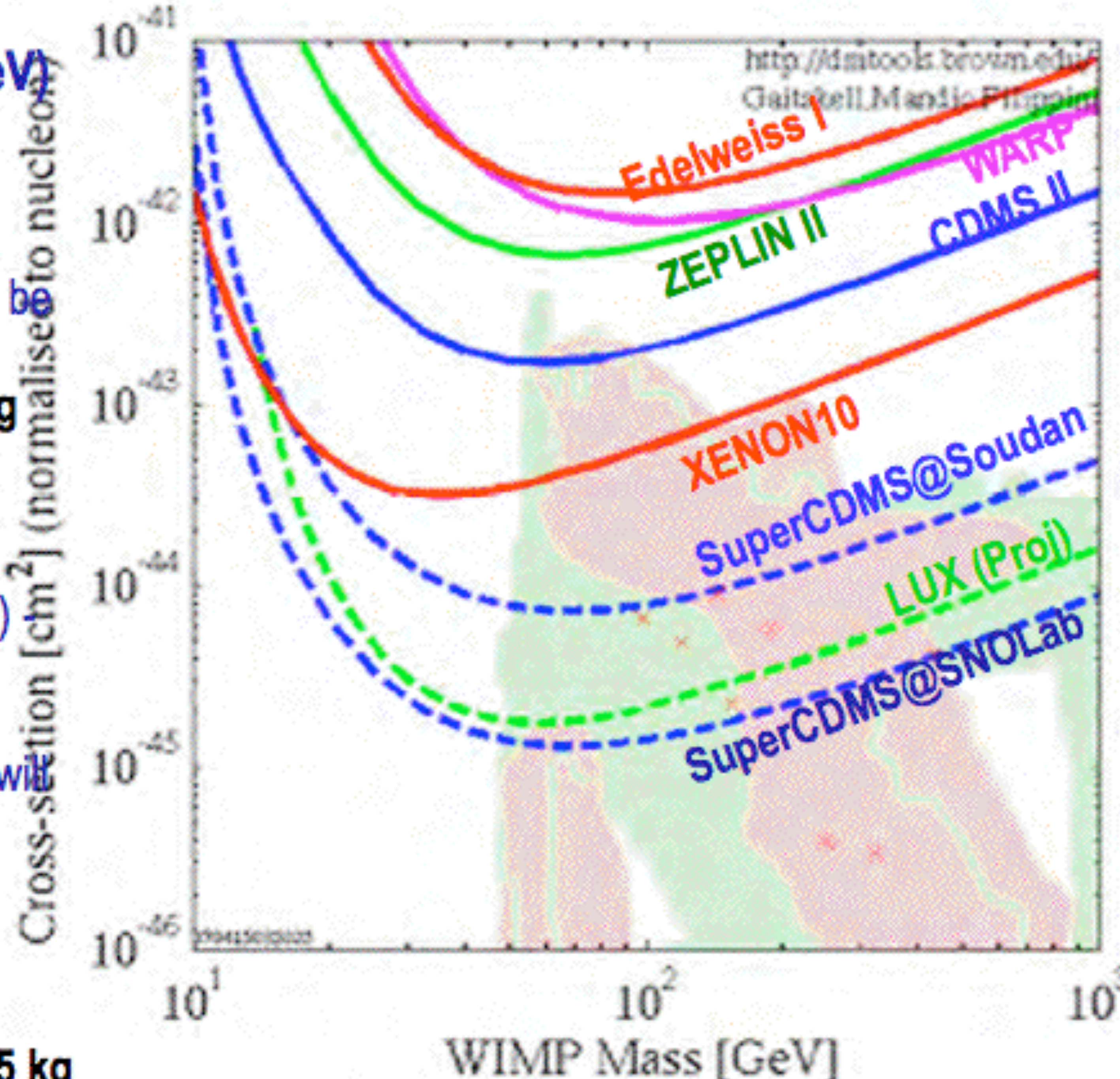


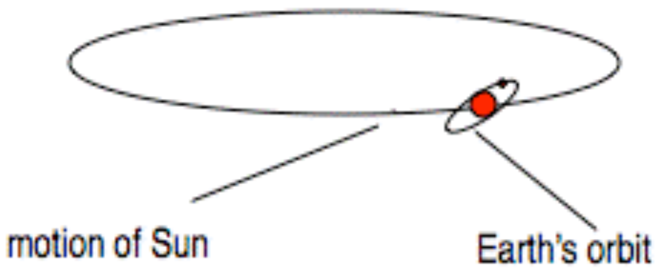
FIG. 1: Upper limit contours (90% confidence level) for recent CDMS data sets, plotted in the cases of (*left*) pure neutron and (*right*) pure proton coupling. We show limits based on Ge (solid) and Si (dash-dot) from the combined Soudan data (black). Dashed curves represent Ge limits using the alternate form factor from [15]. As benchmarks, we also include interpretations of the DAMA/NaI annual modulation signal [10] (filled regions are 3σ-allowed) and limits from other leading experiments: CRESST I [16] as computed in [11] ("×"s), PICASSO [17] (squares), NAIAD [18] (circles), ZEPLIN I [19] (triangles), and Super-Kamiokande [20] (asterisks; an indirect search, based on different assumptions). EDELWEISS [21] and SIMPLE [22] report limits (not shown for clarity) comparable to CDMS Si and PICASSO, respectively. As a theoretical benchmark (see text), horizontal dotted lines indicate expected cross sections for a heavy Majorana neutrino. Plots courtesy of [23].

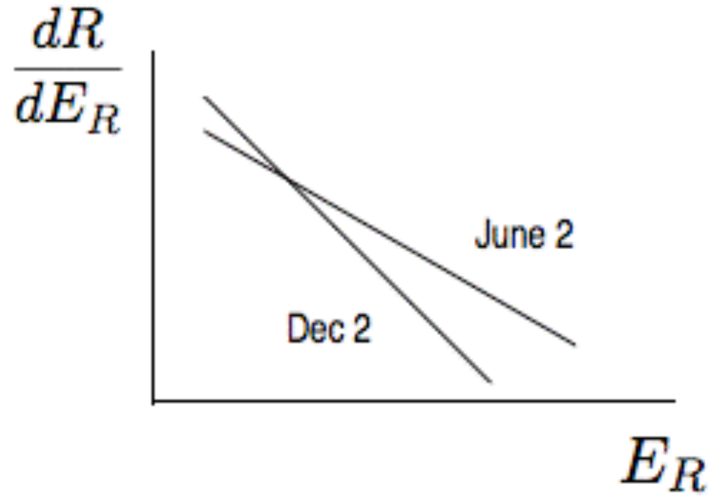


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Edelweiss I
WARP
ZEPLIN II
CDMS II
XENON10
SuperCDMS@Soudan
LUX (Proj)
SuperCDMS@SNOLab
Cross-section [cm^2] (normalised to nucleon)
WIMP Mass [GeV]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^1
10^2
10^3

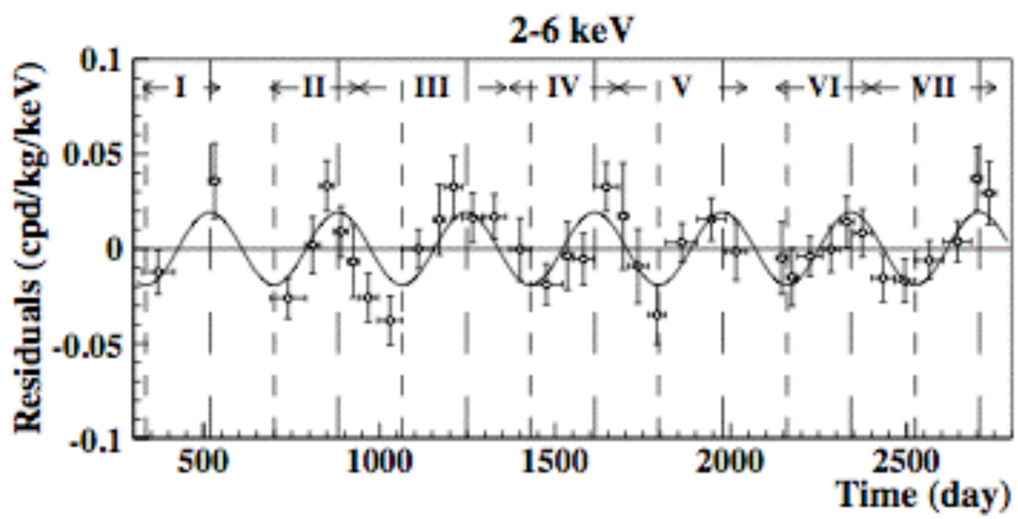
5 kg

Annual Modulation

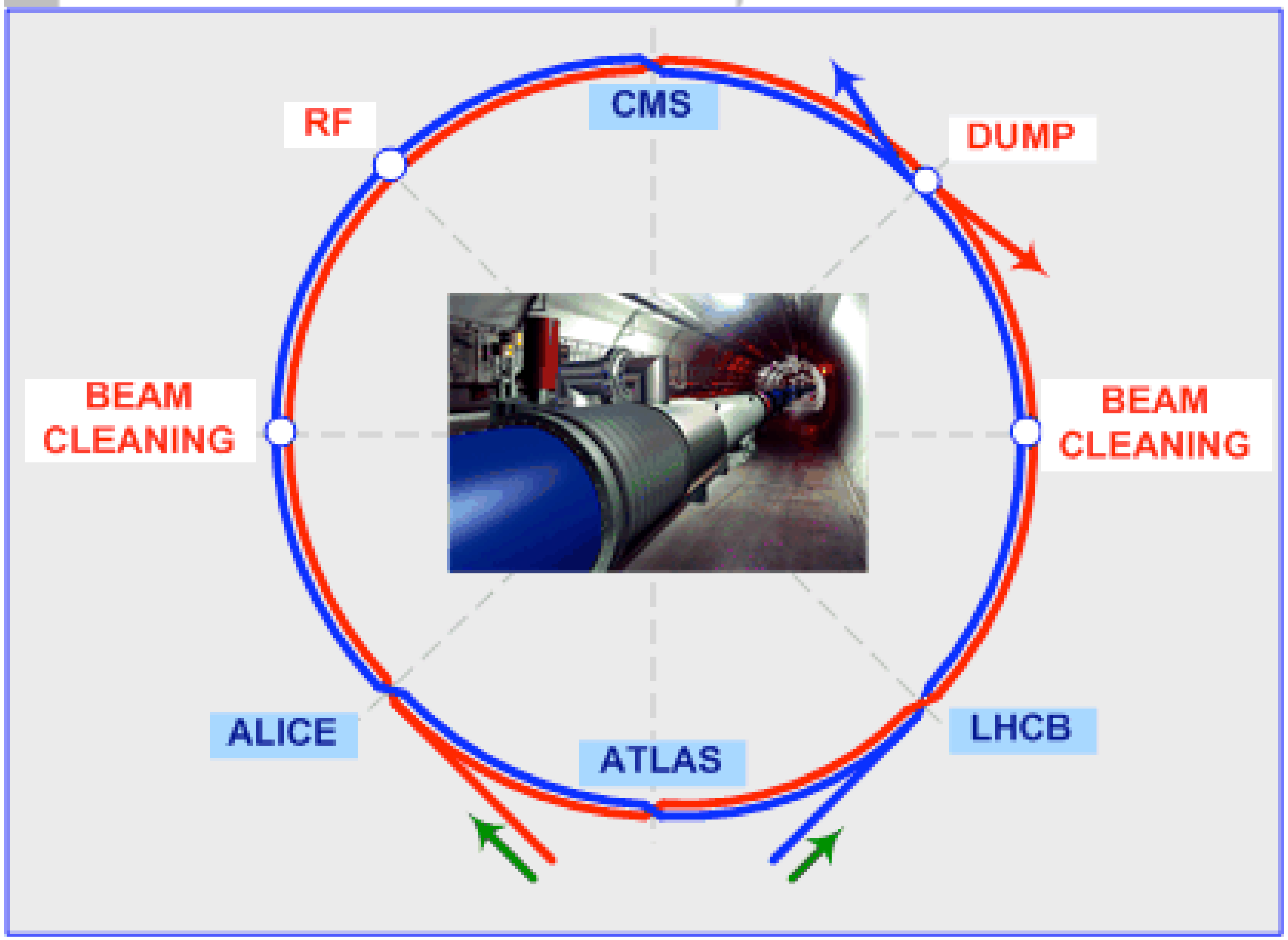




- WIMP wind ~ isotropic in halo frame, v_{rms} ~ 270 km/s
- Sun travels through this cloud at 232 km/s
- Earth adds or subtracts 15 km/s (= 30 km/s X cos 60^0) to solar velocity
- Expect ± 1-few % modulation in rate, energy deposition, depending on target and threshold
- DAMA: possible signal? Now running LIBRA



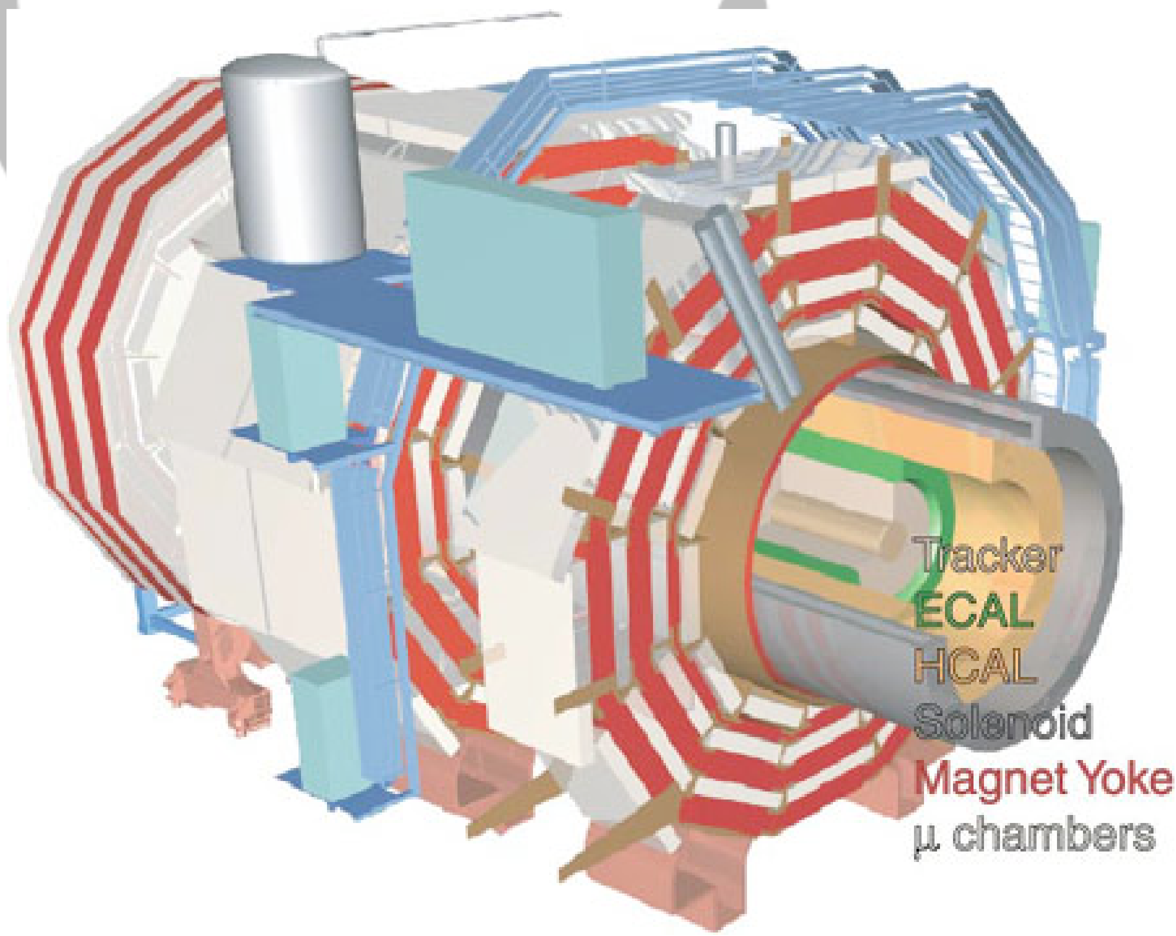
WIMPs @ accelerators



Large Hadron Collider

proton-proton collisions at CM energy of 14 Tev

Compact Muon Solenoid (CMS)

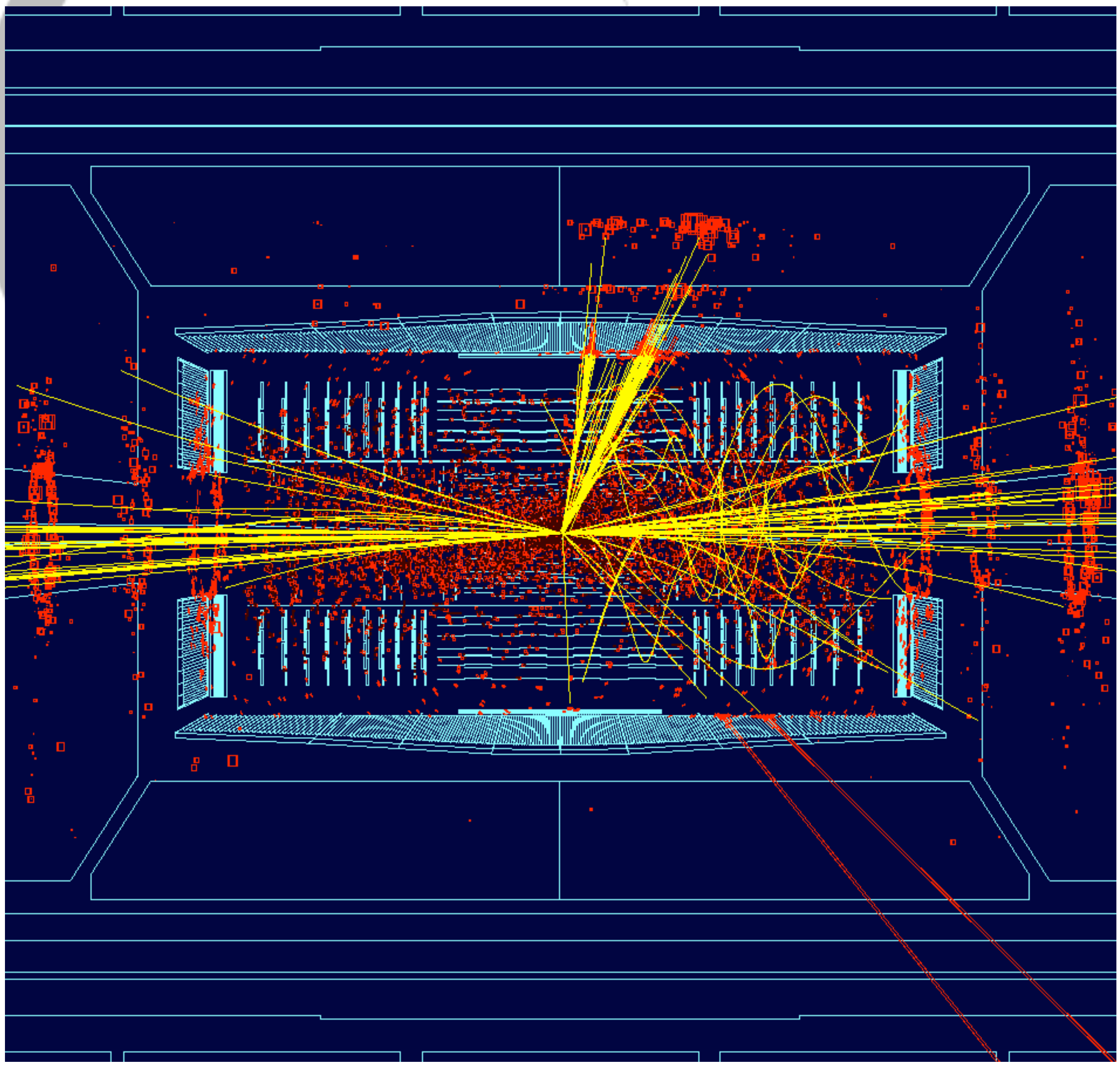


General Purpose detector designed to discover new physics at TeV scale

LSP’s @ CMS

- Must identify SUSY events from Standard Model background
- CMD candidates are stable - escape detector
- Determining LSP properties difficult

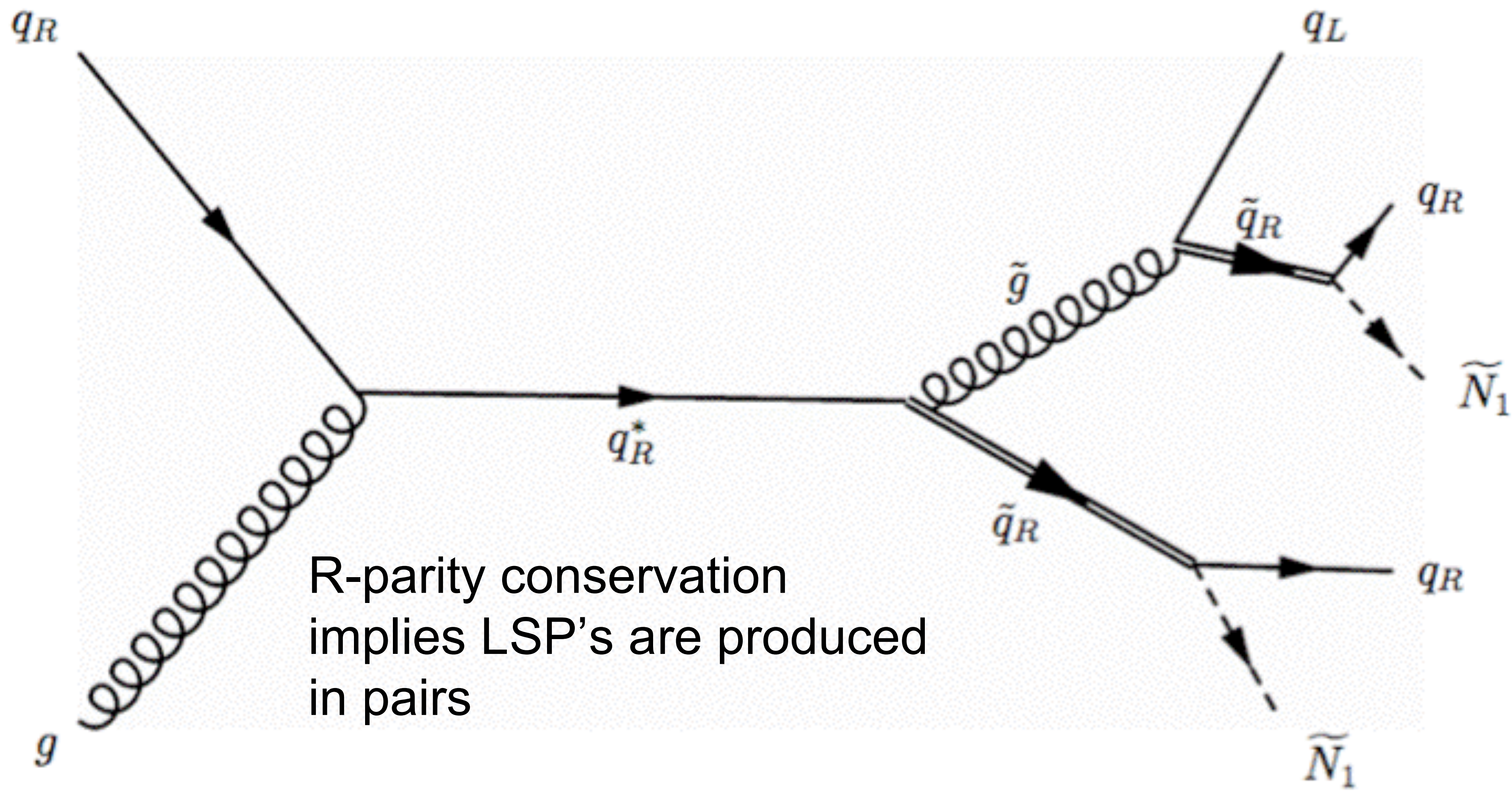
Sample CMS Event



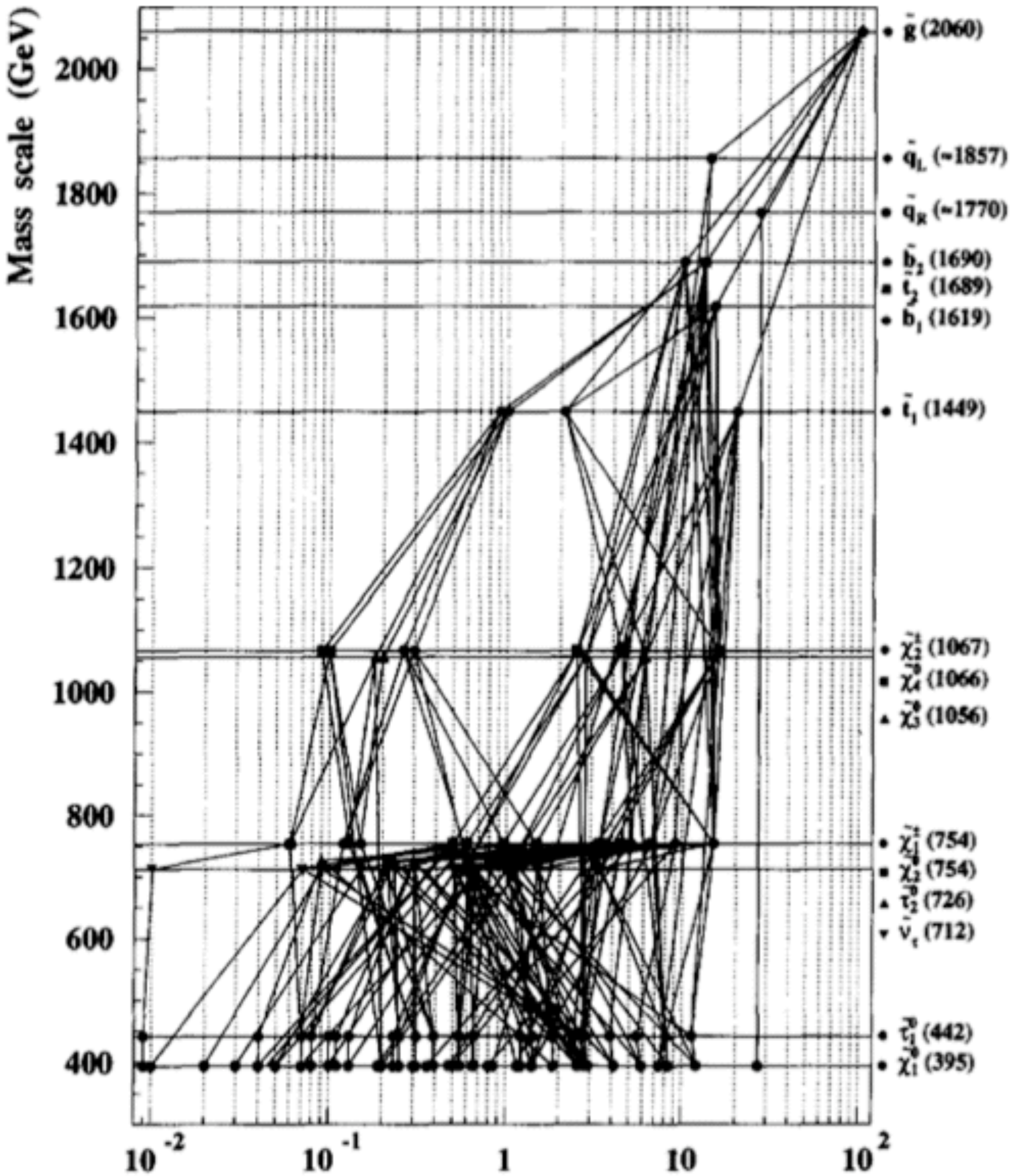
~20 ‘pile-up’ interactions per bunch crossing

LSP’s identified by identifying missing transverse energy

LSP @ CMS

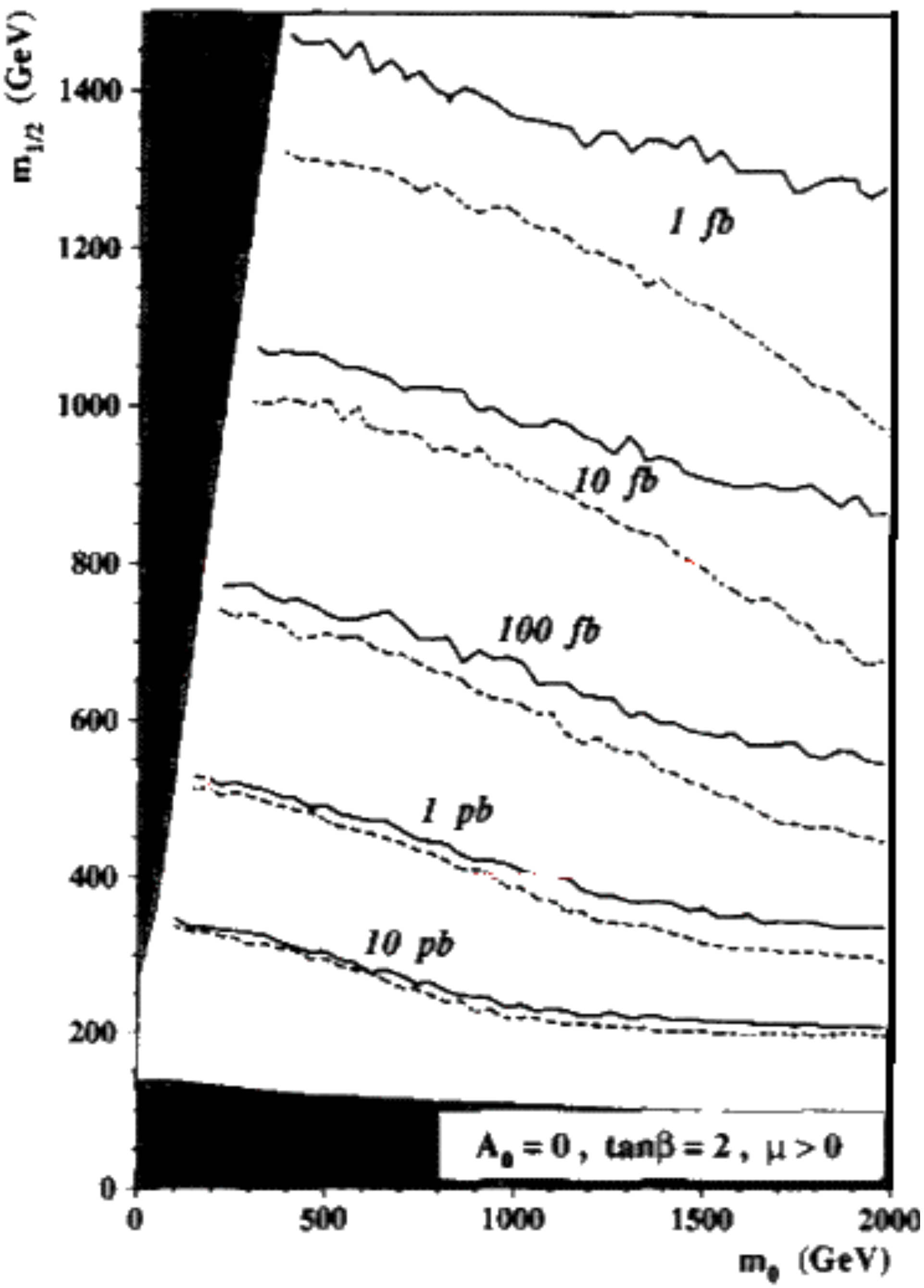


R-parity conservation implies LSP’s are produced in pairs

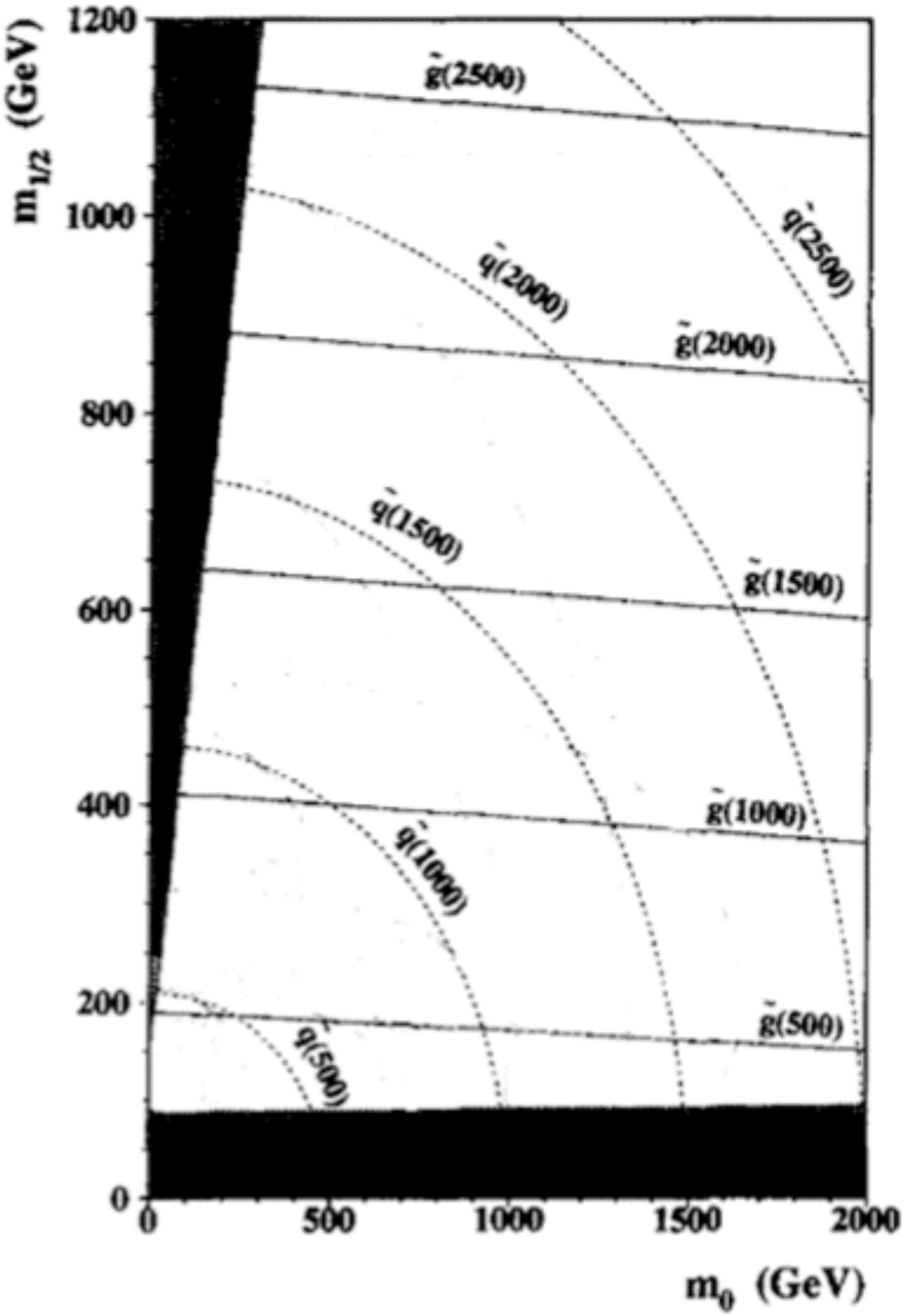


$m_0 = 400\ GeV, m_{1/2} = 900\ GeV$

R-parity conserving SUSY events feature a particle cascade to the stable LSP



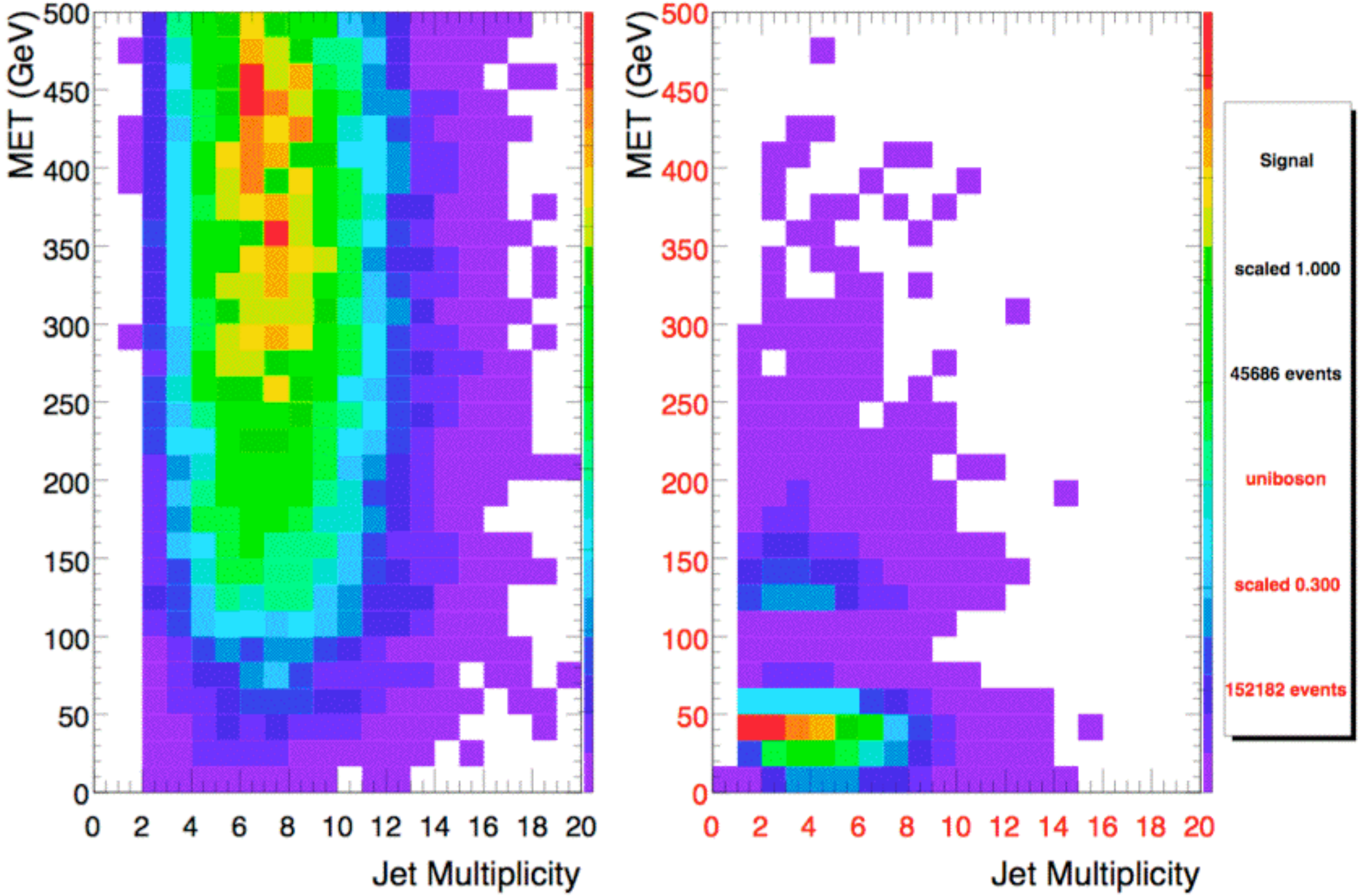
m_{1/2} (GeV)
m_0 (GeV)
1 fb
10 fb
100 fb
1 pb
10 pb
A_0 = 0, tanβ = 2, μ > 0



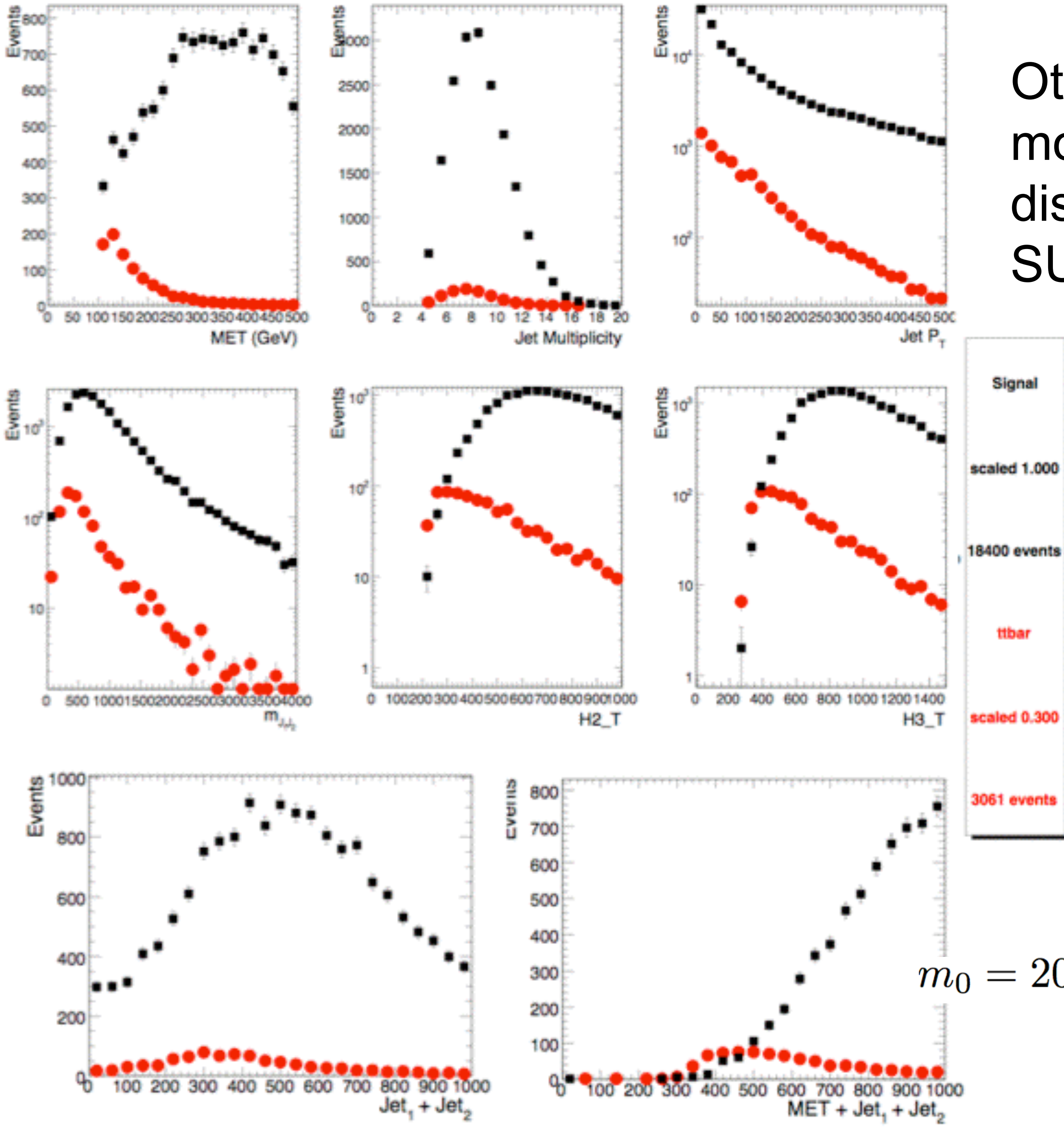
m_{1/2} (GeV)
m_0 (GeV)
g̃(2500)
g̃(2000)
g̃(1500)
g̃(1000)
g̃(500)
q̃(2500)
q̃(2000)
q̃(1500)
q̃(1000)
q̃(500)

SUSY events must be distinguished from SM background

For example, W/Z + jets



Other backgrounds more difficult to distinguish from SUSY

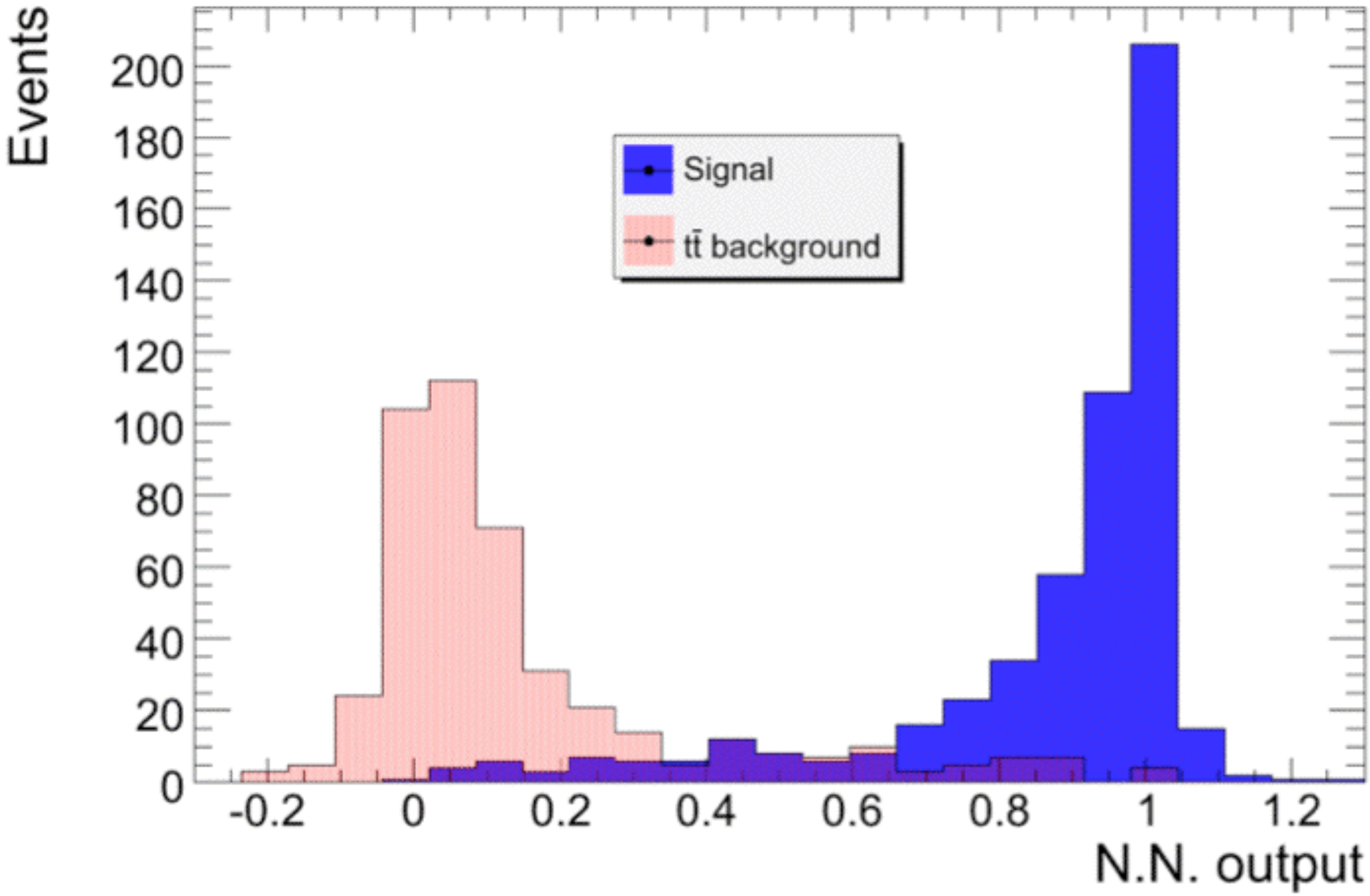


$t\bar{t}$

$m_0 = 200\ GeV, m_{1/2} = 400\ GeV$

Variable	Description	Background NN	
		$t\bar{t}$	SUSY
Individual object kinematics			
0. p_T(jet1)	Transverse momentum of the leading jet	√	-
1. p_T(jet2)	Transverse momentum of second jet	√	-
2. E_T^{miss}	Missing transverse energy	√	-
3. η_{jet1}	Rapidity of leading jet	-	√
4. η_{jet2}	Rapidity of second jet	-	√
Global event kinematics			
5. M(alljets)	Invariant mass of four leading jets	√	√
6. H(alljets)	Sum of energies of four leading jets	√	√
7. H_T(alljets)	Sum of transverse energies of four leading jets	√	√
8. M_T(jet1,jet2)	Transverse mass of 2 leading jets	√	√
9. M_T(jet1,jet2,E_T^{miss})	Transverse mass of 2 leading jets and E_T^{miss}	√	√
10. M_T(jet1,E_T^{miss})	Transverse mass of leading jet and E_T^{miss}	-	√
11. H_T^1	$p_{T(1)} + E_T^{miss}$	√	-
12. H_T^2	$p_{T(1)} + p_{T(2)} + E_T^{miss}$	√	√
13. H_T^3	$p_{T(1)} + p_{T(2)} + p_{T(3)} + E_T^{miss}$	-	√
14. H_T^4	$p_{T(1)} + p_{T(2)} + p_{T(3)} + p_{T(4)} + E_T^{miss}$	√	√
15. N_{jets}	Jet multiplicity	-	-
Angular variables			
16. ΔR(jet1,jet2)	Angular separation between leading two jets	-	√
17. ΔR(jet1,E_T^{miss})	Angular separation between leading jet and E_T^{miss}	-	√
18. ΔR(jet2,E_T^{miss})	Angular separation between second jet and E_T^{miss}	-	-

Neural networks, with kinematic variables as inputs, can be trained to distinguish between signal and background events



Cuts on neural network output selects SUSY events

Outlook

- WIMPs(potenitally the lightest neutralino) are appealing CDM candidates
- Through direct and accelerator searches we continue to look for WIMPs